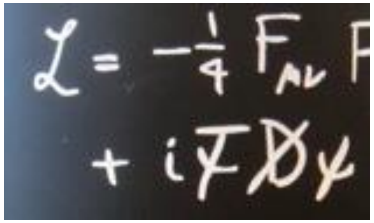
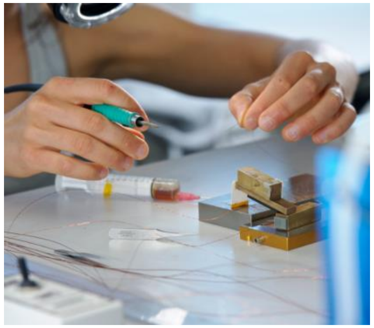
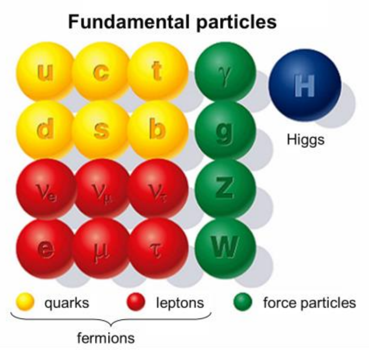
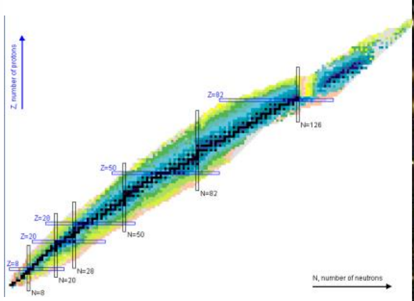
Experiments to measure the electric dipole moment of the neutron

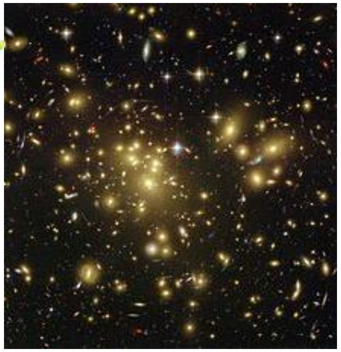
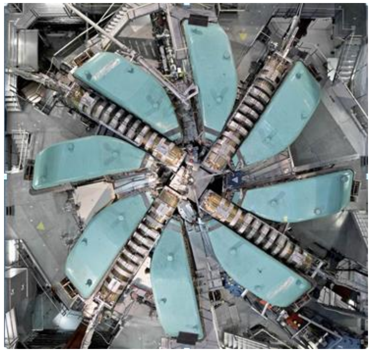
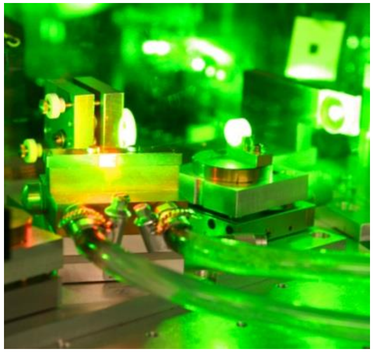
SPIN 2018, Ferrara

K.Kirch, ETH Zurich – PSI Villigen, Switzerland





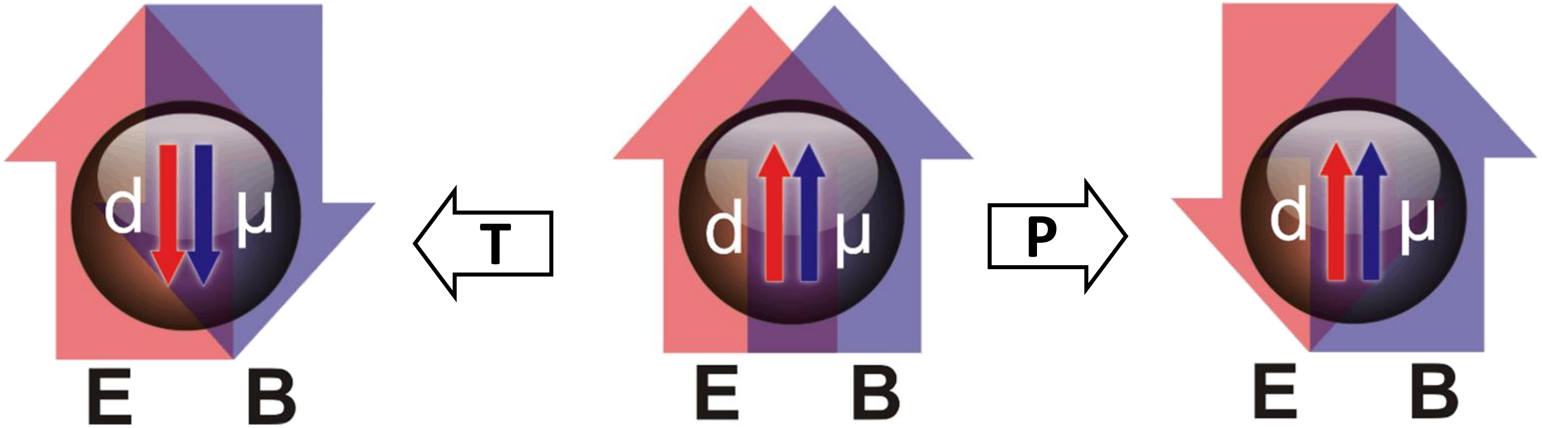
In SPIN2018 …

- several talks on EDMs in storage rings (Rathmann, Nikolaev, Nass, Martin, Shergelashvili, Müller), atomic EDM (Dietrich, Heil, Zimmer), heavy baryons (Ruiz Vidal), related theory (Stadnik, Paradisi, Yamanaka, Gupta, Laszlo), …

- For neutron EDM, besides this talk, see
  - Franke Mo 18:00
  - Fierlinger Wed 15:10
  - Pignol Thu 15:45

- Around the world several nEDM projects at: PSI, ILL, LANL, PNPI, TRIUMF, SNS, and future plans for JPARC, ESS, PIK

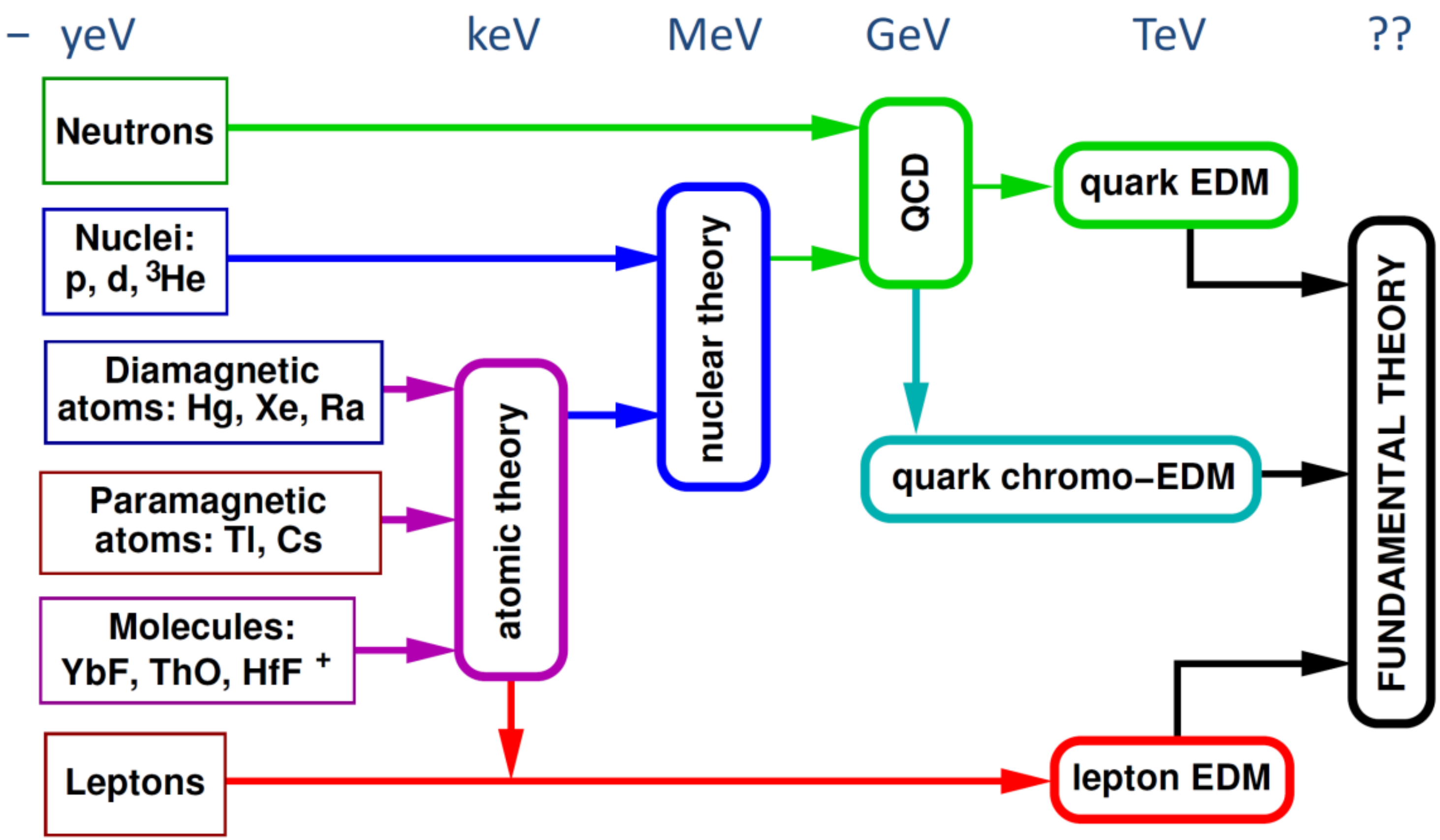
EDM and symmetries



A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP

Purcell and Ramsey, PR78(1950)807; Lee and Yang; Landau

Connecting experiments and theory

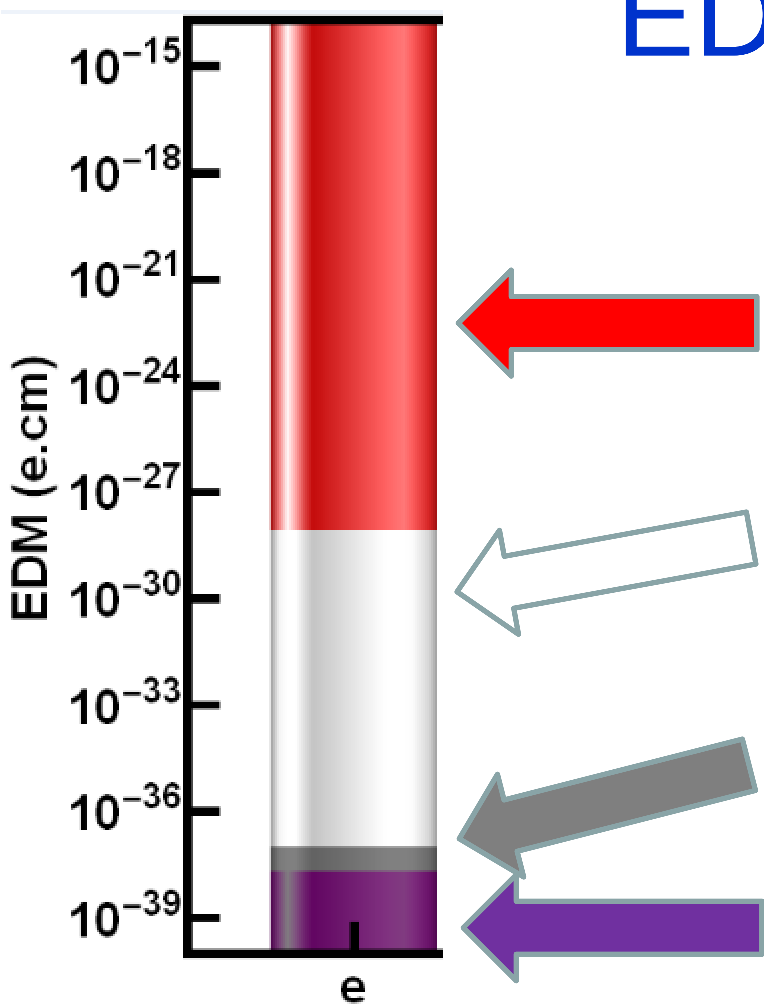


Scheme: courtesy Rob G. E. Timmermans

See also: Pospelov, Ritz,
Ann. Phys. 318(2005)119

See for a 'global analysis':
Chupp, Ramsey-Musolf PRC91(2015)035502

EDM display



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

'safe' BSM discovery territory

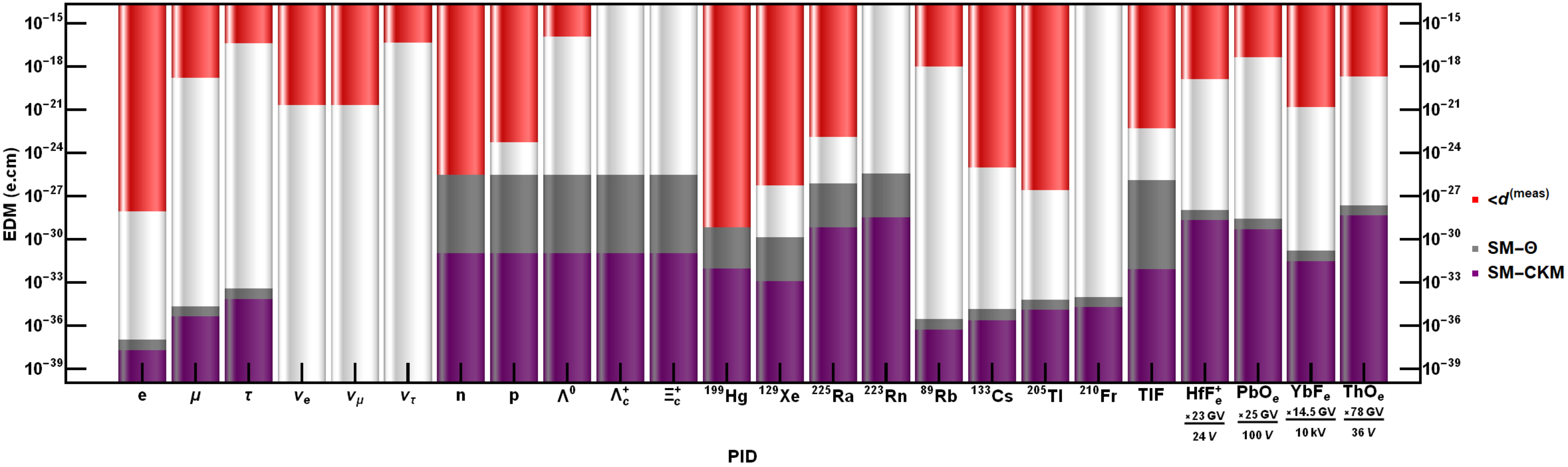
Estimated θ_{QCD} contribution**, assuming θ_{QCD} < 1E-10 *

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

Displays by Prajwal Mohan Murthy
PhD thesis in preparation, ETHZ 2018

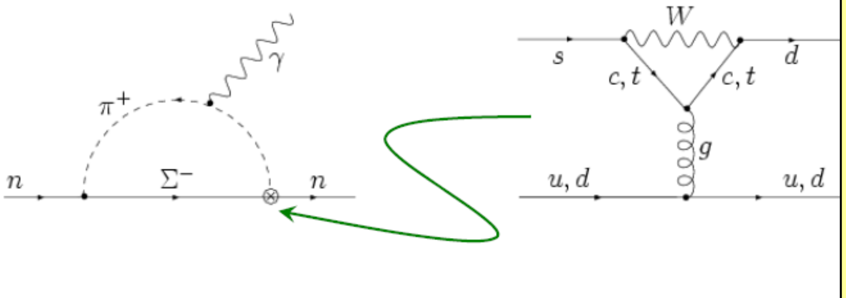
Present status … no signal yet



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

Electric Dipole Moments tiny in SM

- Neutron, Proton, ..

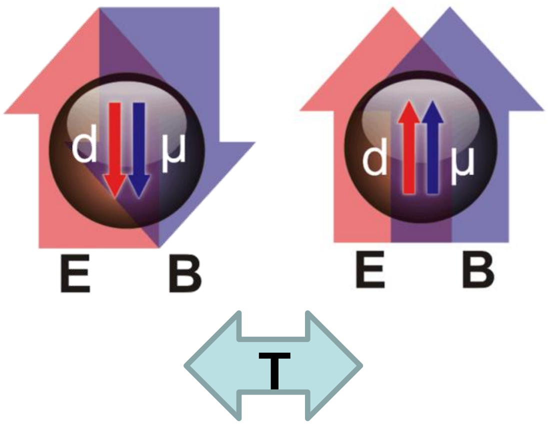


$$d_n \sim 10^{-32} - 10^{-34} e\ cm$$

[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

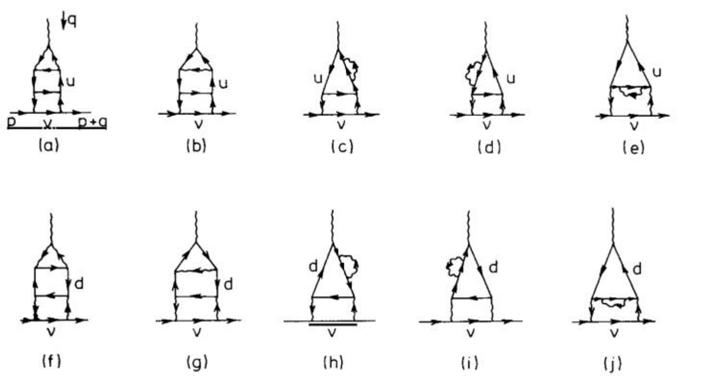


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

[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:
$d_e < 9 \times 10^{-29}$ e•cm
$d_\mu < 2 \times 10^{-19}$ e•cm
$d_\tau < 3 \times 10^{-17}$ e•cm

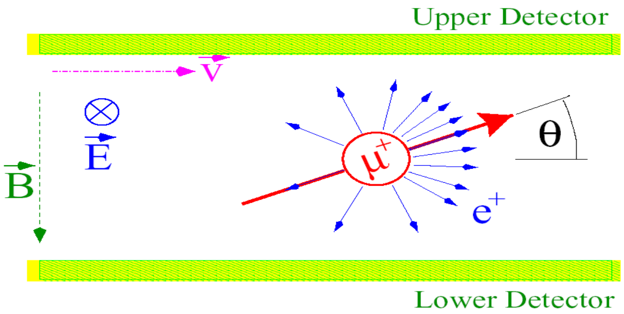
new to me, recently

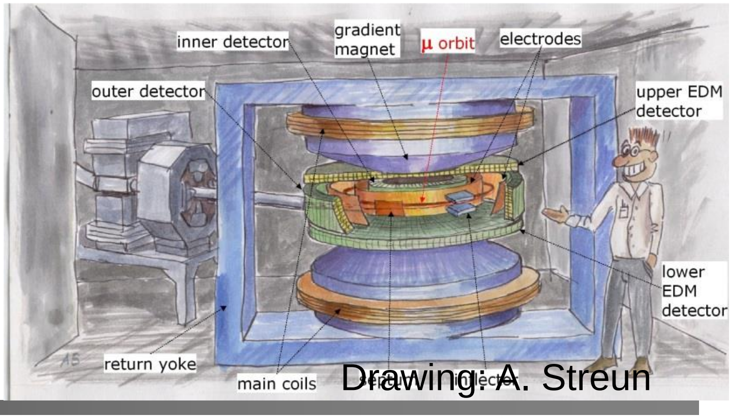
ThO molecule
Baron et al., Science 343(2014)269

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

Possibility for a large Muon EDM?

- In a model independent approach, d_μ uniquely constrains some couplings (M. Pruna arXiv:1710.08311), d_μ is not limited by small d_e but only by the direct experimental limit $d_\mu < 1.8 \times 10^{-19}$ecm (Bennett et al., PRD80(2009)052008)
- If NP in a_μ → d_μ could naturally be of same order, ~10^{-22}ecm (Feng, Matchev, Shadmi, NPB613(2001)366)
- If NP in a_μ and a_e (with the sign of the slight tension in a_e)
  → muon and electron sectors would be decoupled
  → large d_μ possible (Crivellin, Hoferichter, Schmidt-Wellenburg, arXiv:1807.11484)
- Present g-2 experiment will improve sensitivity to d_μ~$10^{-20..21}$ecm
- Dedicated small storage ring could reach d_μ~$10^{-22..23}$ecm at PSI (Adelmann et al., JPG37(2010)085001)



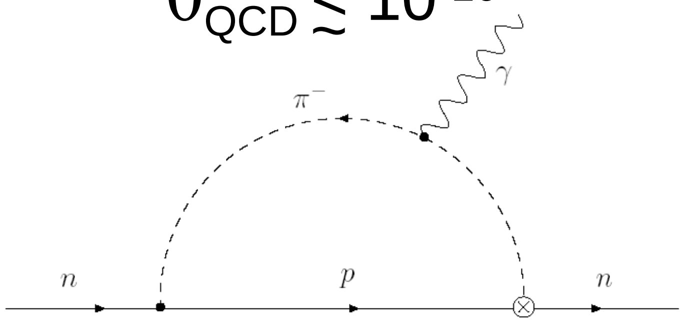


The strong CP problem

$$L_{QCD} \approx L_{QCD}^{\theta_{QCD}=0} + g^2/(32\pi^2)\ \theta_{QCD} G\tilde{G}$$

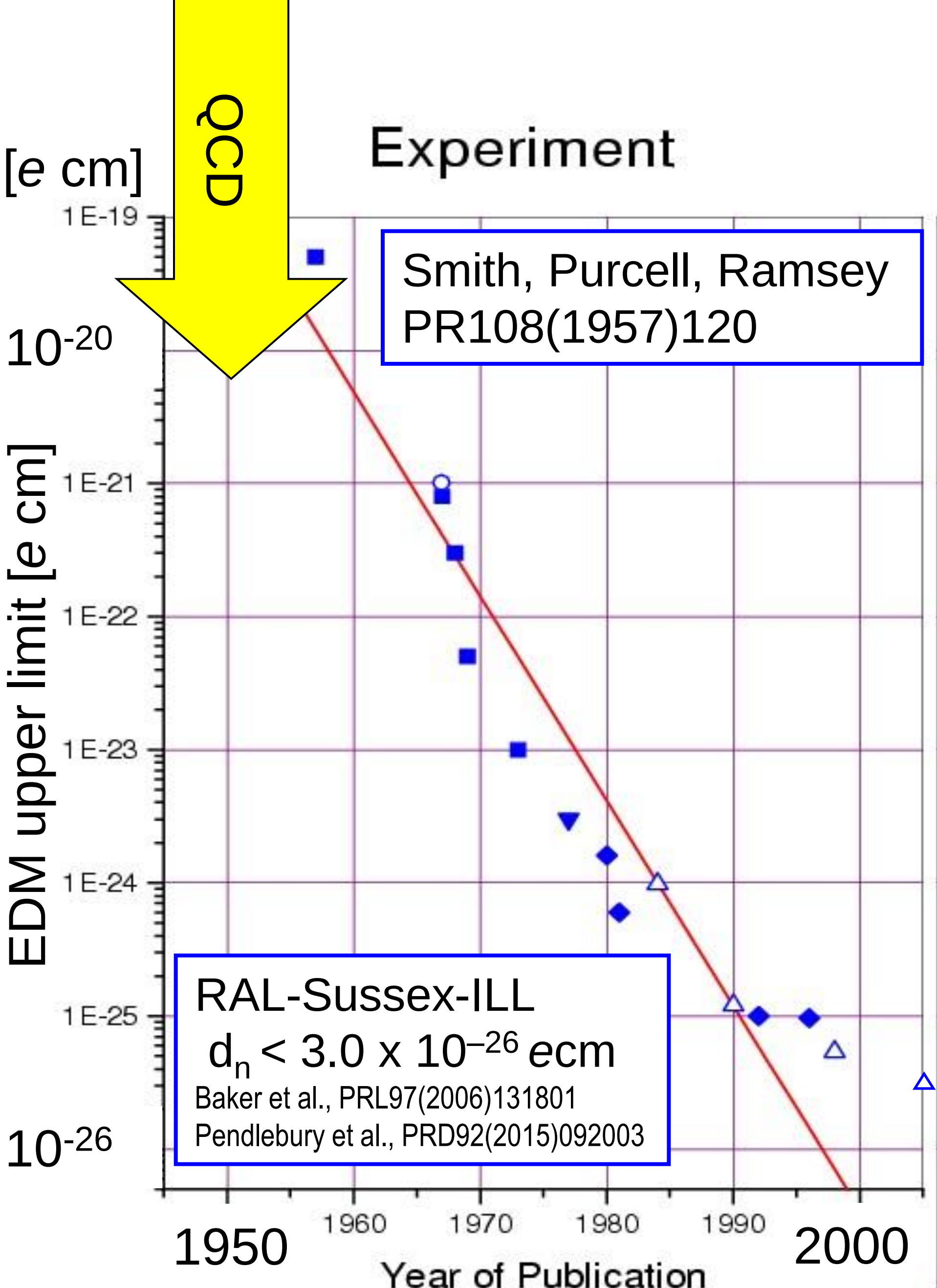
$$d_n \approx 10^{-16}\ e\ \text{cm} \cdot \theta_{QCD}$$

$$\theta_{QCD} \lesssim 10^{-10}$$



Why is θ_{QCD} so small ?

→ accidentally small !?



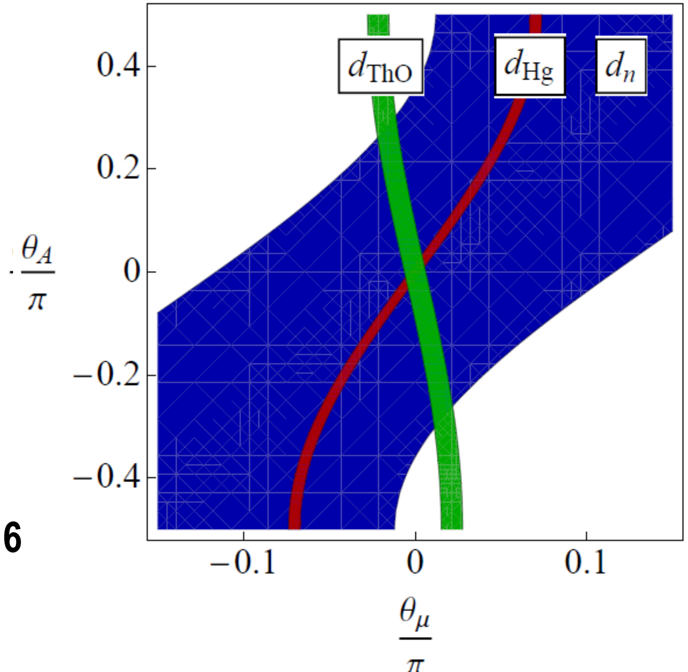
The SUSY CP problem

(for neutron and electron!)

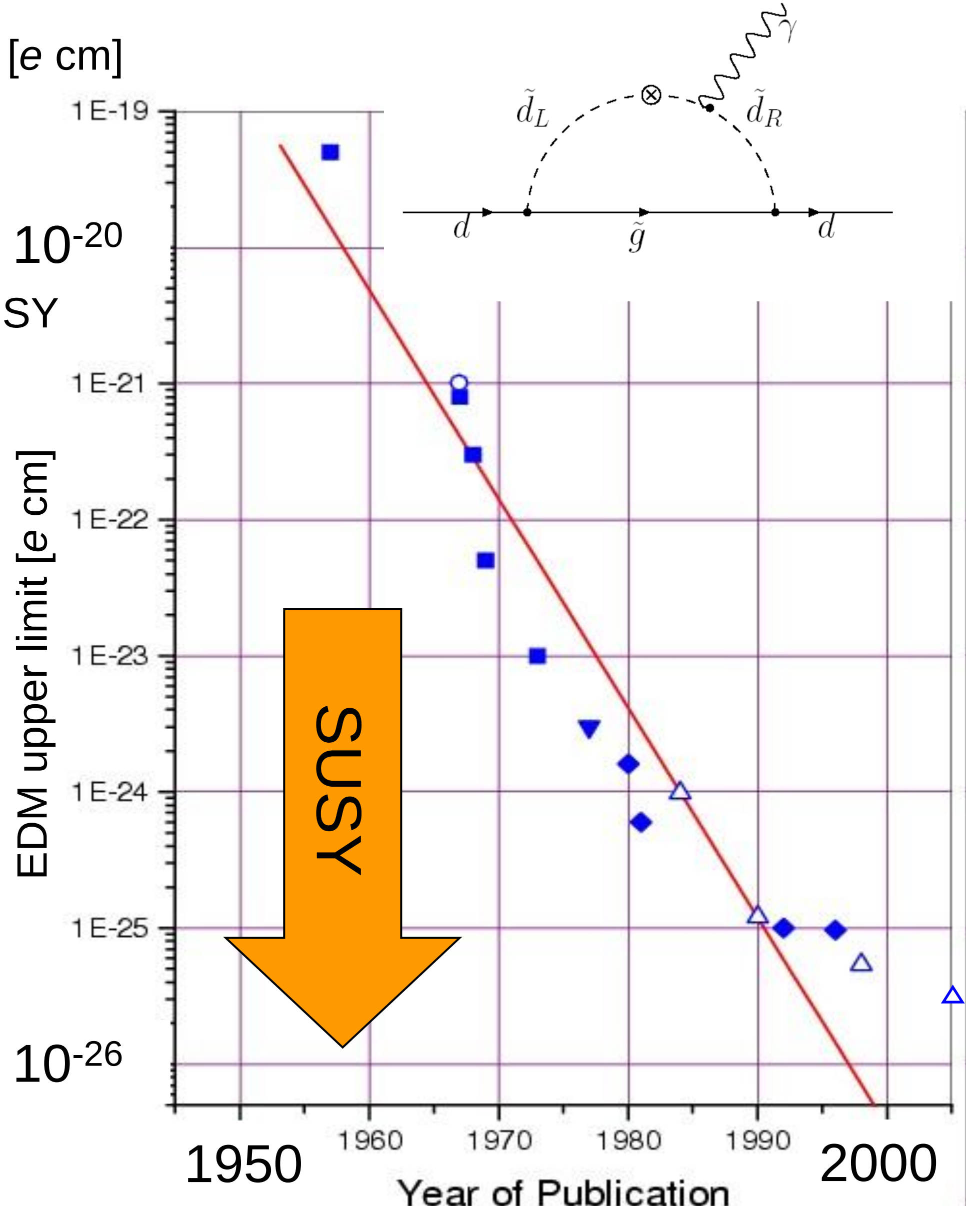
$$d_n \approx 10^{-23}\, e\,\text{cm} \left(\frac{300\ \text{GeV}/c^2}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

Why is ϕ_{SUSY} so small ?

(this is testing M already to 10TeV and you may also ask: why are the masses so huge?)

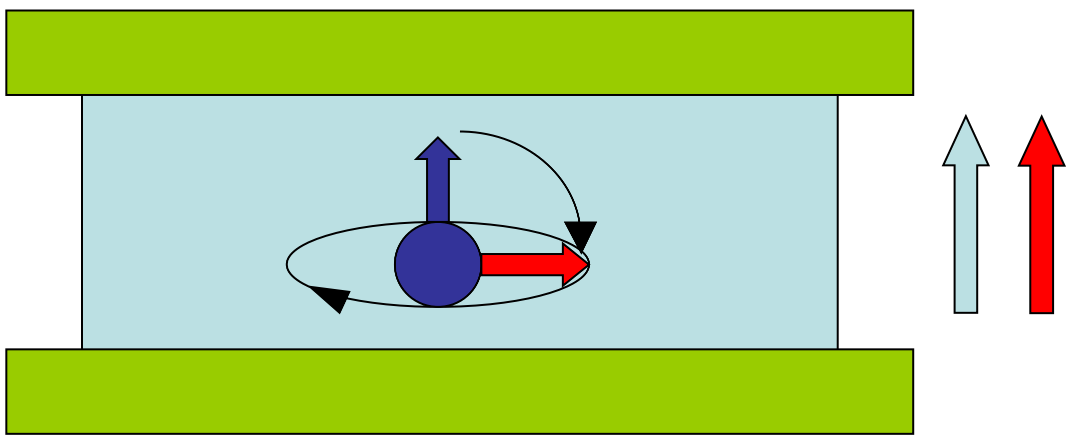


A. Ritz, update 2016



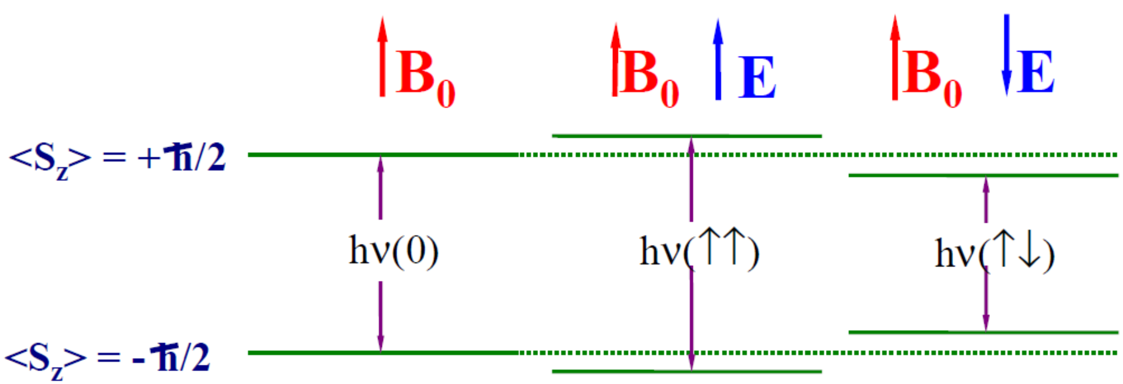
ETH

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



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

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

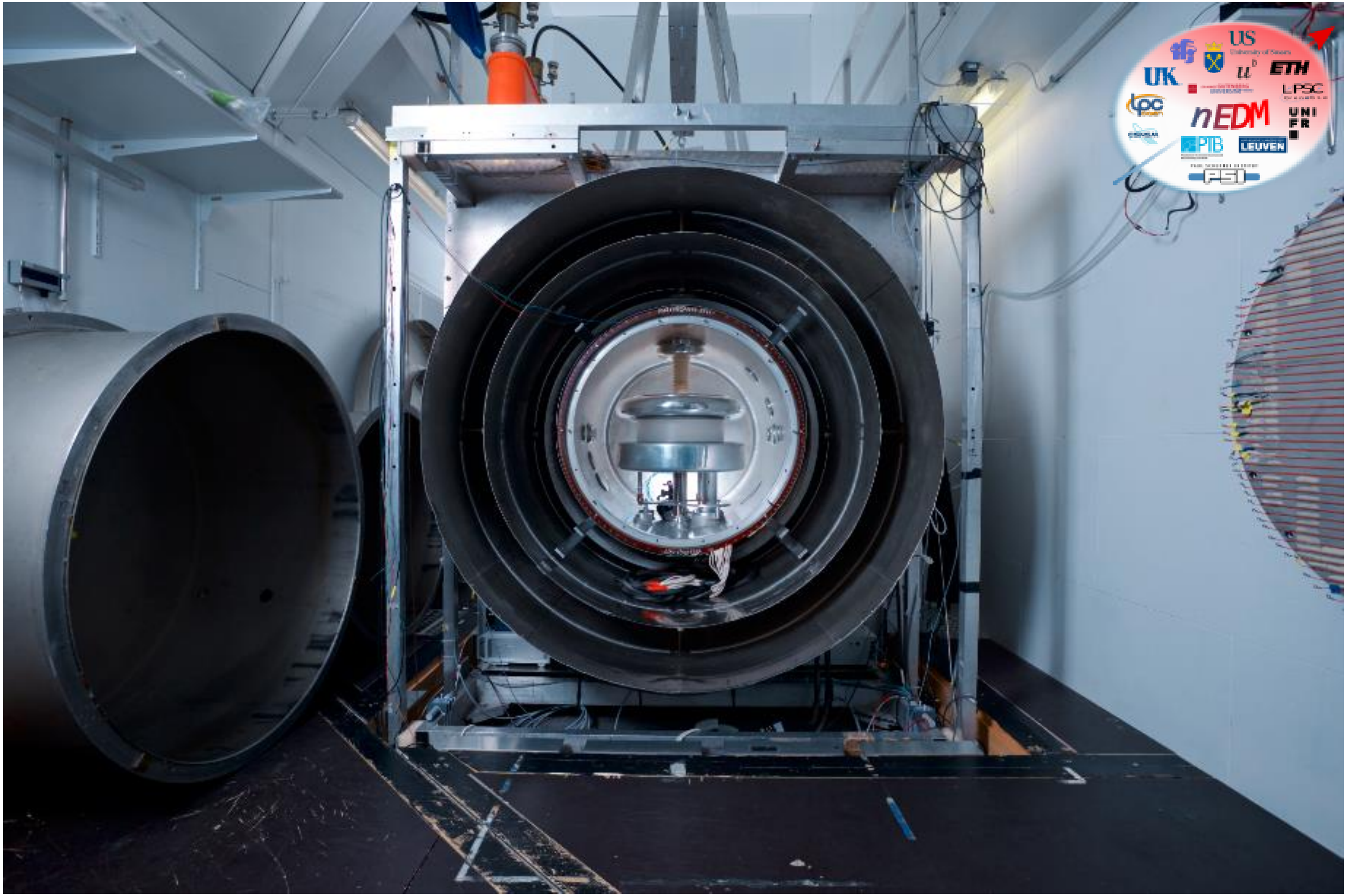


$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

nEDM@PSI

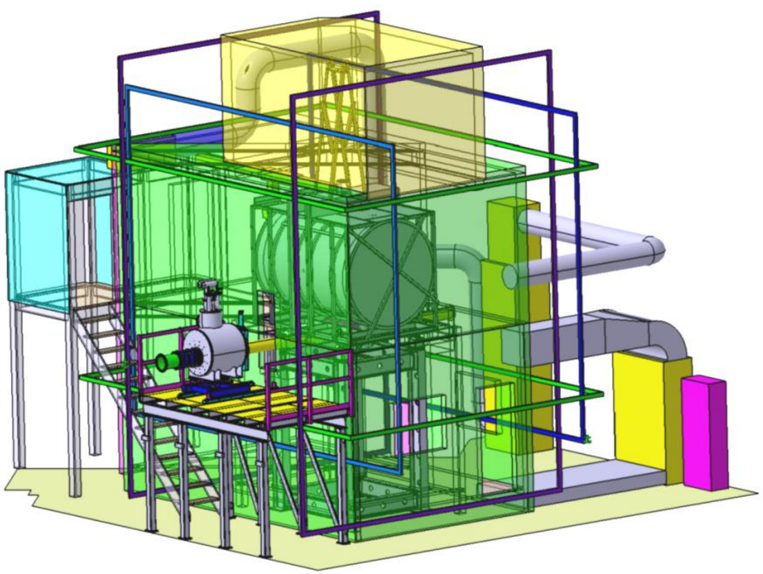
Our collaboration (50 people, 15 institutions, 7 countries) just finished nEDM and starts assembling the n2EDM experiment aiming at an improvement in sensitivity by an order of magnitude.

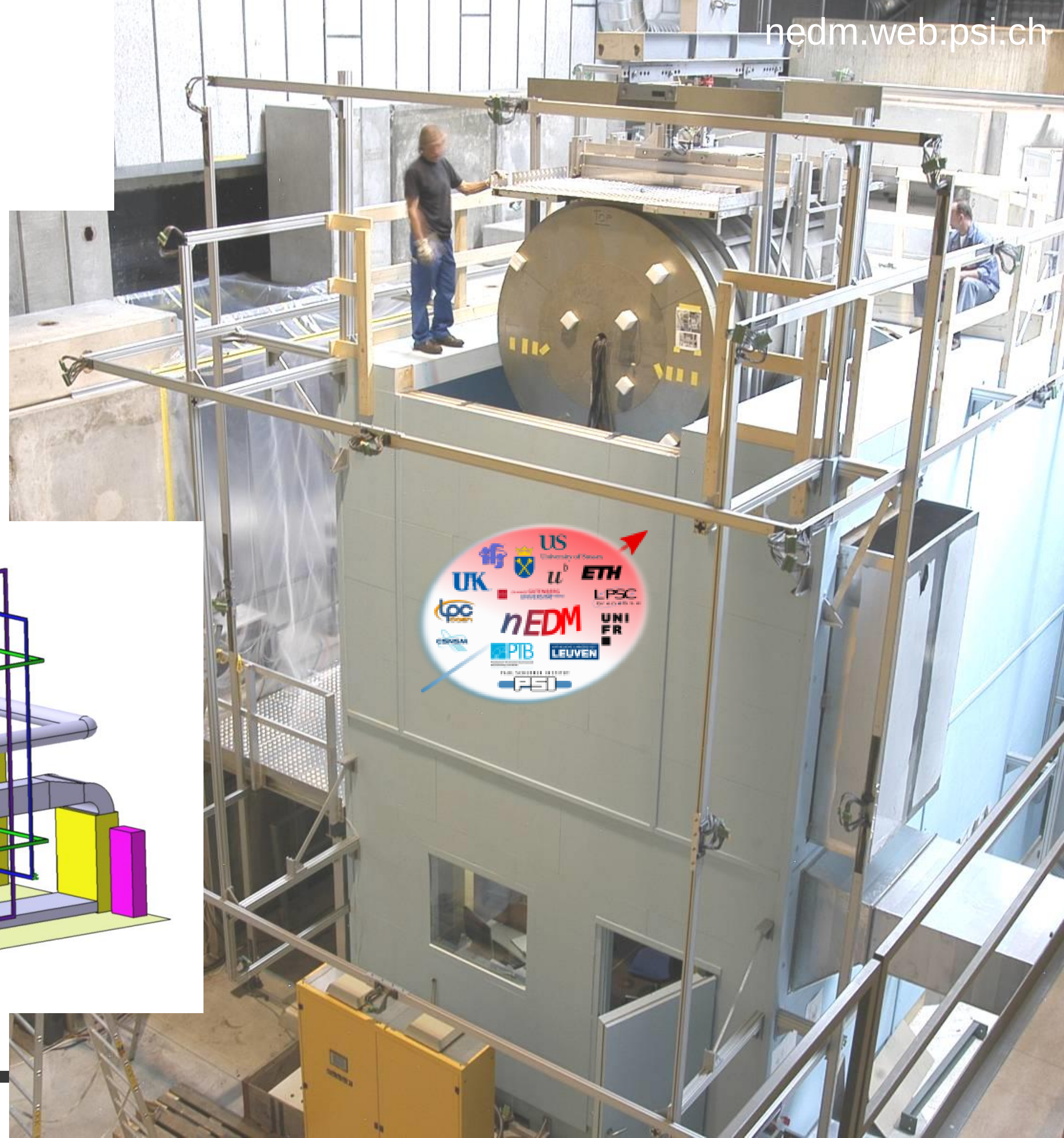
nEDM at PSI



nEDM at PSI 2009 – 17

Coming from ILL:
Sussex-RAL-ILL collaboration
PRL 97 (2006) 131801
Upgraded by nEDM@PSI





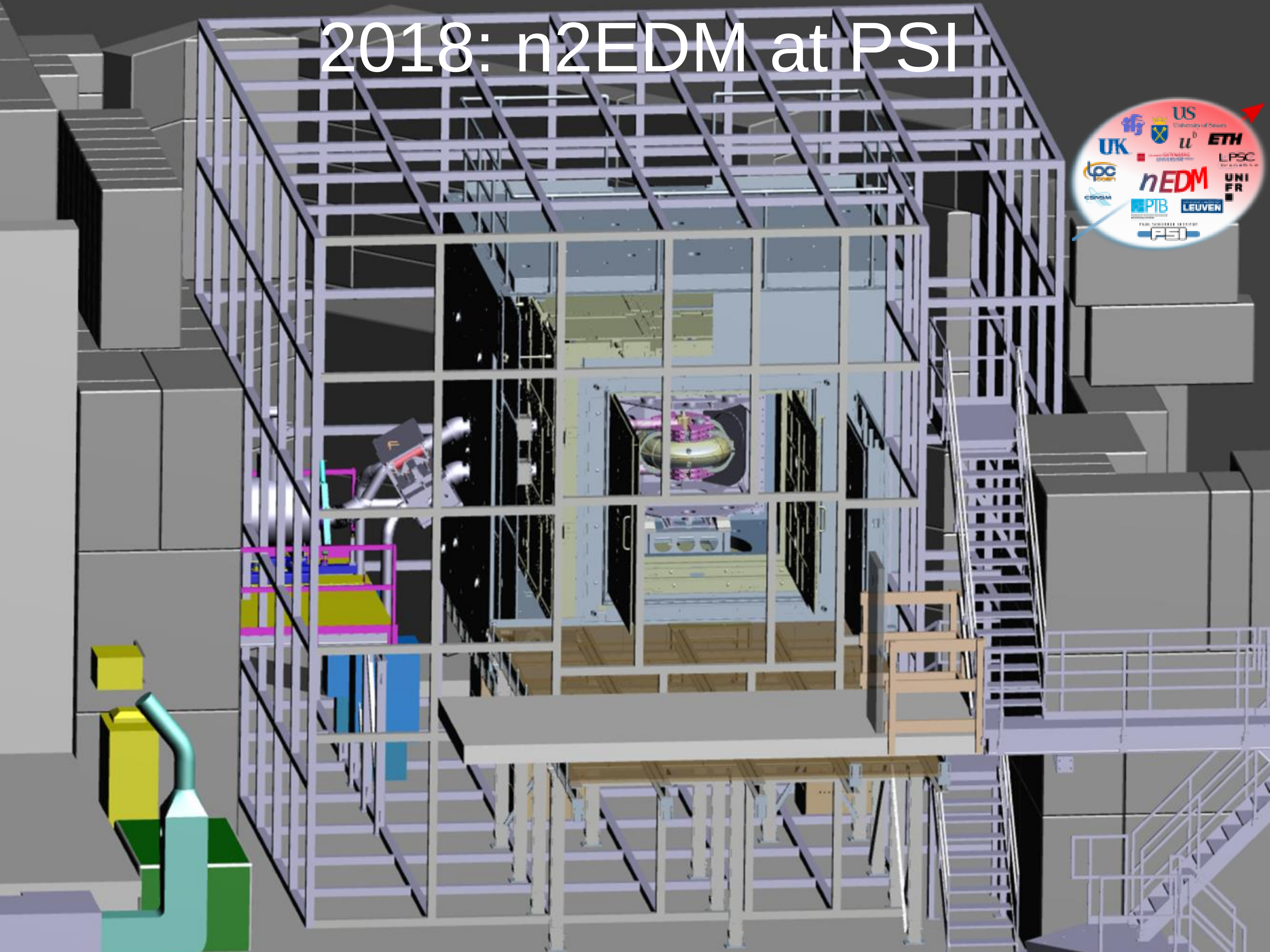
www.psi.ch/nedm/

2018: n2EDM at PSI

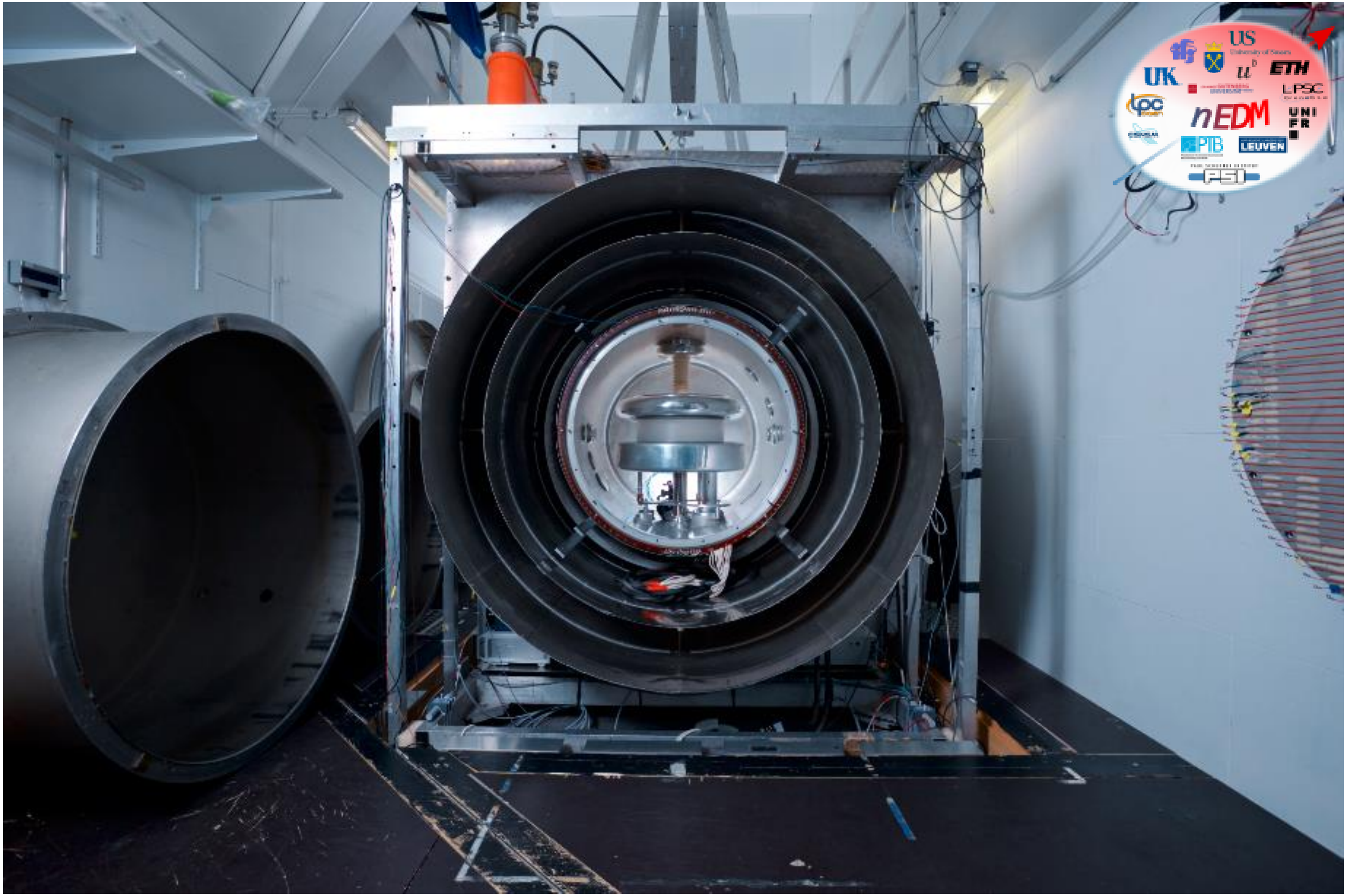
2018: n2EDM at PSI

2018: n2EDM at PSI

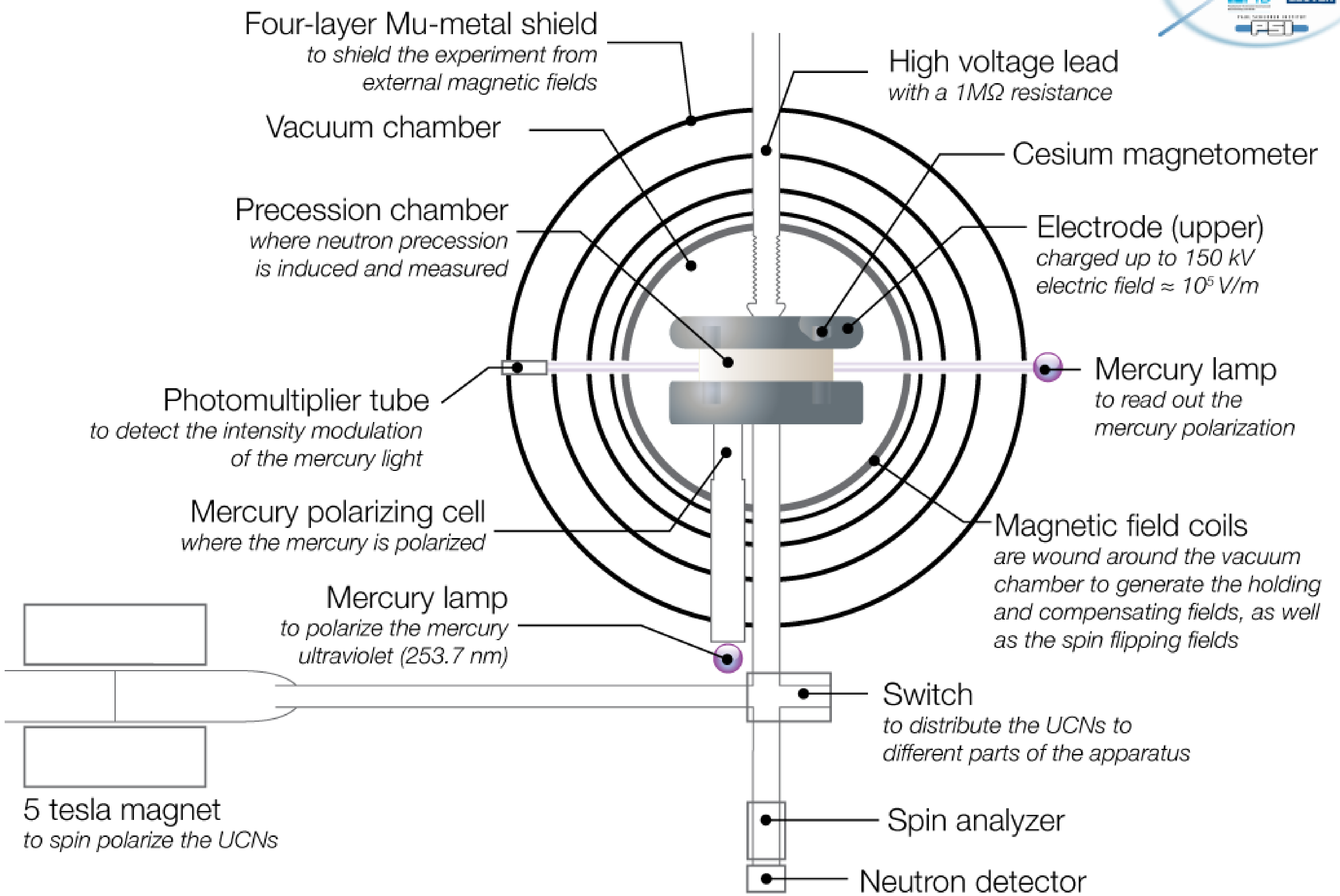
2018: n2EDM at PSI



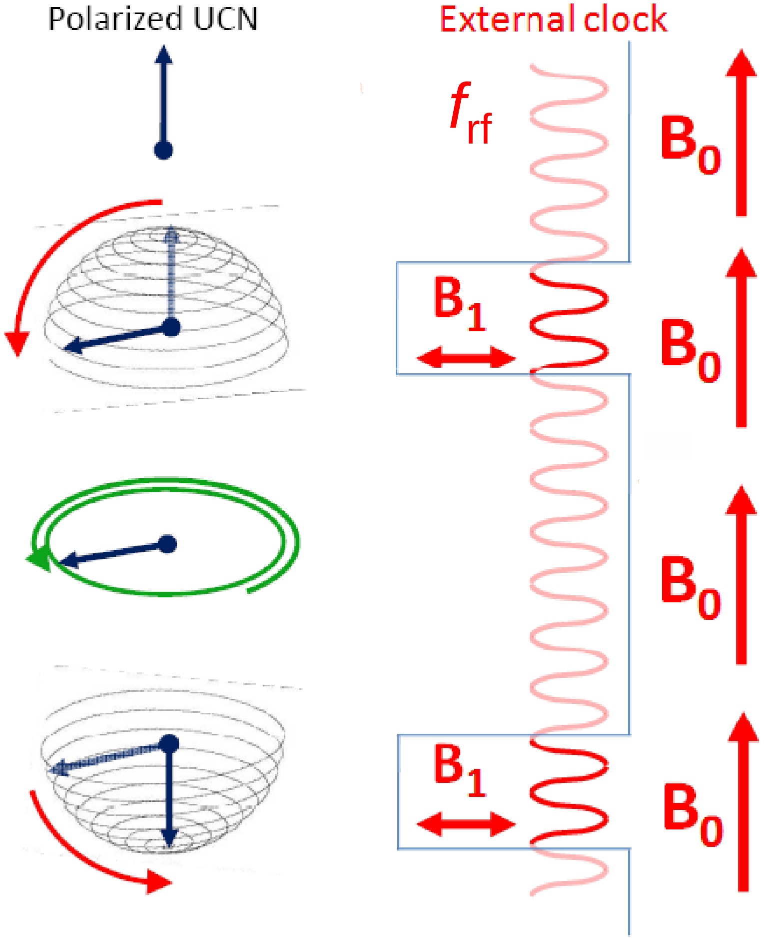
nEDM at PSI

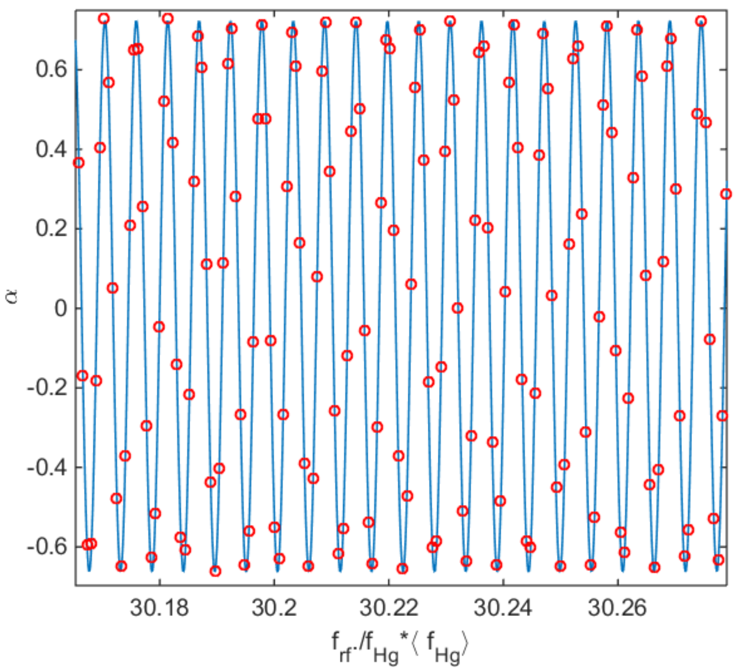


The nEDM spectrometer

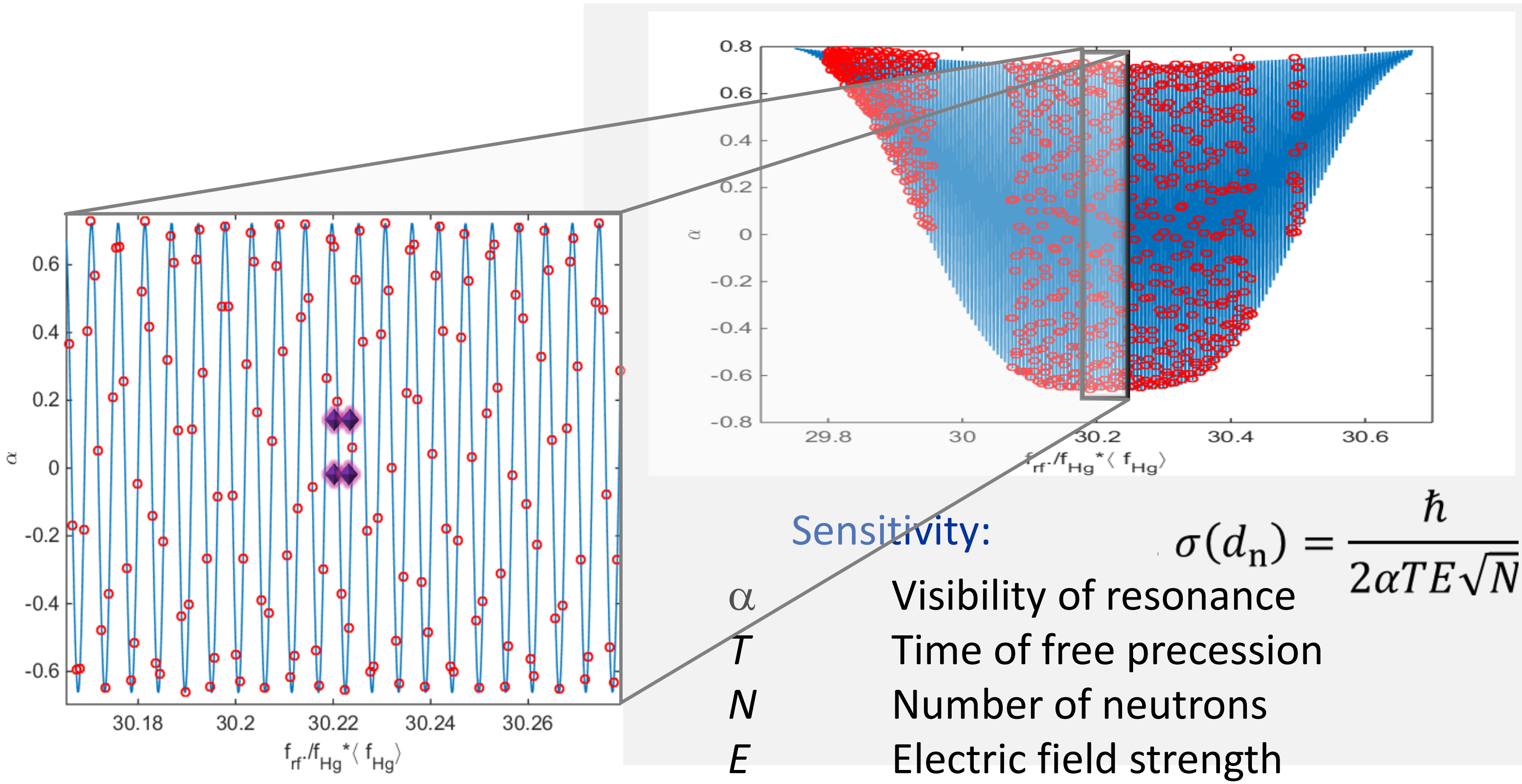


Ramsey's method with UCN





Ramsey's method with UCN

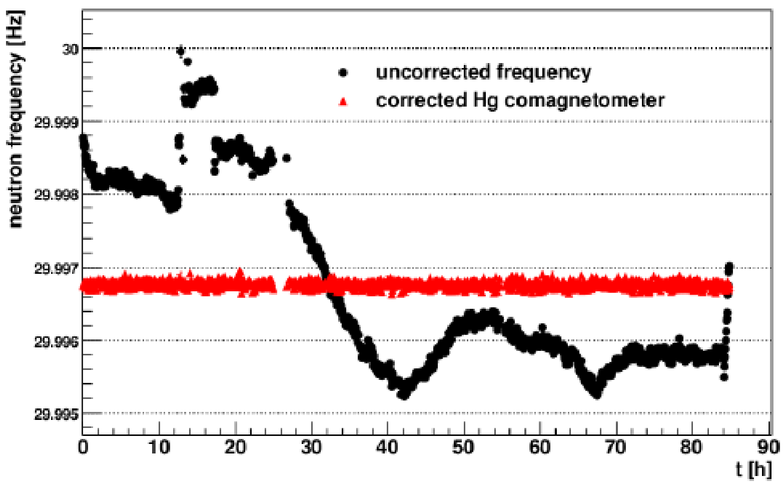


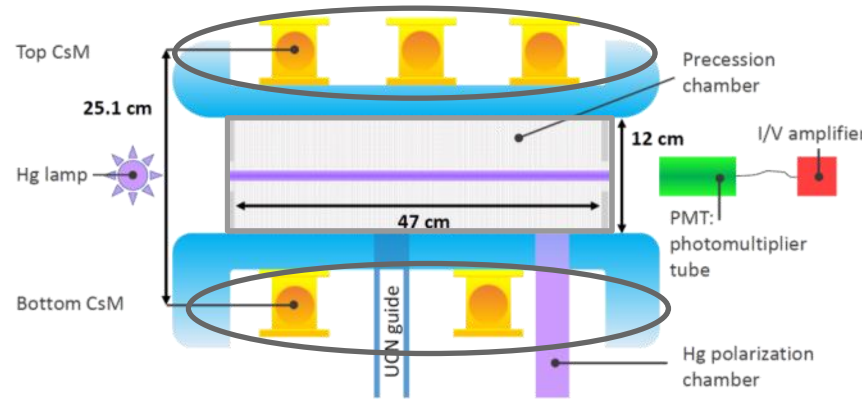
Sensitivity:

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

α	Visibility of resonance
T	Time of free precession
N	Number of neutrons
E	Electric field strength

Frequency ratio R





^{199}Hg

UCN

$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lights}} \ \ldots \right)$$

Magnetic moments

$$\frac{\gamma_n}{2\pi} = 29.164705(55)\ \mathrm{MHz/T}$$

[1.89 ppm]

γ_{Hg} ↑

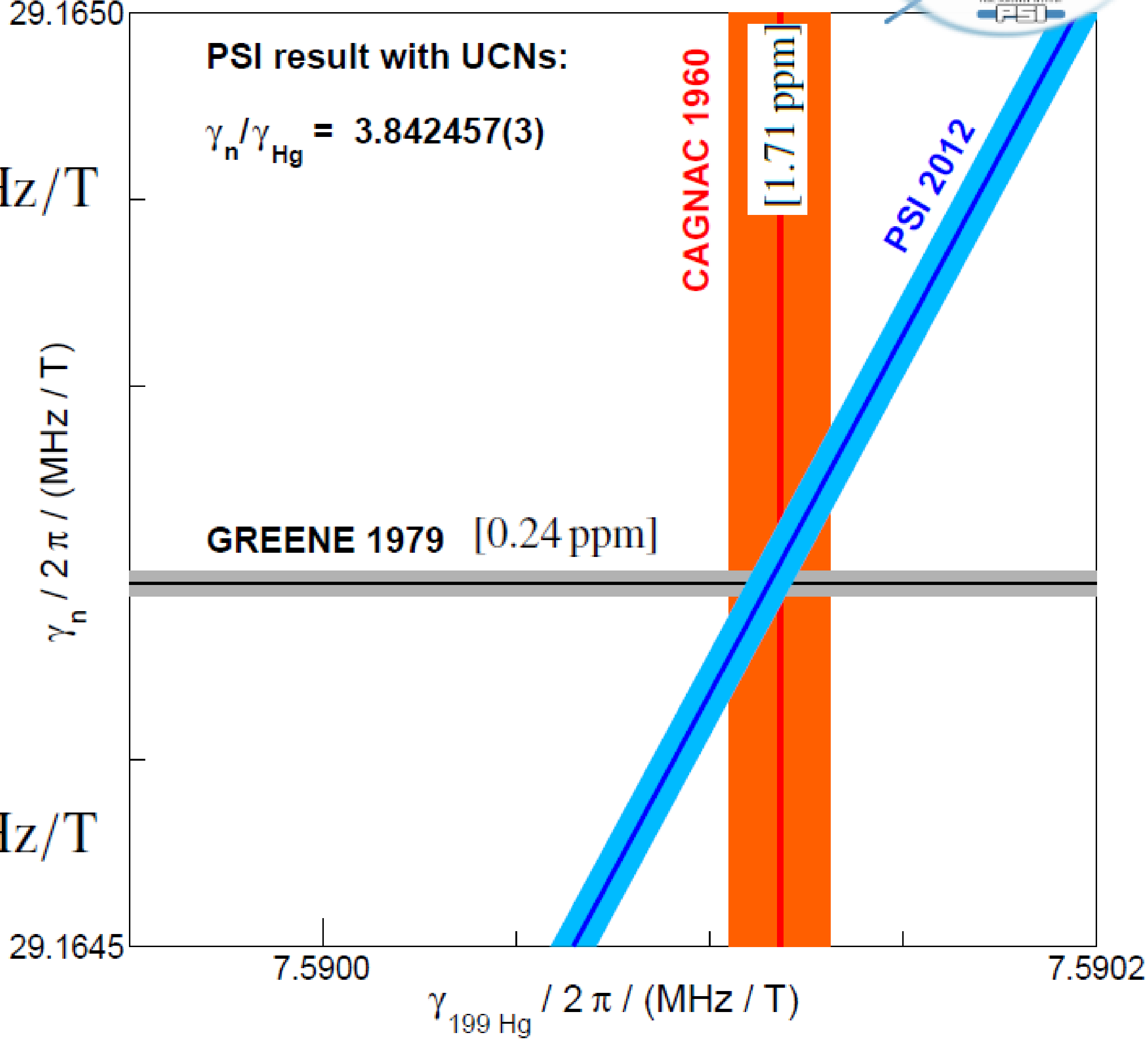
$$\gamma_n/\gamma_{Hg} = 3.8424574(30)$$

[0.78 ppm]

γ_n ↓

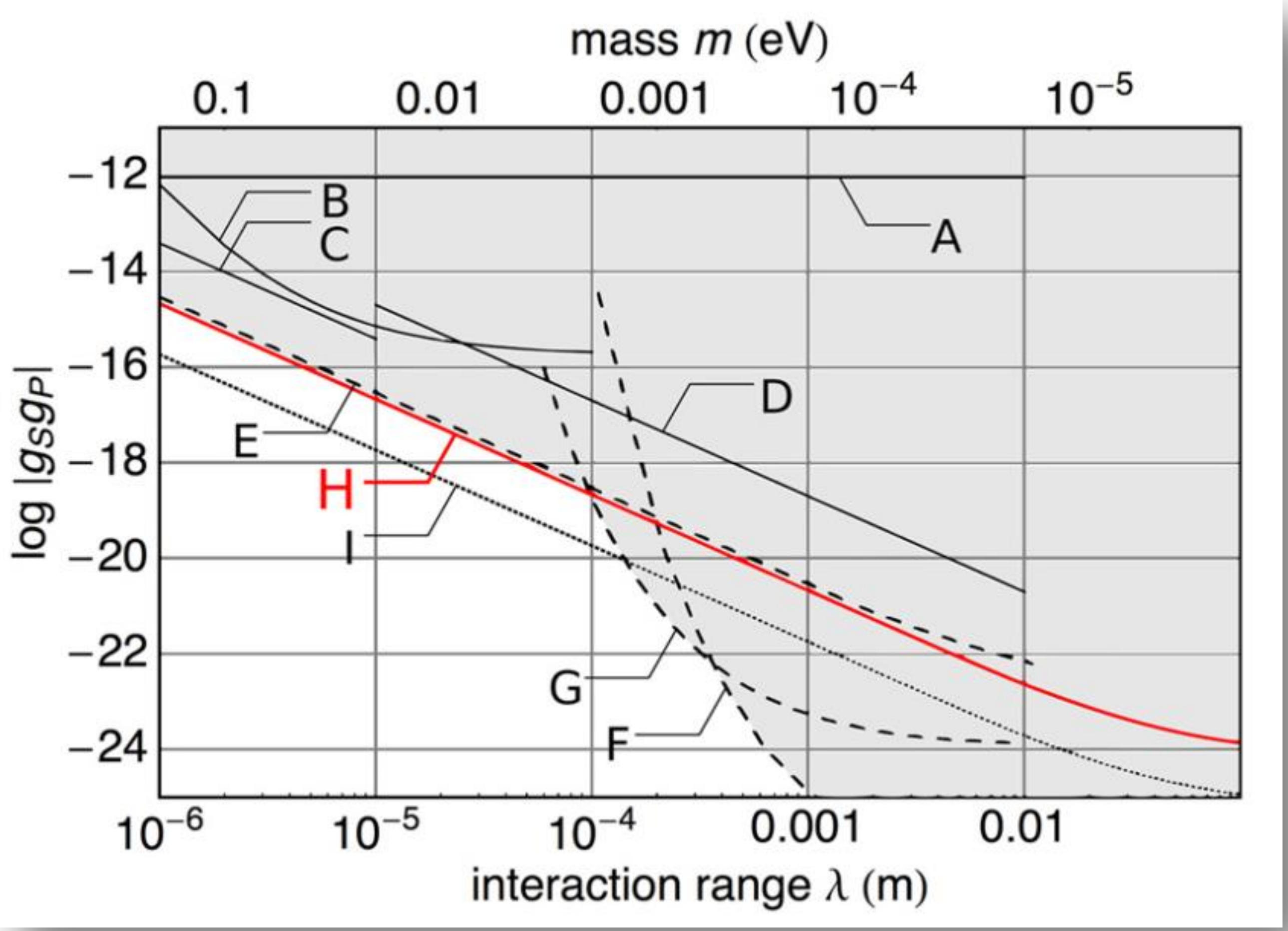
$$\frac{\gamma_{Hg}}{2\pi} = 7.5901152(62)\ \mathrm{MHz/T}$$

[0.82 ppm]



S. Afach et al., PLB 739 (2014) 128

Spin-dependent exotic interactions



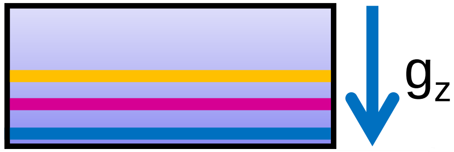
PhD thesis
B. Franke, 2014

S. Afach et al., PLB 745 (2015) 58

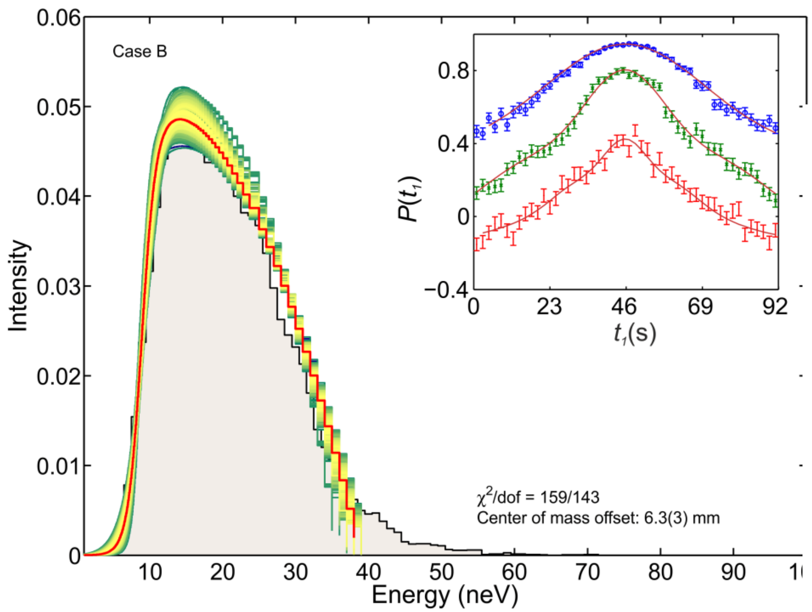
To be updated soon

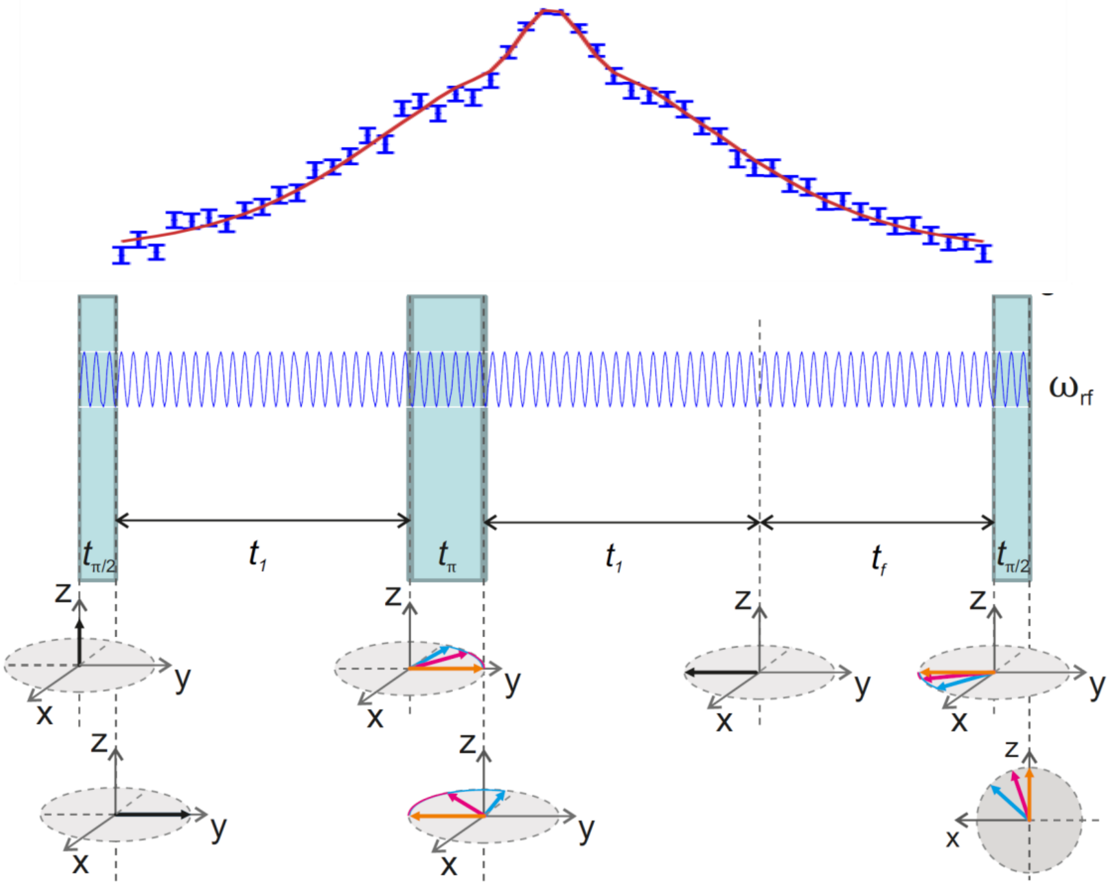
UCN spin-echo spectroscopy

See talk by Guillaume Pignol



A spin-echo recovers energy dependent dephasing for *T = 2t$_1$* in a magnetic field with vertical gradient.

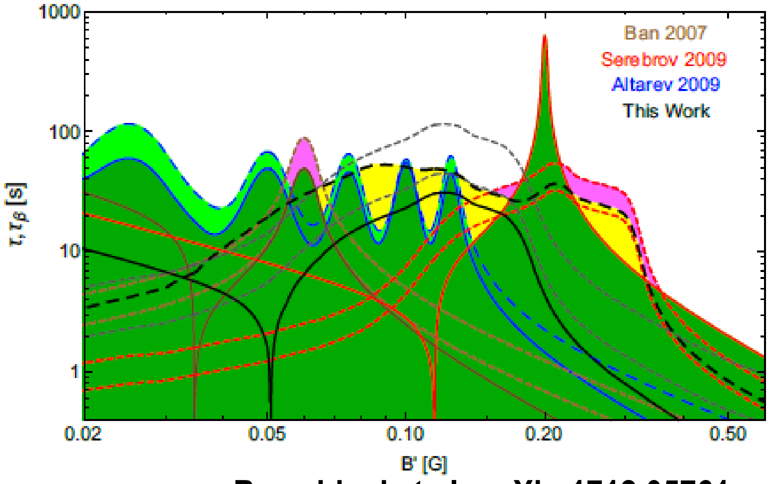




S. Afach et al., PRL114(2015)162502

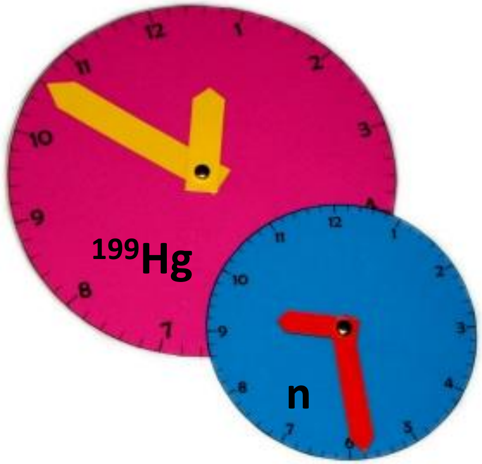
Earlier results using nEDM

- Searches for nn' oscillations
  - G. Ban *et al.*, PRL99 (2007) 161603
  - I. Altarev *et al*., PRD80 (2009) 03200;
  - to be updated soon …



Berezhiani et al., arXiv:1712.05761

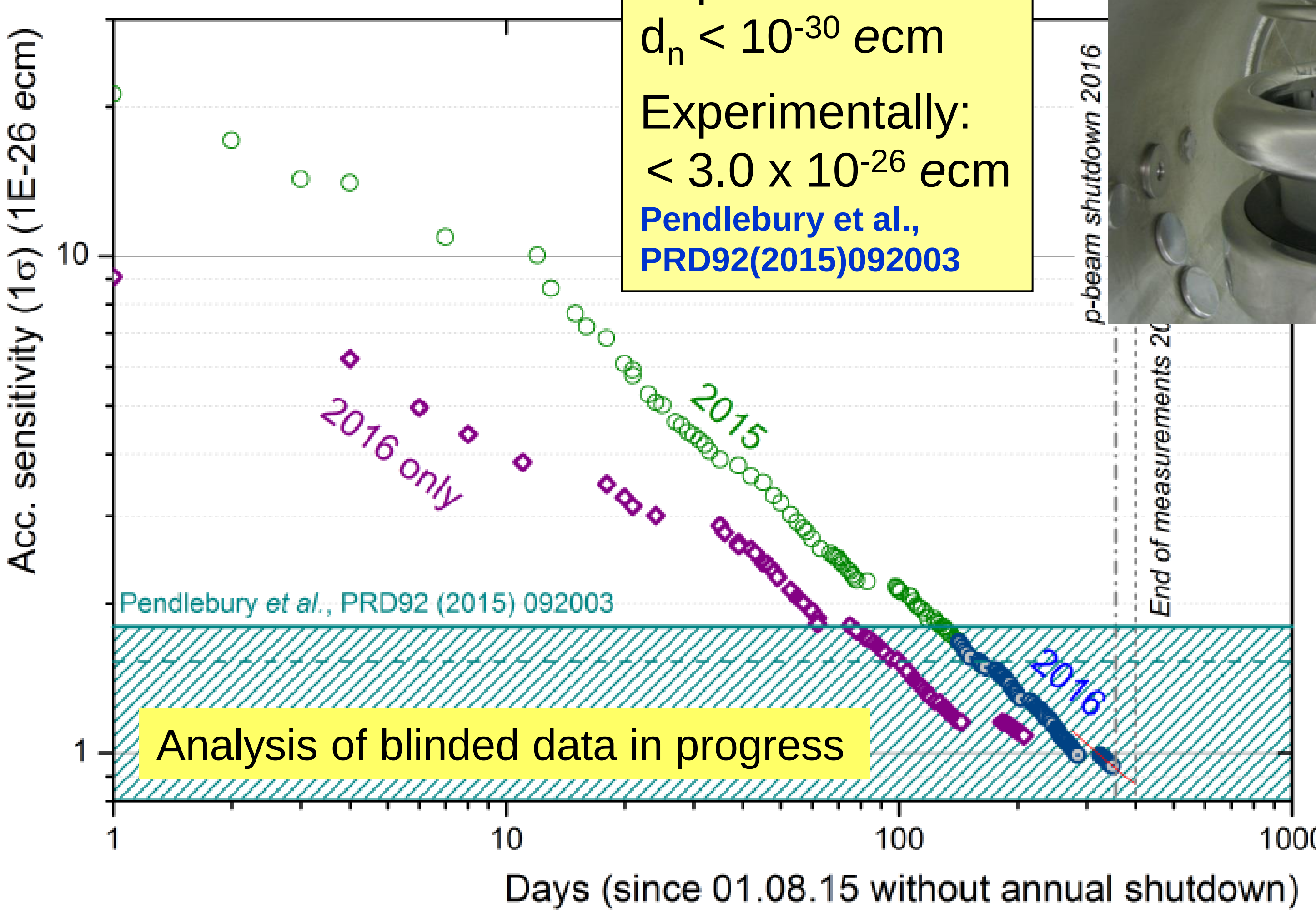
- Searches for Lorentz violation
  - I. Altarev *et al.*,PRL 103 (2009) 081602
  - I. Altarev et al., EPL 92 (2010) 51001
  - to be updated soon …

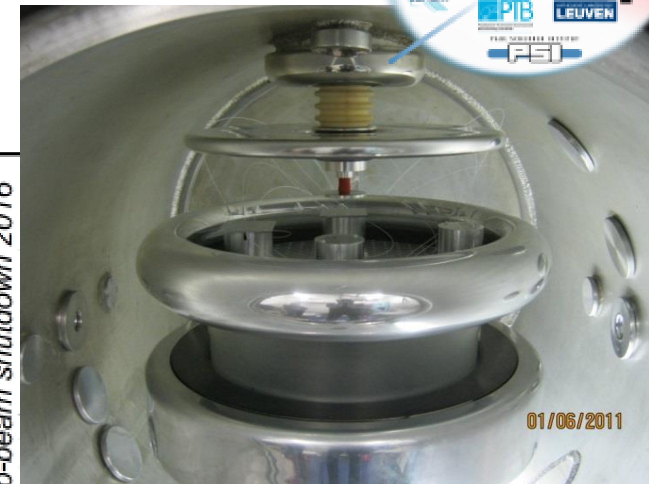


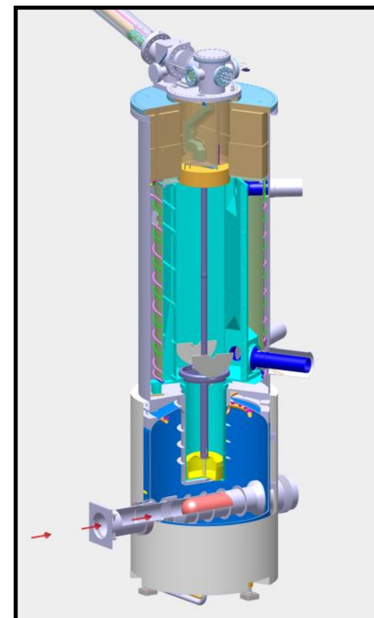
The neutron EDM itself …

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

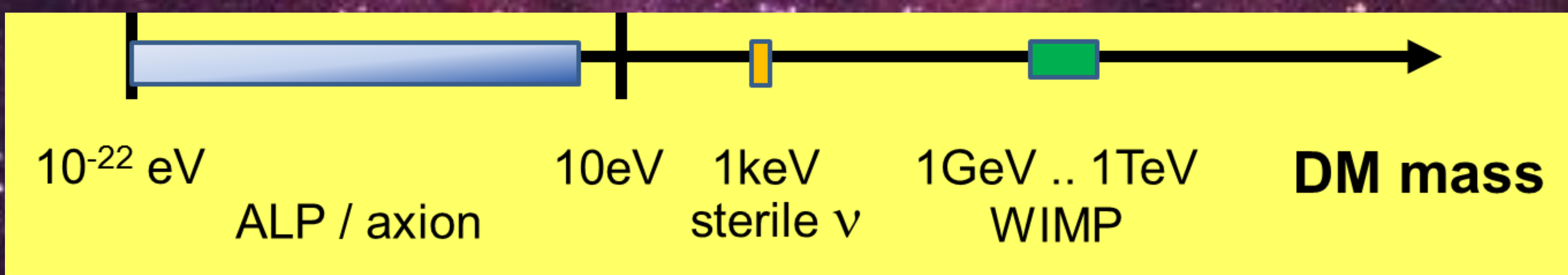
Experimentally:
$< 3.0 \times 10^{-26}$ *e*cm
Pendlebury et al., PRD92(2015)092003



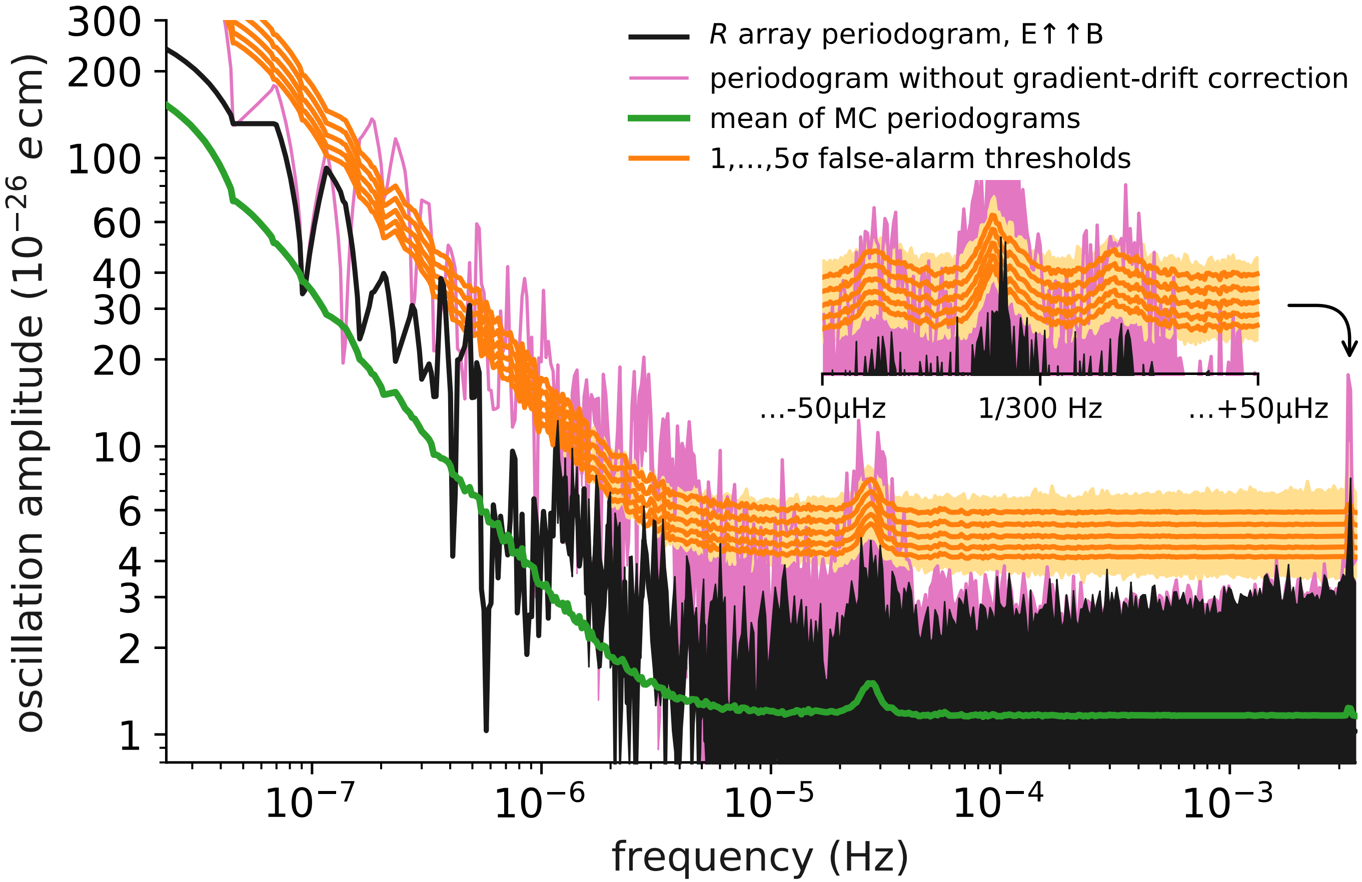




What is the nature of Dark Matter?



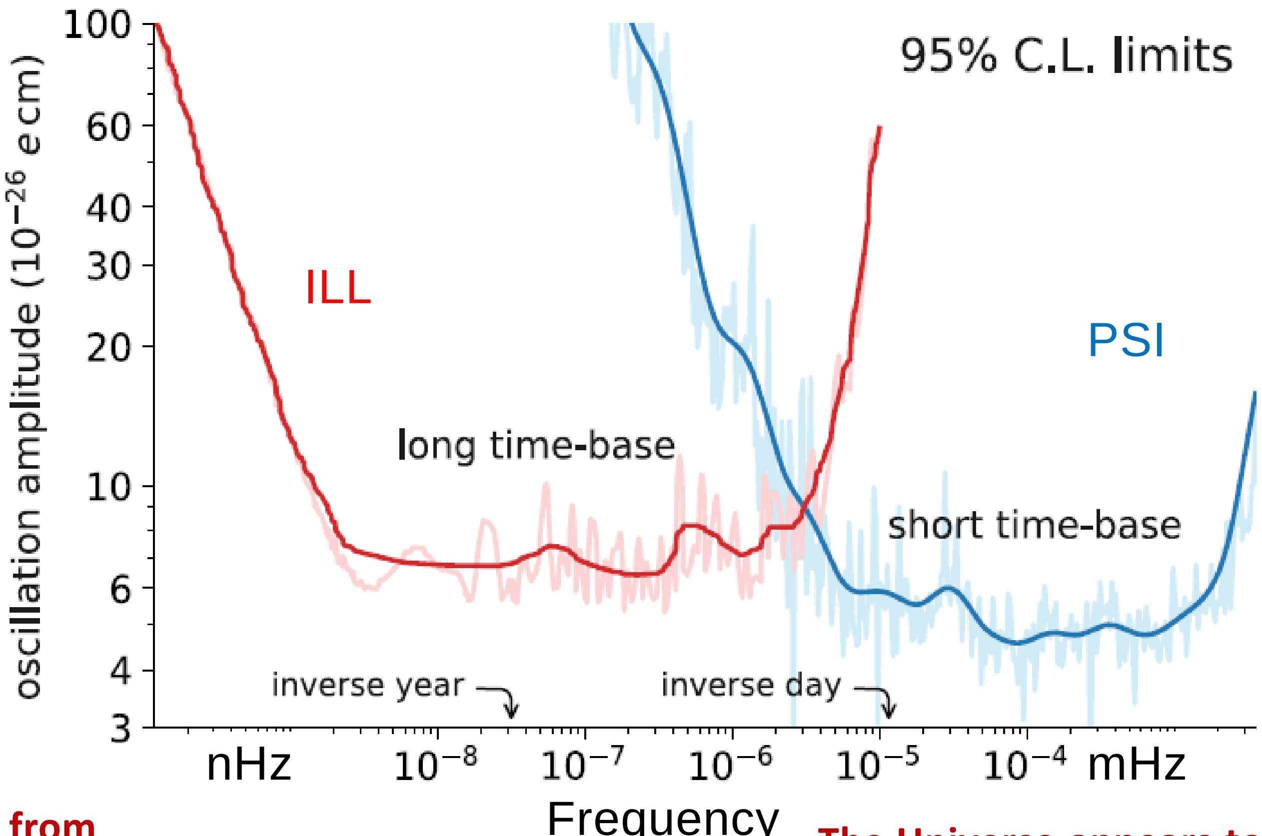
Search for nEDM oscillations with time



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

Search for nEDM oscillations with time

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



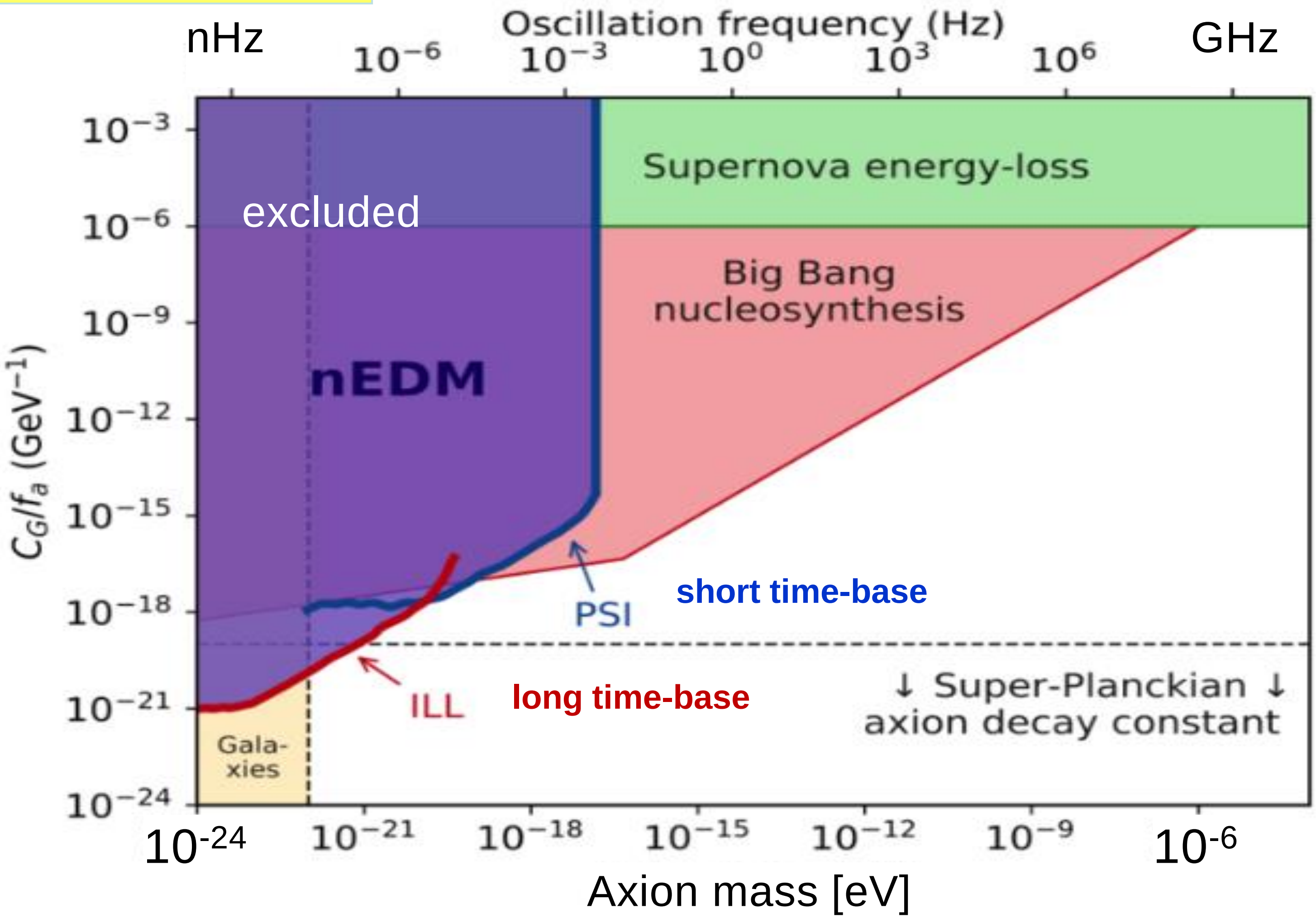
PhD theses
N. Ayres, Sussex
M. Rawlik, ETHZ

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

See talk by Yevgeny Stadnik



Teamed up with theorists Flambaum, Stadnik, Fairbairn, Marsh

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

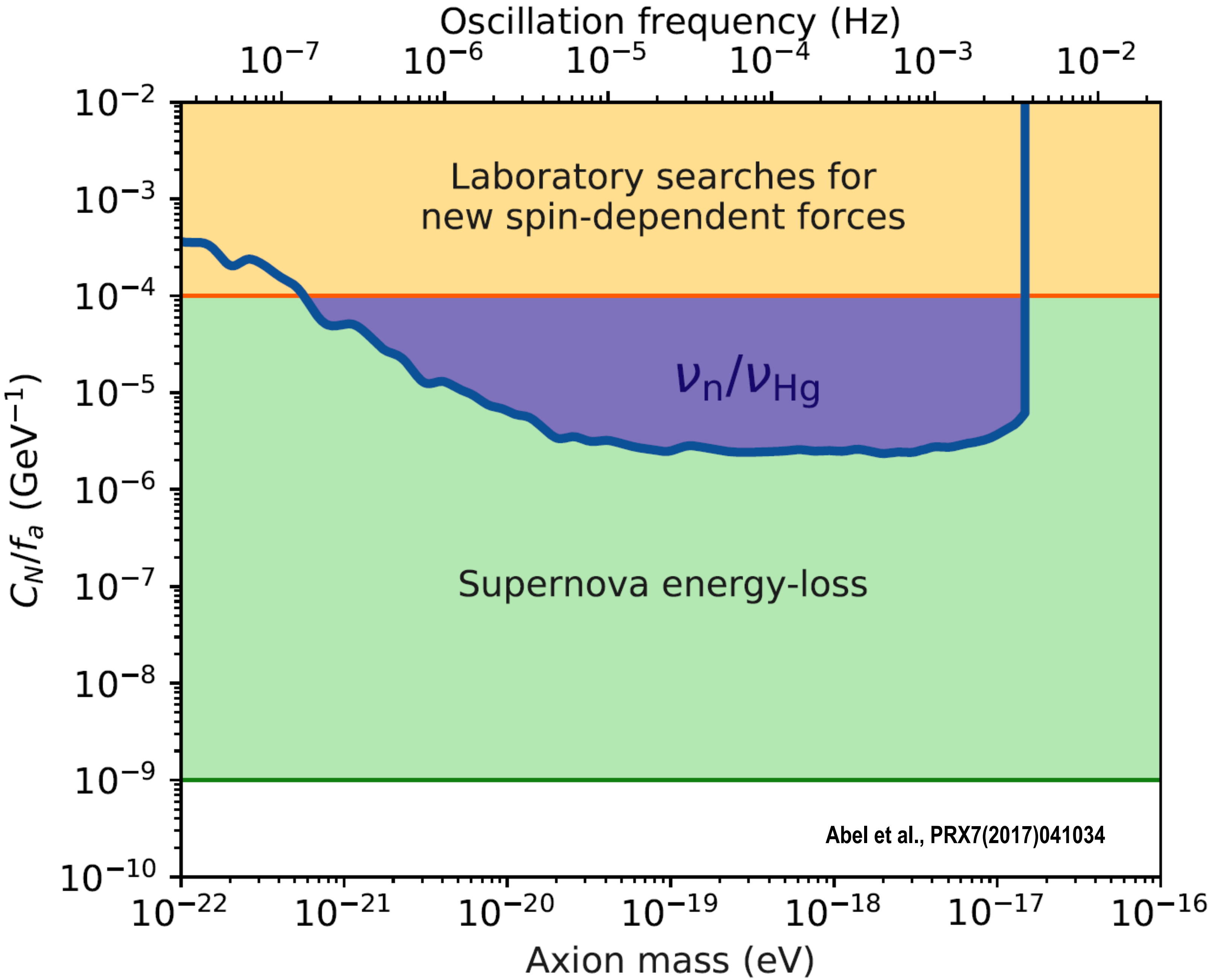
nEDM places the first laboratory limits. on **axion – gluon** couplings

Abel et al., PRX7(2017)041034

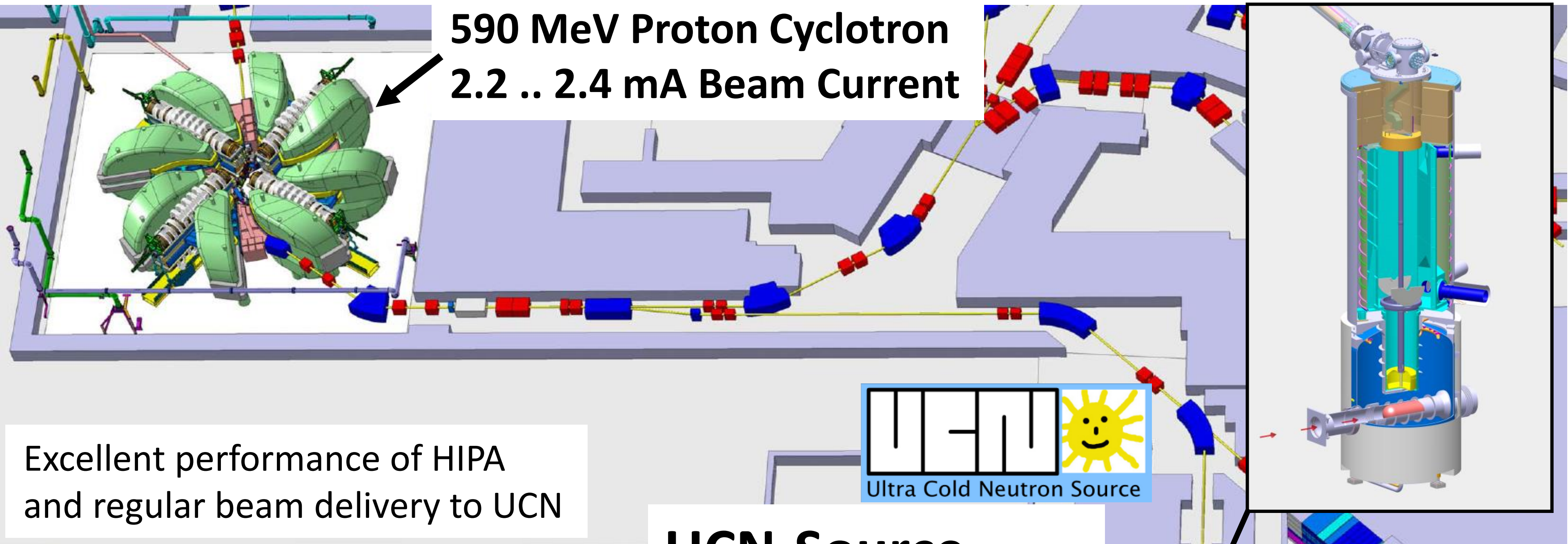
n2EDM baseline:
$\sigma(d_n)$~1E-27*e*cm in 500 days
Commissioning 2020

Thank you

Backup

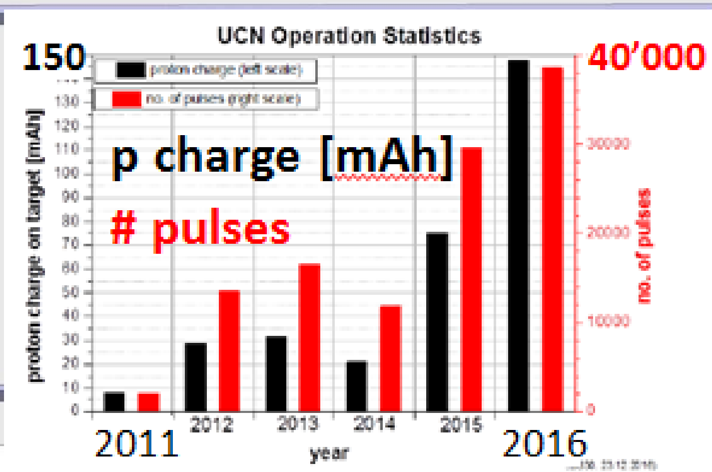

Oscillation frequency (Hz)
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}
C_N/f_a (GeV^{-1})
10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10}
Laboratory searches for
new spin-dependent forces
ν_n/ν_{Hg}
Supernova energy-loss
Abel et al., PRX7(2017)041034
10^{-22} 10^{-21} 10^{-20} 10^{-19} 10^{-18} 10^{-17} 10^{-16}
Axion mass (eV)

Ultracold Neutron Source & Facility



590 MeV Proton Cyclotron
2.2 .. 2.4 mA Beam Current

Excellent performance of HIPA and regular beam delivery to UCN



UCN-Source

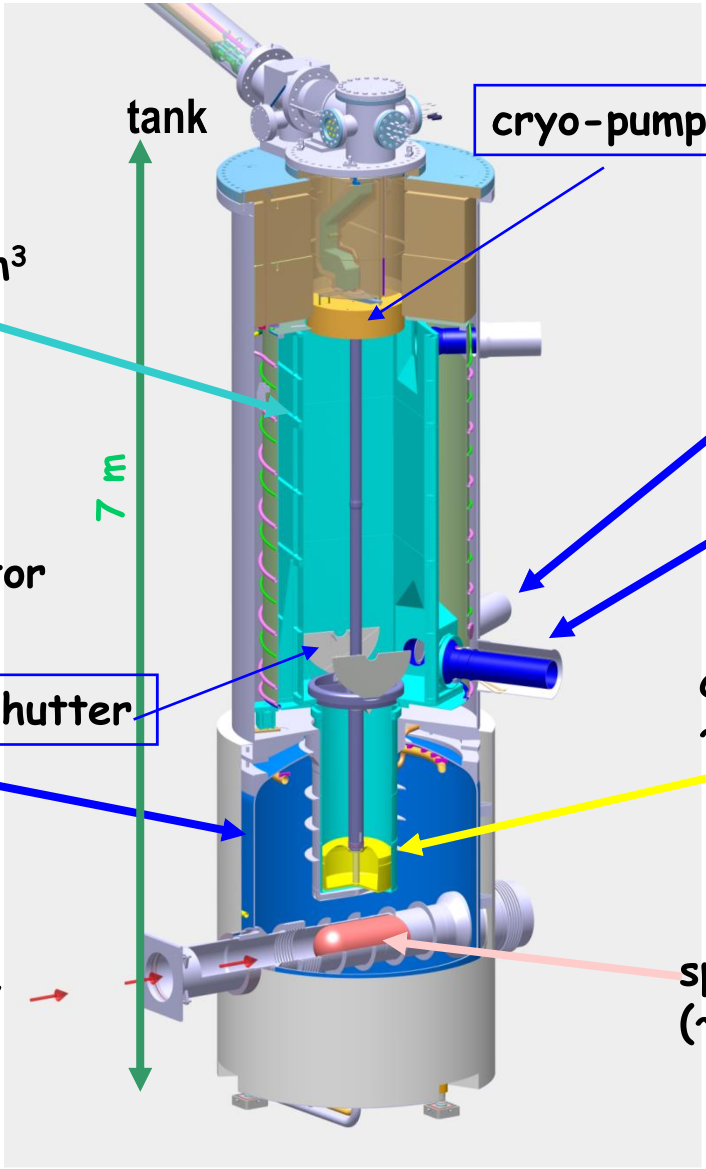
- 1st test: 12/2010
- Safety approval: 06/2011
- UCN start 08/2011
- Reliable performance 2012
- UCN to nEDM since 2012

-> intensity 90x over 2010

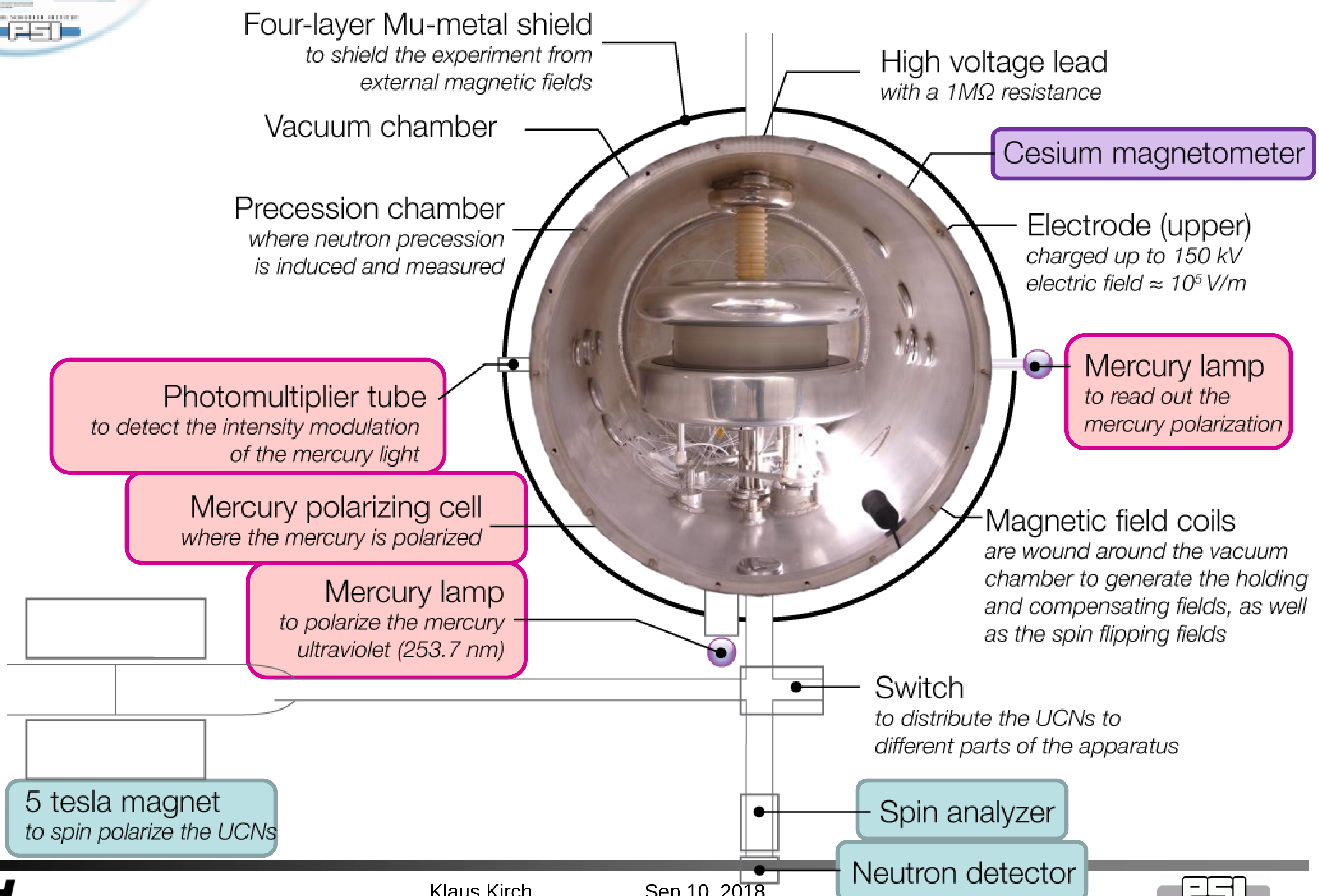
- Increased duty factor 2015: 20 → 40 μA average
- 2016: → 53μA (60 allowed)

The PSI UCN source

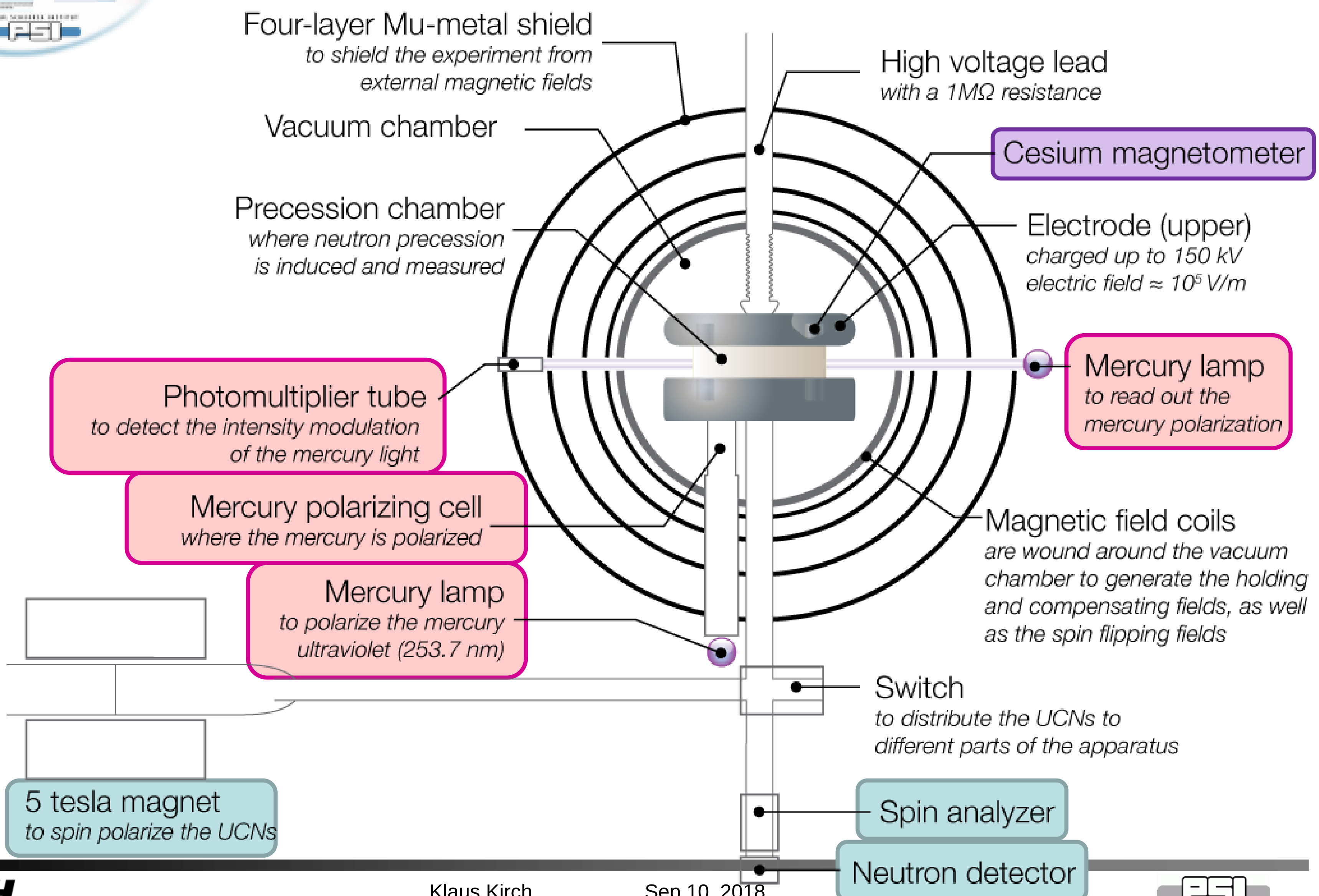
Ultra Cold Neutron Source



The nEDM spectrometer

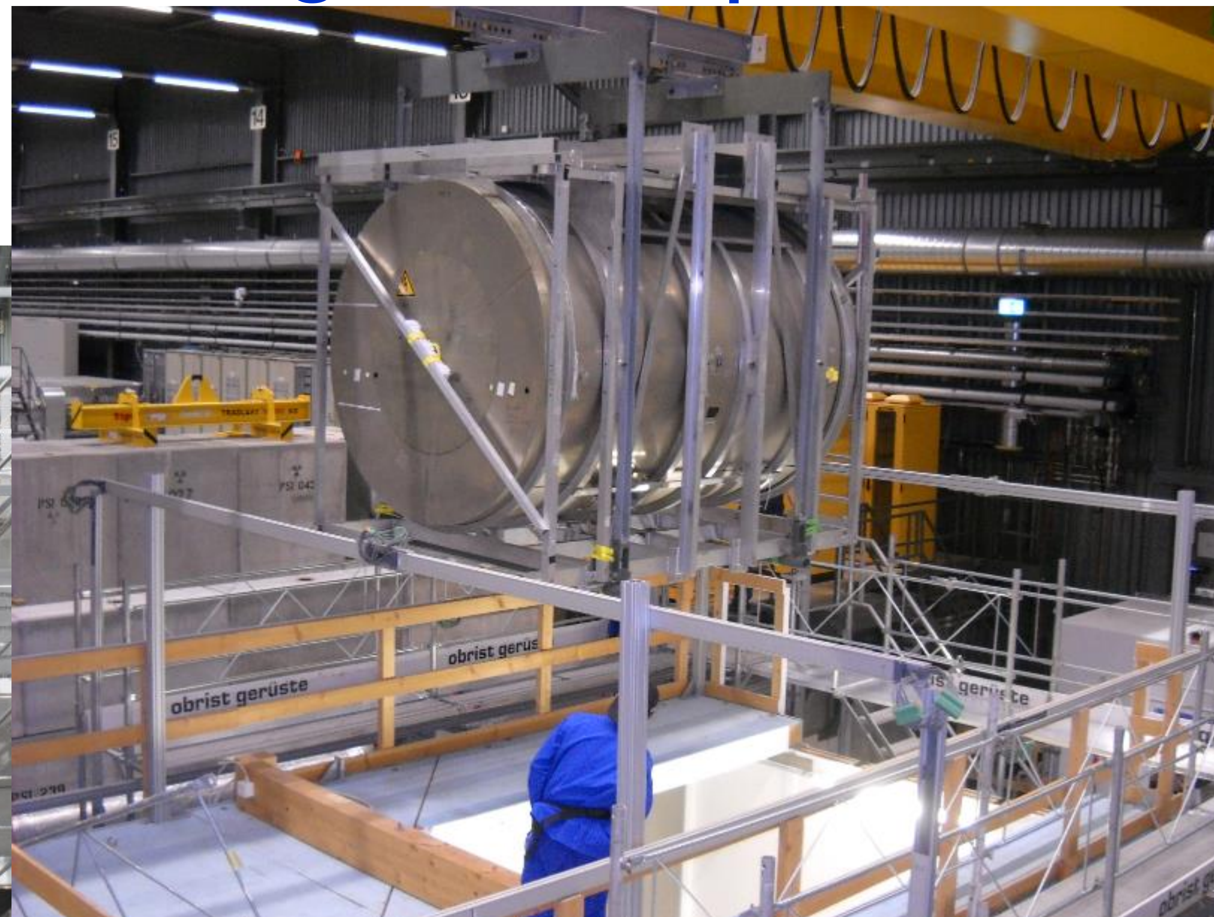


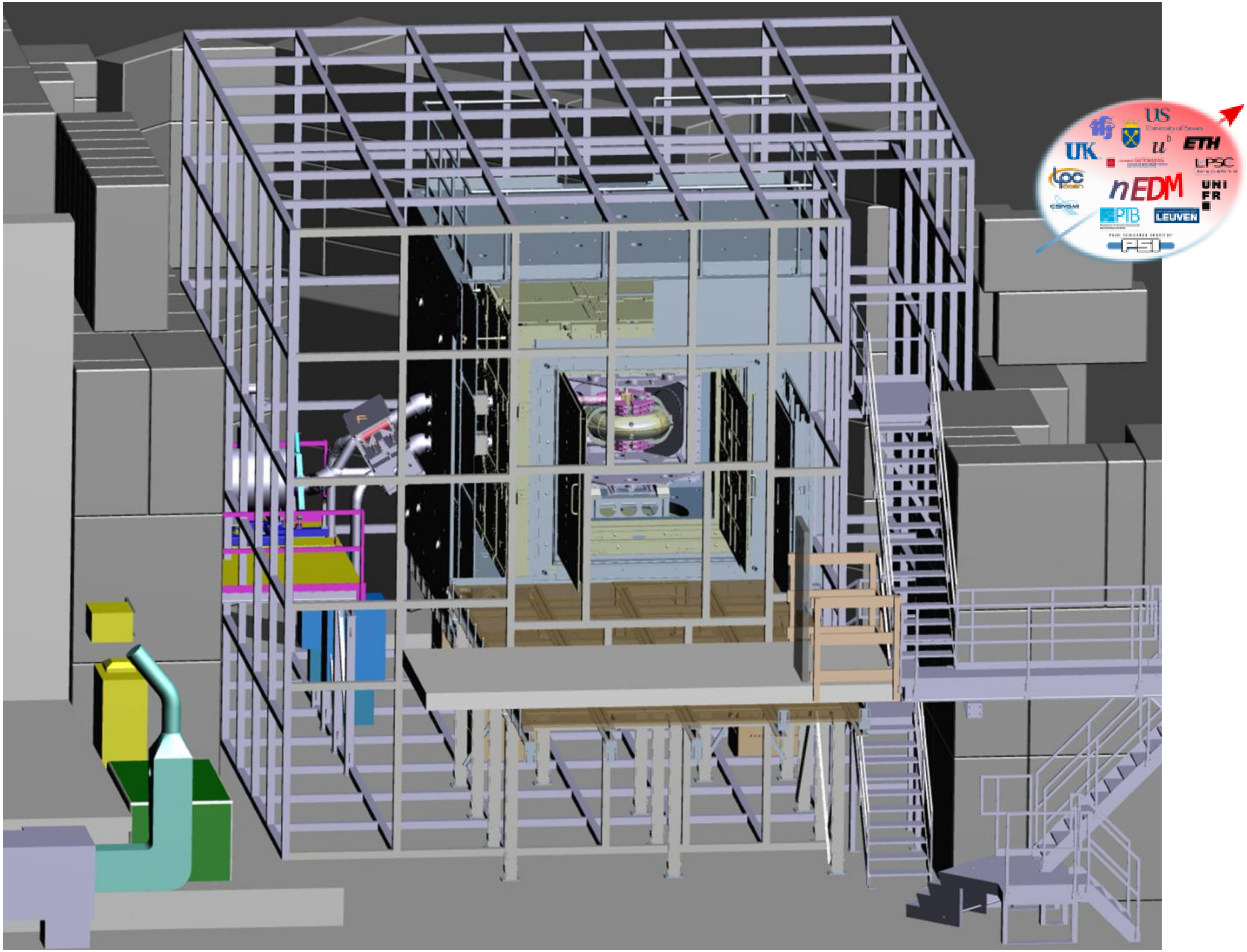
The nEDM spectrometer

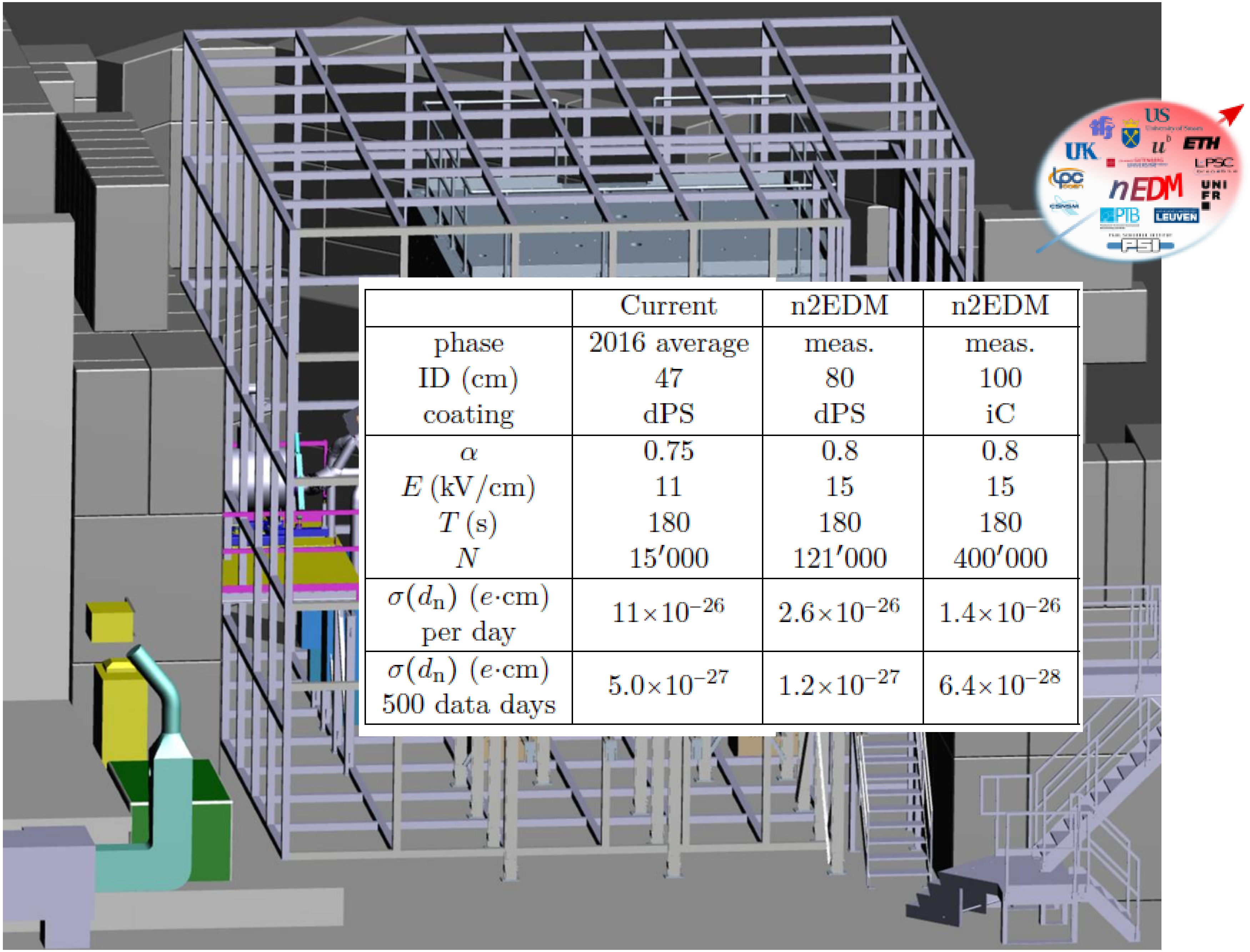


nEDM being taken apart

nEDM being taken apart

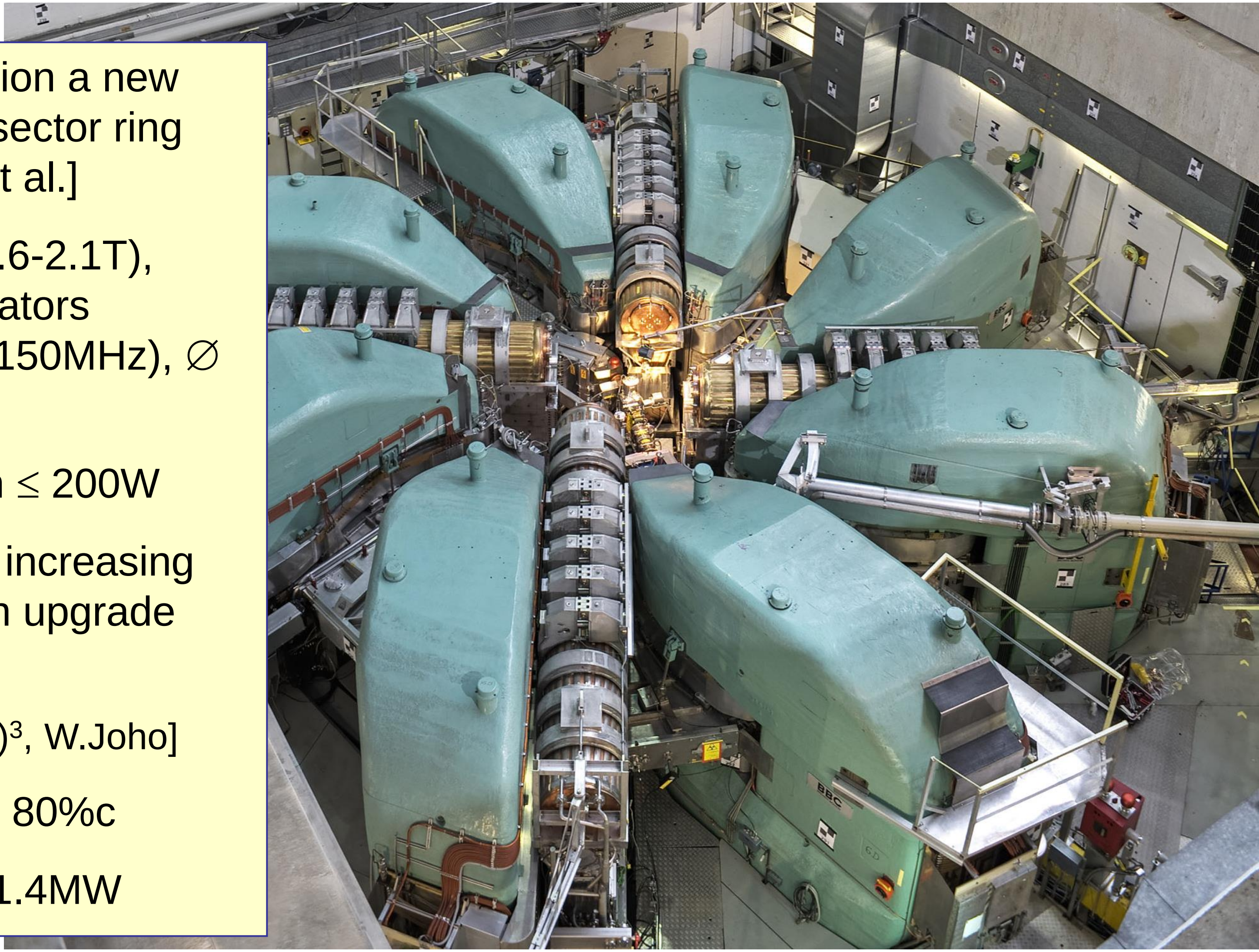



nEDM



	Current	n2EDM	n2EDM
phase	2016 average	meas.	meas.
ID (cm)	47	80	100
coating	dPS	dPS	iC
α	0.75	0.8	0.8
E (kV/cm)	11	15	15
T (s)	180	180	180
N	$15'000$	$121'000$	$400'000$
$\sigma(d_{\rm n})$ (e·cm) per day	11×10^{-26}	2.6×10^{-26}	1.4×10^{-26}
$\sigma(d_{\rm n})$ (e·cm) 500 data days	5.0×10^{-27}	1.2×10^{-27}	6.4×10^{-28}

PSI ring cyclotron

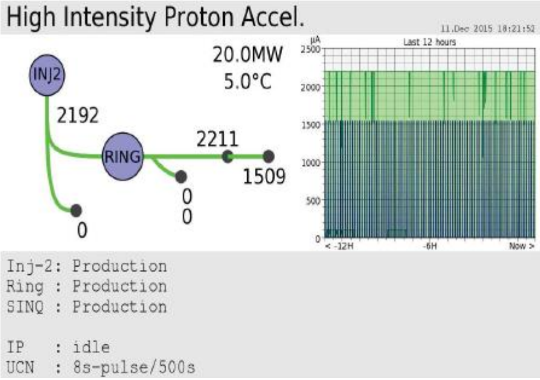


- at time of construction a new concept: separated sector ring cyclotron [H.Willax et al.]
- 8 magnets (280t, 1.6-2.1T), 4 accelerating resonators (50MHz), 1 Flattop (150MHz), ∅ 15m
- losses at extraction ≤ 200W
- reducing losses by increasing RF voltage was main upgrade path

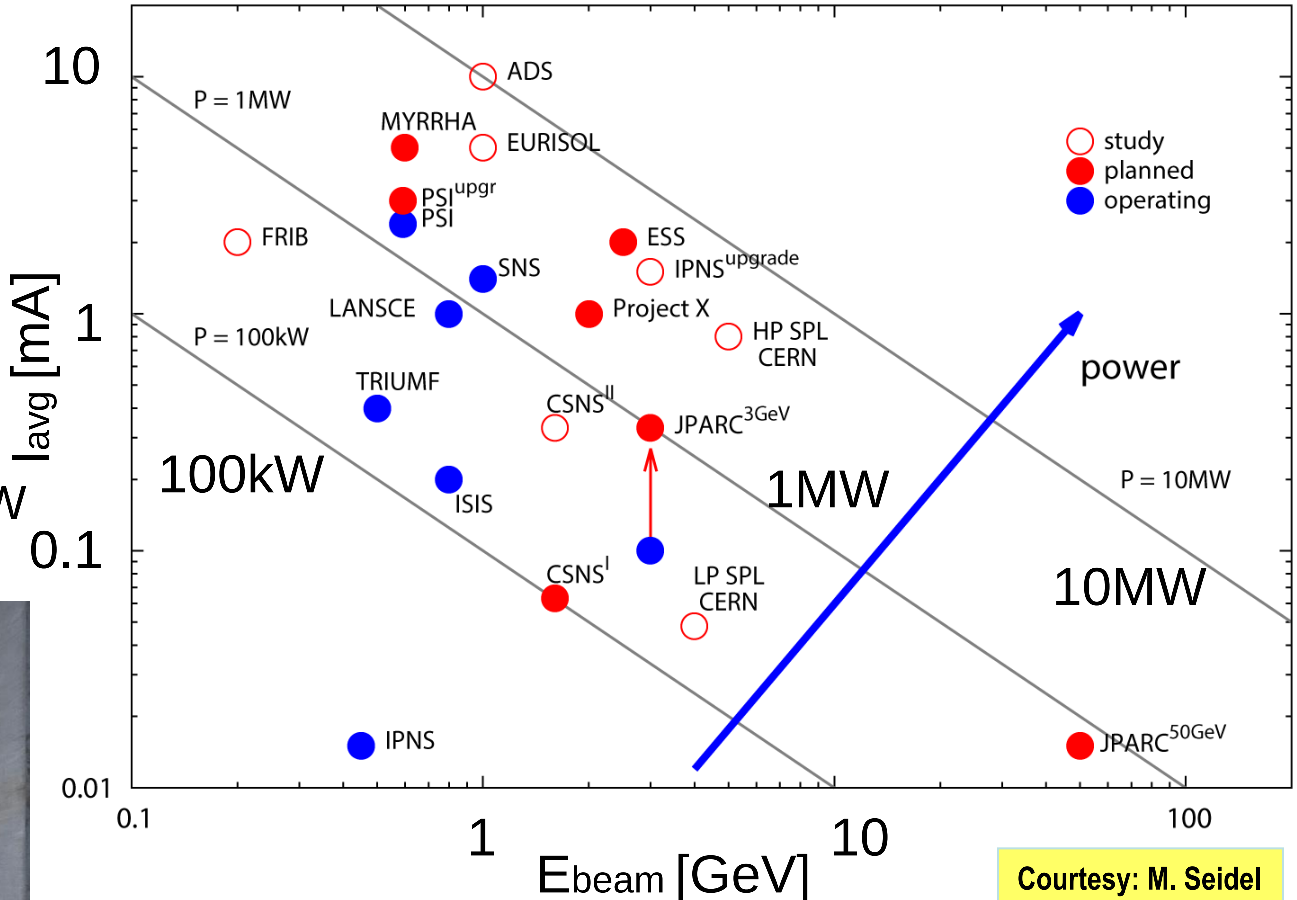
[losses ∝ (turn number)^3, W.Joho]

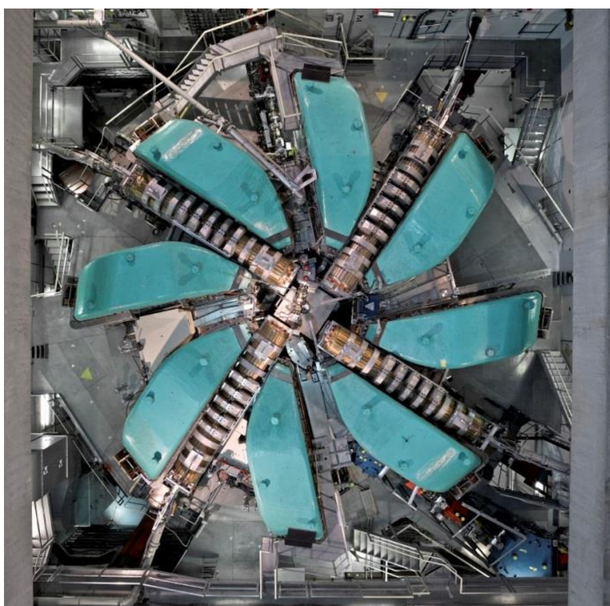
- 590MeV protons at 80%c
- 2.4mA x 590MeV=1.4MW

PSI ring cyclotron



The most powerful proton beam to targets:
590 MeV x 2.4 mA = 1.4 MW

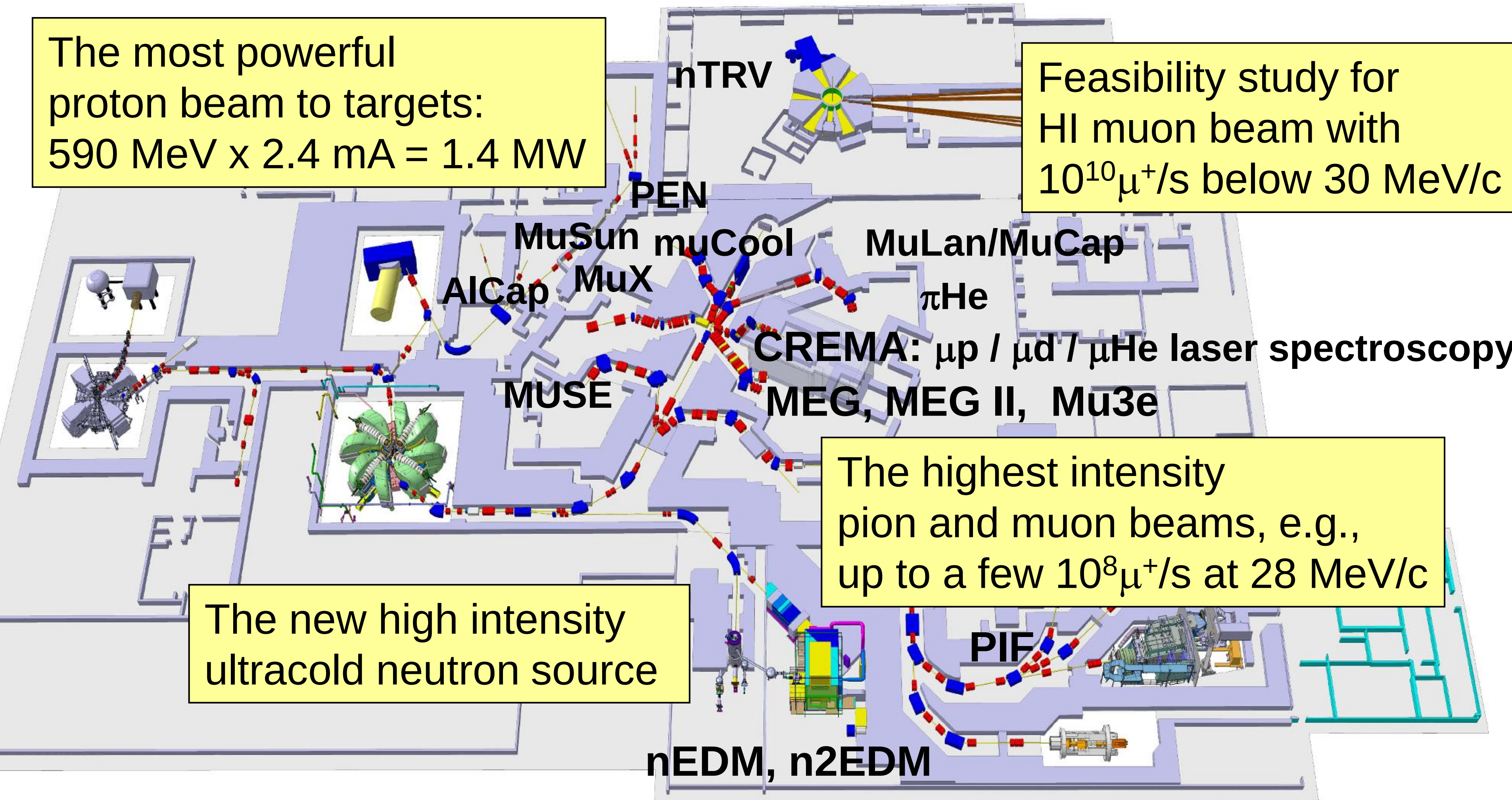




HIPA at PSI is a leading machine at the intensity frontier.
It produces the highest intensities of muons and pions at low momenta and of ultracold neutrons.

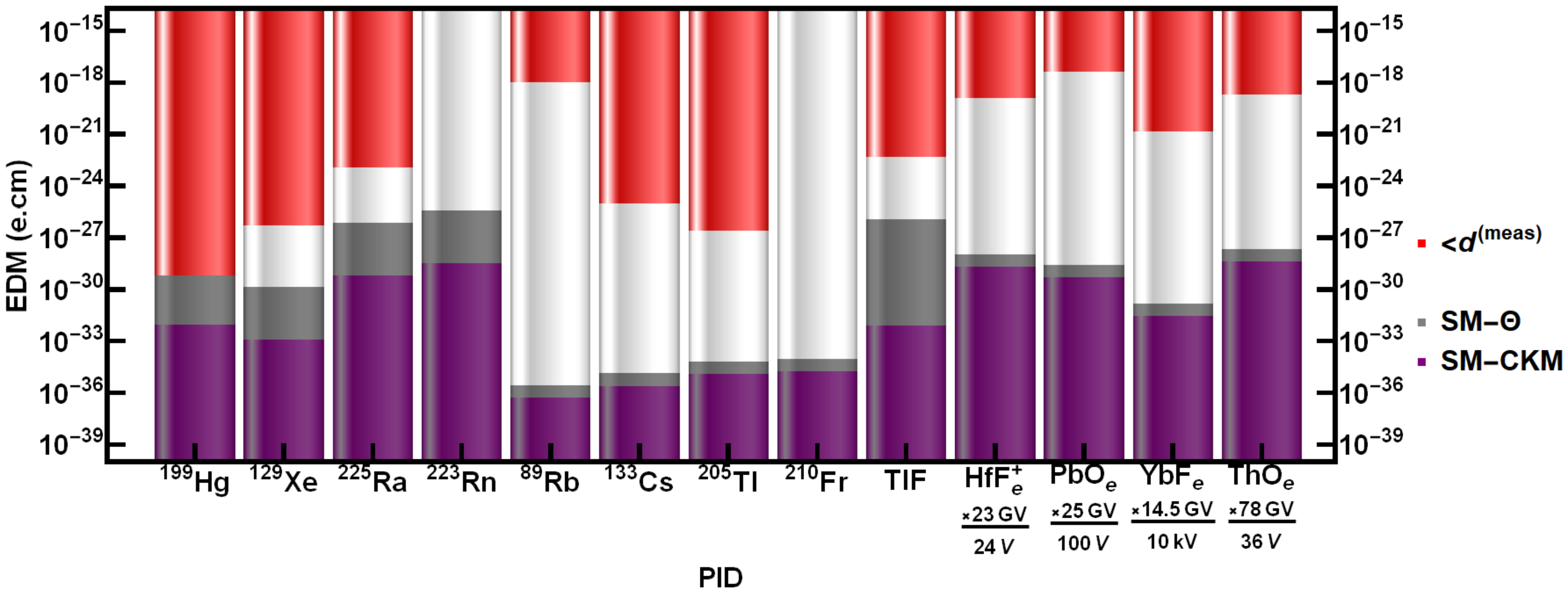
The intensity frontier at PSI: π, μ, UCN

Precision experiments with **the lightest unstable particles** of their kind



Swiss national laboratory with <u>strong international collaborations</u>

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

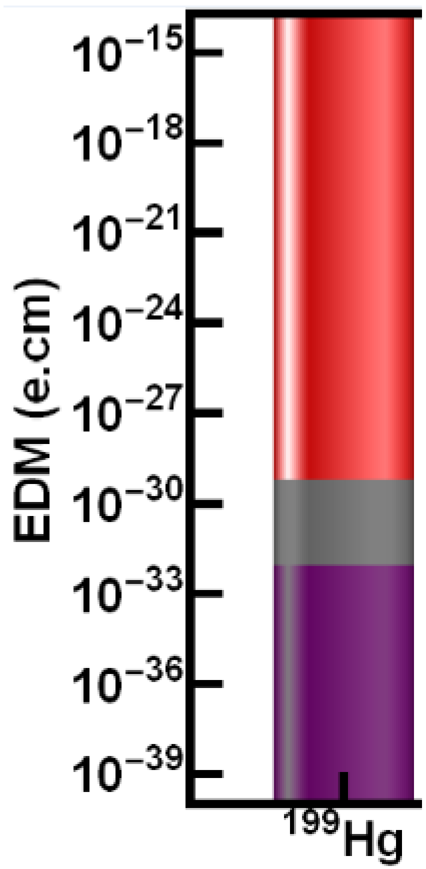


TABLE III. Limits on CP-violating observables from the ^{199}Hg EDM limit. Each limit is based on the assumption that it is the sole* contribution to the atomic EDM. In principle, the result for $\mathbf{d}_n$ supercedes [11] as the best neutron EDM limit.

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

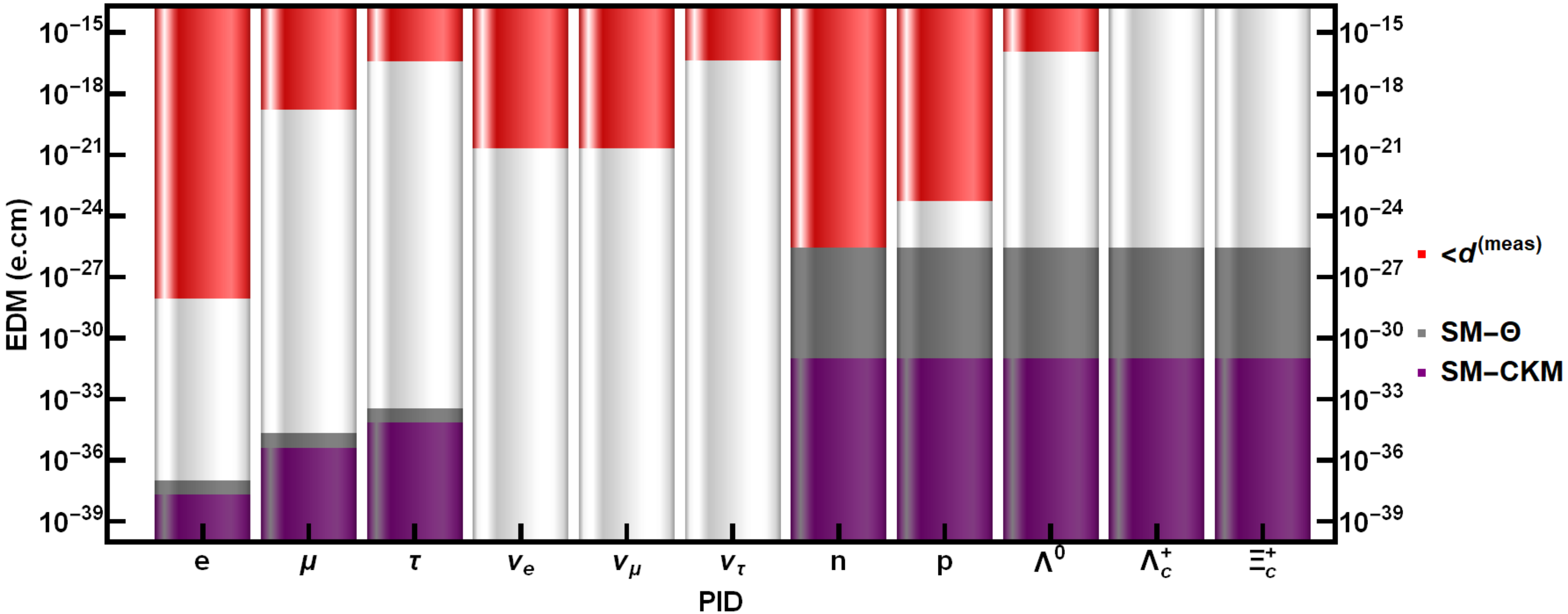
$$|d_{\rm Hg}| < 7.4 \times 10^{-30} e\,{\rm cm}\ (95\%\ {\rm C.L.})$$

Graner et al., PRL116(2016)161601

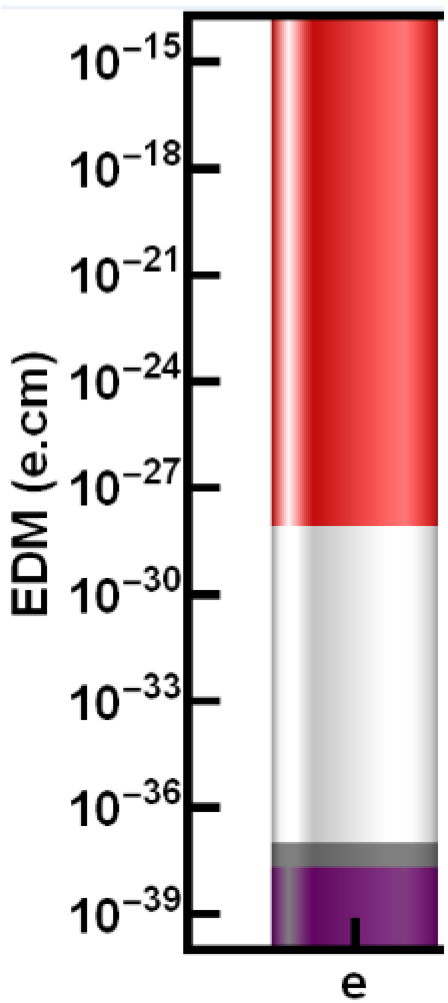
* e.g. otherwise θ_{QCD} ~< 1E-6

Chupp, Ramsey-Musolf, PRC91(2015)035502

Particles



A mix of indirect and direct bounds



Electron:

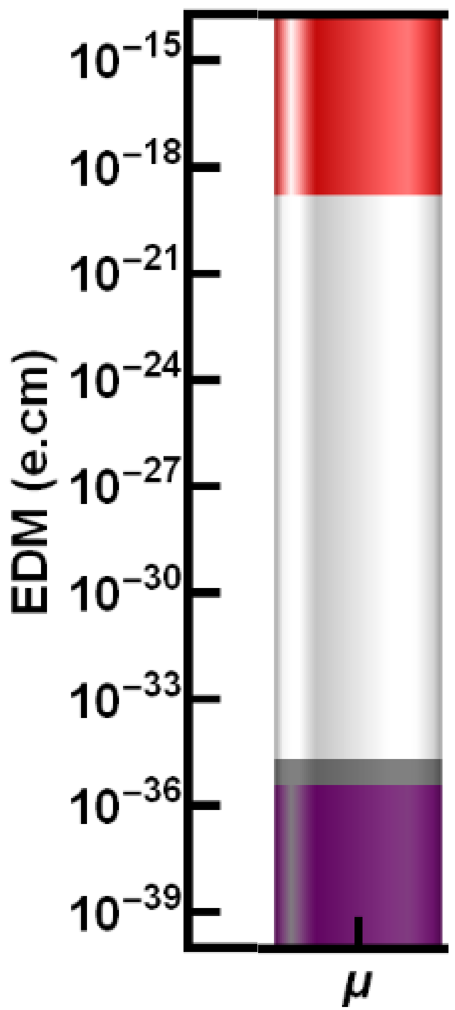
The tightest EDM limit on a fundamental fermion

System	Electron EDM limit	Latest reference	Improving
$^{232}Th^{16}O$	9.4E-29 ecm	NJP19(2017)073029	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

Muon:

The best direct EDM limit on a fundamental fermion



- Side analysis of muon g-2 experiment

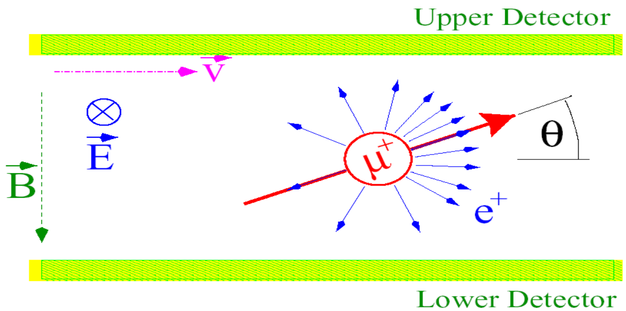
  $$|d_\mu| \leq 1.8 \times 10^{-19}\ e\,\mathrm{cm}\ (95\%\ \mathrm{C.L.}),$$

  Bennett et al., PRD80(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

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

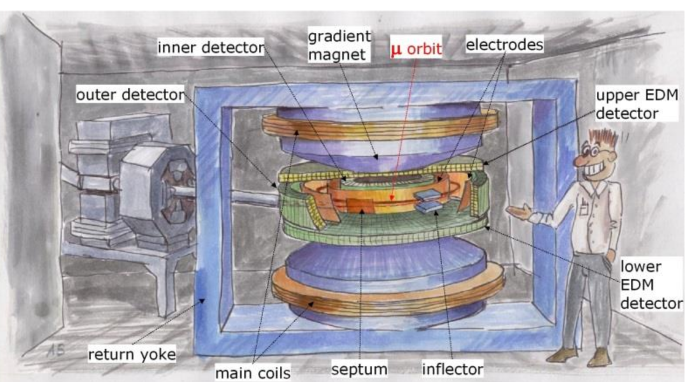
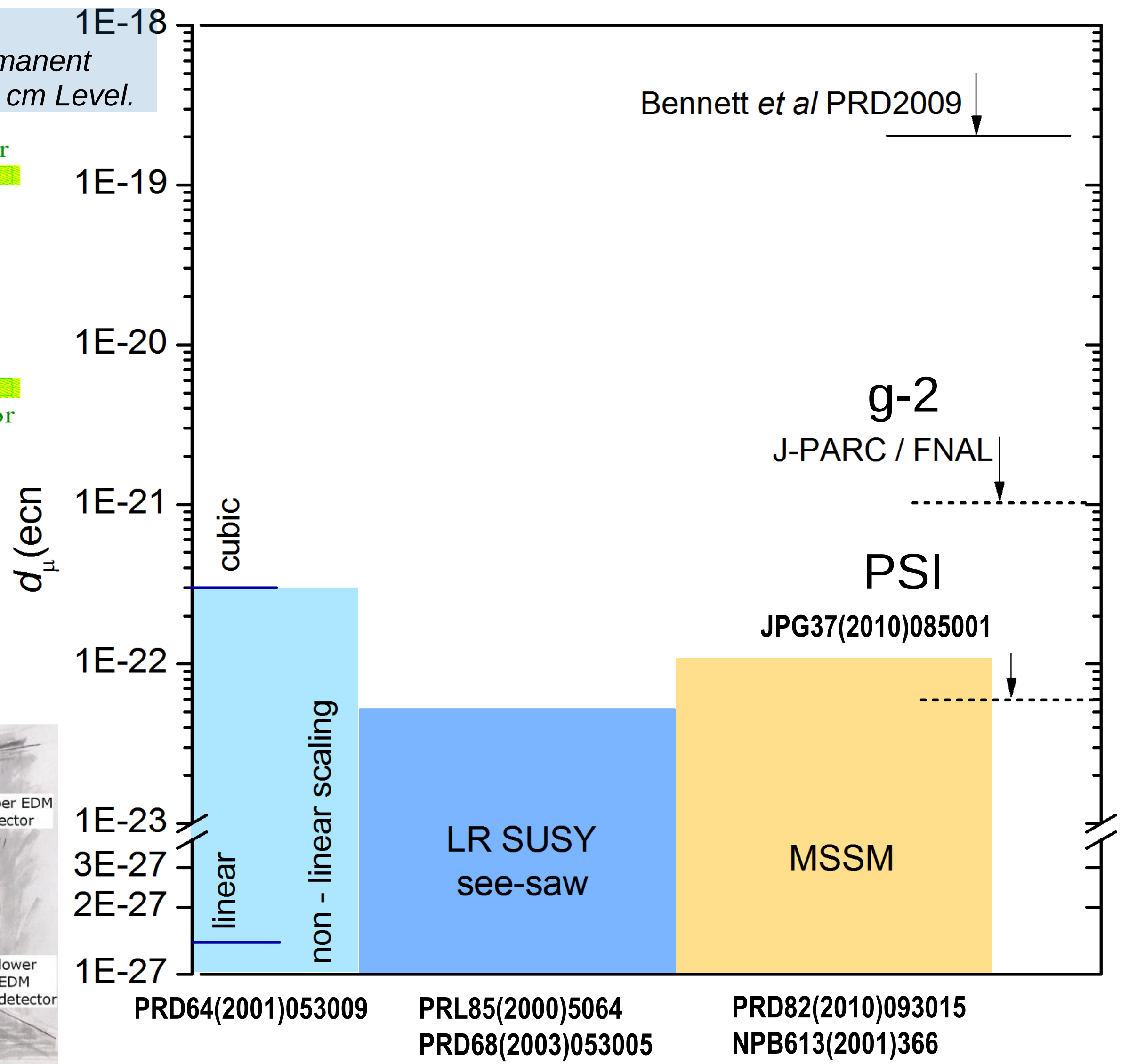


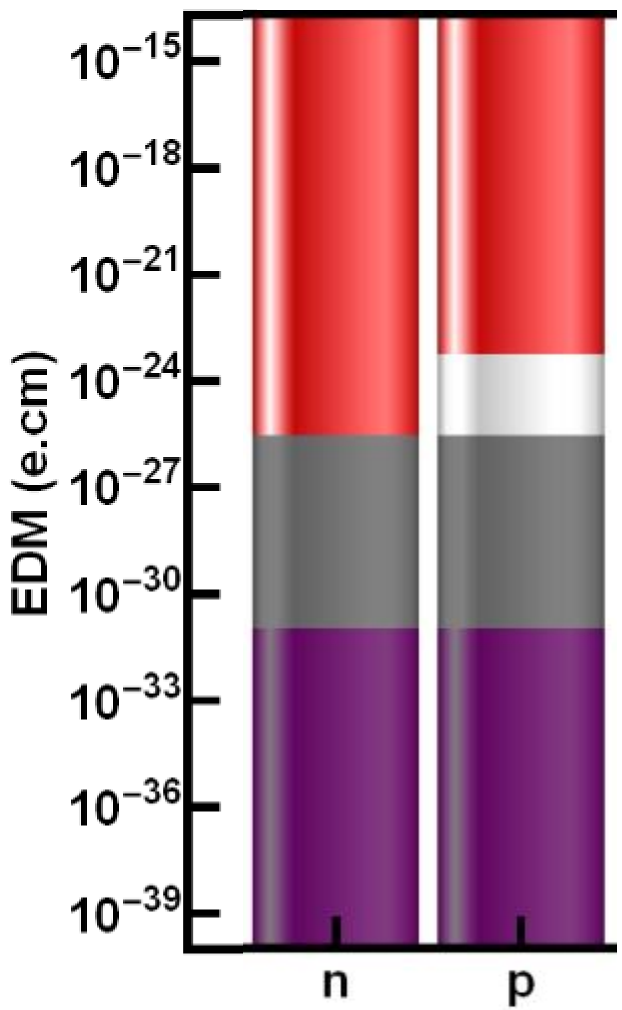
Figure by A. Streun



Courtesy P. Schmidt-Wellenburg

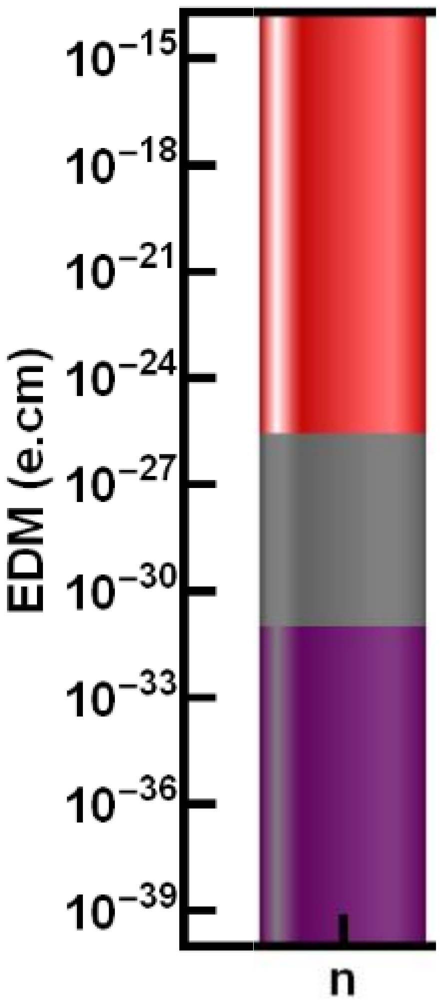
Model independent: M. Pruna arXiv:1710.08311

Neutron and Proton



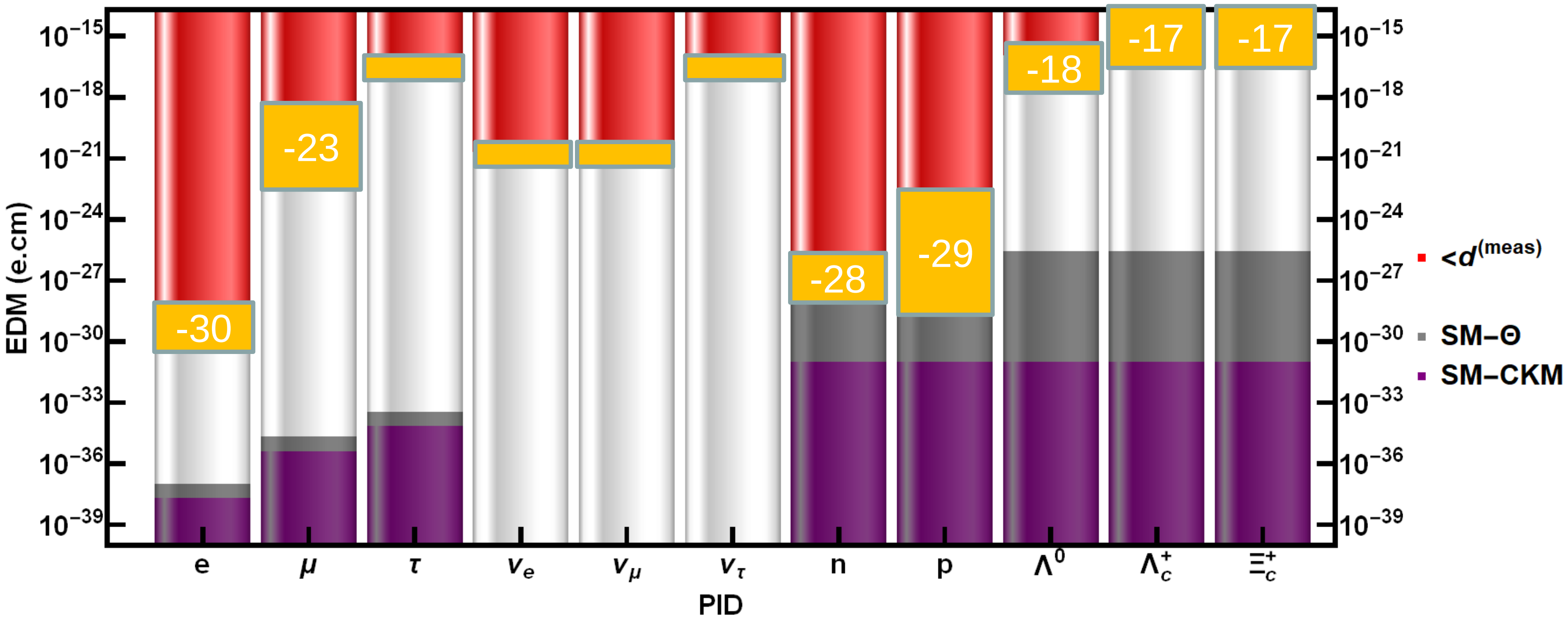
- Present best proton (and neutron) EDM limit derived from ^{199}Hg under the 'sole source assumption'.
- Present best direct nEDM limit 3.0E-26 ecm (**Pendlebury et al., PRD92(2015)092003**)
- neutron EDM constrains θ_{QCD} < 1E-10 under single source assumption (as does ^{199}Hg)
- finite neutron and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

Neutron



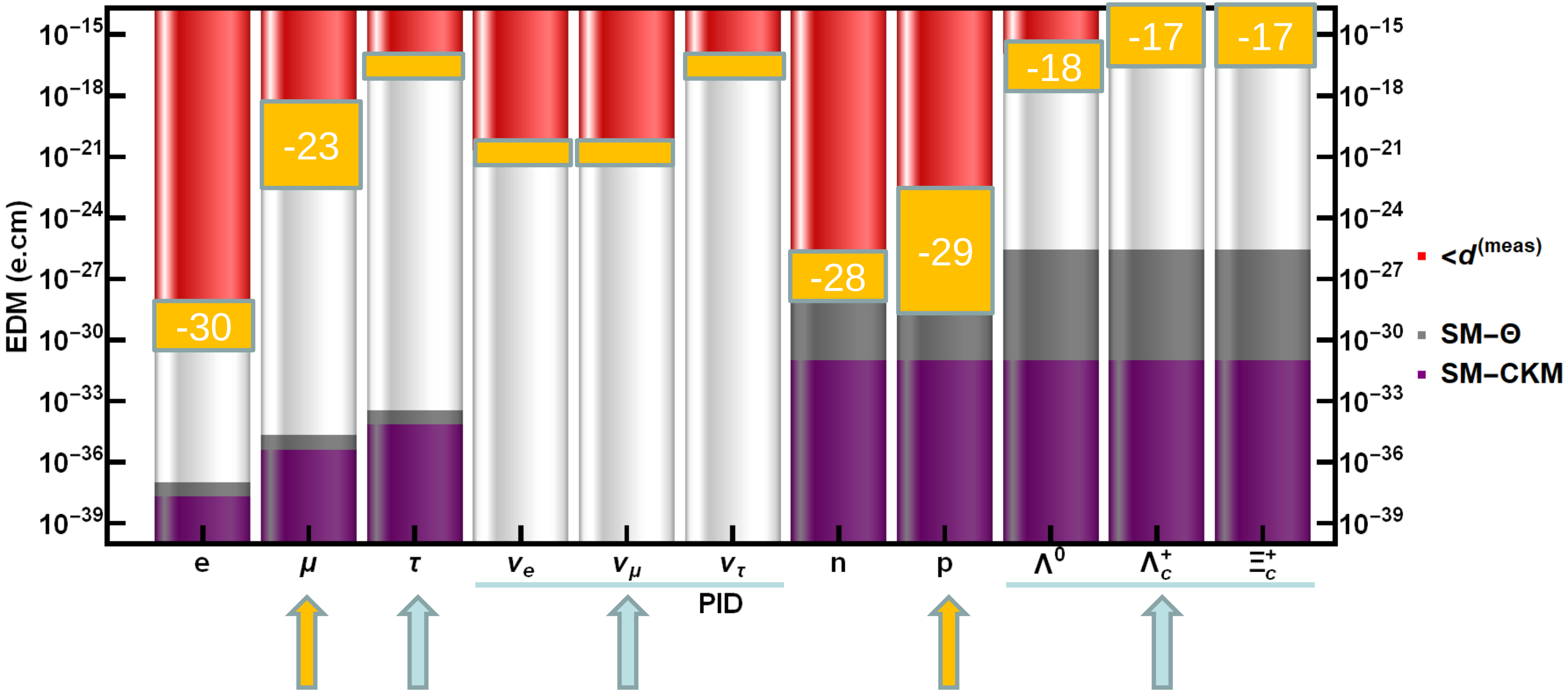
- Several nEDM efforts world-wide: presently leading effort at PSI
  (more at SNS, ILL, LANL, TRIUMF, PNPI, ESS)
- nEDM: the prototype of experimental EDM search for symmetry violations, since 1950
- nEDM poses the strong CP problem
- together with EDM limits of the e^- and ^{199}Hg giving some of the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

Next future 2020s perspectives



Based on reasonable extrapolation and author claims

Next future 2020s perspectives



All these could be accessed in the context of CERN PBC (storage ring and fixed target)