The search for permanent electric dipole moments

Klaus Kirch
PSI-Villigen - ETH Zürich

Permanent electric dipole moments (EDMs) of fundamental systems with spin - particles, nuclei, atoms or molecules violate parity and time reversal invariance. Invoking the CPT theorem, time reversal violation implies CP violation. Although CP-violation is implemented in the standard electro-weak theory, EDM generated this way remain undetectably small. However, this CP-violation also appears to fail explaining the observed baryon asymmetry of our universe. Extensions of the standard theory usually include new sources of CP violation and often predict sizeable EDMs. EDM searches in different systems are complementary and various efforts worldwide are underway and no finite value has been established yet. The prototype of an EDM search is the pursuit of the EDM of the neutron. It has the longest history and at the same time is at the forefront of present research. The talk aims at giving an overview of the field with emphasis on our efforts within an international collaboration at PSI, nedm.web.psi.ch.

The search for permanent electric dipole moments

Klaus Kirch

Paul Scherrer Institut and ETH Zürich

PSI2013: September 9-12, 2013

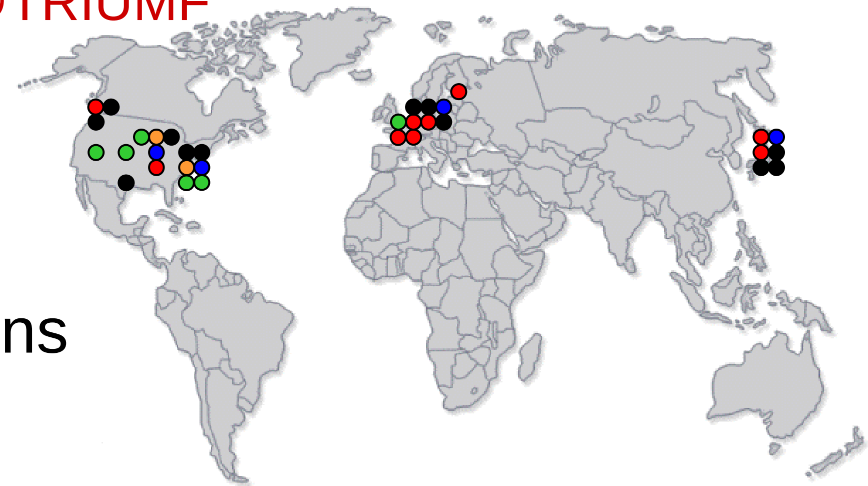
EDM worldwide

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- Neutrons ~200
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC

- Molecules ~50
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma

- Atoms ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto



- Ions-Muons ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC

- Solids ~10
  - GGG@Indiana
  - ferroelectrics@Yale

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

Observed*:

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

SM expectation:

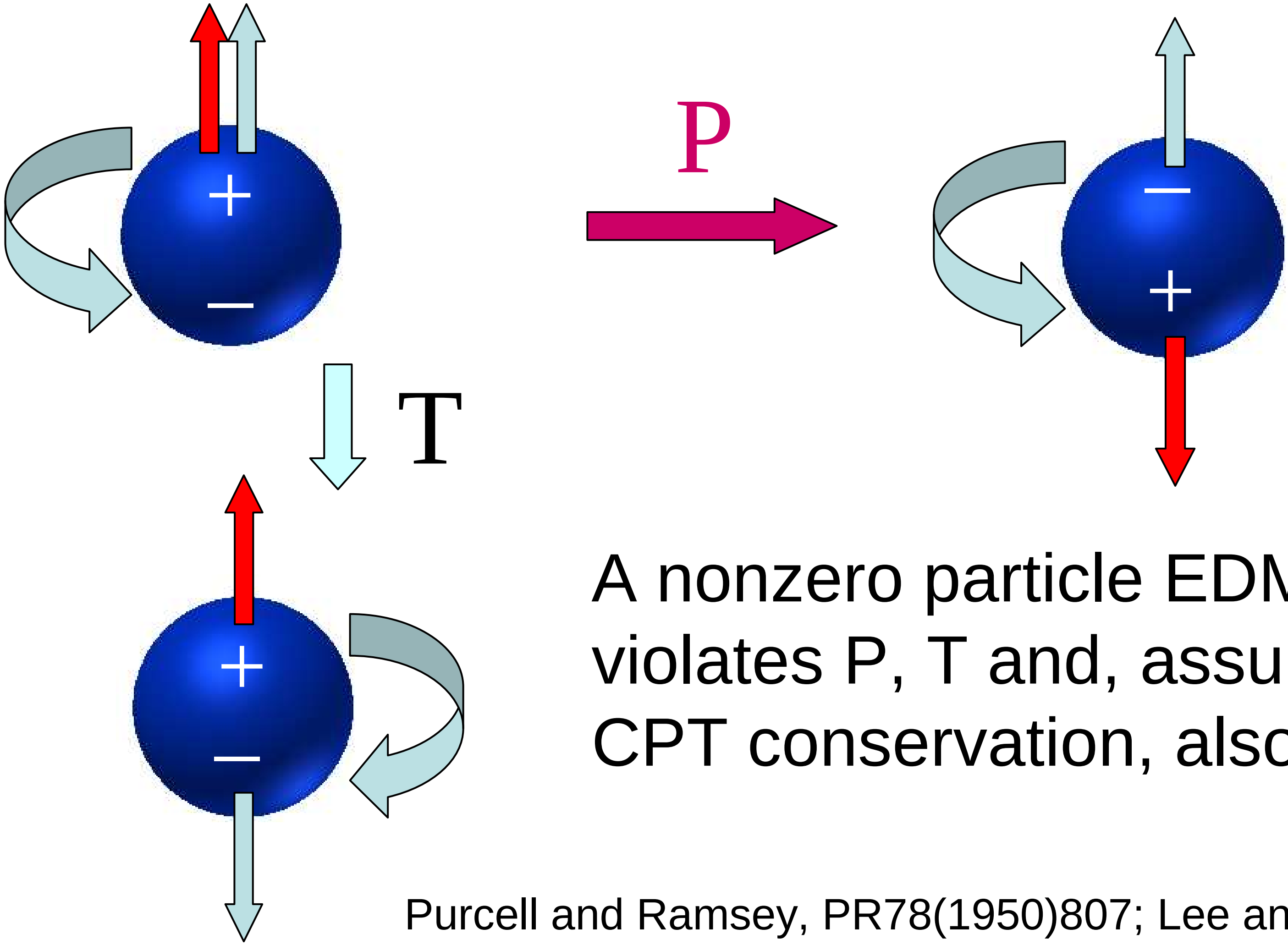
$$(n_B - n_{\bar{B}}) / n_\gamma \sim 10^{-18}$$

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

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

$(6.19 \pm 0.15) \times 10^{-10}$
[E. Komatsu et al. 2011 ApJS 192]

EDM and symmetries

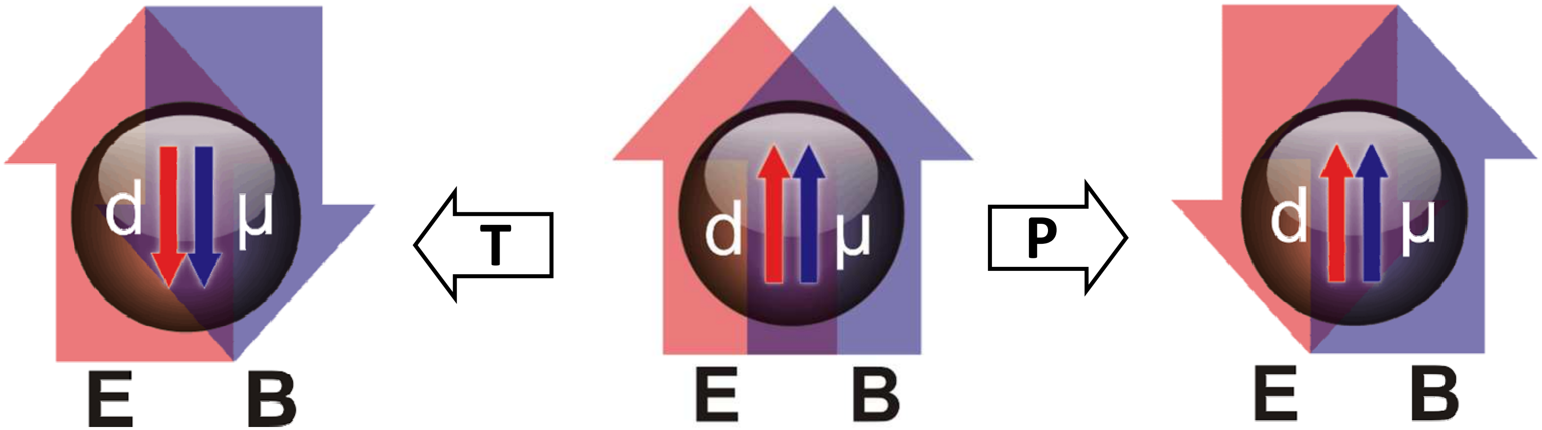


A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP

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

EDM and symmetries

$$H = -\left(d\frac{\vec{\sigma}}{|\vec{\sigma}|}\cdot\vec{E} + \mu\frac{\vec{\sigma}}{|\vec{\sigma}|}\cdot\vec{B} \right)$$

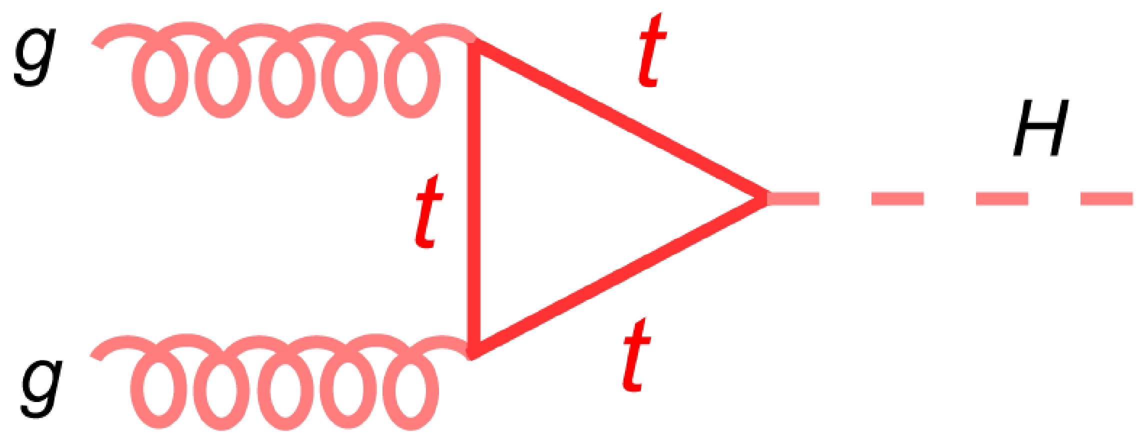


A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP

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

Today´s most spectacular (Standard) Particle Physics:

Direct production of new particles ...



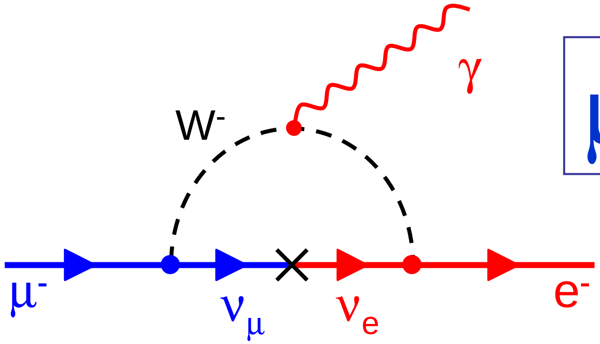
and detection of
decay products

... at the energy frontier: LHC → 14 TeV

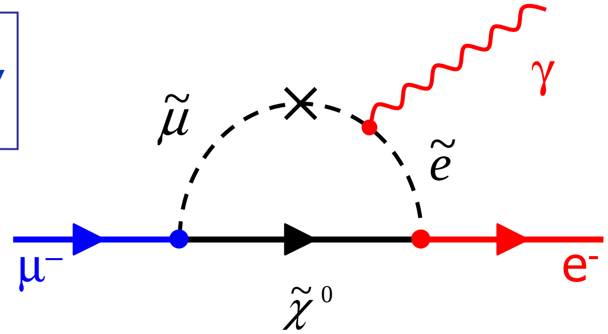
A complementary approach:

Effects of new particles in loops ...

$\boxed{\mu \rightarrow e+\gamma}$



10^{-50} ... 10^{-60} !



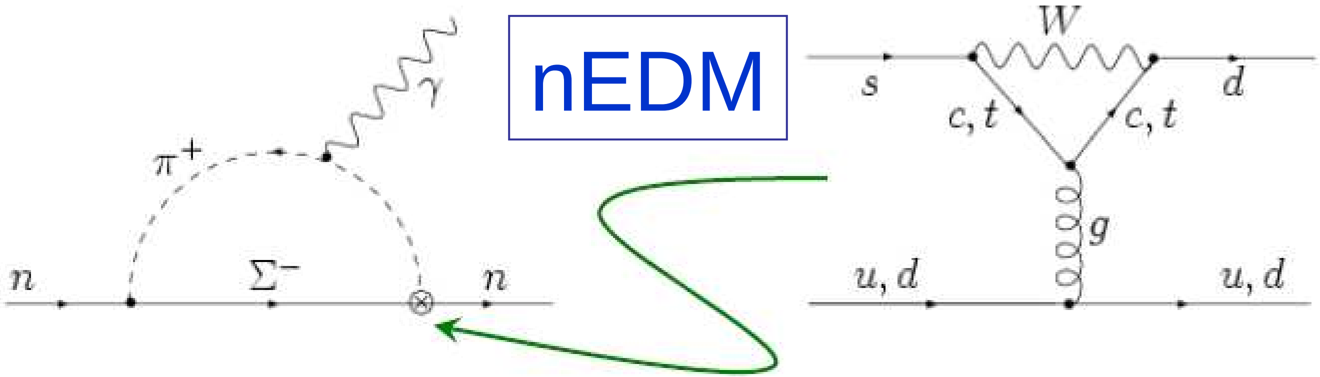
10^{-12} ... 10^{-14} ?

... can be measured best when the expected contribution is small.

or very well known.

A complementary approach:

Effects of new particles in loops ...



... can be measured best when the expected contribution is small.

or very well known.

Precision frontier → high mass scales

Standard Model EDM-expectations?

- Leptons: electroweak negligible

- Neutron, proton, nuclei:
  electroweak negligible, strong?

Standard model lepton EDMs

Fourth order electroweak,

F. Hoogeveen:
The Standard Model Prediction for the Electric Dipole Moment of the Electron,
Nucl. Phys. B 241 (1990) 322

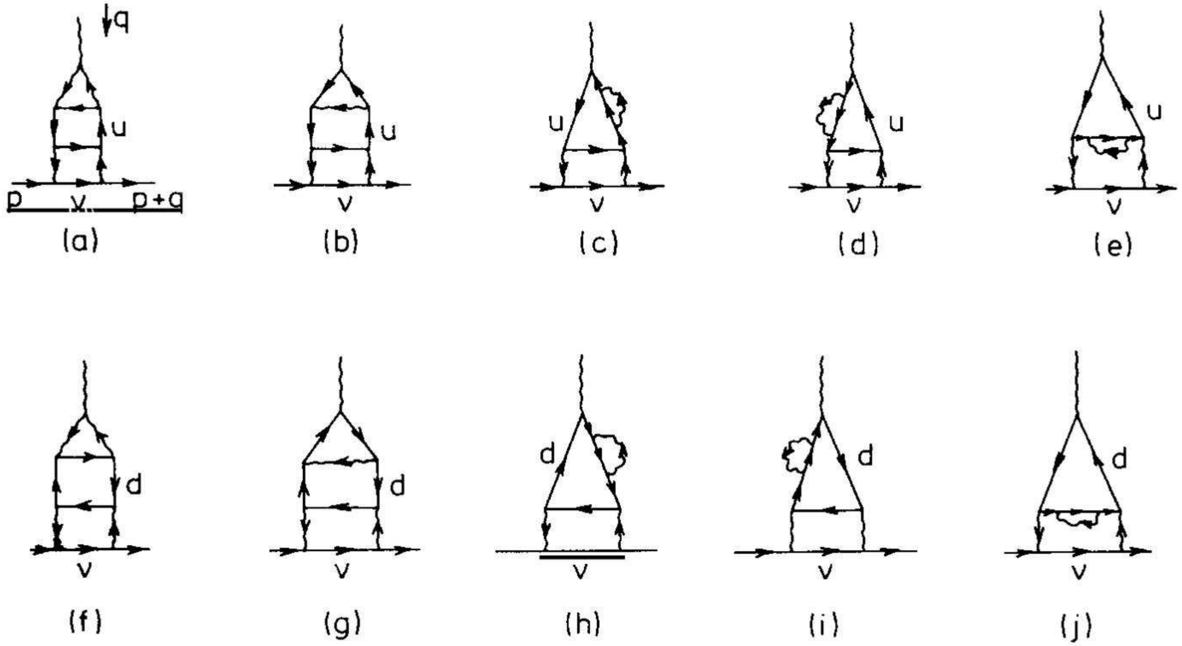


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

… + new physics?

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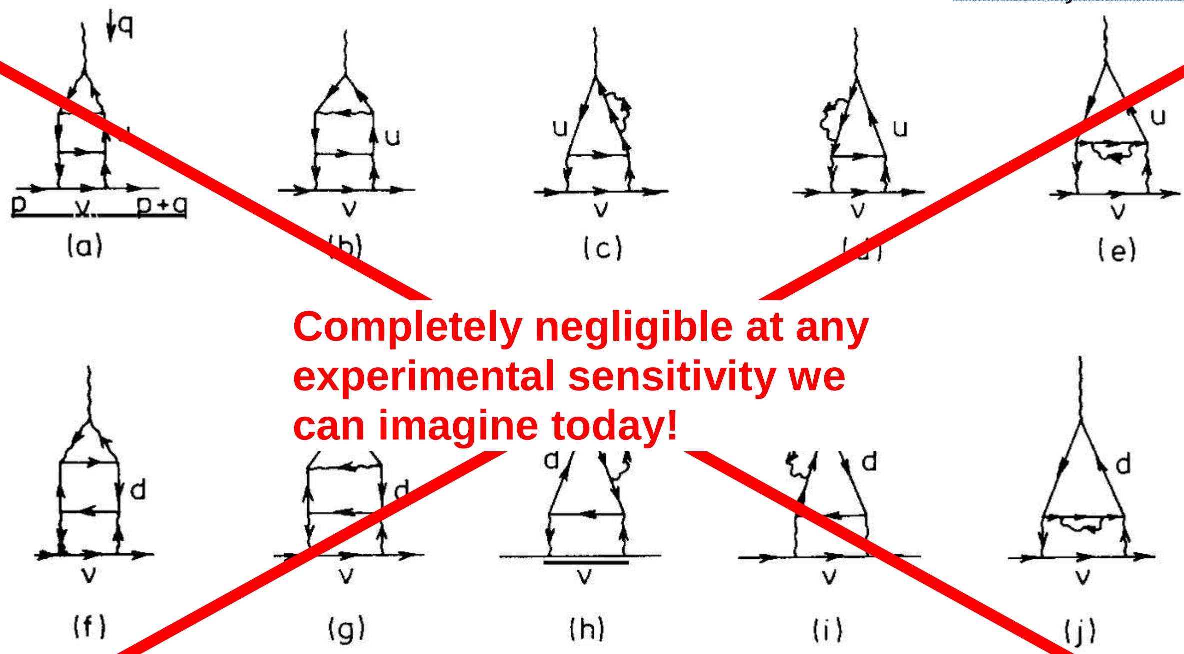

Completely negligible at any experimental sensitivity we can imagine today!

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

… + new physics?

Much greater sensitivity to new, CP-violating physics!

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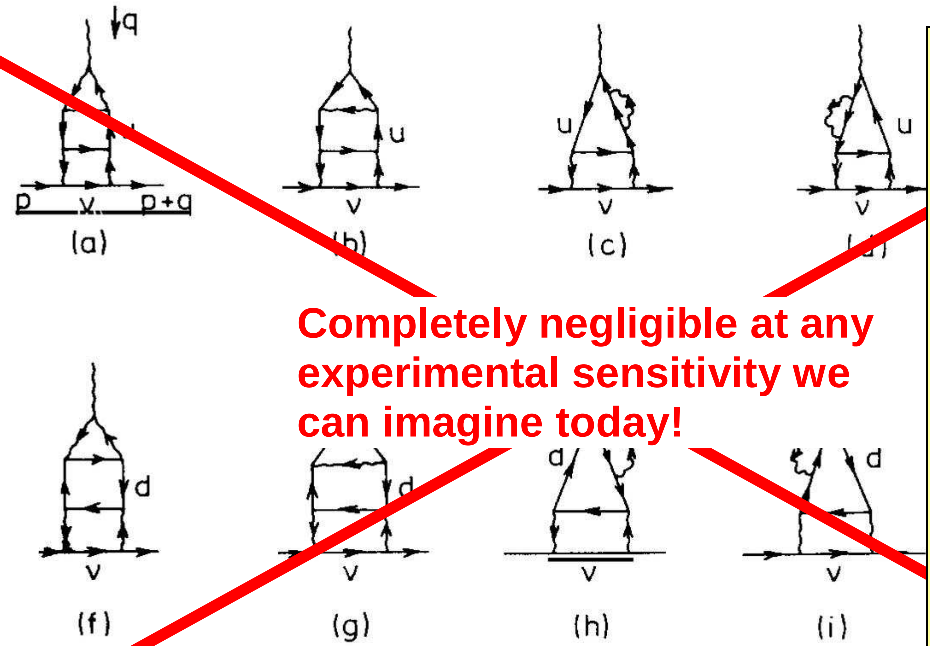


Fig. 4. The ten diagrams which contribute to the edm of the electron. Th
W-propagators.

Completely negligible at any experimental sensitivity we can imagine today!

Expect from SM, approximately:

$d_e \leq 10^{-38}$ e•cm
$d_\mu \leq 10^{-36}$ e•cm
$d_\tau \leq 10^{-35}$ e•cm

Experimentally so far:

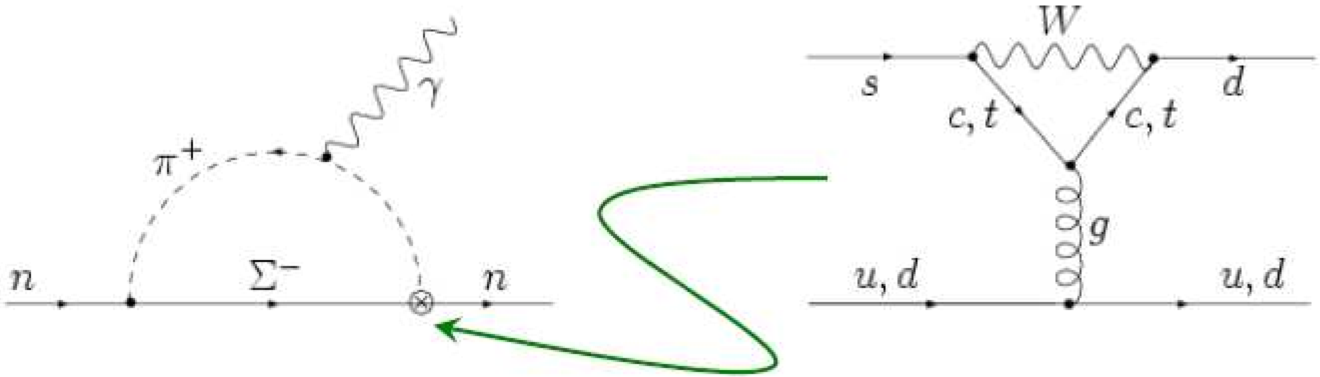
$d_e < 1 \times 10^{-27}$ e•cm
$d_\mu < 2 \times 10^{-19}$ e•cm
$d_\tau < 3 \times 10^{-17}$ e•cm

… + new physics?

Much greater sensitivity to new, CP-violating physics!

Neutron: Standard Model prediction

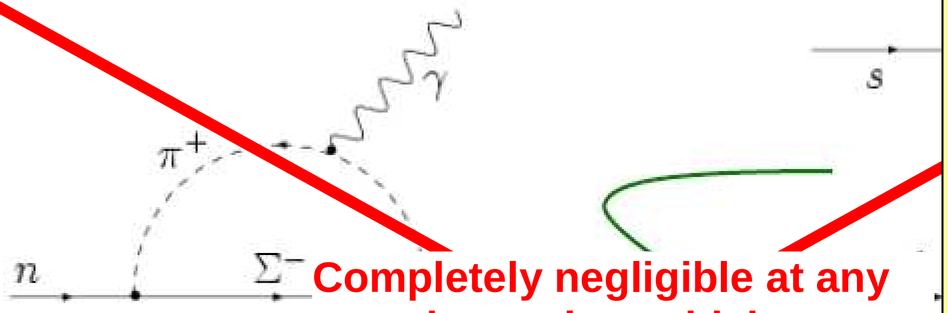
- electroweak -



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

[Khriplovich & Zhitnitsky '86]

Neutron: Standard Model prediction



Completely negligible at any experimental sensitivity we can imagine today!

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

[Khriplovich & Zhitnitsky '86]

Expect from electro-weak SM, approximately:

$d_n \leq 10^{-32}$ e•cm

Experimentally so far:

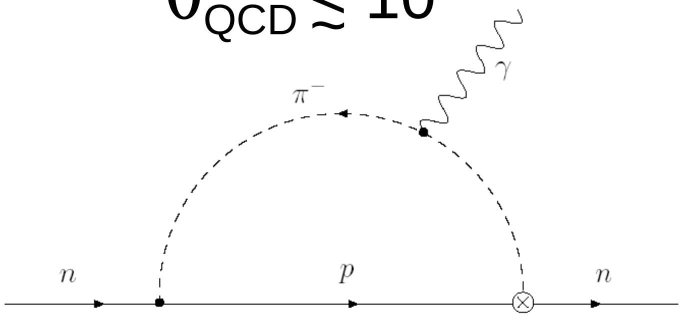
$d_n < 3 \times 10^{-26}$ e•cm

The strong CP problem

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

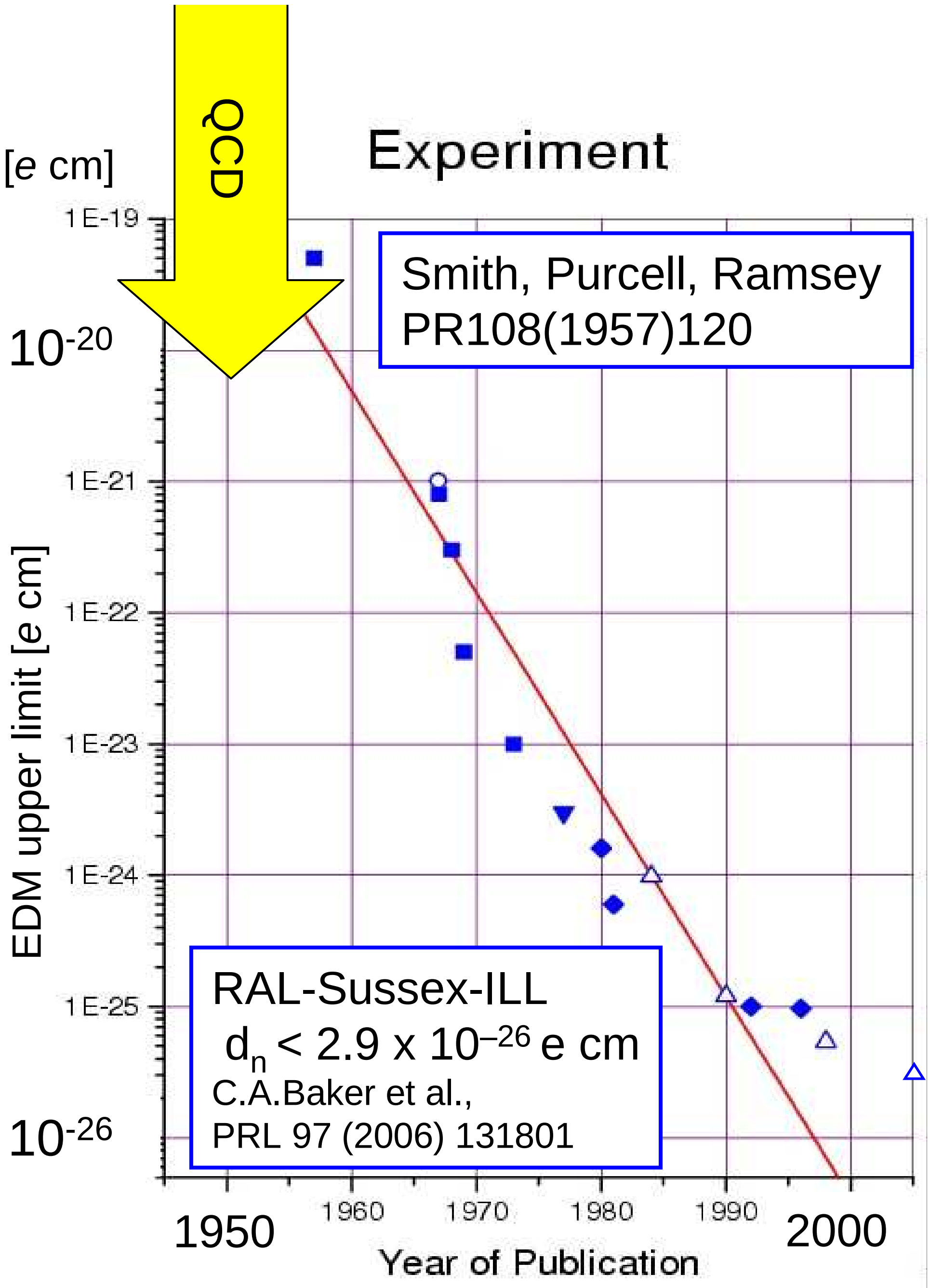
$$d_n \approx 10^{-16}\ e\ \mathrm{cm} \cdot \theta_{QCD}$$

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



Why is θ_{QCD} so small ?

here, e.g., $d_p = - d_n$ and $d_D \sim 1/3\ d_n$



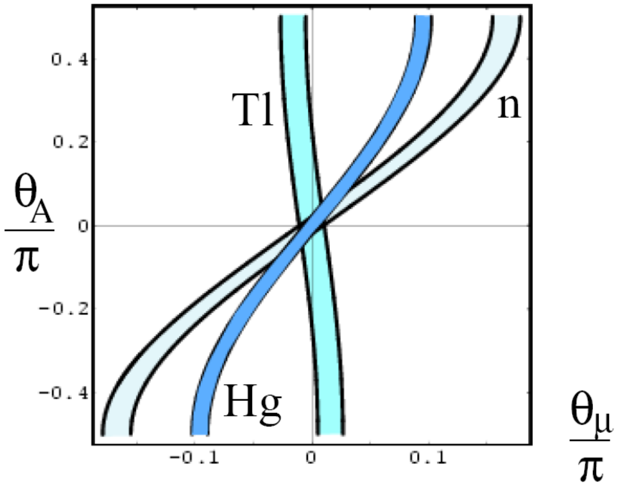
The SUSY CP problem

(for neutron and electron!)

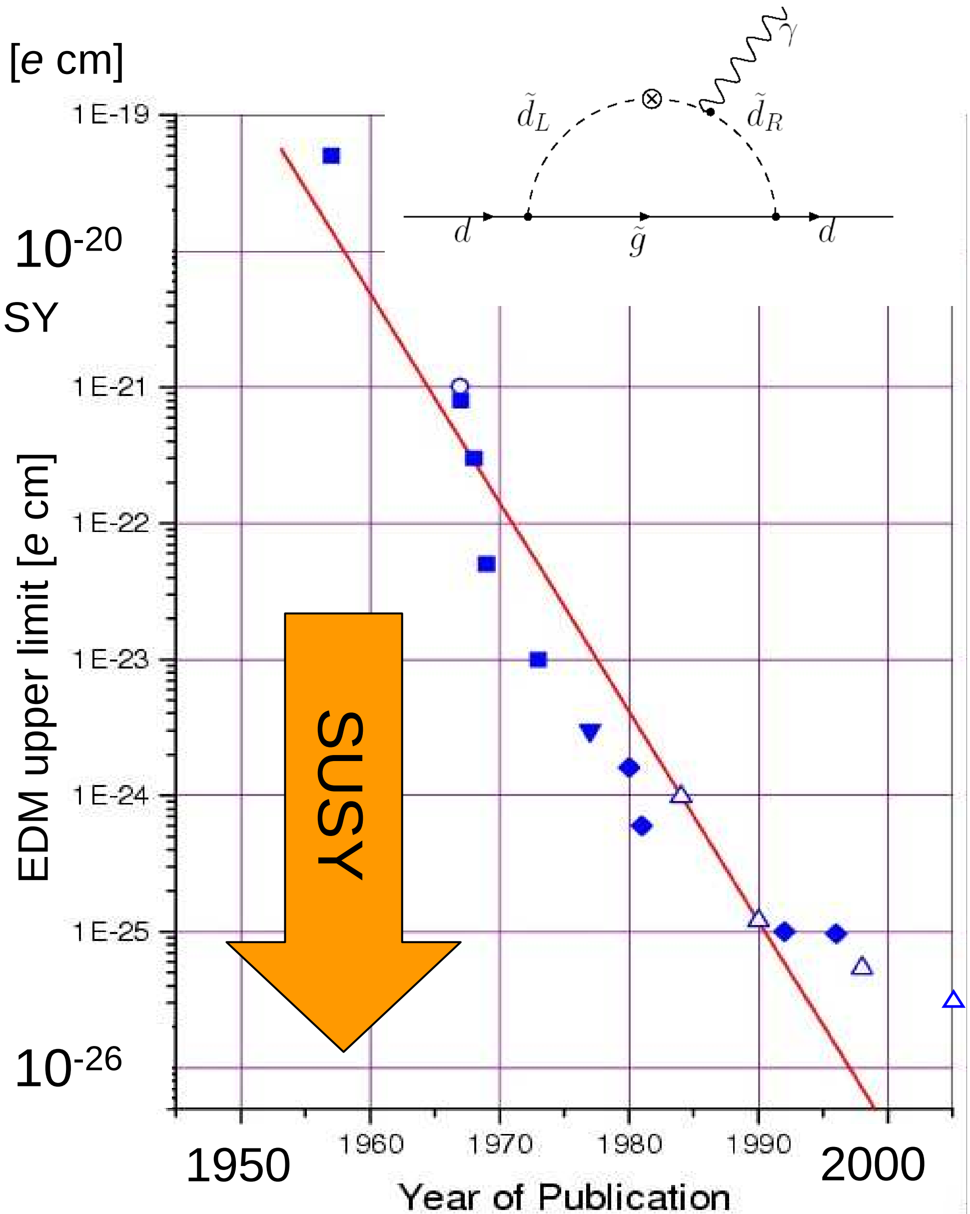
$$d_n \approx 10^{-23}\, e\ \mathrm{cm} \left(\frac{300\ \mathrm{GeV/c^2}}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

Why is ϕ_{SUSY} so small ?

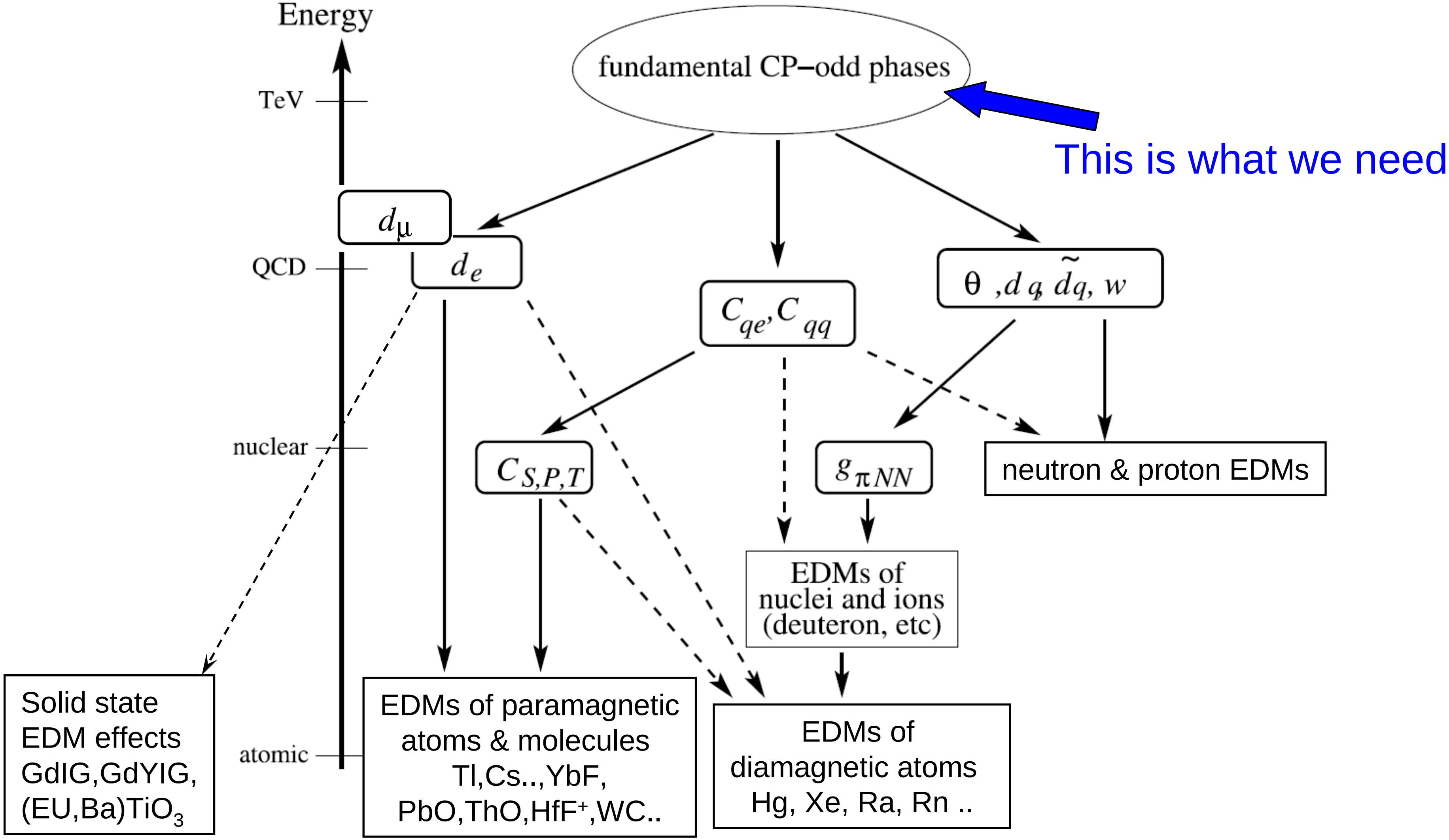
(this is testing M already to 10TeV and you may also ask: why are the masses so huge?)



Pospelov, Ritz, Ann. Phys. 318(2005)119
for M_{SUSY} = 500GeV, tan β = 3

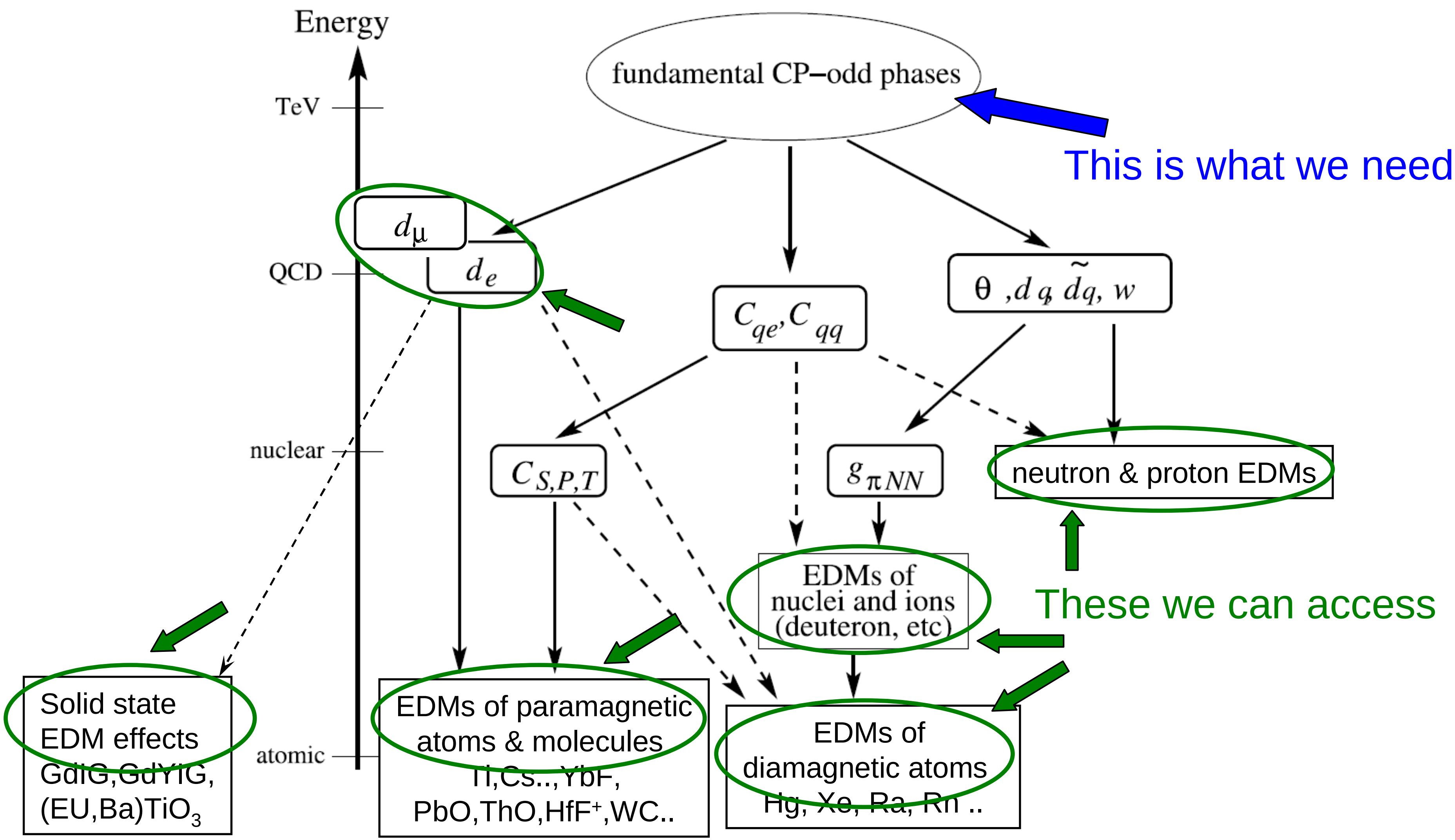


Origin of EDMs



Adapted from:
Pospelov, Ritz, Ann. Phys. 318 (2005) 119
M. Raidal et al., Eur. Phys. J. C 57 (2008) 13

Origin of EDMs



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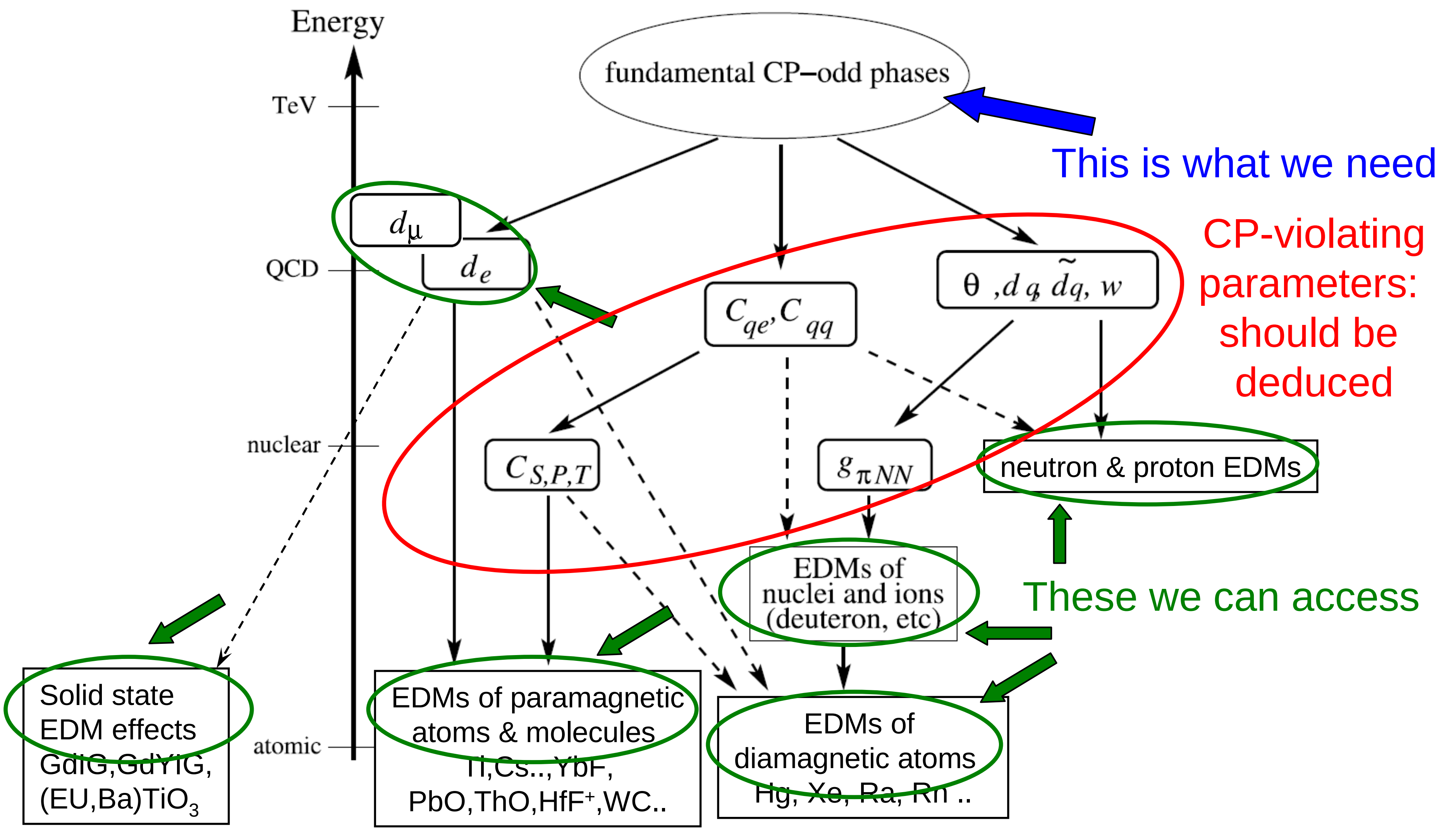

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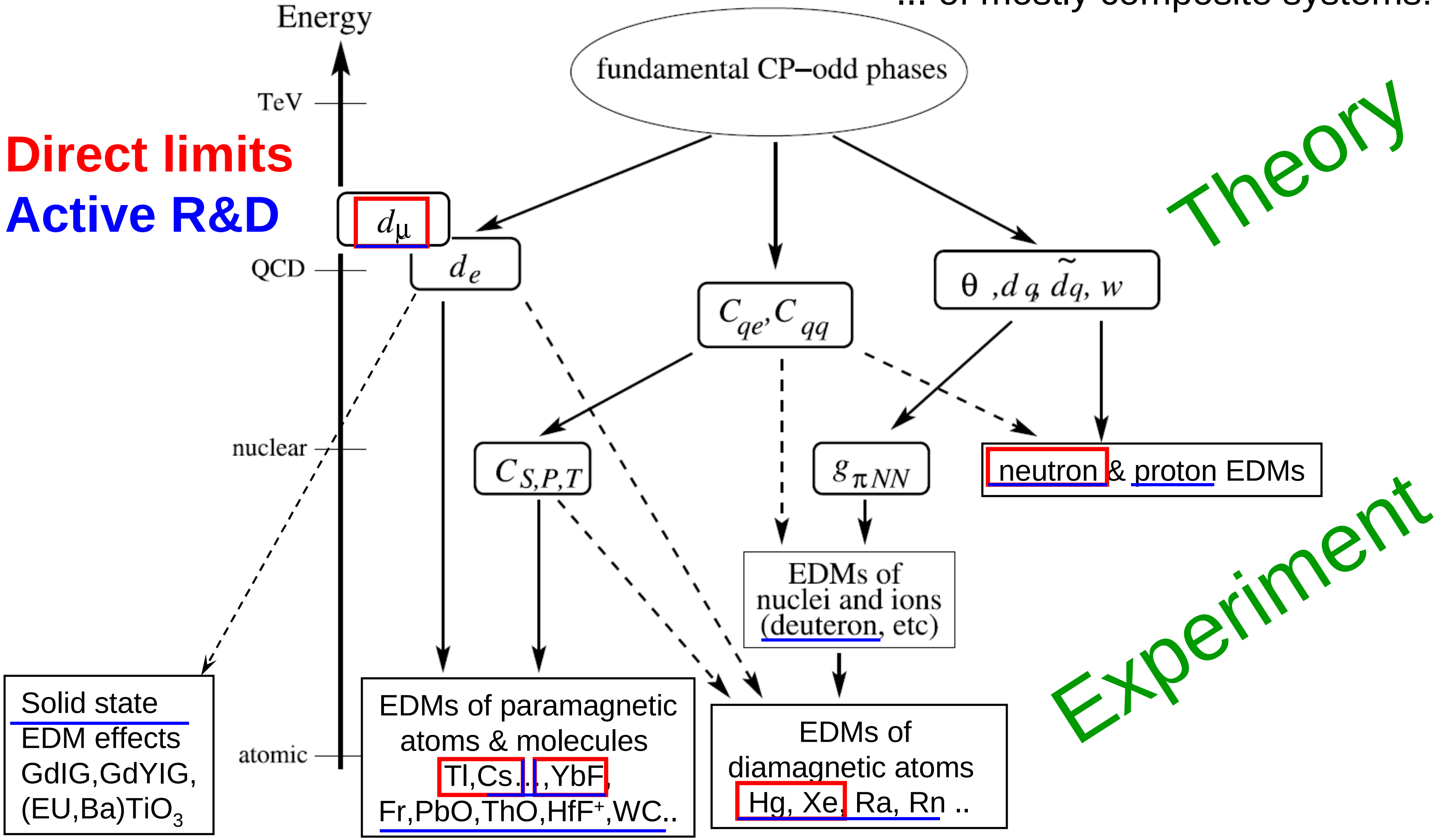
Origin of EDMs

... of mostly composite systems!



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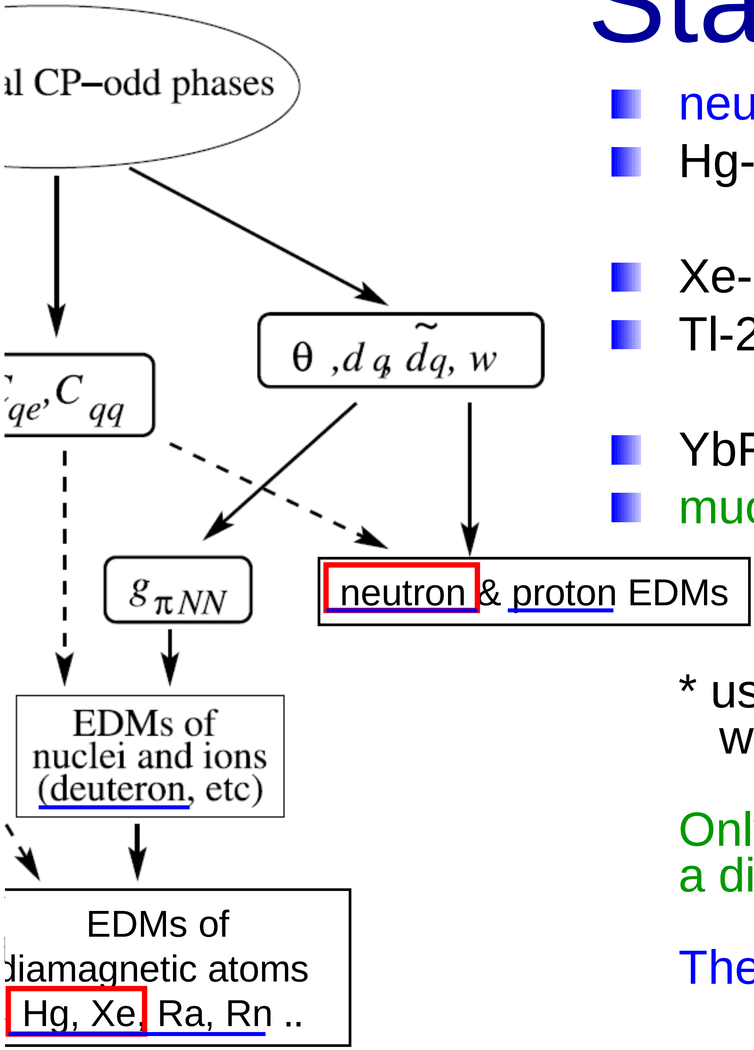
gin of EDMs



State of the art

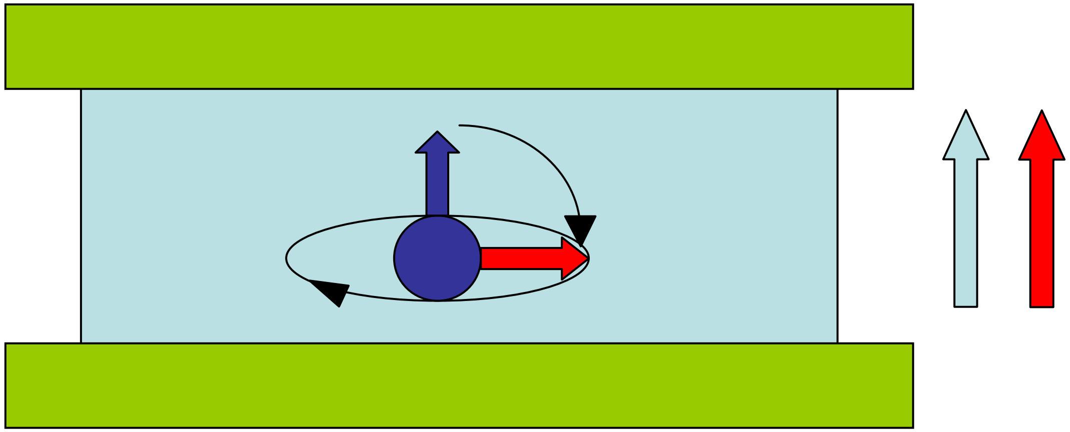
- neutron $d_n < 2.9 \times 10^{-26}$ e cm PRL97(2006)131801
- Hg-199 $d_{Hg} < 3.1 \times 10^{-29}$ e cm PRL102(2009)101601
  → $d_p < 8 \times 10^{-25}$ e cm*
- Xe-129 $d_{Xe} < 6 \times 10^{-27}$ e cm PRL86(2001)22
- Tl-205 $d_{Tl} < 9 \times 10^{-25}$ e cm
  → $d_e < 1.6 \times 10^{-27}$ e cm* PRL88(2002)071805
- YbF → $d_e < 1.05 \times 10^{-27}$ e cm* Nature473(2011)493
- muon $d_\mu < 1.8 \times 10^{-19}$ e cm PRD80(2009)052008

* using the ‚1-miracle assumption', i.e. no cancelations with other CP-odd effects.

Only for one fundamental fermion, the muon, a direct EDM-limits exist.

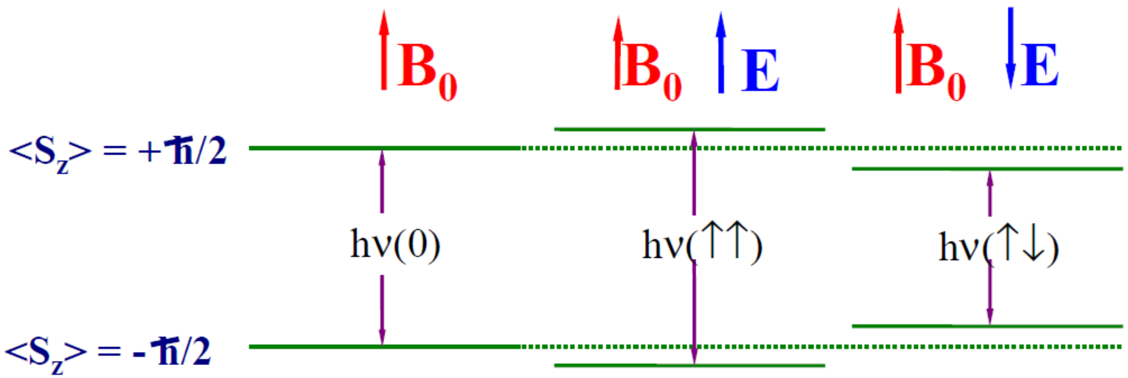
The next ‚simple' system is arguably the neutron.

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



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

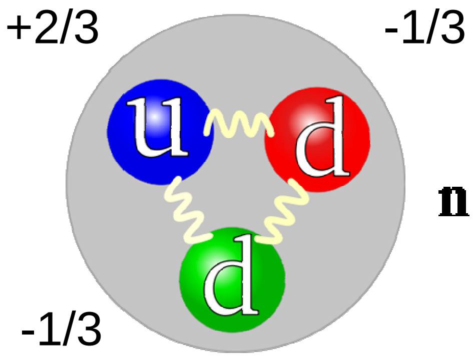
$$h\Delta\nu = 4\, d_n E$$

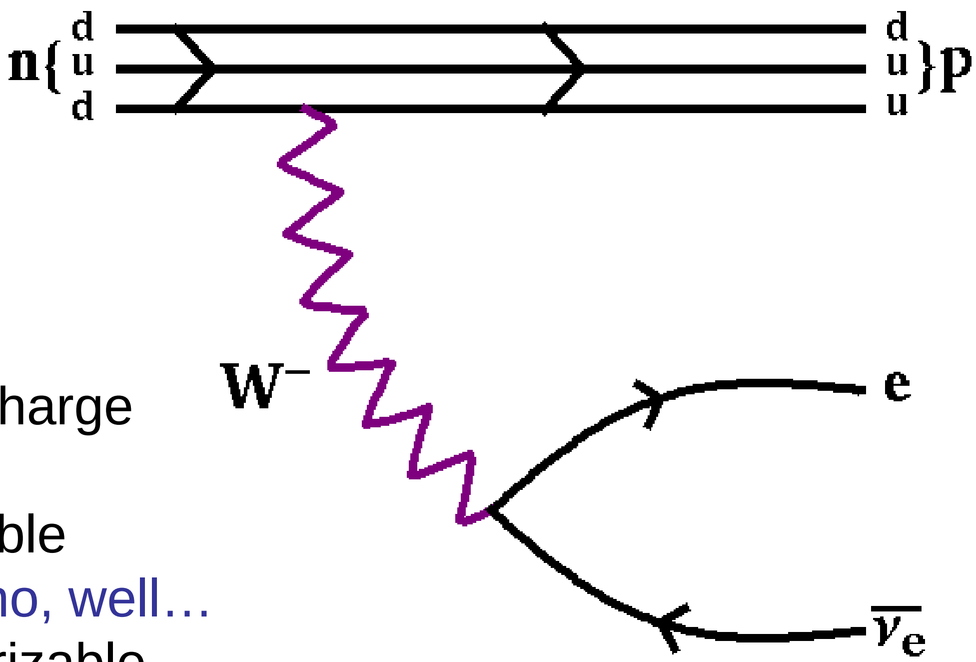


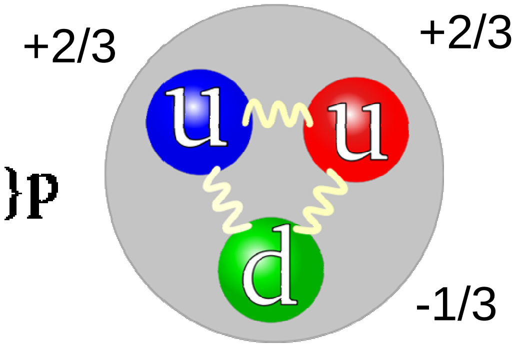
$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

The Neutron

[Chadwick 1932]







- massive
- composite
- no net electric charge
- unstable
- spin ½, polarizable
- electric dipole: no, well…
- electrically polarizable
- takes part in all interactions
- …..

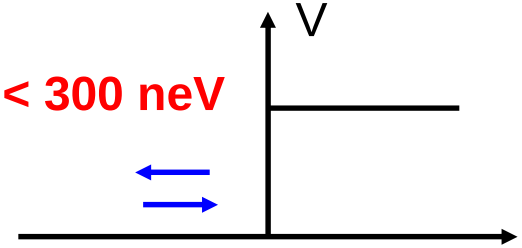
Ultra-cold neutrons

similar to ideal gas with temperatures of milli-Kelvin

move with velocities of few m/s

have kinetic energies of order 100 neV

strong	magnetic	gravitation
Fermi potential V_F	**$V_m = -\mu B$**	**$V_g = m_n gh$**
⇓	⇓	⇓
300 neV	**60 neV T^{-1}**	**100 neV m^{-1}**
	⇓	⇓
$E_n <$ 300 neV	**5 T field -> 300 neV**	**3 m up -> 300 neV**

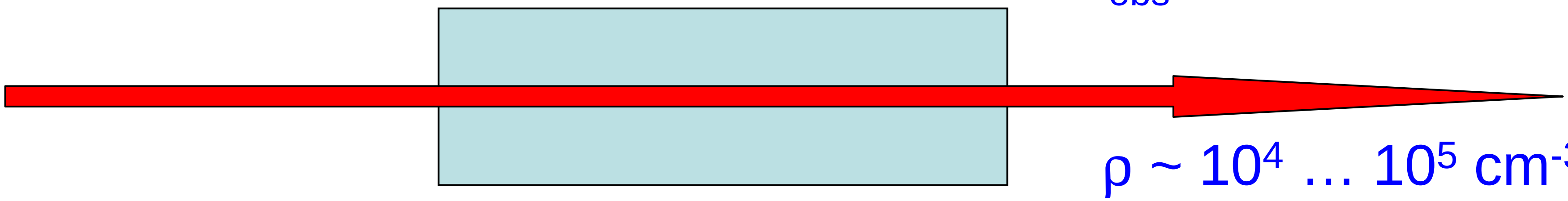


Typical neutron experiments

CN Beam

$v_{CN} \sim 1000$ m/s

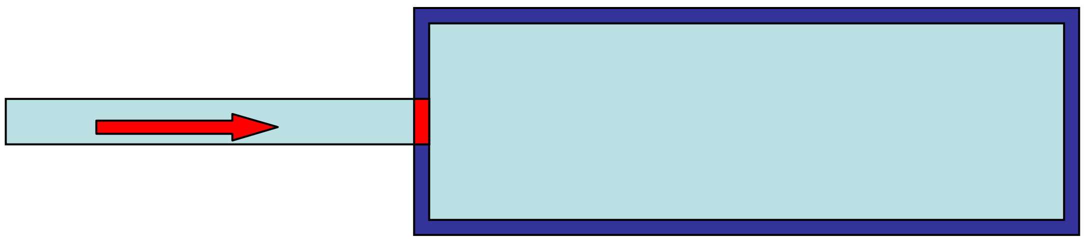
$t_{obs} \sim 10^{-3}$ s



$\rho \sim 10^4 \ldots 10^5$ cm^{-3}

possibly improved quality at new pulsed sources

UCN Storage



$v_{UCN} \sim 5$ m/s

$t_{obs} \sim 10^2\text{-}10^3$ s

$\rho \sim 10$ cm^{-3}

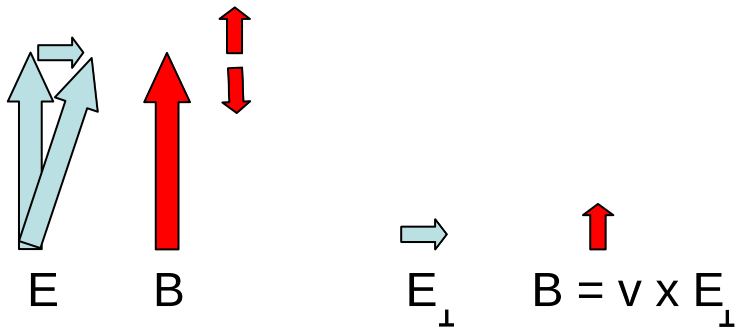
improved density at new UCN sources

Use UCN for nEDM search

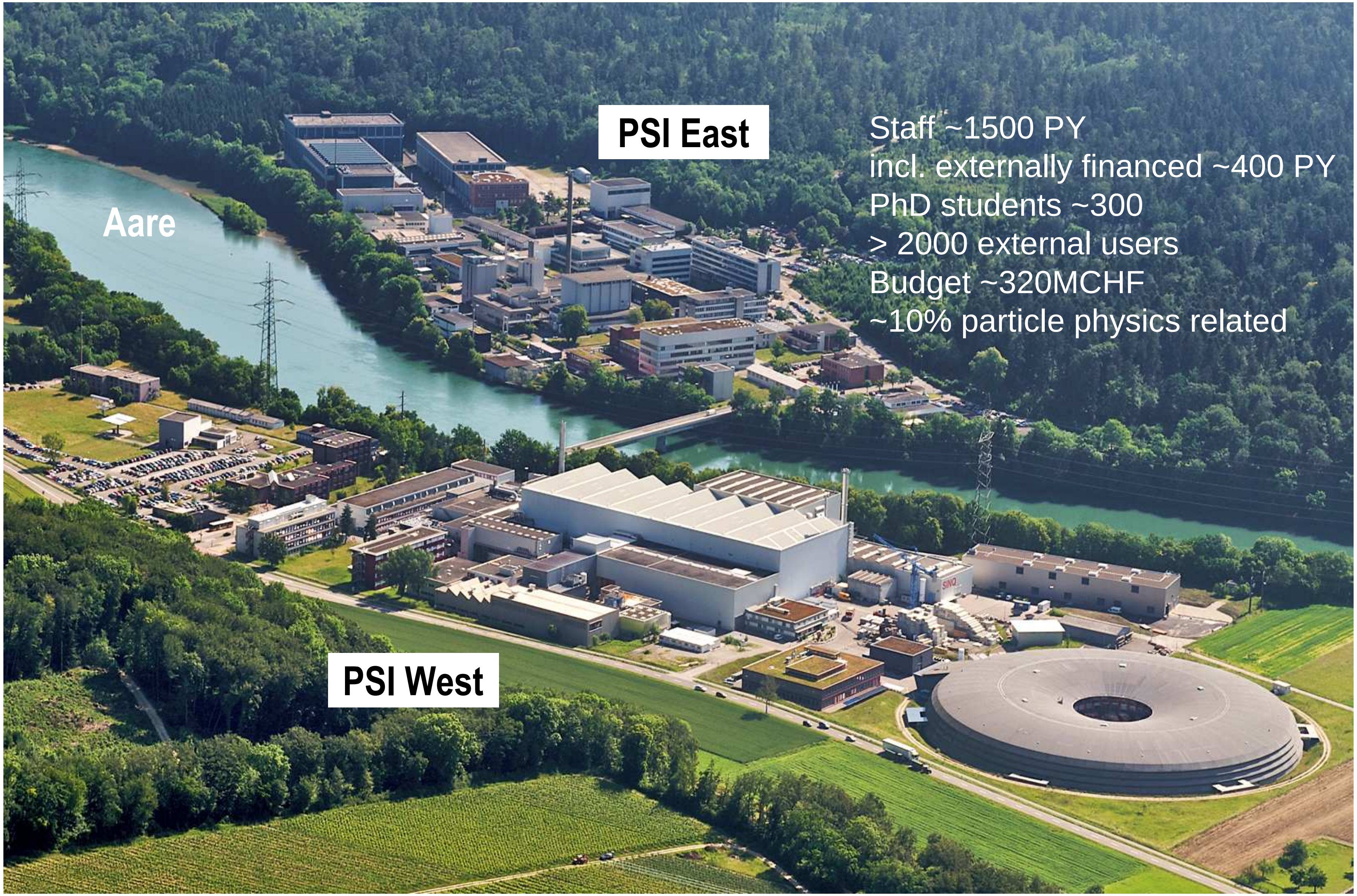
- Statistics:

$$\sigma(d_n) = \frac{\hbar}{2\alpha \underbrace{ET}\sqrt{N}}$$

- Systematics:
  - e.g. v x E effects

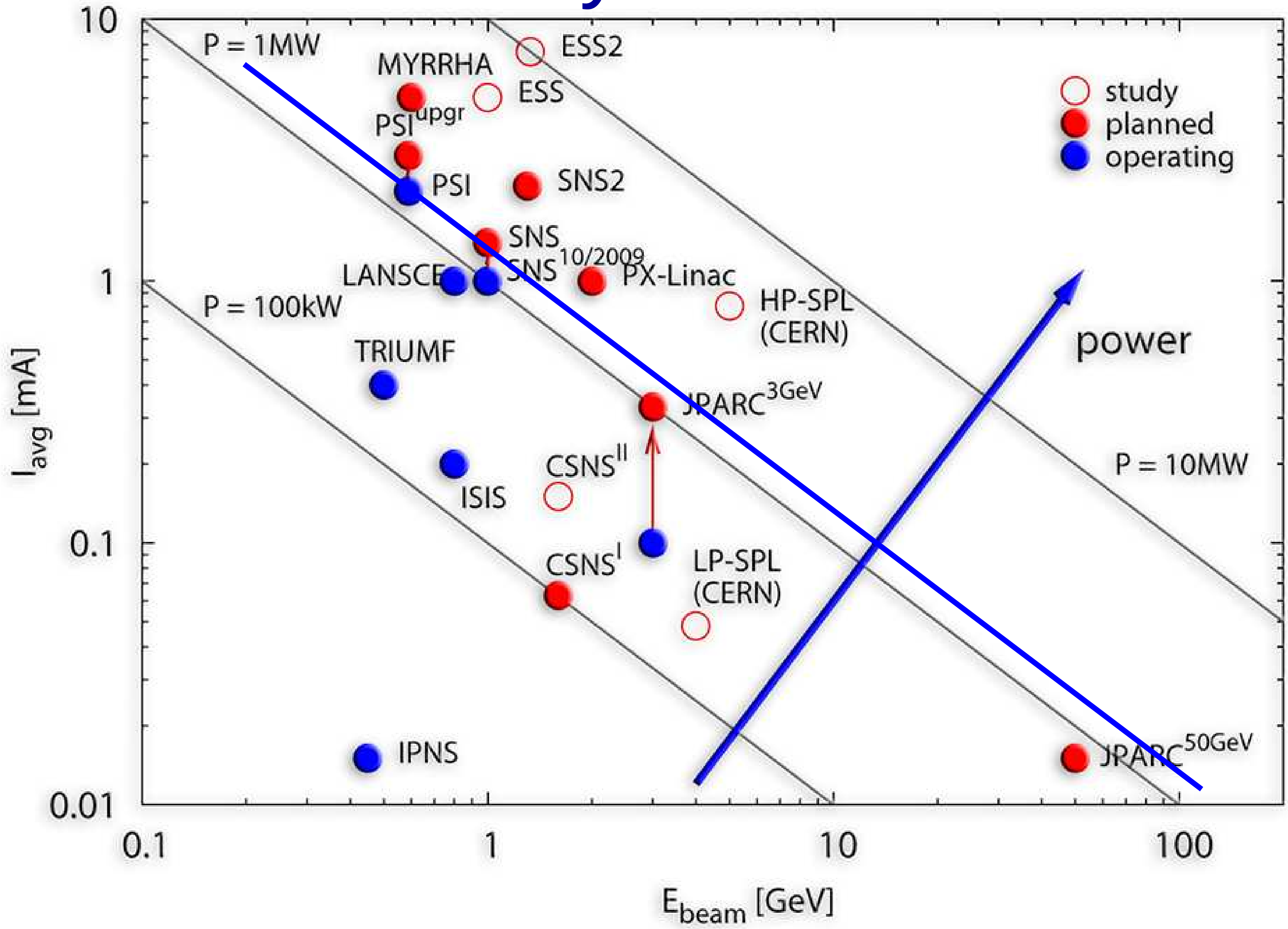


The high intensity&precision frontier at PSI



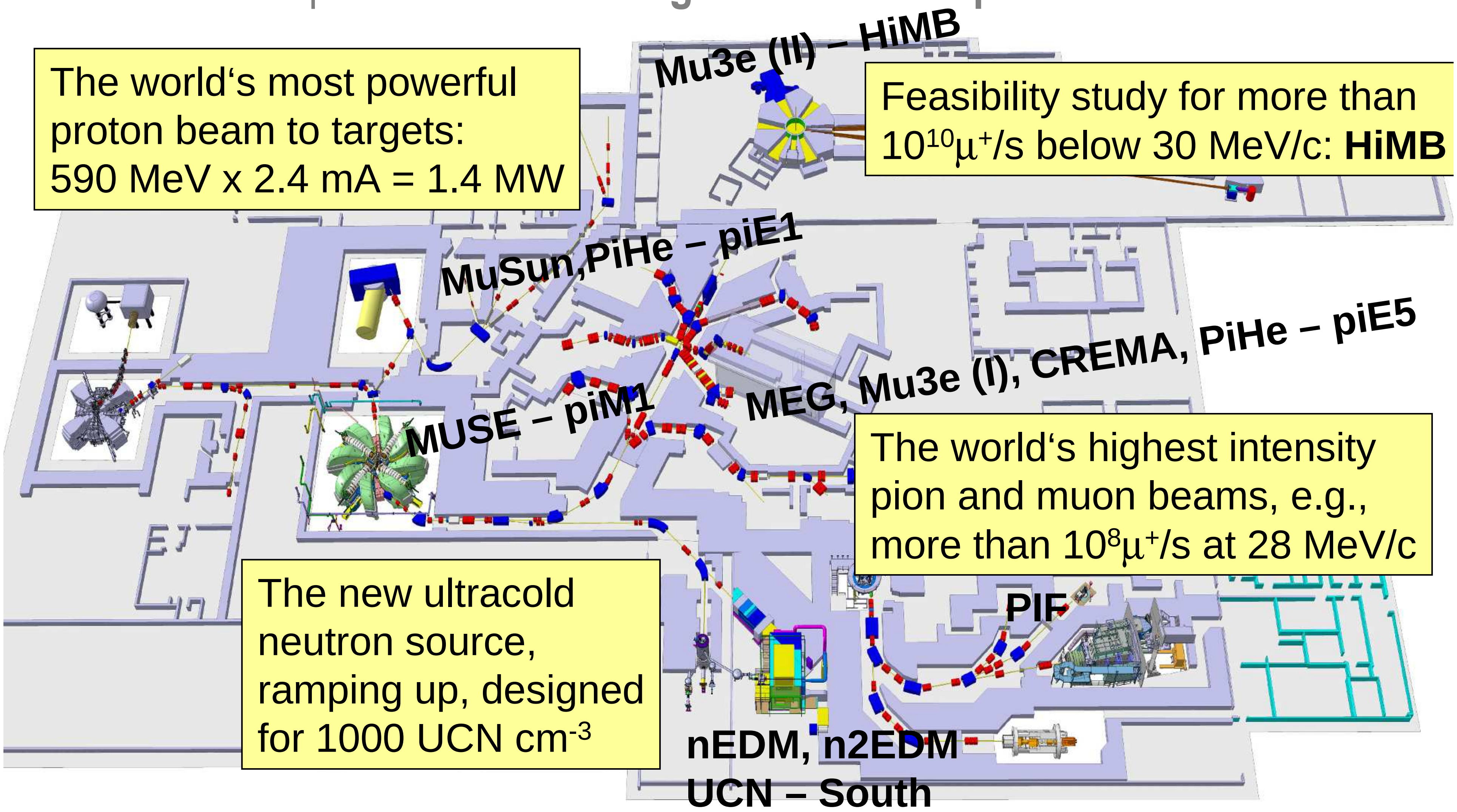
The 590 MeV Ringcyclotron at PSI

Intensity machines



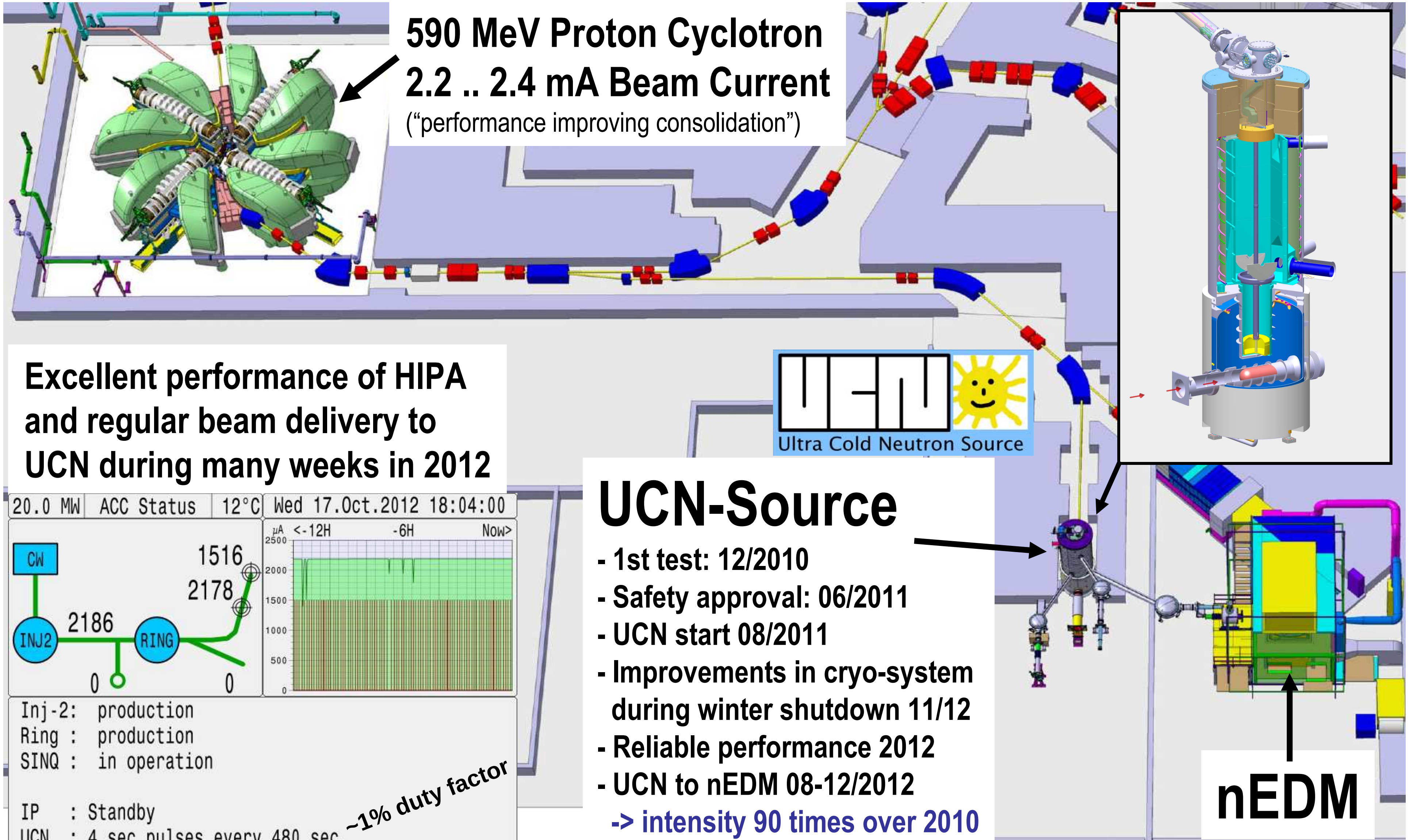
The intensity frontier at PSI: π, μ, UCN

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



Swiss national laboratory with strong international collaborations

High Intensity Proton accelerator & UCN Source



590 MeV Proton Cyclotron
2.2 .. 2.4 mA Beam Current
("performance improving consolidation")

Excellent performance of HIPA and regular beam delivery to UCN during many weeks in 2012

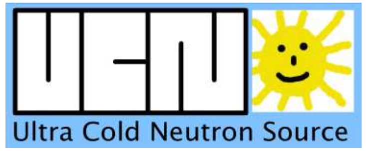
~1% duty factor

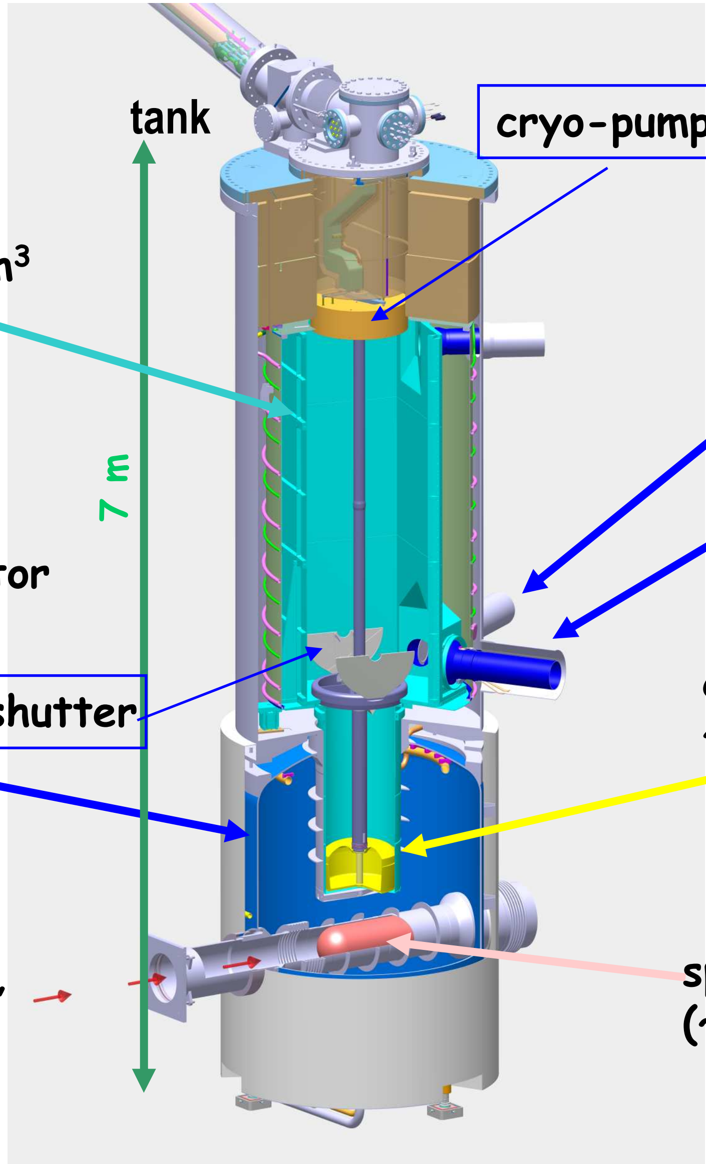
UCN-Source

- 1st test: 12/2010
- Safety approval: 06/2011
- UCN start 08/2011
- Improvements in cryo-system during winter shutdown 11/12
- Reliable performance 2012
- UCN to nEDM 08-12/2012
  -> intensity 90 times over 2010
  -> expect another factor 10-30

nEDM

The PSI UCN source





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

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

heavy water moderator
→ thermal neutrons
3.6m^3 D_2O

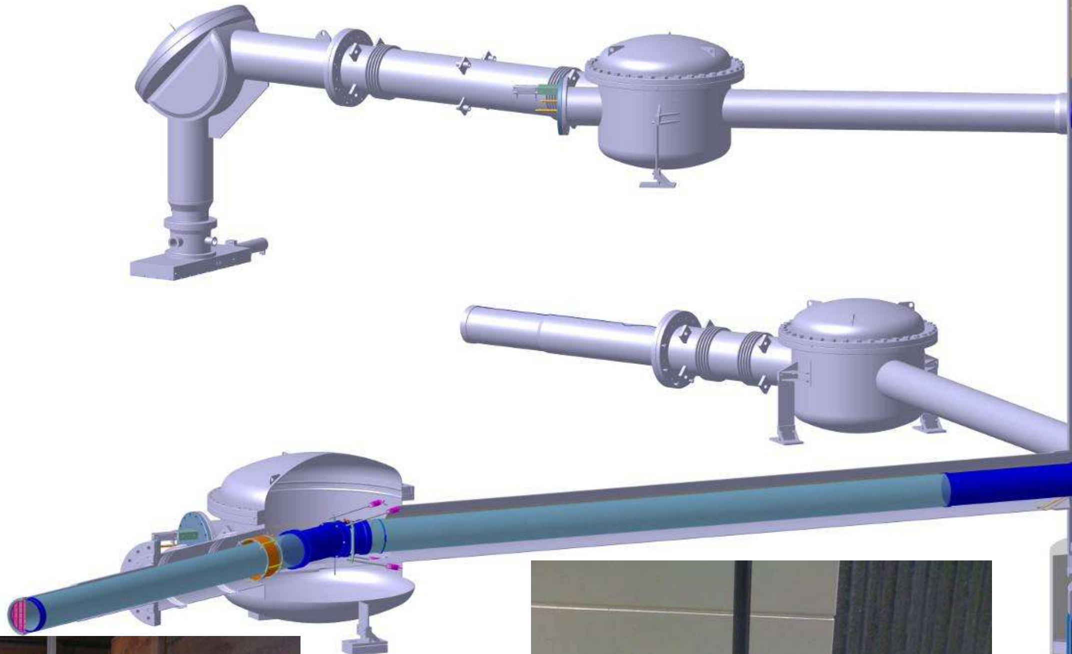
cold UCN-converter
~30 dm^3 solid D_2 at 5 K

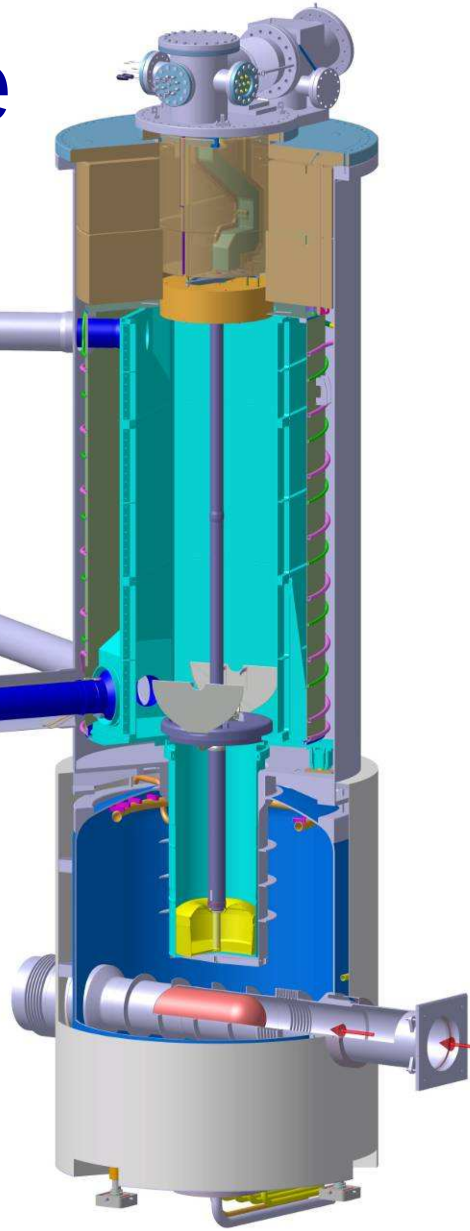
pulsed
1.3 MW p-beam
600 MeV, 2.2 mA,
1% duty cycle

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

The PSI UCN source

Ultra Cold Neutron Source





UCN Tank

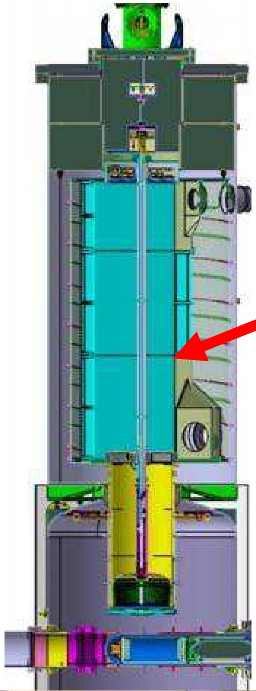
delivery of tank:
Sept. 04, 2008

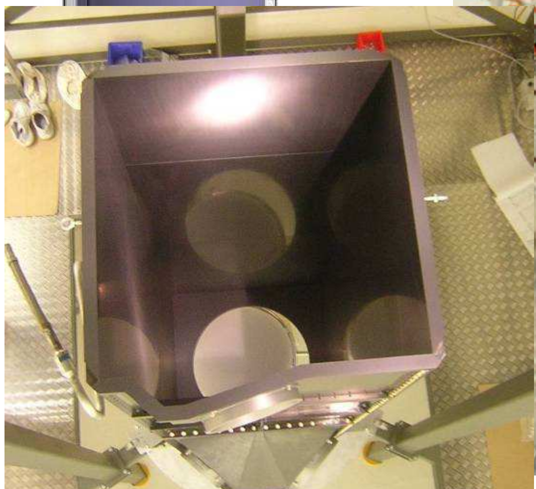
June
2009

December
2009

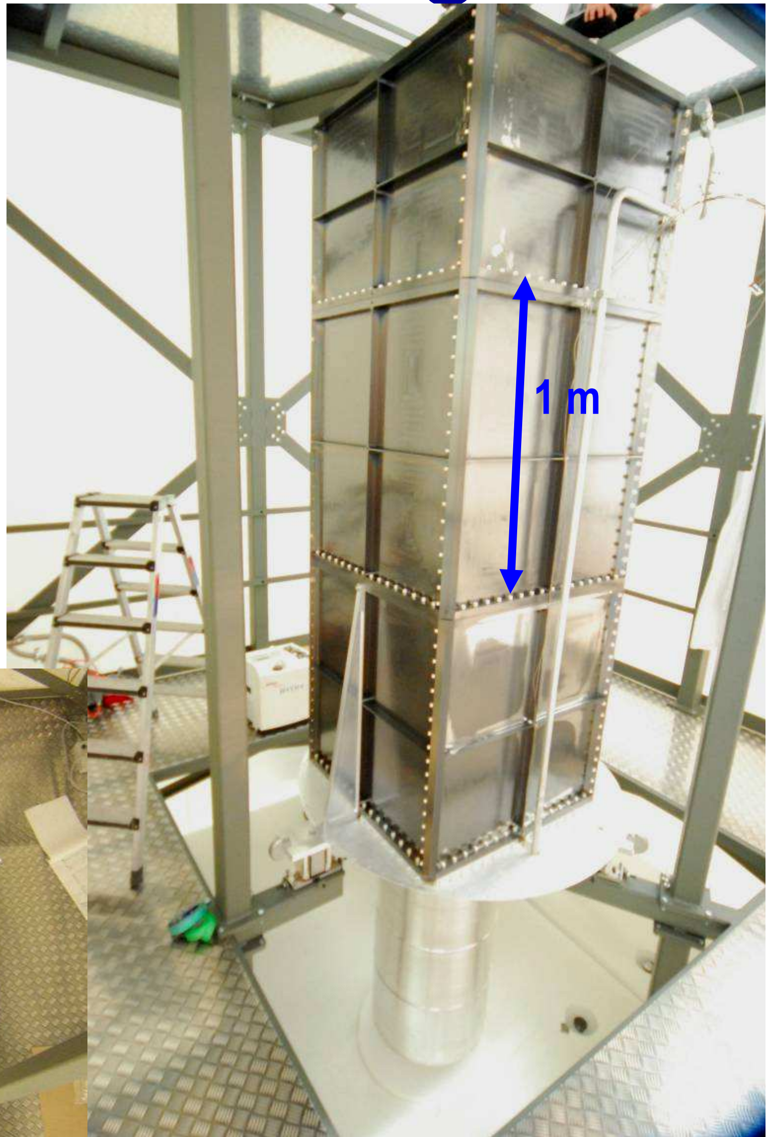
UCN storage volume

Ultra Cold Neutron Source





DLC coating



storage volume in mounting rack

storage volume & thermal shield

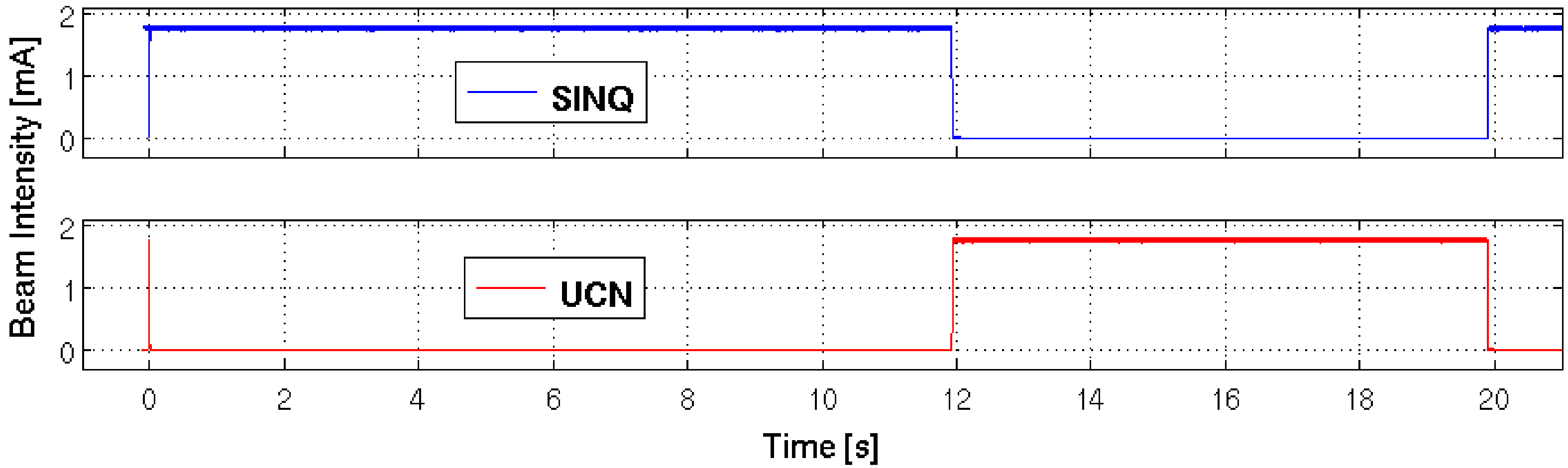
Installation of SD_2 moderator unit

5. November 2010



UCN-Start Dec.16/17/22, 2010

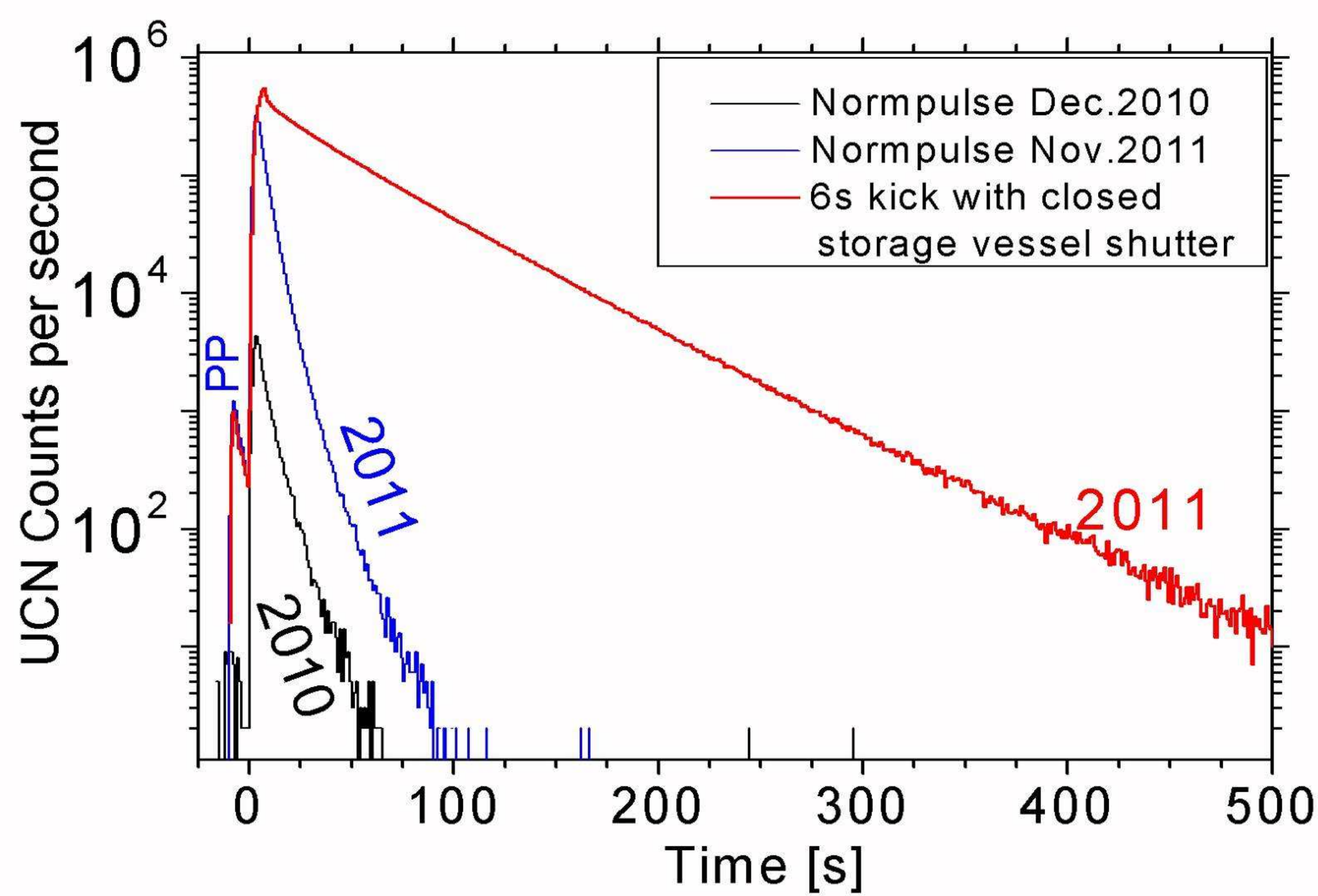
1 MW UCN pulse



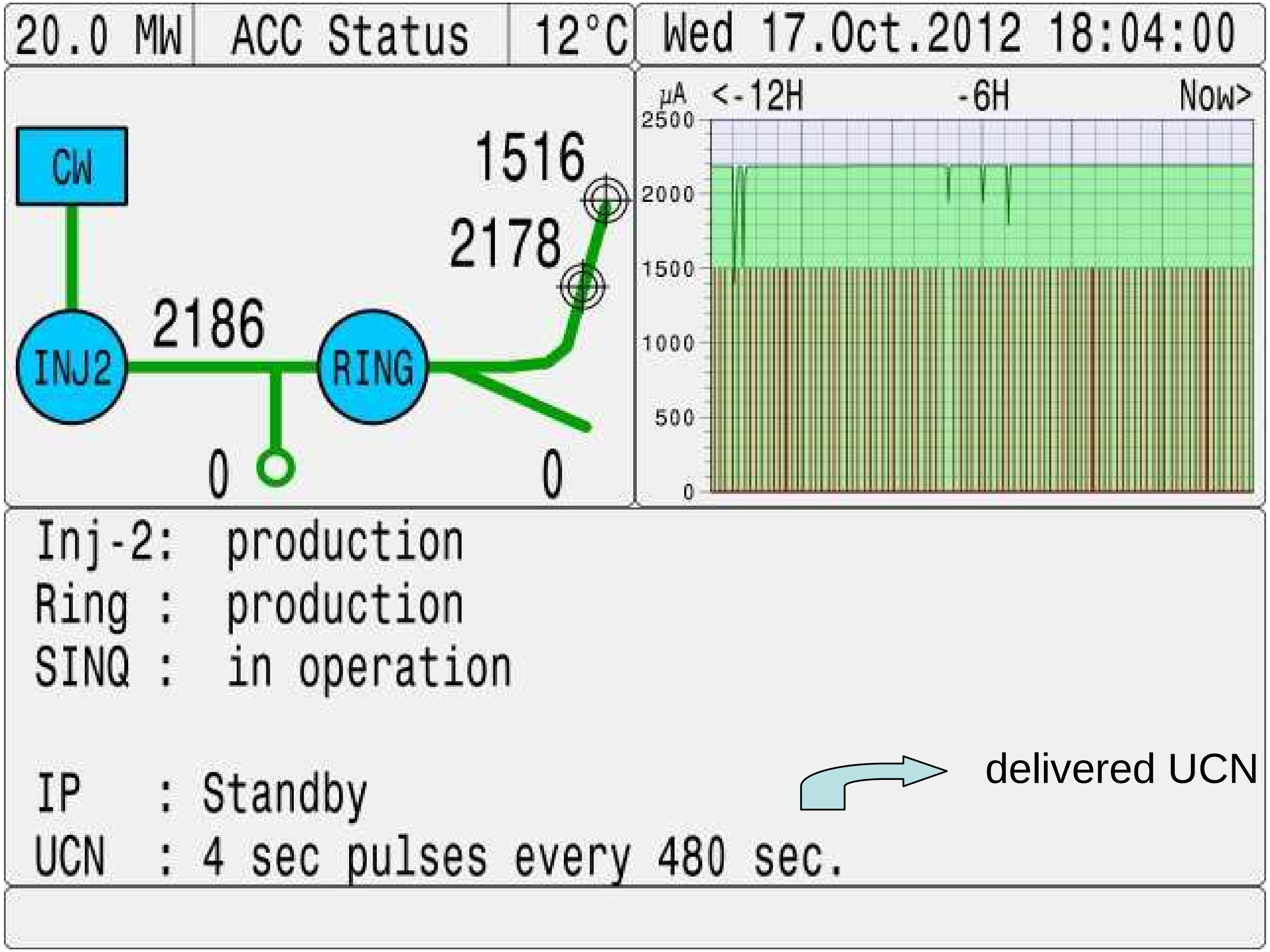
BL2011

Improvement since 2010

Achieved a factor of about 80-90. A factor of 10-30 left to go



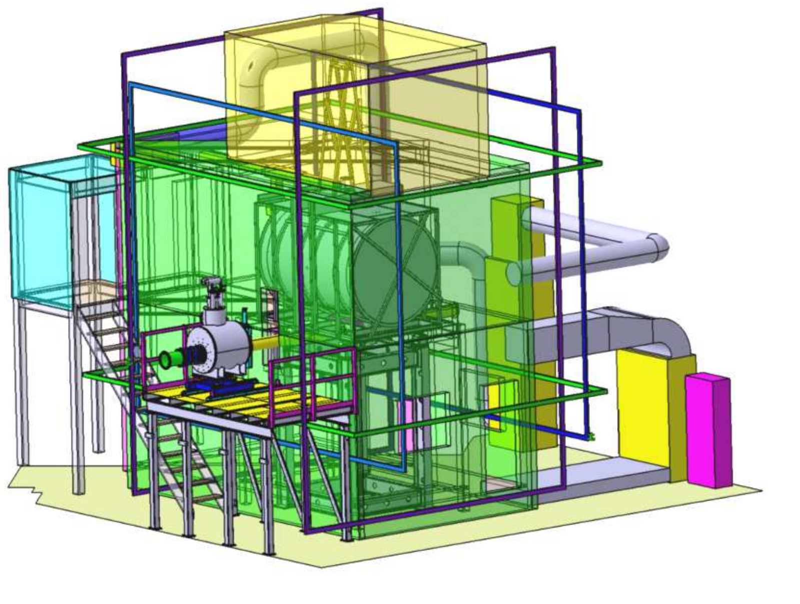
Routine operation in 2012

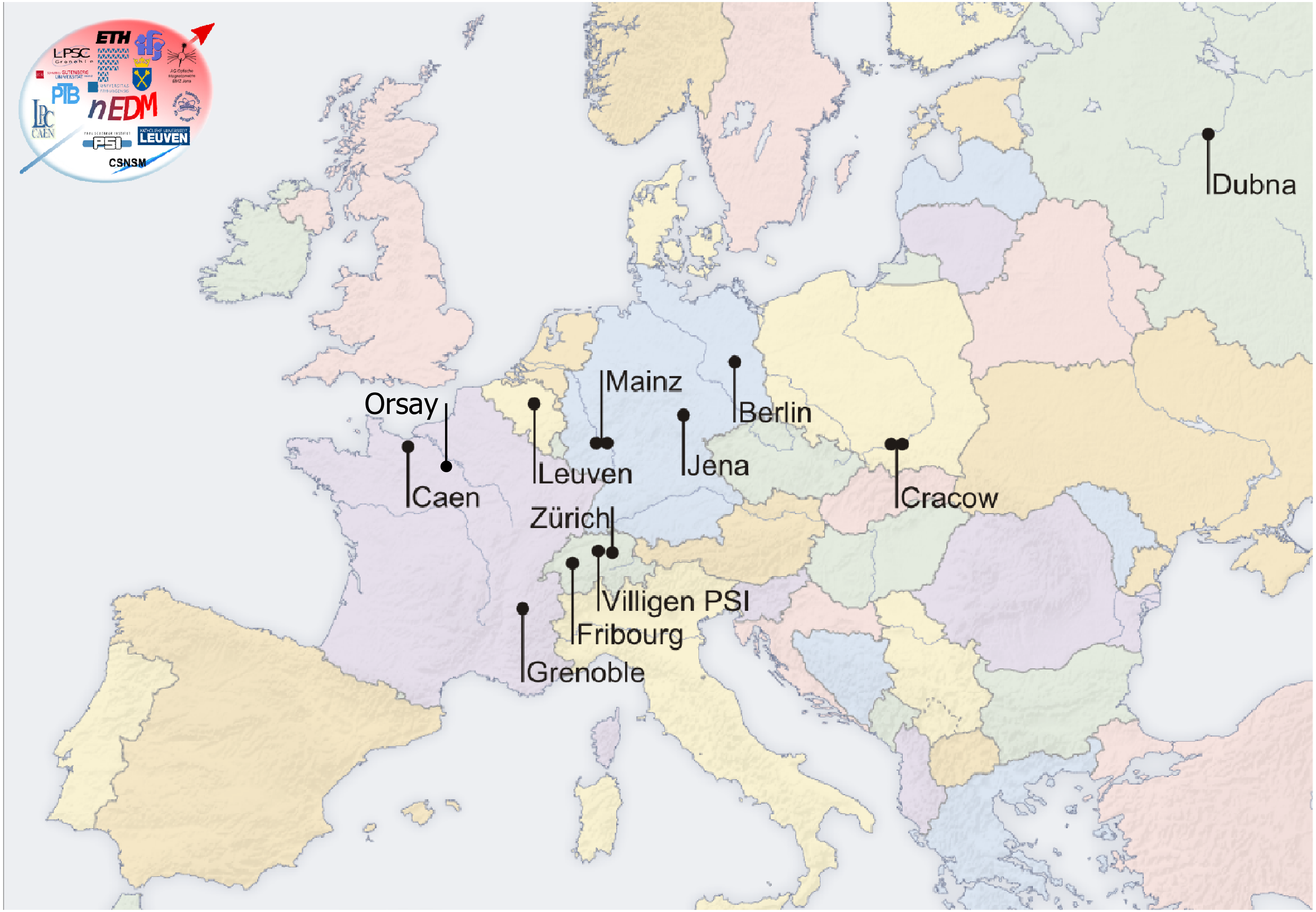


delivered UCN to nEDM

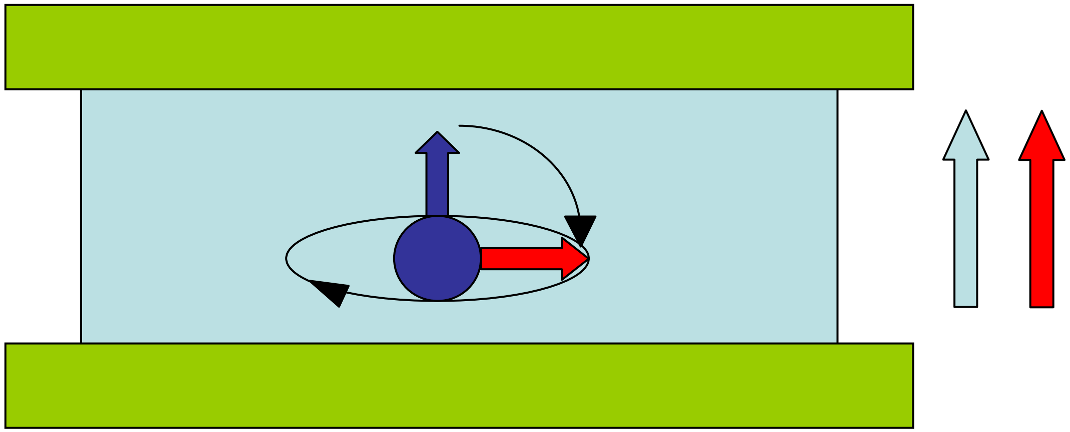
Installing nEDM at PSI in 2009

Coming from ILL
Sussex-RAL-ILL collaboration
PRL 97 (2006) 131801



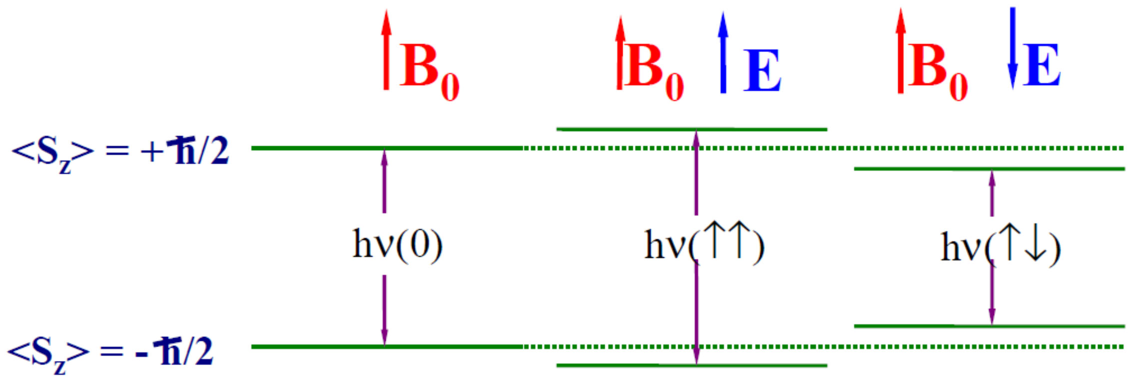

ETH
LPSC
nEDM
PTB
PSI
LEUVEN
CSNSM
Dubna
Mainz
Berlin
Orsay
Jena
Leuven
Caen
Cracow
Zürich
Villigen PSI
Fribourg
Grenoble

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



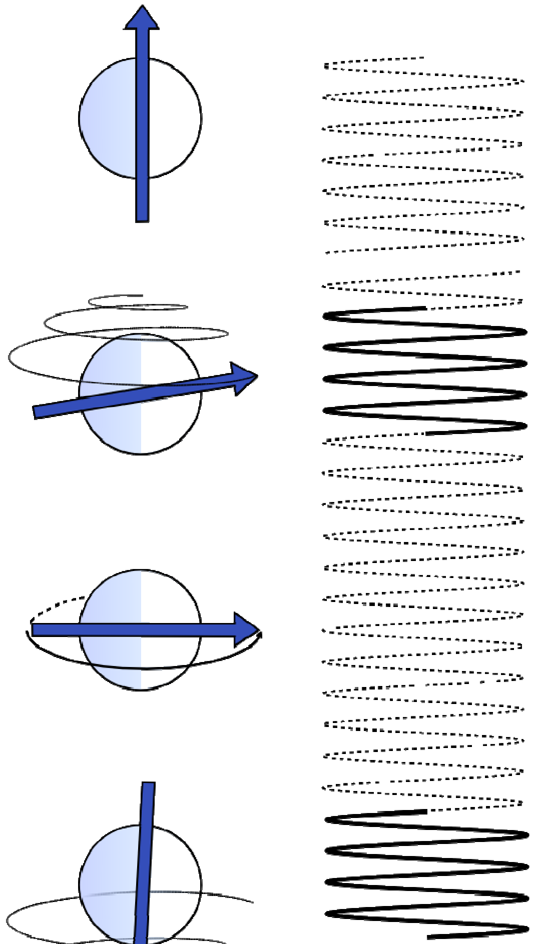
$$h\nu_{\uparrow\uparrow} = 2\,(\mu B + d_n E)$$
$$h\nu_{\uparrow\downarrow} = 2\,(\mu B - d_n E)$$

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



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

The Ramsey method



Spin up neutrons

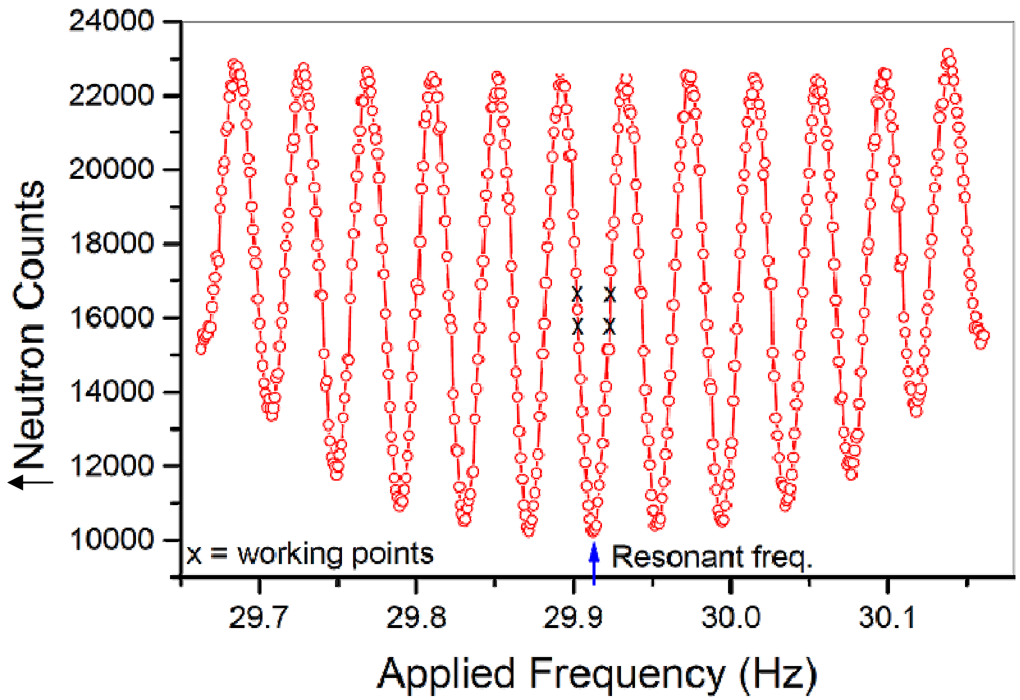
π/2 flip pulse

Free precession

π/2 flip pulse

Neutron clock

external clock



[K. Green et al, Nucl. Instr. Meth. A 404, 381 (1998)]

Statistical sensitivity

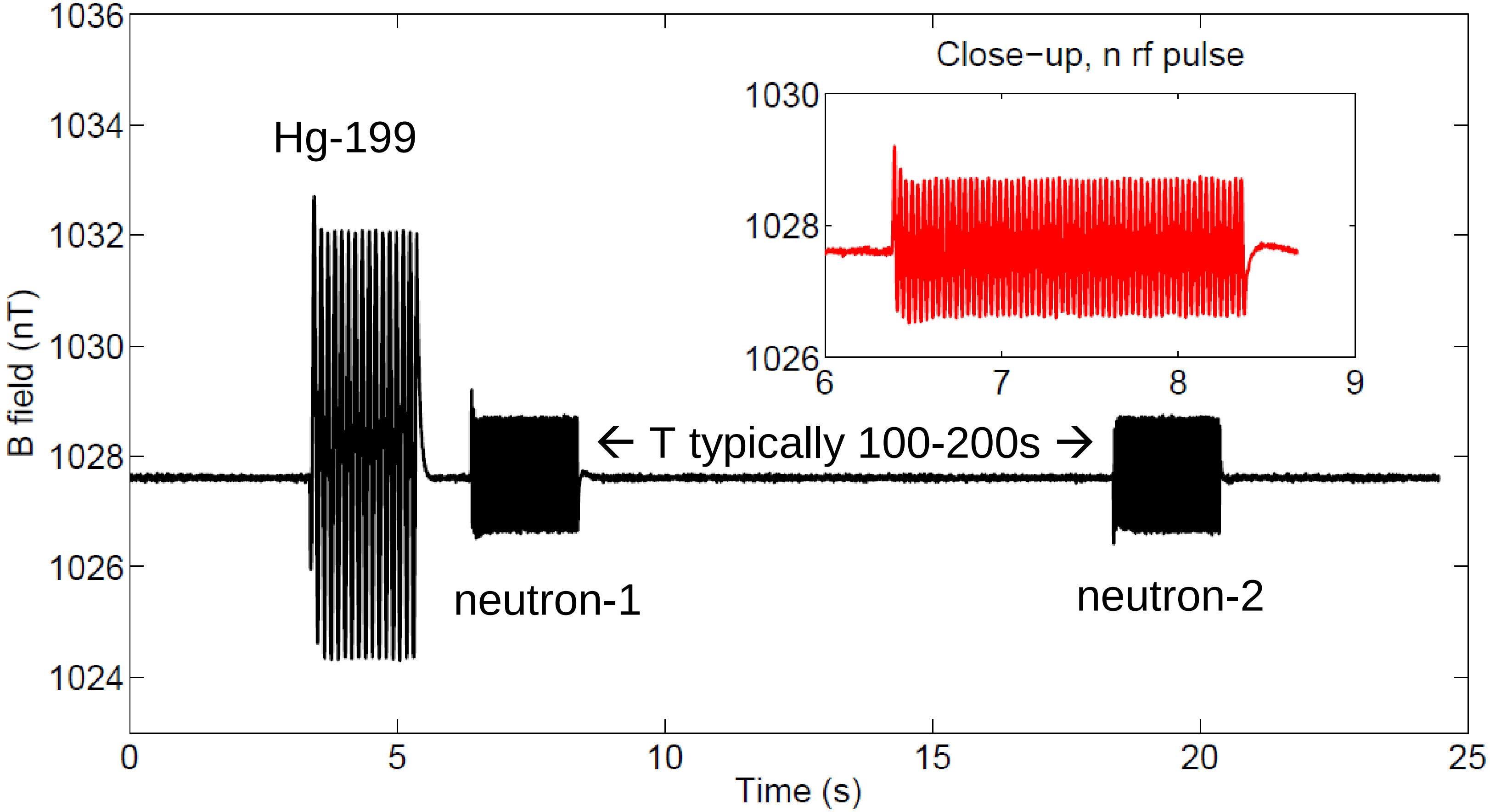
$$\sigma = \frac{\hbar}{2E\alpha T\sqrt{N}}$$

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

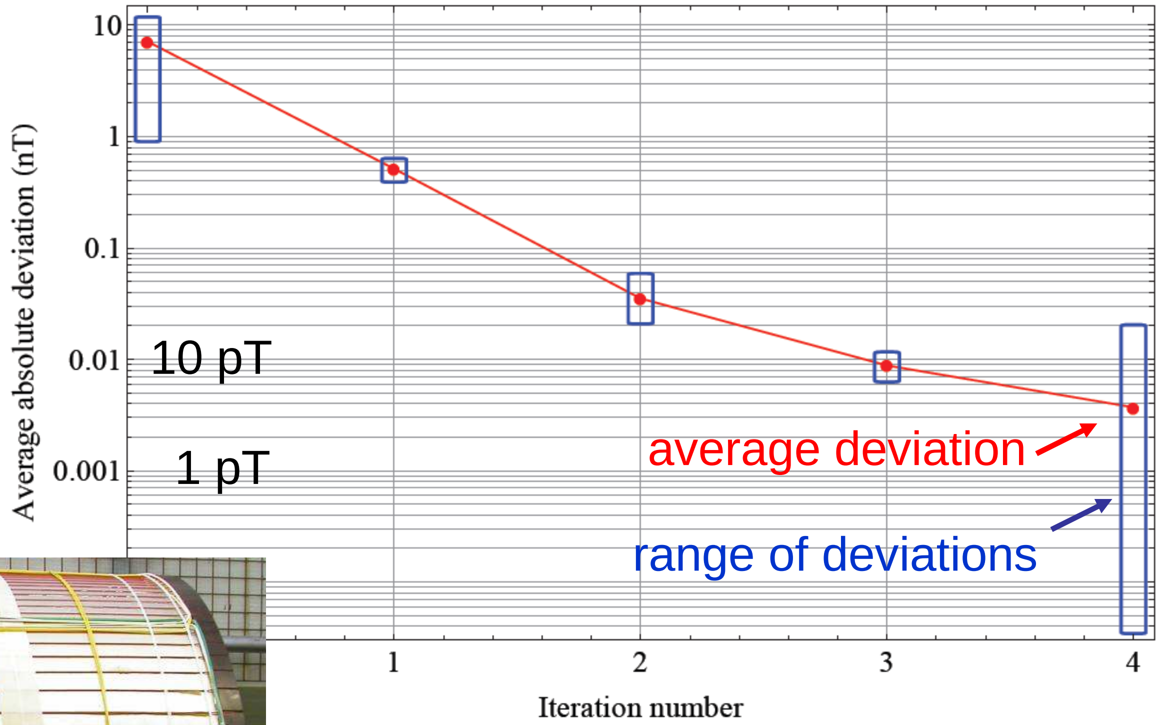

01/06/2011

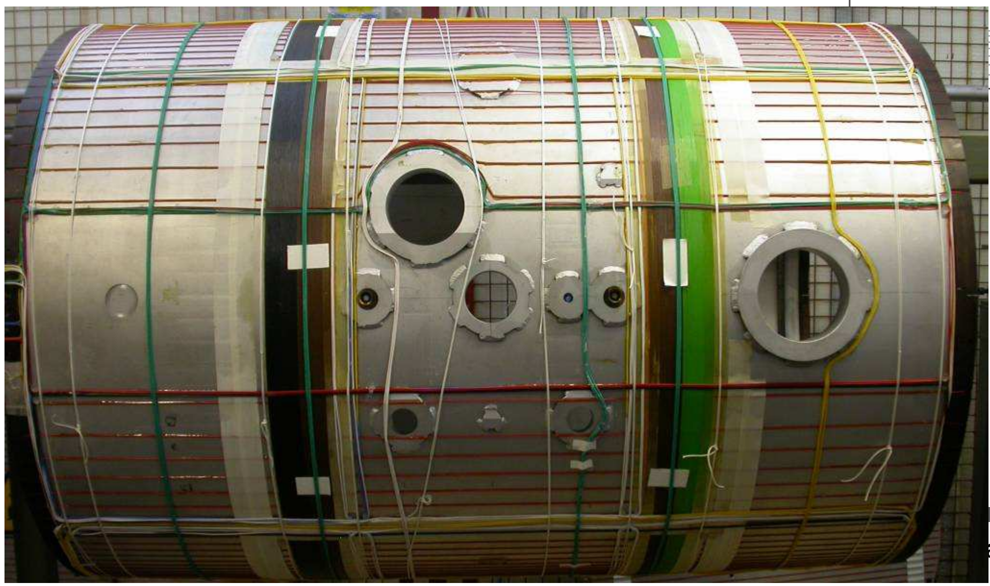

01/06/2011

The π/2-pulses seen by CsM

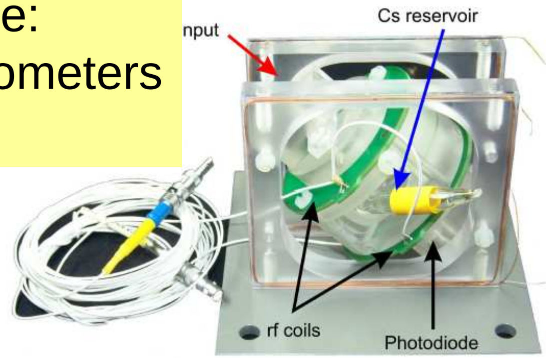


Optimizing the magnetic field homogeneity

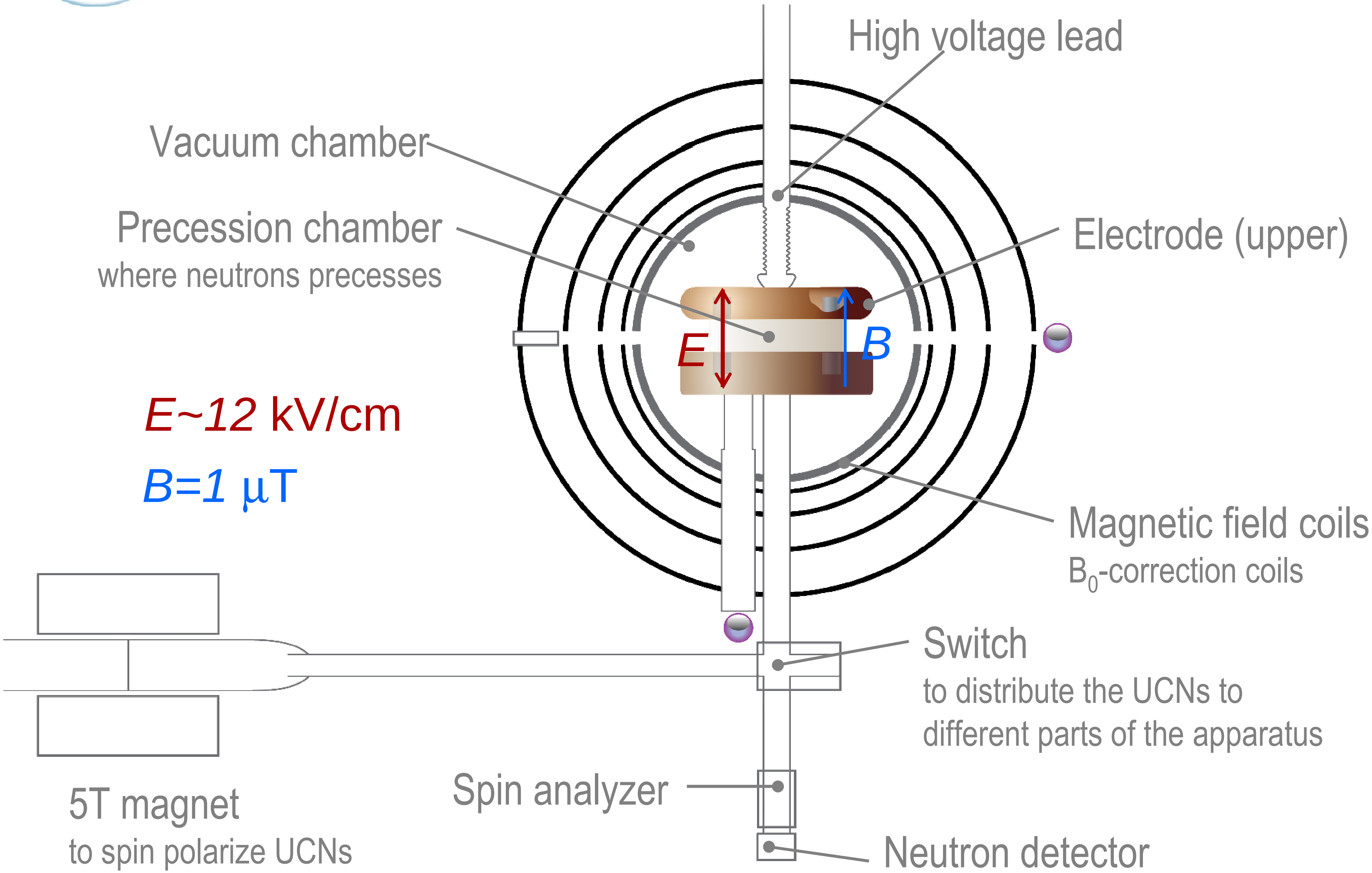




presently in use:
12 Cs magnetometers
33 trim coils



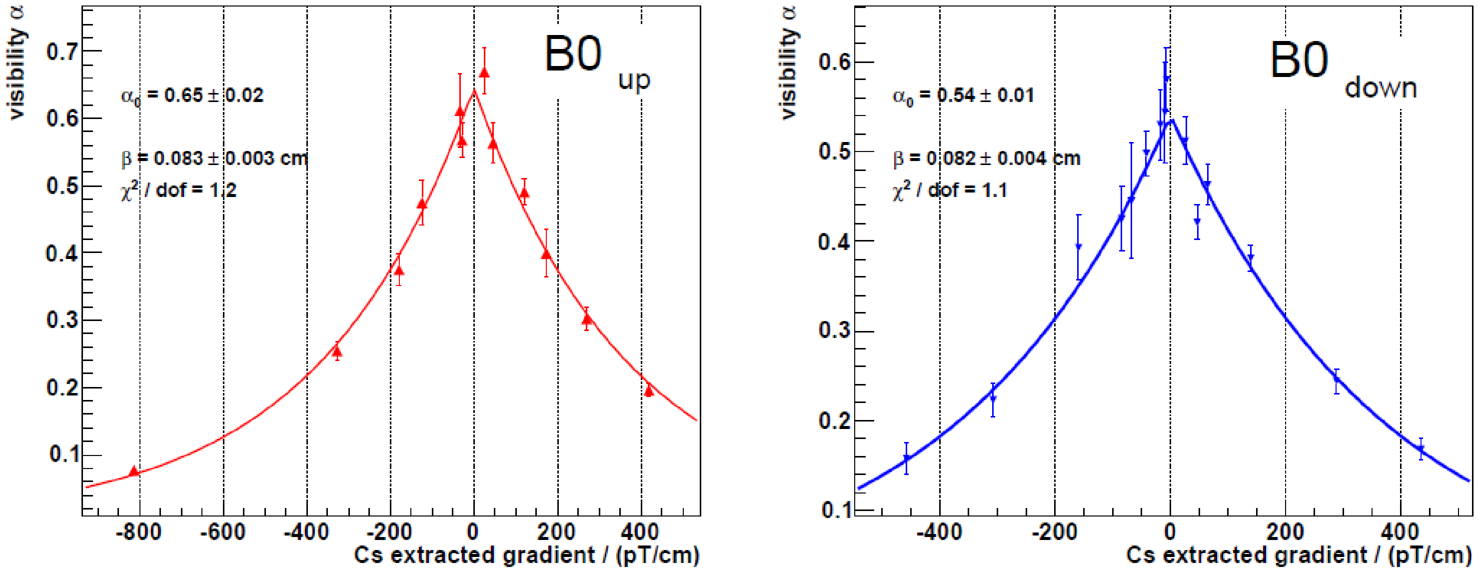
Apparatus



E~12 kV/cm

B=1 μT

Visibility α versus B_z-field gradient

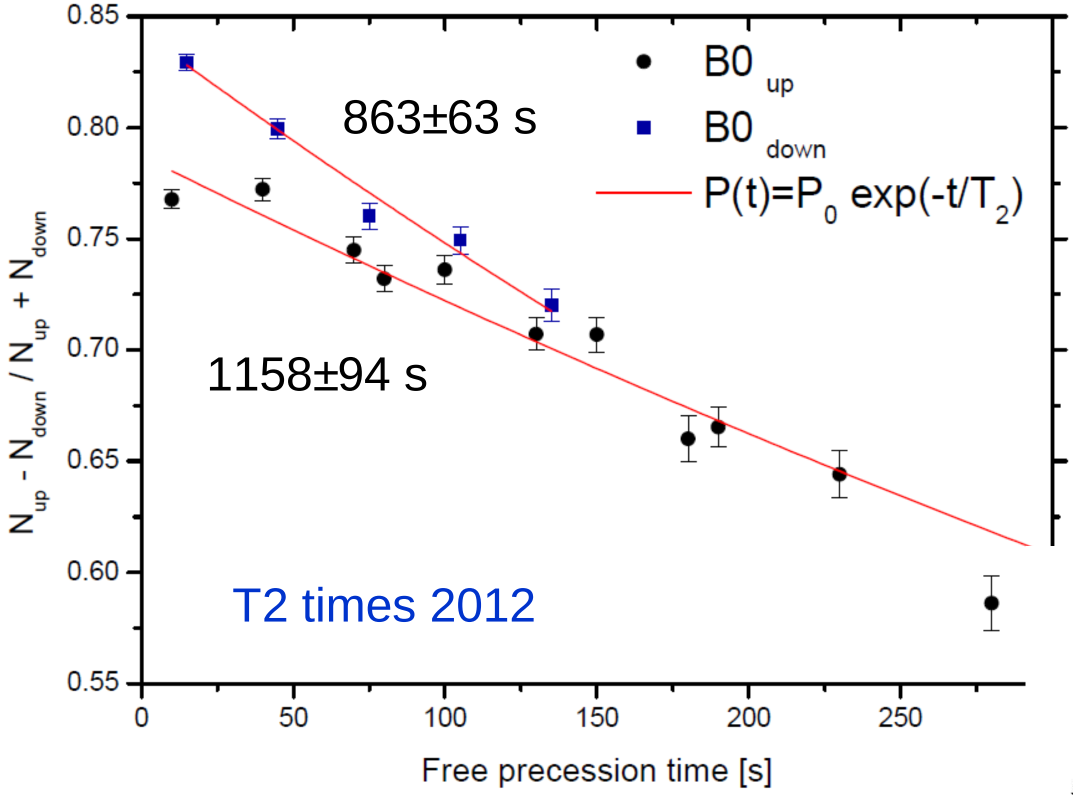


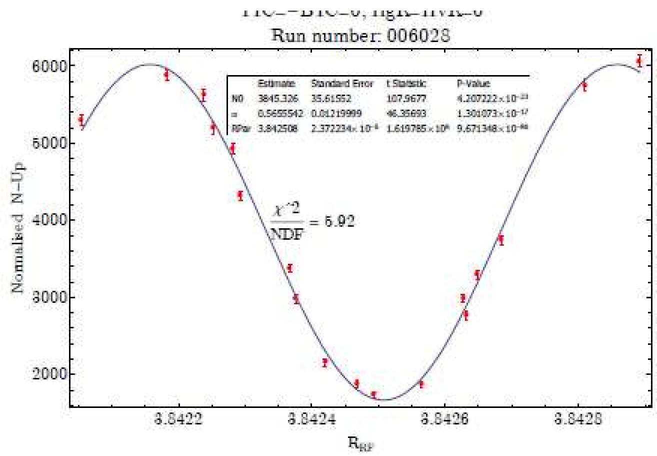
T=180s

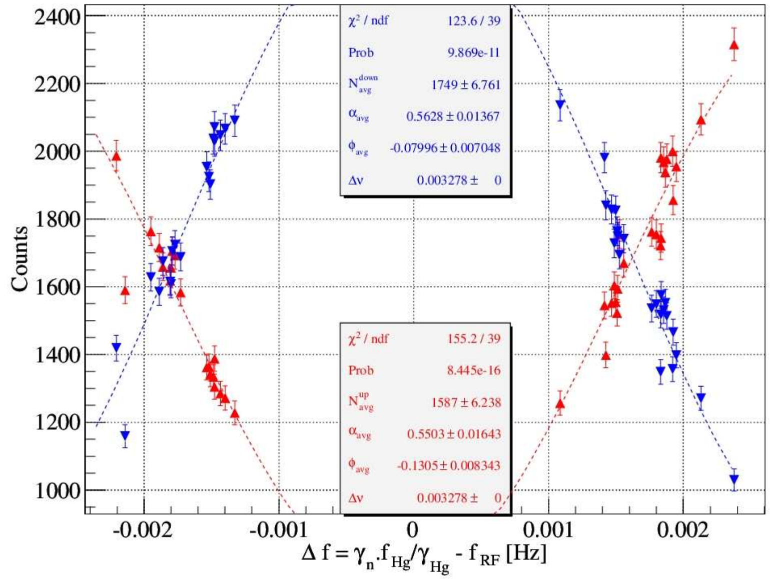
(a) (b)

Figure 39: Visibility of the Ramsey fringe after 180 s of free precession of UCN plotted versus vertical magnetic field gradient extracted by a parametrization of the Cs magnetometer data as described in the text (next-to-linear model). The red curve in (a) shows the case for $B_0^{\uparrow}$ and the blue curve in (b) shows the $B_0^{\downarrow}$ measurement, respectively. The expected G^2 dependence could not be observed, instead the depolarization of UCN with increasing gradient scales with $|G|$.

nEDM – performance 2012



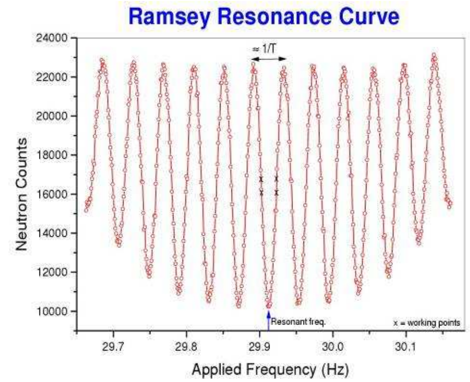




Statistical Sensitivity

projected (and as of Nov. 2012)

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



α = 0.75 (0.68)

E = 12 kV/cm (8.3)

T = 150 s (200s)

N = 350'000 (8'000)

$\sigma(d_n)$ = 4 x 10^{-25} ecm / cycle
400 s

(~ 2-3 x 10^{-25} ecm / day)

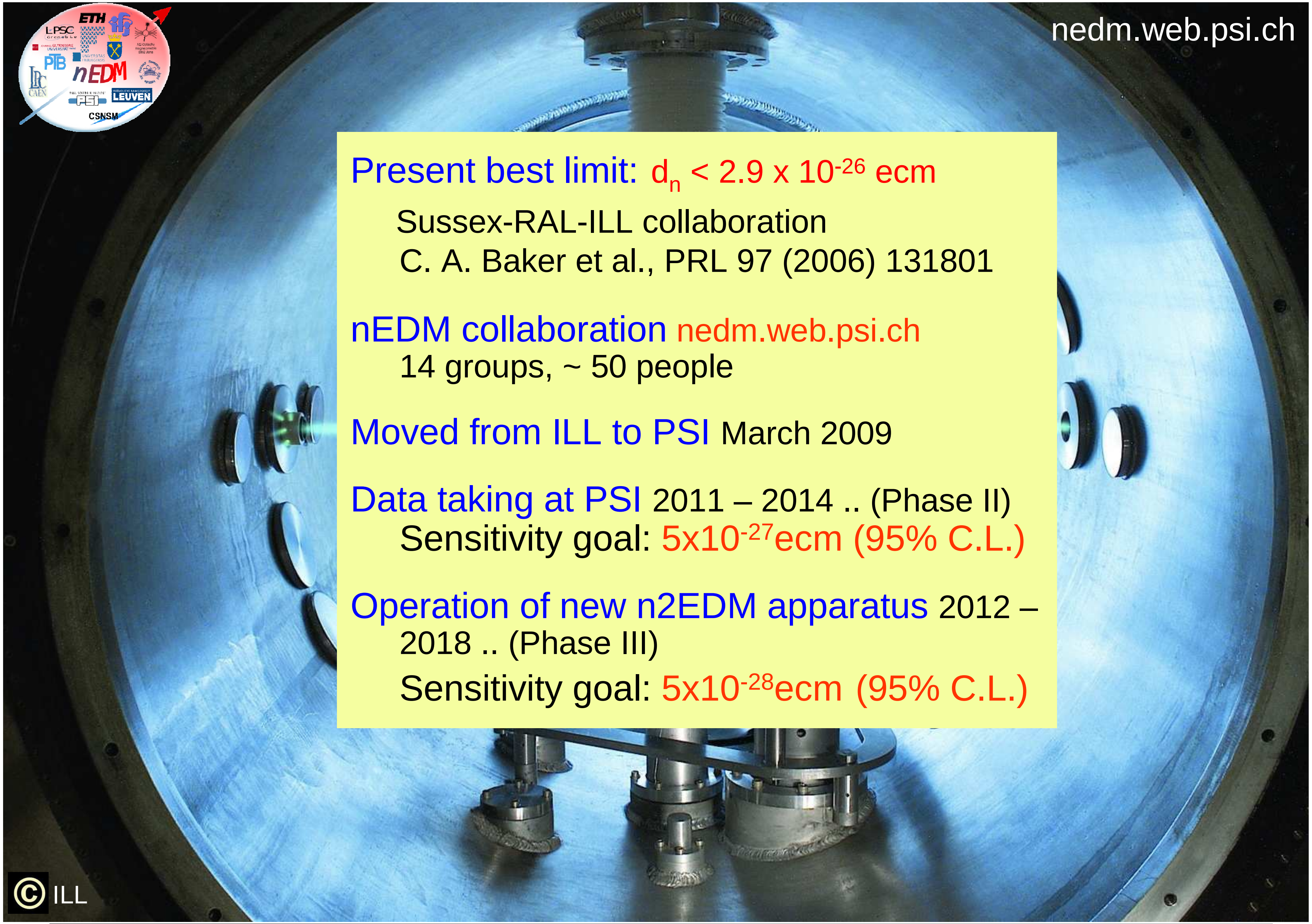
= 3 x 10^{-26} ecm / day

= 3 x 10^{-27} ecm / year
200 nights

Obtain same figures with
E=10kV/cm, T=130s, 200s cycle

After 2 years*, statistics only
d_n = 0: $|d_n|$ < 4 x 10^{-27} ecm (95% C.L.)

* 200 nights each



Present best limit: $d_n < 2.9 \times 10^{-26}$ ecm

Sussex-RAL-ILL collaboration

C. A. Baker et al., PRL 97 (2006) 131801

nEDM collaboration nedm.web.psi.ch

14 groups, ~ 50 people

Moved from ILL to PSI March 2009

Data taking at PSI 2011 – 2014 .. (Phase II)

Sensitivity goal: 5×10^{-27} ecm (95% C.L.)

Operation of new n2EDM apparatus 2012 – 2018 .. (Phase III)

Sensitivity goal: 5×10^{-28} ecm (95% C.L.)


nedm.web.psi.ch
Thank you!
nEDM
ETH
LPSC
PTB
LEUVEN
CSNSM
© ILL

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- Precision measurements of fundamental constants
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- Exotic atoms and molecules
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- Advanced muon and ultracold neutron sources
- Advanced detector technologies

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