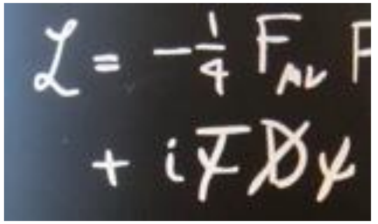
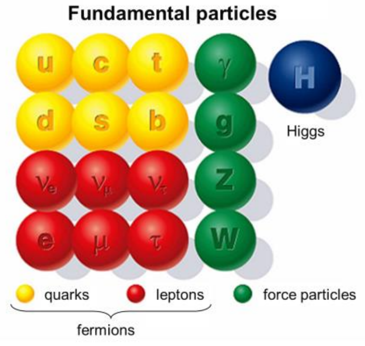
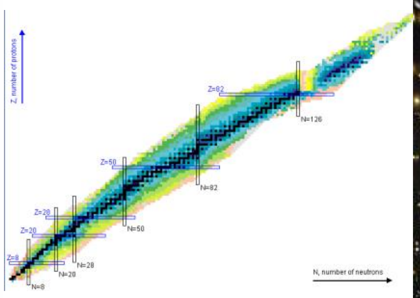


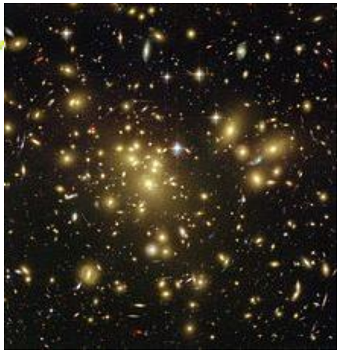
Review on Search for EDM

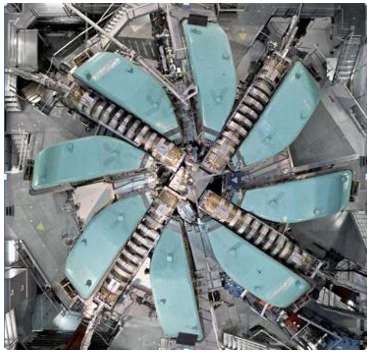
FCCP2019, August 29, 2019

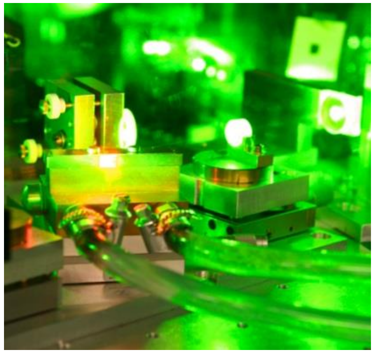
K.Kirch, ETH Zurich – PSI Villigen, Switzerland





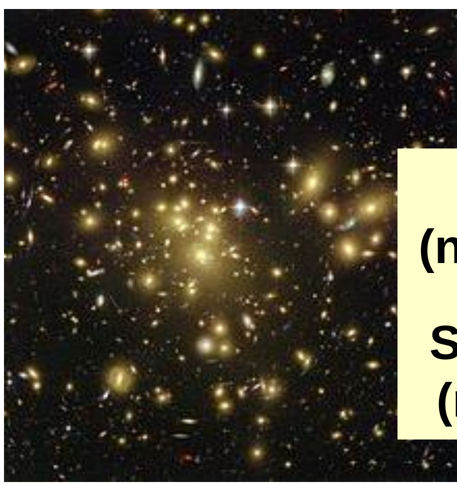






Brief motivation

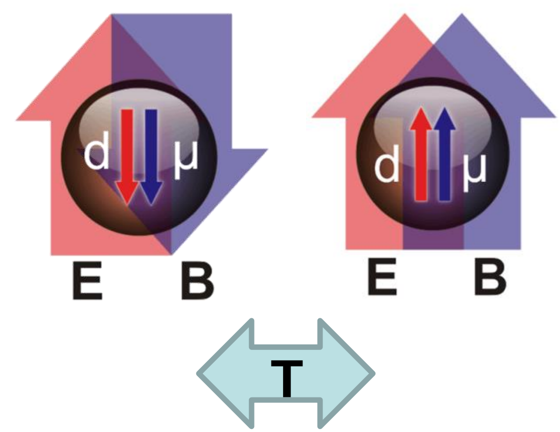
- Permanent EDM of fundamental spin systems are the most sensitive probes of CPV with no SM background yet
- Experiments test new physics (way) beyond TeV scale
- Explanations of the Baryon Asymmetry of the Universe require additional CP violation; could show in EDM
- Hadronic EDM measure θ_{QCD}, e.g.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



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

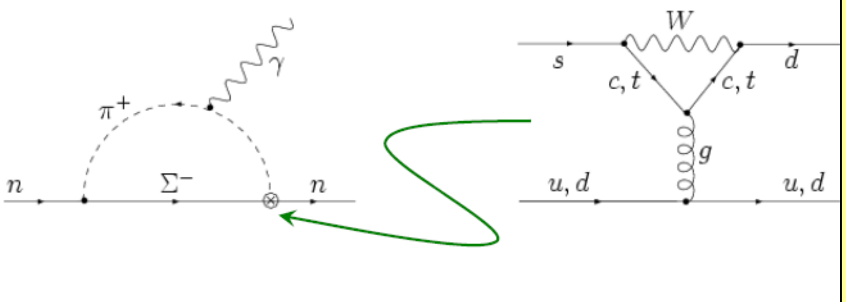
SM expectation:
$(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-18}$

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



Electric Dipole Moments tiny in SM

- Neutron, Proton, ..

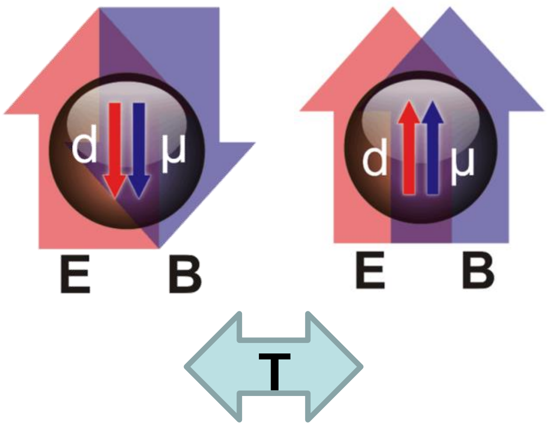


$d_n \sim 10^{-32} - 10^{-34} e\ cm$

[Khriplovich & Zhitnitsky '86]

Expect from SM:
$d_n < 10^{-30}$ e•cm

Experimentally:
$< 3.0 \times 10^{-26}$ e•cm
Pendlebury et al., PRD92(2015)092003



Most sensitive probe of BSM CP violation

- Leptons: 4th order EW

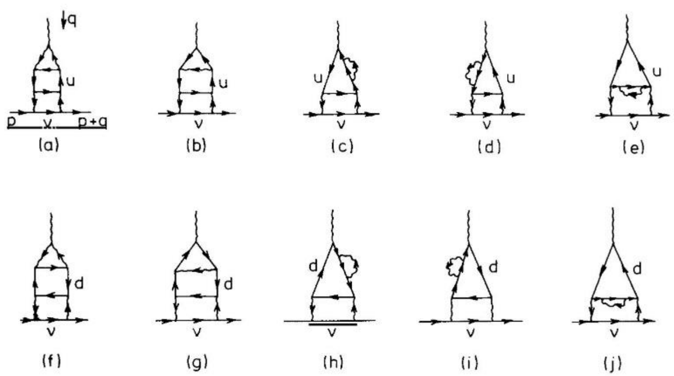


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

[Hoogeveen '90, Pospelov, Ritz 2014]

Expect from SM:
$d_e \leq 10^{-44}$ e•cm
$d_\mu \leq 10^{-42}$ e•cm
$d_\tau \leq 10^{-41}$ e•cm

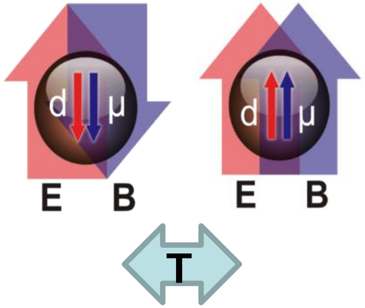
Experimentally:
$d_e < 2 \times 10^{-29}$ e•cm
$d_\mu < 2 \times 10^{-19}$ e•cm
$d_\tau < 3 \times 10^{-17}$ e•cm

ThO molecule
Andreev et al., Nature562(2018)355

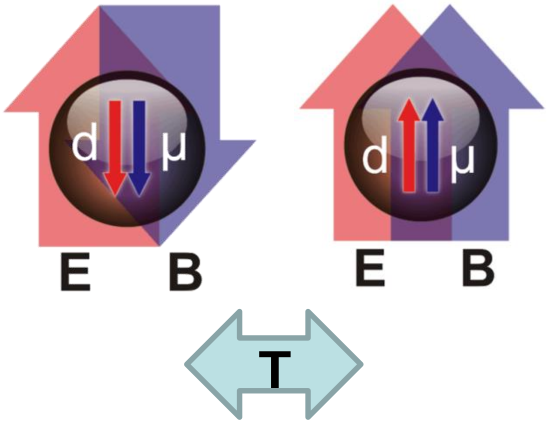
muon g-2 storage ring
Bennett et al., PRD80(2009)052008

EDM Searches

- Why search for permanent electric dipole moments?
- How to measure EDM?
  - search for an interaction of the spin with the electric field
- Which systems are studied experimentally?
  - many: particles, nucleons, nuclei, atoms, molecules, solids
- What are the research fields involved?
  - many: molecular, atomic, neutron, nuclear, particle, solid state, accelerator physics, surface science, chemistry, ...
- What are the technologies involved?
  - many: particle&neutron sources, radioactive ions, exotic molecules, laser, trapping, high voltage, magnetometry, magnetic shields, unprecedented magnetic field control, new materials, ...
- What is the present status?
  - Discovery phase
  - new results further squeeze BSM parameter space
  - many new projects started during the last few years
- What will come next?
  - New techniques and major improvements
  - Discovery and precision measurements in many systems

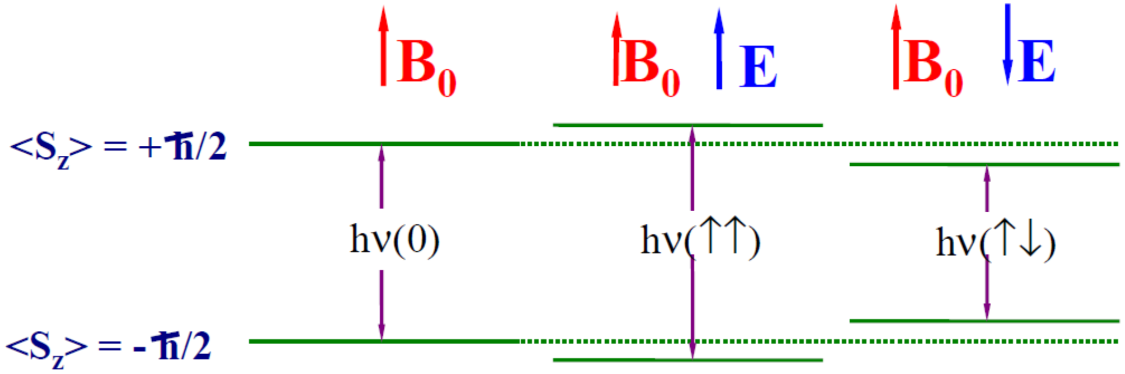


How to measure electric dipole moments ?



How to measure electric dipole moments ?

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

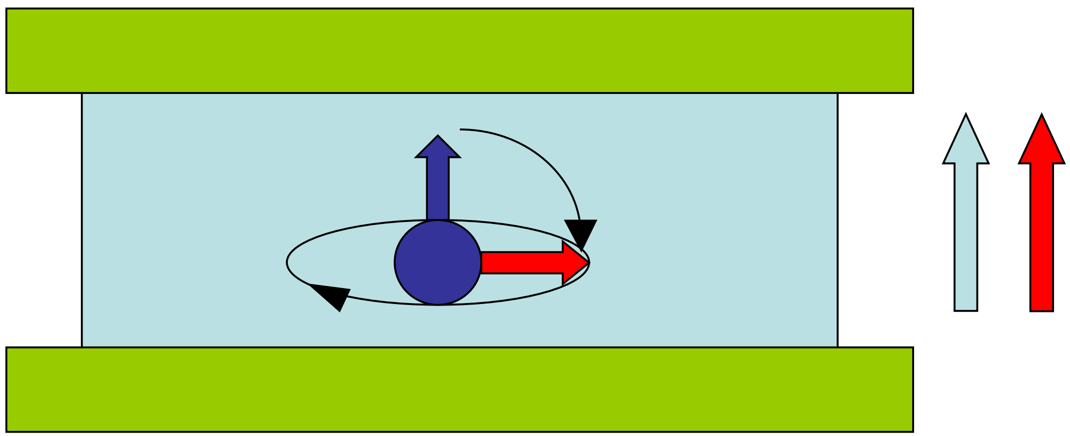


How to measure electric dipole moments ?

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

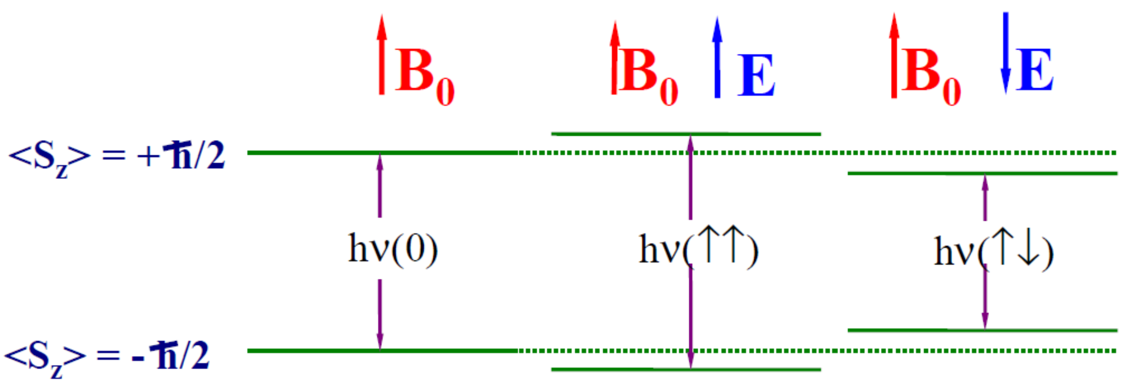
- If that doesn't work: try something else, like
  - cross sections
  - T / CP odd decay correlations
  - …

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



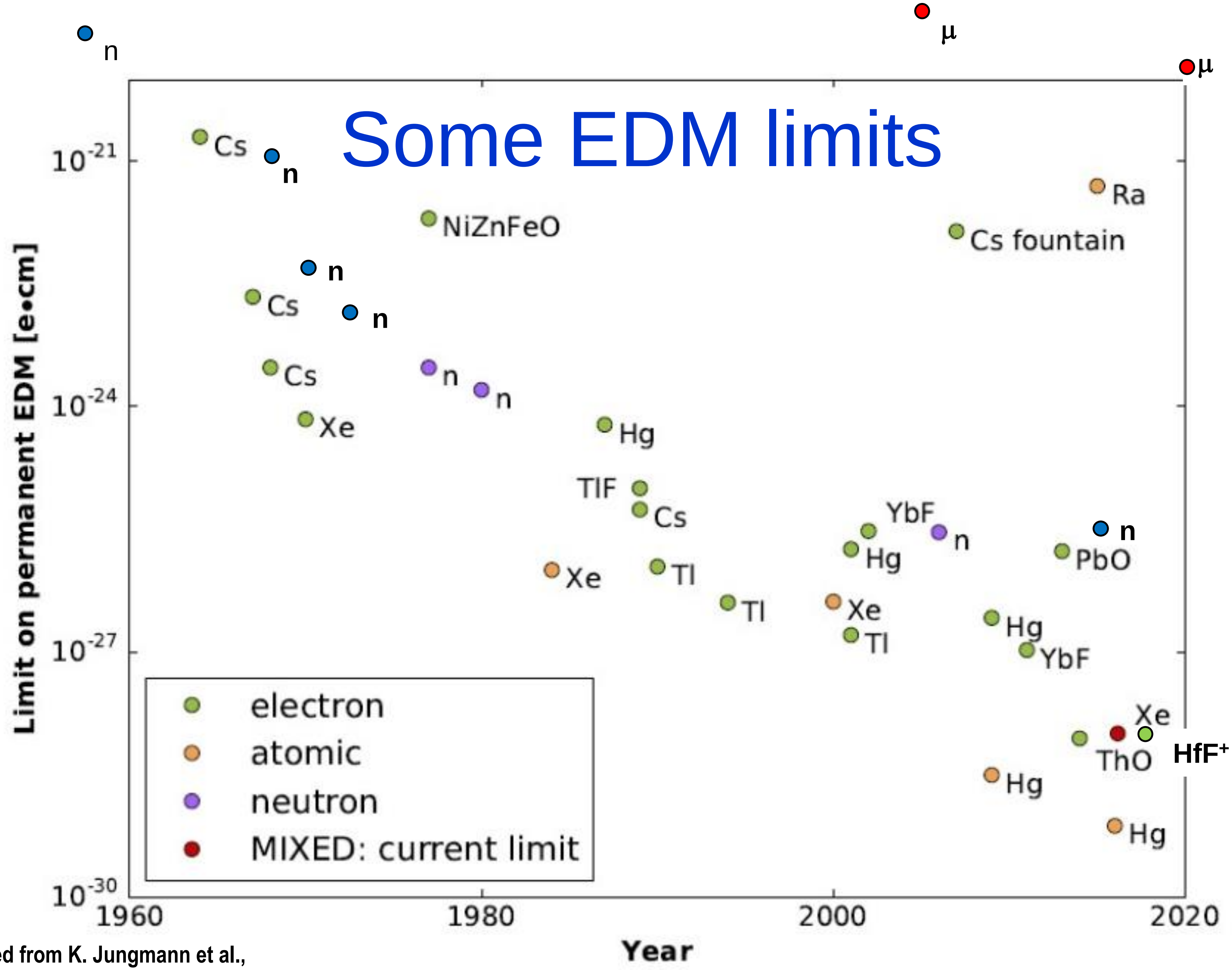
$$h\nu_{\uparrow\uparrow} = 2\,(\mu B + d_n E)$$
$$h\nu_{\uparrow\downarrow} = 2\,(\mu B - d_n E)$$

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



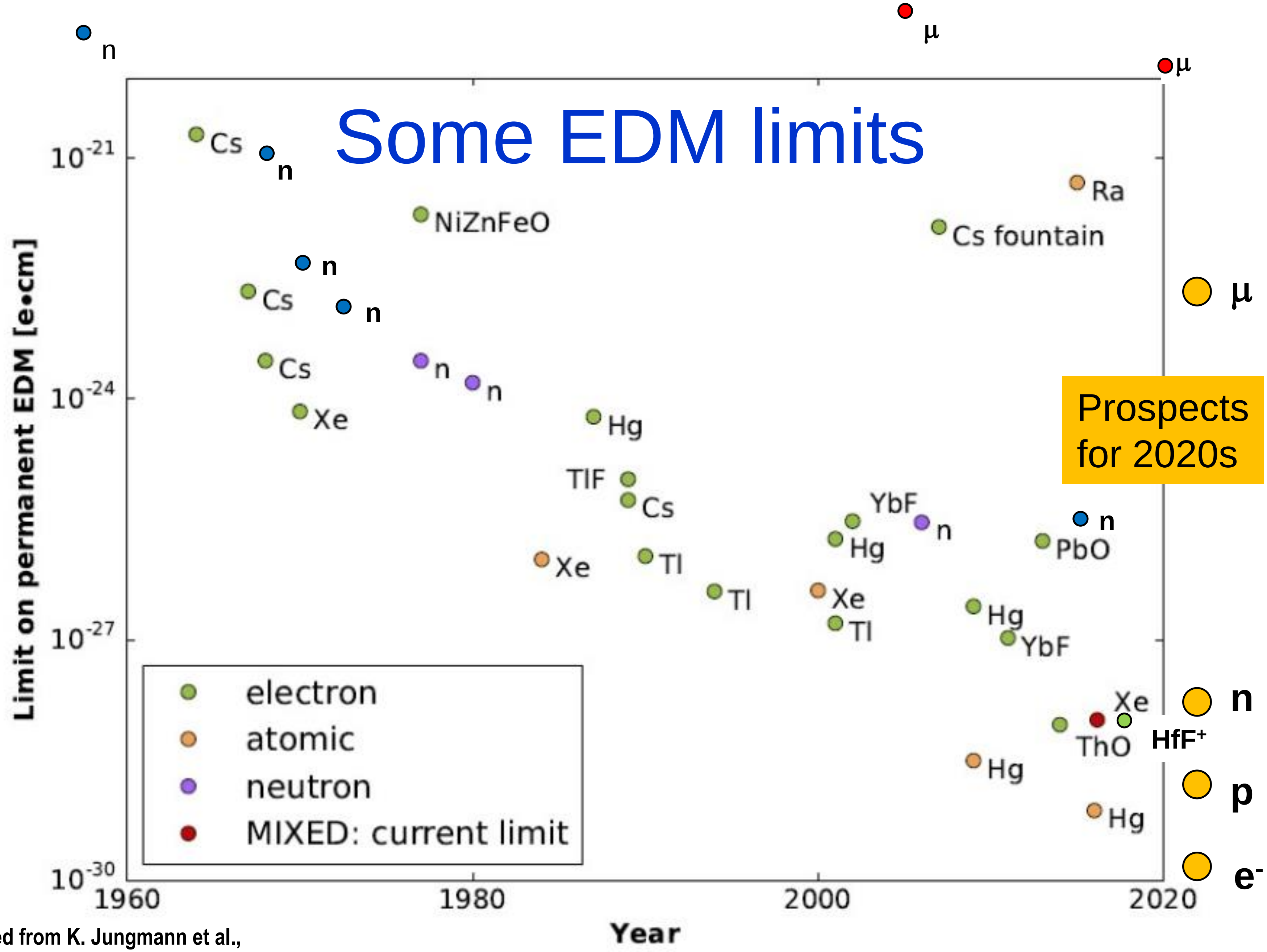
$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

Some EDM limits



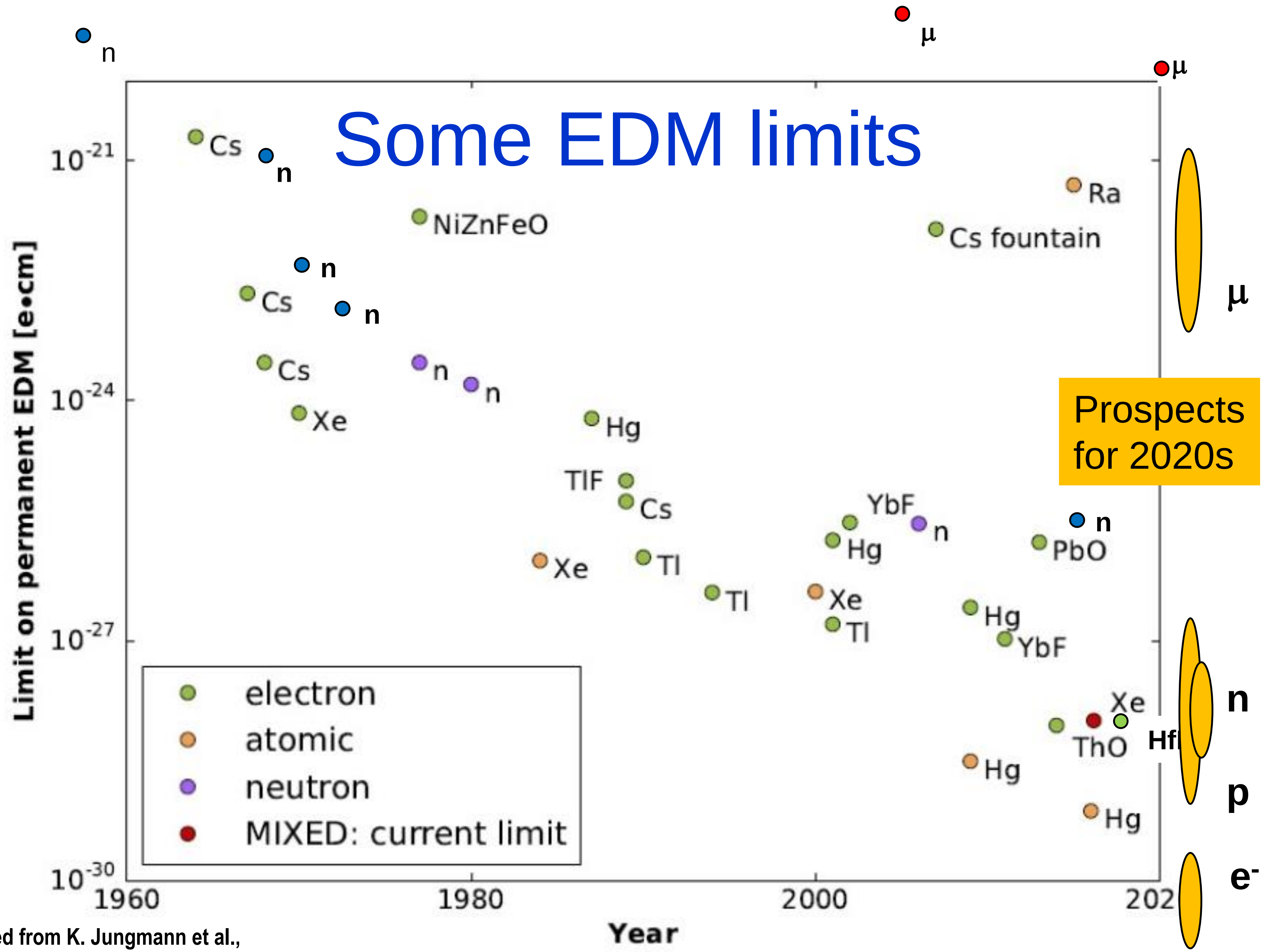
Adapted from K. Jungmann et al.,
JPS Conf. Proc. 18(2017)011017

Some EDM limits



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

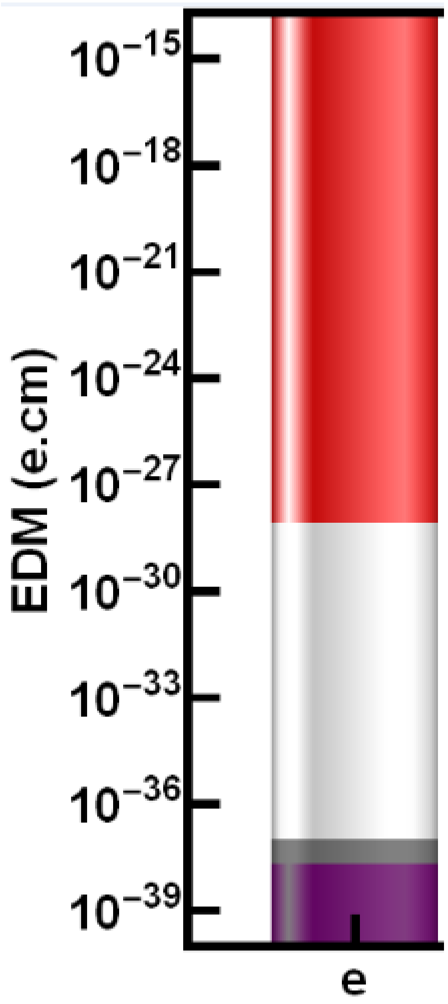
Some EDM limits



Prospects for 2020s

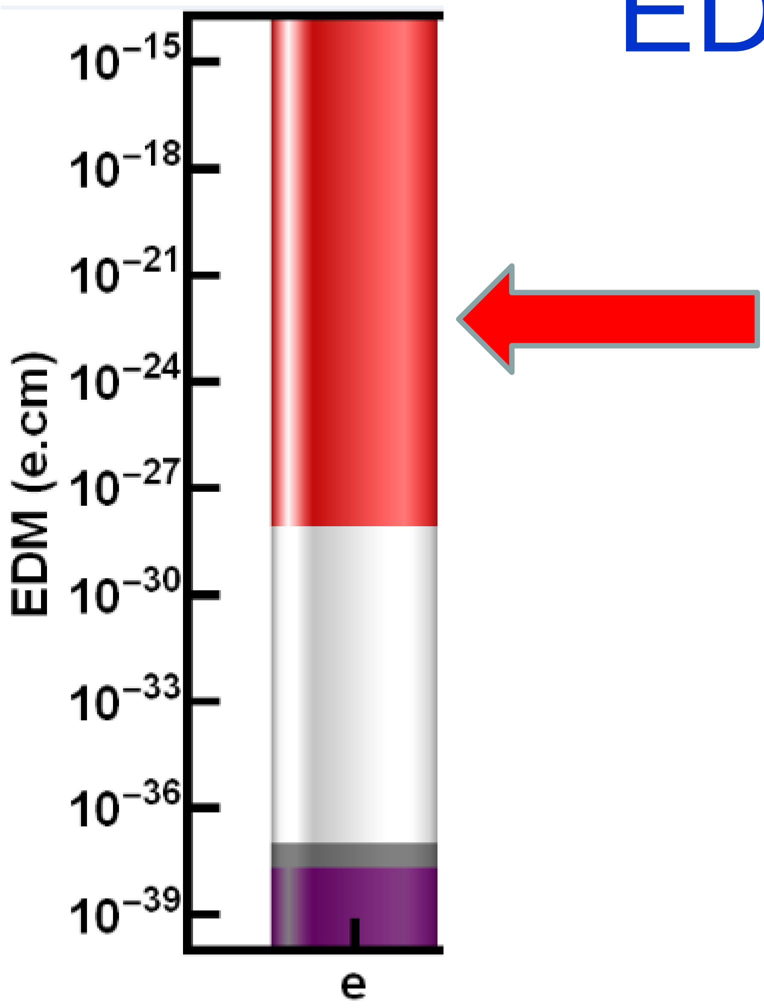
Adapted from K. Jungmann et al., JPS Conf. Proc. 18(2017)011017

EDM display



Displays by Prajwal Mohan Murthy
PhD thesis in preparation, ETHZ 2019

EDM display

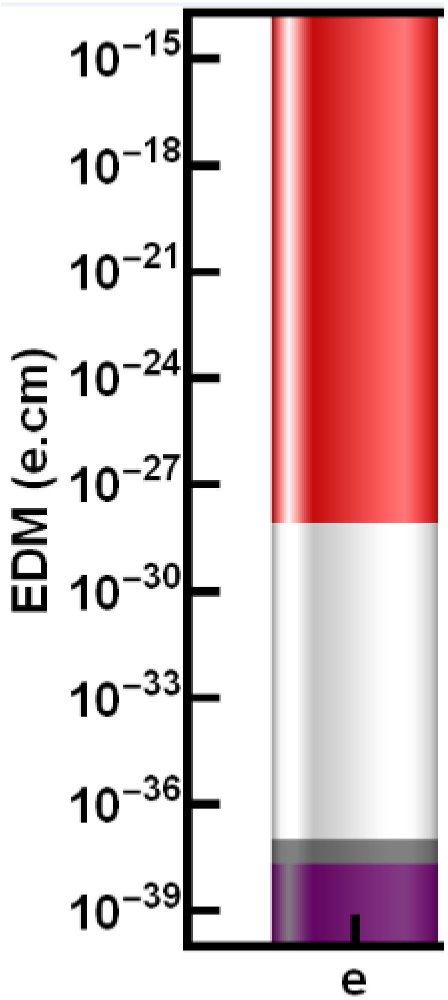


The experimental constraint, can be direct or indirect and under certain assumptions*

* Often a single source of CPV is assumed, e.g. eEDM for molecular EDM or θ_{QCD} for n, 199Hg; here eEDM from measurement on ThO by ACME, NJP19(2017)073029**

**new: Nature562(2018)355

EDM display

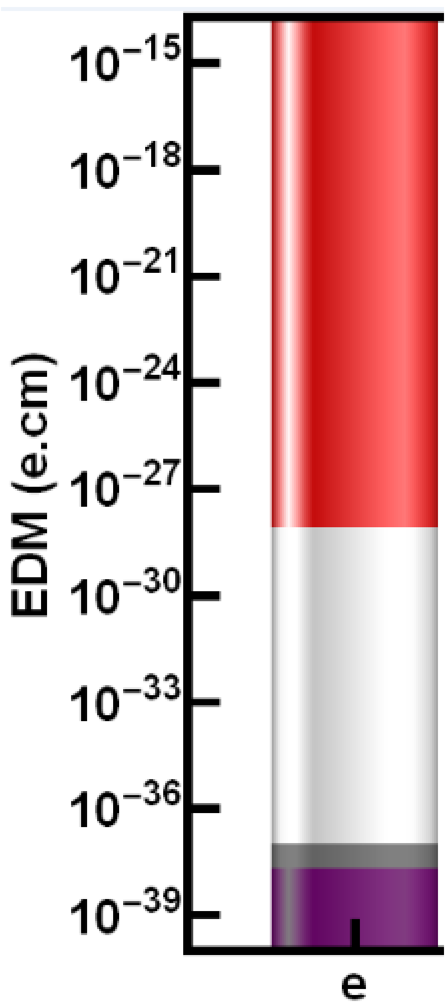


The experimental constraint, can be direct or indirect and under certain assumptions*

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

* 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

EDM display



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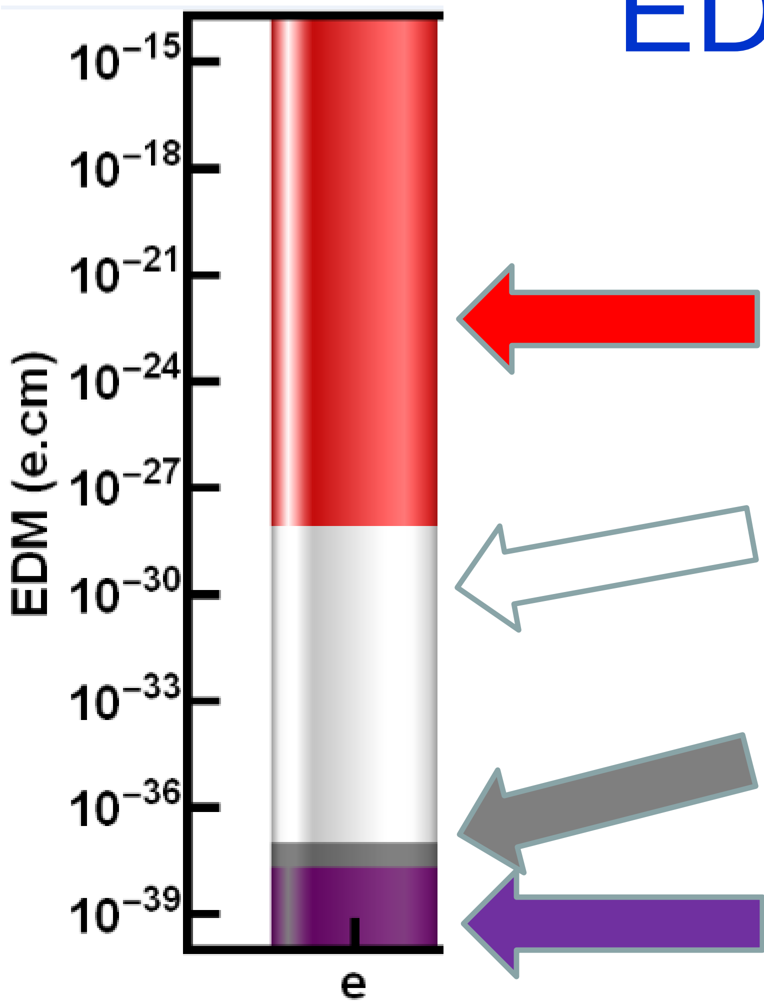
Estimated CKM contribution***

* 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

EDM display



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

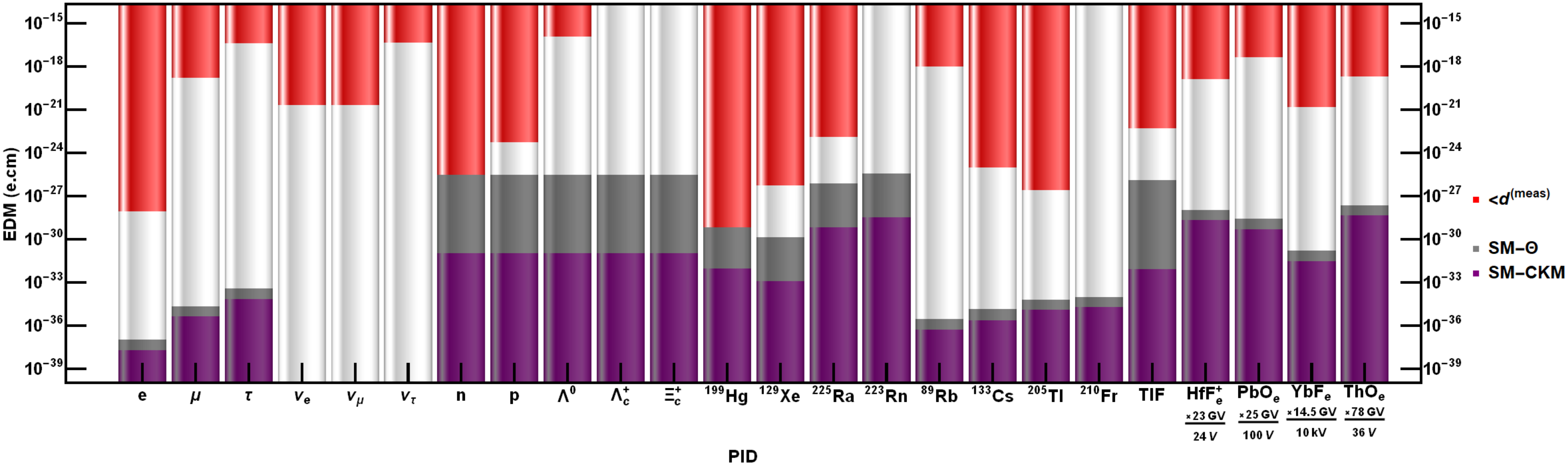
'safe' BSM discovery territory

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

Estimated CKM contribution***

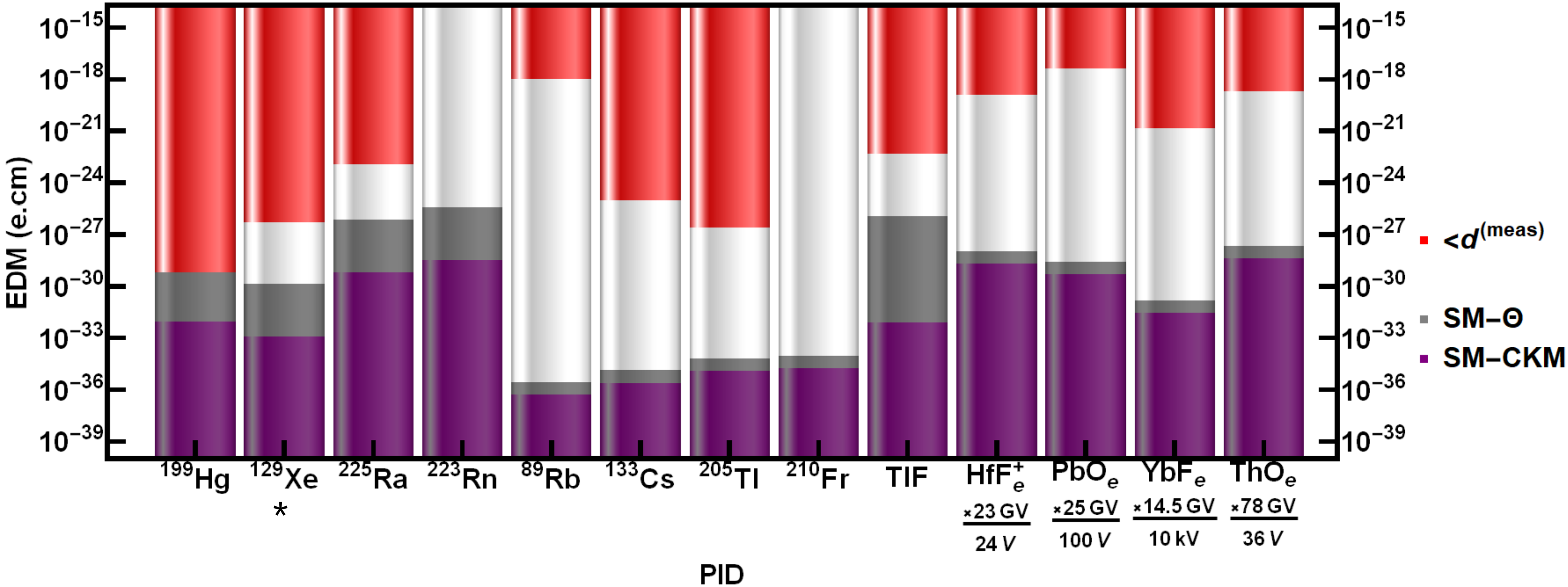
* Often a single source of CPV is assumed, e.g. eEDM for molecular EDM or θ_{QCD} for n, 199Hg;
** see Ghosh&Sato, PLB777(2018)335 for leptons
*** see Pospelov&Ritz, PRD89(2014)056006; eEDM 1E-38 → 1E-44 ecm

An overview



Disclaimer: CKM and strong CP contributions are sometimes rough guesses → needs more theory consultation

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.

*new 129Xe limits being published: PRA100(2019)022505, arXiv:1904.12295, arXiv:1902.02864

The strongest experimental limit: ^{199}Hg

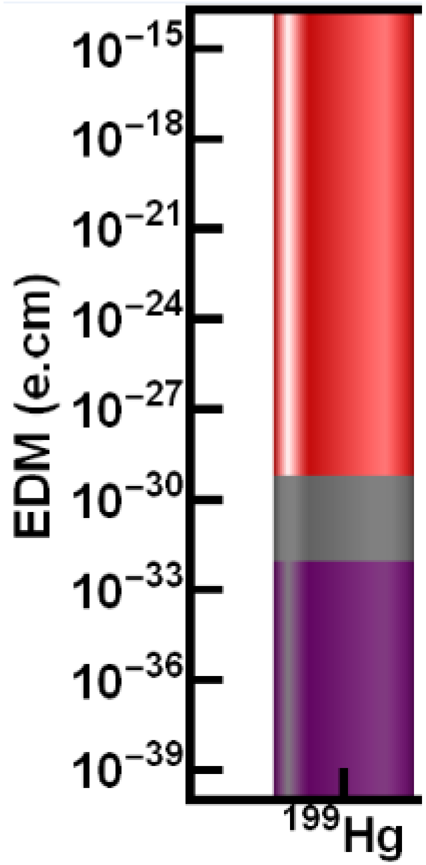


TABLE III. Limits on CP-violating observables from the ^{199}Hg EDM limit. Each limit is based on the assumption that it is the sole*contribution to the atomic EDM. In principle, the result for $\mathbf{d}_n$ supercedes [11] as the best neutron EDM limit.

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

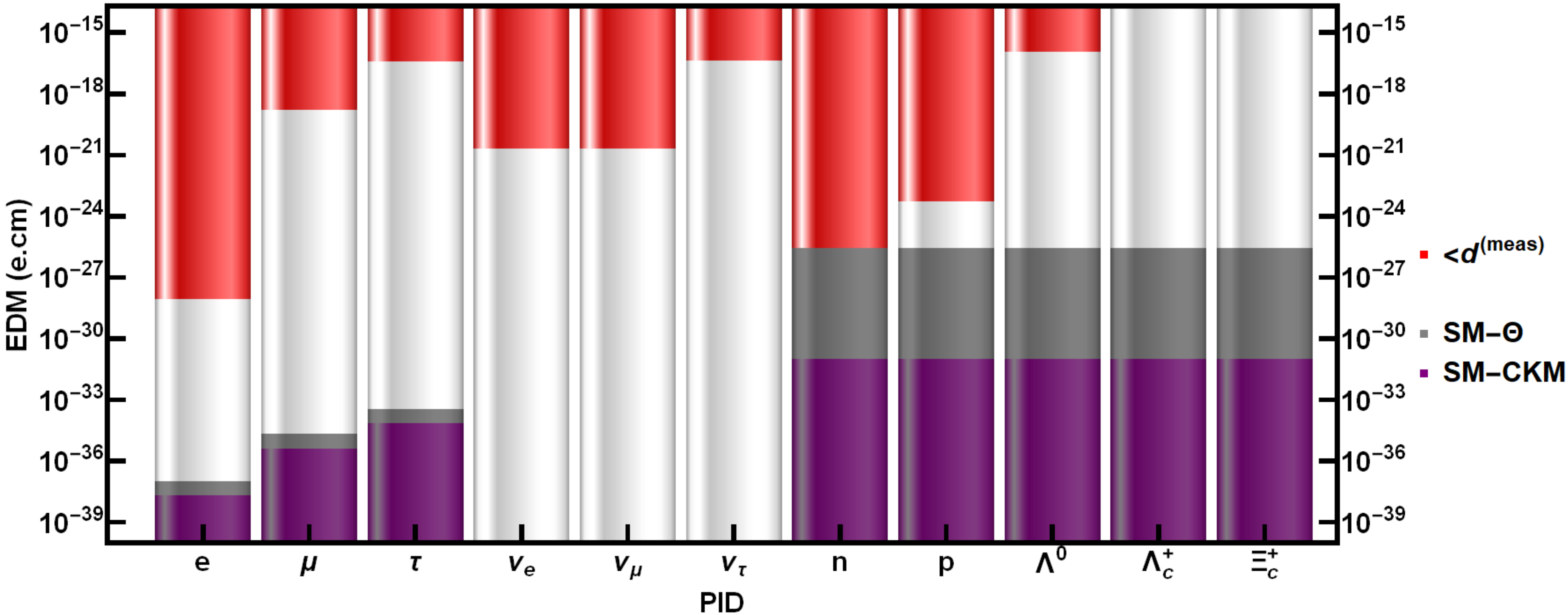
$$|d_{\text{Hg}}| < 7.4 \times 10^{-30} e\,\text{cm}\ (95\%\ \text{C.L.})$$

Graner et al., PRL116(2016)161601, PRL119(2017)119901

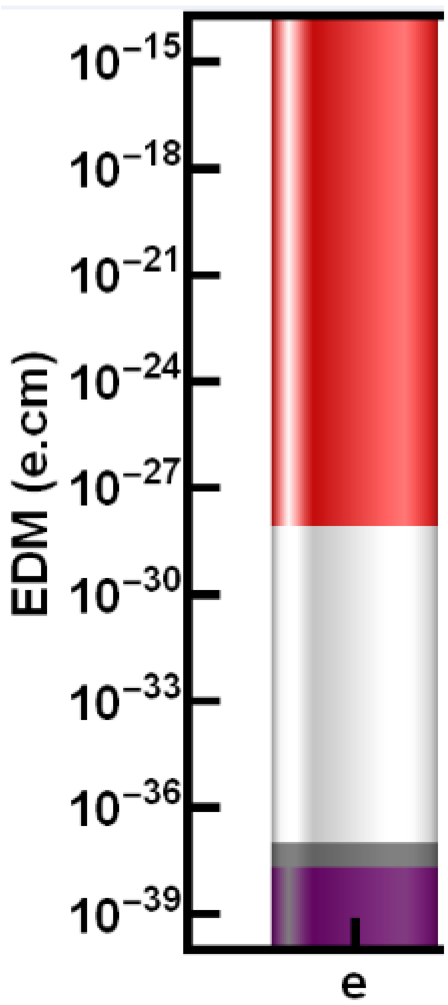
* e.g. otherwise θ_{QCD} ~< 1E-6

Chupp, Ramsey-Musolf, PRC91(2015)035502

Particles



A mix of indirect and direct bounds



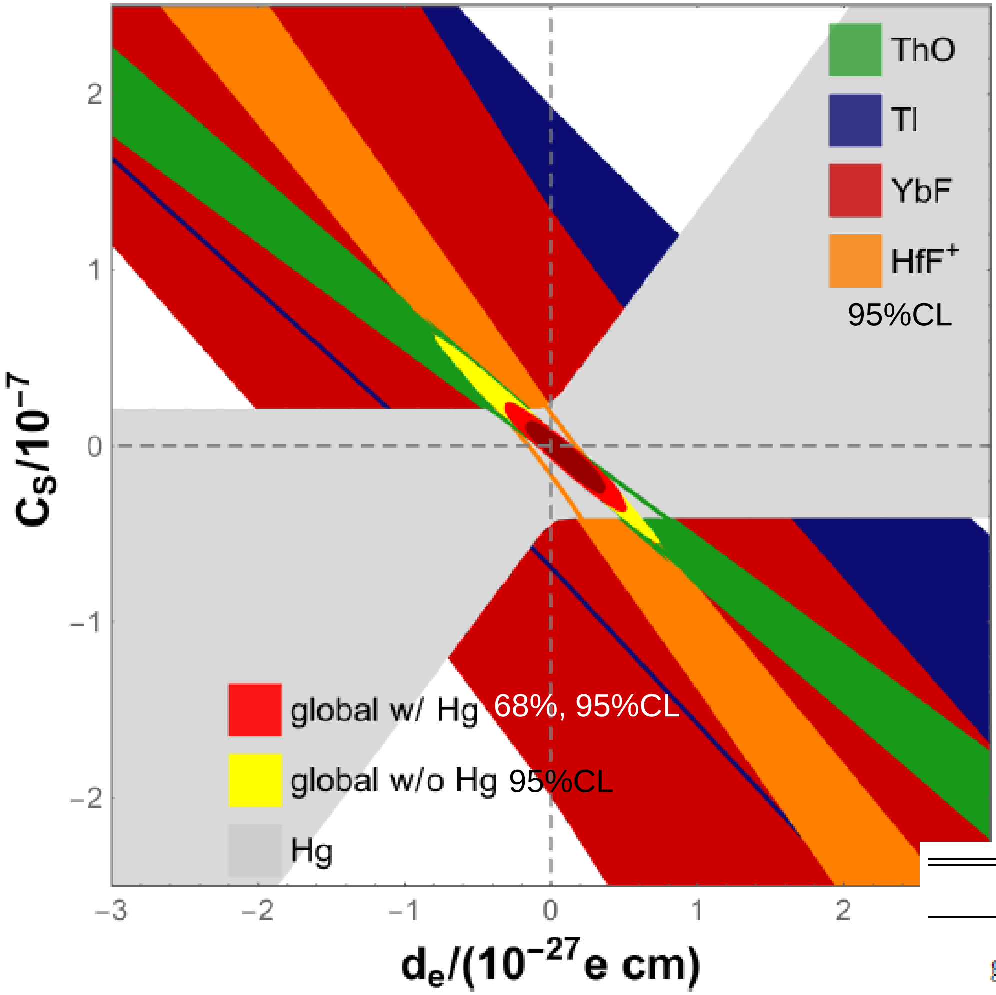
Electron:

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

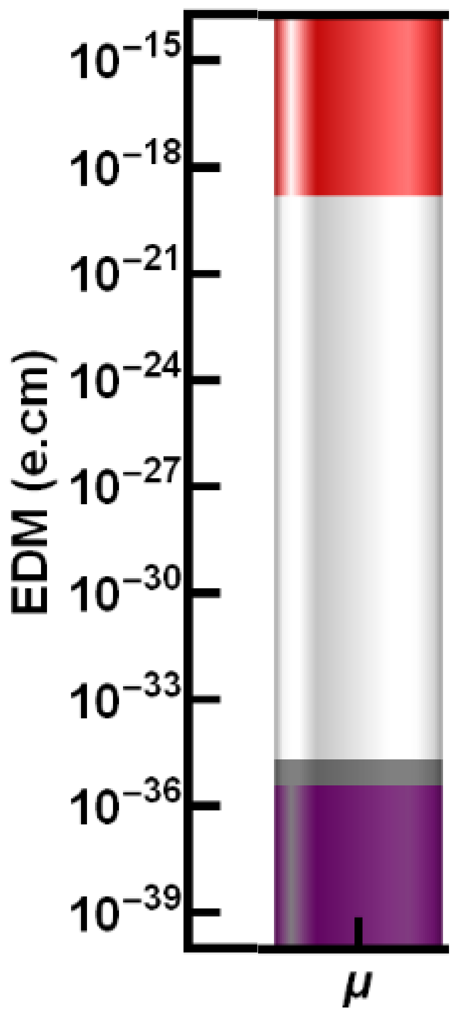
Remarkably: ^{199}Hg and ‘sole source’ → eEDM < 104E-29 ecm

Combining results



Fleig, Jung, JHEP07(2018)012

Fit	$d_e/10^{-28}e$ cm	$C_S/10^{-8}$	Correlation
global (w/ Hg)	1.1 ± 1.7	-0.6 ± 1.2	-96%
	$\lvert d_e \rvert \leq 3.8$	$\lvert C_S \rvert \leq 2.7$	
param. only (w/o Hg)	-0.9 ± 3.2	0.8 ± 2.4	-99%
	$\lvert d_e \rvert \leq 6.4$	$\lvert C_S \rvert \leq 4.9$	



Muon:

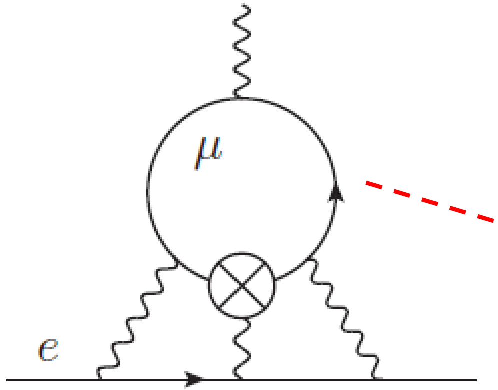
The best direct EDM limit on a fundamental fermion

- Side analysis of muon g-2 experiment

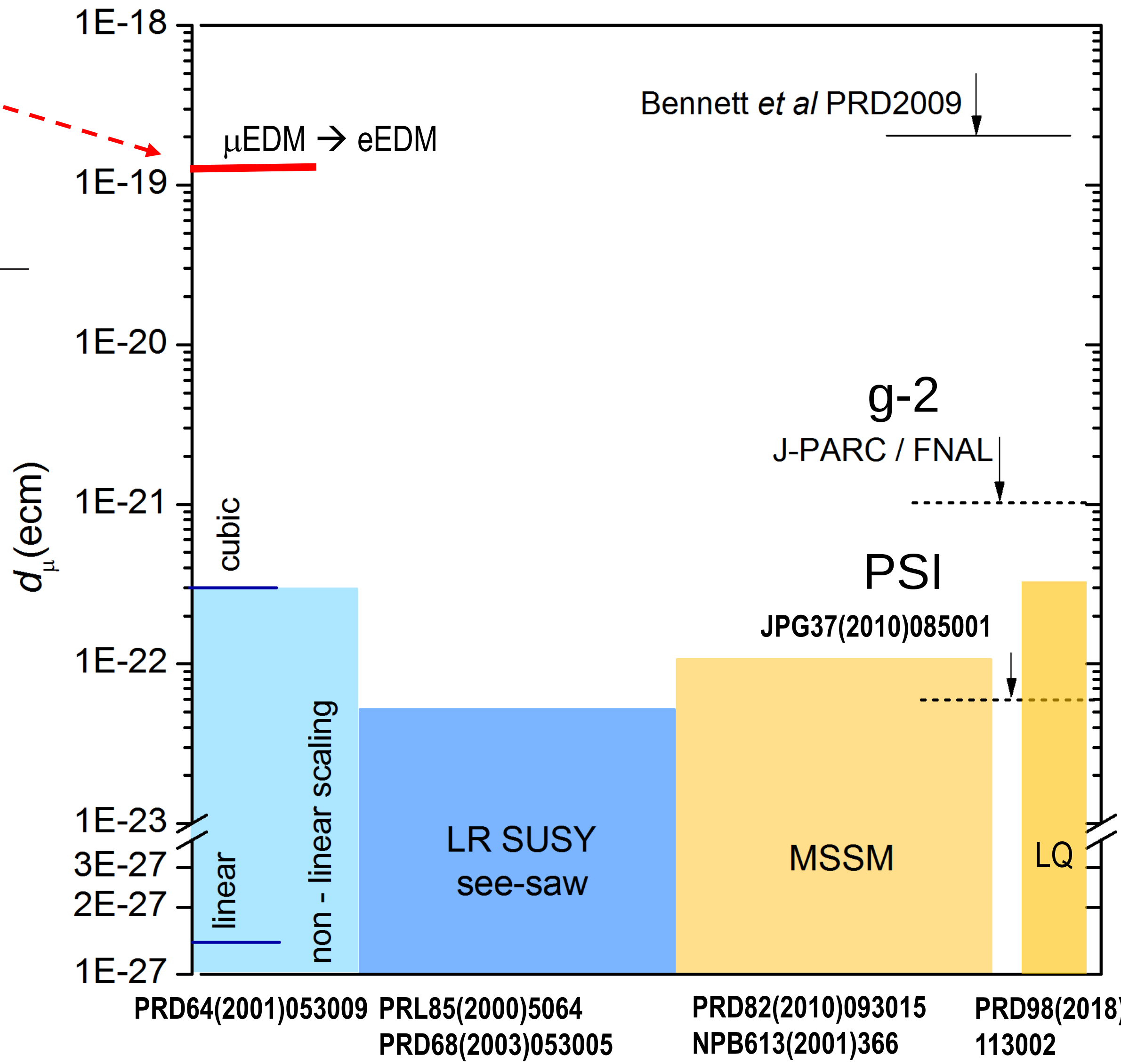
  $$|d_\mu| \leq 1.8 \times 10^{-19}\ e\,\mathrm{cm}\ (95\%\ \mathrm{C.L.}),$$

  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!?

Muon



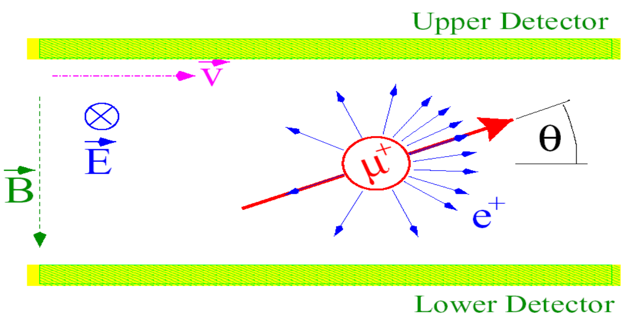
NPB821(2009)285 (τEDM)
PRD98(2018)113002



Model independent: M. Pruna arXiv:1710.08311

Muon

A. Silenko et al.:
J-PARC Letter of Intent: Search for the Permanent Muon Electric Dipole Moment at the 10^{-24} e cm Level.



The muon EDM could be measured with a small storage ring

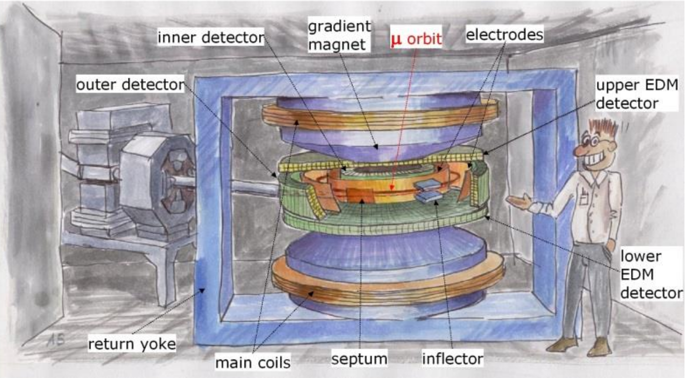
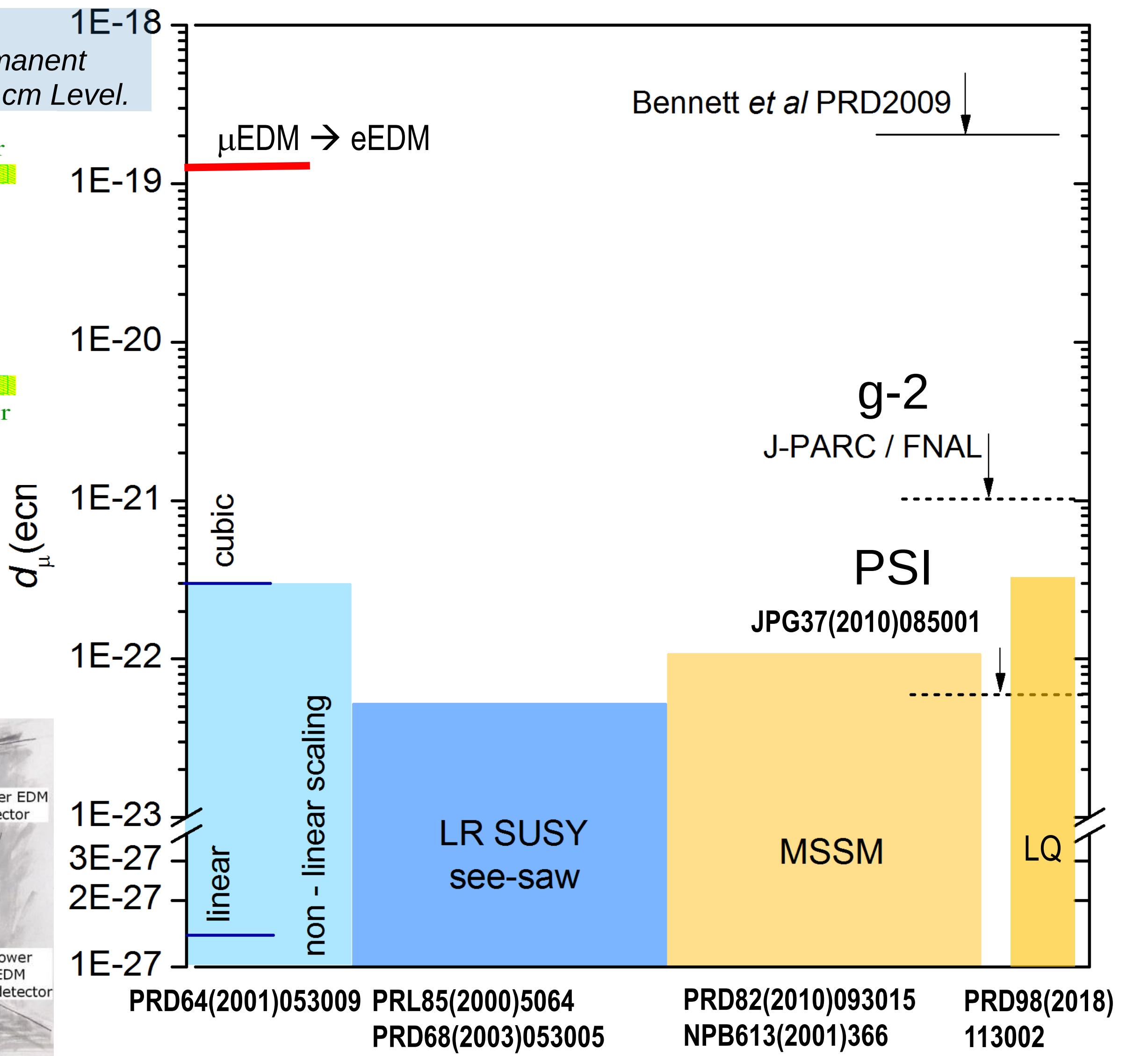
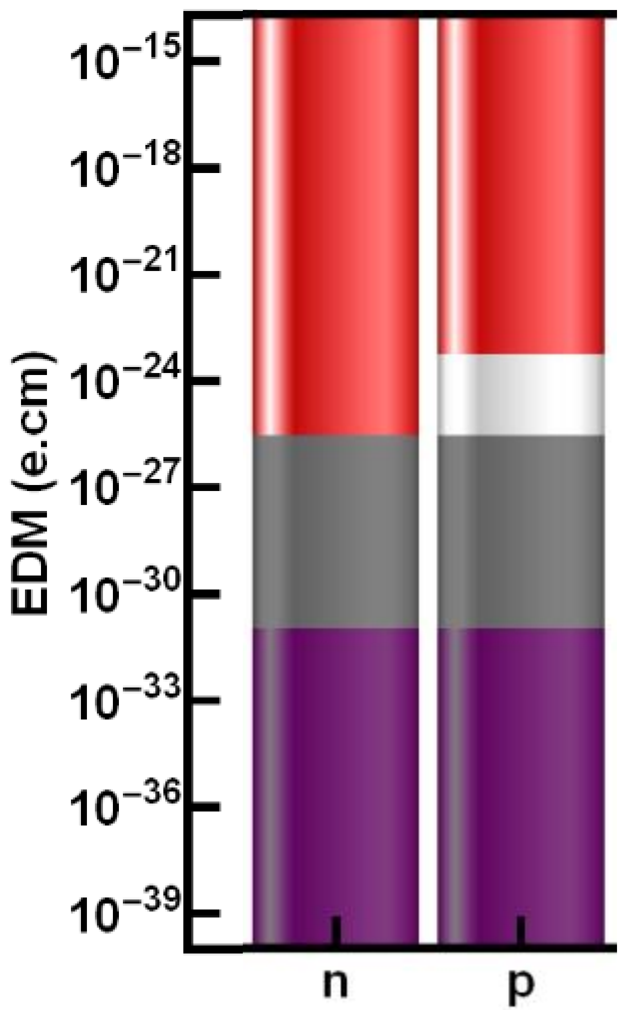


Figure by A. Streun



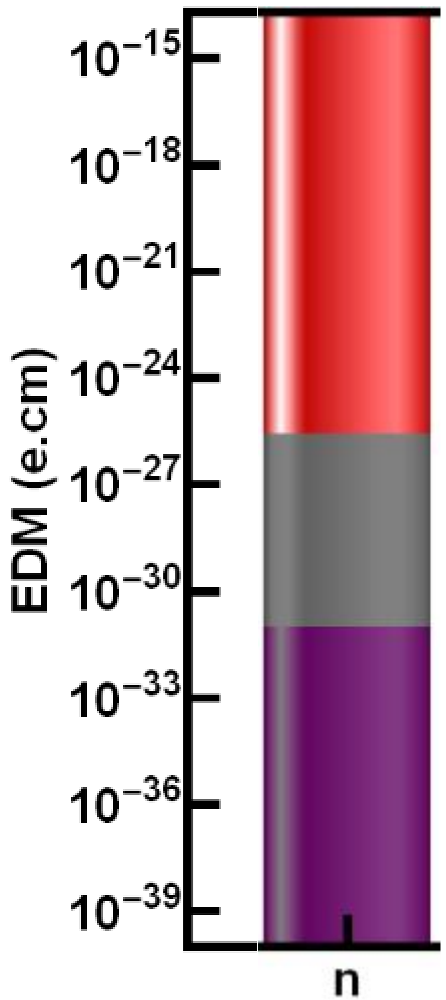
Model independent: M. Pruna arXiv:1710.08311

Neutron and Proton



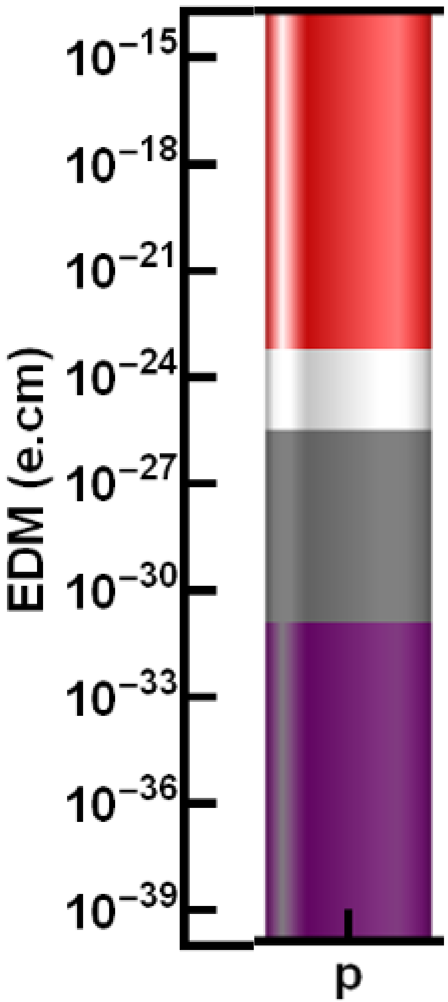
- Present best proton (and neutron) EDM limit derived from ^{199}Hg under the 'sole source assumption'.
- Present best direct nEDM limit 3.0E-26 ecm (Pendlebury et al., PRD92(2015)092003)
- neutron EDM constrains $\theta_{QCD} \lesssim$ 1E-10 under single source assumption (as does ^{199}Hg)
- finite neutron and proton EDM could eventually support or rule out θ_{QCD} as source of EDM signals together with further advanced lattice QCD calculations

Proton



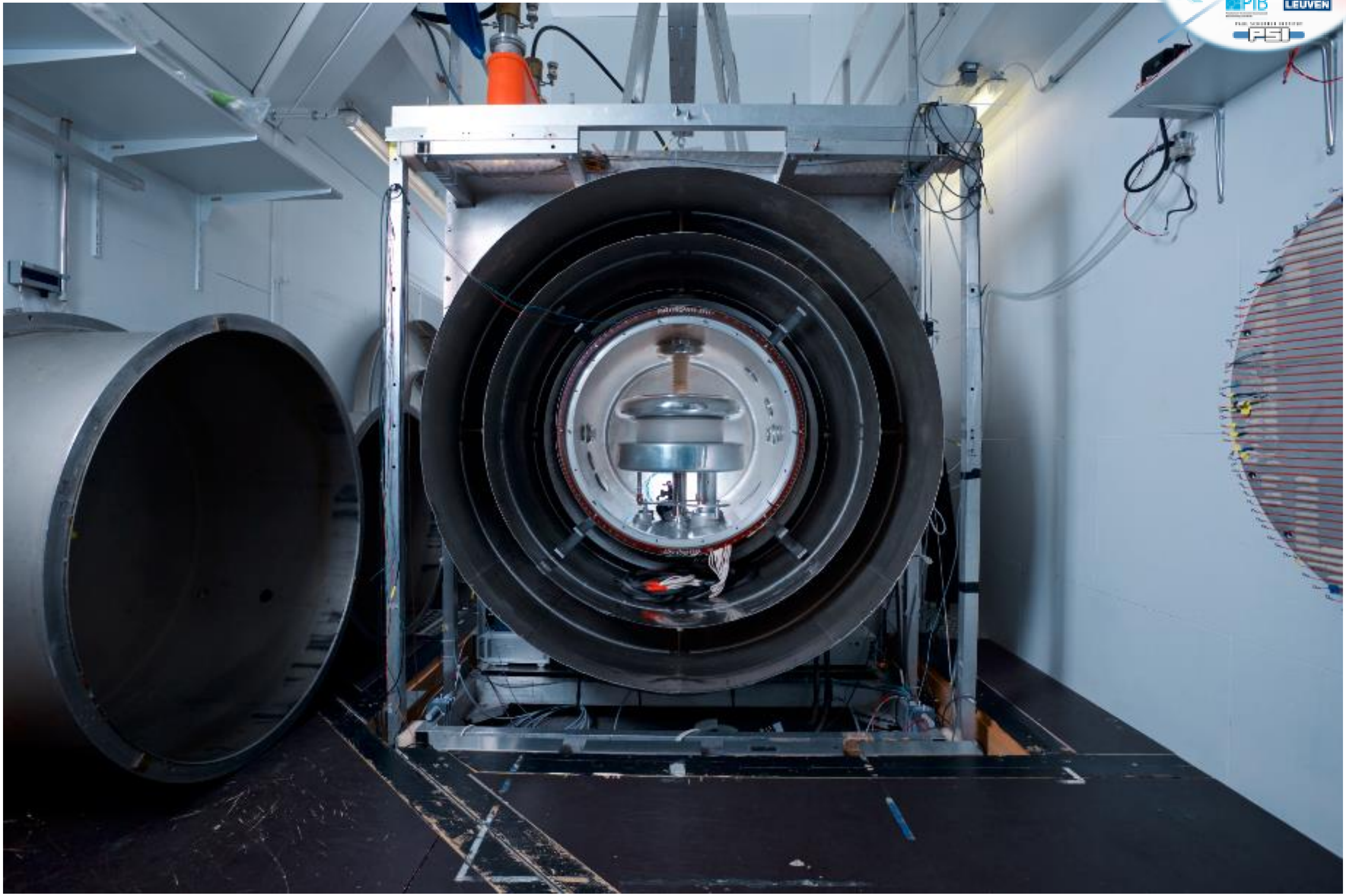
- pEDM
  - Storage ring for p, d, …: JEDI,
    Storage Ring Collaboration, CPEDM
    - Projecting 10^{-29}ecm sensitivity
    - Staged approach with precursor at COSY, demonstrator ring, full pEDM ring
  - Using ^{205}TlF molecules: CeNTREX
    - Projecting $3\text{x}10^{-26}$ecm pEDM sensitivity with 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

nEDM at PSI

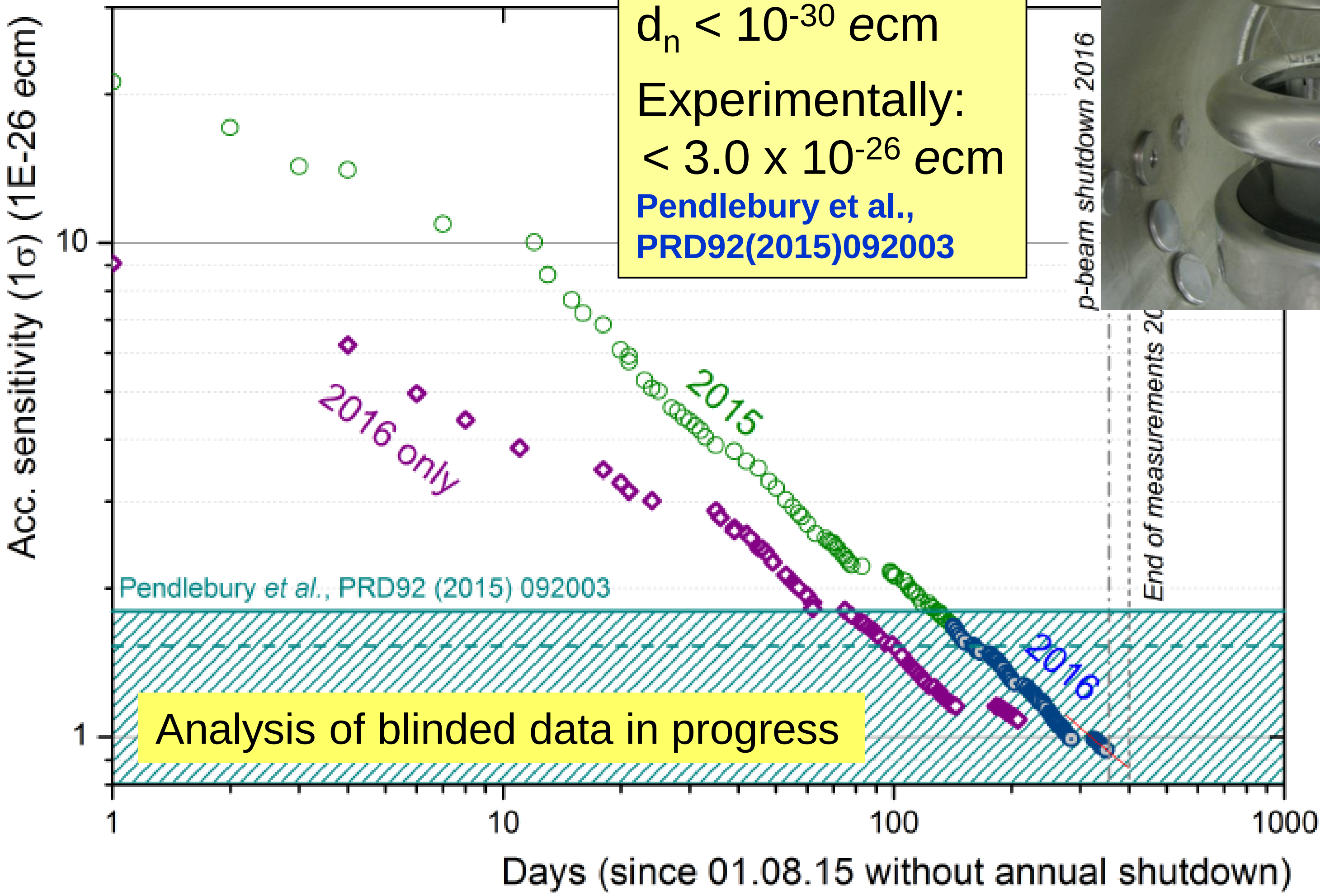


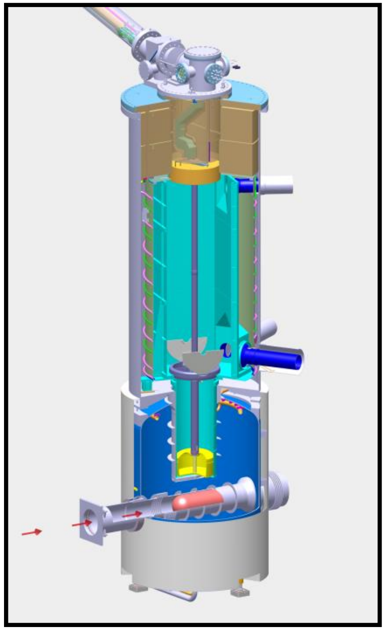
Searching for the neutron EDM

Expect from SM:
$d_n < 10^{-30}$ *e*cm

Experimentally:
$< 3.0 \times 10^{-26}$ *e*cm

Pendlebury et al., PRD92(2015)092003





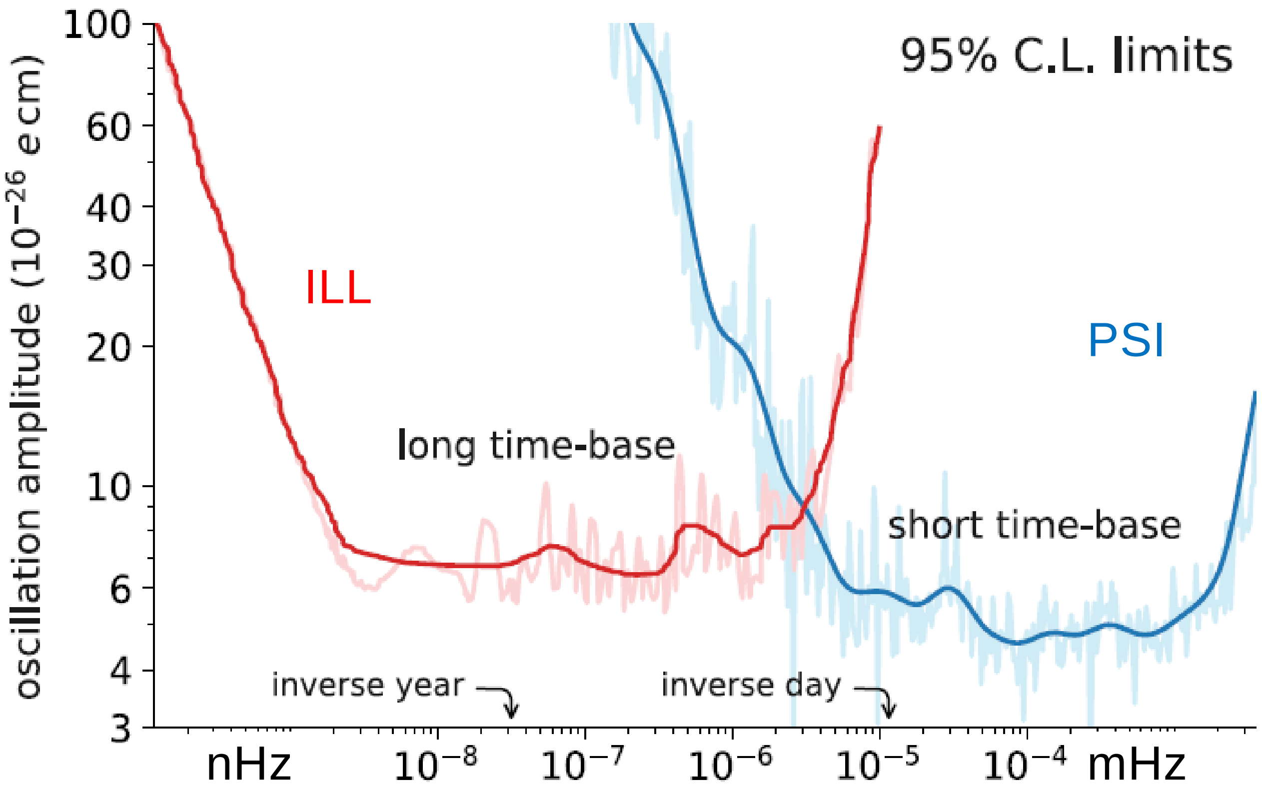
nEDM collaboration moves on to n2EDM

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.

Search for nEDM oscillations with time

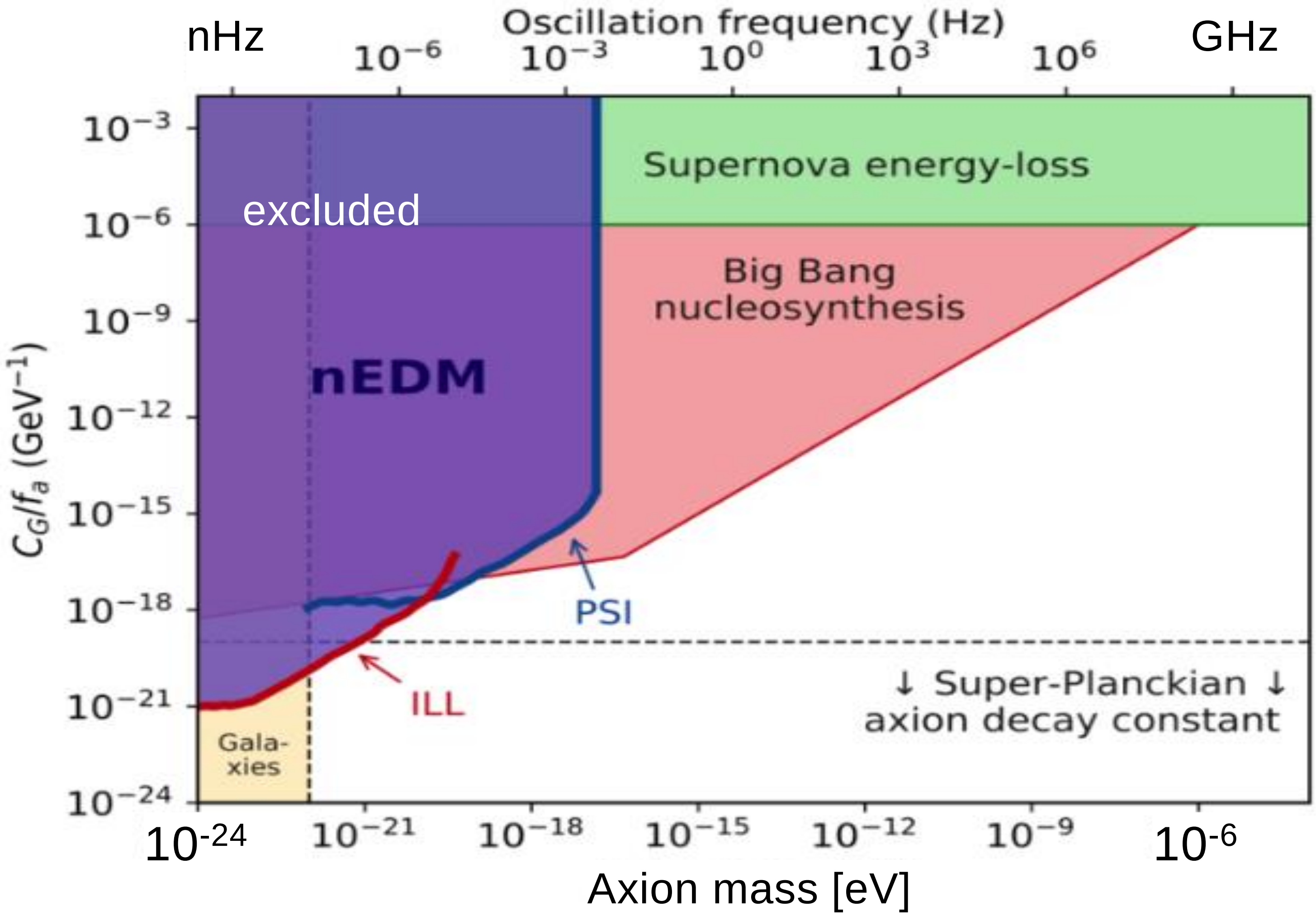
PHYS. REV. X **7**, 041034 (2017)



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

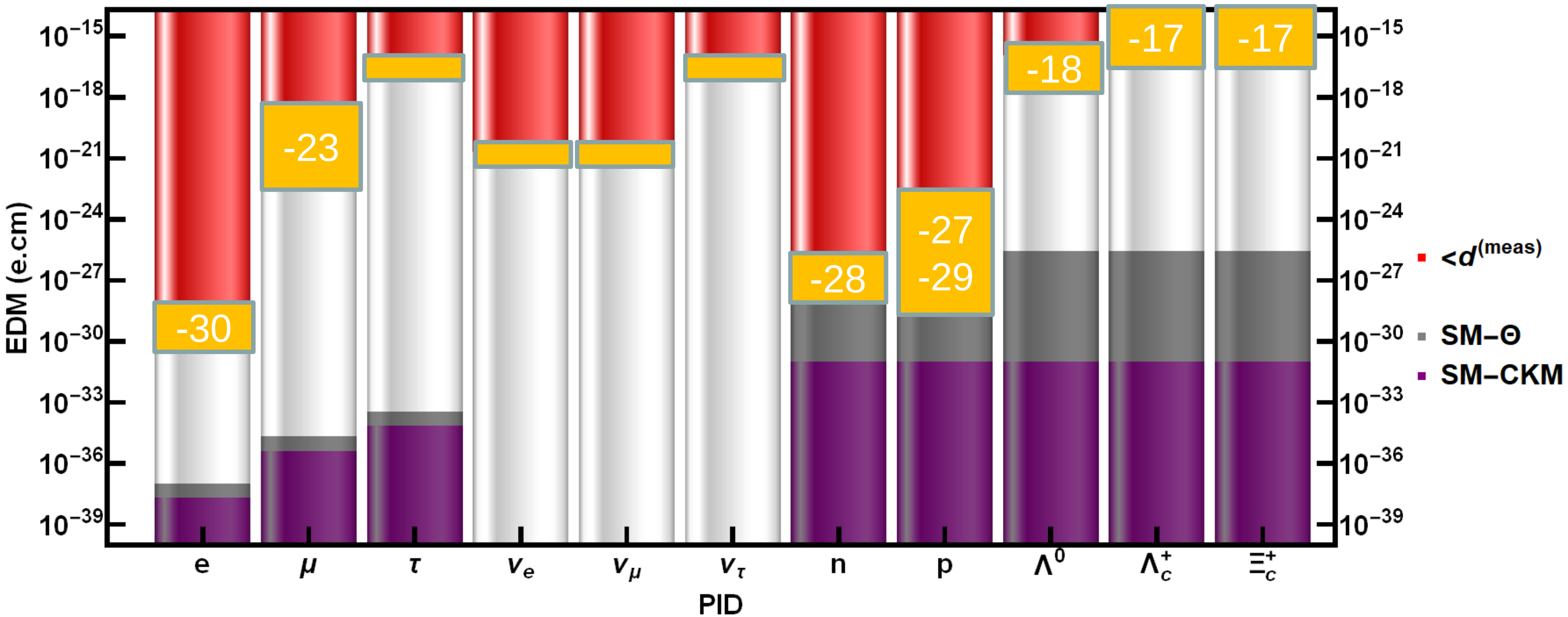


Oscillating nEDM data could come from the interaction of **ultralight axions** which could be the **Dark Matter in the Universe**.

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

Abel et al., PRX7(2017)041034

Future 2020s perspectives



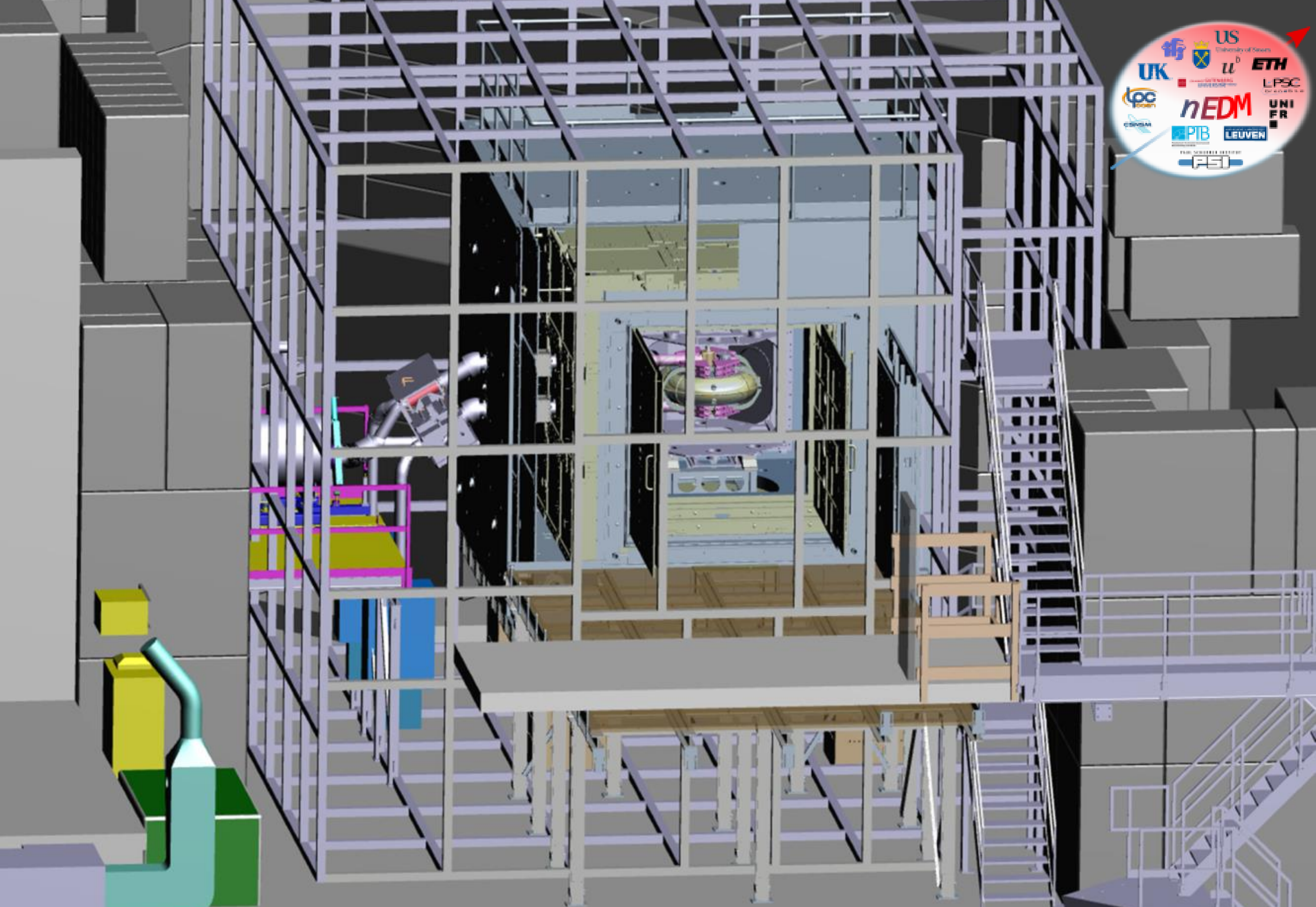
Based on reasonable extrapolation and author claims

2018: n2EDM at PSI

2019: n2EDM at PSI

n2EDM baseline:
$\sigma(d_n)$~1E-27*e*cm in 500 days
Commissioning 2020

2020: n2EDM at PSI

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