^{129}Xe Electric Dipole Moment
Progress and prospects

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1. ^{129}Xe Motivations
2. Brief history
3. HeXe EDM
4. Future prospects

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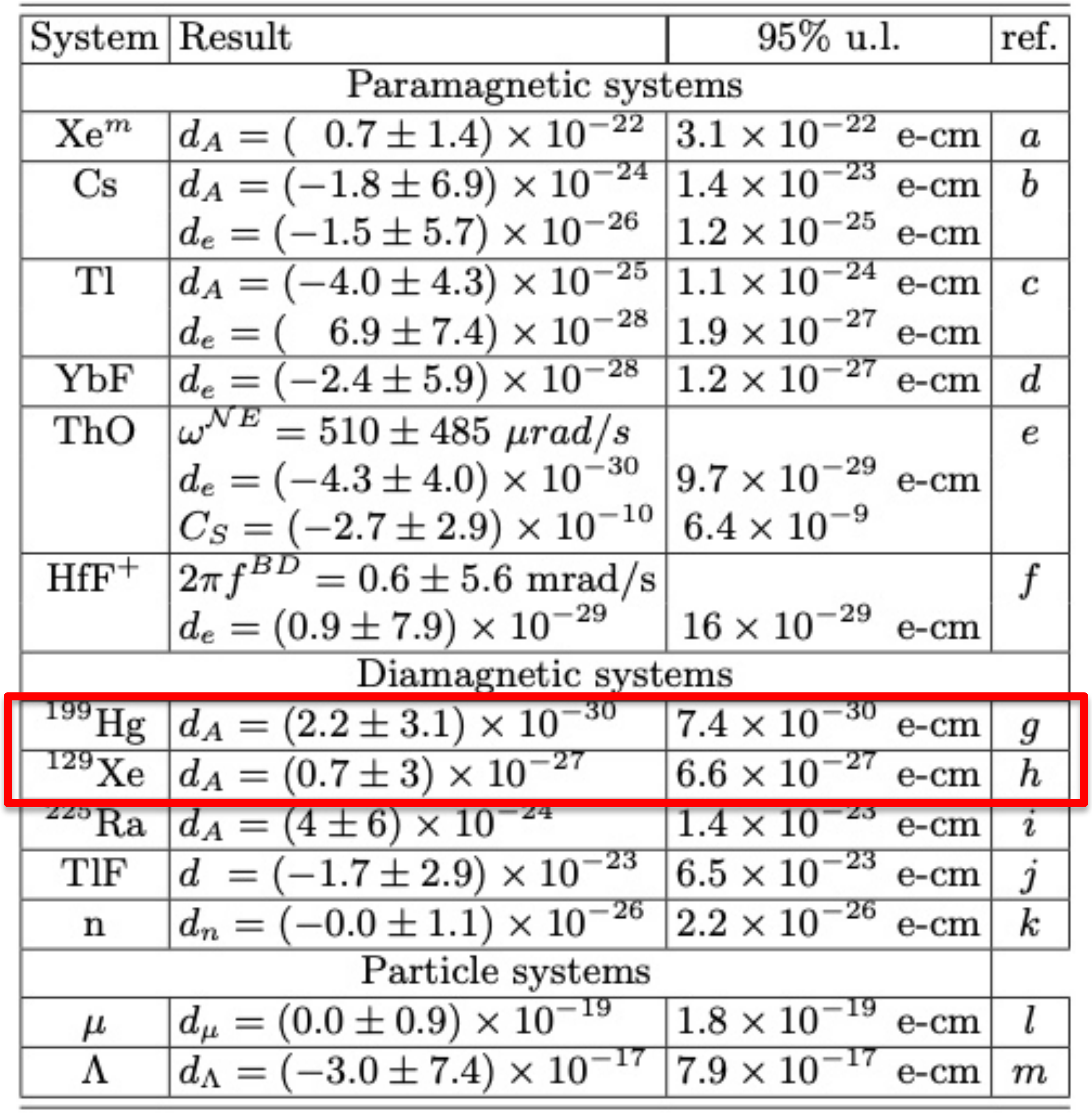
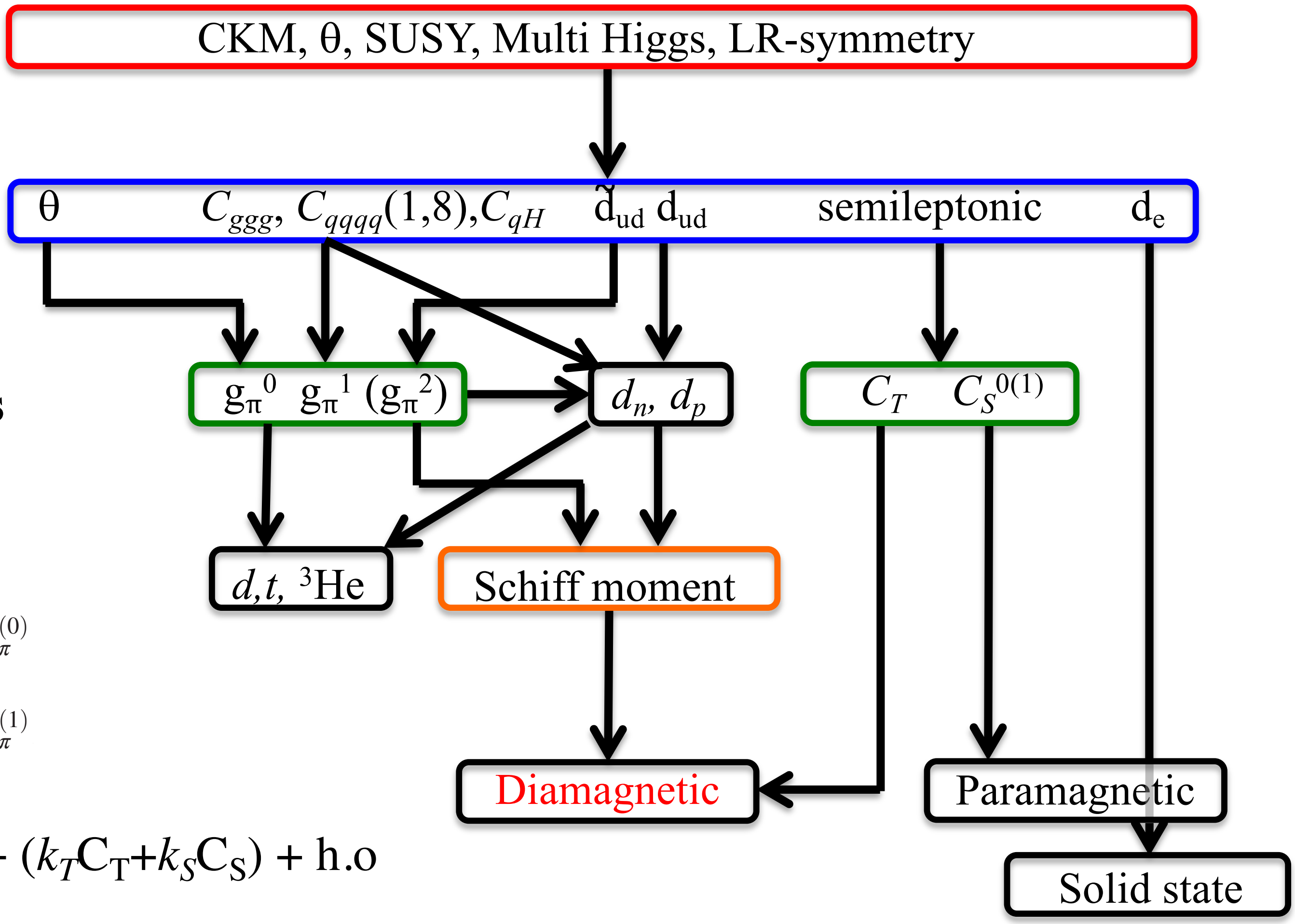
EDM results



System	Result	95% u.l.	ref.
Paramagnetic systems			
Xe^m	$d_A = (\ \ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22} e-cm	a
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$ $d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.4×10^{-23} e-cm 1.2×10^{-25} e-cm	b
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$ $d_e = (\ \ 6.9 \pm 7.4) \times 10^{-28}$	1.1×10^{-24} e-cm 1.9×10^{-27} e-cm	c
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27} e-cm	d
ThO	$\omega^{NE} = 510 \pm 485\ \mu rad/s$ $d_e = (-4.3 \pm 4.0) \times 10^{-30}$ $C_S = (-2.7 \pm 2.9) \times 10^{-10}$	 9.7×10^{-29} e-cm 6.4×10^{-9}	e
HfF^+	$2\pi f^{BD} = 0.6 \pm 5.6$ mrad/s $d_e = (0.9 \pm 7.9) \times 10^{-29}$	 16×10^{-29} e-cm	f
Diamagnetic systems			
$^{199}\mathrm{Hg}$	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30} e-cm	g
$^{129}\mathrm{Xe}$	$d_A = (0.7 \pm 3) \times 10^{-27}$	6.6×10^{-27} e-cm	h
$^{225}\mathrm{Ra}$	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23} e-cm	i
TlF	$d\ = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23} e-cm	j
n	$d_n = (-0.0 \pm 1.1) \times 10^{-26}$	2.2×10^{-26} e-cm	k
Particle systems			
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19} e-cm	l
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	7.9×10^{-17} e-cm	m

EDMs arise from many sources



Fundamental theory

Wilson coefficients (13)

$$\mathcal{L}^{\rm eff}_{\rm CPV} = \sum_{k,d} \alpha_k^{(d)} \left(\frac{1}{\Lambda}\right)^{d-4} \mathcal{O}_k^{(d)}$$

Low energy parameters

$$\bar g^0_{CP} \approx 0.027\, \theta_{QCD}$$

Nucleus level

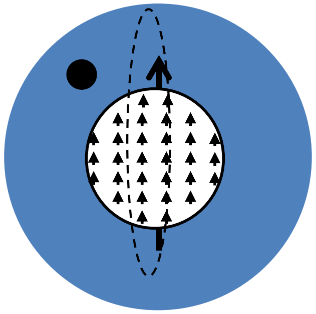
$$S = s_N \bar d_N^{sr} + \left[\frac{m_N g_A}{F_\pi} a_0 + s_N \alpha_{n\bar g_\pi^{(0)}}\right] \bar g_\pi^{(0)} + \left[\frac{m_N g_A}{F_\pi} a_1 + s_N \alpha_{n\bar g_\pi^{(1)}}\right] \bar g_\pi^{(1)}$$

Atom/molecule level

$$d_A = \eta_e d_e + \kappa_S S(\theta_{QCD}, g_\pi) + (k_T C_T + k_S C_S) + \text{h.o}$$

Diamagnetic: Xe, Hg, TlF

$\vec{E} \propto \vec{J}$

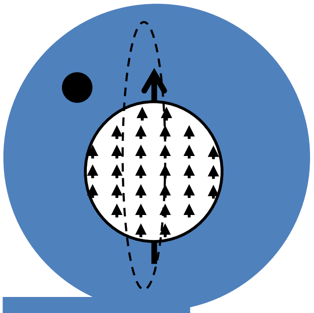


$$\vec{S} = \frac{1}{10}\langle r^2 \vec{r}_p \rangle - \frac{1}{6} Z \langle r^2 \rangle \langle \vec{r}_p \rangle$$ Schiff moment

Rev. Mod. Phys. v. 91 015001 (2019)

A global analysis

TC&MJR Musolf: PHYSICAL REVIEW C **91**, 035502 (2015)



$\vec{E} \propto \vec{J}$

Results

	d_0^{sr}	d_1^{sr}	$\mathbf{C_T}$	$g_\pi^{\ 0}$	$g_\pi^{\ 1}$
neutron	1	-1			
Xe, Hg, TlF, Ra			X	X	X

$$d_A = \alpha_{C_T} C_T + \kappa_S (a_0 \bar{g}_\pi^0 + a_1 \bar{g}_\pi^1 + \cancel{a_2 \bar{g}_\pi^2})$$

$$d_n = \bar{d}_n^{\rm sr} - \frac{e g_A \bar{g}_\pi^{(0)}}{8\pi^2 F_\pi} \left\{ \ln \frac{m_\pi^2}{m_N^2} - \frac{\pi m_\pi}{2 m_N} + \frac{\bar{g}_\pi^{(1)}}{4\bar{g}_\pi^{(0)}} (\kappa_1 - \kappa_0) \frac{m_\pi^2}{m_N^2} \ln \frac{m_\pi^2}{m_N^2} \right\}$$

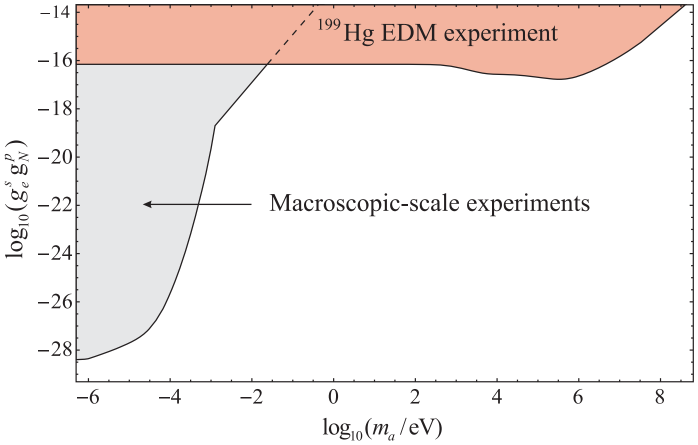
	$\bar{d}_n^{\rm sr}$ (e cm)	$\bar{g}_\pi^{(0)}$	$\bar{g}_\pi^{(1)}$	$C_T^{(0)}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = +1.6 \times 10^{-17}$	$(-4.8\text{-}9.8) \times 10^{-23}$	$(-6.6\text{-}3.2) \times 10^{-9}$	$(-1.0\text{-}0.5) \times 10^{-9}$	$(-3.5\text{-}1.6) \times 10^{-7}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = 0$	$(-4.3\text{-}3.4) \times 10^{-23}$	$(-2.3\text{-}2.9) \times 10^{-9}$	$(-0.6\text{-}1.3) \times 10^{-9}$	$(-3.2\text{-}4.0) \times 10^{-7}$
Range from best values with $\alpha_{g_\pi^1}(\mathrm{Hg}) = -4.9 \times 10^{-17}$	$(-9.3\text{-}2.6) \times 10^{-23}$	$(-1.8\text{-}6.3) \times 10^{-9}$	$(-1.2\text{-}0.4) \times 10^{-9}$	$(-11\text{-}3.8) \times 10^{-7}$
Range from full variation of α_{ij}	$(-12\text{-}12) \times 10^{-23}$	$(-7.9\text{-}7.8) \times 10^{-9}$	$(-1.3\text{-}1.1) \times 10^{-9}$	$(-6.6\text{-}4.6) \times 10^{-7}$
Upper limits (95% c.l.)	2.4×10^{-22}	1.5×10^{-8}	2.4×10^{-9}	1.1×10^{-6}

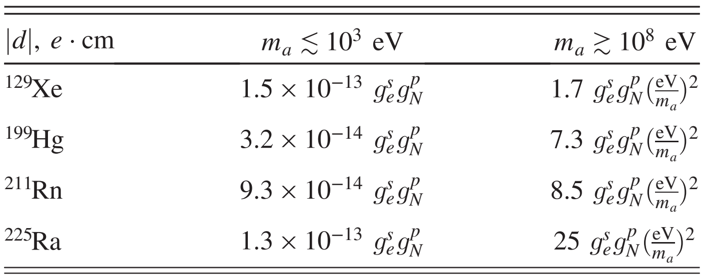
Imporoving Xe (Ra, TLF) improves fit

Axion-like contributions

New constraints on axion-mediated *P*,*T*-violating interaction from electric dipole moments of diamagnetic atoms

V. A. Dzuba,[1] V. V. Flambaum,[1] I. B. Samsonov,[1,2] and Y. V. Stadnik[3]





$\lvert d\rvert$, $e \cdot \mathrm{cm}$	$m_a \lesssim 10^3$ eV	$m_a \gtrsim 10^8$ eV
^{129}Xe	$1.5 \times 10^{-13}\ g_e^s g_N^p$	$1.7\ g_e^s g_N^p (\frac{\mathrm{eV}}{m_a})^2$
^{199}Hg	$3.2 \times 10^{-14}\ g_e^s g_N^p$	$7.3\ g_e^s g_N^p (\frac{\mathrm{eV}}{m_a})^2$
^{211}Rn	$9.3 \times 10^{-14}\ g_e^s g_N^p$	$8.5\ g_e^s g_N^p (\frac{\mathrm{eV}}{m_a})^2$
^{225}Ra	$1.3 \times 10^{-13}\ g_e^s g_N^p$	$25\ g_e^s g_N^p (\frac{\mathrm{eV}}{m_a})^2$

Summary of ^{129}Xe Motivations

- Diamagnetic – nuclear spin system
- Alternative to ^{199}Hg for both theory and experiment
  - ^{199}Hg Theory is difficult/ambiguous
- Discovery potential: not ruled out (model INdependent)
- Can be more sensitive to axions (Stednik&Flambaum)
- Xe comagnetometer for nEDM (e.g. TUCAN)

Diamagnetic systems

System	$\kappa_S = \frac{d}{S}$ (cm/fm^3)	$a_0 = \frac{S}{13.5\bar{g}_\pi^{(0)}}$ (e-fm^3)	$a_1 = \frac{S}{13.5\bar{g}_\pi^{(1)}}$ (e-fm^3)	$a_2 = \frac{S}{13.5\bar{g}^{(}_{\pi}2)}$ (e-fm^3)	s_N (fm^2)
^{129}Xe	0.27×10^{-17} (0.27-0.38)	$-0.008(-0.005$-$(-0.05))$	$-0.006(-0.003$-$(-0.05))$	$-0.009(-0.005$-$(-0.1))$	0.63
^{199}Hg	-2.8×10^{-17}(-4.0-(-2.8))	0.01 (0.005-0.05)	±0.02 (-0.03-0.09)	0.02(0.01-0.06)	1.895 ± 0.035
^{225}Ra	-8.5×10^{-17} (-8.5-(-6.8))	-1.5 (-6-(-1))	+6.0 (4-24)	-4.0 (-15-(-3))	
TlF	-7.4×10^{-14}	-0.0124	0.1612	-0.0248	0.62

Brief history

- 1963: Schiff's theorem/violations

  Motivated by Fairbank's ^{3}He idea
- 1980/4: Ramsey's ^{3}He comagnetometer proposal (nEDM)
- 1984: Forstons/Vold: single species ^{129}Xe
- 1990: Oteiza – first He-Xe comagnetometer
- 2001: Rosenberry – dual He-Xe maser $d_{Xe} < x10^{-27}$ e-cm
- 2014: HeXe @TUM – PTB*

Other efforts

- Romalis – LXe
- Active maser: Tokyo
- TRIUMF Xe (comagnetometer)
- Xe-129/He-3 MIXed (Mainz/Heidelberg/Juelich)

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EDM Measurements

$$H = \boxed{-\vec{\mu}\cdot \vec{B}} - \vec{d}\cdot \vec{E}$$

- Strong electric filed
- Large signal needs POLARIZATION (usually optical pumping)
- MEASURE FREQUENCIES $\propto \frac{1}{\tau^{3/2}}$ Per HV dwell
- **AND MAGNETIC FIELDS - Comagnetometry**

$$\begin{tikzcd}
 & \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{\sqrt{\varphi_n \tau}} \\
\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N} \arrow[ur] \arrow[dr] & \\
 & \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{\sqrt{N}}
\end{tikzcd}$$

Phase-noise limit

Count-rate limit
(P=A=1)

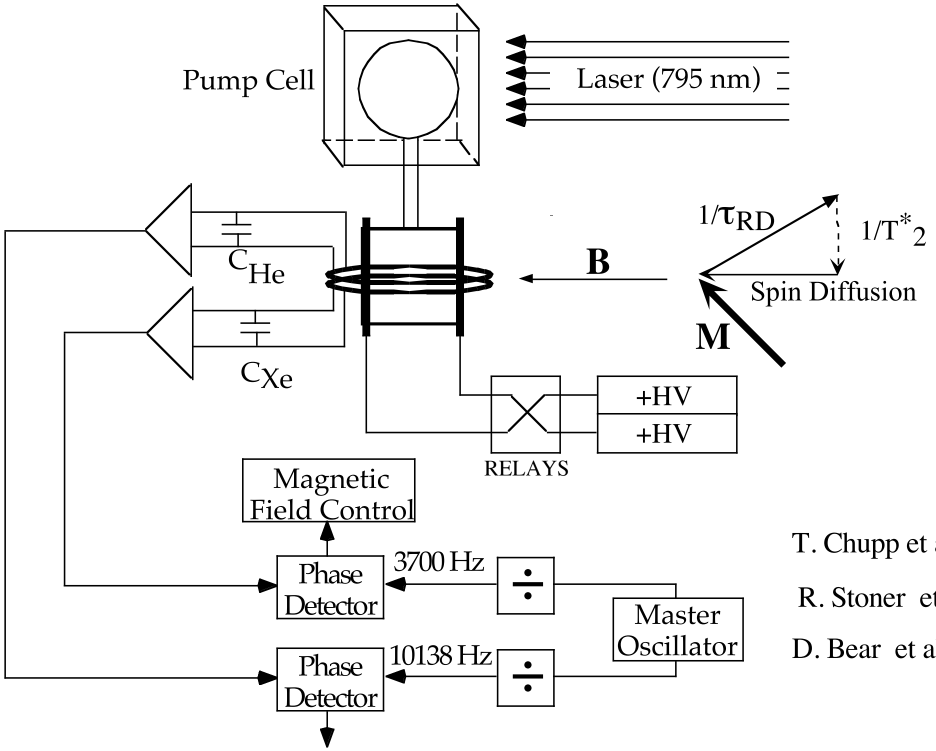
Measurement time
(HV dwell)

VOLUME 86, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 2001

Atomic Electric Dipole Moment Measurement Using Spin Exchange Pumped Masers of ^{129}Xe and ^{3}He

M. A. Rosenberry* and T. E. Chupp
University of Michigan, Ann Arbor, Michigan 48109
(Received 1 August 2000)

- Two species – comagnetometry
- Continuous spin precession
- HV dwell time limited by drifts



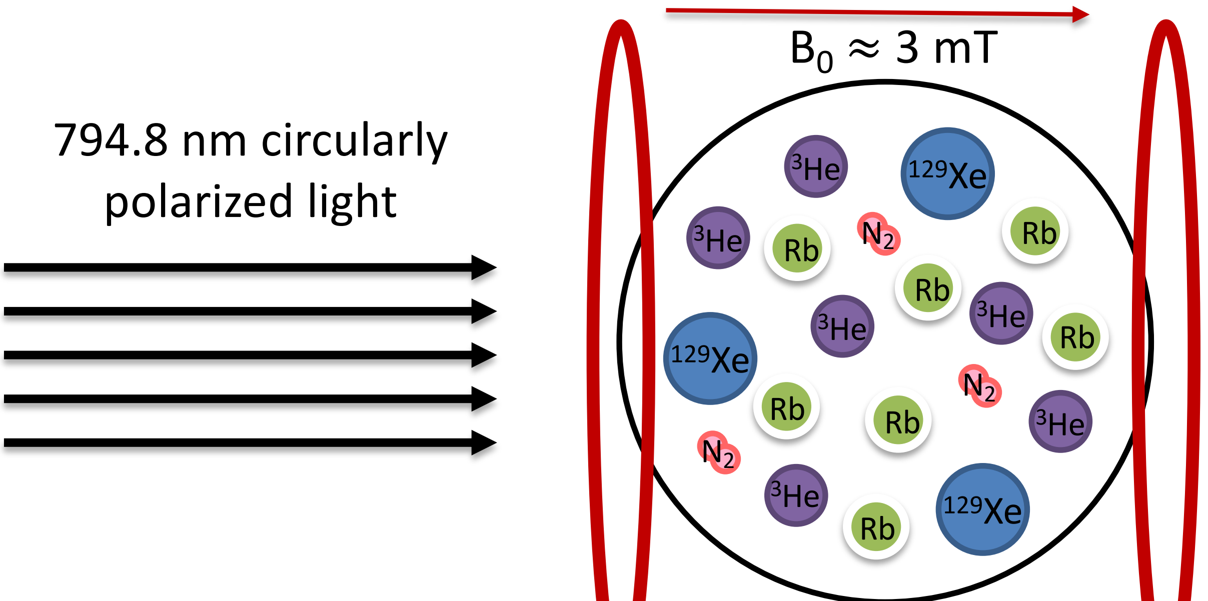
T. Chupp et al. PRL 72, p 2363 (1994)

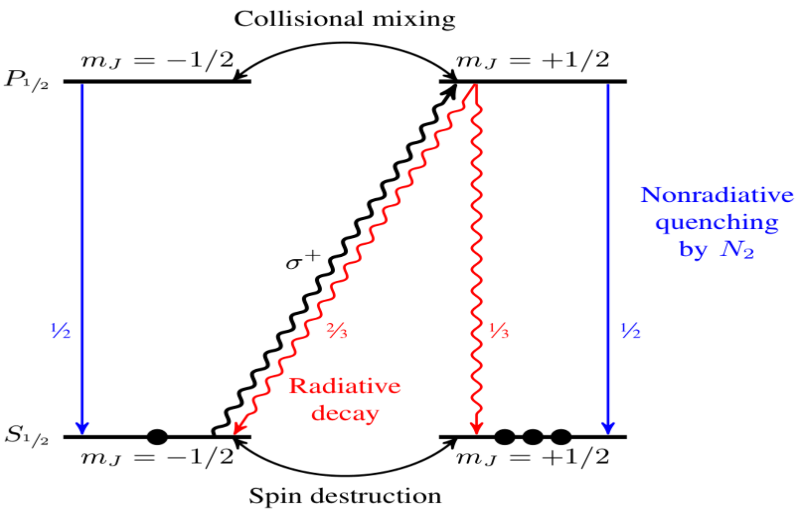
R. Stoner et al. PRL 77, p 3971 (1996)

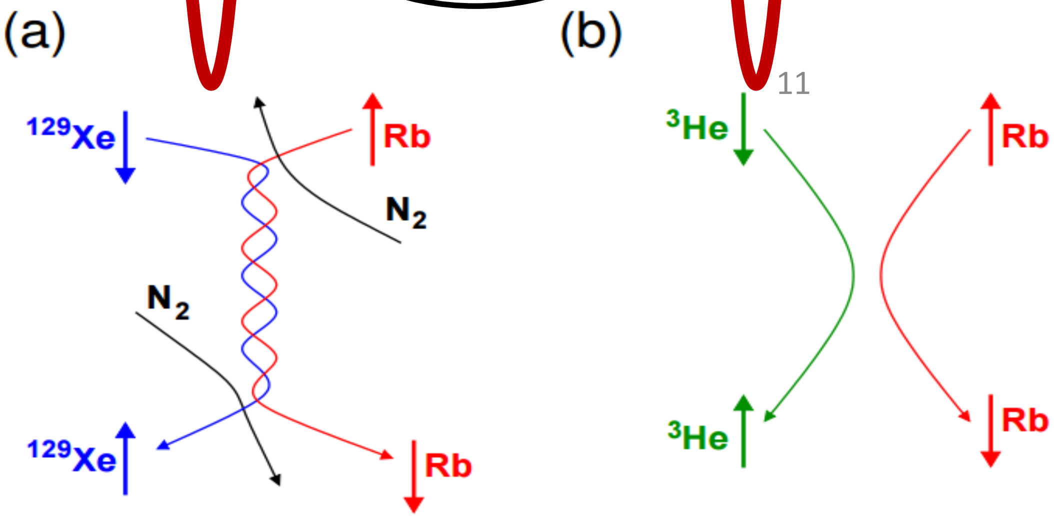
D. Bear et al. PRA 57, p 5006 (1998)

$d_{Xe}=(0.7\pm3.3)\times10^{-27}$ e-cm ($<6.6\times10^{-27}$ e-cm 95%)

Spin-exchange optical pumping (SEOP)


794.8 nm circularly polarized light





M. A. Bouchiat, T. R. Carver, and C. M. Varnum. Phys. Rev. Lett., 5:373 (1960).

Happer et al.; TC et al.; Walker et al.

^{129}Xe EDM with ^{3}He Comagnetometry

HeXe

N. Sachdeva,[1,*] I. Fan,[2] E. Babcock,[3] M. Burghoff,[2] T. E. Chupp,[1] S. Degenkolb,[1,4] P. Fierlinger,[5] E. Kraegeloh,[5,1] W. Kilian,[2] S. Knappe-Grüneberg,[2] F. Kuchler,[5,6] T. Liu,[2] M. Marino,[5] J. Meinel,[5] Z. Salhi,[3] A. Schnabel,[2] J. T. Singh,[7] S. Stuiber,[5] W. A. Terrano,[5] L. Trahms,[2] and J. Voigt[2]

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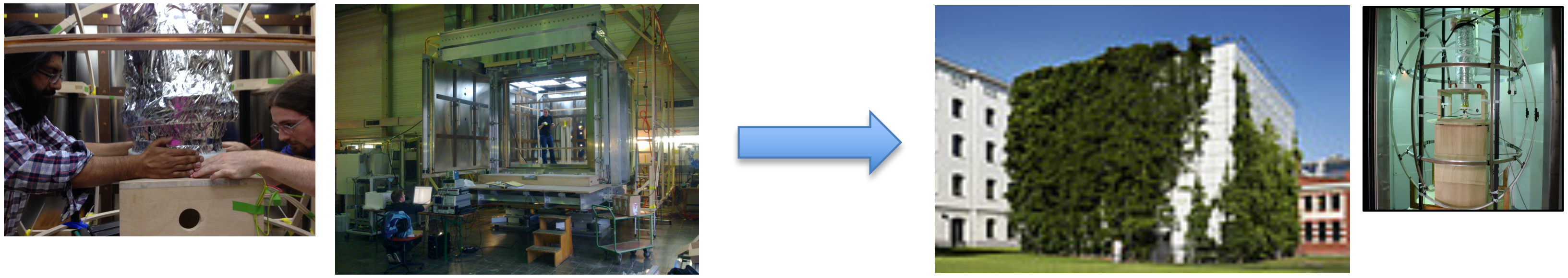
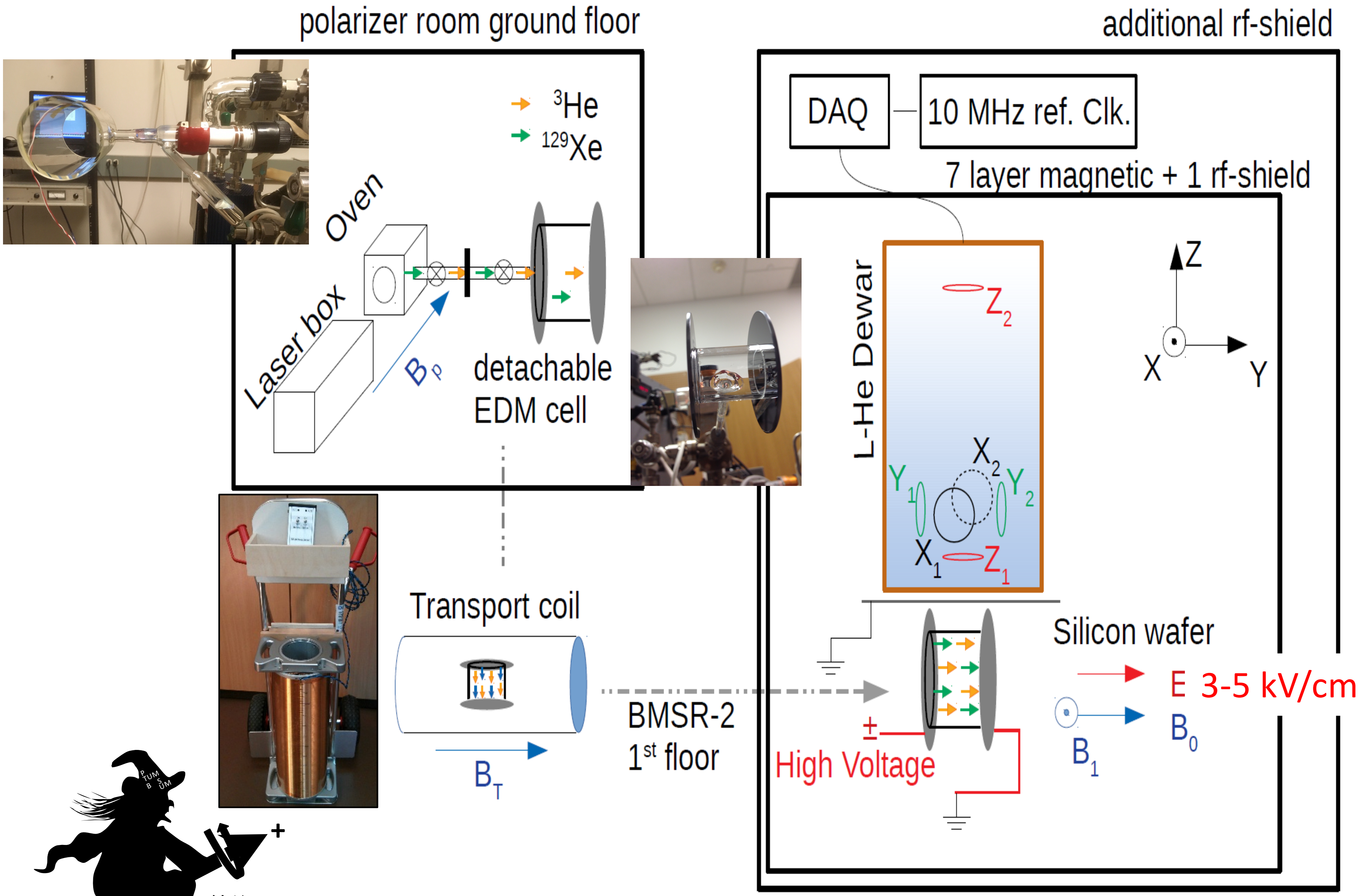
[3] *Jülich Center for Neutron Science, 85748 Garching, Germany*
[4] *Institut Laue-Langevin, 38042 Grenoble, France*
[5] *Excellence Cluster Universe and Technische Universität München, 85748 Garching, Germany*
[6] *TRIUMF, Vancouver, British Columbia V6T 2A3, Canada*
[7] *National Superconducting Cyclotron Laboratory and Department of Physics & Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

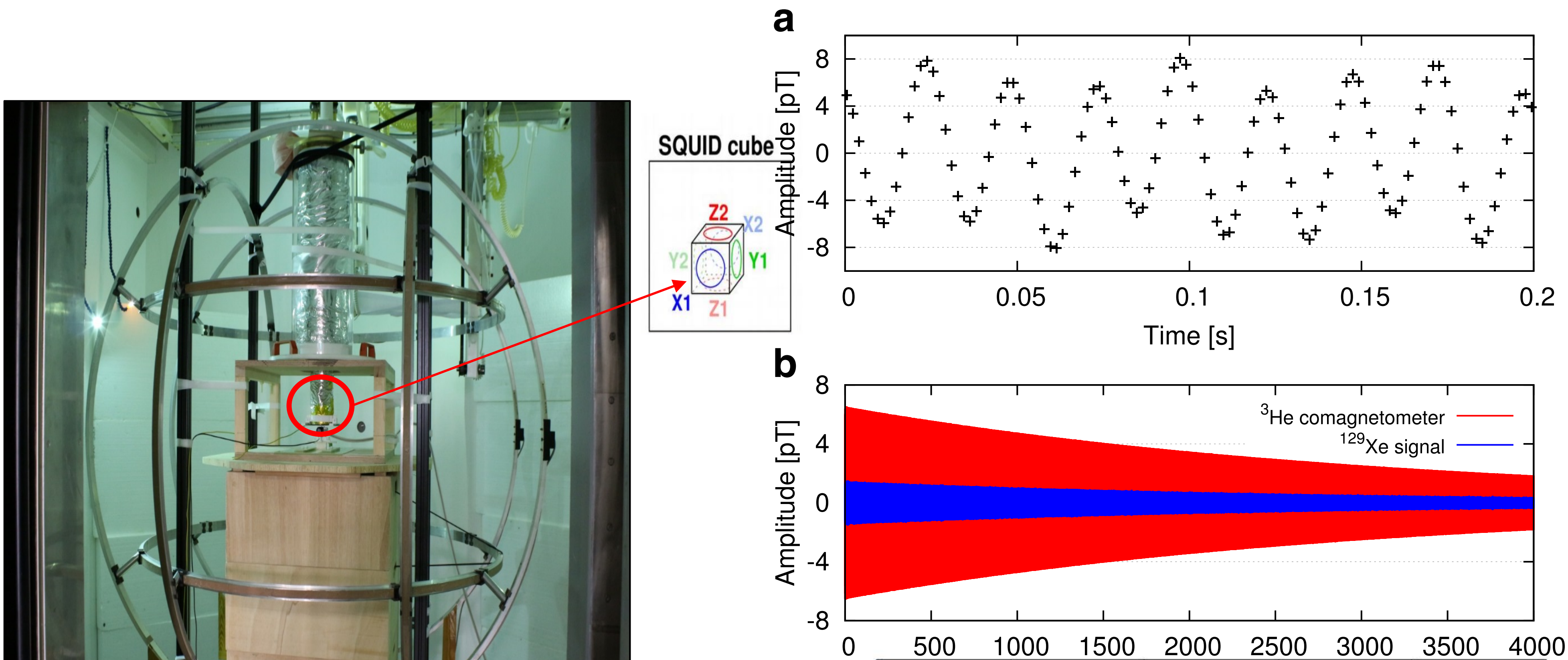
PHYSICAL REVIEW LETTERS **123,** 143003 (2019)

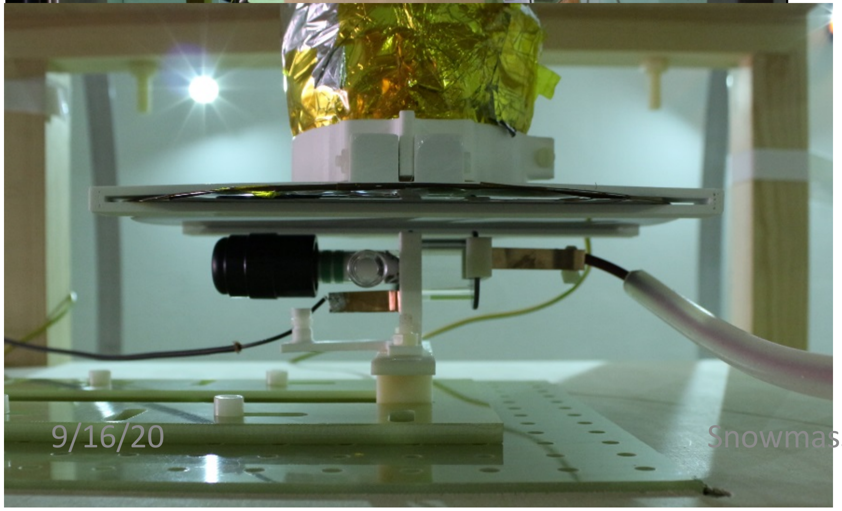


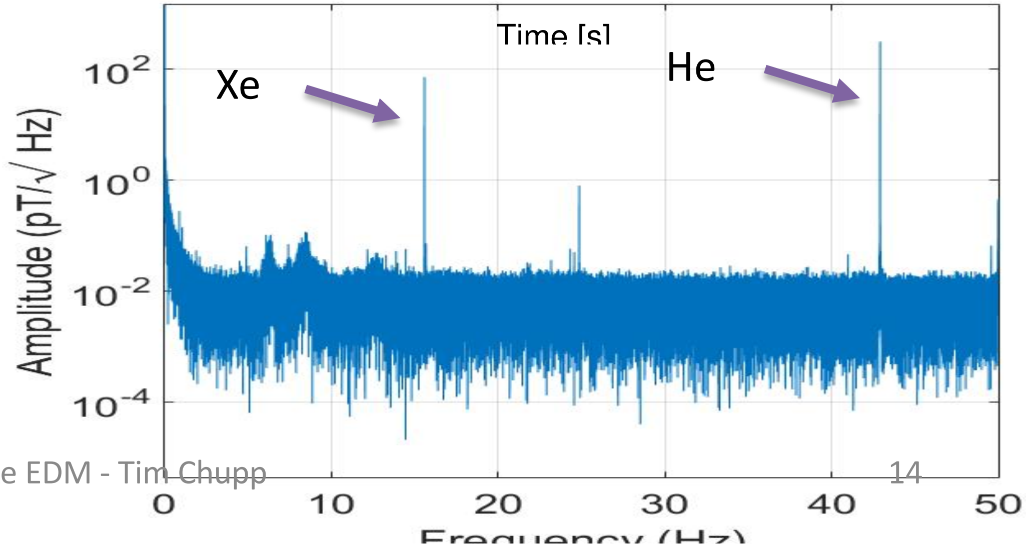
HeXe Overview



SQUID Detection





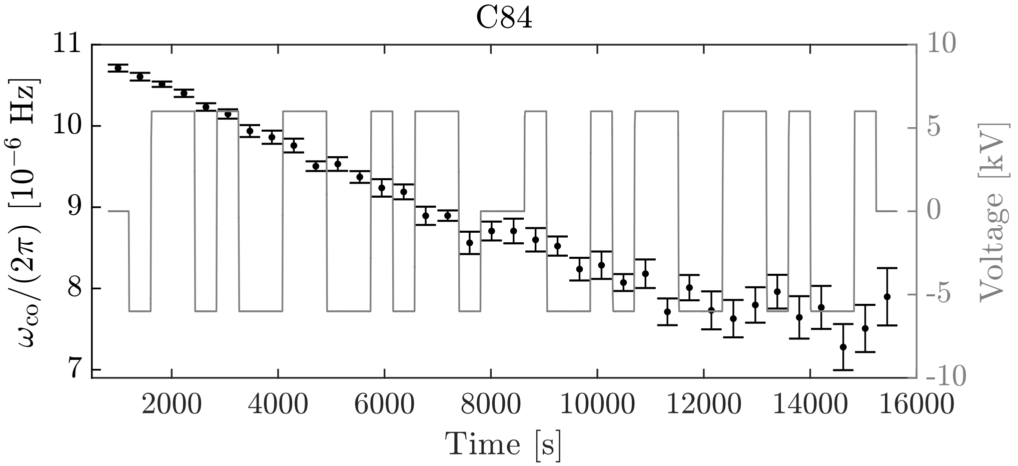


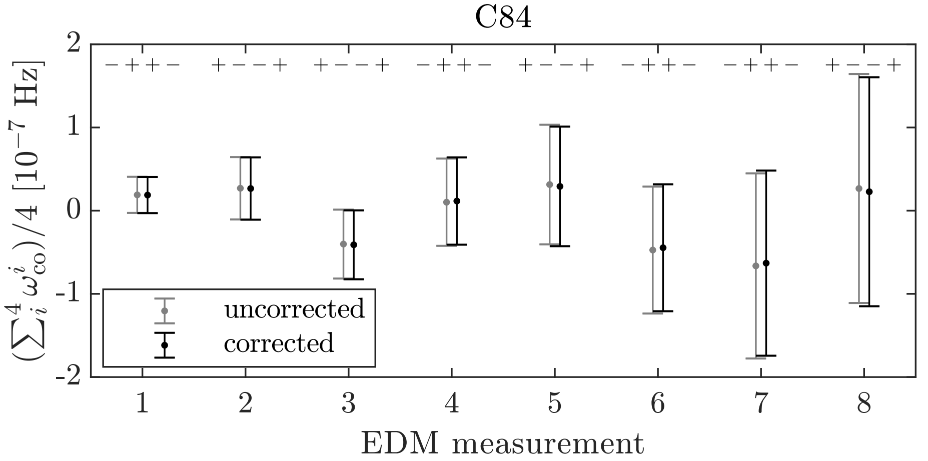
EDM Extraction

Comagnetometer
frequency

$$\omega_{\mathrm{co}} \equiv \omega_{\mathrm{Xe}} - R\omega_{\mathrm{He}}$$

$$R = 1/2.7540816$$





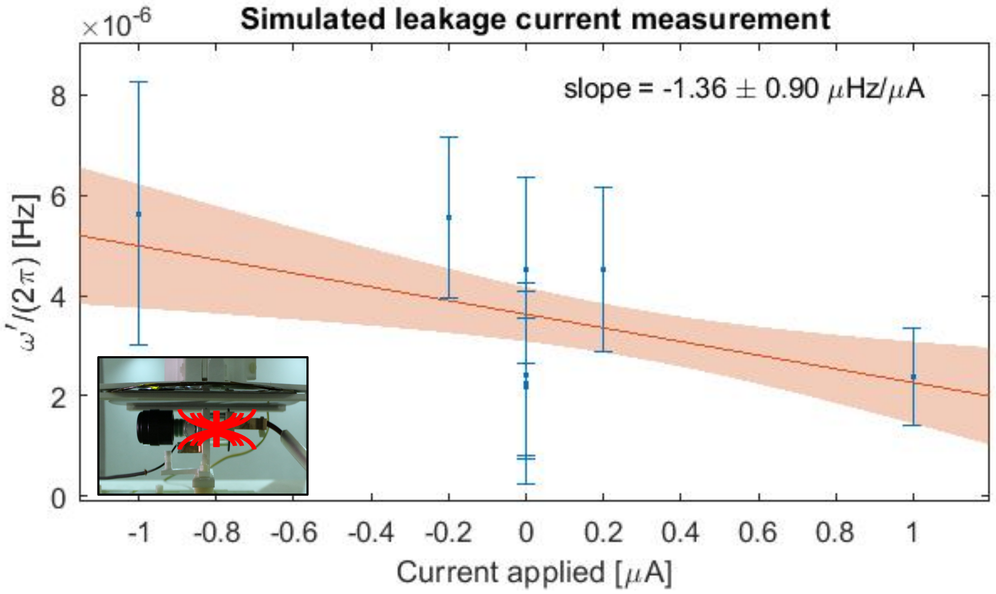
1. BLINDED analysis
2. Segment comagnetometer frequencies combined in groups of 4 are an EDM measurement
3. HV patterns ABBA BAAB … cancel offsets (2), linear drifts (4), quadratic drifts (8) etc.
4. Total of 16/27 runs in 2017/2018

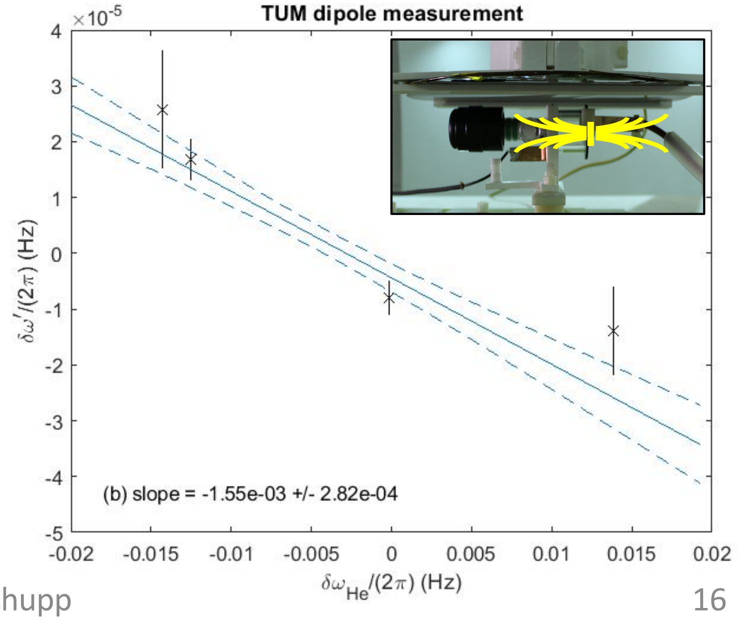
Systematic effects

studied with auxiliary measurements

		Leakage current	**Charging current**	**Cell rotation**	**Cell translation**	
					Linear Gradient	External Dipole (Loop Test)
Auxiliary measurement		Single turn ±0.1–1 μA	±10–20 μA	±5°	N/A	Loop attached to electrode 0–100 μA
Measured linear dependence		$\frac{1}{2\pi}\frac{\partial\omega_{\mathrm{co}}}{\partial I}$	$\frac{1}{2\pi}\frac{\partial\omega_{\mathrm{co}}}{\partial I}$	$\frac{1}{2\pi}\frac{\partial\omega_{\mathrm{co}}}{\partial\theta}$	$\frac{1}{2\pi}\frac{\partial\omega_{\mathrm{co}}}{\partial z}$	$\frac{1}{2\pi}\frac{\partial\omega_{\mathrm{co}}}{\partial\omega_{\mathrm{He}}}$
	2017	$= (1.32 \pm 0.93)$ Hz/A	$= (-0.3 \pm 1.2)$ mHz/A	≤ 1.6 μHz/rad	≤ 90 nHz/m	$= (-1.55 \pm 0.28) \times 10^{-3}$
	2018	$= (-8.6 \pm 7.6)$ mHz/A			≤ 100 nHz/m	
Observed HV-correlated maximum	2017	$I_{\mathrm{leak}} = 97$ pA	$I_{\mathrm{charge}} = 19$ nA	$\delta\theta \leq 33$ μrad	$\delta z \leq 200$ μm	$\frac{\delta\omega_{\mathrm{He}}^{HV}}{2\pi} = (-181.4 \pm 124.4)$ nHz
	2018	$I_{\mathrm{leak}} = 73$ pA	$I_{\mathrm{charge}} = 19$ nA			$\frac{\delta\omega_{\mathrm{He}}^{HV}}{2\pi} = (-82.5 \pm 226.8)$ nHz
False EDM (e cm)	2017	1.2×10^{-28}	1.7×10^{-29}	4.2×10^{-29}	1.3×10^{-29}	2.6×10^{-28}
	2018	4.5×10^{-31}	1.2×10^{-29}	4.0×10^{-29}	1.0×10^{-29}	1.9×10^{-28}

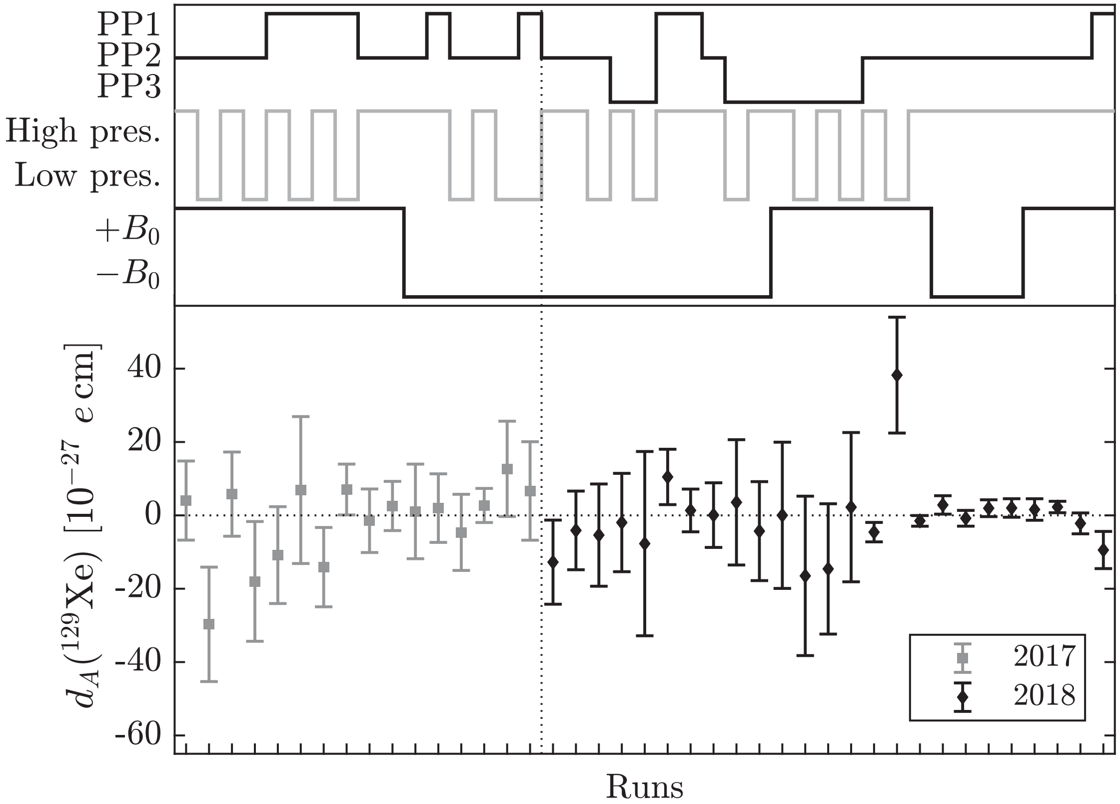
Note loop test covers Leakage, Charge, and MOTION wrt external dipole.





All 2017-18 EDM Data

PRL 123, 143003 (2019)



$$d_A(^{129}\text{Xe}) = (1.4 \pm 6.6_{\text{stat}} \pm 2.0_{\text{syst}}) \times 10^{-28}\ e\,\text{cm}$$

$$|d_A(^{129}\text{Xe})| < 1.4 \times 10^{-27}\ e\,\text{cm}\ (95\%\ \text{C.L.}),$$

Other recent work

PRA **100**, 022505 (2019) - MIXed

arXiv 2008.07975

Future and Prospects

$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N} \propto \frac{1}{\tau^{3/2}}$$ Per HV dwell

Improve S/N

- Polarization improvements/Quiet SQUIDs

Longer τ (time between *E* reversals)

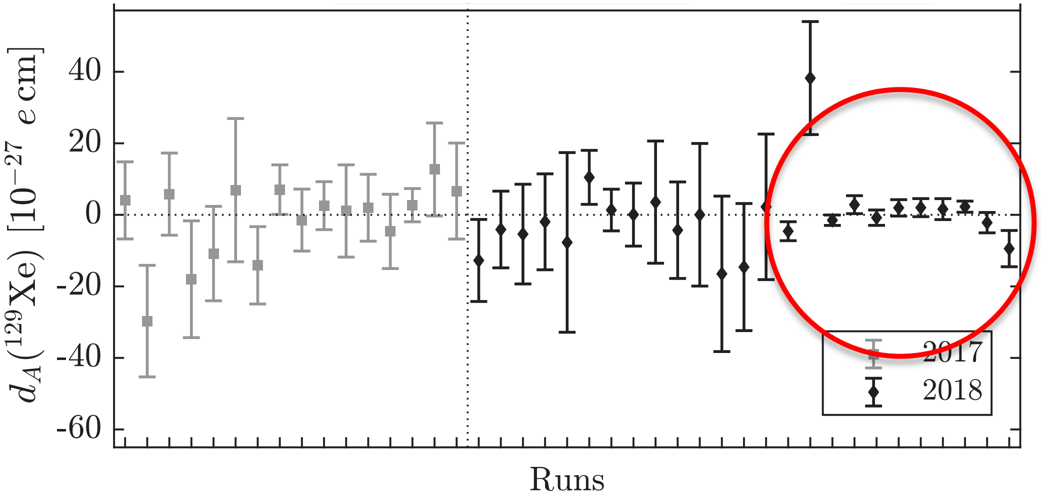
- Control drifts (cell shape, π/2 pulse)

Higher E

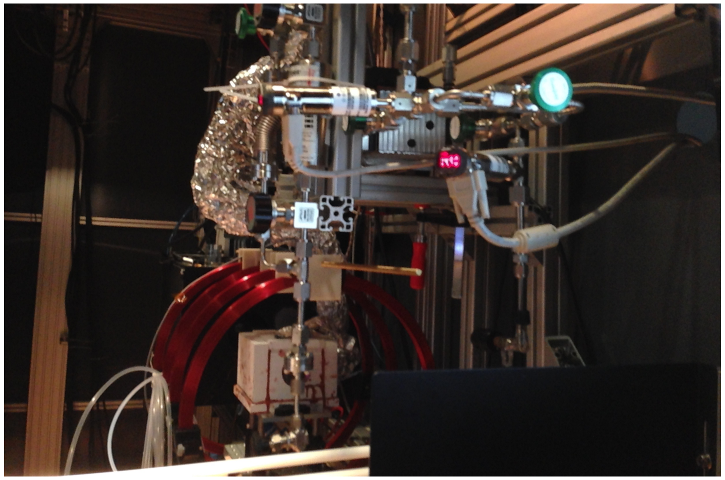
- Gas mixtures

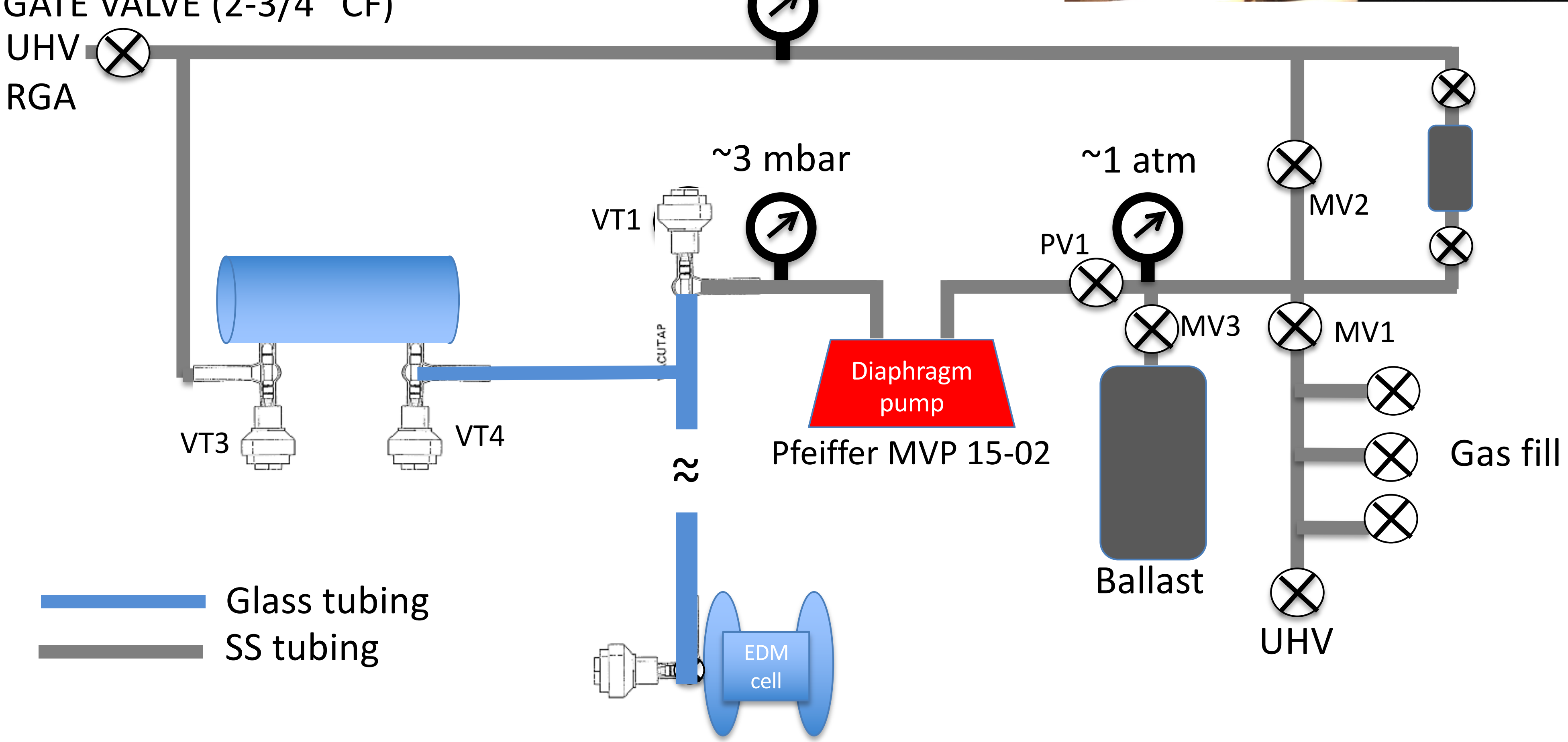
Run Longer/Continuously

- Semi-dedicated MSR
- (LANL nEDM MSR)



Continuous automated polarization





The Takeaway (Conclusions)

1. ^{129}Xe: hadronic (nuclear spin) system
   adds constraints to global fits

2. ^{3}He comagnetometer

3. Recently improved our 2001 limit 5x

4. Path to an additional factors of 10 (of course)

5. Discovery potential (not ruled out)