Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

A new measurement of the permanent electric dipole moment of ^{129}Xe using ^{3}He comagnetometry and SQUID detection

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HeXe Collaboration

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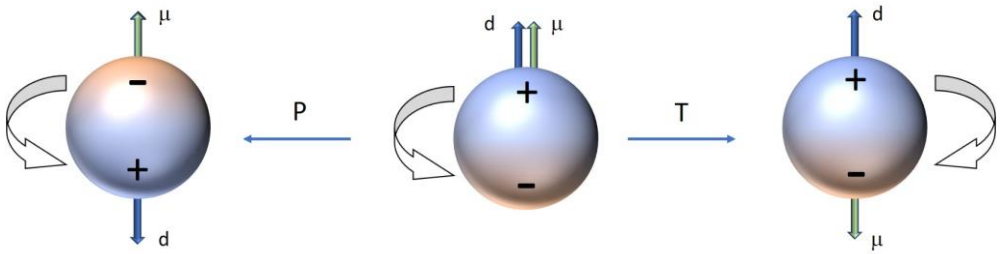
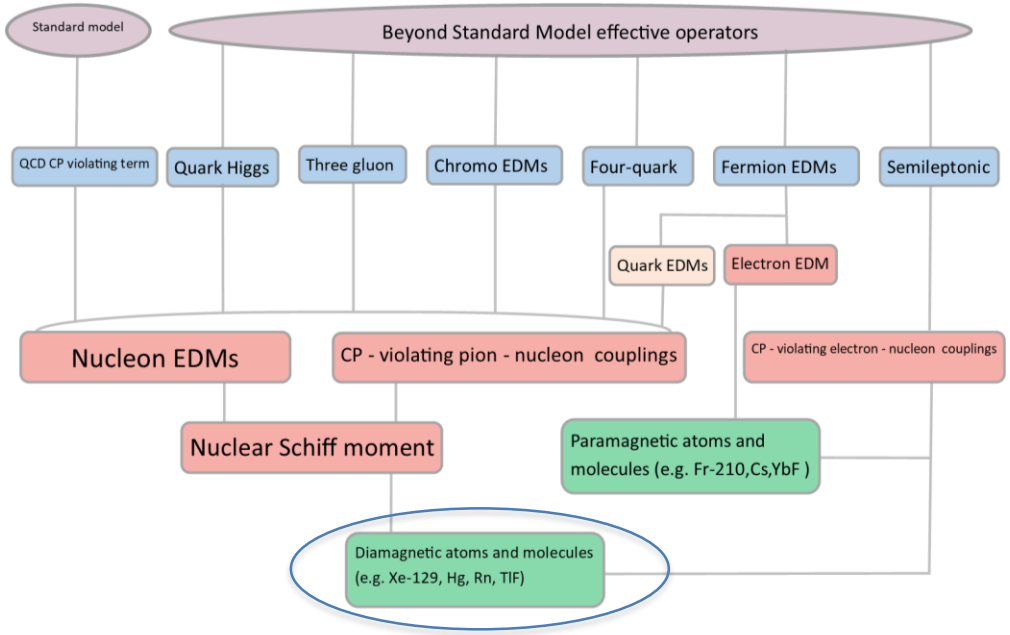
What are we looking for

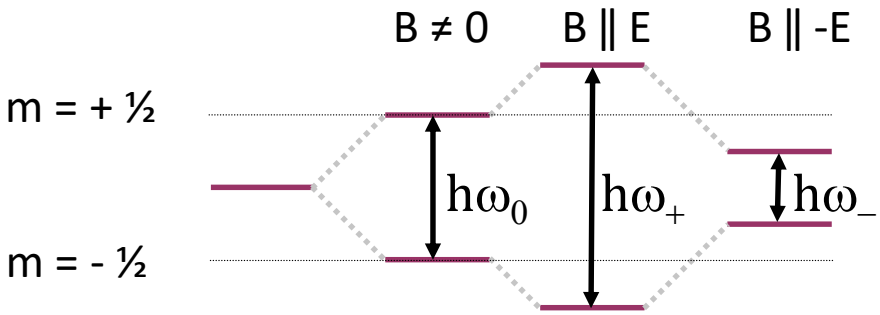




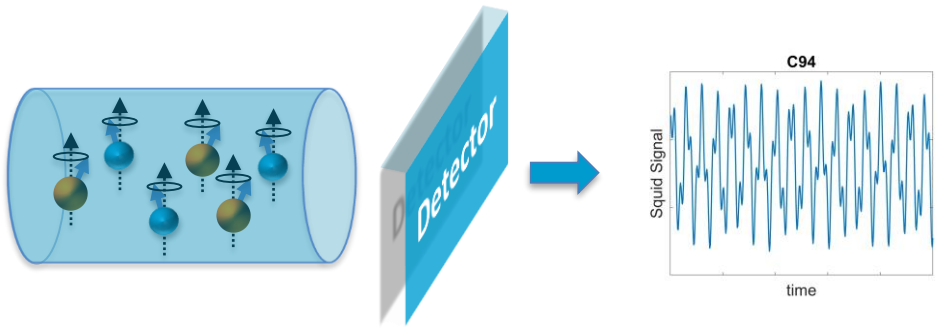
- Permanent EDMs are direct signal of T and P violation
- Assuming CPT symmetry, EDM is experimental probe of CP violation

- new upper limits restrict limits in low energy parameters

Why Xe? Why He-Xe Comagnetometer?



$$\Delta E = \hbar\omega_L = 2(\mu B \pm dE) \rightarrow d = \frac{\hbar\Delta\omega_L}{2(E_+ + E_-)}$$



$$\omega_{Xe} = \frac{\gamma_{Xe}}{\gamma_{He}}\omega_{He} \rightarrow d = \frac{\hbar\left(\Delta\omega_{Xe} - \frac{\gamma_{Xe}}{\gamma_{He}}\Delta\omega_{He}\right)}{2(E_+ + E_-)}$$

- Xe-129 is spin - ½ isotope
- EDM supposed to scale with Z^2
- Long polarization and spin coherence lifetimes
- Problematic: B(t) has to be precisely known ➡ Comagnetometer less sensitive to B field drifts
- He EDM negligible
- He and Xe can be polarized in one cell

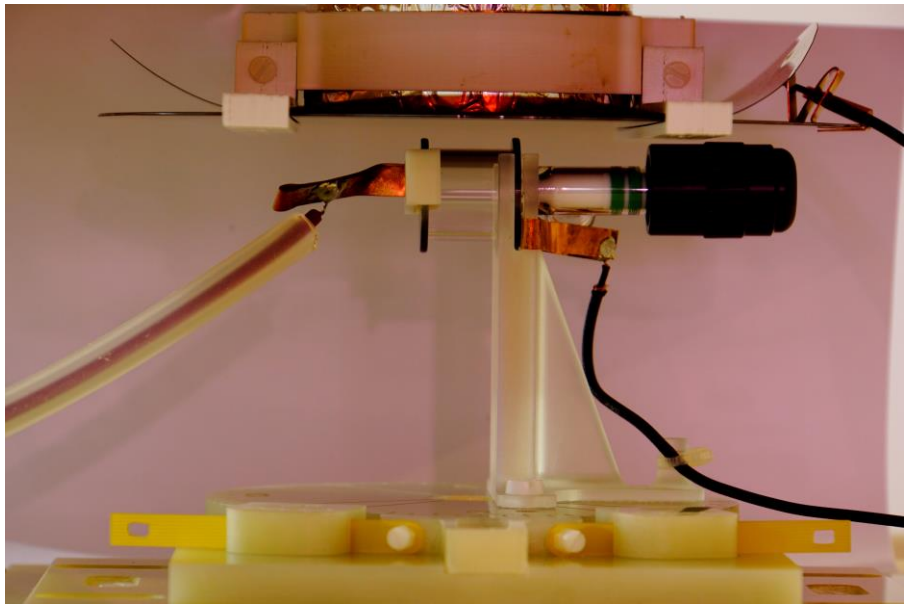
Experimental Setup BMSR - 2

- 3 x 3 x 3 m^3 shielded room
- 7 layer Mu-metal
- 1 Al layer
- Active shielding with compensation coils
- Magnetic gradients smaller than 2 pT/cm

Experimental Setup

- Helmholtz coils
- Low Tc integrated DC SQUIDs
- System noise ≈ 6fT/√Hz
- Commercial HV power supply up to +/-10kV
- Safety electrode at the SQUID system
- Leakage current monitor at the ground electrode
- cylindrical sample cells with slightly different aspect ratios approx. 20 mm diameter and length

Experimental Setup

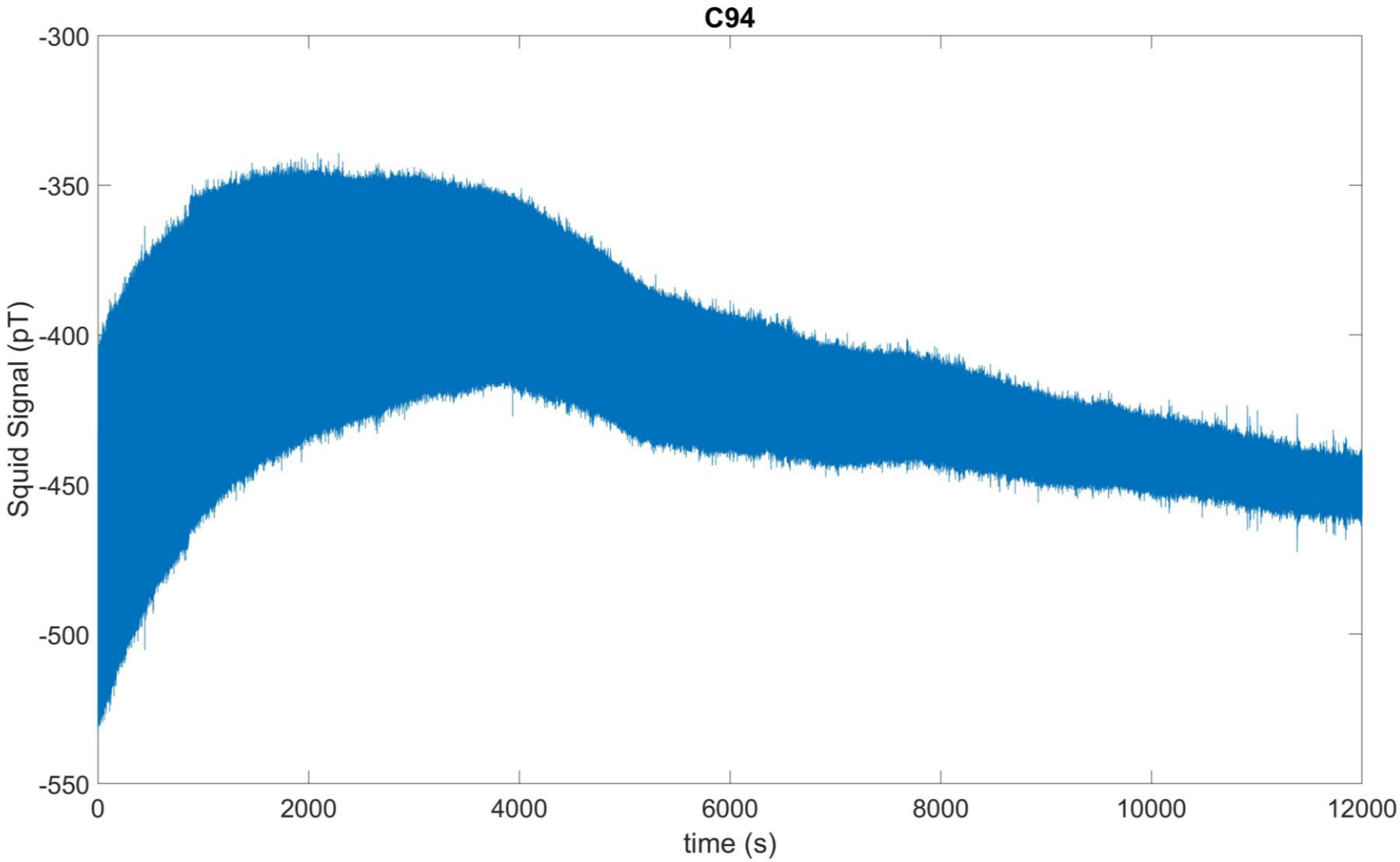


- Helmholtz coils
- Low Tc integrated DC SQUIDs
- System noise ≈ 6fT/√Hz
- Commercial HV power supply up to +/-10kV
- Safety electrode at the SQUID system
- Leakage current monitor at the ground electrode
- cylindrical sample cells with slightly different aspect ratios approx. 20 mm diameter and length

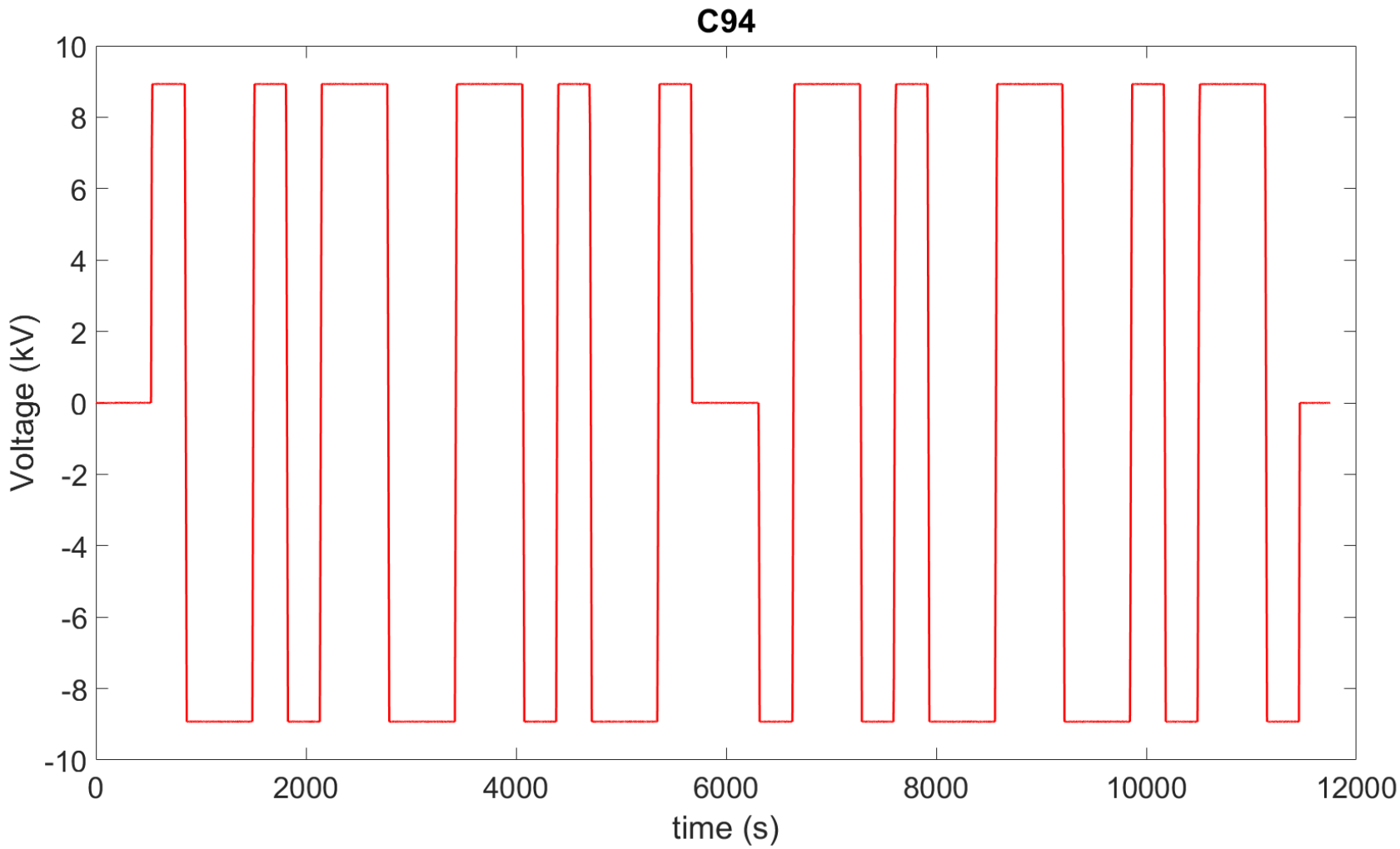
Measurement Campaigns 2017 and 2018

	2017	2018
Pressure (bar)	$P_{high} \approx 0.8$, $P_{low} \approx 0.5$	
HV (kV)	$\pm$ 6	$\pm$ 9
Sample cells	2	3
Runs (typical length (s))	16 (15,000)	25 (20,000 – 45,000)
Subruns	16	64
Segment length (s)	400, 800	100 - 600

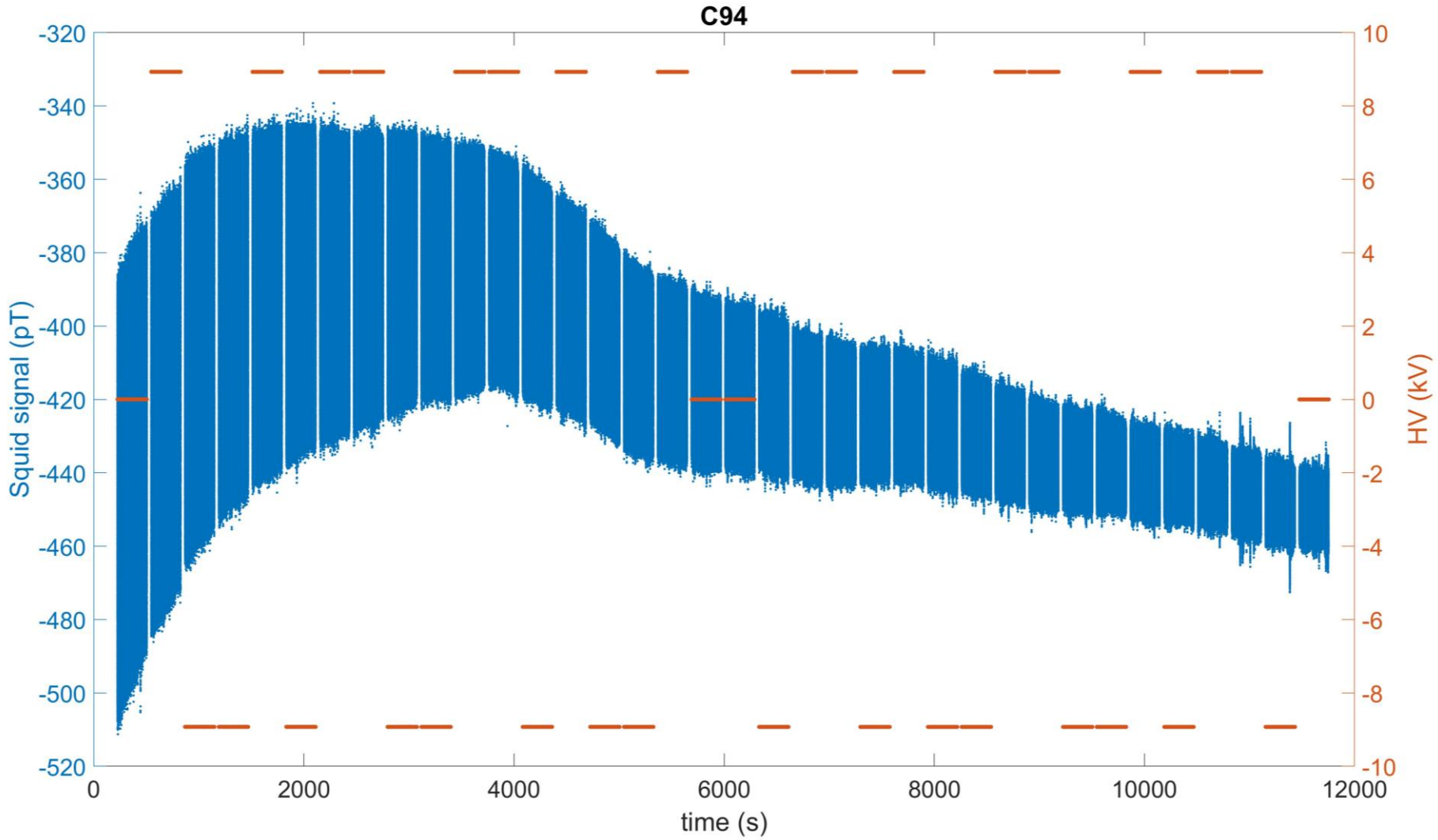
Data Analysis



Data Analysis



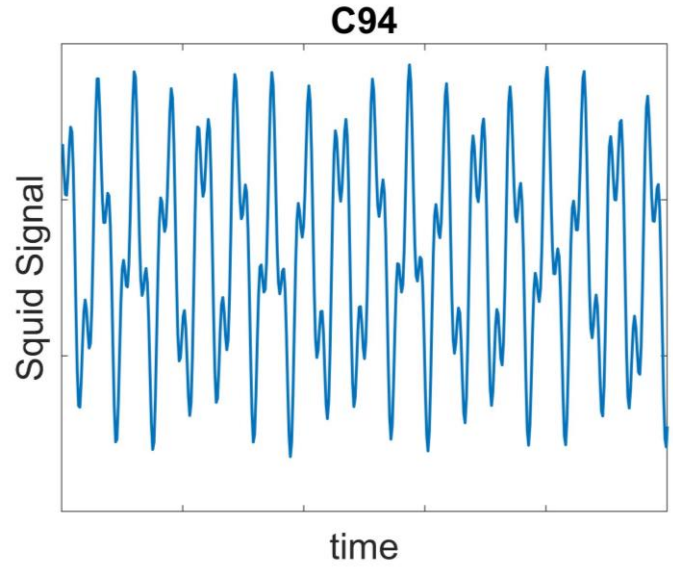
Data Analysis



Data Analysis – SinCos Fit

- Independent data analysis by PTB and University of Michigan
- Magnetometer signal for a block of 20s:

$$A^i(t) = C^i_{He}\sin\left(\omega^i_{He}t + \varphi^i_{He}\right) + C^i_{Xe}\sin\left(\omega^i_{Xe}t + \varphi^i_{Xe}\right) + c^i_0 + c^i t$$



- 8 Parameter fit using Levenberg Marquart Fit
- Obtaining phases from fit parameters
- Blinding Xe phase
- Calculating weighted phase difference: $\Phi^i_{Co} = \Phi^i_{Xe} - \frac{\gamma_{Xe}}{\gamma_{He}}\Phi^i_{He}$
- linear fit on block phases of each segment to obtain Comagnetometer frequency ω_{Co}

Data Analysis

- Comagnetometer frequency:

$$\omega_{Co} = \omega_{Xe} - R\omega_{He} \qquad R = \frac{\gamma_{Xe}}{\gamma_{He}}$$

- Species specific contributions to spin precession frequencies

$$\omega_{He,Xe} = \gamma_{He/Xe}\left(1 - \delta_{He/Xe}\right)\langle B\rangle_{He/Xe} + \omega^{sd}_{He/Xe} + \Omega \cdot \hat{B}$$

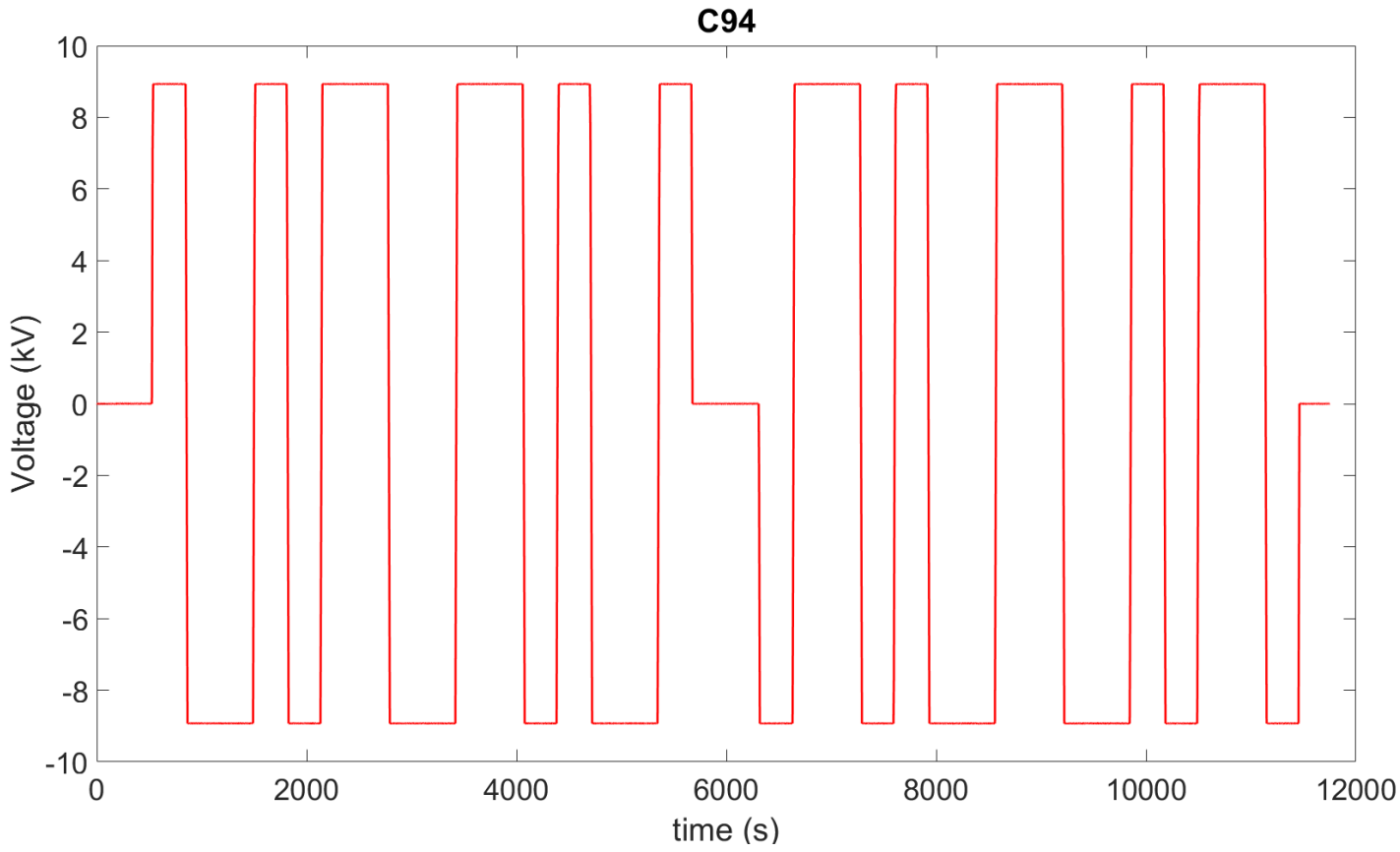
  - Chemical shift, depends on cell pressure, temperature, surrounding material

- Comagnetometer freqency can be expressed by following terms:

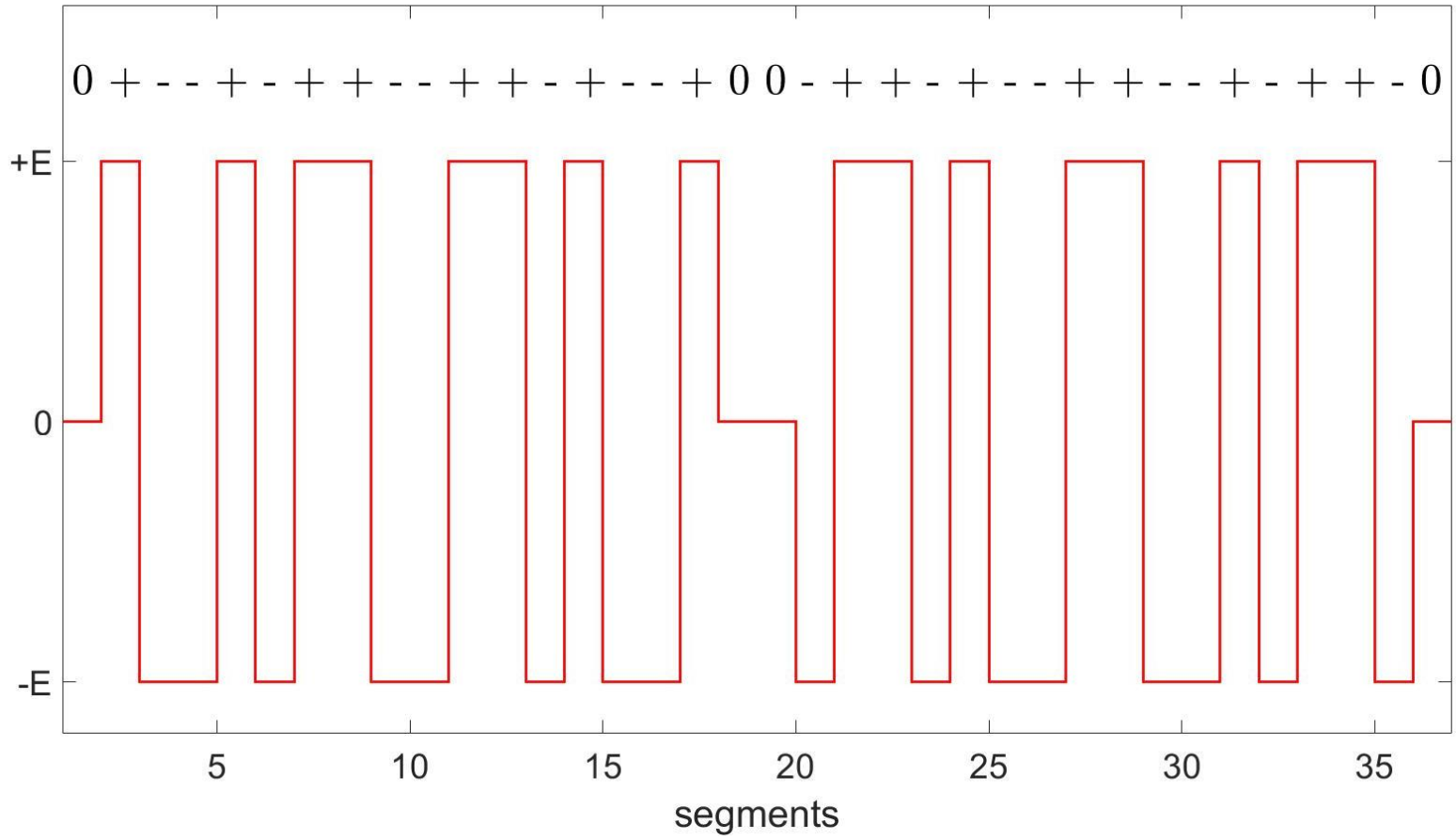
$$\omega_{Co} \approx \omega_d$$

$-\gamma_{He}\Delta RB$	pressure dependence, varying chemical shift
$+\ \gamma_{Xe}(\Delta B_{Xe} - \Delta B_{He})$	different diffusion constants, 2nd order gradients
$+ (1 - R)\vec{\Omega} \cdot \hat{B}$	earth rotation and any change in B direction
$+\ \left(\omega^{sd}_{Xe} - R\omega^{sd}_{He}\right)$	Comagnetometer drift due to cross talk and self shift

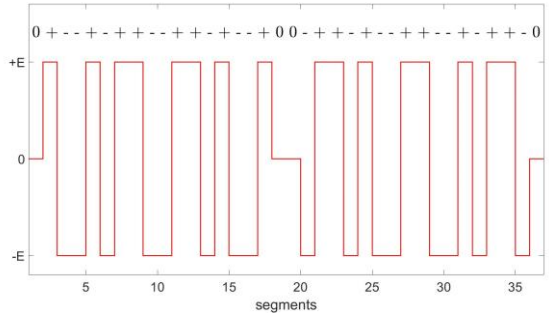
Data Analysis – Comagnetometer Drift



Data Analysis – Comagnetometer Drift



Data Analysis – Comagnetometer Drift



- 36 segments with distinctive E-pattern
- All segments have equal length $t_i = i\Delta t$

Assuming linear drift:

$$\omega_{Co} = a + bt + \omega_d$$

$$\omega_{Co}^1 - \omega_{Co}^2 - \omega_{Co}^3 + \omega_{Co}^4 = a + bt_1 + \omega_d - (a + bt_2 + \omega_d) - (a + bt_3 + \omega_d) + a + bt_4 + \omega_d$$

$$= b(\Delta t - 2\Delta t - 3\Delta t + 4\Delta t) + 4(\omega_{d,1} - \omega_{d,2} - \omega_{d,3} + \omega_{d,4})$$

$$= 4(\omega_{d,1} - \omega_{d,2} - \omega_{d,3} + \omega_{d,4})$$

Data Analysis – Comagnetometer Drift

- Polynomial fit to correct Comagnetometer frequency

$$\omega_{Co_i} = a_0 + a_1 t_i + a_2 {t_i}^2 + \cdots + sgn\left(\hat{E} \cdot \hat{B}\right)\omega_d$$

$$\omega_{Co} = \frac{1}{4}\sum_{i=1}^{4} \omega_{Co_i} = \omega_d + \underbrace{c_1 a_1 \Delta t + c_2 a_2 \Delta t^2 + c_3 a_3 \Delta t^3 + \cdots + c_n\, a_n \Delta t^n}_{\omega_f}$$

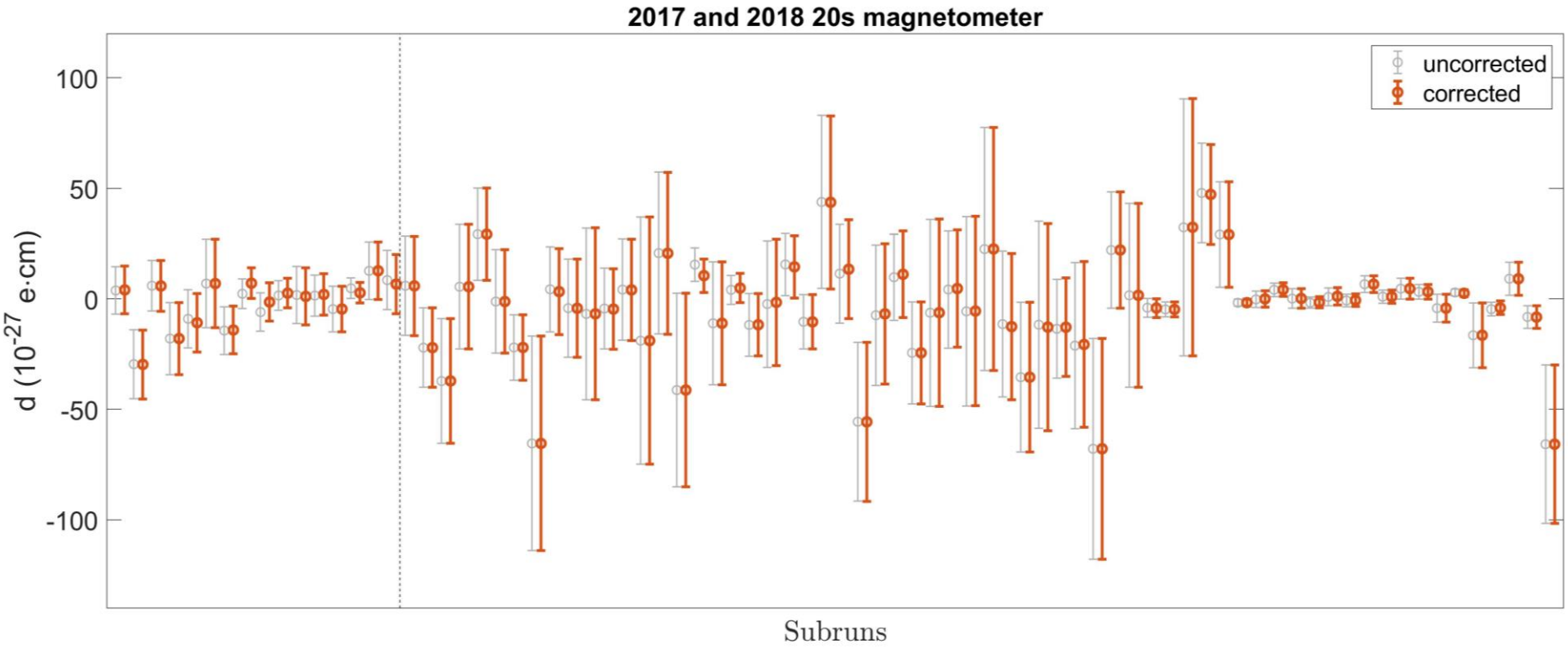
$$c_n = \frac{1}{4}\sum_{i=1}^{n} \mathrm{sgn}\left(\hat{E} \cdot \hat{B}\right) i^n$$

- F-test to determine order of the fit:

$$F = \frac{(sum(res_{i-1})^2 - sum(res_i)^2) \cdot (n-i)}{sum(res_i)^2} \geq 0.6$$

- Uncertainties for the correction obtained from resulting covariance matrix
- Correction applied to the Comagnetometer frequency

Data Analysis – Comagnetometer Drift



$$EDM = (1.43 \pm 6.56_{stat.} \pm 0.40_{Comag.}) \times 10^{-28}\ ecm$$

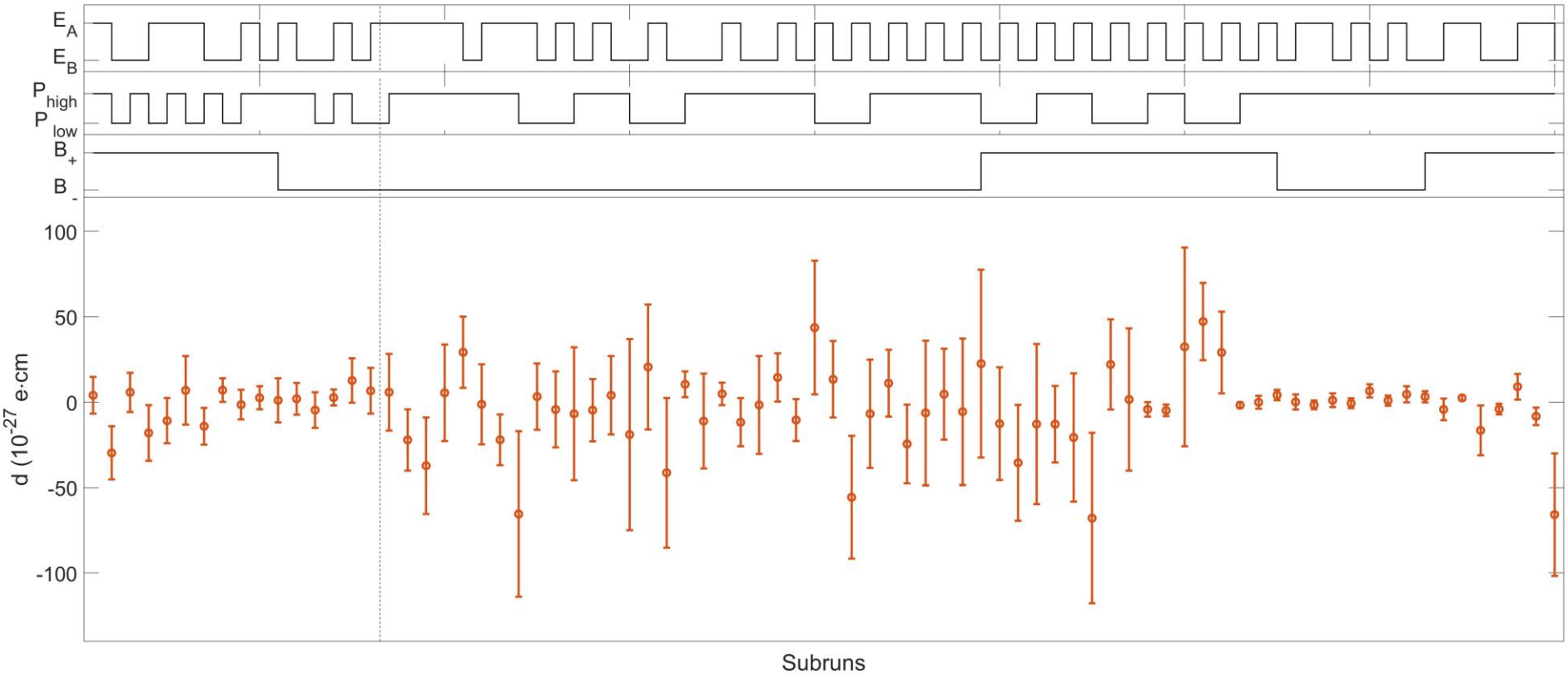
Systematics

	2017 EDM_{false} (e cm)	2018 EDM_{false} (e cm)
Comag. Drift	**$2.6 \cdot 10^{-28}$**	**$4.0 \cdot 10^{-29}$**
Leakage Current	**$1.2 \cdot 10^{-28}$** Auxiliary measurements: frequency measured when wire was wrapped one full turn around the cell and I = $\pm$ 1μA applied -> result scaled with measured I_{leak}	**$4.5 \cdot 10^{-31}$**
Charging Current	**$1.7 \cdot 10^{-29}$** Auxiliary measurements: frequency measured when I_{Charge} = 20μA applied (done by short circuit of cell and applying $\pm$200V using 10MΩ resistor) -> result scaled with measured I_{charge}	**$1.2 \cdot 10^{-29}$**

Systematics

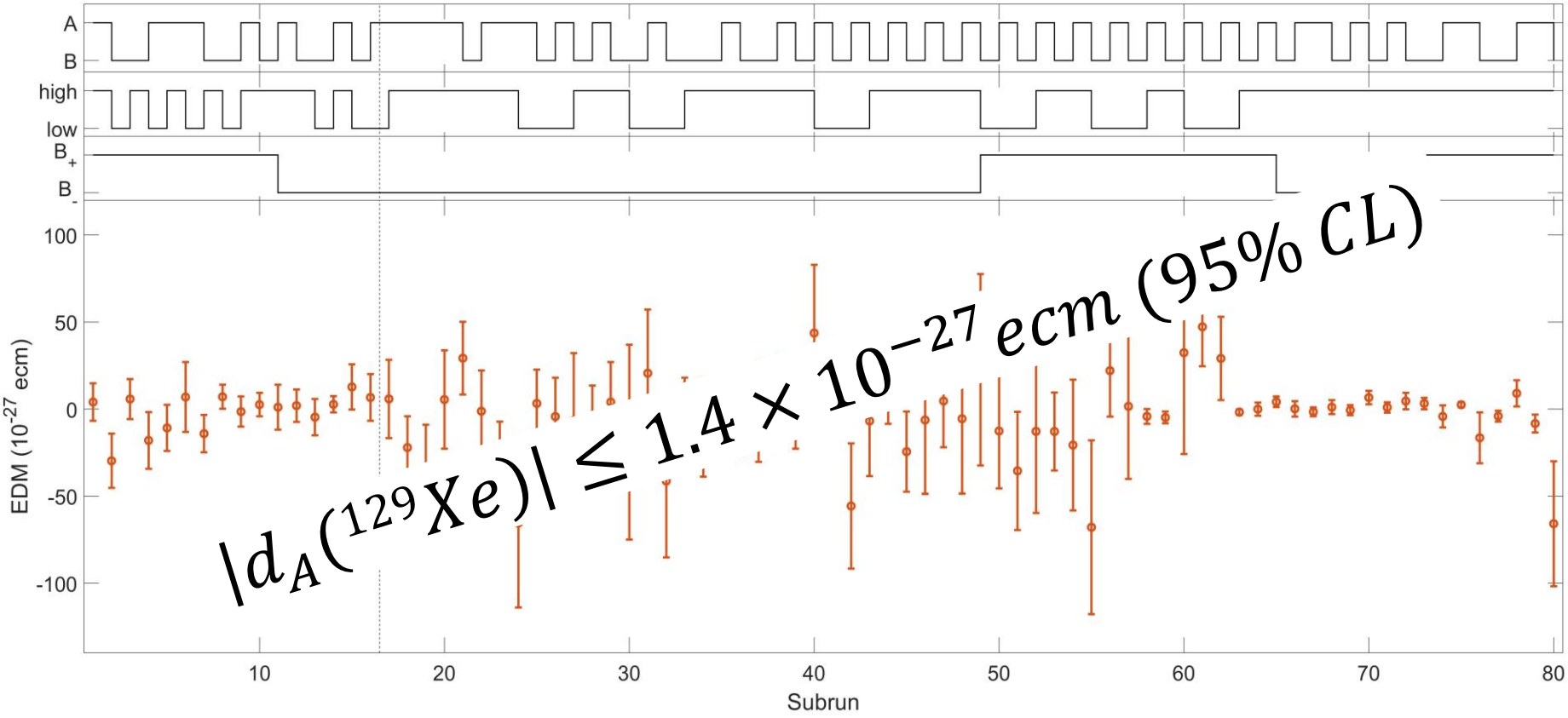
	2017 EDM_{false} (e cm)	2018 EDM_{false} (e cm)
Cell rotation	**$4.2 \cdot 10^{-29}$** Auxiliary measurements: cell movement determined by laser beam measurements, frequency dependence measured by rotating cell $\pm 5°$	**$4.0 \cdot 10^{-29}$**
Cell translation	**$2.6 \cdot 10^{-28}$** Auxiliary measurements: measurements of single species He-3 and loop test with wire attached to electrode, imitating dipole	**$1.9 \cdot 10^{-28}$**
$\left\|\vec{E}\right\|^2$ effects	**$1.2 \cdot 10^{-29}$**	**$2.2 \cdot 10^{-30}$**
$\left\|\vec{E}\right\|$ uncertainty	**$2.6 \cdot 10^{-29}$** Finite Element analysis	**$9.4 \cdot 10^{-30}$**
Geometric Phase	**$< 2 \cdot 10^{-31}$**	**$< 1 \cdot 10^{-31}$**
Total Error	**$3.9 \cdot 10^{-28}$**	**$2.0 \cdot 10^{-28}$**

Final Result



$$EDM = (1.43 \pm 6.56_{stat.} \pm 1.86_{sys.}) \times 10^{-28}\ ecm$$

Final Result



New Limit on the Permanent Electric Dipole Moment of 129Xe Using 3He Comagnetometry and SQUID Detection

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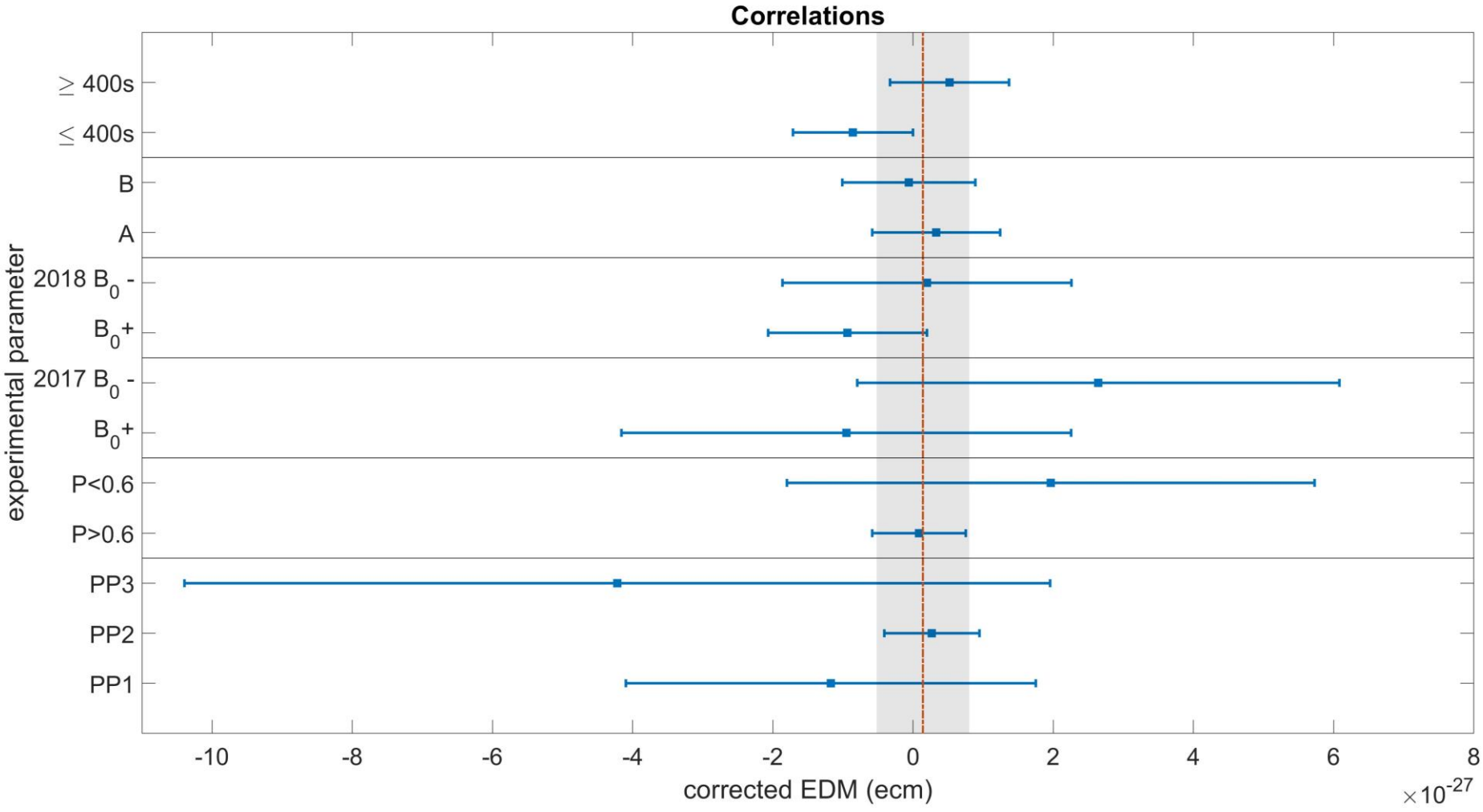
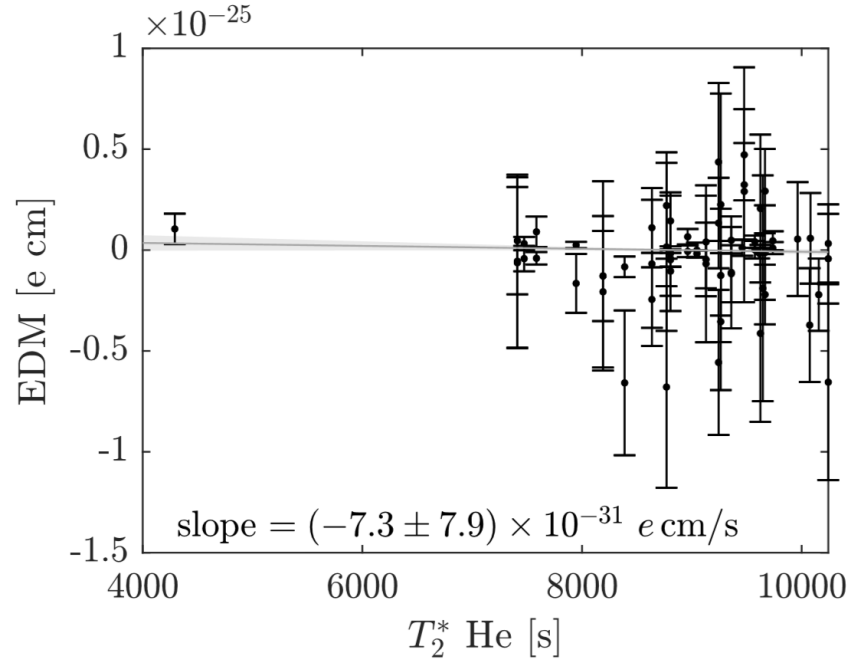
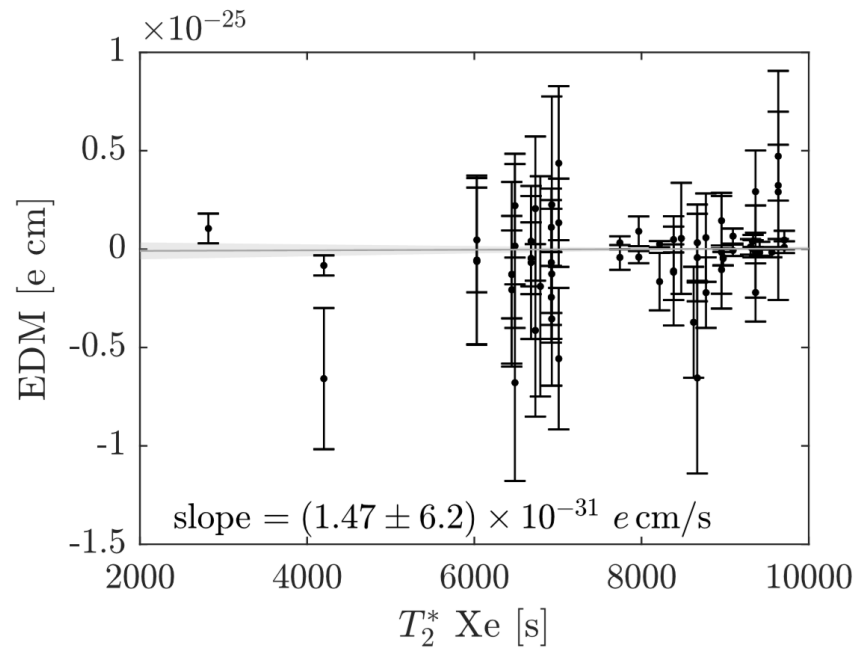
Phys. Rev. Lett. 123, 143003, 2019

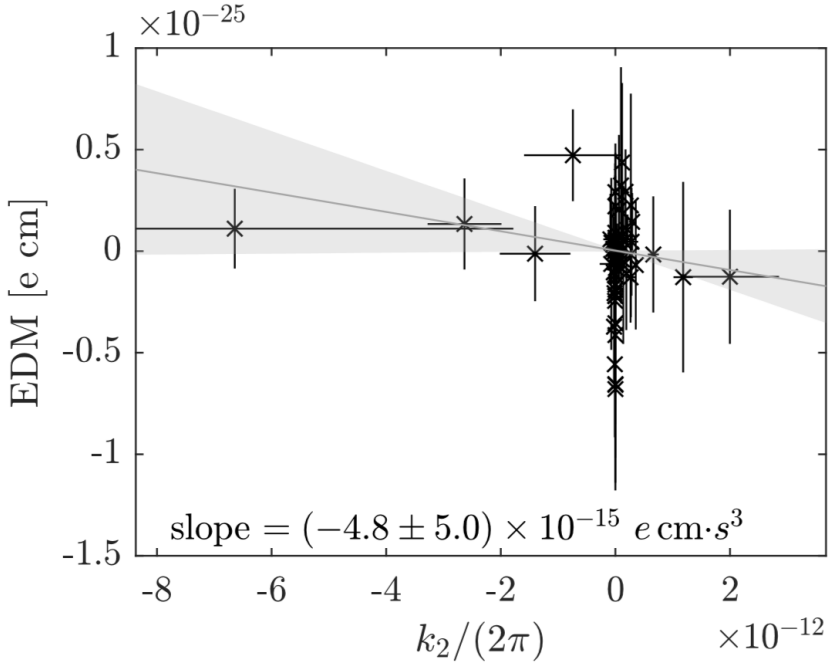
Thank you for your attention!

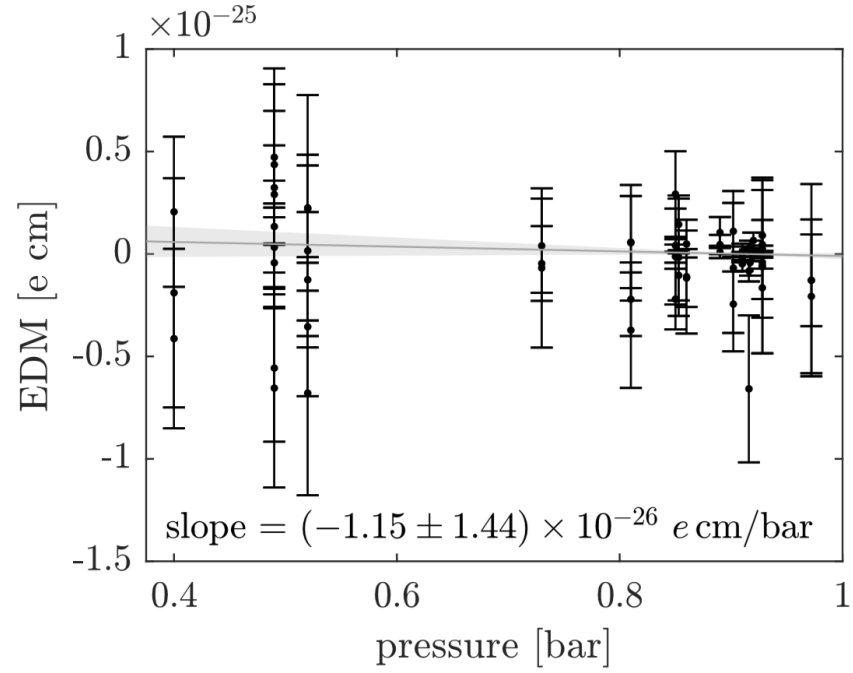
Look on the Correlations




×10^−25
1
0.5
0
-0.5
-1
-1.5
EDM [e cm]
slope = (−7.3 ± 7.9) × 10^−31 e cm/s
4000
6000
8000
10000
T2* He [s]

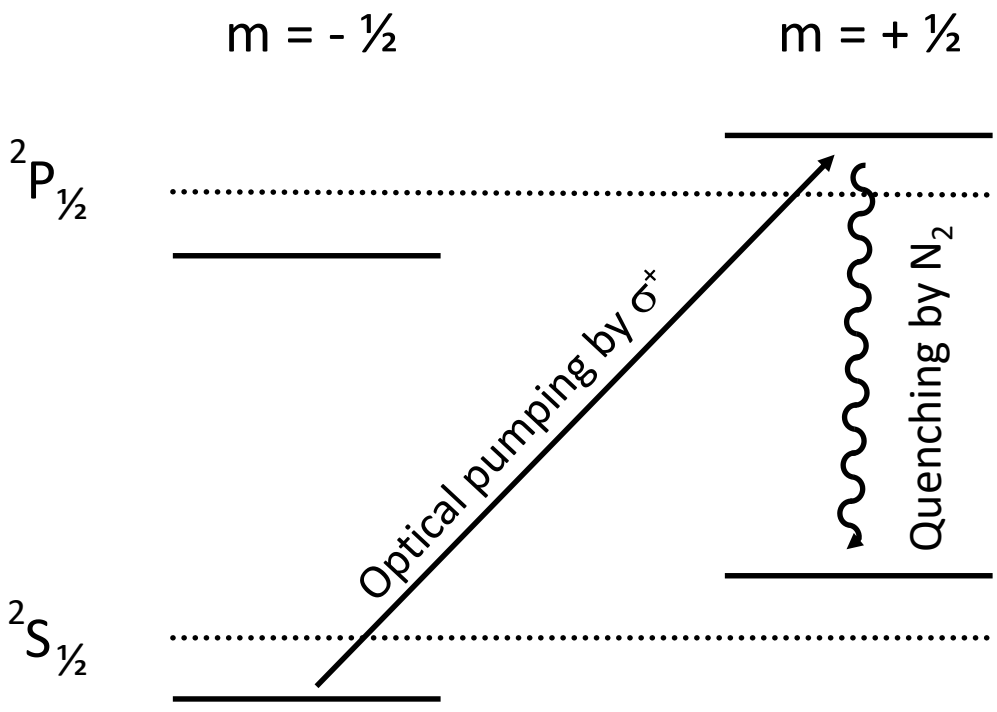

×10^−25
1
0.5
0
-0.5
-1
-1.5
EDM [e cm]
slope = (1.47 ± 6.2) × 10^−31 e cm/s
2000
4000
6000
8000
10000
T2* Xe [s]


×10^−25
1
0.5
0
-0.5
-1
-1.5
EDM [e cm]
slope = (−4.8 ± 5.0) × 10^−15 e cm·s^3
-8
-6
-4
-2
0
2
k2/(2π)
×10^−12

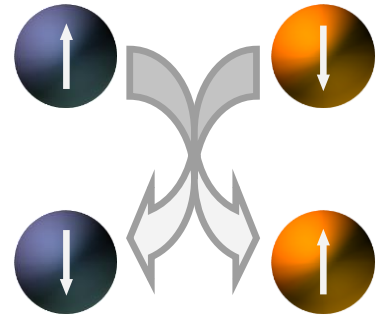

×10^−25
1
0.5
0
-0.5
-1
-1.5
EDM [e cm]
slope = (−1.15 ± 1.44) × 10^−26 e cm/bar
0.4
0.6
0.8
1
pressure [bar]

Experimental Setup – He/Xe Polarization

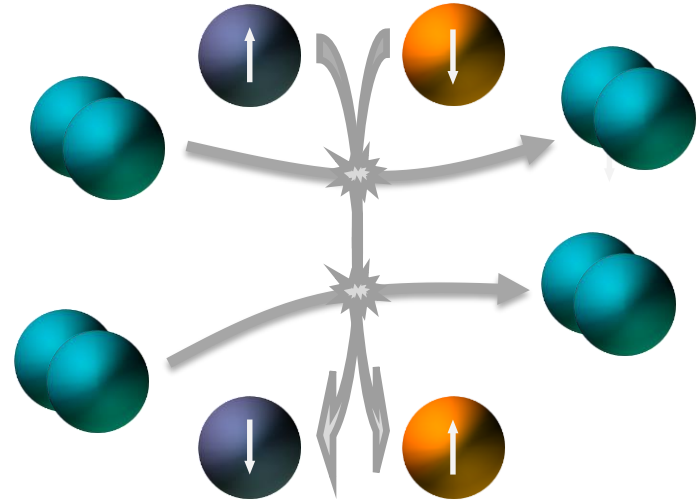
- Polarization by Spin exchange optical pumping
- Rb polarized by σ+ photons
- Quenching gas N_2 to avoid unpolarized light emission from decay



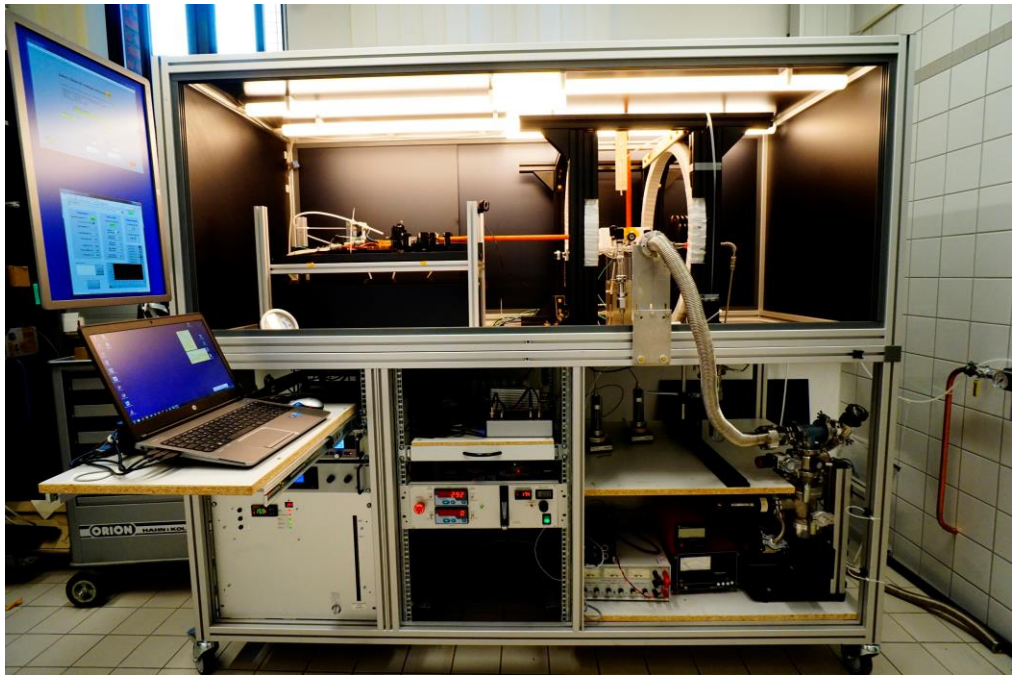
Binary collision
(Rb—He, Rb—Xe)

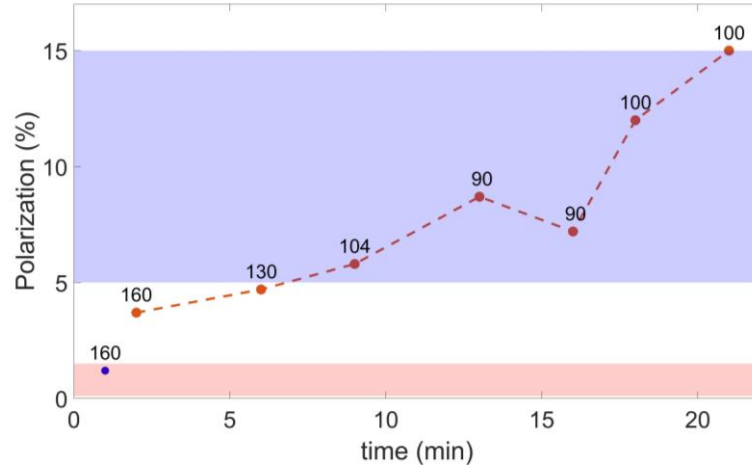


Van der Waals molecules
(Rb—Xe)



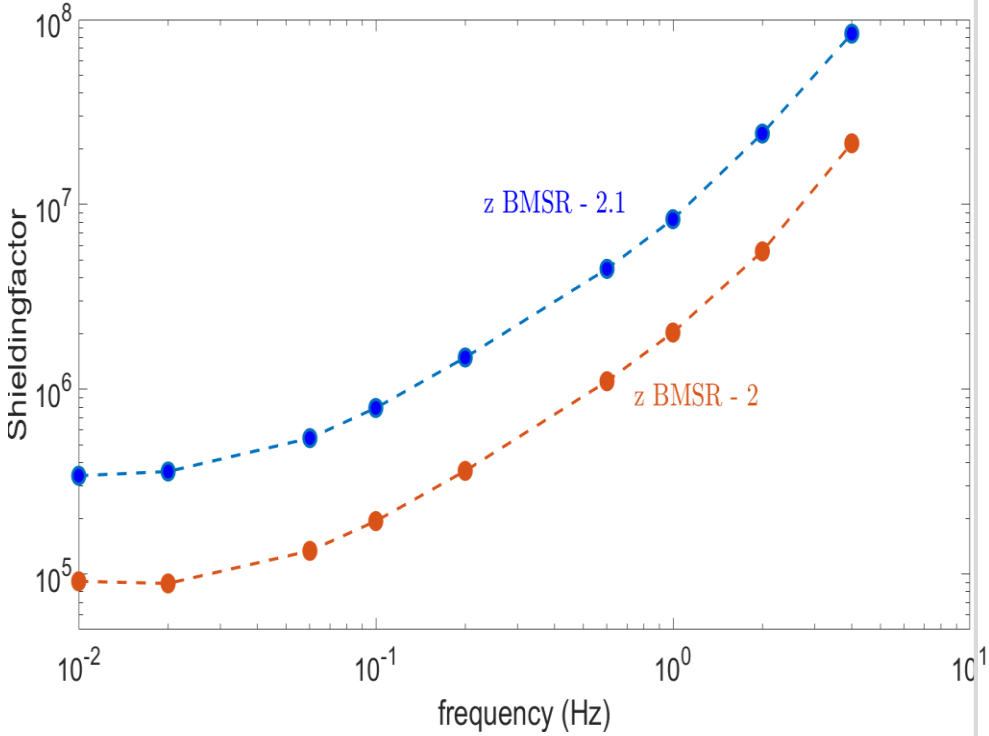
Experimental Setup - He/Xe Polarization





- He – Xe – N_2 Mixture
- ‘simultaneous’ polarization of He and Xe with Rb (effective polarization of He at approx. 160°C, for Xe approx. 90°C)
- different pressure ranges possible

Experimental Setup BMSR - 2



- 3 x 3 x 3 m^3 shielded room
- 7 layer Mu-metal
- 1 Al layer
- Active shielding with compensation coils
- Residual field less than 1 nT
- Magnetic gradients smaller then 2 pT/cm
- Shielding factor @ 0.1Hz
  - passive: $2 \cdot 10^5$
  - active: $2 \cdot 10^7$

	2017	2018
Gas mixture $^{129}Xe/^{3}He/N_2$ (%)	18 / 73 / 9	15 / 75 / 15
Sample cells	2	3
Pressure (bar)	$P_{high} \approx 0.8$, $P_{low} \approx 0.5$	
He / Xe frequency (Hz)	85 / 31	97 / 35
HV (kV)	$\pm$ 6	$\pm$ 9
Sampling rate (Hz)	915.5245	
Runs (typical length (s))	16 (15,000)	25 (20,000 – 45,000)
Subruns	16	64
Segmentlength (s)	400, 800	100 - 600
Blocklength (s)	20	

Data Analysis – SinCos Fit

- Magnetometer signal for a block of the length t:

$$A^i(t) = C^i_{He}\sin\left(\omega^i_{He}t + \varphi^i_{He}\right) + C^i_{Xe}\sin\left(\omega^i_{Xe}t + \varphi^i_{Xe}\right) + c^i_0 + c^i t$$

$\omega^i_{He/Xe} = 2\pi\nu^i_{He/Xe}$ Larmor frequency

$C^i_{He/Xe}$ Amplitudes

$$C^i_{He/Xe}\sin\left(\omega^i_{He/Xe}t + \varphi^i_{He/Xe}\right) = C^i_{He/Xe}\sin\left(\omega^i_{He/Xe}t\right)\cos\left(\varphi^i_{He/Xe}\right) + C^i_{He/Xe}\cos\left(\omega^i_{He/Xe}t\right)\sin\left(\varphi^i_{He/Xe}\right)$$

$$= a^i_{He/Xe}\sin\left(\omega^i_{He/Xe}t\right) + b^i_{He/Xe}\cos\left(\omega^i_{He/Xe}t\right)$$

- Levenberg Marquardt Fit

Data Analysis – SinCos Fit

- Obtaining the phases

$$\varphi^i_{He/Xe} = atan2\left(\frac{b^i_{He/Xe}}{a^i_{He/Xe}}\right) + \pi$$

$$atan2(y,x) = \begin{cases} arctan\left(\frac{y}{x}\right) & x > 0, \\ \pi + arctan\left(\frac{y}{x}\right) & y \geq 0, x < 0, \\ -\pi + arctan\left(\frac{y}{x}\right) & y < 0, x < 0 \end{cases}$$

$$\Phi^i_{He/Xe}(t) = \Phi^{i-1}_{He/Xe}(t) + \bar{\omega}_{He/Xe} \cdot \tau + \varphi^i_{He/Xe} \underbrace{- mod\left(\frac{\Phi^{i-1}_{He/Xe}(t) + \bar{\omega}_{He/Xe} \cdot \tau}{2\pi}\right)}$$

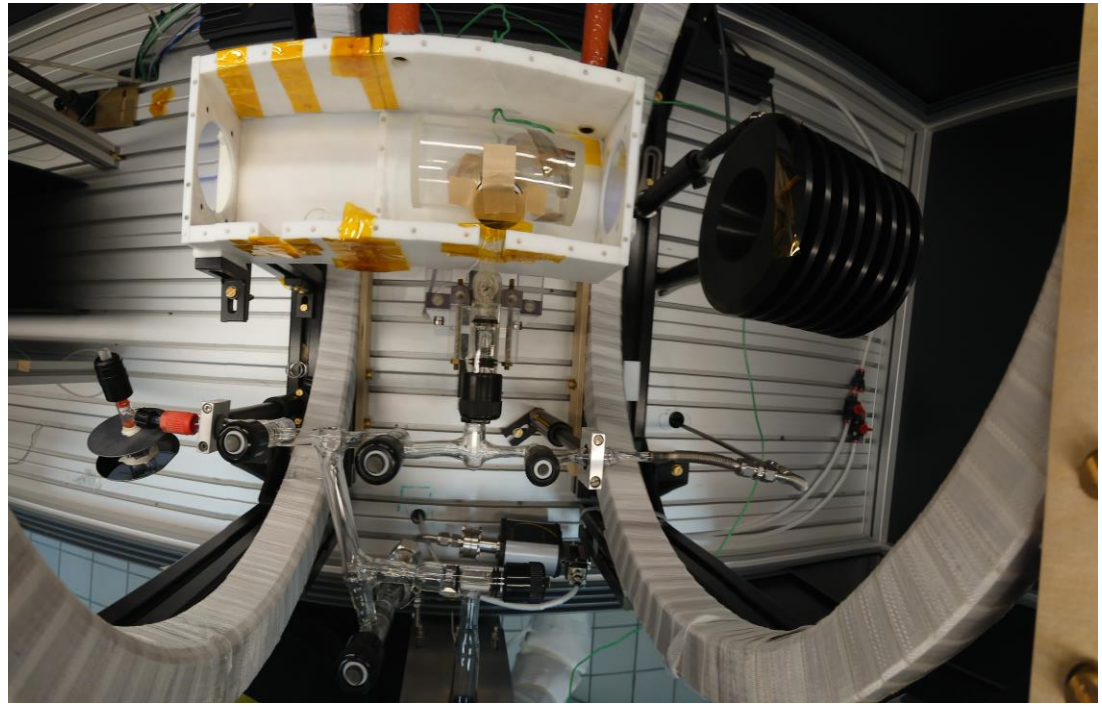
Correction phase if $\omega^i_{He/Xe} \neq \bar{\omega}_{He/Xe}$

- Blinding Xe phase
- Calculate weigthed phase difference: $\Phi^i_{Co} = \Phi^i_{Xe} - \frac{\gamma_{Xe}}{\gamma_{He}} \Phi^i_{He}$
- linear fit on the blockphases of each segment to obtain the Comagnetometer freqency ω_{Co}

Sample cells

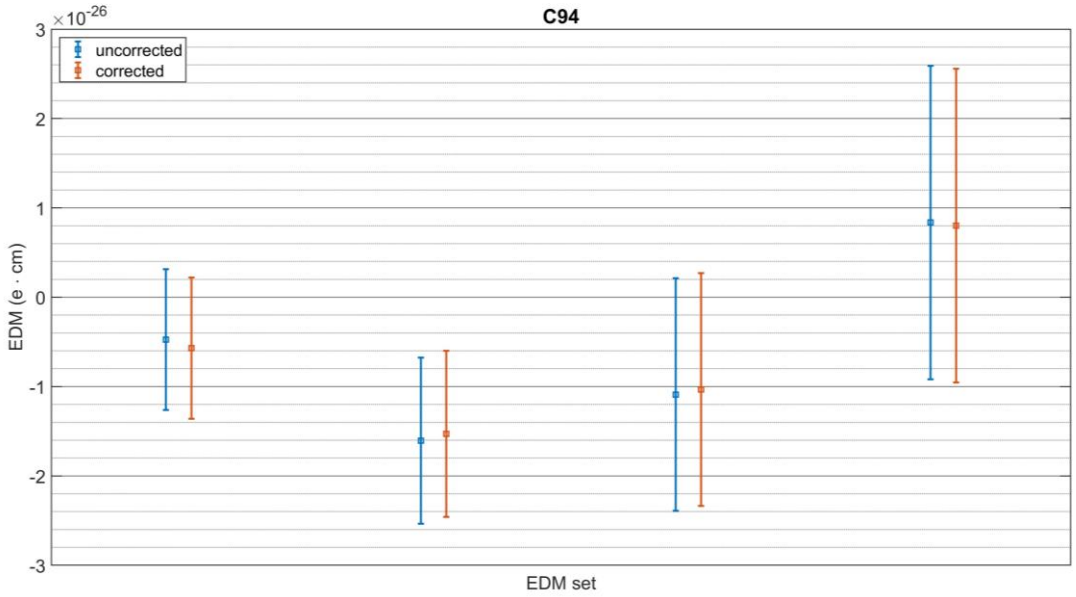
1 (l = 18.5 mm, d = 20.5mm)
2 (l = 21.8 mm, d = 20.4mm)

1 (l = 18.5 mm, d = 20.5mm)
2 (l = 21.8 mm, d = 20.4mm)
3 (l = 21.8 mm, d = 20.4mm)



	2017		2018	
	Observed HV correlated Max	EDM_{false} (e cm)	Observed HV correlated Max	EDM_{false} (e cm)
Comag Drift		$\mathbf{2.6 \cdot 10^{-28}}$		$\mathbf{4.0 \cdot 10^{-29}}$
	I_{Leak} = 97 pA	$\mathbf{1.2 \cdot 10^{-28}}$	I_{Leak} = 73 pA	$\mathbf{4.5 \cdot 10^{-31}}$
Leakage Current	Auxiliary measurements: frequency measured when wire was wrapped one full turn around the cell and I = ± 1μA applied -> result scaled with measured I_{leak}			
	I_{Charge} = 19 nA	$\mathbf{1.7 \cdot 10^{-29}}$	I_{Charge} = 19 nA	$\mathbf{1.2 \cdot 10^{-29}}$
Charging Current	Auxiliary measurements: frequency measured when I_{Charge} = 20μA applied (done by short circuit of cell and applying ±200V using 10MΩ resistor) -> result scaled with measured I_{charge}			

	2017		2018	
	Observed HV correlated Max	EDM_{false} (e cm)	Observed HV correlated Max	EDM_{false} (e cm)
Cell rotation	$\delta\theta \leq 5.5$ μrad/kV	**$4.2 \cdot 10^{-29}$**	$\delta\theta \leq 5.5$ μrad/kV	**$4.0 \cdot 10^{-29}$**
	Auxiliary measurements: cell movement determined by laser beam measurements, frequency dependence measured by rotating cell $\pm 5°$			
Cell translation	(-181.4 $\pm$ 124.4) nHz	**$2.6 \cdot 10^{-28}$**	(-82.5 $\pm$ 226.8) nHz	**$1.9 \cdot 10^{-28}$**
	Auxiliary measurements: measurements of single species He-3 and loop test with wire attached to electrode, imitating dipole			
$\lvert\vec{E}\rvert^2$ effects		**$1.2 \cdot 10^{-29}$**		**$2.2 \cdot 10^{-30}$**
$\lvert\vec{E}\rvert$ uncertainty		**$2.6 \cdot 10^{-29}$**		**$9.4 \cdot 10^{-30}$**
Geometric Phase		**$< 2 \cdot 10^{-31}$**		**$< 1 \cdot 10^{-31}$**
Total Error		**$3.9 \cdot 10^{-28}$**		**$2.0 \cdot 10^{-28}$**


C94
×10^-26
uncorrected
corrected
EDM (e · cm)
EDM set
3
2
1
0
-1
-2
-3