Symmetry test and BSM searches using hyperpolarized gases

W. Heil

Outline:

- Features of $^{3}He/^{129}Xe$ spin-clocks
- $^{3}He/^{129}Xe$ clock-comparison experiments
    - Test of LV
    - Short range interactions mediated by axions
    - Xe-EDM searches
- Conclusion and outlook

Spin 2018 – Ferrara, Italy

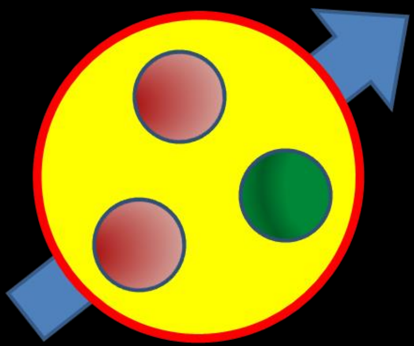
Hyperpolarized gases : ^{3}He, ^{129}Xe, (^{199}Hg)

I= 1/2

μ_n = -1.913 μ_K

μ_{He} = -2.1276 μ_K

μ_{Xe} = -0.7779 μ_K



OP-techniques:

MEOP
SEOP $P \approx \mathcal{O}(1)$

PAMP

0.1 < B (Tesla) < 12

arXiv:1806.07624 (2018)

Schmidt-model (valence neutron): $\mu_{He} = \mu_{Xe} = \mu_n$

More refined models:

^{3}He (Faddeev calculations): J. L. Friar et al. , Phys. Rev.C 37, 2869 (1988)

$$\mu_n \approx 0.9 \cdot \mu_{He}$$

^{129}Xe (core-polarization corrections applied to *ab initio* nuclear shell model calculations):

PRA 80 (2009) 032120

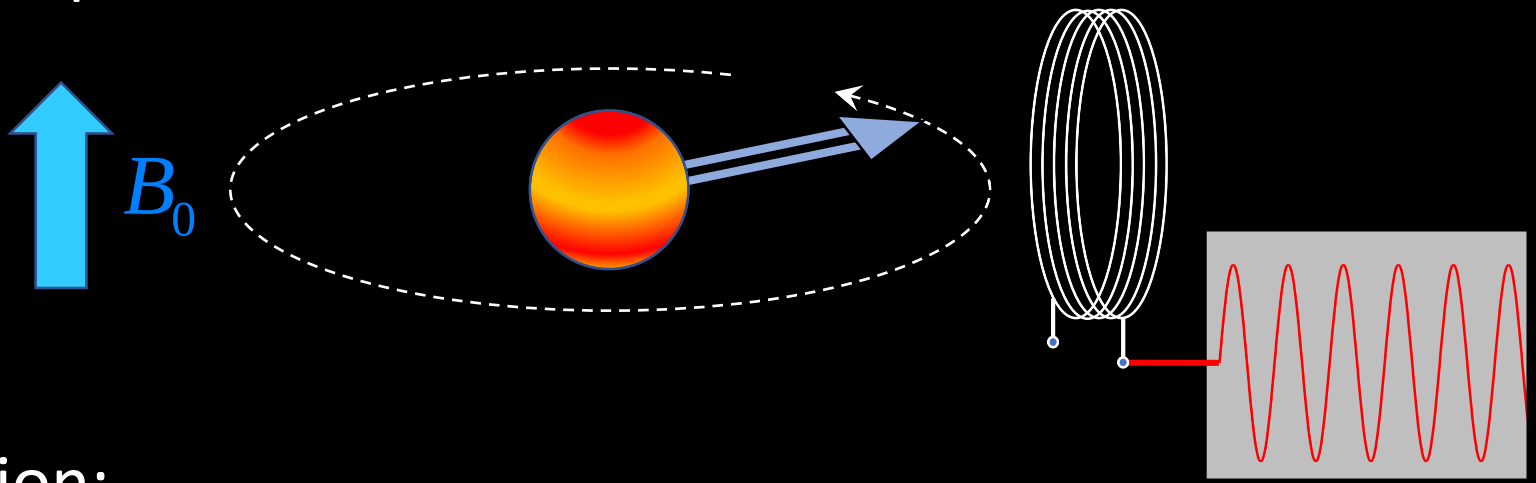
$$\langle s_n \rangle \approx 0.76 \langle s_{Xe} \rangle \qquad \langle s_p \rangle \approx 0.24 \langle s_{Xe} \rangle$$

Spin-clocks

A. Schawlow : "Never measure anything but frequency!"

Maser oscillation

Free spin precession



Relaxation:

T_1-longitudinal relaxation time :

3He : T_1 > 100 h in special glass vessels
129Xe: T_1 ~ 10-20 h

Repetto et al. JMR 252 (2015) 163

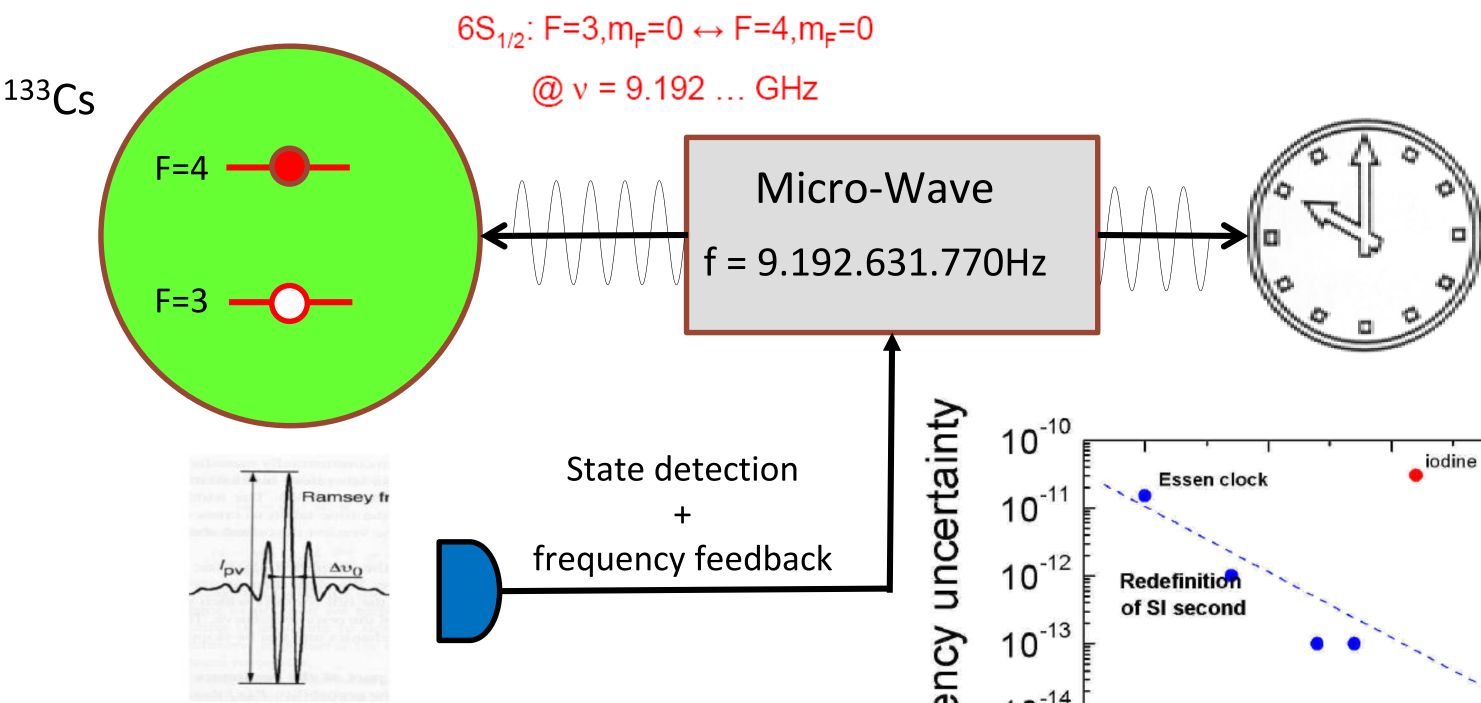
T_2-transverse relaxation time :

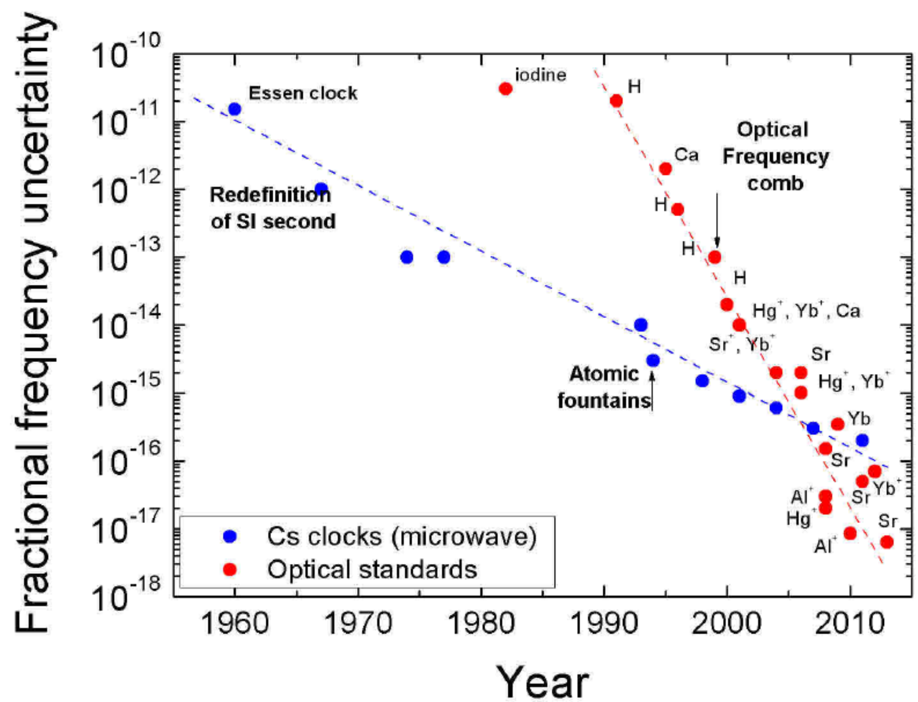
$T_2 < T_1$

Features of $^3He/^{129}Xe$ spin-clocks

Atomic clock ⟷ Spin clock

Oscillator + Frequency divider + Counter





Features of $^{3}He/^{129}Xe$ spin-clocks

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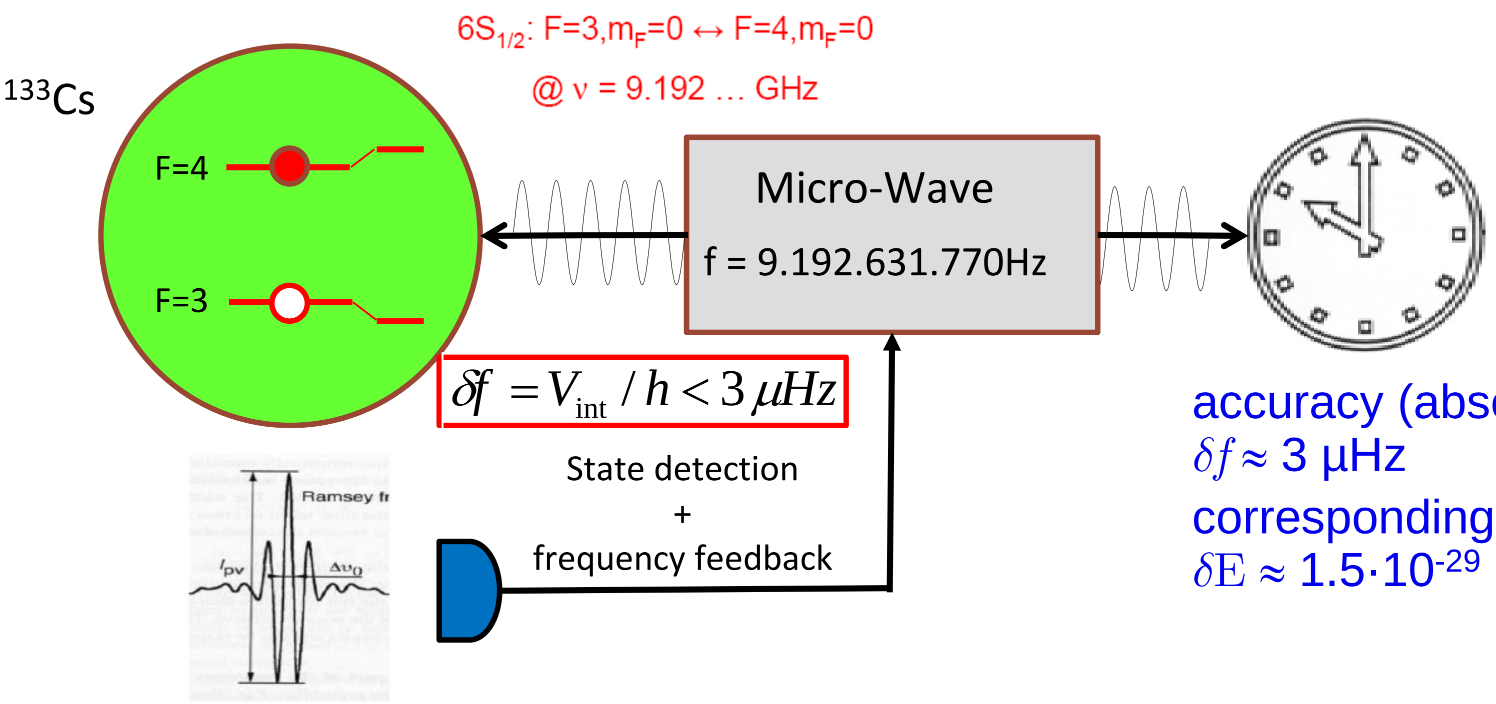
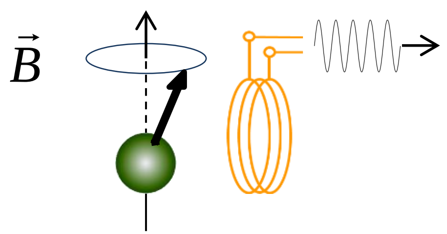


accuracy (absolute scale):
$\delta f \approx 3\ \mu Hz$
corresponding energy shift
$\delta E \approx 1.5\cdot 10^{-29}$ GeV

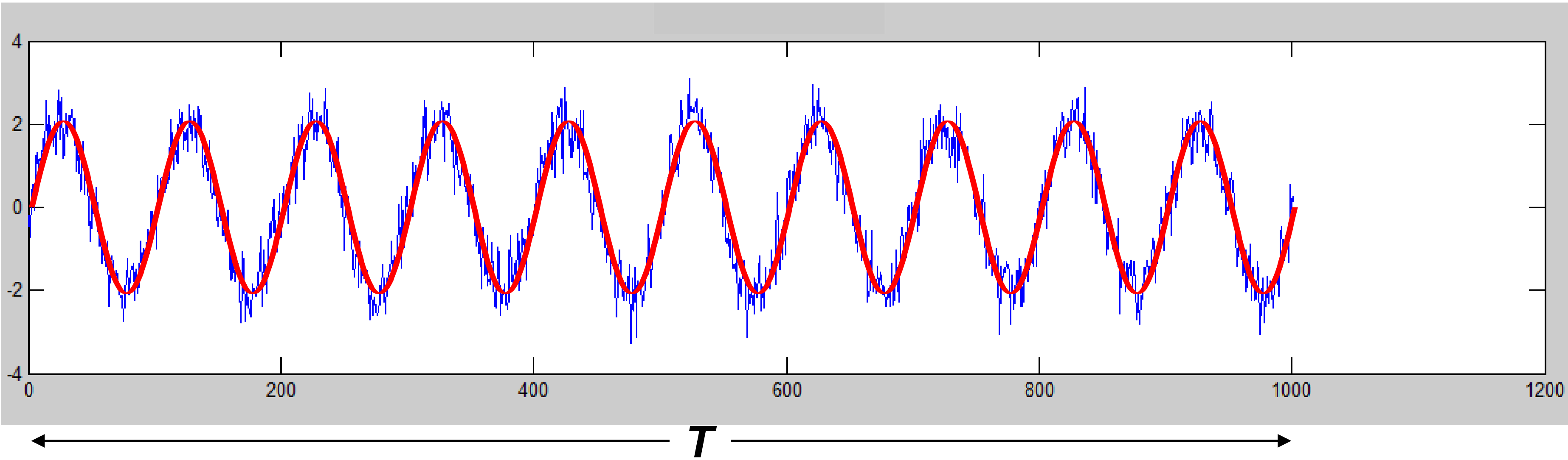
Spin clock :



reference transition at $f \approx 10$ Hz
with $\delta f/f \approx 10^{-13}$
accuracy (absolute scale):
$\delta f \approx 1$ pHz → $\delta E \approx 4\cdot 10^{-36}$ GeV

→ accuracy to trace tiny frequency shifts ≈ 6 orders of magnitude higher

Accuracy of frequency estimation:



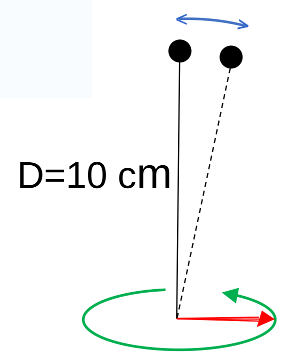
$$\sigma_f \propto \left[\textit{Fourier width} \quad \frac{1}{T} \right] \times \left[\frac{1}{\left[\# \textit{ data points} \quad T \right]^{1/2}} \right] \propto \frac{1}{T^{3/2}}$$

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

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

Caveat (pHz)

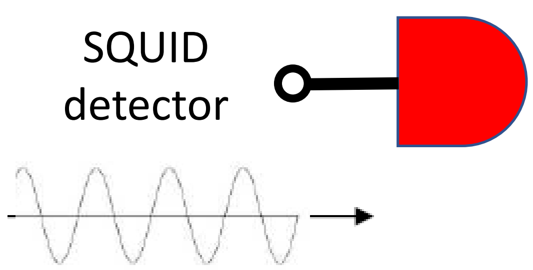
$\Delta x \approx 0.1 \mu m$ /day

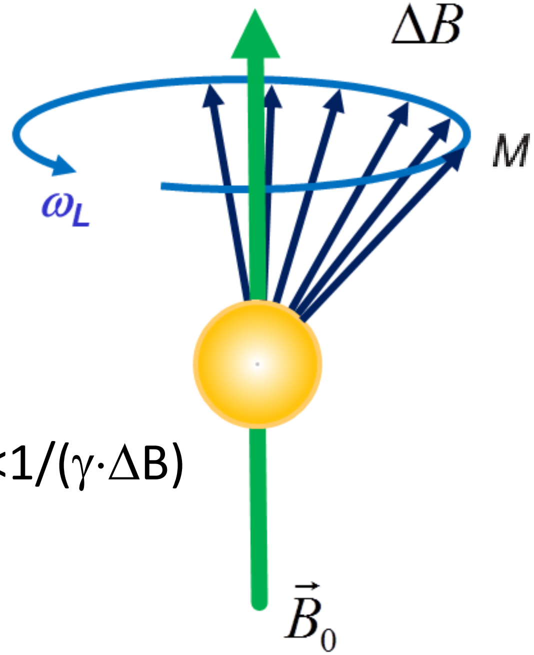


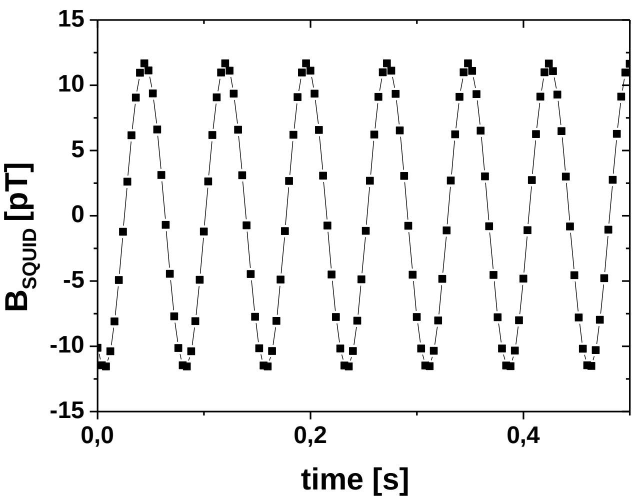
example: SNR = 10000:1 , f_{BW}= 1 Hz , T= 1 day $\Rightarrow \sqrt{\sigma_f^2} \approx pHz$

➡ long spin-coherence times (T_2^*)

$noise \sim 1\, fT/\sqrt{Hz}$







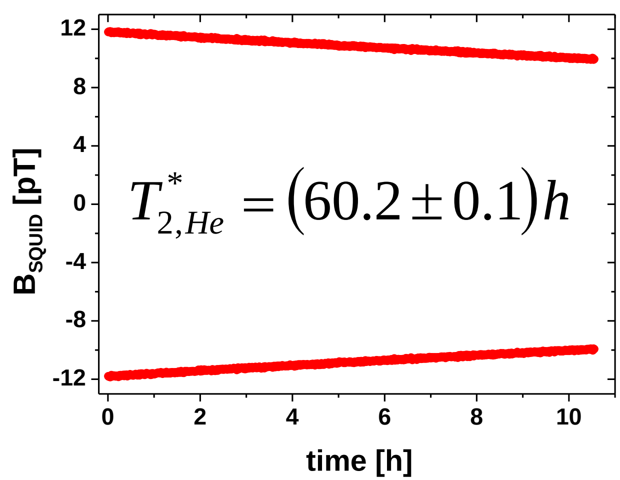
Motional narrowing regime: $\tau_{diff} \ll 1/(\gamma \cdot \Delta B)$

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

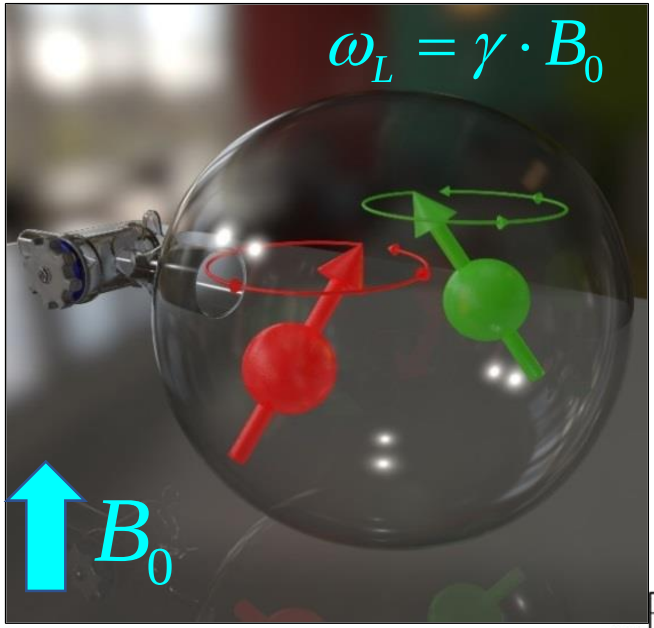
$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{1}{T_{2,\,\text{field}}}$$

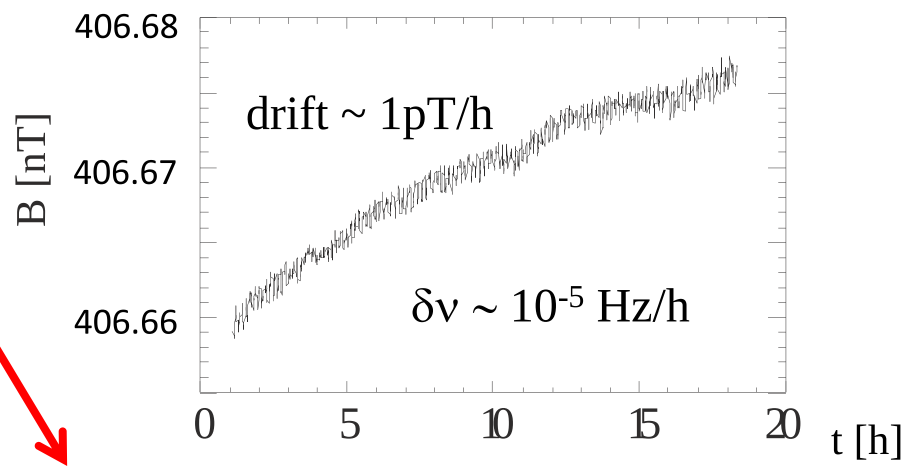
$$\frac{1}{T_{2,\,\text{field}}} \propto R^4 \cdot p \cdot \left|\vec{\nabla} B\right|^2$$

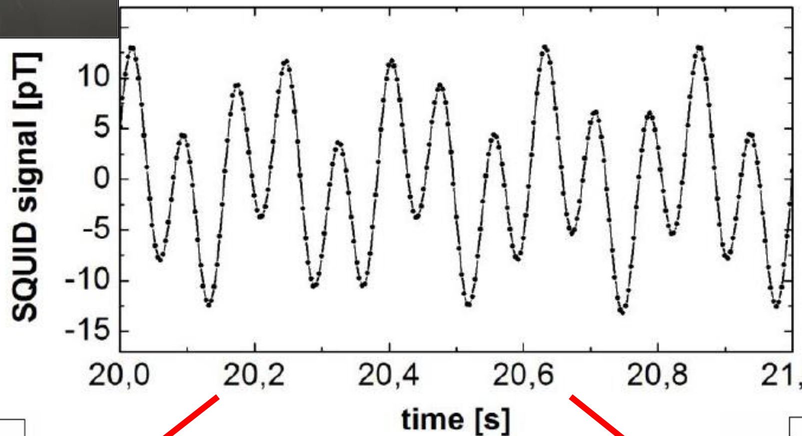
$$T_1 > 100\text{ h} \quad \Longrightarrow \quad \begin{array}{l} Long\ T_2^*: \\ p \sim mbar,\, R \sim 5\,cm,\, B_1 \sim \mu T \end{array}$$



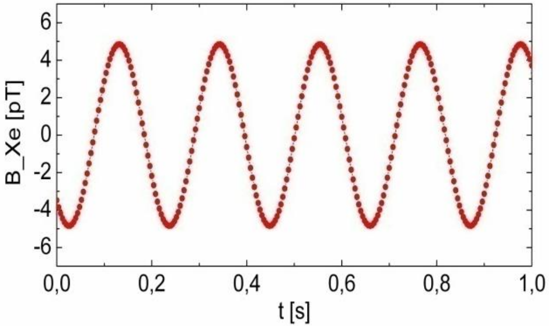
Comagnetometry to get rid of magnetic field drifts



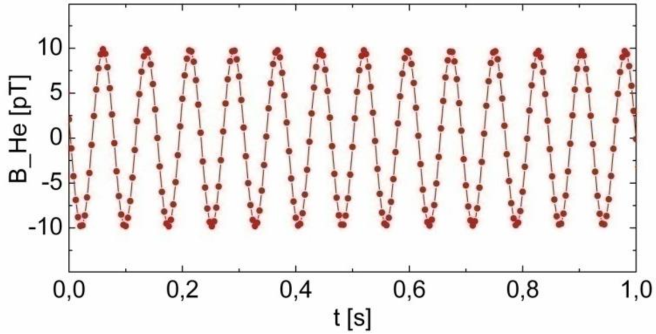




^{129}Xe (4,7 Hz)

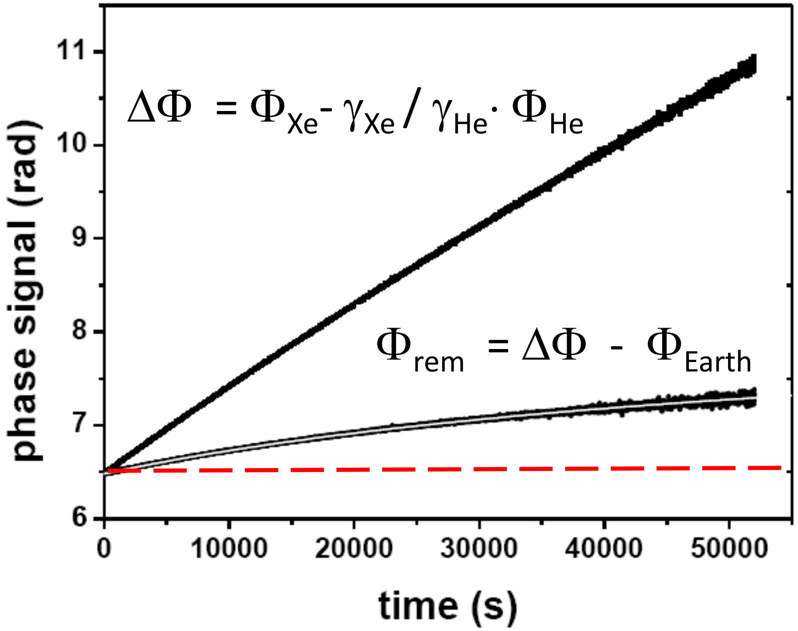


^{3}He (13 Hz)

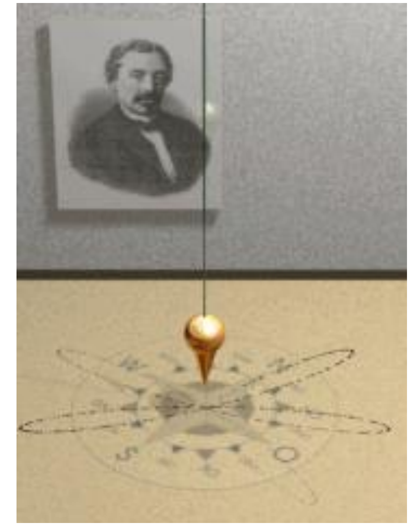


$$\Delta\Phi = \Phi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \Phi_{Xe} = const.$$

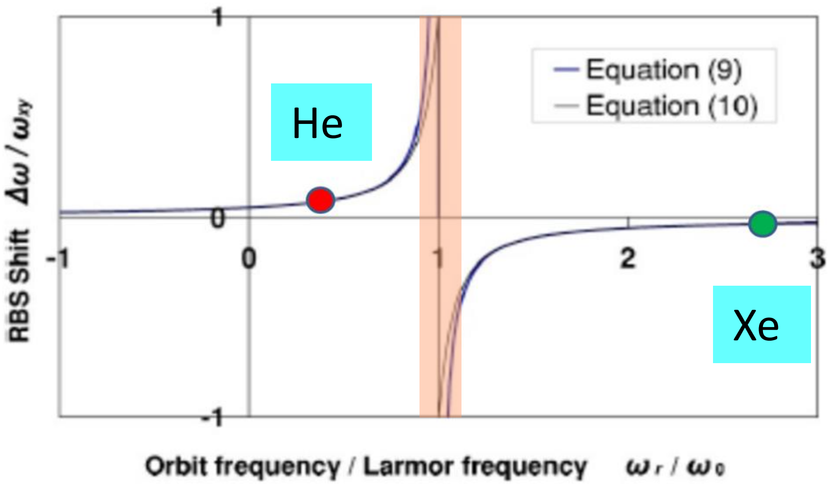
Subtraction of deterministic phase shifts

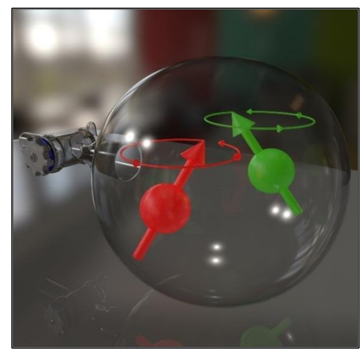


I. Earth‘s rotation



II. Ramsey-Bloch-Siegert shift



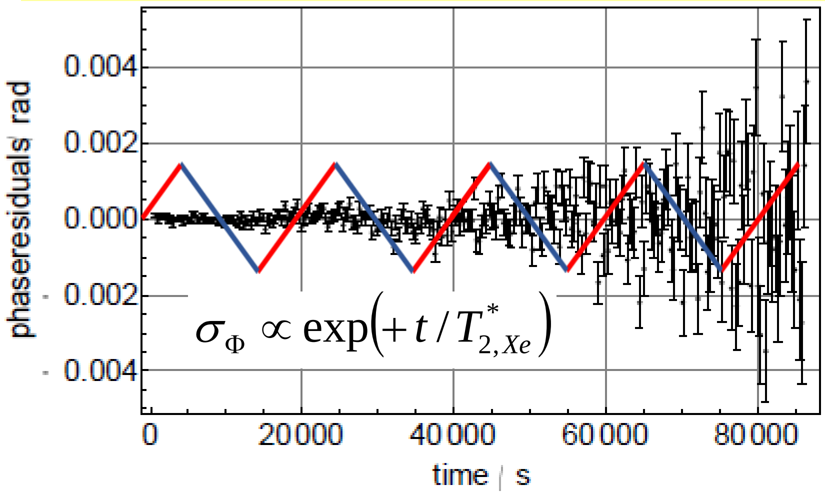


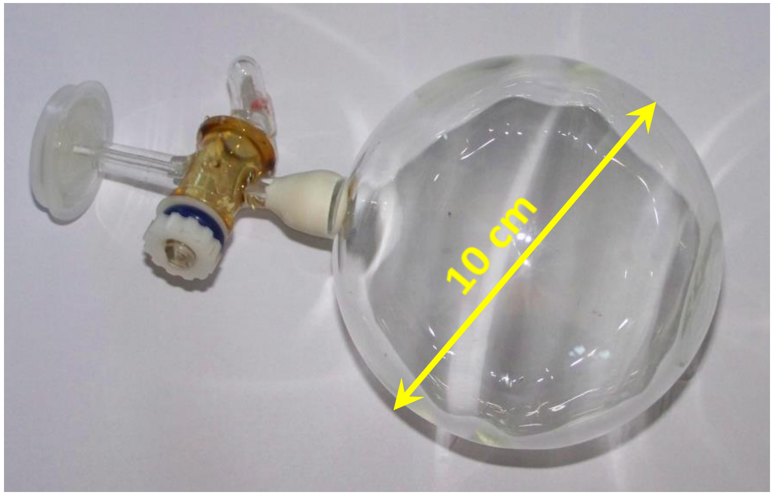
self shift ~ $S_0 \cdot e^{-t/T_2^*}$

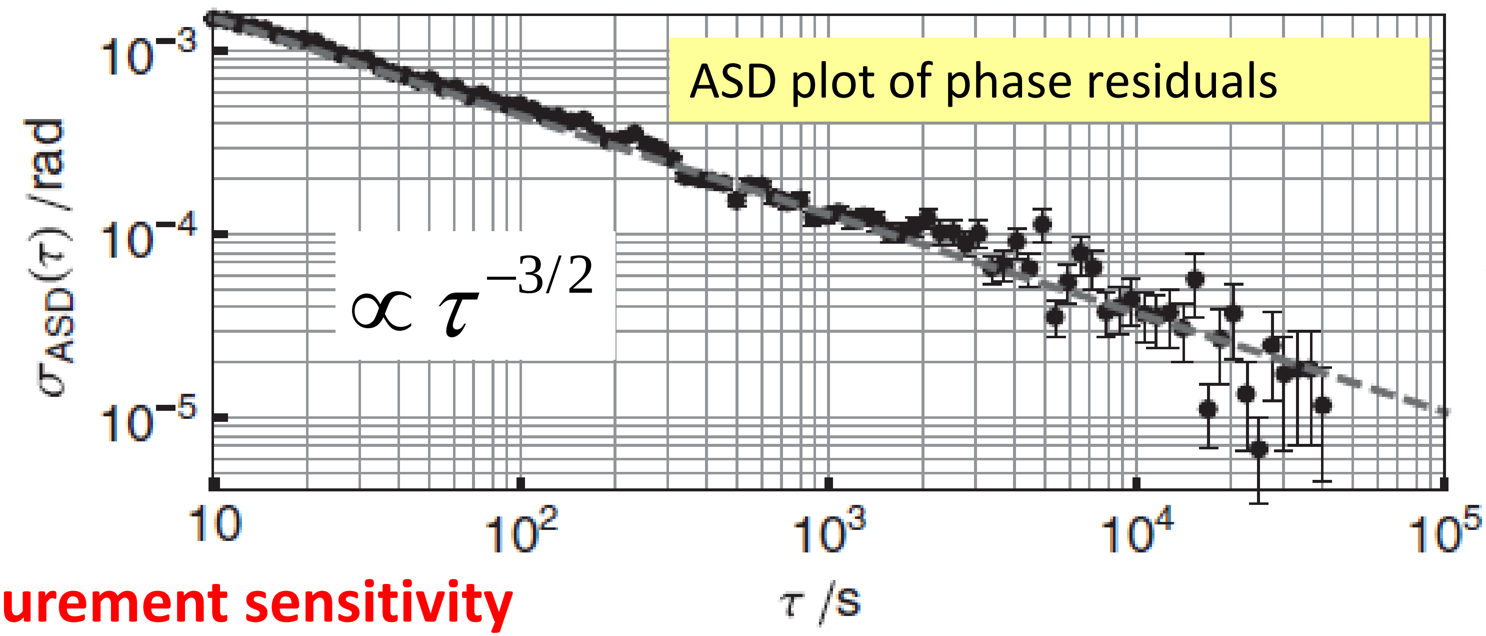
cross-talk ~ $\left(S_0 \cdot e^{-t/T_2^*} \right)^2$

$$\Delta\Phi = c + a_{Earth} \cdot t + a_{He} \cdot e^{-t/T^*_{2,He}} + a_{Xe} \cdot e^{-t/T^*_{2,Xe}} + b_{He} \cdot e^{-2t/T^*_{2,He}} + b_{Xe} \cdot e^{-2t/T^*_{2,Xe}} + \Delta\Phi_{EDM}(t)$$

Phase residuals after subtraction of deterministic phase shifts







$T \approx 3 \cdot T^*_{2,Xe}$

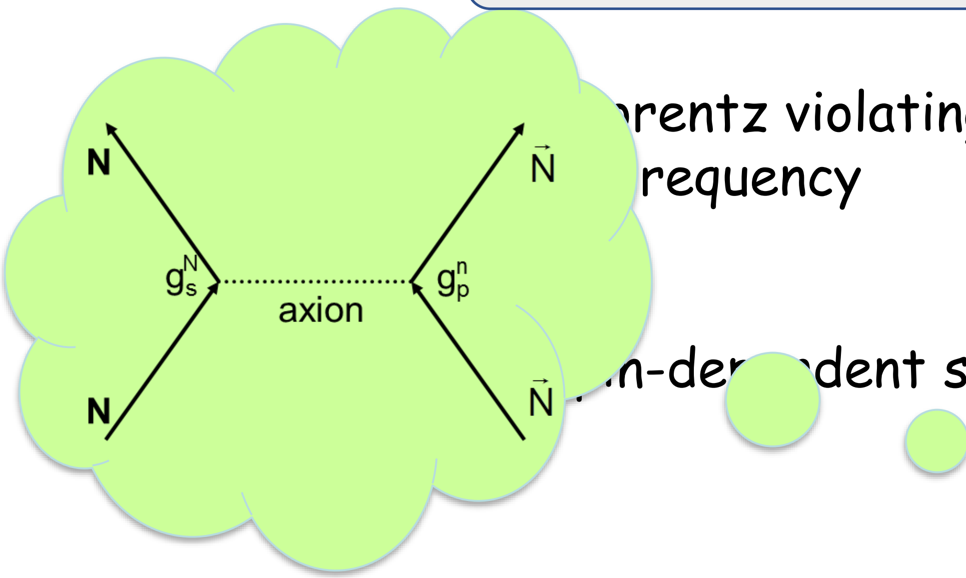
Measurement sensitivity

$$\delta\Phi \approx 10\,\mu rad\ @\ day \Rightarrow \delta f = \frac{\delta\Phi}{2\pi \cdot 86400} \approx 18\,pHz\ @\ day$$

Symmetry tests and BSM searches

$^{3}He/^{129}Xe$: ultra-sensitive probe for
non-magnetic spin interactions of type:

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



...rentz violating sidereal modulation
...requency

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

...n-de...dent short-range interactions

$$V/\hbar = c\ \vec{\sigma}\cdot\hat{r}/\hbar$$

- Search for EDM of Xenon

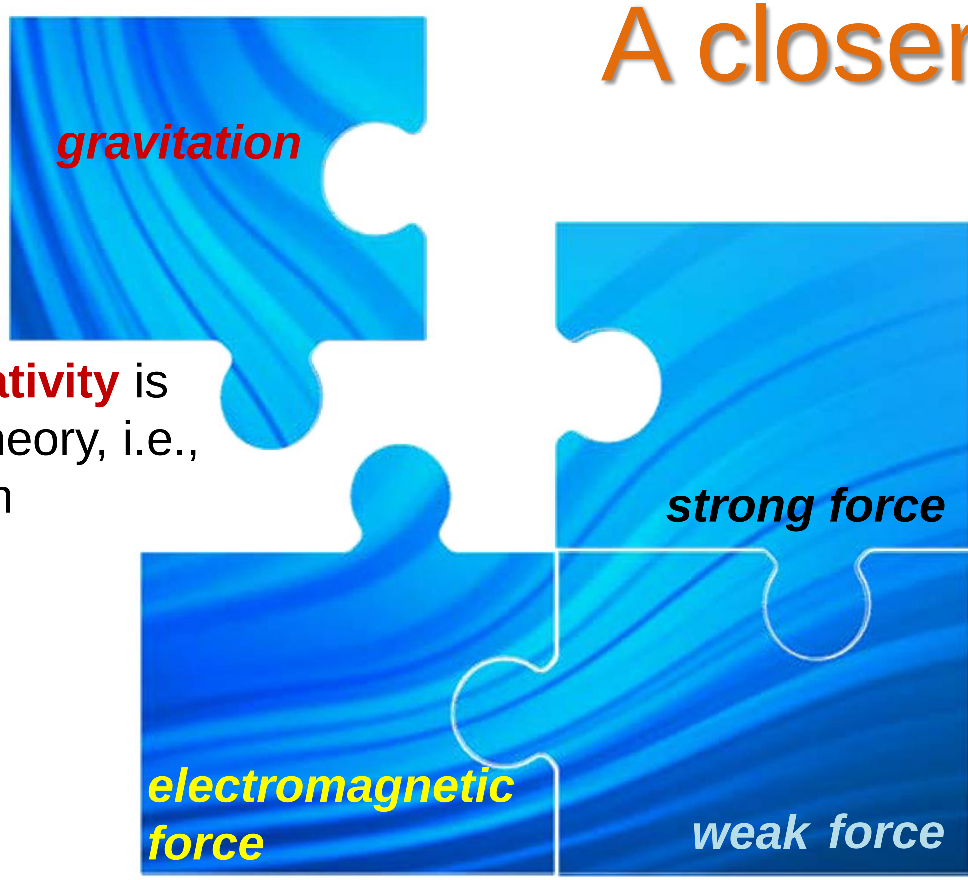
$$V/\hbar = -|d_{Xe}|\ \vec{\sigma}\cdot\vec{E}/\hbar$$

- ...

Observable: $$\Delta\omega = \omega_{L,He} - \frac{\gamma_{He}}{\gamma_{Xe}}\cdot\omega_{L,Xe} = (1-\gamma_{He}/\gamma_{Xe})\cdot V/\hbar$$

Limits on Lorentz and CPT Violation

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

Planck scale: energy scale where gravity meets quantum physics

$M_p \sim 10^{19}$ GeV

Unification theories: string theory, loop quantum gravity,..

Spontaneous Lorentz symmetry breaking in string theory

Background fields (tensor fields) give preferred direction e.g. rest frame of CMB

low-energy world : Lorentz& CPT Violation

SME

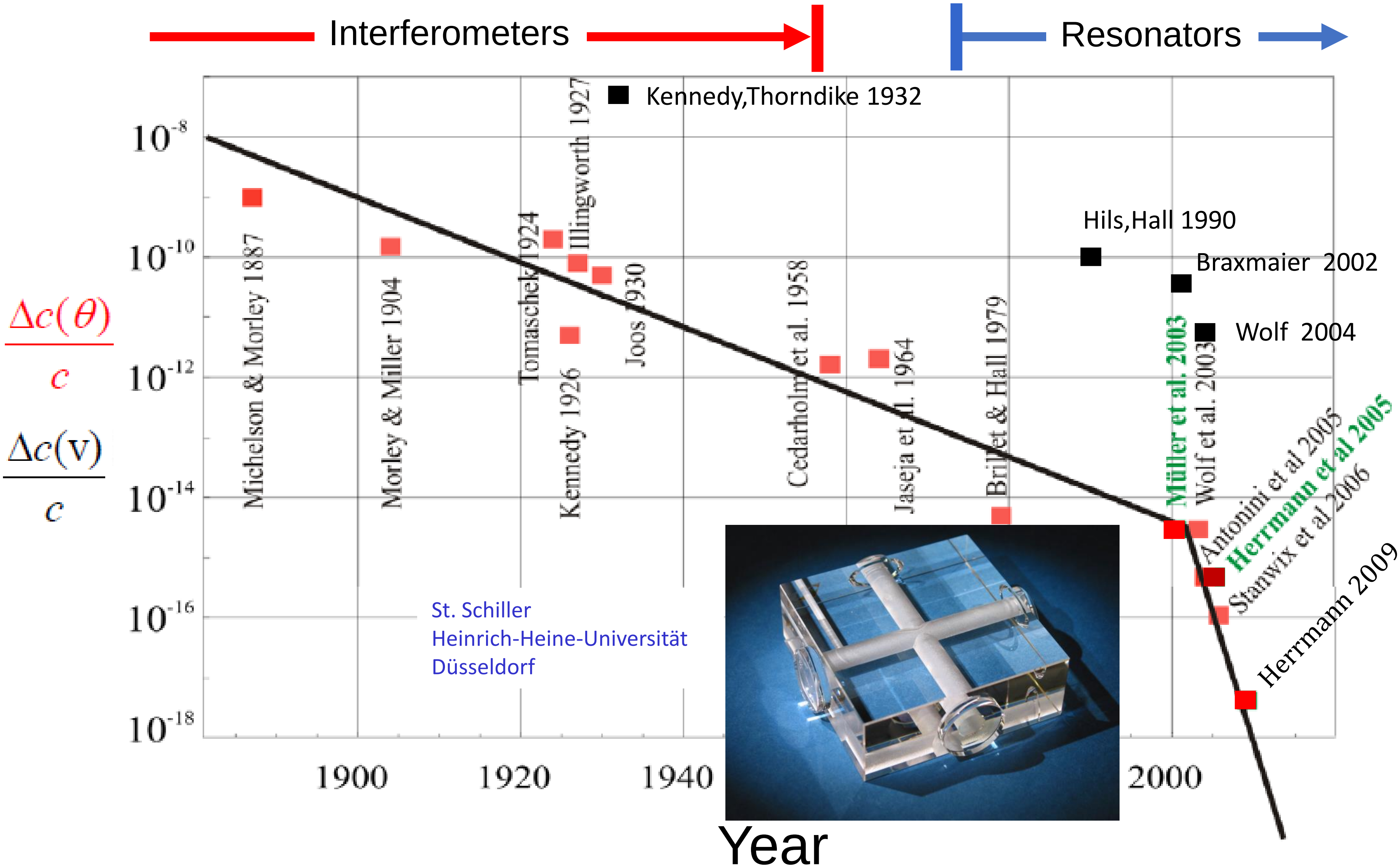
Phys. Rev. D 55, 6760 (1997)
Phys.Rev. D 58, 116002 (1998)

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

Test of constancy of c



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)

$$\left(i\gamma^\mu\partial_\mu - m_w - a^w_\mu\gamma^\mu - b^w_\mu\gamma_5\gamma^\mu + ie^w_\mu\partial^\mu - f^w_\mu\gamma_5\partial^\mu + i\frac{1}{2}g^w_{\lambda\mu\nu}\sigma^{\lambda\mu}\partial^\nu - \frac{1}{2}H^w_{\mu\nu}\sigma^{\mu\nu} + ic^w_{\mu\nu}\gamma^\mu\partial^\nu + id^w_{\mu\nu}\gamma_5\gamma^\mu\partial^\nu \right)\Psi = 0$$

standard DE standard DE | CPT odd | CPT even

Lorentz violating terms

Experimental access:

$$a^w_\mu, b^w_\mu, \ldots \approx \left(\frac{m_w}{M_{Planck}}\right)^k \cdot m_w$$

Neutron: $b^n_\mu \approx \begin{cases} 10^{-19}\,GeV & k=1 \\ 10^{-38}\,GeV & k=2 \end{cases}$

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

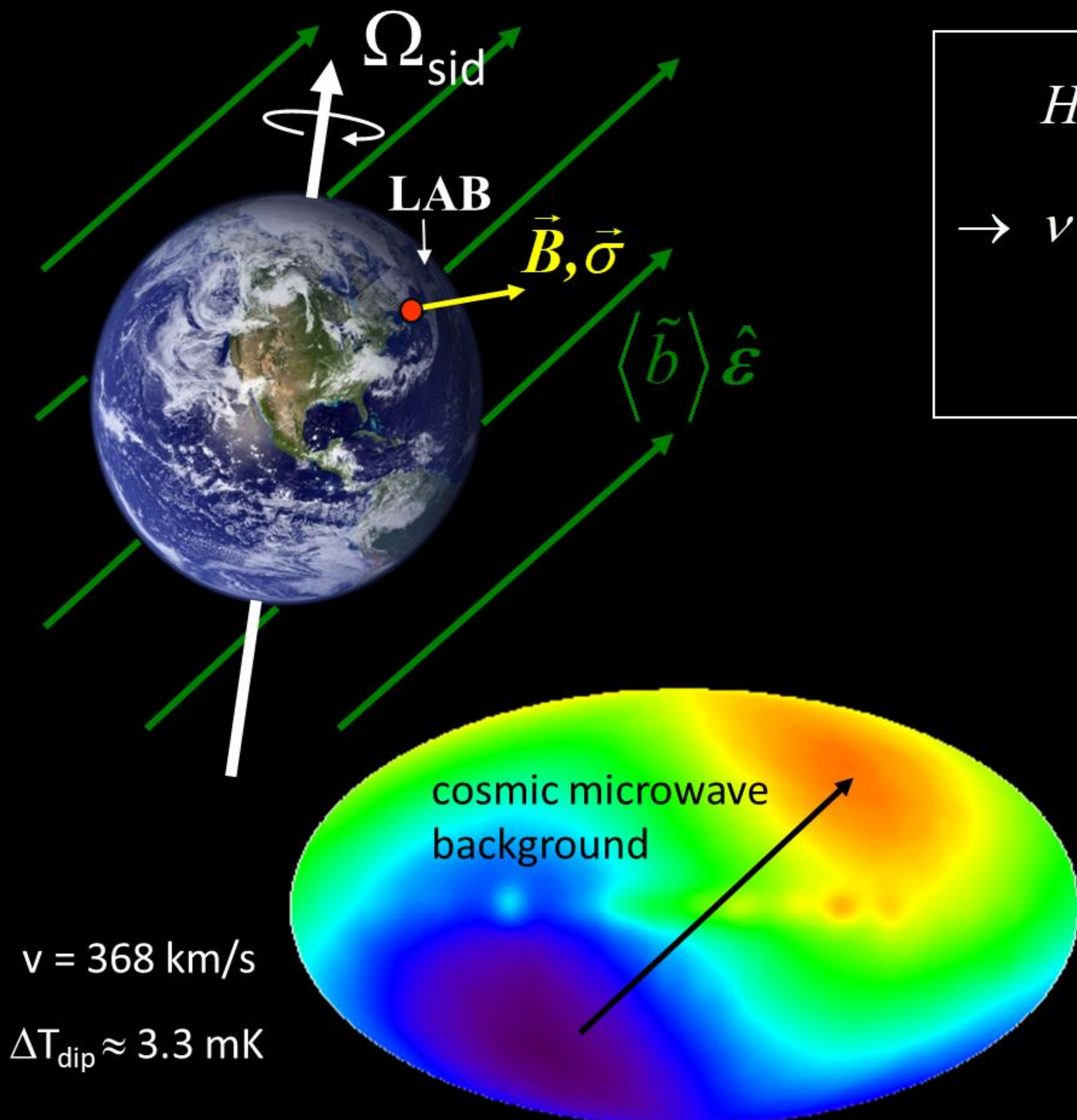
UCN/Hg comparison

He/Xe maser

K/He co-magnetometer

(Hg/Cs comparison through K/He co-magnetometer:) clock comparison experiments — b^n_μ

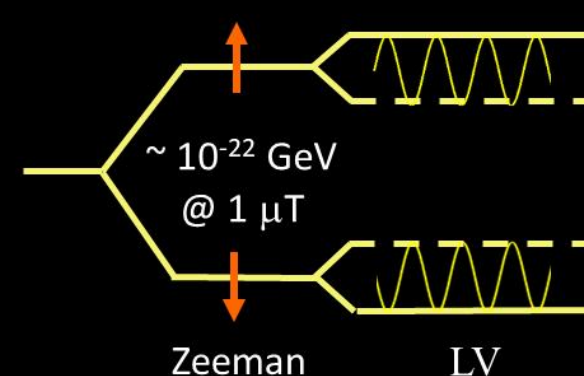
Coupling of spin $\vec{\sigma}$ to background field: $V = -\vec{\tilde{b}} \cdot \vec{\sigma}$



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

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

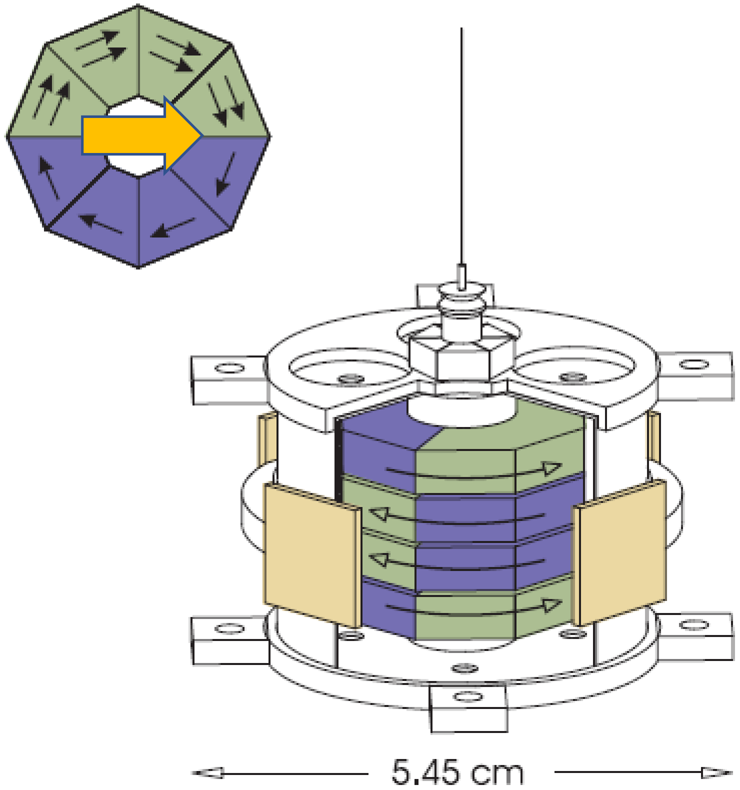
$$\langle \tilde{b} \rangle \hat{\varepsilon} \cdot \hat{B} \sim \cos(\Omega_{sid} \cdot t + \varphi)$$



	Electron (w=e)	Proton (w=p)	Neutron (w=n)
$\tilde{b}_x^w [GeV](1\sigma)$	$(-0.7\pm1.3)\cdot10^{-31}$	--------------	--------------
$\tilde{b}_y^w [GeV](1\sigma)$	$(-0.2\pm1.3)\cdot10^{-31}$	--------------	--------------
$\tilde{b}_\perp^w [GeV](1\sigma)$	--------------	-------------- $< 6.0\cdot10^{-32}$ $< 7.6\cdot10^{-33}$	$< 10^{-31}$ $< 3.7\cdot10^{-33}$ $< 8.4\cdot10^{-34}$

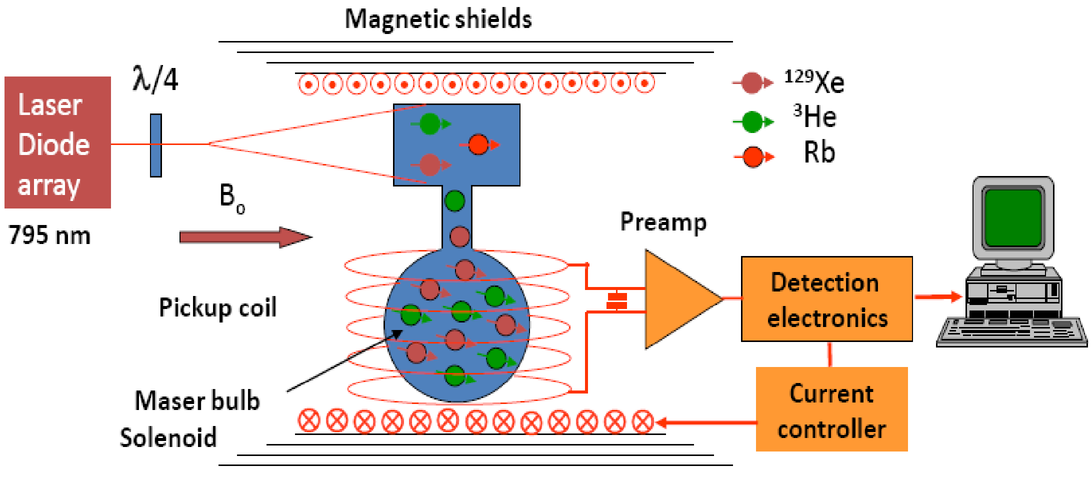
Torsion pendulum

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



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

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



- K-^{3}He co-magnetometer

J. M. Brown et al. *PRL 105 (2010) 151604*

- 3He/129Xe co-magnetometer

F.Allmendinger et al., *PRL 112 (2014) 110801*

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

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

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

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

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

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

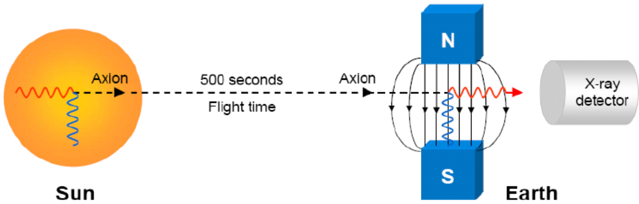
Modern interest: Dark Matter candidate. All couplings to matter are weak

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

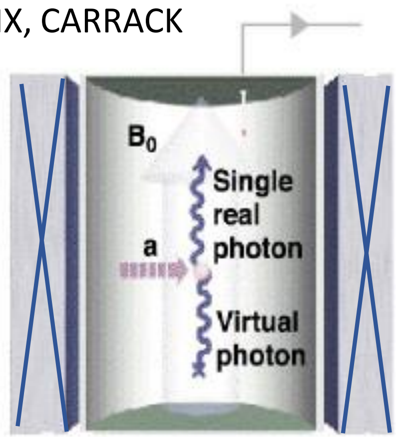
Axions generated in the sun



CAST : CERN AXION SOLAR TELESCOPE

Galactic axions

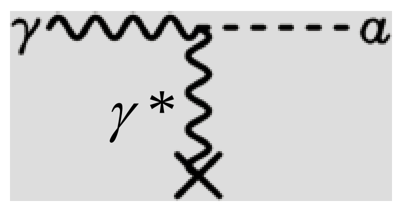
Tunable resonant cavity in magnetic field coupled to a ultra low noise microwave receiver
ADMX, CARRACK



8 Tesla

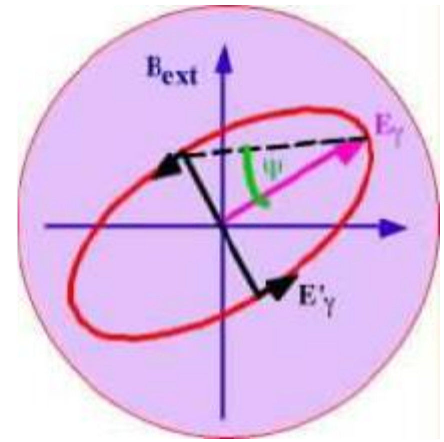
AXION SEARCHES using the Primakoff Effect

Primakoff Effect
Axion conversion into photon (or the inverse)



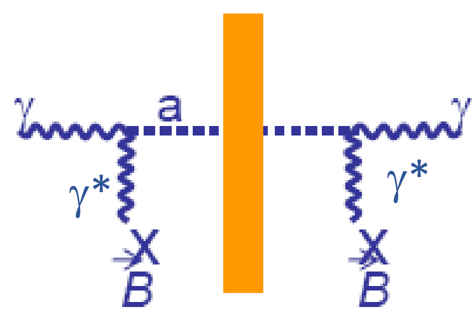
Laboratory axions

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



"Light shinning through wall"
Photonregeneration

(BFRT, OSQAR, ALPS, LIPPS, GammeV)



Short range interaction of the axion

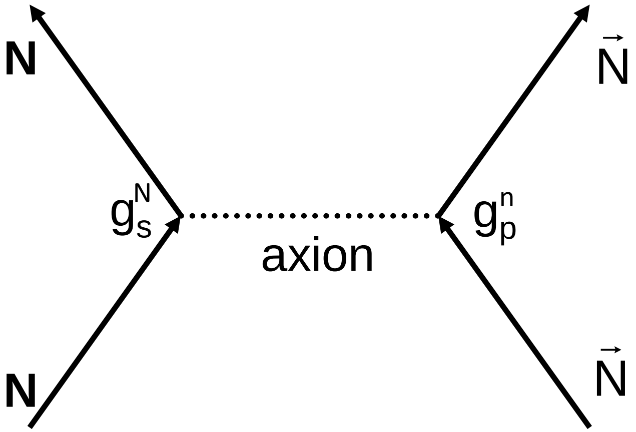
Yukawa-type potential with monopole-dipole coupling:

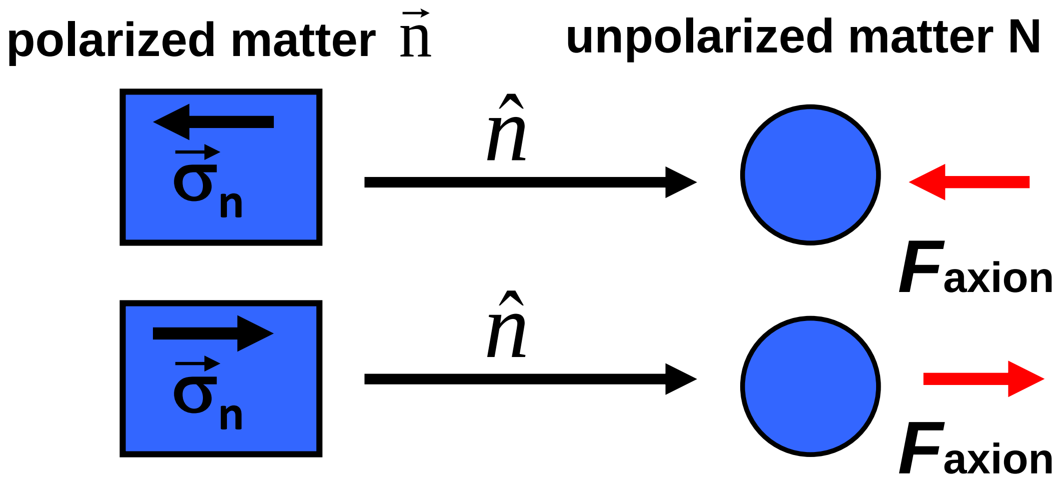
$$V(r) = \kappa \hat{n} \cdot \vec{\sigma} \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-r/\lambda}$$

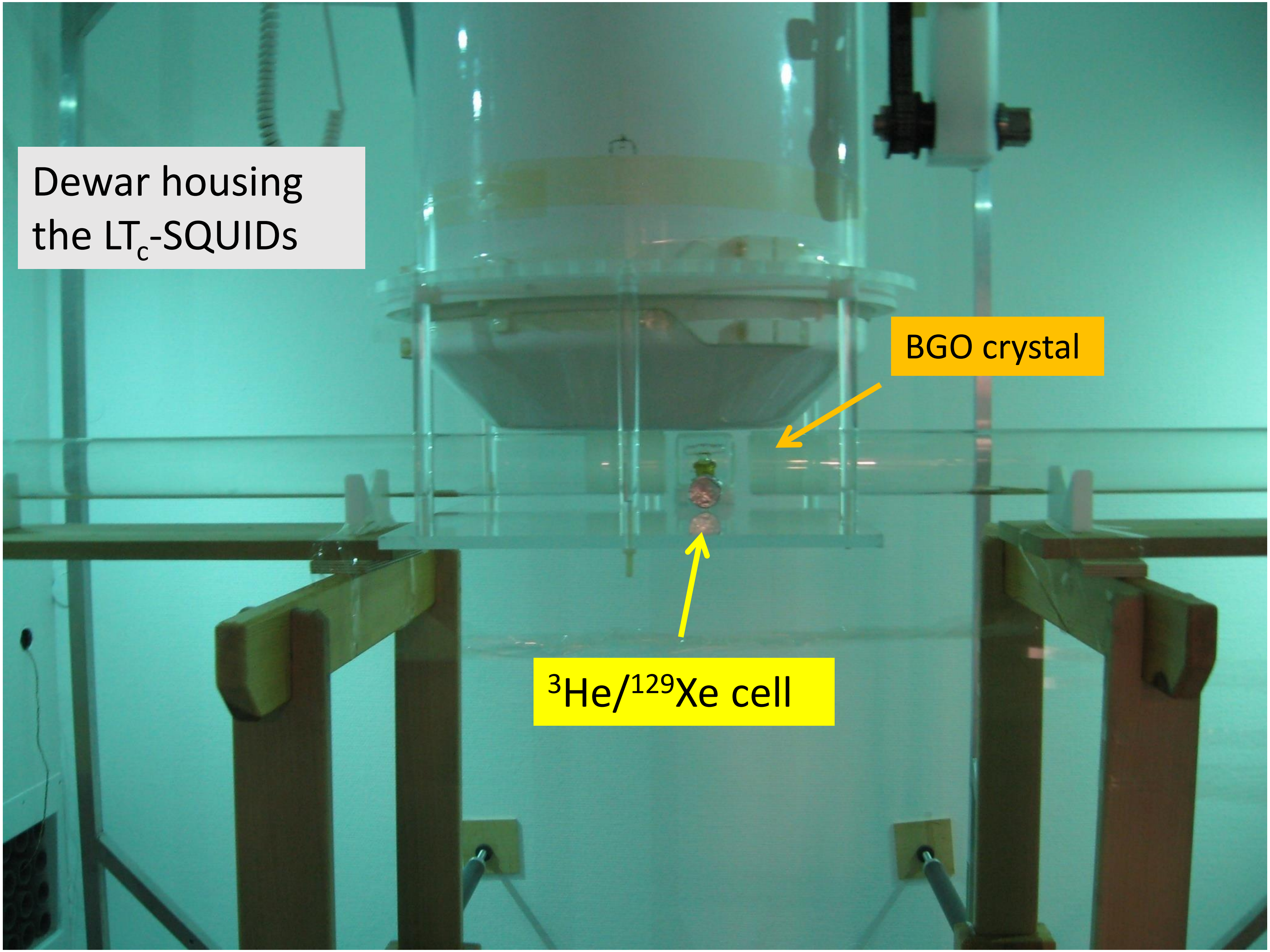
(Moody and Wilczek PRD ***30*** *130 (1984))*

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

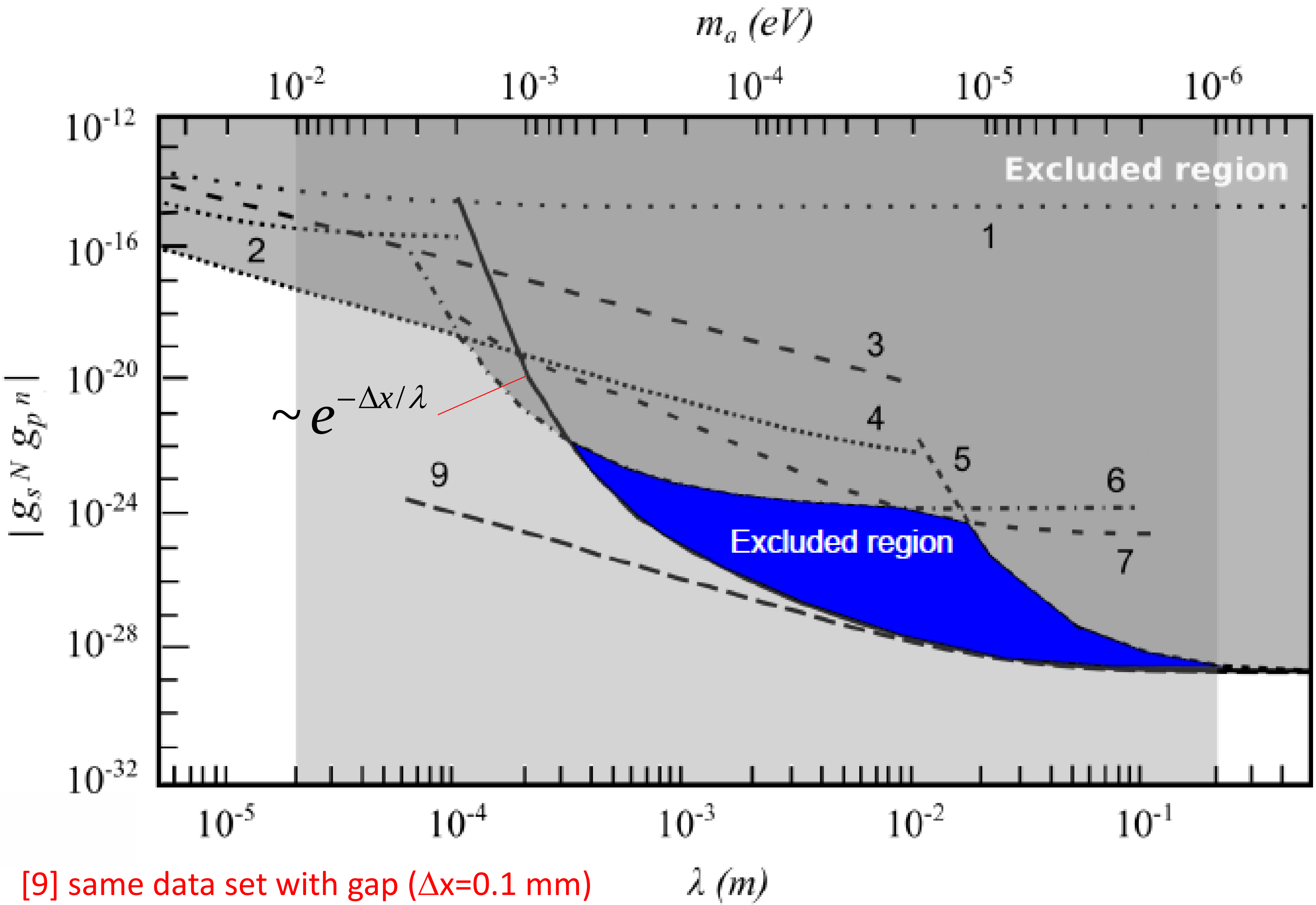
$$\begin{pmatrix} 10^{-6}\,\text{eV} < m_a < 10^{-2}\,\text{eV} \\ 10^{-5}\,\text{m} < \lambda < 10^{-1}\,\text{m} \end{pmatrix}$$



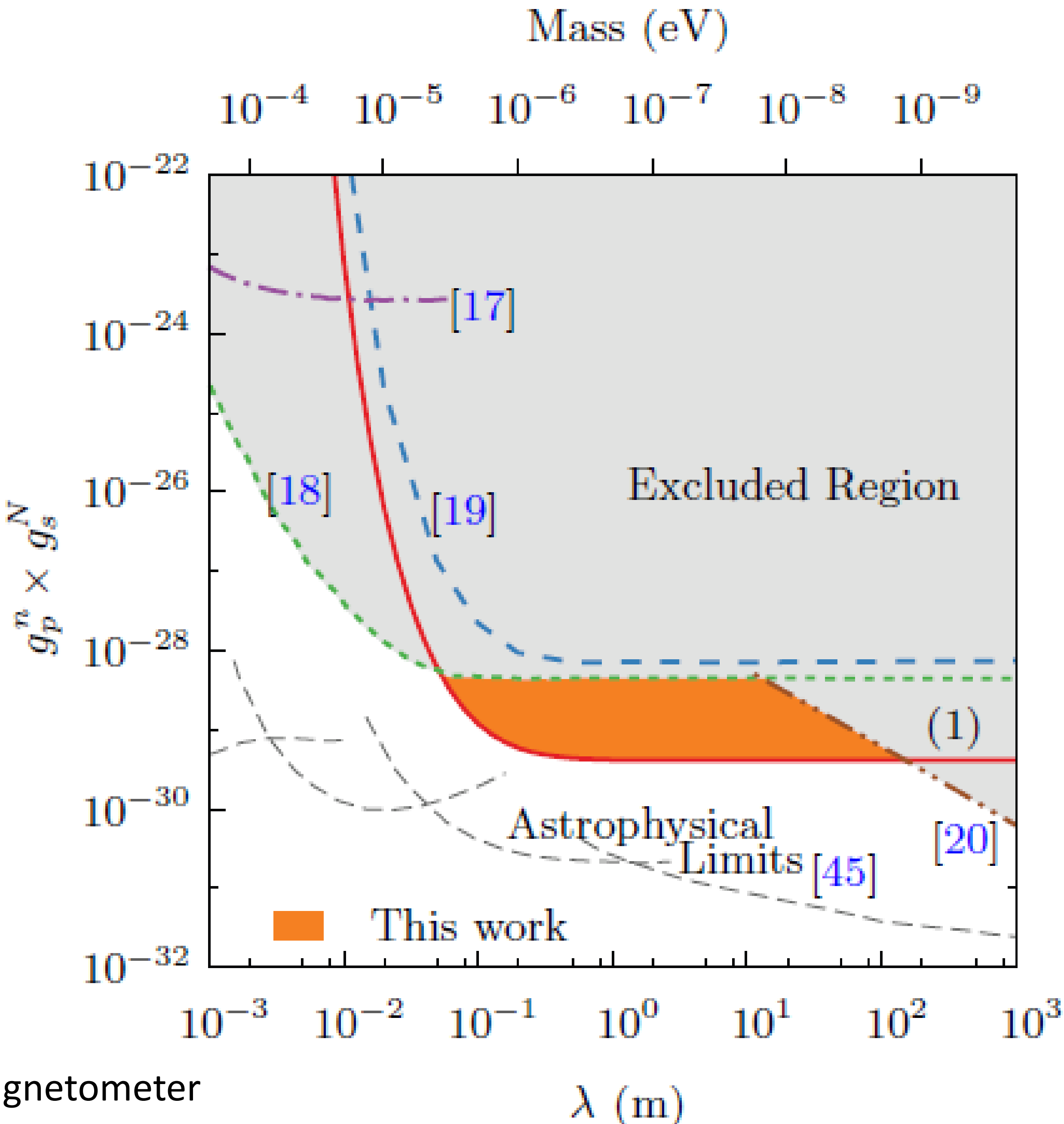



Dewar housing
the LT_c-SQUIDs
BGO crystal
$^{3}He/^{129}Xe$ cell

Exclusion Plot for new spin-dependent forces



[9] same data set with gap (Δx=0.1 mm)

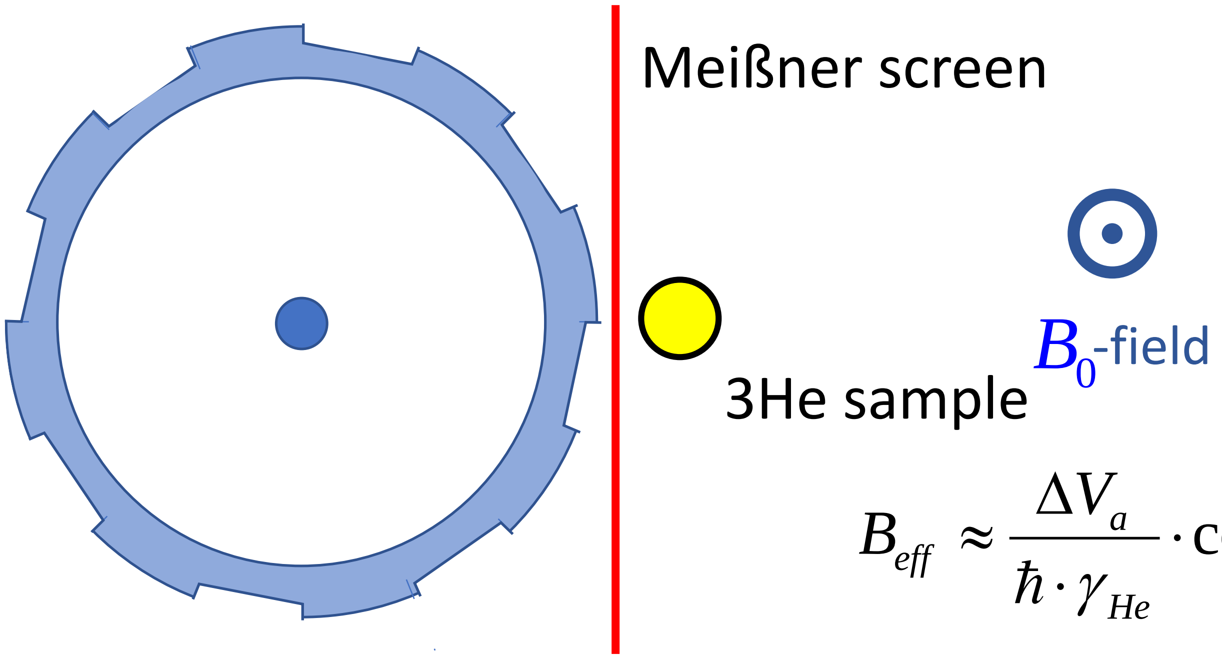


K-3He comagnetometer

Romalis et al. , arXiv:1801.02757

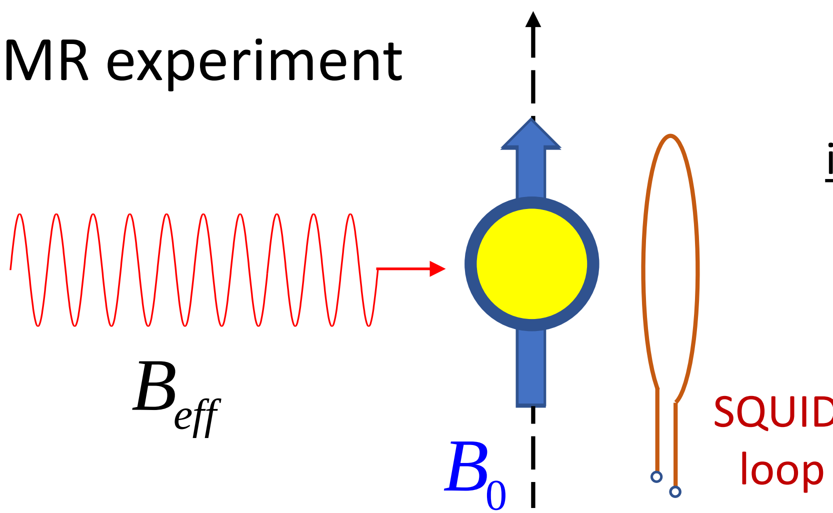
ARIADNE axion experiment

Resonantly detecting axion-mediated forces PRL 113 (2014) 161801



$$B_{eff} \approx \frac{\Delta V_a}{\hbar \cdot \gamma_{He}} \cdot \cos\left(n \cdot \omega_{rot} \cdot t\right)$$

→ classical NMR experiment

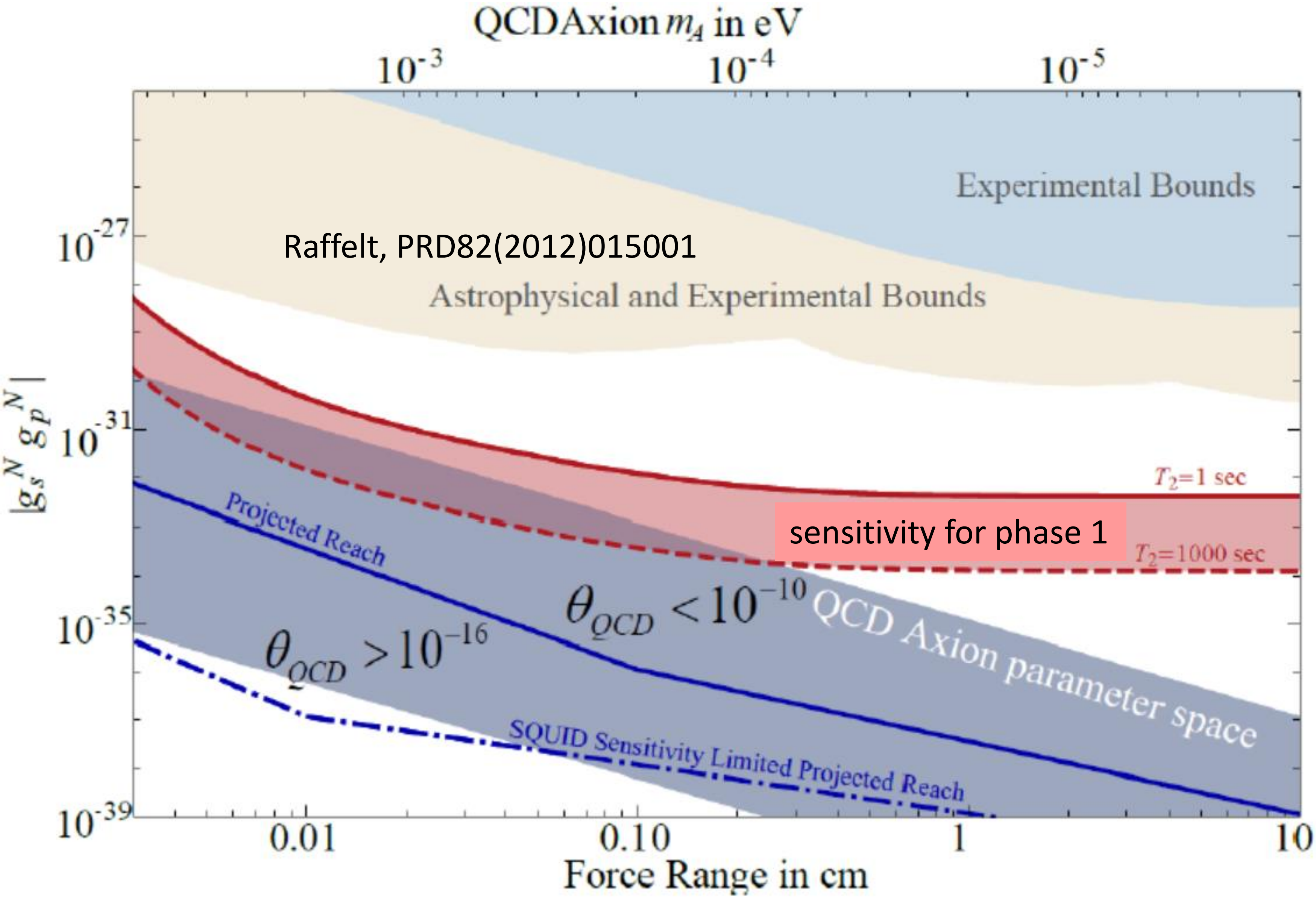


<u>in resonance:</u> $\omega_{L,3He} = n \cdot \omega_{rot}$

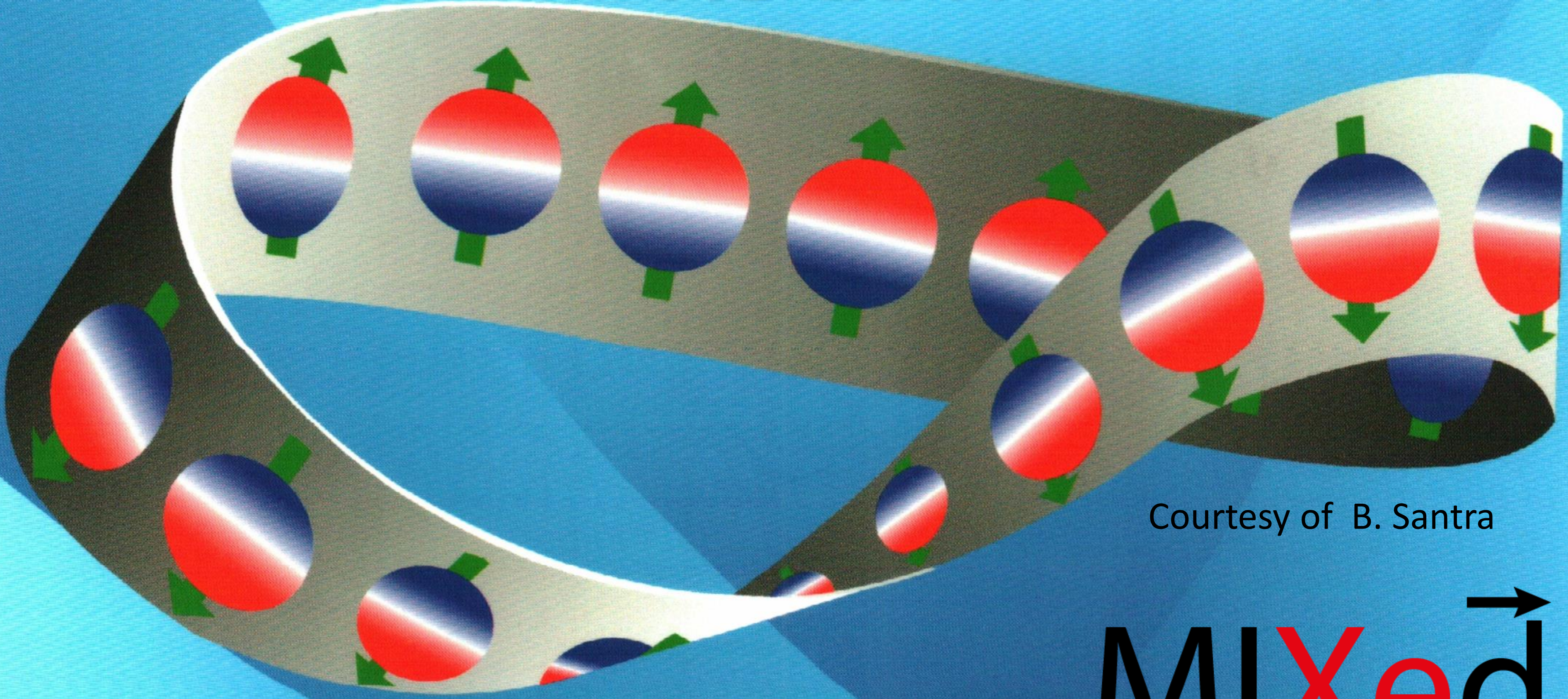
sensitivity ~ $Q = \omega \cdot T_2^*$

(quality factor)

Projected reach for monopole-dipole axion mediated interactions



Measurement of the ^{129}Xe EDM



Courtesy of B. Santra

GUTENBERG JOHANNES UNIVERSITÄT MAINZ

JÜLICH FORSCHUNGSZENTRUM

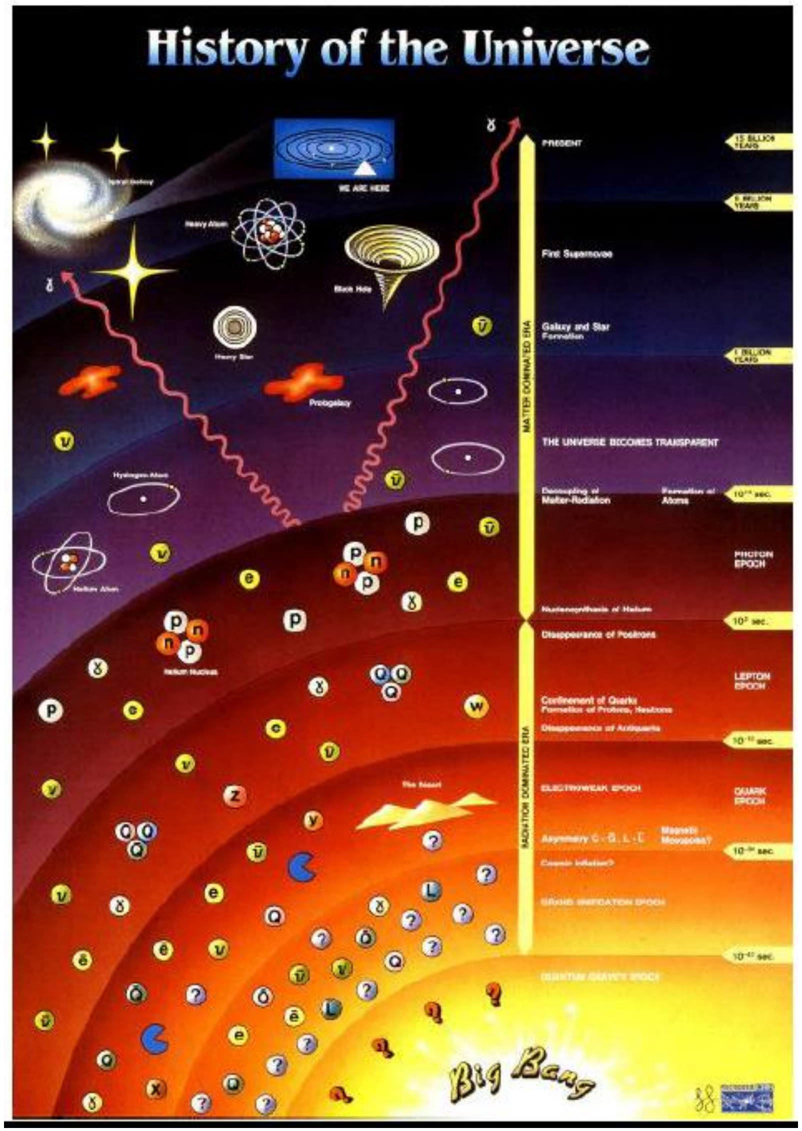
university of groningen

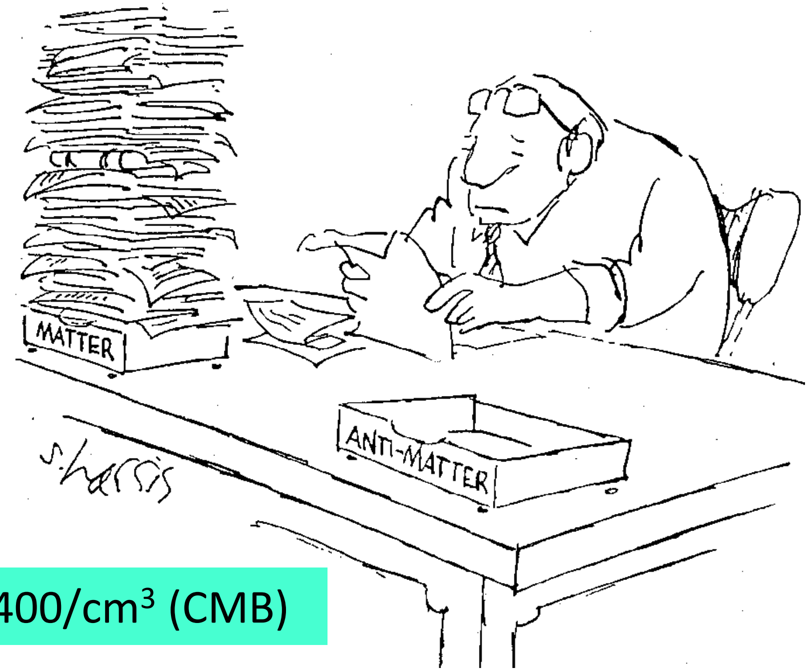
MIXed

Measurement and Investigation of the Xenon-129 electric dipole moment

Our world is composed of matter

... and not antimatter





$n_\gamma \approx 400/cm^3$ (CMB)

$n_b \approx 0.2$ protons/m^3

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 6 \times 10^{-10}$$

SM prediction based on observed flavor-changing CP-violation (CKM-matrix)

$$\eta = \frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 10^{-18}$$

SM CP-odd phases

$$\delta_{CKM} \sim O(1)$$

explains $C\!\!\!/P\!\!\!/$ in K and B meson mixing and decays

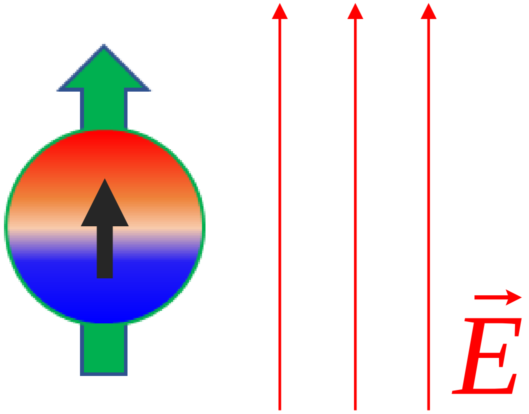
$$\bar{\theta}_{QCD} < 10^{-10}$$

constrained experimentally (d_n, d_{Hg})
(strong CP problem)

Electric dipole moments (EDMs)

of elementary particles
(flavor-diagonal $C\!\!\!/P\!\!\!/$)

$$\Delta E = -\left| d_{EDM} \right| \cdot \vec{\sigma} \cdot \vec{E} \quad \text{(CP-odd)}$$

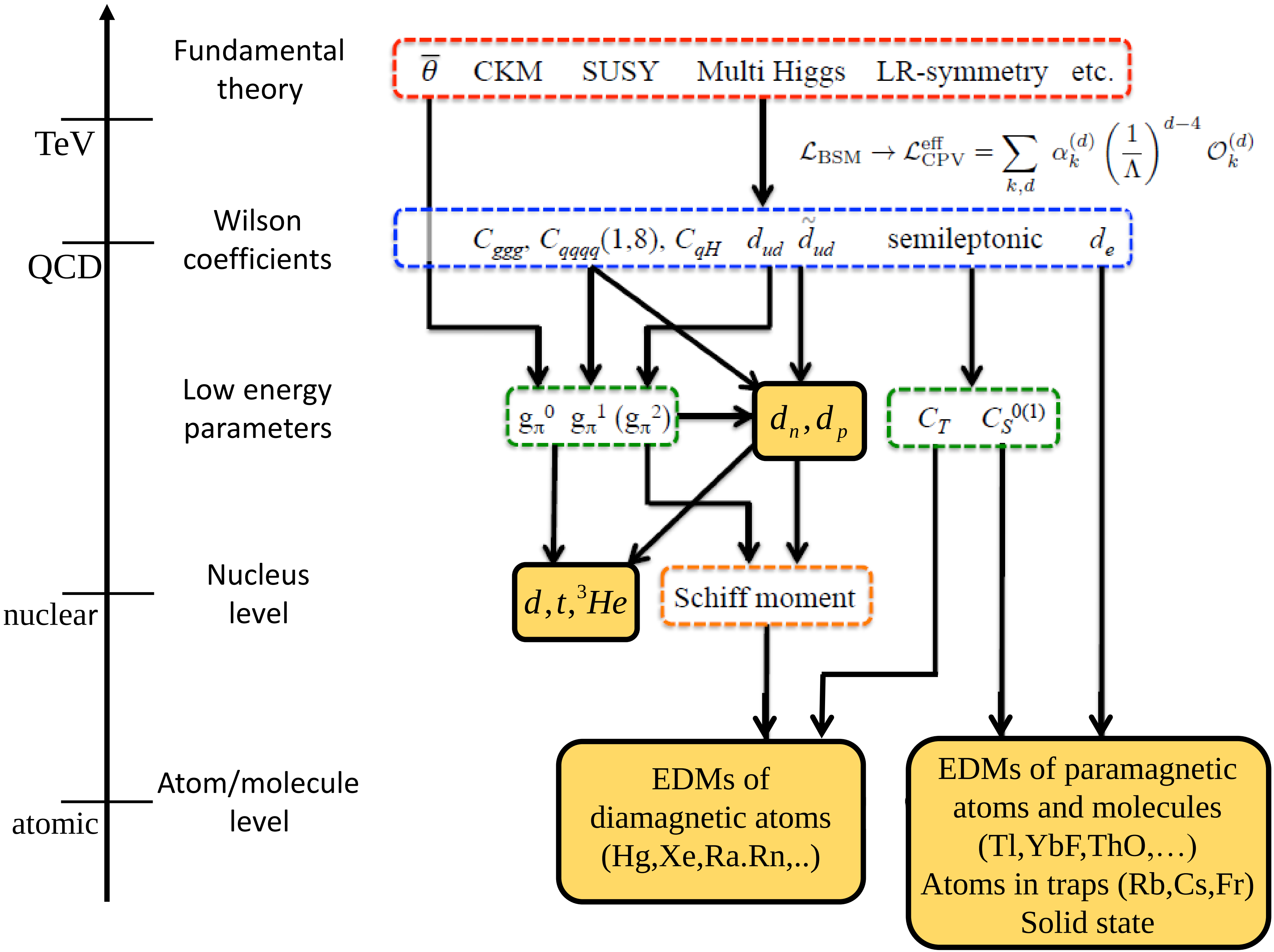


EDM measurement free of SM background

$$d_n \sim 10^{-32} - 10^{-34} \;\; e\,cm \qquad d_e \le 10^{-38} \;\; e\,cm$$

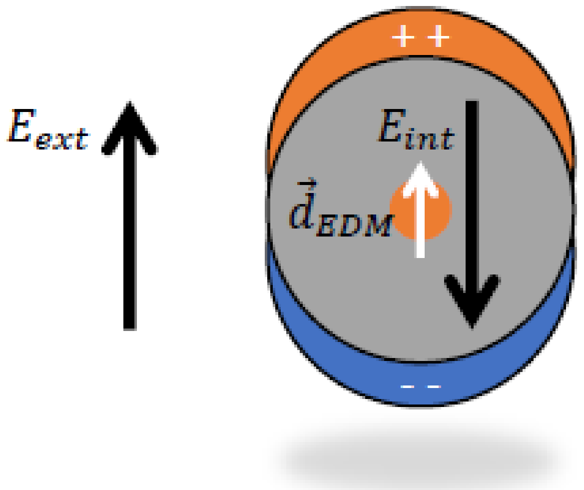
Khriplovich, Zhitnitsky 86

fourth order electroweak



Fundamental theory
TeV
Wilson coefficients
QCD
Low energy parameters
Nucleus level
nuclear
Atom/molecule level
atomic
$\bar{\theta}$ CKM SUSY Multi Higgs LR-symmetry etc.
$\mathcal{L}_{\rm BSM} \to \mathcal{L}^{\rm eff}_{\rm CPV} = \sum_{k,d} \alpha_k^{(d)} \left(\frac{1}{\Lambda}\right)^{d-4} \mathcal{O}_k^{(d)}$
C_{ggg}, $C_{qqqq}(1,8)$, C_{qH} d_{ud} $\tilde{d}_{ud}$ semileptonic d_e
g_π^0 g_π^1 (g_π^2)
d_n, d_p
C_T $C_S^{0(1)}$
$d, t, {}^3He$
Schiff moment
EDMs of diamagnetic atoms (Hg,Xe,Ra.Rn,..)
EDMs of paramagnetic atoms and molecules (Tl,YbF,ThO,…) Atoms in traps (Rb,Cs,Fr) Solid state

Atomic EDM



complete shielding: $\vec{E}_{eff} = \vec{E}_{ext} + \vec{E}_{int} = \varepsilon \cdot \vec{E}_{ext} = 0$

$$\Rightarrow \Delta E_{EDM} = -\vec{d}_{EDM} \cdot \vec{E}_{eff} = -\vec{d}_{EDM} \cdot \varepsilon \cdot \vec{E}_{ext} = 0$$

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

EDM of a system of non-relativistic charged point particles that interact electrostatically can not be measured : $\varepsilon = 0$

Diamagnetic EDMs – „Schiff suppression: ε "

For a finite nucleus, the charge and EDM have different spatial distributions

S- Schiff moment: $$\vec{S} = S\frac{\vec{I}}{I} = \frac{1}{10}\left[\int e\rho(\vec{r})\vec{r}r^2d^3r - \frac{5}{3Z}\vec{d}\int \rho(\vec{r})r^2d^3r\right]$$

Schiff moment is dominant CP-odd N-N interaction for large atoms

$$d_A = k_A \cdot 10^{-17} \cdot \left[\frac{S}{e\ fm^3}\right] e\,cm$$ ($k_{Xe} \sim 0.38$)

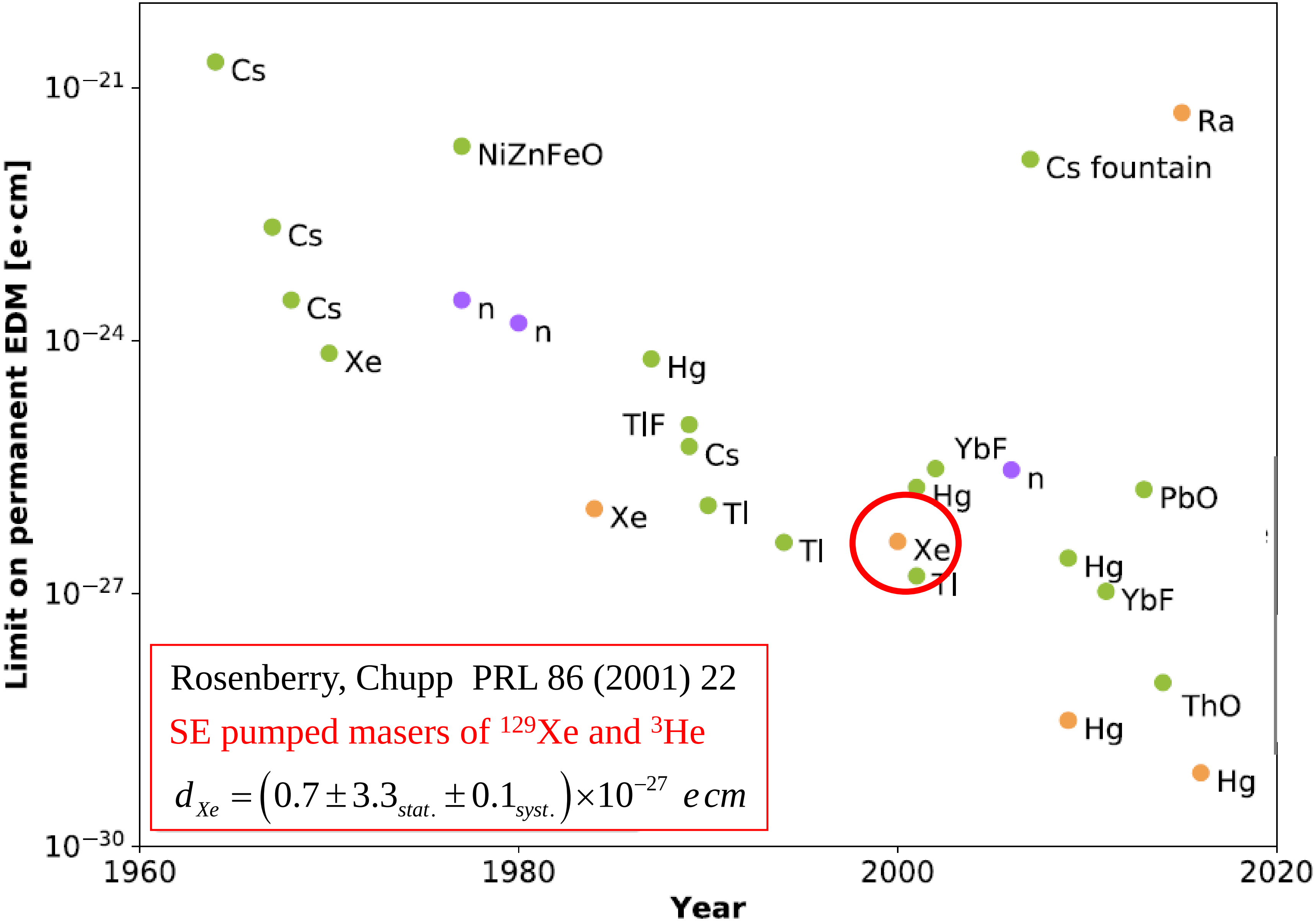
$$S = S\left(\bar{g}^{(i)}_{\pi NN}, d_n, d_p, \ldots\right)$$ (low energy parameters)

- $d_A \sim 10\,Z^2 \left(R_N / R_A\right)^2 d_{nuc} \sim O(10^{-3})\, d_{nuc}$

$$d_A = \varepsilon \cdot d_{nuc}$$

EDM sensitivity: $$\delta d \propto \left(\varepsilon \cdot E_{ext} \cdot SNR \cdot T^{3/2}\right)^{-1}$$

EDM precision experiments (upper limits)

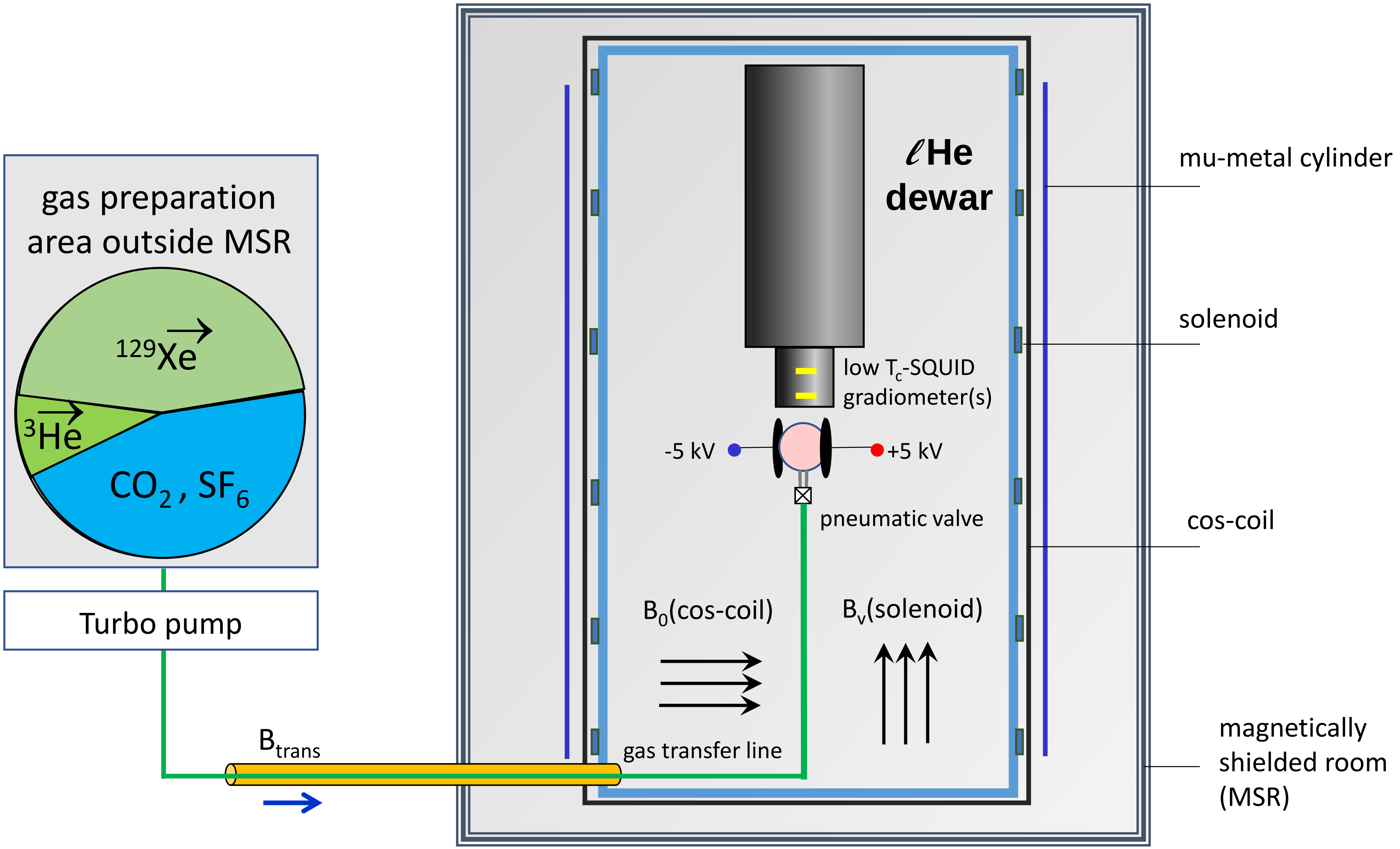


Rosenberry, Chupp PRL 86 (2001) 22

SE pumped masers of ^{129}Xe and ^{3}He

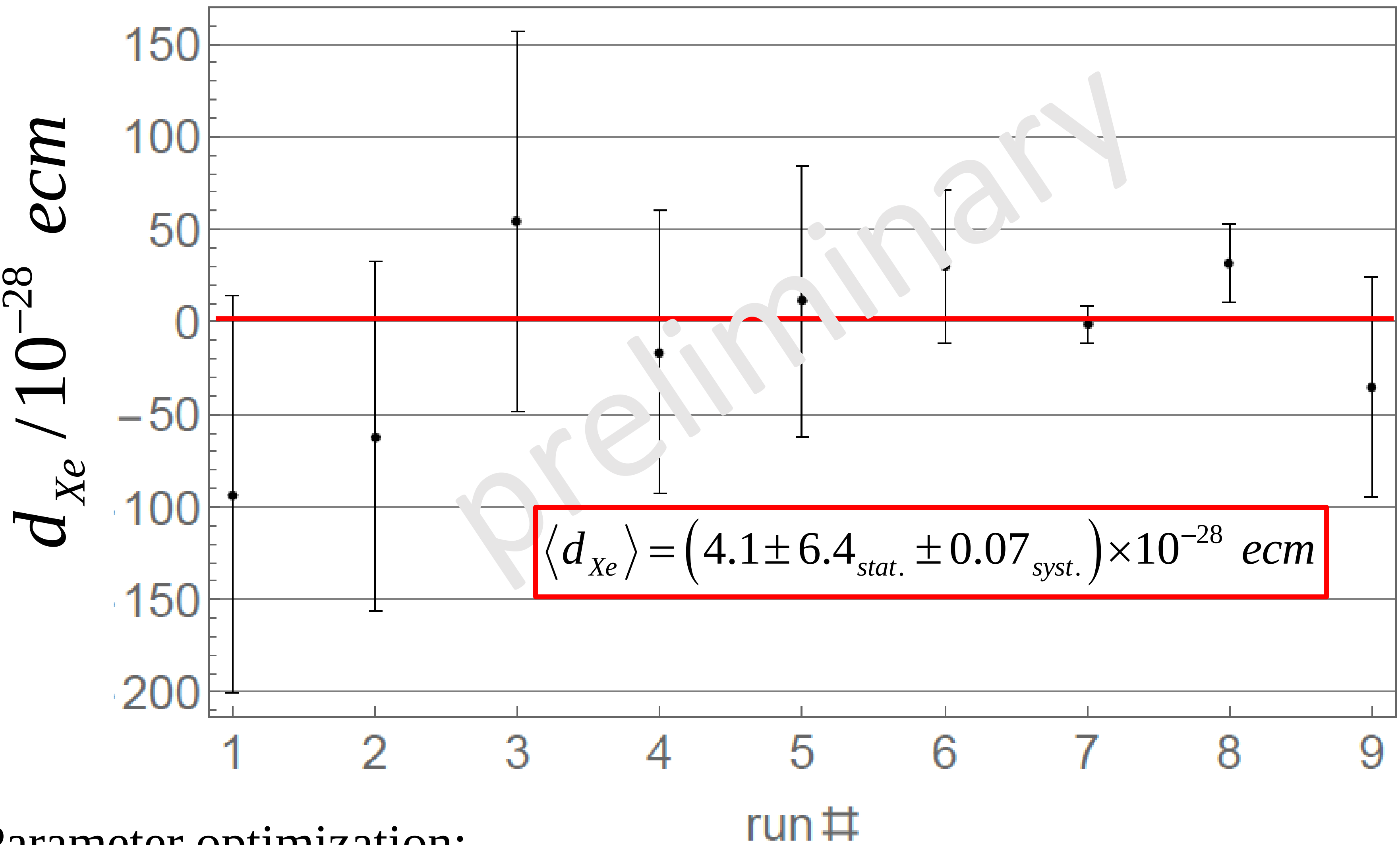
$$d_{Xe} = \left(0.7 \pm 3.3_{stat.} \pm 0.1_{syst.}\right) \times 10^{-27}\ e\,cm$$

Experimental Setup MIXed



→ for details : talk of St. Zimmer

Extracted Xe-EDM limits



Parameter optimization:

$\left|\nabla B_z\right|$; p_{He}, p_{Xe}, p_{bg} (partial pressures); system noise: $\sim SNR \cdot \left(T_2^*\right)^{3/2}$

Comparison: Hg-EDM vs Xe-EDM sensitivity

Hg-EDM:

SNR~ 30000 @ f_{BW} = 1 Hz
<E> = 8 kV/cm
$\delta d_{Hg} = 4.1 \times 10^{-29}$ *ecm/day*

Xe-EDM:

SNR~ 10000 @ f_{BW} = 1 Hz
<E> = 0.8 kV/cm
$T_{2,Xe}{}^{*} \sim 3\ h$
$\delta d_{Xe} = 4 \times 10^{-28}$ *ecm/day*

Improvements:

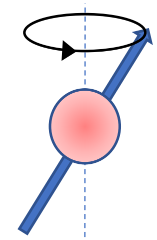
- *<E>*
- $SNR, T_2^* \rightarrow$ *new magnetic shield*

$$noise: 10\ fT/\sqrt{Hz} \rightarrow \sim 1\ fT/\sqrt{Hz}$$
$$|\nabla B|: \quad 10\ pT/cm \quad \rightarrow \sim 3\ pT/cm$$

Parameter	Limit (this work)	Theory
$d_{\rm Xe}$	$1.2 \cdot 10^{-27}$ e cm	95% CL
d_e	$1.2 \cdot 10^{-23}$ e cm	[35, 36]
$C_{T,{\rm n}}$	$2.8 \cdot 10^{-7}$	[35]
$C_{P,{\rm n}}$	$1.0 \cdot 10^{-4}$	[35]
$C_{T,{\rm p}}$	$9.0 \cdot 10^{-7}$	[35]
$C_{P,{\rm p}}$	$3.2 \cdot 10^{-4}$	[35]
S	$3.2 \cdot 10^{-10}$ e fm^3	[35, 40, 41]
d_n	$1.0 \cdot 10^{-22}$ e cm	[42]
d_p	$5.4 \cdot 10^{-21}$ e cm	[42]
g_0	$2.9 \cdot 10^{-9}$	[43]
g_1	$4.0 \cdot 10^{-9}$	[43]
g_2	$2.7 \cdot 10^{-9}$	[43]

[35] V. A. Dzuba, V. V. Flambaum, and S. G. Porsev, Phys. Rev. A 80, (2009).
[36] V. V. Flambaum and I. B. Khriplovich, Zh. Eksp. Teor. Fiz. 89, 1505 (1985).
[42] N. Yoshinaga, K. Higashiyama, R. Arai, Prog. Theor. Phys. 124, (2010).
[43] V. F. Dmitriev, R. A. Sen'kov, and N. Auerbach, Phys. Rev. C 71, 035501 (2005).

Conclusion and Outlook



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

$$T^*_{2,He} \approx 100\,hours$$

$$T^*_{2,Xe} \approx 8\ hours$$

(so far limited by $T_{1,wall}$)

Eur. Phys. J. D 57, 303–320 (2010)

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

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

$$V(r)/\hbar = \langle \tilde{\mathrm{b}} \rangle\, \hat{\varepsilon} \cdot \vec{\sigma} / \hbar \qquad \tilde{b}^n_\perp < 8.4 \times 10^{-34}\ GeV\ \ (68\%\, C.L.)$$

tightest constrains in the matter sector

- Short range spin-dependent interaction (axion search):

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

new upper limits for $g^N_s g^n_p$
in the range 10^{-3} m < λ < 10^1 m

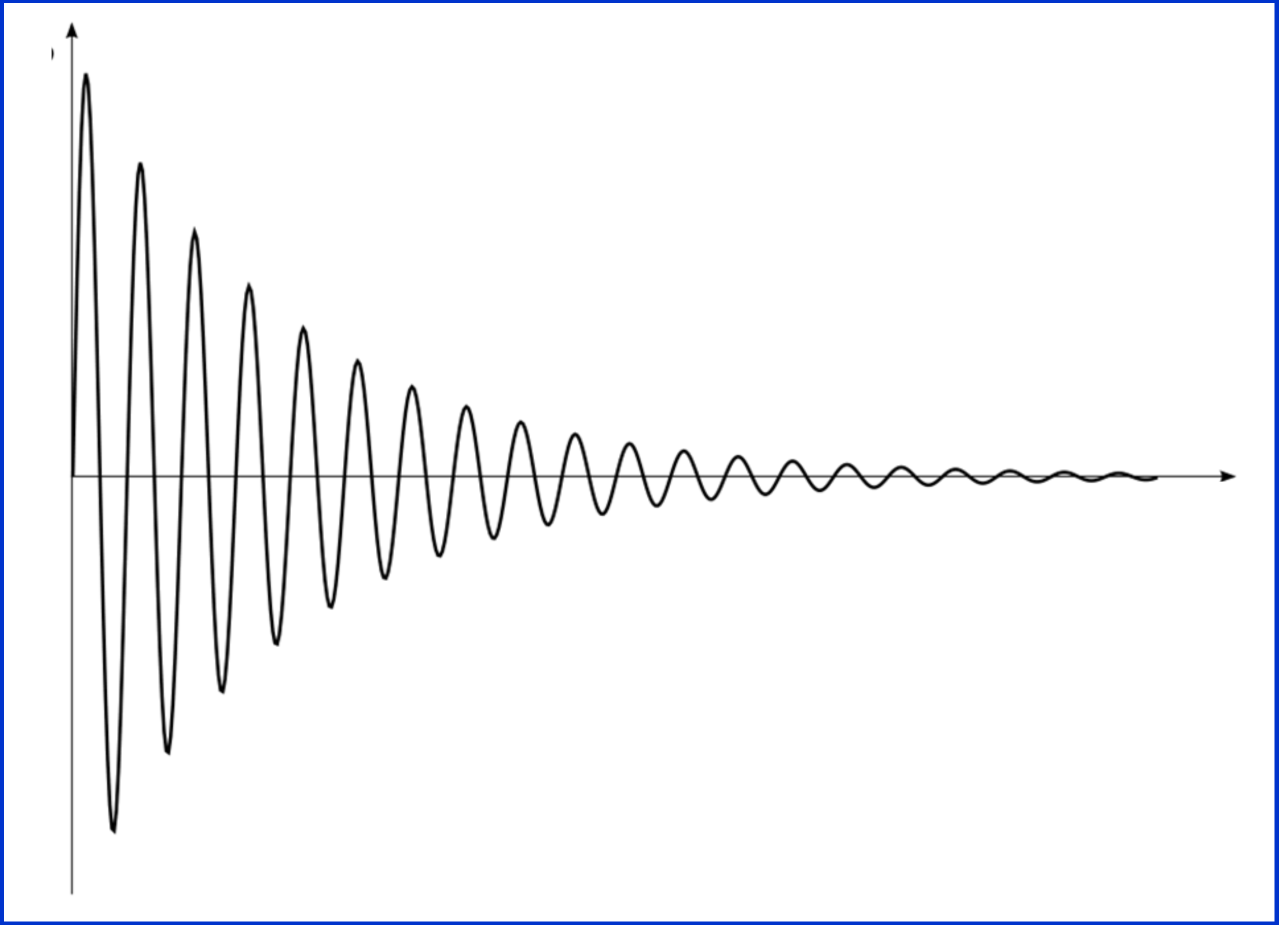
ARIADNE: probing QCD axion parameter space

- ^{129}Xe electric dipole moment (MIXe$\vec{d}$-collaboration):

$$|d_{Xe}| < 1.2 \times 10^{-27}\ ecm\ (95\%\, CL)$$

room for improvements

Thank you for your attention

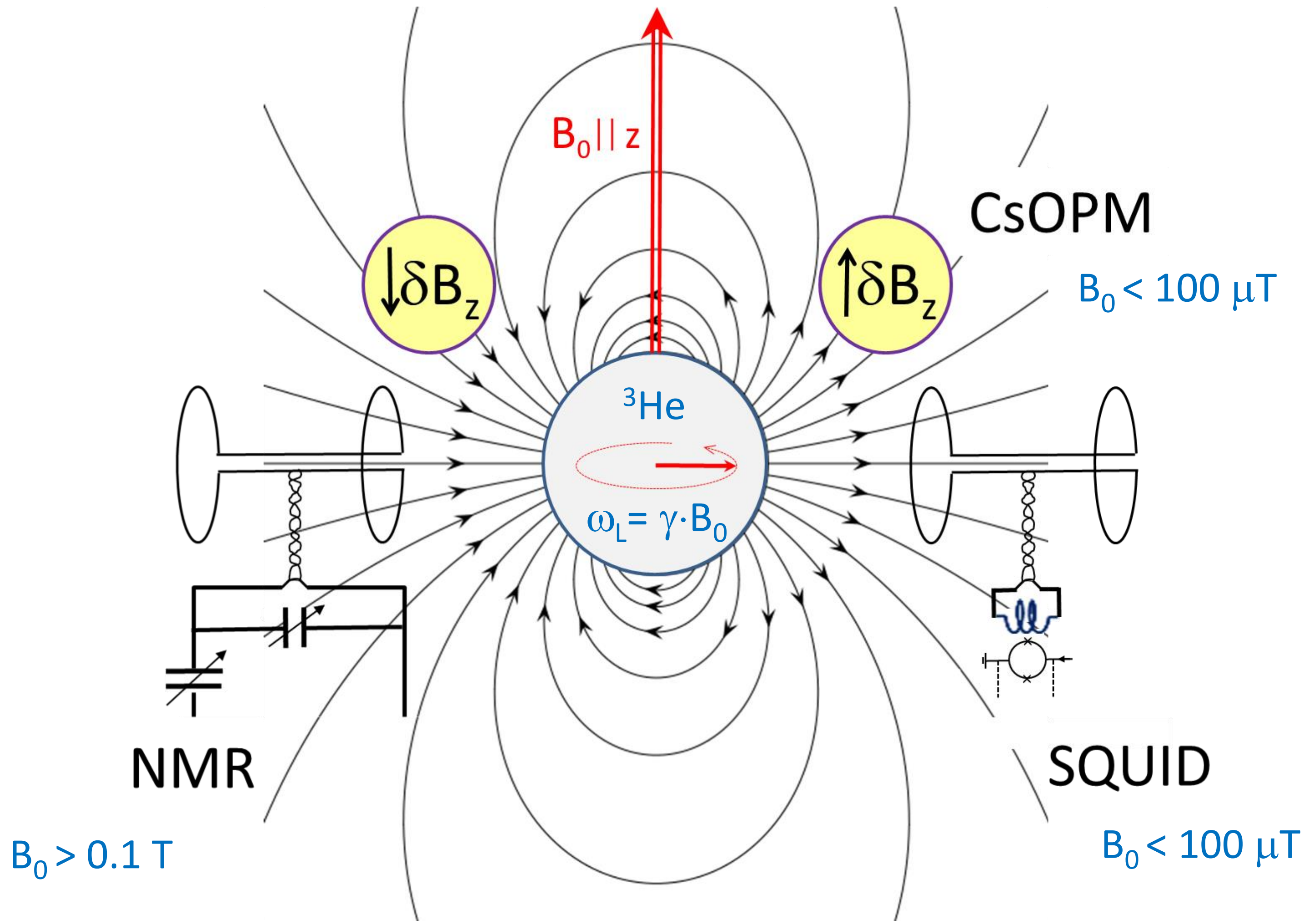


Limits on CP-violating observables from ^{199}Hg EDM limit

$$\mathbf{d}_{\mathrm{Hg}} = -2.4 \times 10^{-4} \mathbf{S}_{\mathrm{Hg}}/\mathrm{fm}^2$$

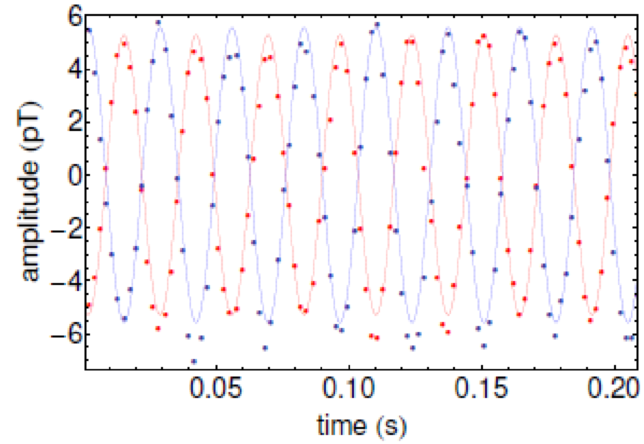
Quantity	Expression	Limit	Ref.
$\mathbf{d}_n$	$\mathbf{S}_{\mathrm{Hg}}/(1.9\ \mathrm{fm}^2)$	$1.6 \times 10^{-26}\ e\,\mathrm{cm}$	[21]
$\mathbf{d}_p$	$1.3 \times \mathbf{S}_{\mathrm{Hg}}/(0.2\ \mathrm{fm}^2)$	$2.0 \times 10^{-25}\ e\,\mathrm{cm}$	[21]
$\bar{g}_0$	$\mathbf{S}_{\mathrm{Hg}}/(0.135\ e\,\mathrm{fm}^3)$	2.3×10^{-12}	[5]
$\bar{g}_1$	$\mathbf{S}_{\mathrm{Hg}}/(0.27\ e\,\mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{g}_2$	$\mathbf{S}_{\mathrm{Hg}}/(0.27\ e\,\mathrm{fm}^3)$	1.1×10^{-12}	[5]
$\bar{\theta}_{QCD}$	$\bar{g}_0/0.0155$	1.5×10^{-10}	[22,23]
$(\tilde{d}_u - \tilde{d}_d)$	$\bar{g}_1/(2 \times 10^{14}\ \mathrm{cm}^{-1})$	$5.7 \times 10^{-27}\ \mathrm{cm}$	[25]
C_S	$\mathbf{d}_{\mathrm{Hg}}/(5.9 \times 10^{-22}\ e\,\mathrm{cm})$	1.3×10^{-8}	[15]
C_P	$\mathbf{d}_{\mathrm{Hg}}/(6.0 \times 10^{-23}\ e\,\mathrm{cm})$	1.2×10^{-7}	[15]
C_T	$\mathbf{d}_{\mathrm{Hg}}/(4.89 \times 10^{-20}\ e\,\mathrm{cm})$	1.5×10^{-10}	see text

Schematic layout of the He-3 nuclear magnetometer based on free spin precession



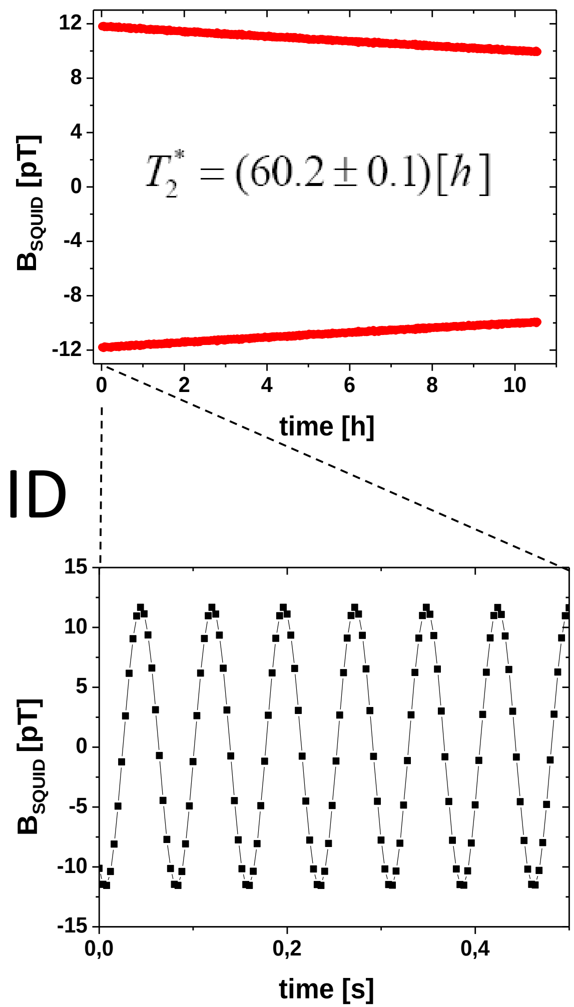
Recorded free spin precession signal

CsOPM $f_L \approx 37Hz$

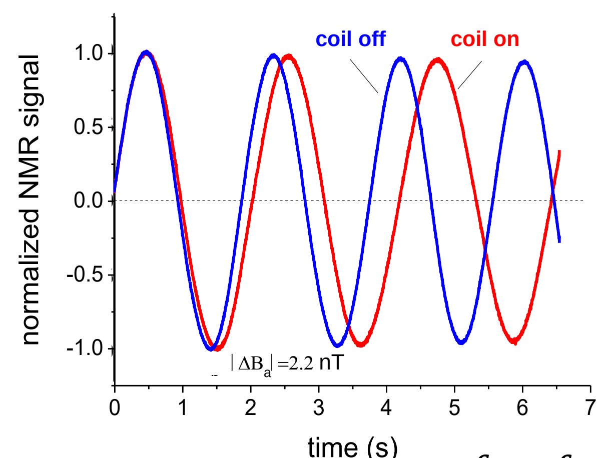


SQUID

$f_L \approx 13Hz$



NMR

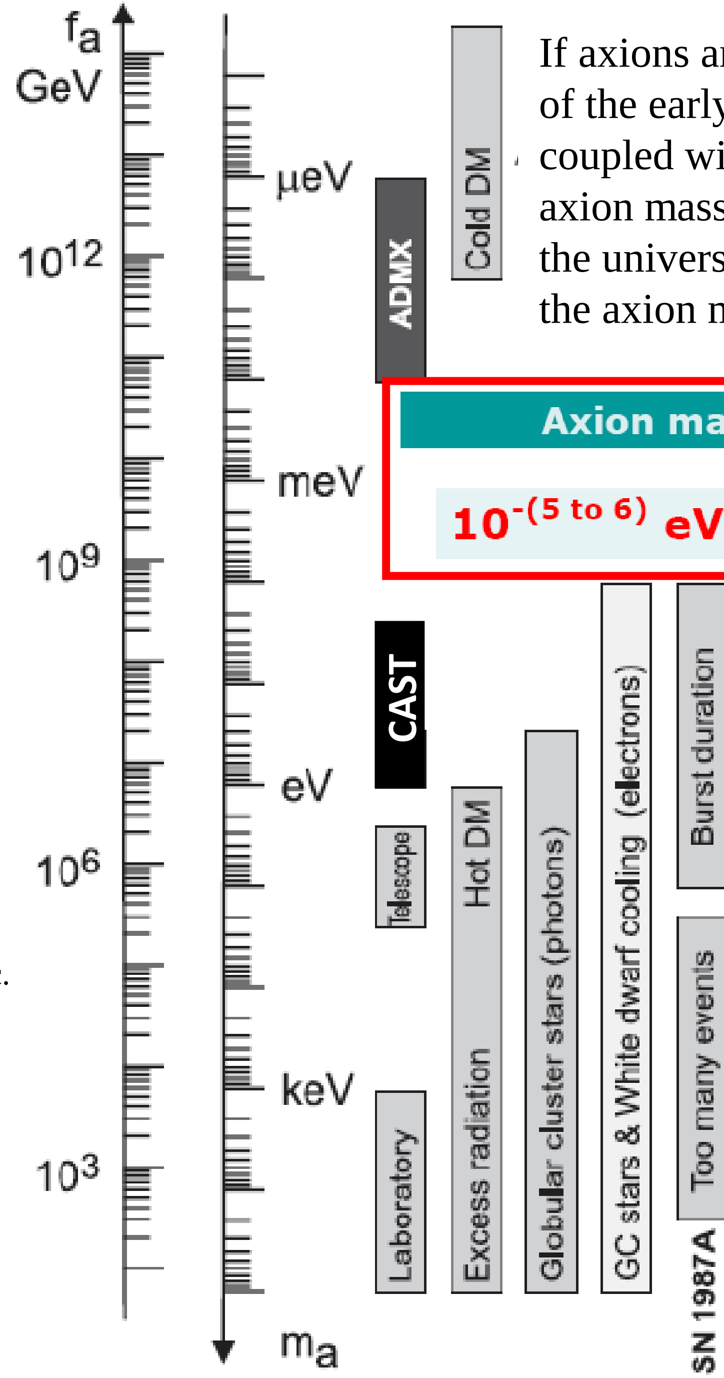


$f = f_L - 48.6MHz$

C. Gemmel et al., Eur. Phys. J. D 57, 303 (2010)

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).



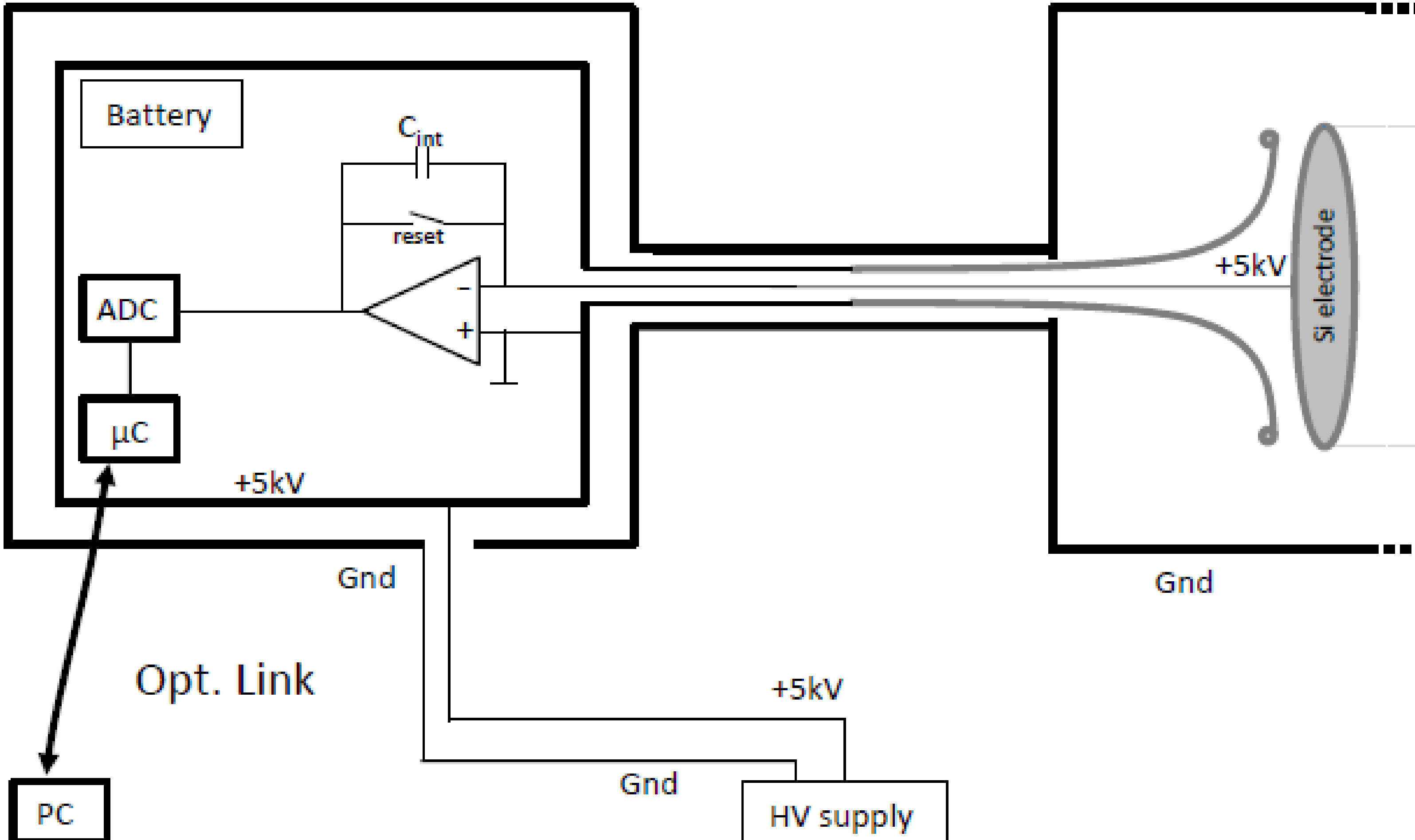
If axions are dark matter, they are a relic of the early universe. A particular scenario coupled with the requirement that the axion mass density not severely overclose the universe results in a lower bound to the axion mass.

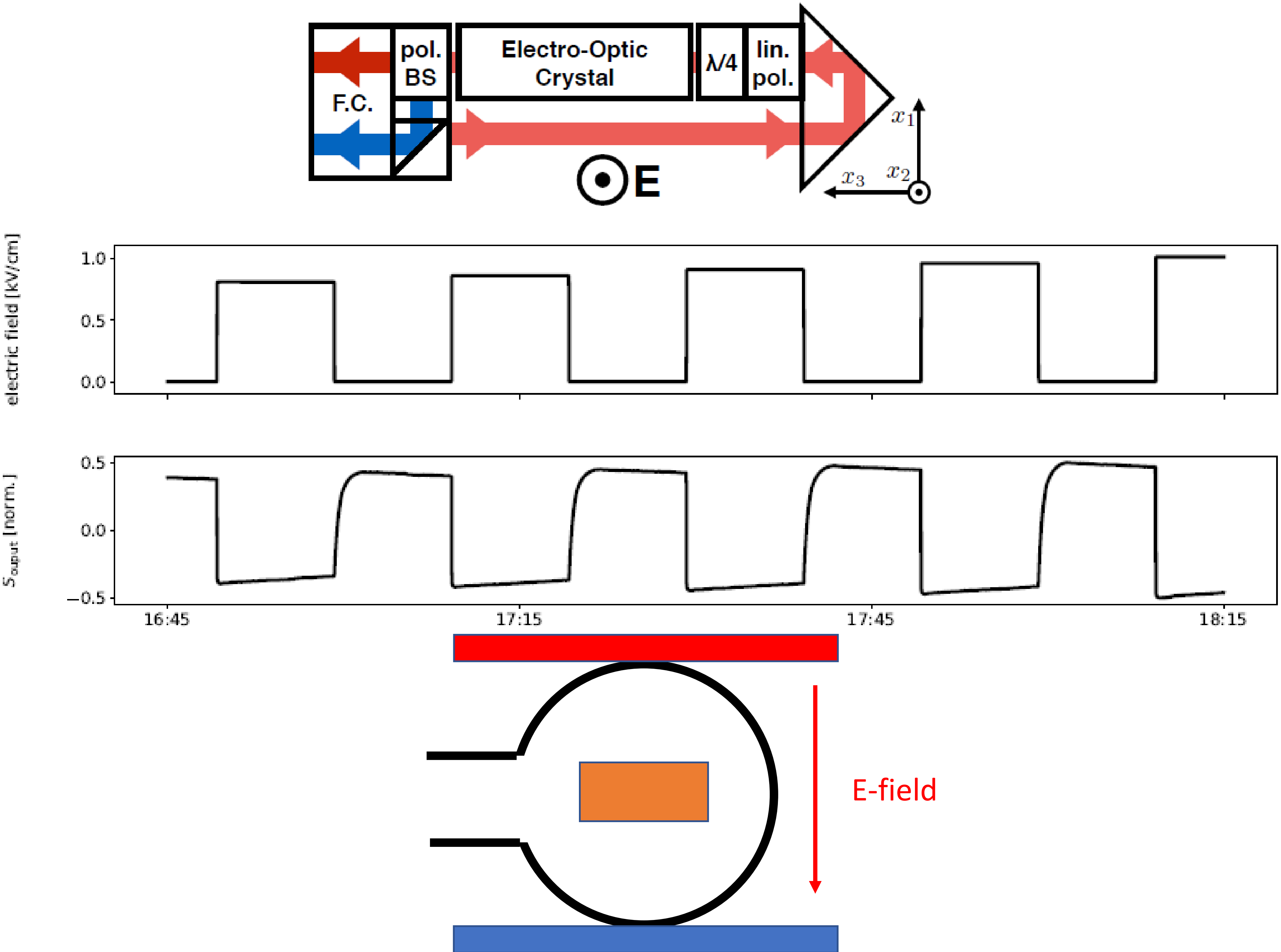
Axion mass window

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

Current Axion Search Experiments

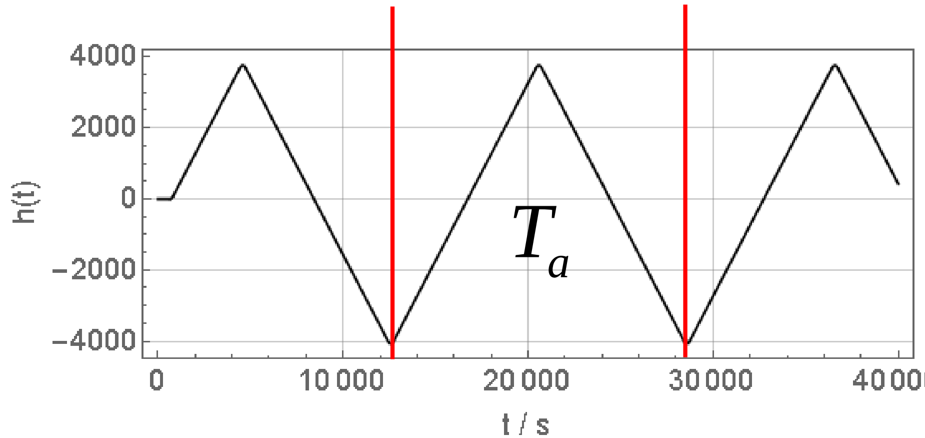
- Solar Axion Telescope – „CAST“
- Dark Matter Axion Search – „ADMX“
- Vacuum Optical Properties –“PVLAS“ etc.
- Photon Disappearance Experiments
- New Force Search – Torsion Pendulums, etc.

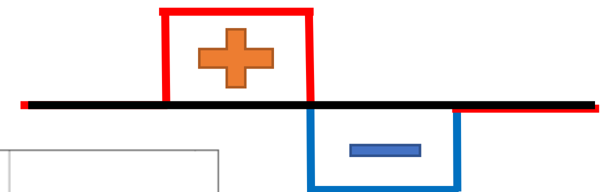

Battery
C_{int}
reset
ADC
µC
+5kV
+5kV
Si electrode
Gnd
Gnd
Opt. Link
+5kV
Gnd
HV supply
PC



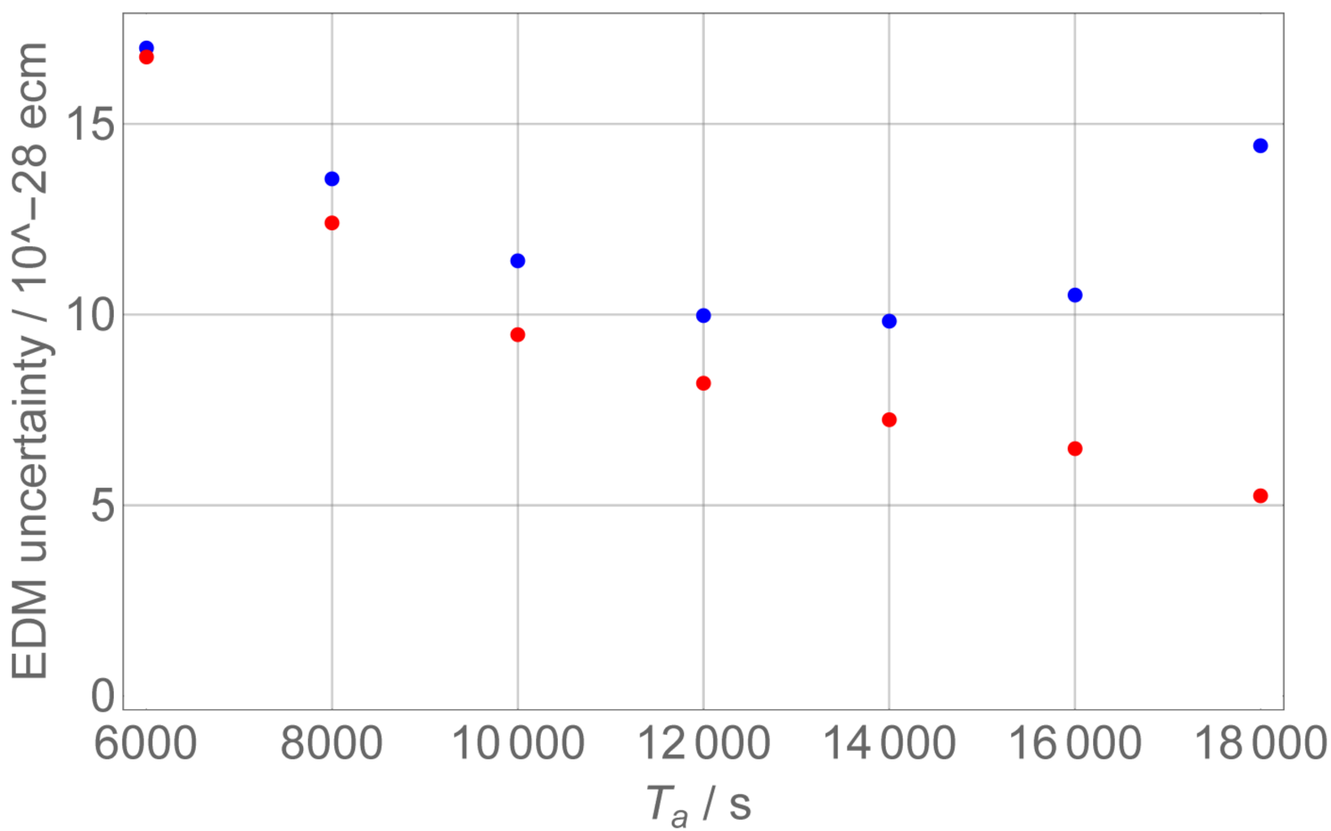
pol. BS
Electro-Optic Crystal
λ/4
lin. pol.
F.C.
E
x_1
x_2
x_3
electric field [kV/cm]
1.0
0.5
0.0
S_{ouput} [norm.]
0.5
0.0
−0.5
16:45
17:15
17:45
18:15
E-field

Influence of Electric field switching period





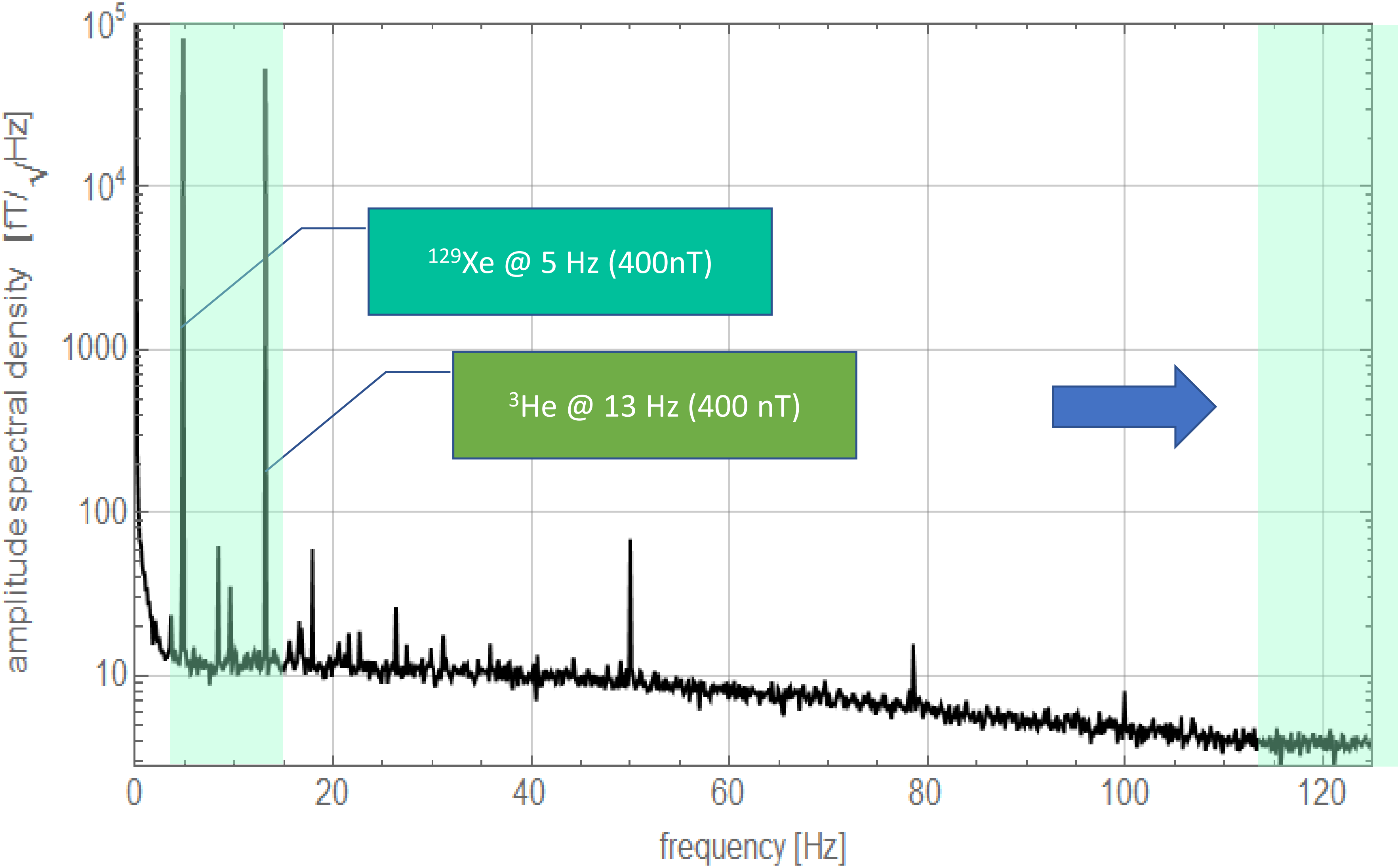
E=800 V/cm



Total error (correlation with exponential terms)

Uncorrelated error

SNR ~ 10000:1



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

Results of automatic gradient compensation

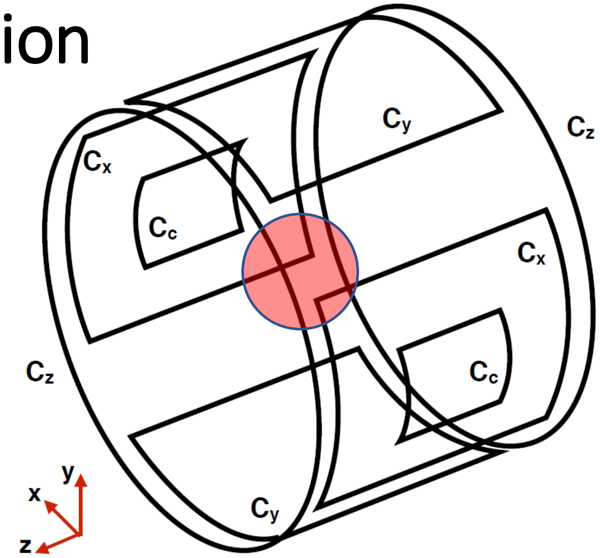
(Downhill-simplex algorithm)

Spherical cell (diameter 10 cm)

filled with 30 mbar of polarized ^{3}He

~ 10 min per iteration step

total measurement time: ~ 4 hours



$$S_{He} \propto \exp\left(-t / T_2^*(\nabla B)\right)$$

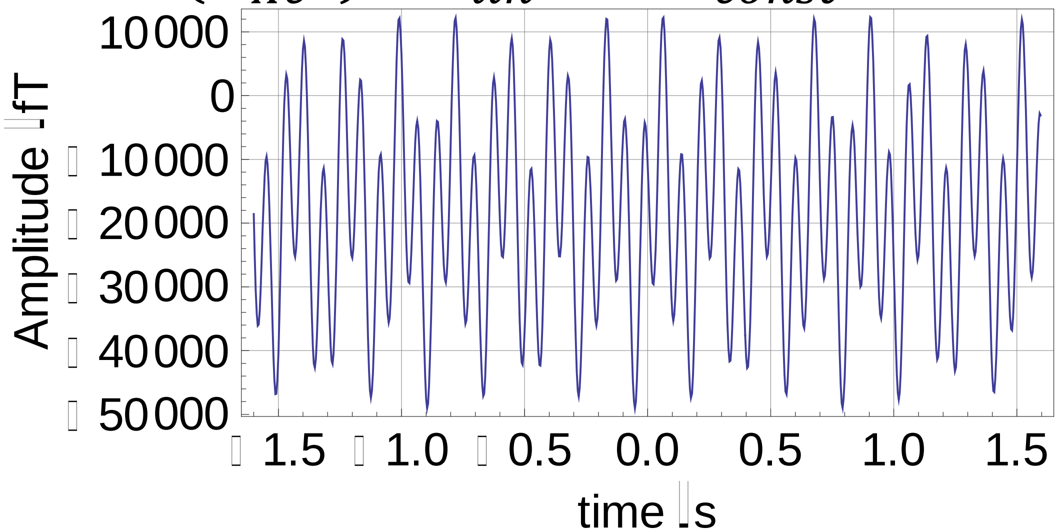
Iteration	C_x / mA	C_y / mA	C_z / mA	C_c / mA	Spin coherence time T_2* / s
start	0	0	0	0	7499
0	0	0.15	0	0	9758
1	0.11	0.11	-0.30	0.11	14750
3	0.30	0.30	-0.34	0.01	26590
5	0.33	0.30	-0.60	0.02	35120
13	0.30	0.40	-0.67	0.18	37686

effective gradients

start: ~30 pT/cm

13: < 10 pT/cm

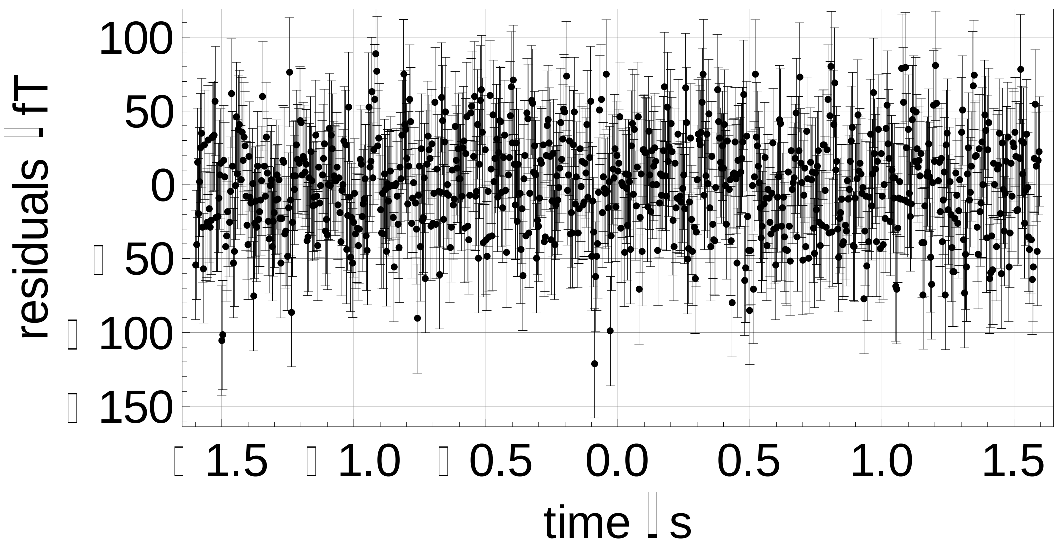
$$B_S(t) = c_{He} \cdot \cos(\omega_{He} t) + s_{He} \cdot \sin(\omega_{He} t) + c_{Xe} \cdot \cos(\omega_{Xe} t) + s_{Xe} \cdot \sin(\omega_{Xe} t) + c_{lin} \cdot t + c_{const}$$

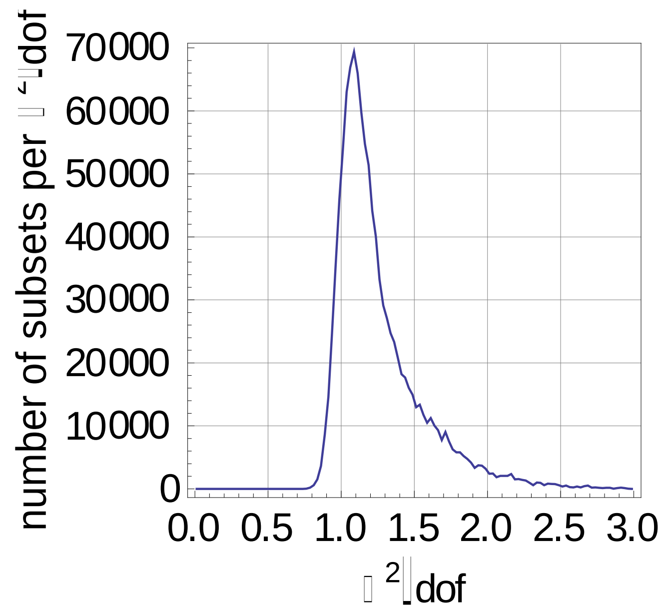


Fitting subset

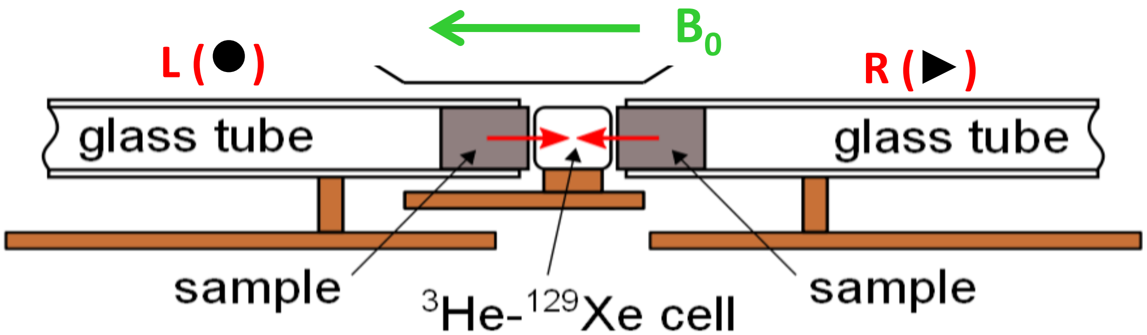
subset left:

χ^2/dof = 1.03

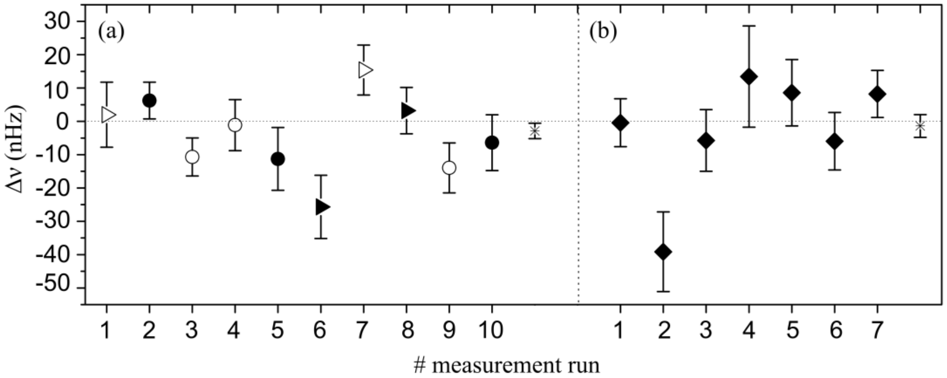




Results



control runs:
no mass was moved



10 measurements (~9 hours)

gap (Δx) = 2.2 mm

Mass sample: BGO crystal (ρ=7.13 g/cm³)

$$\overline{\overline{\Delta\nu}}_{sp} = (-2.9 \pm 6.9 \pm 0.4)\ \mathrm{nHz}\quad (95\%\ \mathrm{C.L.})$$

Analysis:

$$|\delta(\overline{\overline{\Delta\nu}}_{sp})| \geqslant 2 \cdot V_\Sigma / h$$

Potential after integration over unpolarized/polarized matter sample

$$V_\Sigma = V_{\Sigma,\infty} \cdot \eta(\lambda) = 2\pi N\kappa \frac{\lambda^2}{D} \cdot e^{-\Delta x/\lambda} \times \left(1 - e^{-D/\lambda}\right) \cdot \left(1 - e^{-d/\lambda}\right) \cdot \eta(\lambda) \ .$$

$$\left|g_s^N g_p^n\right| \leq f(\lambda)$$