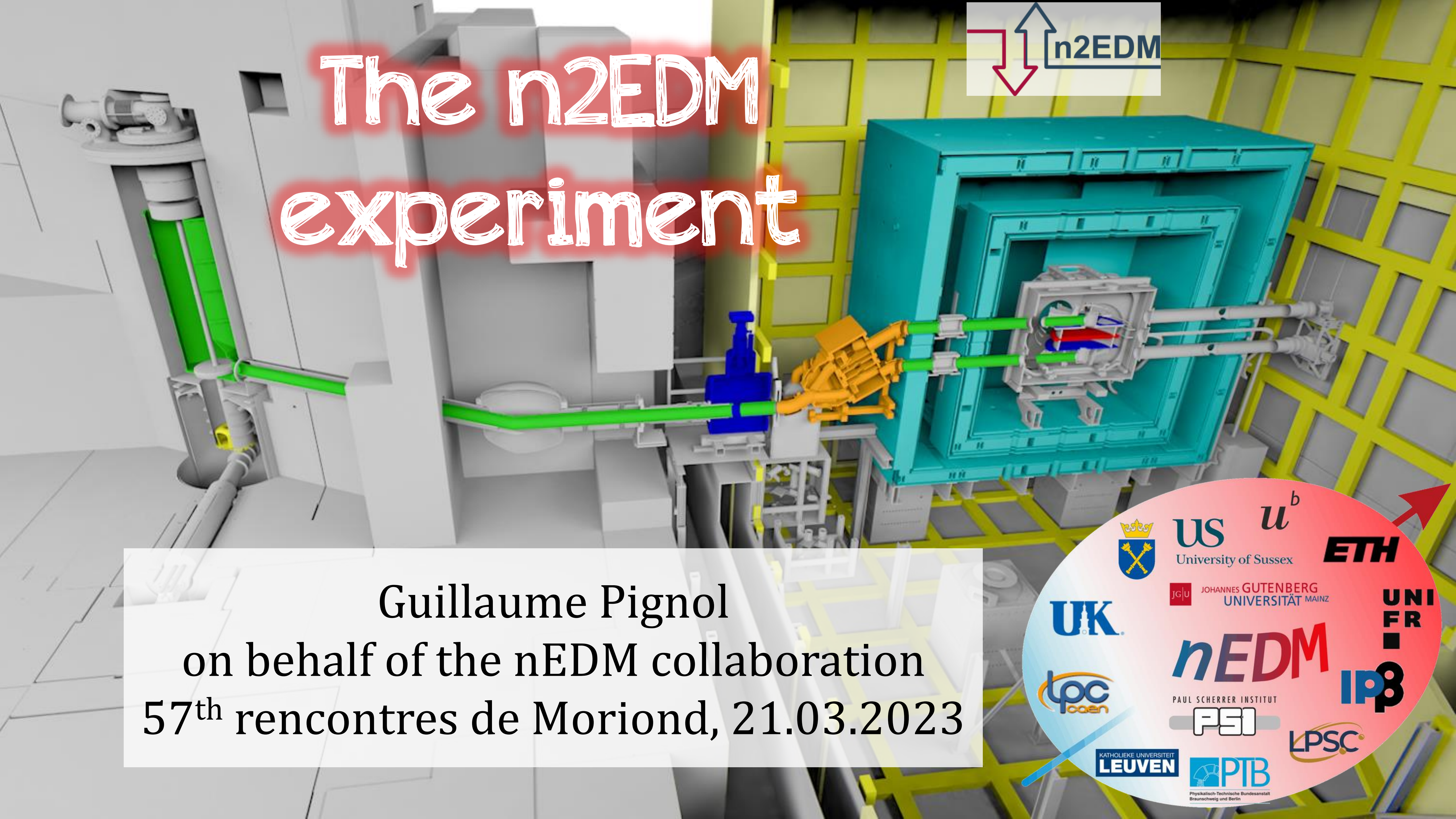
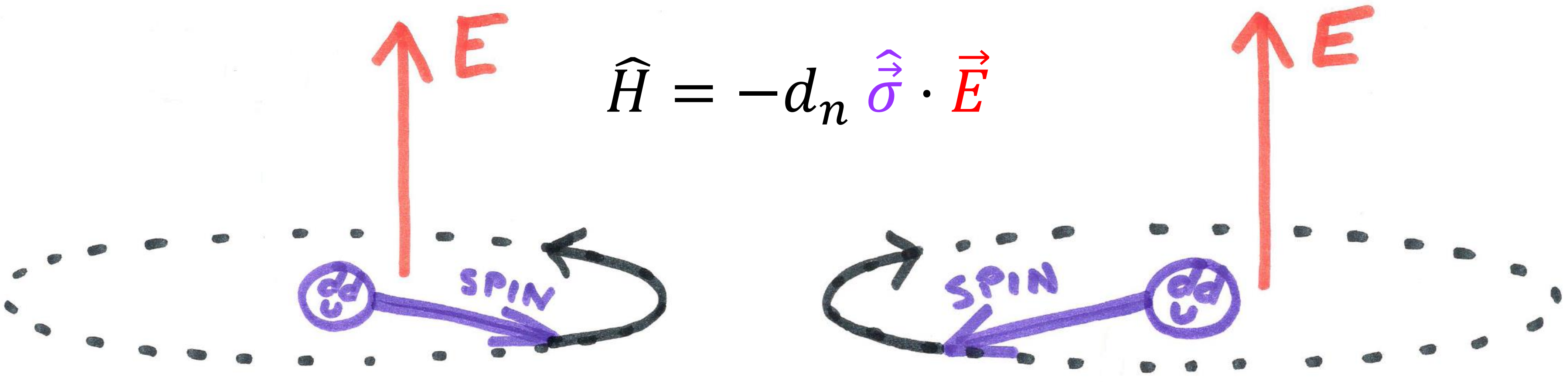


The n2EDM experiment

Guillaume Pignol
on behalf of the nEDM collaboration

57th rencontres de Moriond, 21.03.2023

EDM: coupling between spin and E-field



$$\hat{H} = -d_n \, \hat{\vec{\sigma}} \cdot \vec{E}$$

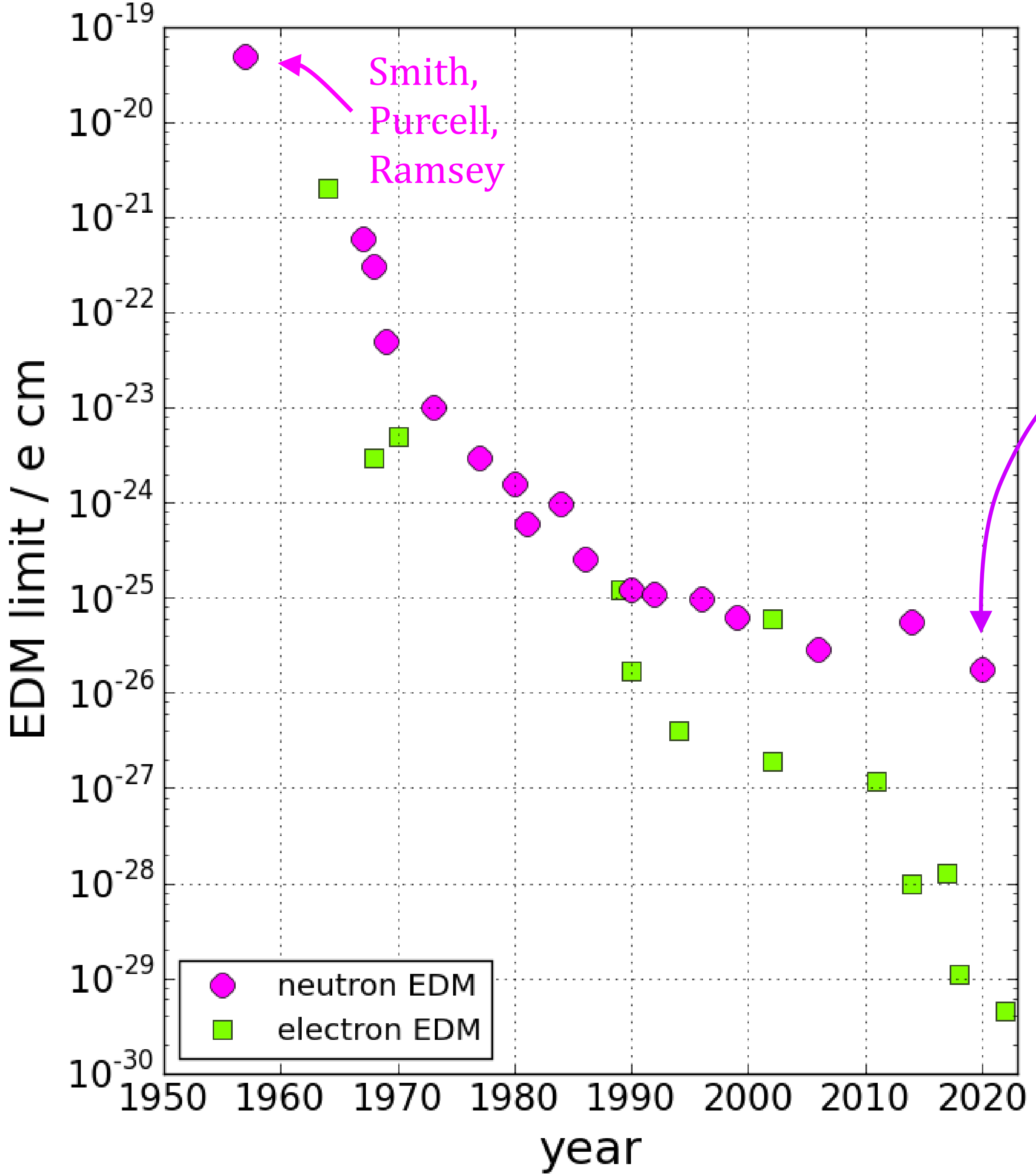
>> PLAY >>

<< REWIND <<

If $d_n \neq 0$ the process and its time reversed version are different.

Violation of T CPT **Violation of CP**

EDM limits



Best limit from the nEDM experiment @PSI

$$|d_n| < 1.8 \times 10^{-26}\ e\ \text{cm}$$ Abel et al, PRL (2020)

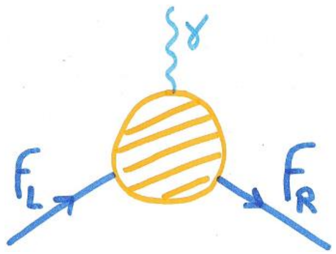
Nuclear magneton

$$\mu_N = \frac{e\hbar}{2m_N}$$

In natural units $|d_n| < 2 \times 10^{-12} \times \mu_N / c$

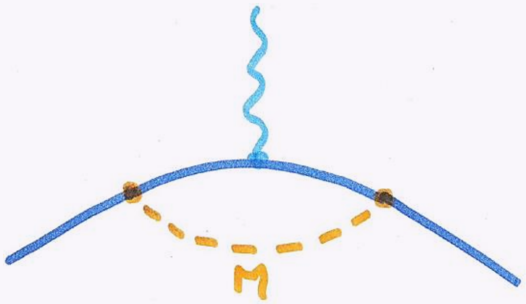
In comparison $\mu_n = -1.9130427(5)\ \mu_N$

Sources of neutron EDM



$$\mathcal{L} = -\frac{i d}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 f\, F^{\mu\nu} \to \hat{H} = -d\hat{\sigma}E$$

Typical 1-loop contribution for quark EDM

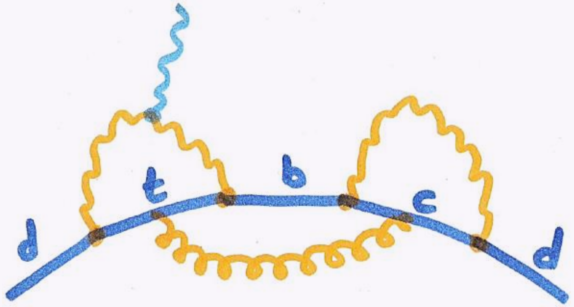


$$d_n \sim e\frac{g^2}{16\pi^2}\sin(\phi_{\text{CPV}})\frac{m_q}{M^2}$$

$\to M >$ TeV if phase ~ 1

CKM contribution

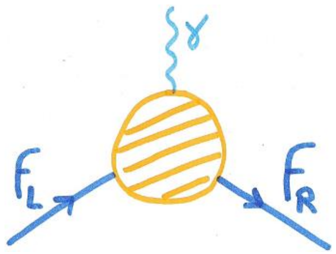
Leading order for quark EDMs at 3 loops! Frog diagram.



Negligible CKM prediction (*) $d_n \sim 10^{-32}\, e$ cm

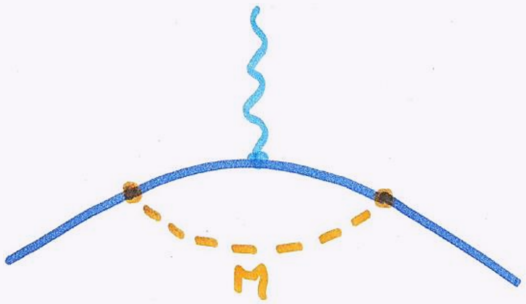
* The "long distance" contribution dominates over quark EDMs, still super-small.

Sources of neutron EDM



$$\mathcal{L} = -\frac{id}{2}\bar{f}\sigma_{\mu\nu}\gamma_5 f\, F^{\mu\nu} \rightarrow \hat{H} = -d\hat{\sigma}E$$

Typical 1-loop contribution for quark EDM

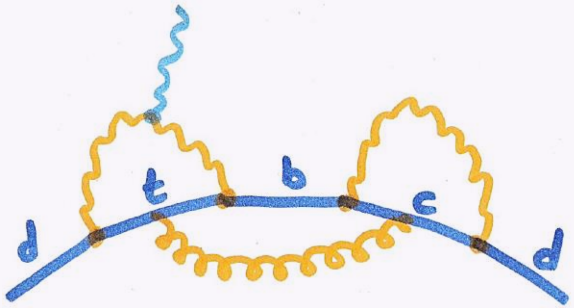


$$d_n \sim e\frac{g^2}{16\pi^2}\sin(\phi_{\mathrm{CPV}})\frac{m_q}{M^2}$$

$\rightarrow M >$ TeV if phase ~ 1

CKM contribution

Leading order
for quark EDMs at 3 loops!
Frog diagram.



Negligible CKM prediction (*) $d_n \sim 10^{-32}\, e$ cm

* The "long distance" contribution dominates over quark EDMs, still super-small.

The SM QCD theta term $\frac{\alpha_s}{8\pi}\bar{\theta}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$

generates a potentially enormous neutron EDM : $d_n \sim -0.02 \times \bar{\theta}\,\mu_N/c$

$\rightarrow |\bar{\theta}| < 10^{-10} \rightarrow$ « Strong CP problem »

EDMs beyond the SM: modified Higgs couplings

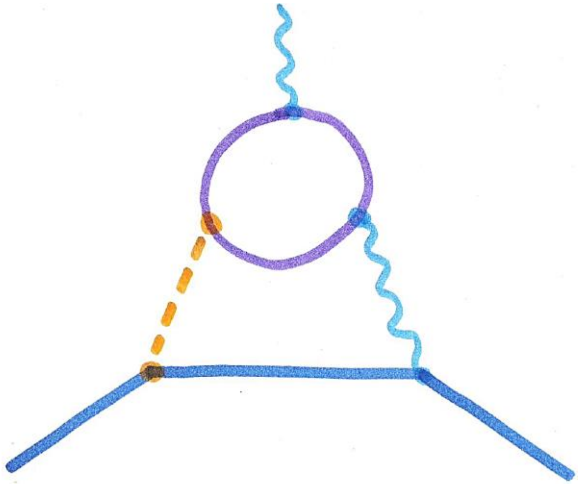
Modified Higgs-fermion Yukawa coupling

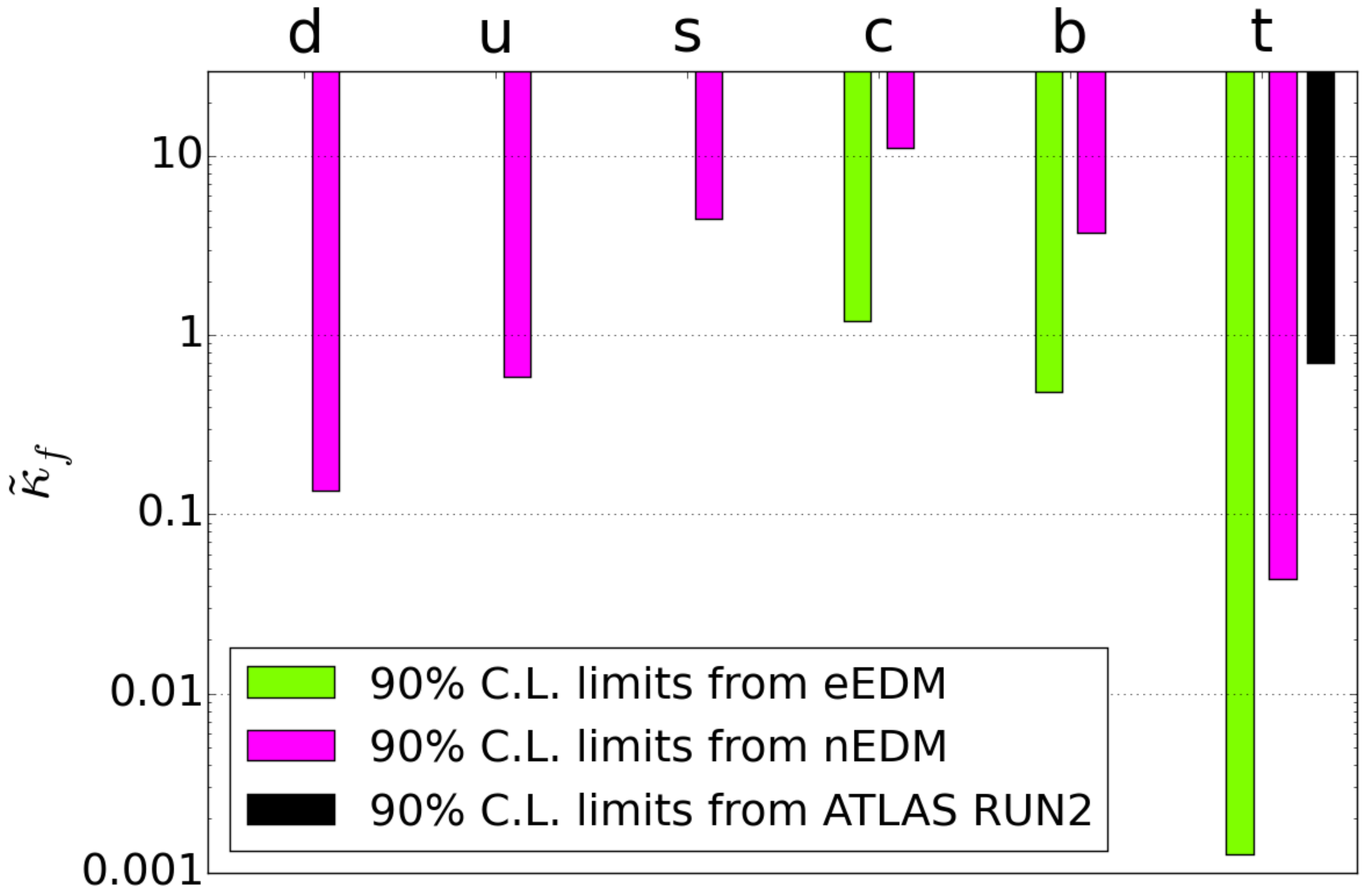
$$\mathcal{L} = -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f h + i\tilde{\kappa}_f \, \bar{f} \gamma_5 f h \right)$$

CPV

Generates EDM at 2 loops

Barr, Zee, PRL 65 (1990)





Brod, Haich, Zupan, 1310.1385
Brod, Stamou, 1810.12303
Brod, Skodras, 1811.05480
ATLAS, PRL 125, 061802 (2020)

Systematic approach: ladder of Effective Field Ths

UV complete BSM theory,

$\mathcal{L}_{\rm UV}$: Scale $= \Lambda \gg m_H \sim 100$ GeV

EFT with SM fields: quarks, leptons, gauge bosons, Higgs

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \mathcal{L}_{D=5} + \sum_{a=1}^{3045} \frac{c_a}{\Lambda^2} O_a^{(6)} + \mathcal{L}_{D=7} + \cdots$$

EFT with hadrons, leptons and photons

Isospin-diagonal, CPV operators

$$-\mathcal{L}_{\rm EDM} = \frac{1}{2} d_n \, \bar{n} \sigma_{\mu\nu} i \gamma_5 n \, F^{\mu\nu} + \frac{G_F}{\sqrt{2}} C_S^0 \, \bar{n} n \, \bar{e} i \gamma_5 e + \cdots$$

Observables: EDMs of nucleons, atoms, molecules…

$$\hat{H} = -d \, \hat{\vec{\sigma}} \cdot \vec{E}$$

European Strategy Particle Physics 1910.11775

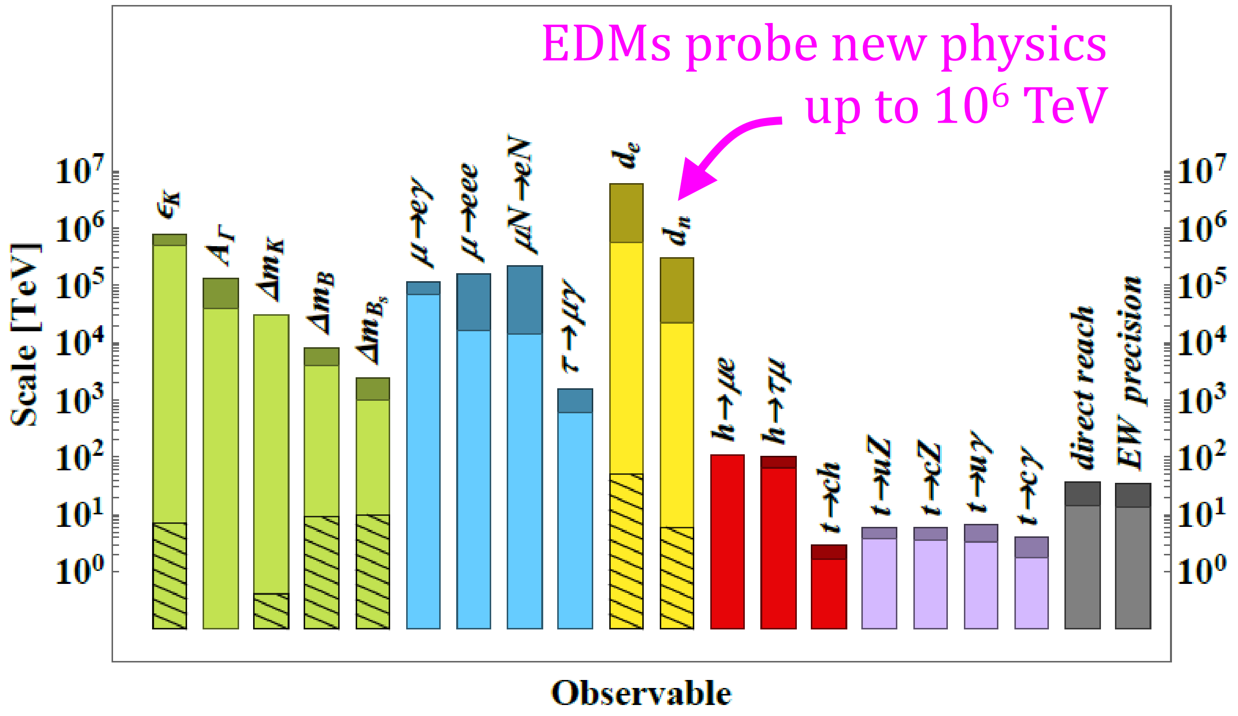
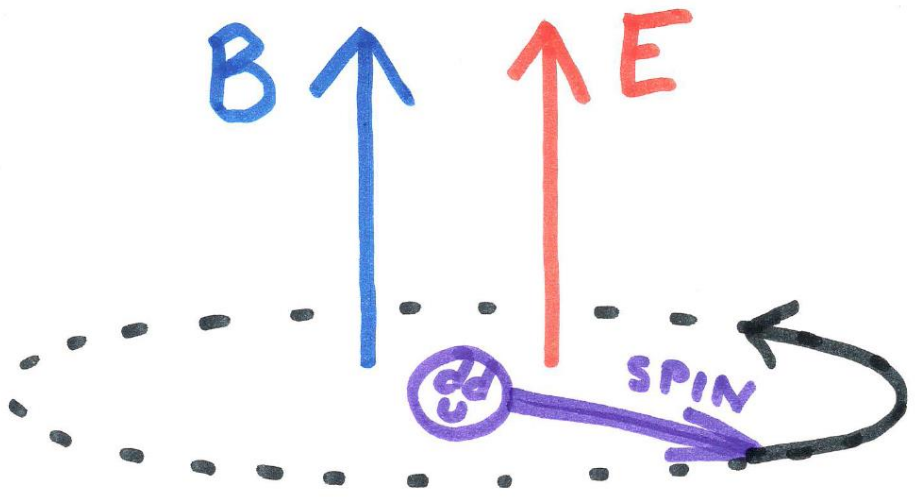


Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and EW precision measurements. The operator coefficients are taken to be either ~ 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects,

Basics of nEDM measurement



Larmor frequency

~ 30 Hz @ $B = 1$ μT

$$2\pi f = \frac{2\mu_n}{\hbar} B \pm \frac{2d_n}{\hbar} |E|$$

If $d_n \sim 10^{-26}$ e cm and $E \sim 10$ kV/cm

duration of one full turn ~ 1 year

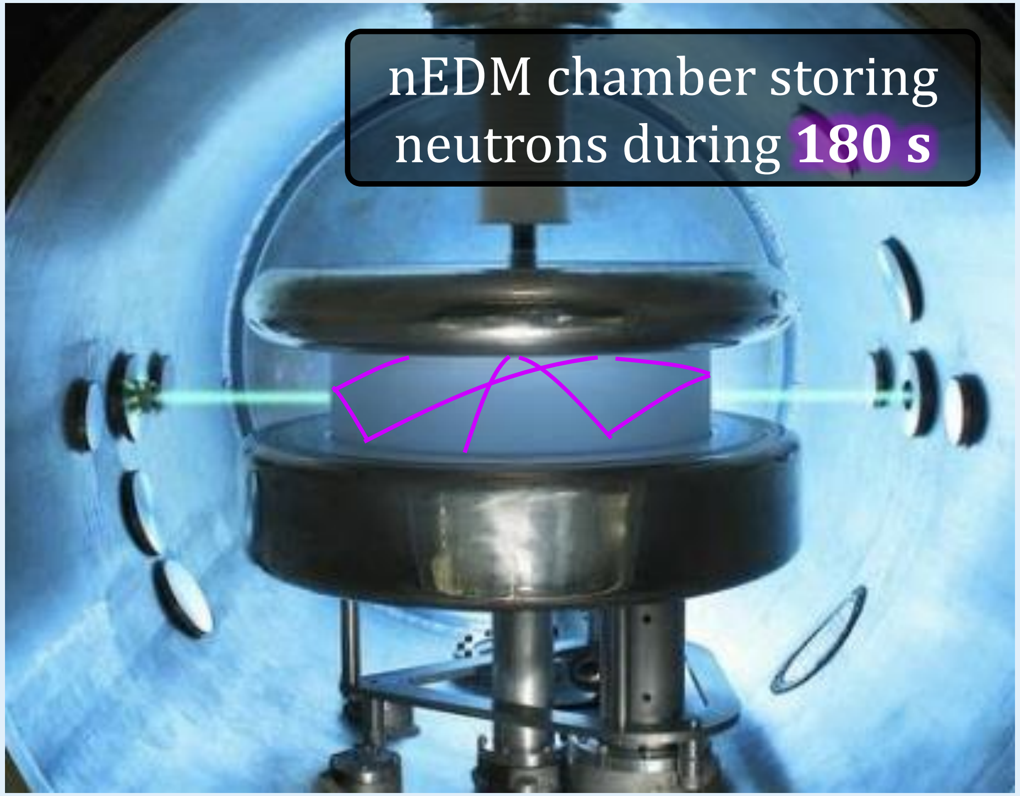
To detect such a minuscule coupling

- Long interaction time
- High intensity/statistics
- Control the magnetic field

- **Long interaction time**
- **High intensity/statistics**
- **Control the magnetic field**

Use Ultracold neutrons

Neutrons with velocity <5m/s can undergo total reflection and be stored in material "bottles"



Use big magnetic shielding

+ Use quantum magnetometry

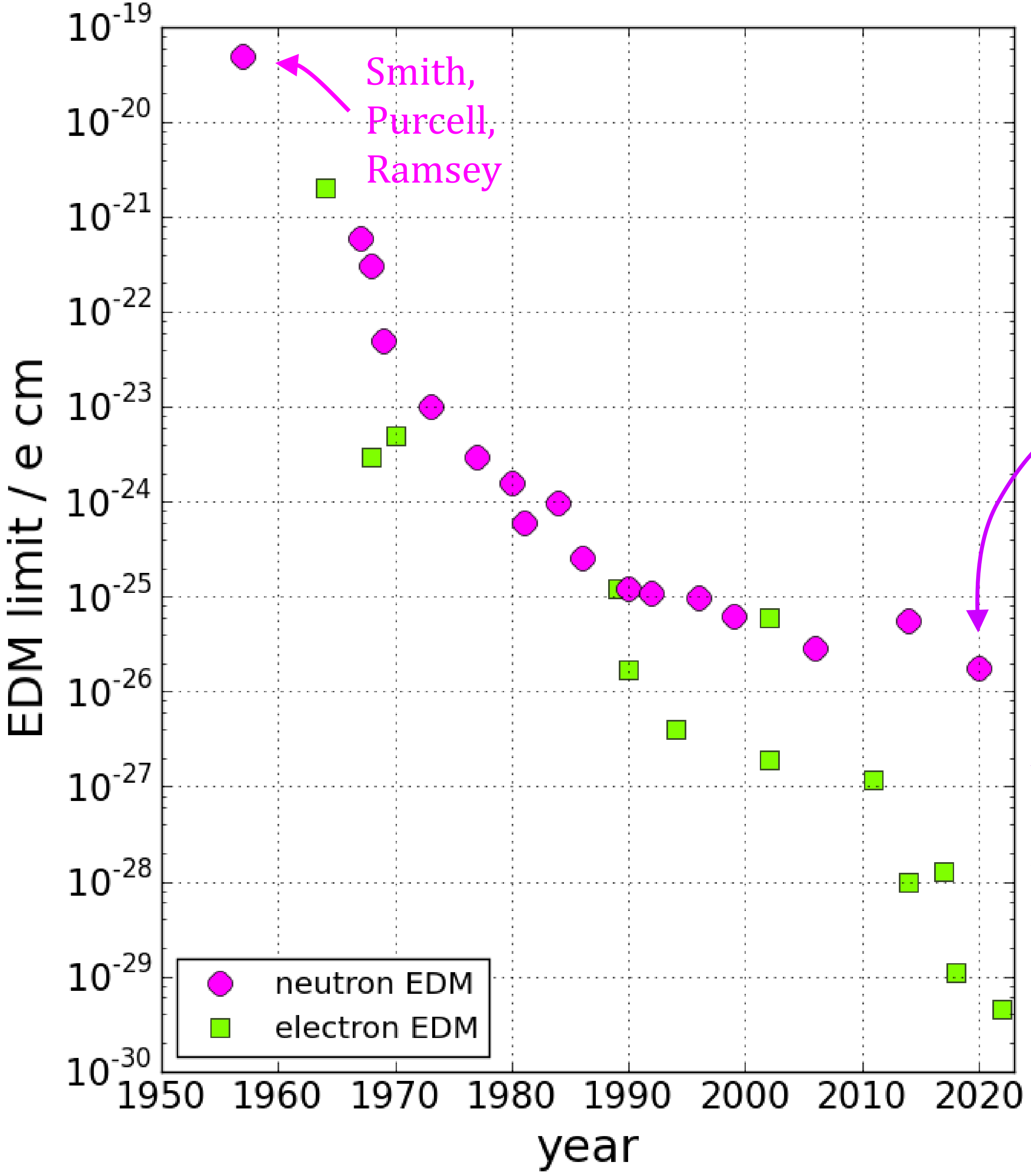
With mercury and cesium atoms

Abel et al, PRL (2020)

$$d_n = (0.0 \pm 1.1_{stat} \pm 0.2_{syst}) \times 10^{-26}\ ecm$$

Limited by the number of UCNs (~500 million counts)

Uniformity of the B-field



Next generation nucleon EDM

Best limit from the nEDM experiment @PSI

$|d_n| < 1.8 \times 10^{-26}\ e\ \mathrm{cm}$ Abel et al, PRL (2020)

Design sensitivity of 4 new experiments:

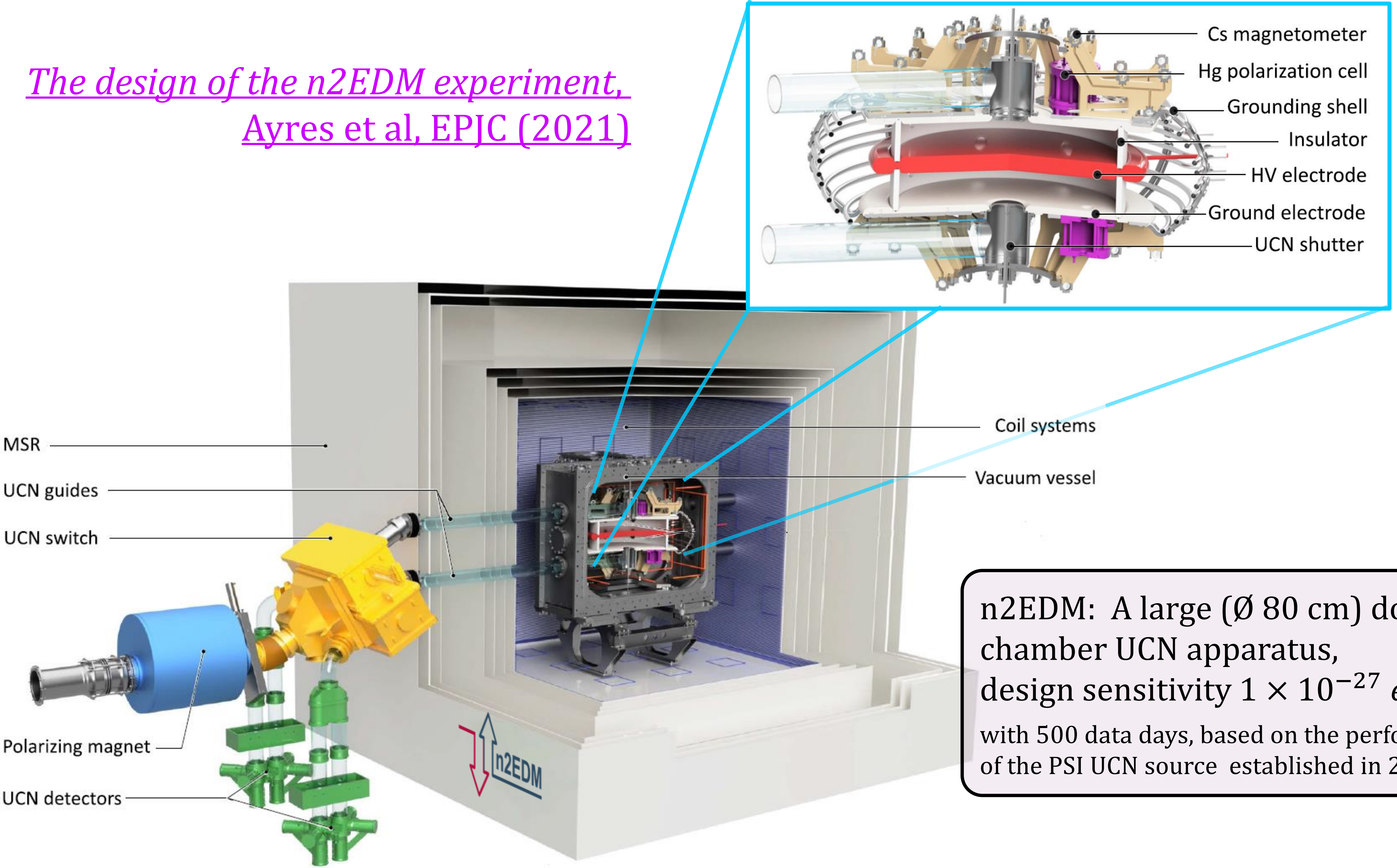
n2EDM@PSI + panEDM@ILL + LANL + TUCAN@TRIUMF

Design sensitivity cryogenic nEDM@SNS

Possible reach proton EDM

CKM background uncertain, possibly 10^{-31} e cm

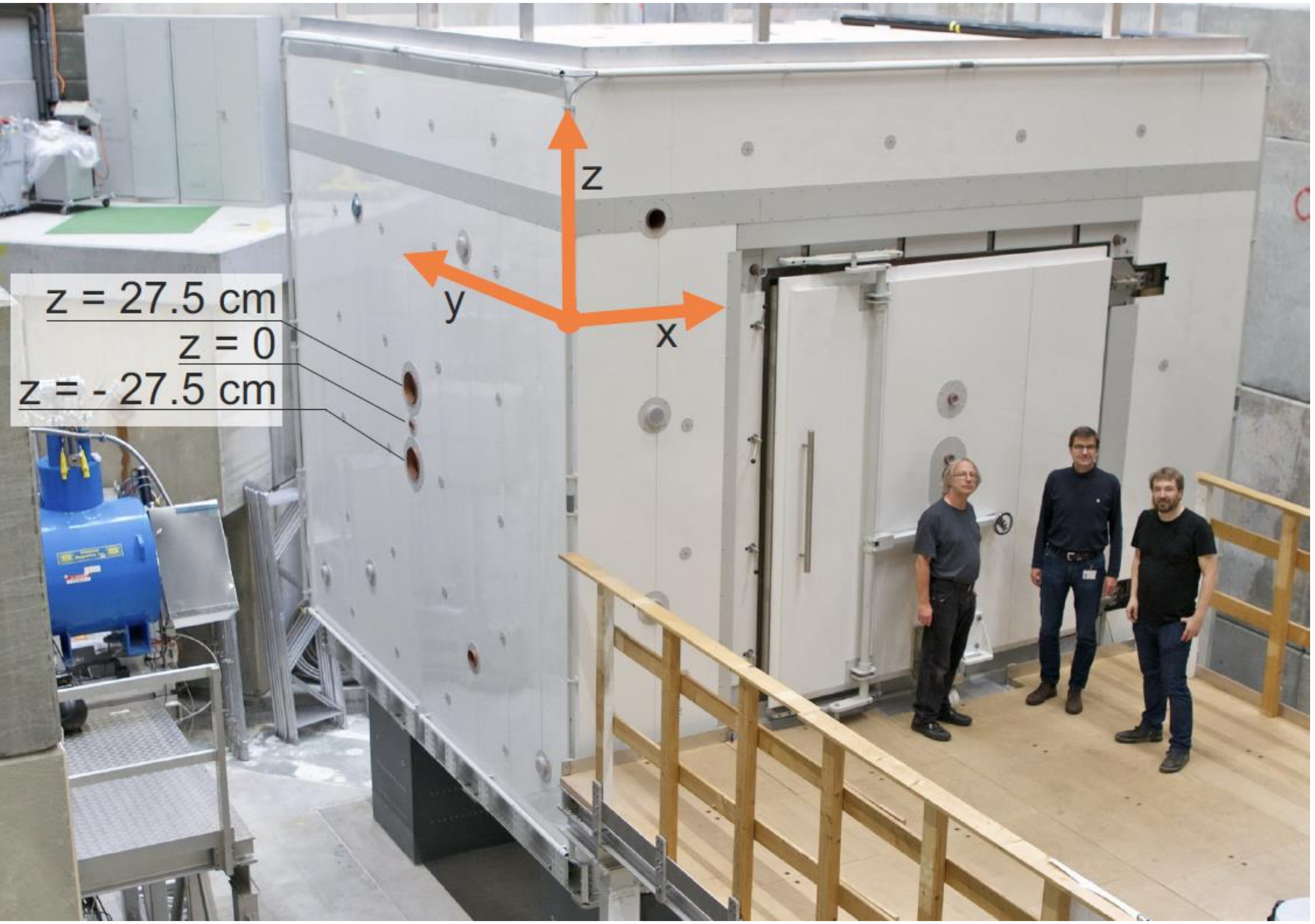
The design of the n2EDM experiment, Ayres et al, EPJC (2021)



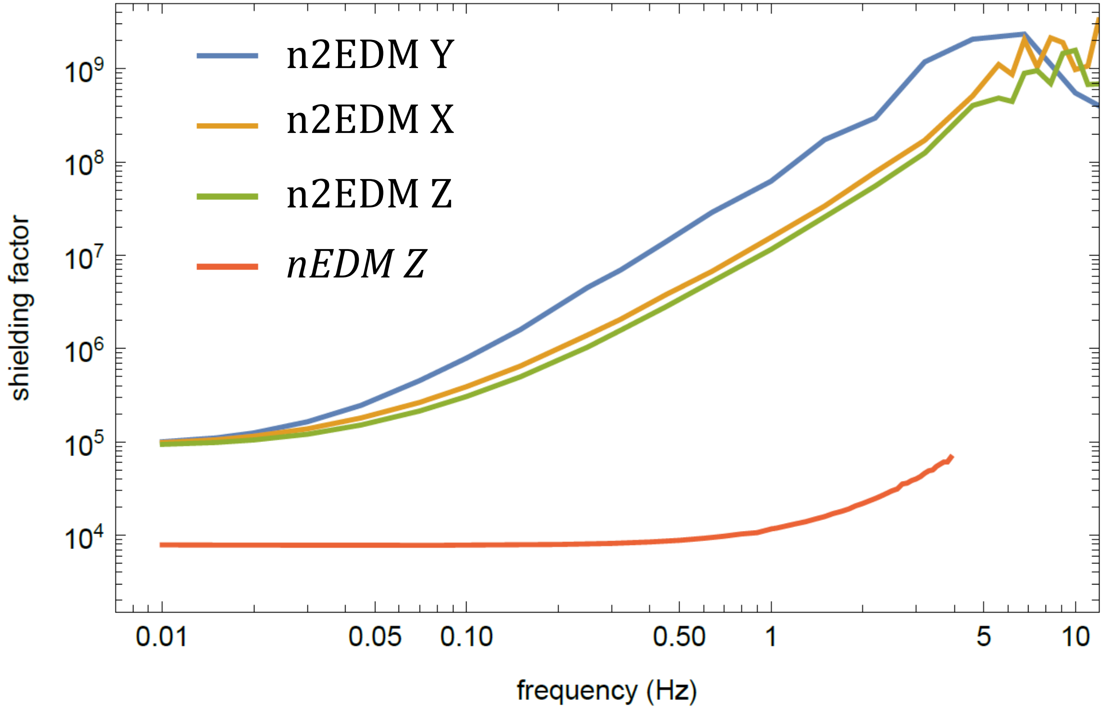
n2EDM: A large (Ø 80 cm) double-chamber UCN apparatus, design sensitivity 1×10^{-27} e cm

with 500 data days, based on the performance of the PSI UCN source established in 2016

Commissioning of the n2EDM Magnetically Shielded Room in 2020

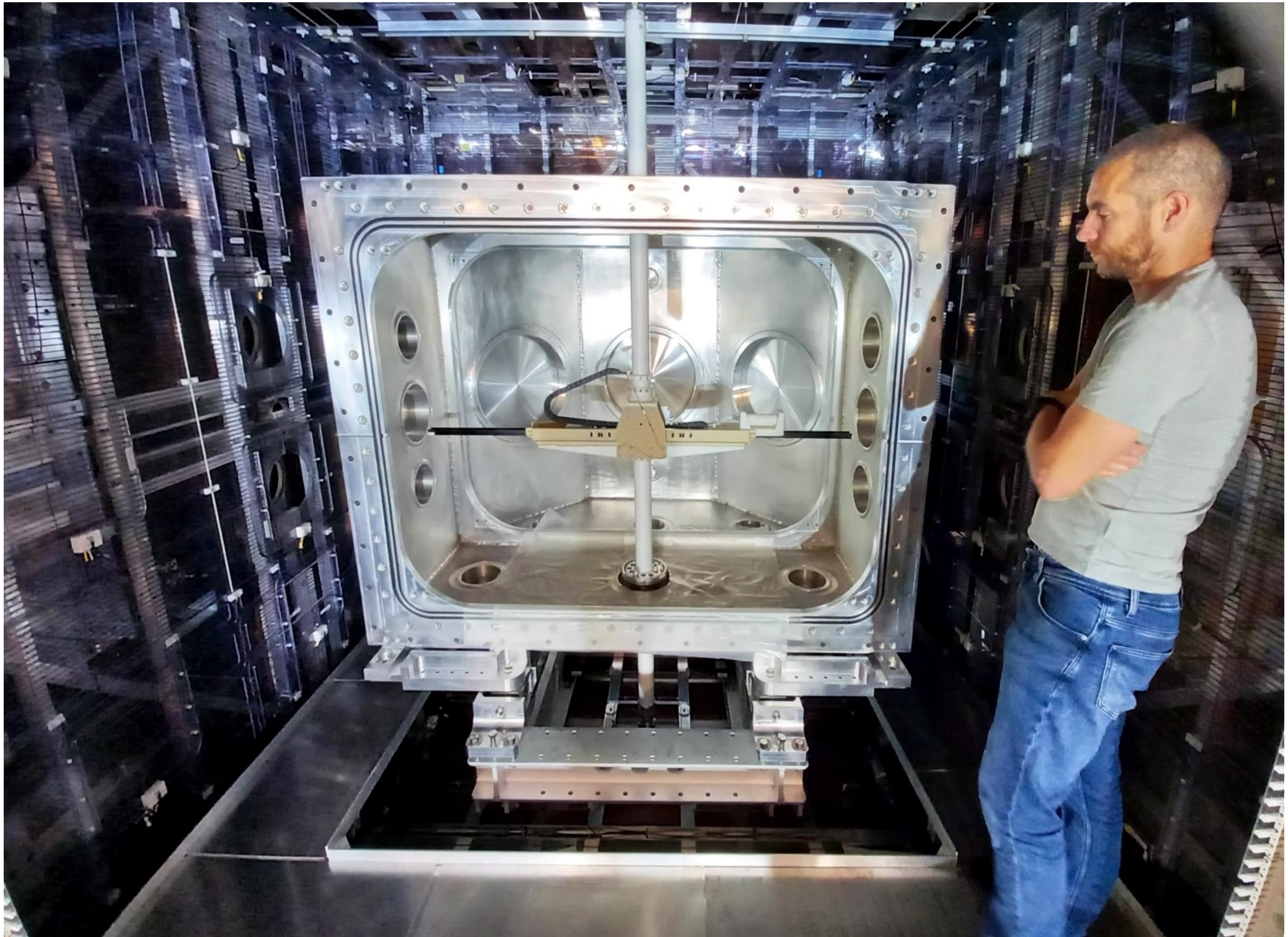


- Setup and optimization of the degaussing
- Characterization of the remanent field
- Measurement of the shielding factors

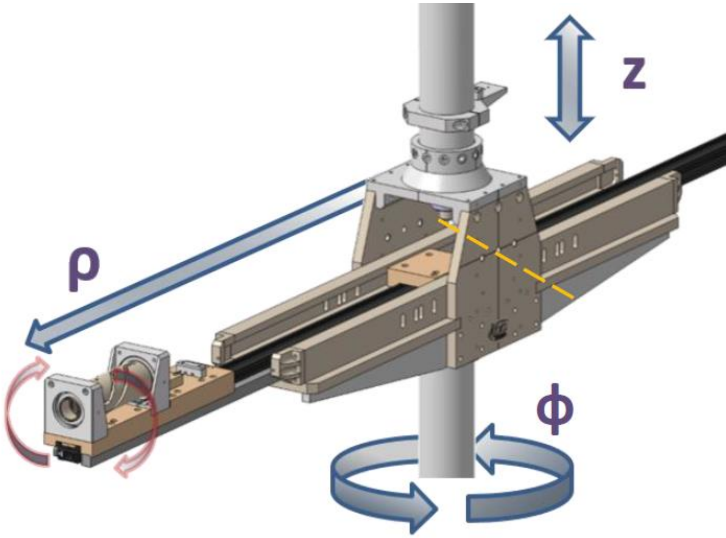


The very large n2EDM magnetically shielded room with an exceptional performance for fundamental physics measurements, Review of Scientific Instruments 93, 095105 (2022) n2EDM

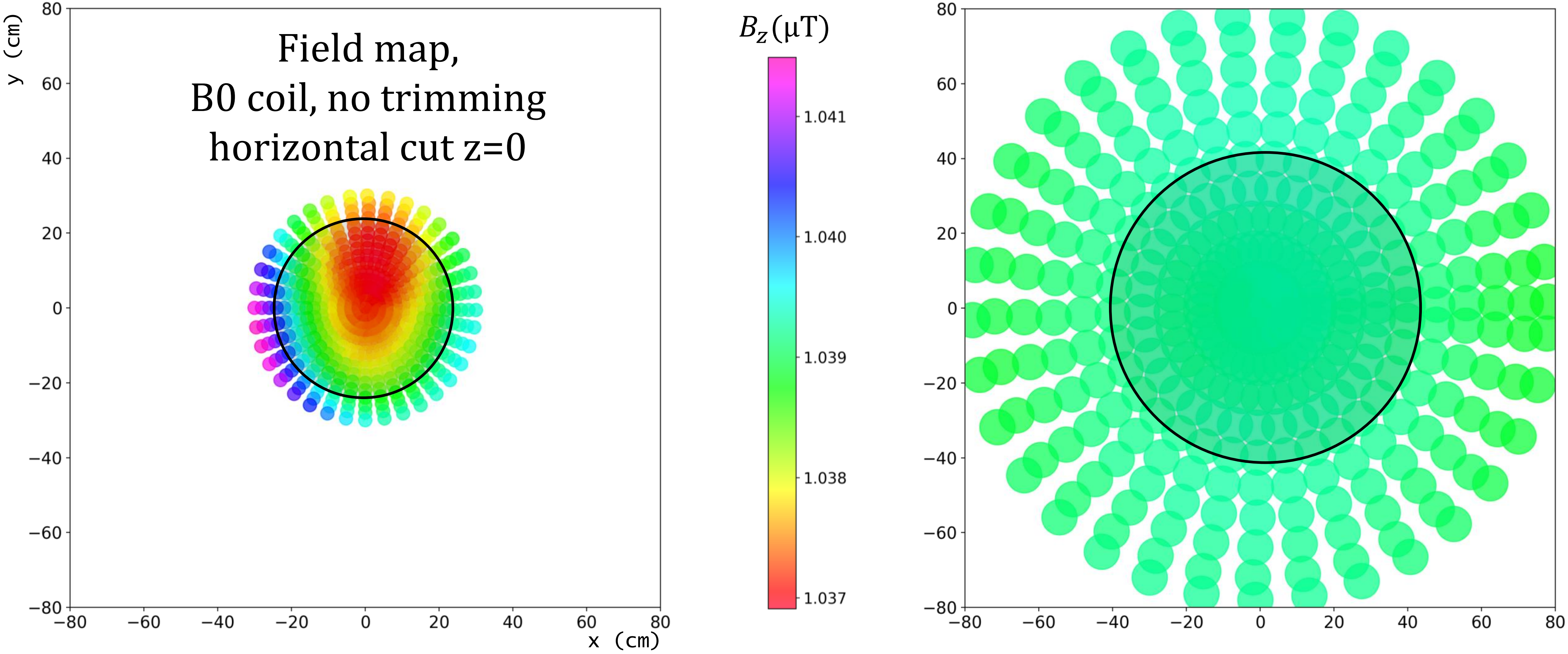
B-field commissioning 2022



Installation of the B-field mapper in the empty vacuum vessel



Record uniformity of the vertical B-field



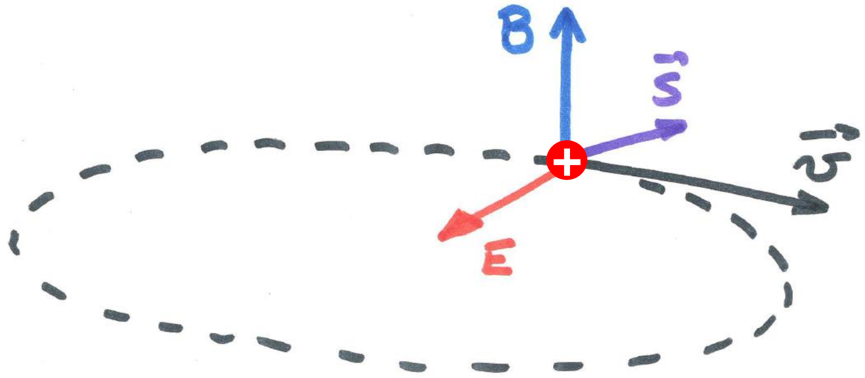
nEDM 2017 $\sigma(B_z) = 900$ pT

In the precession chamber Ø 47 cm

n2EDM 2022 $\sigma(B_z) = 60$ pT

In one chamber Ø 80 cm

EDMs in storage rings - charged particles



Differences with classic EDM schemes:

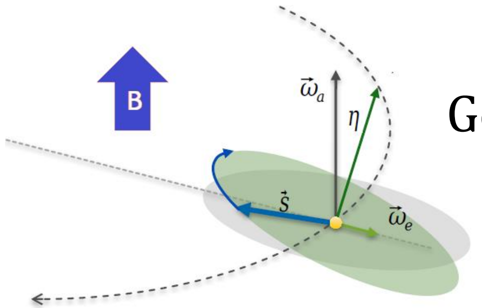
- The beloved configuration $\vec{\boldsymbol{E}} \parallel \vec{\boldsymbol{B}}$ **does not work** to store charged particles!
- Relativistic motional fields $\vec{E} \times \vec{v}$ and $\vec{B} \times \vec{v}$ are not small.

Spin precession in the rotating frame: Thomas-BMT equation

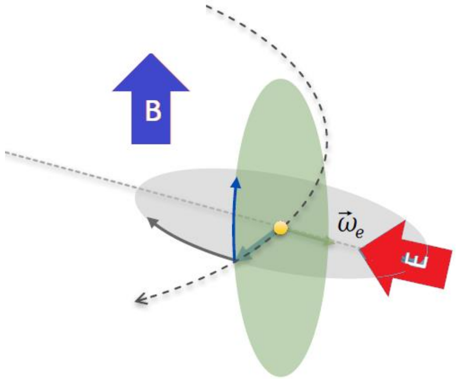
$$\vec{\omega} = \frac{q}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E}\right] + \frac{2}{\hbar}d\left[\vec{v} \times \vec{B} + \vec{E}\right]$$

Term due to magnetic dipole,
Precession in the horizontal plane,
can be set to ~0 by choosing $\vec{B}, \vec{E}, \vec{v}$
« frozen spin »

Term due to electric dipole.
Precession out of plane



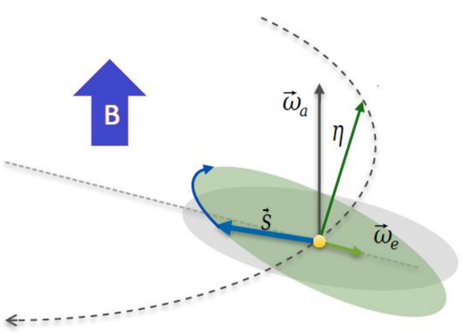
General situation, reduced EDM sensitivity



Frozen spin
EDM sensitive

EDMs in storage rings – prospects

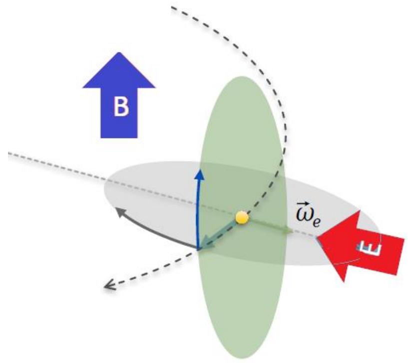
muon EDM



g-2 experiments at

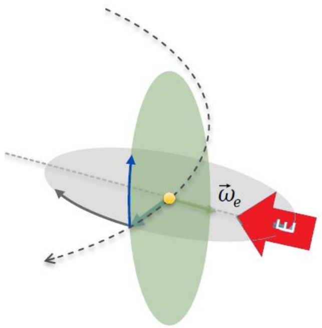
- FNAL : magic moment
  $p = 3$ GeV, radius 7m
- JPARC : no E field,
  $p = 300$ MeV, radius 33 cm

Sensitivity $\mathcal{O}(10^{-21}\ e\ \text{cm})$



- Dedicated EDM exp. at PSI
  frozen spin
  $p = 28$ MeV, radius ~ 10 cm
  Sensitivity $\mathcal{O}(10^{-23}\ e\ \text{cm})$

proton EDM prospect: $\mathcal{O}(10^{-29}\ e\ \text{cm})$



Pure electrostatic ring at the magic moment $p = 700$ MeV

$$\vec{\omega} = \frac{q}{m}\left(a - \frac{1}{\gamma^2 - 1}\right)\vec{v} \times \vec{E} + 2d\vec{E}$$

N.B: radial B field control < 10 aT (**!!**)

- US based srEDM collaboration
plans to design a 800 m long ring, $E = 44$ kV/cm
to be built in the BNL tunnel

- EU based JEDI/CPEDM collaborations
Start with a prototype E/B ring
Then precision ring, 500 m long, $E = 80$ kV/cm

Outlook

New generation neutron EDM experiments are coming!
Proton EDM concept pursued for the distant future

n2EDM status at PSI:
- magnetically operational, with record B-field quality
- first runs with ultracold neutrons scheduled in summer 2023

Thank you!