SEARCH FOR A

PERMANENT ELECTRIC DIPOLE MOMENT OF ^{129}Xe

WITH A He/Xe CLOCK-COMPARISON EXPERIMENT

SPIN Symposium 2018 - Ferrara

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September 11, 2018

MIXed collaboration

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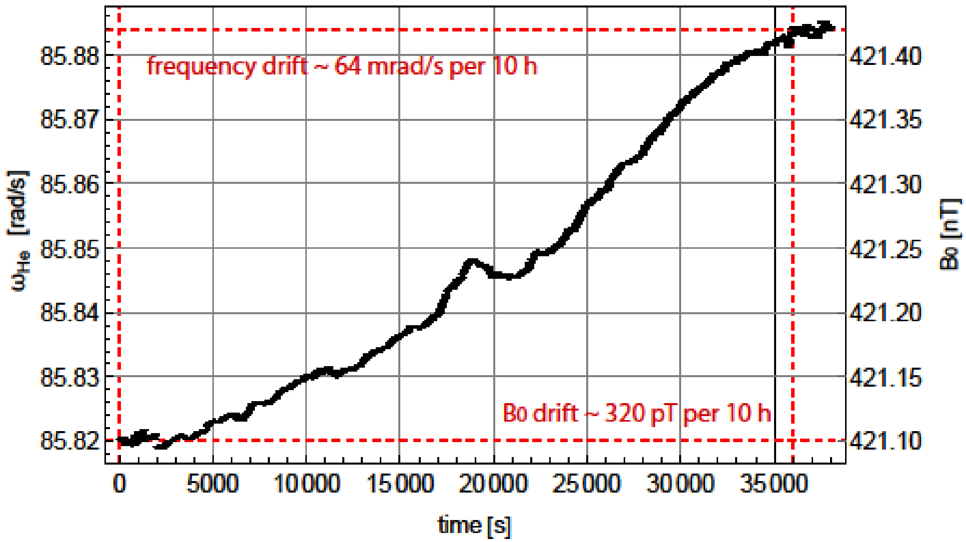
Precession frequency:

$$\omega^{\pm}{}_{Xe} = \gamma_{Xe} \cdot B \pm \frac{2}{\hbar} d_{Xe} \cdot E$$

$$B \equiv B(t)$$



He/Xe comagnetometry:

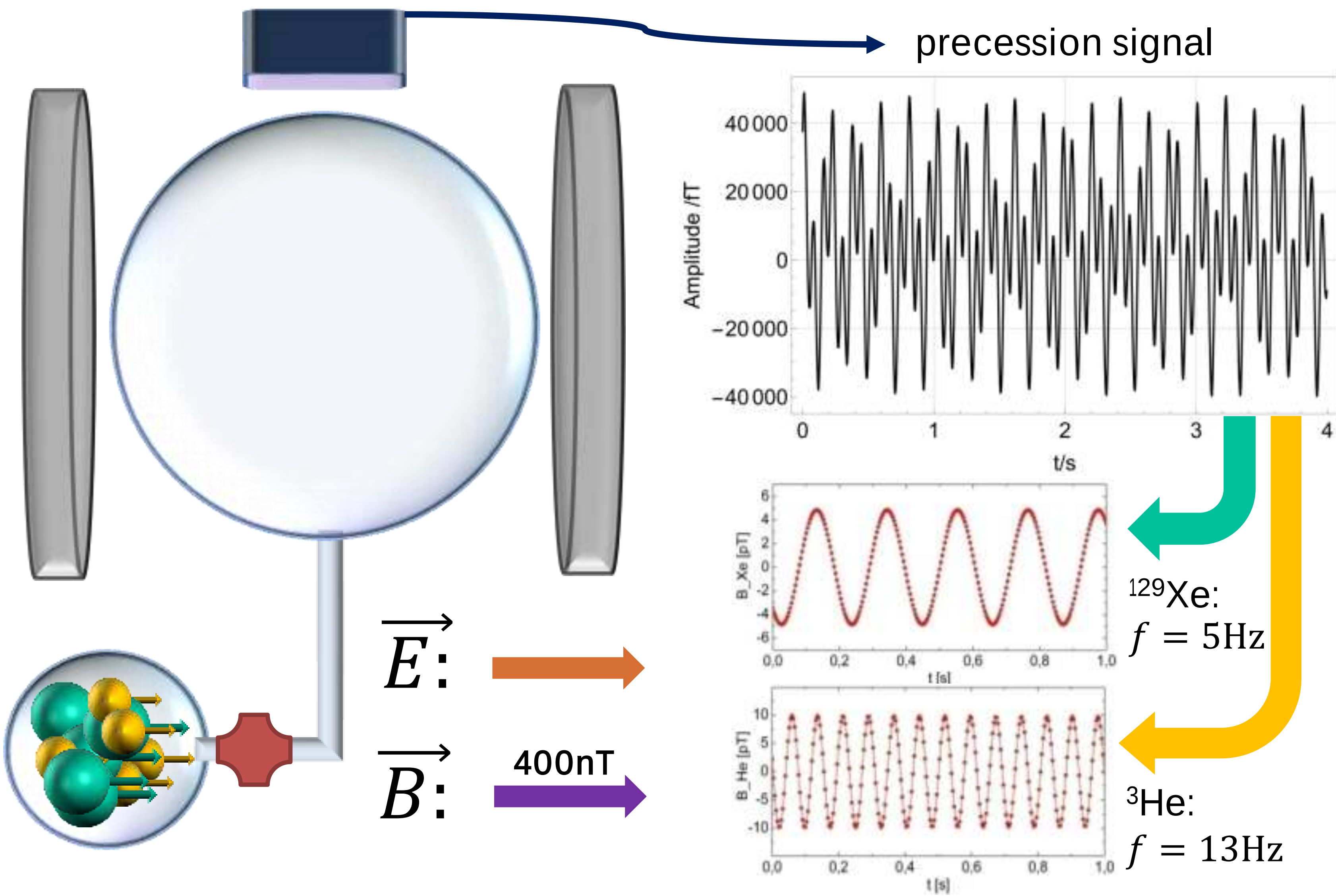
- co-located polarized ^{3}He and ^{129}Xe gas sample
  - ➢ normalization of the magnetic field with ^{3}He precession (magnetometer)

Weighted frequency difference:

$$\Delta\tilde{\omega}^{\pm} = \omega^{\pm}{}_{Xe} - \frac{\gamma_{Xe}}{\gamma_{He}} \omega^{\pm}{}_{He}$$

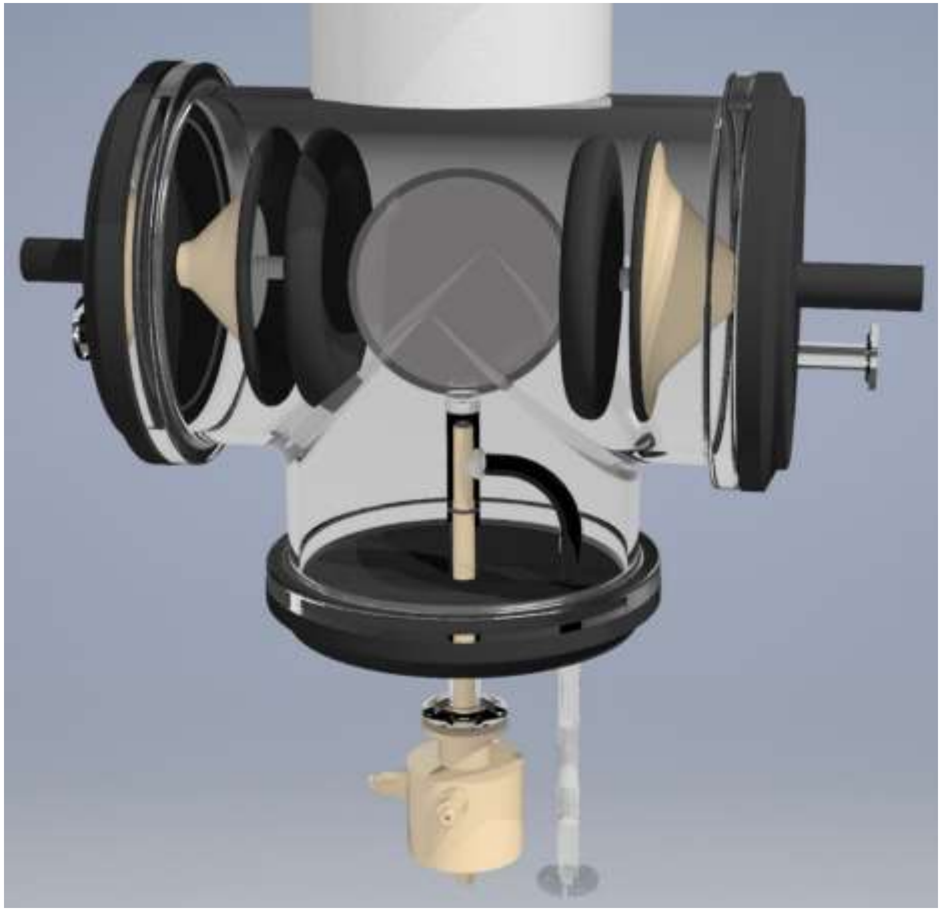
$$= \left[\gamma_{Xe} \cdot B \pm \frac{2}{\hbar} d_{Xe} \cdot E\right] - \frac{\gamma_{Xe}}{\gamma_{He}} \left\{\gamma_{He} \cdot B \pm \frac{2}{\hbar} d_{He} \cdot E\right\}$$

New observable: $\Delta\tilde{\omega}^{\pm} = \pm \frac{2}{\hbar} d_{Xe} \cdot E$ independent on Zeeman-term


precession signal
Amplitude /fT
40000
20000
0
−20000
−40000
0
1
2
3
4
t/s
$\overrightarrow{E}$:
$\overrightarrow{B}$:
400nT
B_Xe [pT]
t [s]
B_He [pT]
t [s]
^{129}Xe:
$f = 5\text{Hz}$
^{3}He:
$f = 13\text{Hz}$

EDM SETUP

low electromagnetic noise



- EDM cell (10cm)
- Valve + Filling line
- Sensor (SQUID gradiometer)
- Electrodes +- 4kV (0.8kV/cm)
- HV Feedthrough
- Conductive casing (SF6)

-> High SNR & T2*

Magnetic field system

two perpendicular fields

Gas periphery

storage, mixing, and transfer without polarization losses

Magnetically Shielded Room at Forschungszentrum Jülich

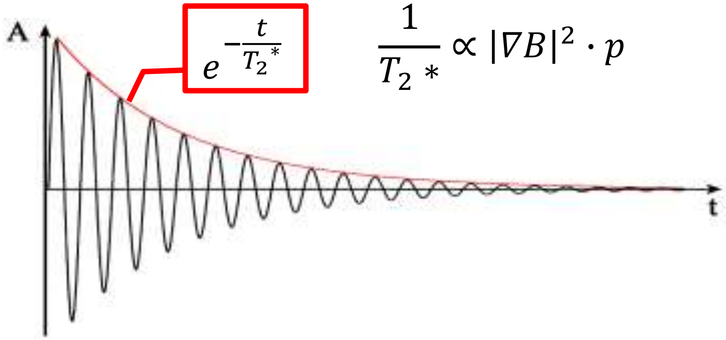
$$\frac{1}{T_2 *} \propto |\nabla B|^2 \cdot p$$

Magnetically Shielded Room at Forschungszentrum Jülich

- One layer aluminium (RF-shield) + two layers mu metal
- Shielding factor (static): $S \approx 300$
- Residual magnetic field: $B_{\mathrm{res}} \approx 20\mathrm{nT}$
- Magnetic field gradients: $\nabla B_{\mathrm{res}} \approx 200\mathrm{pT/cm}$

Characteristic time constant of coherent spin precession:

$$e^{-\frac{t}{T_2{}^*}}$$



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

∇B_{res} not sufficient for long coherent spin precession - $T_2^* \sim 1\ \mathrm{min}$

Initial initiative to reduce the magnetic field gradients: additional mu-metal cylinder

- Firmly installed inside the mu-metal cylinder
  - *limited spatial access*
- Magnetic holding field ($B \approx 400\text{nT}$)
  - *has to be as homogeneous as possible*

- Two perpendicular magnetic fields
  - *to initiate spin flip (field rotation)*

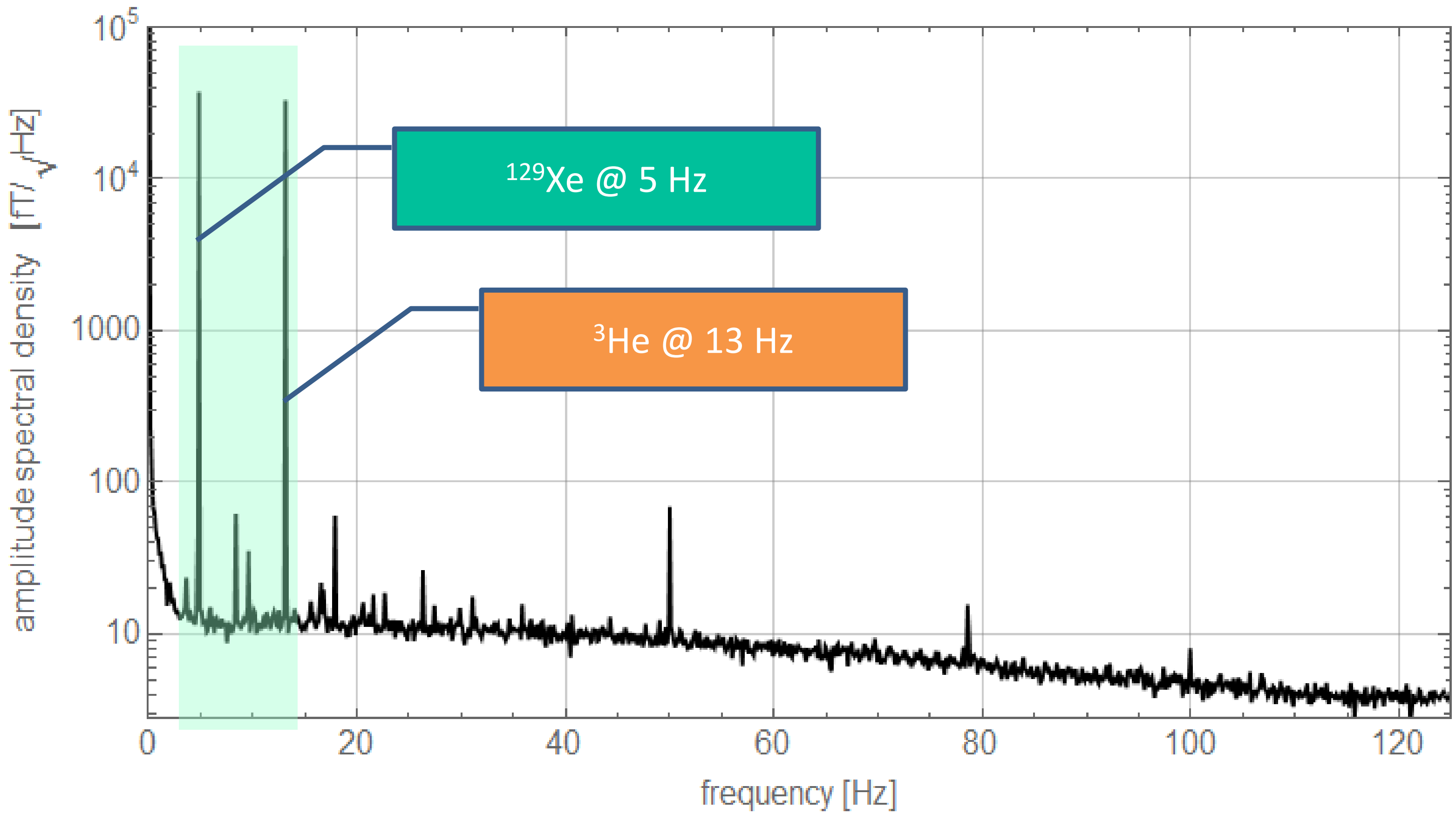
→ Cosine-Theta-Coil + Solenoid

Magnetic field gradients actively reduced to $\nabla B \approx 10\ \text{pT/cm}$

Achievable spin coherence time ($p = 100\ \text{mbar}$):

$T_2^*(^{129}\text{Xe}) \approx 3\ \text{h}$ -> $T = 3 \cdot T_2^* \approx 9\ \text{h}$

in Magnetically Shielded Room (MSR) at Forschungszentrum Jülich



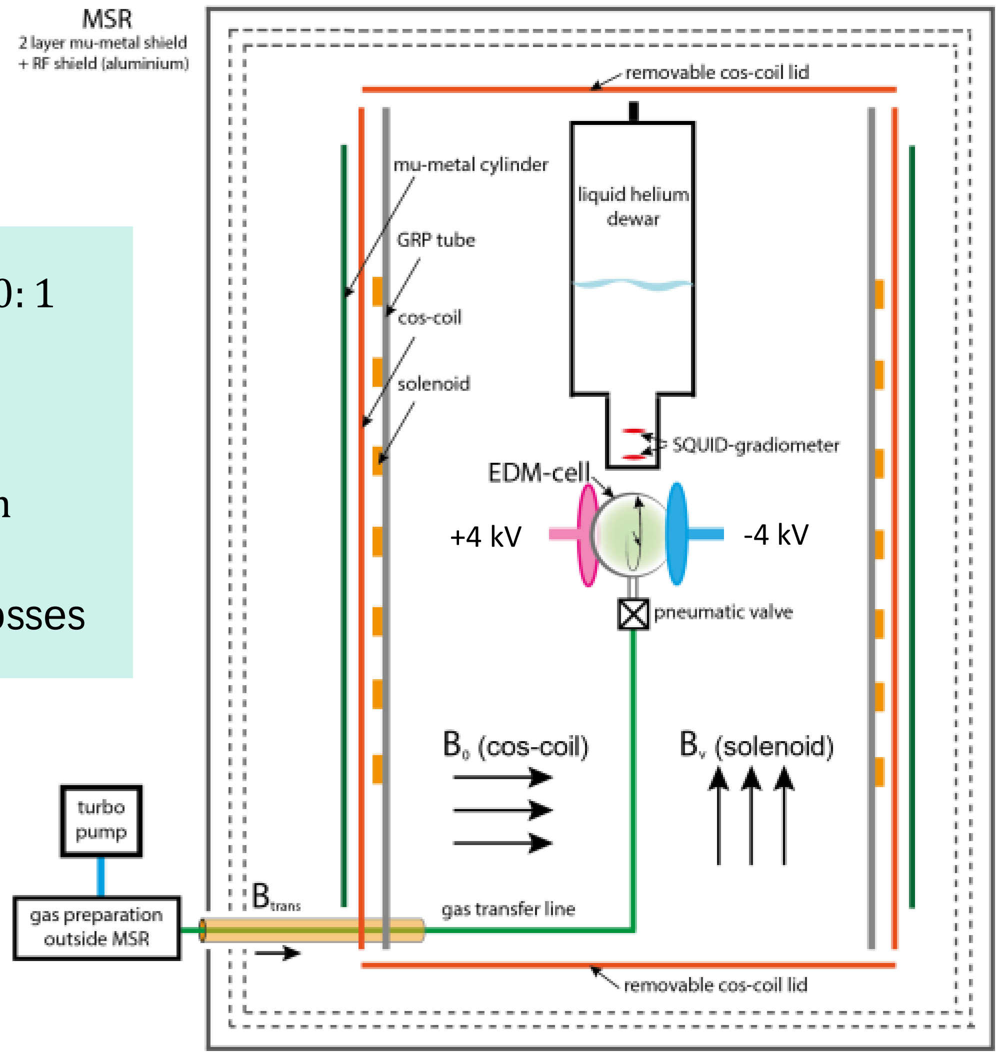
Achievements so far:

SQUID system + MSR $\rightarrow SNR \approx 10000:1$

EDM cell + B-field $\rightarrow T \approx 9\,\mathrm{h}$

HV + grounded casing $\rightarrow E = 0.8\,\mathrm{kV/cm}$

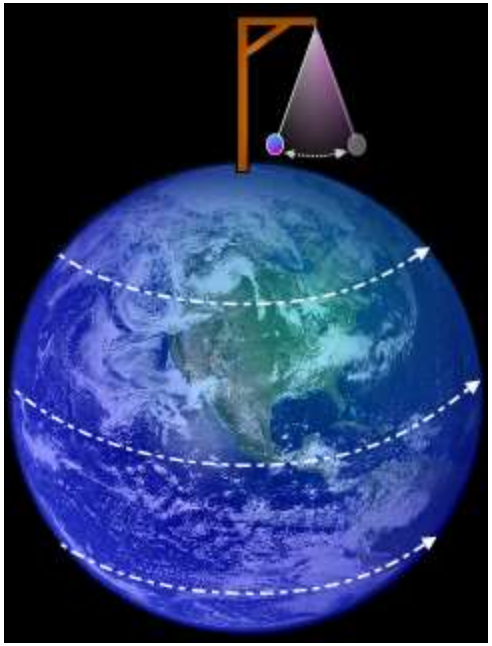
gas mixing & transfer w/o polarization losses



Weighted phase difference: $$\Delta\widetilde{\Phi}_{EDM}(t) = \int \Delta\widetilde{\omega}_{EDM}(t)\,dt \overset{d=0}{=} const.$$

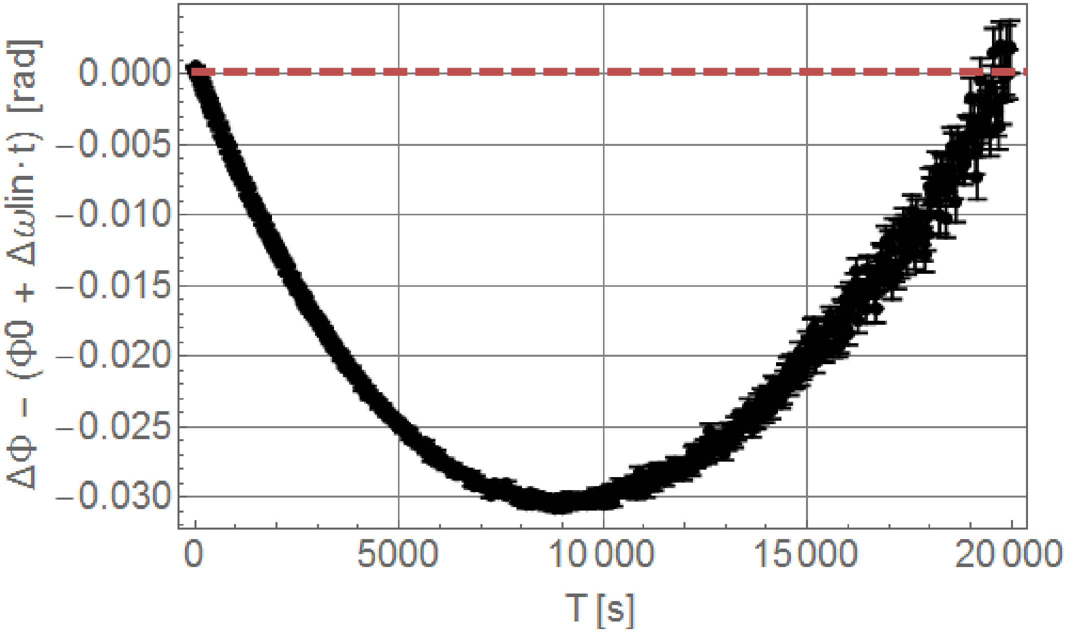
$$\Delta\widetilde{\Phi}(t) = \boxed{\Phi_0 + \Delta\omega_{lin}\cdot t + E_{He}\cdot e^{-\frac{t}{T_2{}^*(He)}} + E_{Xe}\cdot e^{-\frac{t}{T_2{}^*(Xe)}} + F_{He}\cdot e^{-\frac{2t}{T_2{}^*(He)}} + F_{Xe}\cdot e^{-\frac{2t}{T_2{}^*(Xe)}}}$$

deterministic phase shifts



$$\Omega_{\oplus} = \frac{2\pi}{24\ \mathrm{h}} = 7.3\cdot 10^{-5}\,\frac{\mathrm{rad}}{\mathrm{s}}$$

Bloch-Siegert-shift: He/He, Xe/Xe and He/Xe, Xe/He



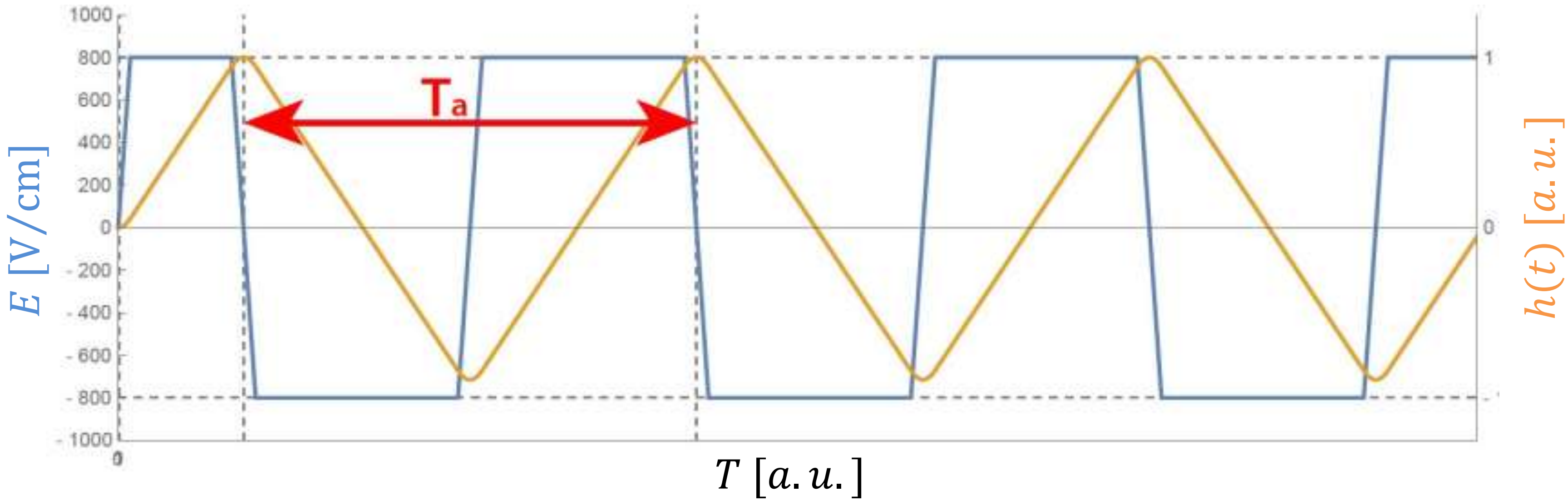
Weighted phase difference: $$\Delta\tilde{\Phi}_{EDM}(t) = \int \Delta\tilde{\omega}_{EDM}(t)\,dt = \int \frac{2}{\hbar} d \cdot E(t)\,dt$$

$$\Delta\tilde{\Phi}(t) = \Phi_0 + \Delta\omega_{lin} \cdot t + E_{He} \cdot e^{-\frac{t}{T_2{}^*(He)}} + E_{Xe} \cdot e^{-\frac{t}{T_2{}^*(Xe)}} + F_{He} \cdot e^{-\frac{2t}{T_2{}^*(He)}} + F_{Xe} \cdot e^{-\frac{2t}{T_2{}^*(Xe)}} + d_{Xe} \cdot h(t)$$

deterministic phase shifts

EDM phase

BUT: $h(t)$ has to be chosen to be uncorrelated with deterministic phase shifts!!!



Electric field reversed every few hours, depending on $T_2{}^*$ (usually $T_a = T_2{}^* = 3\ \mathrm{h}$)

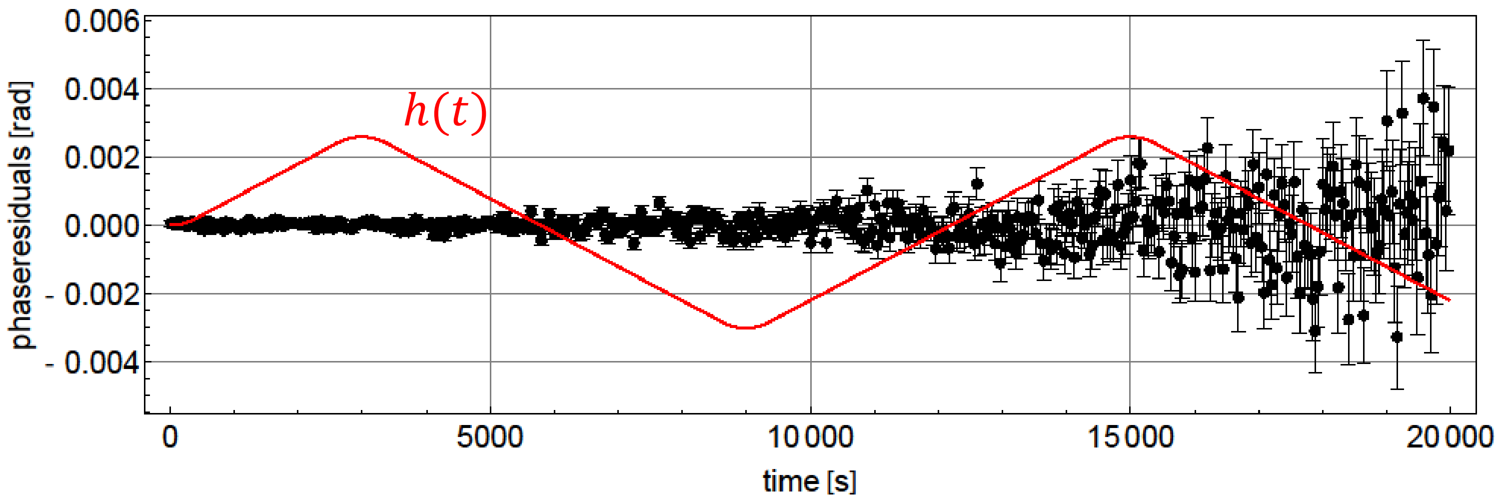
Fit-residuals of the weighted phase difference:

$$\Delta\tilde{\Phi}_{res}(t) = \Delta\tilde{\Phi}(t) - \left[\Phi_0 + \Delta\omega_{lin}\cdot t + E_{He}\cdot e^{-\frac{t}{T_2{}^*(He)}} + E_{Xe}\cdot e^{-\frac{t}{T_2{}^*(Xe)}} + F_{He}\cdot e^{-\frac{2t}{T_2{}^*(He)}} + F_{Xe}\cdot e^{-\frac{2t}{T_2{}^*(Xe)}}\right]$$

measured wpd

deterministic phase shifts

EDM run #2 - July 2017



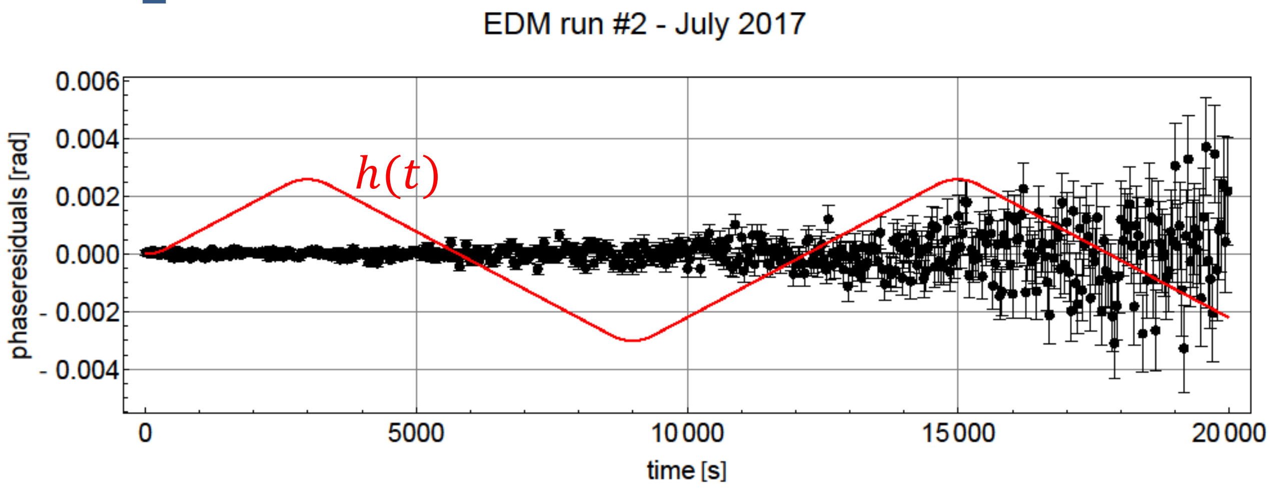
Phase residuals are statistically distributed around zero

possible Xe-EDM (EDM phase modulation) smaller than statistical sensitivity → determinate upper limit

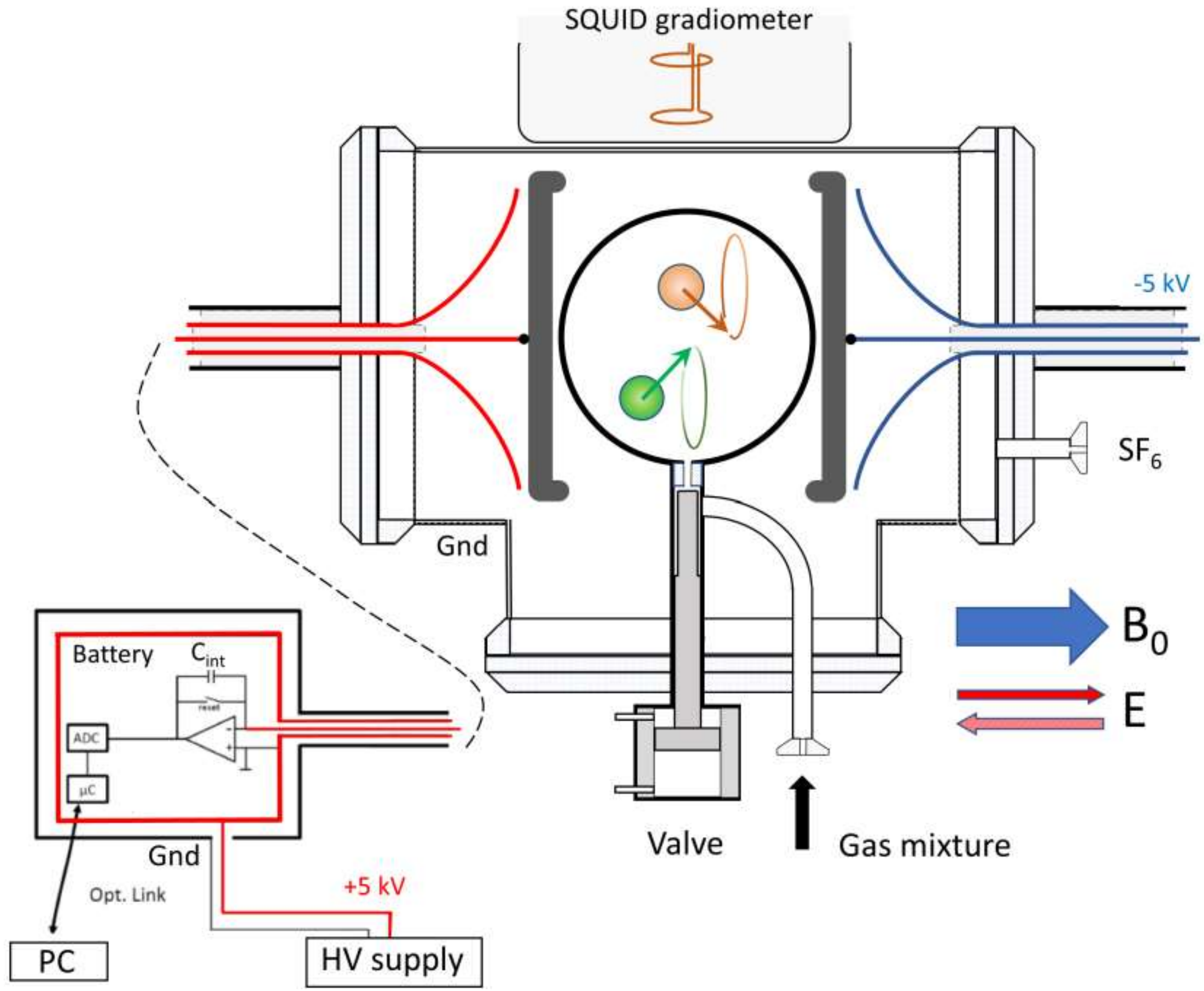
SYSTEMATICS (FALSE-EDM)

Fit-residuals of the weighted phase difference:

$$\Delta\tilde{\Phi}_{res}(t) = \Delta\tilde{\Phi}(t) - \left[\Phi_0 + \Delta\omega_{lin}\cdot t + E_{He}\cdot e^{-\frac{t}{T_2{}^*(He)}} + E_{Xe}\cdot e^{-\frac{t}{T_2{}^*(Xe)}} + F_{He}\cdot e^{-\frac{2t}{T_2{}^*(He)}} + F_{Xe}\cdot e^{-\frac{2t}{T_2{}^*(Xe)}}\right]$$



origin	false EDM
Leakage currents	$-1.9\cdot 10^{-30}e\text{cm}$
Charging currents	$-6.7\cdot 10^{-33}e\text{cm}$
Geometric phase	$-0.5\cdot 10^{-29}e\text{cm}$
Motional magnetic field	$-6.2\cdot 10^{-43}e\text{cm}$



SQUID gradiometer
-5 kV
SF6
Gnd
B0
E
Battery
Cint
ADC
μC
Gnd
Opt. Link
+5 kV
Valve
Gas mixture
PC
HV supply

- Electric current I_{leak} in or close to the EDM cell causes additional magnetic field B_{leak}

Comagnetometry helps out...

BUT: Corresponding magnetic field gradients change the precession frequency differently for each species due to different centers of mass!

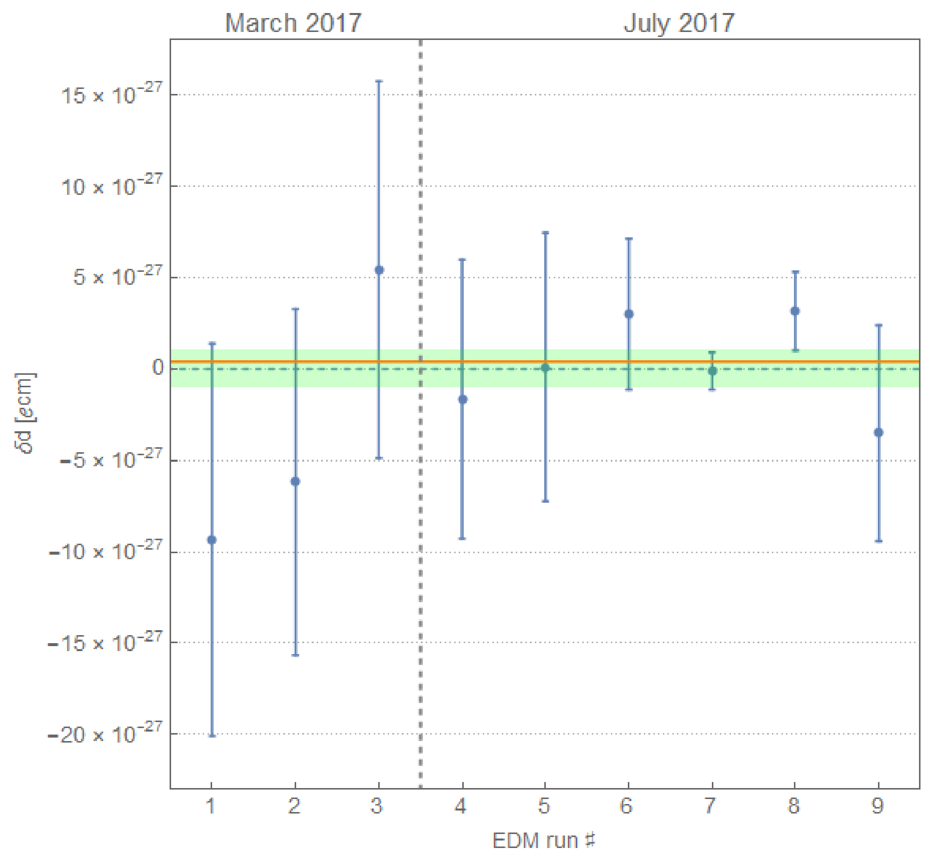
$$B_{leak}(r) = \mu_0 \cdot \frac{I_{leak}}{2\pi \cdot r} \qquad I_{leak} \approx 10\mathrm{pA} \quad \rightarrow \quad \nabla B_{leak} = \frac{dB_{leak}(r)}{dr} < 5 \cdot 10^{-3}\mathrm{pT/cm}$$

correlation to the electric field -> false-EDM

$\nabla d_{leak} < 2 \cdot 10^{-30} e\mathrm{cm}$ conservative estimation!!

Preliminary fit results (incl. statistical error) from nine individual measurement runs in 2017

	EDM run	$d_{Xe}[10^{-27} ecm]$
march	# 1	-9.35 ± 10.74
march	# 2	-6.19 ± 9.47
march	# 3	5.43 ± 10.31
july	# 4	-1.66 ± 7.64
july	# 5	1.11 ± 7.35
july	# 6	2.99 ± 4.13
july	# 7	-0.11 ± 1.02
july	# 8	3.17 ± 2.15
july	# 9	-3.51 ± 5.91



Weighted mean (incl. systematic error):

$$d_{Xe} = \left(-4.7 \pm 6.4_{stat} \pm 0.07_{sys}\right) \cdot 10^{-28} ecm$$

The Xe-EDM experiment was (is) a great success!

The experimental setup works the way we planned:

SQUID + MSR: $SNR \sim 10000:1$ mu-metal cylinder & gradient coils: $\mathrm{T} \sim 9\ \mathrm{h}$

With first measurements (~ one day effective measurement time):

Former upper limit (2001): $|d_{Xe}| < 7.3 \cdot 10^{-27} e\mathrm{cm}\ (95\%\ \mathrm{CL})$ M. A. Rosenberry and T. E. Chupp Phys. Rev. Lett. 86, 22 – (2001)

New upper limit (preliminary): $|d_{Xe}| < 1.5 \cdot 10^{-27} e\mathrm{cm}\ (95\%\ \mathrm{CL})$

…will be published soon!

Follow-up measurements in MSR in Jülich...

New EDM cell with higher storage time

New HV supply

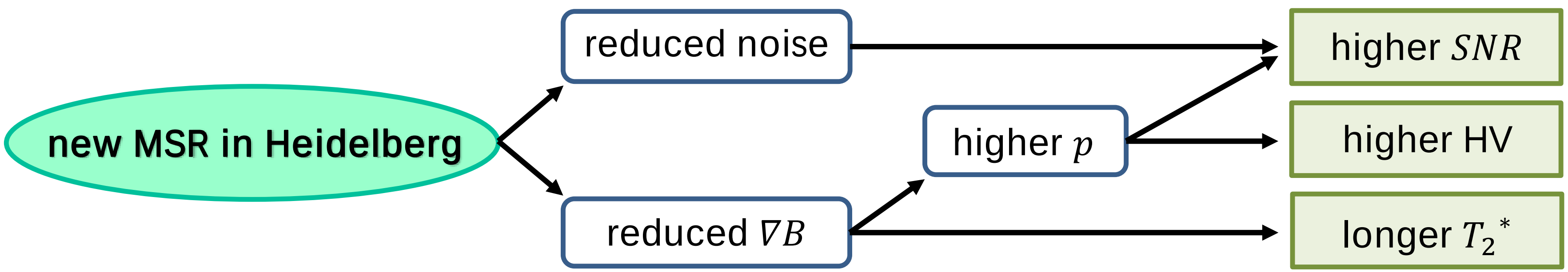
Automation

...but *how can we improve big time?*

$$\delta d_{Xe} \approx 4 \cdot 10^{-28} ecm \,/\, \mathrm{day} \quad \leftrightarrow \quad \delta d_{Hg} \approx 4 \cdot 10^{-29} ecm \,/\, \mathrm{day}$$

Reminder:

$$\sigma_d \propto \left(\varepsilon \cdot E \cdot SNR \cdot T^{3/2}\right)^{-1} \qquad \frac{1}{T_2*} \propto |\nabla B|^2 \cdot p$$



serious competition with ^{199}Hg-EDM in sight...

Thank you for your attention.

MIXed

Measurement and Investigation of the Xenon-129 electric dipole moment