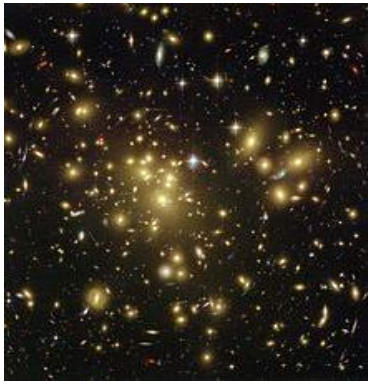
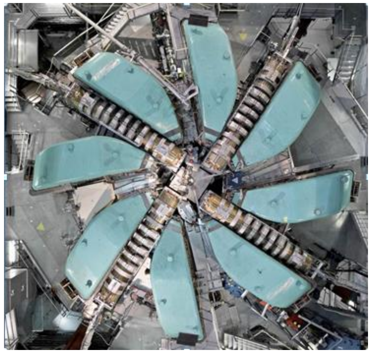
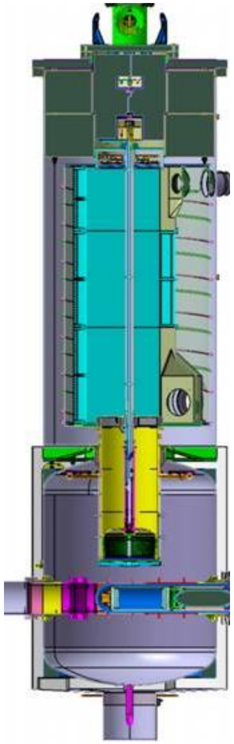
EDM search experiments

WE Heraeus seminar
‘Towards Storage Ring EDM Measurements’
March 29-31, 2021

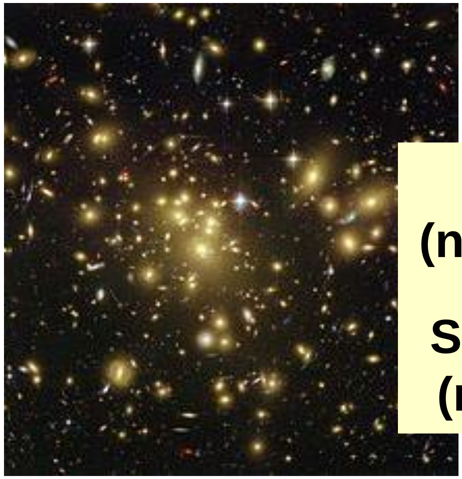
K.Kirch, ETH Zurich – PSI Villigen, Switzerland



Some motivation

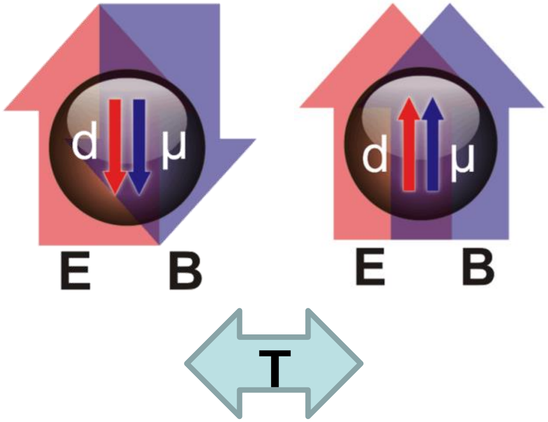
- Permanent EDM of fundamental spin systems are the most sensitive probes of CPV with no SM background yet
- Experiments test new physics (way) beyond TeV scale
- Explanations of the Baryon Asymmetry of the Universe require additional CP violation; could show in EDM
- Hadronic EDM measure θ_{QCD}, e.g. $\theta_{QCD} \approx 10^{16}$x d_n / *e*cm
- θ_{QCD}= 0 might be due to axions; EDM very sensitive probe



Observed:
$(n_B\text{-}n_{\bar{B}})/n_\gamma=6\text{x}10^{-10}$

SM expectation:
$(n_B\text{-}n_{\bar{B}})/n_\gamma \sim 10^{-18}$

Sakharov 1967:
B-violation
C & CP-violation
non-equilibrium
JETP Lett.5(1967)24

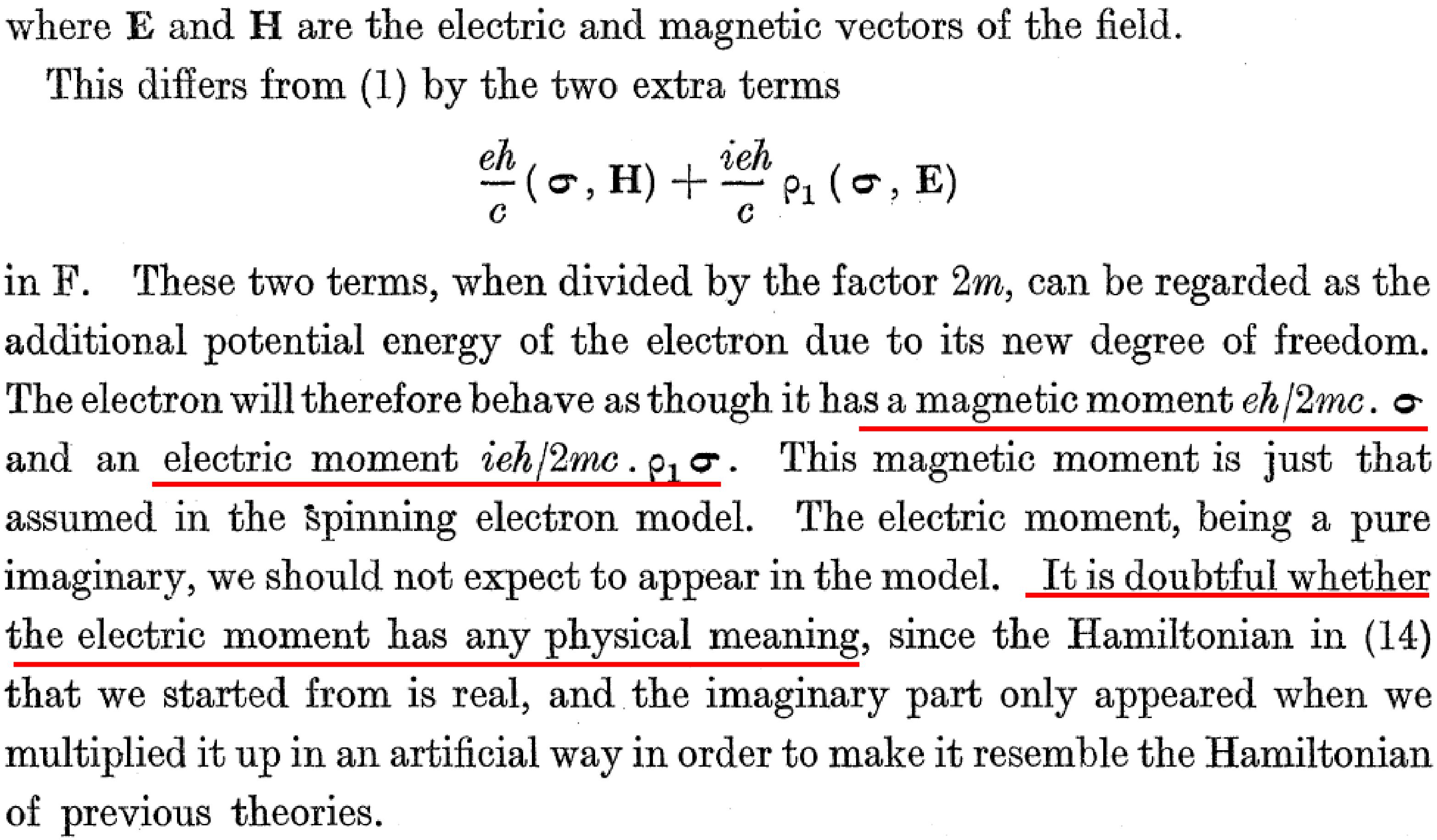


PROCEEDINGS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Quantum Theory of the Electron

P. A. M. Dirac

Proc. R. Soc. Lond. A 1928 **117**, doi: 10.1098/rspa.1928.0023,
published 1 February 1928

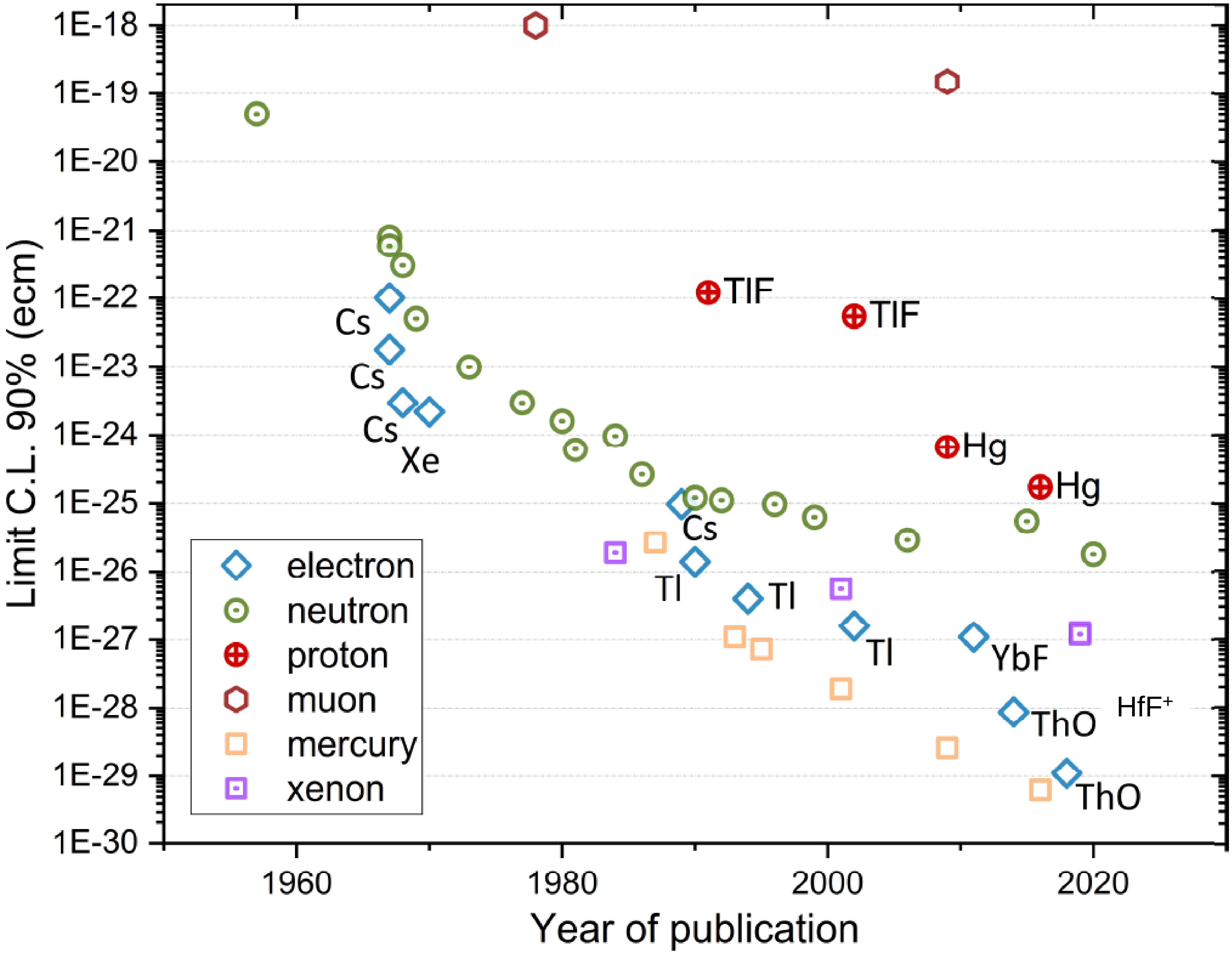


where **E** and **H** are the electric and magnetic vectors of the field.

This differs from (1) by the two extra terms

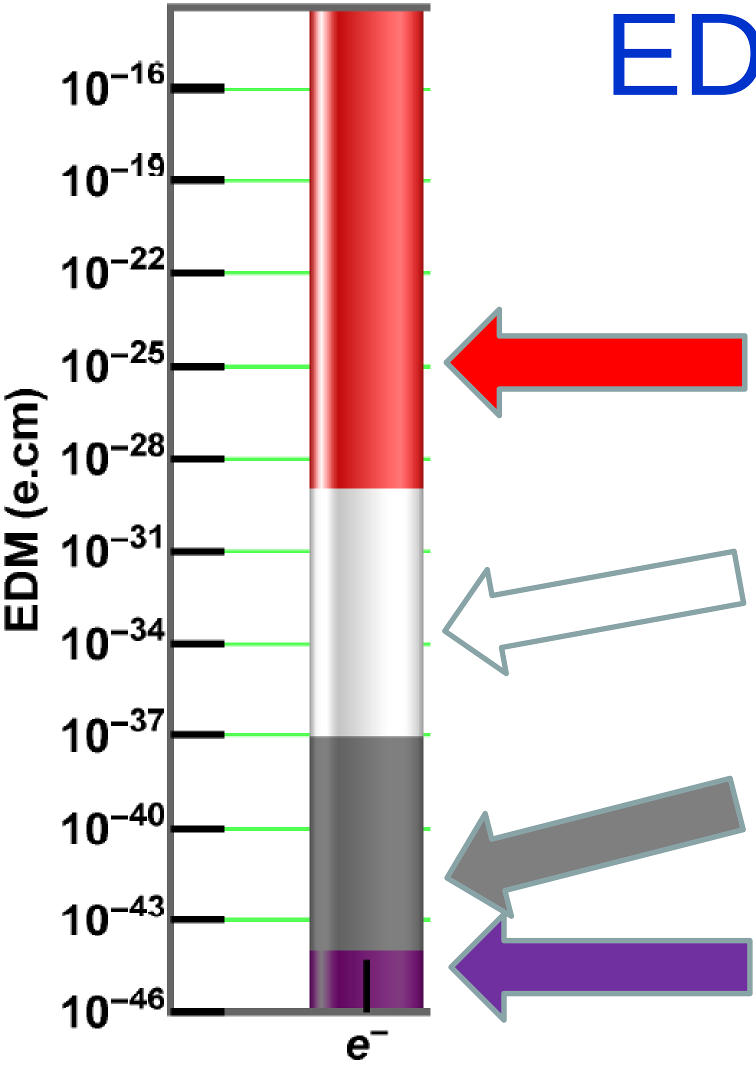
$$\frac{eh}{c}(\boldsymbol{\sigma}, \mathbf{H}) + \frac{ieh}{c}\rho_1(\boldsymbol{\sigma}, \mathbf{E})$$

in F. These two terms, when divided by the factor $2m$, can be regarded as the additional potential energy of the electron due to its new degree of freedom. The electron will therefore behave as though it has a magnetic moment $eh/2mc \, . \, \boldsymbol{\sigma}$ and an electric moment $ieh/2mc \, . \, \rho_1 \boldsymbol{\sigma}$. This magnetic moment is just that assumed in the spinning electron model. The electric moment, being a pure imaginary, we should not expect to appear in the model. It is doubtful whether the electric moment has any physical meaning, since the Hamiltonian in (14) that we started from is real, and the imaginary part only appeared when we multiplied it up in an artificial way in order to make it resemble the Hamiltonian of previous theories.



EPJ Web of Conferences **234**, 01007 (2020) P. Schmidt-Wellenburg, KK

EDM display



The experimental constraint, can be direct or indirect and under certain assumptions*

'safe' BSM discovery territory

Estimated θ_{QCD} contribution**, we have assumed $\theta_{QCD} < 1E\text{-}10$ * everywhere

Estimated CKM contribution***

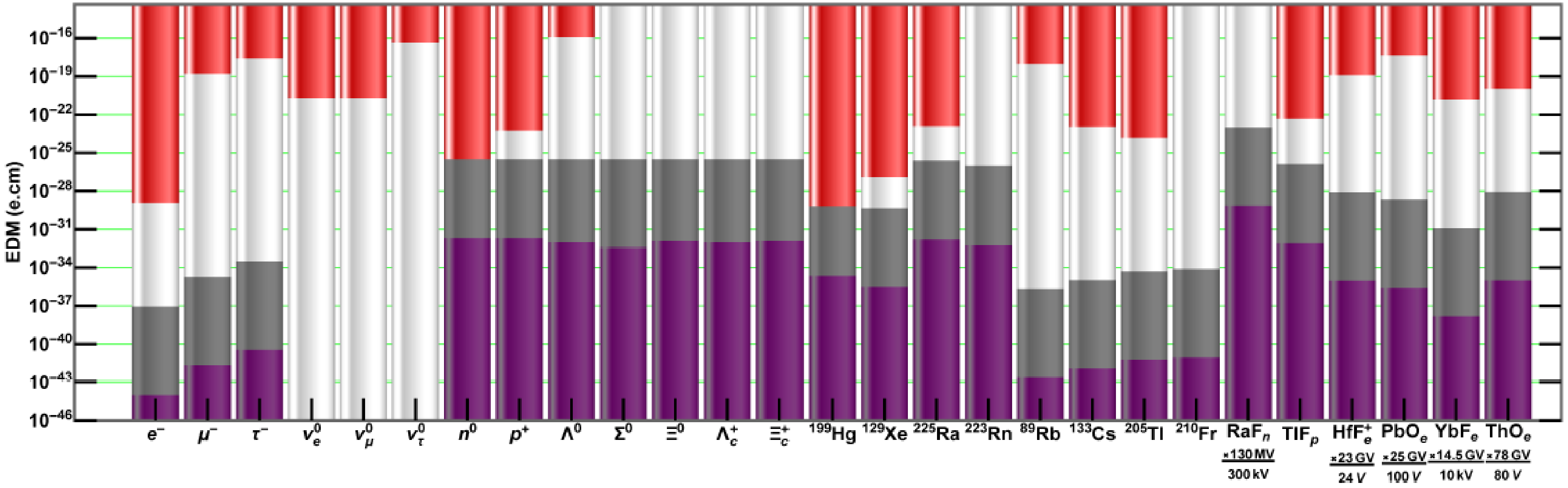
---

* Often a single source of CPV is assumed, e.g. eEDM for molecular EDM or θ_{QCD} for n, 199Hg;

** see Ghosh&Sato, PLB777(2018)335 for leptons

*** see Pospelov&Ritz, PRD89(2014)056006; eEDM 1E-38 → 1E-44 ecm

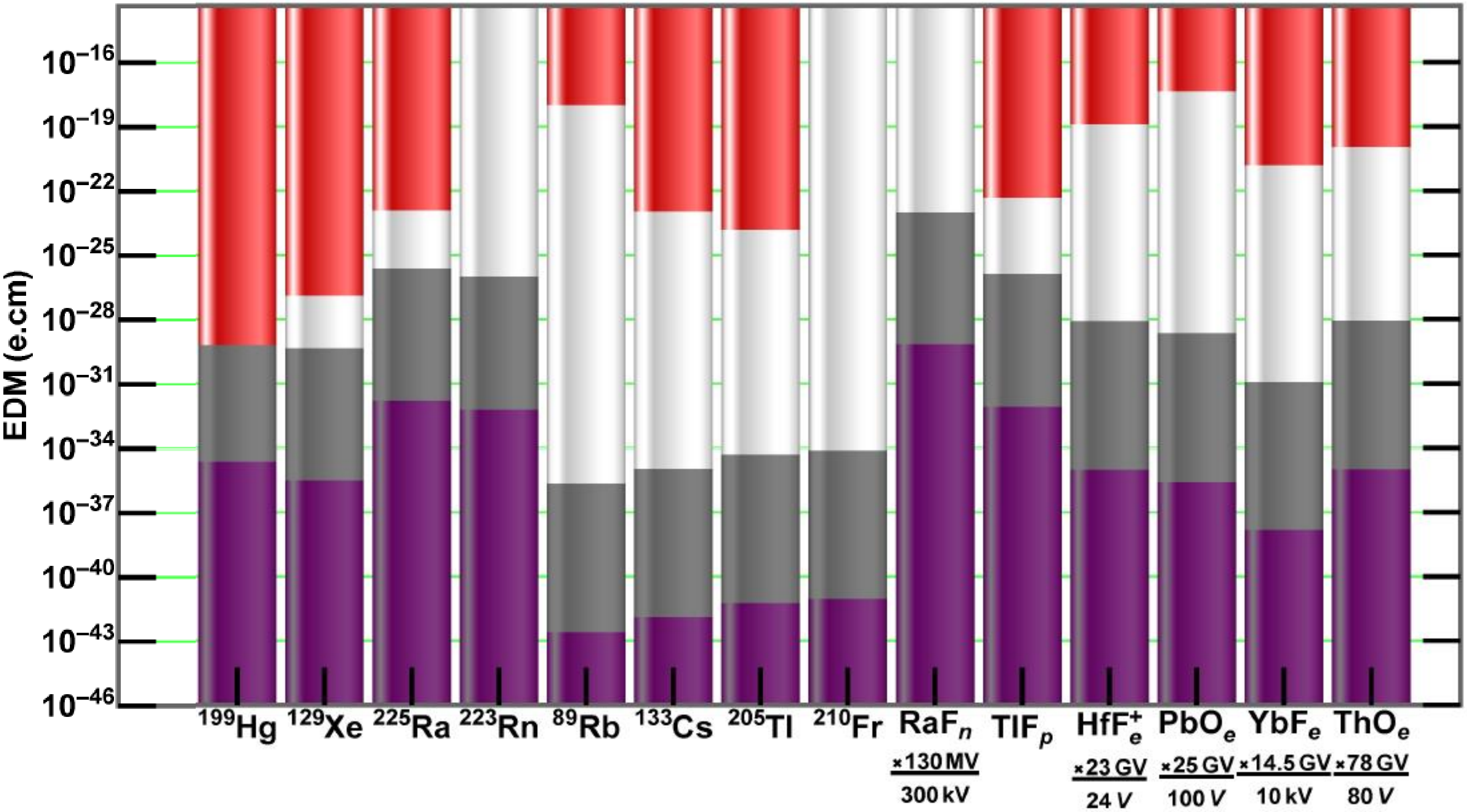
An overview



Disclaimer: CKM and strong CP contributions are sometimes rough guesses → would need some more careful evaluation

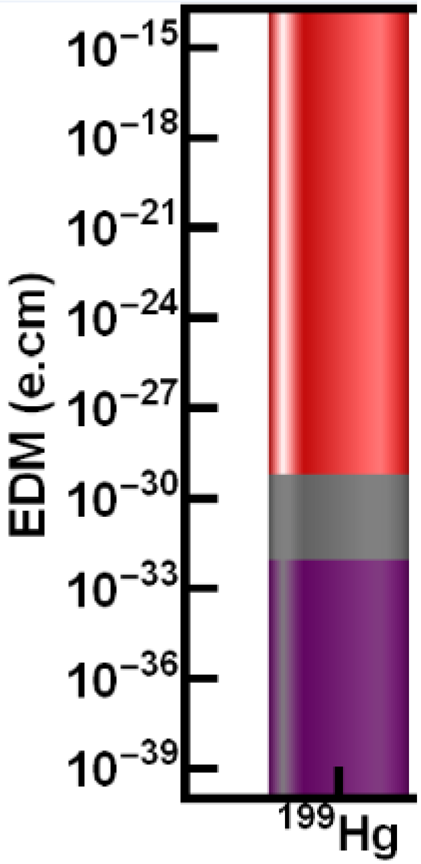
Graphics courtesy P. Mohanmurthy

Atoms and molecules



Extract the best limits for eEDM, CPV eN interactions and nuclear moments.
Need to disentangle various sources. Need atomic and nuclear theory.
Uncertainties in the theoretical calculations can be unknown and large.

The strongest experimental limit: ^{199}Hg



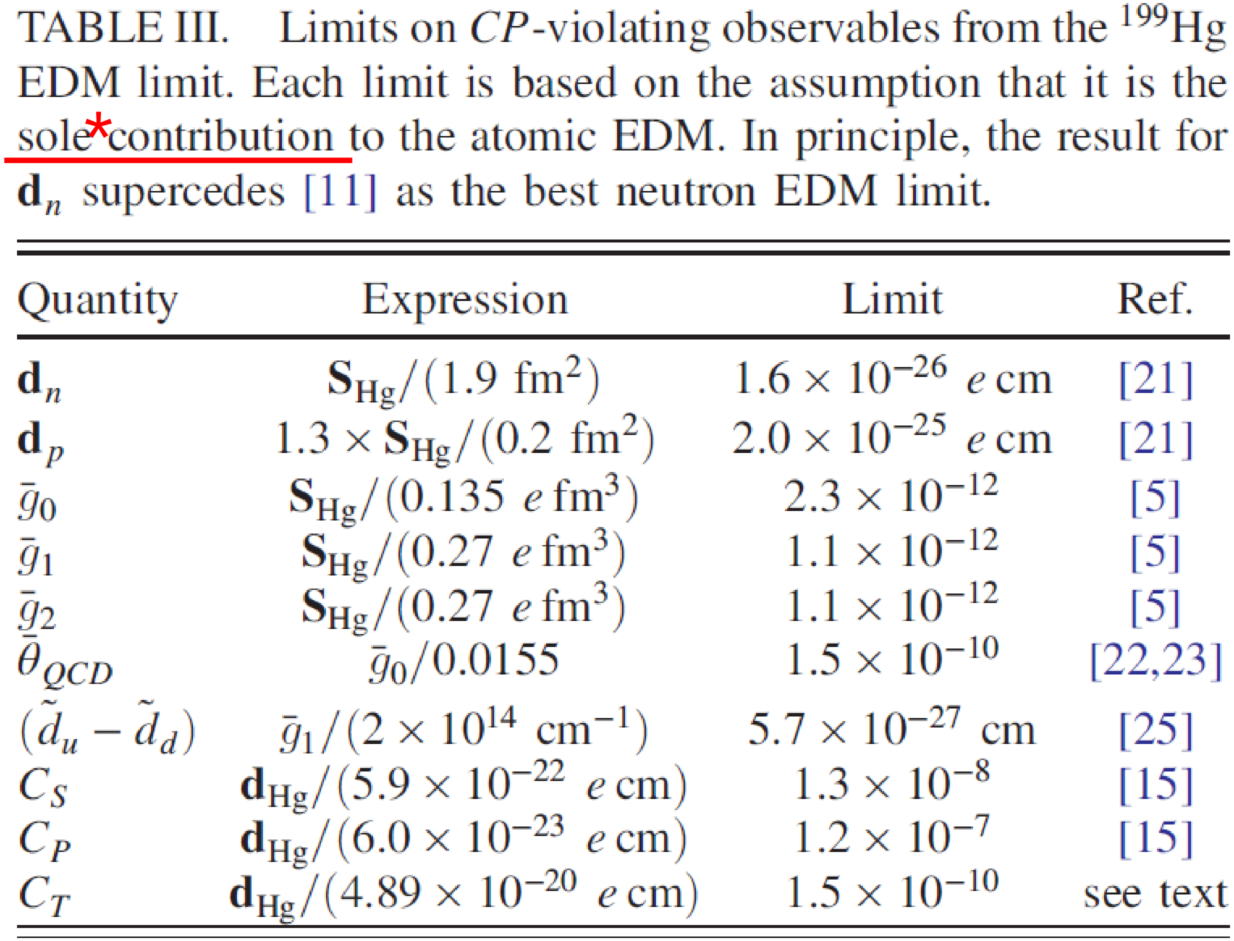


TABLE III. Limits on CP-violating observables from the ^{199}Hg EDM limit. Each limit is based on the assumption that it is the sole* contribution to the atomic EDM. In principle, the result for $\mathbf{d}_n$ supercedes [11] as the best neutron EDM limit.

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

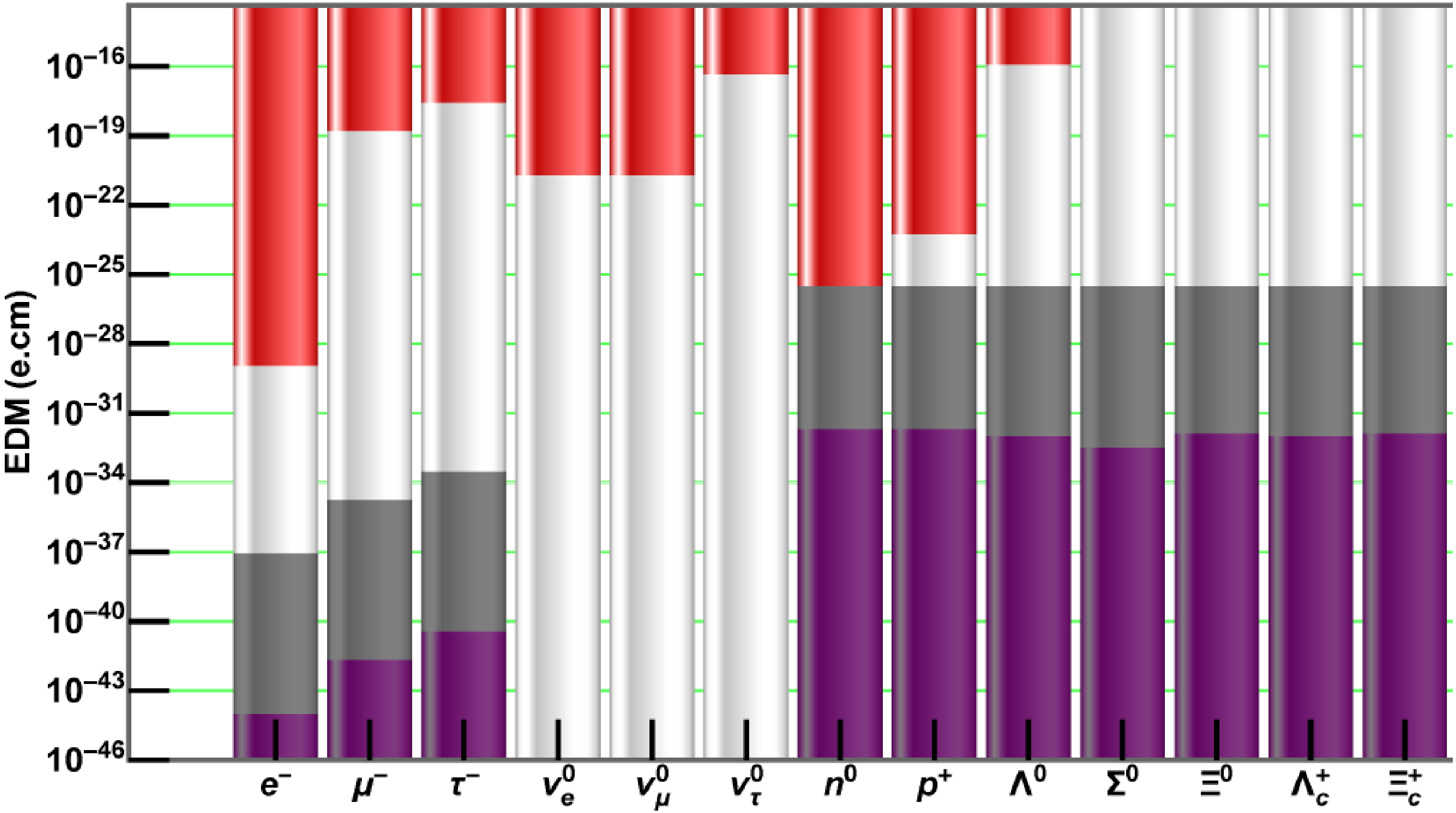
$$|d_{\mathrm{Hg}}| < 7.4 \times 10^{-30} e\,\mathrm{cm}\ (95\%\ \mathrm{C.L.})$$

Graner et al., PRL116(2016)161601

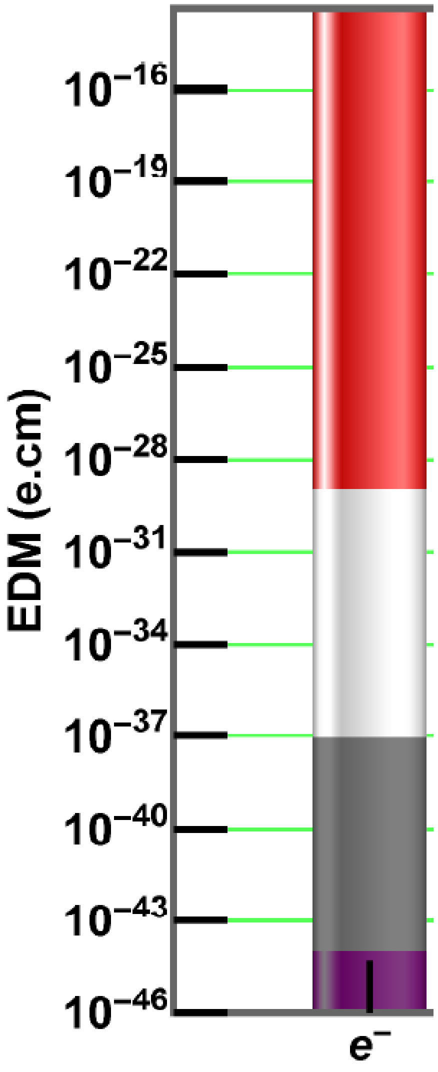
* e.g. otherwise θ_{QCD} ~< 1E-6

Chupp, Ramsey-Musolf, PRC91(2015)035502

Particles



A mix of indirect and direct bounds



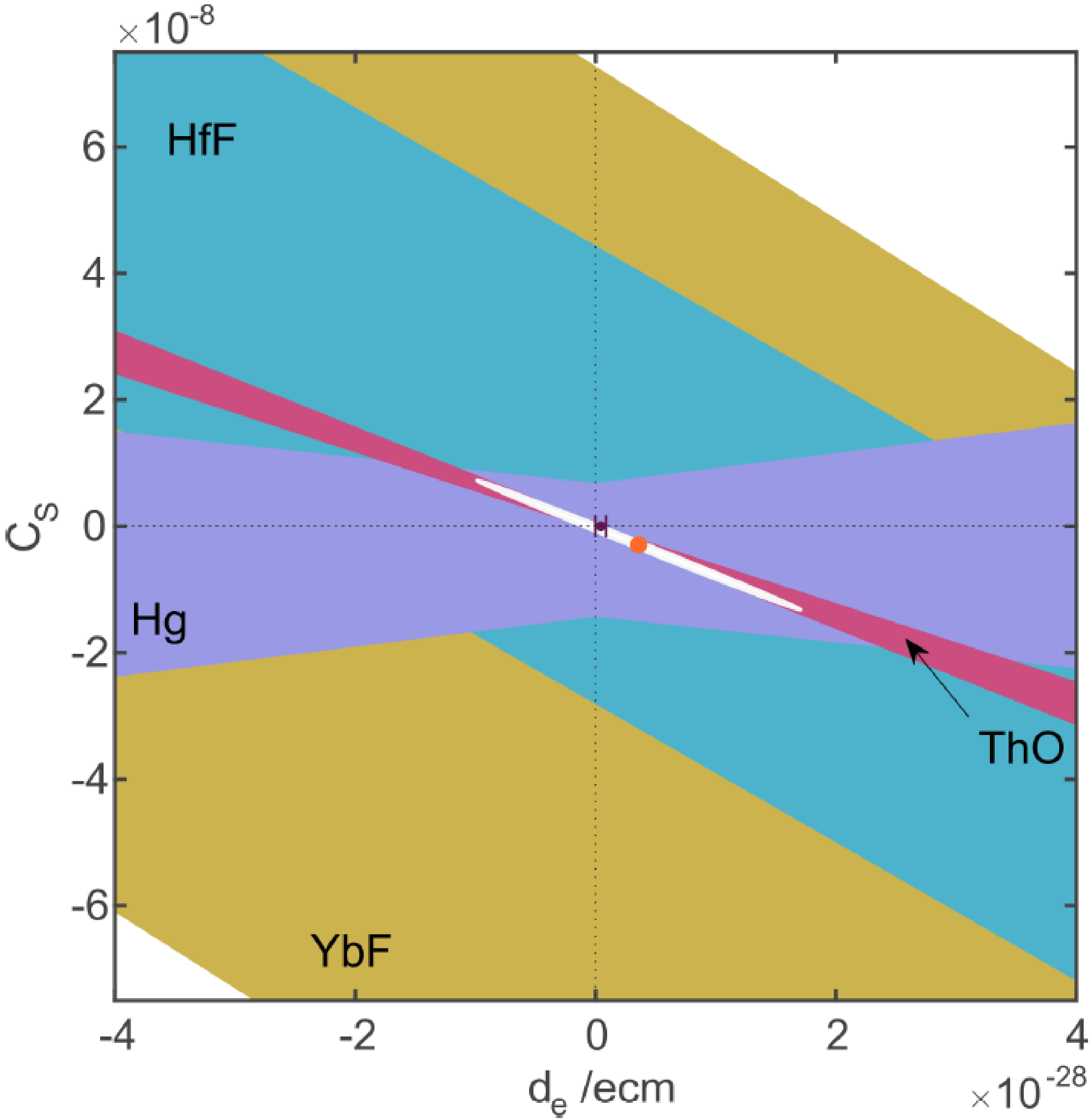
Electron:

The tightest EDM limit on a fundamental fermion

System	Electron EDM limit	Latest reference	Improving
$^{232}Th^{16}O$	2.0E-29 ecm	**Nature562(2018)355**	y
$^{180}Hf^{19}F+$	13E-29 ecm	**PRL119(2017)153001**	y
$^{174}Yb^{19}F$	105E-29 ecm	**NJP14(2012)103051**	y

Remarkably: ^{199}Hg and ‘sole source’ → eEDM < 104E-29 ecm

Combining results

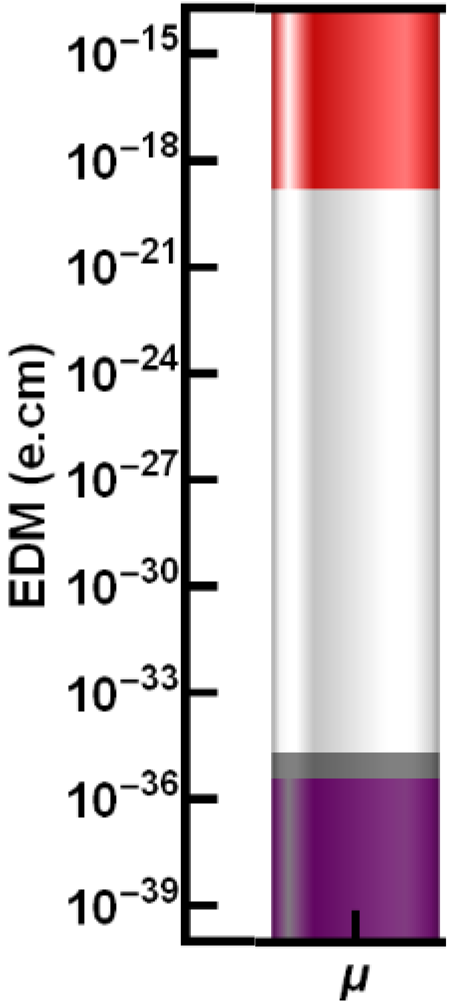


EPJ Web of Conferences **234**, 01007 (2020)

update of Fleig, Jung, JHEP07(2018)012

Muon:

The best direct EDM limit on a fundamental fermion



- Side analysis of muon g-2 experiment

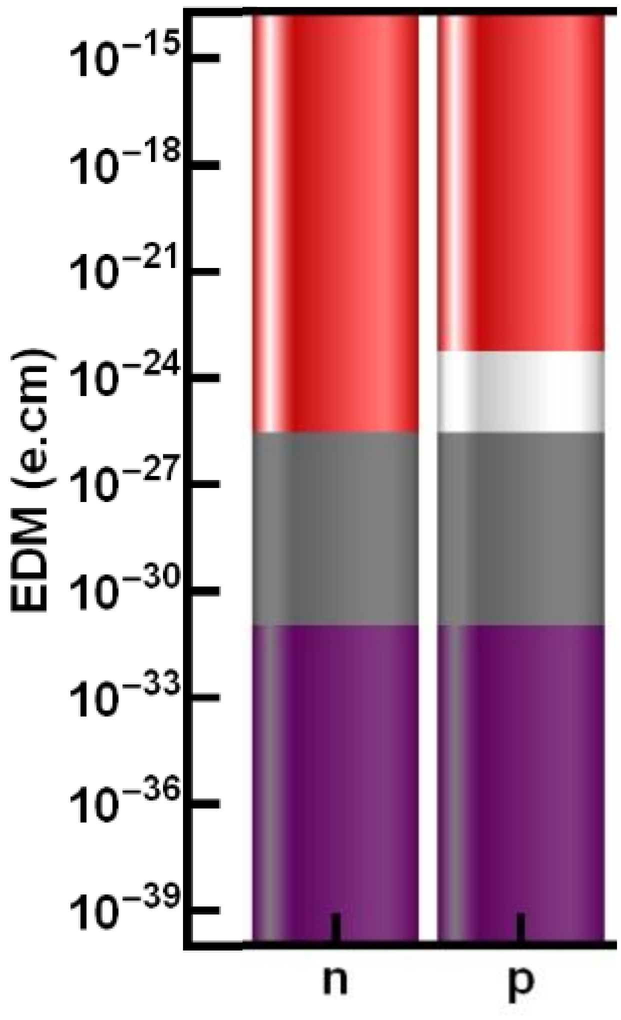
  $$|d_\mu| \leq 1.8 \times 10^{-19}\ e\,\mathrm{cm}\ (95\%\ \mathrm{C.L.}),^{*}$$

  Bennett et al., RD80(2009)052008

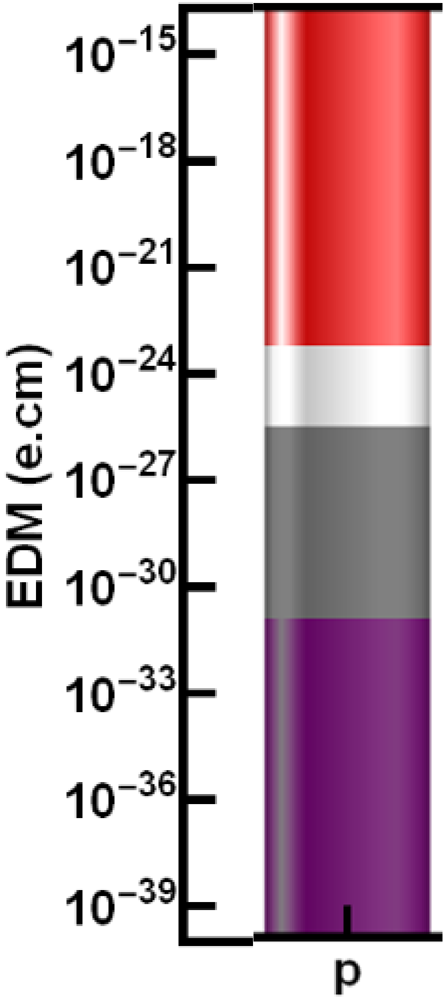
- Improvement to ~1E-21 ecm possible as byproduct of new g-2
- Improvement to few E-23 ecm with dedicated (small) storage ring
  - demonstrator for frozen spin ring EDM
  - BSM theory motivation!?

*indirectly, using e-EDM Limit and sole source assumption: < 0.9E-19 ecm, see PRD98(2018)113002

Neutron and Proton



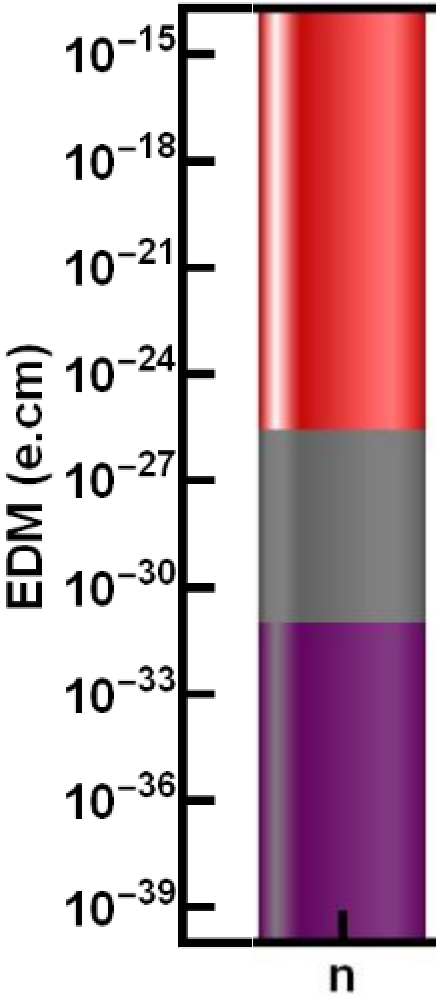
- Present best proton (and neutron) EDM limit derived from ^{199}Hg under the 'sole source assumption'.
- Present best direct nEDM limit 1.8E-26 ecm (**Abel et al., PRL124(2020)081803**)
- neutron EDM constrains $\theta_{QCD} <$ 1E-10 under single source assumption (as does ^{199}Hg)
- finite neutron and proton EDM could eventually support or rule out θ_{QCD} as source of EDM signals together with advanced lattice QCD



Proton

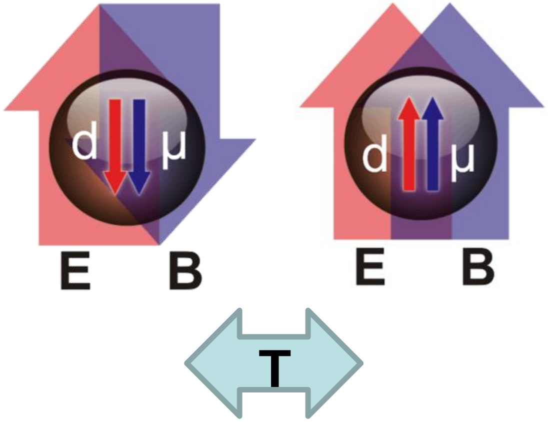
- pEDM
  - Storage ring for p, d, …: JEDI, Storage Ring Collaboration, CPEDM
    - Projecting 10^{-29}ecm sensitivity
    - Staged approach with precursor at COSY, demonstrator ring, full pEDM ring
  - Using ^{205}TlF molecules: CeNTREX
    - Projecting $3x10^{-26}$ecm pEDM sensitivity with generation-1 TlF beam
    - Expecting 10-100x improvement when implementing generation-2 laser cooling

Neutron



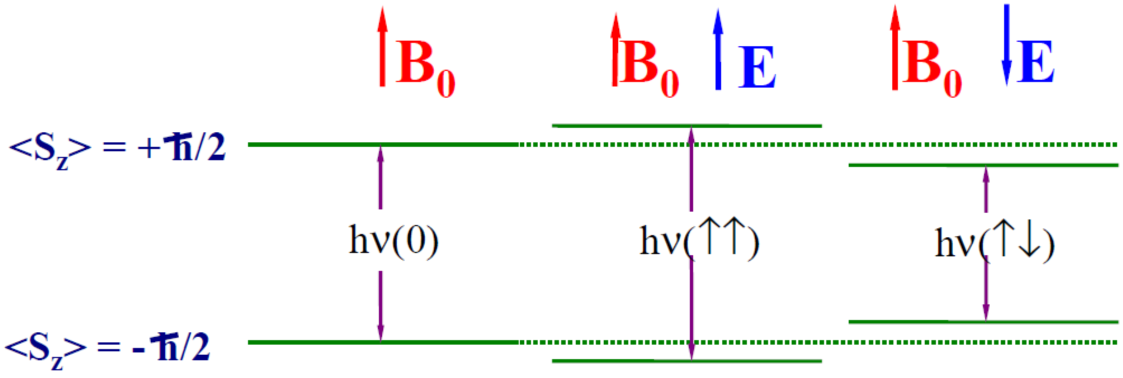
- Several nEDM efforts world-wide: presently leading effort at PSI
  (more at SNS, ILL, LANL, TRIUMF, PNPI, ESS)
- nEDM: the prototype of experimental EDM search for symmetry violations, since 1950
- nEDM poses the strong CP problem
- together with EDM limits of the e^- and ^{199}Hg giving some of the tightest BSM constraints
- Discovery potential at the current limit; could be SM-QCD contribution

How to measure electric dipole moments ?



How to measure electric dipole moments ?

- Measure spin precession frequencies in electric (and magnetic) fields

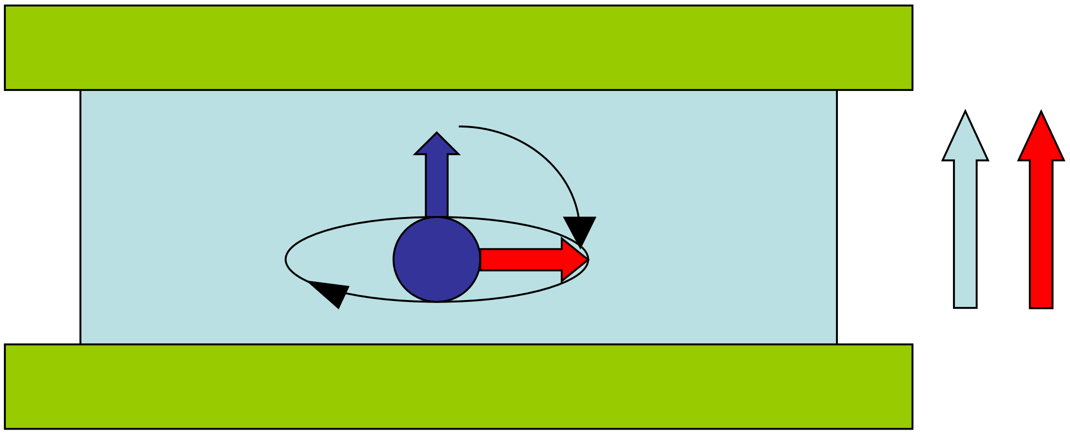


How to measure electric dipole moments ?

- Measure spin precession frequencies in electric (and magnetic) fields

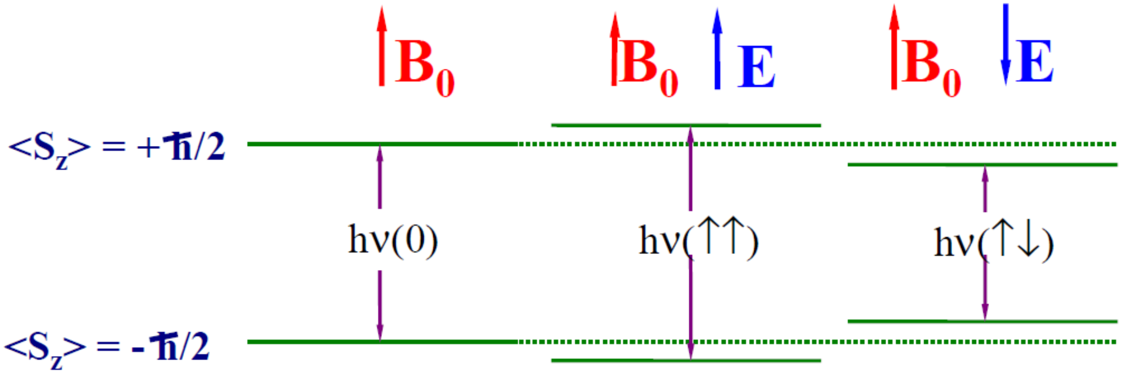
- If that doesn’t work: try something else, like
  - cross sections
  - T / CP odd decay correlations
  - …

How to measure the neutron (or other) electric dipole moment ?



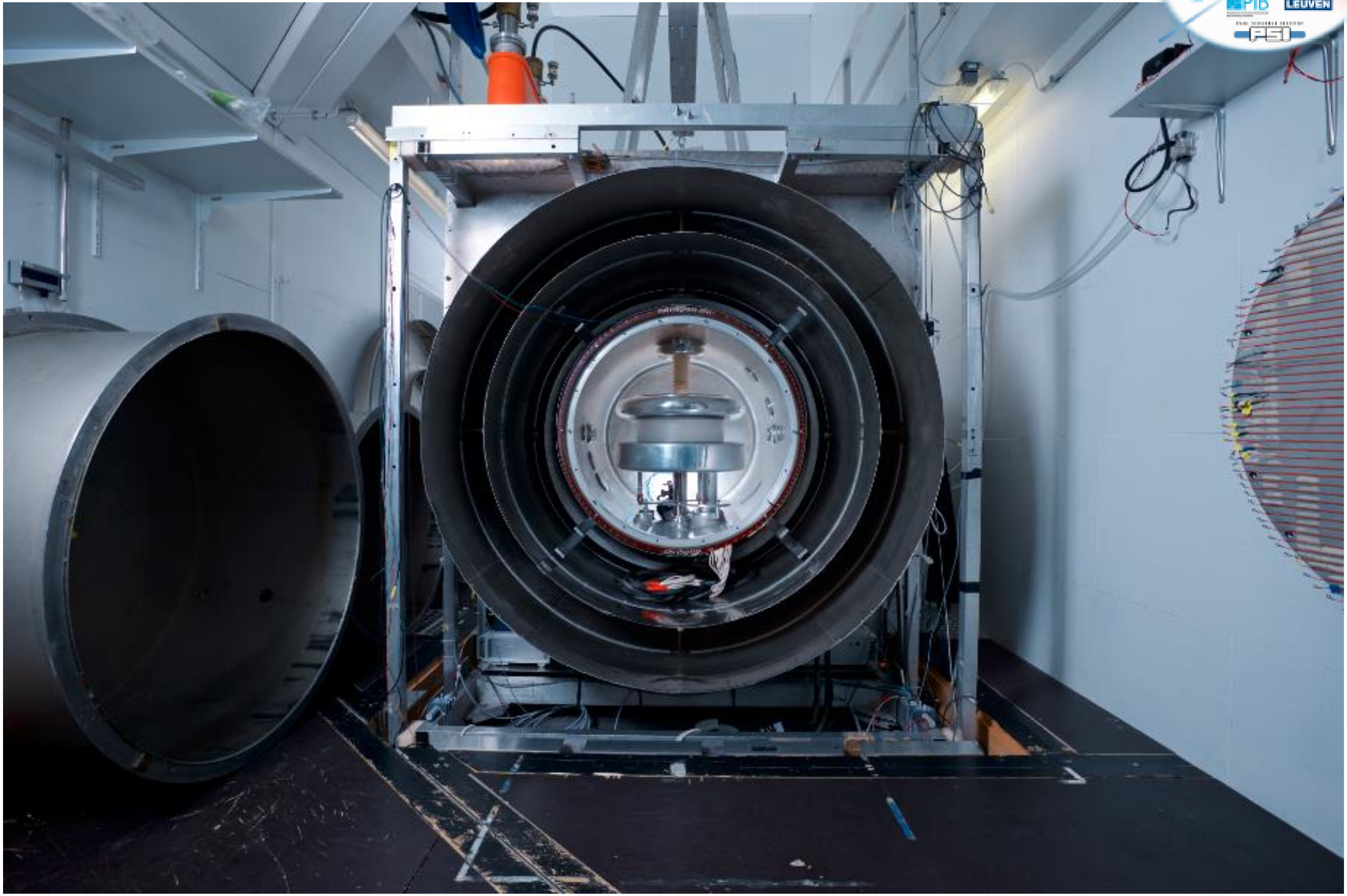
$$h\nu_{\uparrow\uparrow} = 2\,(\mu B + d_n E)$$
$$h\nu_{\uparrow\downarrow} = 2\,(\mu B - d_n E)$$

$$h\Delta\nu = 4\, d_n E$$

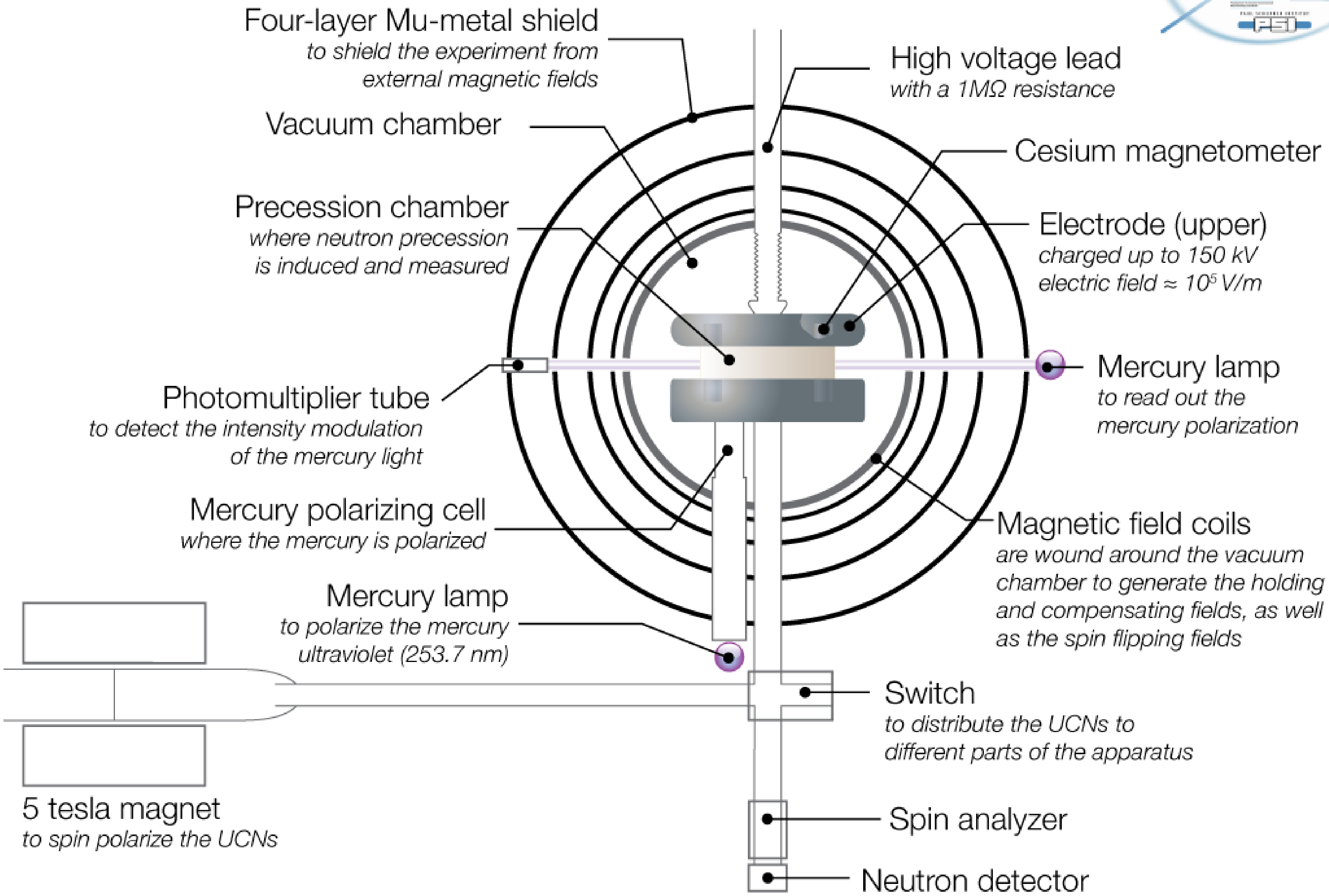


$$\sigma(d_n) = \frac{\hbar}{2\alpha E T\sqrt{N}}$$

nEDM at PSI



The nEDM spectrometer



Four-layer Mu-metal shield
to shield the experiment from external magnetic fields

Vacuum chamber

Precession chamber
where neutron precession is induced and measured

Photomultiplier tube
to detect the intensity modulation of the mercury light

Mercury polarizing cell
where the mercury is polarized

Mercury lamp
to polarize the mercury ultraviolet (253.7 nm)

5 tesla magnet
to spin polarize the UCNs

High voltage lead
with a 1MΩ resistance

Cesium magnetometer

Electrode (upper)
charged up to 150 kV
electric field ≈ 10^5 V/m

Mercury lamp
to read out the mercury polarization

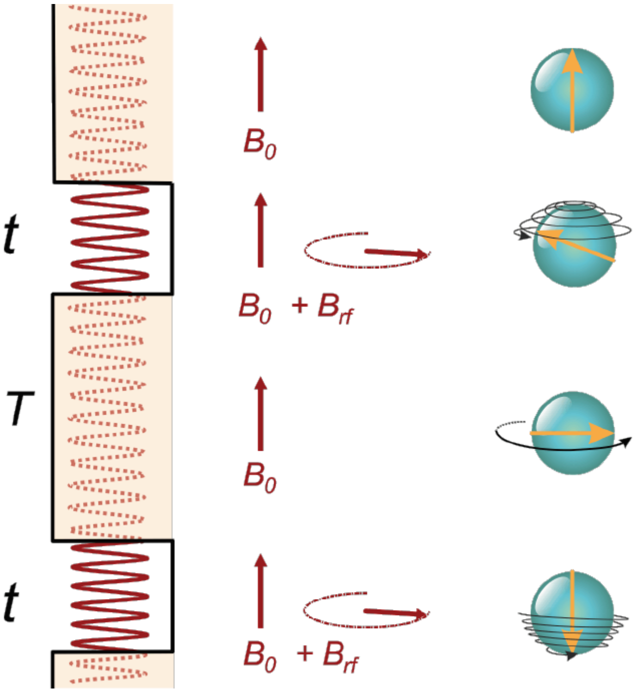
Magnetic field coils
are wound around the vacuum chamber to generate the holding and compensating fields, as well as the spin flipping fields

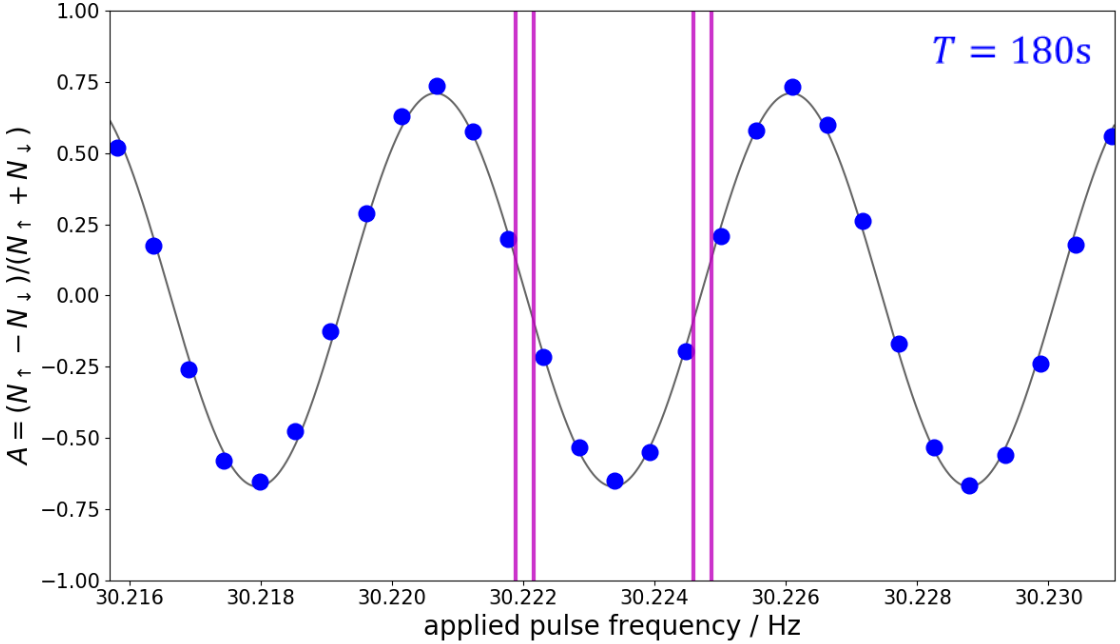
Switch
to distribute the UCNs to different parts of the apparatus

Spin analyzer

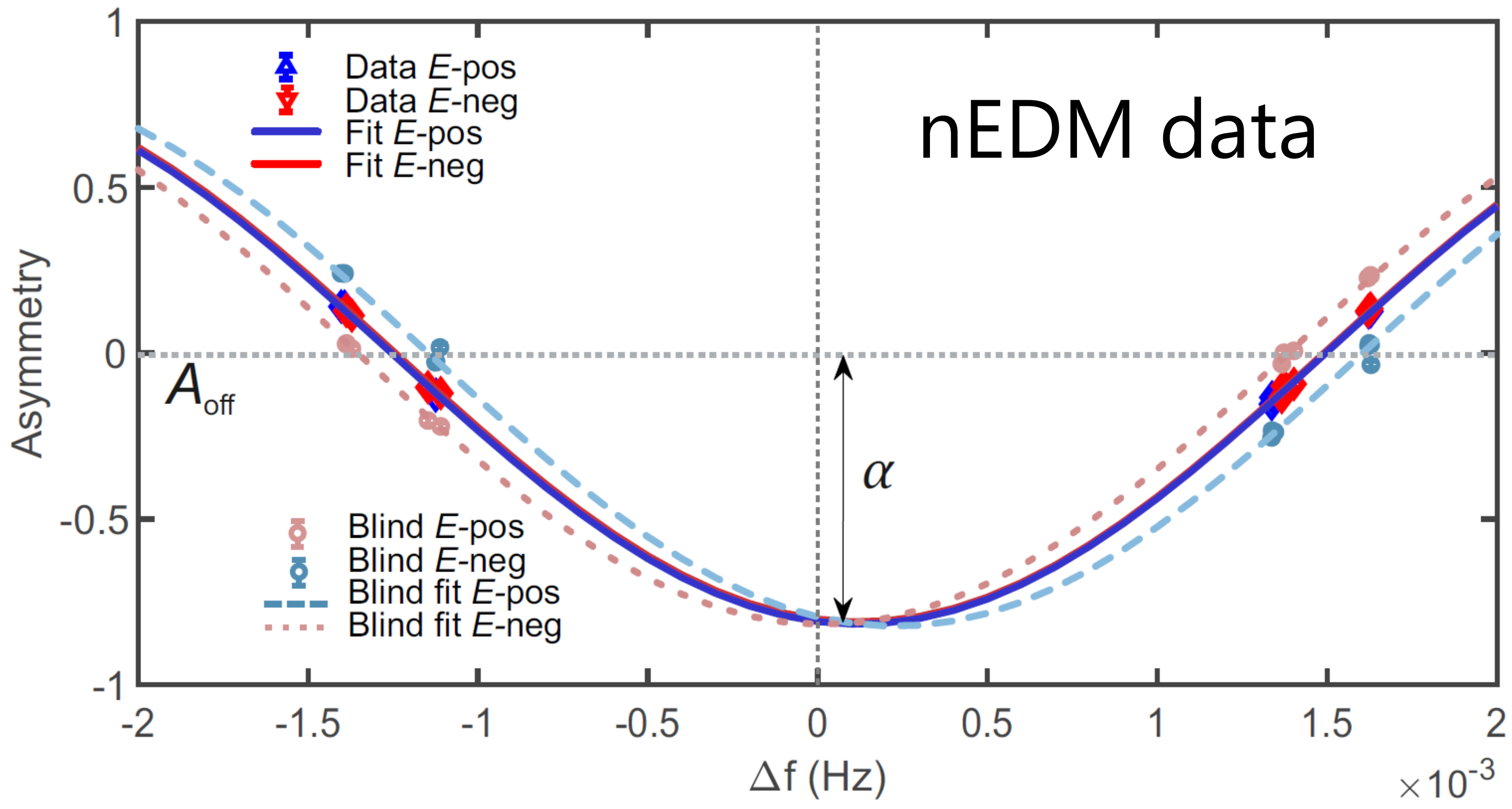
Neutron detector

Ramsey’s method





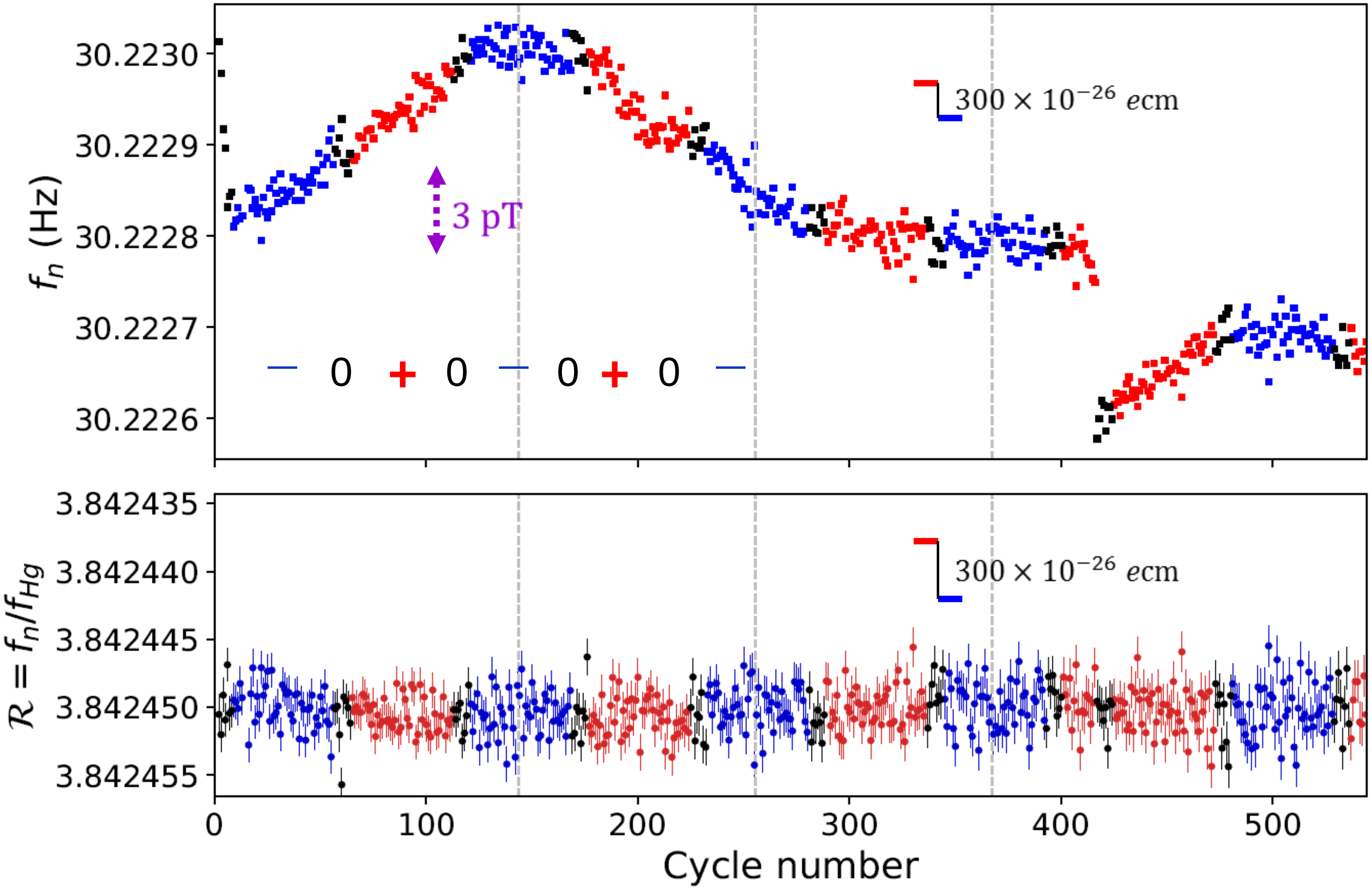
Statistical sensitivity: $\sigma d_n = \dfrac{\hbar}{2\,\alpha\, E\, T\sqrt{N}}$



1 cycle (5 mins):

- **We set the applied frequency**
- **We measure A**
- **We get 1 value for f_n**

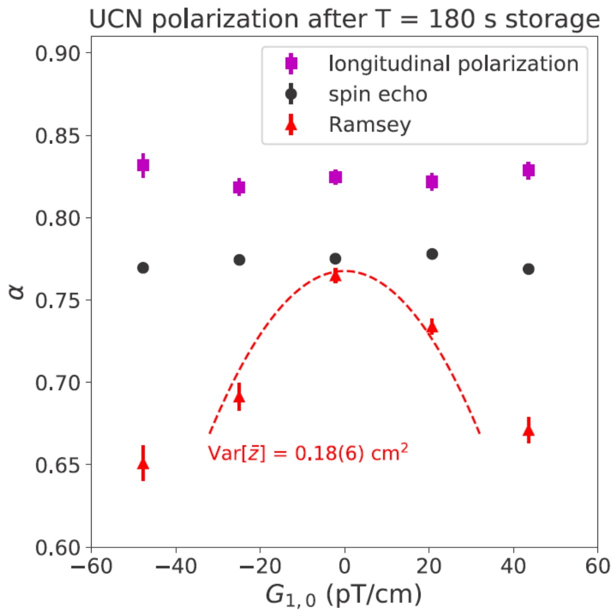
A sequence of cycles (nEDM data)



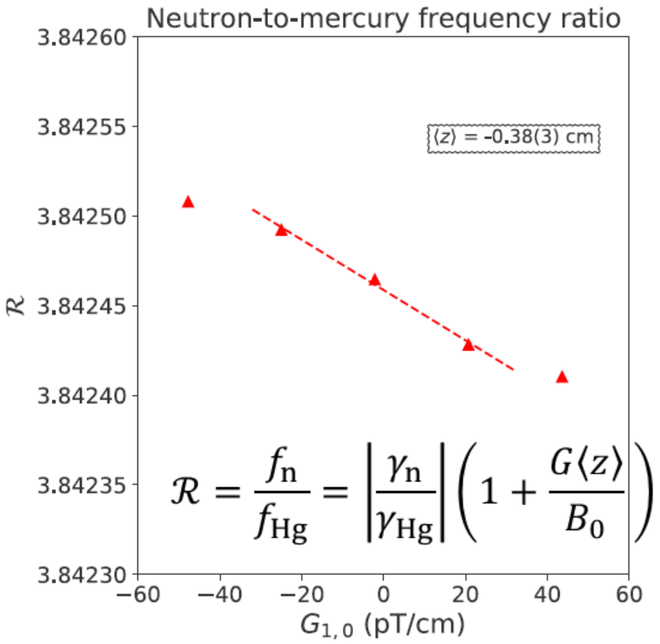
B-field fluctuations (random and correlated with E) are corrected for at each cycle with the mercury magnetometer by measuring $f_{\mathrm{Hg}} = \frac{\gamma_{\mathrm{Hg}}}{2\pi} B$

Control of the B-field gradients

1) UCN magnetic depolarization



2) Gravitational shift



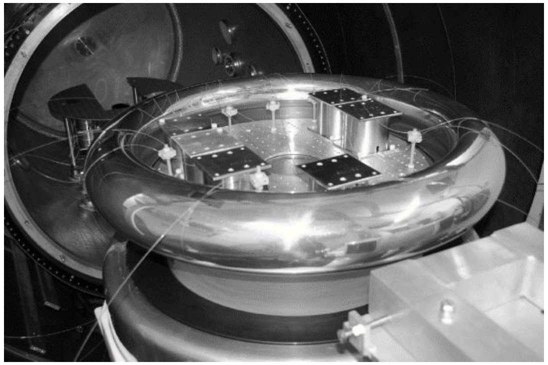
$$\mathcal{R} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right|\left(1 + \frac{G\langle z\rangle}{B_0}\right)$$

PHYSICAL REVIEW A **99**, 042112 (2019)

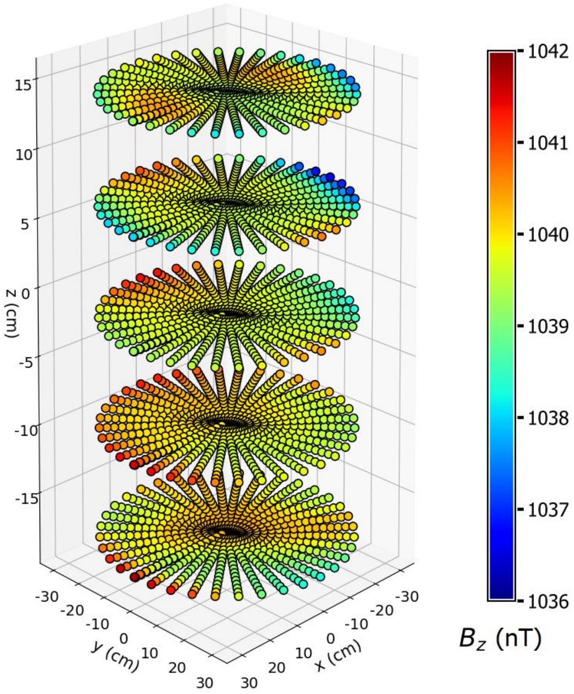
Magnetic-field uniformity in neutron electric-dipole-moment experiments

Control of the B-field gradients

3) 15 Cesium magnetometers



Optically Pumped Cs Magnetometers Enabling a High-Sensitivity Search for the Neutron EDM,
Phys.Rev. A 101 (5) (2020) 053419

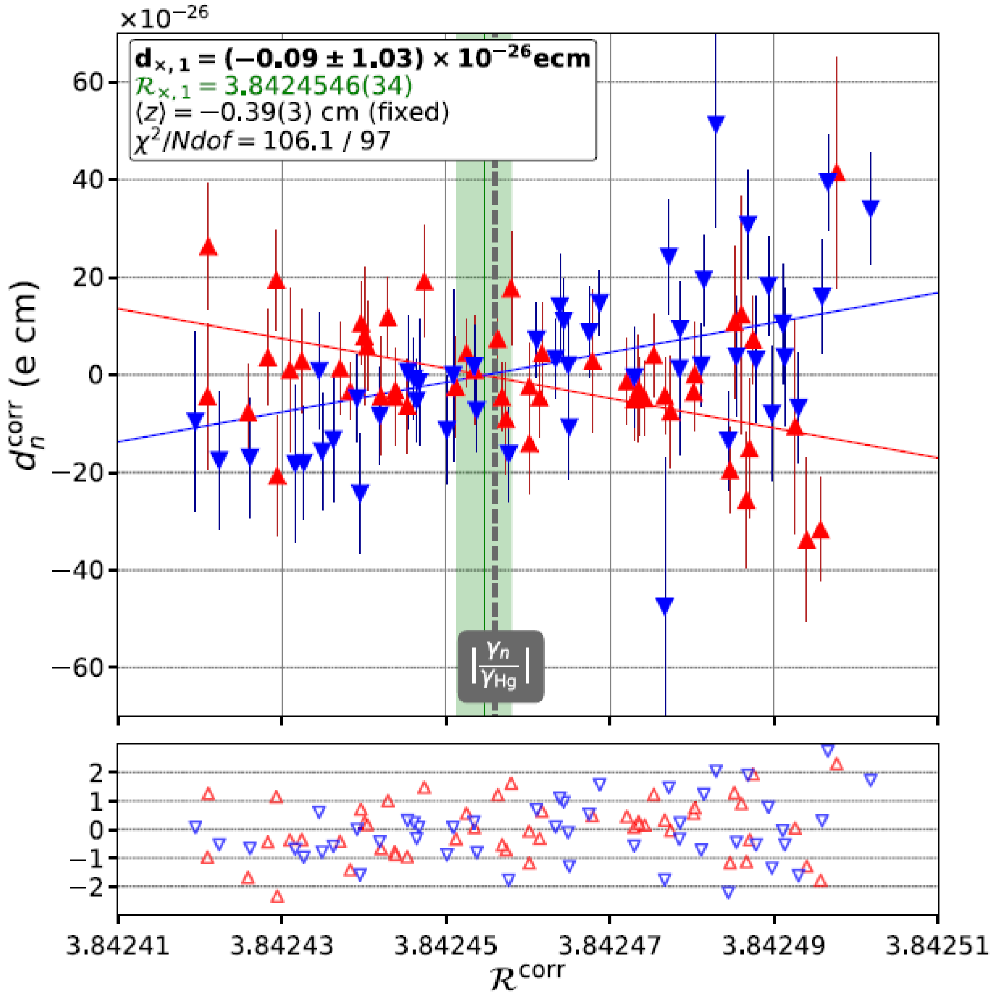


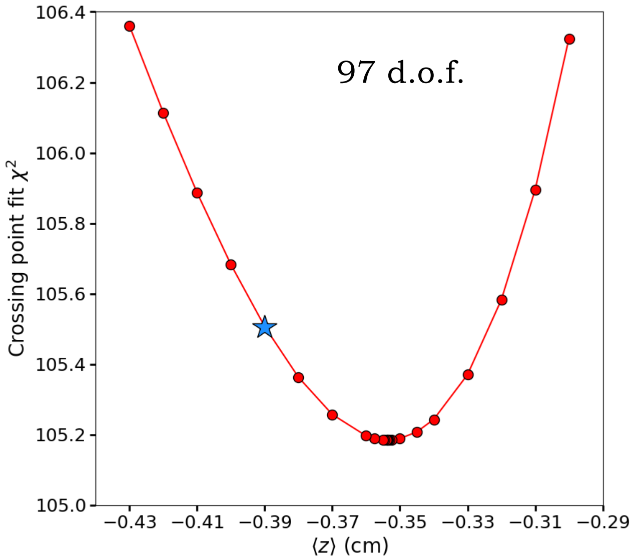
4) Field mapping

arXiv:2103.09039

5) Scan for magnetic contaminations at BMSR2, PTB Berlin

Crossing point analysis





Budget of systematic errors

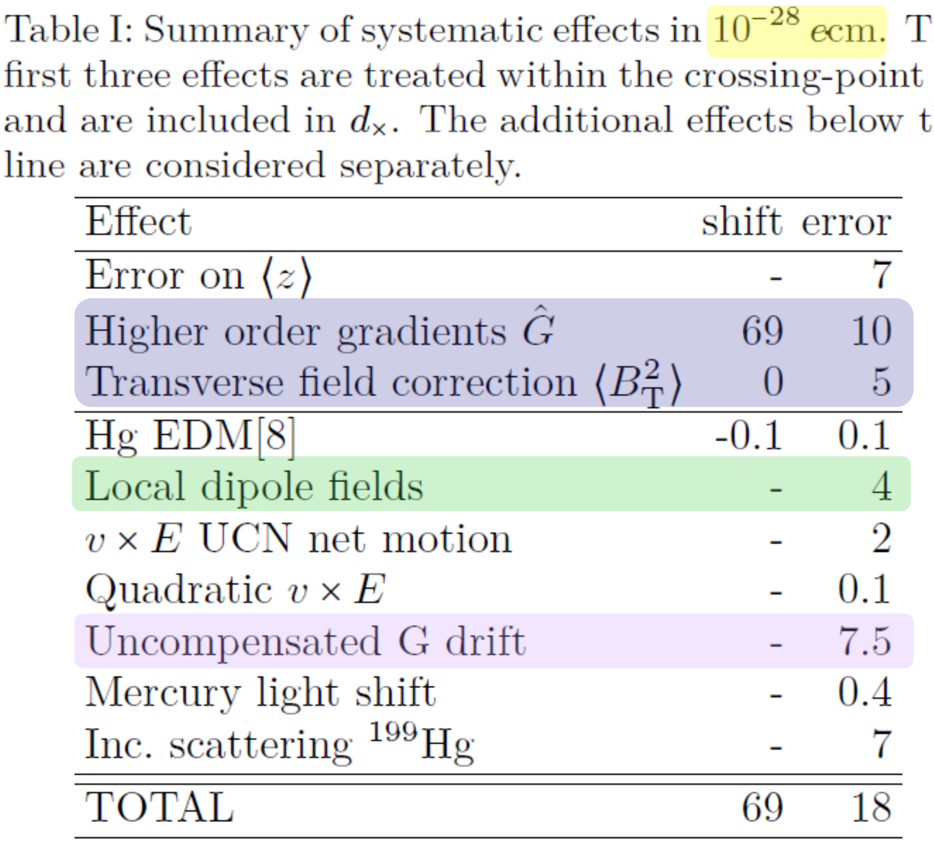


Table I: Summary of systematic effects in 10^{-28} $e$cm. The first three effects are treated within the crossing-point fit and are included in $d_\times$. The additional effects below the line are considered separately.

Effect	shift	error
Error on $\langle z \rangle$	-	7
Higher order gradients $\hat{G}$	69	10
Transverse field correction $\langle B_{\mathrm{T}}^2 \rangle$	0	5
Hg EDM[8]	-0.1	0.1
Local dipole fields	-	4
$v \times E$ UCN net motion	-	2
Quadratic $v \times E$	-	0.1
Uncompensated G drift	-	7.5
Mercury light shift	-	0.4
Inc. scattering ^{199}Hg	-	7
TOTAL	69	18

False Hg EDM

Other effects

Field mapping

PTB contamination scans

Cesium magnetometers

← was not anticipated…
therefore poorly controlled

Previous result (ILL), J.M. Pendlebury *et al*, Phys. Rev. D **92** 092003 (2015)

$$d_n = \left(-0.2 \pm 1.5_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}}\right) \times 10^{-26}\, e\mathrm{cm}$$

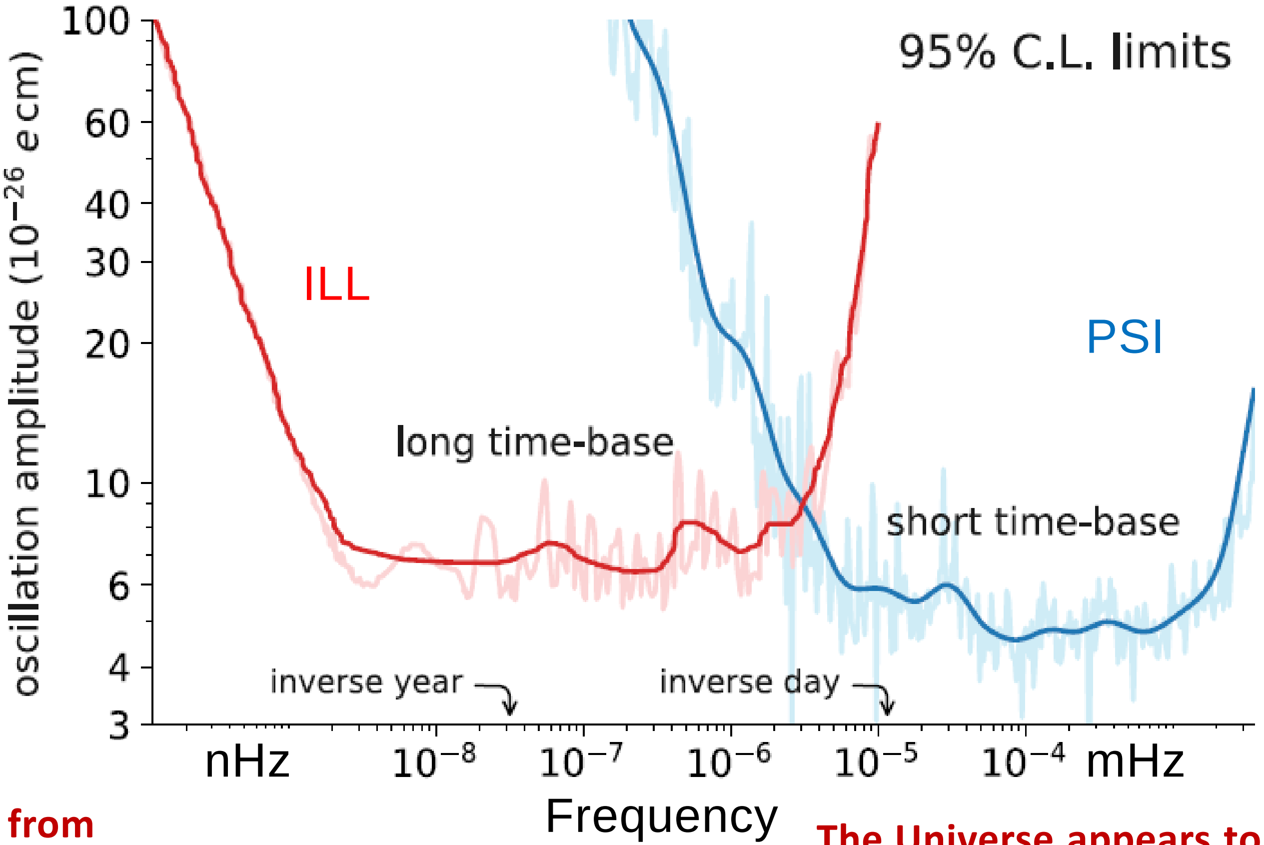
NEW RESULT (PSI)

$$d_n = \left(\ 0.0\ \pm\ 1.1_{\mathrm{stat}}\ \pm\ 0.2_{\mathrm{syst}}\right) \times 10^{-26}\, e\mathrm{cm}$$

PRL124(2020)081803

Search for nEDM oscillations with time

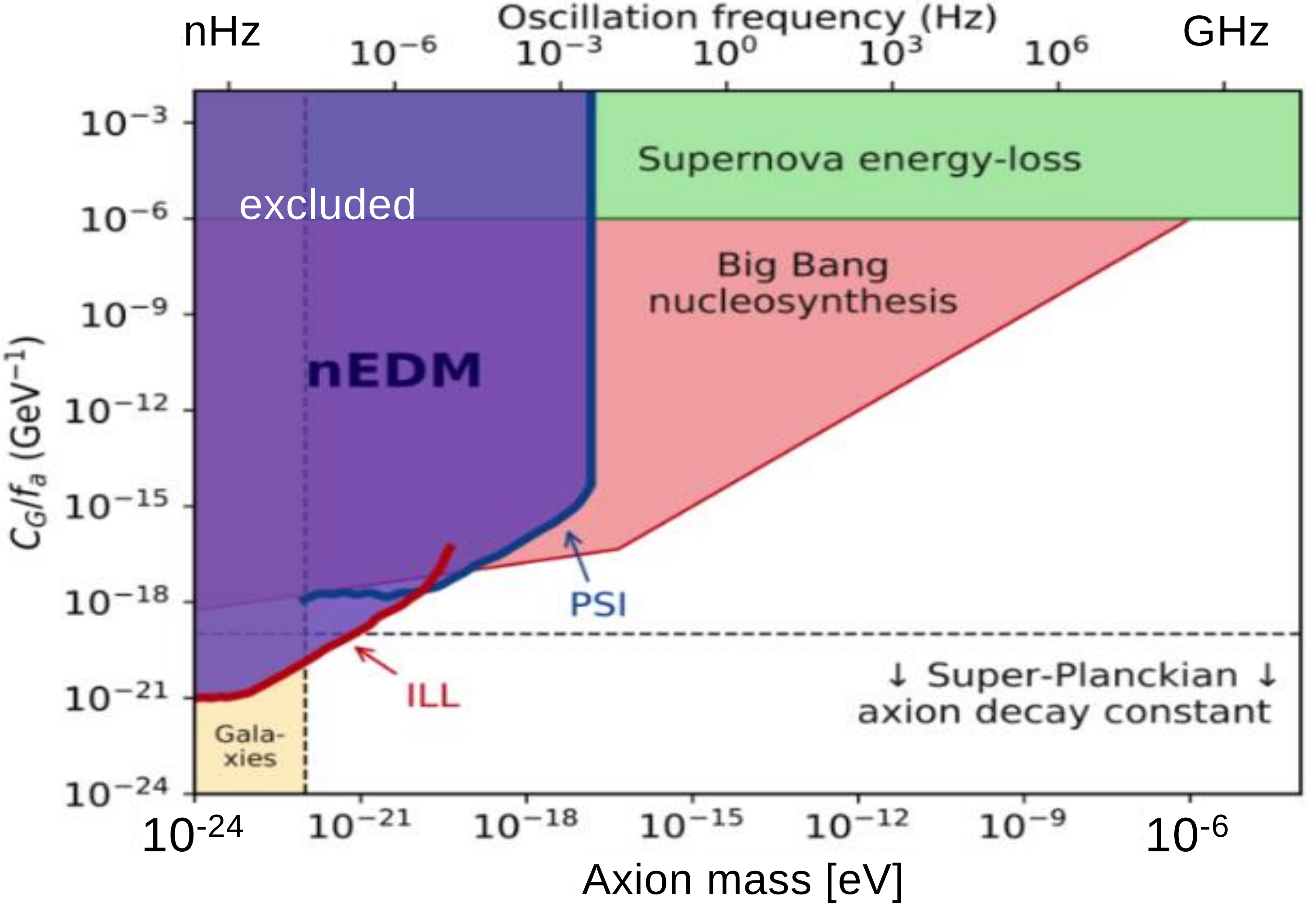
PHYS. REV. X **7**, 041034 (2017)



nEDM data from
ILL (1998-2002) and PSI (2015-16) has been analyzed for time variations of the nEDM. None have been found, setting the most stringent oscillating EDM limits so far.

The Universe appears to roughly contain
5% ordinary matter (H, He, stars, us, …), 27% **Dark Matter** and 68% Dark Energy. The nature of the Dark components is yet unknown.

nEDM search for ultra-light axion dark matter



Oscillating nEDM data could come from the interaction of **ultralight axions** which could be the **Dark Matter in the Universe**.

nEDM places the first laboratory limits. on **axion – gluon** couplings

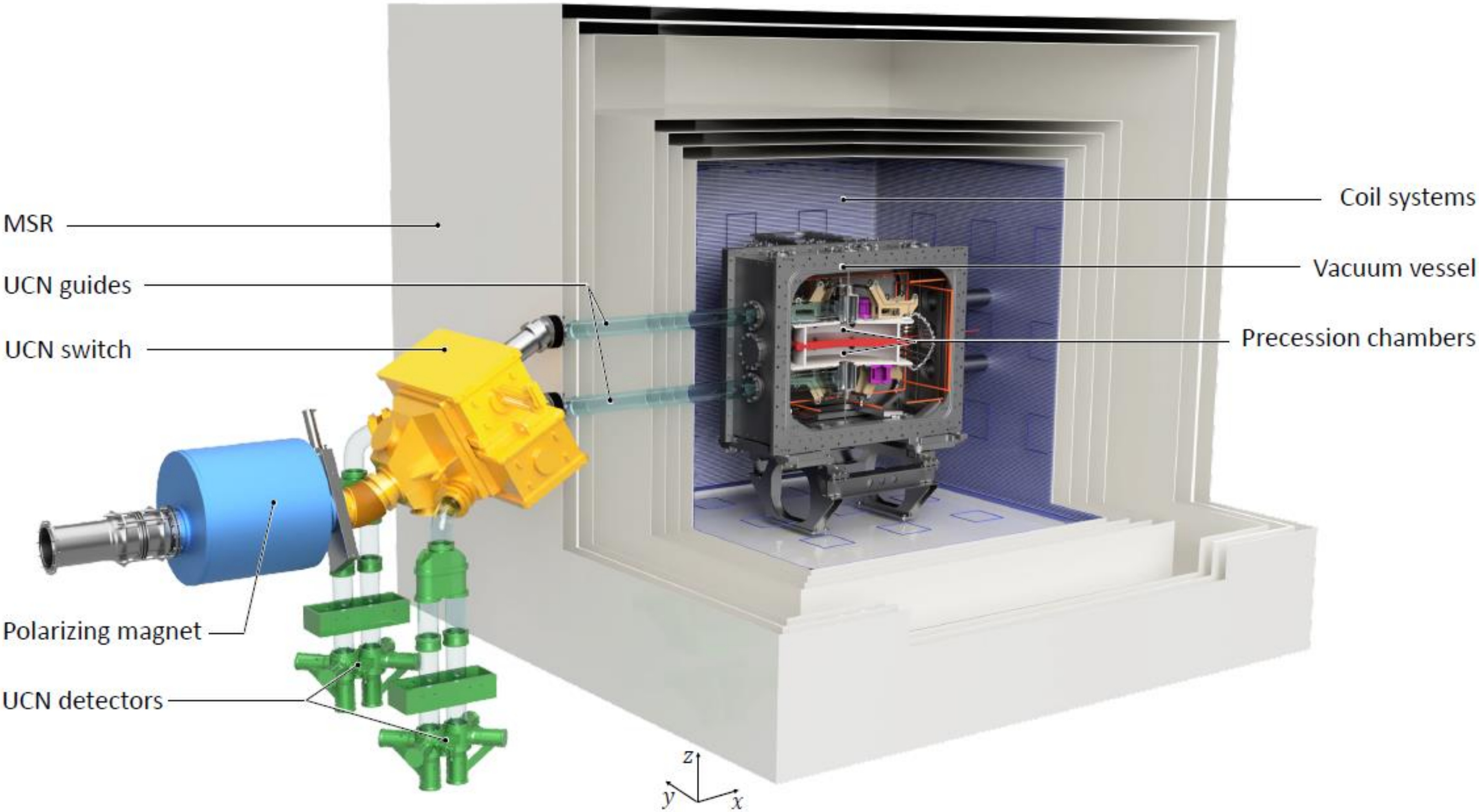
Abel et al., PRX7(2017)041034

nEDM collaboration moves on to n2EDM

nEDM collaboration:
50 researchers from 15 institutions and 7 countries. Part of the collaboration in front of nEDM.

Constructing n2EDM
Meanwhile UCN area South has just been cleared of the nEDM setup and is being prepared for n2EDM which will be 10 times more sensitive.

n2EDM


MSR
UCN guides
UCN switch
Polarizing magnet
UCN detectors
Coil systems
Vacuum vessel
Precession chambers
z
y
x

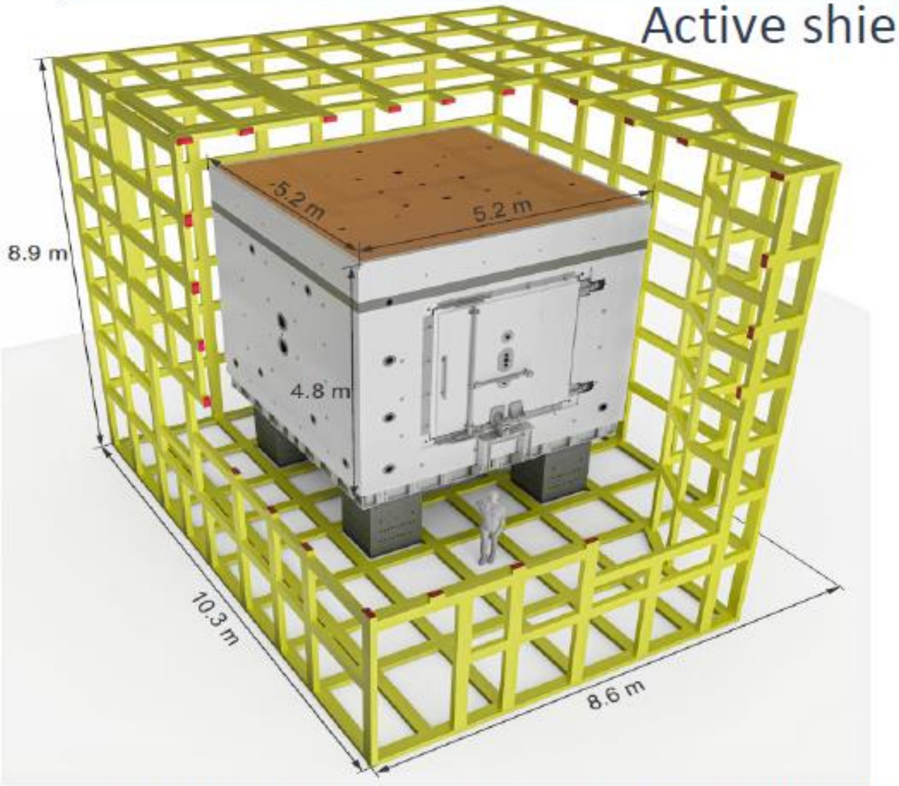
2018: n2EDM at PSI

2018: n2EDM at PSI

2019: n2EDM at PSI

2020: n2EDM at PSI

Active shielding



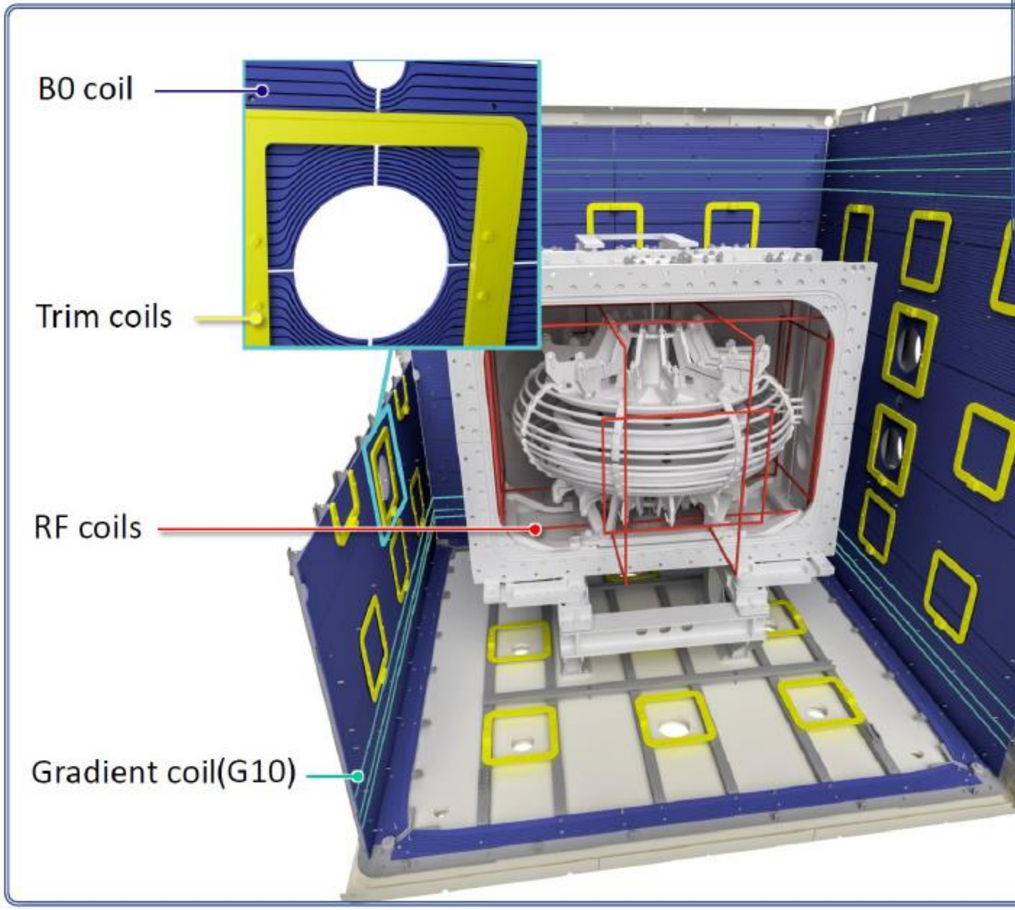
M. Rawlik *et al.,* Am. J. Physics 86(8), 602 (2018)

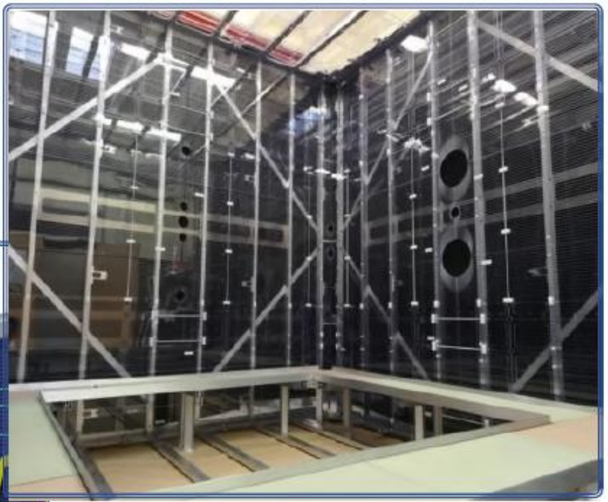
- 8 actively-controlled coils
- Spanning a volume of ~1000m^3
- Compensates field disturbances from outside
- Stable and uniform magnetic field around MSR


hrist gerüste

Magnetic-field generation: coil systems

- Produce a very uniform B0 field (1µT)
- Produce specific gradients
- Hold the UCN polarisation
- Neutron spin manipulation





Coil system and vacuum tank ready at LPC Caen

Magnetic field measurement

Hg magnetometry

Polarized Hg atoms
(laser readout)

Function:

-Correction field drifts

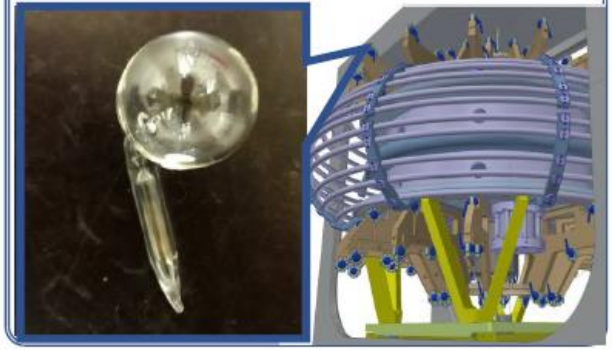
-Compensation of systematics related to first-order gradients

Cs magnetometry

Array of 112 Cs sensors

Function:

Instantaneous measurement of magnetic-field uniformity



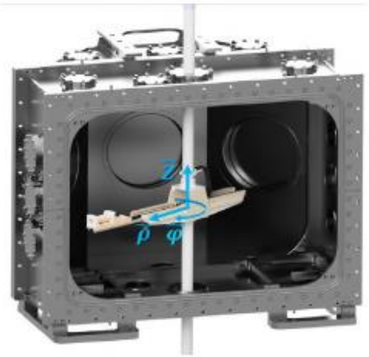
Mapping

Based on fluxgate sensor

Function (Offline):

-Coil’s cartography

-Control high-order gradients



G. Ban *et al.*, Nucl. Instrum. Methods A 896, 129 (2018)

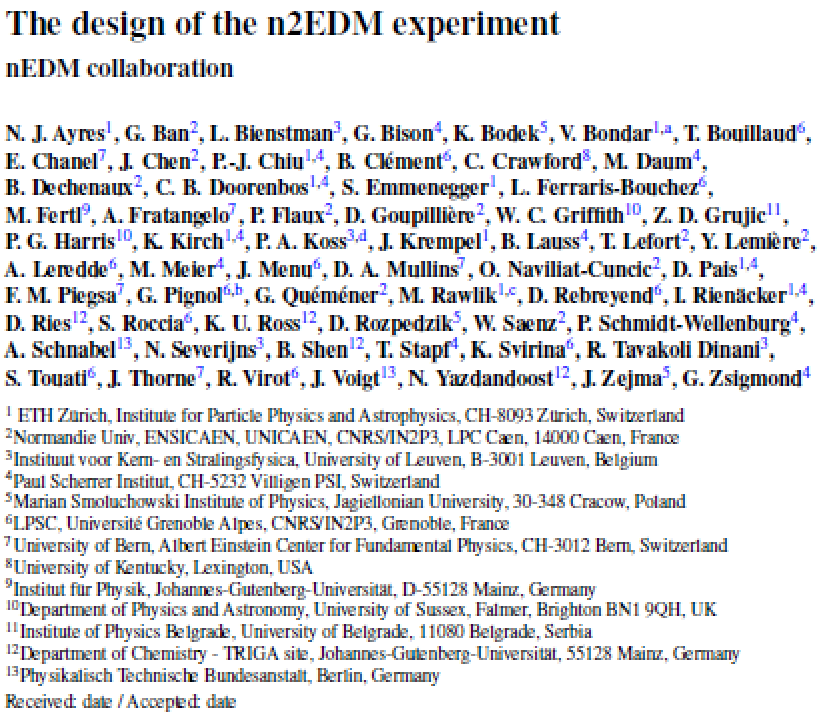
C. Abel *et al.*, Phys.Rev. A 101 (5) (2020) 053419

C. Abel *et al.*, Mapping of the magnetic field to correct systematics, in preparation for Phys. Rev. A (2021), arXiv:2103.09039

n2EDM

Technical design report published on arxiv 01/21

→ EPJ C



The design of the n2EDM experiment

nEDM collaboration

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n2EDM

The design of the n2EDM EXPERIMENT

The nEDM Collaboration

Baseline design sensitivity: $1\text{x}10^{-27}$ecm + upgrade options

Thank you!


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