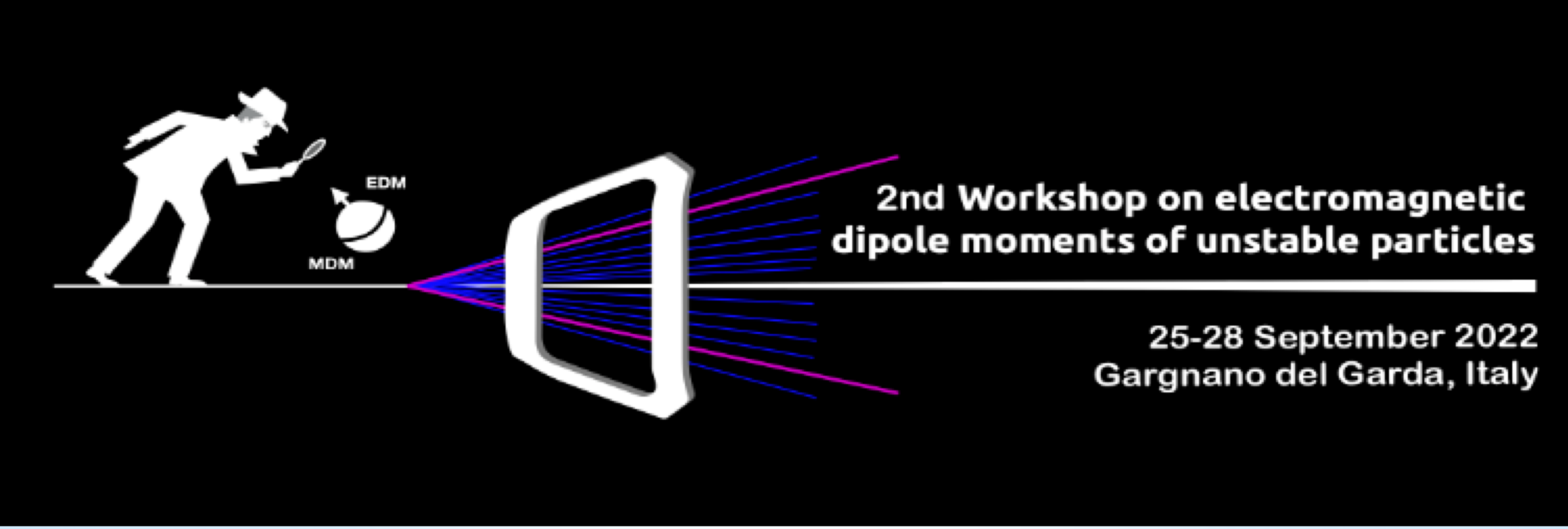
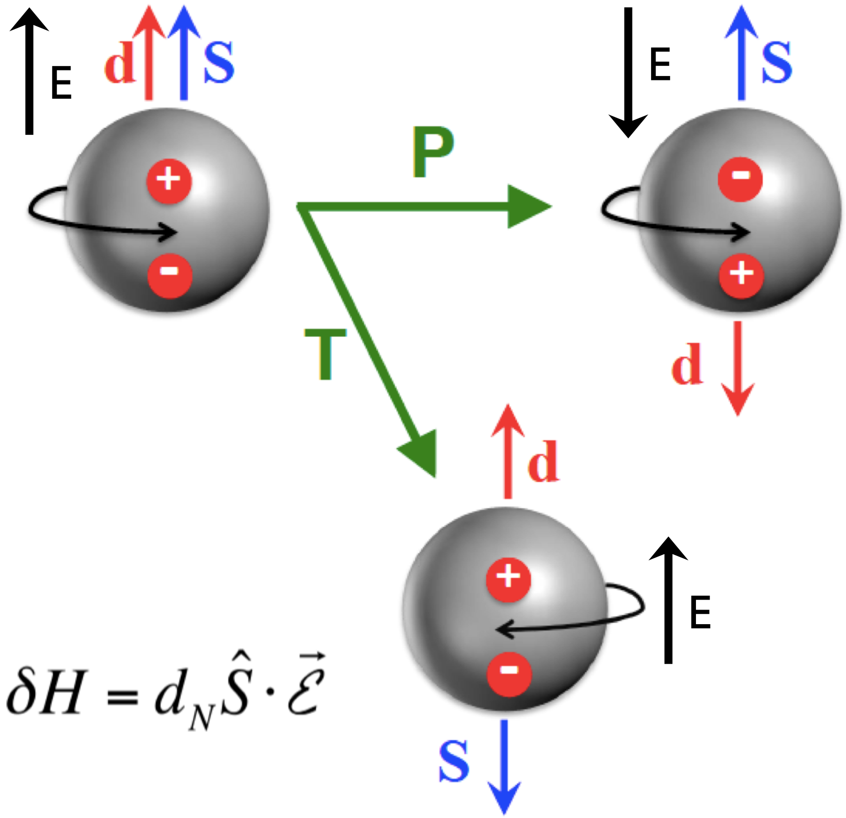



# *Status of EDM searches and perspectives.

**Frederic Teubert**

**CERN, EP-LBD**




$$\delta H = d_N \hat{S} \cdot \vec{\mathcal{E}}$$

# Preamble

**Purcell and Ramsey (1950)** first search for neutron EDM ($d_n < 2\times10^{-18}$ e cm). **P** and **T** must be conserved to a good approximation.

Since 1956 we know **P is not conserved** in weak interactions (***β*** decay), and since 1964 we know **CP is also not conserved** in weak interactions ($K^0$ decays).

If **CPT** holds, then **CP violation implies non zero EDM** → Most of the theories suggested at the time to explain K decays ruled out by EDMs.

**Within the SM**, leading order qEDM interactions come in pairs for which the only phase in the SM cancels → **negligible EDMs**.

$$H_{\mathrm{T,P-odd}} = -d\mathbf{E}\cdot\frac{\mathbf{S}}{S} \rightarrow \mathcal{L}_{\mathrm{CP-odd}} = -d\frac{i}{2}\overline{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu},$$

dim-5 operator

However, **strong interactions** within the SM also include a phase leading to possible CP violation ($\theta_{QCD}$) (dim-4 operator)→ **Strong CP problem (motivation for axion searches).**

# Why continue to bother with EDMs?

$d_n^{SM} \sim (10^{-16}\ e\ cm) \times \theta_{QCD} + (1\text{-}6) \times 10^{-32}\ e\ cm.$

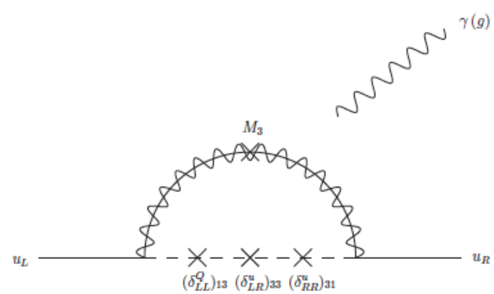
$d_n^{BSM} \sim (10^{-16}\ e\ cm) \times (v/\Lambda)^2 \times \sin(\Phi) \times y_f F$

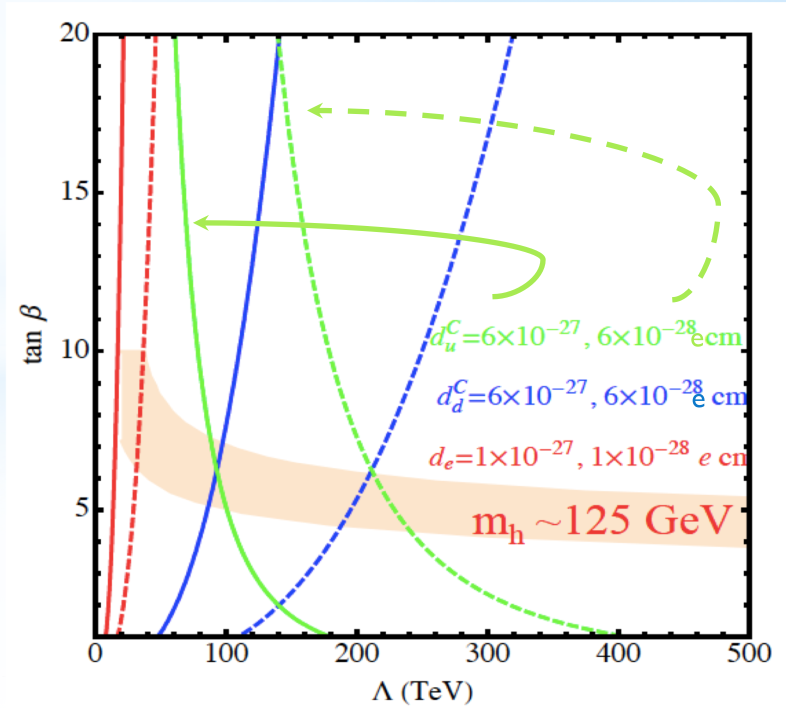
**sin(Φ)** → CPV phase must be large enough to explain baryogenesis.
**$(v/\Lambda)^2$** → BSM mass scale?
**$y_f$F** → BSM dynamics: perturbative? strongly coupled? dependence on other parameters?

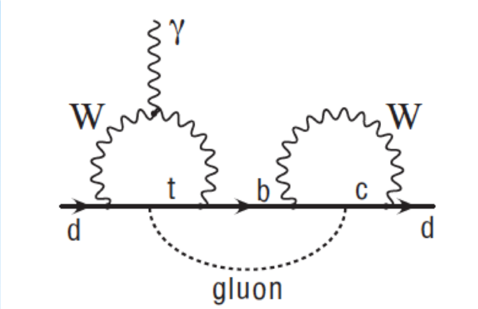
EDMs provide information on the three "frontiers": cosmic frontier (baryon asymmetry), high energy frontier (scale of BSM) and intensity frontier (couplings of BSM).

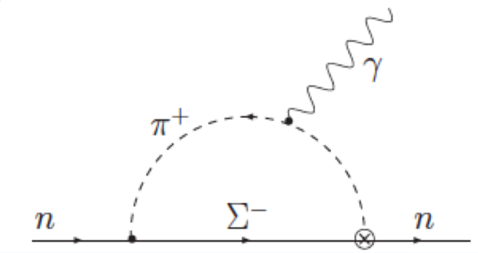
For example, take "minimally unnatural SUSY" → **probing scales at several 100 TeV!**

$$\tilde{d}_u \simeq \frac{\alpha_s}{4\pi} M_3 \left(\delta^u_{LL}\right)_{13} \left(\delta^u_{LR}\right)_{33} \left(\delta^u_{RR}\right)_{31} \times \frac{3}{M^2_{sc}} \log\left(\frac{M^2_{sc}}{M^2_3}\right) \sin\phi_{\tilde{u}\mu}$$
$$\sim 3 \frac{\delta m_u}{\Lambda^2_{SUSY}} \log\left(\frac{\Lambda^2_{SUSY}}{M^2_3}\right) \sin\phi_{\tilde{u}\mu}$$
$$\sim 1 \times 10^{-26}\ \text{cm} \left(\frac{3}{\tan\beta}\right) \left(\frac{\theta^2_u}{1/3}\right) \left(\frac{M_3}{1\ \text{TeV}}\right) \left(\frac{100\ \text{TeV}}{\Lambda_{SUSY}}\right)^3$$
$$\times \left[\log\left(\frac{\Lambda^2_{SUSY}}{M^2_3}\right)/10\right] \left(\frac{\sin\phi_{\tilde{u}\mu}}{0.1}\right)$$






# SM predictions for nucleons EDMs

$$d_d \sim \mathrm{Im}(V_{tb}V_{td}^{*}V_{cd}V_{cb}^{*})\alpha_s m_d G_F^2 m_c^2 \times \text{loop suppression}$$

**<$10^{-33}$ e cm**

Direct quark EDMs vanish at one and two loop level!

Longer distance contributions dominate. Can be as large as **$10^{-31}$**.

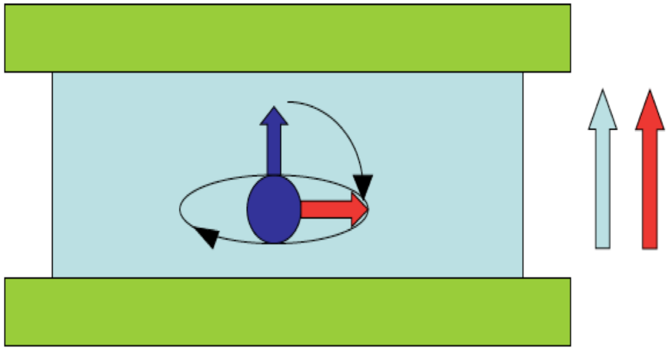
**So, at what values do we need to worry about the SM uncertainty in the predictions?**

Consider an outrageous overestimate for $d_n$ that puts loop factors like $\alpha_s/4\pi$ to be one, and chooses constituent quark masses (rather than current quark):

$$d_n \sim \mathrm{Im}(VVVV)\ G_F^2 m_c^2 \times 100\ \mathrm{MeV} < 10^{-29}\ \mathrm{cm.}$$

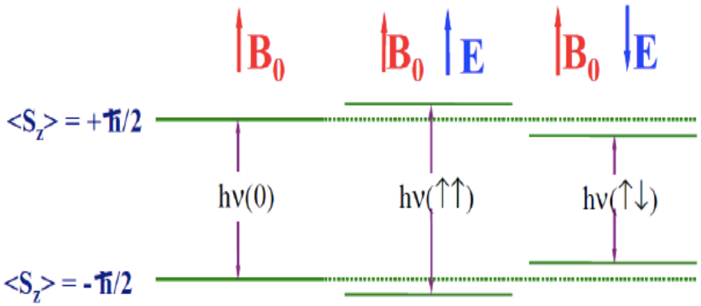
**Therefore, any nonzero neutron/proton EDM above $10^{-29}$ e cm is guaranteed to be NP.**

# Status of neutron EDM measurements



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

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




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

Key to any EDM measurement: see **small effect** due to coupling to **E**, in a background of much **larger B** using **T-odd** signature.

Measure **Larmor precession** with E parallel (antiparallel) to B.

Need **large E**(~10 kV/cm), and **well know B**(ΔB~fT) that does not change between measurements.

Since 1980 advances in **UCN production** (specially at ILL Grenoble) improved dramatically the statistical uncertainty due to the **increase in observation time (T)**, requiring **advances in magnetic shielding**.

Currently sensitivity is still **dominated by the statistical uncertainty**. The main systematic uncertainty is due to the reproducibility of B **(key role of the comagnetometer).**

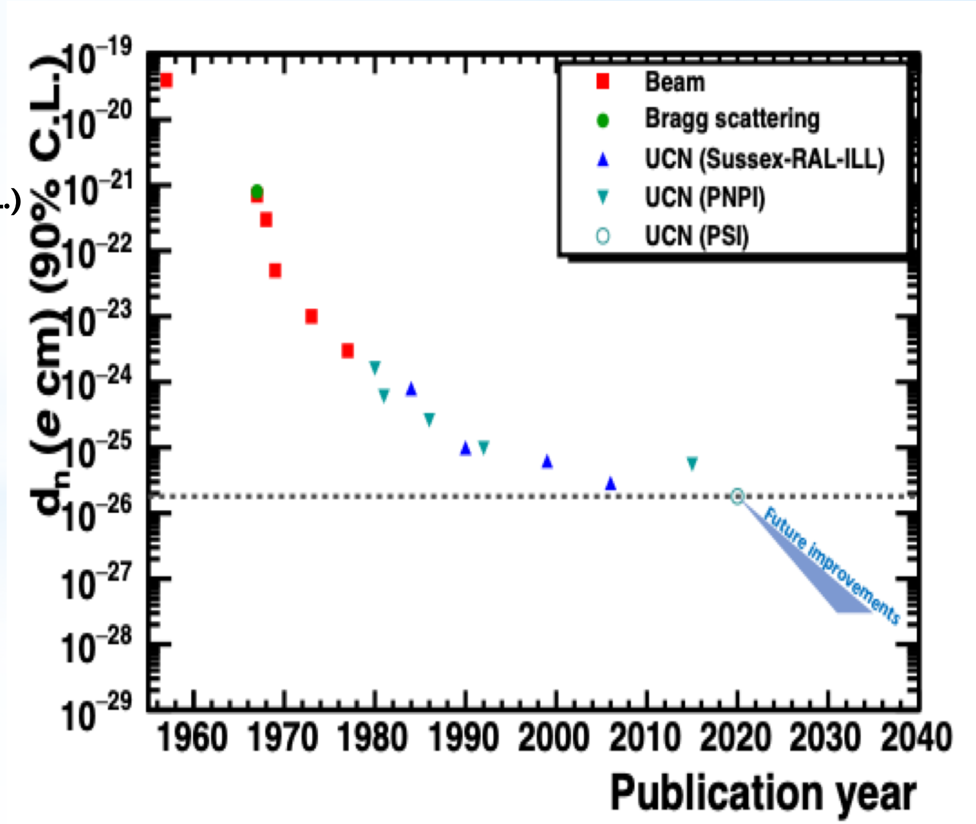
# Status of neutron EDM measurements

Best current sensitivity from PSI (nEDM Collab.), with data collected (2015-16):

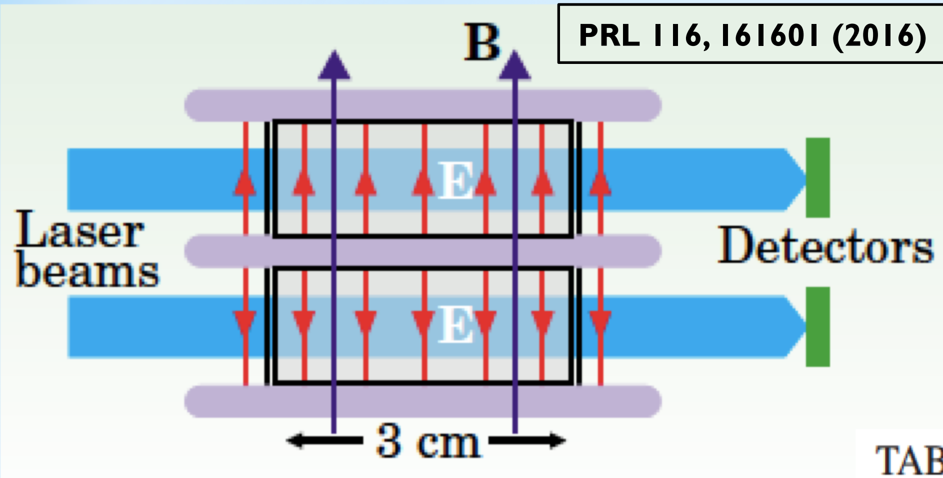
**$d_n < 1.8\times10^{-26}$ e cm @90% CL.** PRL 124, 081803 (2020)

To improve need more intense sources of UCN. Future efforts at **PNPI-ILL**, **PSI, LANL, TRIUMF** and in particular **SNS (Oak Ridge)** promise sensitivities **at (or below) $10^{-27}$ e cm.**

| Experiment | Location | UCN source | Features | Sensitivity (90% C.L.) |
|---|---|---|---|---|
| n2EDM | PSI | Spallation, $SD_2$ | Ramsey method, double cell, $^{199}$Hg comagnetometer | $1\times10^{-27}$ e cm |
| PanEDM | ILL | Reactor, LHe | Ramsey method, double cell, $^{199}$Hg comagnetometer | $1\times10^{-27}$ e cm |
| LANL nEDM | LANL | Spallation, $SD_2$ | Ramsey method, double cell, $^{199}$Hg comagnetometer | $3\times10^{-27}$ e cm |
| Tucan | TRIUMF | Spallation, LHe | Ramsey method, double cell, $^{129}$Xe comagnetometer | $1\times10^{-27}$ e cm |
| nEDM@SNS | ORNL | In-situ production in LHe | Cryogenic, double cell, $^3$He comagnetometer, $^3$He as the spin analyzer | $3\times10^{-28}$ e cm |



# Status of AMO EDM measurements: $^{199}$Hg (Diamagnetic)




PRL 116, 161601 (2016)

**Tabletop experiment** at U. Washington (**Seattle**). Laser beamed through two cells with Hg vapor. **Analysis phase**, light plane polarized → nuclear **spin precessed around B**.

Two cells **opposite E (10kV/cm)**. Latest result using four cells.

**$|d_{Hg}| < 7.4\times10^{-30}$ e cm @95% CL.**

However, **interpretation not straightforward: $d_{dia}$** dominant contribution nuclear-spin dependent e-N interaction (**$C_T$**) and **Schiff** moment (long range pion and short range four-nucleon interaction).

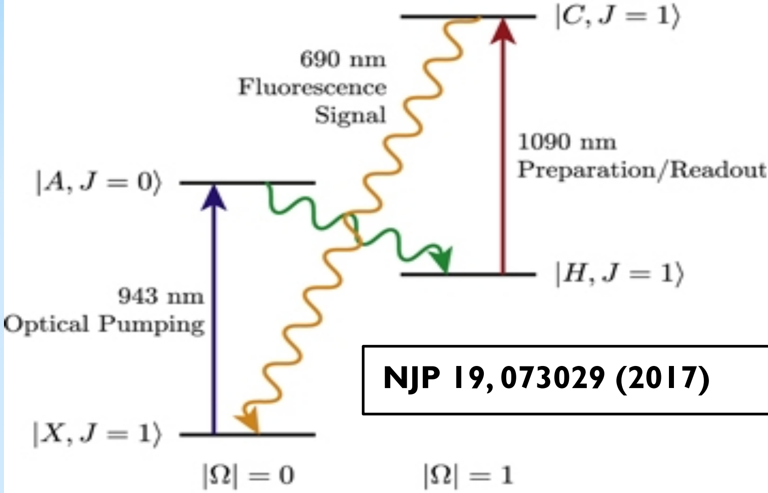
**Diamagnetic atoms**

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

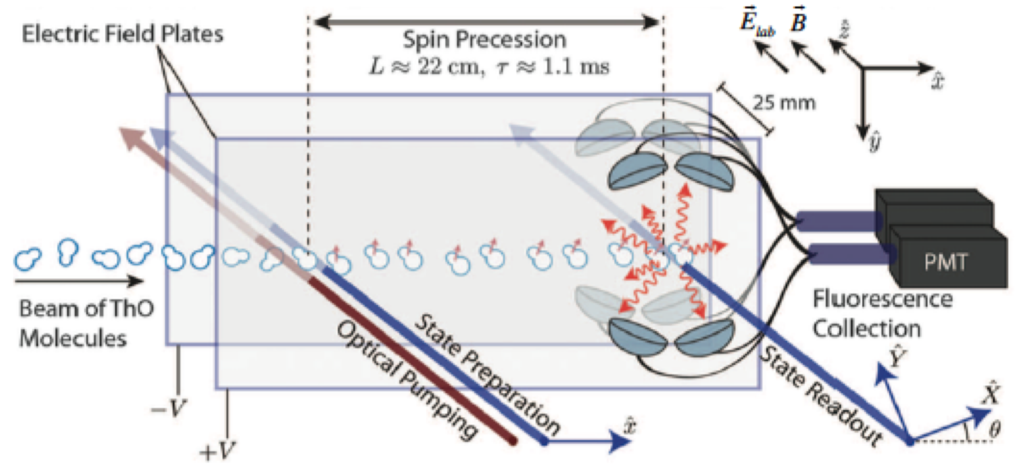
TABLE III. Limits on *CP*-violating observables from the $^{199}$Hg EDM limit. Each limit is based on the assumption that it is the sole contribution to the atomic EDM. In principle, the result for $\mathbf{d}_n$ supercedes [11] as the best neutron EDM limit.

| Quantity | Expression | Limit | Ref. |
|---|---|---|---|
| $\mathbf{d}_n$ | $\mathbf{S}_{\mathrm{Hg}}/(1.9\ \mathrm{fm}^2)$ | $1.6\times10^{-26}\ e\,\mathrm{cm}$ | [21] |
| $\mathbf{d}_p$ | $1.3\times\mathbf{S}_{\mathrm{Hg}}/(0.2\ \mathrm{fm}^2)$ | $2.0\times10^{-25}\ e\,\mathrm{cm}$ | [21] |
| $\bar{g}_0$ | $\mathbf{S}_{\mathrm{Hg}}/(0.135\ e\,\mathrm{fm}^3)$ | $2.3\times10^{-12}$ | [5] |
| $\bar{g}_1$ | $\mathbf{S}_{\mathrm{Hg}}/(0.27\ e\,\mathrm{fm}^3)$ | $1.1\times10^{-12}$ | [5] |
| $\bar{g}_2$ | $\mathbf{S}_{\mathrm{Hg}}/(0.27\ e\,\mathrm{fm}^3)$ | $1.1\times10^{-12}$ | [5] |
| $\bar{\theta}_{QCD}$ | $\bar{g}_0/0.0155$ | $1.5\times10^{-10}$ | [22,23] |
| $(\tilde{d}_u-\tilde{d}_d)$ | $\bar{g}_1/(2\times10^{14}\ \mathrm{cm}^{-1})$ | $5.7\times10^{-27}\ \mathrm{cm}$ | [25] |
| $C_S$ | $\mathbf{d}_{\mathrm{Hg}}/(5.9\times10^{-22}\ e\,\mathrm{cm})$ | $1.3\times10^{-8}$ | [15] |
| $C_P$ | $\mathbf{d}_{\mathrm{Hg}}/(6.0\times10^{-23}\ e\,\mathrm{cm})$ | $1.2\times10^{-7}$ | [15] |
| $C_T$ | $\mathbf{d}_{\mathrm{Hg}}/(4.89\times10^{-20}\ e\,\mathrm{cm})$ | $1.5\times10^{-10}$ | see text |

# Status of AMO EDM measurements: $^{232}Th^{16}O$ (Paramagnetic)




NJP 19, 073029 (2017)




In **paramagnetic** systems with one (or more) unpaired $e^-$, EDMs are dominated by $\mathbf{d_e}$ and the nuclear **spin-independent e-N interaction ($\mathbf{C_S}$).** Great advantage is **large internal E-field (GV/cm).**

Paramagnetic atoms

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

**ACME II** experiment (Harvard), uses ThO molecule metastable states. The EDM signal is a **rotation of the electron spin** that reverses with the sign of E. The EDM frequency shift **($\Delta\omega^{EDM}$)** is the rotation angle divided by the transit time (τ~1.1ms). The angle is measured from the detection of fluorescence signal (690 nm).

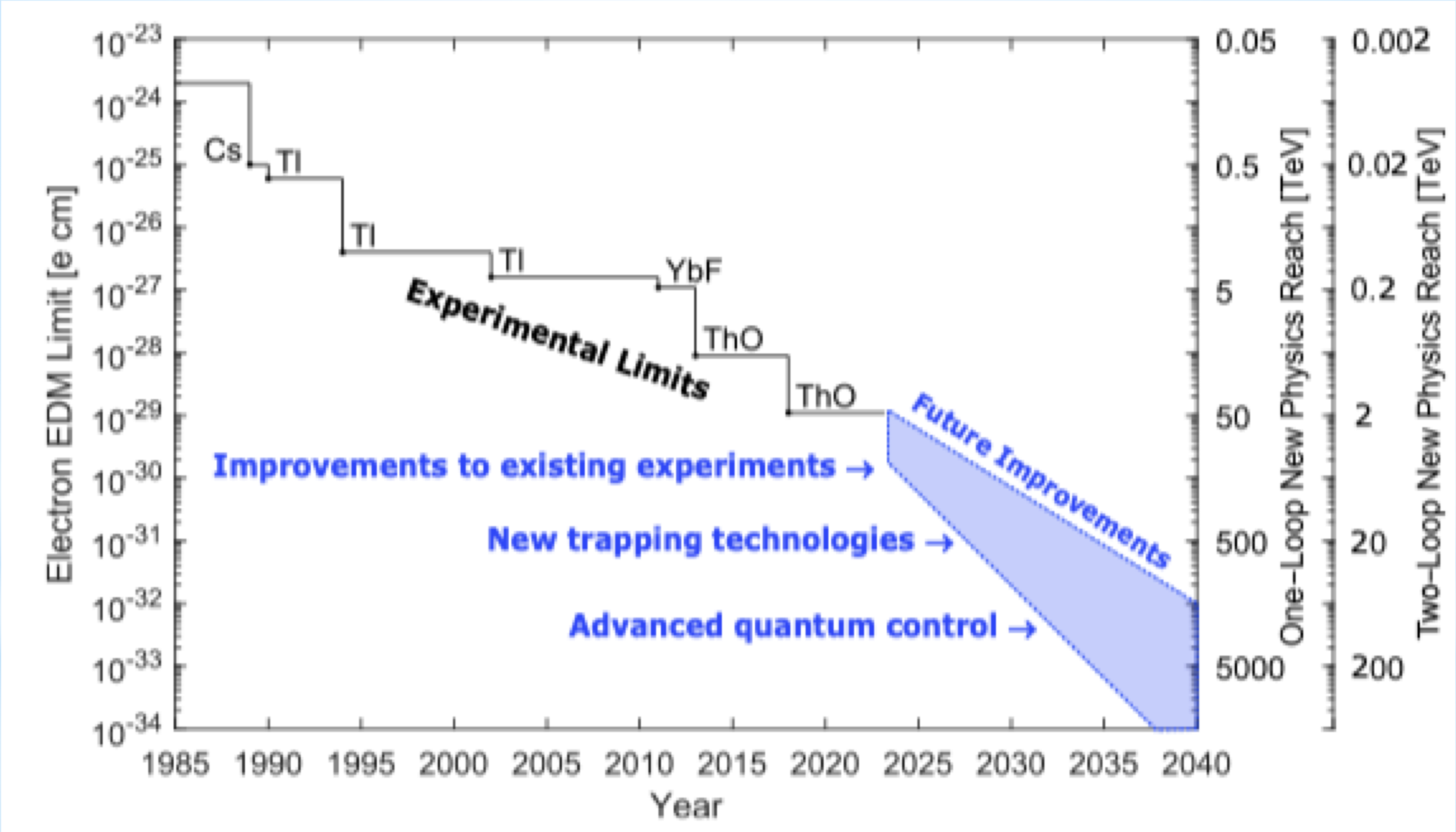
**$\Delta\omega^{EDM}$ = (5.1±3.7±3.1)mrad/s → $|d_e| < 1.1\times10^{-29}$ e cm @90% CL. ($C_S$=0)**

Main syst. are due to imperfect reversal of E and other sources of B.

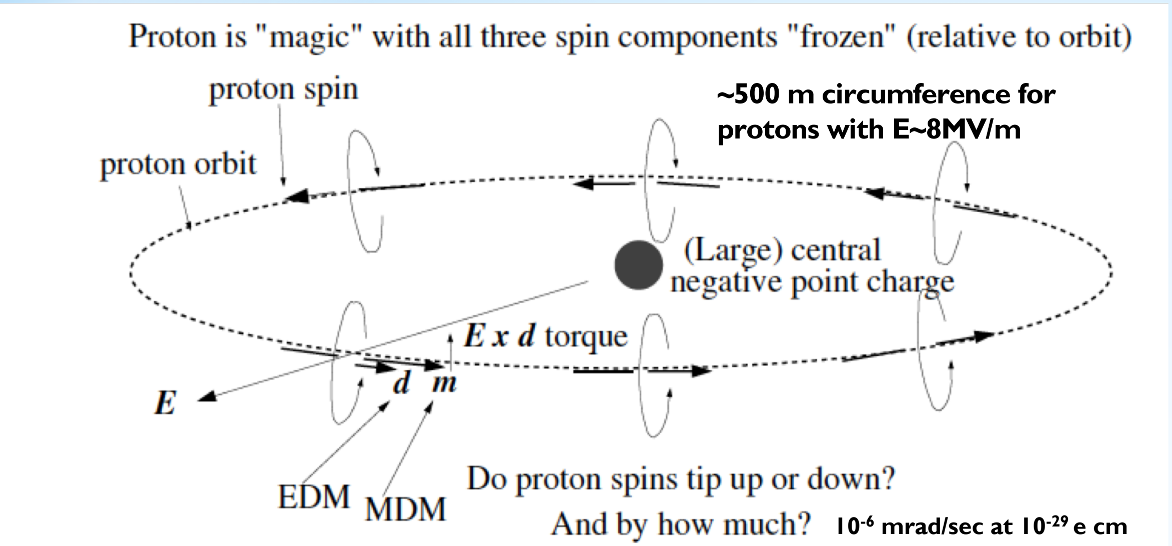
Nature 562, 355-360 (2018)

# Prospects of AMO EDM measurements

In the near future improved **coherence time** (using advanced molecular cooling techniques), improved **sensitivity** (using frozen gas) or by applying advanced quantum techniques to stablish coherent states, will improve the limits by several orders of magnitude.



# Storage Ring: experimental method




$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} + \left(-a_\mu + \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\frac{\vec{E}}{c}\right].$$

$$\vec{\omega}_{EDM} = -\eta\frac{q}{2m}\left(\cancel{\vec{\beta}\times\vec{B}} + \frac{\vec{E}}{c}\right) = -\frac{\eta}{2mc}\vec{F},$$

**"Frozen spin"** in **all-electric storage ring** is only possible for **e, μ** or **p**, with **"magic"** momentum (**15, 3094** or **701**) MeV. Not possible for deuteron without B-field.

**Proton experiment:** Inject **transverse polarized** protons at **0.7** GeV (~100 bunches of ~$10^8$ protons). Use RF solenoid to **rotate spins**, producing protons with both helicities. Measure difference between **vertical polarization** at earlier and later times, extracting part of the beam in a polarimeter.

To reach $10^{-29}$ e cm, requires **impractical small B** (few aT). Therefore, **inject both CW and CCW rotating beams**. In the presence of a radial B field, a vertical separation will develop → **key issue is monitoring beam trajectory!**

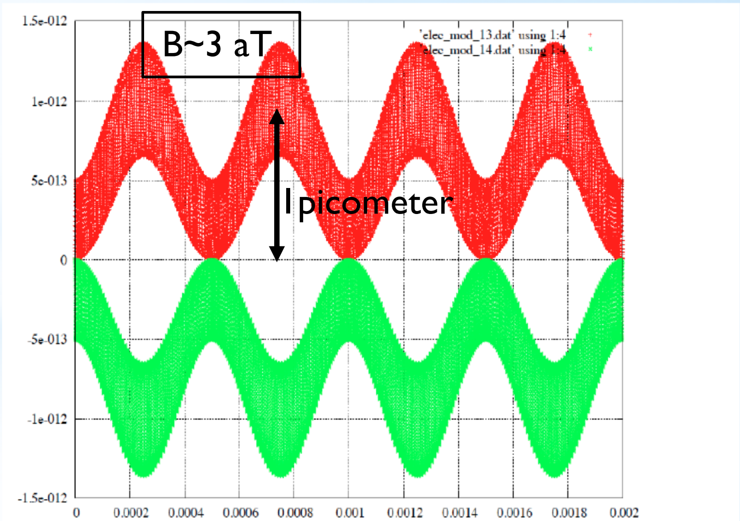



*Figure 11.3: Simulation results for counter-rotating particles. The vertical beam position in meters [m] is shown here vs. time [s] for a constant radial B-field of 0.3 pG, and using eq. (11.7) to modulate the vertical tune (using f=1KHz). The two colors correspond to clockwise (red) and counter-clockwise (green) rotations for an average radial B-field directed outwards in the radial direction.*

# Storage Ring: Experimental method

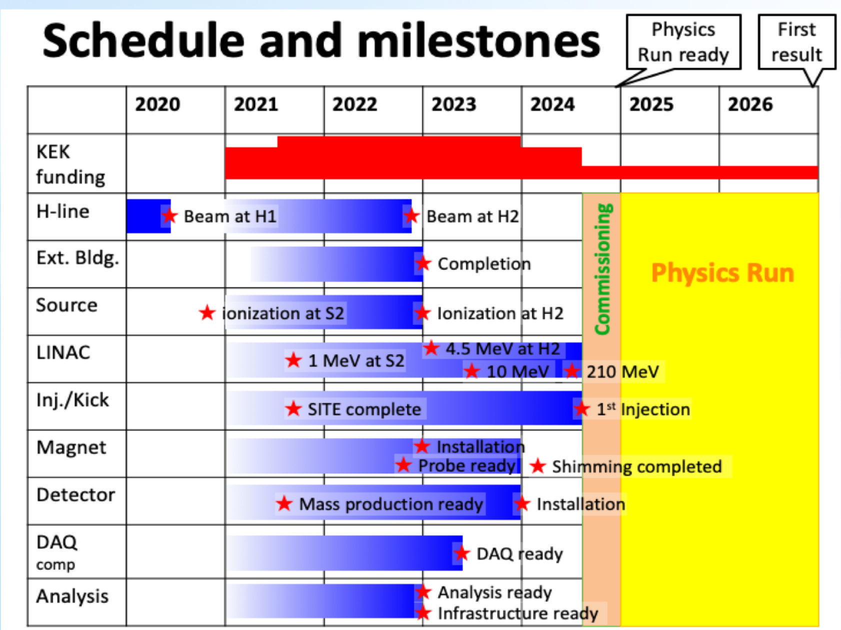
**Expected proton sensitivity:** with **P=0.8**, **A=0.6**, **$E_0$=8 MV/m** over 65% of the ring, **$N_{tot,c}$ = 5x$10^{10}$** particles/cycle, **f=0.011**, **$T_{tot}$=$10^7$ sec** and **SCT=$10^3$sec** →

$$\sigma_d = \frac{2\hbar}{PAE_0\sqrt{N_{tot,c}T_{tot}f\,\tau_{SCT}}}.$$

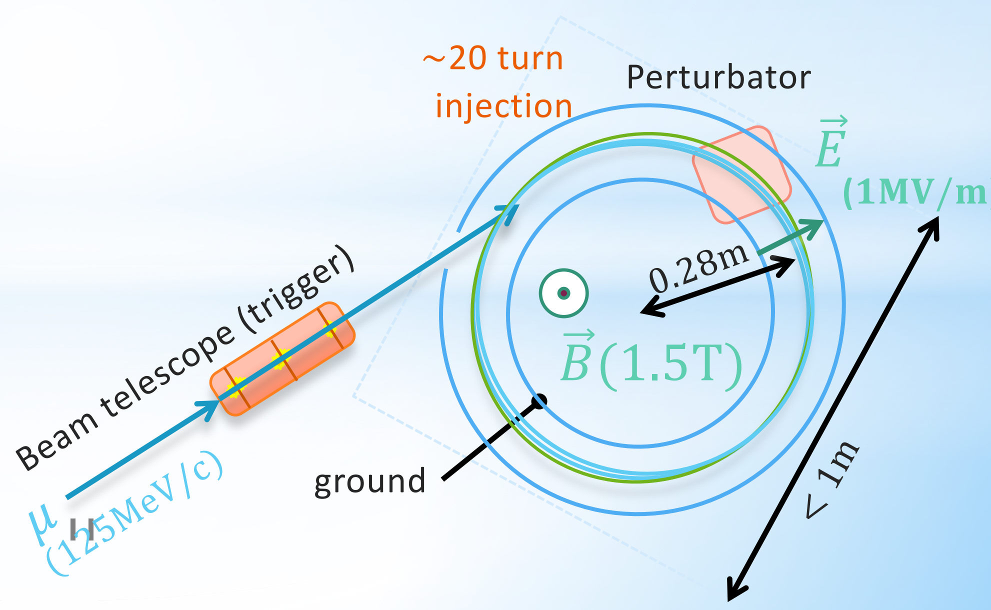
**$\sigma_d$=2.5x$10^{-29}$ e cm (1 year data taking)**

Current limit for **EDM of muons** ( $d_\mu < 1.8\times10^{-19}$ e cm @95% C.L.) as a byproduct of the g-2 measurement. New proposals for compact storage rings at JPARC and PSI could reach sensitivities of O($10^{-23}$-$10^{-21}$) e cm. In these proposals E and $\gamma$ must be chosen such that **$\omega_a$=0**. Spin coherence time is limited by the muon lifetime in the lab frame.

**JPARC g-2/EDM storage magnet at H-line, expected sensitivity O($10^{-21}$) e cm**

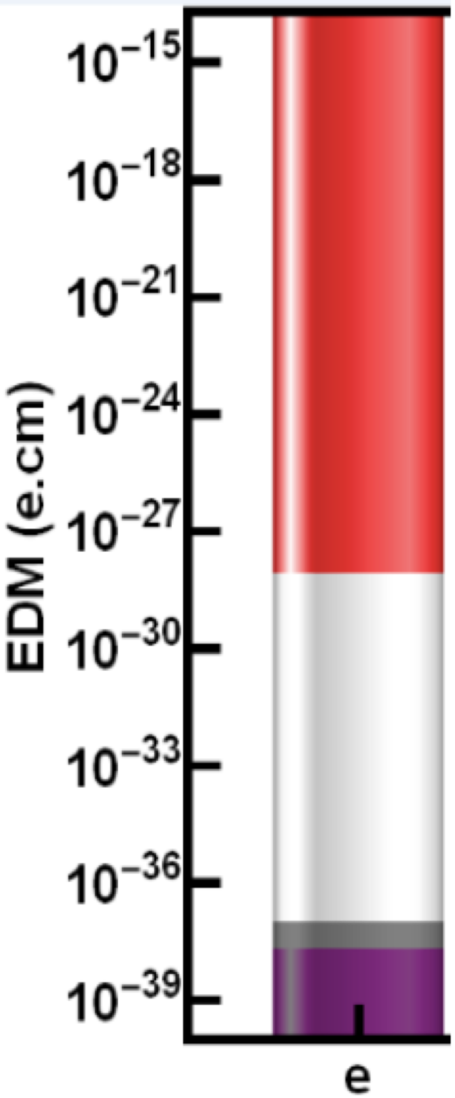



**$\mu$-EDM at PSI proposal, expected sensitivity O($10^{-23}$) e cm**



# EDM display

Displays by Prajwal Mohan Murthy
PhD thesis ETHZ 2018




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

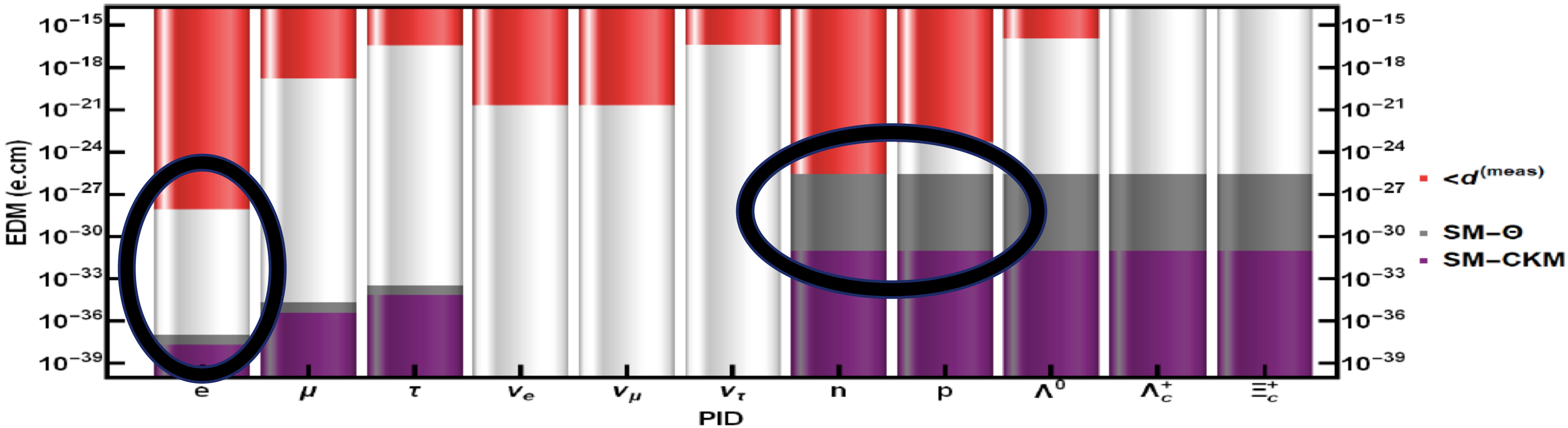
'safe' BSM discovery territory

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

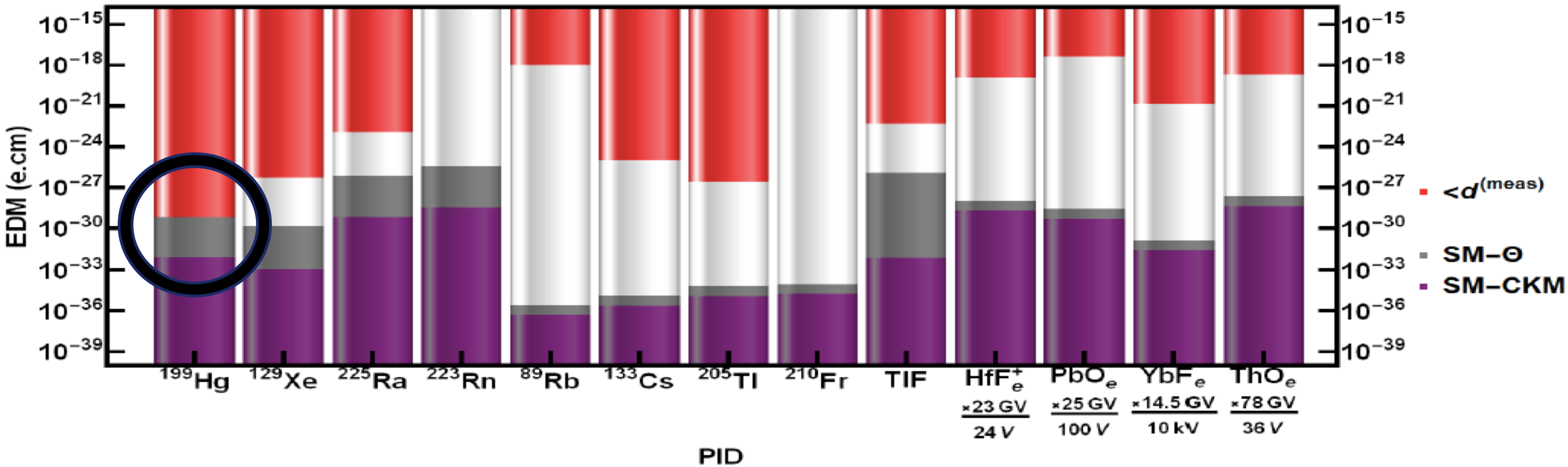
Estimated CKM contribution***

* Often a single source of CPV is assumed, e.g. eEDM for molecular EDM or $\theta_{QCD}$ for n, 199Hg;
** see Ghosh&Sato, PLB777(2018)335 for leptons
*** see Pospelov&Ritz, PRD89(2014)056006; eEDM 1E-38 → 1E-44 ecm

# Particles




# Atoms and molecules



# Messages to take home

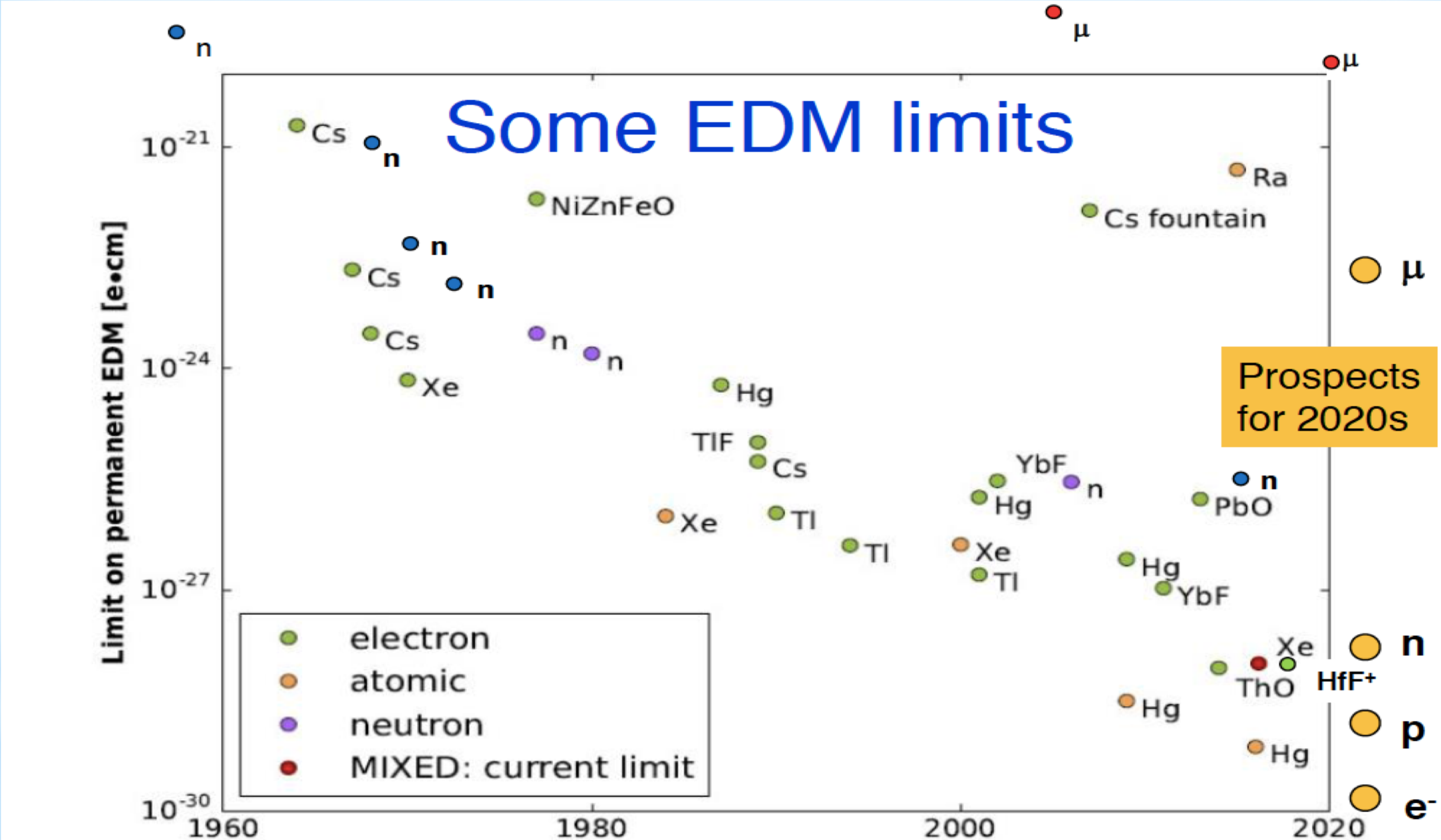
**EDMs** are very sensitive probes for **new CP-violating mechanisms**…(for instance, current limits constrain to $O(10^{-4})$ CP-odd $H \rightarrow \gamma\gamma$ operator, …) these searches are considered to be one of the **most promising paths towards NP**.

The search in **different systems** (leptons, nucleons, atoms, molecules, etc…) are **complementary** and needed to **discriminate between EDM sources** ($\theta_{QCD}$,$C_{ggg}$, $C_{qqqq}$ $C_{qH}$,$d_n$,$C_T$,$C_S$,…). In this sense, proposals like the ones discussed in this workshop to measure **EDMs for charm, strange baryons and tau leptons are very welcome.**

Current (and future) efforts in **neutron EDMs** are **limited** by the available **sources of UCN**. **Statistics is not a problem for a proton (deuteron) storage ring**. Moreover, the possibility to have **CW (CCW) beams** in an **all-electrical storage ring** is a key aspect to be able to control systematic **uncertainties at the $10^{-30}$-$10^{-29}$** level. The other key aspect is the **BPMs to control the beam trajectories.**

# *BACKUP SLIDES

# Status of EDM measurements




Adapted from K. Jungmann et al.,
JPS Conf. Proc. 18(2017)011017