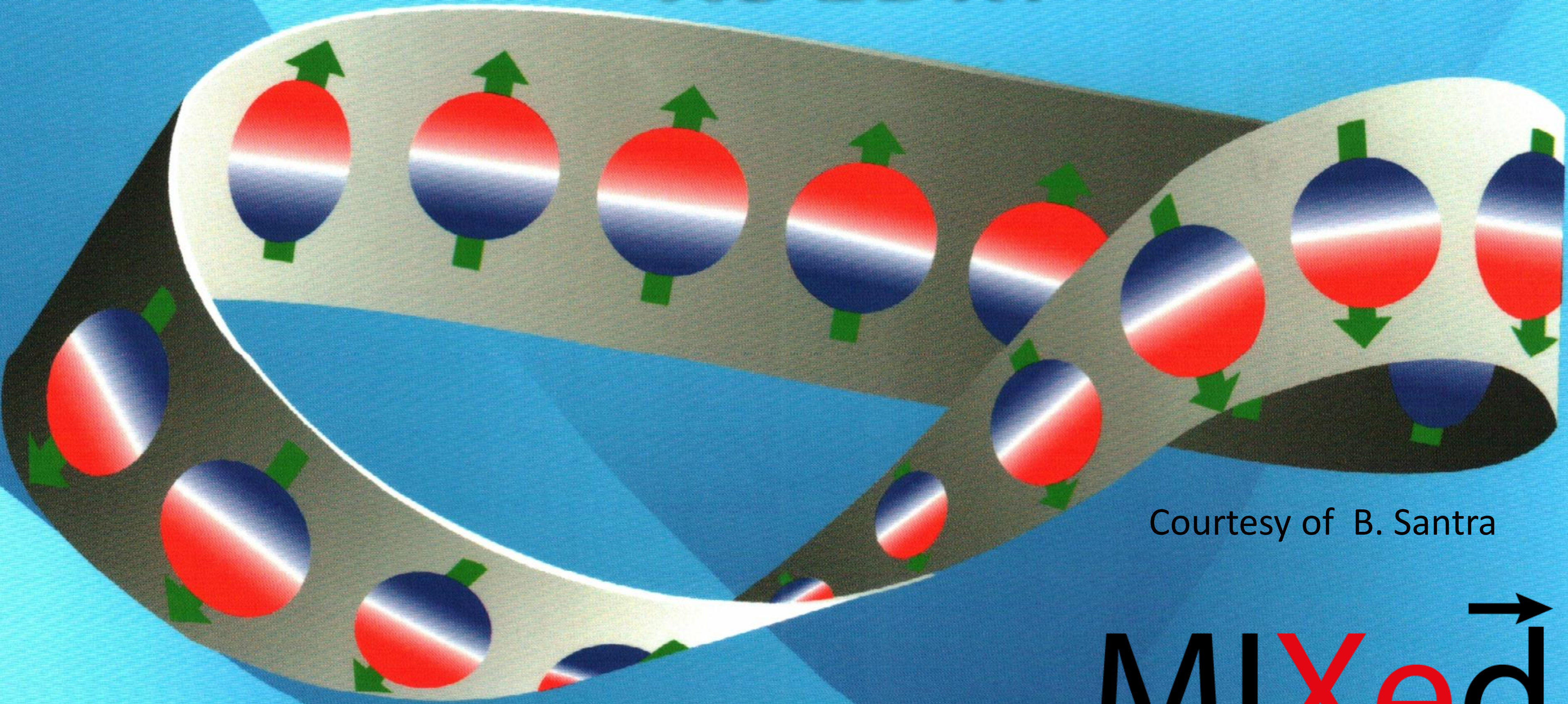
Measurement of the ^{129}Xe EDM

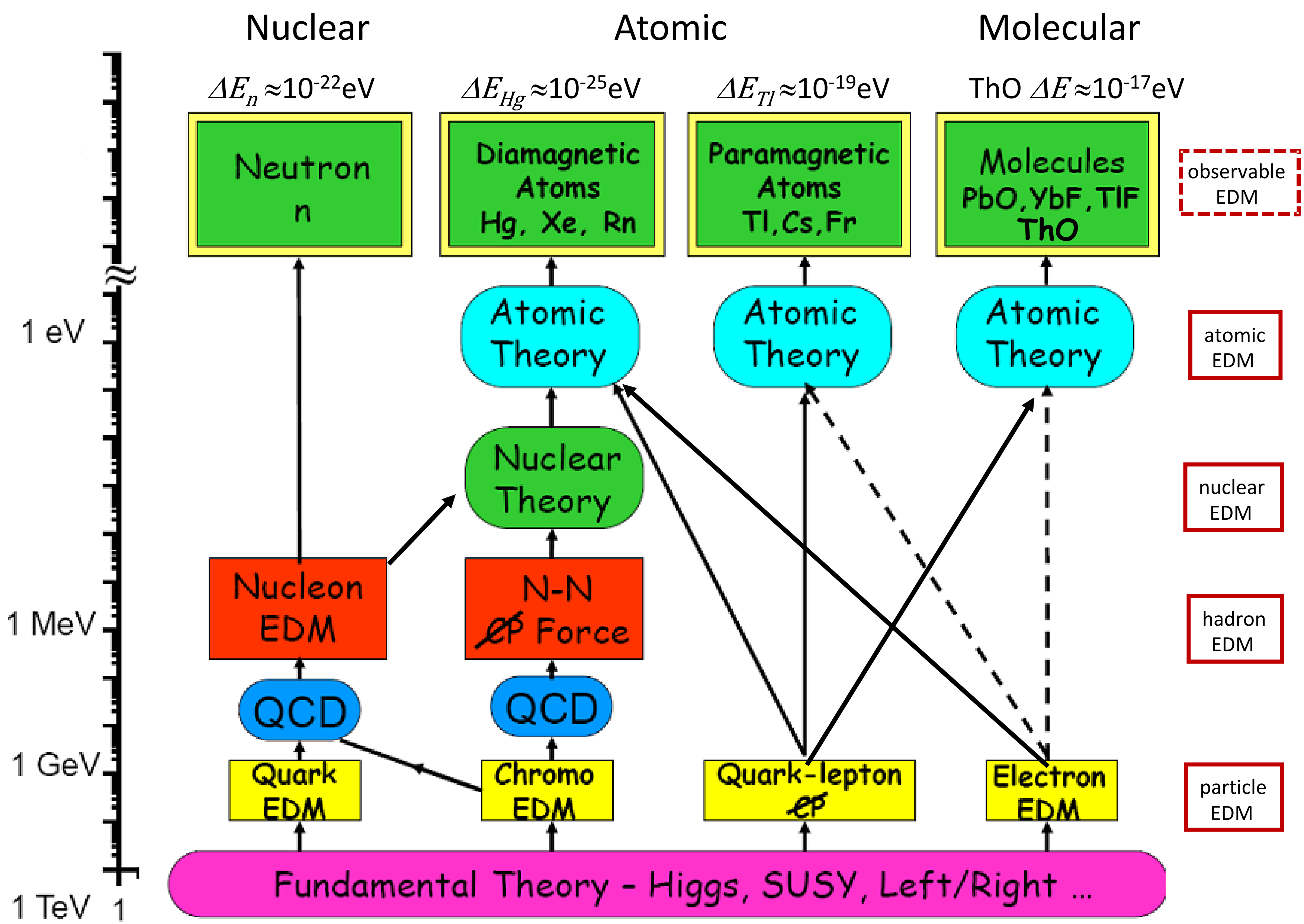
W. Heil



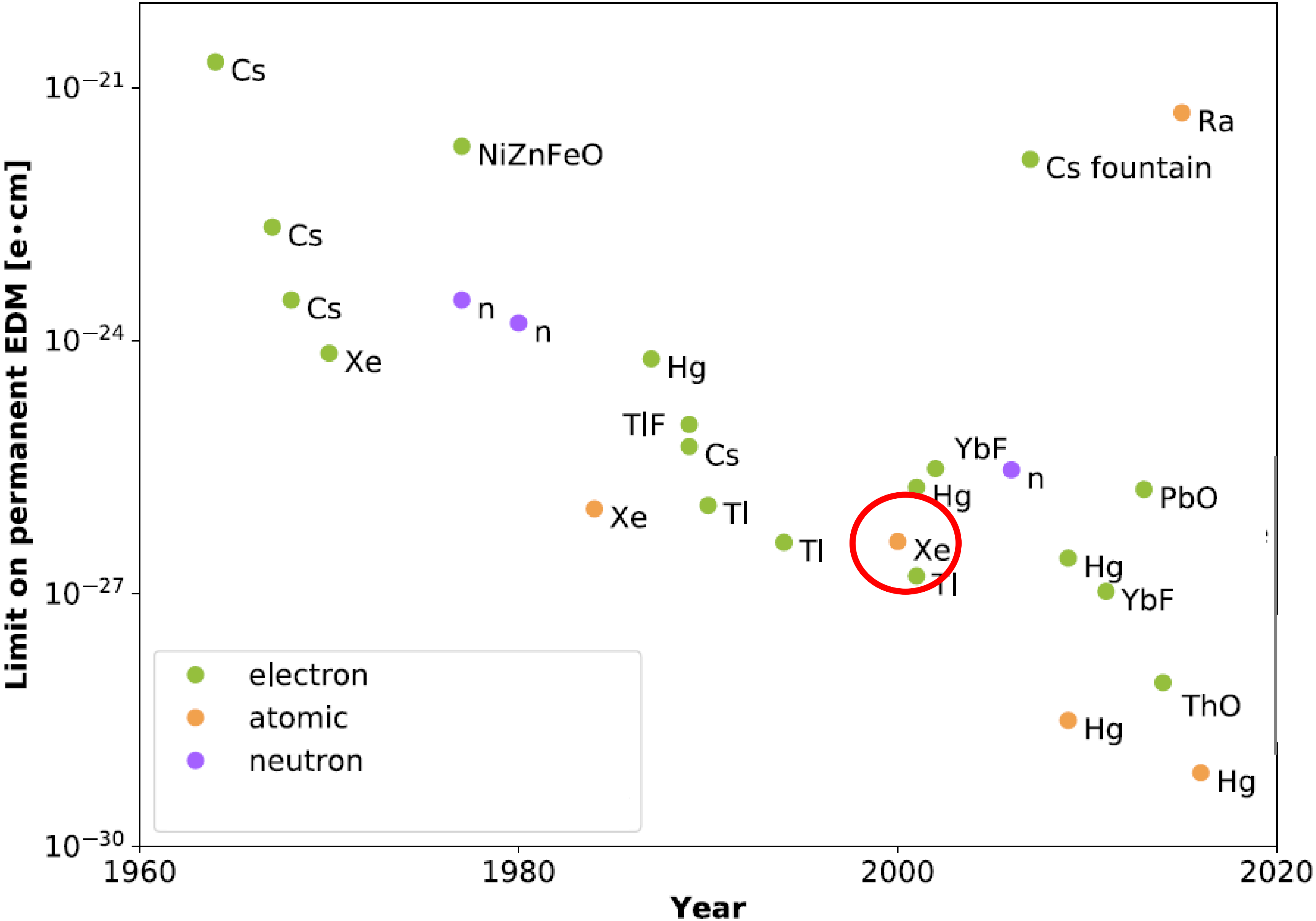
Courtesy of B. Santra

MIXed

Measurement and Investigation of the Xenon-129 electric dipole moment


Nuclear
Atomic
Molecular
$\Delta E_n \approx 10^{-22}$eV
$\Delta E_{Hg} \approx 10^{-25}$eV
$\Delta E_{Tl} \approx 10^{-19}$eV
ThO $\Delta E \approx 10^{-17}$eV
Neutron n
Diamagnetic Atoms Hg, Xe, Rn
Paramagnetic Atoms Tl,Cs,Fr
Molecules PbO,YbF,TlF ThO
observable EDM
1 eV
Atomic Theory
Atomic Theory
Atomic Theory
atomic EDM
Nuclear Theory
nuclear EDM
Nucleon EDM
N-N CP Force
1 MeV
hadron EDM
QCD
QCD
1 GeV
Quark EDM
Chromo EDM
Quark-lepton CP
Electron EDM
particle EDM
1 TeV
1
Fundamental Theory - Higgs, SUSY, Left/Right ...

EDM precision experiments (upper limits)



Finite size violation of Schiff screening

Diamagnetic EDMs – „Schiff suppression: ε "

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

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

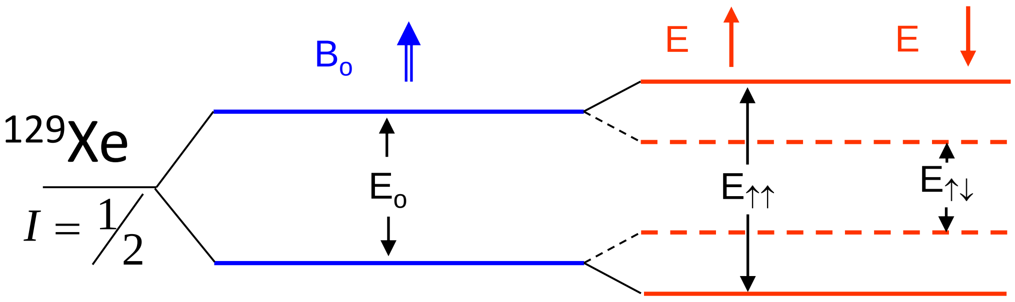
Schiff moment is dominant CP-odd N-N interaction for large atoms

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

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

- $d_A \sim 10\, Z^2 \left(R_N / R_A\right)^2 d_{nuc} \sim O(10^{-3})\, d_{nuc}$ $\quad d_A = \varepsilon \cdot d_{nuc}$
- Nuclear deformation can enhance heavy atom EDMs (e.g., 225Ra, 223Rn)

^{129}Xe electric dipole moment

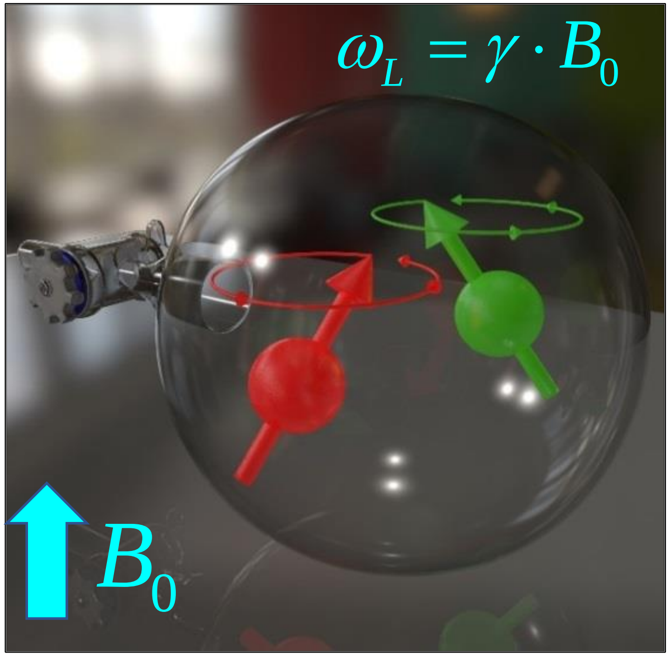


Zeeman: $\mu B_0 \approx 10^{-13}$ eV

$d_{Xe} \cdot E \approx 10^{-25}$ eV

$$\delta\omega_{EDM} = \Delta\omega_{\uparrow\uparrow} - \Delta\omega_{\uparrow\downarrow} = 4 \cdot E \cdot d_{Xe} / h$$

Comagnetometry to get rid of magnetic field drifts



Observable:

weighted frequency (phase) difference

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

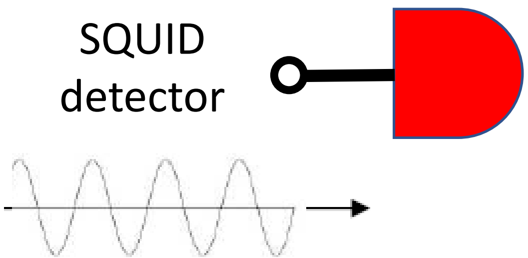
$$\Delta\phi = \phi_{Xe} - \frac{\gamma_{Xe}}{\gamma_{He}}\phi_{He}$$

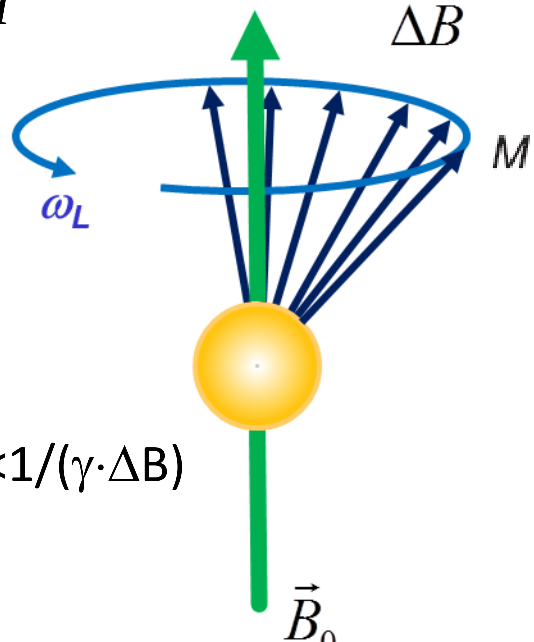
$$\delta\omega_{EDM} = \Delta\omega_{\uparrow\uparrow} - \Delta\omega_{\uparrow\downarrow} = 4 \cdot E \cdot d_{Xe} / h$$

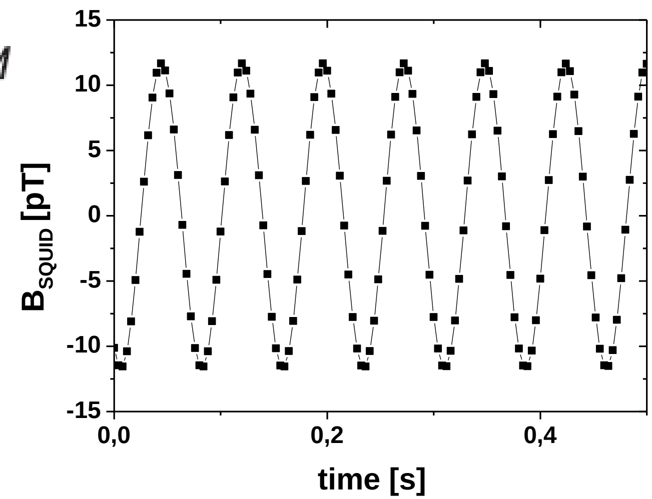
EDM sensitivity: $\delta d \propto \left(\varepsilon \cdot E_{ext} \cdot SNR \cdot T^{3/2}\right)^{-1}$

➡ **long spin-coherence times (T_2*), high SNR, high E-field**

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





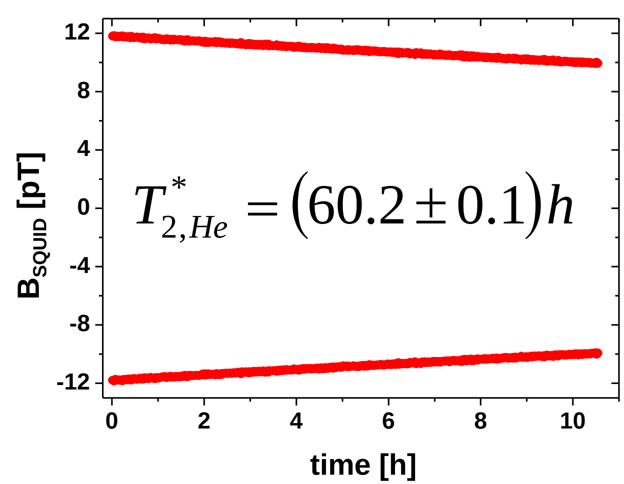


Motional narrowing regime: $\tau_{diff} << 1/(\gamma \cdot \Delta B)$

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

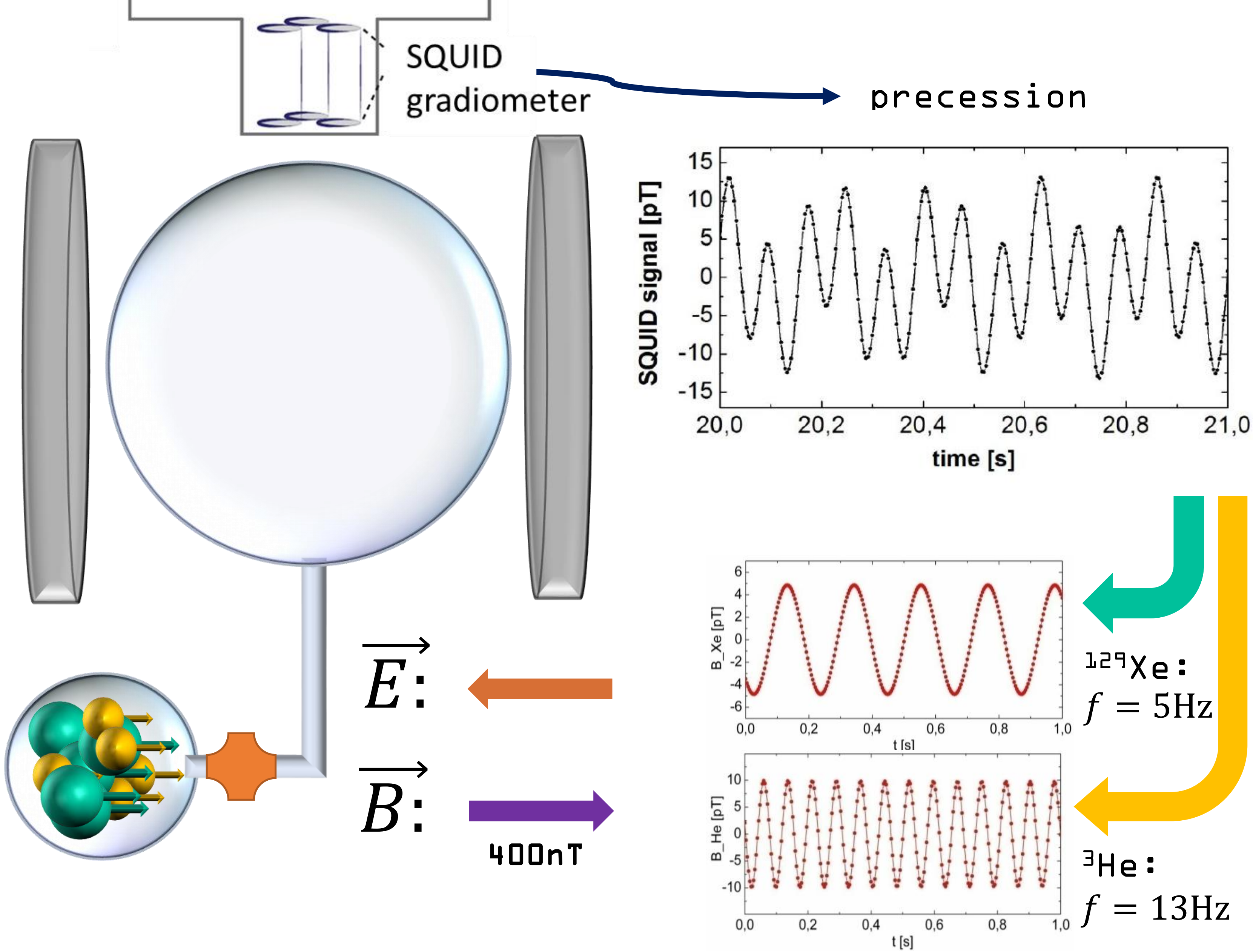
$$\frac{1}{T_2^*} = \frac{1}{T_1} + \frac{1}{T_{2,\text{ field}}}$$

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

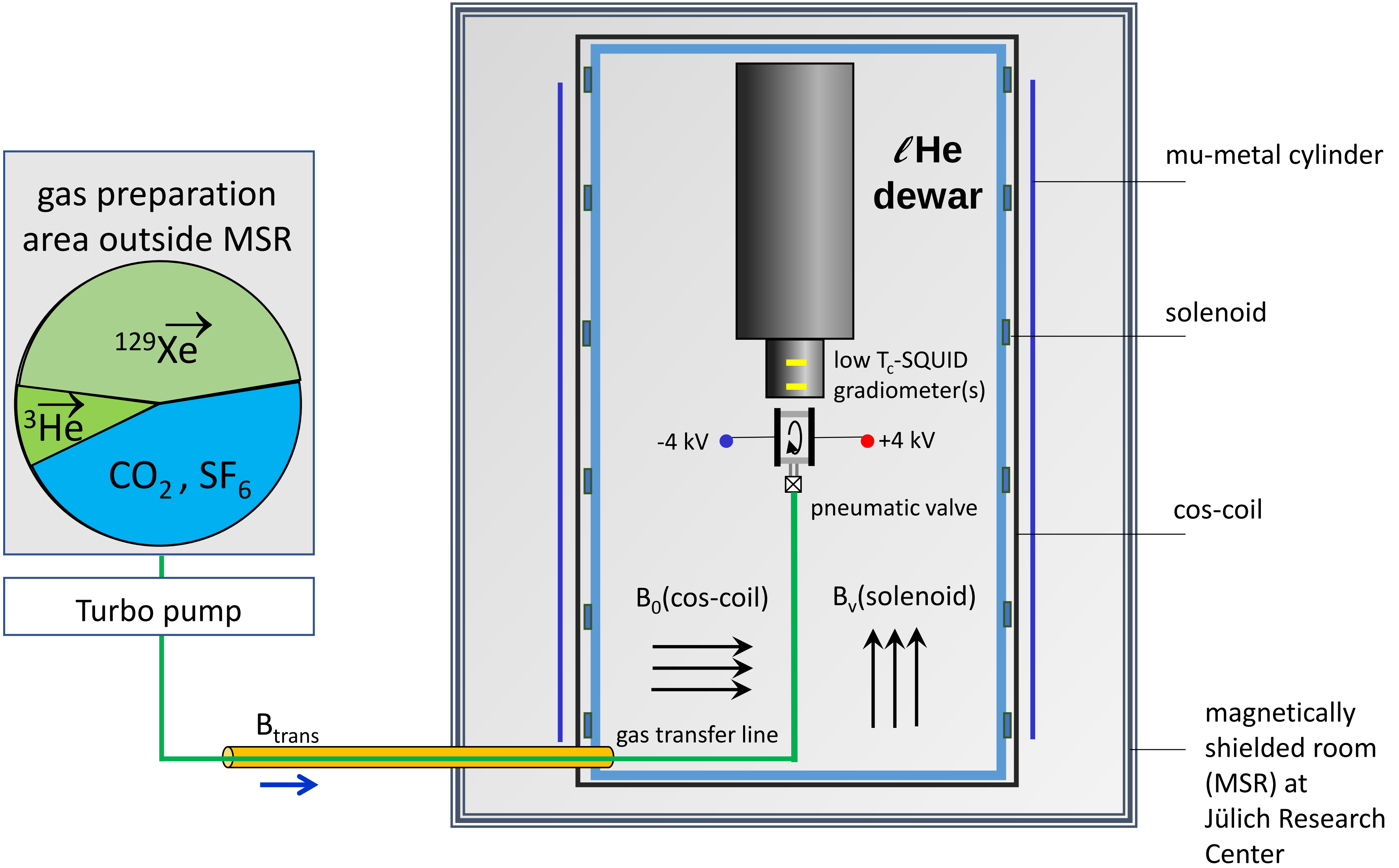


$$T_1 > 100\,\text{h} \implies \begin{array}{l} Long\ T_2^* : \\ p \sim mbar, R \sim 5\,cm, B_1 \sim \mu T \end{array}$$

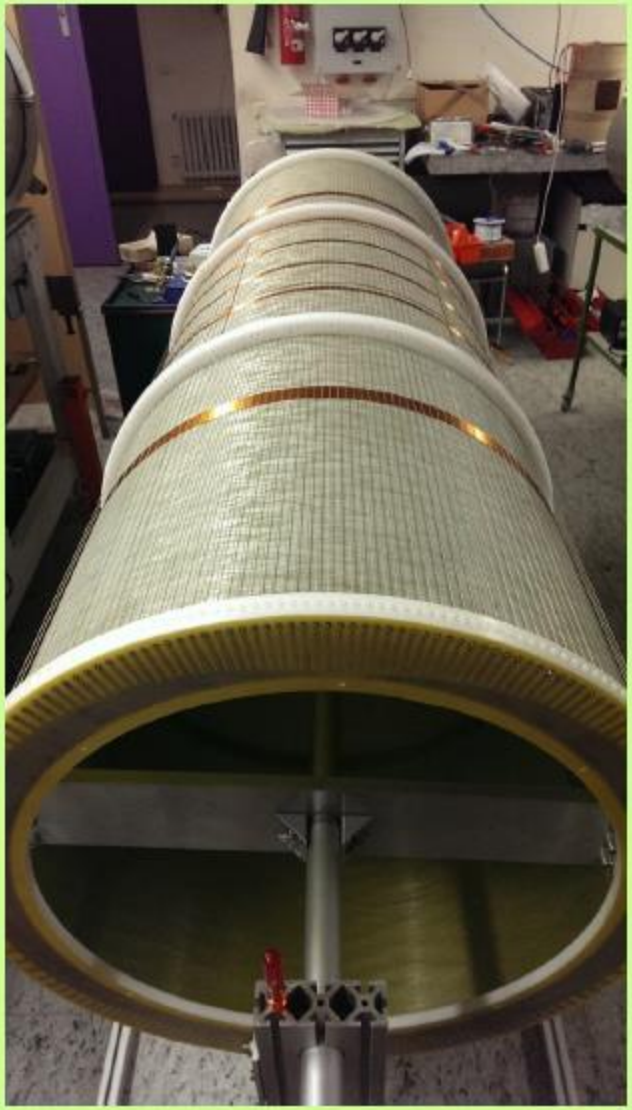
PRINCIPLE OF MEASUREMENT



Experimental Setup: **Overview**

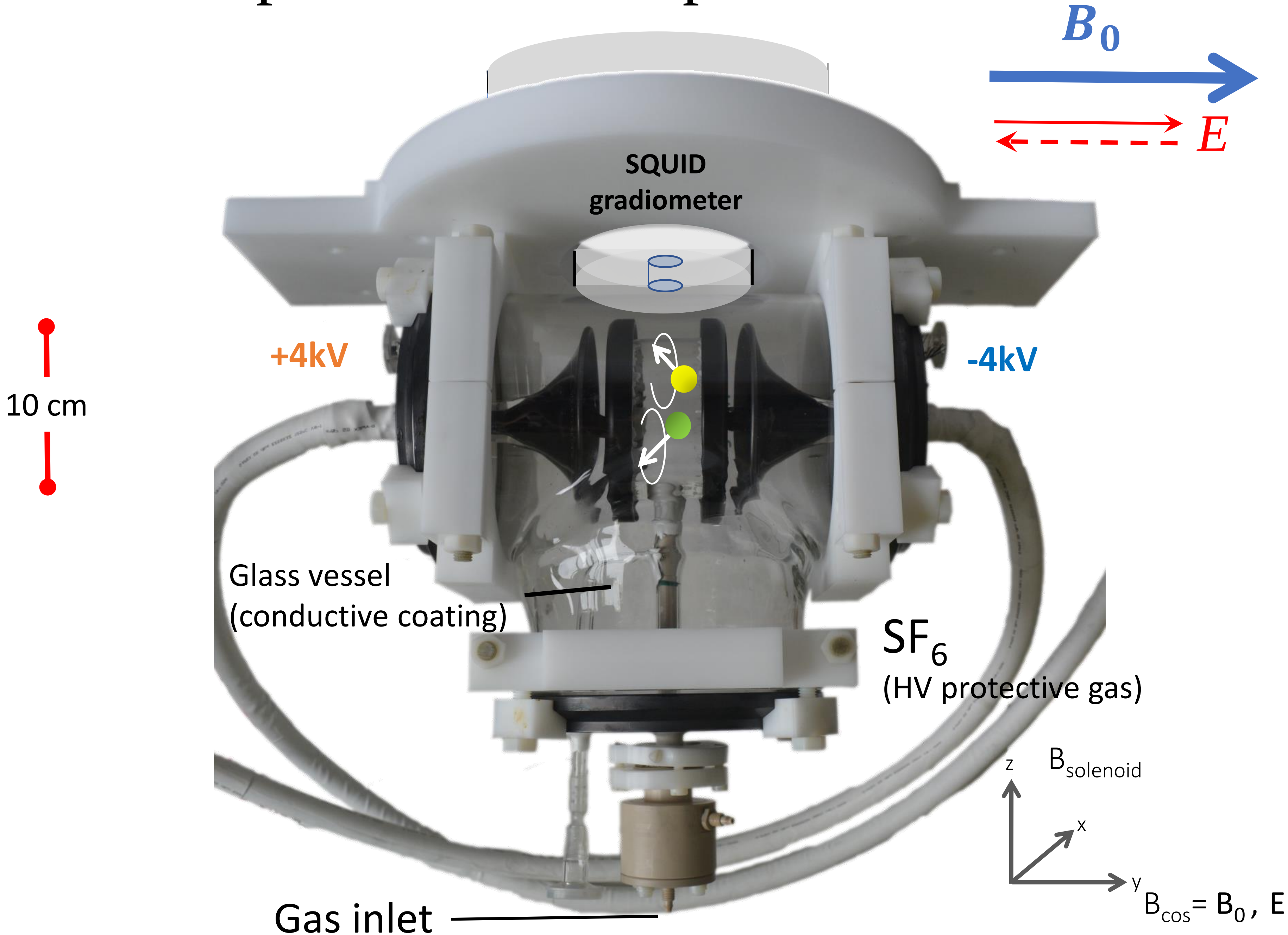


Coil assembly

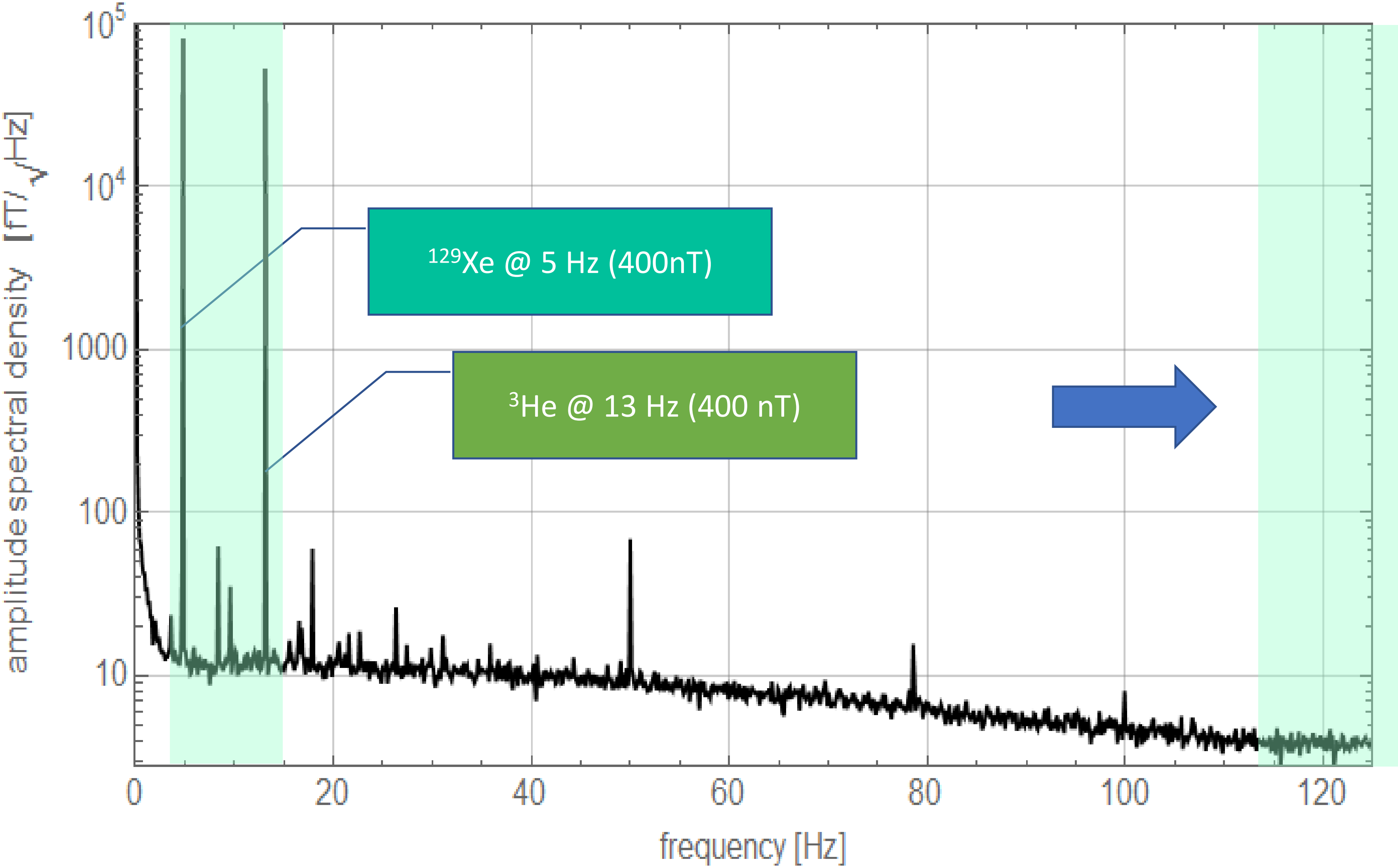


Non-magnetic ℓHe Dewar
housing three low-T_c SQUID gradiometers

Experimental Setup: **EDM-Cell**



$SNR \sim 10000{:}1$



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

Results of automatic gradient compensation

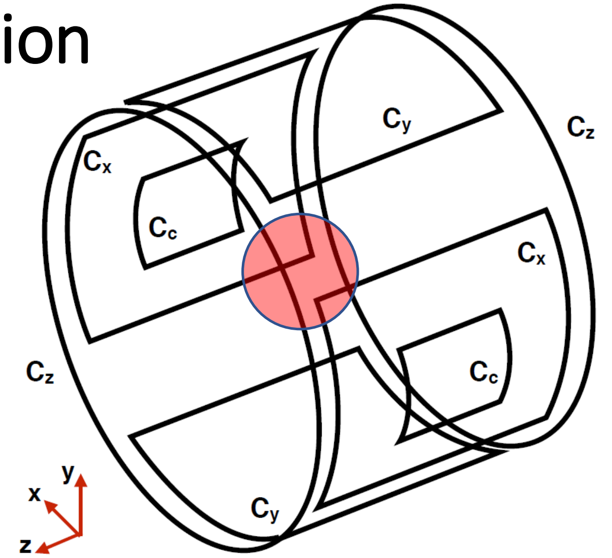
(Downhill-simplex algorithm)

Spherical cell (diameter 10 cm)

filled with 30 mbar of polarized ^3He

~ 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	effective gradients
start	0	0	0	0	7499	~30 pT/cm
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	< 10 pT/cm

Weighted phase difference (no EDM):

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

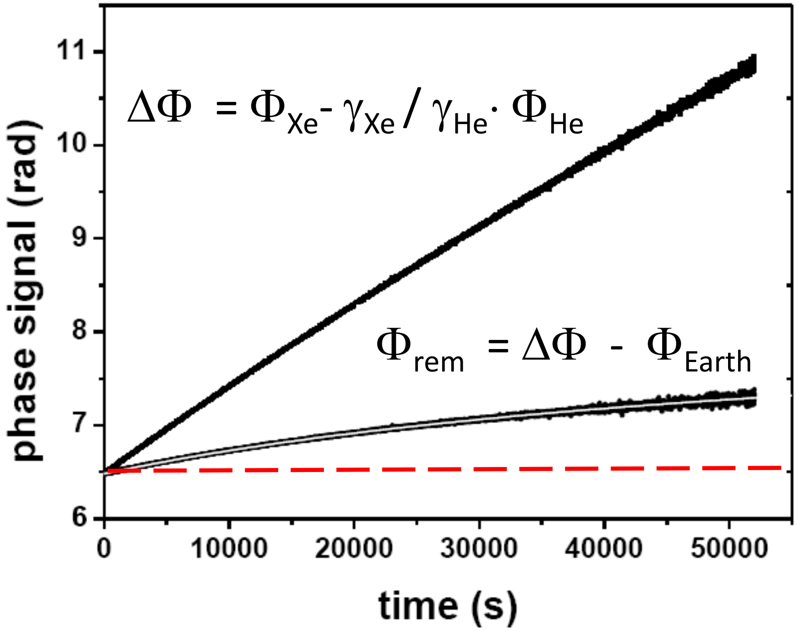
The detection of the free precession of co-located ^{3}He/^{129}Xe sample spins can be used as ultra-sensitive probe for non-magnetic spin interactions of type:

$$V_{non-magn.} = \vec{a} \cdot \vec{\sigma}$$

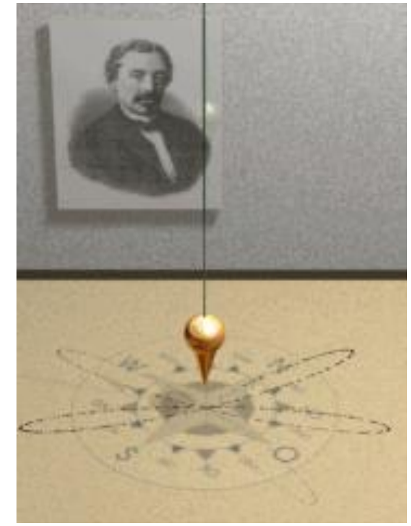
Search for EDM of Xenon: $V(r)/\hbar = -|\mathrm{d}_{\mathrm{Xe}}|\vec{\sigma} \cdot \vec{E}/\hbar$

$$\Delta\Phi_{EDM}(t) = \int_0^t (2|d_{Xe}|\sigma \cdot E / \mathrm{h})\, dt \propto t$$

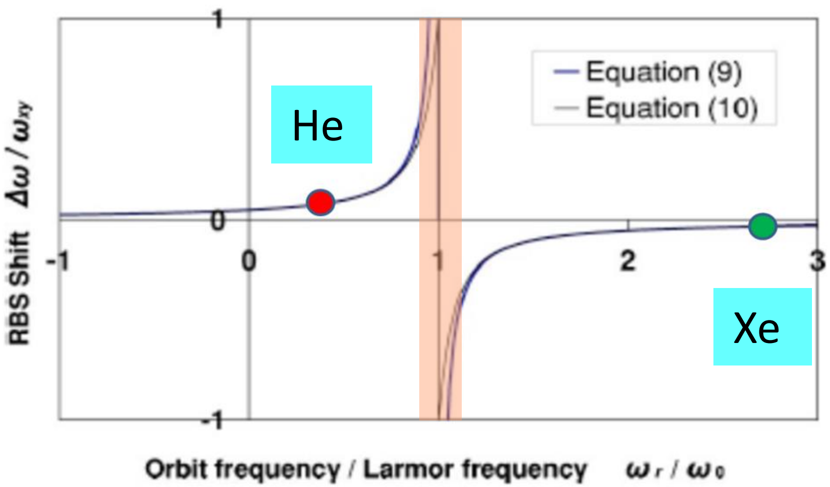
Subtraction of deterministic phase shifts

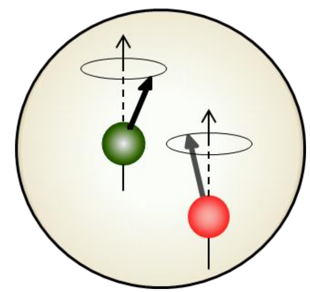


I. Earth‘s rotation



II. Ramsey-Bloch-Siegert shift



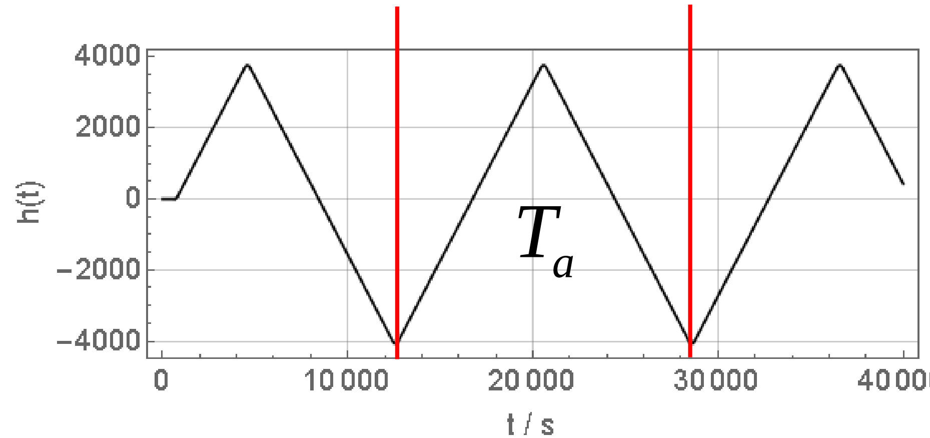


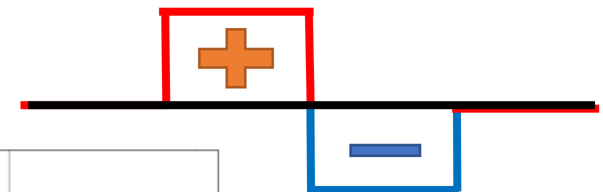
self shift ~ $S_0 \cdot e^{-t/T_2^*}$

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

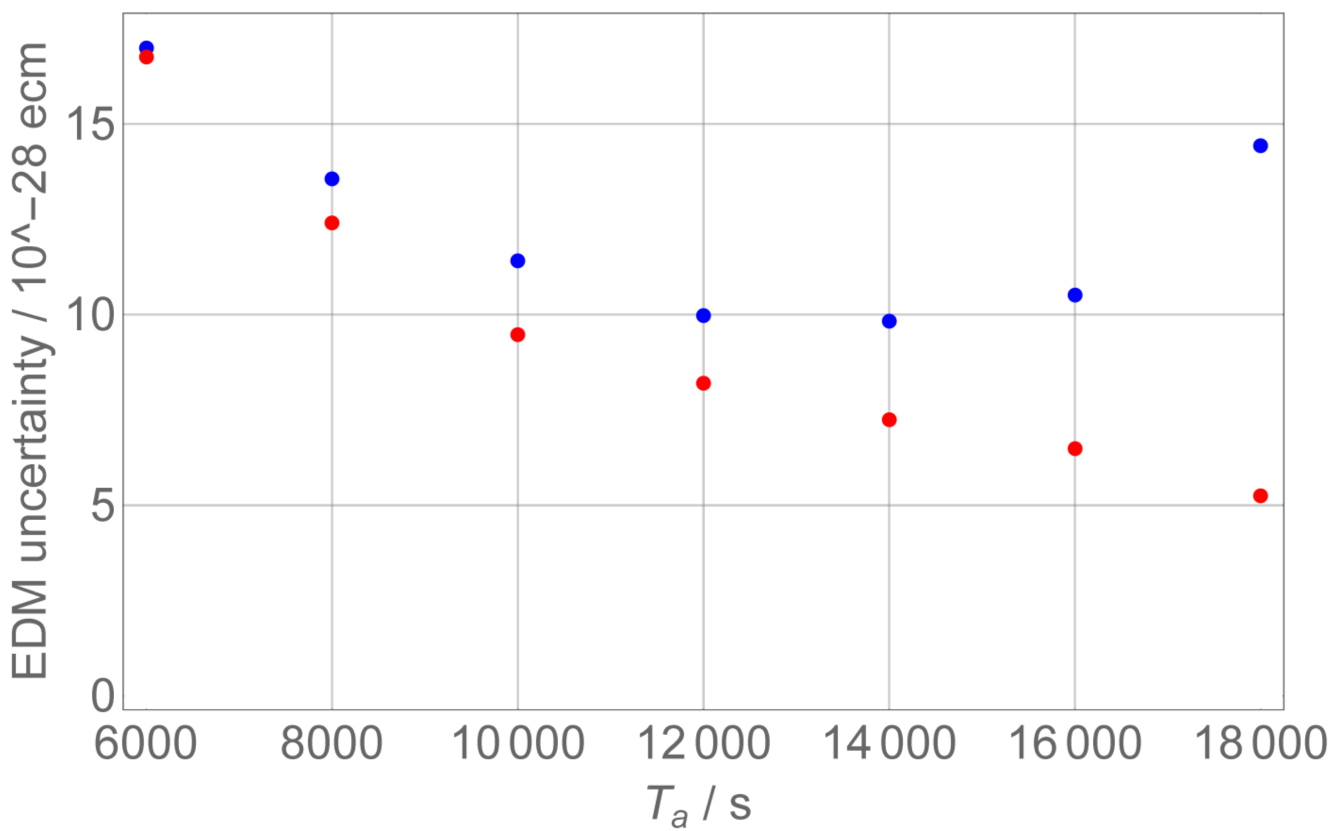
$$\Delta\Phi = c + a_{Earth} \cdot t + a_{He} \cdot e^{-t/T_{2,He}^*} + a_{Xe} \cdot e^{-t/T_{2,Xe}^*} + b_{He} \cdot e^{-2t/T_{2,He}^*} + b_{Xe} \cdot e^{-2t/T_{2,Xe}^*} + \Delta\Phi_{EDM}(t)$$

Influence of Electric field switching period





E=800 V/cm

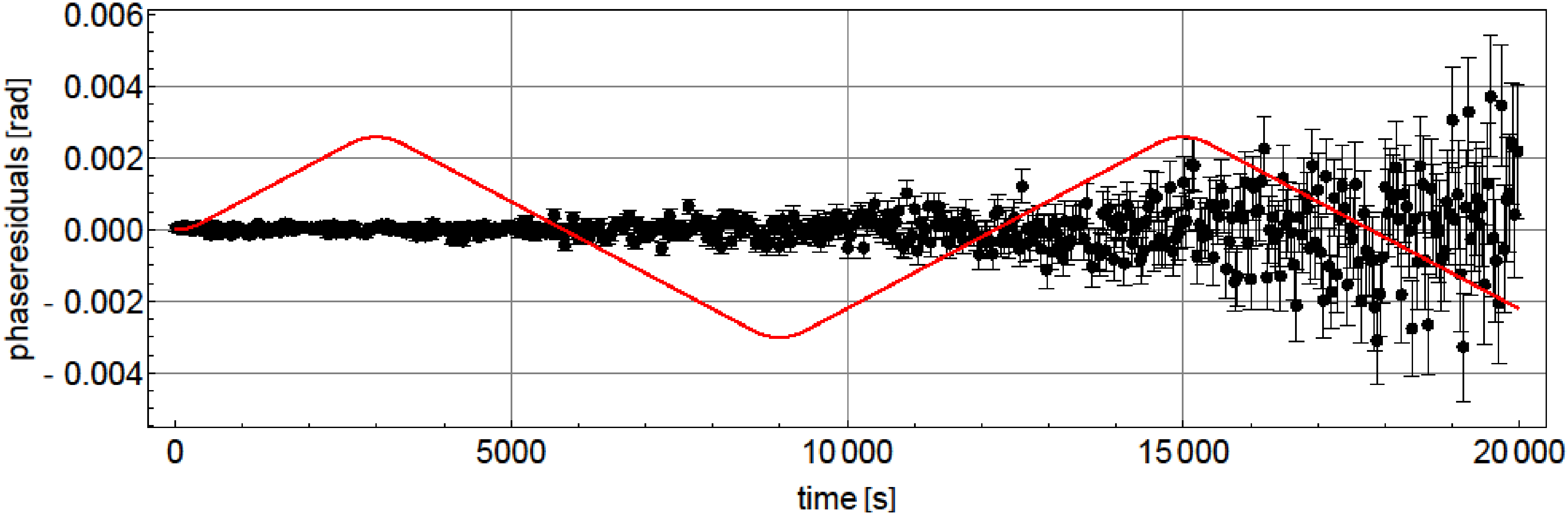


Total error (correlation with exponential terms)

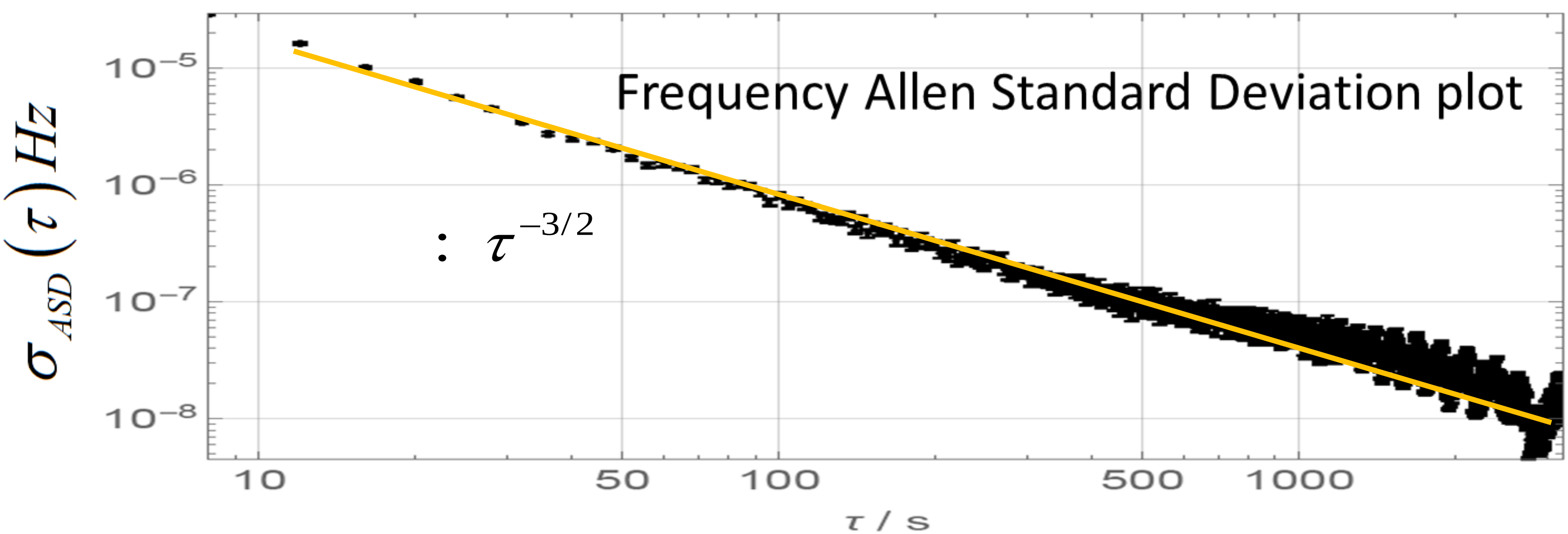
Uncorrelated error

EDM run #2 - July 2017

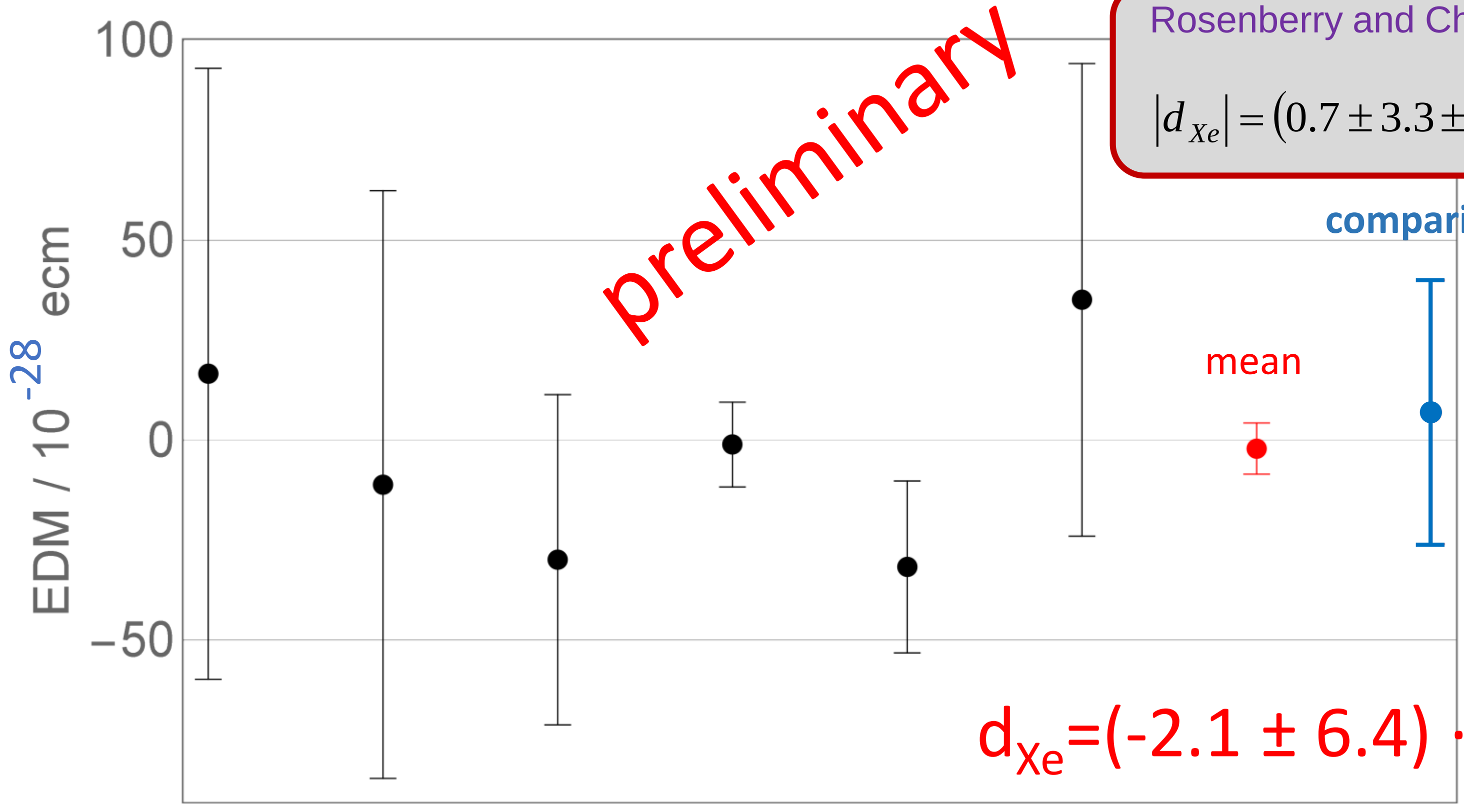
possible Xe-EDM (EDM phase modulation) smaller than statistical se



Phase residuals are statistically distributed ar



Xe-EDM results



Rosenberry and Chupp, PRL 86,22 (2001)

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

$$d_{Xe} = (-2.1 \pm 6.4) \cdot 10^{-28}\ \text{ecm}$$

Evaluation of systematics still ongoing

Conclusion and outlook

Xe-EDM:

- ^{129}Xe EDM limit improved by a factor of 5

$SNR \sim 10000 \ @ \ f_{BW} = 1\ Hz$
$\langle E \rangle = 0.8\ kV/cm$
$T_{2,Xe}{}^{*} \sim 3\ h \rightarrow 9h$ *EDM-runs*
$\delta d_{Xe} = 4 \times 10^{-28}\ ecm/day$

	Room for improvements	Factor
Jülich Research Center	Increase the electric field strength (now: E=800 V/cm)	4 to 5
	Increase Xe and He partial pressure (tradeoff between signal strength and spin coherence time)	2
University Heidelberg	New Magnetically Shielded Room at Heidelberg improves noise level and reduces magnetic field gradients	10
	Increase measurement time to 200 days	10

Thank you for your attention.

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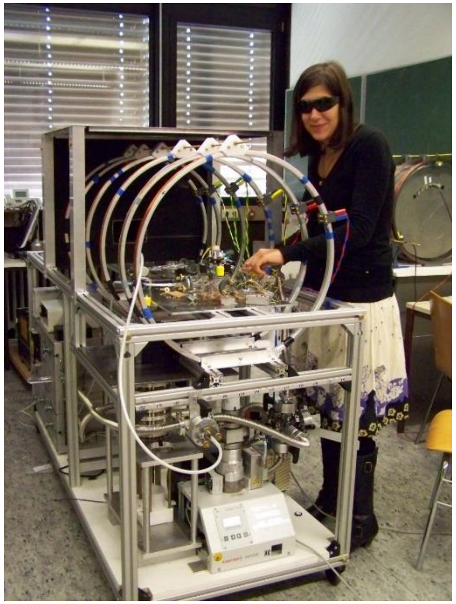
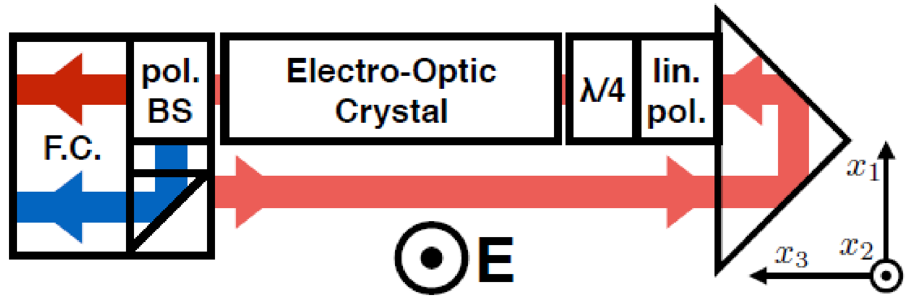
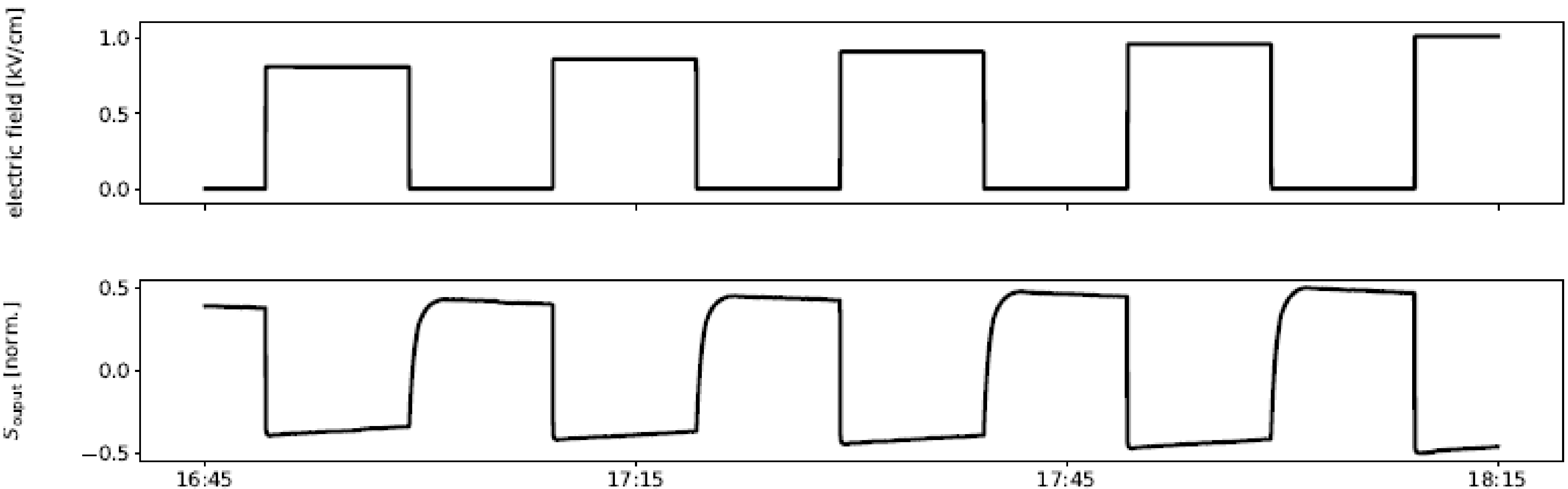
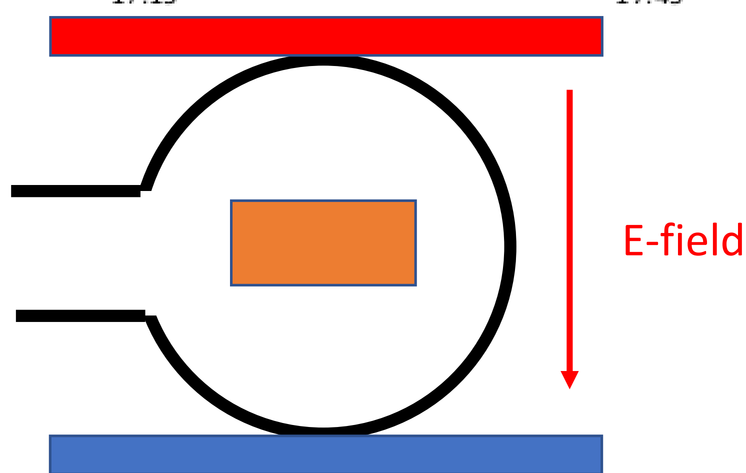
Measurement and Investigation of the Xenon-129 electric dipole moment

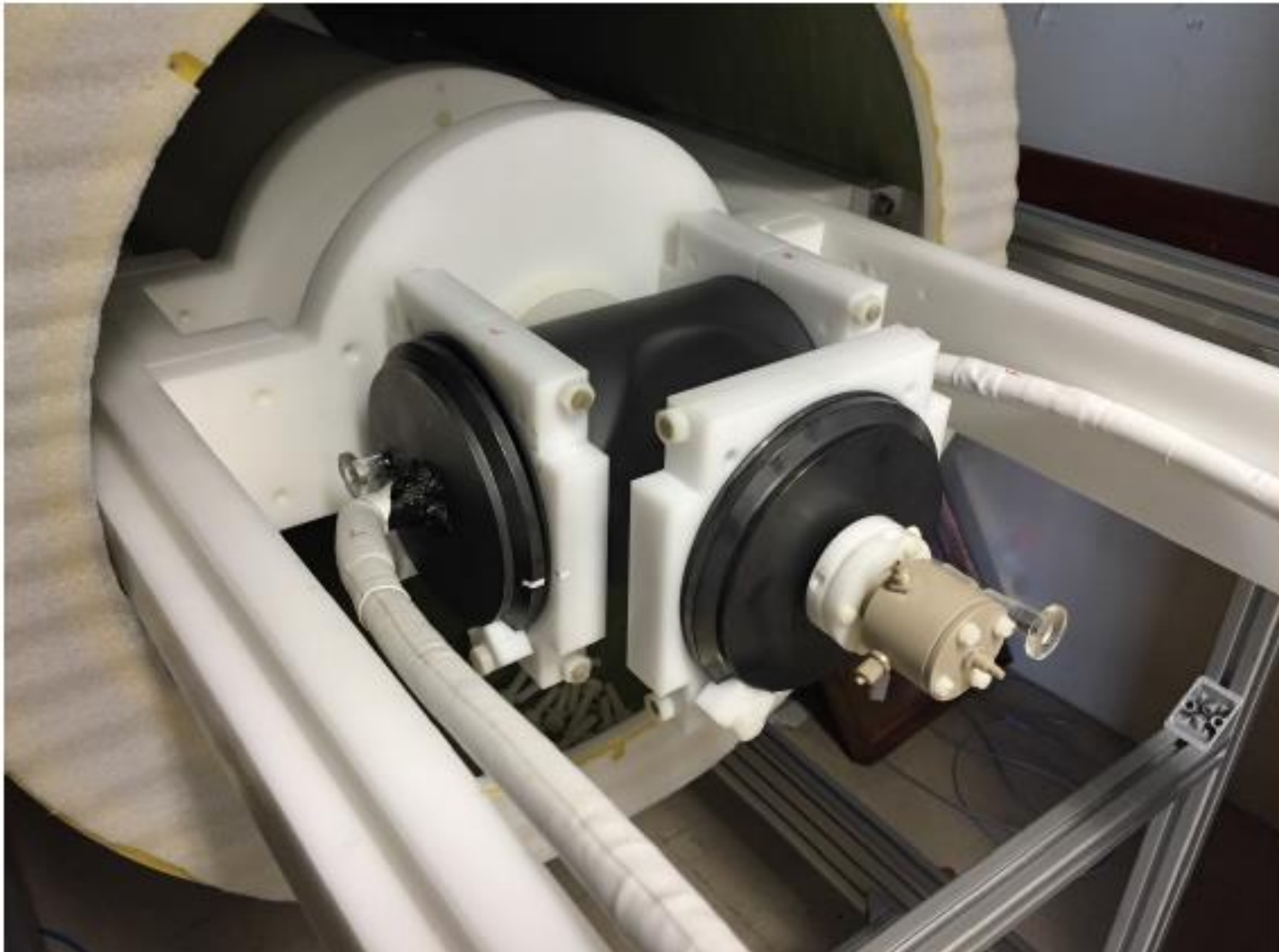


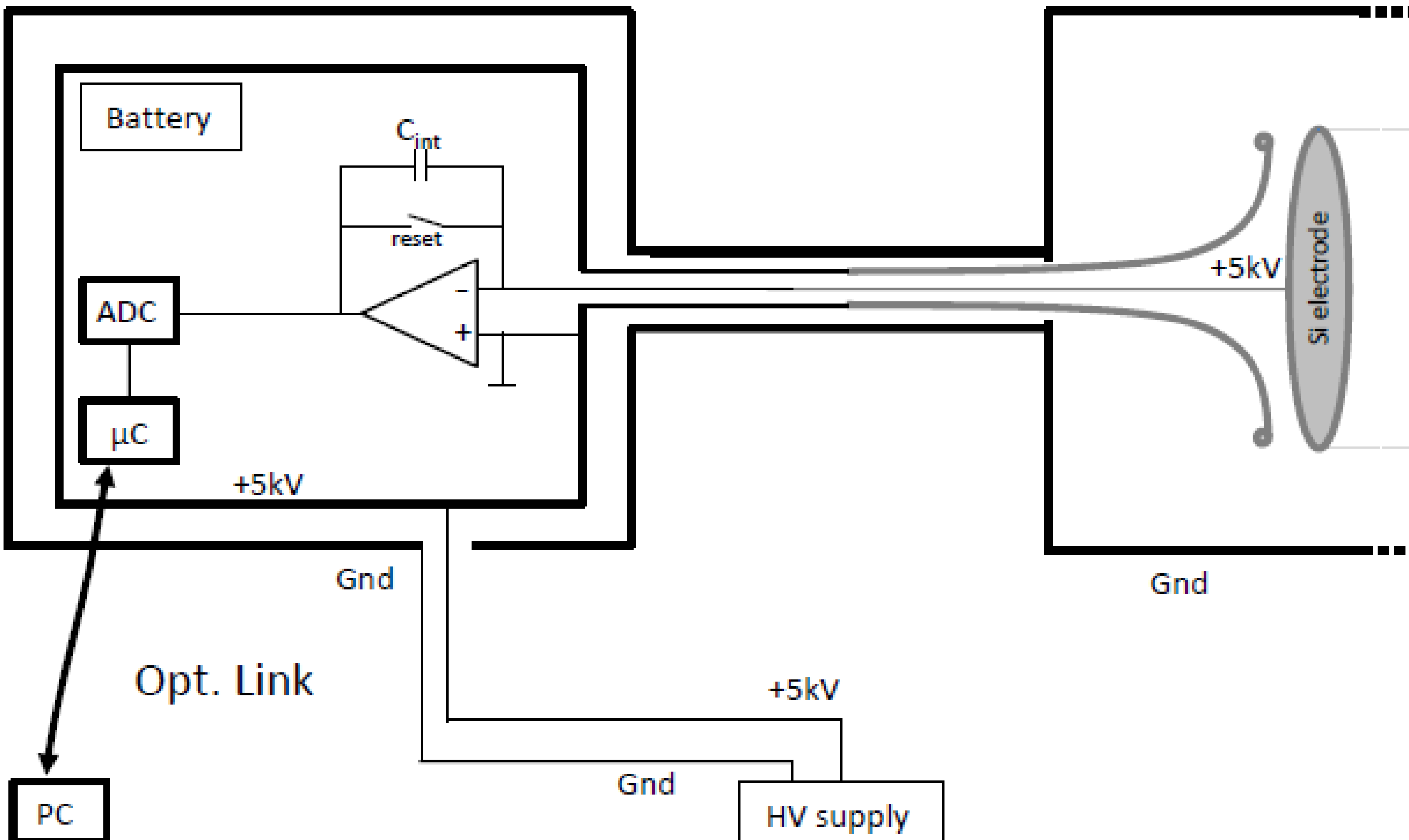

pol.
BS
F.C.
Electro-Optic
Crystal
λ/4
lin.
pol.
E
x_1
x_2
x_3


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

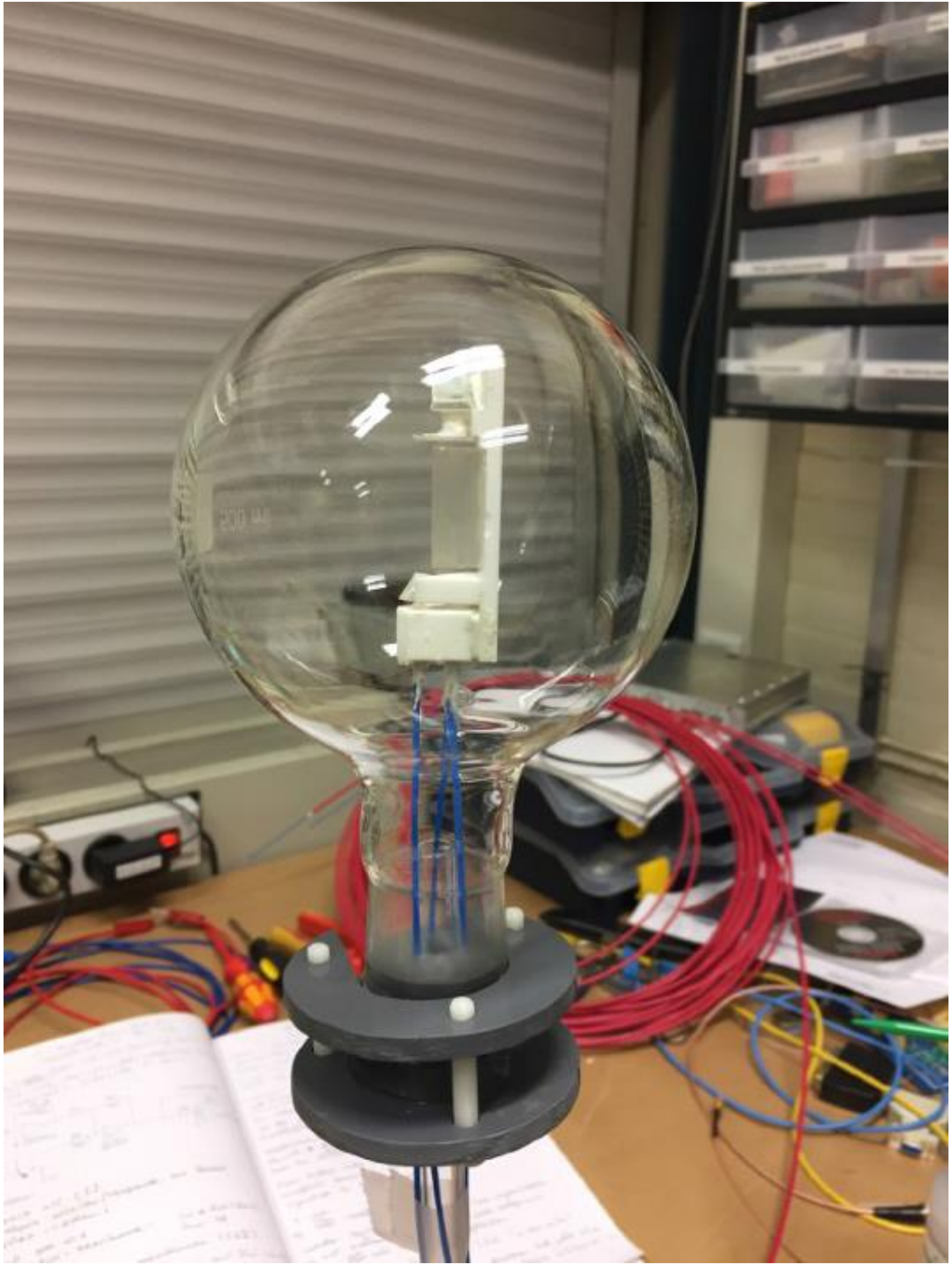

E-field

Precession Measurement

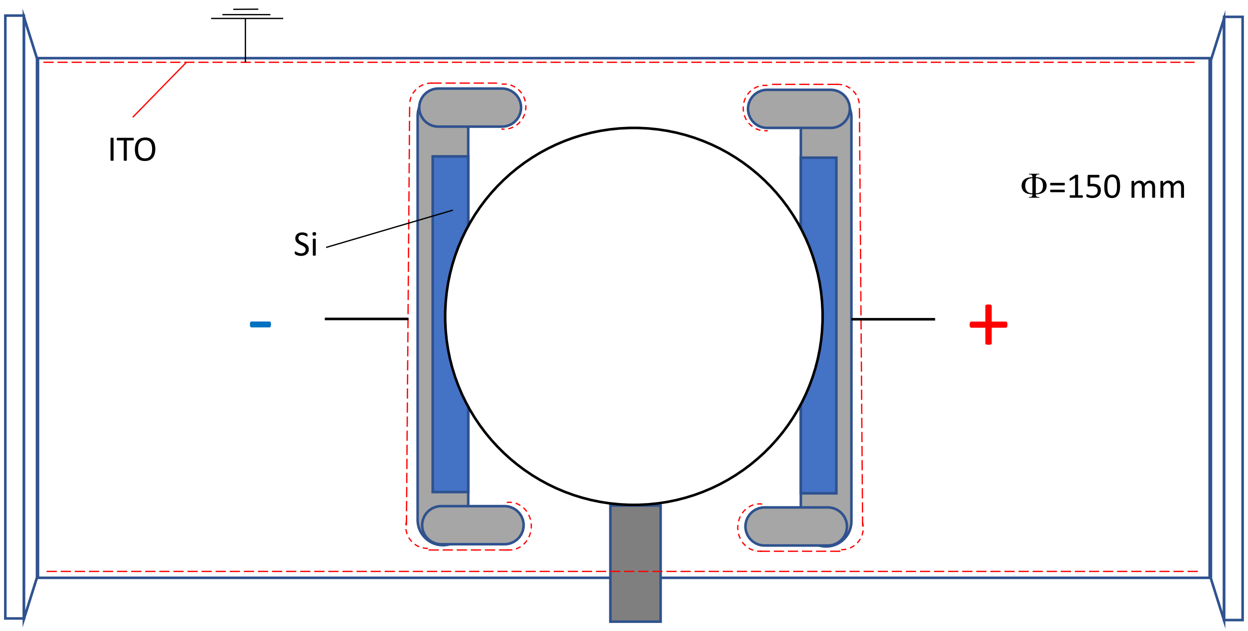


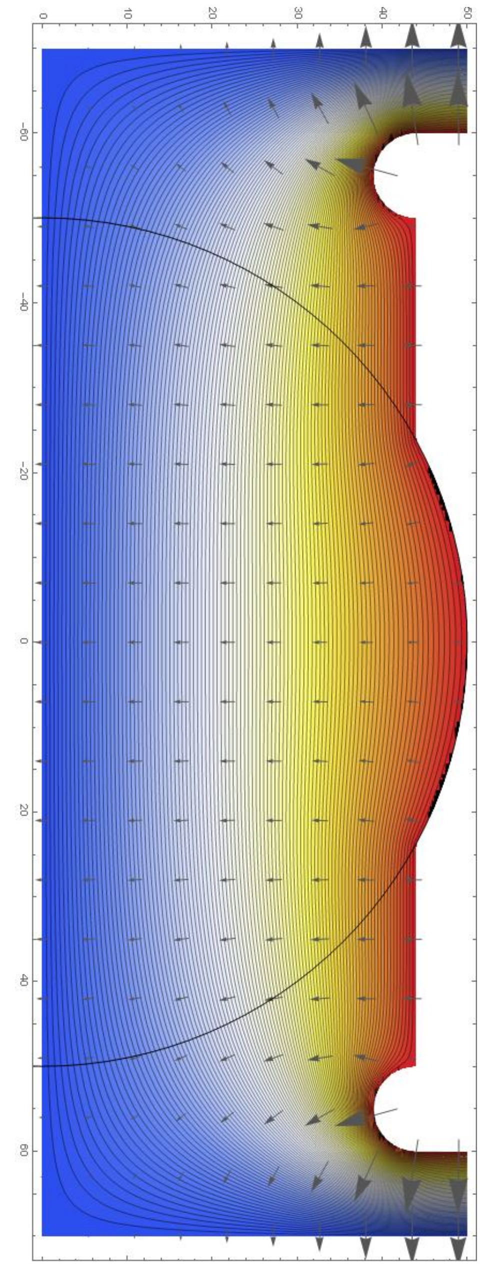


Battery
Cint
reset
ADC
μC
+5kV
Si electrode
+5kV
Gnd
Gnd
Opt. Link
+5kV
Gnd
HV supply
PC

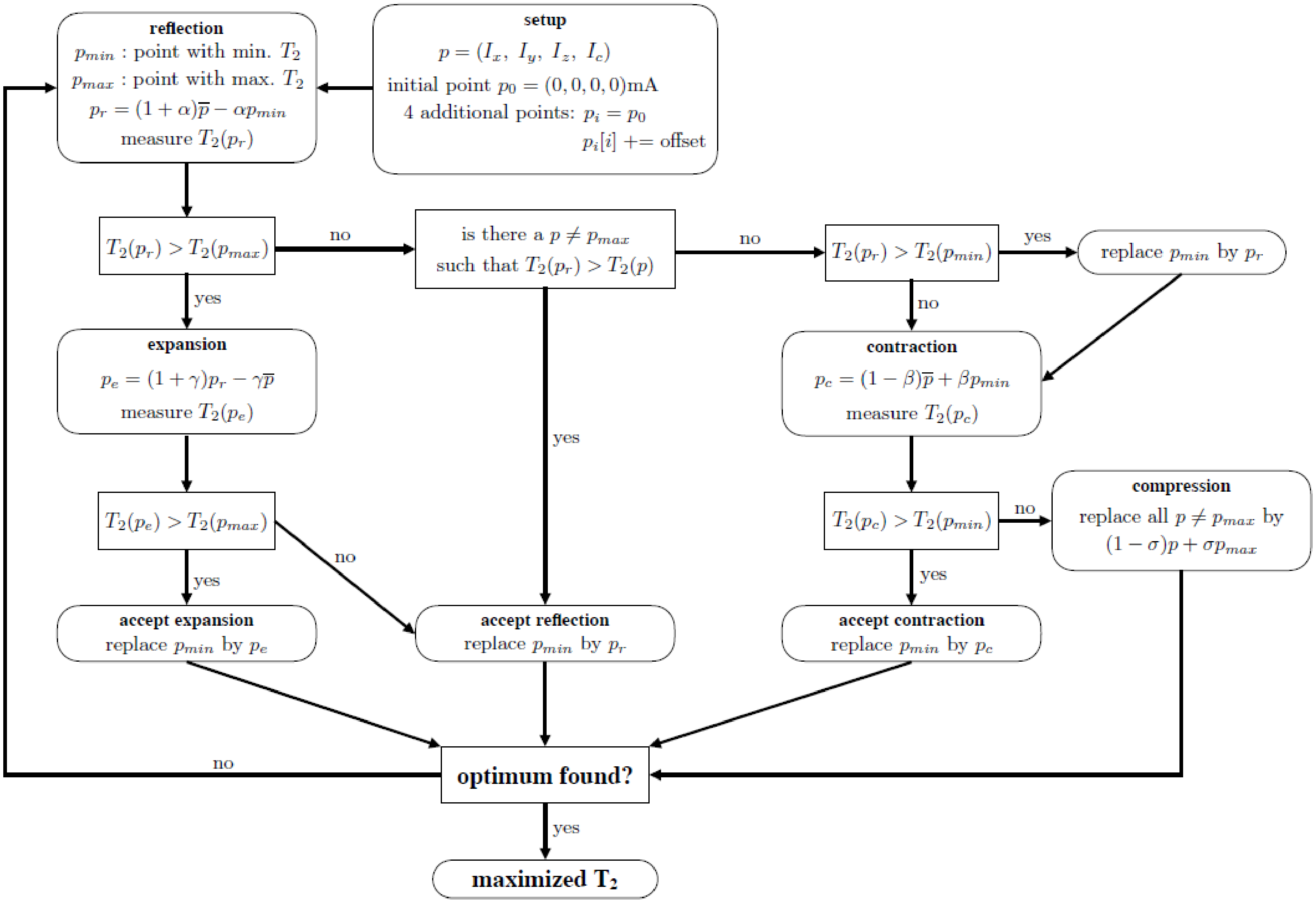


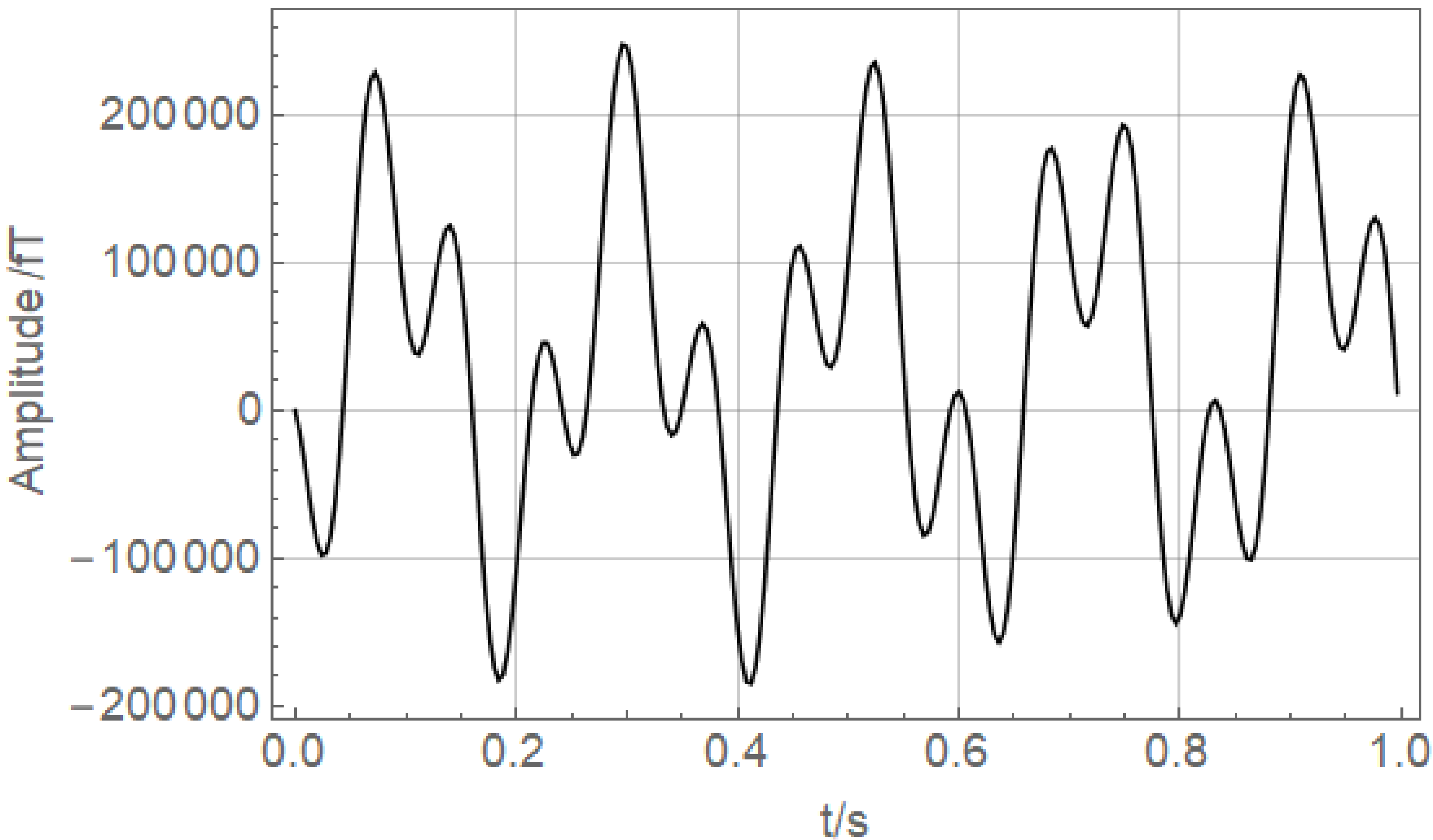
EDM-cell





Downhill-simplex algorithm





200 000
100 000
0
−100 000
−200 000
Amplitude /fT
0.0
0.2
0.4
0.6
0.8
1.0
t/s

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:

$$V_{non-magn.} = \vec{a} \cdot \vec{\sigma}$$

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

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

- Search for spin-dependent short-range interactions

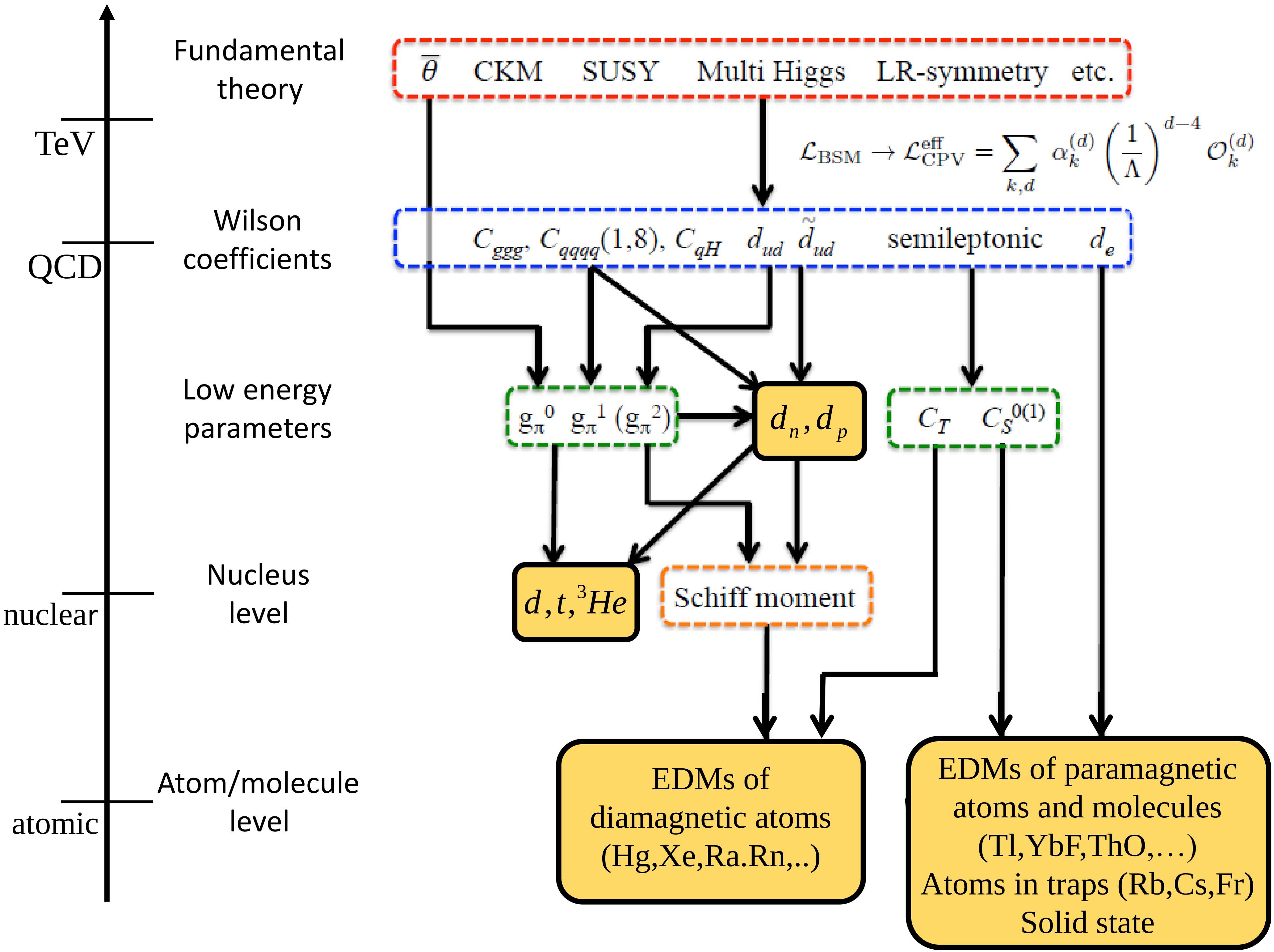
$$V(r)/\hbar = c\vec{\sigma} \cdot \hat{n}/\hbar$$

- Search for EDM of Xenon

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

…

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



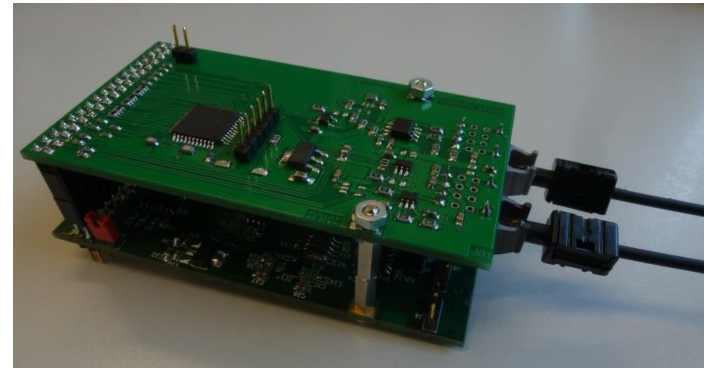
Fundamental theory
TeV
Wilson coefficients
QCD
Low energy parameters
Nucleus level
nuclear
Atom/molecule level
atomic
$\bar{\theta}$ CKM SUSY Multi Higgs LR-symmetry etc.
$\mathcal{L}_{\rm BSM} \to \mathcal{L}^{\rm eff}_{\rm CPV} = \sum_{k,d} \alpha_k^{(d)} \left(\frac{1}{\Lambda}\right)^{d-4} \mathcal{O}_k^{(d)}$
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

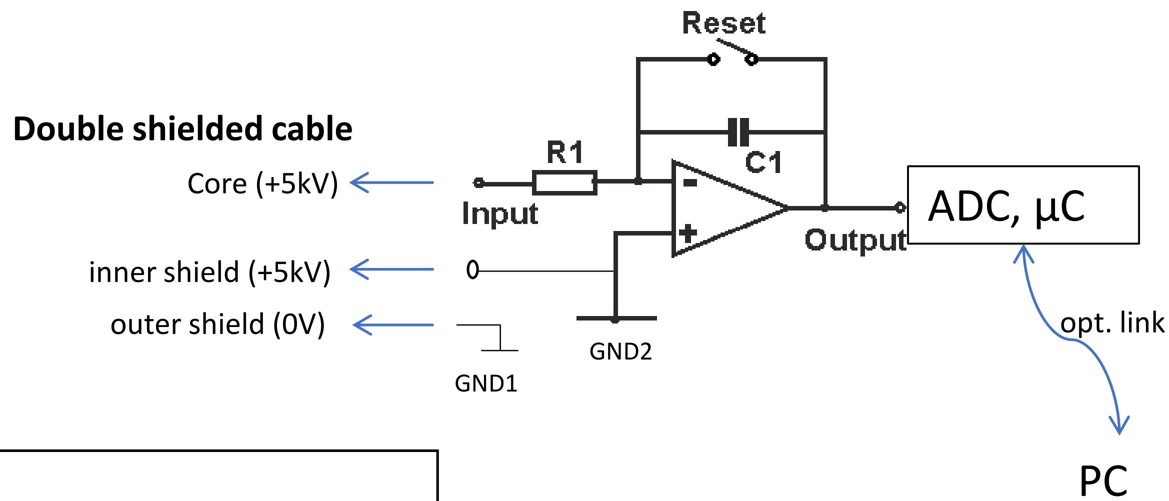
Measurement of leakage currents

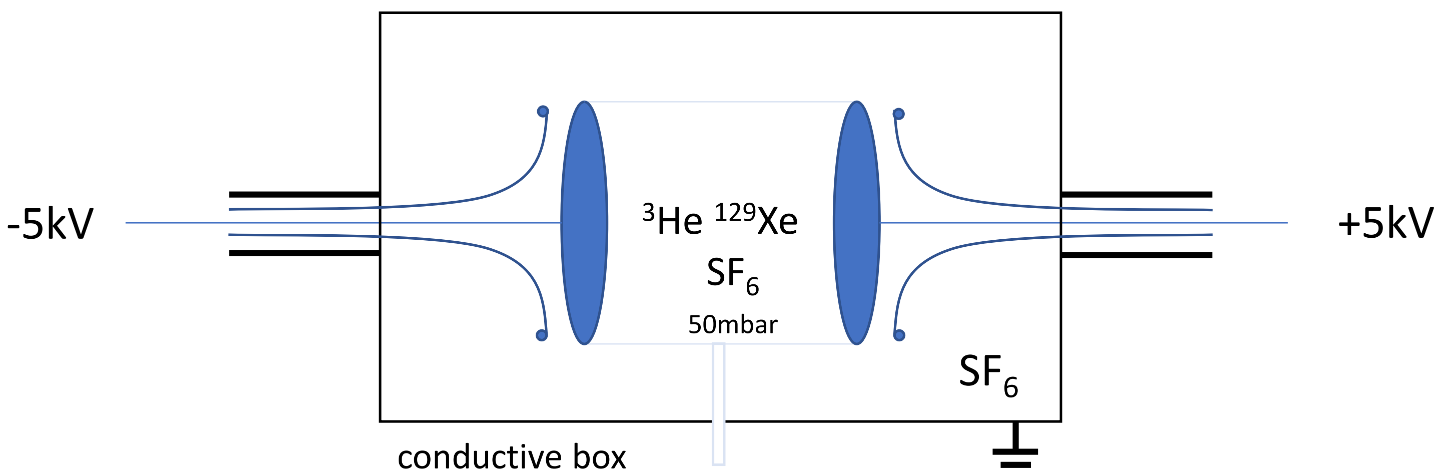
Resolution ~100 fA

At high potential (+5 kV)

Battery powered, optical interface

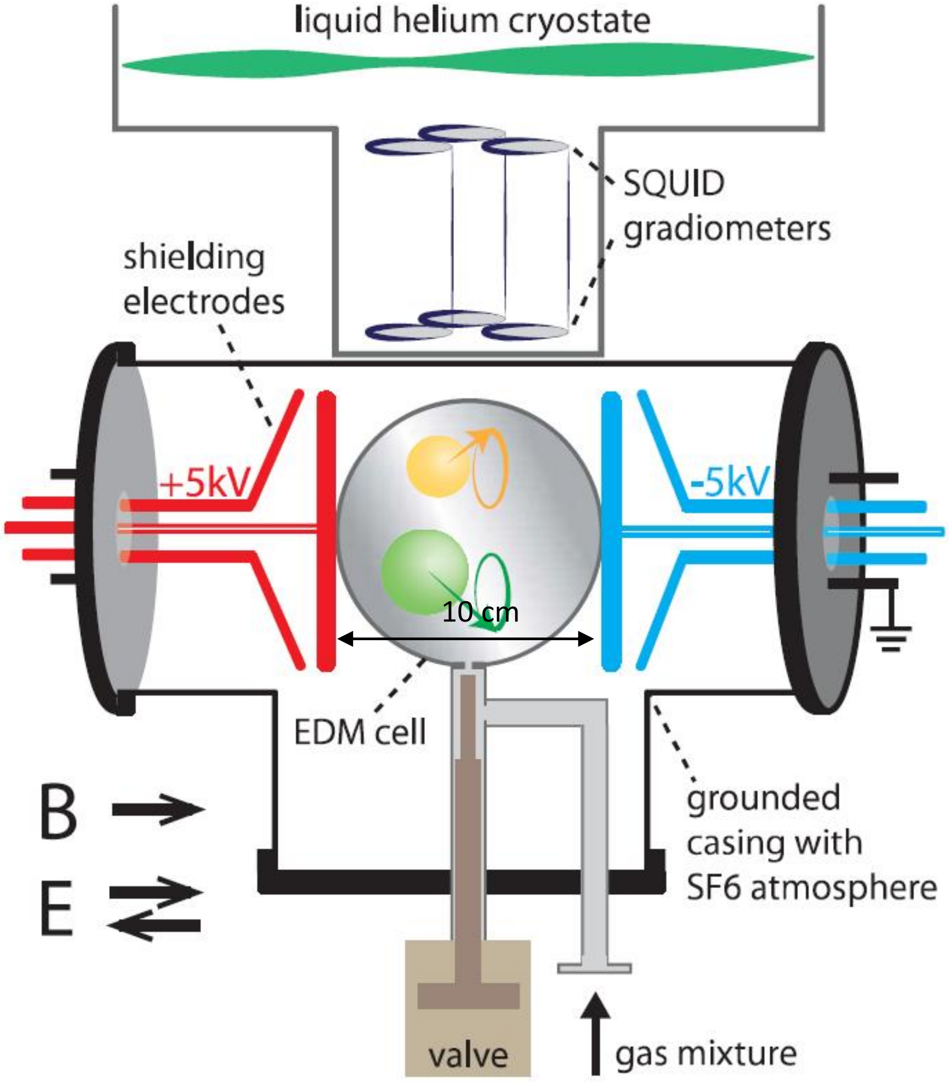






Setup

Measuring the free induction decay of polarized ^{3}He and ^{129}Xe with SQUID gradiometers



- Heavy atoms (relativistic treatment) + finite size: $\varepsilon \neq 0$

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

– 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]

$\eta(d_n, d_p, \bar{g}_0, \bar{g}_1, \bar{g}_2)$ → $\bar{\Theta}_{QCD}$

- General finding:

Paramagnetic EDMs:

„Schiff enhancement“ ($\varepsilon >> 1$)

Diamagnetic EDMs:

„Schiff suppression“ ($\varepsilon << 1$)

- Diamagnetic atoms:

Phys. Rep. 397 (04) 63; Phys. Rev. A 66 (02) 012111.

$$d(^{129}Xe) = 10^{-3} d_e + 5.2x10^{-21} C_T + 5.6x10^{-23} C_S + 6.7x10^{-26}\eta \approx 6.7x10^{-26}\eta$$

Results: Hg-EDM

$$d_{\mathrm{Hg}} = (-2.20 \pm 2.75_{\mathrm{stat}} \pm 1.48_{\mathrm{syst}}) \times 10^{-30}\ e\,\mathrm{cm},$$

$$\left|d_{Hg}\right| < 7.4\times10^{-30}\ ecm \quad (95\%\ \mathrm{CL})$$

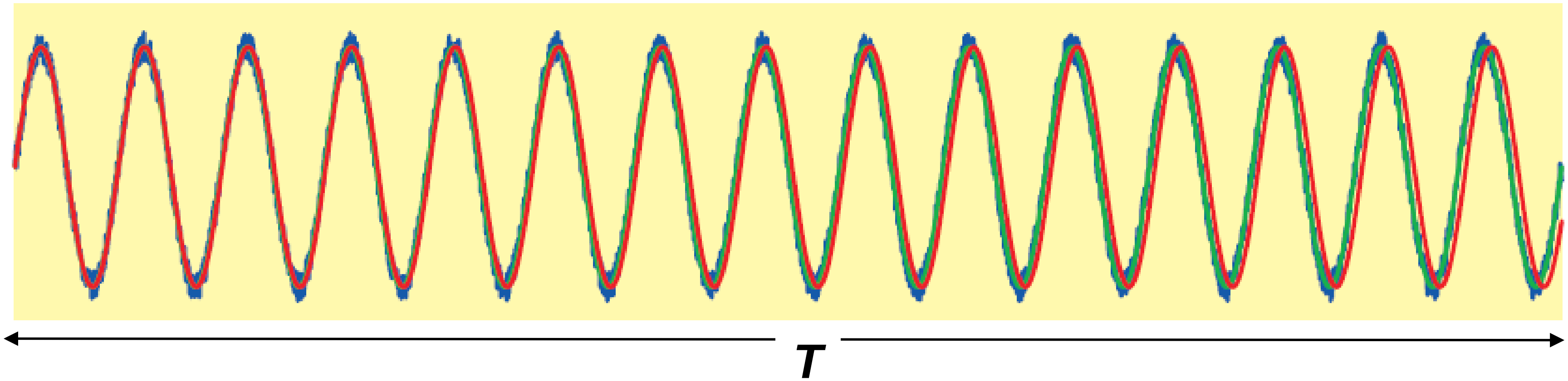
Limits on CP-violating observables from ^{199}Hg EDM limit

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

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

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

Accuracy of frequency estimation:



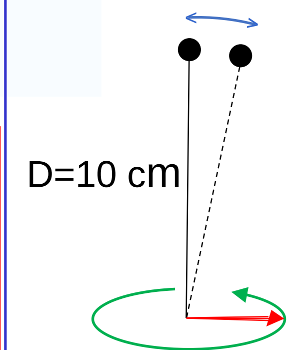
$$\sigma_f \propto \left[\textit{Fourier width} \quad \frac{1}{T} \right] \times \left[\frac{1}{\left[\textit{\# data points} \quad T \right]^{1/2}} \right] \propto \frac{1}{T^{3/2}}$$

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 $\Rightarrow \sqrt{\sigma_f^2} \approx pHz$

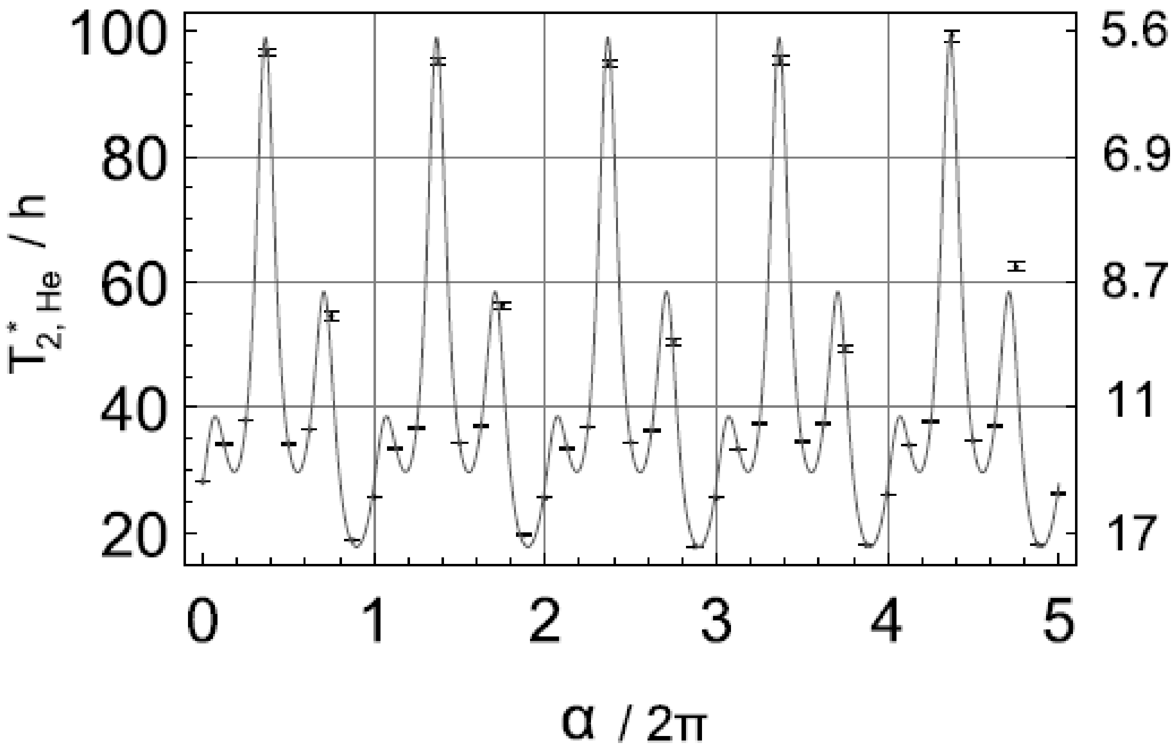
Magnetically shielded room (MSR) at Jülich Research Center

Minimizing magnetic field gradients

(arXiv:1608.01830v1)

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

$$0 < a(\lambda) < 0.5 \qquad \lambda = \frac{D^2}{\gamma^2 B_0^2 R^4} \propto \frac{1}{p^2}$$



$\left|\vec{\nabla} B_z\right|\ pT/cm$

sensitivity:

$\delta\left|\vec{\nabla} B_z\right| \approx 30\, fT/cm$

.... systematics (cont.)

- motional magnetic fields $\vec{B}_m = \frac{1}{c^2}\left(\vec{v} \times \vec{E}\right)$

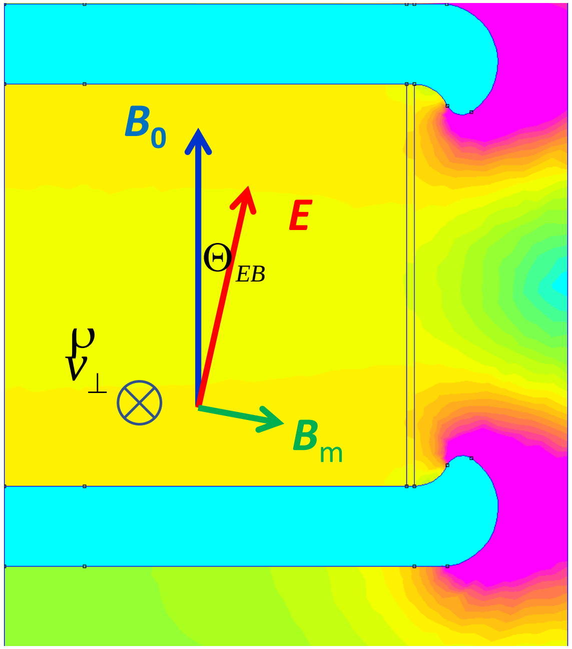
$$B = B_0 + \underbrace{\Theta_{EB}}_{=0} \cdot B_m + \frac{1}{2} \cdot \frac{B_m^2}{B_0}$$

$\langle \vec{v} \rangle = \vec{0}$

→ *PRA 53 (1996) R3705*

$$f_m = \frac{(2\pi)^2}{6} (\gamma v E / c^2)^2 f_0 \tau_c^2$$

$$\approx 3 \times 10^{-12}\, nHz$$



- parameter correlations

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- ....