Electric Dipole Moments

Peter Fierlinger
Technical University of Munich

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  - Physics
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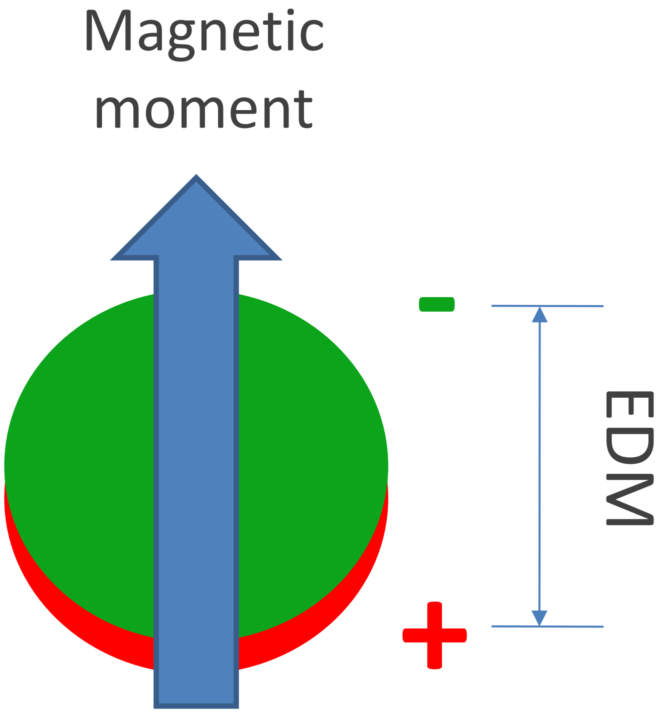
- Neutron EDM and current generation
- Future
  - Neutron
  - Proton
  - 129-Xe
- Spin-offs
  - Axions & Dark Matter
  - Medicine

Electric Dipole Moments

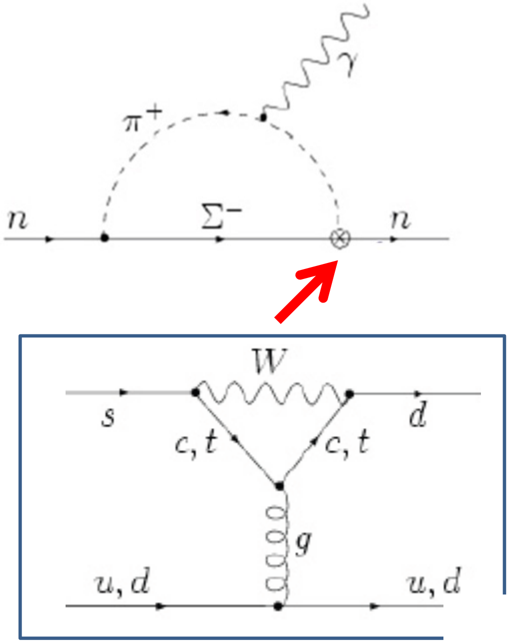


$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

- A „*fundamental*“ electric dipole moment (EDM) violates P and T symmetry *Purcell and Ramsey, PR78(1950)807*
- Needed to explain baryon asymmetry in the Universe
- Also point-like particles could have an EDM
- Upper limits are among the most precisely measured quantities: $d_n < 1.8 \cdot 10^{-26}$ ecm
- Current limits far away from SM predictions
- A ‘model killer‘ – sensitivity well beyond LHC

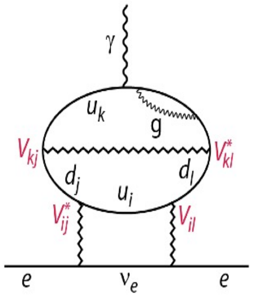
EDMs & Standard Model

CP violation from CKM



Neutron EDM $d_n \approx 10^{-32}$ ecm

Side note: $d_{\text{electron}} < 10^{-38}$ ecm…



Strong Interaction

CP-odd term in Lagrangian:

$$L_\theta = \bar{\theta}\,\frac{\alpha_s}{8\pi}\,G\tilde{G}$$

$$d_n(\bar{\theta}) \sim \bar{\theta}\,\frac{e}{m_n}\,\frac{m_*}{\Lambda_{QCD}} \sim 6.10^{-17}\,\bar{\theta}\,e\cdot cm$$

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

Strong CP problem, Axions

details:

Rev. Mod. Phys. ***91****, 015001 (2019)*
Phys. Rev. C ***91****, 035502 (2015)*
Prog. Part. Nucl. Phys. ***71****, 21 (2013)*

Atomic and molecular EDMs

Schiff moment:

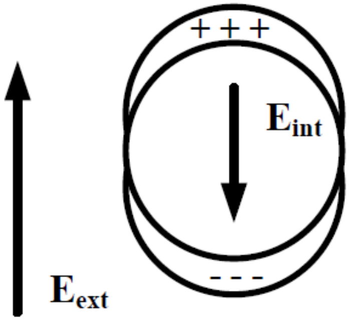
Non-perfect cancellation of E_{ext} in atomic shell

- Paramagnetic atoms: relativistic effects in electronic shell

$$d_a \propto d_e Z^3$$ Sandars, 1968

- Diamagnetic atoms: finite size of nucleus counteracts field cancelation

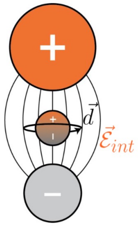
$$d_a \propto d_{nucl} Z^2$$ Schiff 1963; Sandars, 1968; Feinberg 1977; ... - 2010



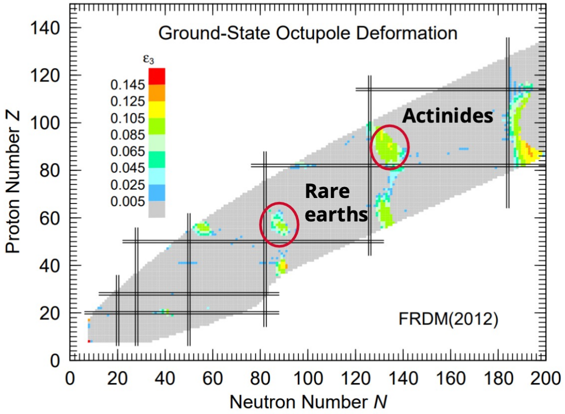
$$\mathbf{E}_{ext} + \mathbf{E}_{int} = 0$$

Many possibilities for further EDM enhancements:

- Deformed nuclei (Ra, Rn, also Fr, Ac, Pa)
- Large electric fields of polar molecules (YbF, ThO, BaF, TlF, SrF...) and molecular ions (HfF+,…), multi-atom polar molecules



L. P. Gaffney *et al.*, Nature 497, 199 (2013)



EDMs and new physics

$$\mathscr{L}_{\mathrm{eff}} = \mathscr{L}_{\mathrm{SM}} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Dim. 6:

$$d_n \propto \frac{m_q}{\Lambda^2} \cdot e \cdot \phi_{\mathrm{CPV}}$$

For nEDM ~ $d_n < 10^{-26}$ ecm:

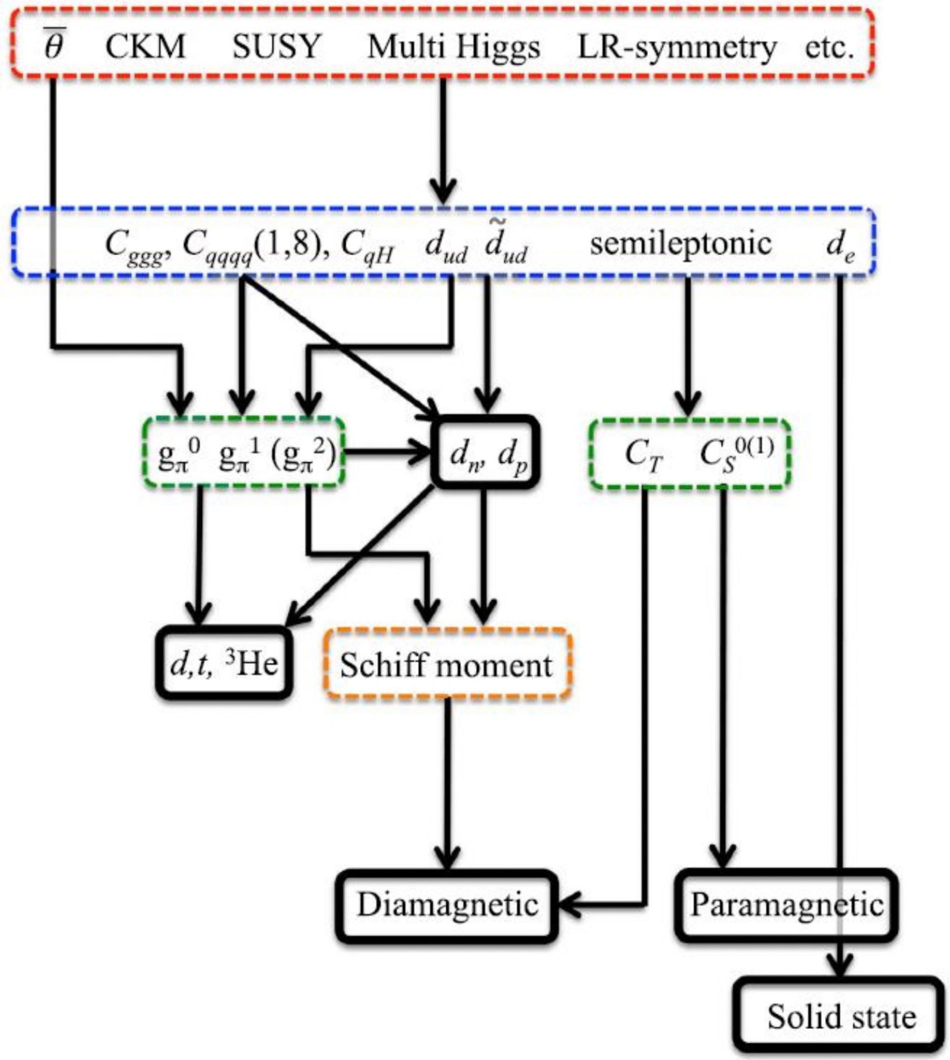
$$\Lambda \sim 10 - 100\ \mathrm{TeV}$$

Side note:

EFTs also connect EDMs and flavor physics

E.g. scalar leptoquarks would cause
d_τ & d_n & flavor physics signals.

Dekens, DeVries, Jung, Vos, JHEP 01 (2019) 069



Coefficients and experiments

e and μ EDM

Nuclear-spin-dependent e-N coupling C_T,

Nuclear-spin independent couplings C_S^0

Intrinsic quark EDMs and chromo EDMs

Meson-nucleon couplings $g_\pi^{0,1,(2)}$

… Linear equation system -> matrix…

- Paramagnetic atoms

$$d_{para} = \eta_{d_e} d_e + k_{C_S} \bar{C}_S$$

- Polar molecules

$$\Delta\omega_{para}^{\not{P}\not{T}} = \frac{-d_e E_{eff}}{\hbar} + k_{C_S}^{\omega} \bar{C}_S$$

- Diamagnetic atoms

$$d_{dia} = \kappa_S S(\bar{g}_\pi^{0,1}) + k_{C_T} C_T + \ldots$$

- Nucleons

$$d_{n,p} = d_{n,p}^{lr}(\bar{g}_\pi^{0,1}) + d_{n,p}^{sr}(\tilde{d}_{u,d}, d_{u,d})$$

- Fundamental fermions

$$d_e, d_\mu, (d_\tau)$$

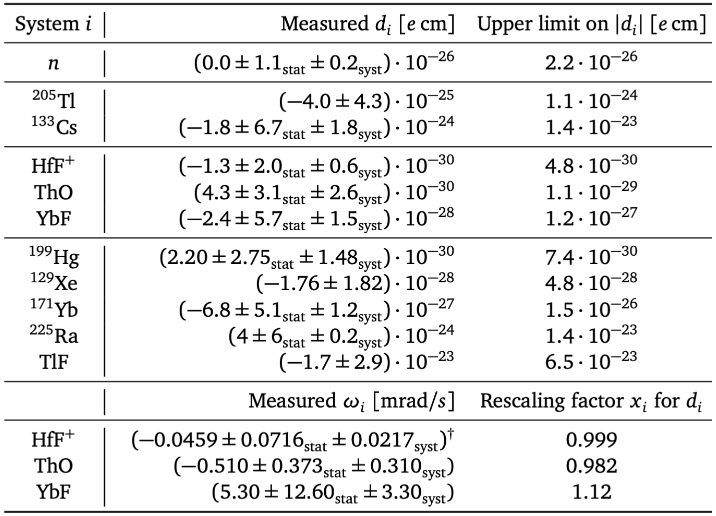
…Higher orders (199-Hg!) :

$$d_A = (k_T C_T + k_S C_S) + \eta_e d_e + \kappa_S S + \text{ h.o. (MQM)}$$

T. Chupp, PF, M.J. Ramsey-Musolf, J. Singh, Rev. Mod. Phys. 91, 015001 (2019)

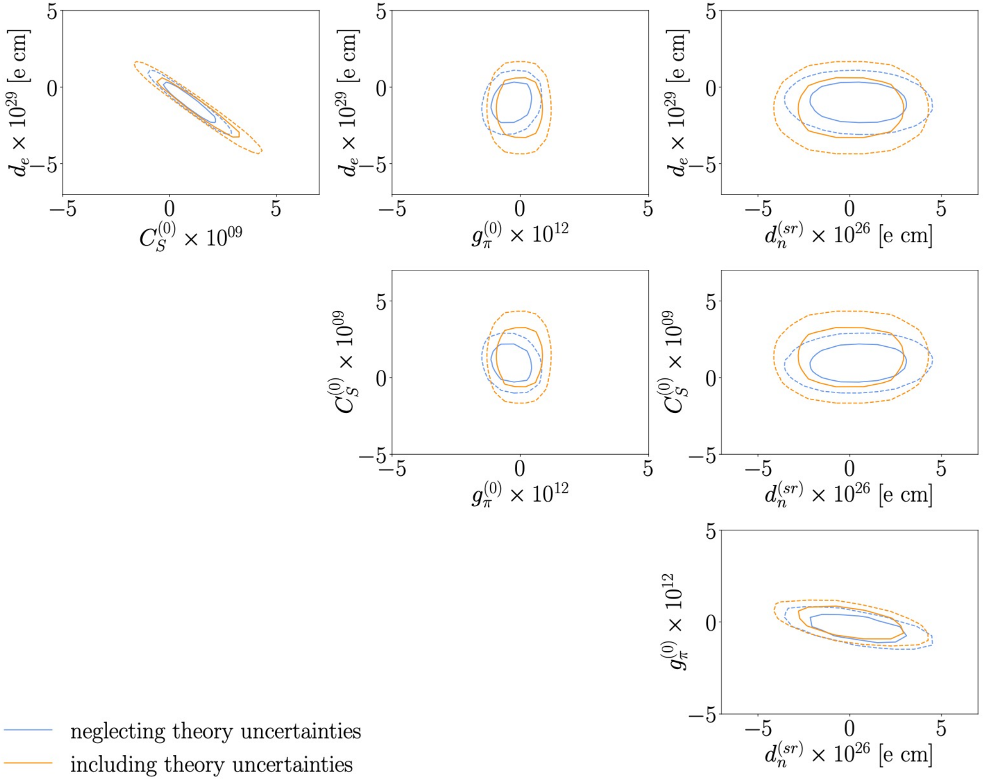
Analysis of EDM results

„Sole-source“ analysis:



System i	Measured d_i [e cm]	Upper limit on $\|d_i\|$ [e cm]
n	$(0.0 \pm 1.1_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-26}$	$2.2 \cdot 10^{-26}$
^{205}Tl	$(-4.0 \pm 4.3) \cdot 10^{-25}$	$1.1 \cdot 10^{-24}$
^{133}Cs	$(-1.8 \pm 6.7_{\text{stat}} \pm 1.8_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$
HfF$^+$	$(-1.3 \pm 2.0_{\text{stat}} \pm 0.6_{\text{syst}}) \cdot 10^{-30}$	$4.8 \cdot 10^{-30}$
ThO	$(4.3 \pm 3.1_{\text{stat}} \pm 2.6_{\text{syst}}) \cdot 10^{-30}$	$1.1 \cdot 10^{-29}$
YbF	$(-2.4 \pm 5.7_{\text{stat}} \pm 1.5_{\text{syst}}) \cdot 10^{-28}$	$1.2 \cdot 10^{-27}$
^{199}Hg	$(2.20 \pm 2.75_{\text{stat}} \pm 1.48_{\text{syst}}) \cdot 10^{-30}$	$7.4 \cdot 10^{-30}$
^{129}Xe	$(-1.76 \pm 1.82) \cdot 10^{-28}$	$4.8 \cdot 10^{-28}$
^{171}Yb	$(-6.8 \pm 5.1_{\text{stat}} \pm 1.2_{\text{syst}}) \cdot 10^{-27}$	$1.5 \cdot 10^{-26}$
^{225}Ra	$(4 \pm 6_{\text{stat}} \pm 0.2_{\text{syst}}) \cdot 10^{-24}$	$1.4 \cdot 10^{-23}$
TlF	$(-1.7 \pm 2.9) \cdot 10^{-23}$	$6.5 \cdot 10^{-23}$
	Measured ω_i [mrad/s]	Rescaling factor x_i for d_i
HfF$^+$	$(-0.0459 \pm 0.0716_{\text{stat}} \pm 0.0217_{\text{syst}})^\dagger$	0.999
ThO	$(-0.510 \pm 0.373_{\text{stat}} \pm 0.310_{\text{syst}})$	0.982
YbF	$(5.30 \pm 12.60_{\text{stat}} \pm 3.30_{\text{syst}})$	1.12

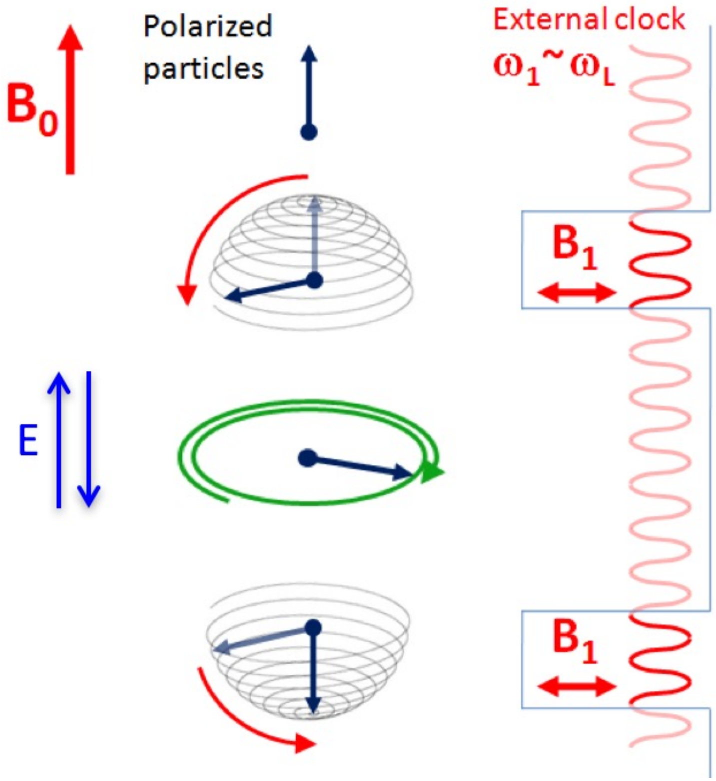
https://arxiv.org/pdf/2403.02052



Joint analysis:

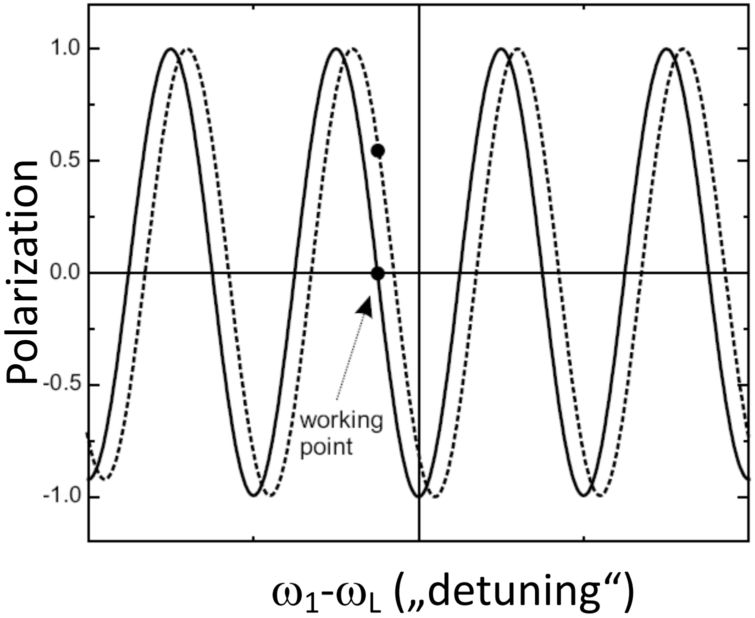
- eEDM searches only sensitive to small part of parameter space
- Best hadronic measurements: n, Hg … show strong correlations in (5D-)parameter space
- „Weak“ limits dominate sensitivity to EFT parameters: e.g. ^{129}Xe very important!

Ramsey‘s method



$$H = -(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E})$$

- Every point is a measurement
- An EDM shifts the curve sideways
- “Working point”



… A precision measurement

Orders of magnitude:

$$\mu_{\mathrm{N}} \times \frac{1\mu\mathrm{T}}{2\pi\hbar} = 8\ \mathrm{Hz}$$

$$10^{-26} e\ \mathrm{cm} \times \frac{1\ \mathrm{MV}}{m} \times \frac{1}{2\pi\hbar} = 24\ \mathrm{nHz}$$

Measuring an EDM *d*:

$$\begin{tikzcd}[column sep=large] & \frac{h}{2ET_2}\frac{1}{\sqrt{\phi_n T_2}} \\ \delta d \sim \frac{h}{ET_2}\frac{1}{S/N} \arrow[ur] \arrow[dr] & \\ & \frac{h}{2ET_2}\frac{1}{\sqrt{N_{\mathrm{n}}}} \end{tikzcd}$$

… “continuous” investigation of spin precession, limited by phase noise

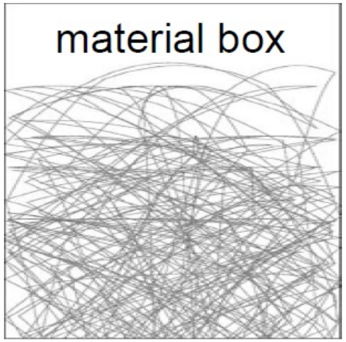
… particle counting experiment, limited by the number of detected particles

Neutron EDM

Typical for ”next-gen”: factor 10 improvement envisaged (10^{-27} ecm)

Experiments: LANL, ILL/TUM “PanEDM”, PSI, TRIUMF

- Trapped ultra-cold neutrons in box at room temperature:
  - N ~ 10^5, counted at end of Ramsey experiment
  - 10^4 repetitions ~ 100 days



- Magnetic fields:
  - Undetected field drifts: ~ 1 fT over 250 s

$$d_{false:\Delta B} = \frac{2\mu\Delta B}{4E}$$

  - T_2 in gradient is volume dependent
  - Magnetometers: ^{199}Hg, Cs, ^{129}Xe, ^{3}He, SQUIDs (in-situ or surrounding)

- A very delicate indirect systematic effect: Bloch-Siegert-shift

Ramsey-Bloch-Siegert shift

Most critical issue for next-generation measurements:

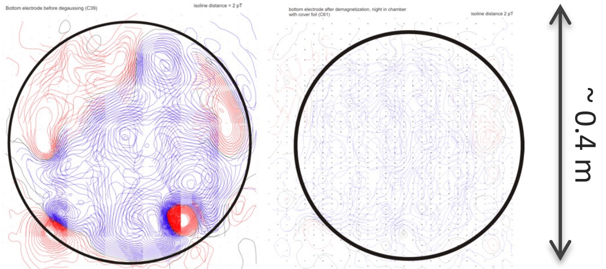
$$\Delta\omega = \frac{\omega_{xy}^2}{2(\omega_0-\omega_r)}$$

$$\omega_{xy}^2 = \left(\frac{\partial B_{0z}}{\partial z}\alpha\right)^2 + \left(\frac{E\times v}{c^2}\right)^2 + \boxed{2\frac{\partial B_{0z}}{\partial z}\alpha\cdot\frac{E\times v}{c^2}}$$

- dB/dz < 0.3 nT/m to match 10^{-27} ecm statistical precision
- Consequence: "everything" in an experiment is magnetic!

Example:
Dipole fields in EDM chambers

SQUID measurements of alu electrodes @ PTB Berlin



200 pT pp

demagnetized:
20 pT pp

20 pT in 3 cm ~ 5 x error budget!

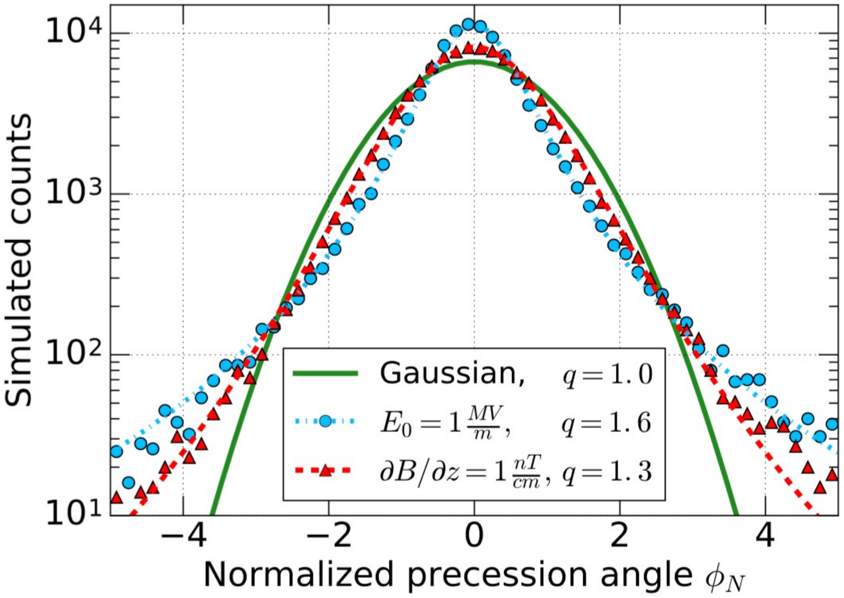
Further: P. G. Harris et al., Phys. Rev. A 73, 014101 (2006), also: G. Pignol, arXiv:1201.0699 (2012).

Pendlebury et al., Phys. Rev. A ***70****, 032102 (2004)*

New systematics?

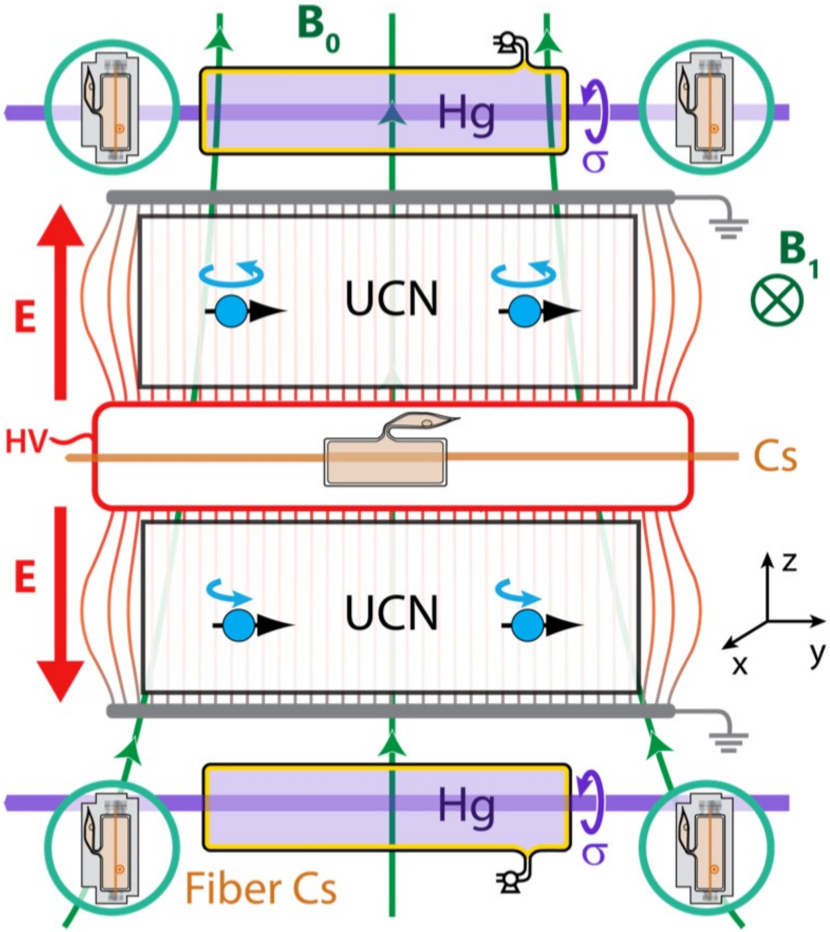
The only conceptially new feature found in the last years:
„Tsallis distributions“

- Spin distribution in rotating frame deviates from Gauss-shape
- Distributions can also have higher moments: possible identification of origin of false effects
- Skewness -> would lead to wrong estimation of a frequency shift?
- Could also show up elsewhere?

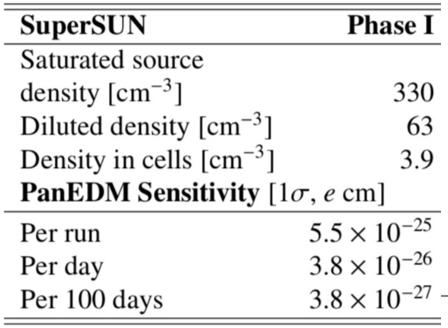


M. Bales, PF et al., Eur. Phys. Lett. 116,43002 (2016)

The PanEDM experiment



- Current generation:
  - old idea, very careful implementations
- Two problems:
  - Statistics: many trapped UCN needed
  - Systematics: magnetic fields control at fT level
- Status:
  - UCN measurements since summer 2023!



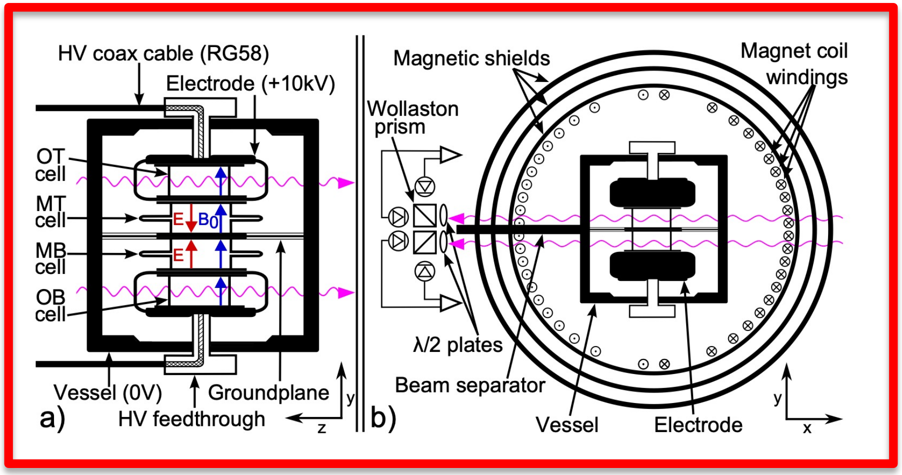
SuperSUN	**Phase I**
Saturated source density [cm^{-3}]	330
Diluted density [cm^{-3}]	63
Density in cells [cm^{-3}]	3.9
PanEDM Sensitivity [1σ, e cm]	
Per run	5.5×10^{-25}
Per day	3.8×10^{-26}
Per 100 days	3.8×10^{-27}

D. Wurm et al., EPJ Web of Conferences 219, 02006 (2019)

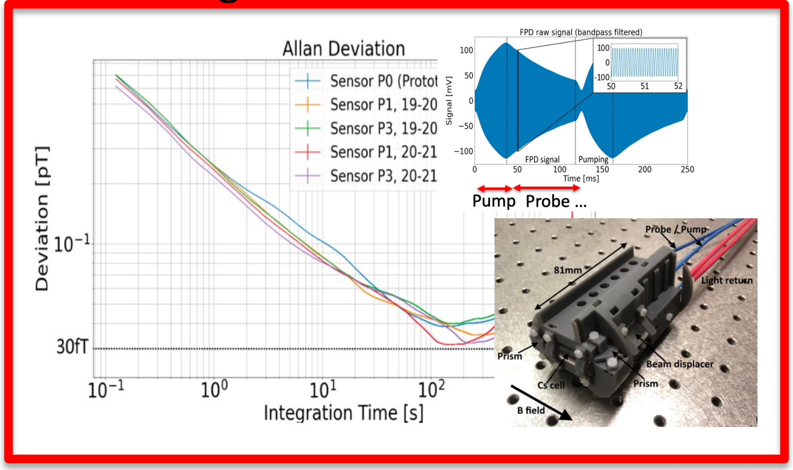
The PanEDM experiment

E.g.: Extreme magnetic shielding

Multiple measurement cells - ideas borrowed from 199Hg EDM:

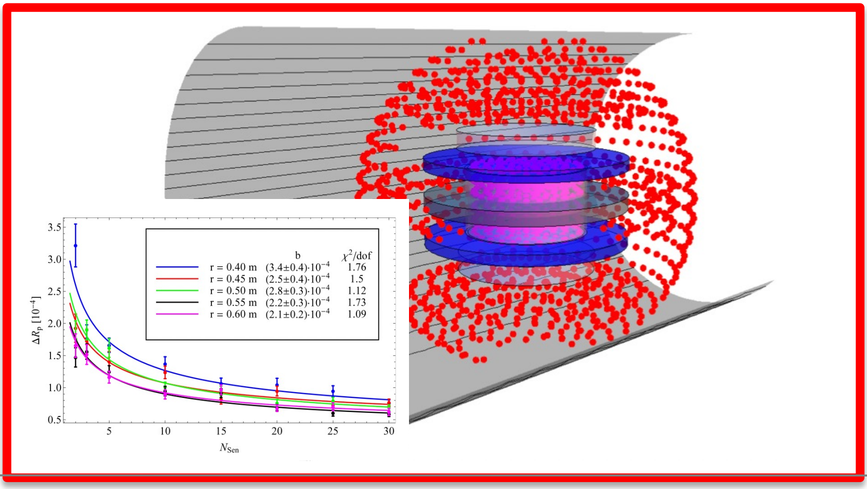


Atomic magnetometers



M. Rosner, PF et al., Appl. Phys. Lett. 120, 161102 (2022)

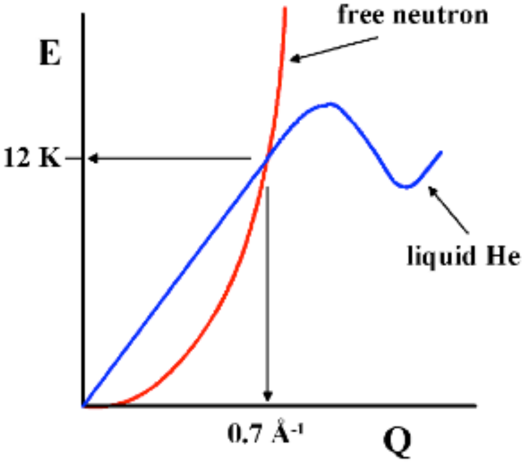
„Almost“ a 4-pi magnetometer

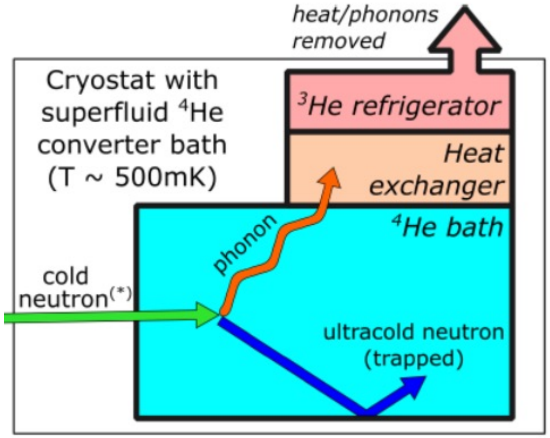


UCN for PanEDM: SuperSUN

The SuperSUN ultra-cold neutron source at ILL Grenoble

- UCN production & accumulation in superfluid helium
- Transfer of UCN to experiment into vacuum





(*)not trappable: E~1 meV vs. U_{wall}~200 neV

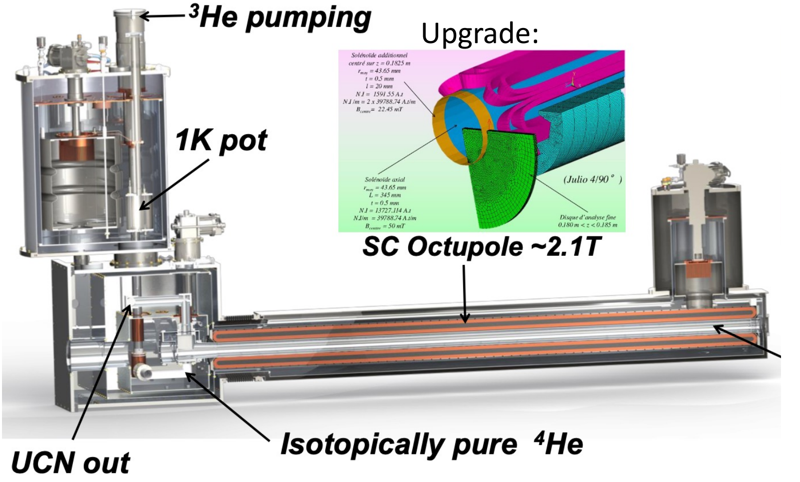
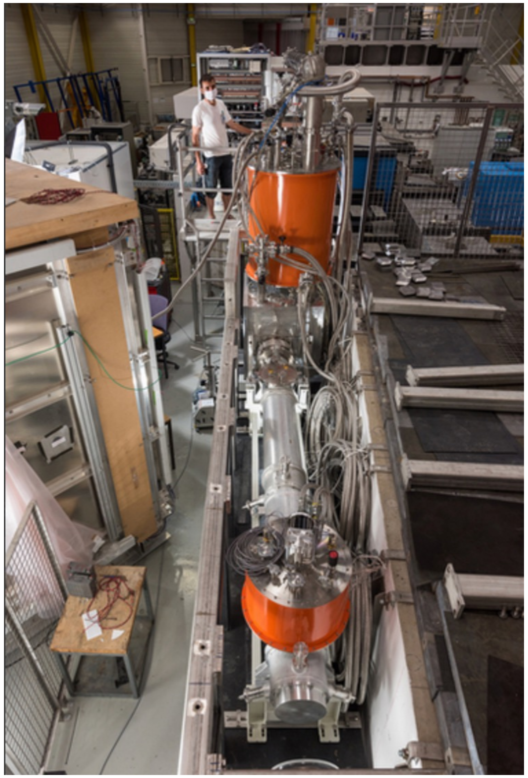
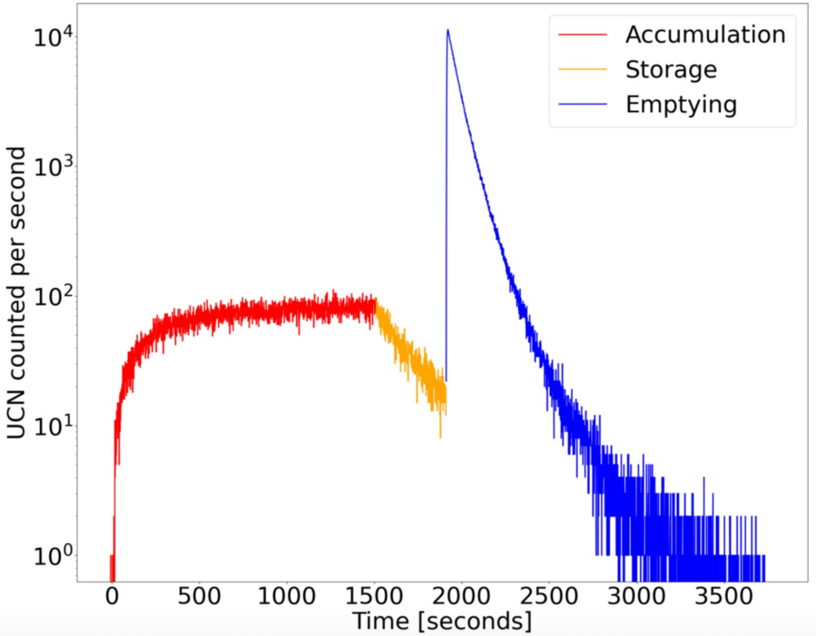


Figure credit: S. Degenkolb

UCN for PanEDM: SuperSUN

The (only) UCN source that delivers as theoretically predicted: enables factor 10 improvement.

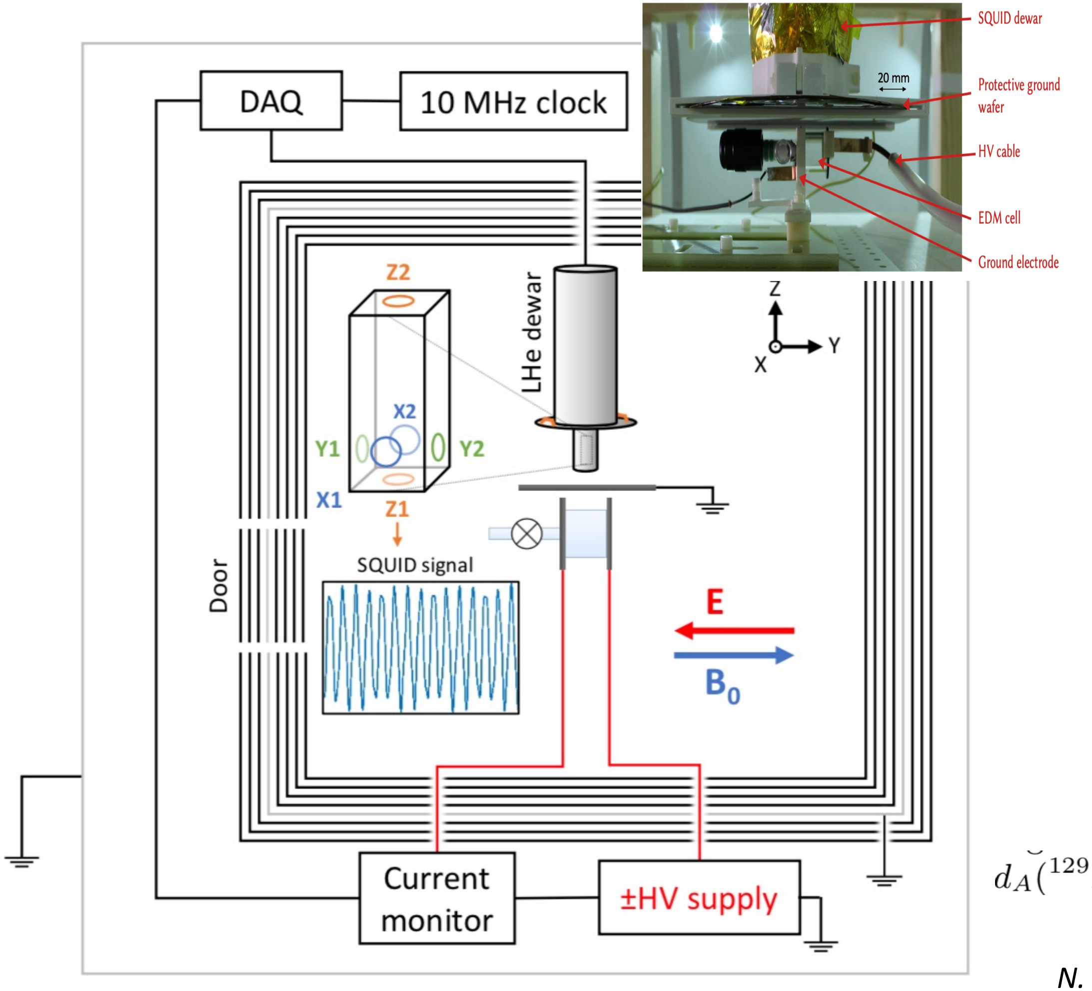


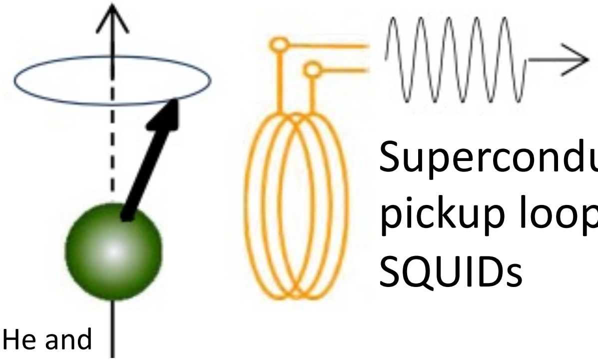


https://www.ill.eu/news-and-events/news/scientific-news/supersun-instrument-ready-for-use

Atom EDM: ^{129}Xe

SEOP-hyperpolarized 3-He / 129-Xe co-magnetometer





^{3}He and ^{129}Xe spins

Superconducting pickup loops + SQUIDs

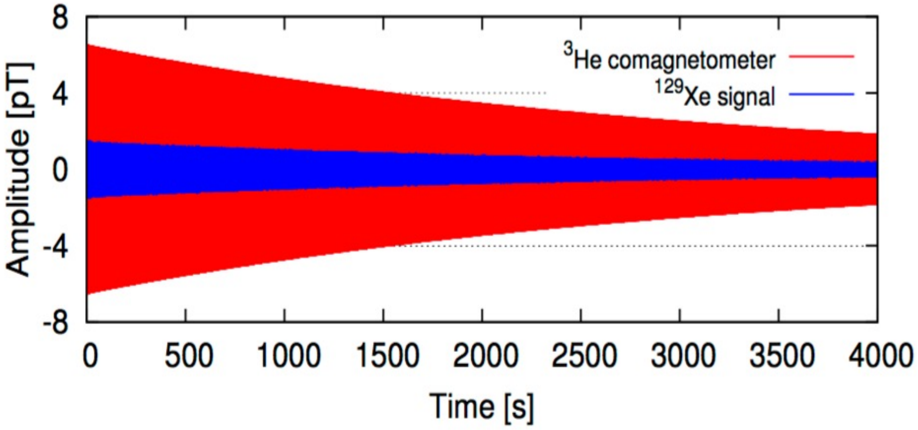
$$\sigma = \frac{\hbar}{2E}\delta\omega = \frac{\hbar}{2E}\frac{\epsilon}{T^{3/2}S\sqrt{N}}$$

$$d_A(^{129}\mathrm{Xe}) = (0.26 \pm 2.33_{\mathrm{stat}} \pm 0.72_{\mathrm{syst}}) \times 10^{-27}\ e\,\mathrm{cm}$$

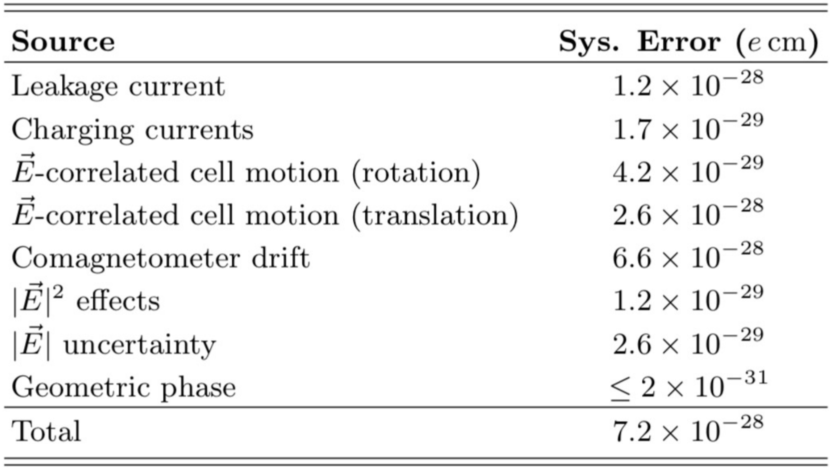
N. Sachdeva, .. PF … et al, Phys. Rev. Lett. 123, 143003 (2019)

Atom EDM: ^{129}Xe

Data:



Systematic effects:



Source	Sys. Error (e cm)
Leakage current	1.2×10^{-28}
Charging currents	1.7×10^{-29}
$\vec{E}$-correlated cell motion (rotation)	4.2×10^{-29}
$\vec{E}$-correlated cell motion (translation)	2.6×10^{-28}
Comagnetometer drift	6.6×10^{-28}
$\lvert\vec{E}\rvert^2$ effects	1.2×10^{-29}
$\lvert\vec{E}\rvert$ uncertainty	2.6×10^{-29}
Geometric phase	$\leq 2 \times 10^{-31}$
Total	7.2×10^{-28}

Upgrade currently being developed:

- ^{129}Xe has no „free“ enhancement factor: measurement must be done really well!
- New effort started: collaboration by former competitors, using new specialized lab at TUM, 4-pi magnetometry/3D-reconstruction, AI methods (all needed for nEDM, pEDM)

Future directions in the field

Nucleon EDM:

Neutron: (beyond factor-10-approaches)

    Joint US & Europe initiative planned
    Strong pulsed beam at ESS

Proton, light nuclei:

    charged particles, storage ring

Diamagnetic atoms:

    ^{199}Hg, ^{129}Xe - US & Europe jointly

Polar molecules, paramagnetic systems:

    Polar molecule ions in traps
    Polyatomic molecules

Elementary particles:

    Muon, Tau

Future directions in the field*

* Peter's biased selection!

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New ideas may actually have significant physics reach!

- Cryogenic, novel detection methods, semiconductor based technology
- Multiple cells allow for massively advanced control of systematics
- ERC Syn.-grant in third stage of review, for Ramsey-beamline at ESS (Sweden) as starting point
- First version will be an ultra-light ALP (axion) search!

Future directions in the field*

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No problem with statistics!

- Storage ring concept with relativistic protons
- Strong local experience: demonstrator setup at TUM
- ALP search as first physics case of demo experiment

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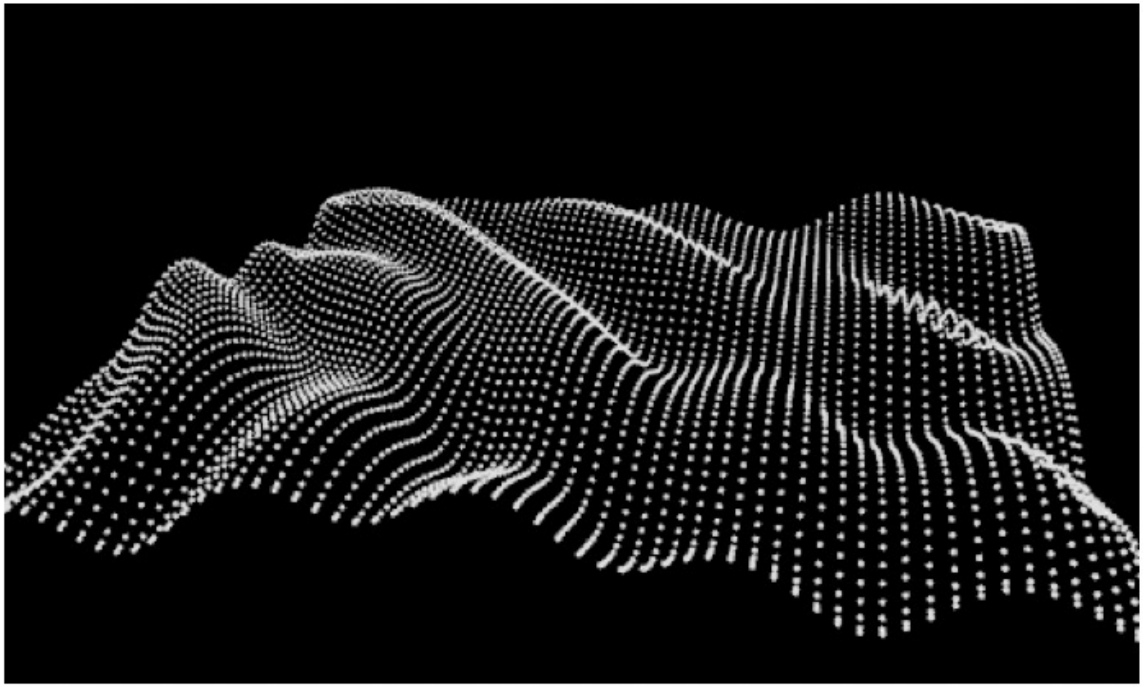
Elementary particles:

- Muon, Tau

- Atom EDMs = necessary magnetometer development for n & p EDMs
- Most methods are quantum sensing
- The world’s most accurate atomic magnetometers are built at TUM
- ^{129}Xe (TUM-based collaboration) achieved the leading limit in 2019 (10^{-43} J energy resolution!)
- New ^{129}Xe & ^{199}Hg measurements done as collaboration of former competitors! (TUM, UHD, LANL, Bonn)

Axion-like Particles (ALPs)

- ALPs are not the QCD axions!
- Many possibilities, e.g. 10^{-14} – 10^{-22} eV



Extremely long wavelength DM field as superposition of many “particles”

Axion-like Particles (ALPs)

axion field amplitude ┈┈┈➤ $\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$

$$\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\frac{\partial_\mu a}{f_a}\bar{\Psi}_f\gamma^\mu\gamma_5\Psi_f$$

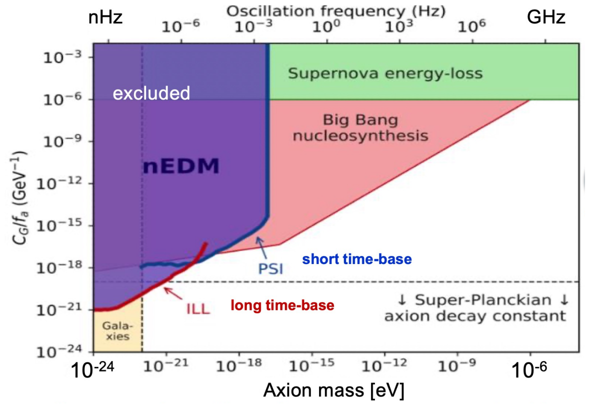
$$\boxed{H_\mathrm{e} \propto a\vec{\boldsymbol{\sigma}}\cdot\vec{\boldsymbol{E}}^*}$$

$$\boxed{H_\mathrm{wind} \propto \vec{\boldsymbol{\sigma}}\cdot\vec{\boldsymbol{\nabla}}a}$$

Oscillating EDM!

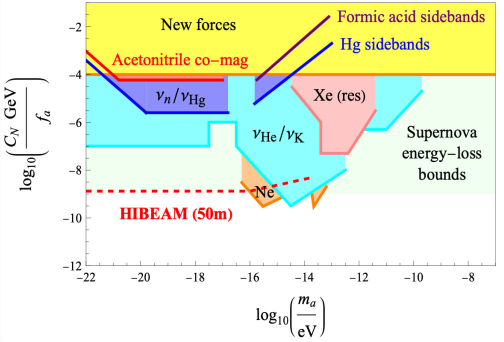
Oscillating B-field!

Abel et al., PRX7 (2017) 041034

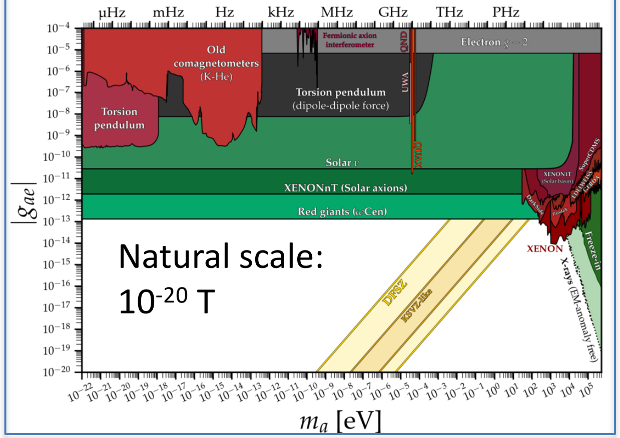


$$d_n(t) = 5.9\times10^{-22}\,C_G\left(\frac{10^{-22}\,\mathrm{eV}}{m_a}\right)\left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)\cos(m_a t)\;e\cdot\mathrm{cm}$$

PF et al., arxiv:2404.15521



https://github.com/cajohare/AxionLimits/blob/master/docs/ae.md

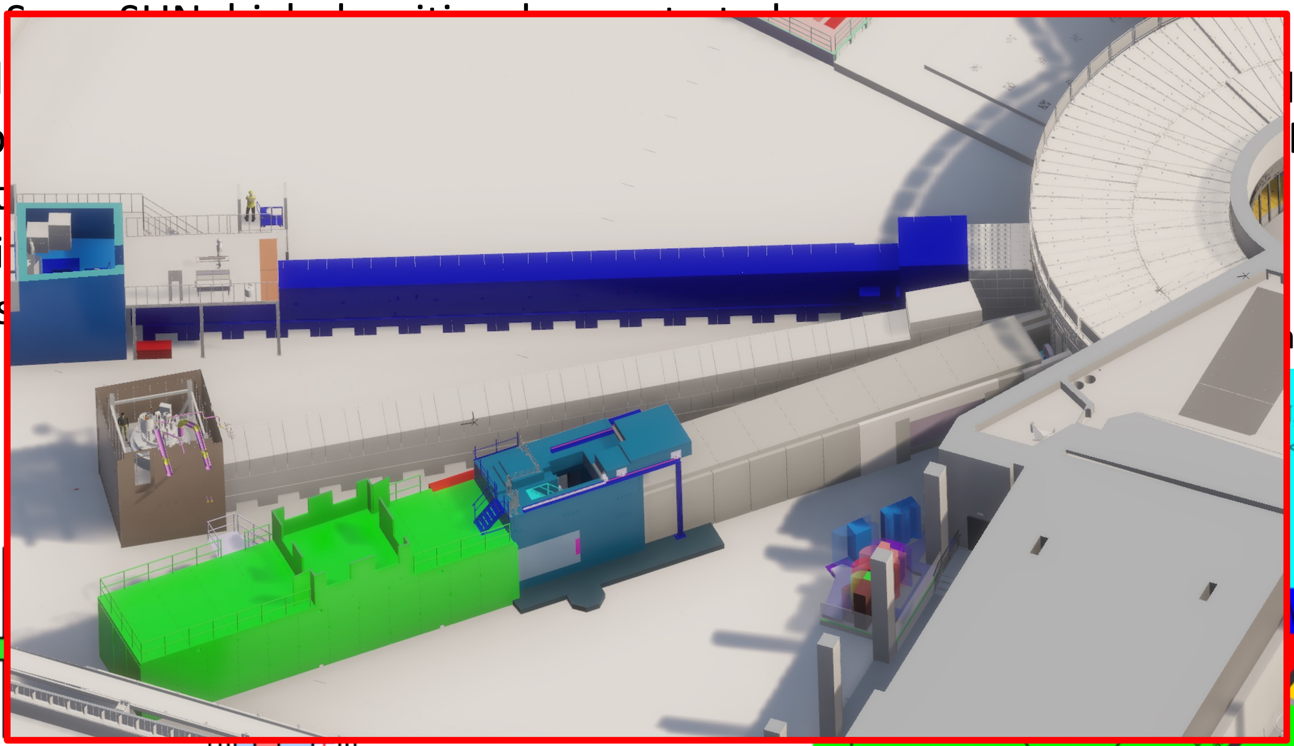


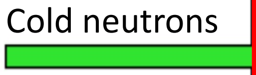
Natural scale:
10^{-20} T

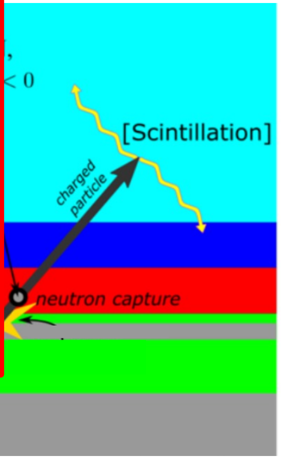
Future: Neutron EDM

Factor 1000 improvement in statistics feasible

- Based on
- 100 simul ques
- No transp EDM cell
- Uses exist
- Part of joi
- Time lines :





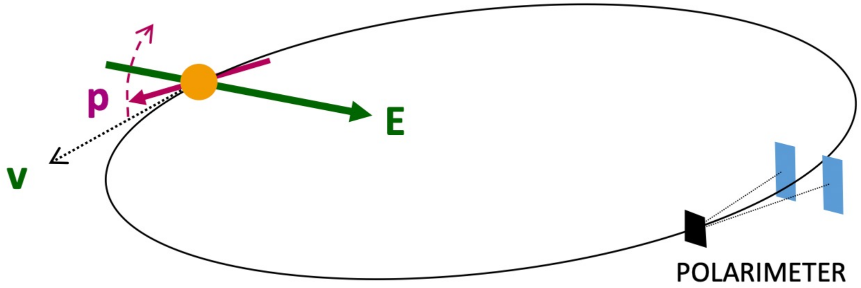


Experiment concept: *S. Degenkolb, PF, O. Zimmer, EPJ Web of Conferences (2019)*

Future: Proton EDM

Electrostatic storage ring with $d_p < 10^{-29}$ ecm reach

- Relativistic motion causes B field in frame of moving particle
- Frozen horizontal spin precession: p || s at magic momentum
- EDM turns s out of plane
- Purely electric ring only for G > 0
- “hybrid“ ring with B- and E-field for other isotopes



	$G=\frac{g-2}{2}$	p/GeV/c	E_R/MV/m	B_V/T
proton	1.79	0.701	10	0
deuteron	−0.14	1.0	−4	0.16
^{3}He	−4.18	1.285	17	-0.05

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s}$$

$$\vec{\Omega} = \frac{e\hbar}{mc}\left[G\vec{B} + \left(G - \frac{1}{\gamma^2-1}\right)\vec{v} \times \vec{E} + \frac{1}{2}\eta(\vec{E} + \vec{v} \times \vec{B})\right]$$

$$\vec{d} = \eta\frac{e\hbar}{2mc}\vec{S}, \quad \vec{\mu} = 2(G+1)\frac{e\hbar}{2m}\vec{S}, \quad G = \frac{g-2}{2}$$

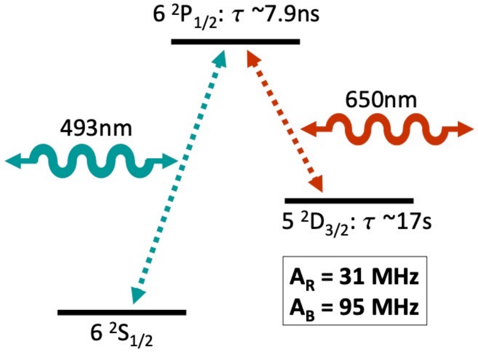
E.g. V. Anastassopoulos, …PF … et al., Rev Sci Intr. 87, 115116 (2016), *https://arxiv.org/pdf/2205.00830.pdf*

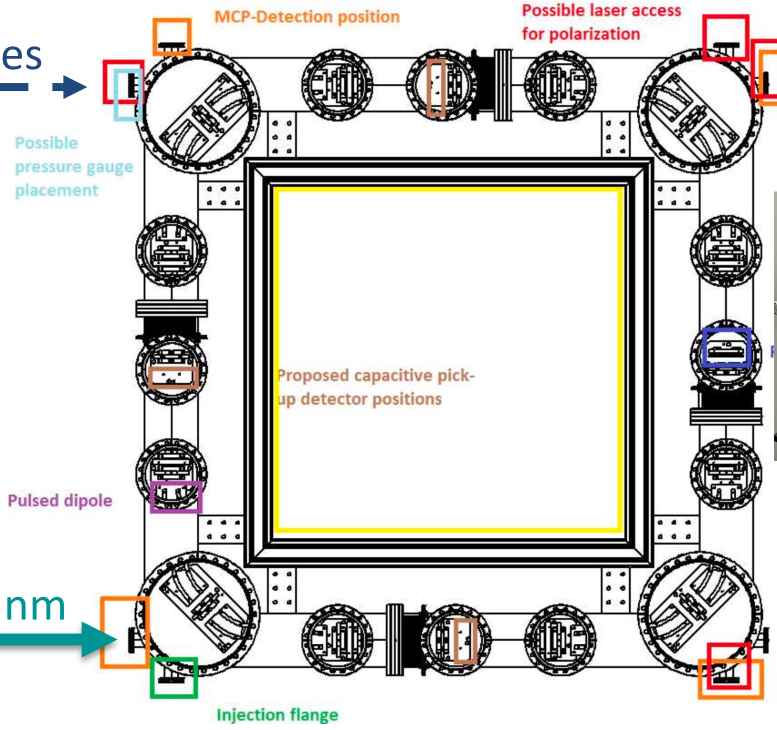
V. Bargmann, L. Michel and V. L. Telegdi, Phys. Rev. Lett. 2 (1959) 435.

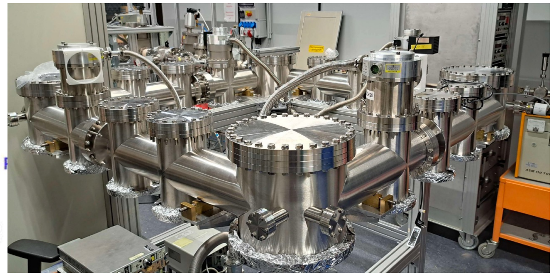
Technology demonstrator: table-top storage ring at TUM

- Non-relativstic electrostatic storage with polarized ^{138}Ba+ (spin-locking etc.)
- Tests systematics of pEDM
- Side product in future: ultra-light ALP & (electron)EDM search

30 keV, ^{138}Ba+ ion bunches







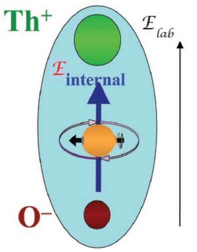
Laser 493 nm

Laser 650 nm

Side Note: electron EDM searches

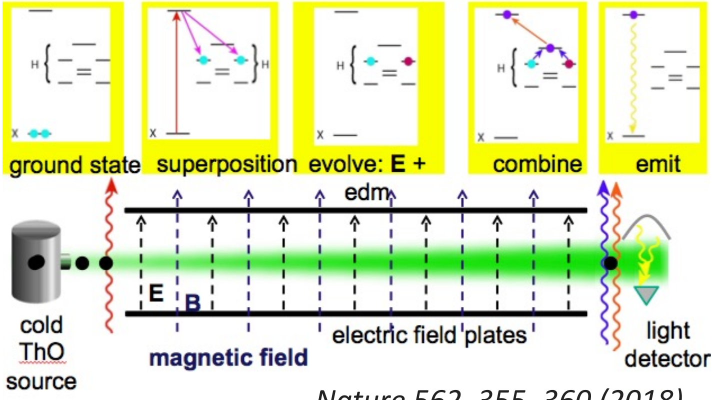
(Polyatomic) polar molecules/ions:

- ~ 100 GV/cm internal electric field, massive enhancement factors
- polarizable with small ext. E-field
- Small magnetic moment = low effect of B-field quality
- Lasers to select states
- Sensitivity to d_e, not to other parameters
- Lots of potential: long list of technological advancements



ThO:

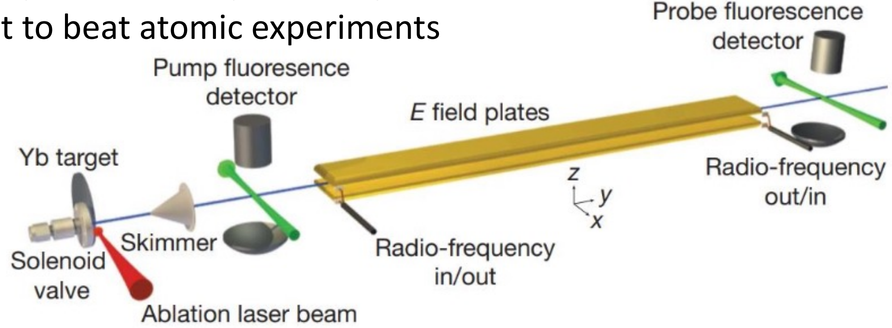
- Spin precession in cryogenic beam



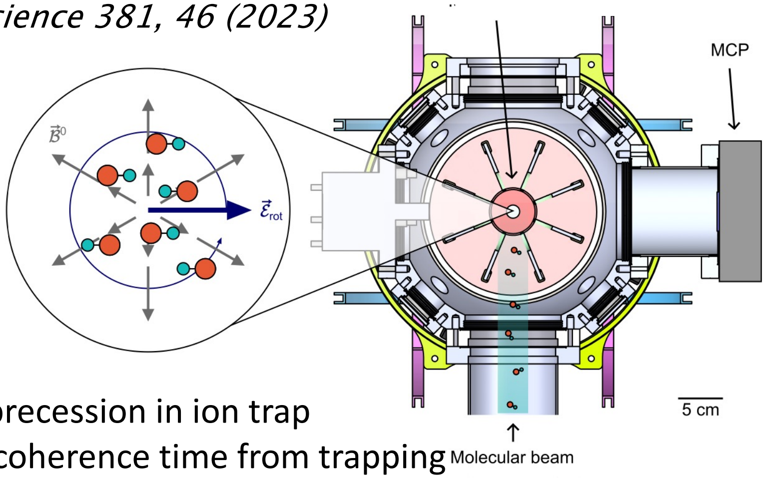
Nature 562, 355–360 (2018)

YbF:

- Spin precession in pulsed supersonic beam
- First to beat atomic experiments



HfF+: *Science 381, 46 (2023)*



- Spin precession in ion trap
- Long coherence time from trapping

…eEDM improvements

Laser cooling:
Longer observation time (linear)
Higher particle density (sqrt)
Much longer coherence time (linear)

Laser trapping:
Profits from other fields: rapid advances in technology
Allows assembly of molecules

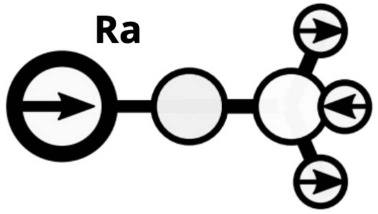
Polyatomic molecules:
Cooling techniques also work for complicated molecules
Large internal fields also present
Allows combination of deformed nuclei and trapping

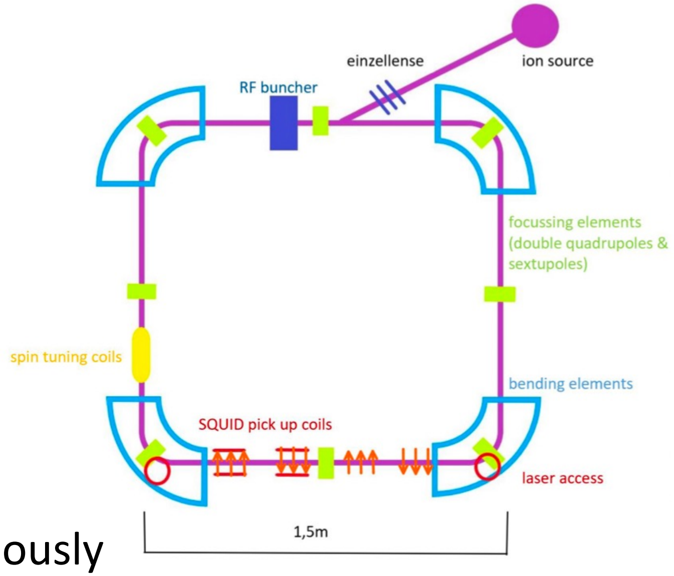
Q. Sci. & Tech. 5, 044011 (2020)

Electrostatic storage ring as particle trap:
Non-relativistic, fully electrostatic particle trapping
Laser and SQUID access to atomic state manipulation
Hours of storage times, different configurations simultaneously

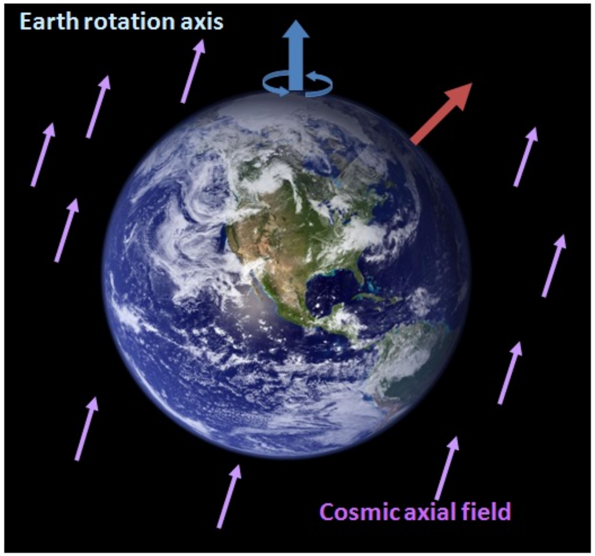
C. Brandenstein,… PF… et al., EPJ Web of Conferences 282, 01017 (2023)

$RaOCH3^+$ molecule ion





Exotic effects and EDMs



Sidereal or daily modulations of spin precession?

$$V = \frac{\hbar}{2}\gamma_n \, \sigma \cdot \mathbf{B} + \sigma \cdot \tilde{\mathbf{b}}$$

Best limit for free neutron: b < 2.10^{-20} eV

I. Altarev et al., PRL ***103****, 081602 (2009)*

More general approach... an EDM tensor?

$$V = b_i \sigma_i - \ \mu_{ij} \ \sigma_i B_j \ - \ d_{ij} \ \sigma_i E_j$$

(simplified...) $d_{ij} \approx \frac{e\hbar c}{\mathcal{E}_{\rm LV}}$

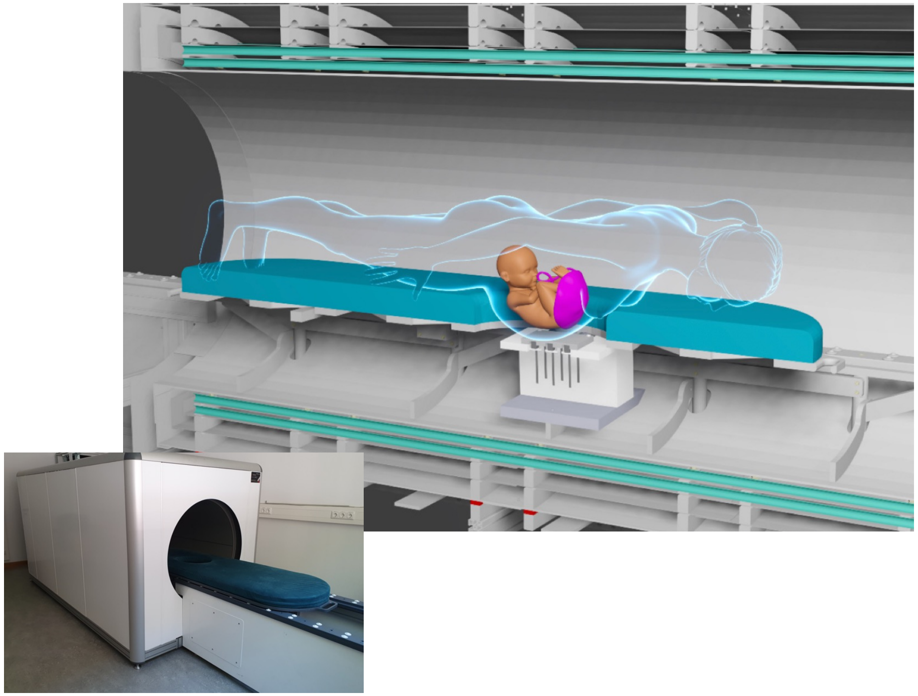
Energy scale → $\mathcal{E}_{\rm LV} > 10^{10}$ GeV

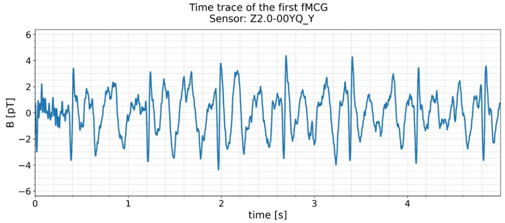
Later: Romalis et al., … > 10^{13} GeV

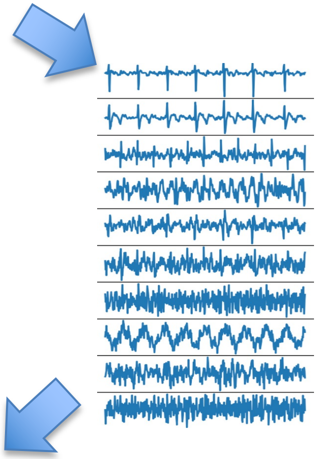
I. Altarev et al., EPL, 92 (2010) 51001

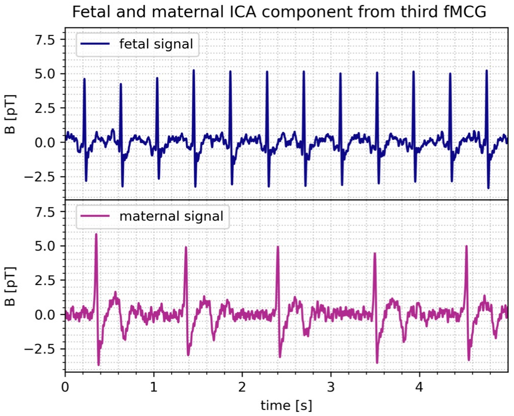
„4-pi magnetometry“ for EDM – spin-off: biomagnetic sensing

- Muscles and nerves produce magnetic fields, signals ~ pT level
- EDM measurements are sensitive to < aT at mHz, ~ 10 fT at 10 Hz
- Collaboration of TUM Ph/EI, German Heart Center: development of a new generation of fetal magnetocardiography (fMCG)









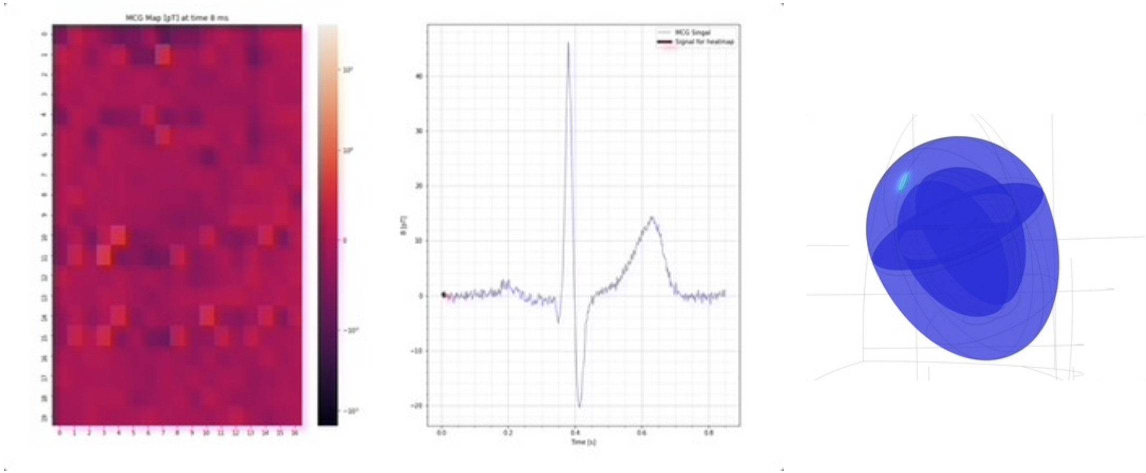
D. Wurm, PF et al., Journal of Clinical Medicine 12, 3380 (2023)

The TUM low field lab

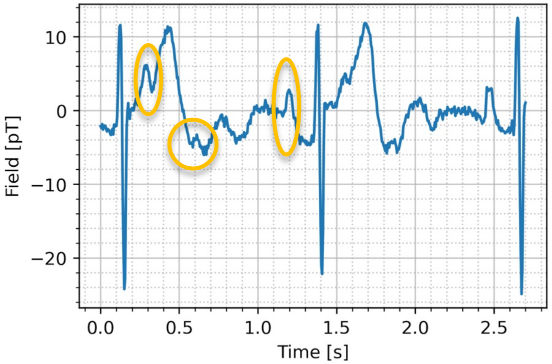
- Just in commissioning phase (sign-off **this week**!)
- Based on leading TUM expertise in low-field research
- Already now: most silent magnetic noise spectra every measured at low frequency!
- Hub for (4-pi) magnetometer developments (like ^{129}Xe EDM)
- New features in human heart beat
- Spatial reconstruction of heart muscle function from non-invasive magnetic detection possible

World-leading low field environment:

First spatially resolved magnetic heart maps



Magnetic measurements are not ECG signals:



Summary

- EDM searches: *quantum sensing* in particle physics
- Every aspect in an EDM experiment needs to be a world-record
- EDMs and DM/ALP physics related also experimentally, with synergies

- Most promising current-gen nEDM search: PanEDM (best existing UCN source)
- New approaches are comparably large-scale collaborations and have significant discovery potential:
  - Future nEDM, pEDM and ^{129}Xe EDM (magnetometry)
  - Massive (but unconventional) use of semiconductor technology and TES sensors

- EDM magnetometry offers extremely sensitive tools: breakthroughs with big impact may happen beyond the EDM searches (e.g. new insights in the human heart and brain!)