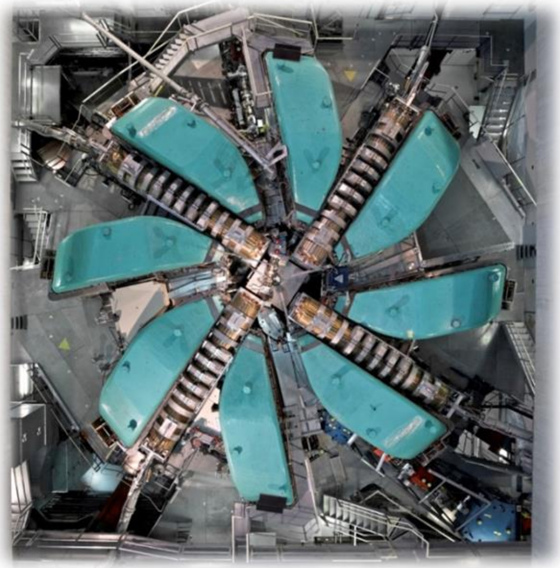
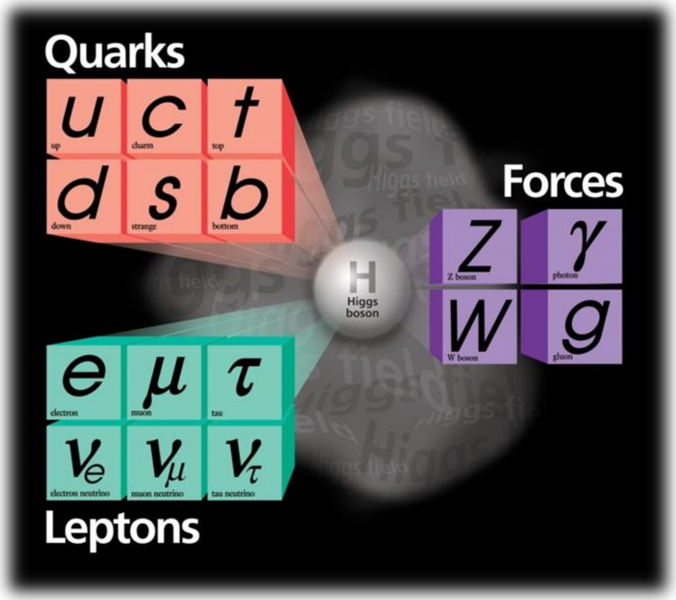
Fundamental Physics with neutrons and muons

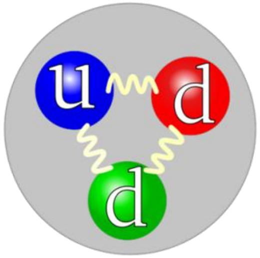
K.Kirch, ETH Zürich – PSI Villigen, Switzerland





Fundamental Physics

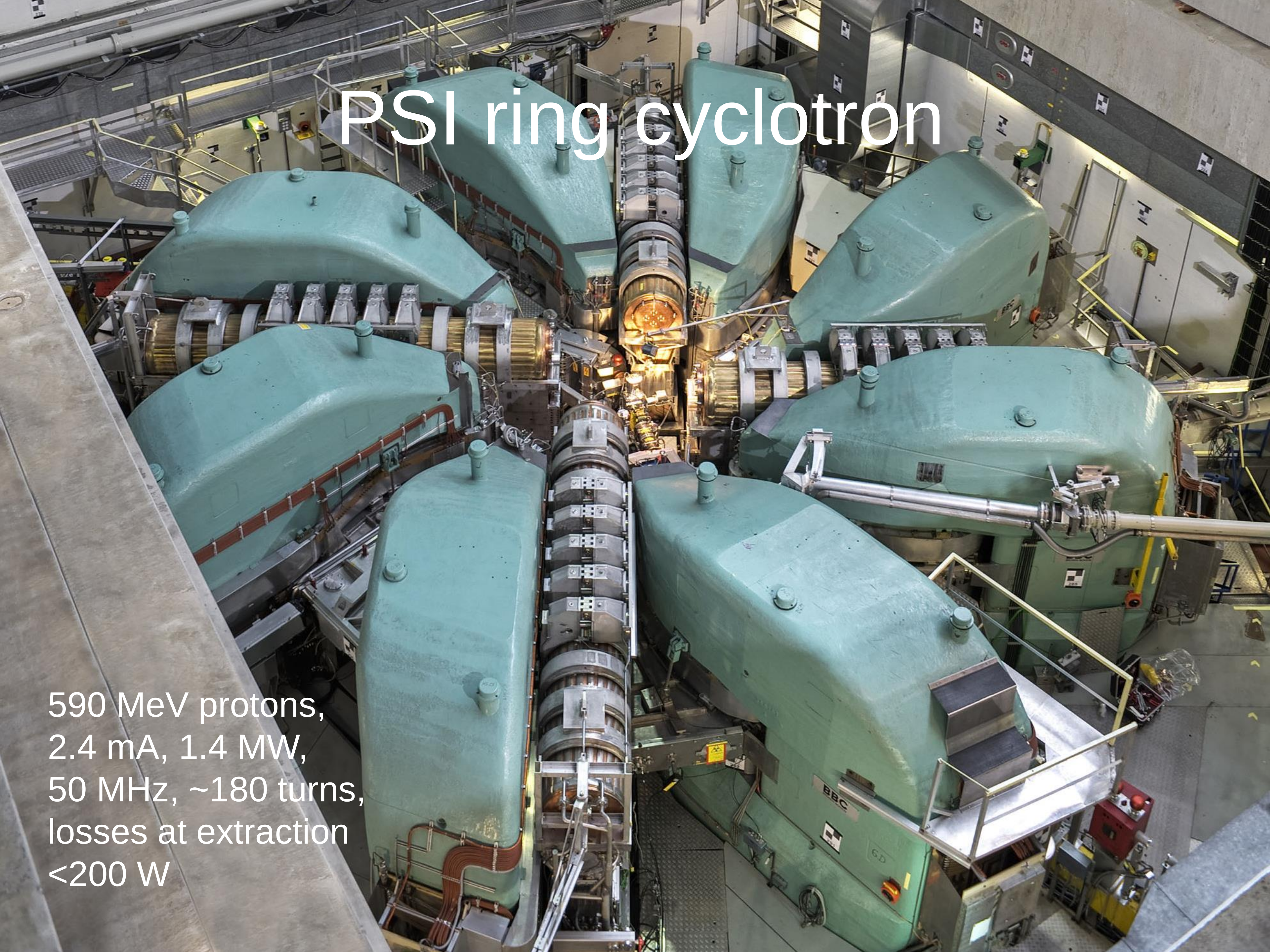
- The Standard Model of Particle Physics SM: a (the?) most successful theory to date
  - ~consistent with all laboratory results, some tensions**, theory & application to cosmology and astrophysics suggest beyond SM (**arguably all pointing to effects in flavor physics)
- Laboratory experiments
  - Precision measurements of SM input parameters
    - 19 param., masses, couplings, mixings, CP phases, Θ_{QCD}, Higgs vev
  - Searches for deviations & inconsistencies
    - Dark Matter, BAU, CPV, cLFV, B, L, Lorentz, Gravity, Dark Energy…



Neutrons and Muons

- Produce them as free particles
  - A proton beam traversing carbon targets produces pions which subsequently decay to muons
  - Protons impacting on a lead target/beam dump produce spallation neutrons
- Want them 'slow' to allow stopping in low mass material or storage in traps
  - Low momentum and slow muon beams: kinetic energies from 4 MeV to few keV, sometimes μ^+,M even sub-eV
  - Ultracold neutrons with kinetic energies below ~250 neV

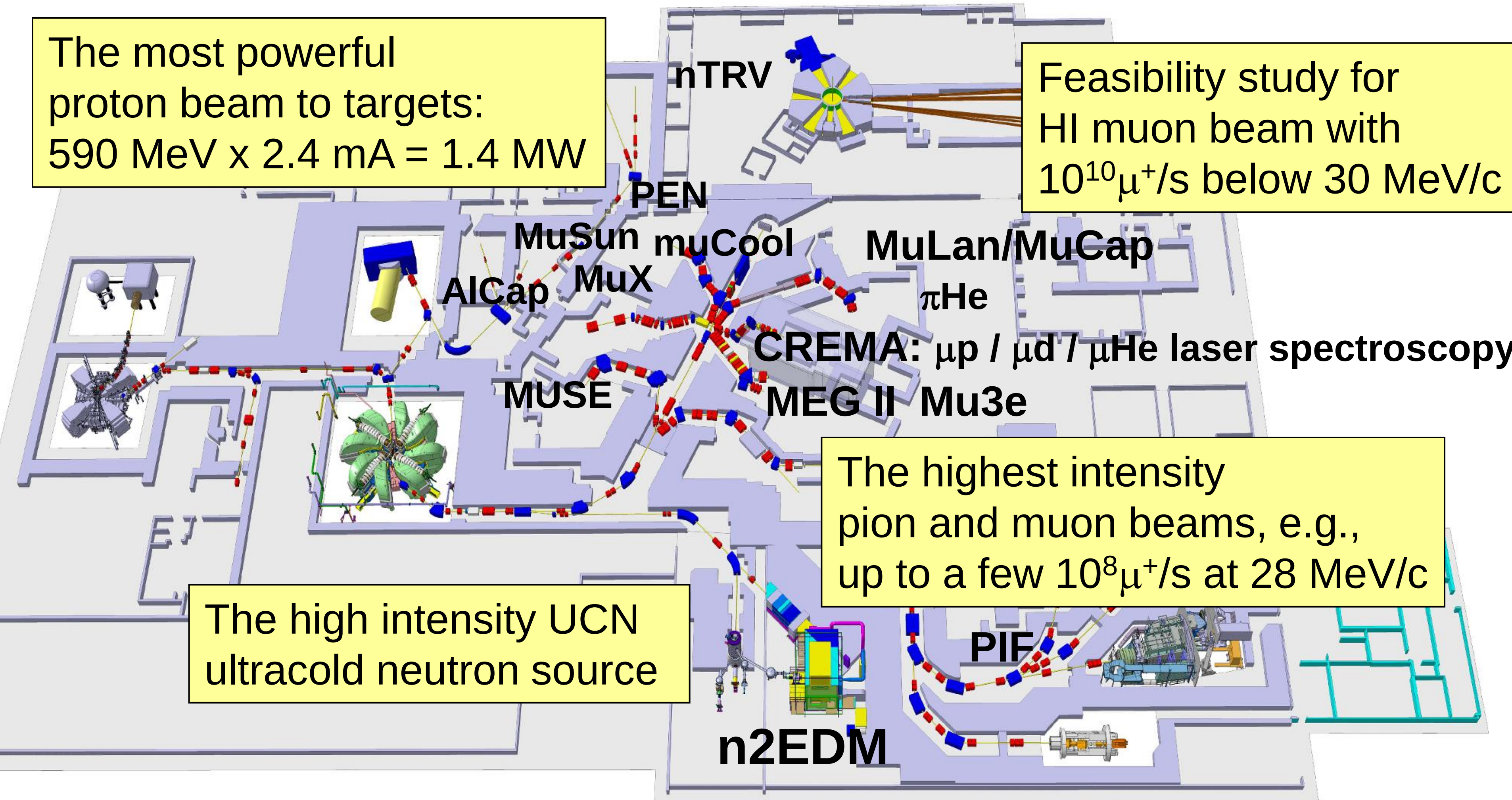
PSI ring cyclotron



590 MeV protons,
2.4 mA, 1.4 MW,
50 MHz, ~180 turns,
losses at extraction
<200 W

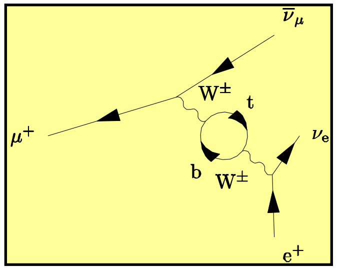
The intensity frontier at PSI: π, μ, UCN

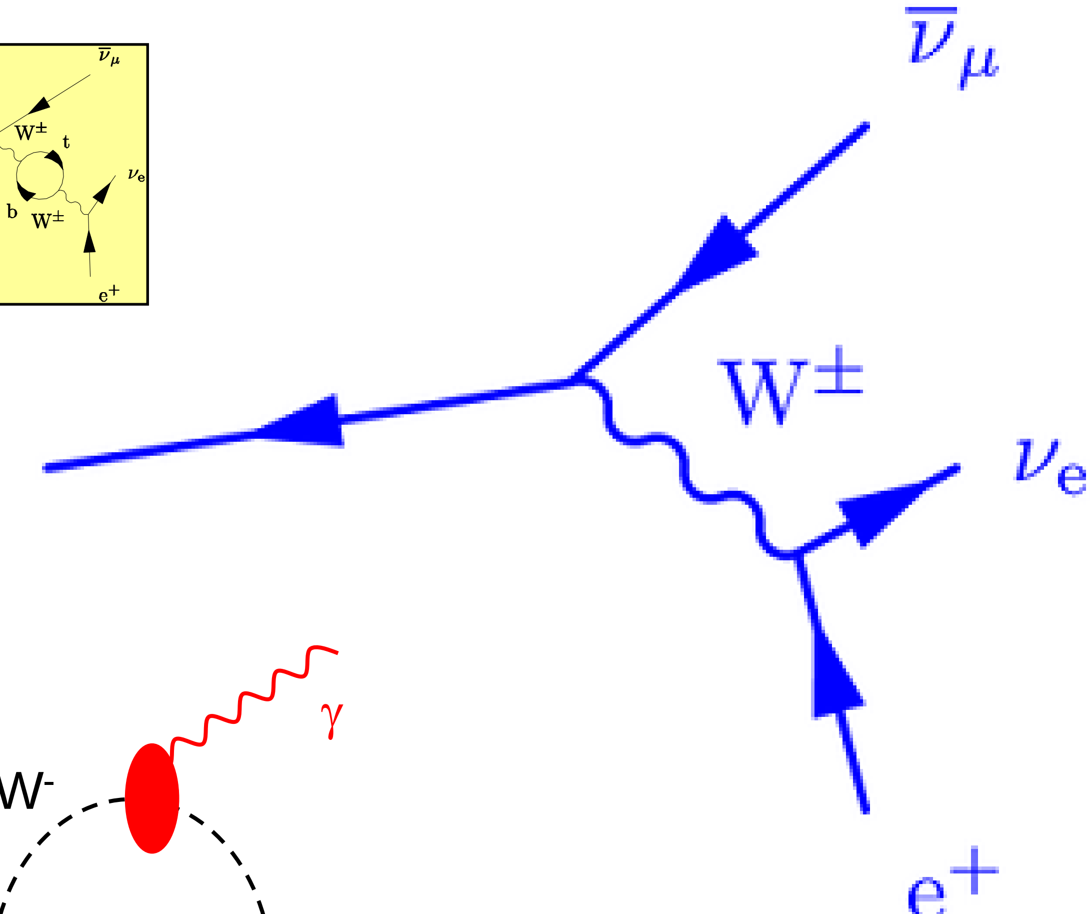
Precision experiments with **the lightest unstable particles** of their kind

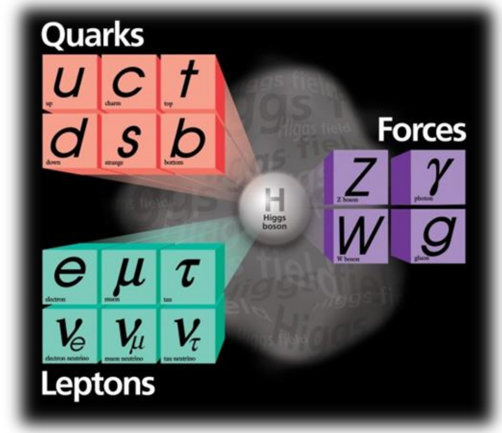


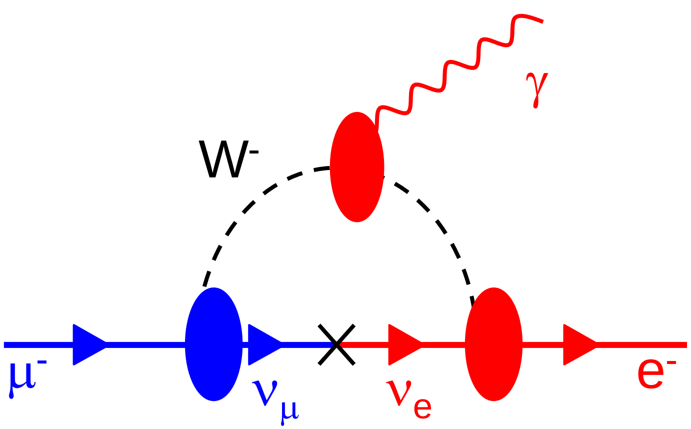
Swiss national laboratory with strong international collaborations

What muons do and don't





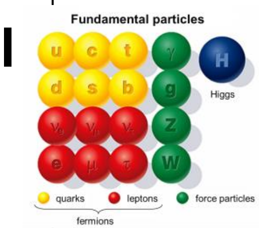




The weak coupling constant G_F

Fundamental electro-weak parameters of the Standard Model

α	G_F	m_Z
0.00037ppm	4.1 → 0.5 ppm	23ppm

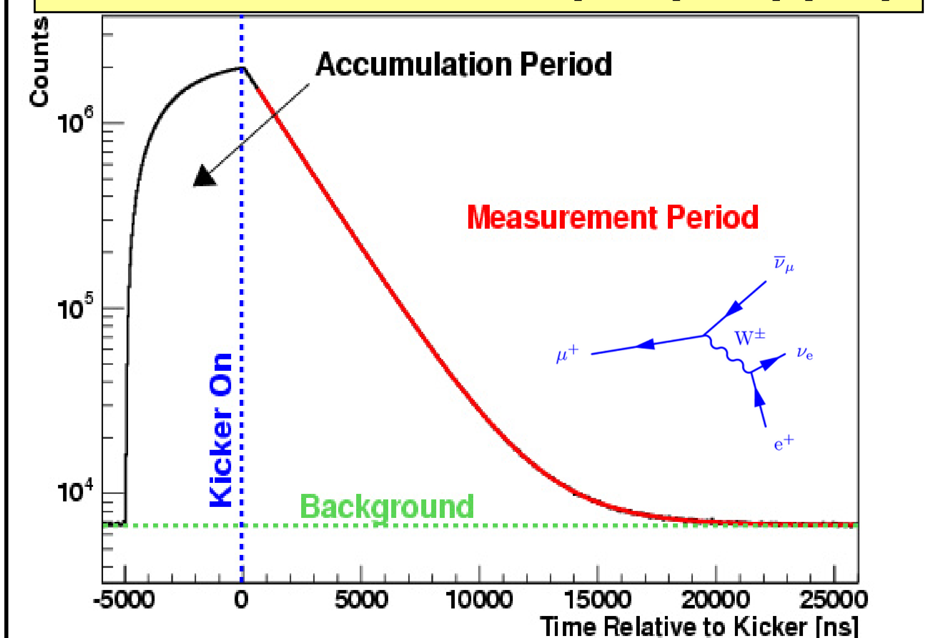


MuLan: The most precise measurement of any lifetime:

$$G_F(\text{MuLan}) = 1.1663787(6) \times 10^{-5}\ \text{GeV}^{-2}\ (0.5\ \text{ppm})$$

V. Tishchenko et al., PRD 87(2013)052003

τ = 2 196 980.3 ± 2.2 ps (1.0 ppm)

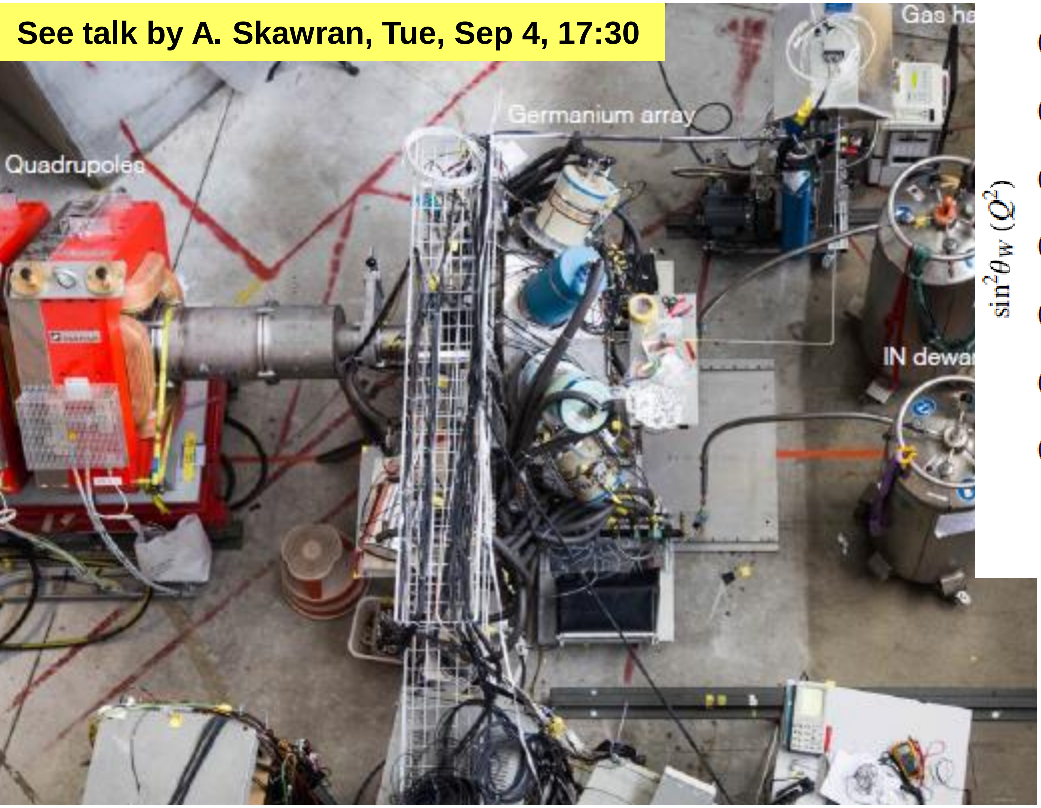


$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F(\rho) \left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right)$$

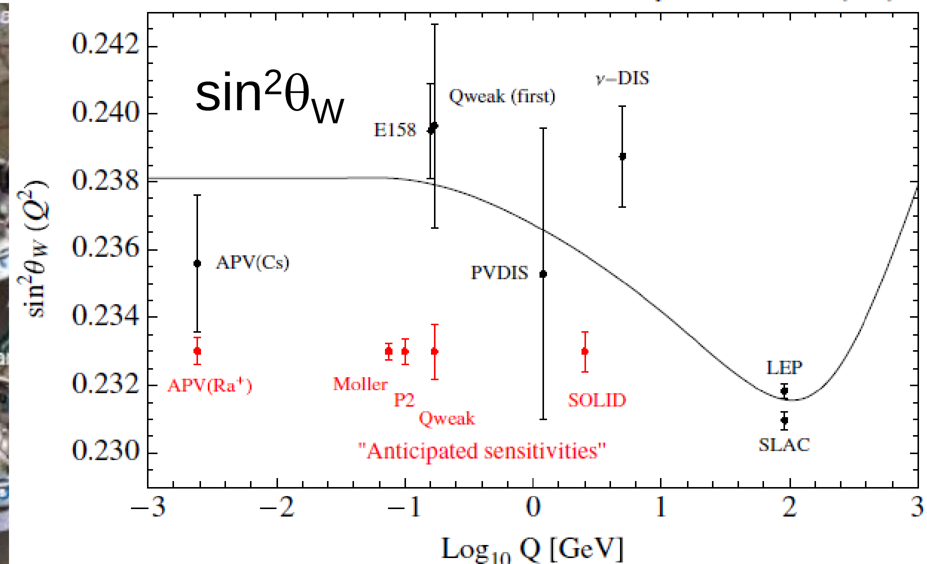
MuX: charge radius of ^{226}Ra

PSI R-16-01, see A.Knecht http://indico.psi.ch/getFile.py/access?contribId=10&sessionId=2&resId=0&materialId=slides&confId=5459

See talk by A. Skawran, Tue, Sep 4, 17:30

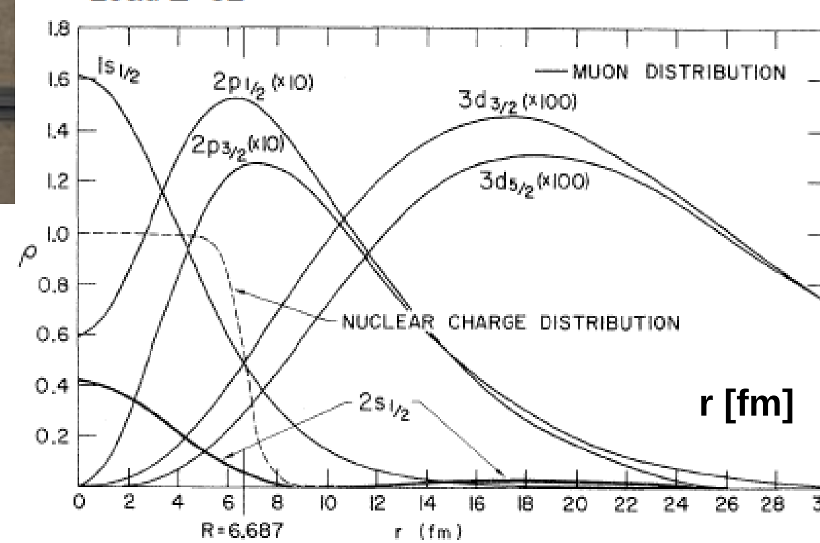


Davoudiasl, Lee, Marciano, Phys. Rev. D 92, 055005 (2015)



Lead Z=82

Kessler et al., PRC 11, 1719 (1975)



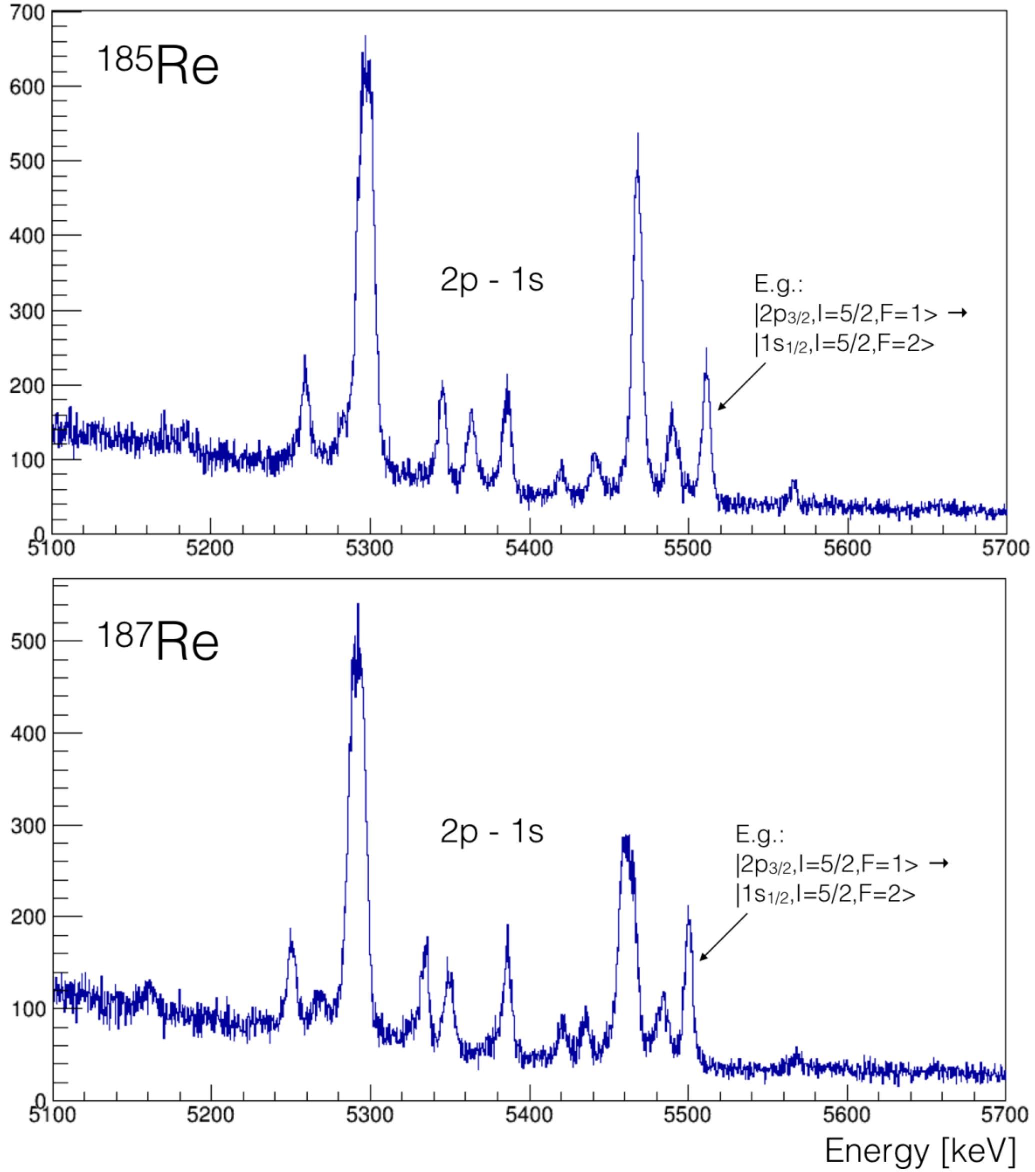
A measurement of the rms charge radius of ^{226}Ra to <0.2% using 5μg target mass.

μ^- stop in 100bar H2, transfer to D admixture and finally to the heavy nucleus, then cascade and emit Xrays up to 6 MeV.

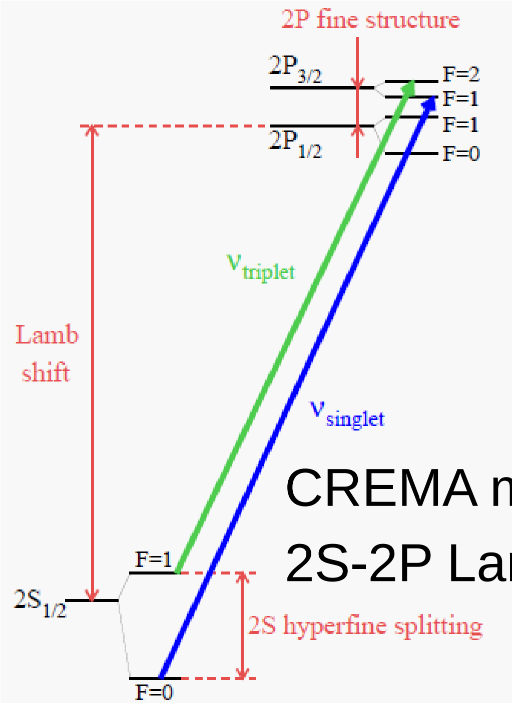
A campaign with Miniball at PSI?

- Unprecedented efficiency in medium and heavy muonic atom spectroscopy
- Coincidence spectroscopy in the muonic cascade
- Access to charge radii, hyperfine structure, quadrupole moments, …
- Access to nuclear matrix elements through muon capture
- Can use isotopes down to μg quantities

Interested? Contact us.

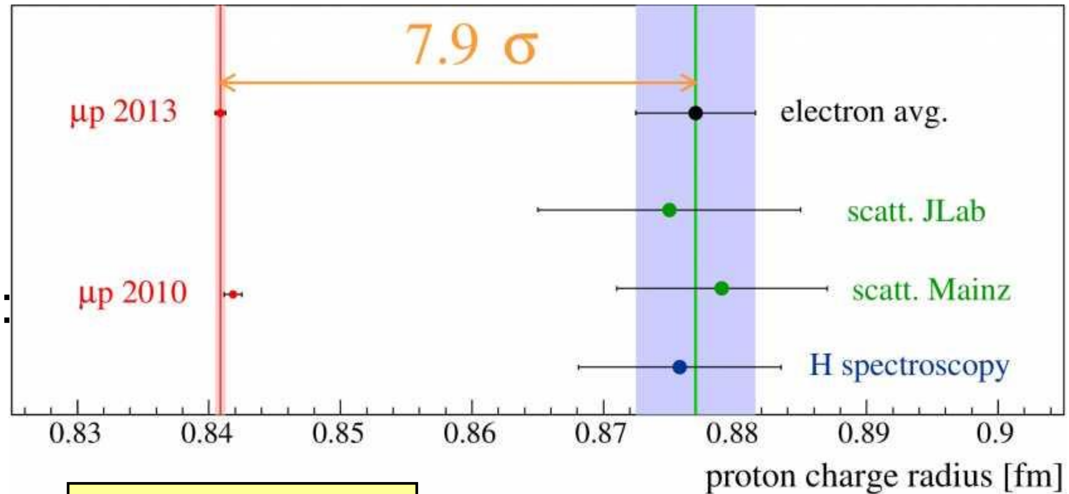


Proton charge radius puzzle

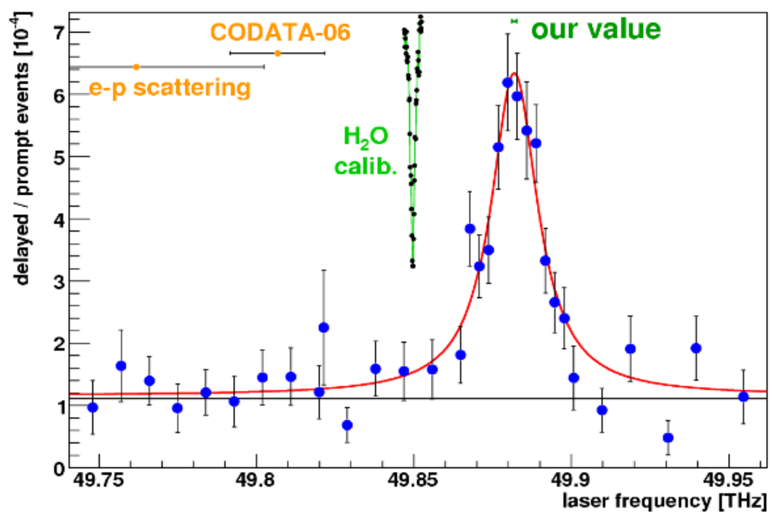


CREMA measurement:

2S-2P Lambshit of μp



r_p=0.84087(39) fm

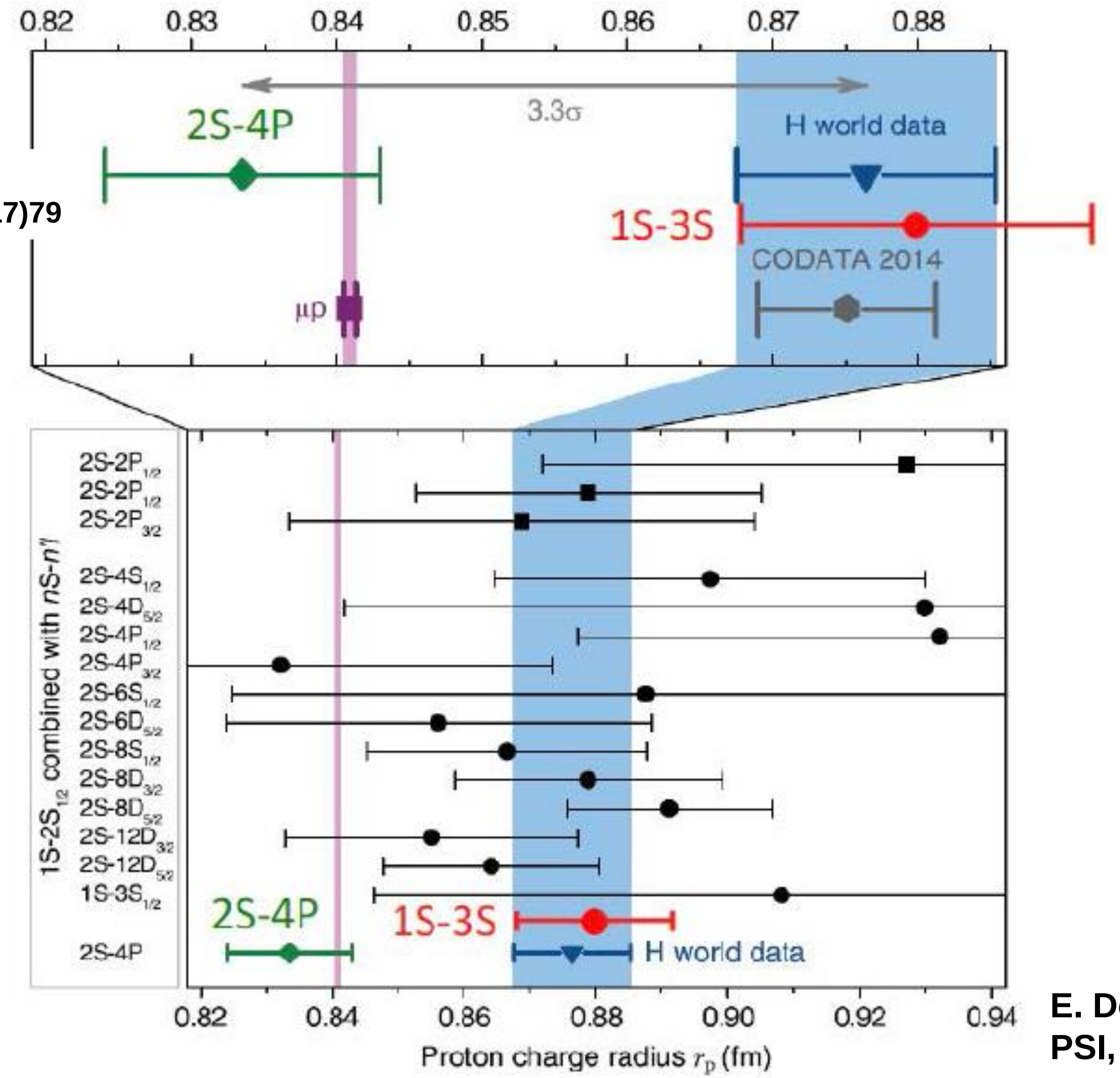


https://www.psi.ch/muonic-atoms/

R. Pohl et al., Nature 466 (2010) 213
A. Antognini et al., Science 339 (2013) 417
R. Pohl et al., Science 353 (2016) 669

Proton charge radius – still puzzling

A.Beyer et al., Science 358(2017)79



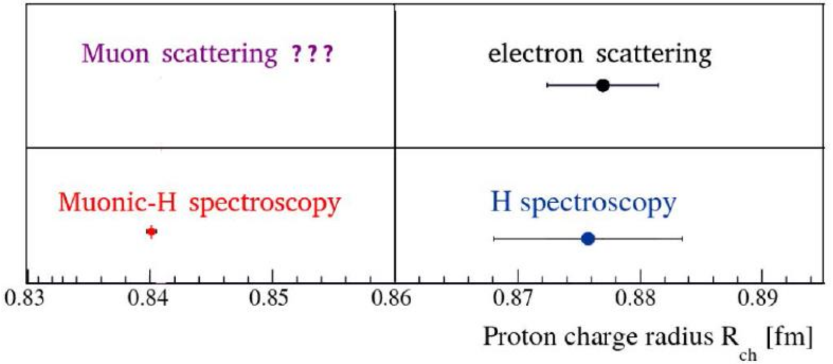
H.Fleurbaey et al., PRL120(2018)183001

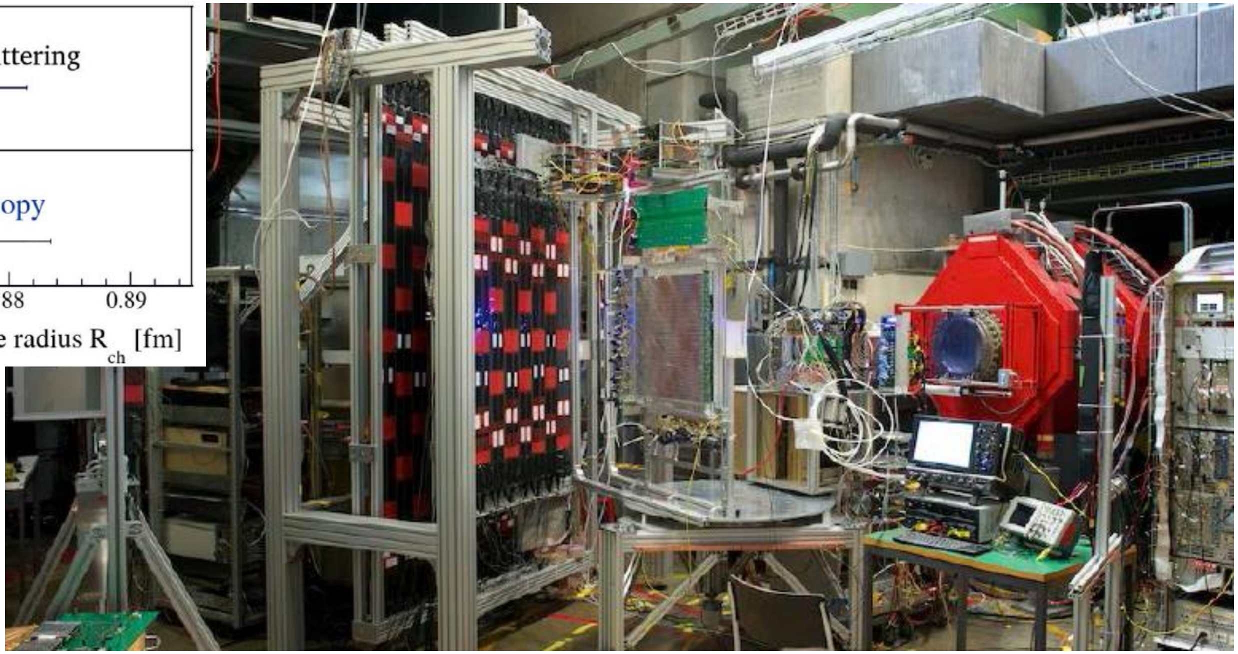
E. Downie, MUSE, PSI, 02/2018

MUSE

PSI R-12-01, see E.Downie http://indico.psi.ch/getFile.py/access?contribId=6&sessionId=2&resId=0&materialId=slides&confId=5459

- Scattering of μ^+, e^+, μ^-, e^- at low Q^2 on hydrogen to compare cross sections and charge radii, determine two-photon contributions and test μ-e universality
  - 115, 153, 210 MeV/c beam momenta, 20º-100º scattering angles, tracking incoming and outgoing particles
  - Production data taking planned for 2019/20

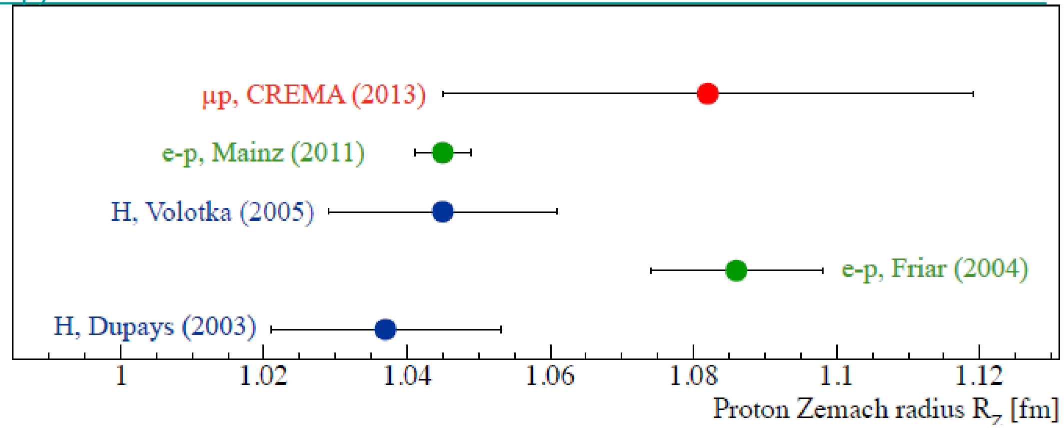




R. Gilman et al., arXiv:1709.09753

CREMA - HyperMu

PSI R-16-02, see A.Antognini http://indico.psi.ch/getFile.py/access?contribId=12&sessionId=0&resId=0&materialId=slides&confId=4353

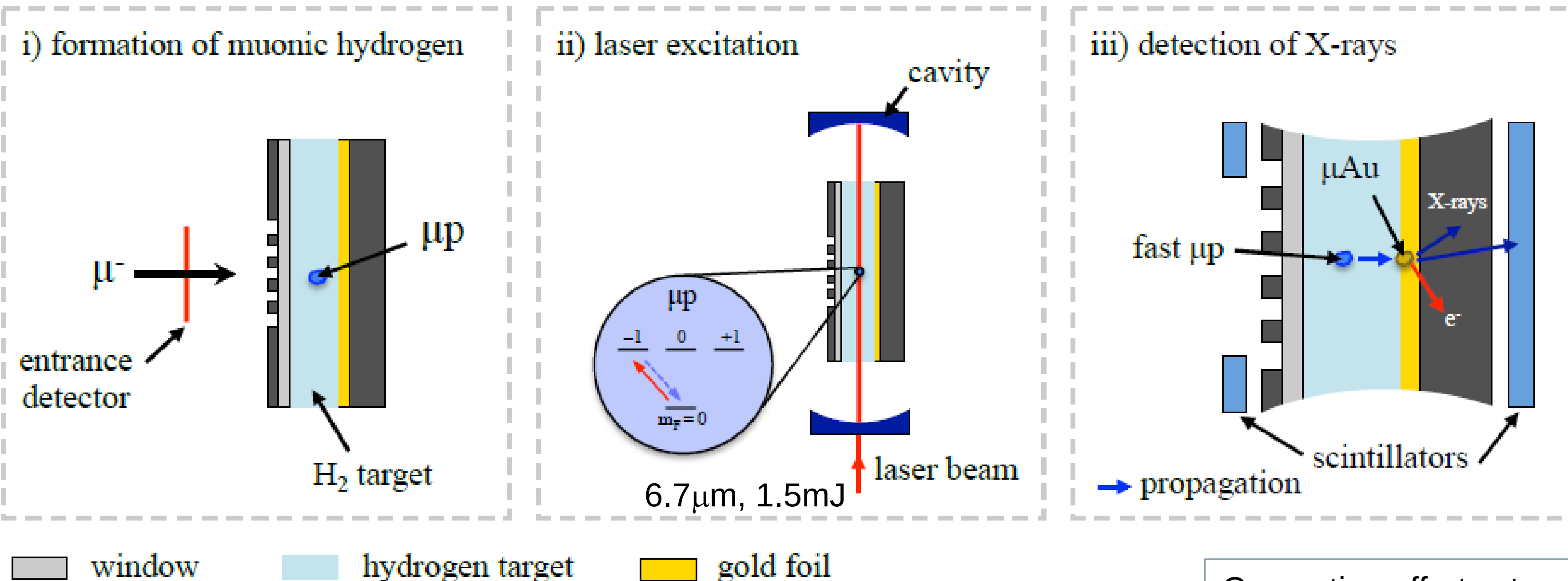


μp 1S HFS to ppm

→ Zemach radius to 0.25% …

$$r_Z = \int |r| d^3r \int \rho_E(r - r') \rho_M(r') d^3r'.$$

→ 'magnetic radius' of the proton

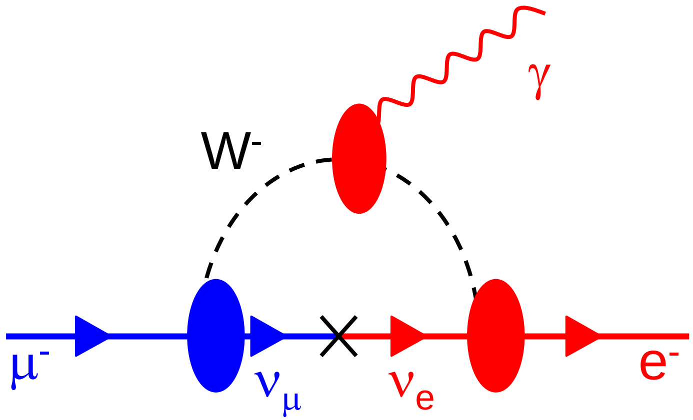


A.Antognini et al., Proposal to PSI, 2016
S.Schmidt et al., arXiv:1808.07240

Competing efforts at
J-PARC and RIKEN-RAL

Charged Lepton Flavor Violation:
tiny in the Standard Model

- cLFV suppressed by $(\delta m_\nu/m_W)^4$
  → SM not observable
  → accidentally small !?
- Plenty of room for new physics
  - Sensitive to multi-TeV mass scales
  - … and to light particles
- New experimental efforts underway
  - MEG II, Mu3e
  - Mu2e, COMET, DeeMe



Expect from SM:

$BR(\mu\text{-}e\gamma) < 10^{-50}$

Experimentally so far:

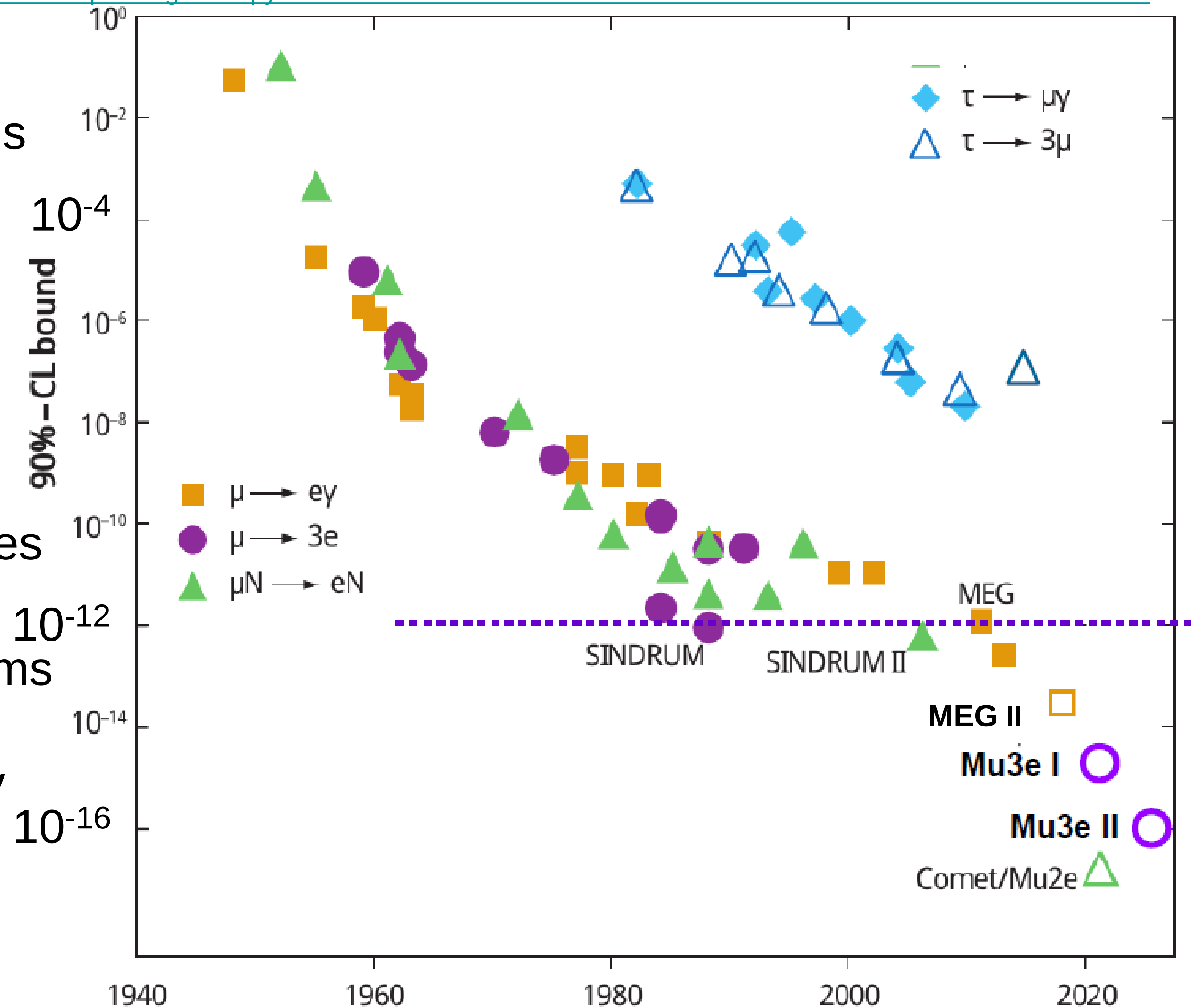
$< 4.2 \times 10^{-13}$

A.M. Baldini et al., EPJC76(2016)434

Search for cLFV

Mu3e R-12-03, see A.Schöning http://indico.psi.ch/getFile.py/access?contribId=5&sessionId=2&resId=0&materialId=slides&confId=5459
MEG II, R-99-05, see T.Mori http://indico.psi.ch/getFile.py/access?contribId=7&sessionId=2&resId=0&materialId=slides&confId=5459

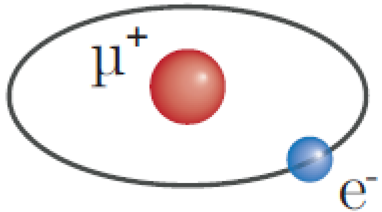
- Present best bounds from experiments at PSI
- New efforts at PSI, FNAL, JPARC aiming at 10-10'000 x improved sensitivities
- Need highest intensity muon beams and unprecedented detector technology

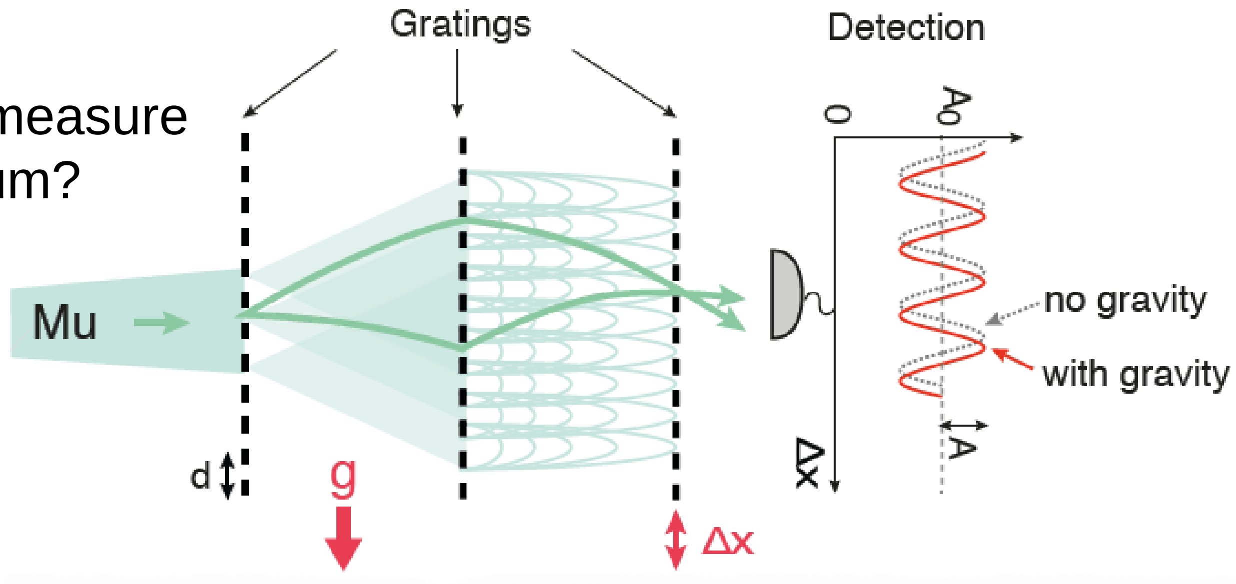


More muon things ongoing

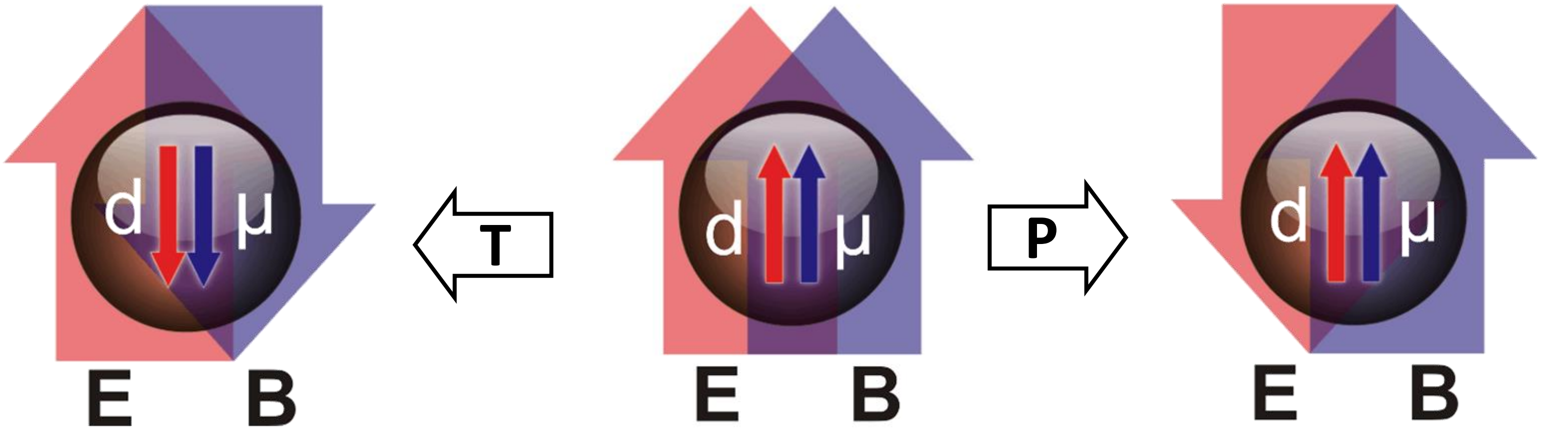
- HiMB: the high intensity muon beam line project at PSI, see A.Knecht https://indico.uu.se/event/324/session/23/contribution/126/material/slides/0.pdf
- muCool: High brilliance slow positive muon beam, see A.Eggenberger R-14-01 http://indico.psi.ch/getFile.py/access?contribId=13&sessionId=3&resId=0&materialId=slides&confId=4353
- Cold muonium production, see A.Soter http://indico.psi.ch/getFile.py/access?contribId=9&sessionId=2&resId=0&materialId=slides&confId=5459

Will it be possible to measure the free fall of muonium?





EDM and symmetries

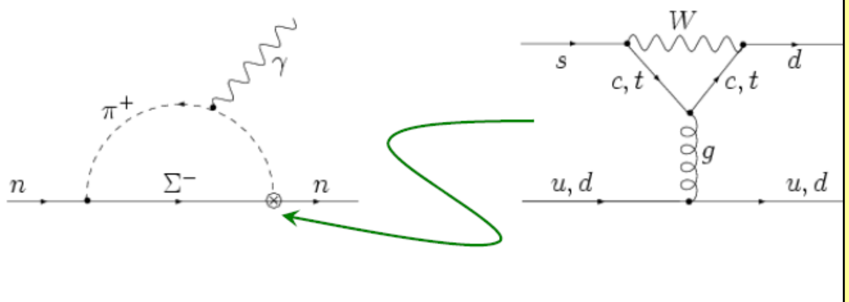


A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP

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

Electric Dipole Moments tiny in SM

- Neutron, Proton, ..



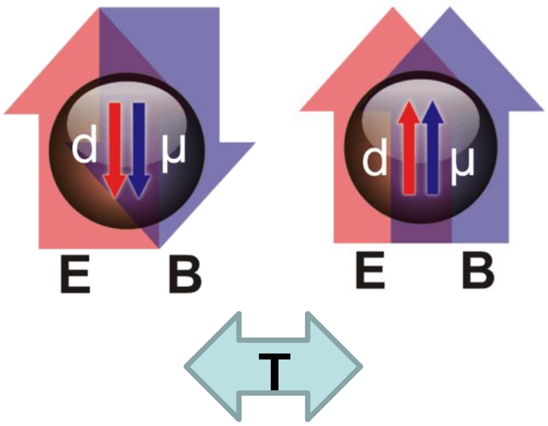
$$d_n \sim 10^{-32} - 10^{-34} e\ cm$$

[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

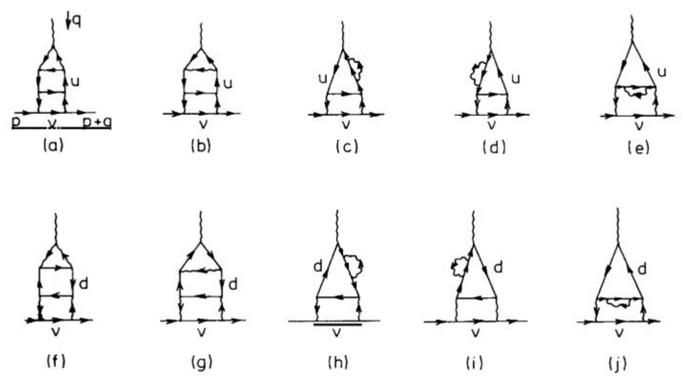


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

[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

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

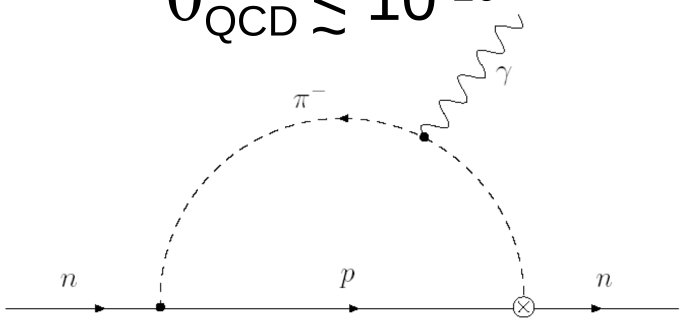
muon g-2 storage ring
Bennett et al., PRD80(2009)052008

The strong CP problem

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

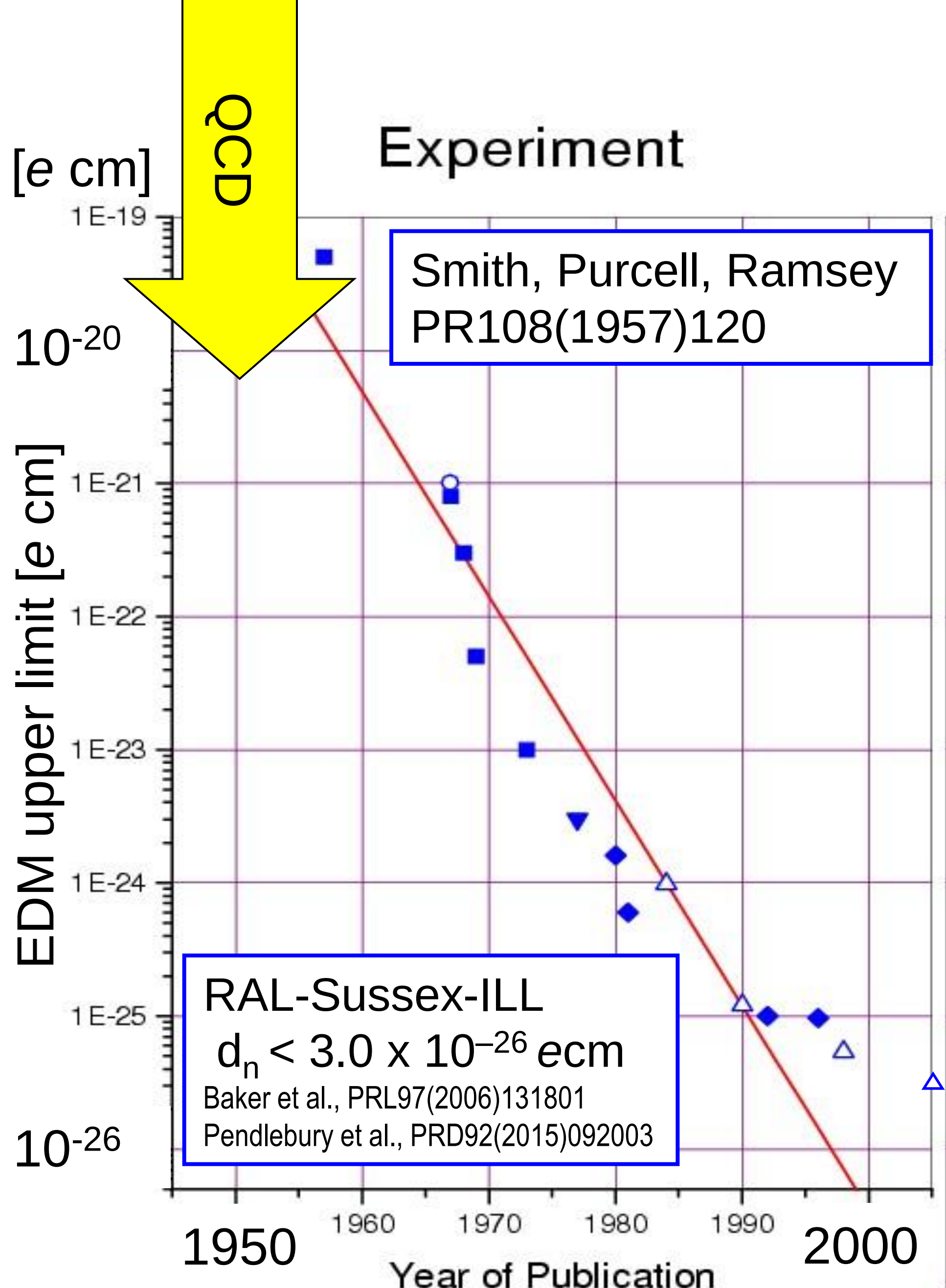
$$d_n \approx 10^{-16}\ e\ \text{cm} \cdot \theta_{QCD}$$

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



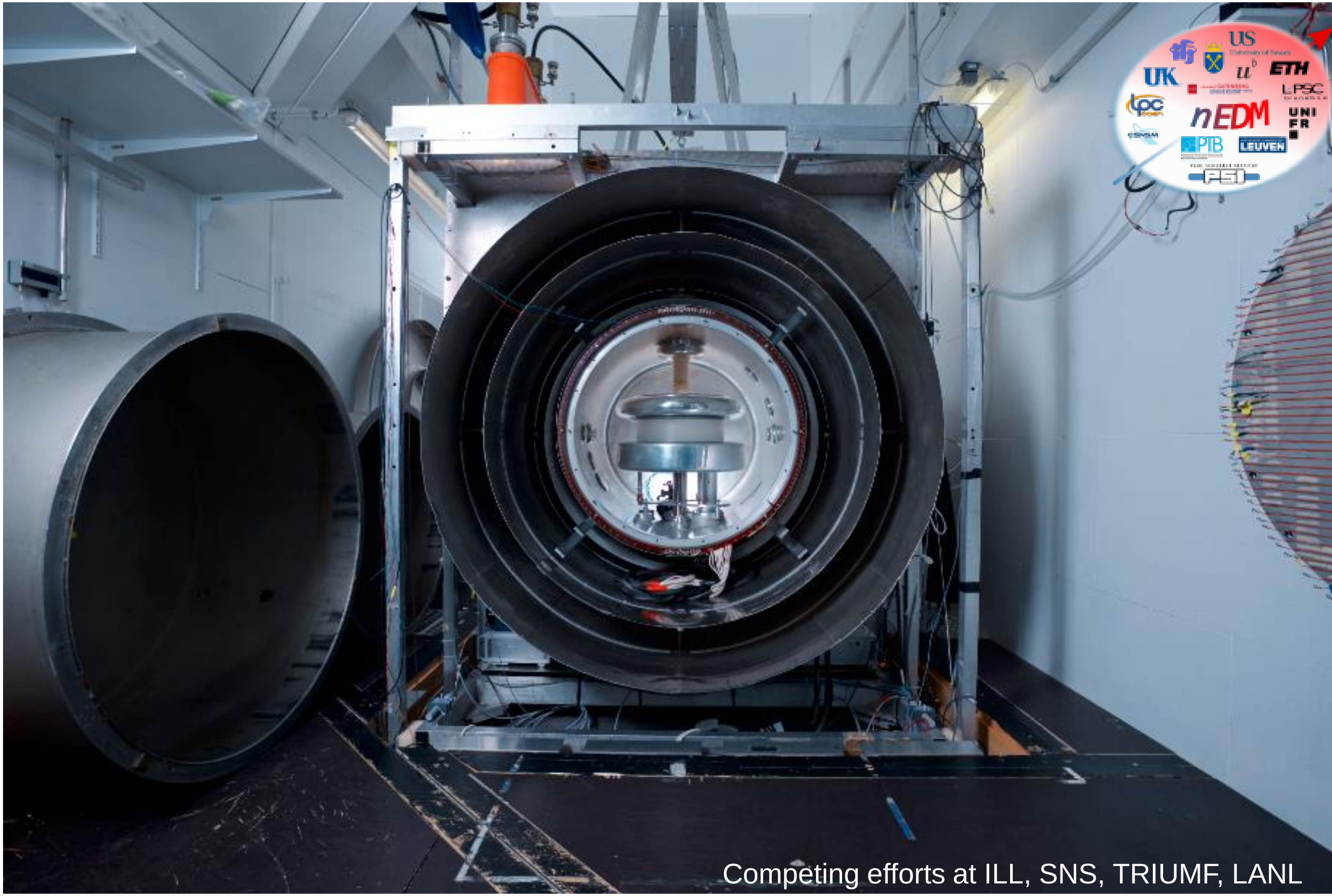
Why is θ_{QCD} so small ?

→ accidentally small !?



nEDM at PSI

PSI R-05-03, see G.Bison http://indico.psi.ch/getFile.py/access?contribId=8&sessionId=2&resId=0&materialId=slides&confId=5459

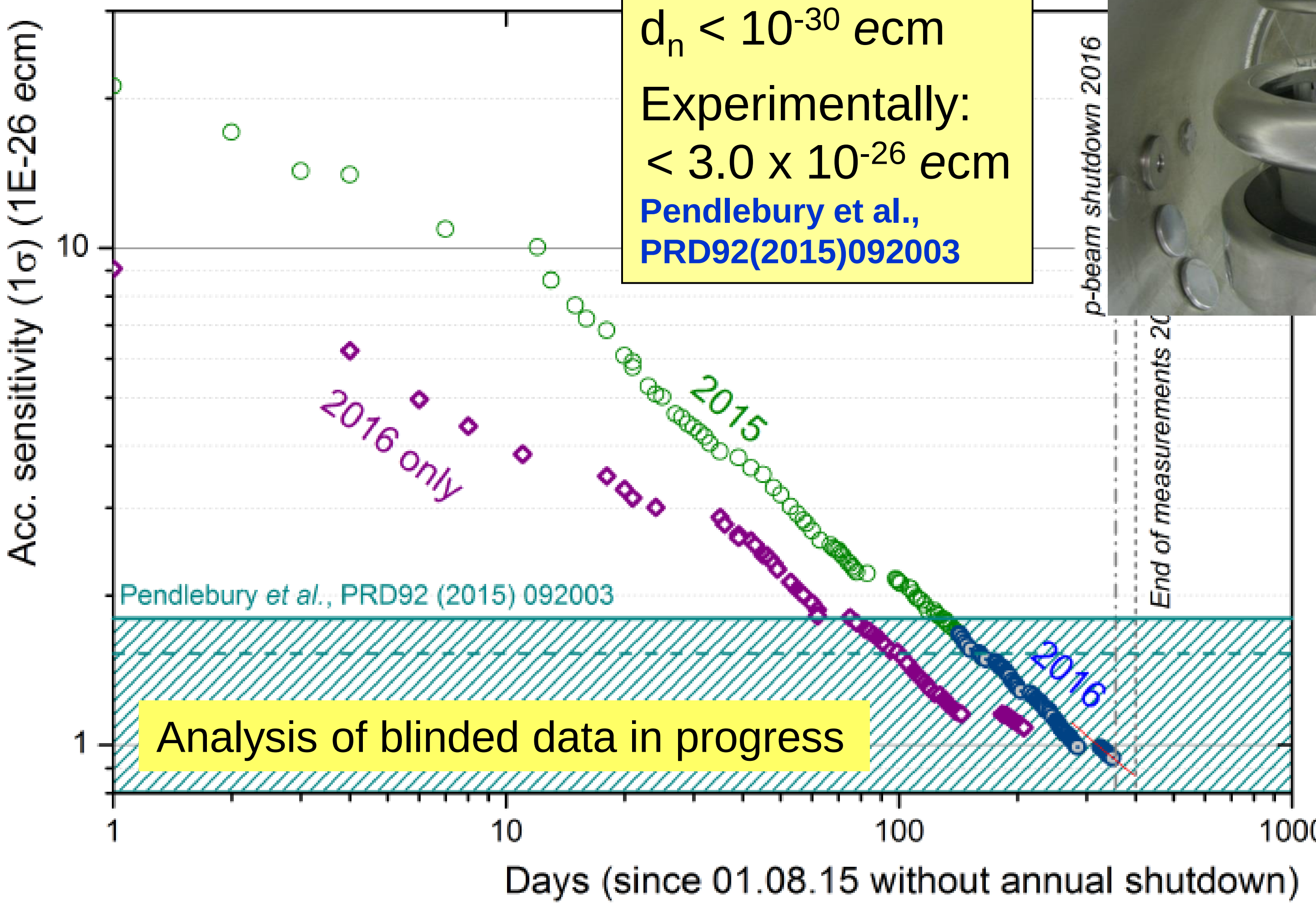


Searching for the neutron EDM

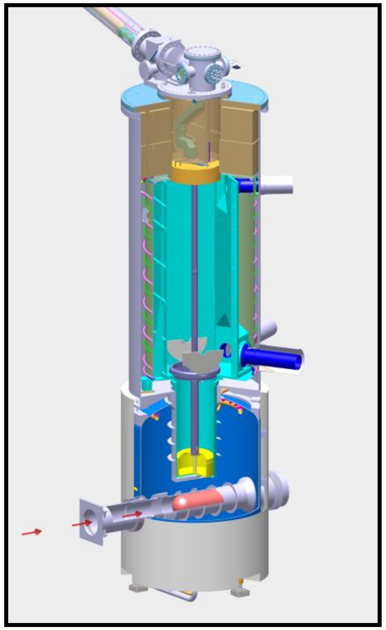
Expect from SM:
$d_n < 10^{-30}$ *e*cm

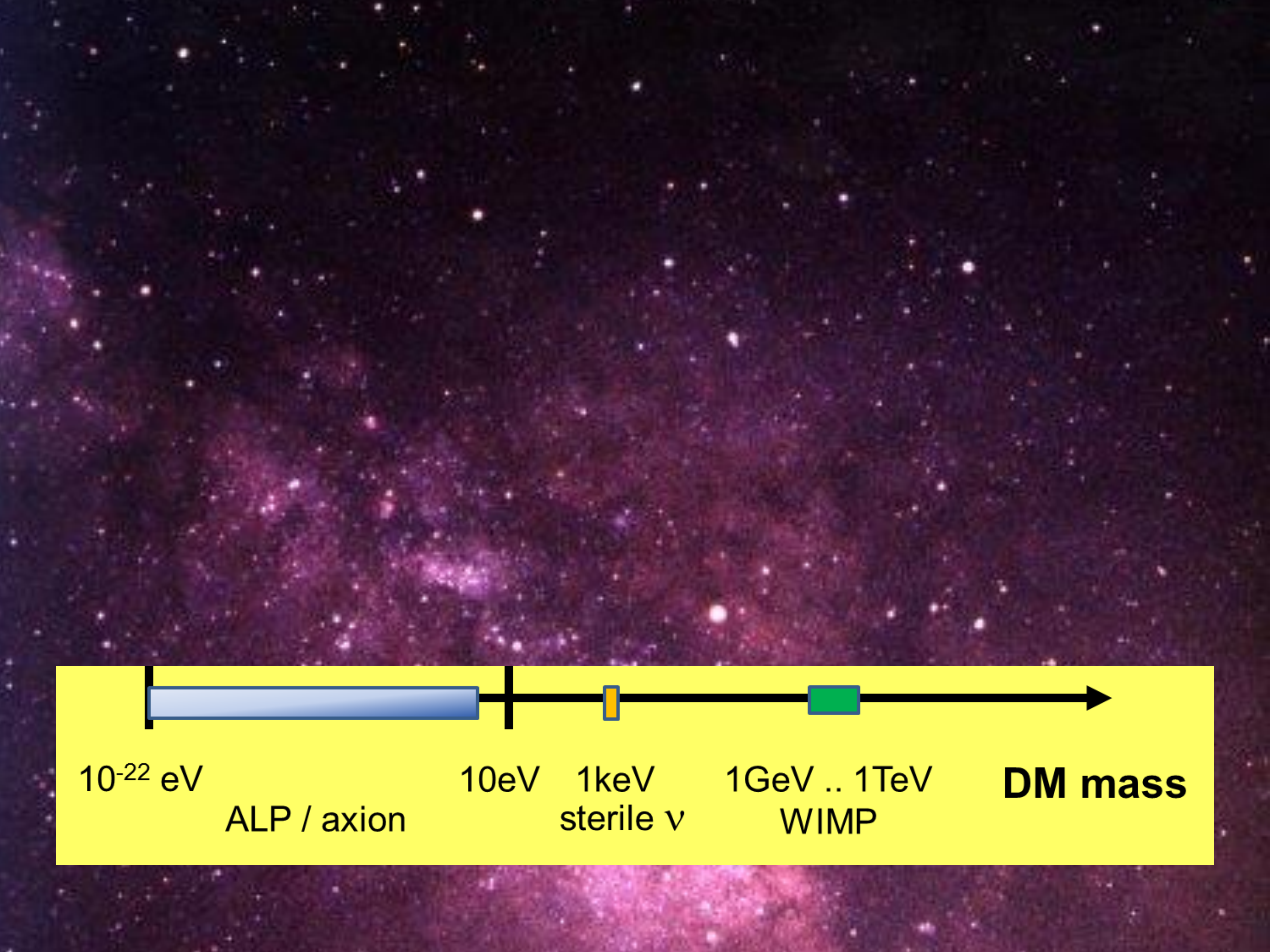
Experimentally:
$< 3.0 \times 10^{-26}$ *e*cm

Pendlebury et al., PRD92(2015)092003



Analysis of blinded data in progress

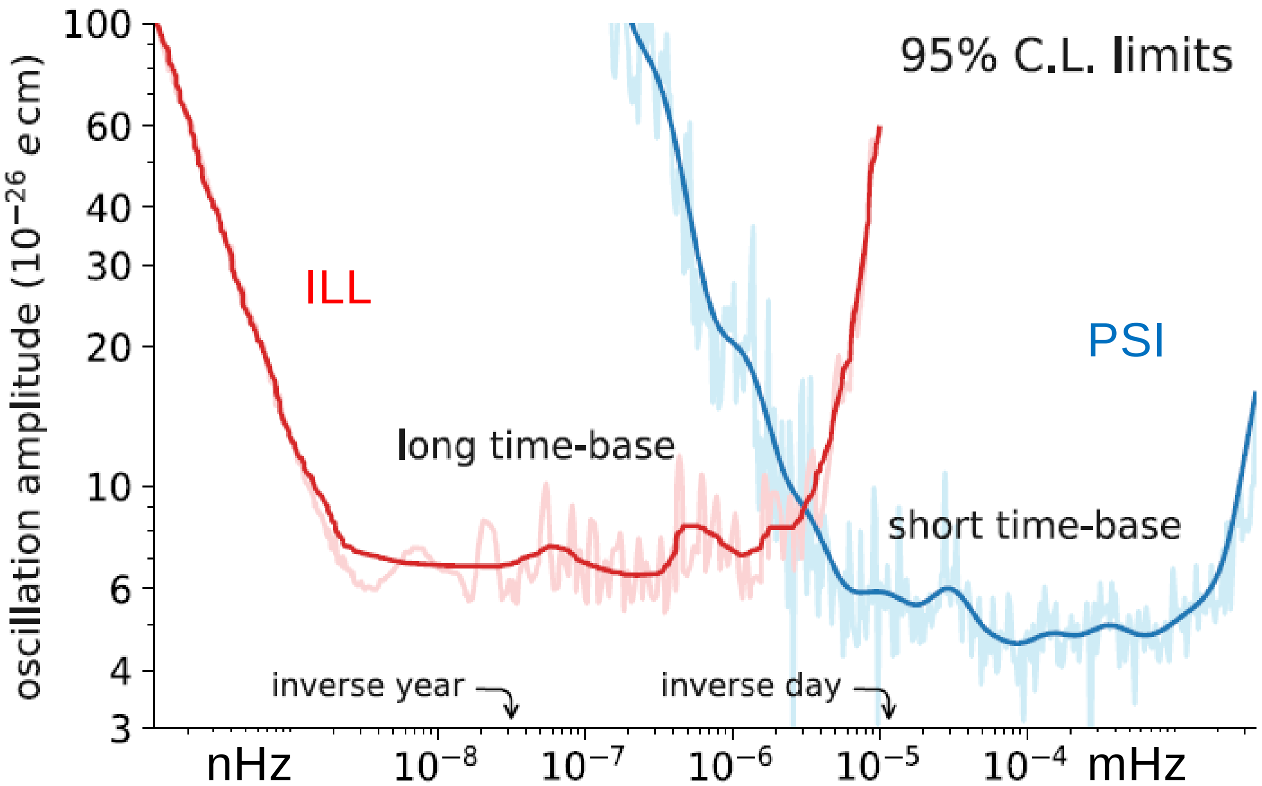




10-22 eV
10eV
1keV
1GeV .. 1TeV
DM mass
ALP / axion
sterile ν
WIMP

Search for nEDM oscillations with time

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

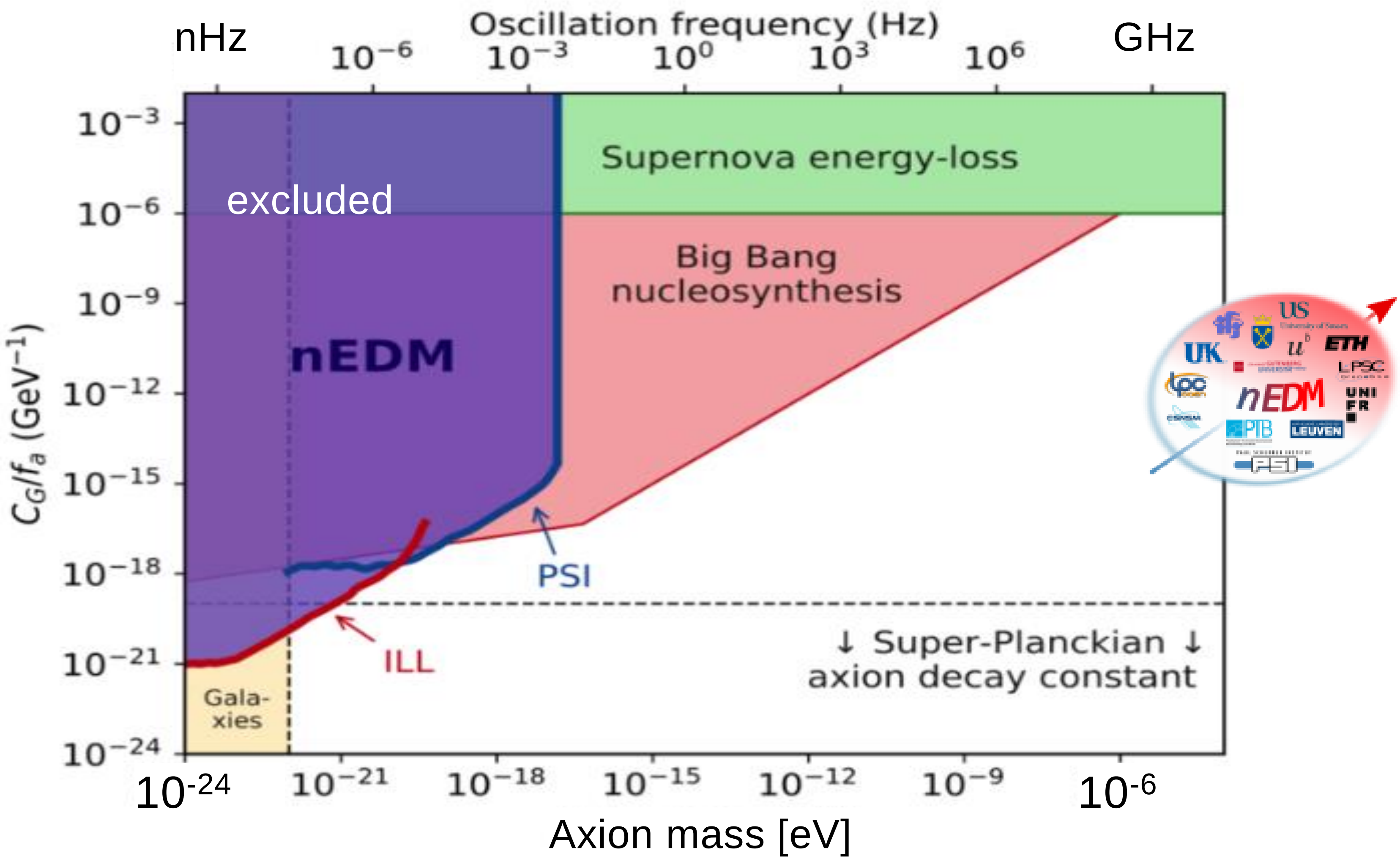


PhD theses
N. Ayres, Sussex
M. Rawlik, ETHZ

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



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

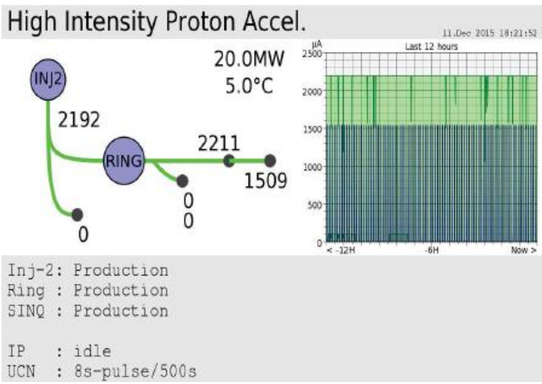
The end: Take home

- High intensity, precision physics can test our understanding of fundamental physics at all mass scales
- Slow muons and UCN are excellent probes
  - to best measure some SM parameters
  - to search for cracks in the standard picture
- Next generation experiments again need higher intensites: R&D for more intense and much colder beams under way

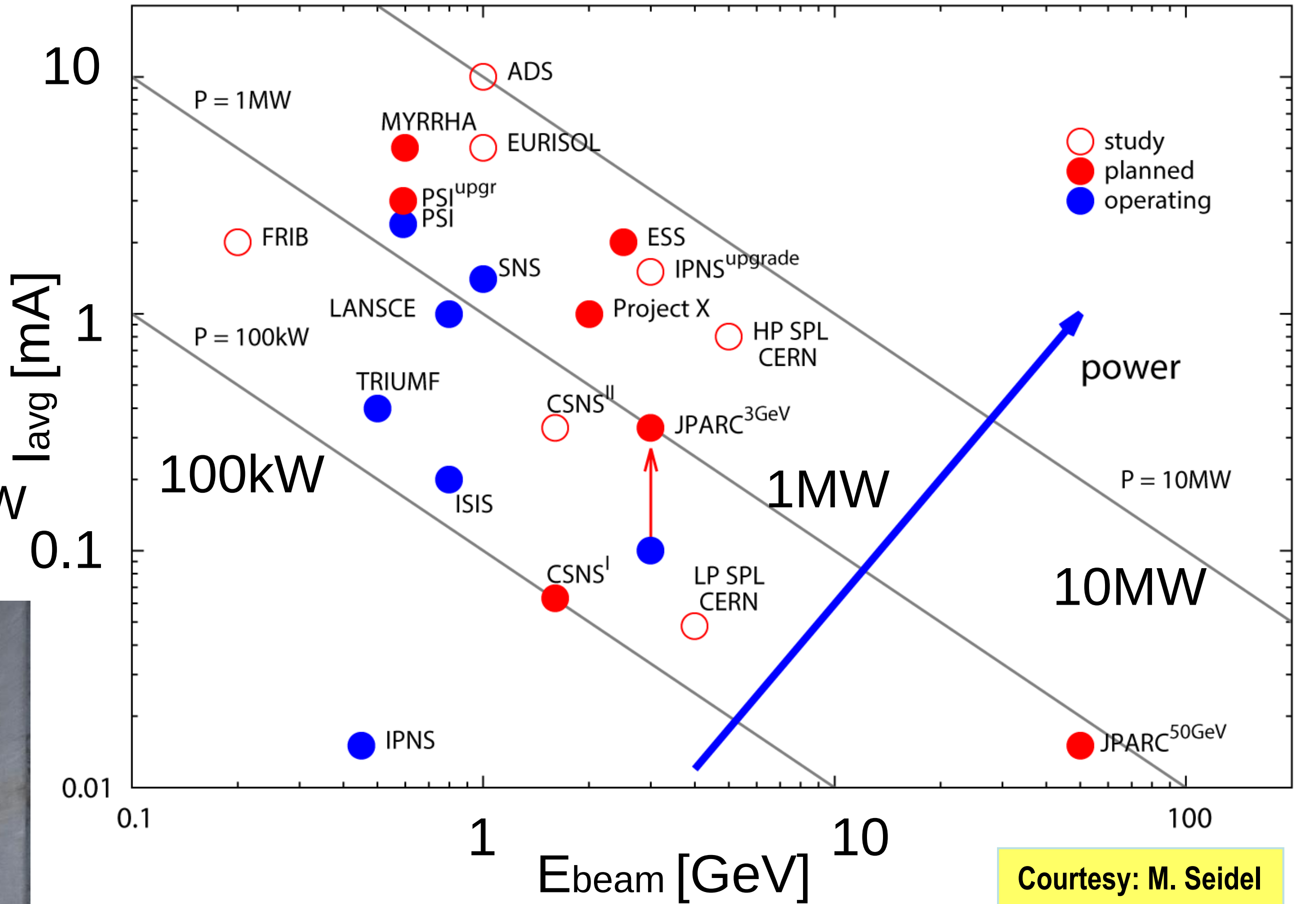
- don’t forget to contact me with ideas for muonic atom spectroscopy

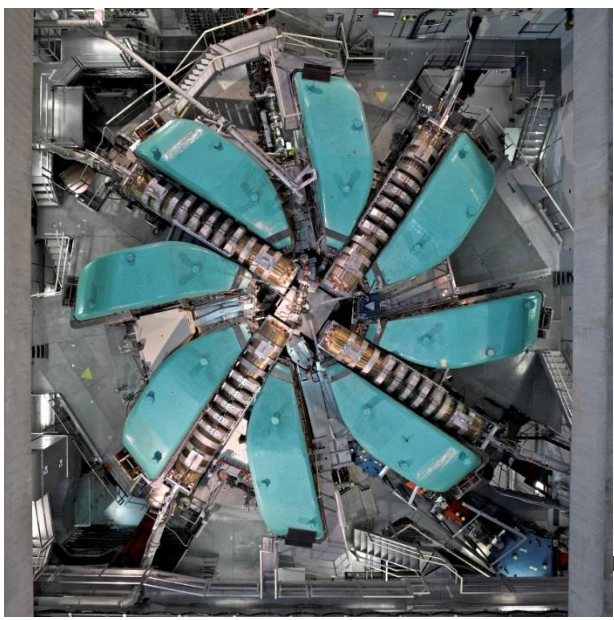
Backup

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.

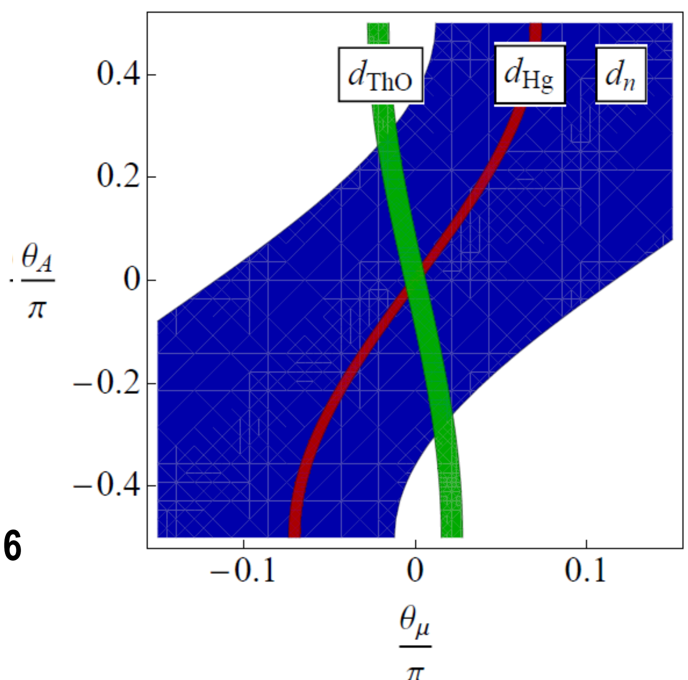
The SUSY CP problem

(for neutron and electron!)

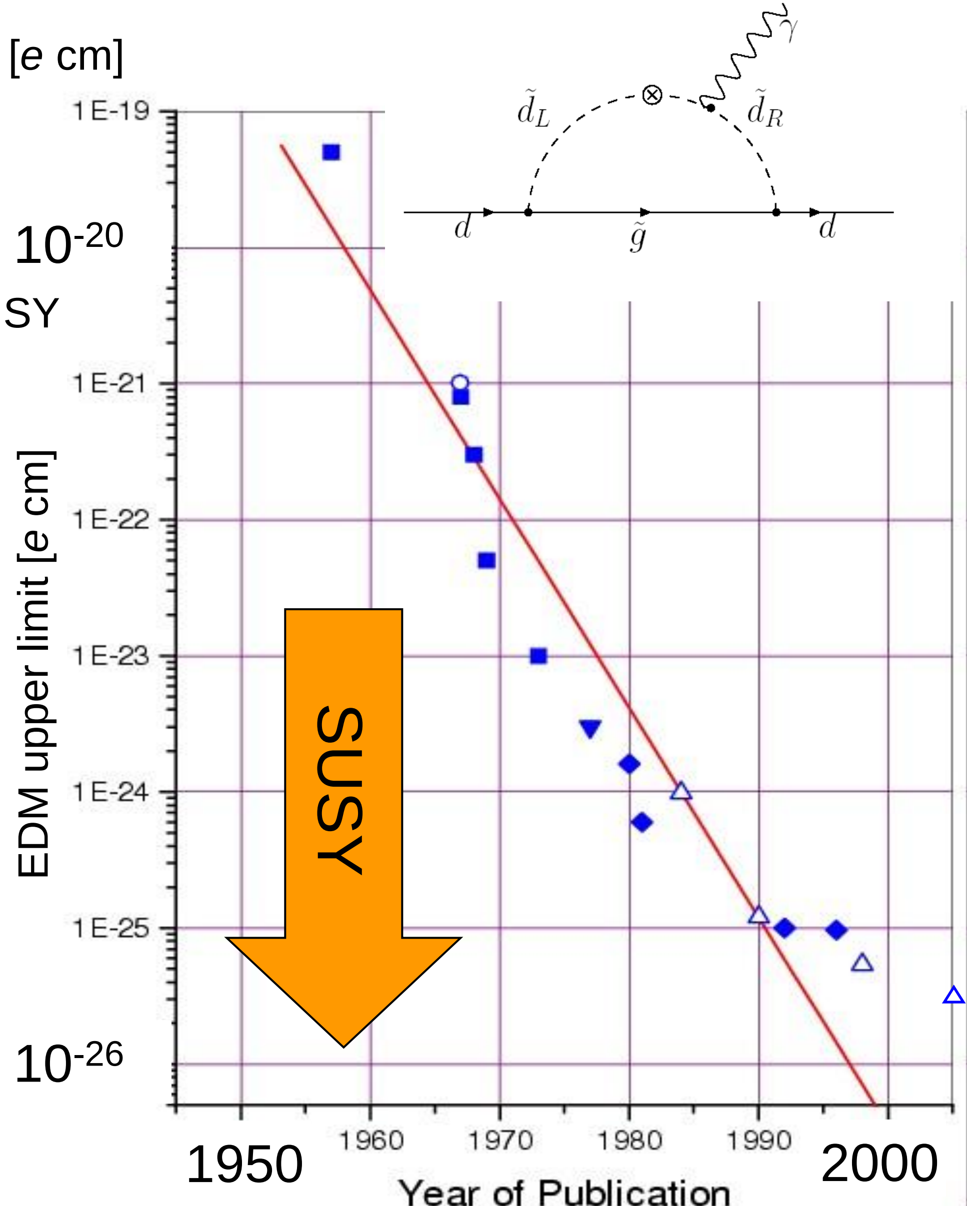
$$d_n \approx 10^{-23}\, e\ \mathrm{cm} \left(\frac{300\ \mathrm{GeV/c^2}}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

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



Caution: β decay and G_F

$$V_{ud} = 0.974\,17 \pm 0.000\,21$$ (2 x 10^{-4})

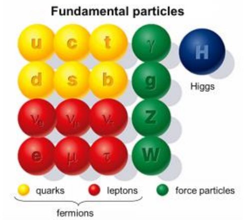
from superallowed $0^+ \rightarrow 0^+$ via

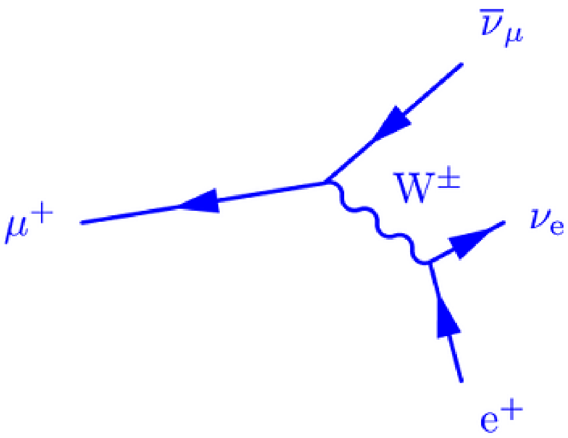
$$|V_{ud}|^2 = \frac{K}{2G_F^2(1+\Delta_R^V)\overline{\mathcal{F}t}}$$

Δ_R^V : Nucleus independent radiative corrections dominating uncertainty

using

$$G_F(\text{MuLan}) = 1.1663787(6) \times 10^{-5}\ \text{GeV}^{-2}$$ (5 x 10^{-7})

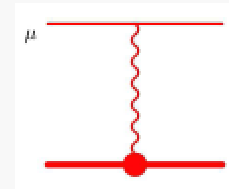




G_F determined assuming validity of the SM.
In a model independent analysis G_μ it is not yet better constrained than 3-4 x 10^{-4}

Hyperfine splitting vs. 2S-2P spectroscopy

- The 2S-2P energy splitting (Lamb shift)

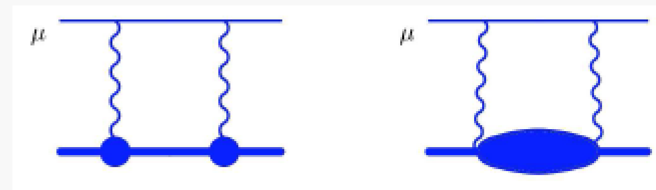


$$E_L^{\mathrm{th}} = 206.0336(15) - 5.2275(10)R_E^2 + 0.0332(20)\ \mathrm{meV}$$

$$\Delta E_{\text{finite size}} = \frac{2\pi Z\alpha}{3}|\phi(0)|^2 R_E^2$$

$$R_E = -\frac{6}{G_E(0)}\frac{dG_E}{dQ^2}\Big|_{Q^2=0}$$

$$R_E^2 \approx \int d\vec{r}\,\rho_E(\vec{r})r^2$$



TPE: Two photon exchange

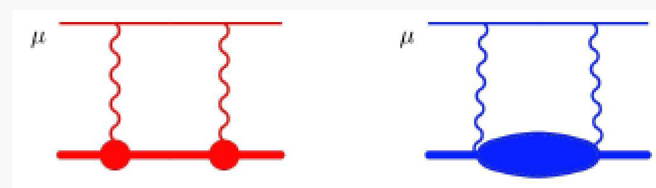
- The hyperfine splitting $\Delta E^0_{\mathrm{HFS}} \sim (Z\alpha)\langle\vec{\mu}_\mu \cdot \vec{\mu}_N\rangle\,|\phi(0)|^2$

$$\Delta E^{\mathrm{th}}_{\mathrm{HFS}} = 182.819(1) - 1.301 R_Z + 0.064(21)\ \mathrm{meV}$$

$$\Delta E_{\text{finite size}} = -2(Z\alpha)m_r\,\Delta E^0_{\mathrm{HFS}}\,R_Z$$

$$R_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left(G_E(Q^2)\frac{G_M(Q^2)}{1+\kappa_p} - 1\right)$$

$$R_Z = \int d^3\vec{r}\,|\vec{r}|\int d^3\vec{r}'\rho_E(\vec{r}-\vec{r}')\rho_M(\vec{r}')$$



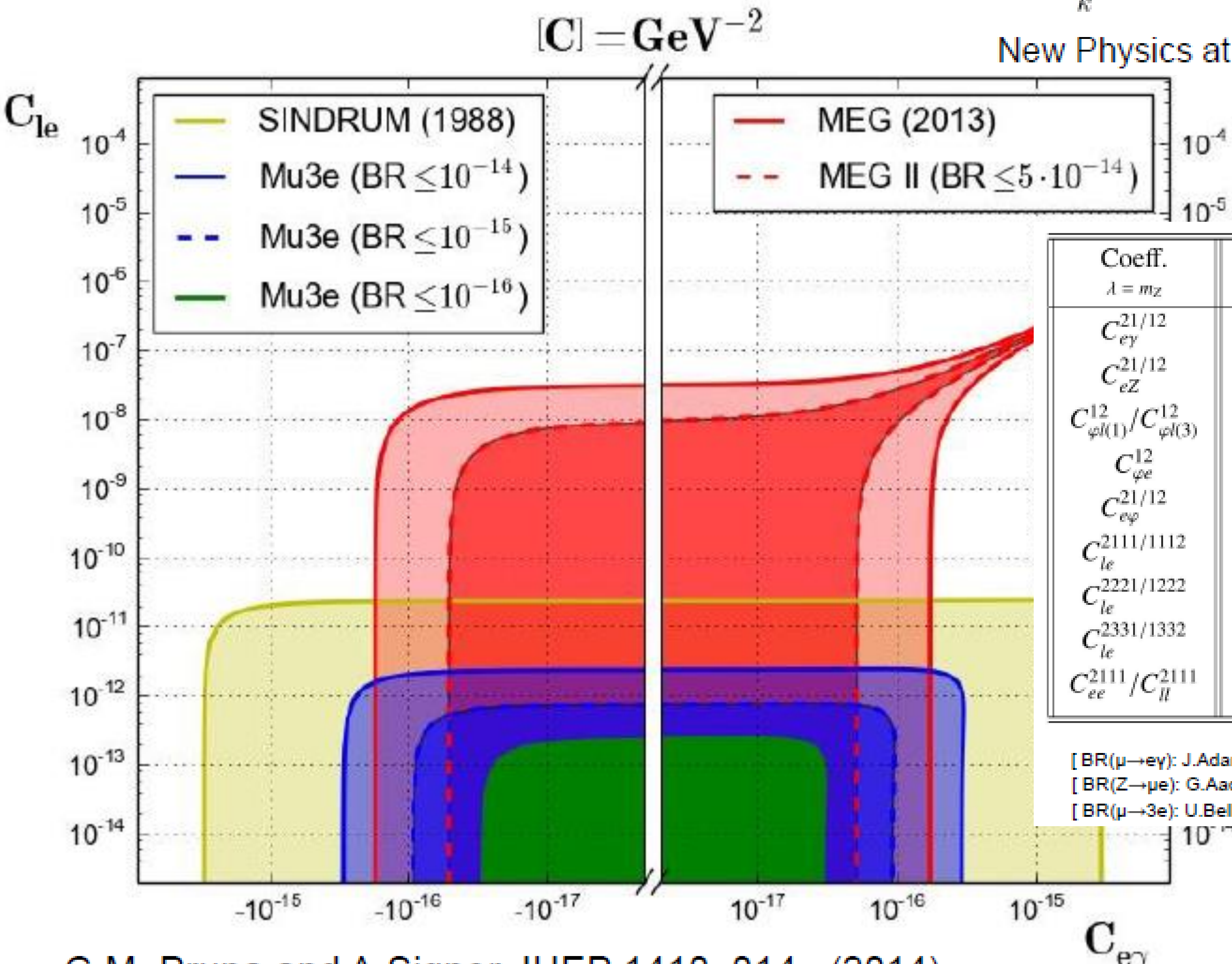
TPE: Two-photon-Exchange

A. Antognini BVR47, PSI 09.02.2016 – p. 2

MEG and Mu3e complementarity

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

New Physics at scale $\Lambda \gg M_Z$



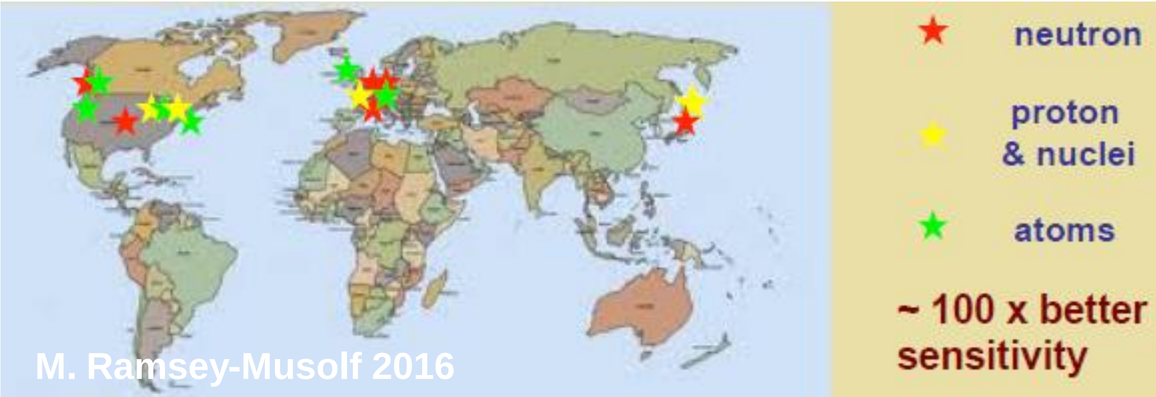
Coeff. $\lambda = m_Z$	$\mu^+ \to e^+\gamma$ BR$\leq 5.7 \cdot 10^{-13}$	$Z \to e^\pm\mu^\mp$ BR$\leq 7.5 \cdot 10^{-7}$	$\mu^+ \to e^+e^-e^+$ BR$\leq 1.0 \cdot 10^{-12}$
$C_{e\gamma}^{21/12}$	$2.5 \cdot 10^{-16}$		$3.8 \cdot 10^{-15}$
$C_{eZ}^{21/12}$	$1.4 \cdot 10^{-13}$	$3.9 \cdot 10^{-8}$	$4.0 \cdot 10^{-8}$
$C_{\varphi l(1)}^{12}/C_{\varphi l(3)}^{12}$	$2.5 \cdot 10^{-10}$	$3.9 \cdot 10^{-8}$	$3.5 \cdot 10^{-11}$
$C_{\varphi e}^{12}$	$2.5 \cdot 10^{-10}$	$3.9 \cdot 10^{-8}$	$3.7 \cdot 10^{-11}$
$C_{e\varphi}^{21/12}$	$2.8 \cdot 10^{-8}$		$8.7 \cdot 10^{-6}$
$C_{le}^{2111/1112}$	$4.4 \cdot 10^{-8}$		$3.1 \cdot 10^{-11}$
$C_{le}^{2221/1222}$	$2.1 \cdot 10^{-10}$		
$C_{le}^{2331/1332}$	$1.2 \cdot 10^{-11}$		
$C_{ee}^{2111}/C_{ll}^{2111}$			$1.1 \cdot 10^{-11}$

[BR(μ→eγ): J.Adam et al. (MEG), Phys. Rev. Lett. 110, 201801, (2013)]
[BR(Z→μe): G.Aad et al. (ATLAS), Phys. Rev. D90, 072010, (2014)]
[BR(μ→3e): U.Bellgardt et al. (SINDRUM), Nucl.Phys. B299, 1, (1988)]

G.M. Pruna and A.Signer JHEP 1410, 014 , (2014)

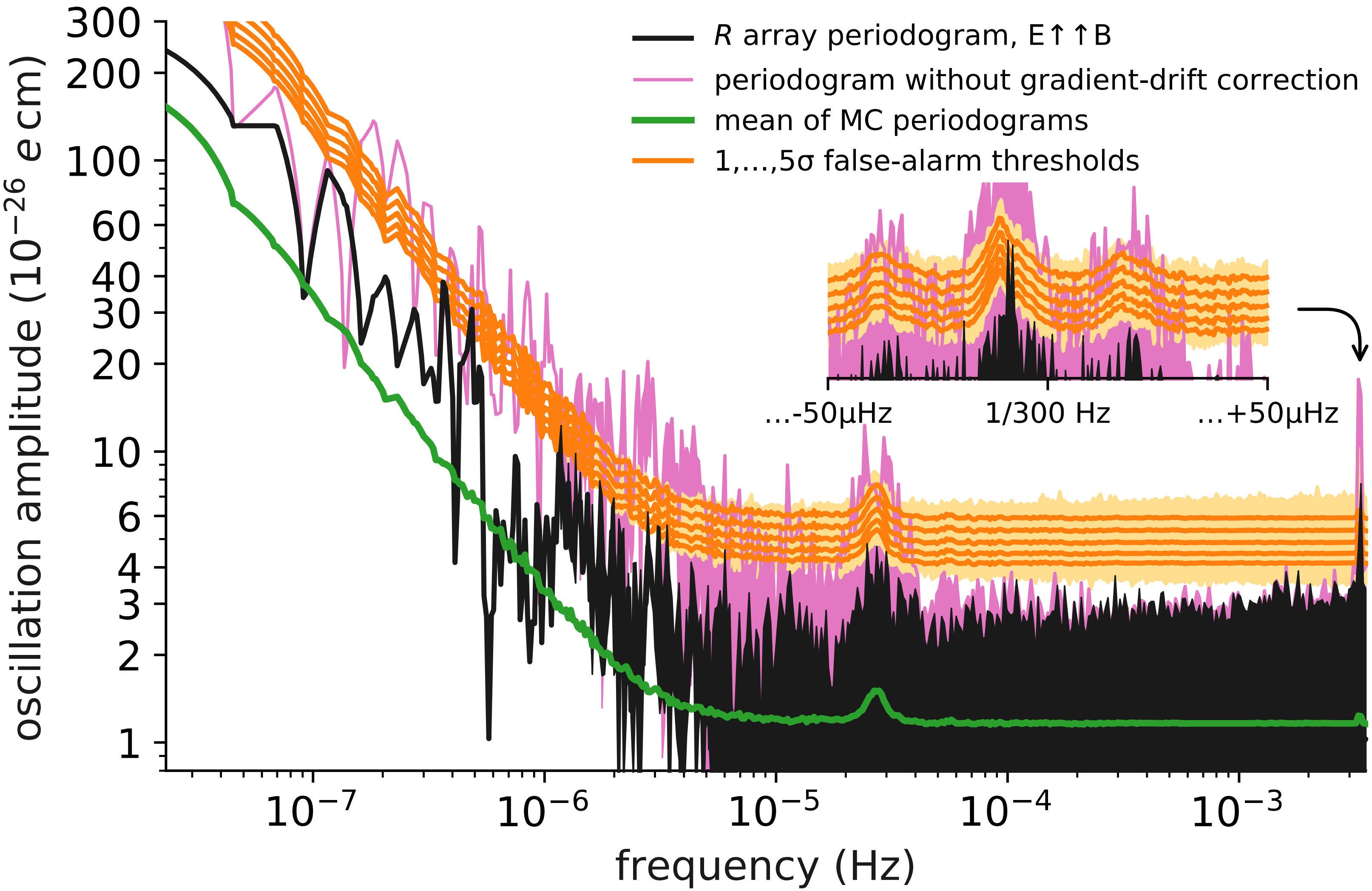
Progress with EDM searches

- Electron EDM: Next improvements from polar molecules (e.g. YbF, ThO) expected; some searches with paramagnetic atoms (Cs, Fr)
- Nuclear EDM: Hg-199 $d_{Hg} \leq 7.4 \times 10^{-30}$ e•cm **(Graner et. al, PRL116(2016)161601)**, other efforts use different diamagnetic atoms (Xe-129, Ra-225)
- Neutron EDM: Various international collaborations
- Muon EDM: new g-2 experiments
- Other charged particle EDM: Proton, Deuteron, …
  R&D by storage ring collaboration, JEDI with precursor at COSY, CPEDM in CERN's PBC study

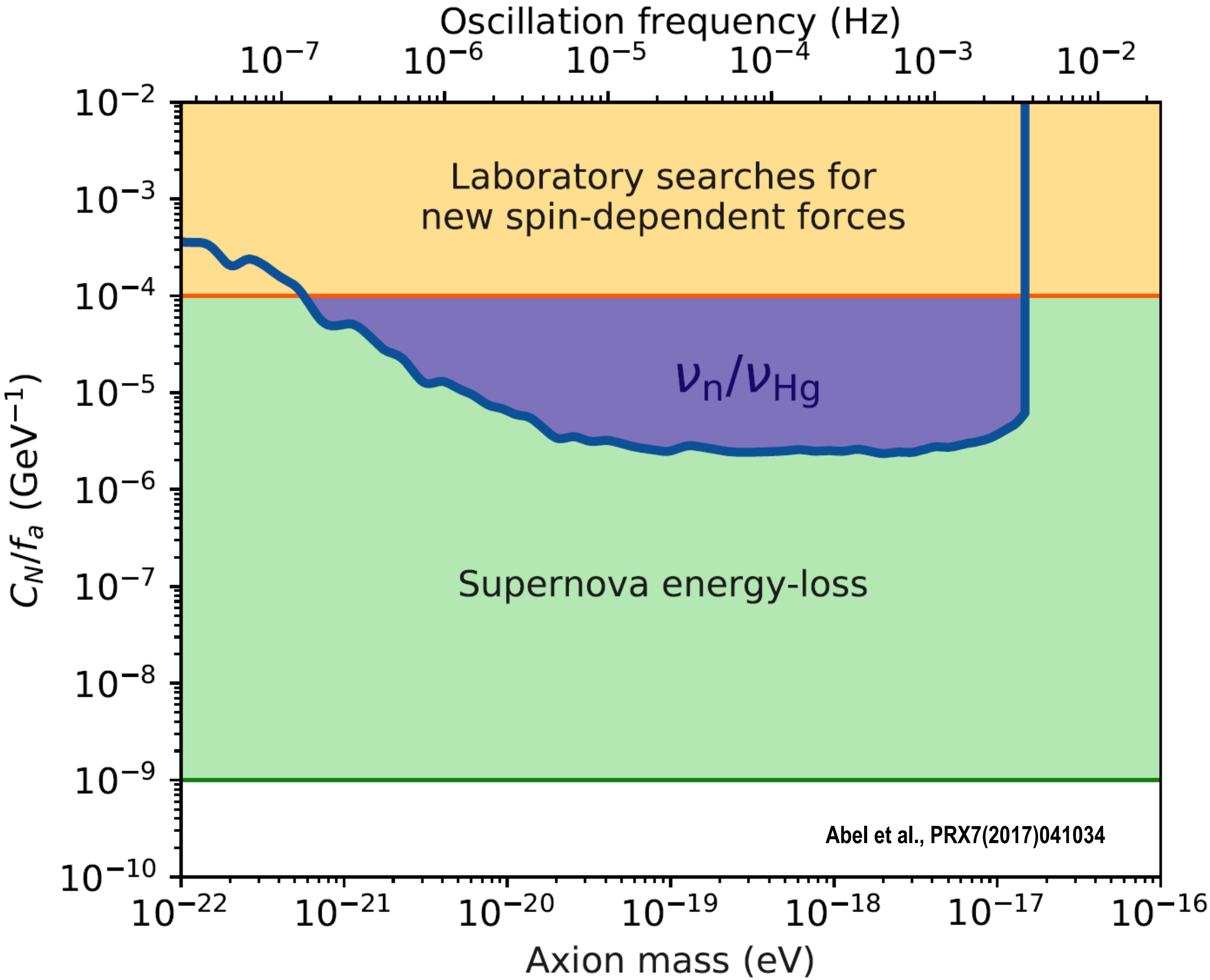


Need multiple systems, to discover finite EDM and to eventually disentangle BSM physics

Some unique opportunities in Europe



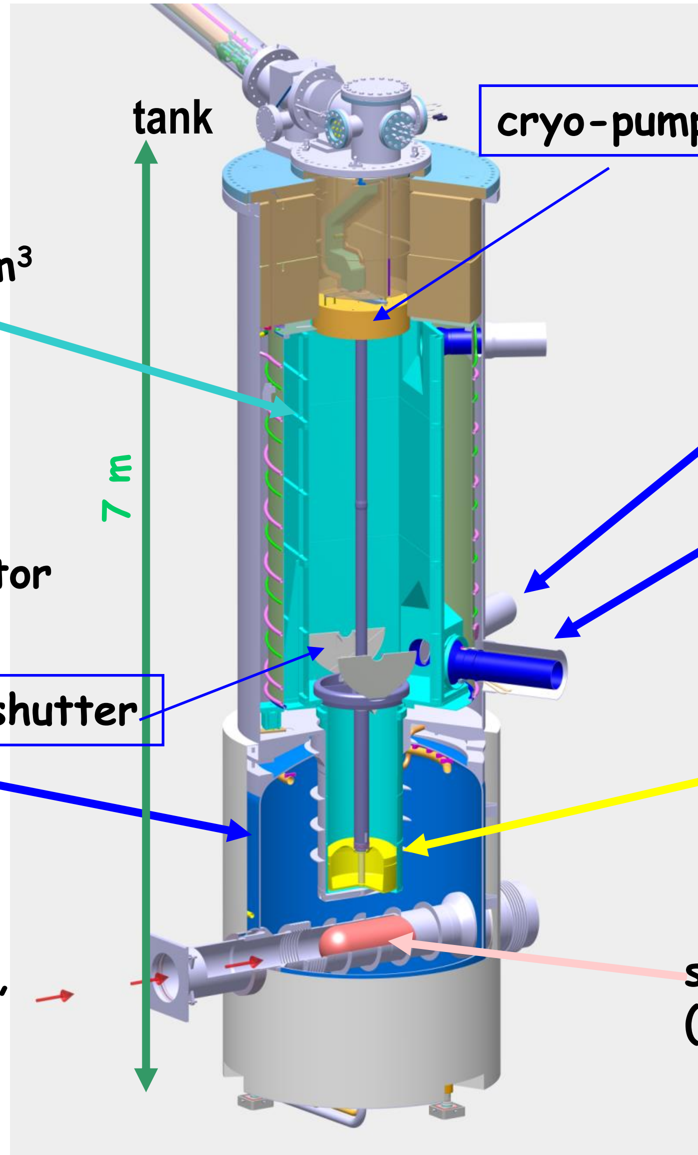
$$d_n(t) = 5.9 \times 10^{-22}\, C_G \left(\frac{10^{-22}\,\mathrm{eV}}{m_a}\right)\left(\frac{10^{16}\,\mathrm{GeV}}{f_a}\right)\cos(m_a t)\; e\cdot\mathrm{cm}$$


Oscillation frequency (Hz)
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}
10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9} 10^{-10}
C_N/f_a (GeV^{-1})
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)

The PSI UCN source

Ultra Cold Neutron Source

DLC coated
UCN storage vessel
height 2.5 m, ~ 2 m^3



cryo-pump

UCN guides towards
experimental areas
8.6m(S) / 6.9m(W)

heavy water moderator
→ thermal neutrons
3.6m^3 D_2O

SV-shutter

cold UCN-converter
~30 dm^3 solid D_2 at 5 K

pulsed
1.4 MW p-beam
590 MeV, 2.4 mA,
2% duty cycle

spallation target (Pb/Zr)
(~ 8 neutrons/proton)

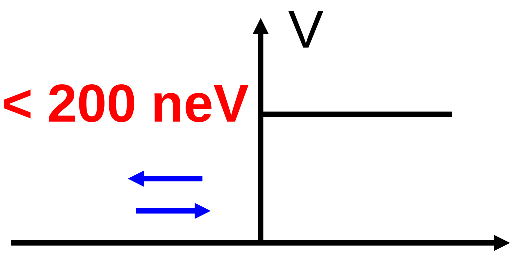
www.psi.ch/ucn/

Ultracold neutrons

ideal gas with temperature of milli-Kelvin

move with velocities of few m/s

strong	magnetic	gravitation
Fermi potential V_F	**$V_m = -\mu B$**	**$V_g = m_n g h$**
↓	↓	↓
200 neV	**60 neV T^{-1}**	**100 neV m^{-1}**
	↓	↓
$E_n < 200$ neV	**3.3 T field → 200 neV**	**2 m → 200 neV**



Nature has probably violated CP when generating the Baryon asymmetry !?

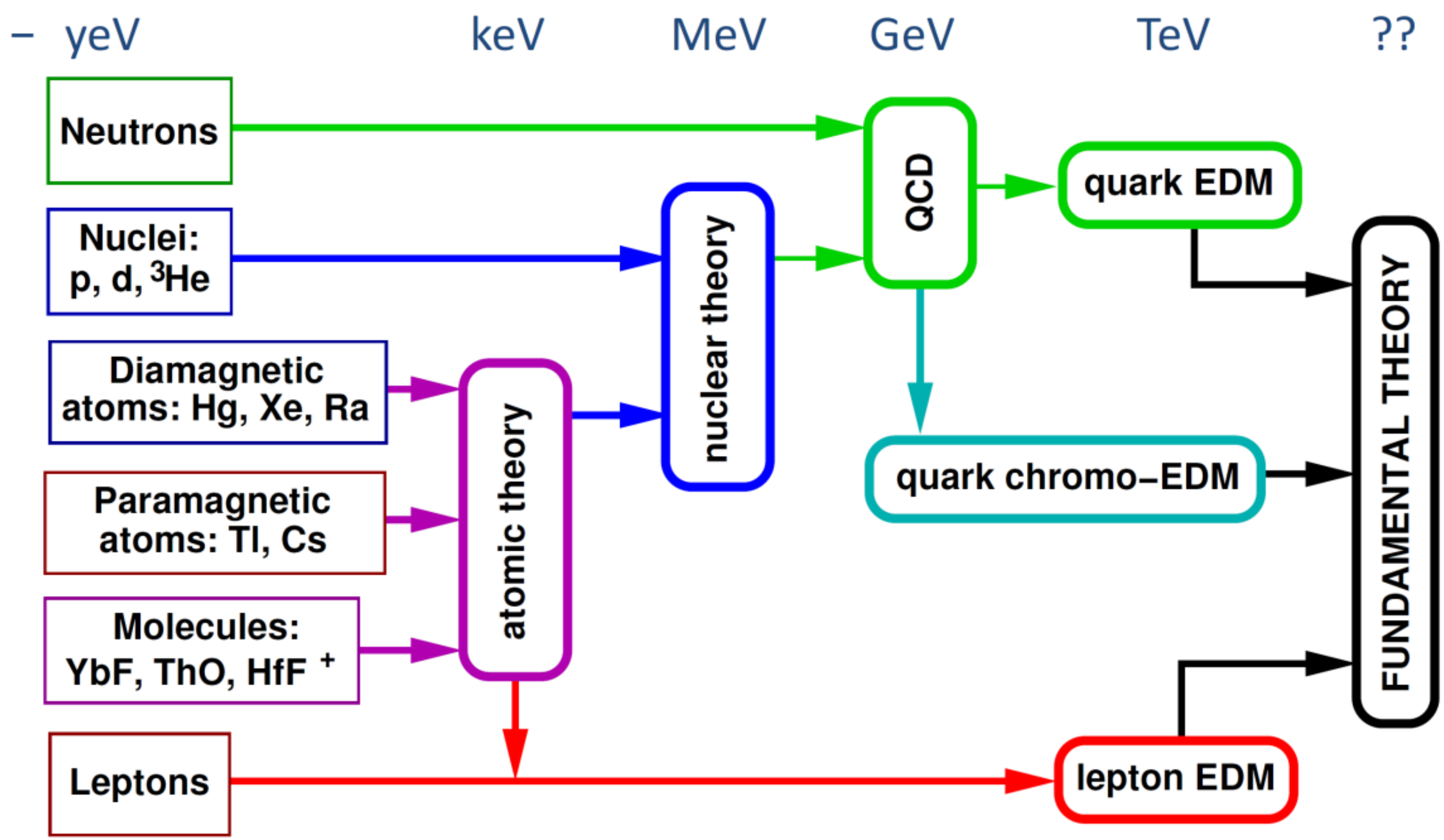
Observed*:
$(n_B - n_{\bar{B}}) / n_\gamma = 6 \times 10^{-10}$

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]

* WMAP + COBE, 2003
$n_B / n_\gamma = (6.1 \pm^{0.3}_{0.2}) \times 10^{-10}$

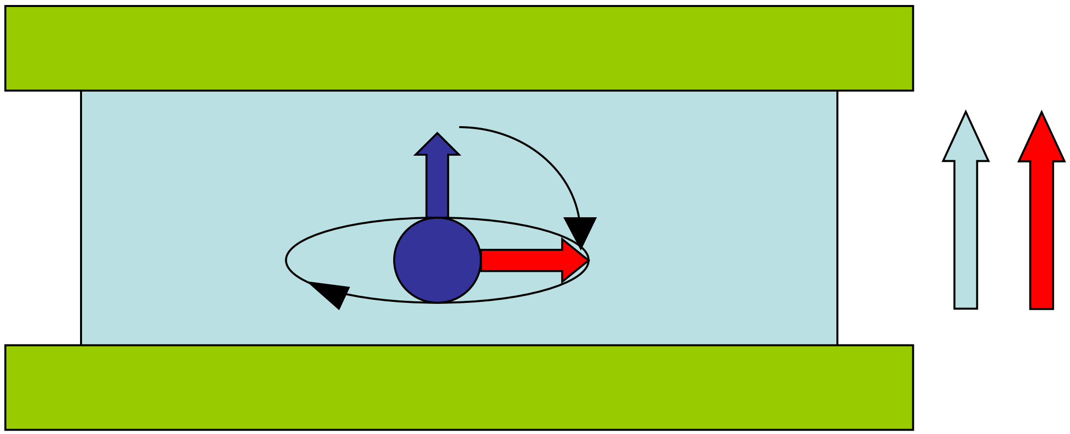
Connecting experiments and theory



Scheme: courtesy Rob G. E. Timmermans

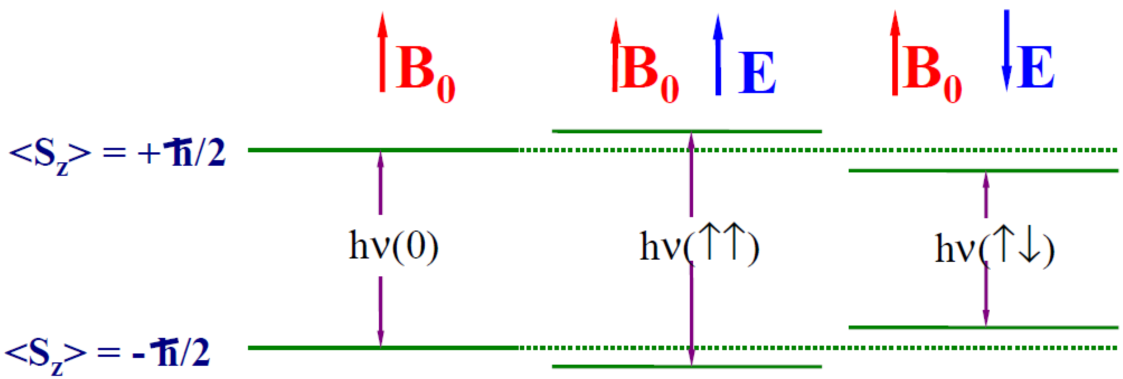
See also: Pospelov, Ritz, Ann. Phys. 318(2005)119

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



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

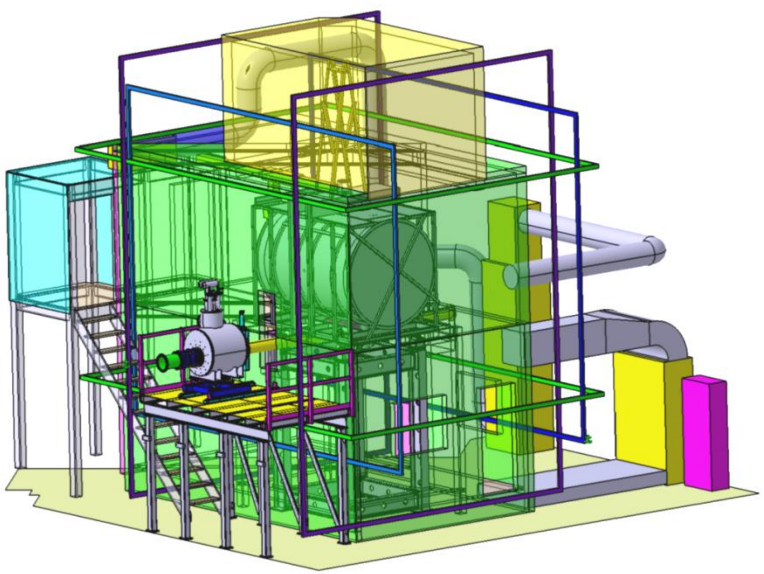
$$h\Delta\nu = 4\, d_n\, E$$

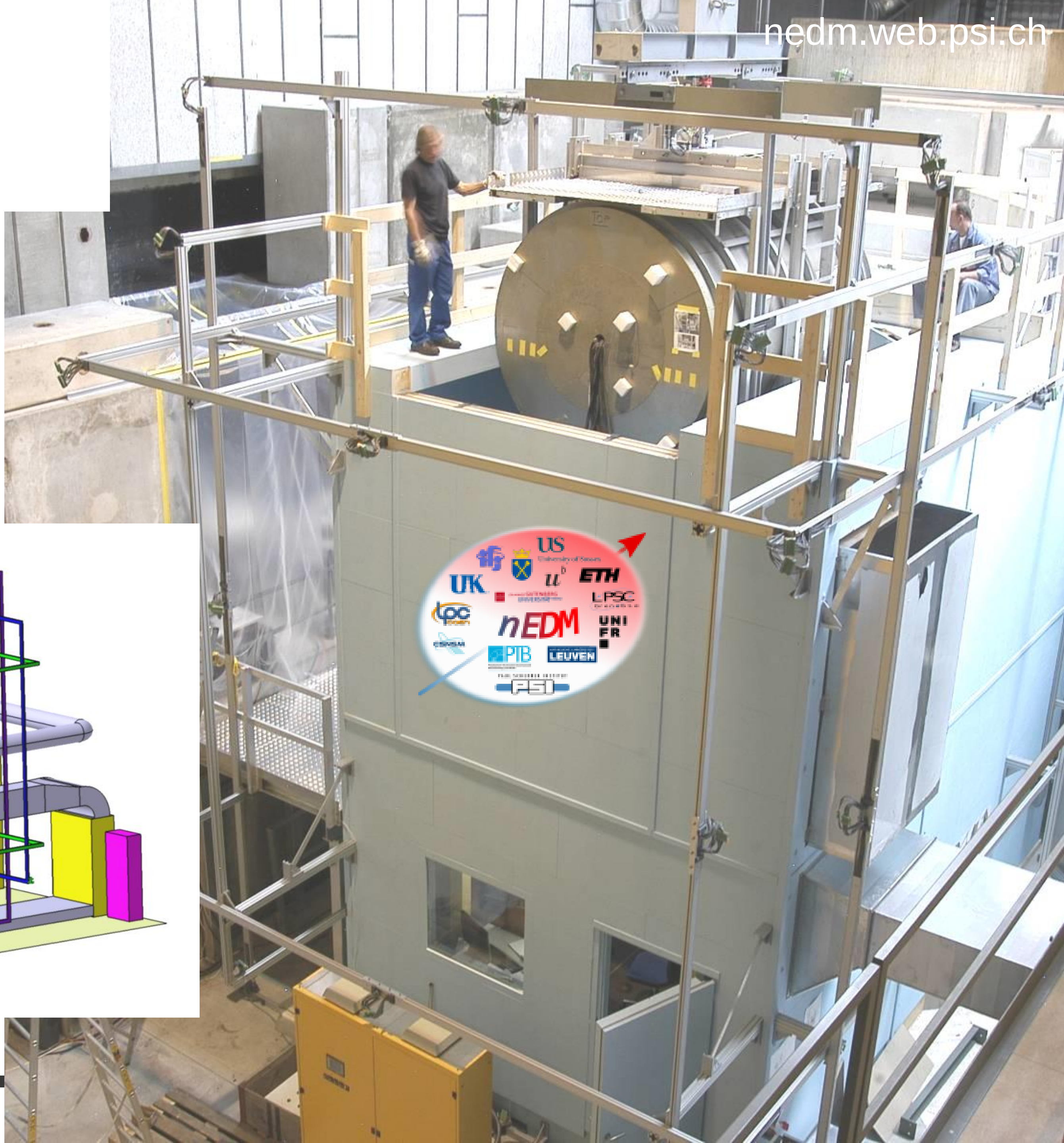


$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

nEDM at PSI 2009 – 17

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

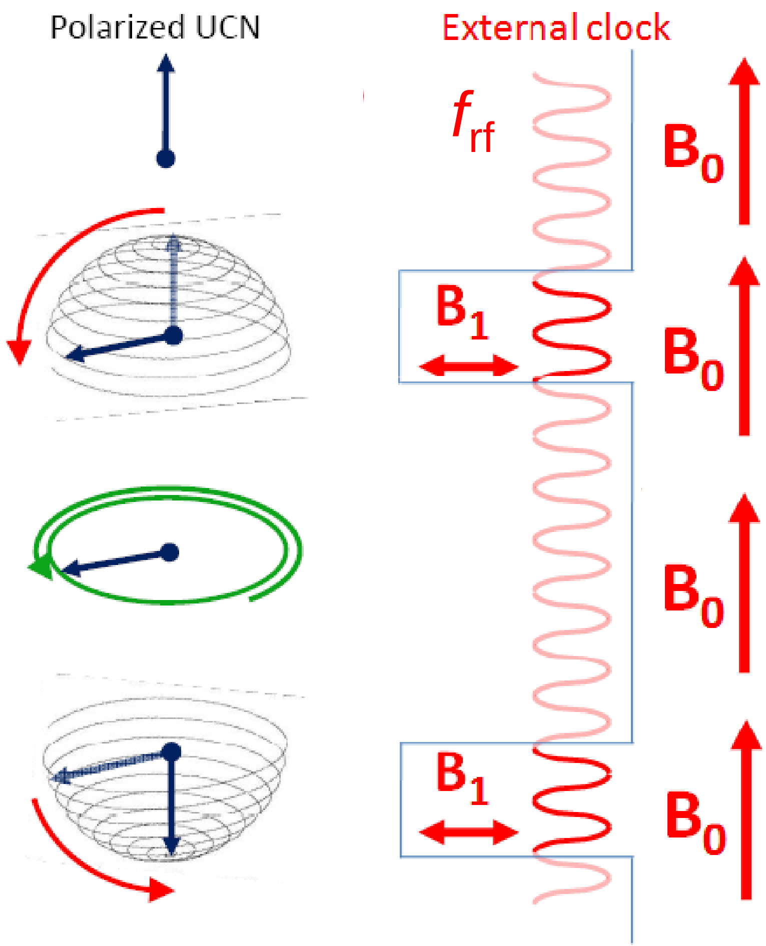


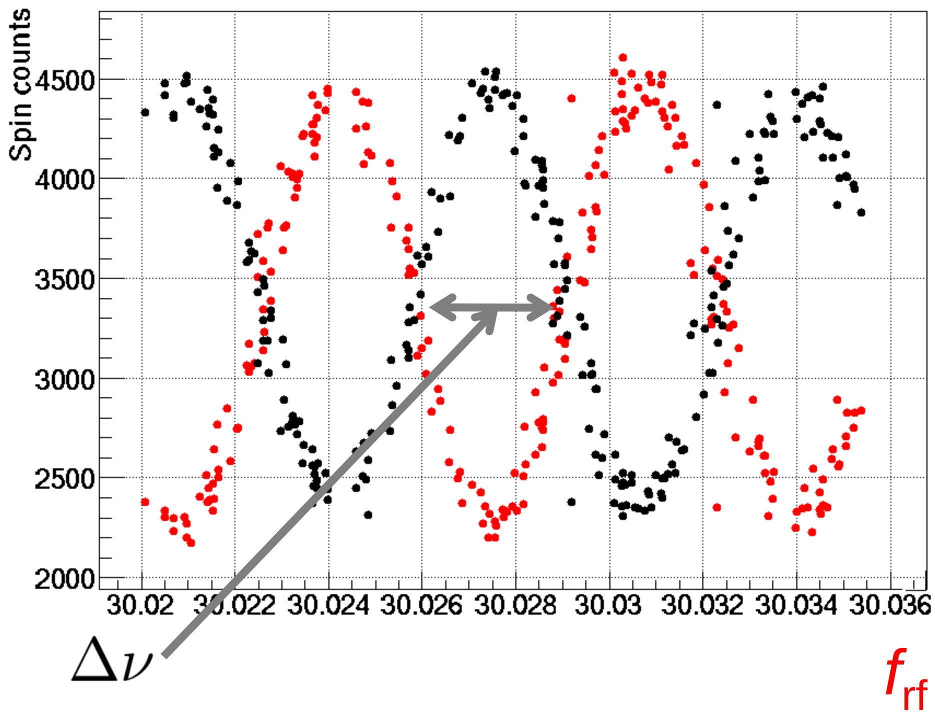


www.psi.ch/nedm/

ETH

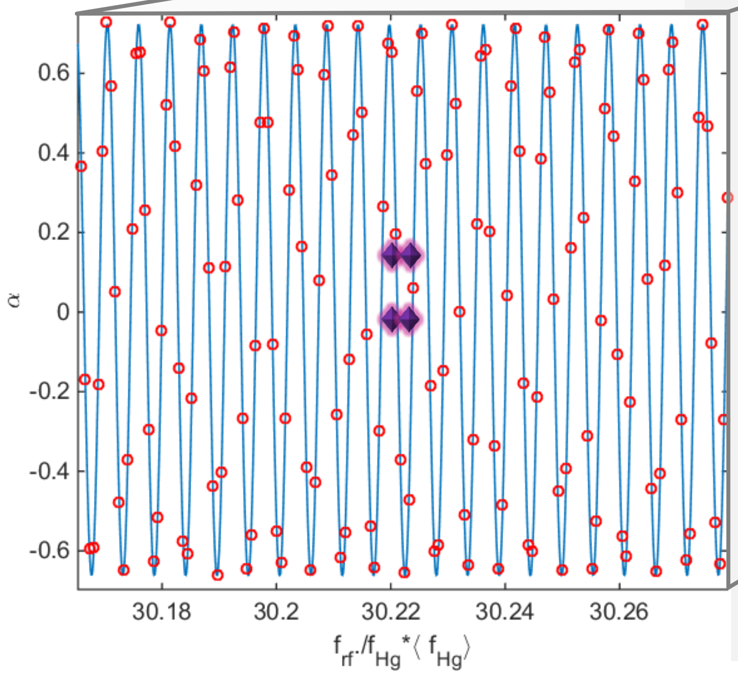
Ramsey's method with UCN

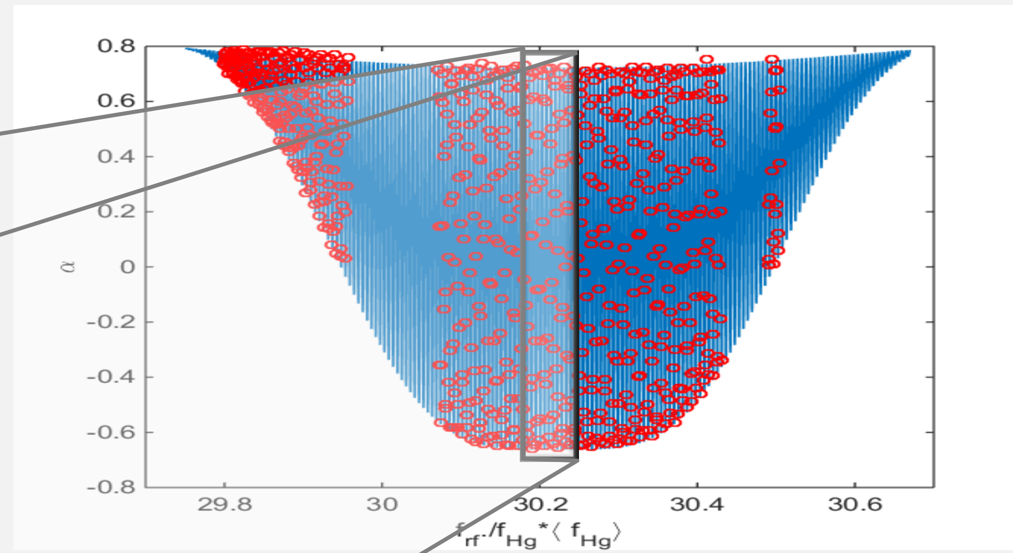




$$\sigma(f_n) = \frac{\Delta\nu}{\alpha\sqrt{N}\pi}$$

Ramsey's method with UCN



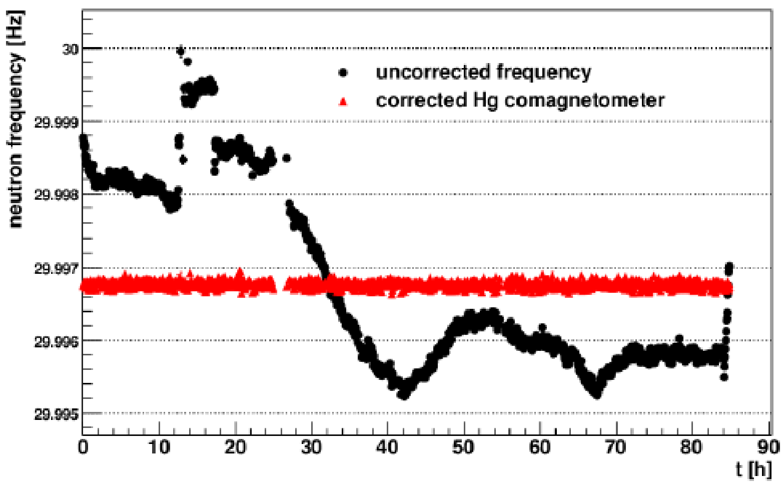


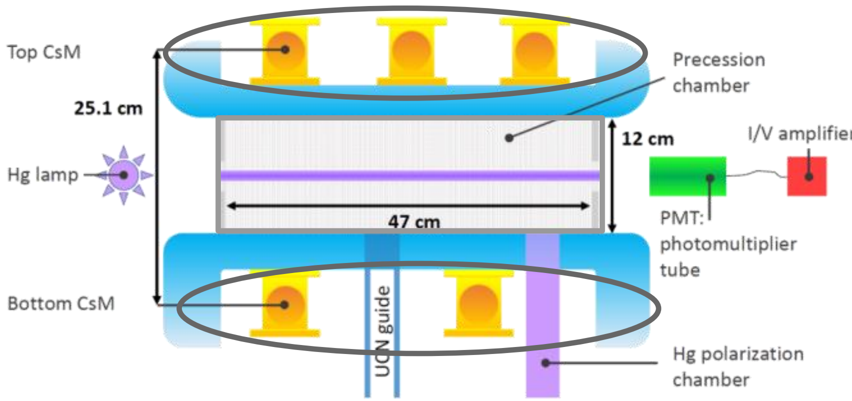
Sensitivity:

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

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

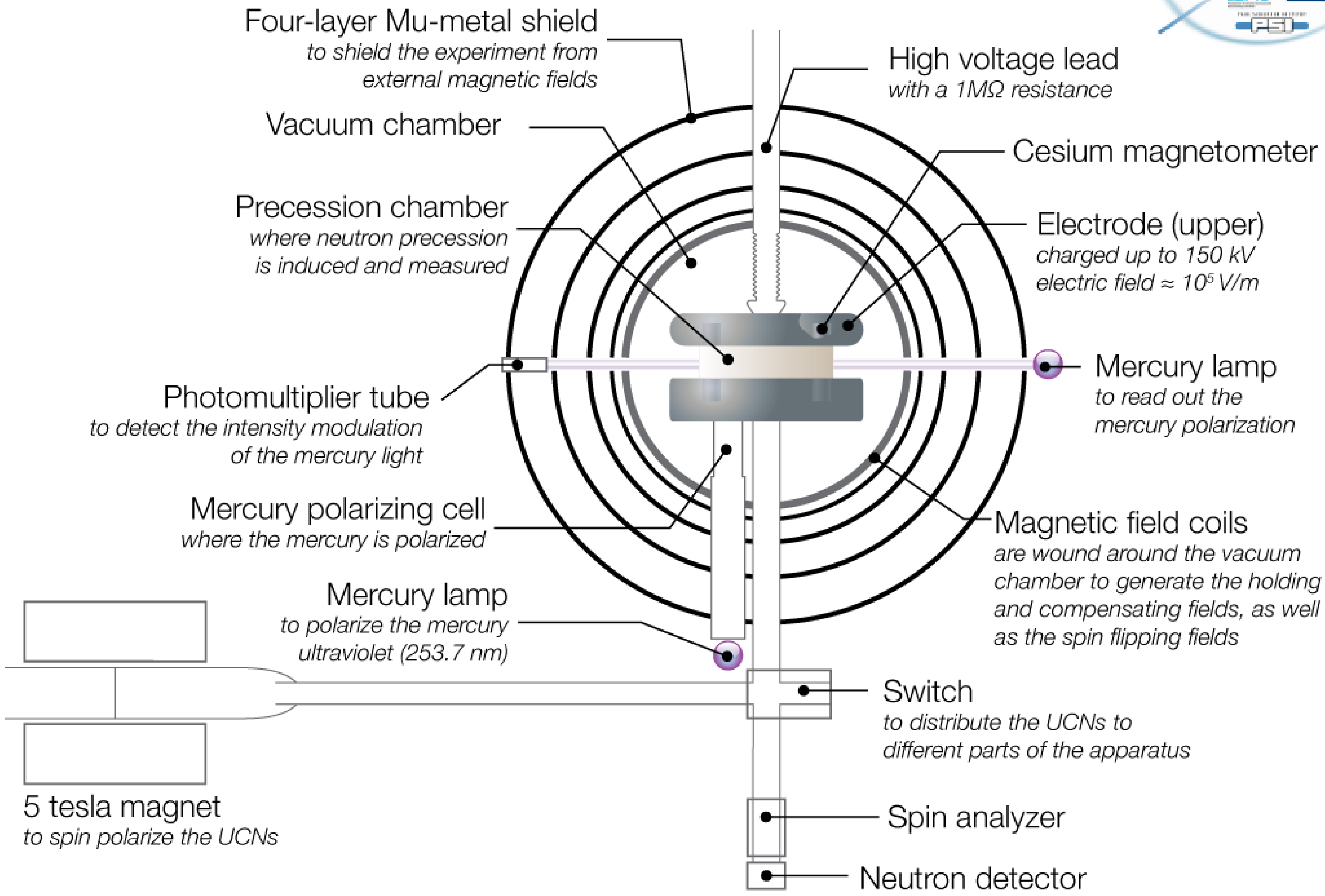
Frequency ratio R





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

The nEDM spectrometer



Magnetic moments

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

[1.89 ppm]

↑ γ_{Hg}

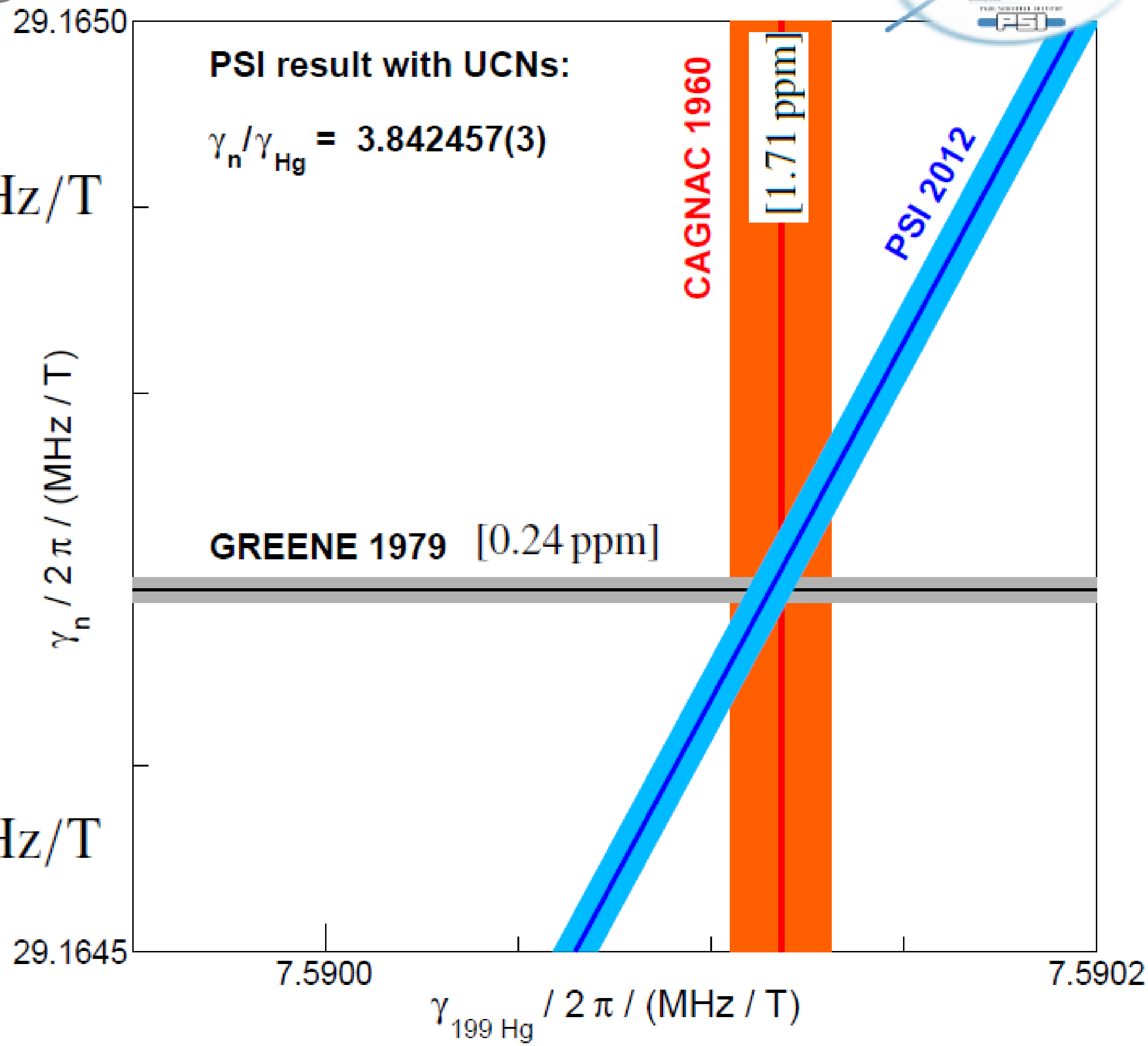
$$\gamma_n/\gamma_{Hg} = 3.8424574(30)$$

[0.78 ppm]

↓ γ_n

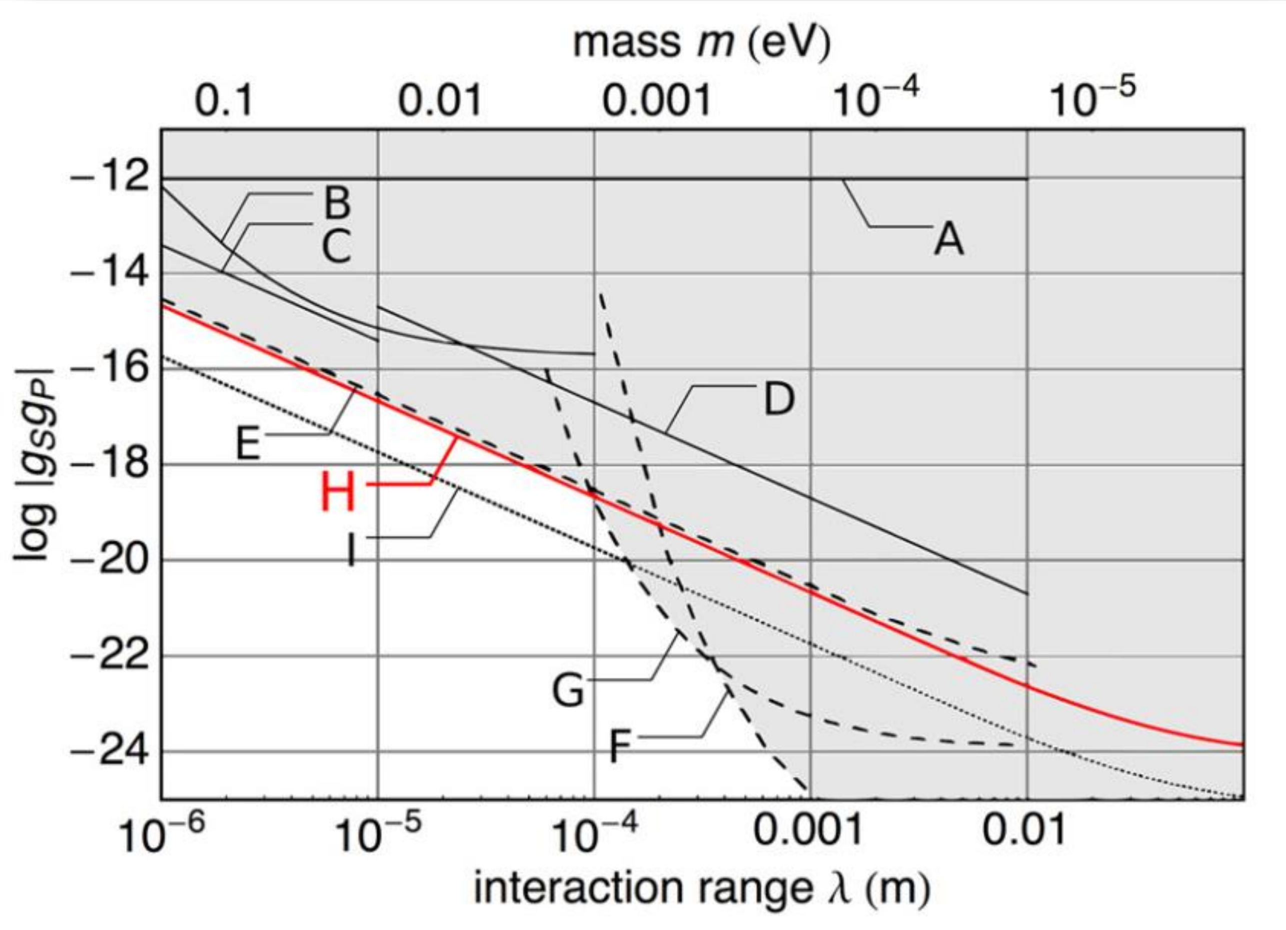
$$\frac{\gamma_{Hg}}{2\pi} = 7.5901152(62)\ \mathrm{MHz/T}$$

[0.82 ppm]



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

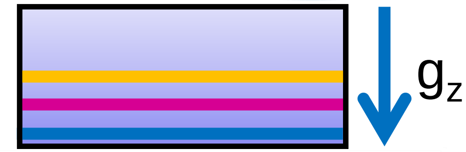
Spin-dependent exotic interactions

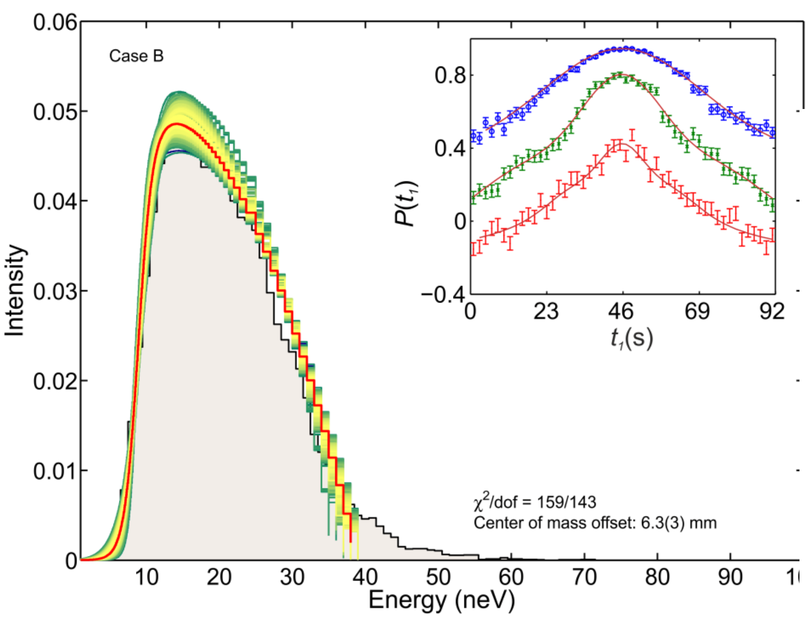


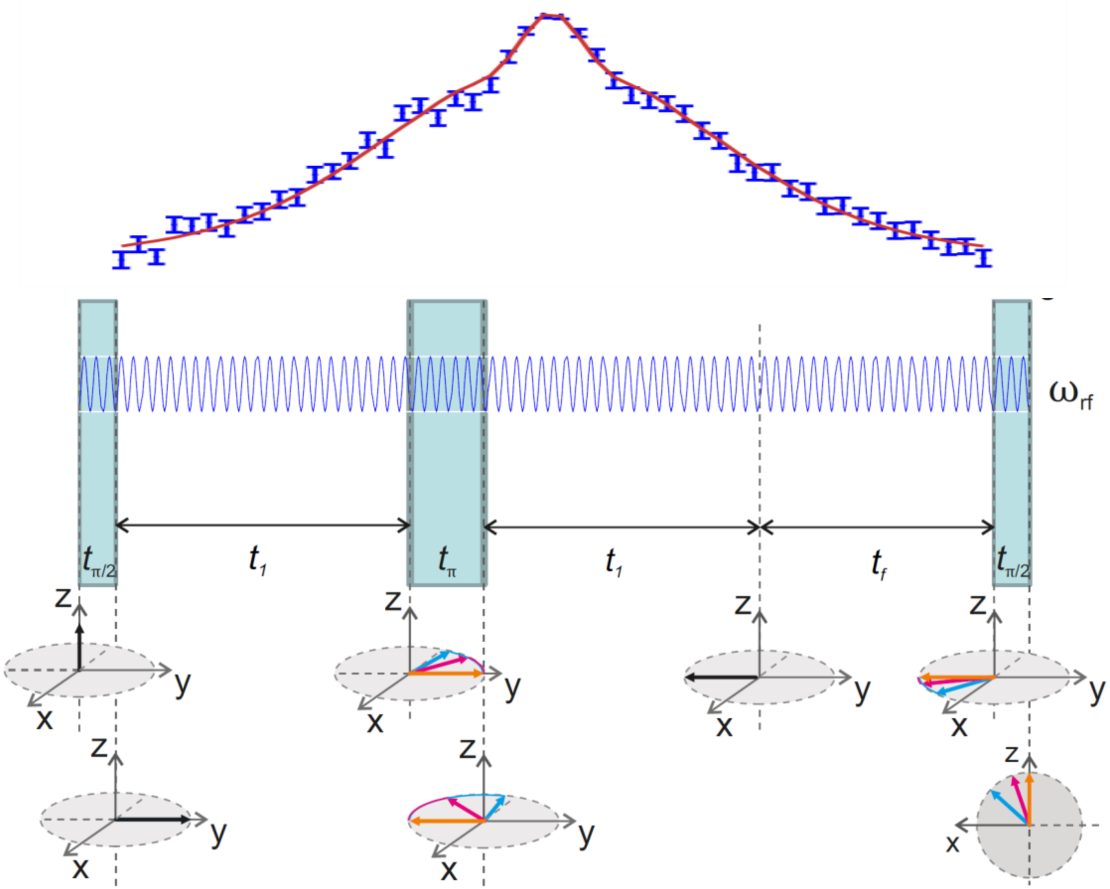
S. Afach et al., PLB 745 (2015) 58

Spin-echo spectroscopy

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