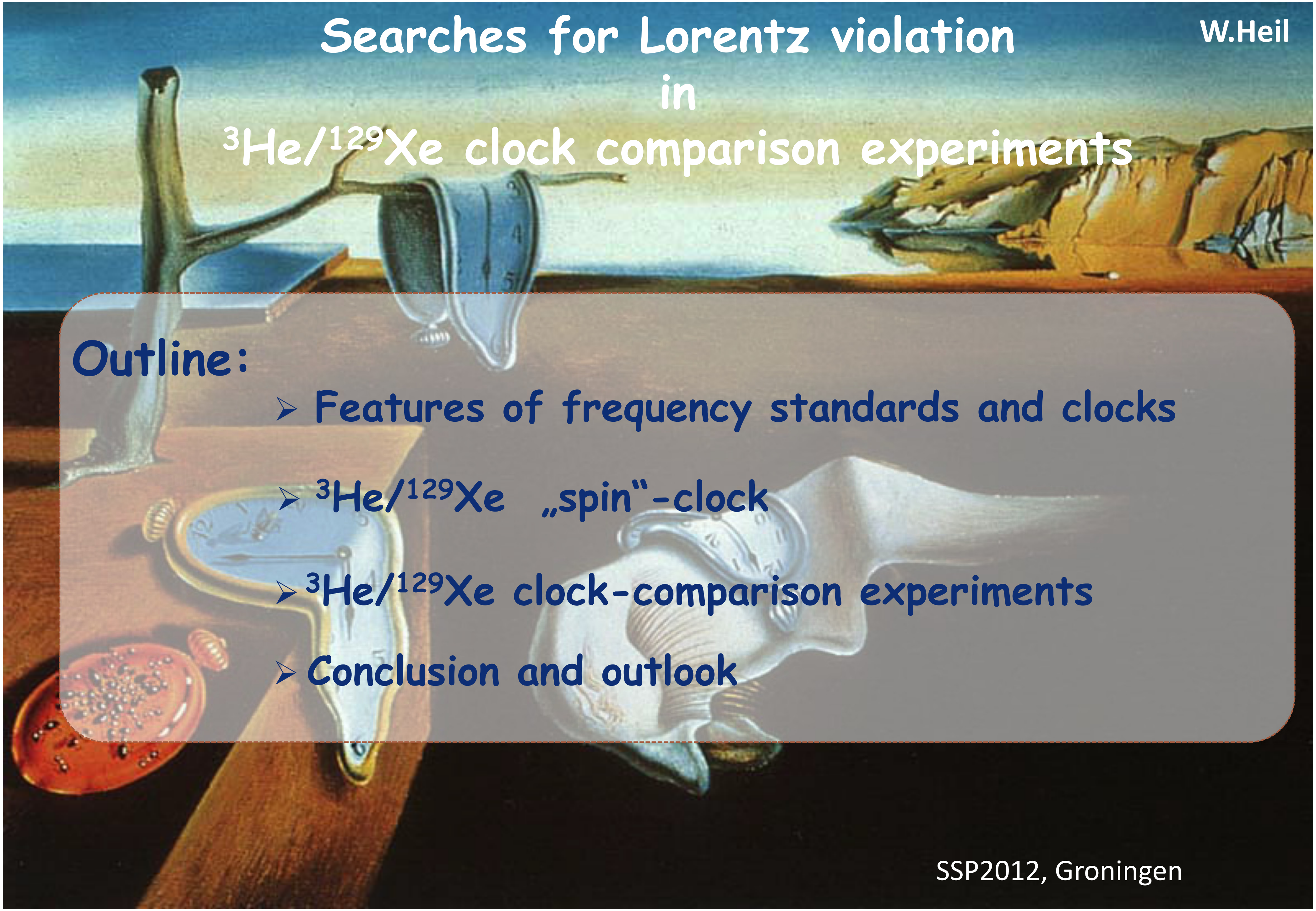


Searches for Lorentz violation in ^{3}He/^{129}Xe clock comparison experiments

W.Heil

Outline:

- Features of frequency standards and clocks
- ^{3}He/^{129}Xe „spin"-clock
- ^{3}He/^{129}Xe clock-comparison experiments
- Conclusion and outlook

SSP2012, Groningen

Atomic Clocks

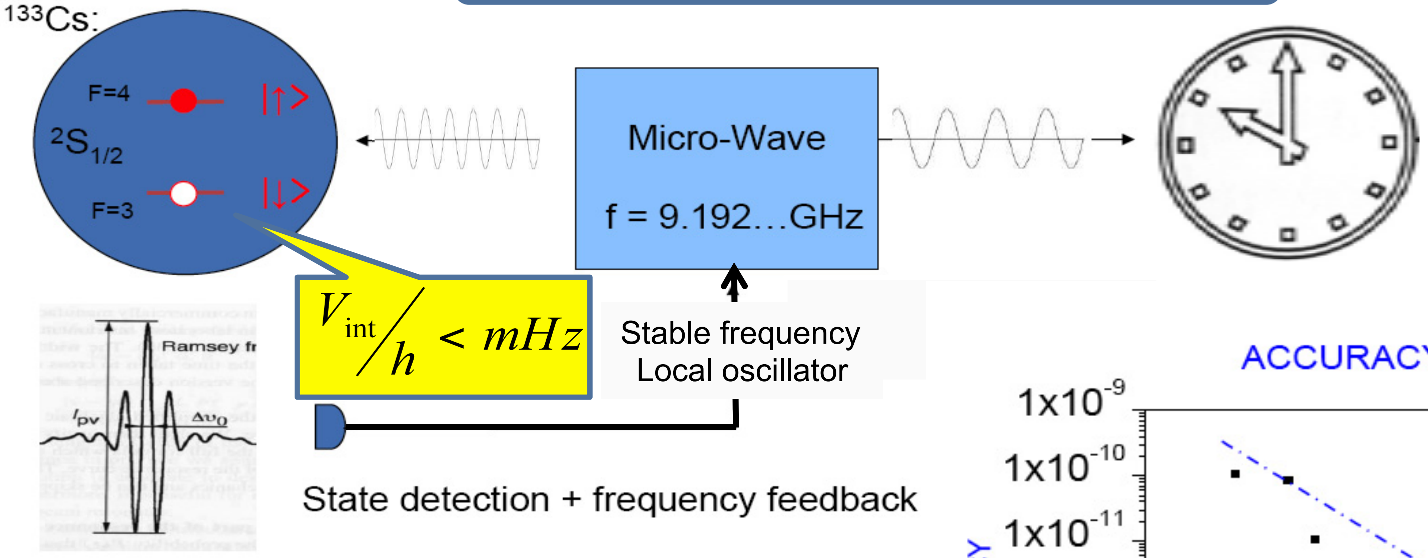
Oscillator + Frequency divider + Counter

$6S_{1/2}$: $F=3, m_F=0 \leftrightarrow F=4, m_F=0$

@ ν = 9.192 … GHz

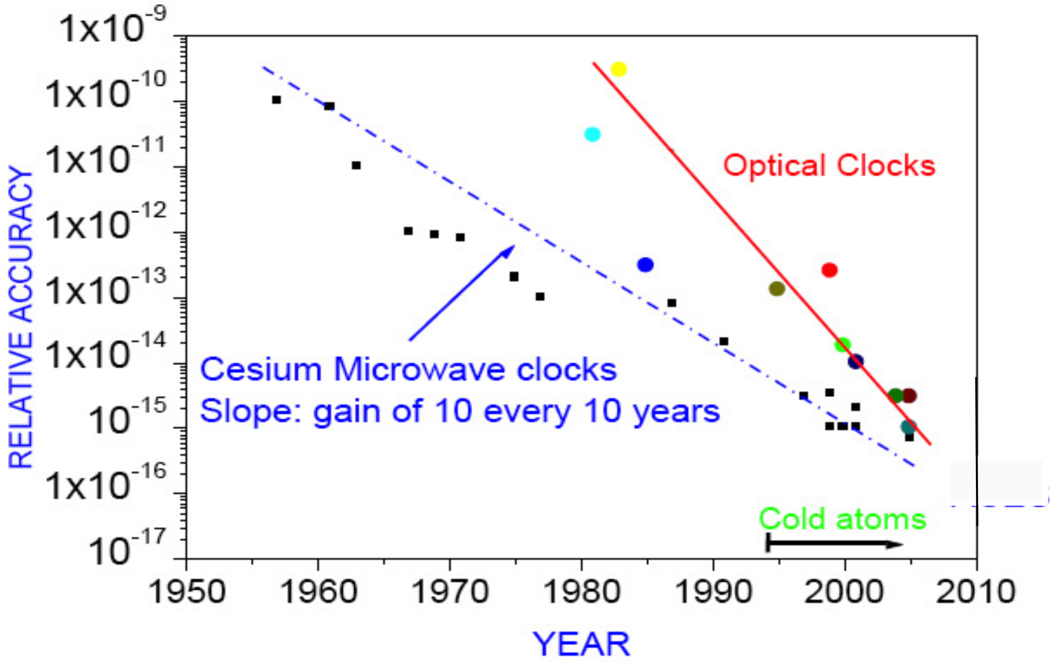
1 second = 9,192, 631,770 cycles

Current accuracy:
Microwave: 6×10^{-16}
Optical : 3×10^{-17}



≈ 1 ns / day

ACCURACY OF THE ATOMIC TIME



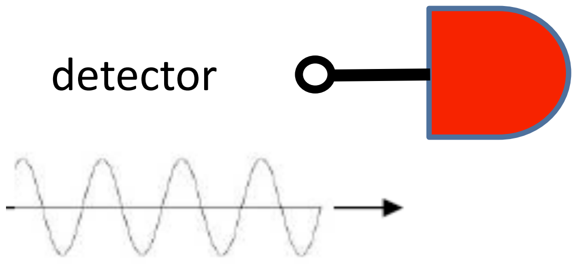
sensitivity (absolute scale): $\delta\nu \approx$ mHz

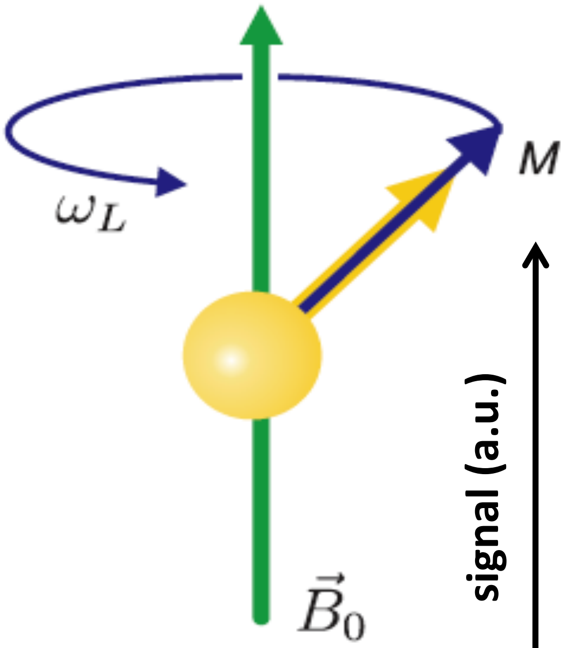
better:
reference transition at f ≈ 1 Hz with
$\delta f / f \approx 10^{-14}$

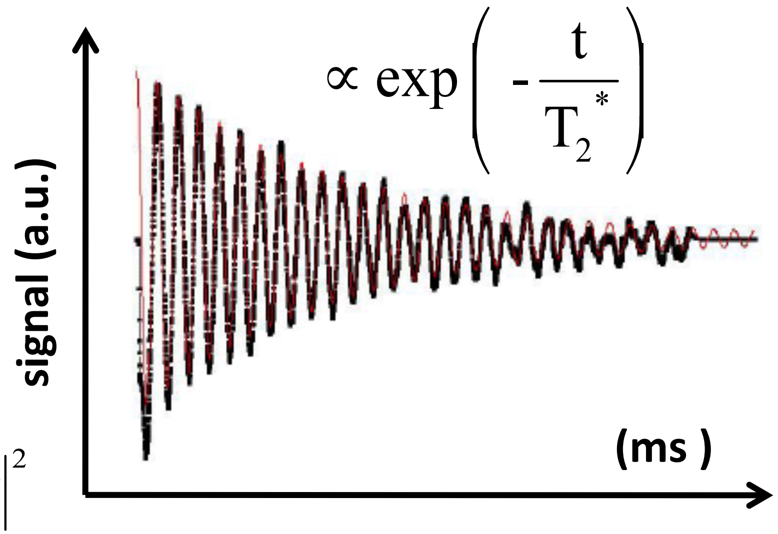
⇒ „nuclear spin -clock“

Clock based on nuclear spin precession „ spin-clock“

A magnetic moment *M* is associated with the atomic spin.







(G. D. Cates, et al., Phys. Rev. A 37, 2877)

$$\frac{1}{T_2^*}=\frac{1}{T_1}+\frac{1}{T_{2,\text{field}}}$$

$$\frac{1}{T_{2,\text{field}}}\approx\frac{4R^4\gamma^2}{175D}\left(\left|\vec{\nabla}B_{1,z}\right|^2+\left|\vec{\nabla}B_{1,y}\right|^2+2\left|\vec{\nabla}B_{1,x}\right|^2\right)\propto R^4\cdot p\cdot\left|\vec{\nabla}B\right|^2$$

$T_1 > 100\,\text{h} \Longrightarrow$

Long T_2^* :

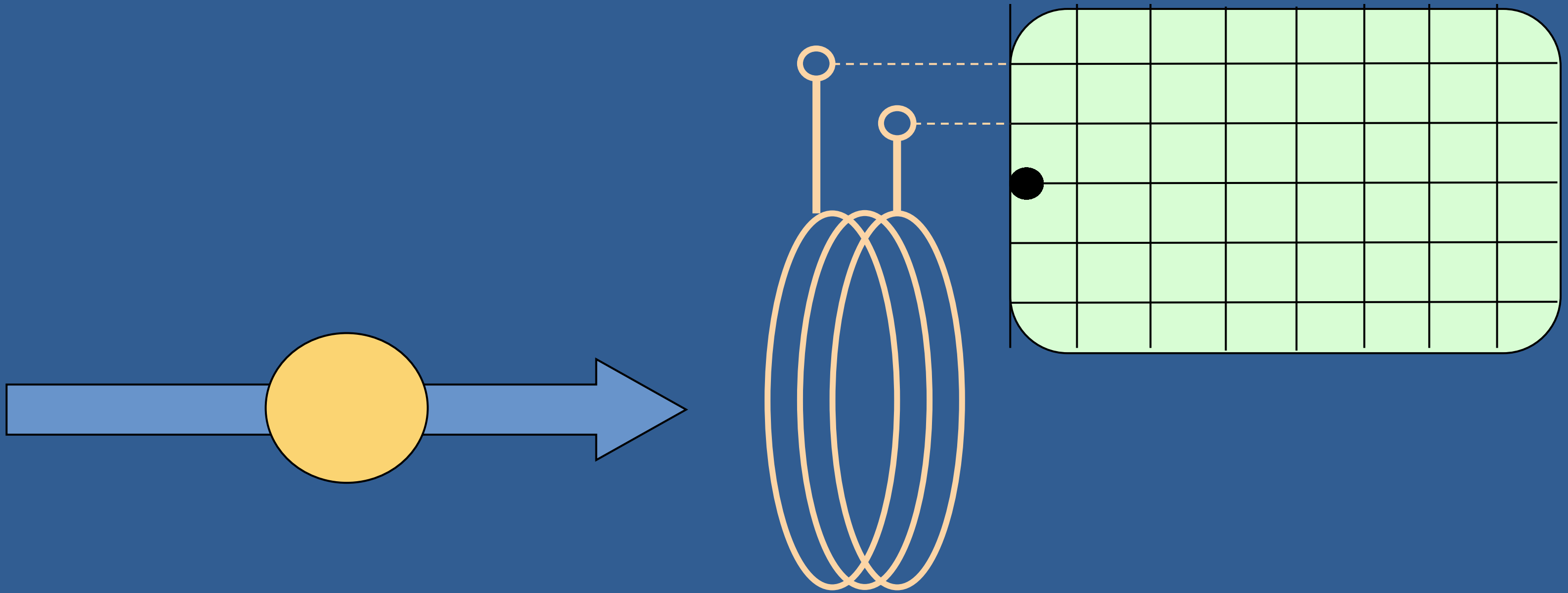
$p\sim mbar, R\sim 3\,cm, B_1\sim \mu T$

This moment precesses in a magnetic field.

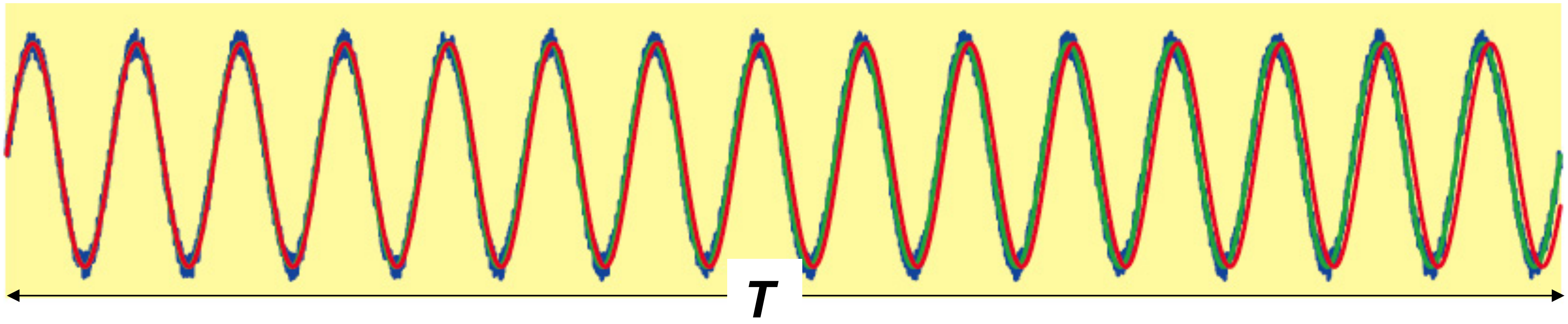
$$\boxed{\omega_L=2\pi\nu_L=\gamma\left|\vec{B}\right|}$$

Spin-clock: Detection of free spin precession:

- long spin coherence times T_2^*> 1 day @ $\Delta f/f \sim 10^{-14}$
- free spin precession: no induced frequency shifts due to feedback phase error, light shift, etc. (Maser, Cs-M)
- use of LT_c-SQUIDs to detect the spin precession signal
  - intrinsic noise of SQUID: ~ 1 fT/√Hz
- no feedback coupling between detector and spin sample



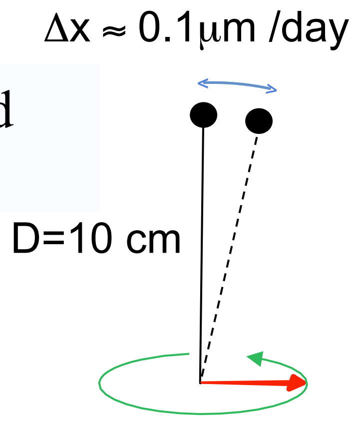
FREQUENCY ESTIMATION



Accuracy of frequency determination:

$$\sigma_f \propto \left[\text{Fourier width} \quad \frac{1}{T}\right] \times \left[\frac{1}{\left[\#\text{ data points} \quad T\right]^{1/2}}\right] \propto \frac{1}{T^{3/2}}$$

If the noise w[n] is **Gaussian distributed**, the Cramer-Rao Lower Bound (CRLB) sets the lower limit on the variance σ_f^2



$$\boxed{\sigma_f^2 \ge \frac{12}{(2\pi)^2 \cdot (SNR)^2 \cdot f_{BW} \cdot T^3} \times C(T_2^*)}$$

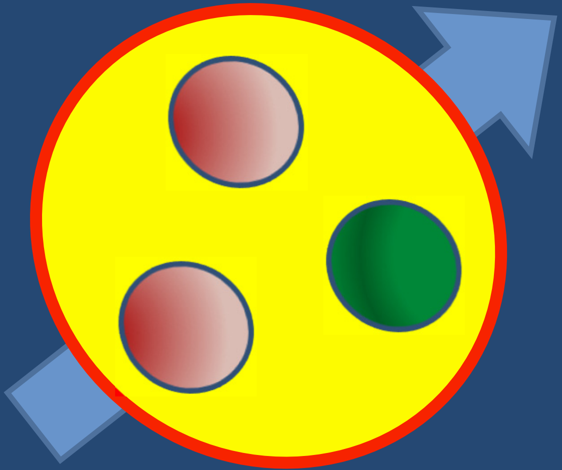
example: SNR = 10000:1 , f_{BW}=1 Hz , T= 1 day ⇒ $\sqrt{\sigma_f^2} \approx pHz$

^{3}He/^{129}Xe „spin"-clock

$\mu_n = -1.913\ \mu_K$

$\mu_{He} = -2.1276\ \mu_K$

$\mu_{Xe} = -0.7779\ \mu_K$

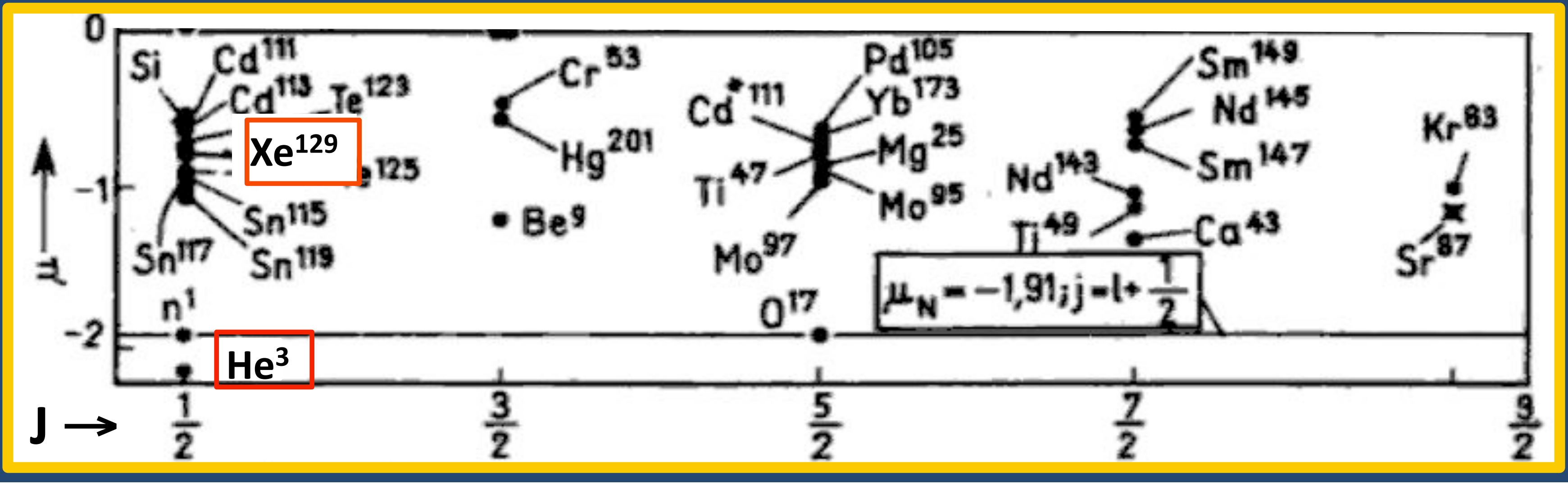


OP-techniques:

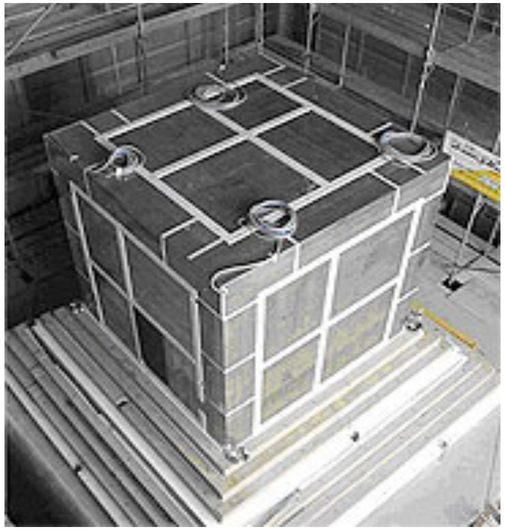
MEOP

SEOP

Schmidt-model:



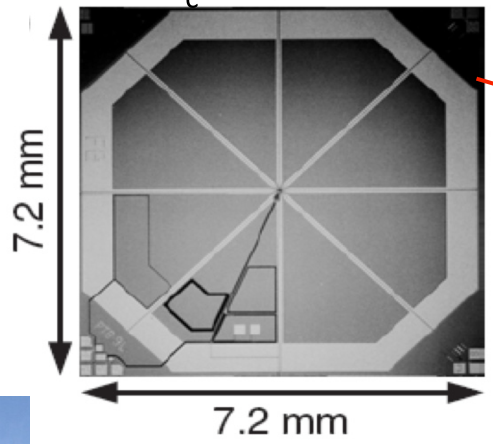
BMSR 2, PTB Berlin



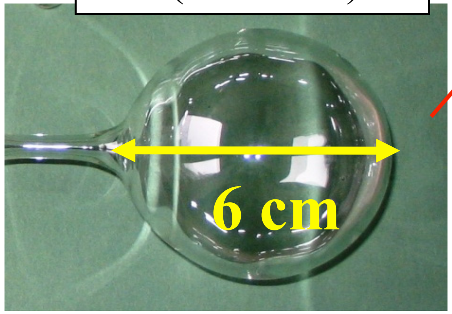
The 7-layered magnetically shielded room (residual field < 2 nT)

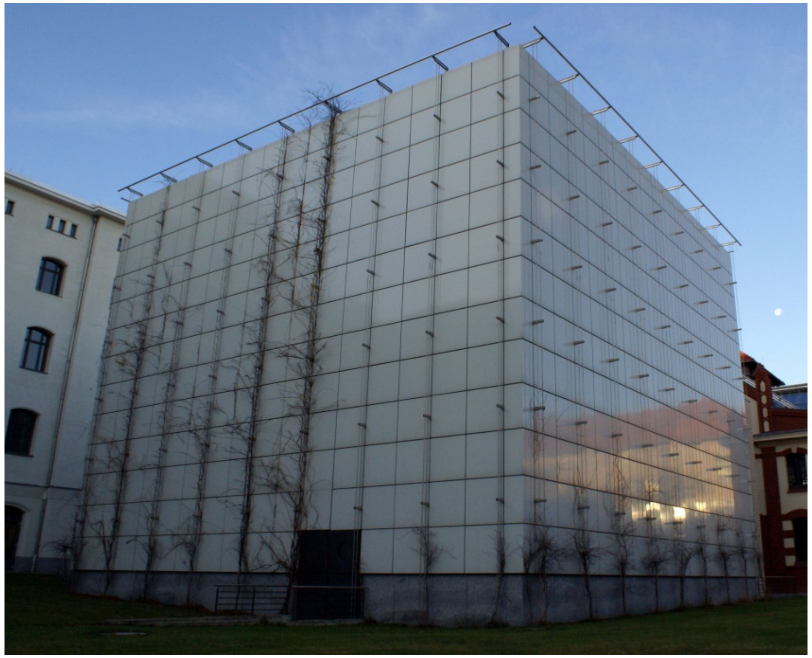
J. Bork, et al., Proc. Biomag 2000, 970 (2000).

LT$_c$- SQUID



^{3}He (4.5 mbar)



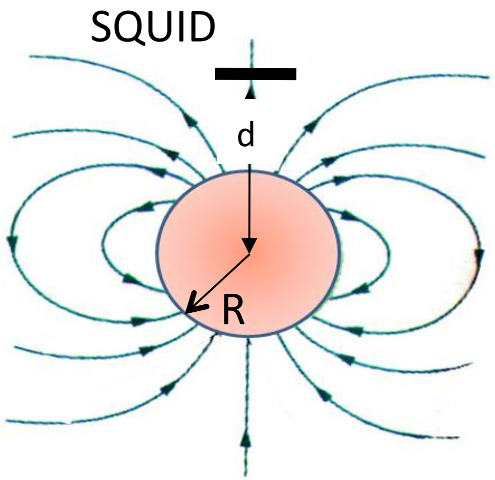


magnetic guiding field ≈ 0.4 μT
(Helmholtz-coils)

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

^{3}He free spin-precession signal

Eur. Phys. J. D 57, 303–320 (2010)



Signal:

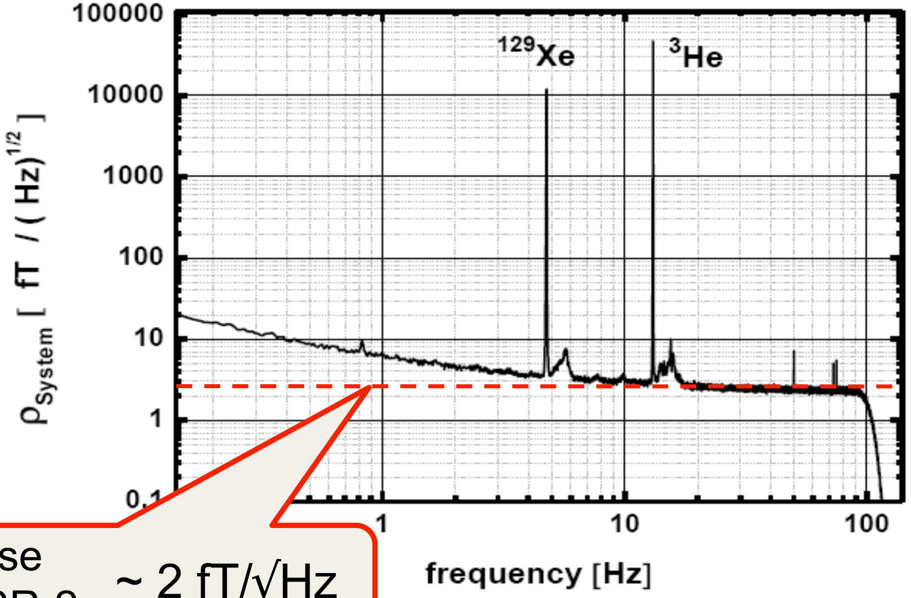
$$\Delta B[pT] \approx 220 \cdot p[mbar] \cdot P \cdot \left(\frac{R}{d}\right)^3$$

parameters:

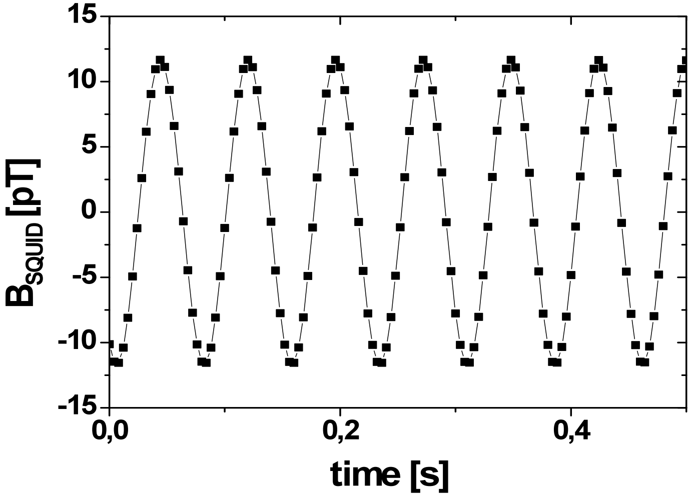
p_{He}= 1-3 mbar ; P = 10-50%

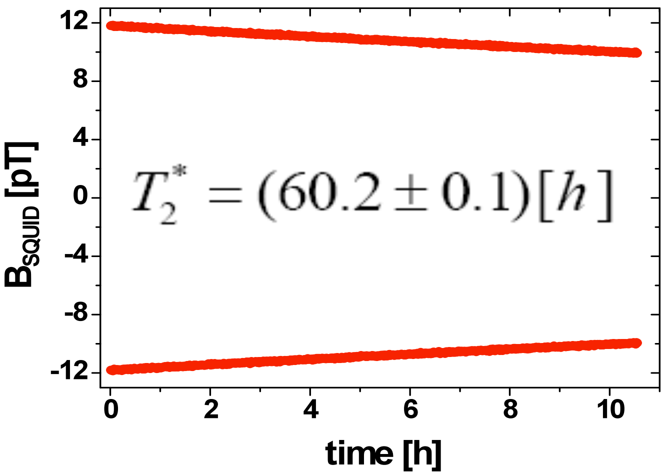
R =2.9 cm; d = 6cm

→ ΔB = 10-30 pT



system noise inside BMSR-2 ~ 2 fT/√Hz





$$T_2^* = (60.2 \pm 0.1)[h]$$

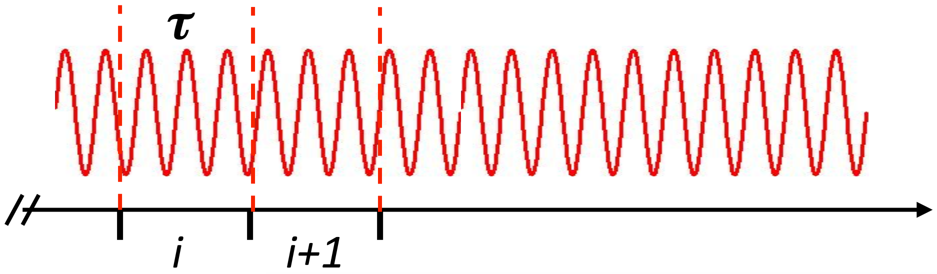
Note:

At present, the Xe spin coherence time T_2^* is limited to

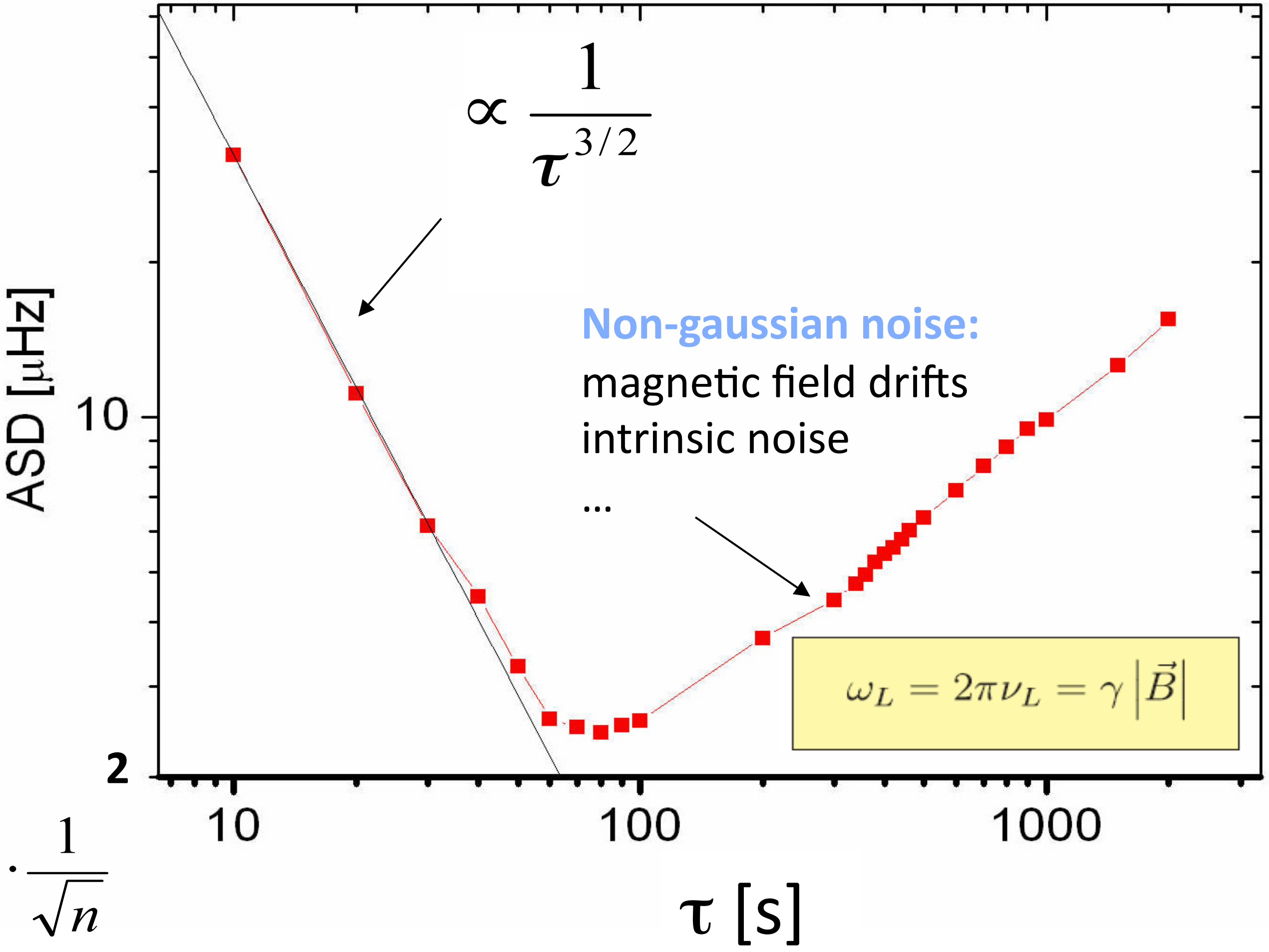
$$\boxed{3\text{ h} < T_2^* < 4\text{ h}}$$

due to wall relaxation

Test of CRLB via Allan Standard Deviation (ASD)



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



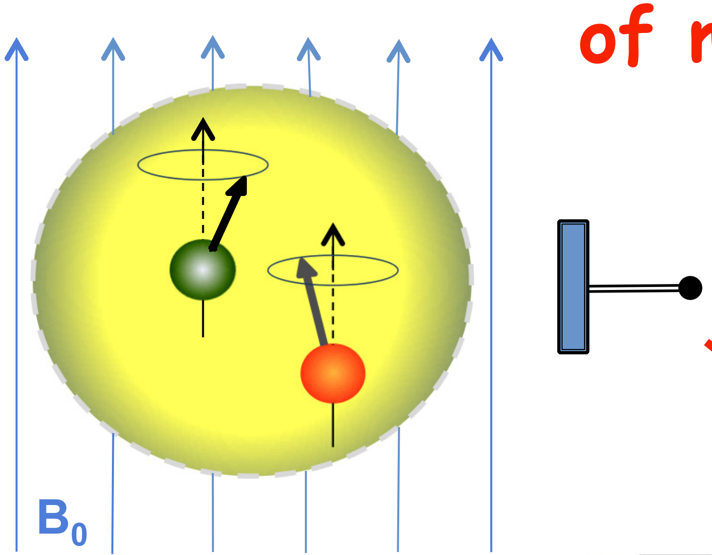
$$\propto \frac{1}{\tau^{3/2}}$$

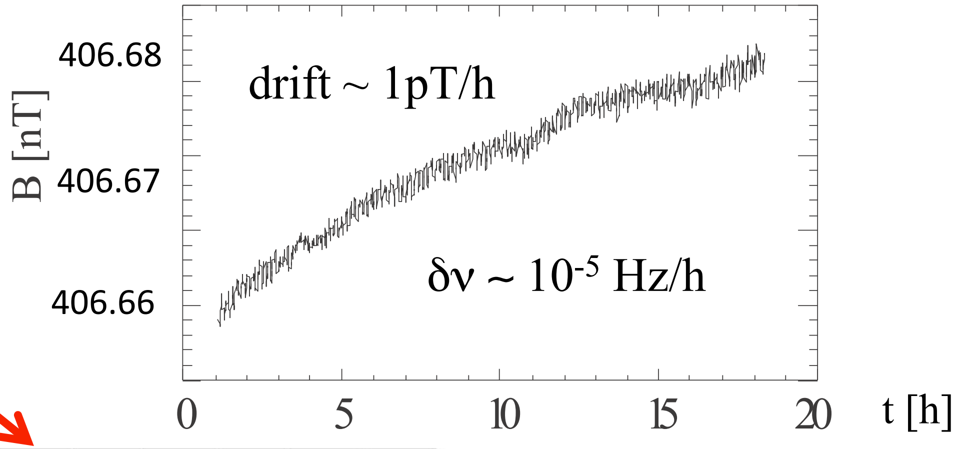
Non-gaussian noise:
magnetic field drifts
intrinsic noise
…

$$\omega_L = 2\pi\nu_L = \gamma\left|\vec{B}\right|$$

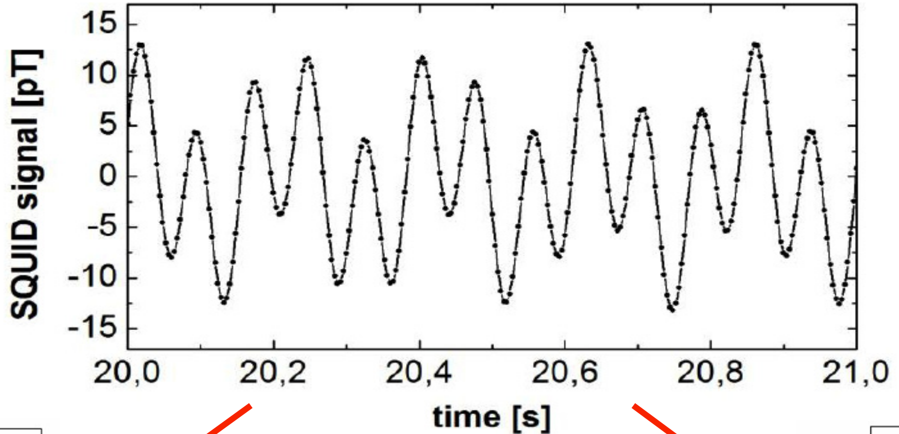
$$\sigma_{\upsilon} \propto \frac{1}{(60s)^{3/2}}\cdot\frac{1}{\sqrt{n}}$$

^{3}He / ^{129}Xe clock comparison to get rid of magnetic field drifts

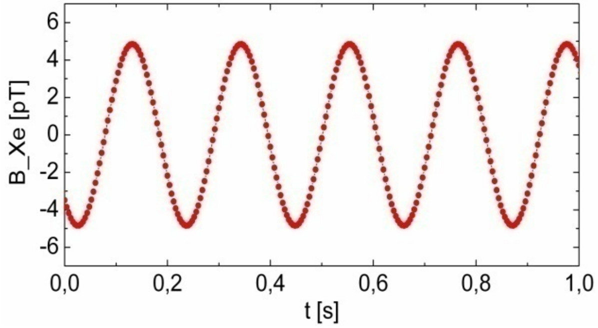




$$\omega_L = 2\pi\nu_L = \gamma\left|\vec{B}\right|$$

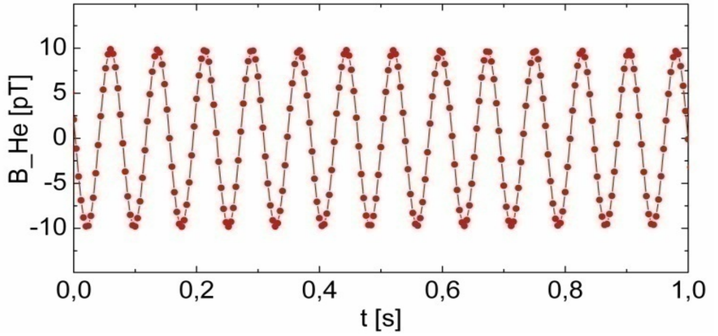


^{129}Xe **(4,7 Hz)**

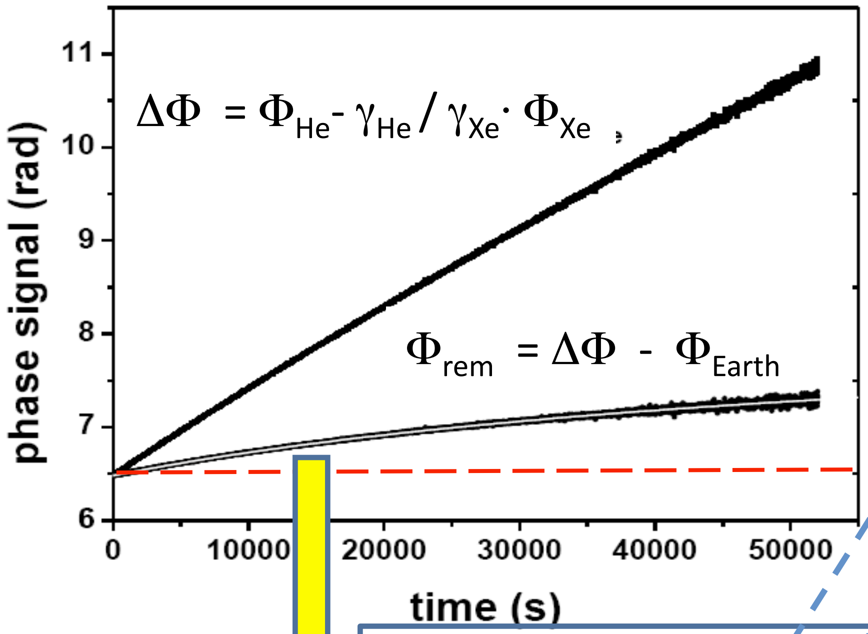


$$\Delta\Phi = \Phi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \Phi_{Xe} \overset{!}{=} const.$$

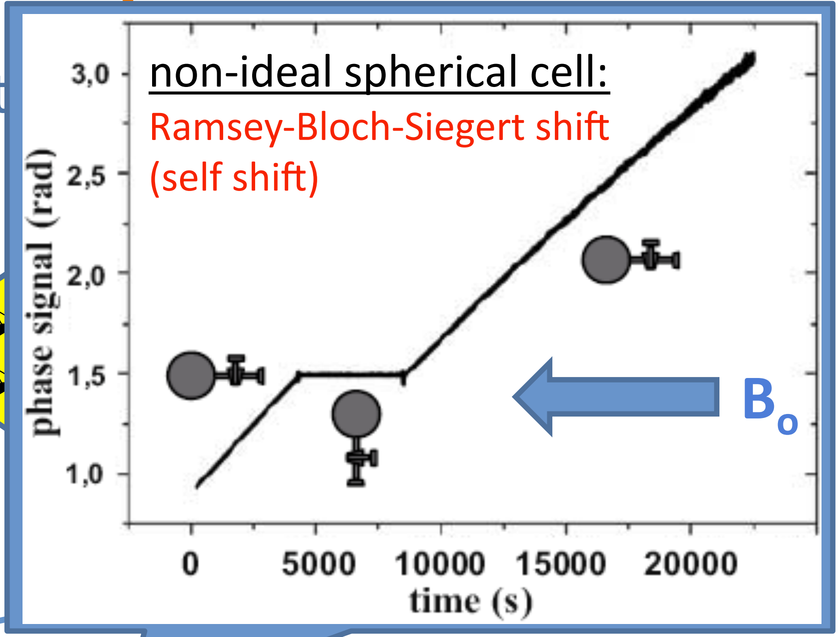
^{3}He **(13 Hz)**



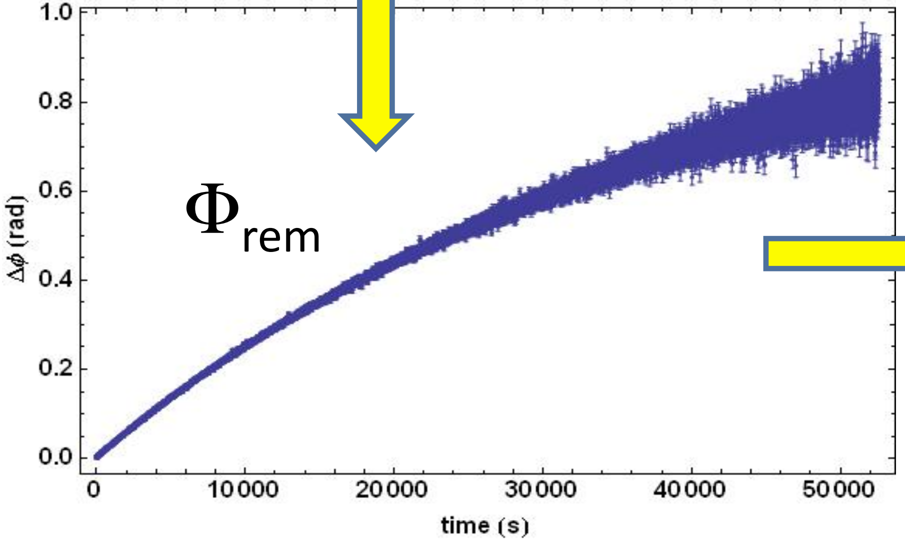
Subtraction of deterministic phase shifts

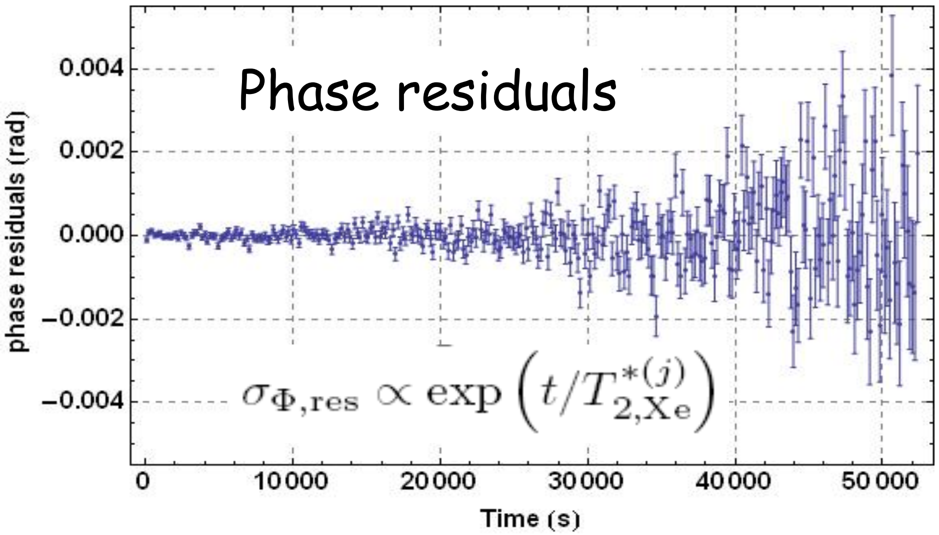


I. Eart

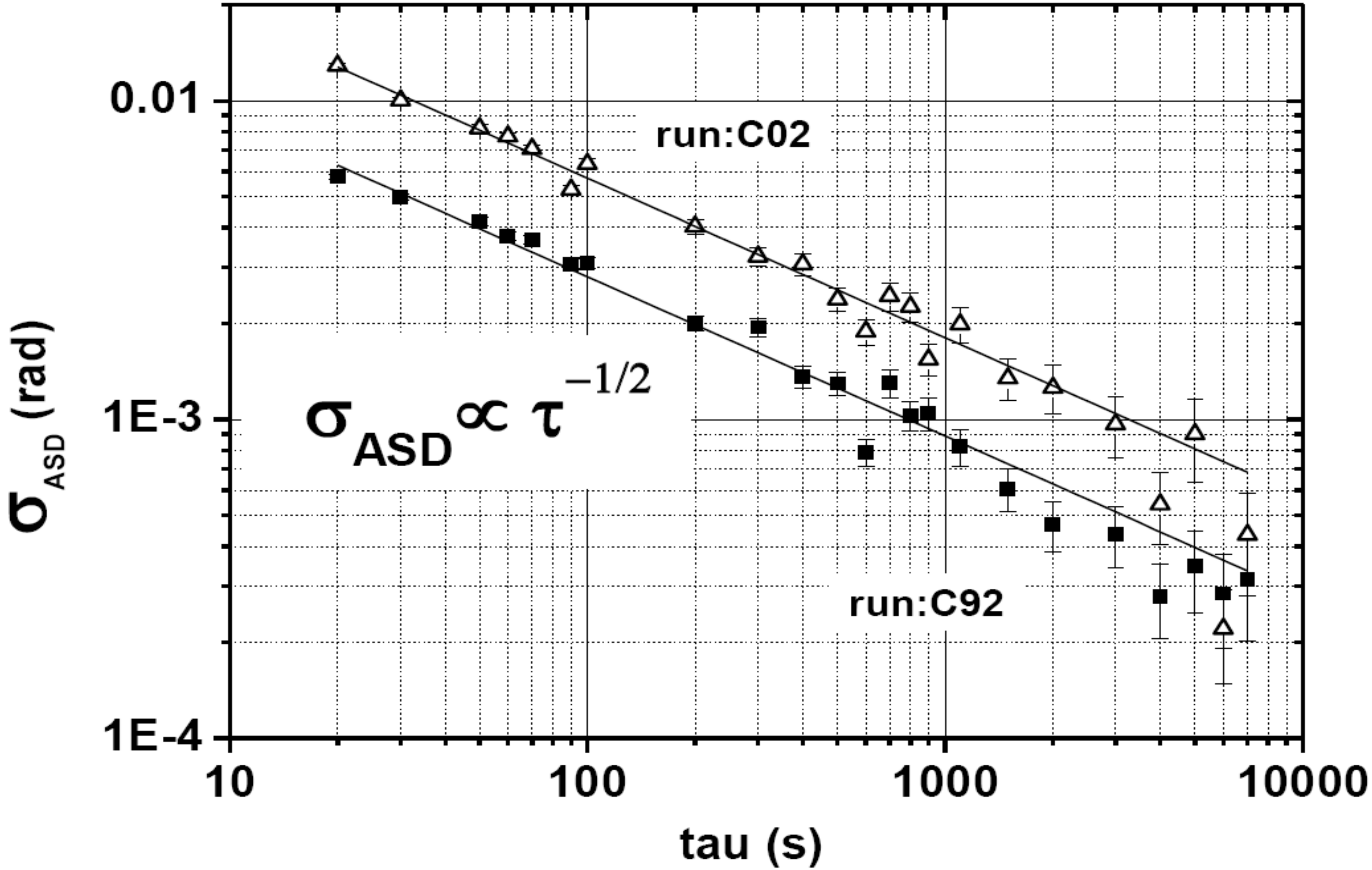


II. $$Fit = c + a_{lin} \cdot t + a_{He} \cdot e^{-t/T^*_{2,He}} + a_{Xe} \cdot e^{-t/T^*_{2,Xe}} + \Phi(t)_{spin\text{-}coupling}$$





ASD of phase residuals



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 of type:

$$V_{non-magn.} = \vec{a} \cdot \vec{\sigma} \equiv - \vec{\mu}_{PM} \cdot \vec{B}_{PM}$$

- Search for a Lorentz violating sidereal modulation of the Larmor frequency

$$V(r)/\hbar = \langle \tilde{b} \rangle \hat{\varepsilon} \cdot \vec{\sigma} / \hbar$$

- Search for spin-dependent short-range interactions

$$V(r)/\hbar = c\,\vec{\sigma} \cdot \hat{n} / \hbar$$

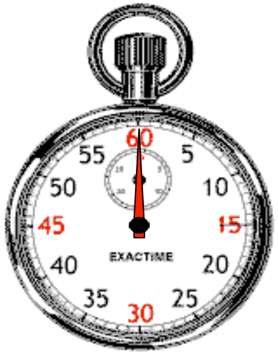
- Search for EDM of Xenon

$$V(r)/\hbar = -|d_n|\,\vec{\sigma} \cdot \vec{E} / \hbar$$

- ...

Observable:

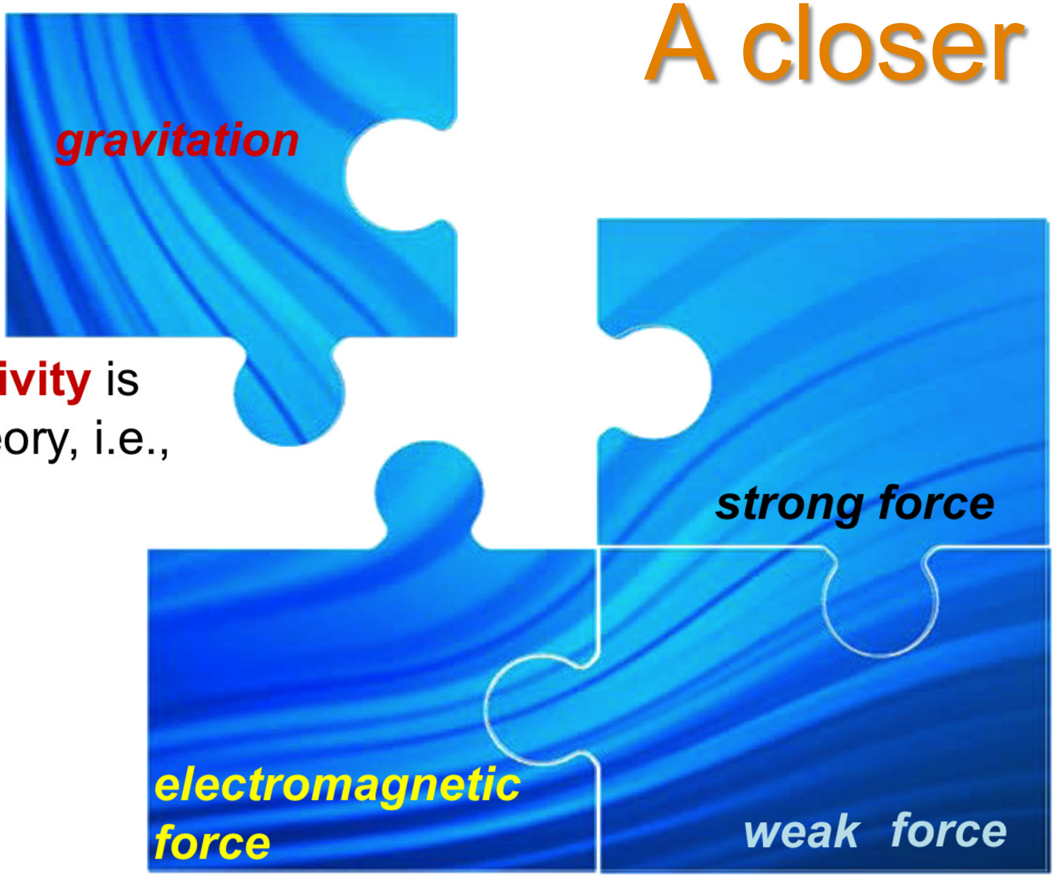
$$\Delta\omega = \omega_{L,He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \omega_{L,Xe} \neq 0$$



Search for a Lorentz violating sidereal modulation

preferred direction in space-time

A closer look…



Standard Model (SM) of particle physics

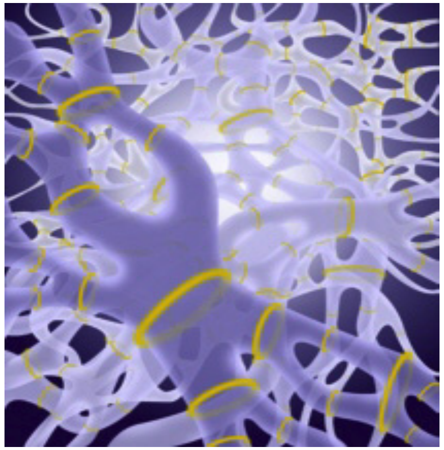
General relativity is a classical theory, i.e., non-quantum

SM: relativistic quantum field theory

Courtesy of C. Lämmerzahl

Unification theories:

string theory, loop quantum gravity,..



Planck scale: energy scale where gravity meets quantum physics

$M_p \sim 10^{19}$ GeV

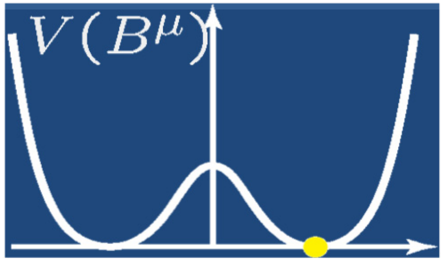
Fundamental Theory:
Lorentz & CPT invariant

String theory
M theory

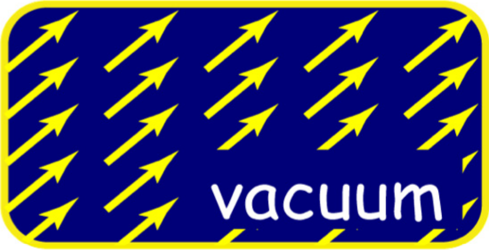
~ Planck scale
10^{19} GeV

Spontaneous Lorentz symmetry breaking in string theory

e.g. Lorentz vector field makes non zero vacuum expectation value



$\langle B^\mu \rangle \neq 0$



Background fields (tensor fields) give preferred direction
e.g. rest frame of CMB → *talk of Ralf Lehnert*

Effective theory:
„low-energy“
Lorentz & CPT violating

low-energy
world

Standard-Model
extension (SME)

D. Colladay and V.A. Kostelecky, Phys. Rev. D 55, 6760 (1997); Phys.Rev. D 58, 116002 (1998)

Traditional tests of Lorentz symmetry & special relativity

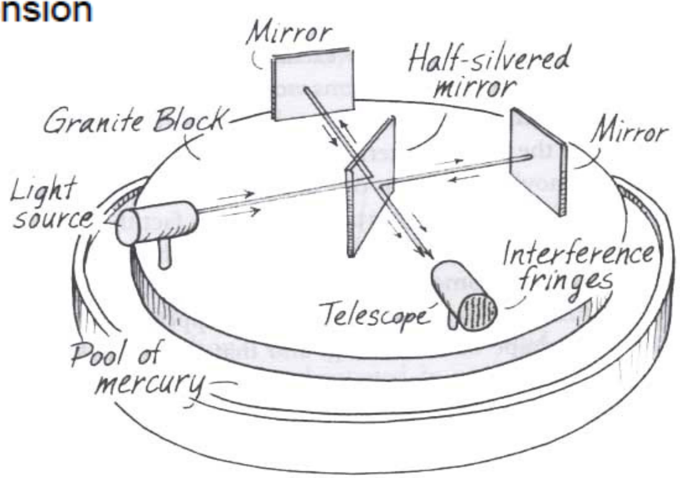
photon sector:

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}}_{\text{Standard Lagrangian}} \underbrace{-\frac{1}{4}(k_F)_{\kappa\lambda\mu\nu}F^{\kappa\lambda}F^{\mu\nu}}_{\text{Lorentz Invariance violating Extension}}$$

$(k_F)\kappa\lambda\mu\nu$: 19 independent parameters

- **Michelson-Morley**
  isotropy of speed of light

$$\boxed{c(\theta) = c}$$



Michelson (1881,Potsdam)
Michelson&Morley (1887,Cleveland)

- **Kennedy-Thorndike**
  boost-independence of speed of light

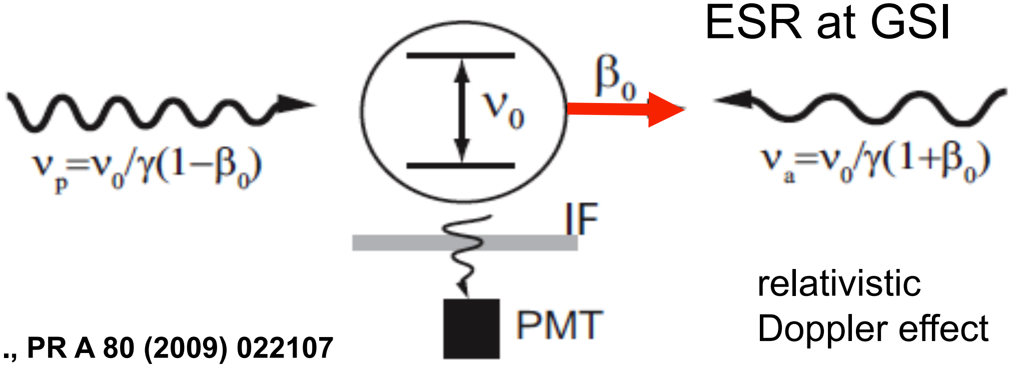
$$\boxed{c(v) = c}$$

- **Ives-Stillwell**
  special-relativistic time dilation

$$\boxed{\frac{\nu_p \cdot \nu_a}{\upsilon_0^2} = 1 + \varepsilon\left(\beta^2\right)}$$

Li⁺ - ions

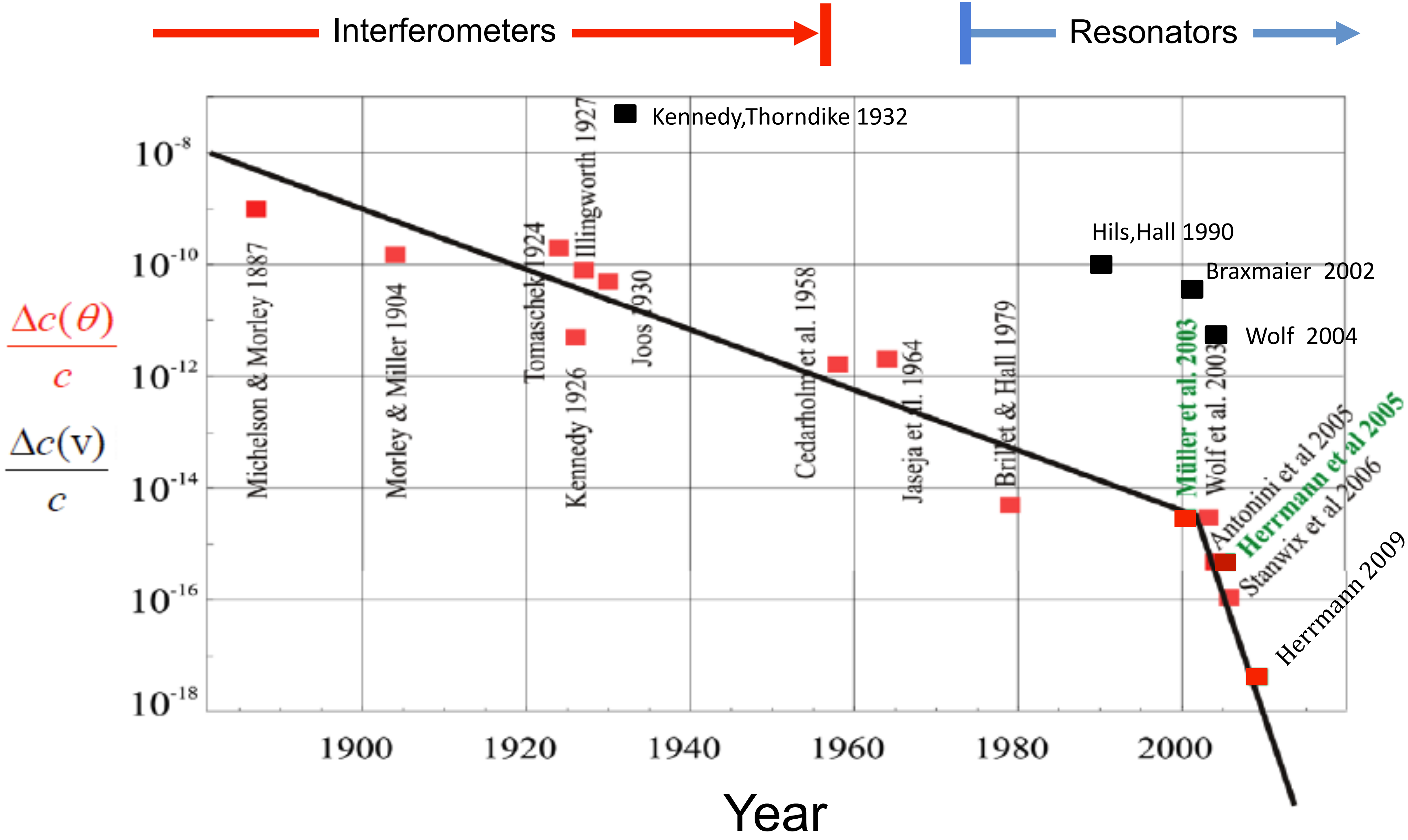
ESR at GSI



relativistic
Doppler effect

C.Novotny et al., PR A 80 (2009) 022107

Test of constancy of c



Modern Tests of Lorentz violation

Topics:

- searches for CPT and Lorentz violations involving

-birefringence and dispersion from cosmological sources
-clock-comparison measurements
-CMB polarization
-collider experiments
-electromagnetic resonant cavities
-equivalence principle
-gauge and Higgs particles
-high-energy astrophysical observations
-laboratory and gravimetric tests of gravity
-matter interferometry
-neutrino oscillations
-oscillations and decays of K, B, D mesons
-particle-antiparticle comparisons
-space-based missions
-spectroscopy of hydrogen and antihydrogen
-spin-polarized matter

Fifth Meeting on

CPT AND LORENTZ SYMMETRY

June 28-July 2, 2010

Indiana University, Bloomington

* Theoretical studies of CPT and Lorentz violation involving

-physical effects at the level of the SM, General Relativity, and beyond
-origins and mechanisms for violations classical and quantum issues in field theory, particle physics, gravity, and strings

Standard-Model Extension

- matter sector -

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

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

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

Experimental access:

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

coupling strength

Cs- fountain Wolf et al., PRL **96,** 060801 (2006)

Torsion pendulum B.Heckel et al. PRD 78 (2008) 092006

Antihydrogen spectroscopy

Astrophysics

Hg/Cs comparison

UCN/Hg comparison

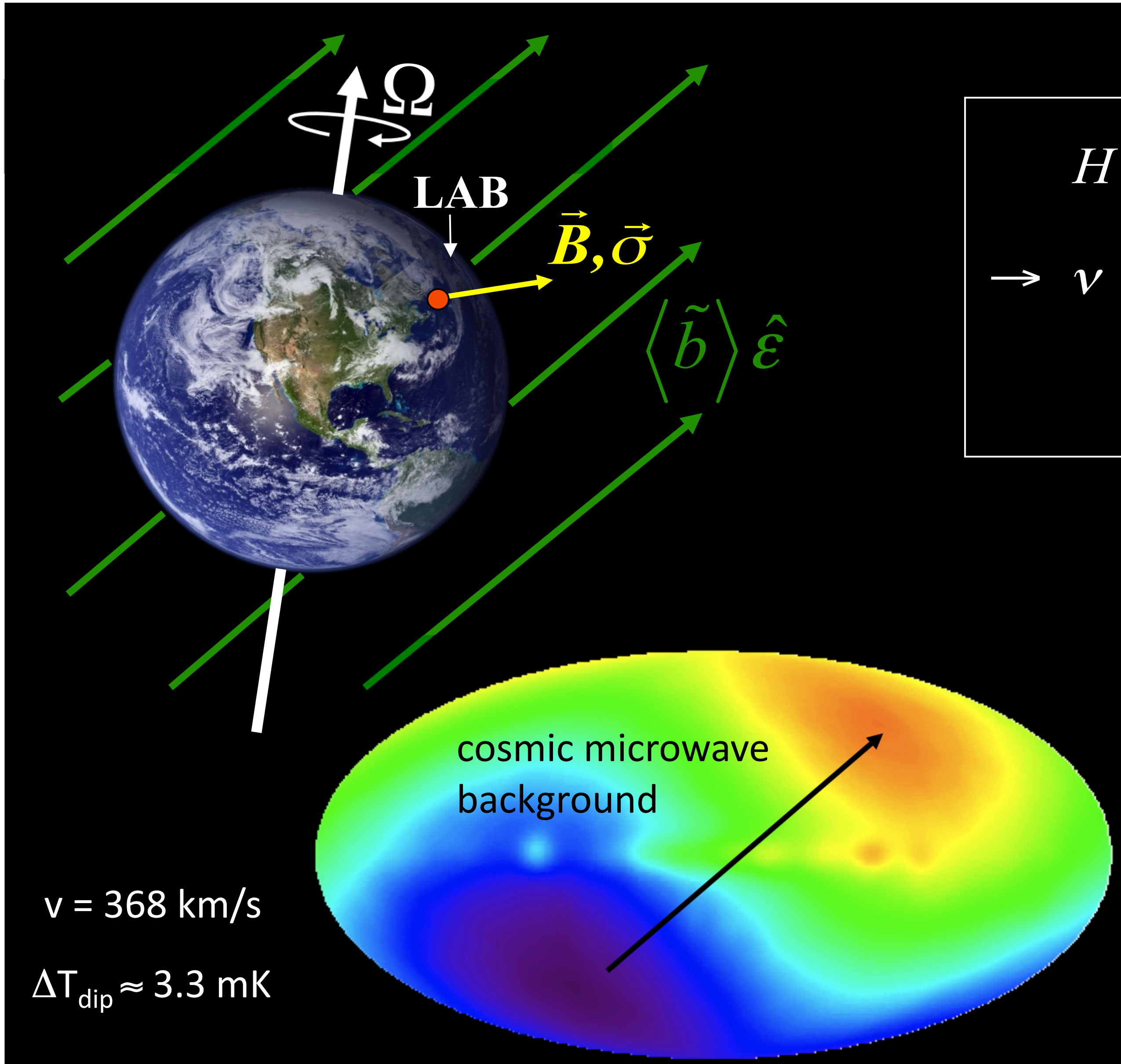
He/Xe maser

K/He co-magnetometer

clock comparison experiments

$\boxed{b^{n}_{\mu}}$

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

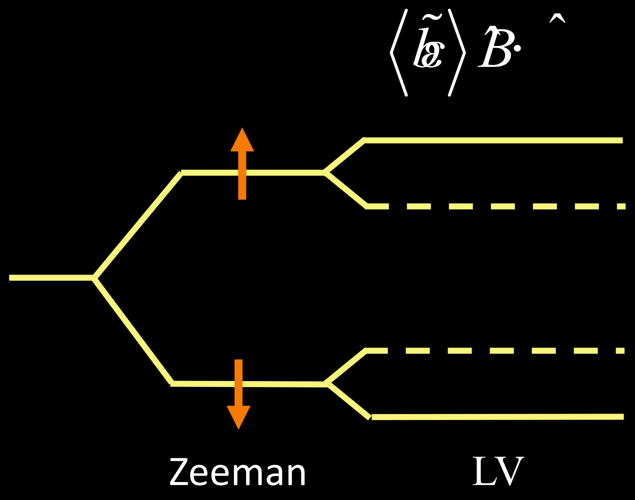


v = 368 km/s

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

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

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

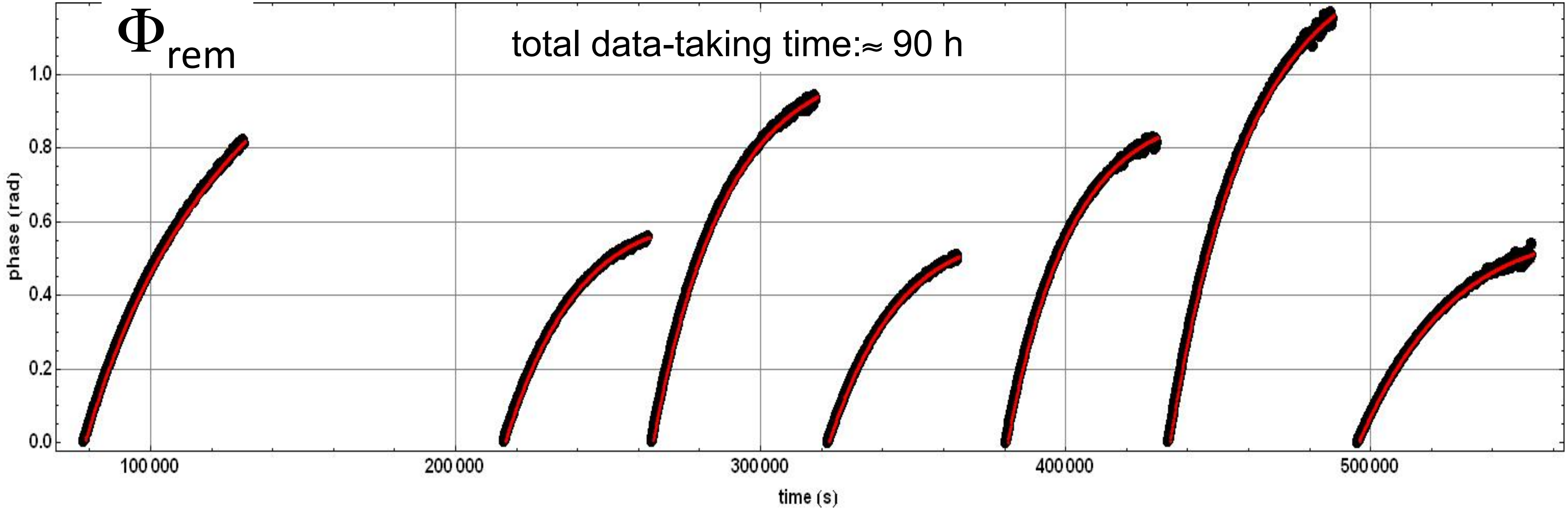


$$\sim \quad a_s\cdot\sin(\Omega_s\cdot t) - a_c\cdot\cos(\Omega_s\cdot t)$$

Search for a sidereal modulation of the weighted phase difference

March 2009 run:

$$\Phi_{rem} = \Phi_{He} - \gamma_{He} / \gamma_{Xe} \cdot \Phi_{Xe} - \Phi_{Earth}$$


Φ_{rem}

total data-taking time:≈ 90 h

$$Fit = \sum_{n=1}^{7} \left\{ c_n + a_{lin,n} \cdot t + a_{He,n} \cdot e^{-t/T_{2,He,n}} + a_{Xe,n} \cdot e^{-t/T_{2,Xe,n}} \right\} + a_s \cdot \sin(\Omega_s \cdot t) - a_c \cdot \cos(\Omega_s \cdot t)$$

expect strong correlated error for $T_{SD} > T_2^*$ $\Omega_s = 2\pi/T_{SD} = 2\pi/(23^h:56^m:4.091^s)$.

Results of χ^2-fit for the sidereal phase amplitudes a_c and a_s together with their correlated and uncorrelated 1σ-errors .

To demonstrate the strong dependence of the correlated error on Ω_s, corresponding fit results are shown for multiples of Ω_s: $\Omega'_s = g\cdot\Omega_s$.

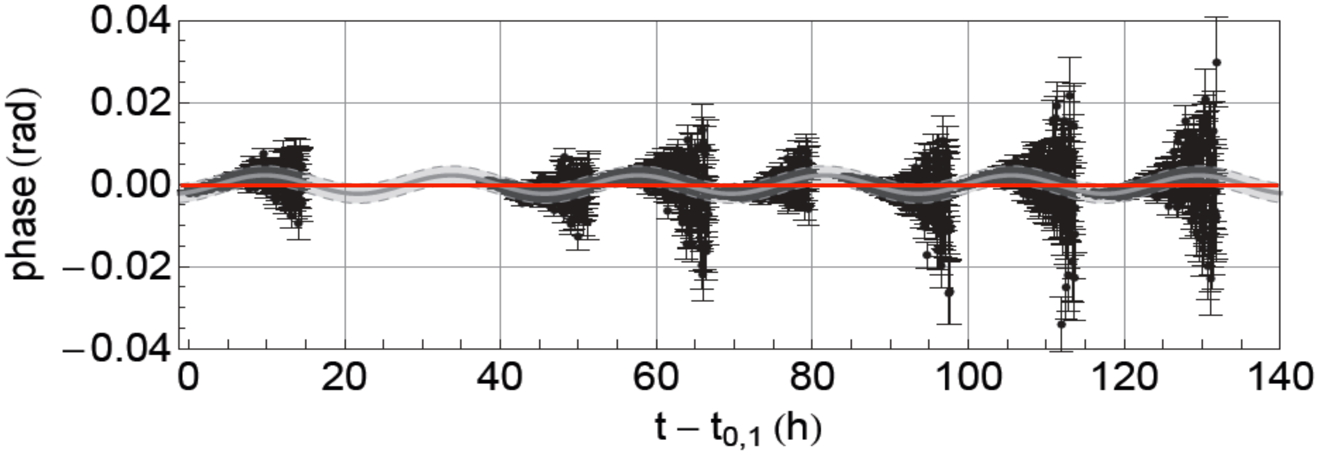
	a_c mrad	σ_{ac}^{corr}	σ_{ac}^{uncorr}	**a_s mrad**	σ_{as}^{corr}	σ_{as}^{uncorr}
$\Omega_s = 2\pi / T_{SD}$	-0.882	0.814	0.015	-2.067	1.057	0.019
$2\cdot\Omega_s$	-0.048	0.120	0.016	-0.149	0.112	0.017
$3\cdot\Omega_s$	-0.184	0.052	0.019	-0.011	0.043	0.016
$4\cdot\Omega_s$	-0.001	0.034	0.018	0.057	0.030	0.016

Phaseamplitude of the sidereal modulation:

$$a_{\max} = \sqrt{a_s^2 + a_c^2} = (2.25 \pm 2.29)\ mrad\ (95\%\ CL)$$

Phase residuals with fit-results for

$$a_s \cdot \sin(\Omega_s \cdot t) - a_c \cdot \cos(\Omega_s \cdot t)$$



In terms of frequency:

$$\upsilon_\perp = a_{\max}\cdot\frac{\Omega_s}{2\pi} = (26.1 \pm 26.6)\,\mathrm{nHz} \qquad \text{(95\% C.L.)}$$

Kostelecky et al. , Phys. Rev. D 60, 116010 (1999)

free neutron:

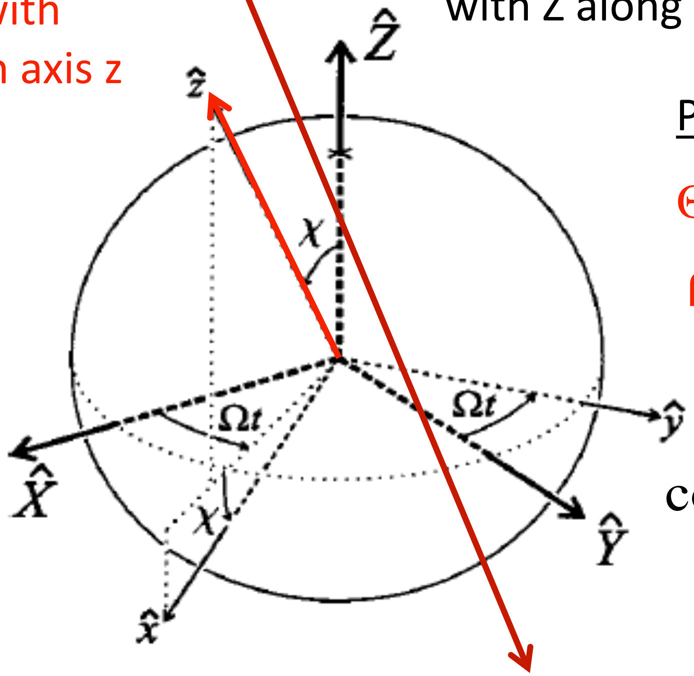
n : $\mu = -1.913\ \mu_K$

Schmidt-Model

^{3}He: $\mu = -2.1276\ \mu_K$

^{129}Xe: $\mu = -0.7779\ \mu_K$

Lab-frame with quantization axis z



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

PTB Berlin:

$\Theta = 52{,}5164^0$ north

$\rho = 28^0$ (north-south)

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

$$\sin\chi\cdot\left|-3.5\cdot\tilde{b}_\perp^n + 0.012\cdot\tilde{d}_\perp^n + 0.012\cdot\tilde{g}_{D,\perp}^n\right| \le 2\pi\cdot\delta\upsilon_\perp\cdot\hbar$$

$$\tilde{b}_\perp^n = \le 3.72\cdot 10^{-32}\ GeV \quad (95\% \quad C.L.\ )$$

PRD 82 (2010) 111901

Tightest constrains on SME parameters on neutron sector:

V. Alan Kostelecký[a] and Neil Russell[b] [arXiv:0801.0287]

Coefficient	Proton	Neutron	Electron
$\tilde{b}_X\ [GeV]$	$< 10^{-31}$	$< 10^{-32}$	$< 10^{-31}$
$\tilde{b}_Y\ [GeV]$	$< 10^{-31}$	$< 10^{-32}$	$< 10^{-31}$
$\lvert\tilde{b}_\perp\rvert\ [GeV]$	$< 10^{-31}$	$< 10^{-32}$	

$$\tilde{b}^n \approx \left(\frac{m_n}{M_P}\right)^k \cdot m_n \quad k = 1\ excluded$$

$$\Rightarrow \text{exp. } upgrade\text{: } k = 2\text{ !}$$

our result:

$$\tilde{b}_\perp^n = \leq 3.72 \cdot 10^{-32}\ GeV \quad (95\%\ \ C.L.)$$

- Torsion pendulum

B.R.Heckel et al., PRD 78 (2008) 092006

$$\tilde{b}_X^e = (-0.9 \pm 1.4) \times 10^{-31}\ \text{GeV}$$

- K-^{3}He co-magnetometer

$$\tilde{b}_\perp^n < 3.7 \cdot 10^{-33}\ GeV\,(68\%\ C.L.)$$

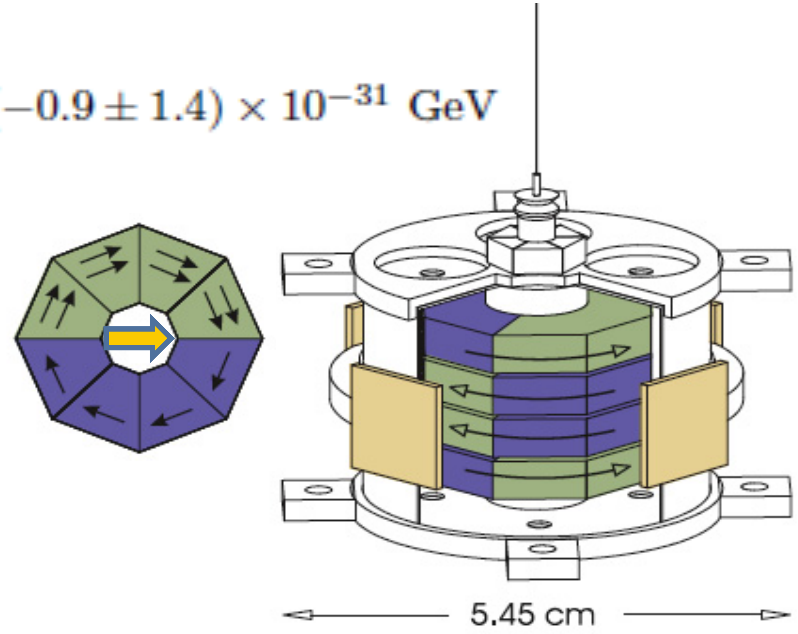
J. M. Brown et al. *Phys. Rev. Lett., 105, 151604 (2010).*

- Spin maser experiments with ^{3}He and ^{129}Xe

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

$$\tilde{b}_\perp^n \equiv \sqrt{(\tilde{b}_X^n)^2 + (\tilde{b}_Y^n)^2} = (4.0 \pm 3.3) \times 10^{-31}\ \text{GeV}$$

(95% C.L.)



March 2012 run
at
PTB

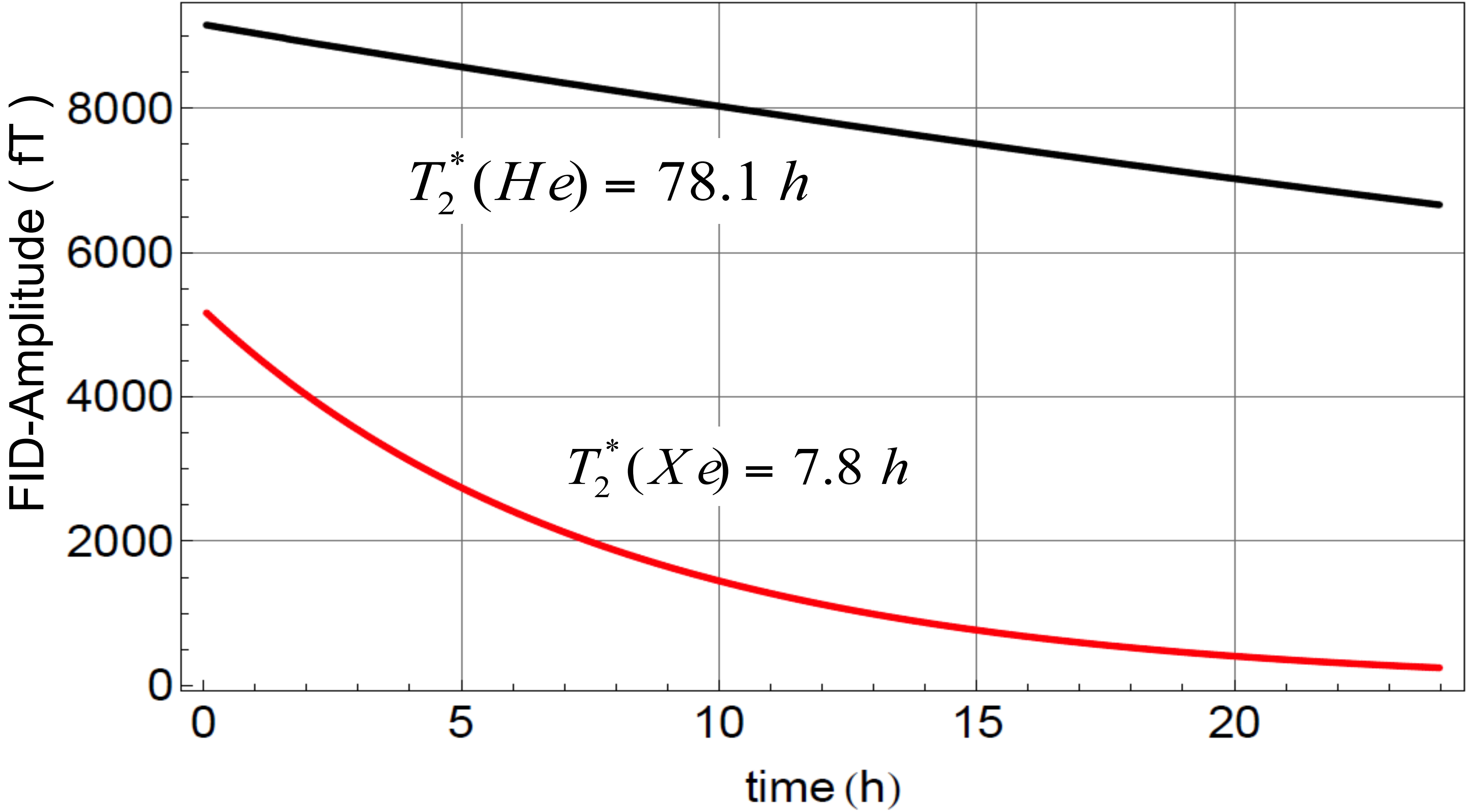
(1) conventional runs with B-field fixed

(2) active rotation of B-field (2 h / turn)

T_2^*- improvements:

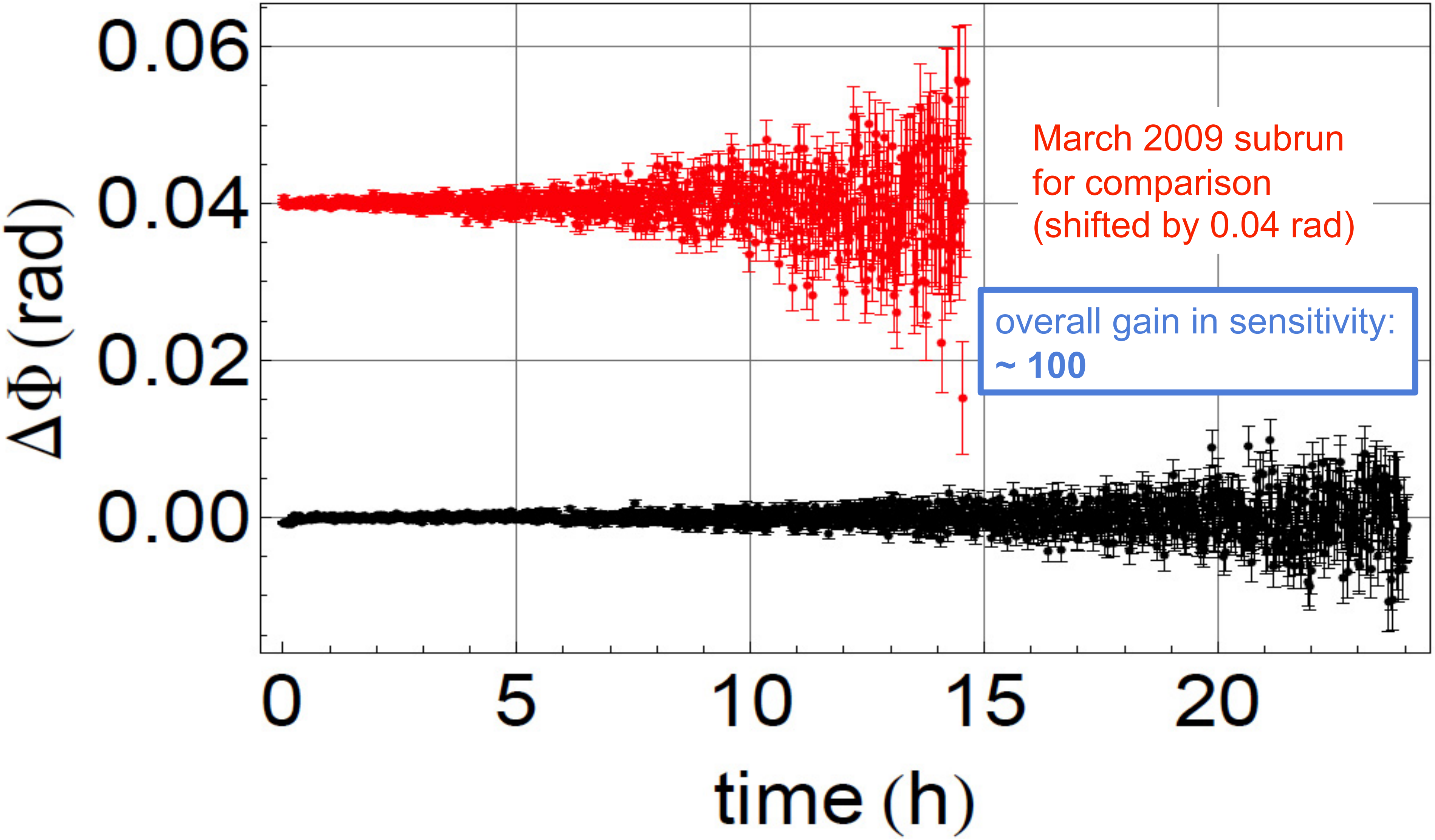
pure ^{3}He @ p=2.5 mbar : $T_2^*(He) = 124\ h$

Gas mixture: p_{He}= 2.7 mbar, p_{Xe}= 4.9 mbar, p_{N2}= 24.8 mbar



Phase residuals:

- total data taking time: 165 h (90 h March 2009) **~1.8**
- gain in SNR: **2-3**
- gain due to CRLB power law (~1/T$^{3/2}$) : **2.8**
- reduction of correlated error: **~ 7**



March 2009 subrun for comparison (shifted by 0.04 rad)

overall gain in sensitivity: **~ 100**

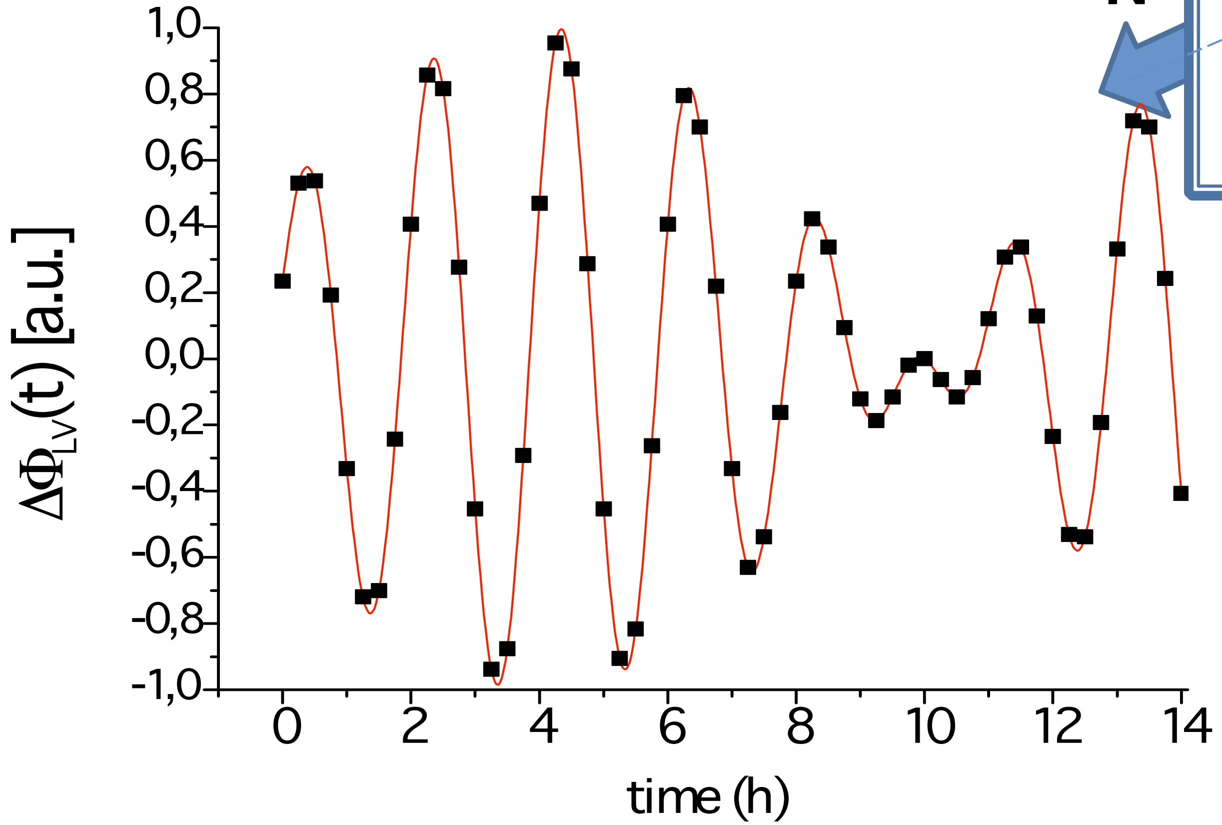
(2) rotation of B-field (quantization axis)

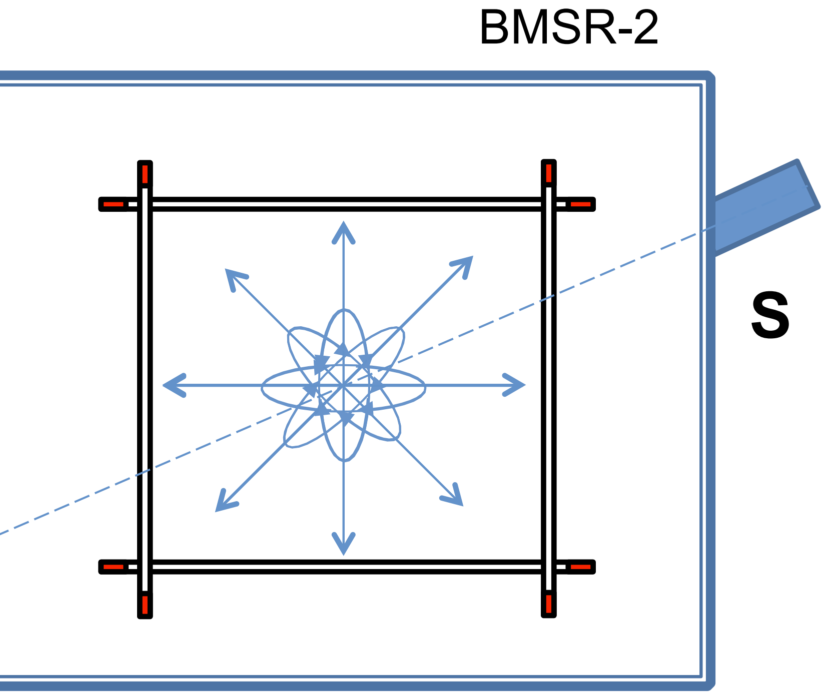
5 subruns (~ 14 h each)

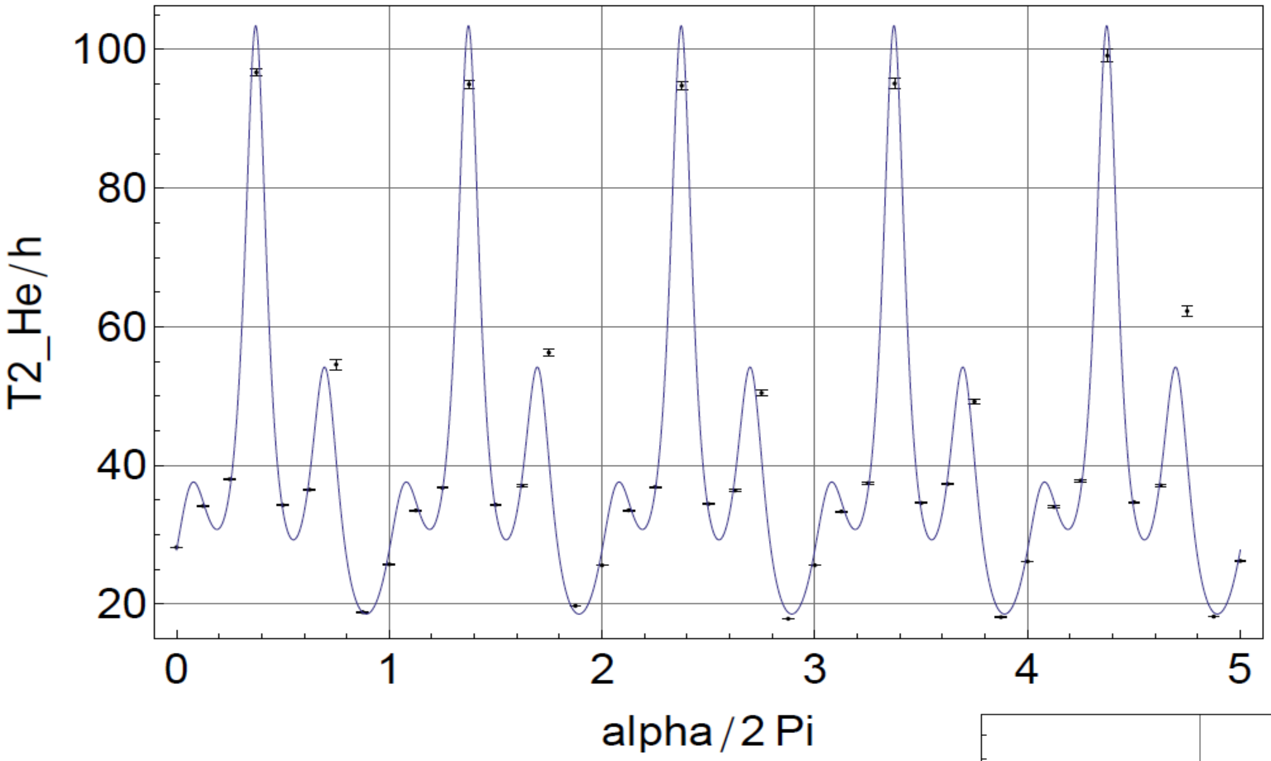
Sequence:

...
field rotation (45^0) : 2.5 min
measurement (static): 12.5 min
...

expected LV-signal: $\sim \sin\left(\Omega_s \cdot t + \Phi\right) \cdot \sin \chi(t)$

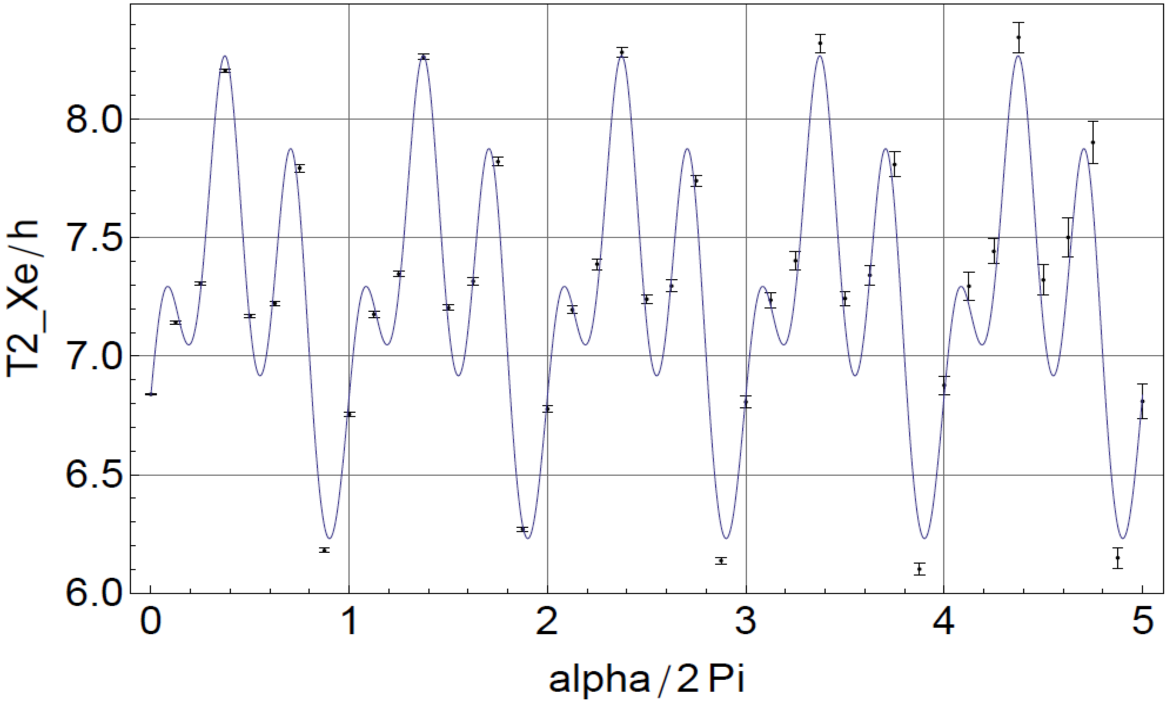






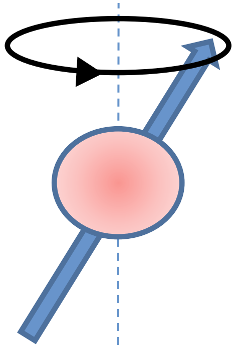
Change of the absolute field gradient during rotation and its effect on T_2^*

$$\frac{1}{T_2^*} \propto \left|\nabla B\right|^2$$



data analysis ongoing

Conclusion and Outlook



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

$$T^*_{2,He} \approx 60\,hours \quad (\,T^*_{2,He} = 124\ h,\ \text{March 2012 run}\,)$$

$$T^*_{2,Xe} = 3-4\ hours \quad (\,T^*_2(Xe) \approx 8\,h\ @\ T_{1,wall} \sim 11\ h\,)$$

Eur. Phys. J. D **57**, 303–320 (2010)

- Search for neutron spin coupling to a Lorentz and CPT-violating background field

$$V(r)/\hbar = \left\langle \widetilde{\mathrm{b}} \right\rangle \hat{\varepsilon} \cdot \vec{\sigma} / \hbar$$

K-^{3}He and ^{3}He/^{129}Xe co-magnetometer set the tightest limits on SME-parameters

•K-^{3}He co-magnetometer : $\widetilde{b}^n_\perp < 3.7 \cdot 10^{-33}\ GeV\,(68\%\ C.L.)$ *PRL 105, 151604 (2010)*

•^{3}He-^{129}Xe co-magnetometer : $\widetilde{b}^n_\perp \leq 3.72 \cdot 10^{-32}\ GeV\,(95\%\ \ C.L.\,)$ *PRD 82, 111901 (2010)*

March 2012 run: expected gain in sensitivity ~ 100 to trace LV interactions

- Short range spin-dependent interaction:

$$V(r) = \frac{g_S g_P}{8\pi}\frac{(\hbar)^2}{m_n}(\sigma_n \cdot \vec{n})\left[\frac{1}{r\lambda} + \frac{1}{r^2}\right] e^{-r/\lambda}$$

J.E.Moody, F.Wilczek
PRD 30 (1984) 130

September 2010 run

- ^{129}Xe electric dipole moment (Groningen-Heidelberg-Mainz collaboration):

Proposal: $|d_{Xe}| < 10^{-31}\ ecm$

$|d_{Xe}| = (0.7 \pm 3.3 \pm 0.1) \times 10^{-27}$ ecm

Rosenberry and Chupp, PRL 86,22 (2001)

present sensitivity of ^{3}He/^{129}Xe-comagnetometer: < 0.1 nHz per day

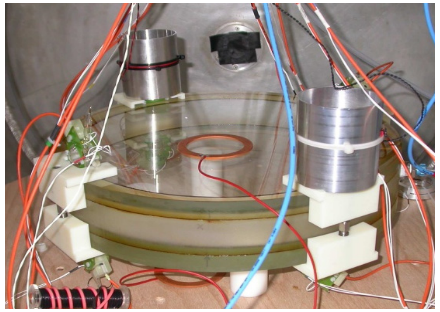
➢ Magnetometry (^{3}He)

low field : ≈ 1μ Tesla

$$\langle \delta B \rangle \approx 1 f\ T @\ 200\ s \longrightarrow$$

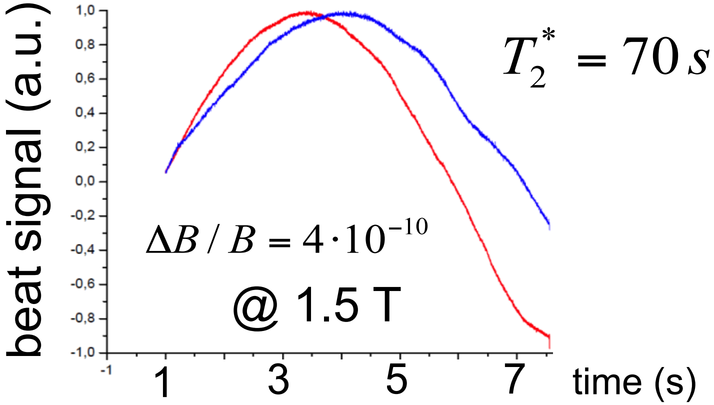
magnetometer for
nEDM experiment
at PSI

$T_2^* > 30\,\text{min}$



high field : > 1 Tesla

ultra-high sensitive
magnetometer to monitor
relative field changes of
≈ 10^{-12}



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

probing fundamental symmetries

Institut für Physik, Universität Mainz:
C. Gemmel, W. Heil, H.Hofsetz, S. Karpuk, Y. Sobolev,
K.Tullney
Physikalisch-Technische-Bundesanstalt, Berlin:
M. Burghoff, W. Kilian, S. Knappe-Grüneberg,
W. Müller, A. Schnabel, F. Seifert, L. Trahms

Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg:
F. Allendinger, U. Schmidt

Thank you for your attention

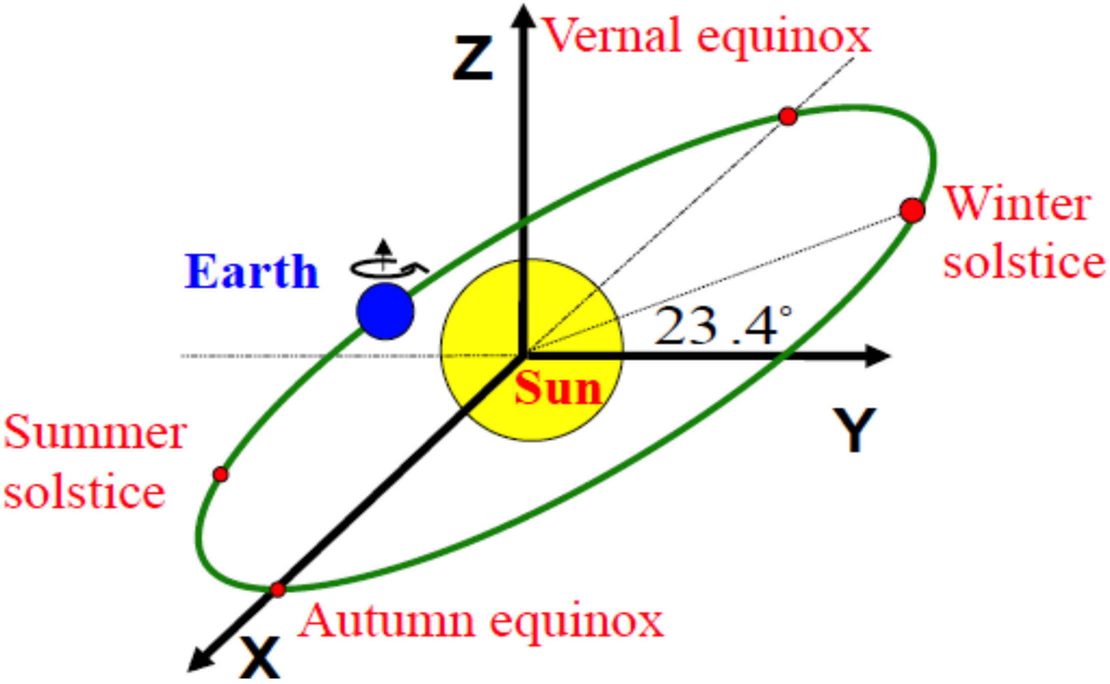
Standard Model Extension (SME)

How to detect Lorentz violation?

Lorentz violation is realized as a coupling of particle fields and the background fields, so the basic strategy is to find the Lorentz violation is;

(1) choose the coordinate system to compare the experimental result
(2) write down Lagrangian including Lorentz violating terms under the formalism
(3) write down the observables using this Lagrangian

The standard choice of the coordinate is Sun-centred coordinates



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

Gerardus 't Hooft,: QCD has a non-trivial vacuum structure that in principle permits CP-violation

$$L_{\overline{\theta}} = \frac{\alpha_s \overline{\theta}}{8\pi} \vec{G}_{\mu\nu} \cdot \vec{\tilde{G}}^{\mu\nu}$$

from neutron EDM we get: $d_n \approx 10^{-16} \cdot \overline{\theta} < 3 \cdot 10^{-26} \ e \cdot cm$

Original proposal for Axion (R. Peccei, H.Quinn PRL 38(1977),1440) as possible solution to the „Strong CP Problem“ that cancels the CP violating term in the QCD Lagrangian

$$L_a = \xi \frac{\alpha_s}{8\pi f_a} a(x) \vec{G}_{\mu\nu} \cdot \vec{\tilde{G}}^{\mu\nu}$$

$$\langle \alpha \rangle = -f_\alpha \frac{\overline{\theta}}{\xi}$$

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

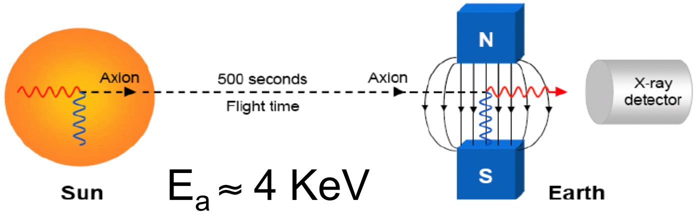
Axions, if they exist, will be very light and will mediate a macroscopic CP- force

$$m_a \approx \frac{m_\pi \cdot f_\pi}{f_a} \approx 6\mu eV \cdot \left(\frac{10^{12}\ GeV}{f_a} \right)$$

f_a : energy scale P.Q.-symmetry is spontaneously broken

AXION SEARCHES using the Primakoff Effect

Axions generated in the sun



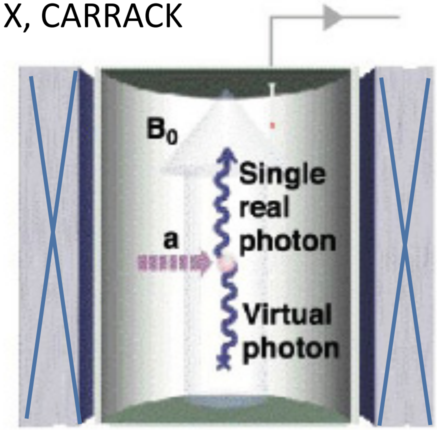
$E_a \approx 4$ KeV

CAST : CERN AXION SOLAR TELESCOPE

Galactic axions

Tunable resonant cavity in magnetic field coupled to a ultra low noise microwave receiver

ADMX, CARRACK

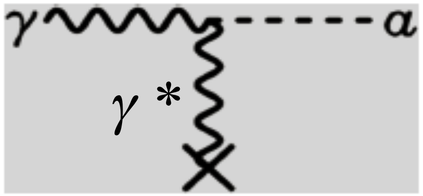


8 Tesla

1GHz: 4 μeV

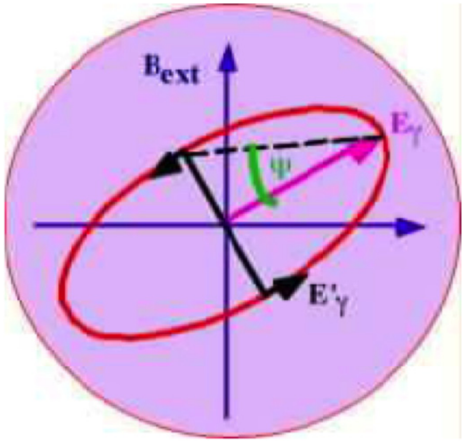
Primakoff Effect

Axion conversion into photon (or the inverse)



Laboratory axions

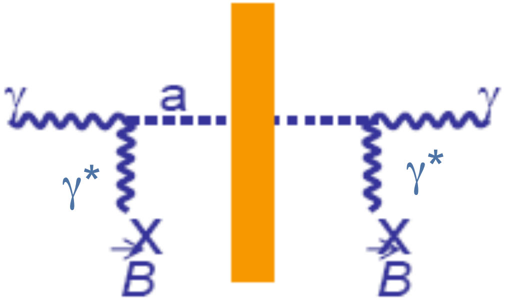
Polarised laser through vacuum in a strong magnetic field (PVLAS)



“Light shines through the wall”

Photonregeneration

(BFRT, OSQAR, ALPS, LIPPS, GammeV)

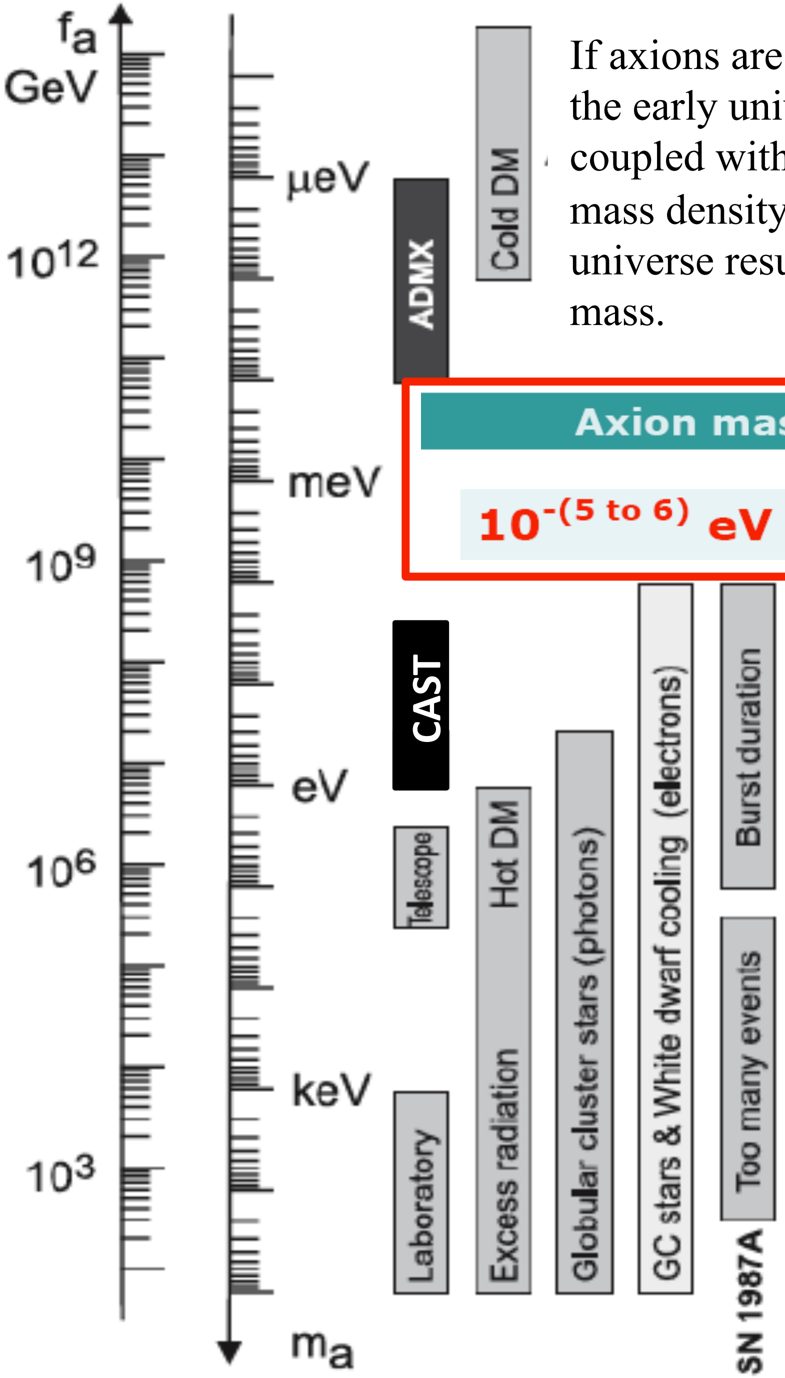


THE CURRENT BOUNDS

C. Hagmann, H. Murayama, G.G. Raffelt, L.J. Rosenberger, and K. van Bibber
2008 Rev. Part. Physics.
Phys. Lett. B 667,1 (2008).

Current Axion Search Experiments

- Solar Axion Telescope – „CAST“
- Dark Matter Axion Search – „ADMX“
- Vacuum Optical Properties –“PVLAS“ etc.
- Photon Disappearance Experiments
- New Force Search – Torsion Pendulums, etc.



If axions are dark matter, they are a relic of the early universe. A particular scenario coupled with the requirement that the axion mass density not severely overclose the universe results in a lower bound to the axion mass.

Axion mass window

$$10^{-(5\text{ to }6)}\ \text{eV} < m_a < 10^{-(2\text{ to }3)}\ \text{eV}$$

Short range interaction of the axion

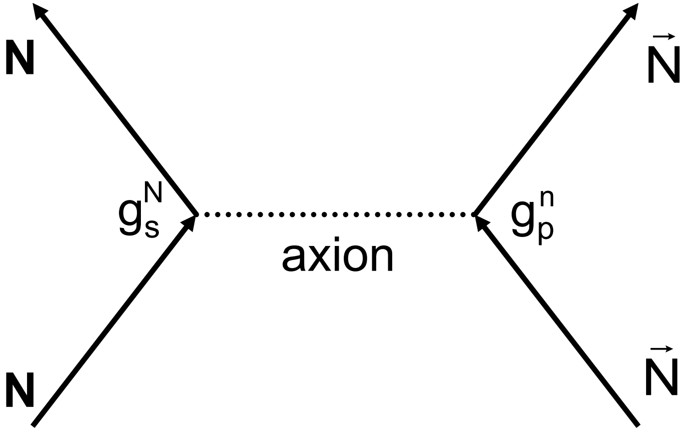
Yukawa-type potential with monopole-dipole coupling:

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

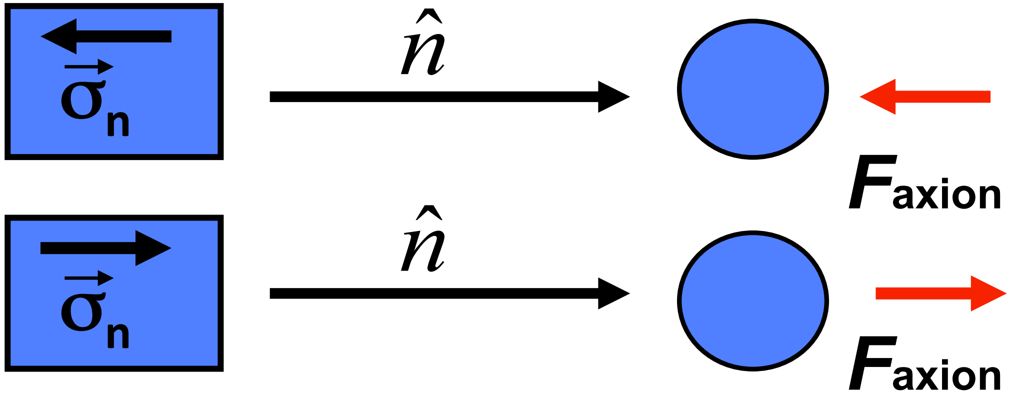
*(Moody and Wilczek PRD **30** 130 (1984))*

$$\text{with:} \qquad \kappa = \frac{\hbar^2 g_s g_p}{8\pi\, m_n} \;, \qquad \lambda = \frac{\hbar}{m_a c}$$

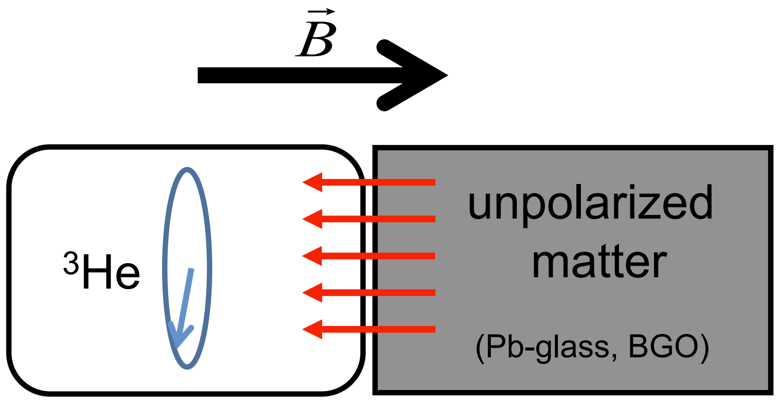
$$\begin{pmatrix} 10^{-6}\,\text{eV} < m_a < 10^{-2}\,\text{eV} \\ 10^{-5}\,\text{m} < \lambda < 10^{-1}\,\text{m} \end{pmatrix}$$



polarized matter $\vec{n}$ **unpolarized matter N**



How to measure?



Position: Close

$$\omega_{\text{L,He}}(t) = \gamma_{\text{He}} \cdot B(t)$$

$$\omega_{\text{Close}}(t) = \omega_{\text{L,He}}(t) + \Delta\omega$$

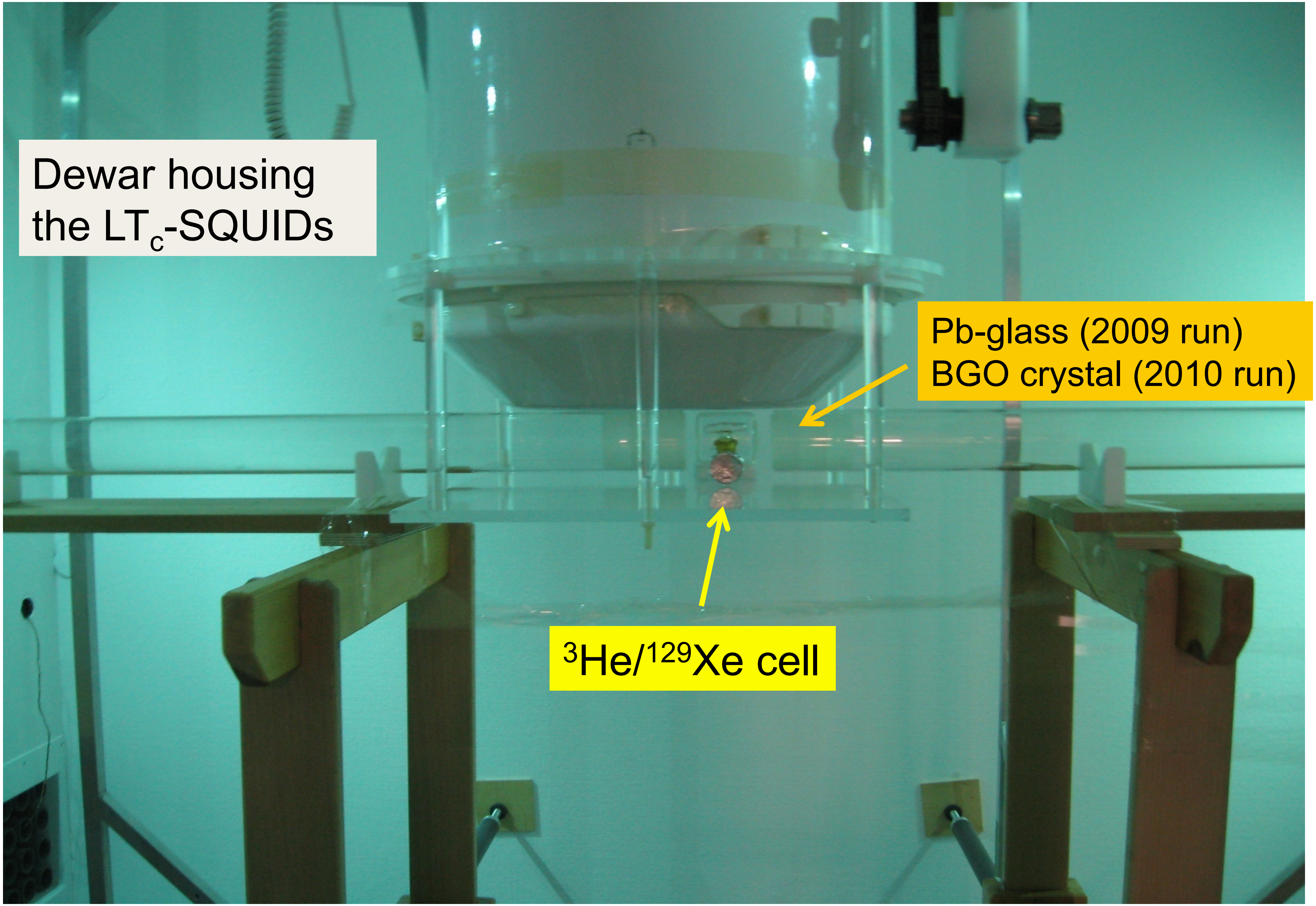
$$\left(\text{with:} \quad \Delta\omega = 2\pi \cdot \delta\nu = \bar{V} / \hbar\right)$$

Position: Far

$$\omega_{\text{Far}}(t) = \omega_{\text{L,He}}(t)$$

$$\Rightarrow \boxed{\Delta\omega = \omega_{\text{Close}} - \omega_{\text{Far}}}$$

Requirement: $\omega_{\text{L,He}}(t) = const.$



Dewar housing
the LT$_c$-SQUIDs

Pb-glass (2009 run)
BGO crystal (2010 run)

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

Data processing for extraction of short-range interaction effect:

1. To cancel magnetic field influence we calculate the weighted phase difference:

$$\Delta\Phi\left(t\right)=\Phi_{He}-\frac{\gamma_{He}}{\gamma_{Xe}}\cdot\Phi_{Xe} \qquad \neq \text{const}$$

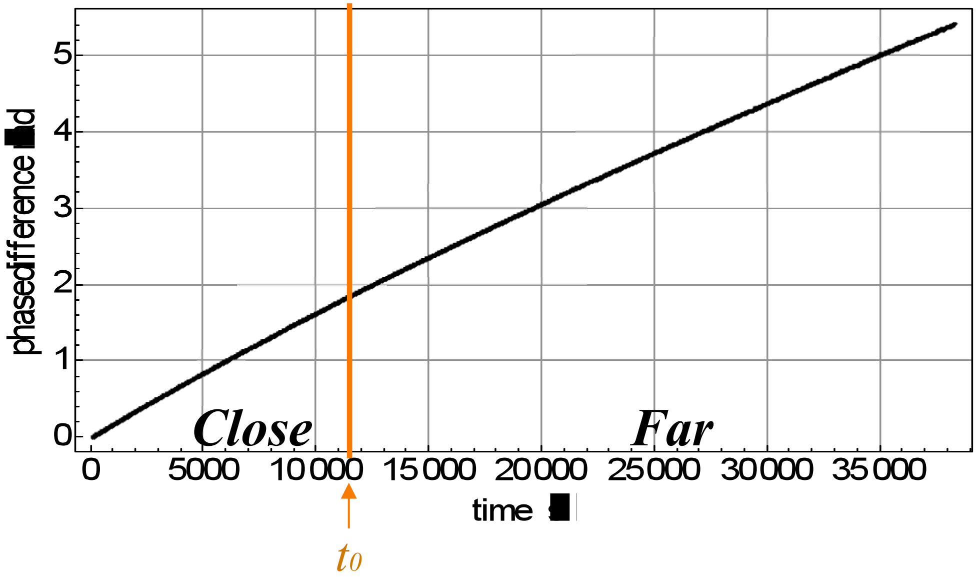
2. Temporal dependence can be described by:

$$f(t)= c+(a_{ER}+a_{CS}+a_{SR})\cdot t+a_{He}\cdot e^{-t/T2,He}+a_{Xe}\cdot e^{-t/T2,Xe}$$

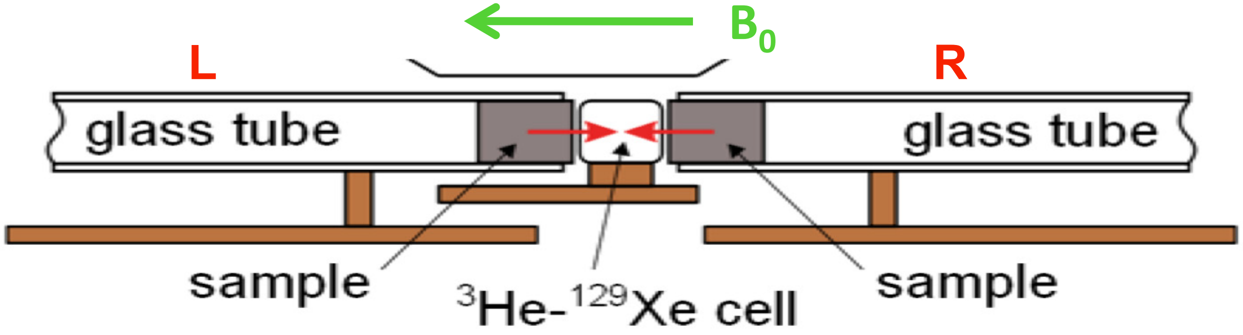
Ramsey-Bloch-Siegert-Shift

- Earth rotation
- chemical shift
- short range !

$$\Delta\omega_{SR} =(a_{SR,close} - a_{SR,far})\cdot \left(1 - \frac{\gamma_{He}}{\gamma_{Xe}}\right)^{-1}$$



Results



September 2010:

11 measurements (~9 hours)

gap = 2.2 mm

Mass sample: BGO crystal with density ρ=7.13 g/cm³

=> $\overline{\Delta\nu_{SR}}$ = (-0.78 ± 1.22 ± 0.15) nHz

	$\Delta\nu_{SR}$ [nHz]	$\delta(\Delta\nu)_{corr.}$ [nHz]	$\delta(\Delta\nu)_{uncorr.}$ [nHz]
C53-**R**	25.17	6.19	0.68
C54-**R**	-7.39	4.28	0.56
C55-**L**	-1.87	4.63	0.52
C60-**L**	15.19	5.19	0.57
C63-**L**	2.34	3.40	0.44
C65-**L**	1.10	4.26	0.54
C67-**R**	-3.82	4.09	0.53
C68-**R**	-7.46	3.39	0.43
C71-**R**	8.04	3.09	0.40
C80-**L**	18.35	3.95	0.51
C82-**L**	-22.00	4.43	0.56

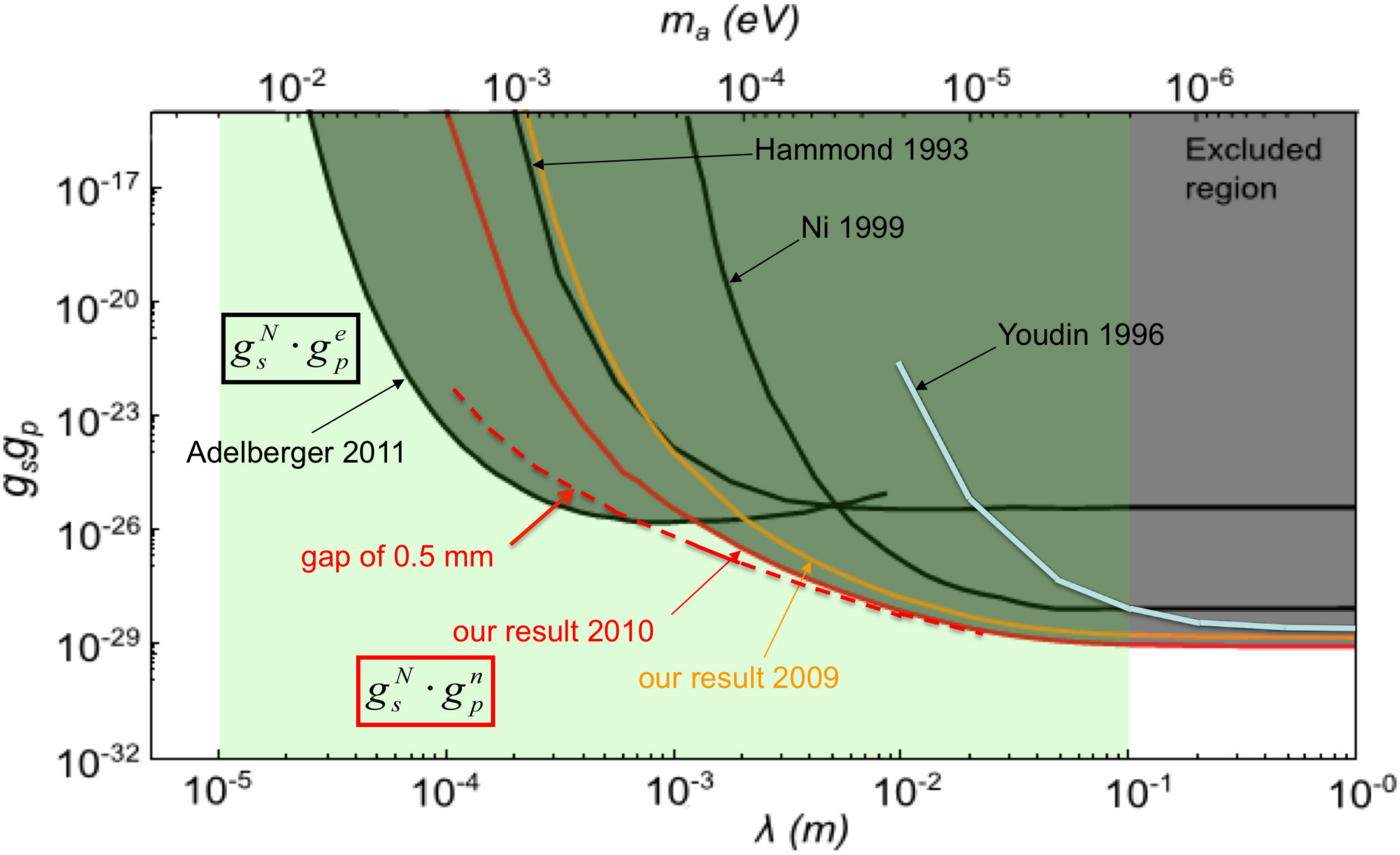
Analysis:

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

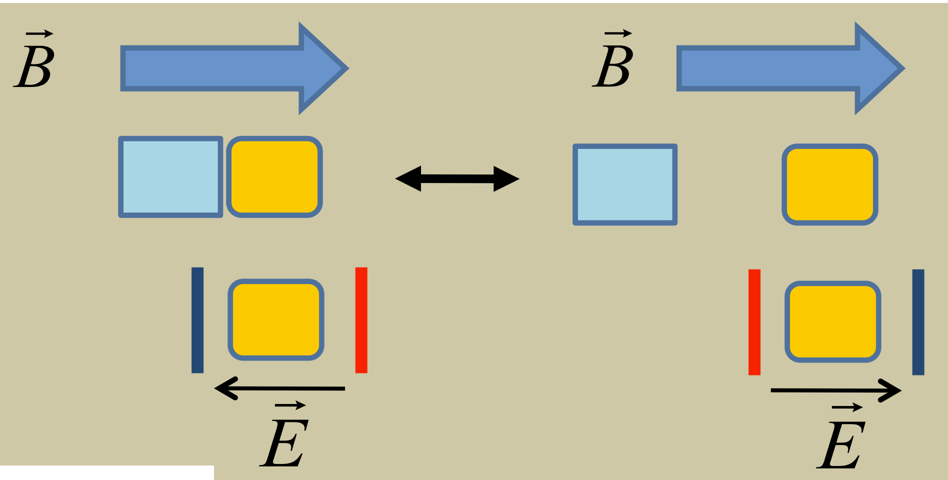
Average potential $<V^*(\lambda)>$ was calculated numerically for our cells (Ø= 6 cm, l = 6 cm), a gap of 2.2 mm between cell inner volume and BGO crystal (Ø= 57 mm, l = 81 mm). Due to the inequation $<V^*(\lambda)>/h < \Delta(\delta\nu)$ the sensitivity level of $g_S g_P$ can be determined by:

$$g_S g_P < 4\,(2\pi)^2\, m_n\, \delta(\overline{\Delta\nu})_{corr} \,/\, (NV\,\hbar <V^*(\lambda)>)$$

Exclusion Plot for new spin-dependent forces



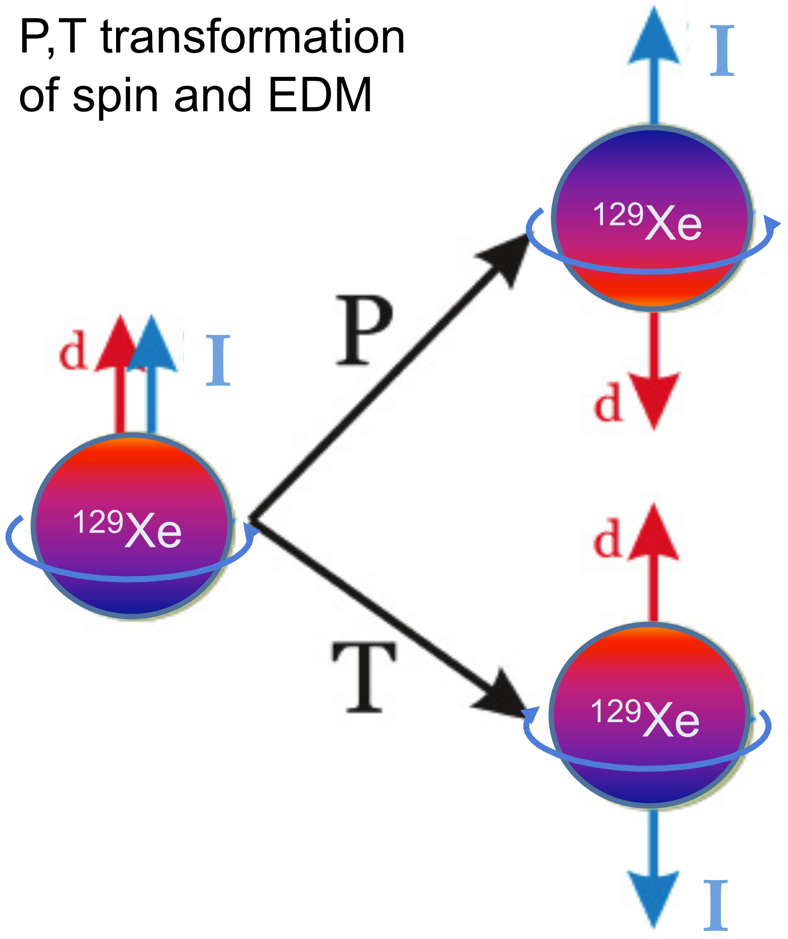
Search for a Xe EDM



short range int.

Xe EDM search

P,T transformation of spin and EDM

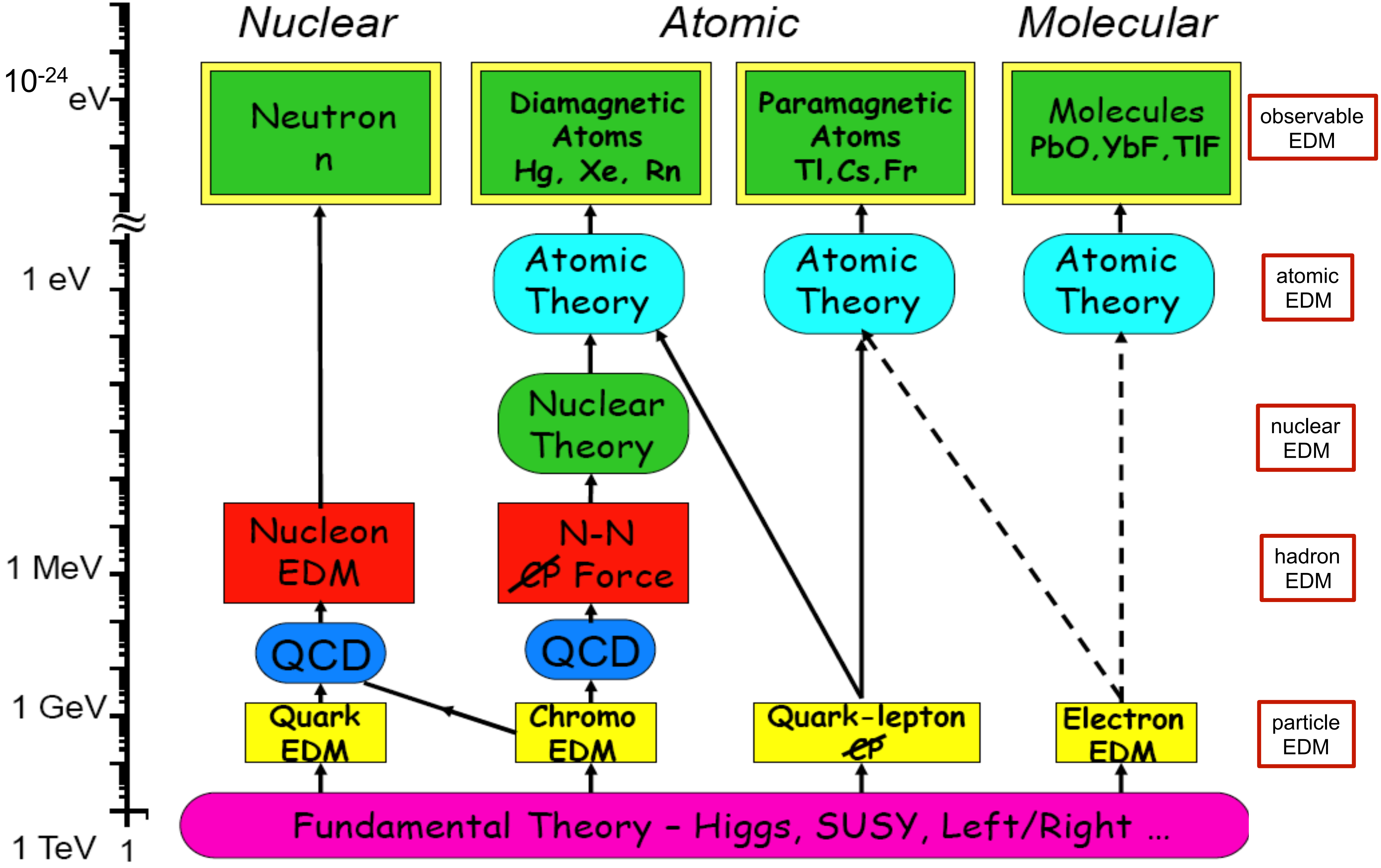


violate
Parity & Time Reversal Symmetry
(and also CP)

→ could offer hint to Matter-Anti-matter Puzzle

Standard-model: CKM-$\cancel{CP}$ too small to produce observed baryon asymmetry

$$\boxed{\eta_{\exp} = \frac{n_B - n_{\overline{B}}}{n_\gamma} = (6.0 \pm 0.3) \cdot 10^{-10}}$$



Nuclear

Atomic

Molecular

10^{-24} eV

1 eV

1 MeV

1 GeV

1 TeV

1

Neutron
n

Diamagnetic
Atoms
Hg, Xe, Rn

Paramagnetic
Atoms
Tl, Cs, Fr

Molecules
PbO, YbF, TlF

observable
EDM

Atomic Theory

Atomic Theory

Atomic Theory

atomic
EDM

Nuclear Theory

nuclear
EDM

Nucleon
EDM

N-N
$\cancel{CP}$ Force

hadron
EDM

QCD

QCD

Quark
EDM

Chromo
EDM

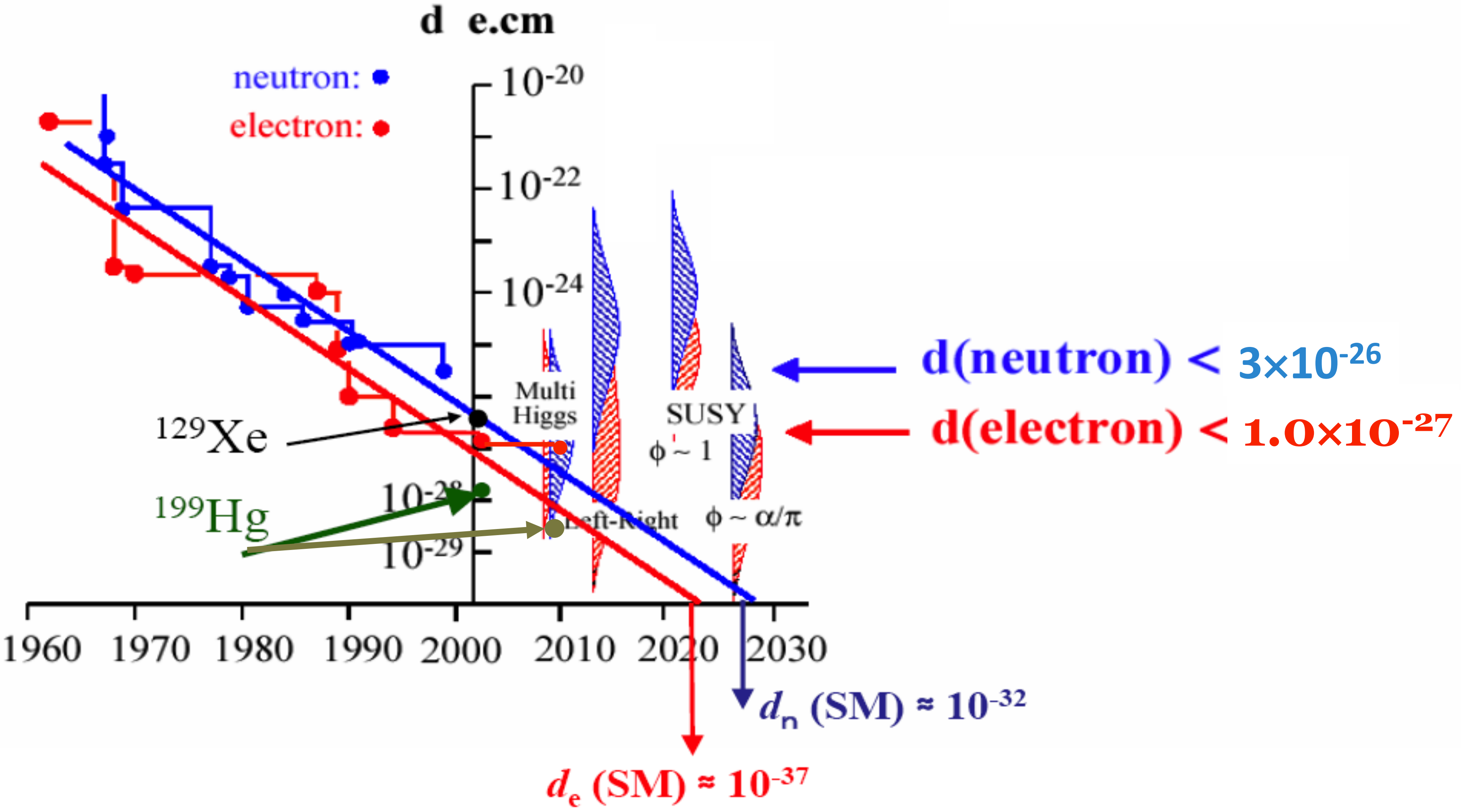
Quark-lepton
$\cancel{CP}$

Electron
EDM

particle
EDM

Fundamental Theory - Higgs, SUSY, Left/Right ...

Experimental upper limits on EDM



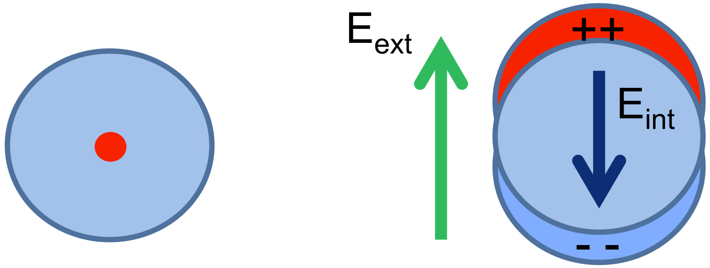
d(neutron) < 3×10^{-26}

d(electron) < 1.0×10^{-27}

d_n (SM) ≈ 10^{-32}

d_e (SM) ≈ 10^{-37}

Atomic EDM's



$E_{ext} + E_{int} = 0$

- L.I.Schiff (*PR* ***132*** *2194,1963*):

  System of non-relativistic charged point particles that interact electrostatically can not have an EDM

- Heavy atoms (relativistic treatment):

$$|d(^{199}\mathrm{Hg})| < 3.1 \times 10^{-29}\ e\ \mathrm{cm}\ (95\%\ \mathrm{C.L.})$$

PRL 102, 101601 (2009)

Parameter	^{199}Hg	Best alternate limit
d_e (*e* cm)	3.0×10^{-27}	YbF:1.0×10^{-27}
d_n (*e* cm)	5.8×10^{-26}	n: 2.9×10^{-26}
C_S	5.2×10^{-8}	Tl:2.4×10^{-7}
C_T	1.5×10^{-9}	TlF:4.5×10^{-7}
C_{PS}	5.1×10^{-7}	TiF: 3×10^{-4}
η	8.0×10^{-5}	Xe: 5×10^{-2}

– $d_e \neq 0 \rightarrow d_{atom} \neq 0$ $\sim Z^3\alpha^2 d_e$

– P,T-odd eN interaction

  Tensor-Pseudotensor $\sim Z^2 G_F C_T$

  Scalar- Pseudoscalar $\sim Z^3 G_F C_S$

– Nuclear EDM – finite size

  Schiff moment induced by P,T-odd N-N interaction $\sim 10^{-25}\ \eta$ [ecm]

- Diamagnetic atoms:

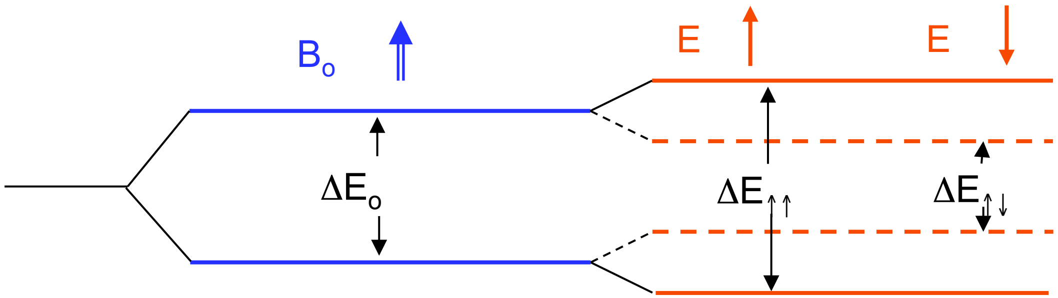
Ginges & Flambaum, Phys. Rep. 397 (04) 63.
Dzuba, Flambaum, Ginges, Phys. Rev. A 66 (02) 012111.

$$d\left(^{199}Hg\right) = 10^{-2} d_e + 2.0\times10^{-20} C_T + 5.9\times10^{-22} C_S + 6\times10^{-23} C_{PS} + 3.9\times10^{-25}\eta \quad [\mathrm{ecm}]$$

$$d\left(^{129}Xe\right) = 10^{-3} d_e + 5.2\times10^{-21} C_T + 5.6\times10^{-23} C_S + 1.2\times10^{-23} C_{PS} + 6.7\times10^{-26}\eta$$

6× less sensitive to CP violating interactions

Measurement sensitivity: ^{129}Xe electric dipole moment



$$h \cdot \Delta \nu = h \cdot \left(\Delta \upsilon_{\uparrow\uparrow} - \Delta \upsilon_{\uparrow\downarrow} \right) = 4 \cdot E \cdot |d_{Xe}|$$

Rosenberry and Chupp, PRL 86,22 (2001)

$|d_{Xe}| = (0.7 \pm 3.3 \pm 0.1) \times 10^{-27}$ ecm

Observable:
weighted frequency difference

$$\Delta \upsilon_{\uparrow\uparrow} = \Delta \upsilon_{\uparrow\uparrow}^{He,EDM} - (\gamma_{He}/\gamma_{Xe}) \cdot \Delta \upsilon_{\uparrow\uparrow}^{Xe,EDM} \approx -(\gamma_{He}/\gamma_{Xe}) \cdot \Delta \upsilon_{\uparrow\uparrow}^{Xe,EDM}$$

$$\Delta \upsilon_{\uparrow\downarrow} = \Delta \upsilon_{\uparrow\downarrow}^{He,EDM} - (\gamma_{He}/\gamma_{Xe}) \cdot \Delta \upsilon_{\uparrow\downarrow}^{Xe,EDM} \approx -(\gamma_{He}/\gamma_{Xe}) \cdot \Delta \upsilon_{\uparrow\downarrow}^{Xe,EDM}$$

sensitivity limit:

$$\boxed{|d_{Xe}| < \frac{\pi \cdot \hbar}{2E \cdot (\gamma_{He}/\gamma_{Xe})} \cdot \delta \upsilon}$$

from 2010 run: $\delta \nu$ = 0.2 nHz @ 1 day

assume : E=2 kV/cm

$$\Rightarrow \quad |d_{Xe}| < 4 \cdot 10^{-29} ecm$$

Then we will reach

… after 100 days of data taking: $|d_{Xe}| \approx 4 \cdot 10^{-30} ecm$

Proposed setup

Collaboration:

University of Mainz
KVI Groningen
University of Heidelberg
PTB Berlin

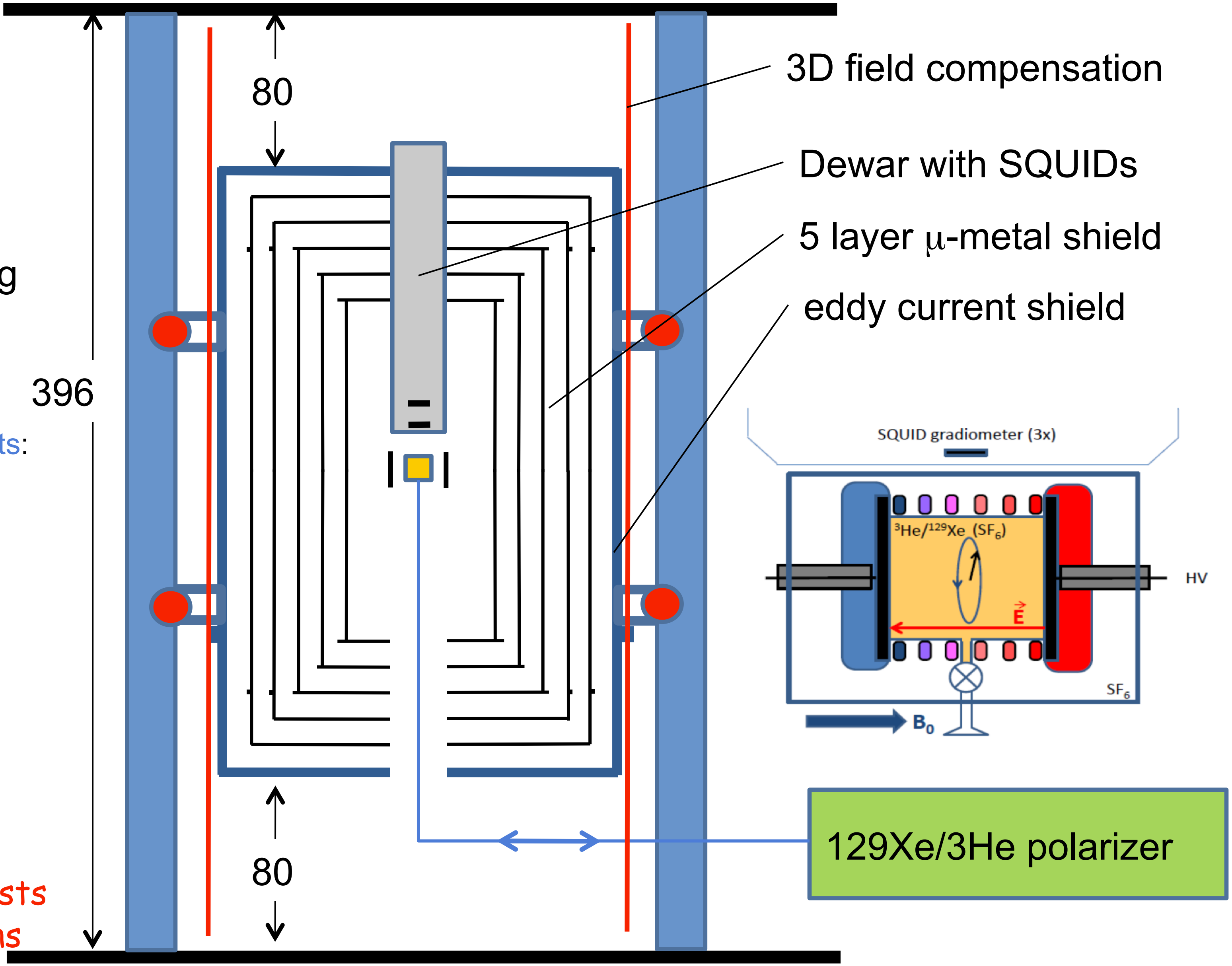
There is room for improvements:

- Increase of SNR of Xe
  (P_{xe}: 10% ⇒ 70%)
- Increase of $T_{2,Xe}$
  5h (at present) ⇒ 10-20 h

➢ $\delta d_{Xe} < 10^{-31}$ ecm

…new sensitivity levels for

- ➢ Lorentz-invariance tests
- ➢ short range interations



3D field compensation

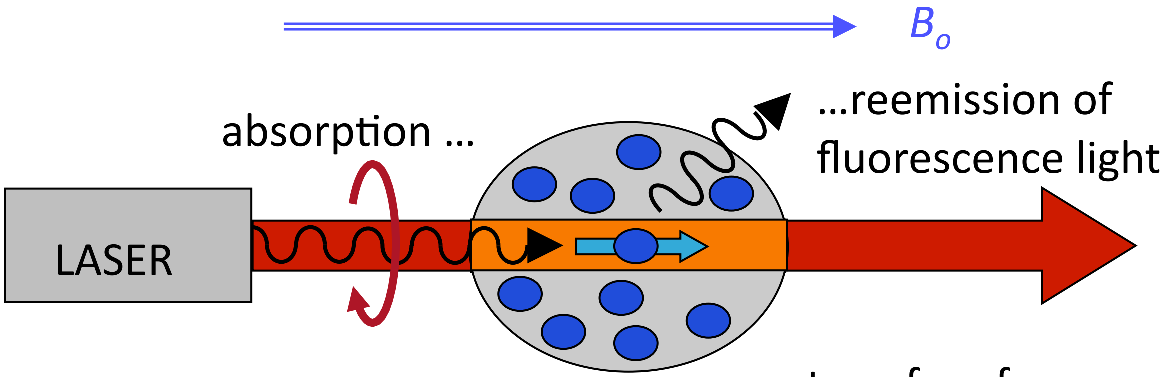
Dewar with SQUIDs

5 layer μ-metal shield

eddy current shield

129Xe/3He polarizer

Optical Pumping

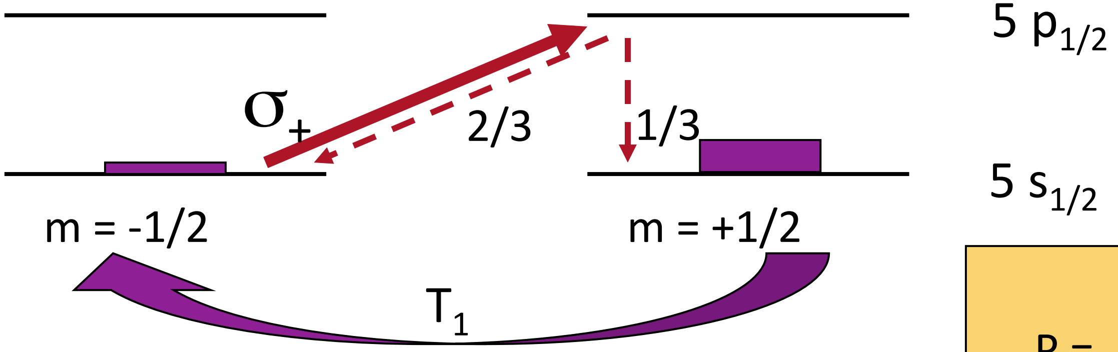


absorption …

…reemission of fluorescence light

…transfer of angular momentum

Rb-pumping



rate equation:

$$N \cdot \frac{dP}{dt} = \xcancel{2 \cdot \eta(P) \cdot \frac{dL}{dt}} / \hbar - P \cdot N / T_1$$

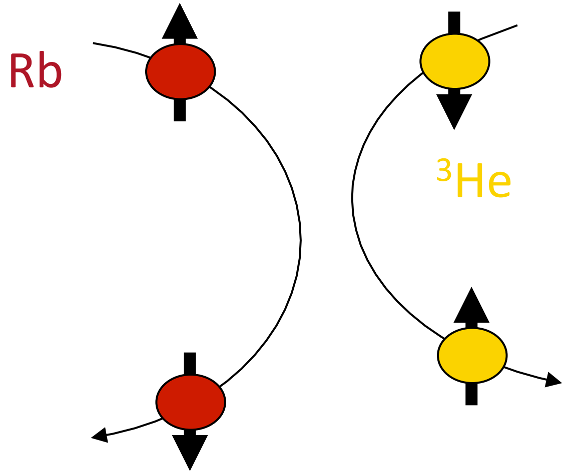
$$P = \frac{N(1/2) - N(-1/2)}{N(1/2) + N(-1/2)}$$

$$= 1 - (2/3)^n$$

Optical Pumping of ^{3}He

history :

- Spin exchange with optically pumped Rb-vapour (SEOP)
  (Bouchiat et al., Phys. Rev. Lett. 5 (1960) 373)



$p_{He} \approx$ 1-10 bar

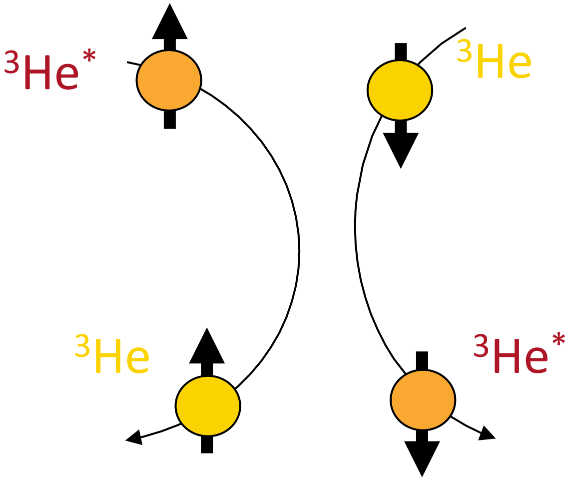
$$H_{HFI} = \alpha \cdot \vec{S}_{Rb} \cdot \vec{I}_{He} \quad \left(\Delta E / \hbar \approx 10^8\, Hz\right)$$

$$collision \;\; time : \tau_c \approx 10^{-12}\, s$$

$$\Gamma_{SE} \approx \left\langle \left(\tau_c \cdot \Delta E / \hbar\right)^2 \cdot \sigma_{SE} \cdot v_r \right\rangle \cdot [Rb]$$

$$\approx 10^{-8} \cdot \langle \sigma_{SE} \cdot v_r \rangle \cdot [Rb] \approx \frac{1}{3}\left[h^{-1}\right]$$

- Optical pumping of metastable ^{3}He*-atoms (MEOP)
  (Colegrove et al., Phys. Rev. 132 (1963) 2561)



$p_{He} \approx$ 1 mbar

$$\Gamma_{ME} \approx \langle \sigma_{ME} \cdot v_r \rangle \cdot \lfloor {}^3 He_{\_}$$

$$\approx 1\left[s^{-1}\right]$$

PHYSICAL REVIEW VOLUME 132, NUMBER 6 15 DECEMBER 1963

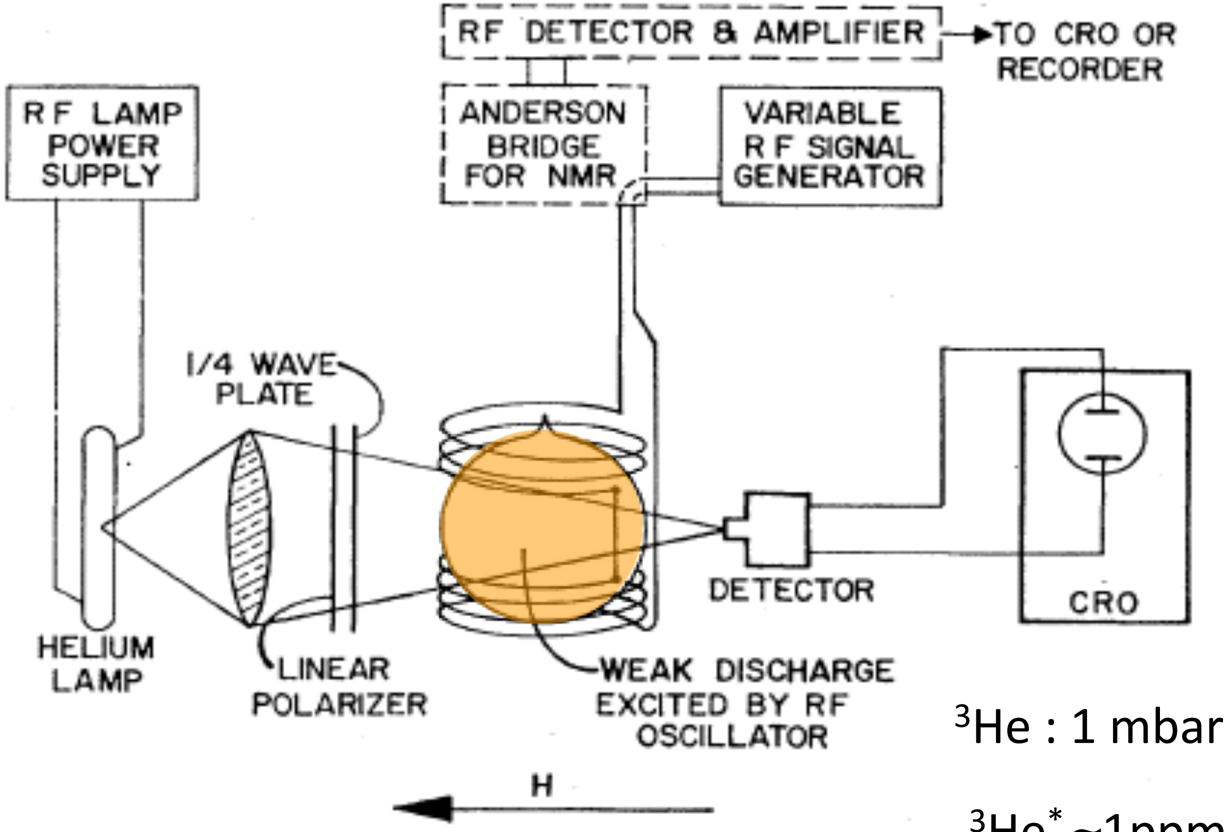
Polarization of He^3 Gas by Optical Pumping

F. D. COLEGROVE, L. D. SCHEARER,* AND G. K. WALTERS*
Texas Instruments Incorporated, Dallas, Texas

(Received 5 August 1963)

MEOP: Metastabilty Exchange Optical Pumping

L.D. Schearer



^{3}He : 1 mbar

$^3He^* \approx$1ppm

In terms of frequency:

$$\upsilon_\perp = a_{\max} \cdot \frac{\Omega_s}{2\pi} = (26.1 \pm 26.6)\,\mathrm{nHz}$$ (95% C.L.)

Kostelecky et al. , Phys. Rev. D 60, 1160[illegible] (1999)

free neutron:

n : μ = -1.913 μ_K

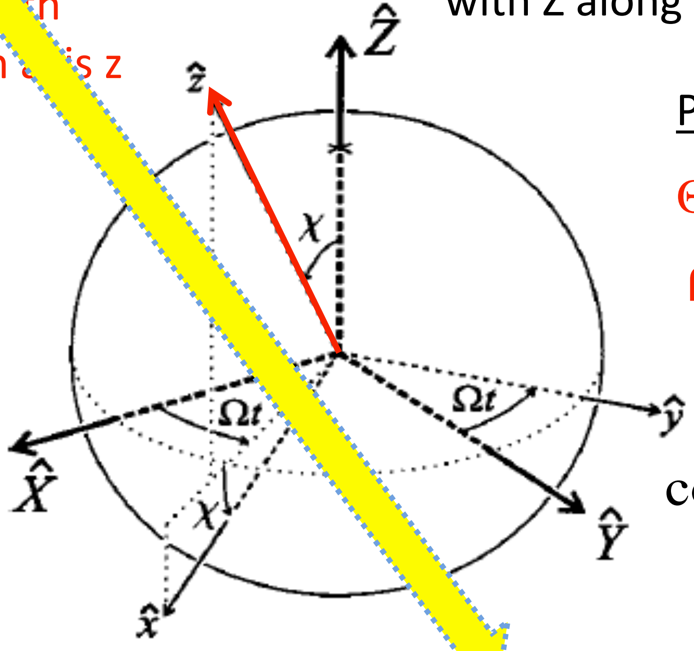
Schmidt-Model

^{3}He: μ = -2.1276 μ_K

^{129}Xe: μ = -0.7779 μ_K

Lab-frame with quantization axis z

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



PTB Berlin:

Θ= 52,5164^0 north

ρ= 28^0 (north-south)

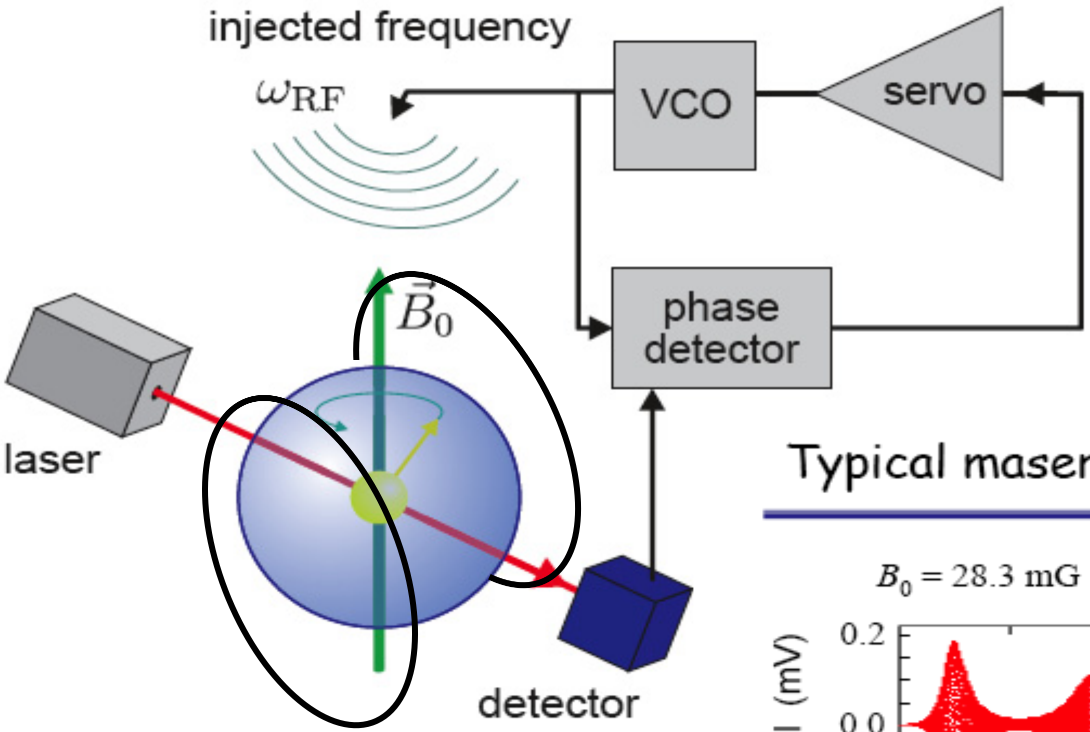
$$\cos\chi = \cos\theta \cdot \cos\rho$$
$$= 0.543$$

$$\sin\chi \cdot \left| -3.5 \cdot \tilde{b}^n_\perp + 0.012 \cdot \tilde{d}^n_\perp + 0.012 \cdot \tilde{g}^n_{D,\perp} \right| \leq 2\pi \cdot \delta\upsilon_\perp \cdot \hbar$$

$$\tilde{b}^n_\perp \leq 3.72 \cdot 10^{-32}\ GeV \quad (95\% \quad C.L.)$$

Feedback loop to get long coherence times …

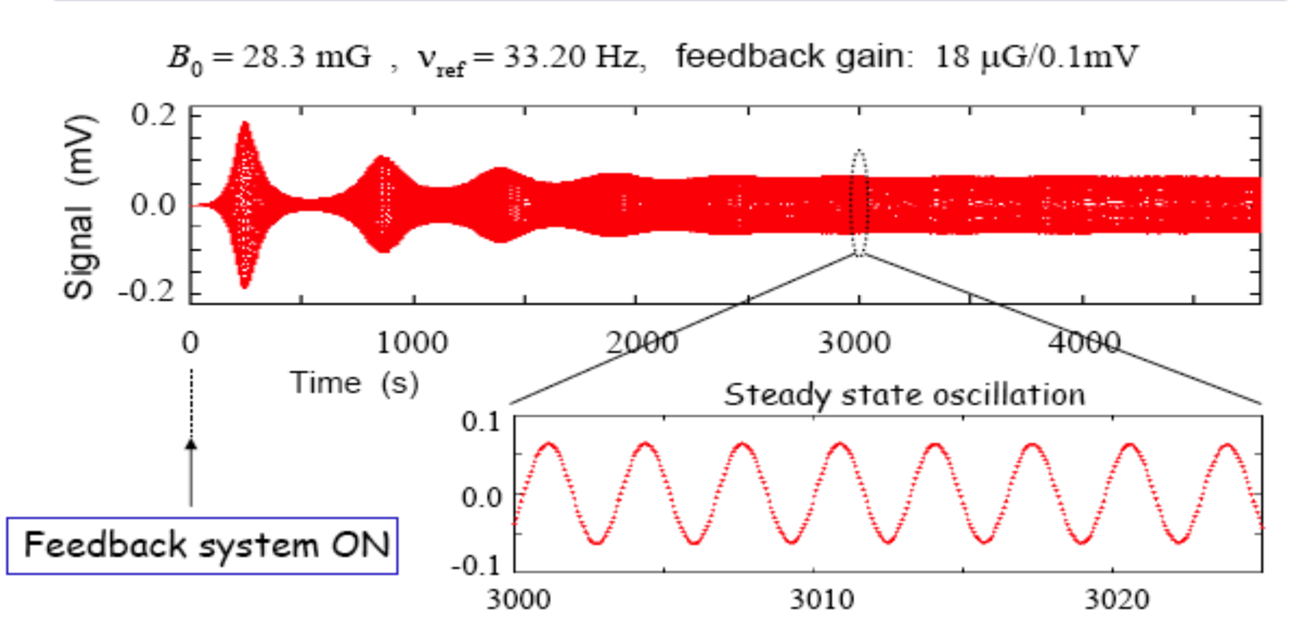
(Cs-Magnetometer, Maser, …)



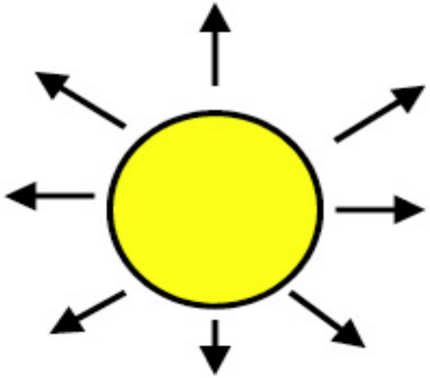
but …

- ➢ frequency shifts due to feedback phase error
- ➢ light shift
- ➢ …

Typical maser oscillation signal

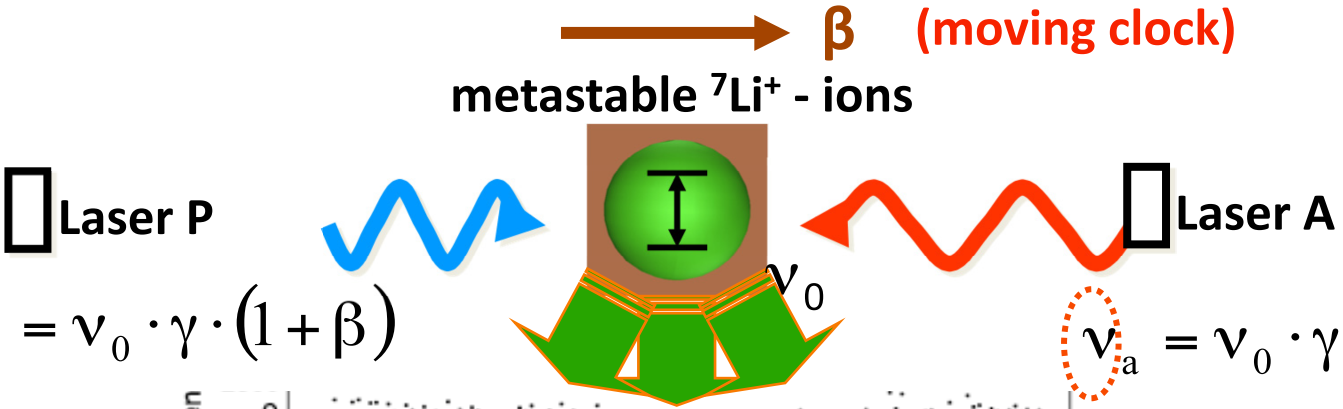


Astrophysics limits on axion



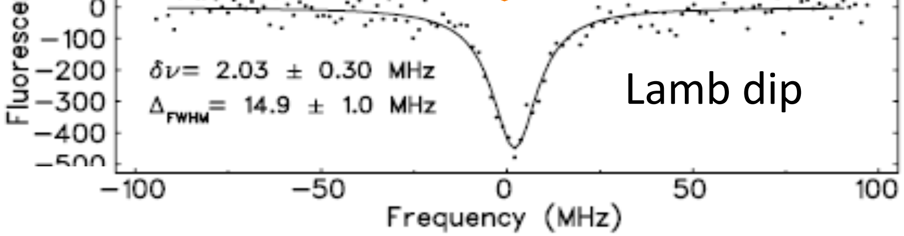
Observation	Bound on Coupling	Bound on Mass
Solar ^{8}B Neutrino Flux	$g_{a\gamma\gamma} < 5\times10^{-10}\,\mathrm{GeV}^{-1}$	$m_a < 1\,\mathrm{eV}$
Lifetime of HB Stars	$g_{a\gamma\gamma} < 1\times10^{-10}\,\mathrm{GeV}^{-1}$	$m_a < 0.3\,\mathrm{eV}$
Cooling rate of White Dwarf G117-B15A	$\frac{C_e m_e}{f_a} < 1\times10^{-13}$	$m_a < 0.005\,\mathrm{eV}$
Cooling rate of SN1987A	$\frac{C_N m_N}{f_a} < 6\times10^{-10}$	$m_a < 0.02\,\mathrm{eV}$

G. Raffelt, Lecture Notes in Physics **741** (2008)



$\nu_p = \nu_0 \cdot \gamma \cdot (1+\beta)$

$\nu_a = \nu_0 \cdot \gamma \cdot (1-\beta)$



$$\frac{\nu_a \cdot \nu_p}{\nu_0^2} \equiv \gamma_{MS}^2 \cdot (1-\beta^2)$$

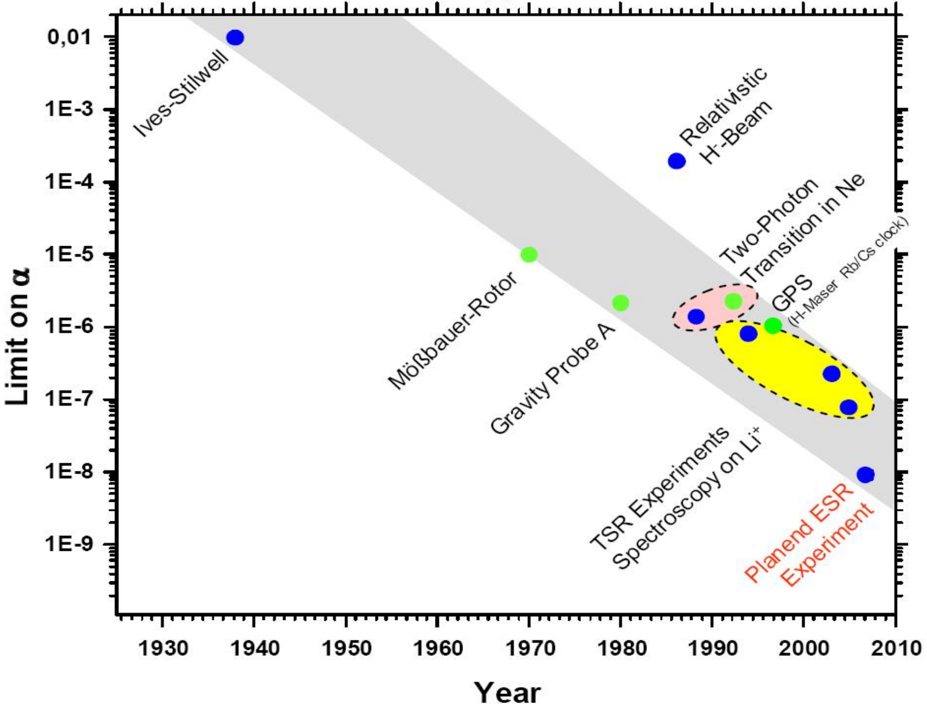
$$= 1 + 2 \cdot \hat{\alpha} \cdot \beta^2$$

$$\boxed{\hat{\alpha} < 2.2 \times 10^{-7}}$$

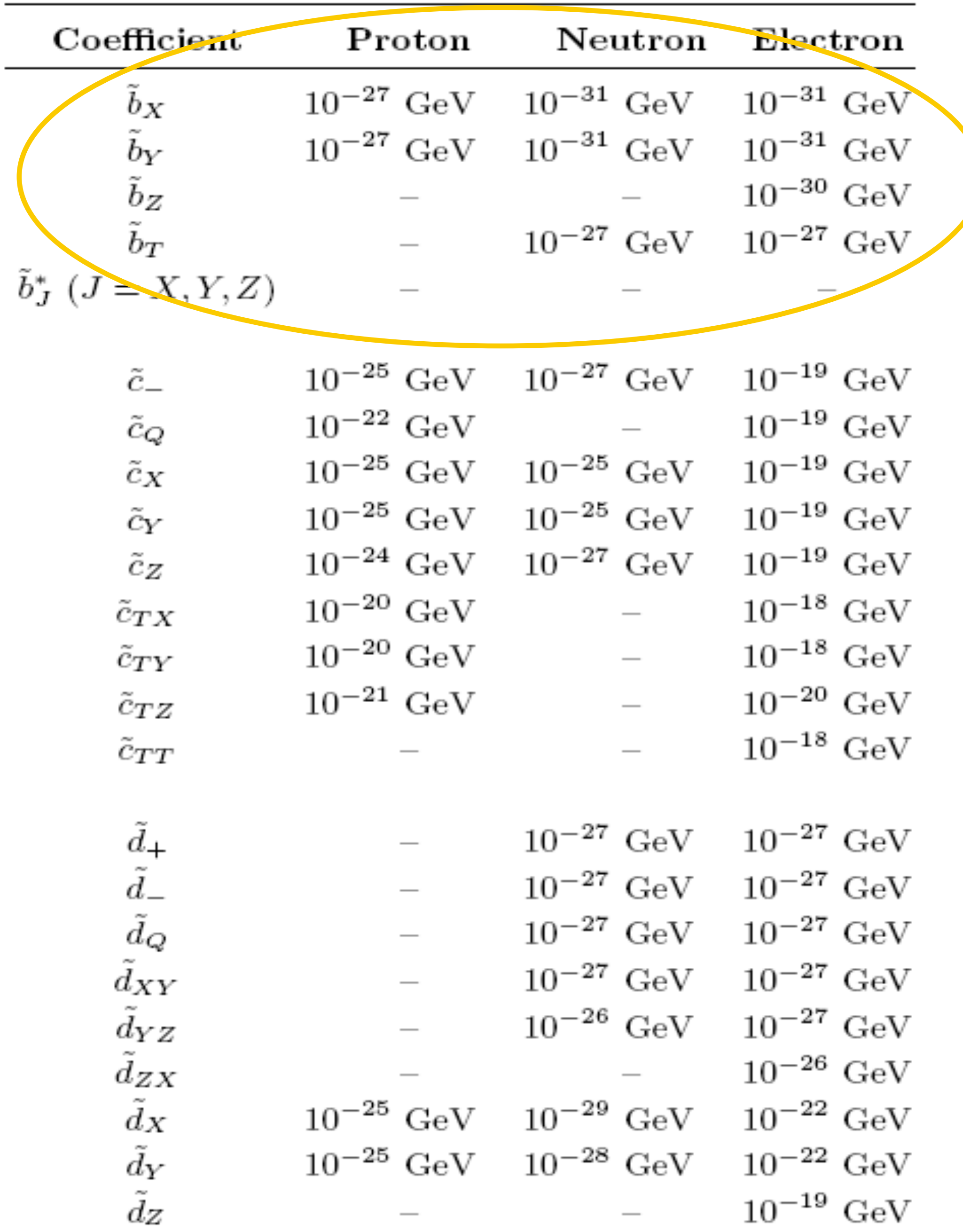
$$|c^p_{XX} + c^p_{YY} - 2c^p_{ZZ}| \lesssim 10^{-11},$$
$$|c^p_{TJ} + c^p_{JT}| \lesssim 10^{-8} \ (J = X, Y, Z),$$
$$|c^e_{XX} + c^e_{YY} - 2c^e_{ZZ}| \lesssim 10^{-5},$$
$$\text{and } |c^e_{TJ} + c^e_{JT}| \lesssim 10^{-2} \ (J = X, Y, Z).$$

Ch.D.Lane, PRD 72 (2005) 016005

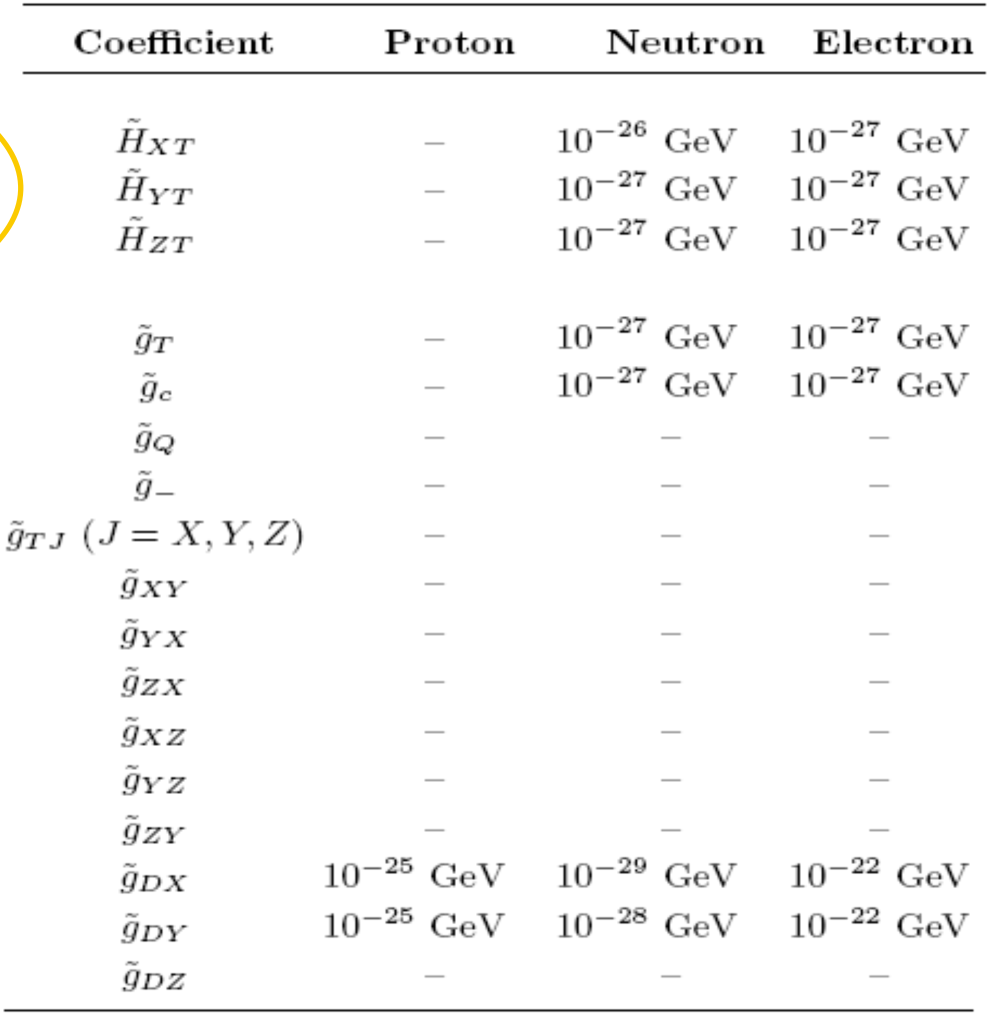
Evolution of the upper bound of α



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

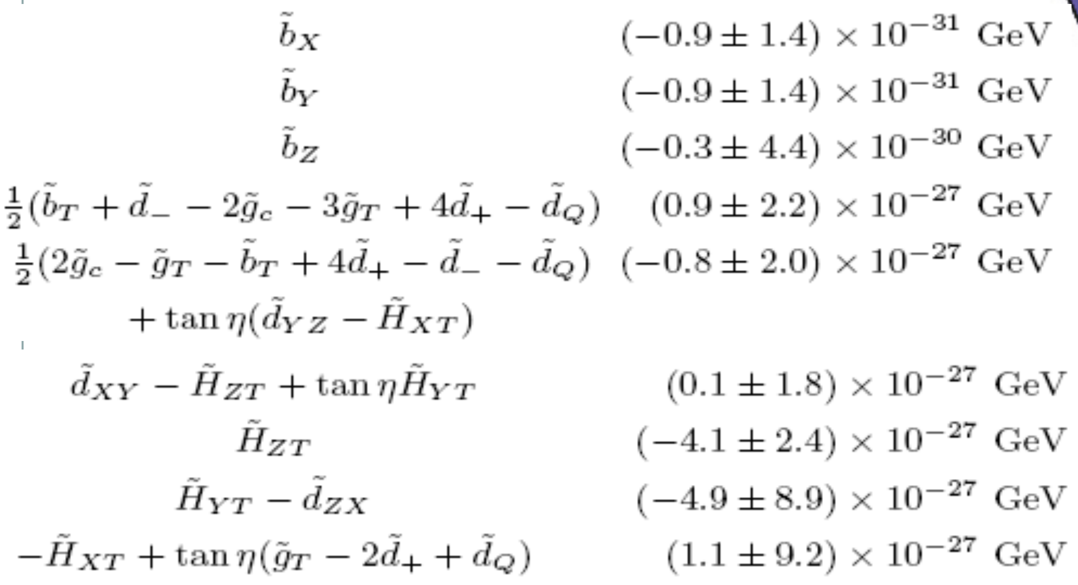


Coefficient	Proton	Neutron	Electron
$\tilde{H}_{XT}$	–	10^{-26} GeV	10^{-27} GeV
$\tilde{H}_{YT}$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{H}_{ZT}$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{g}_T$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{g}_c$	–	10^{-27} GeV	10^{-27} GeV
$\tilde{g}_Q$	–	–	–
$\tilde{g}_-$	–	–	–
$\tilde{g}_{TJ}$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

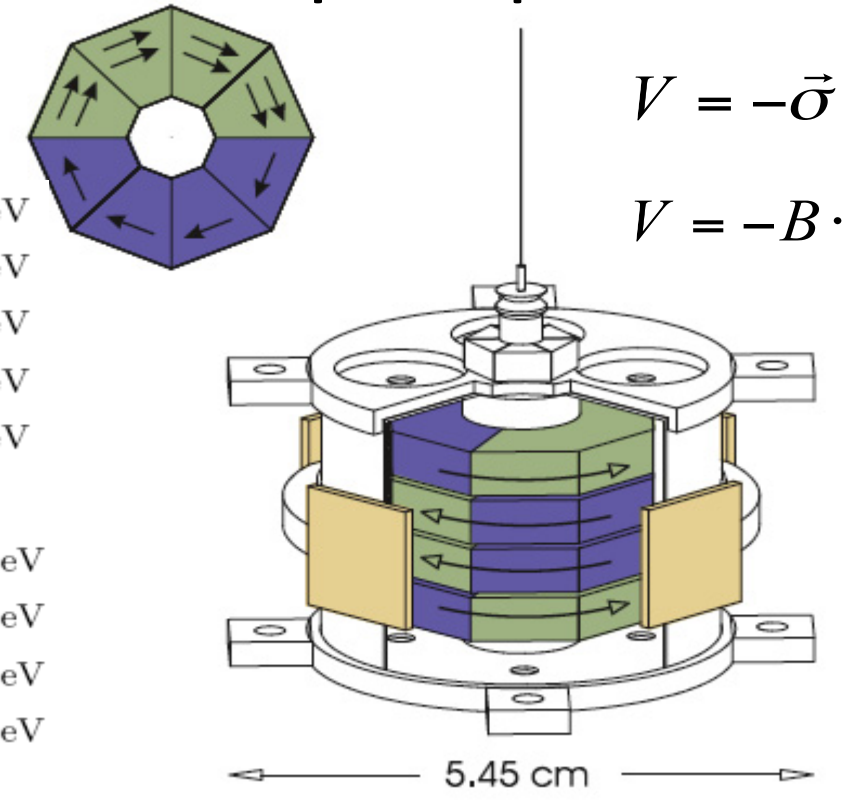
Torsion pendulum

B.R.Heckel et al., PRD 78 (2008) 092006



$\tilde{b}_X$	$(-0.9 \pm 1.4) \times 10^{-31}$ GeV
$\tilde{b}_Y$	$(-0.9 \pm 1.4) \times 10^{-31}$ GeV
$\tilde{b}_Z$	$(-0.3 \pm 4.4) \times 10^{-30}$ GeV
$\frac{1}{2}(\tilde{b}_T + \tilde{d}_- - 2\tilde{g}_c - 3\tilde{g}_T + 4\tilde{d}_+ - \tilde{d}_Q)$	$(0.9 \pm 2.2) \times 10^{-27}$ GeV
$\frac{1}{2}(2\tilde{g}_c - \tilde{g}_T - \tilde{b}_T + 4\tilde{d}_+ - \tilde{d}_- - \tilde{d}_Q)$ $+ \tan\eta(\tilde{d}_{YZ} - \tilde{H}_{XT})$	$(-0.8 \pm 2.0) \times 10^{-27}$ GeV
$\tilde{d}_{XY} - \tilde{H}_{ZT} + \tan\eta \tilde{H}_{YT}$	$(0.1 \pm 1.8) \times 10^{-27}$ GeV
$\tilde{H}_{ZT}$	$(-4.1 \pm 2.4) \times 10^{-27}$ GeV
$\tilde{H}_{YT} - \tilde{d}_{ZX}$	$(-4.9 \pm 8.9) \times 10^{-27}$ GeV
$-\tilde{H}_{XT} + \tan\eta(\tilde{g}_T - 2\tilde{d}_+ + \tilde{d}_Q)$	$(1.1 \pm 9.2) \times 10^{-27}$ GeV

spin-coupled interactions



$$V = -\vec{\sigma} \cdot \vec{A}$$

$$V = -B \cdot \vec{\sigma} \cdot \vec{v} / c$$

Antihydrogen Spectroscopy (→ J. Walz)

1S–2S frequency difference: $\Delta^{H-\bar{H}} \nu_{1S-2S} \approx -(b_3^e - b_3^p)/\pi$

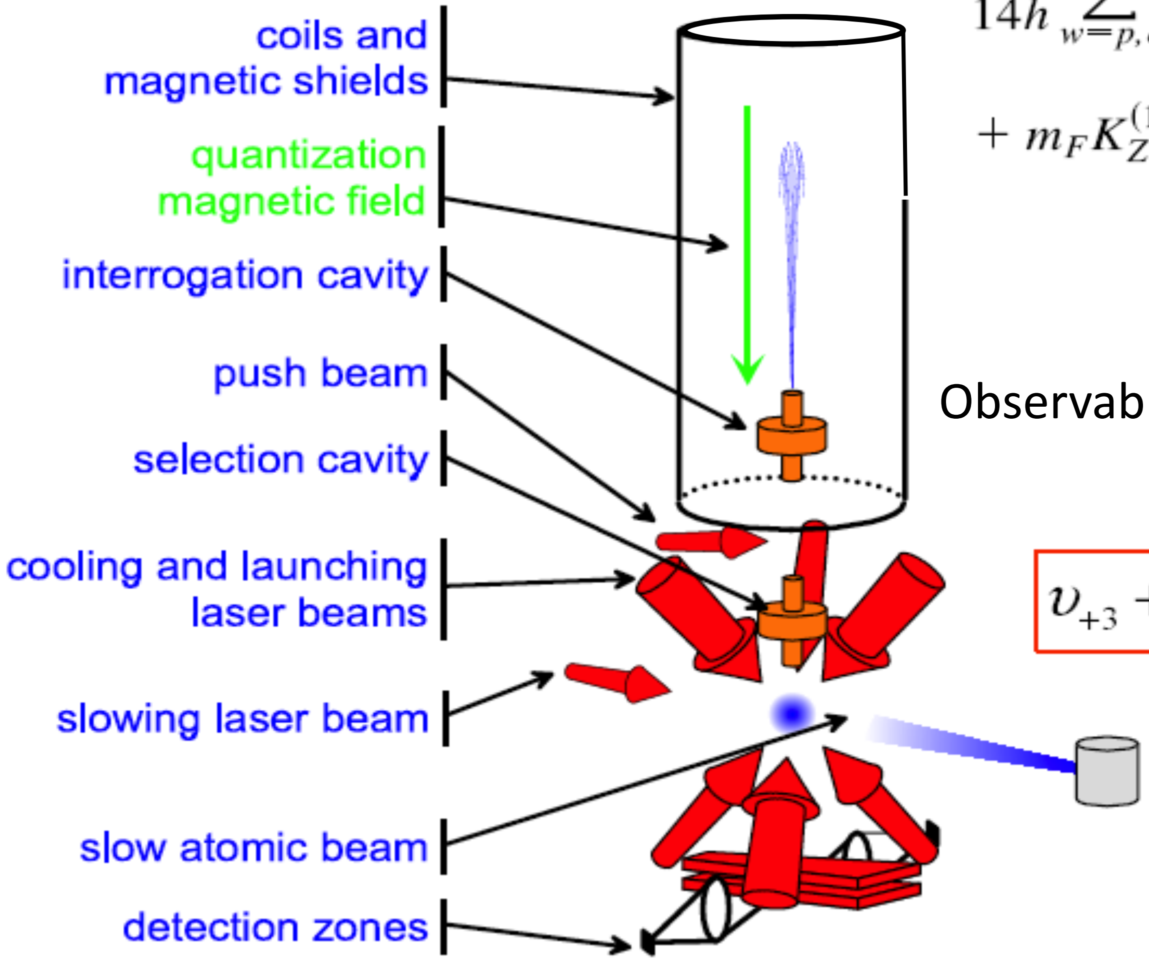
Ground state HFS frequency difference: $\Delta^{H-\bar{H}} \nu_{HFS} \approx -2b_3^p/\pi$

Fundamental physics tests using Rb and Cs fountains

Wolf et al., PRL **96,** 060801 (2006)

Cs $|3, m_F\rangle \leftrightarrow |4, m_F\rangle$ transition in the SME

$$\delta\nu = \frac{m_F}{14h}\sum_{w=p,e}(\beta_w \tilde{b}_3^w - \delta_w \tilde{d}_3^w + \kappa_w \tilde{g}_d^w) - \frac{m_F^2}{14h}(\gamma_p \tilde{c}_q^p) + m_F K_Z^{(1)} B + \left(1 - \frac{m_F^2}{16}\right) K_Z^{(2)} B^2$$



Observable free of 1st order Zeeman-effect

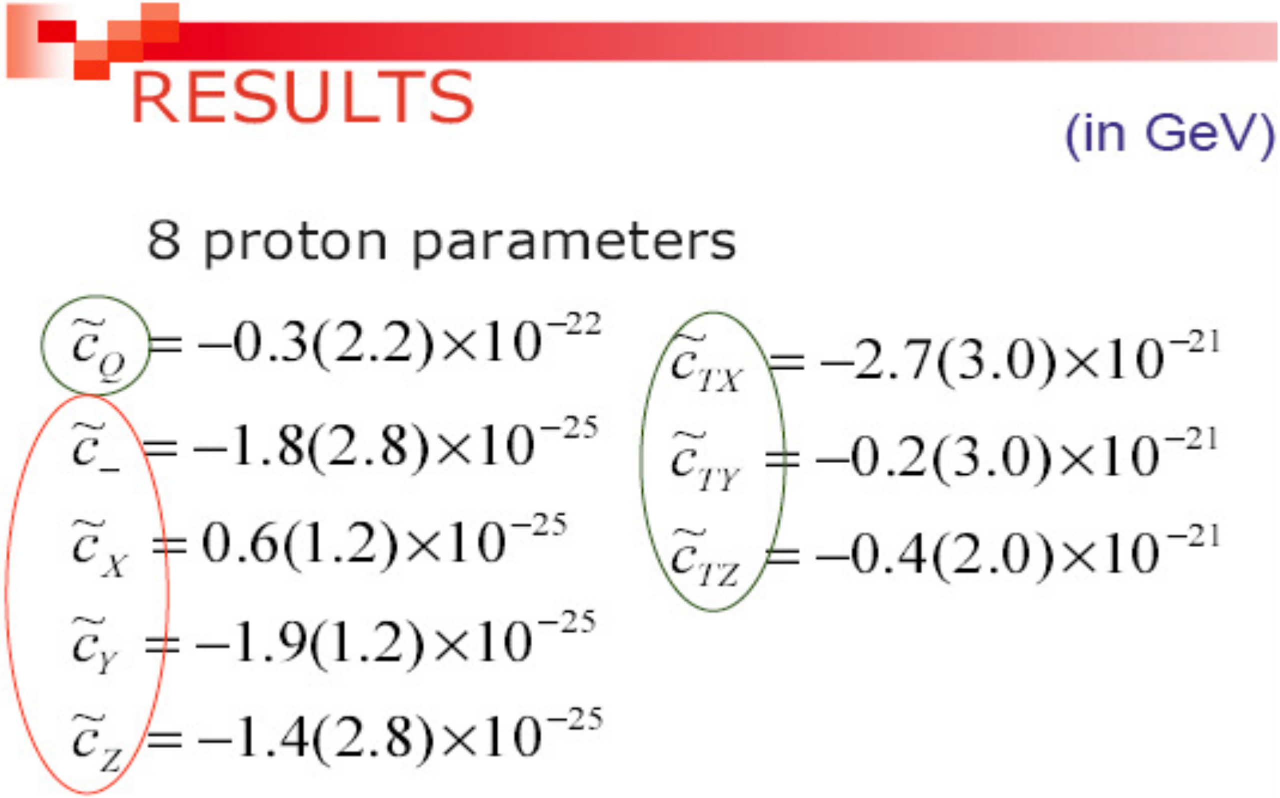
$$\boxed{\upsilon_{+3} + \upsilon_{-3} - 2\upsilon_0 = \tfrac{1}{7h} K_p \tilde{c}_q^{\,p} - \tfrac{9}{8} K_z^{(2)} B^2}$$

$$\boxed{\tilde{c}_q^{\,p} = A + C_{\Omega_\oplus}\cos(\omega_\oplus t) + S_{\Omega_\oplus}\sin(\omega_\oplus t) + C_{2\Omega_\oplus}\cos(2\omega_\oplus t) + S_{2\Omega_\oplus}\sin(2\omega_\oplus t)}$$

$\Omega_\oplus$: Earth‘s orbital motion

$\omega_\otimes$: Earth‘s rotation frequency

A, C_i, S_i, are functions of the 8 proton components: $\tilde{c}_Q, \tilde{c}_X, \tilde{c}_Y, \tilde{c}_Z, \tilde{c}_-, \tilde{c}_{TX}, \tilde{c}_{TY}, \tilde{c}_{TZ}$



RESULTS

(in GeV)

8 proton parameters

$\tilde{c}_Q = -0.3(2.2)\times10^{-22}$

$\tilde{c}_- = -1.8(2.8)\times10^{-25}$

$\tilde{c}_X = 0.6(1.2)\times10^{-25}$

$\tilde{c}_Y = -1.9(1.2)\times10^{-25}$

$\tilde{c}_Z = -1.4(2.8)\times10^{-25}$

$\tilde{c}_{TX} = -2.7(3.0)\times10^{-21}$

$\tilde{c}_{TY} = -0.2(3.0)\times10^{-21}$

$\tilde{c}_{TZ} = -0.4(2.0)\times10^{-21}$

Relaxation of ^{129}Xe

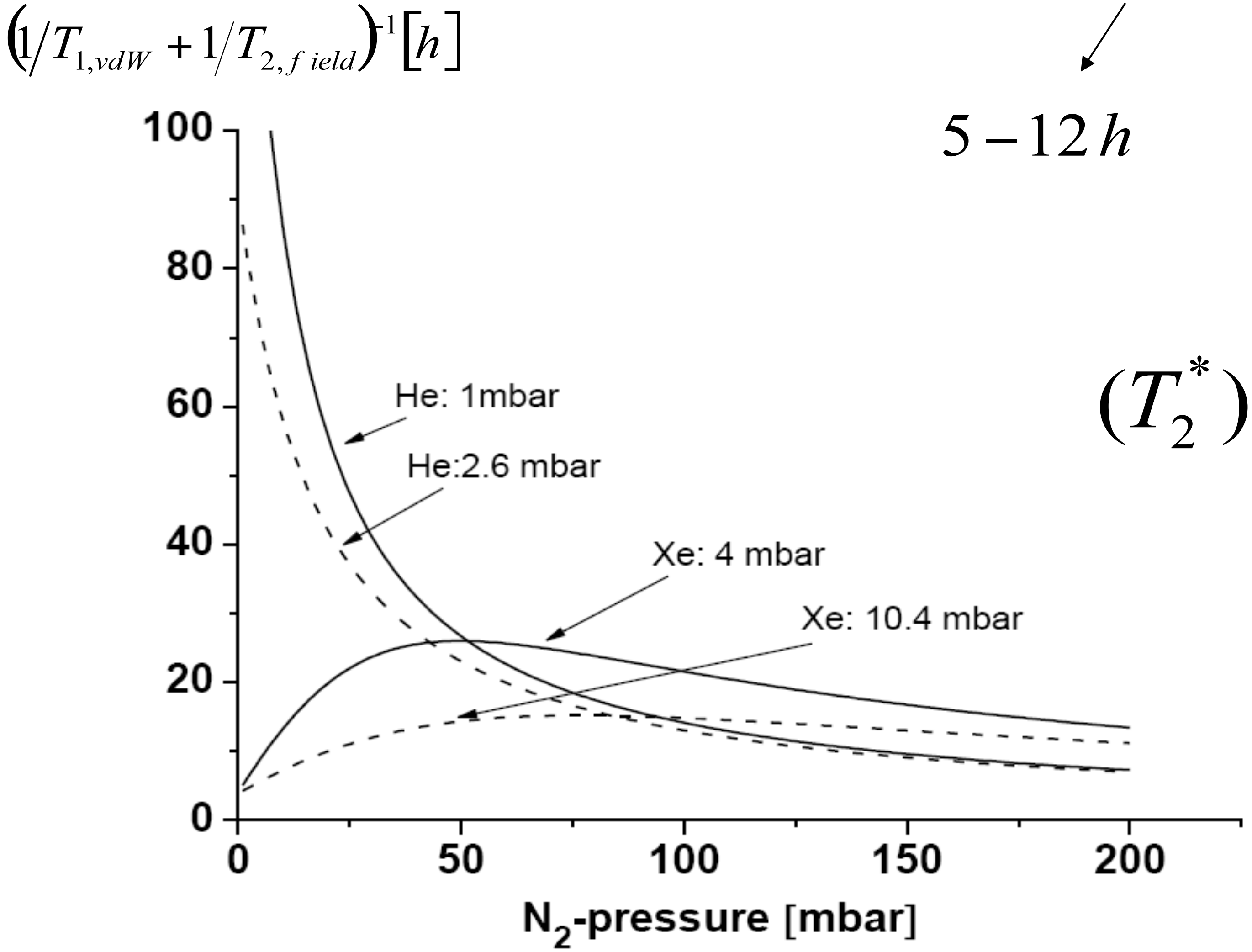
$$\frac{1}{T_2^*} = \frac{1}{T_{1,wall}} + \frac{1}{T_{1,vdW}} + \frac{1}{T_{2,field}}$$

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

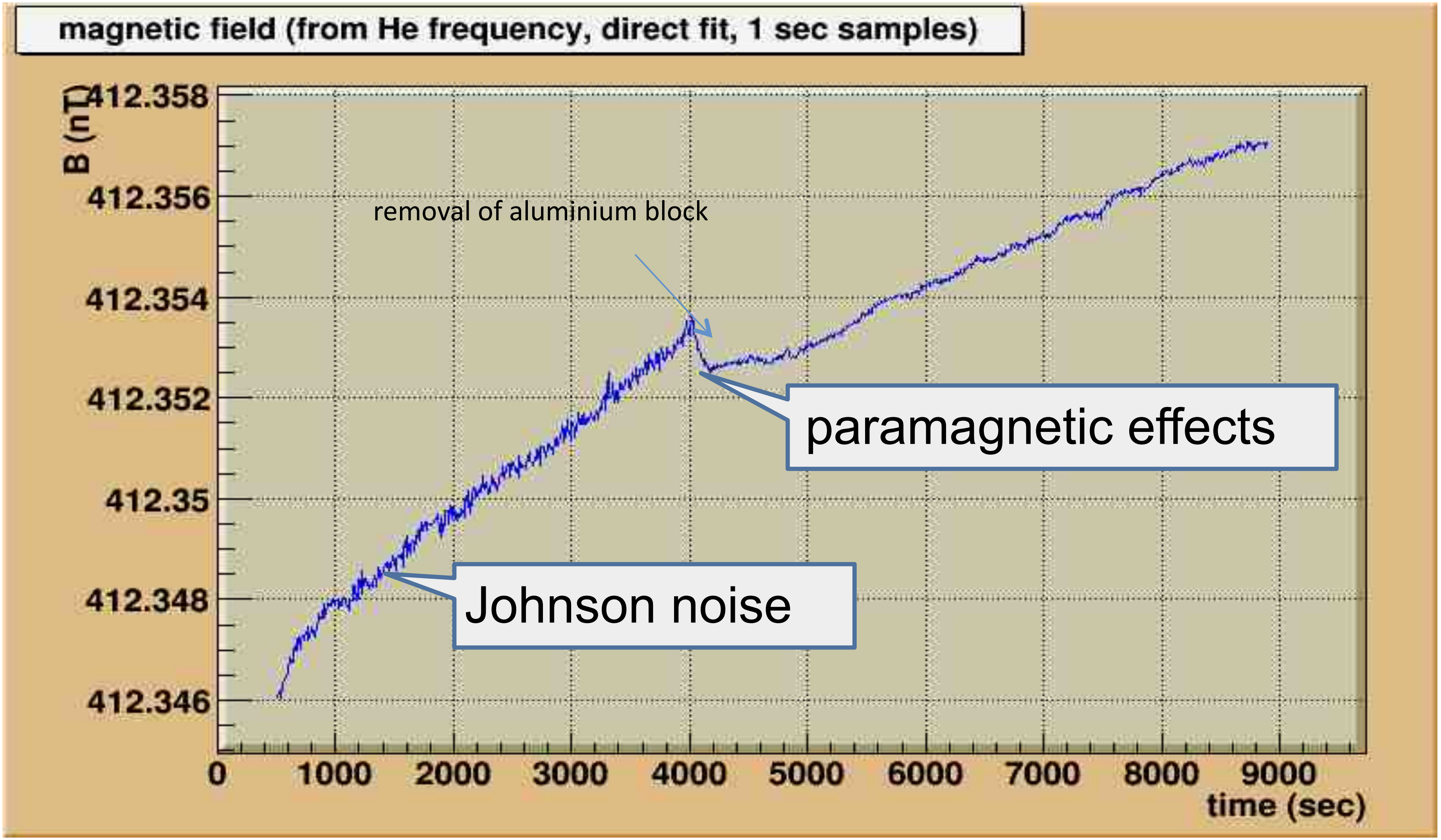
$T_{1,vdW}$: $\frac{1}{4.1h}\cdot\frac{1}{(1+1.05\cdot[N_2]/[Xe])}$

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

(measured)



Magnetic field (measured via the He spin precession signal) in presence of a conductor (aluminium cylinder : diameter 56 mm, length 70 mm)



paramagnetic effects

Johnson noise

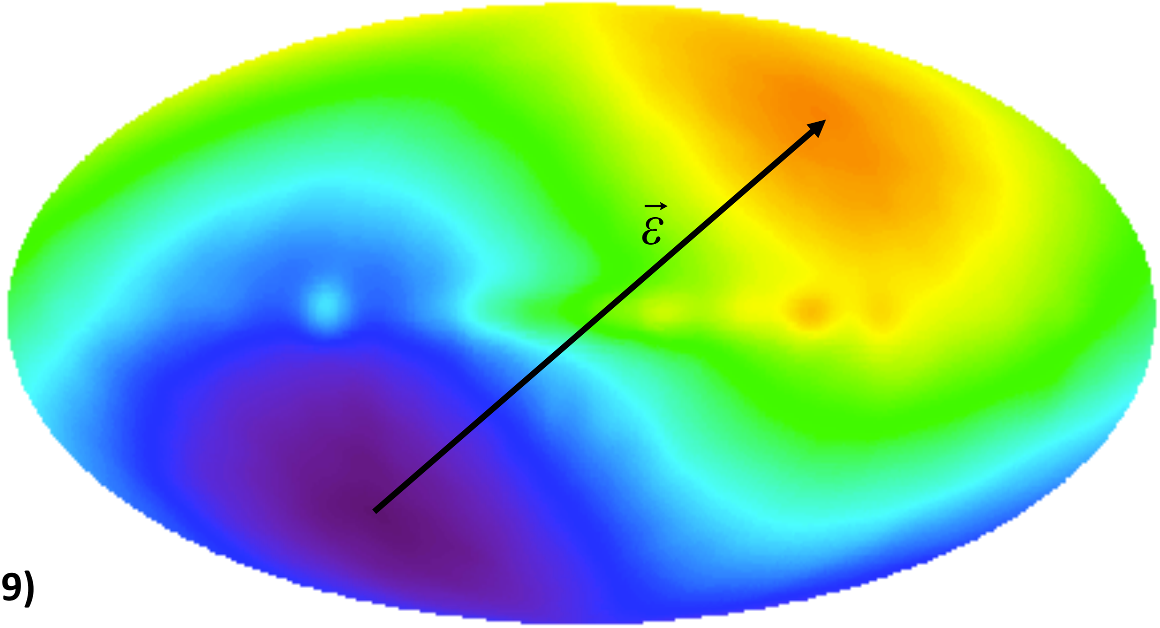
CMB dipole

v = 368 km/s

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

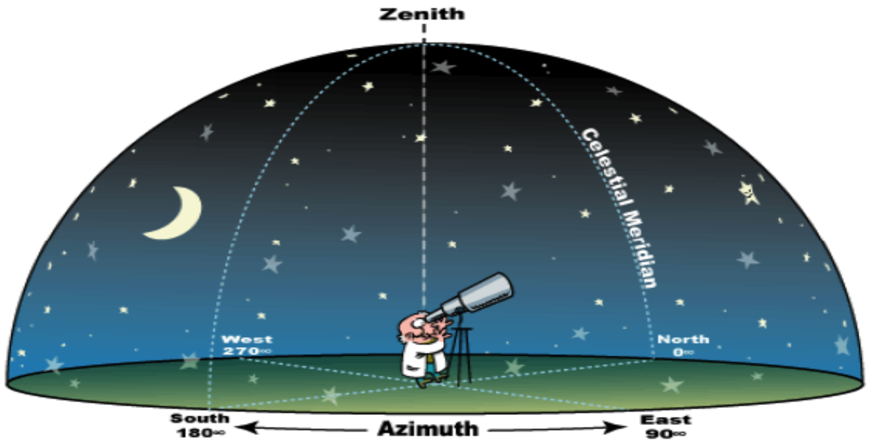
galactic coordinate system

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



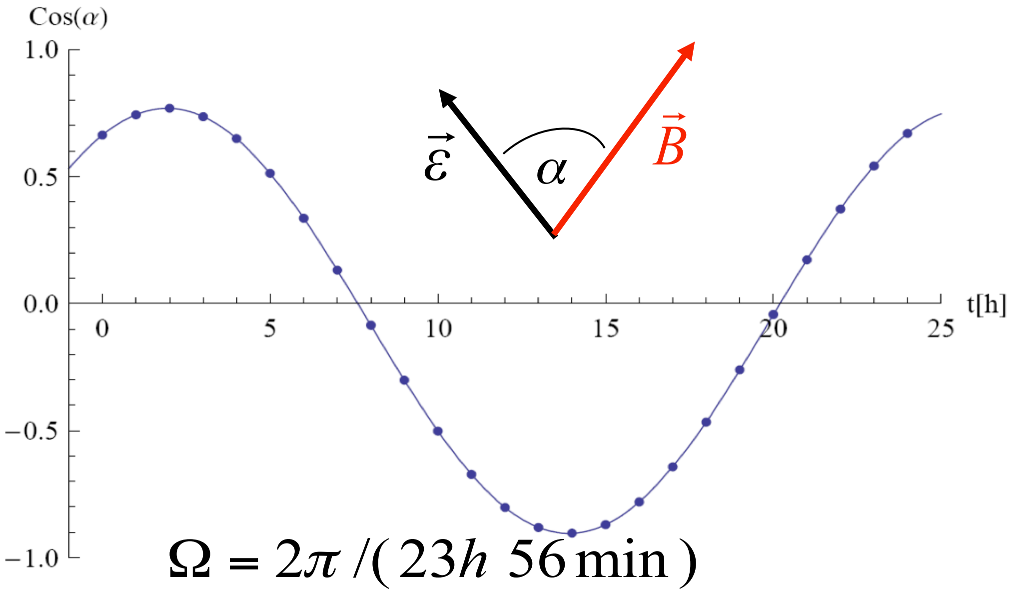
horizon coordinate system

(observer's local horizon)



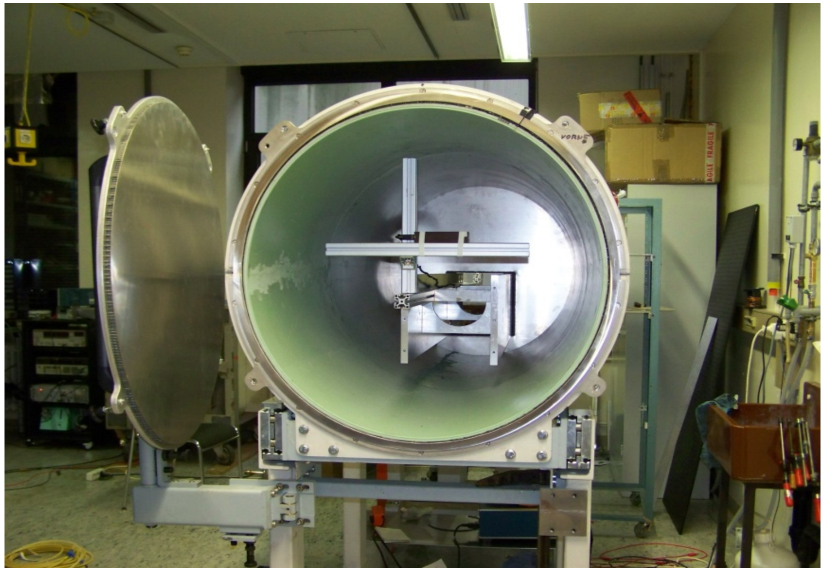
measurement on 01.10.2007 at

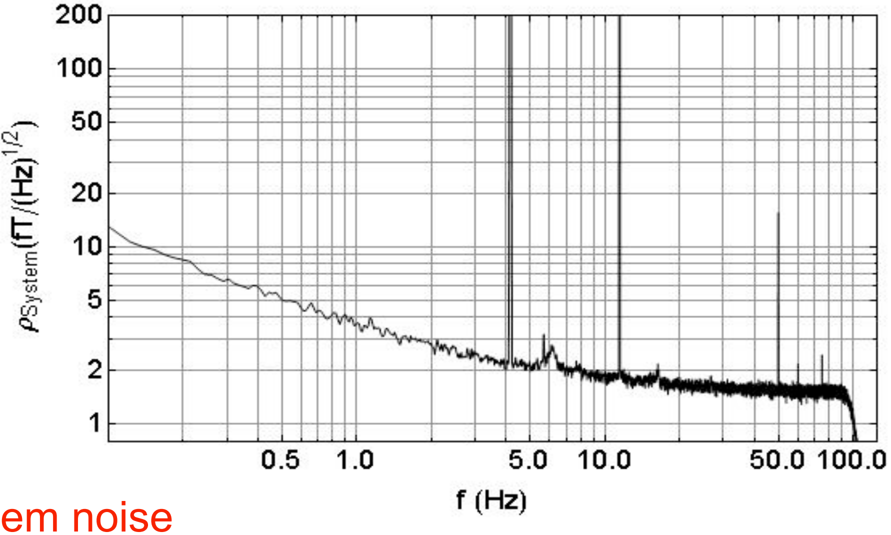
PTB-Berlin (52° 31´ north, 13° 25´ east)



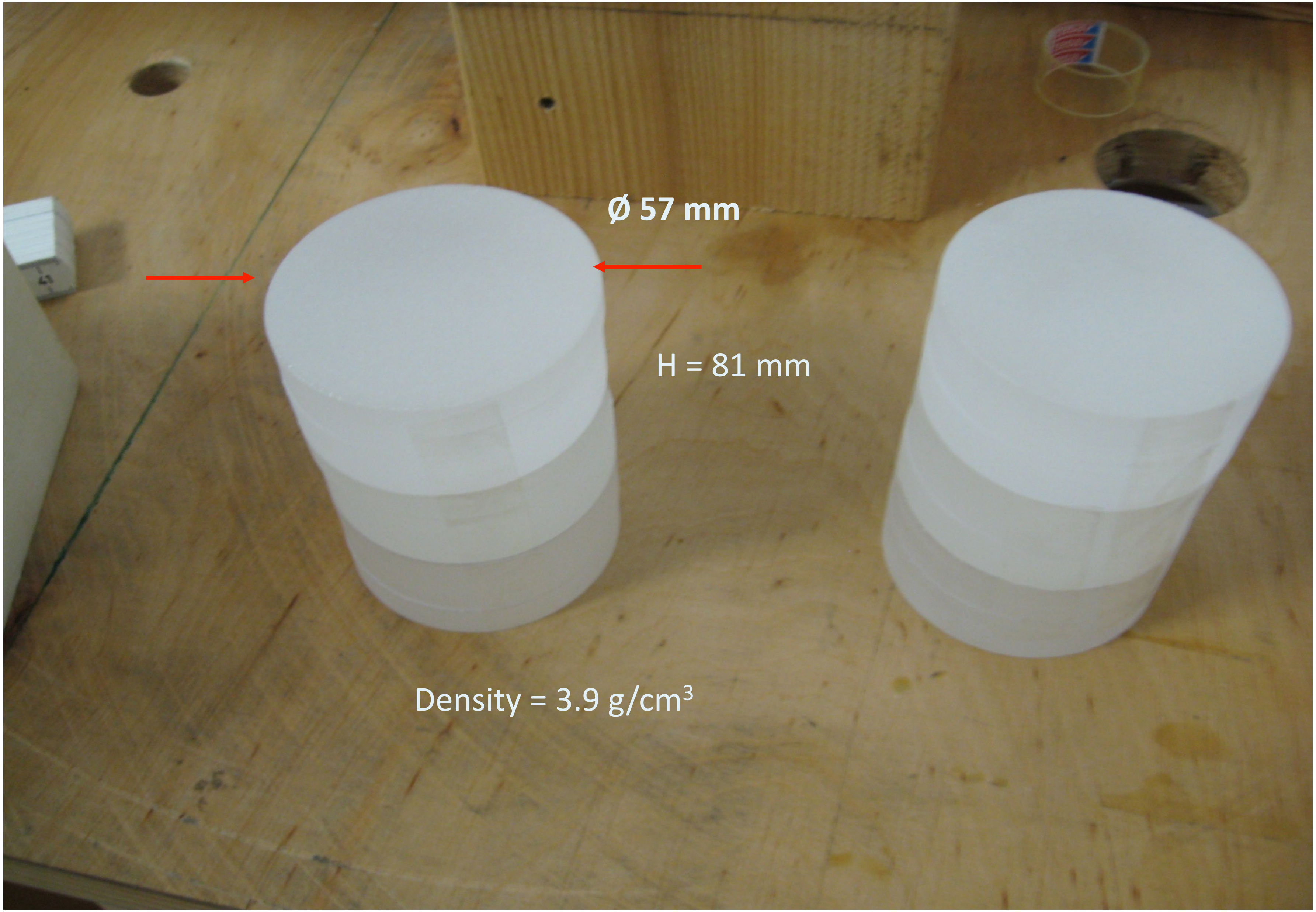
$$\Omega = 2\pi / (23h\ 56\,\text{min})$$

Prototype of cylindrical μ-metal shield



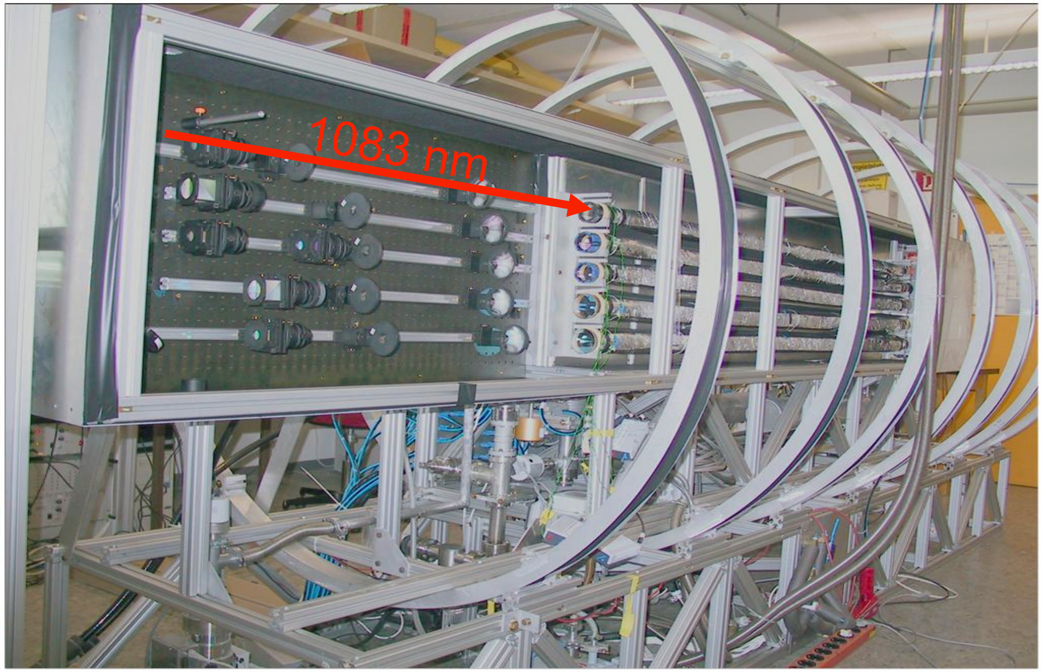


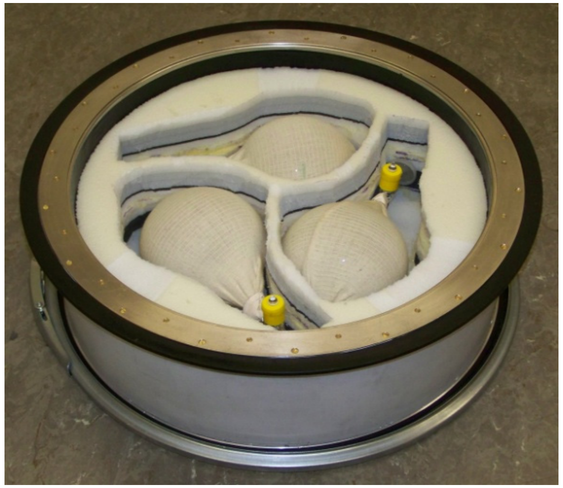
no elevated system noise
inside inner shield made out
of metglas (amorphous metal alloy ribbon)



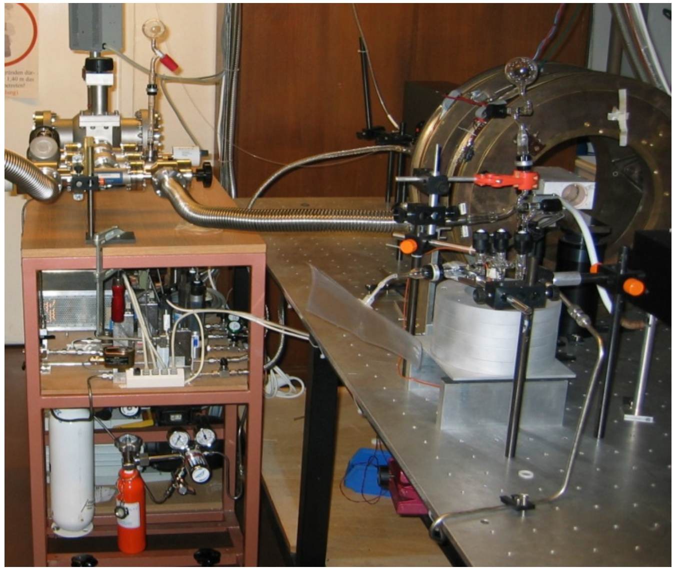
Lead glass samples

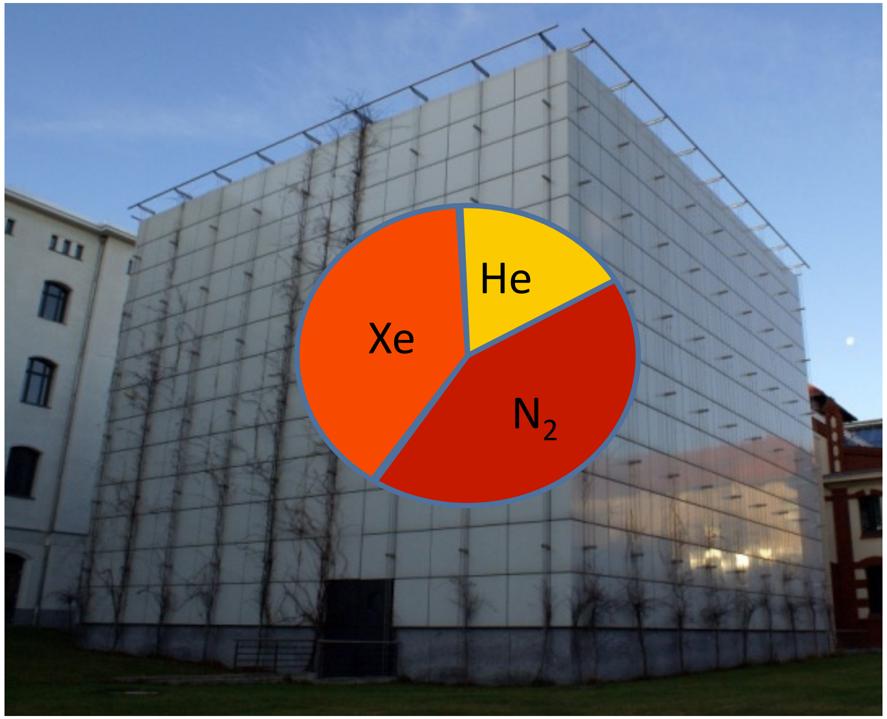
MEOP Polarizer Mainz: ^{3}He





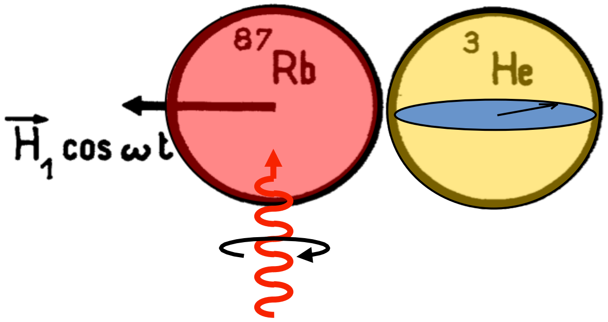
SEOP Polarizer PTB: Xe

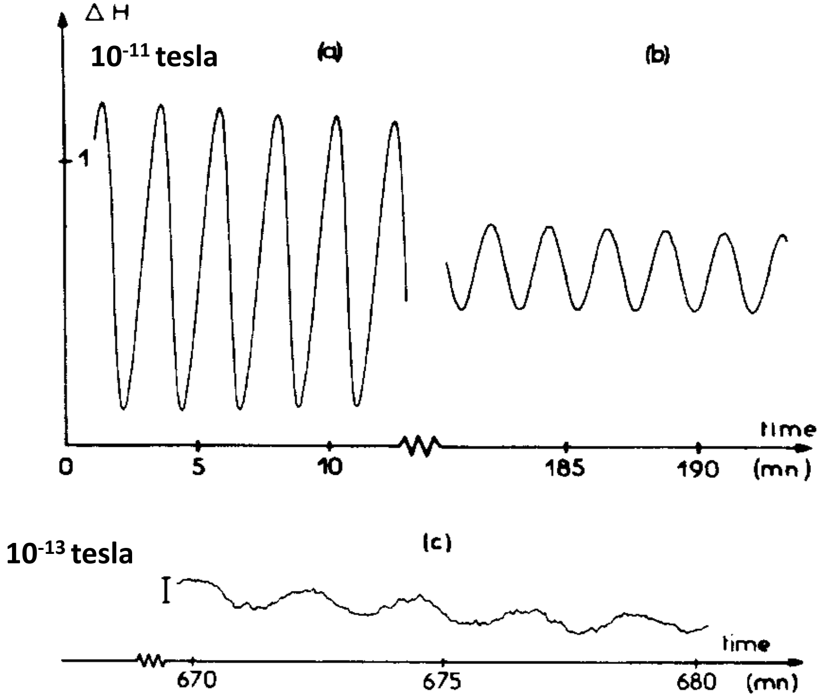




Detection of magnetic field produced by oriented nuclei

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





Results:

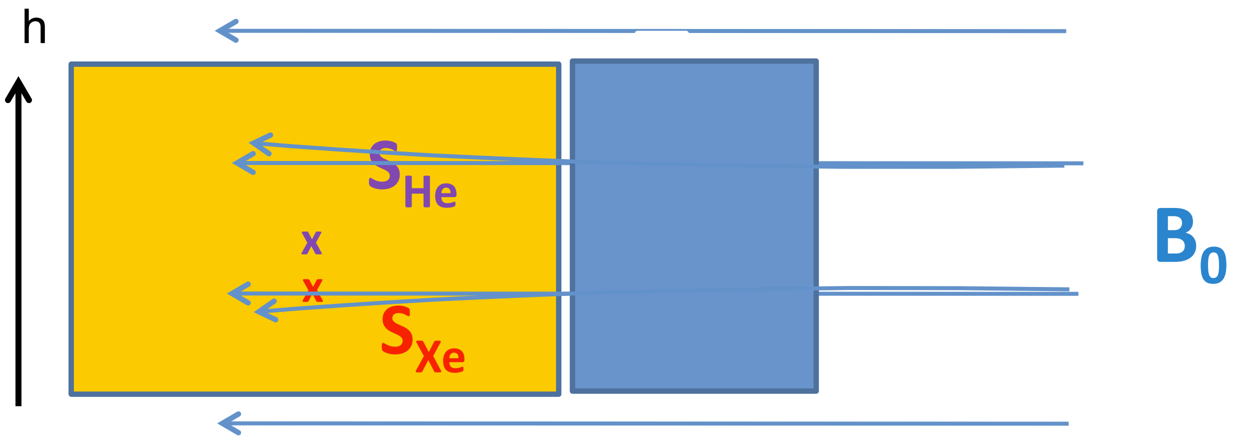
- ^{3}He spin precession: T_2* = 2h 20min
- sensitivity of Rb-magnetometer:
  100fT@ BW 0.3 Hz
- $P_{He} \approx$ 5% @ 4 mbar

Improvement of measurement sensitivity:

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

False effects :

Barometric formula : $p(h) = p^0\ exp(\frac{-h}{h^0}).$ $h^0 = \frac{RT}{Mg}$



$$\Delta h = S_{He} - S_{Xe} \approx 1.5\times10^{-7}\ m$$

assume: $\Delta\left(\frac{\partial B}{\partial h}\right) \approx 20\ \frac{pT}{cm}$

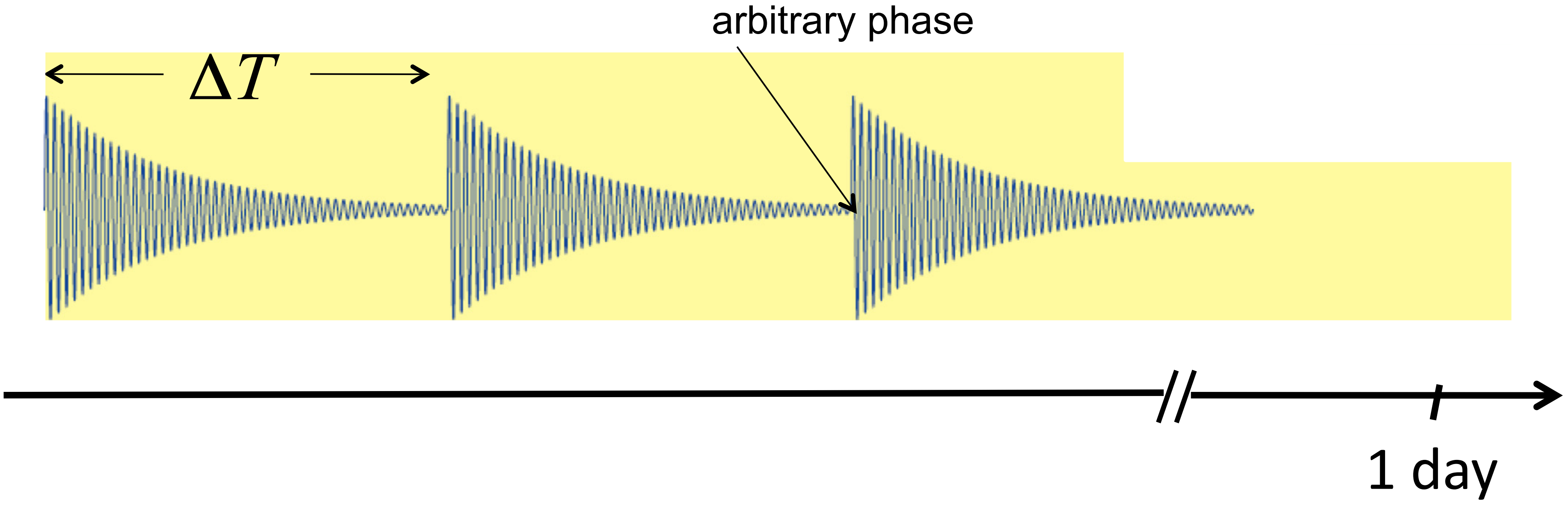
$$\Rightarrow \mathbf{\Delta B} \approx 0.3\ f\ T \Rightarrow \Delta\upsilon \approx 10\, nHz$$

drops out in $\delta\nu = ½\ (\Delta\nu_{right\ sample} - \Delta\nu_{left\ sample}) = (4.8 \pm 7.0 \pm 0.4)\ nHz$

From the measured value of $\delta\nu$ we get:

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

Gain in sensitivity compared to measurements with short coherence times:



$$\sigma_\nu \propto \left(1/_{\Delta T^{3/2}}\right)\sqrt{n} = \left(1/_{T^{3/2}}\right)\frac{T}{\Delta T} \qquad (\text{with}:\ n = \frac{T}{\Delta T})$$

Example „short spin coherence time“:

ΔT = 5 min → ≈ 300 × less sensitive !