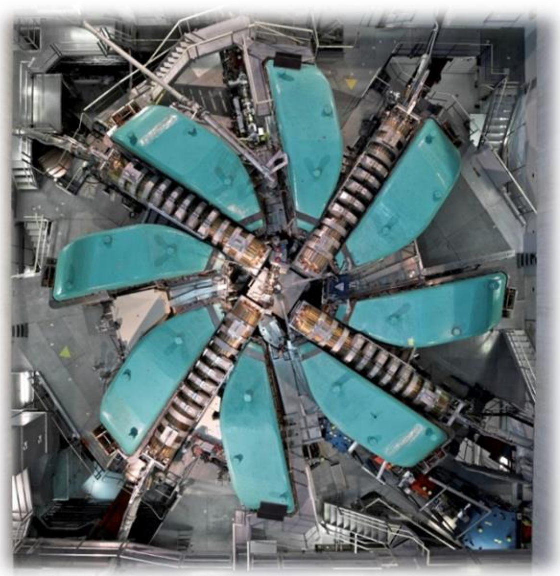
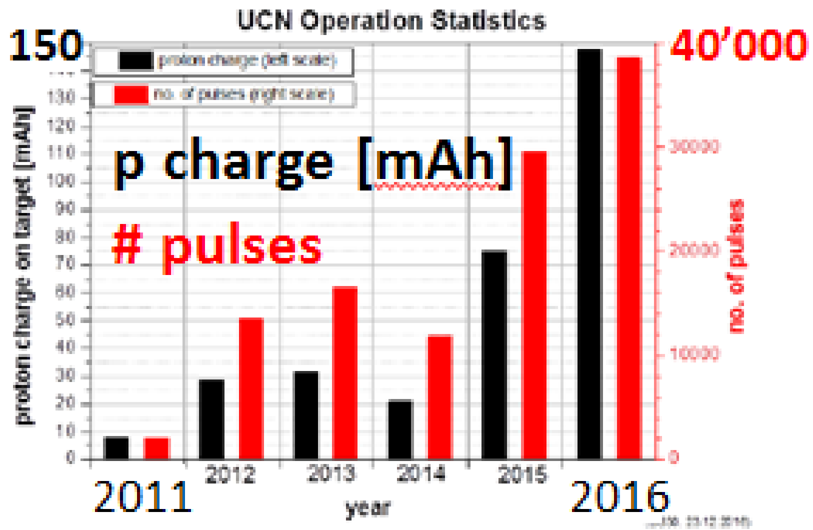
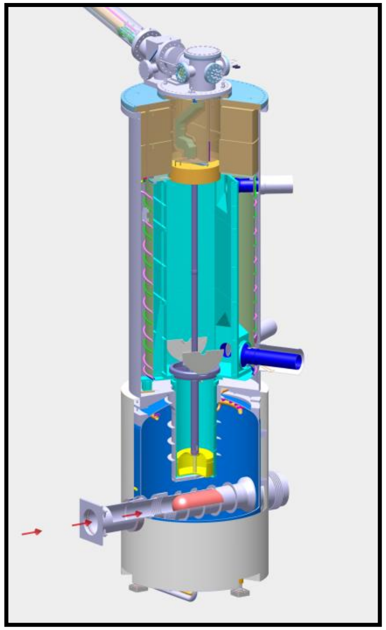
The electric dipole moment of the neutron

K.Kirch, ETH Zürich – PSI Villigen, Switzerland



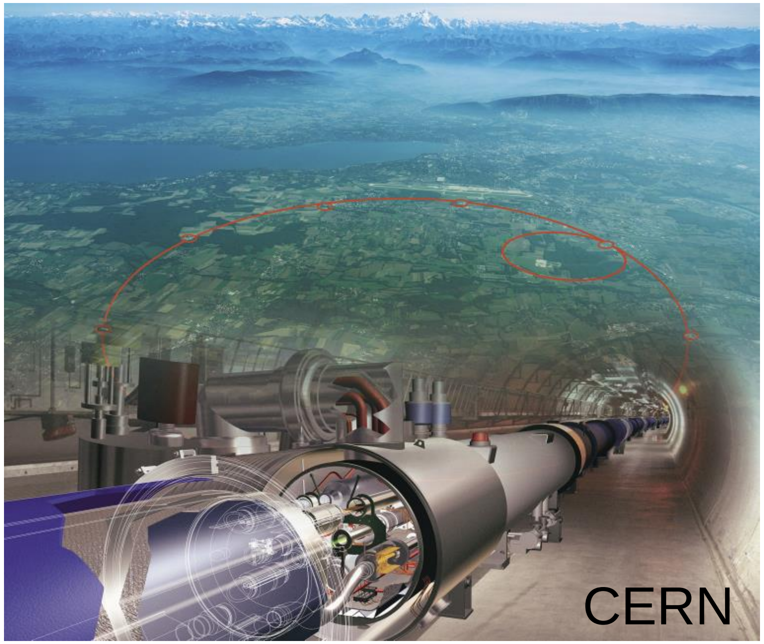




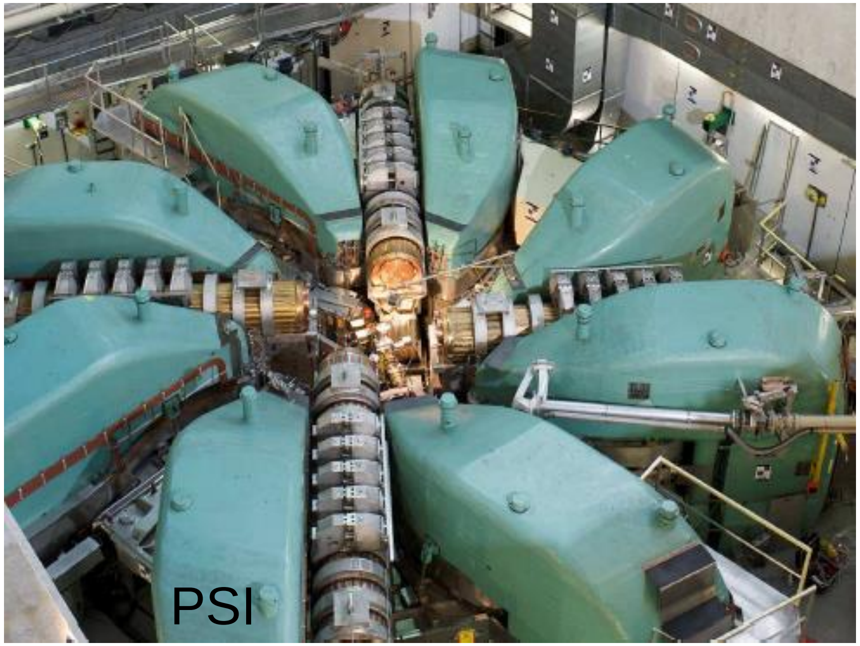

GERMANY
FRANCE
PSI
Schaffhausen
Lake Constance
Basel
Winterthur
Sankt Gallen
Zürich
AUSTRIA
LIECHTENSTEIN
Biel
Luzern
BERN
Neuchâtel
Lausanne
Lac Léman
CERN
Genève (Geneva)
ITALY
Lugano
Lake Como
Lake Maggiore
ITALY
FRANCE
Milan

Complementary approaches in fundamental particle physics

High Energy

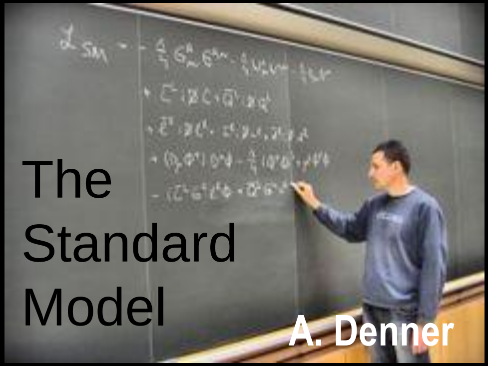


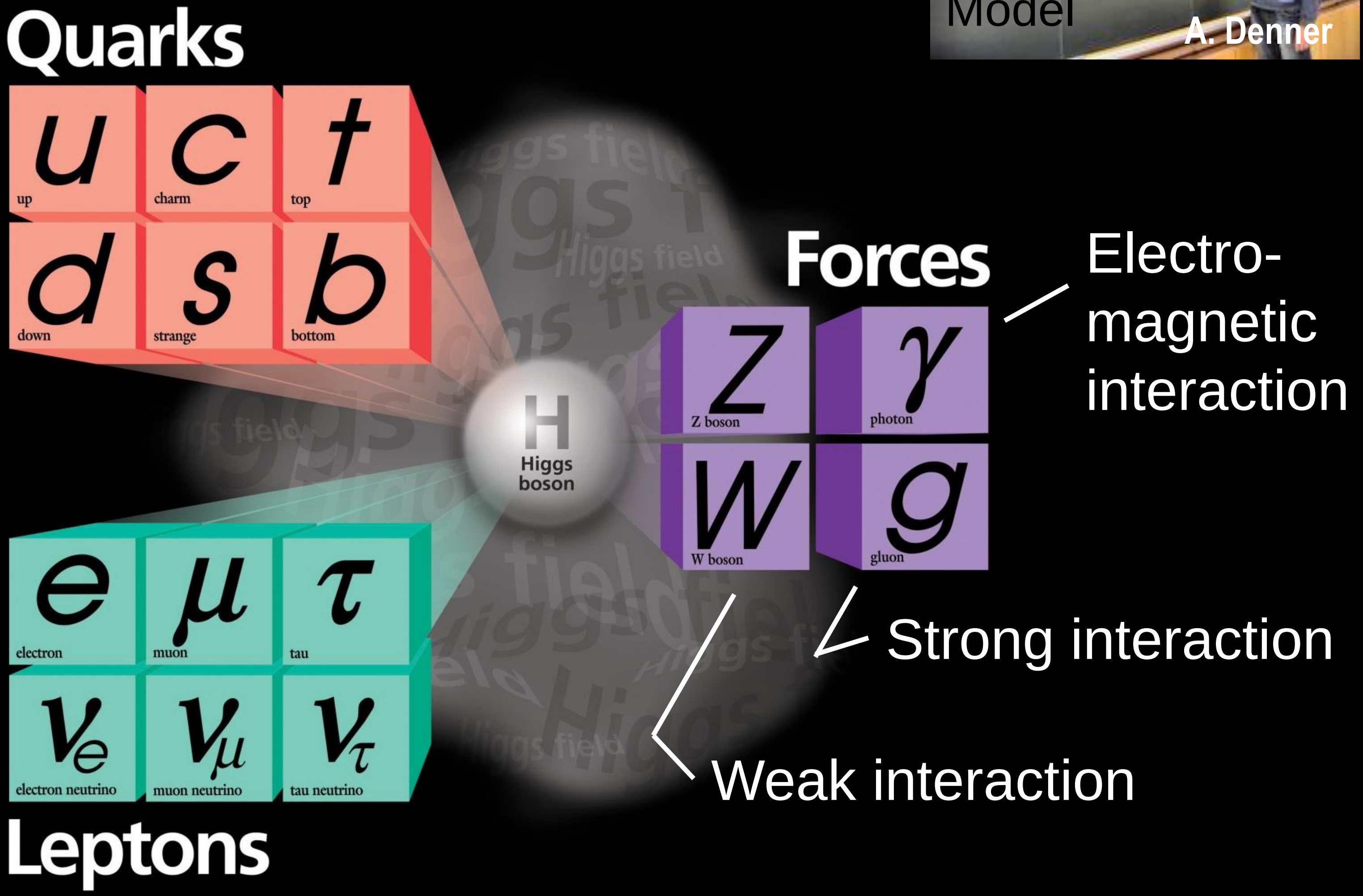
High Intensity



Both test our current understanding of fundamental particles and interactions.

The building blocks



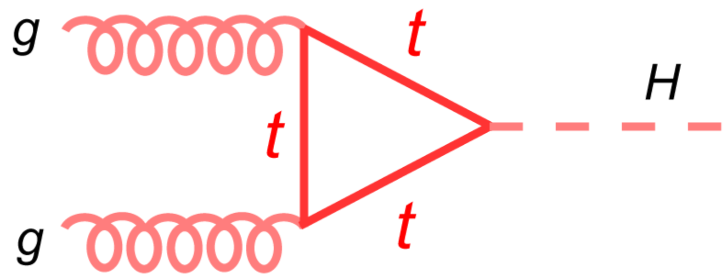


Source: FNAL

Search for new physics

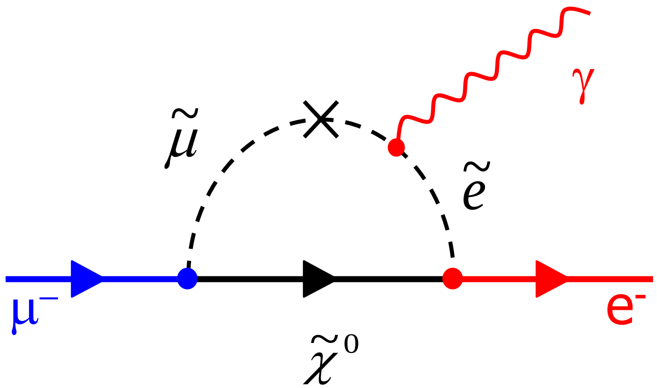
High Energy

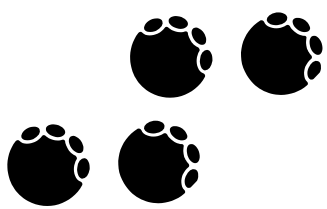
direct production of new particle



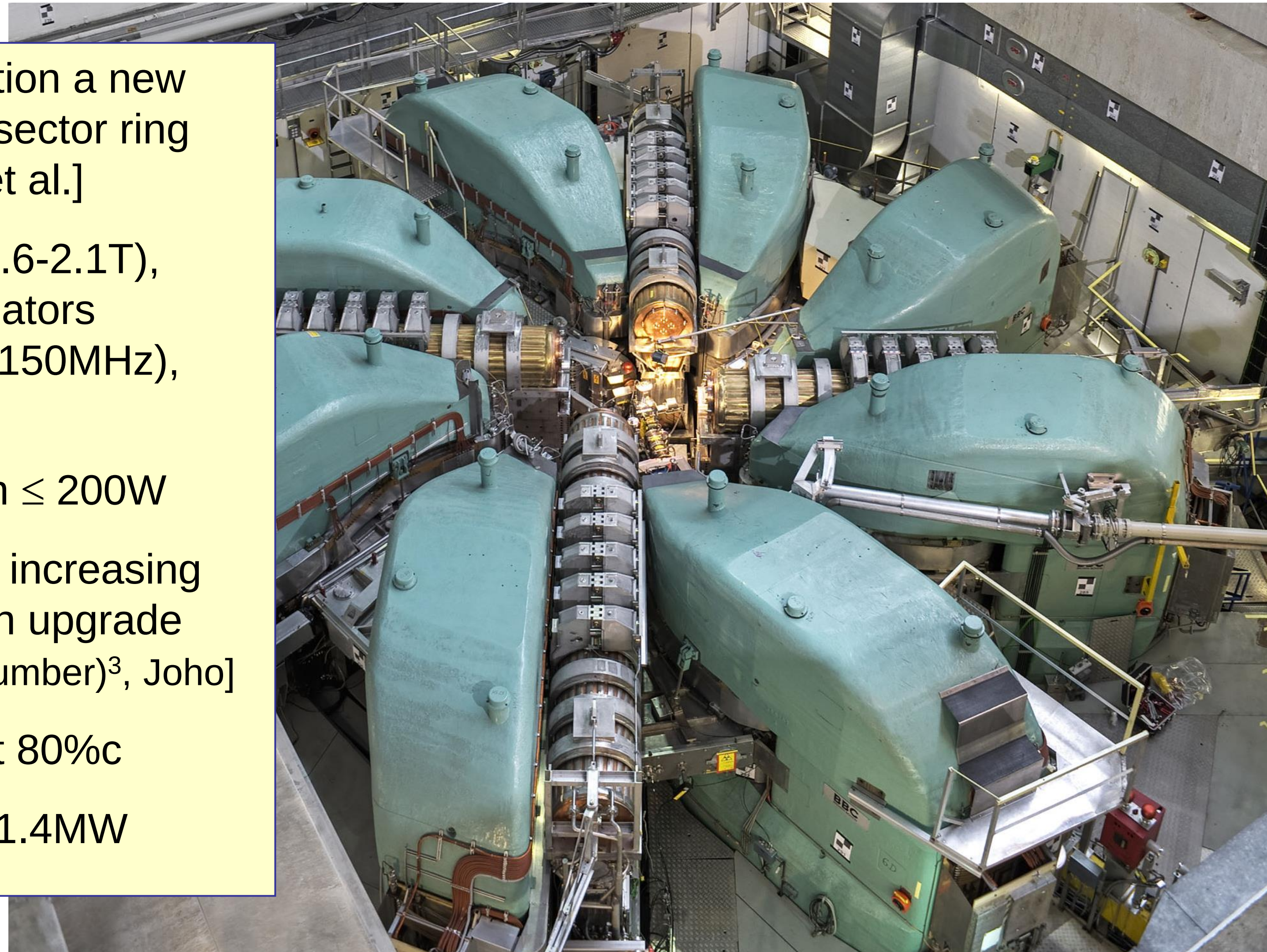
High Intensity

For example:
Search for $\mu \rightarrow e\gamma$



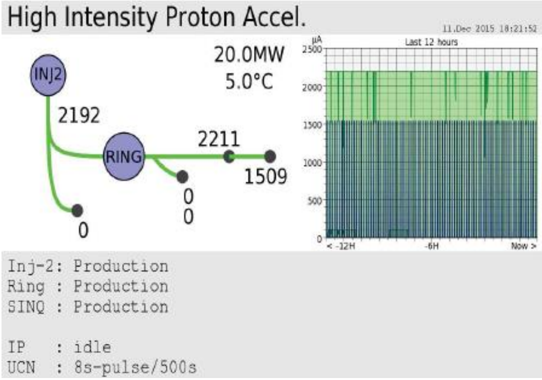


PSI ring cyclotron

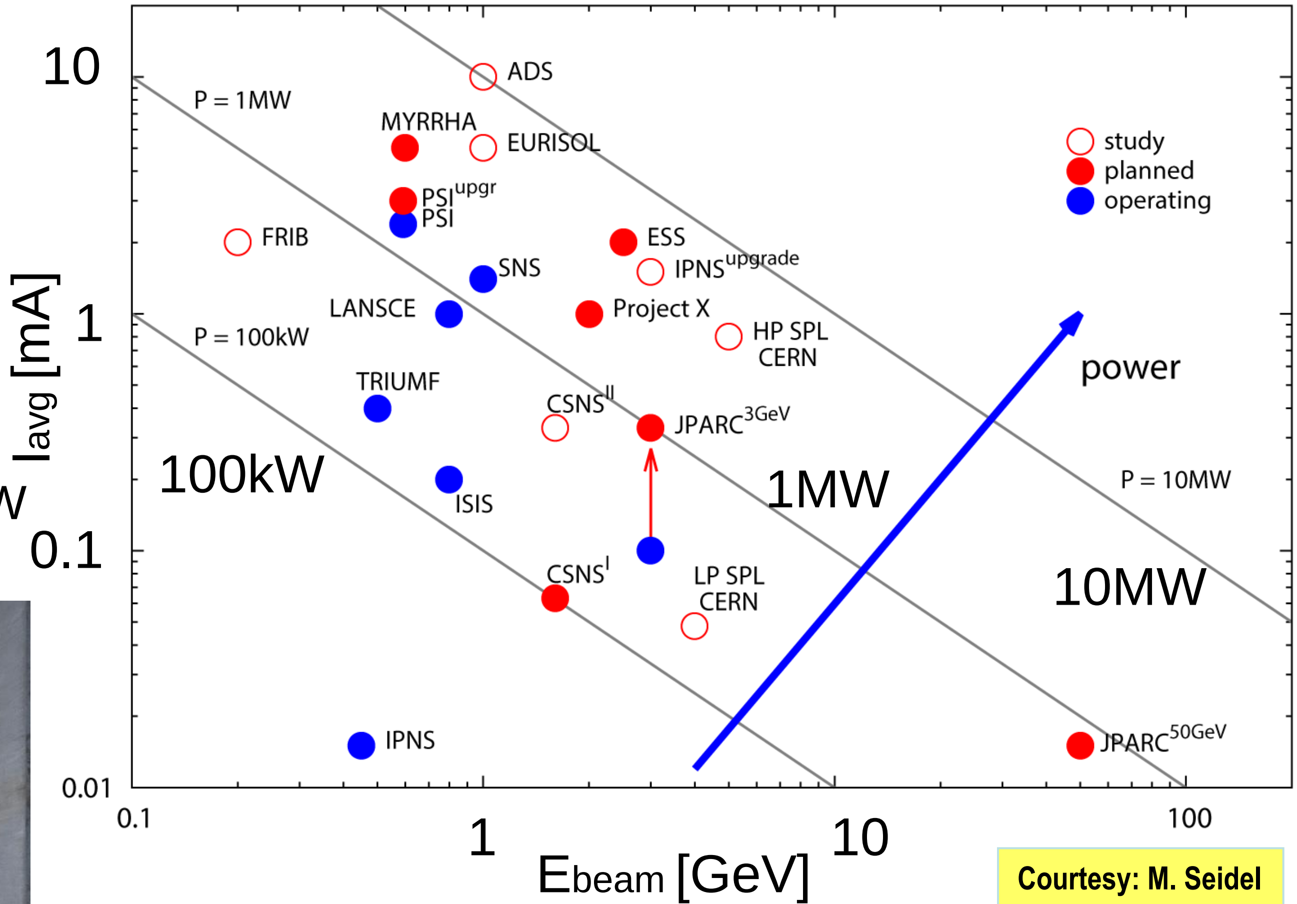


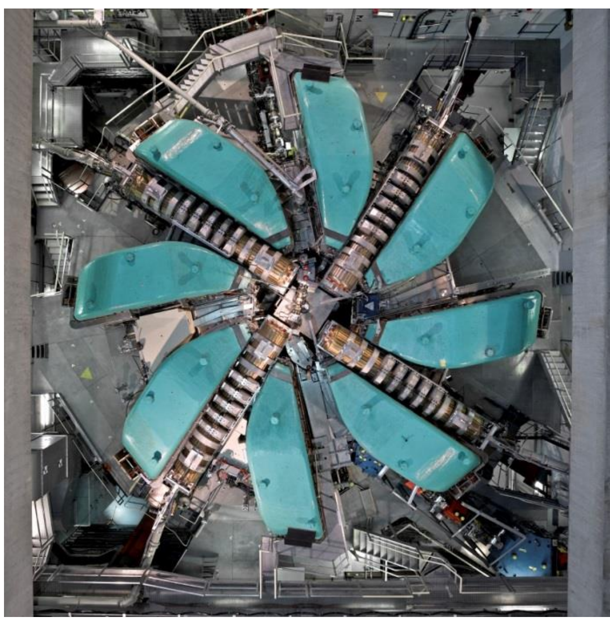
- at time of construction a new concept: separated sector ring cyclotron [H.Willax et al.]
- 8 magnets (280t, 1.6-2.1T), 4 accelerating resonators (50MHz), 1 Flattop (150MHz), ∅ 15m
- losses at extraction ≤ 200W
- reducing losses by increasing RF voltage was main upgrade path [losses $\propto$ (turn number)^3, 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





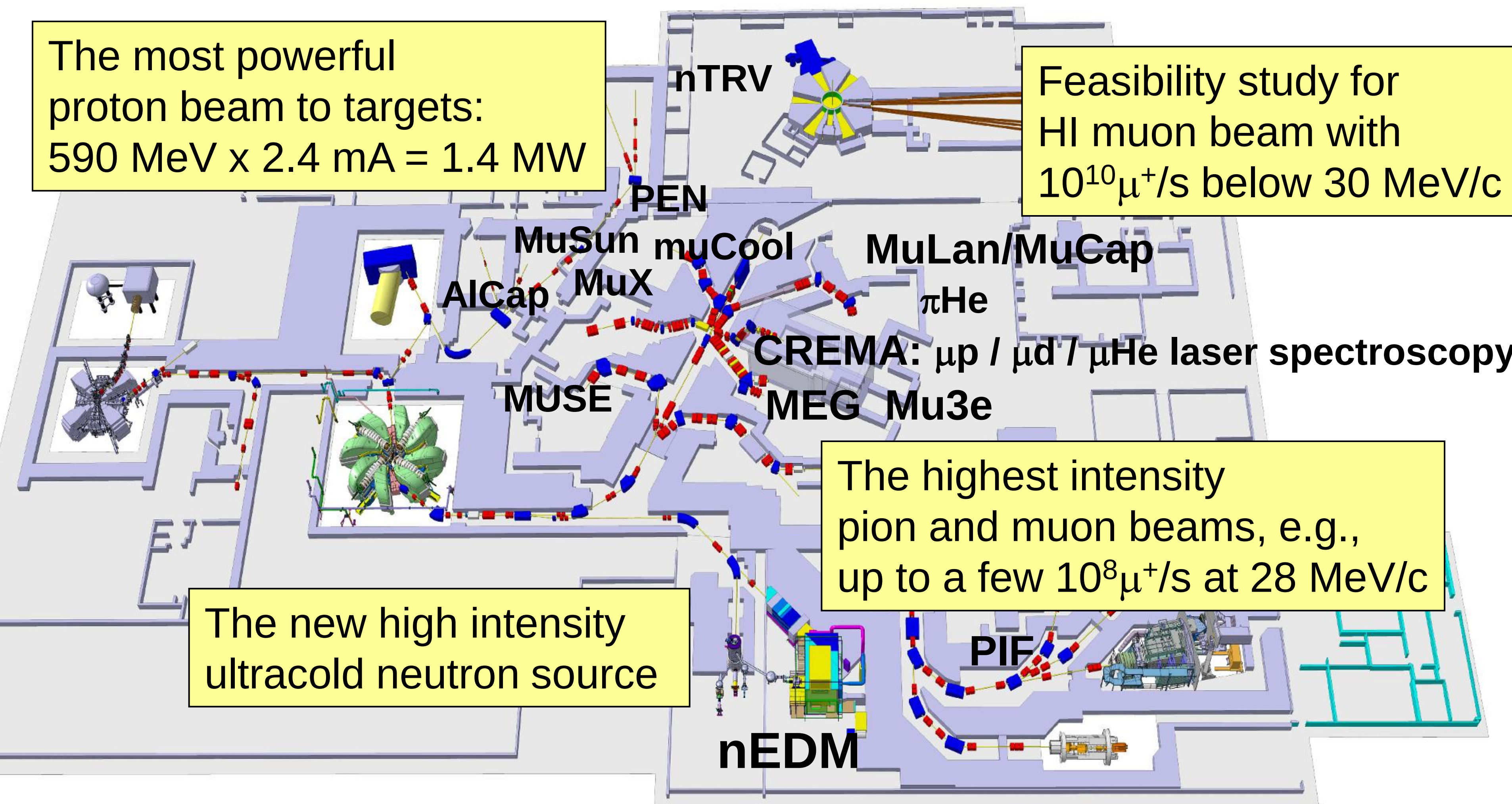
HIPA at PSI is a leading machine at the intensity frontier.
It produces the highest intensities of muons and pions at low momenta and of ultracold neutrons.

The intensity frontier at PSI: π, μ, UCN

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

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

Feasibility study for
HI muon beam with
$10^{10}\mu^+$/s below 30 MeV/c



The highest intensity
pion and muon beams, e.g.,
up to a few $10^8\mu^+$/s at 28 MeV/c

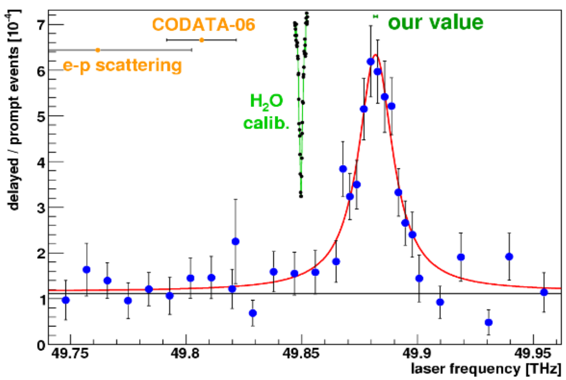
The new high intensity
ultracold neutron source

Swiss national laboratory with strong international collaborations

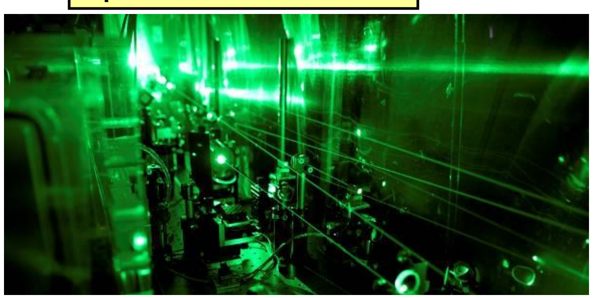
Fundamental physics with muons

Bound state QED

The most precise value of the **proton charge radius** via a measurement of the Lambshift in muonic hydrogen



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

Weak interaction

The most precise measurement of any lifetime: **MuLan**´s μ^+ and a 0.6 ppm determination of the **Fermi coupling constant**

τ = 2 196 980.3 ± 2.2 ps (1.0 ppm)

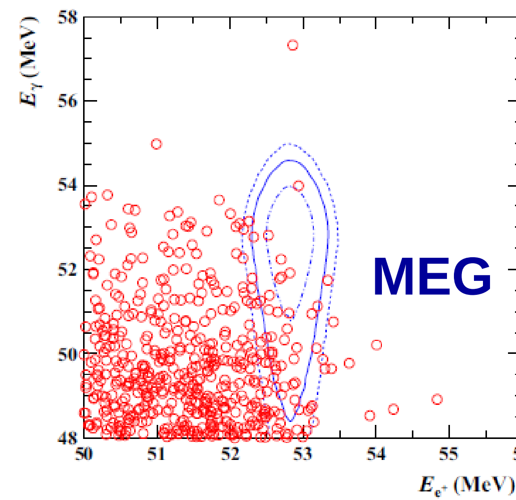
The most precise measurement (10ppm) of the μ^- lifetime in pure hydrogen yields **MuCap**´s 1% determination of the μ^-p capture rate resolving the longstanding issue with the **Pseudoscalar coupling g_p**

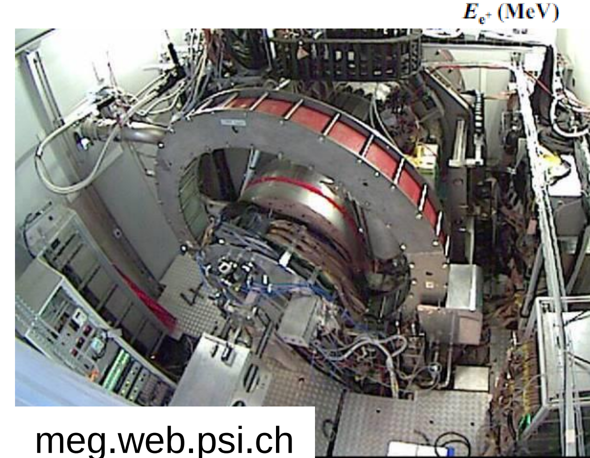
www.npl.washington.edu/muon/

D.M. Webber et al., PRL 106(2011)041803
V.A.Andreev et al., PRL 110(2013)012504

New physics search

The best rare decay limit:
A new **search for $\mu \rightarrow e\gamma$** yields a branching **less than 4.2×10^{-13}**

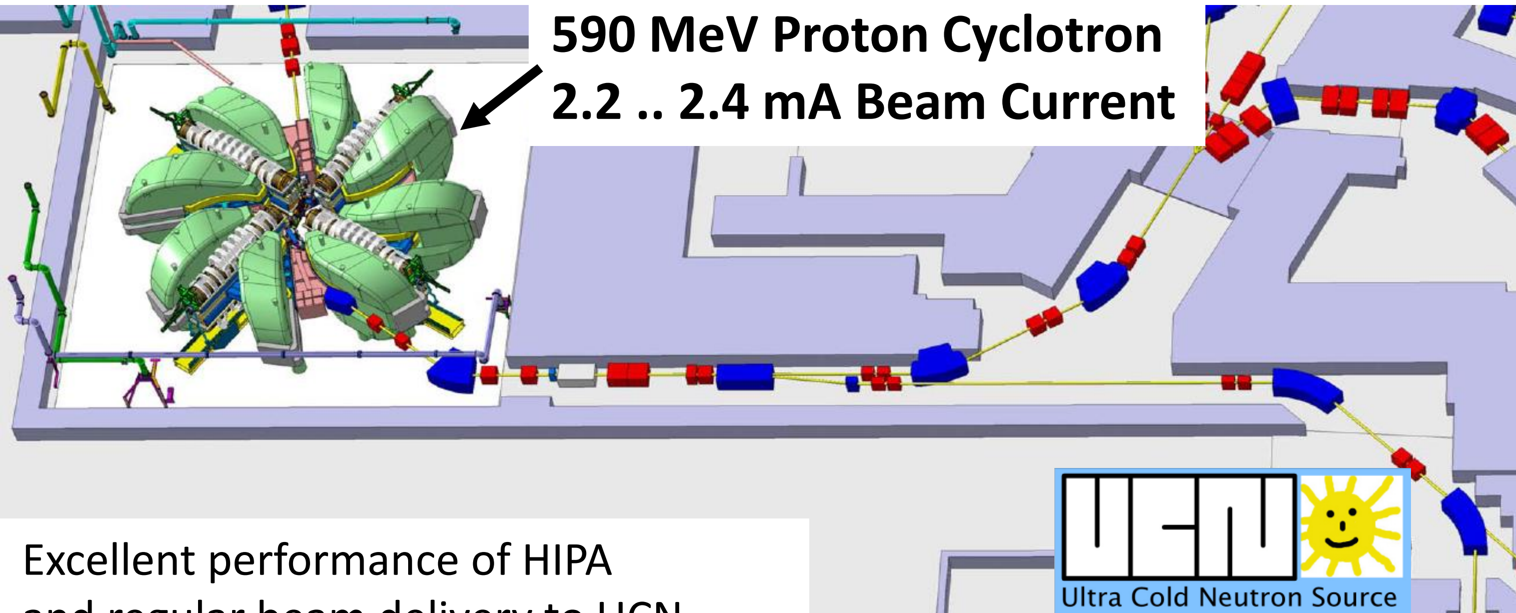


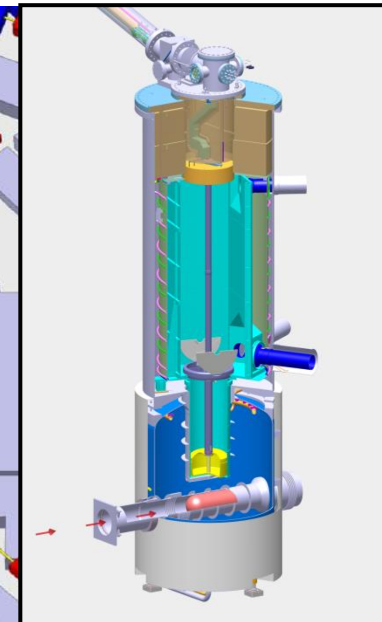


meg.web.psi.ch

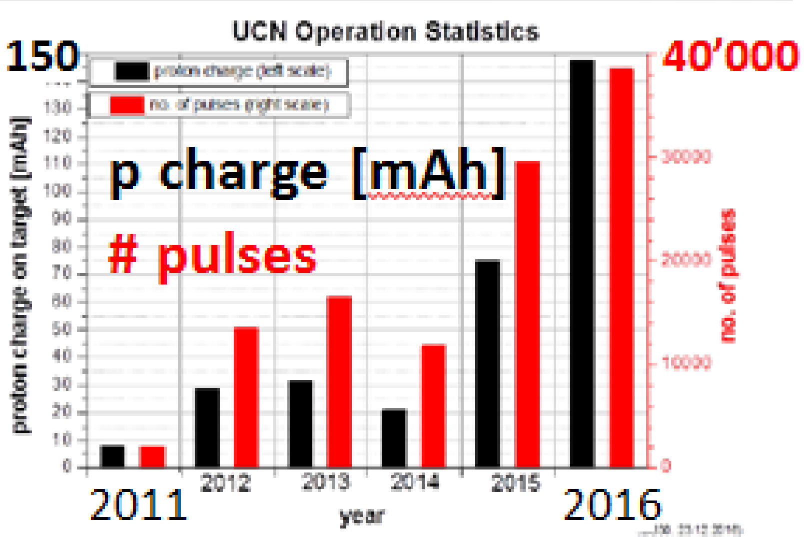
A.M. Baldini et al. EPJ C 76 (2016), 434

Ultracold Neutron Source & Facility





Excellent performance of HIPA
and regular beam delivery to UCN

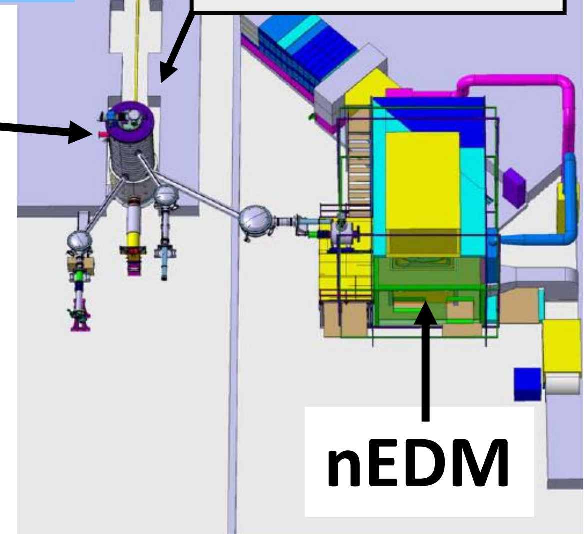


UCN-Source

- 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
- 2018: towards 60μA average



The PSI UCN source

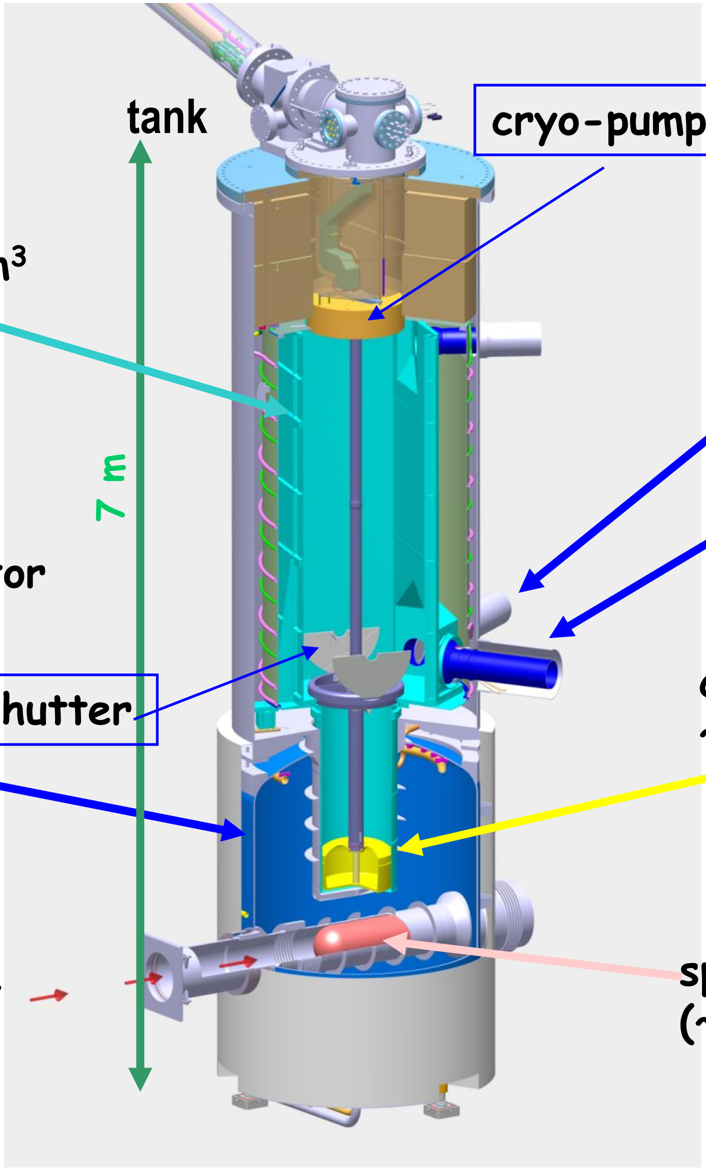
Ultra Cold Neutron Source

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

heavy water moderator
→ thermal neutrons
3.6m^3 D_2O

SV-shutter

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



cryo-pump

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

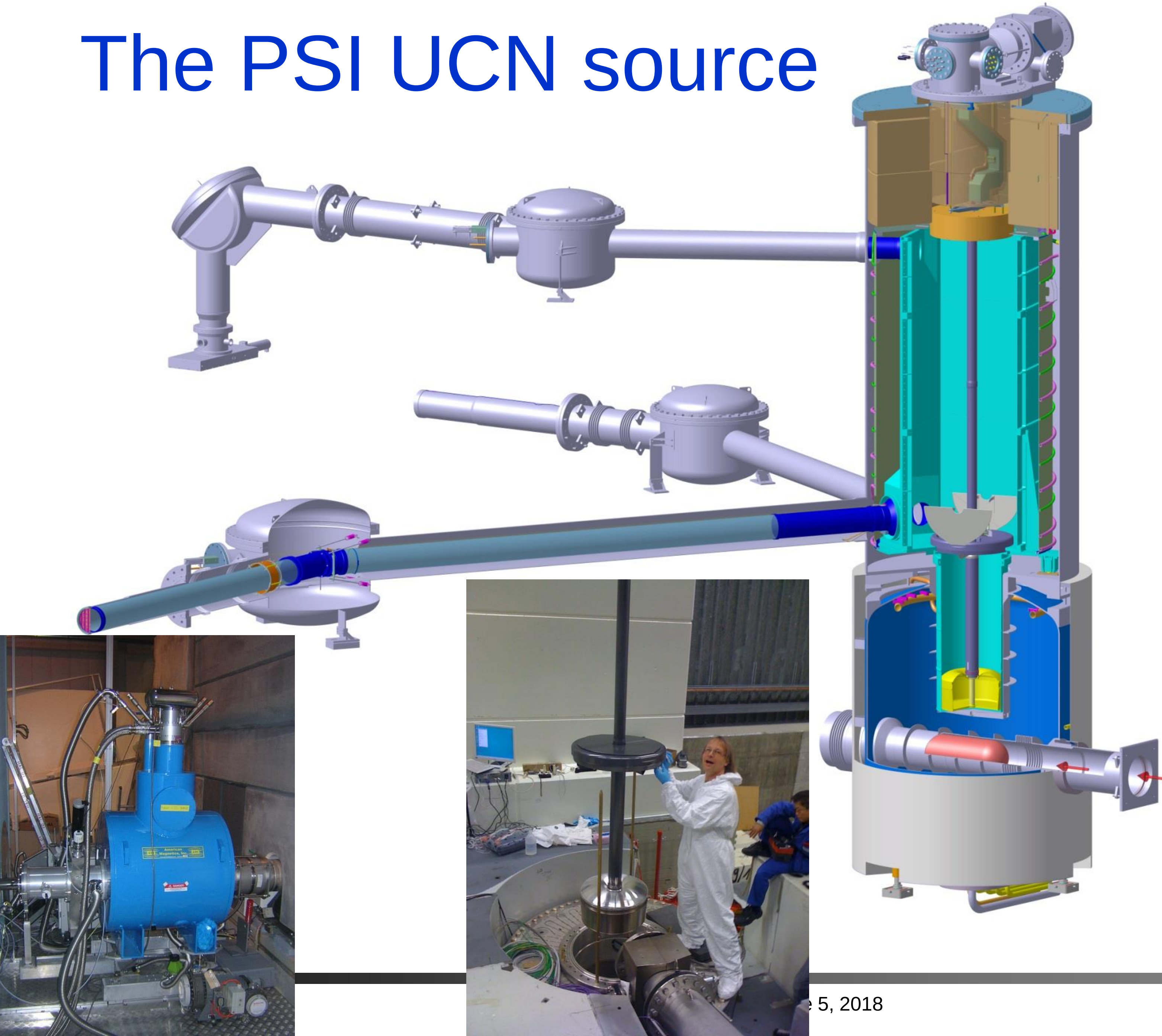
cold UCN-converter
~30 dm^3 solid D_2 at 5 K

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

www.psi.ch/ucn/

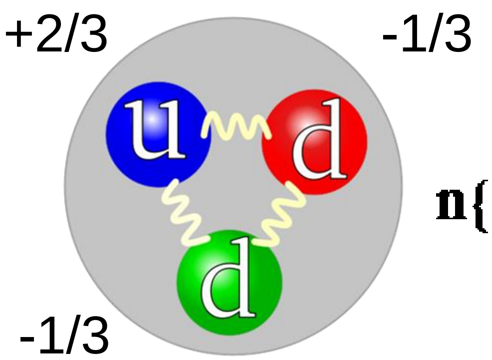
The PSI UCN source

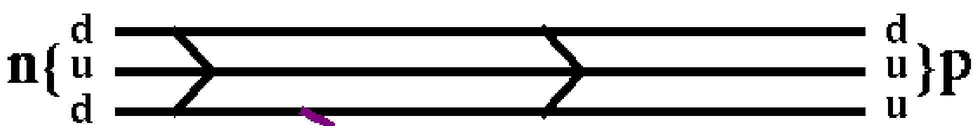
Ultra Cold Neutron Source

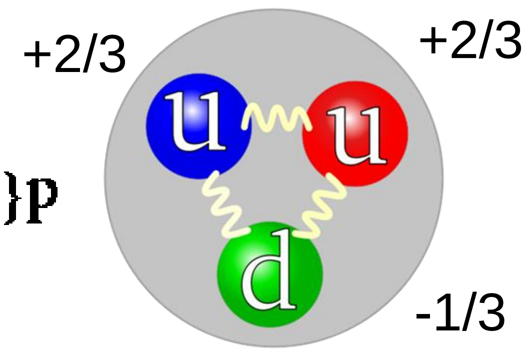


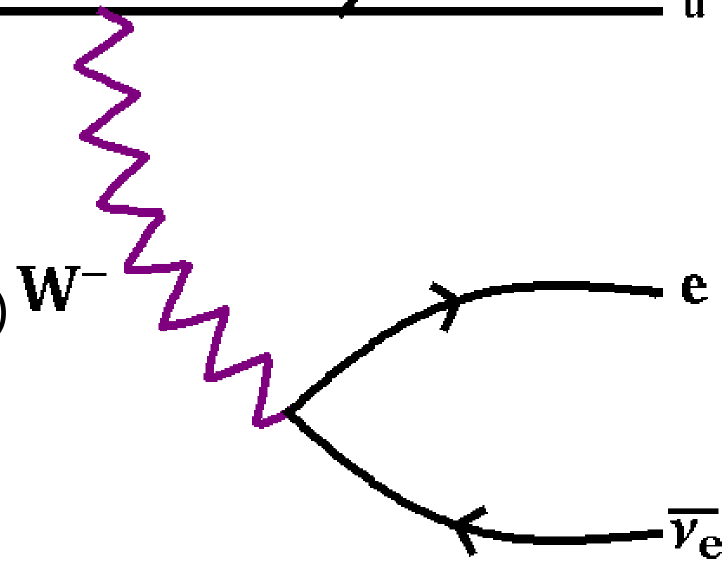
22.07.2010

The Neutron









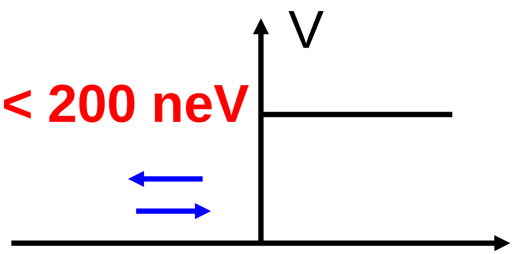
- massive
- composite
- no net electric charge (?)
- unstable
- spin ½, polarizable
- electric dipole (?)
- electrically polarizable
- takes part in all (known) interactions
- …..

Ultracold neutrons

ideal gas with temperature of milli-Kelvin

move with velocities of few m/s

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



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

Observed*:

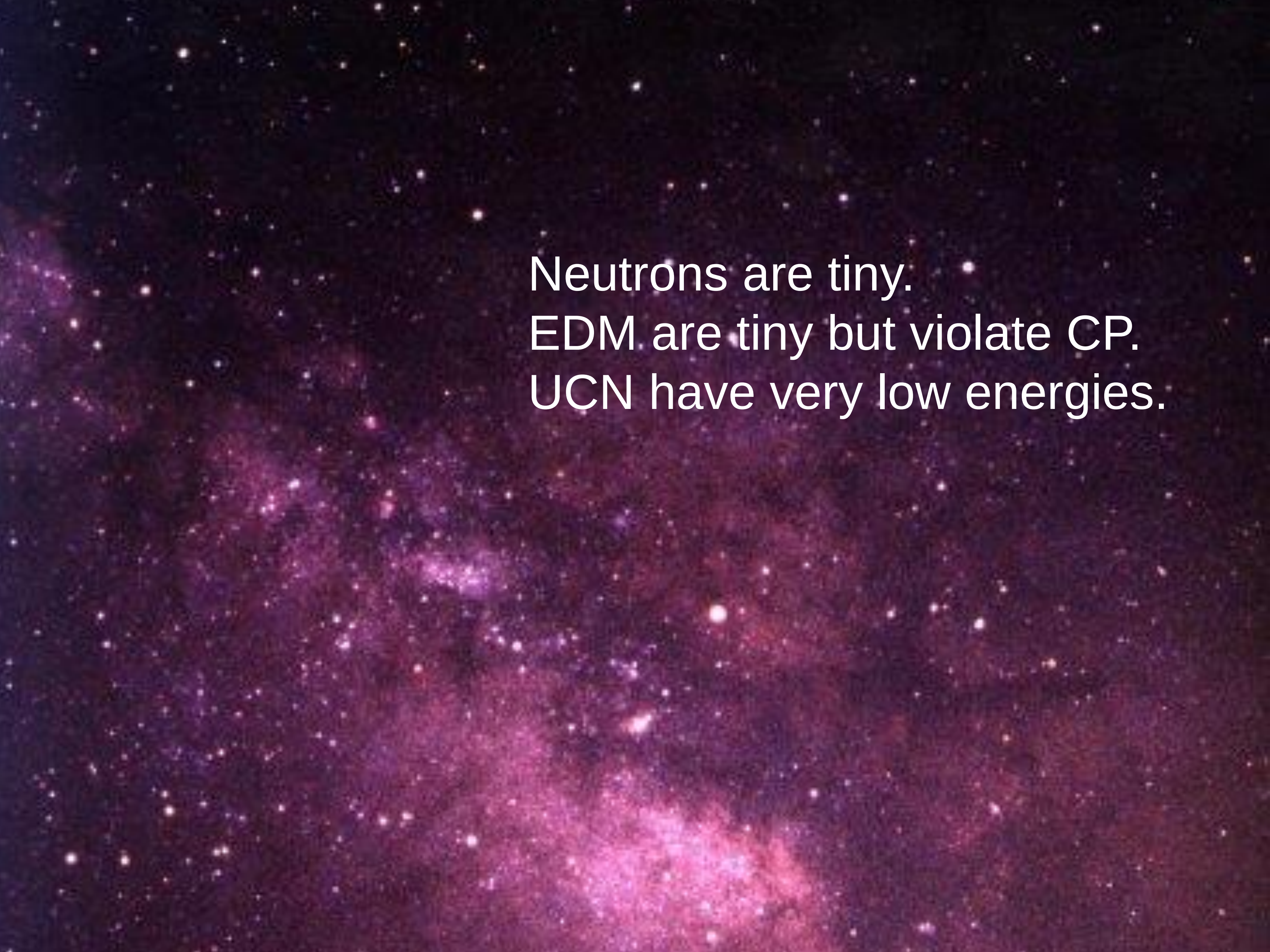
$$(n_B - n_{\bar{B}}) / n_\gamma = 6 \times 10^{-10}$$

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]

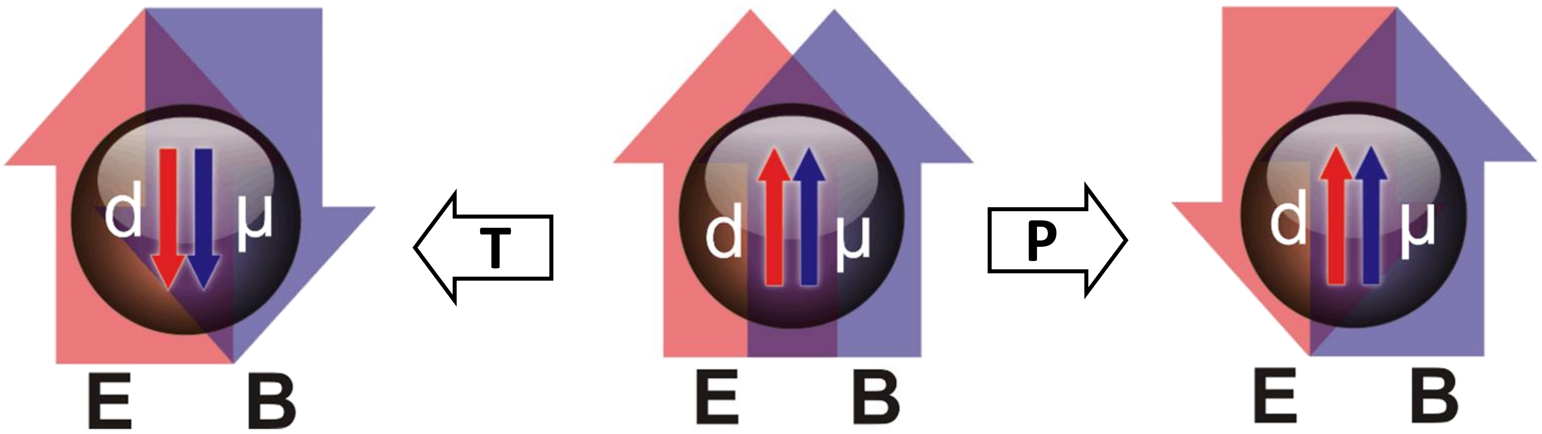
* WMAP + COBE, 2003
$n_B / n_\gamma = (6.1 \pm^{0.3}_{0.2}) \times 10^{-10}$


Neutrons are tiny.
EDM are tiny but violate CP.
UCN have very low energies.

Neutrons are tiny.
EDM are tiny but violate CP.
UCN have very low energies.

Yet, you will see that they are sensitive to energies of TeV and even up to 10^{19}GeV.

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

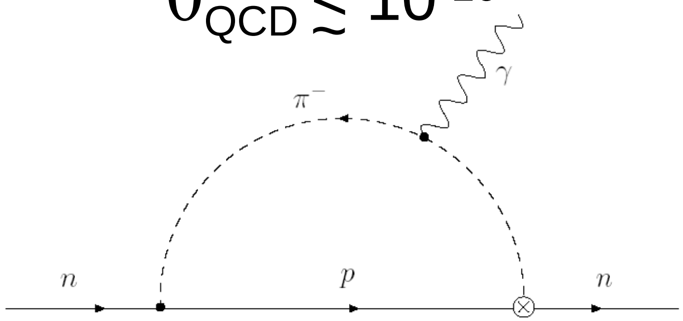
Caveat:

The strong CP problem

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

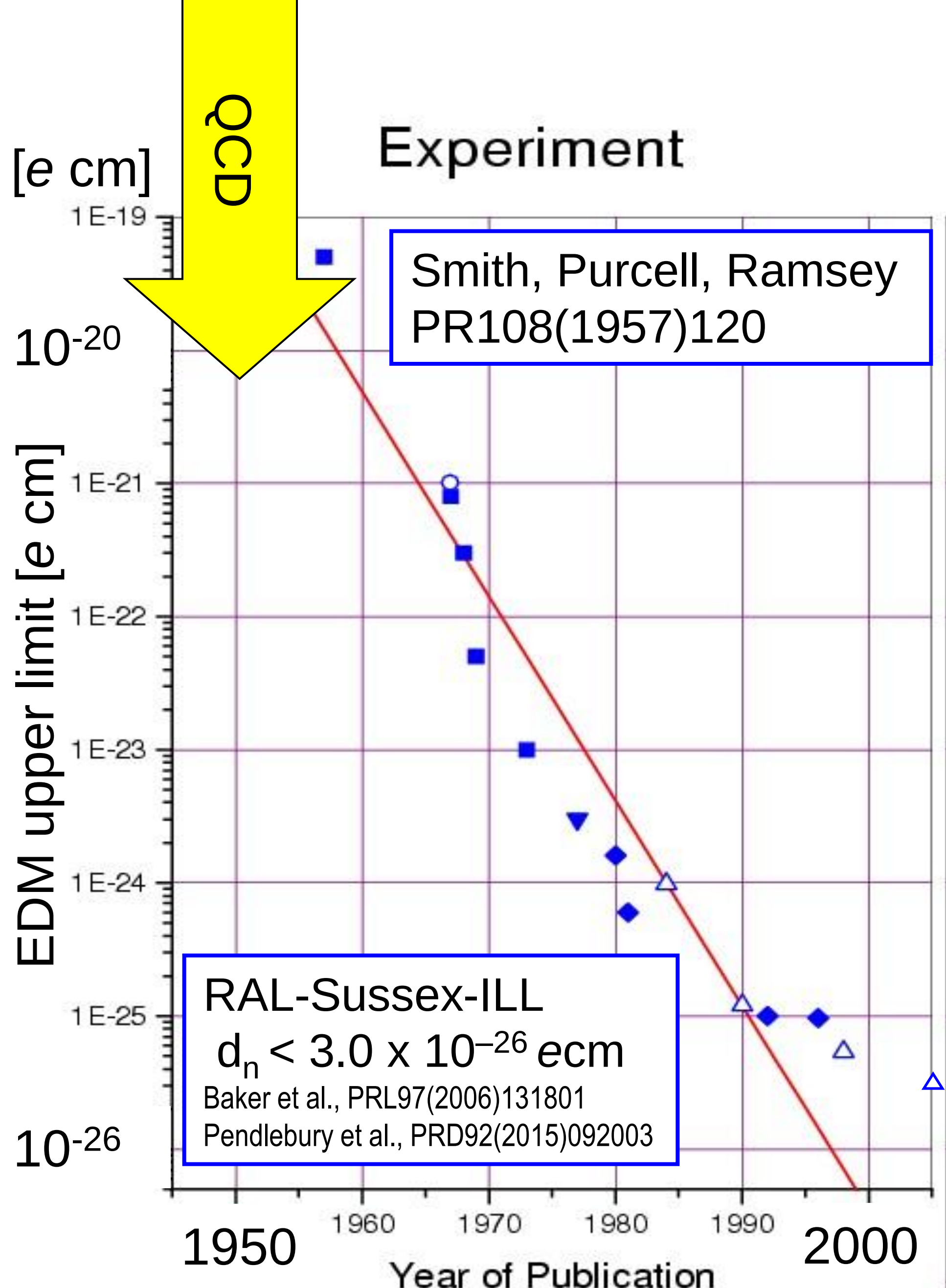
$$d_n \approx 10^{-16}\ e\ \mathrm{cm} \cdot \theta_{QCD}$$

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



Why is θ_{QCD} so small ?

→ accidentally small !?



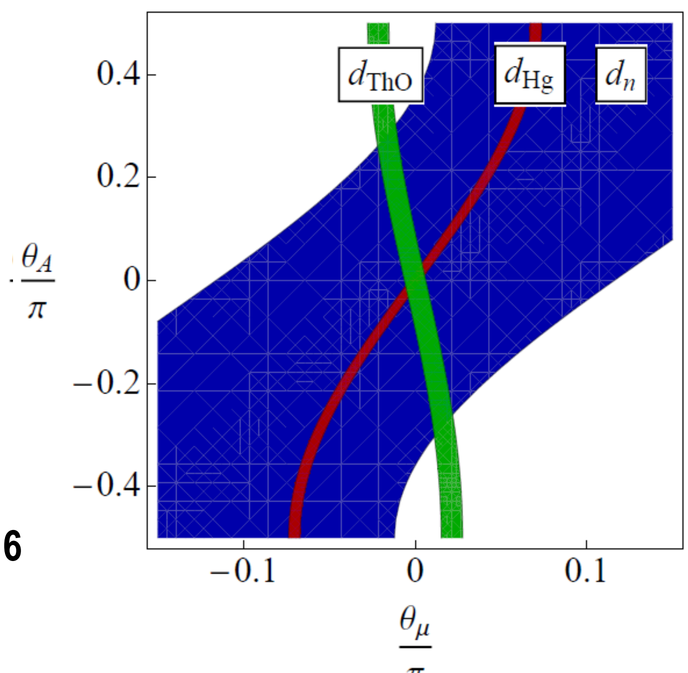
The SUSY CP problem

(for neutron and electron!)

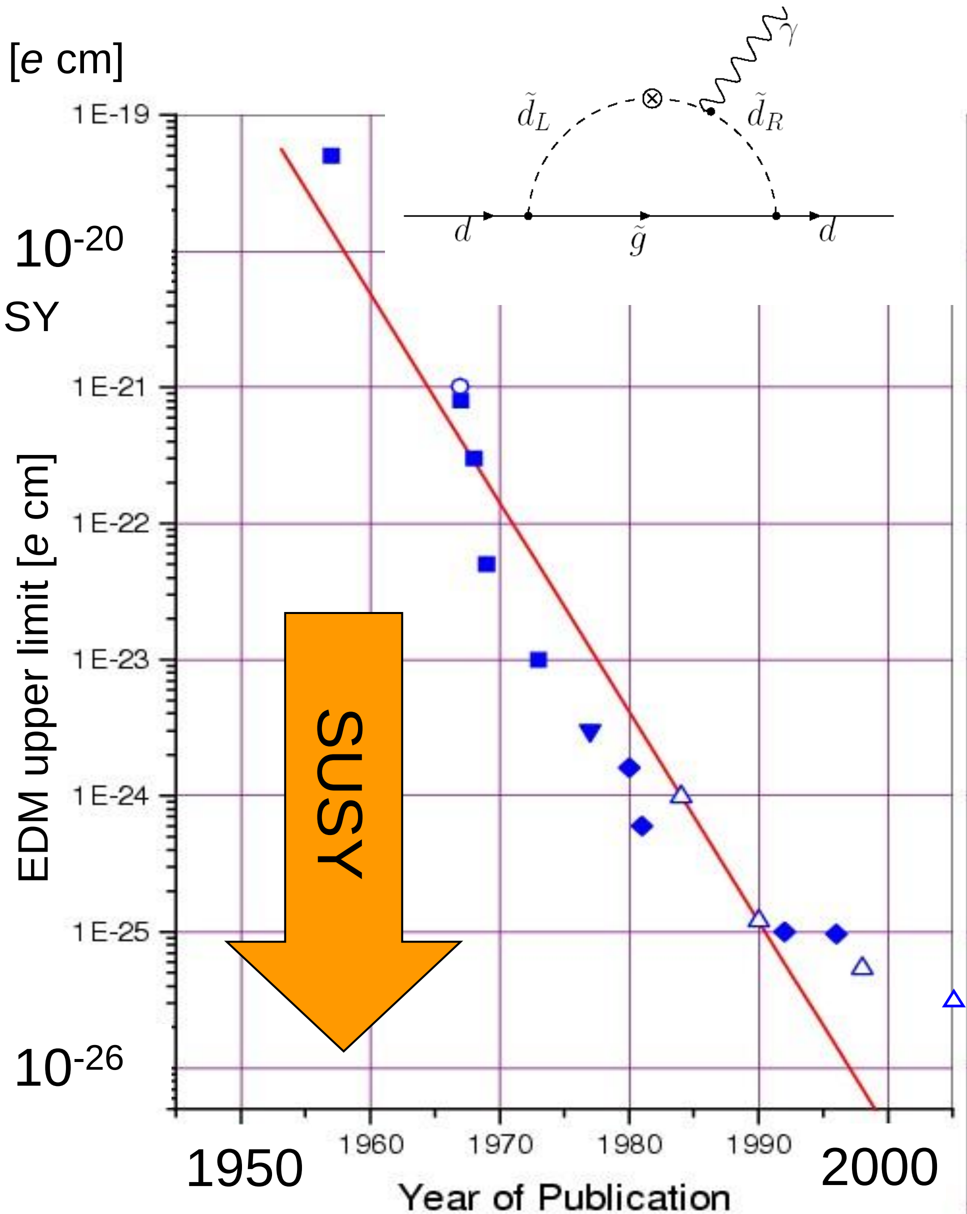
$$d_n \approx 10^{-23}\, e\ \text{cm} \left(\frac{300\ \text{GeV}/c^2}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

Why is ϕ_{SUSY} so small ?

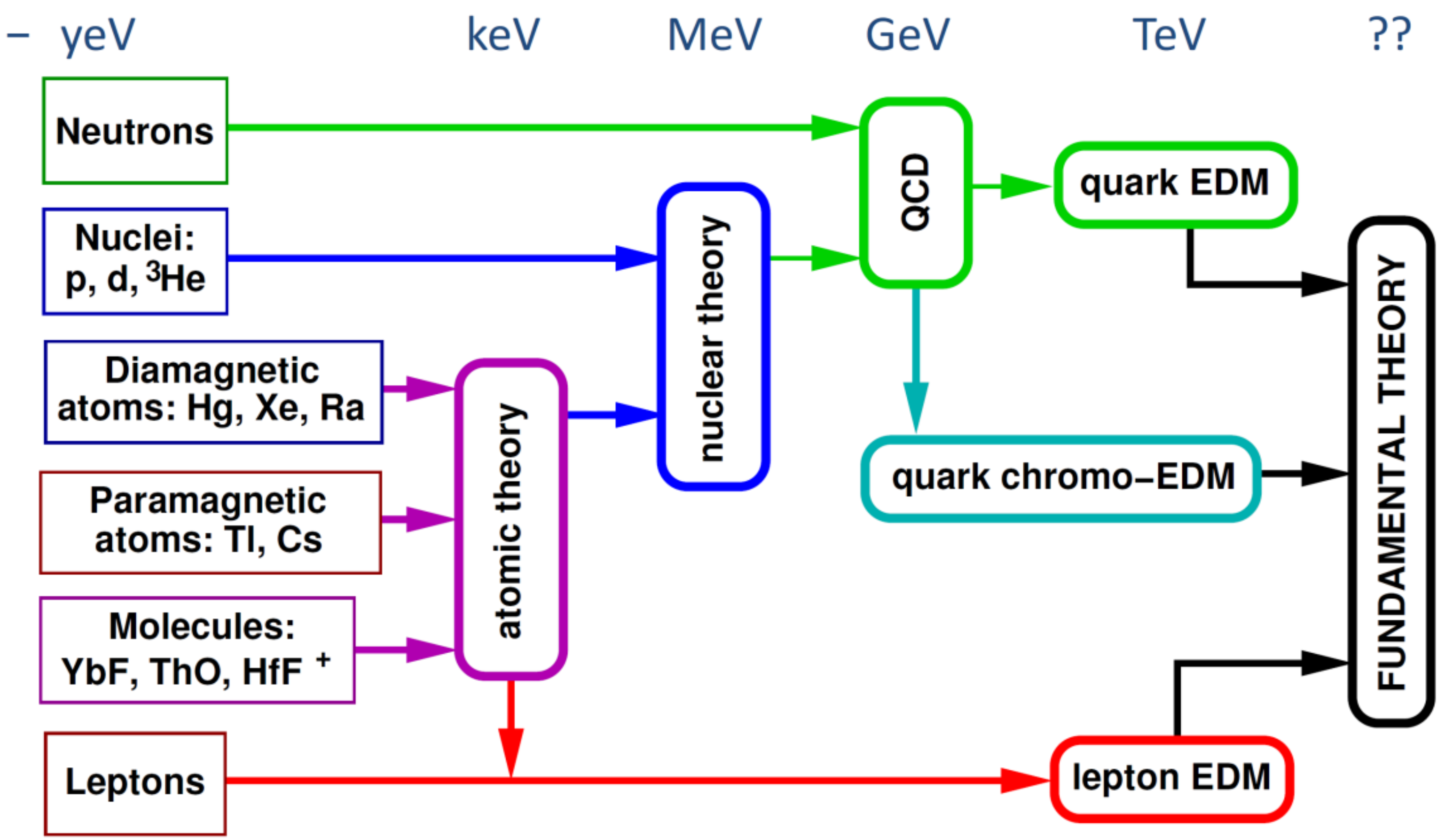
(this is testing M already to 10TeV and you may also ask: why are the masses so huge?)



A. Ritz, update 2016



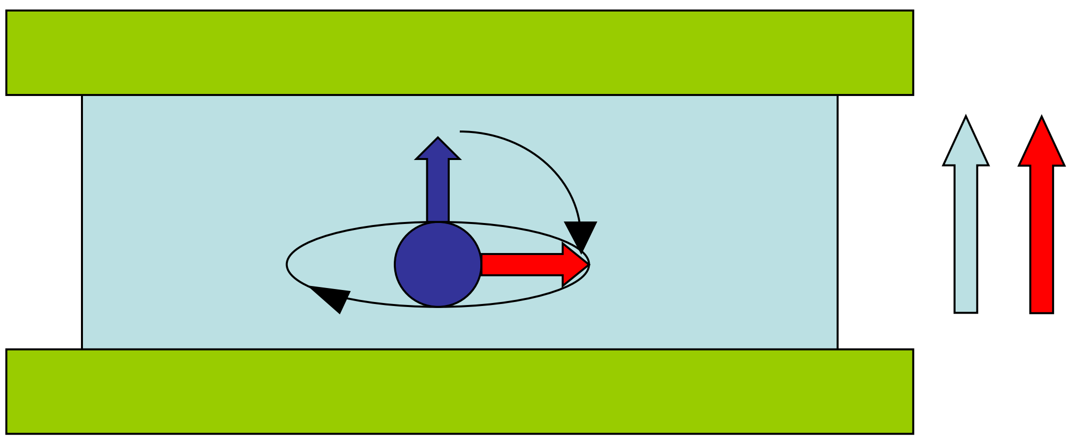
Connecting experiments and theory



Scheme: courtesy Rob G. E. Timmermans

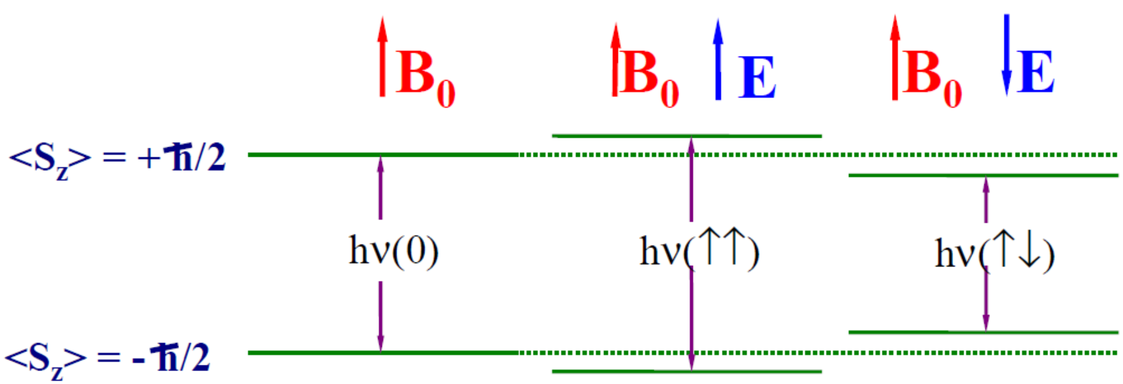
See also: Pospelov, Ritz, Ann. Phys. 318(2005)119

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



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

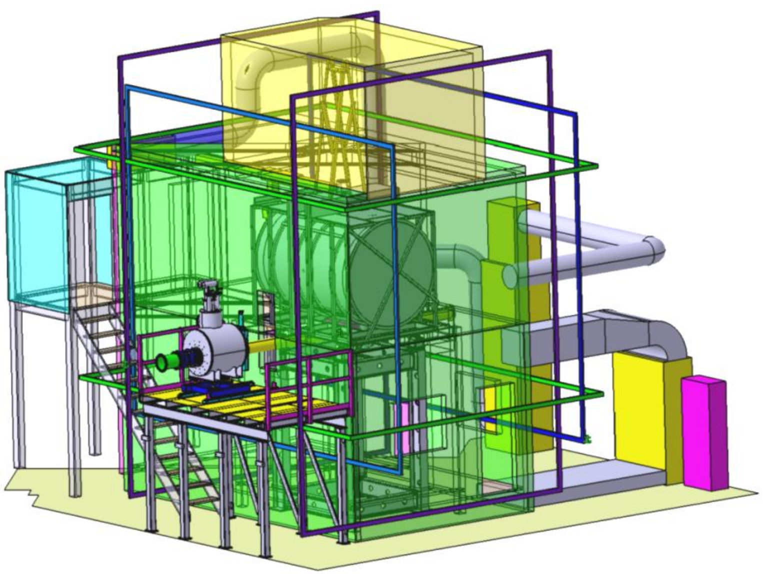
$$h\Delta\nu = 4\, d_n\, E$$



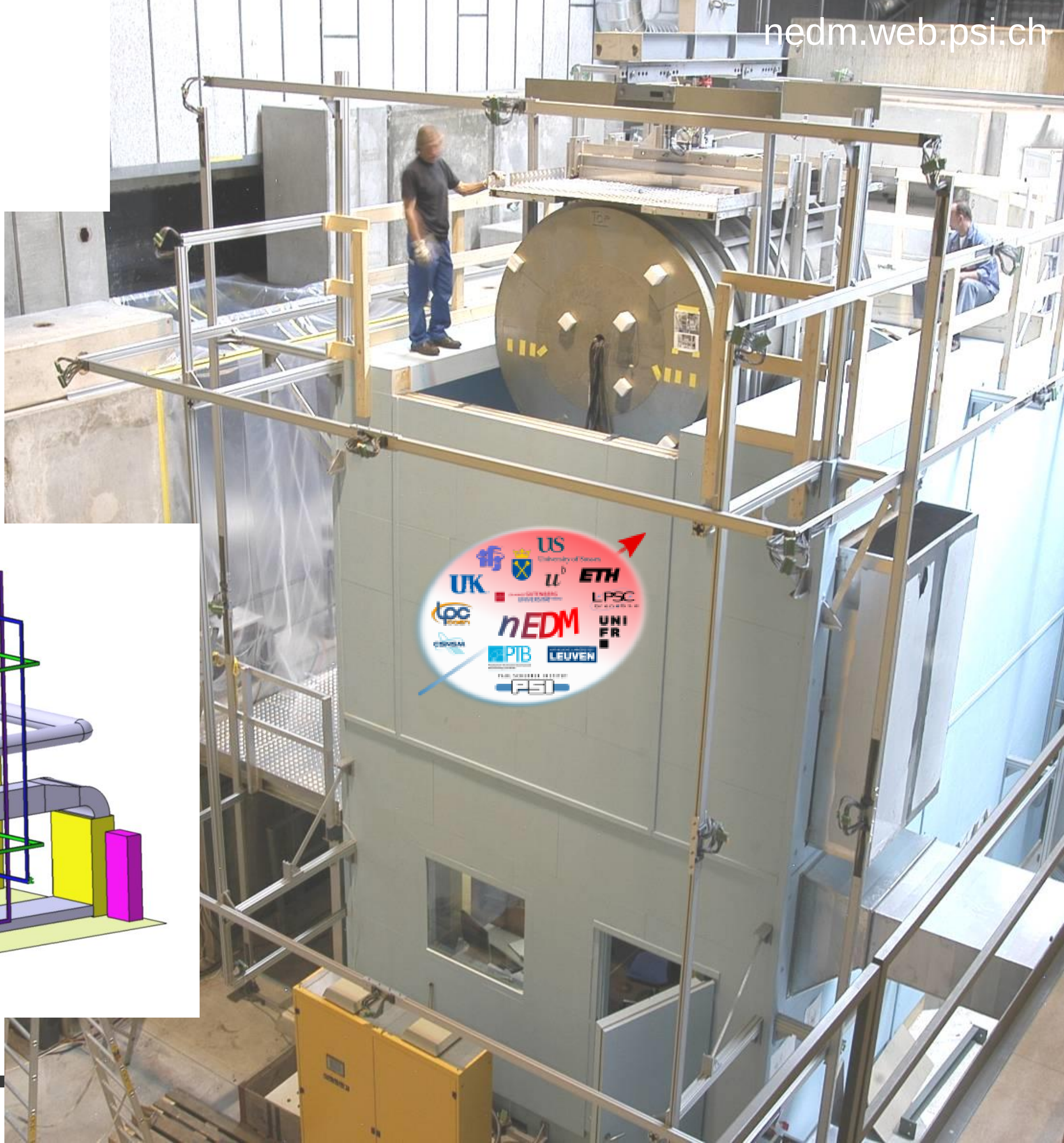
$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

nEDM at PSI 2009 – 17

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



www.psi.ch/nedm/

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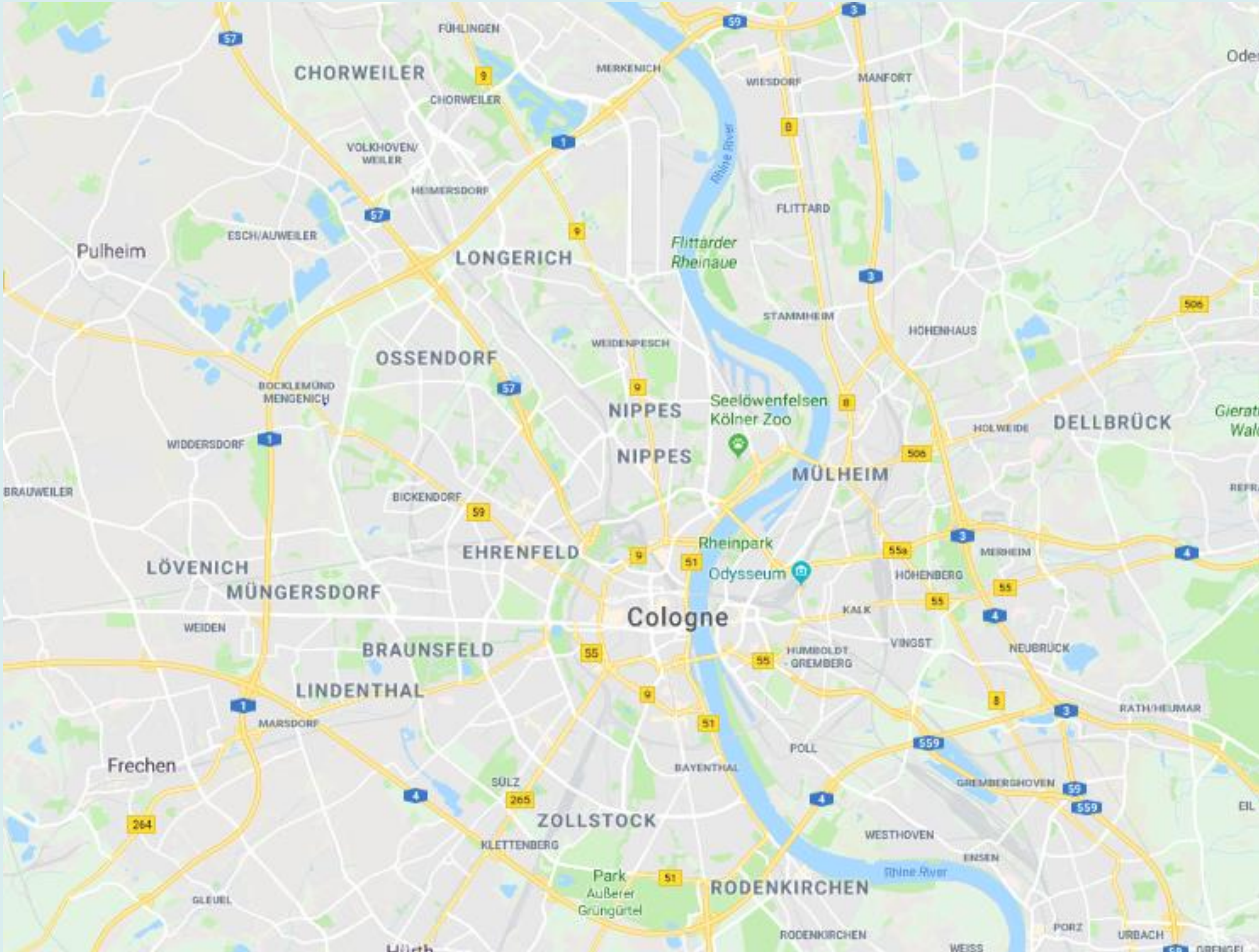
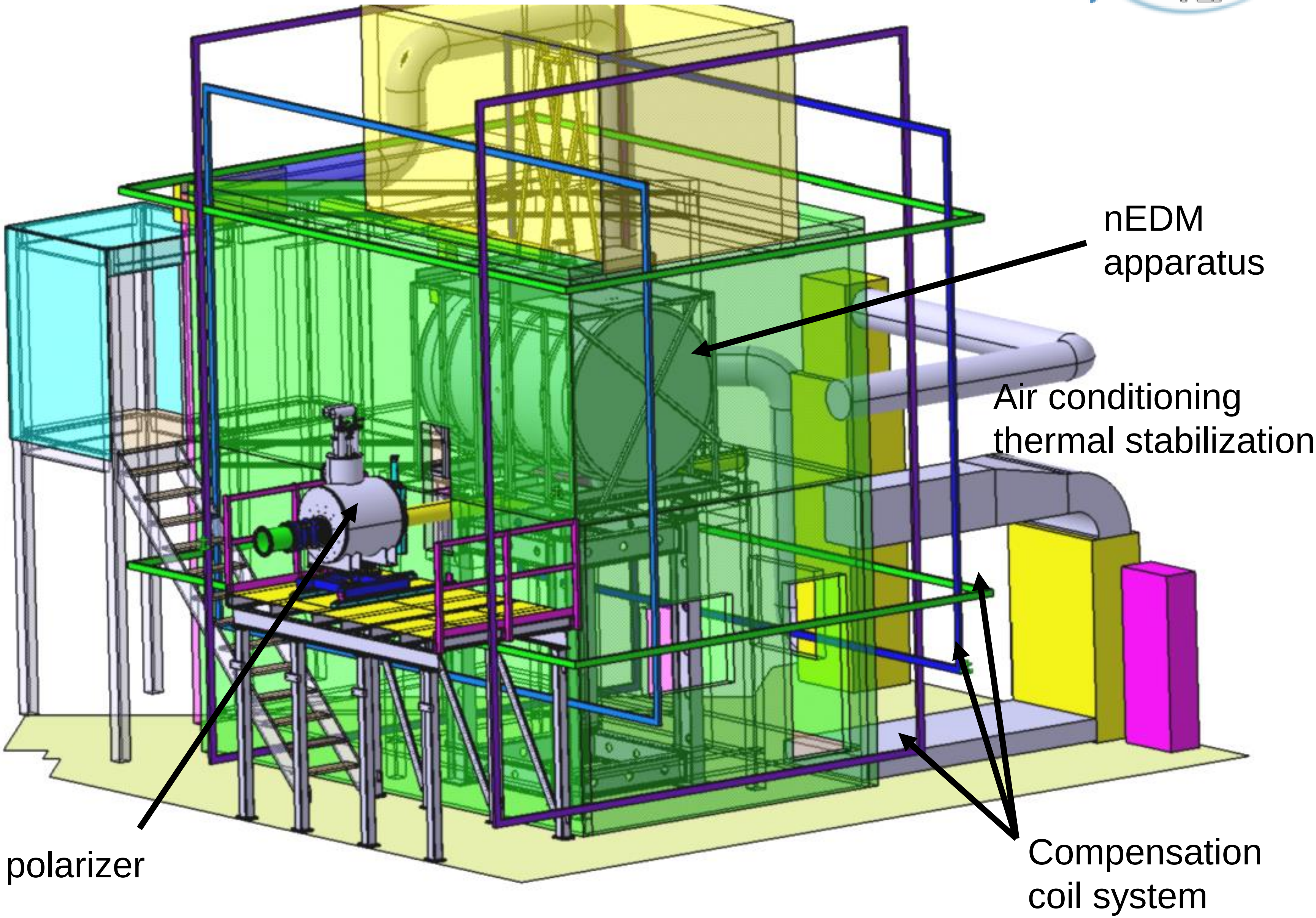
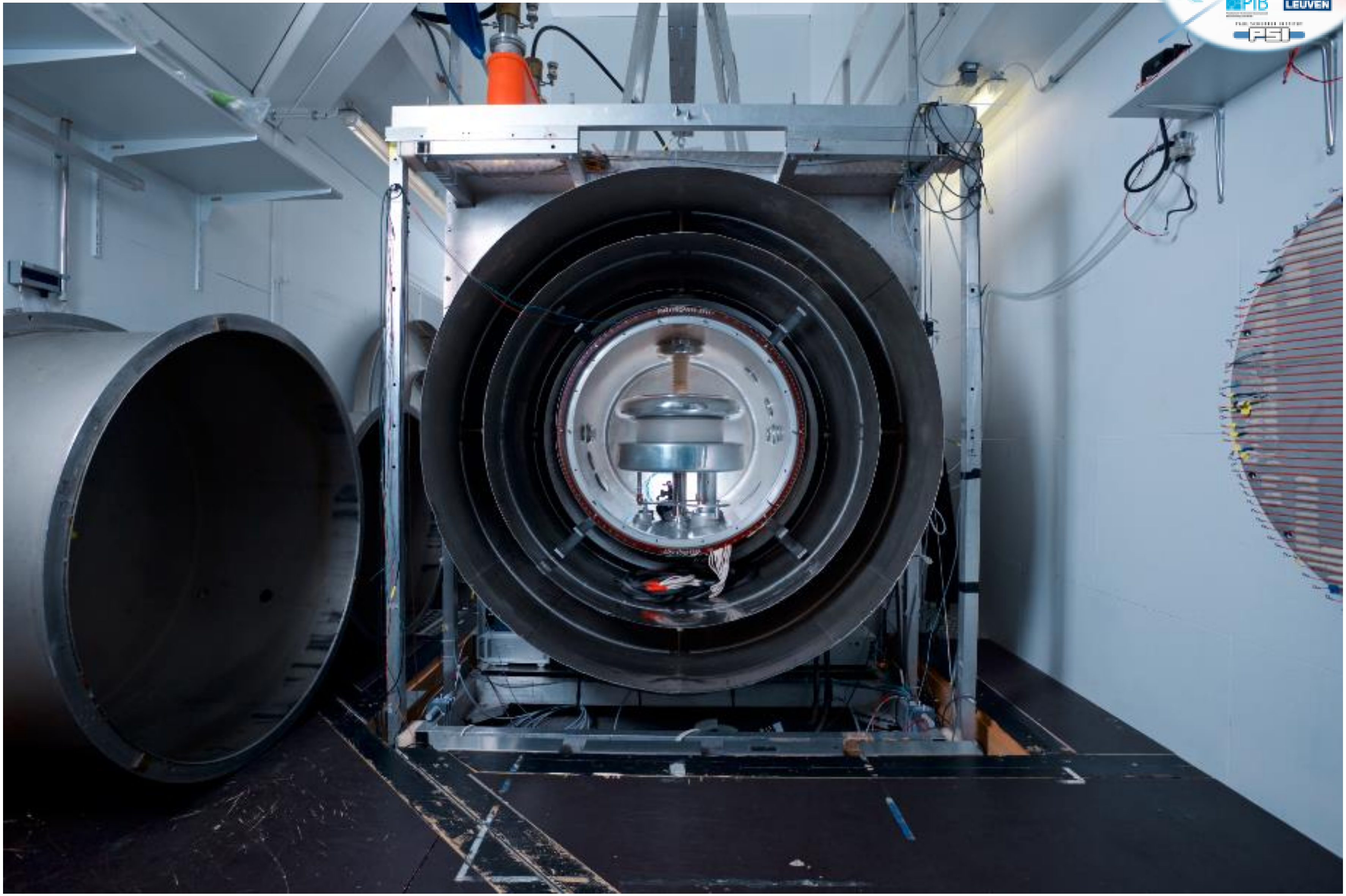

CHORWEILER
FÜHLINGEN
MERKENICH
WIESDORF
MANFORT
Odent
VOLKHOVEN/
WEILER
HEIMERSDORF
FLITTARD
Pulheim
ESCH/AUWEILER
LONGERICH
Flittarder
Rheinaue
Rhine River
STAMMHEIM
HÖHENHAUS
WEIDENPESCH
OSSENDORF
BOCKLEMÜND
MENGENICH
NIPPES
Seelöwenfelsen
Kölner Zoo
HOLWEIDE
DELLBRÜCK
Gierath
Wald
WIDDERSDORF
MÜLHEIM
BRAUWEILER
BICKENDORF
REFRAT
Rheinpark
EHRENFELD
MERHEIM
LÖVENICH
Odysseum
HÖHENBERG
MÜNGERSDORF
Cologne
KALK
WEIDEN
VINGST
BRAUNSFELD
HUMBOLDT
- GREMBERG
NEUBRÜCK
LINDENTHAL
RATH/HEUMAR
MARSDORF
POLL
Frechen
BAYENTHAL
SÜLZ
GREMBERGHOVEN
EIL
ZOLLSTOCK
KLETTENBERG
WESTHOVEN
ENSEN
Park
Äußerer
Grüngürtel
RODENKIRCHEN
GLEUEL
PORZ
URBACH
Hürth
WEISS
GRENGEL

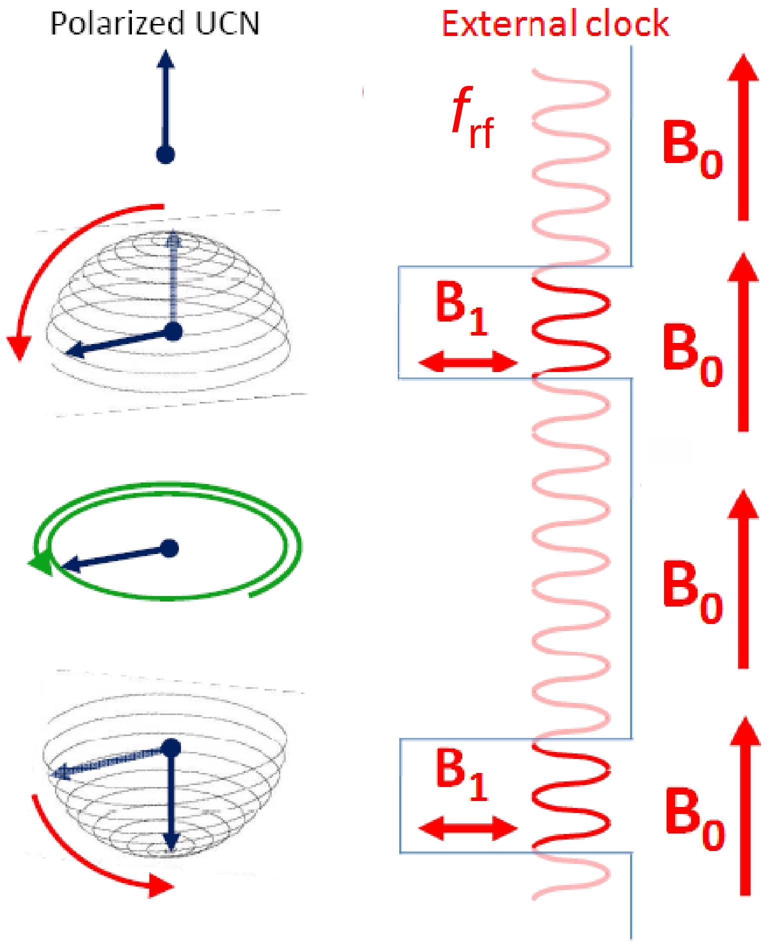
nEDM setup at PSI

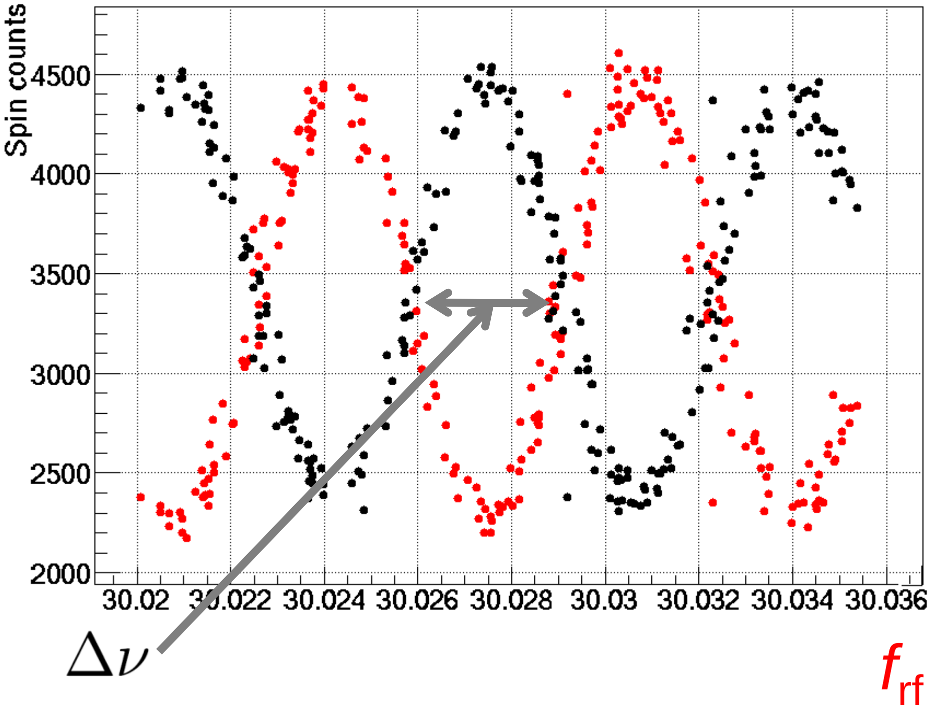


nEDM at PSI



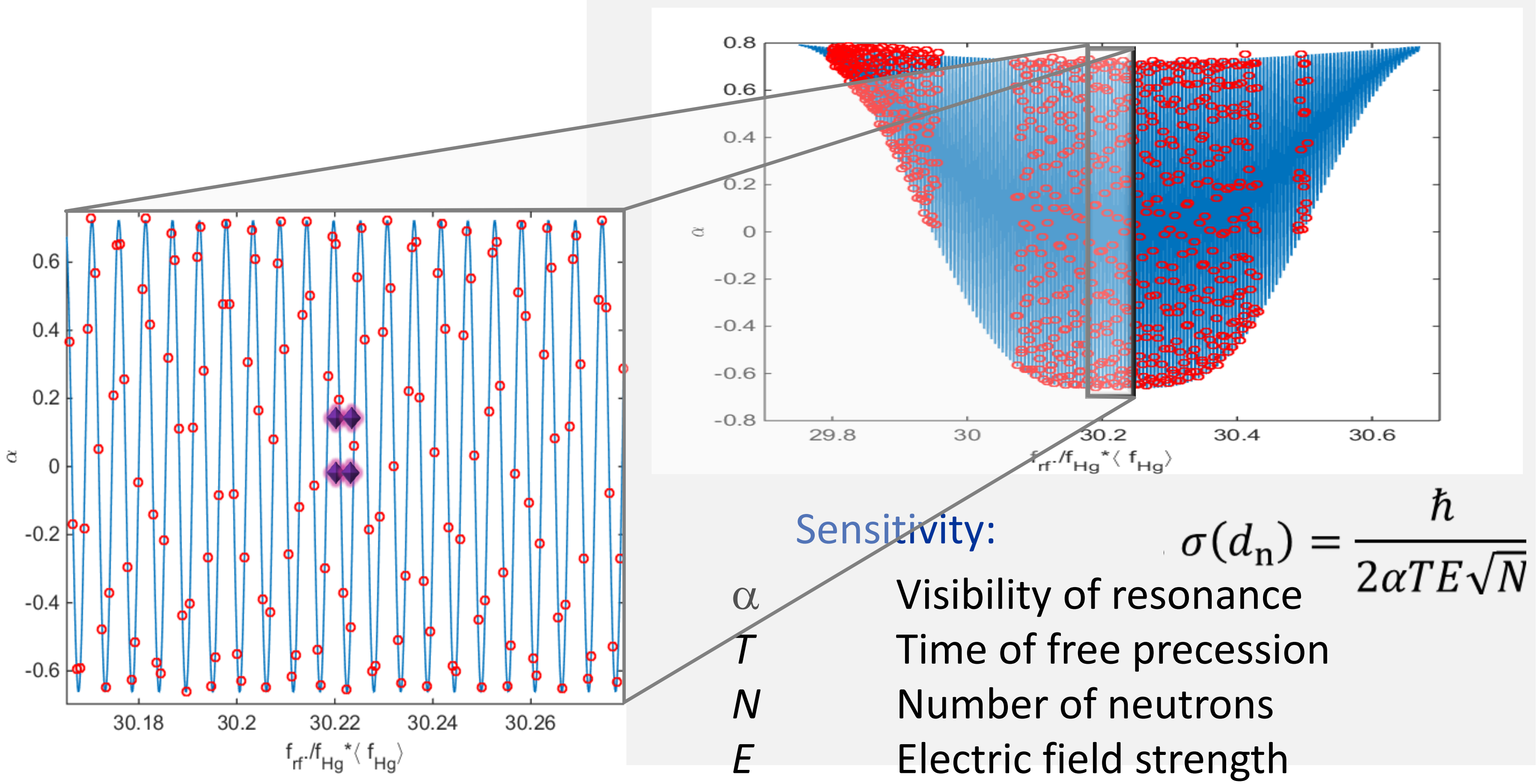
Ramsey's method with UCN





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

Ramsey's method with UCN

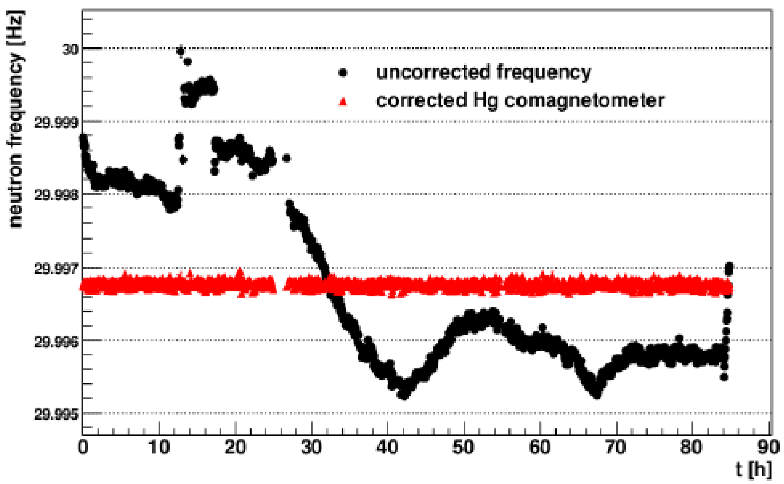


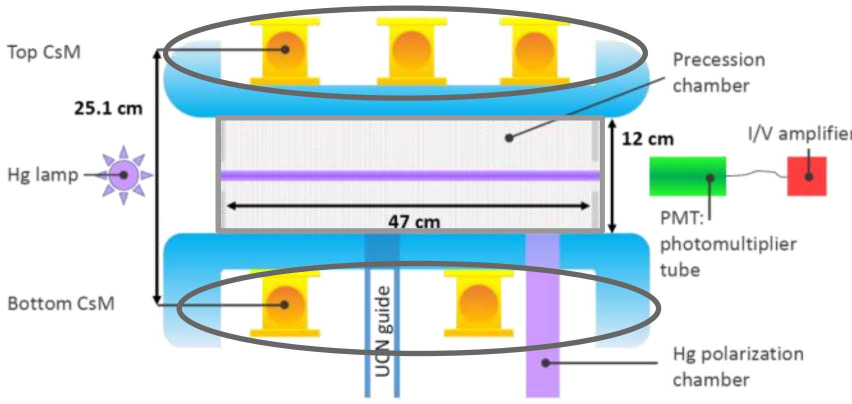
Sensitivity:

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

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

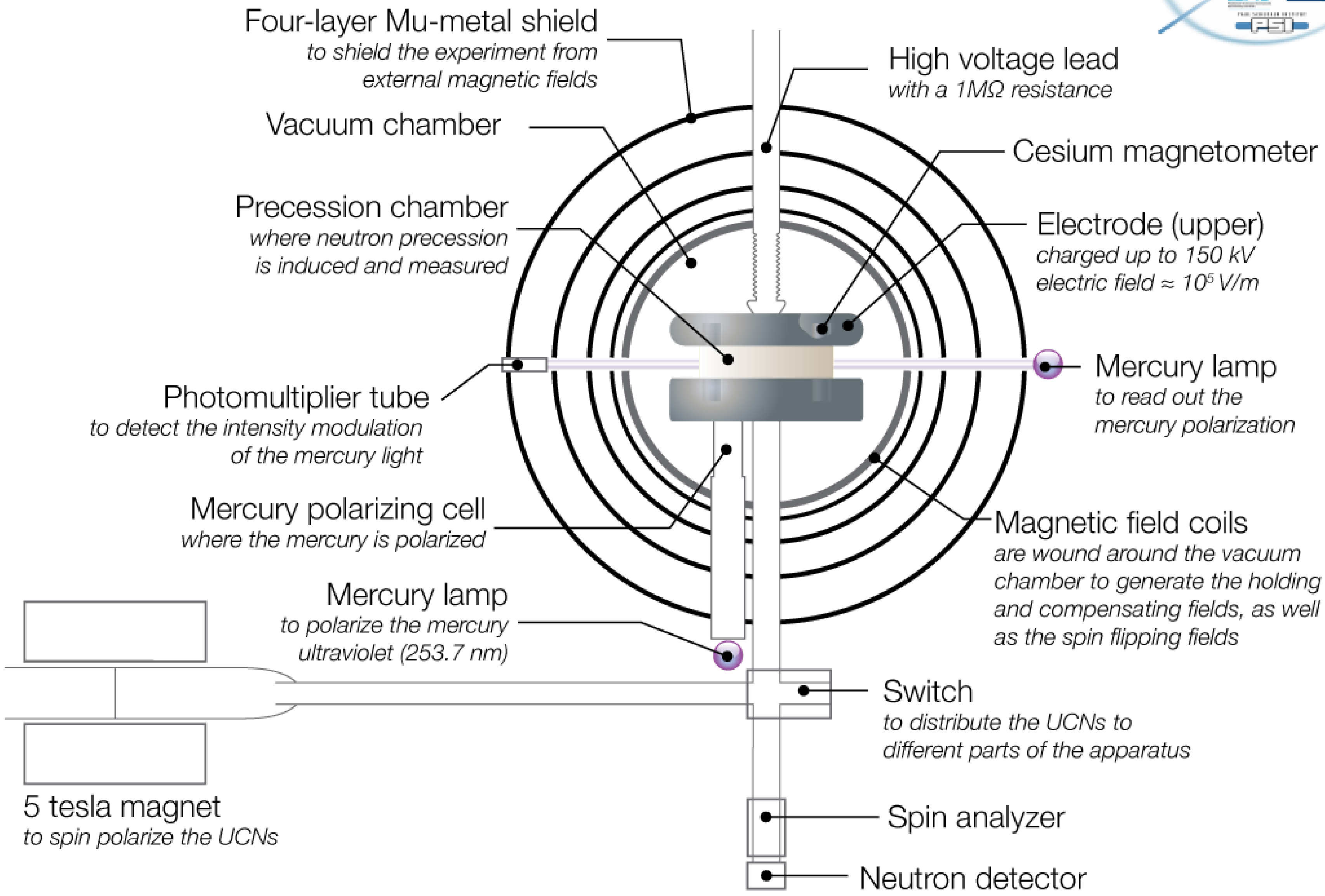
Frequency ratio R



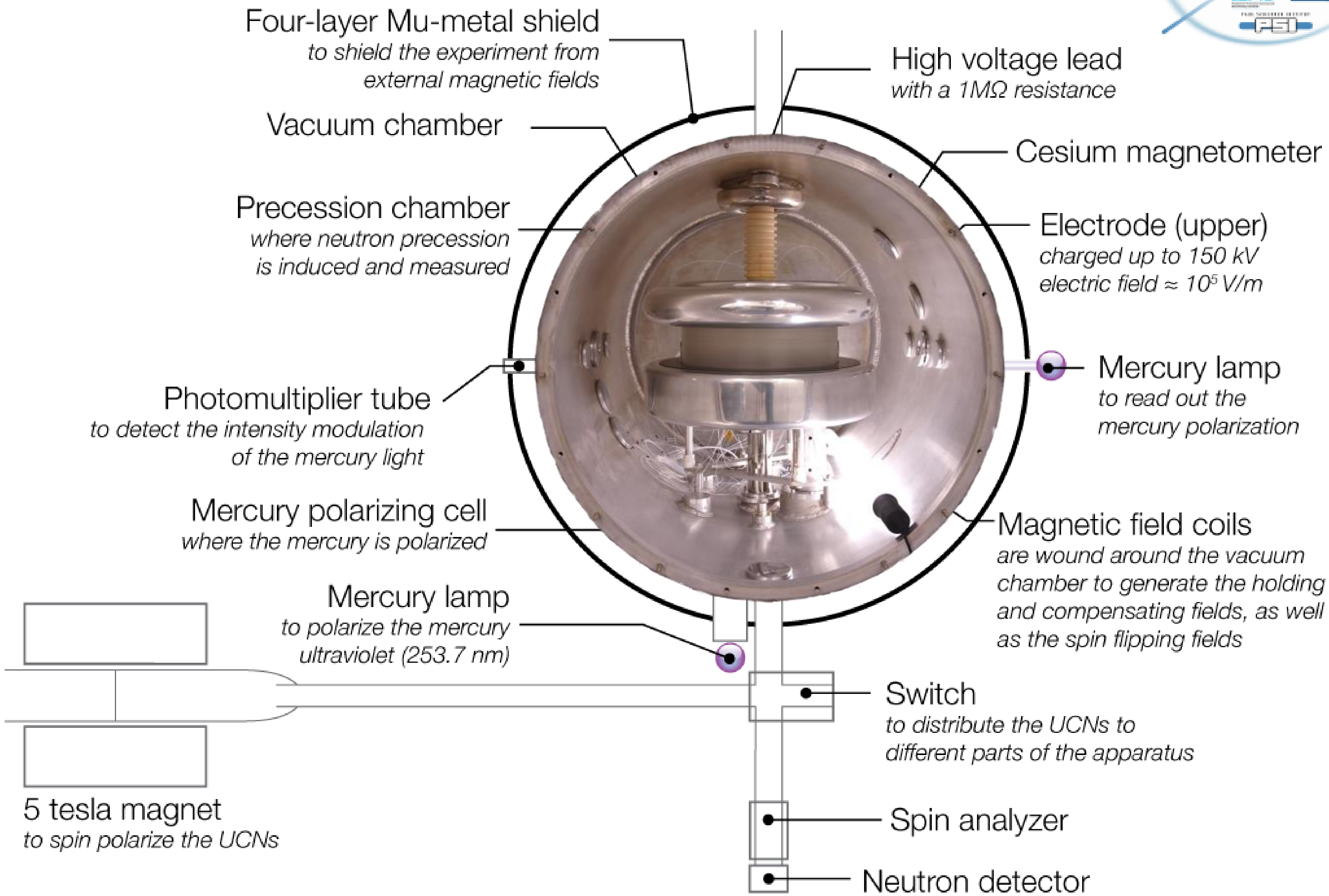


$$R = \frac{\langle f_{\mathrm{UCN}} \rangle}{\langle f_{\mathrm{Hg}} \rangle} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}} \left(1 \mp \frac{\partial B}{\partial z} \frac{\Delta h}{|B_0|} + \frac{\langle B^2{}_{\perp} \rangle}{|B_0|^2} \mp \delta_{\mathrm{Earth}} + \delta_{\mathrm{Hg-lights}}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

The nEDM spectrometer



The nEDM spectrometer



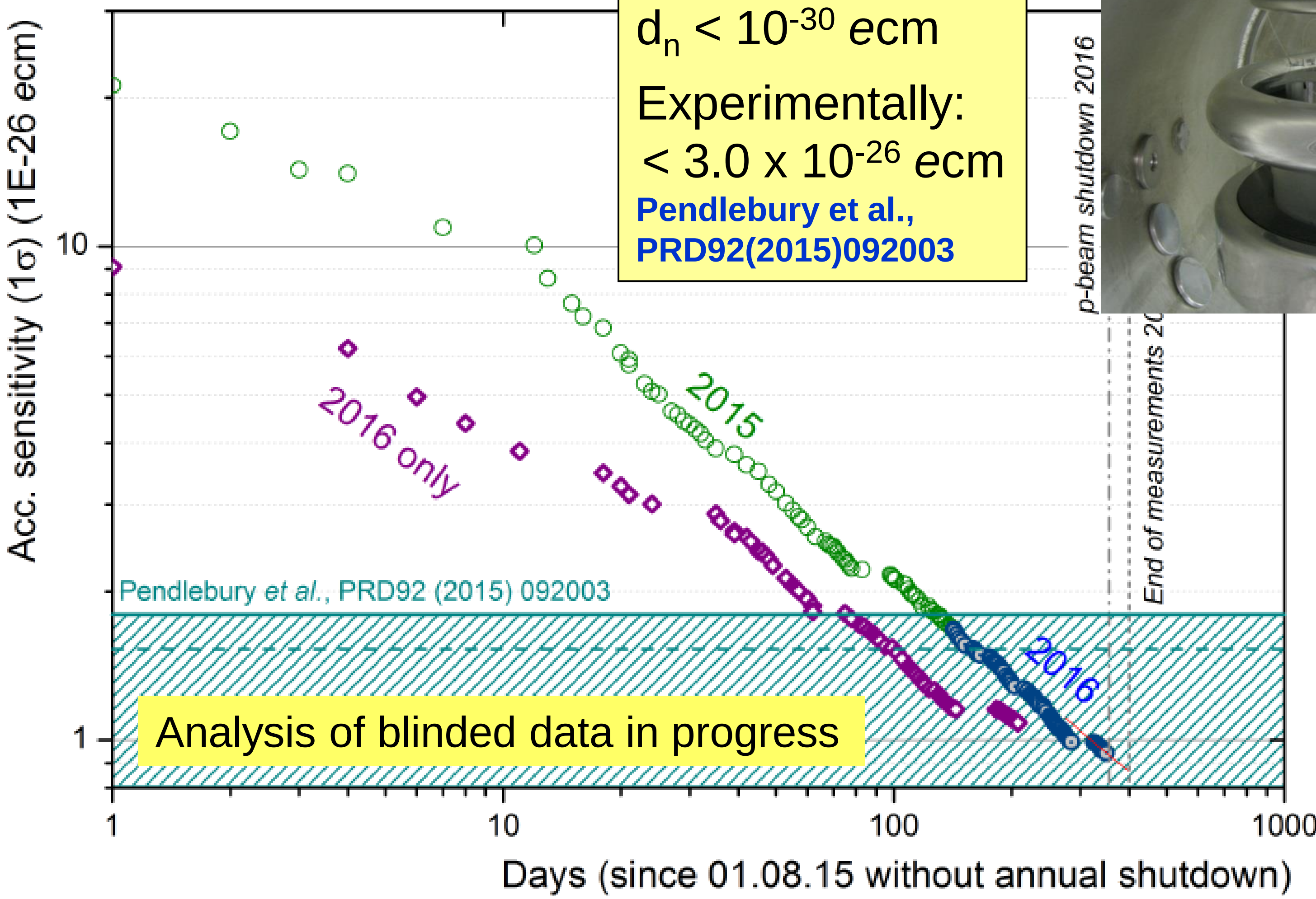

01/06/2011

Searching for the neutron EDM

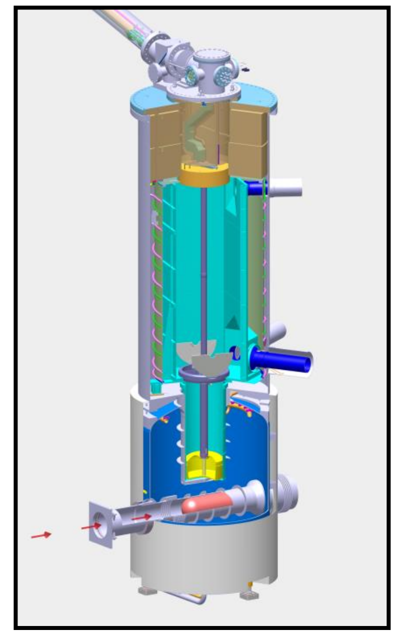
Expect from SM:
$d_n < 10^{-30}$ ecm

Experimentally:
$< 3.0 \times 10^{-26}$ ecm

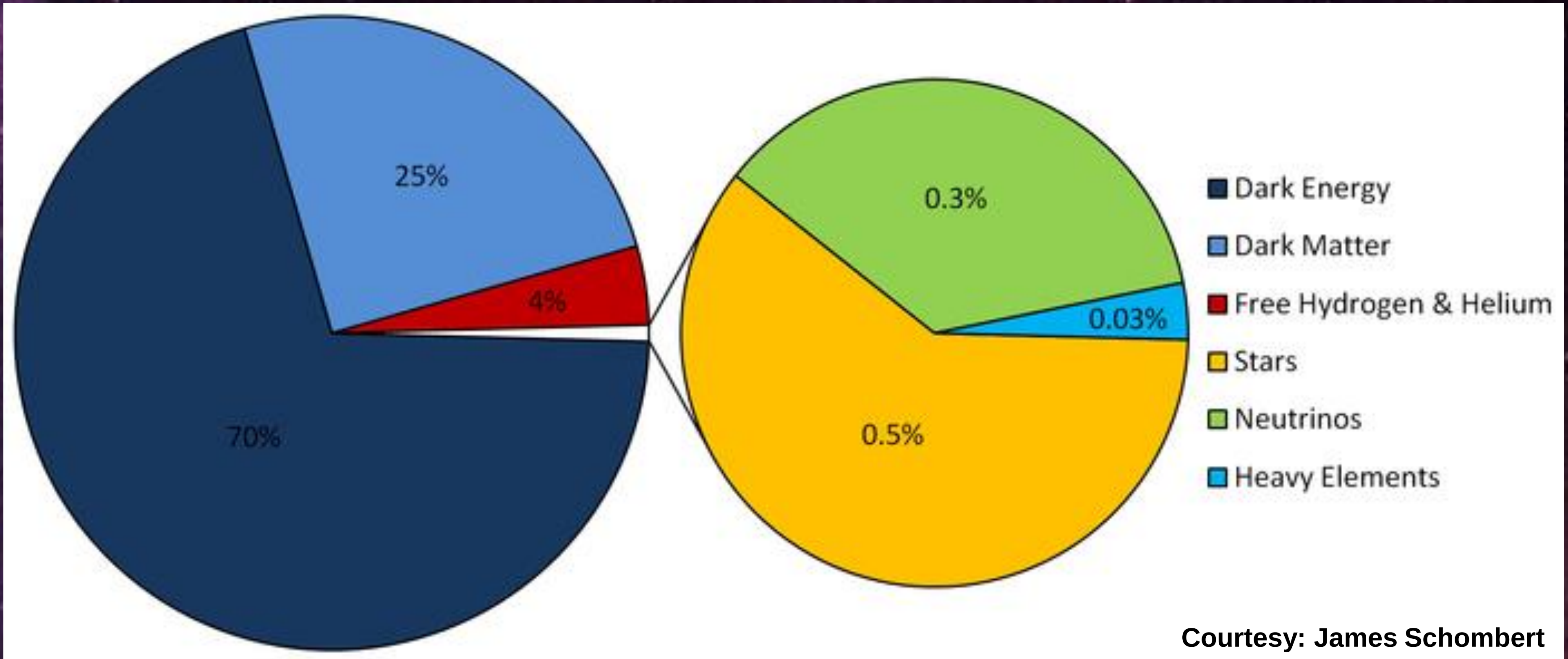
Pendlebury et al., PRD92(2015)092003



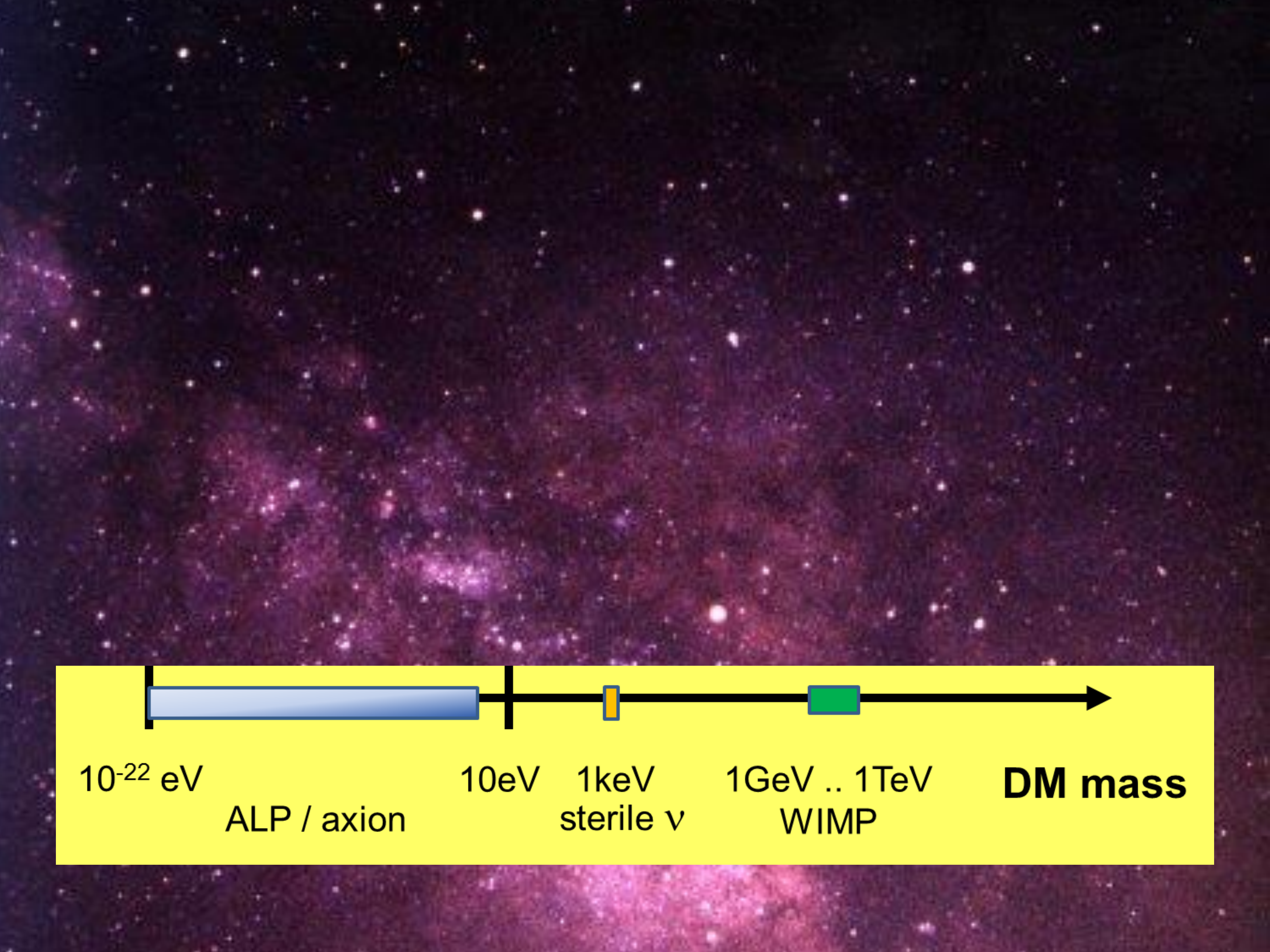
Analysis of blinded data in progress



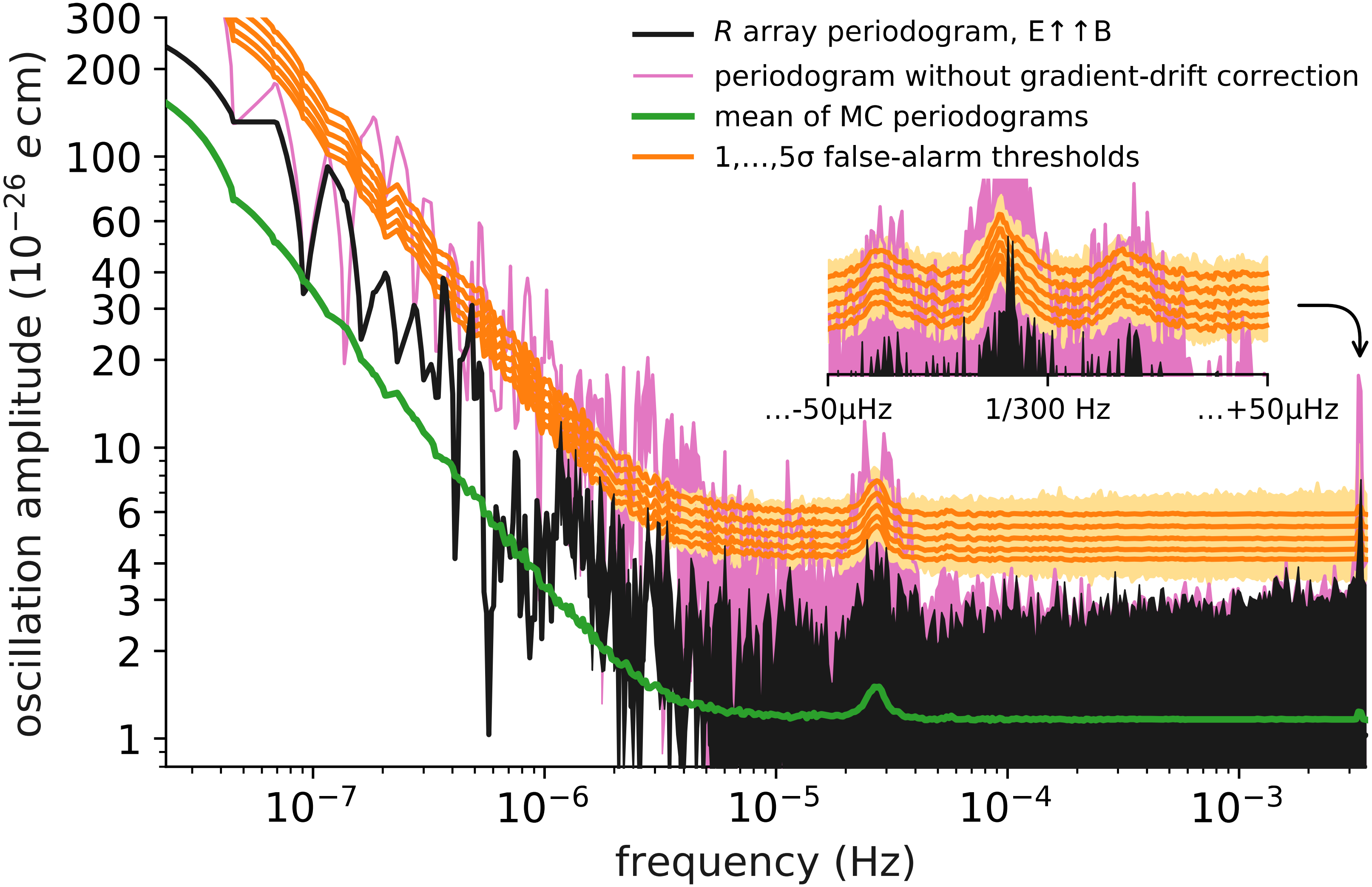
The energy budget of the Universe



Courtesy: James Schombert



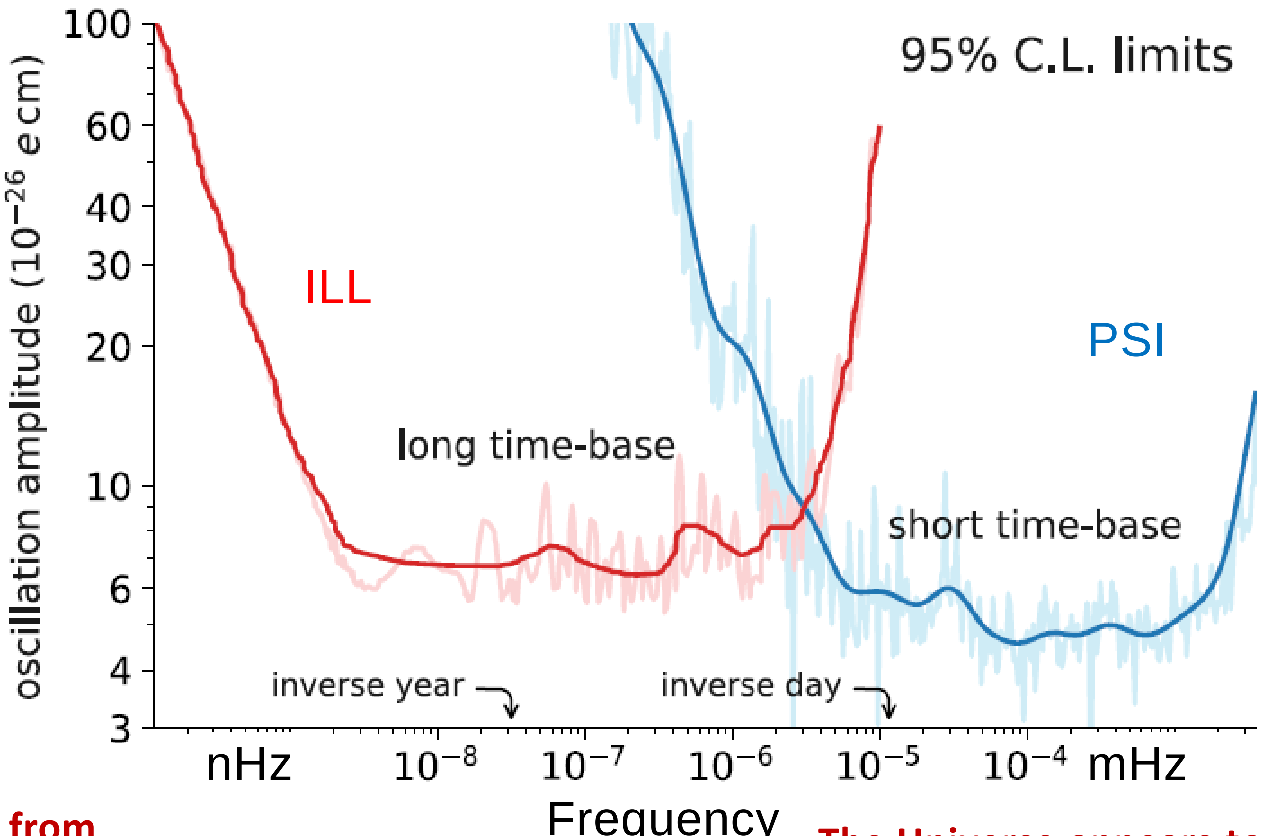
10^-22 eV
ALP / axion
10eV
1keV
sterile ν
1GeV .. 1TeV
WIMP
DM mass



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

Search for nEDM oscillations with time

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

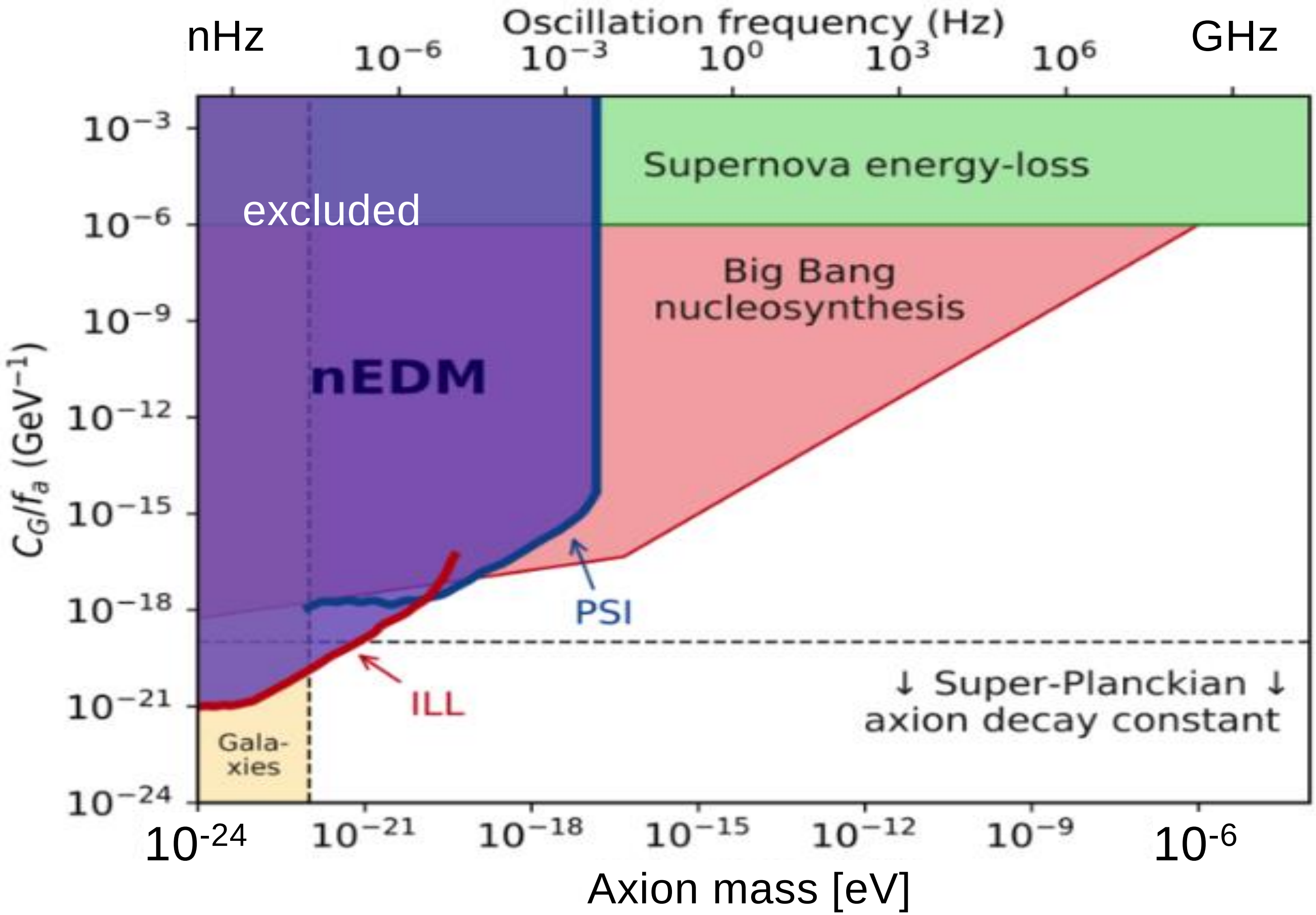


PhD theses
N. Ayres, Sussex
M. Rawlik, ETHZ

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



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

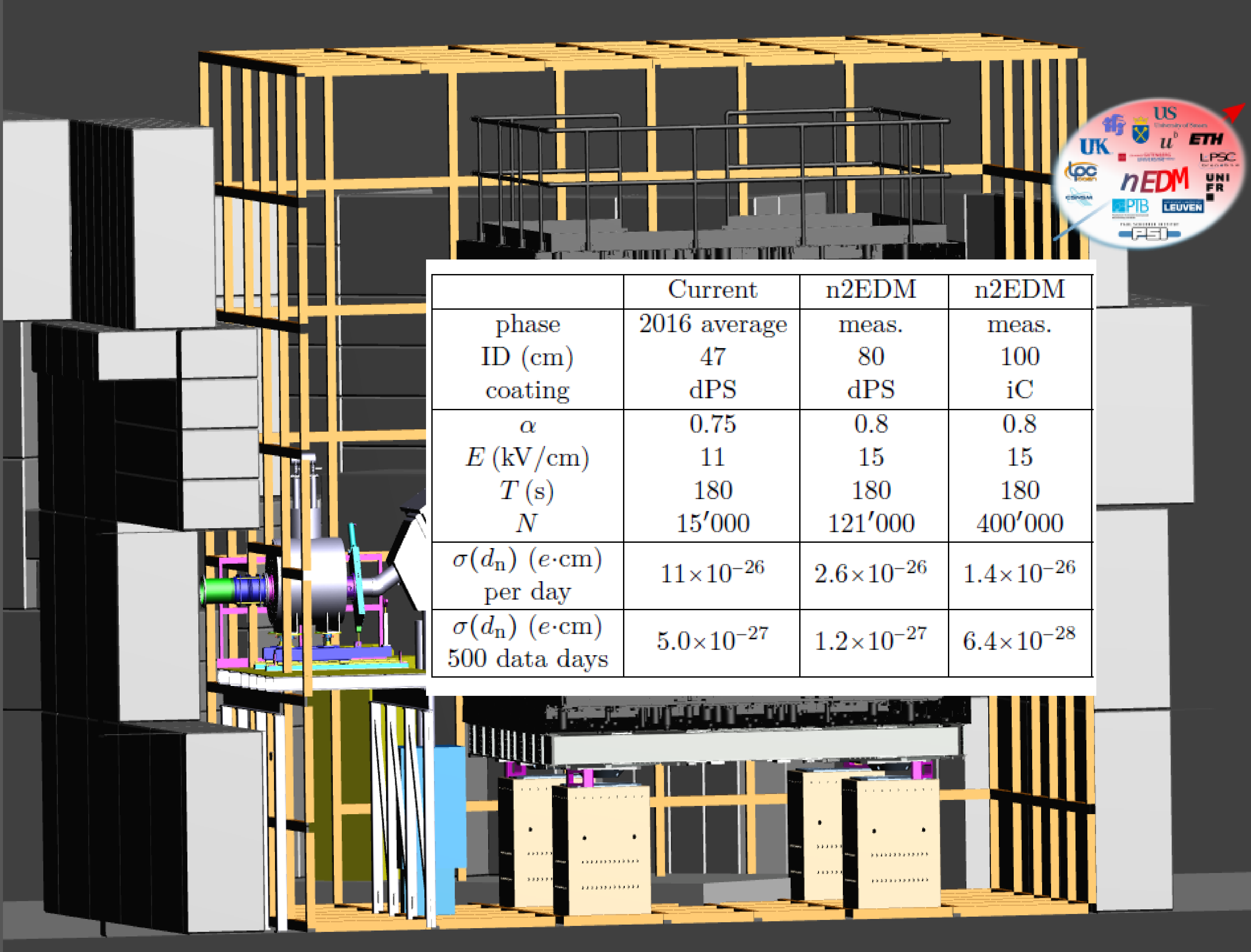
Abel et al., PRX7(2017)041034

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.

US
UK
ETH
LPSC
nEDM
UNI FR
PTB
LEUVEN
PSI



	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	$15'000$	$121'000$	$400'000$
$\sigma(d_\mathrm{n})$ (e·cm) per day	11×10^{-26}	2.6×10^{-26}	1.4×10^{-26}
$\sigma(d_\mathrm{n})$ (e·cm) 500 data days	5.0×10^{-27}	1.2×10^{-27}	6.4×10^{-28}

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Thank you

Zuoz Summer School

August 12-18, 2018

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https://www.psi.ch/particle-zuoz-school/ltp-zuoz-summer-school