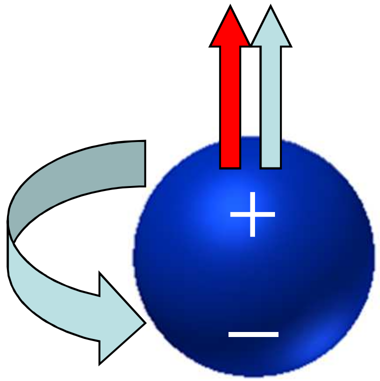
The search for permanent electric dipole moments

Klaus Kirch

Paul Scherrer Institut and ETH Zürich



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

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

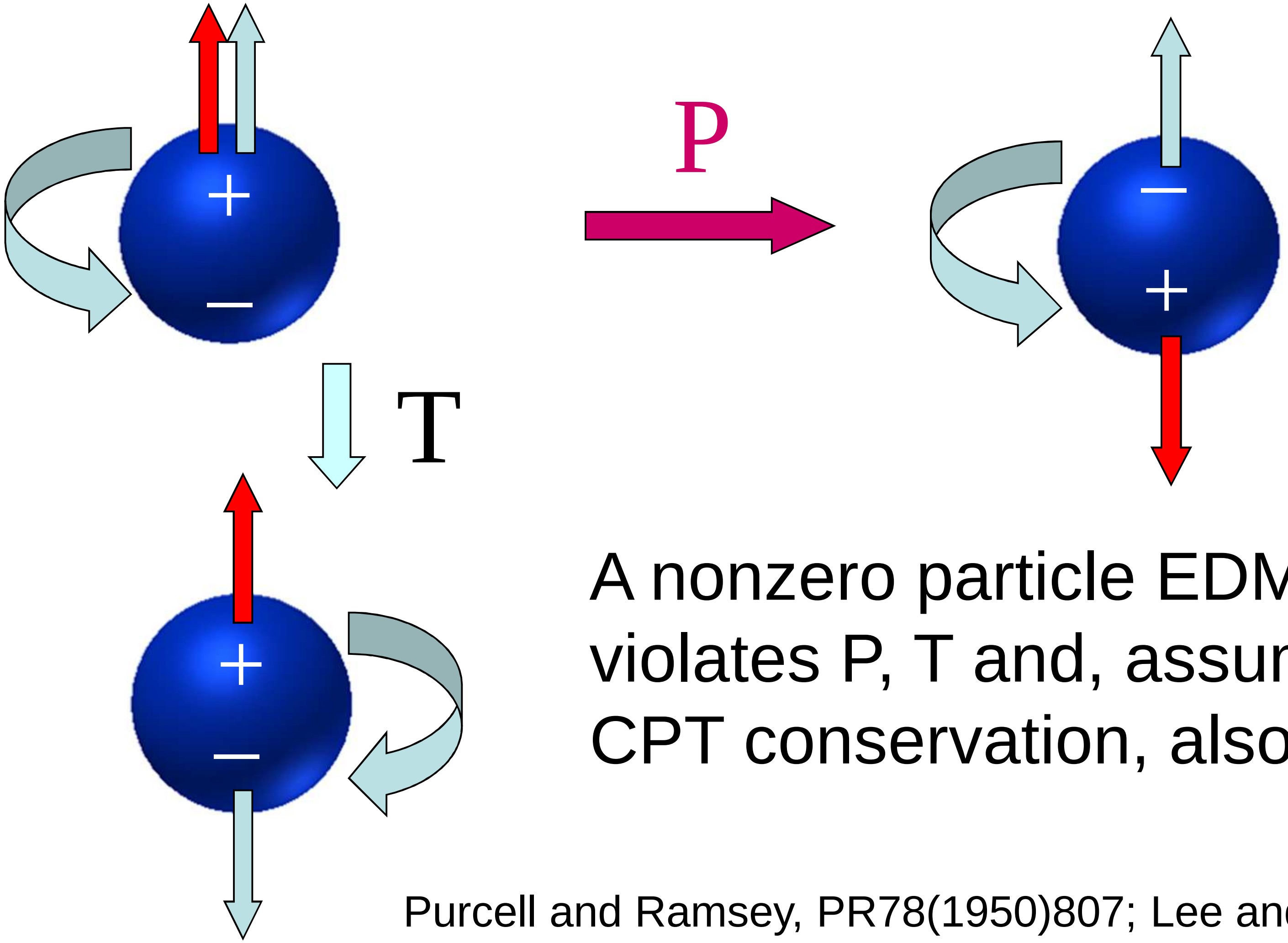
SM expectation:
$(n_B - n_{\bar{B}}) / n_\gamma \sim 10^{-18}$

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

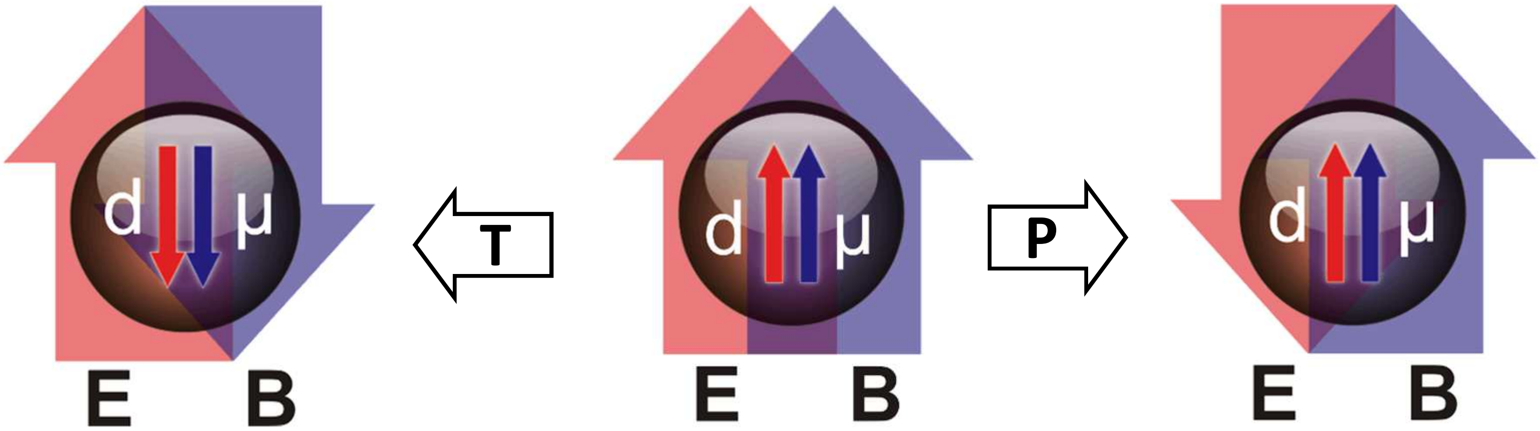


A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP

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

EDM and symmetries

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

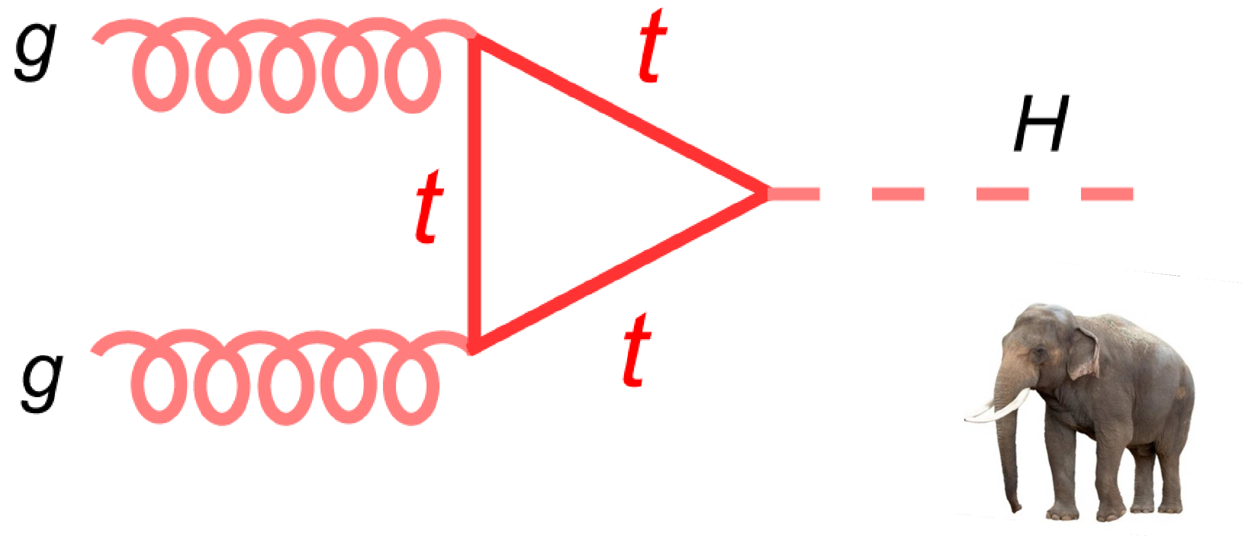


A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP

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

Today´s most spectacular (Standard) Particle Physics:

Direct production of new particles ...

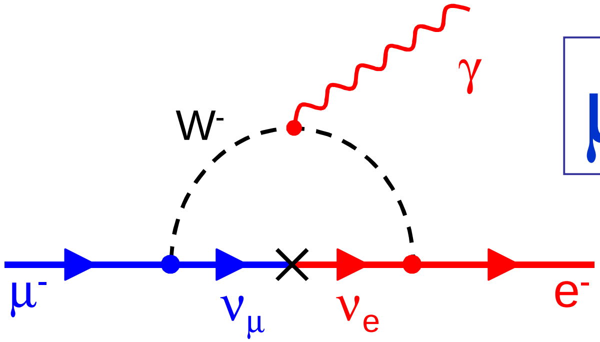


and detection of
decay products

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

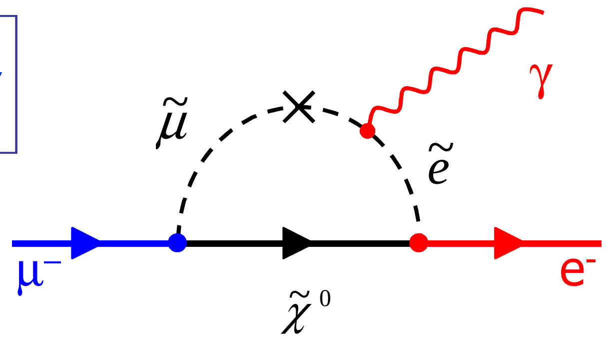
A complementary approach:

Effects of new particles in loops ...



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

$\mu \rightarrow e+\gamma$



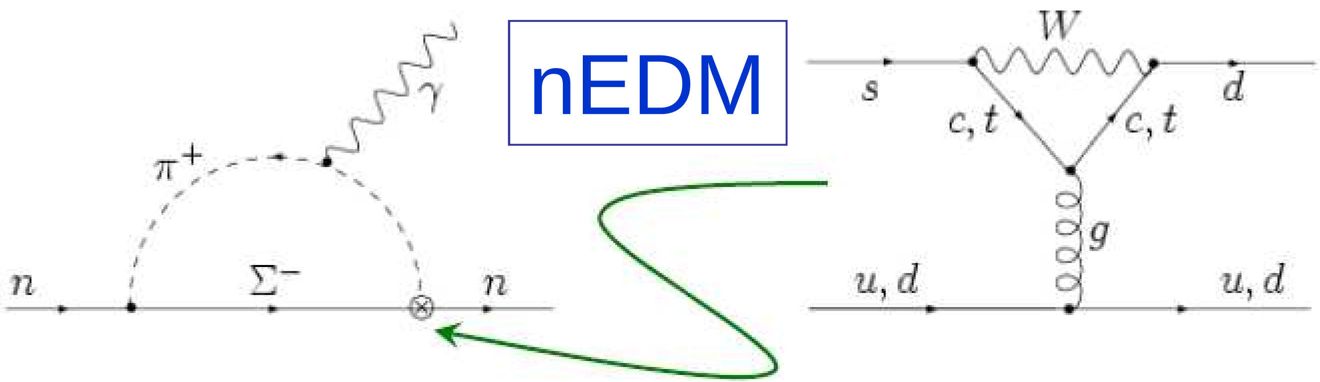
10^{-12} ... 10^{-14} ?

... 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

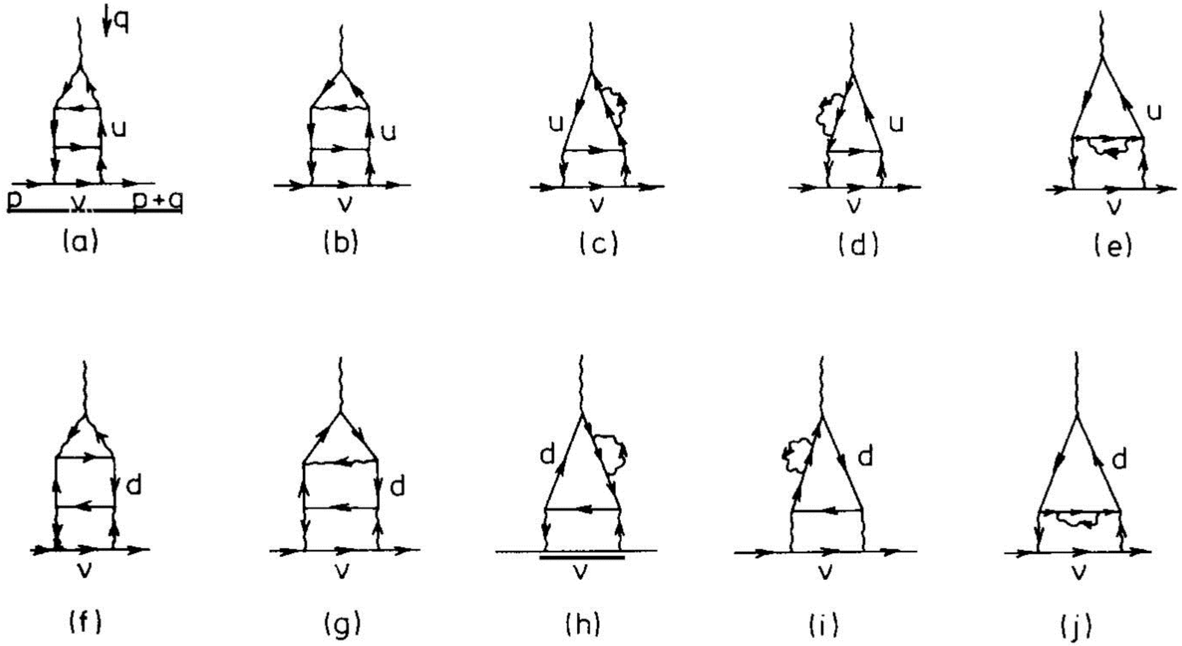


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

… + new physics?

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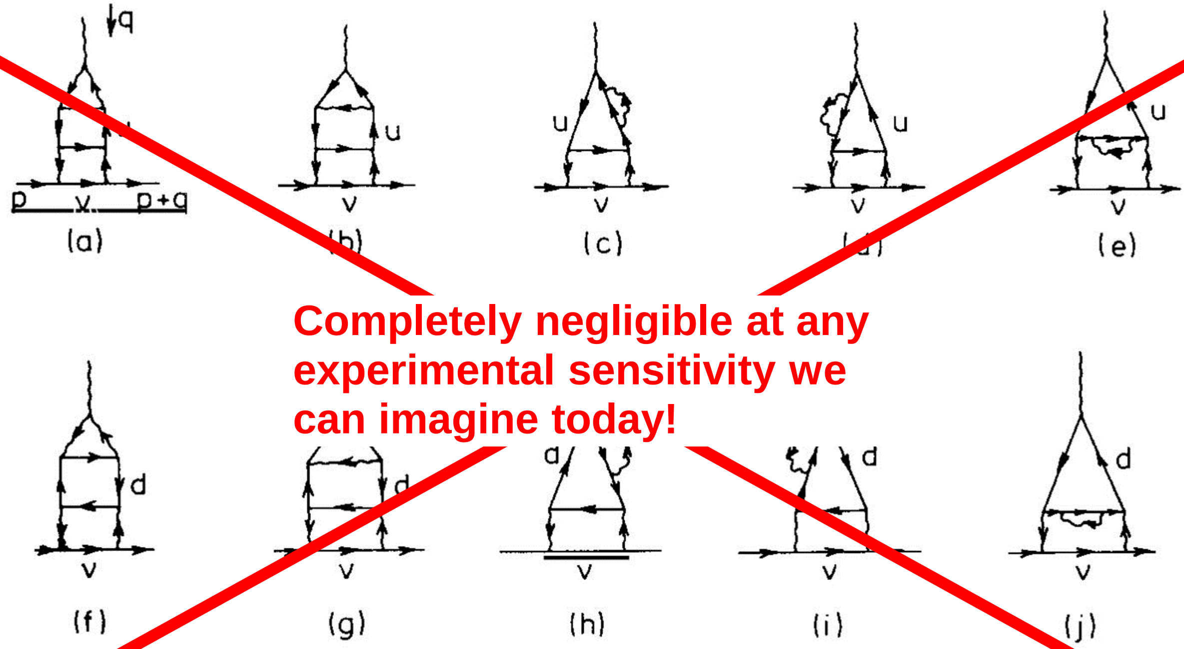

Completely negligible at any experimental sensitivity we can imagine today!

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!

Standard model lepton EDMs

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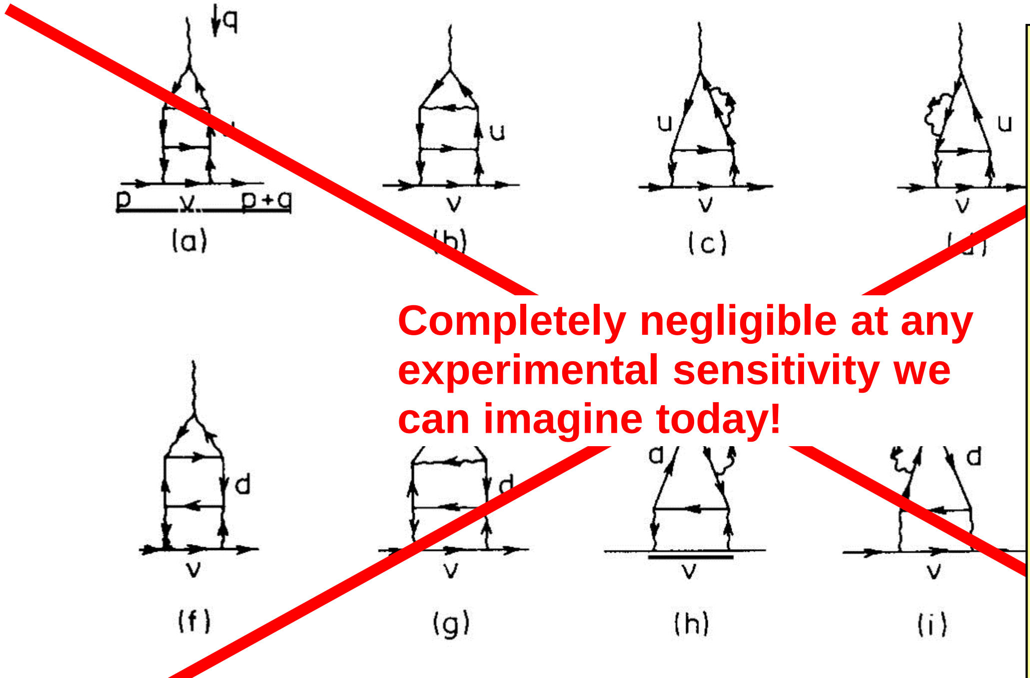


Fig. 4. The ten diagrams which contribute to the edm of the electron. Th... W-propagators.

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:

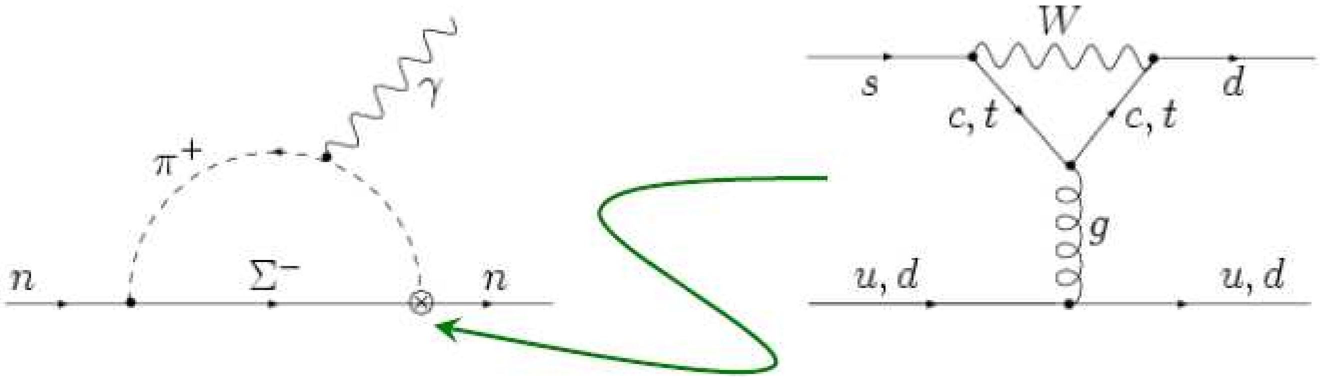
$d_e < 1 \times 10^{-27}$ e•cm
$d_\mu < 2 \times 10^{-19}$ e•cm
$d_\tau < 3 \times 10^{-17}$ e•cm

… + new physics?

Much greater sensitivity to new, CP-violating physics!

Neutron: Standard Model prediction

- electroweak -

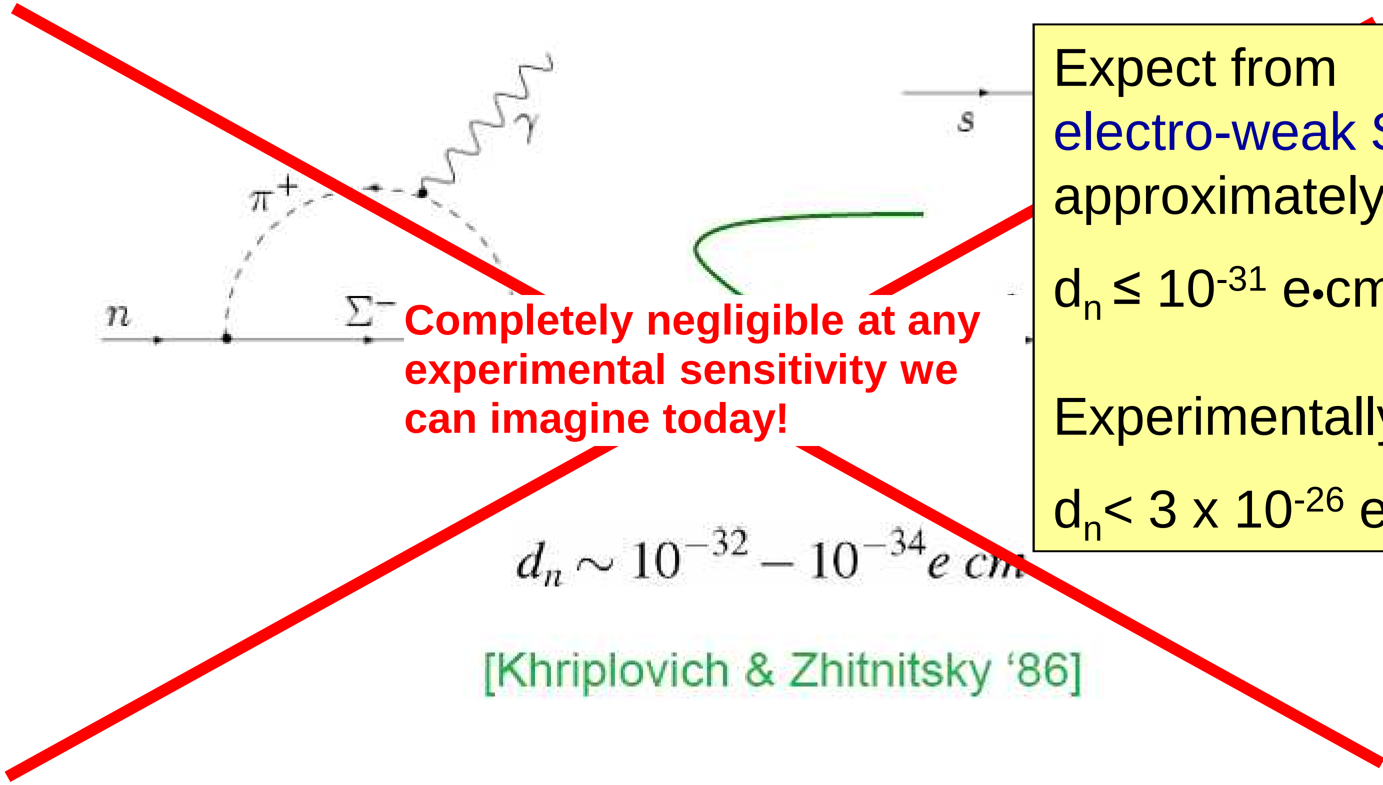


$$d_n \sim 10^{-32} - 10^{-34} e\ cm$$

[Khriplovich & Zhitnitsky '86]

See also: Mannel&Uraltsev hep-ph/1202.6270 : ~10^{-31} *e cm*
Shabalin 1983, McKellar et al. 1987

Neutron: Standard Model prediction



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

[Khriplovich & Zhitnitsky '86]

Expect from electro-weak SM, approximately:

$d_n \leq 10^{-31}$ e•cm

Experimentally so far:

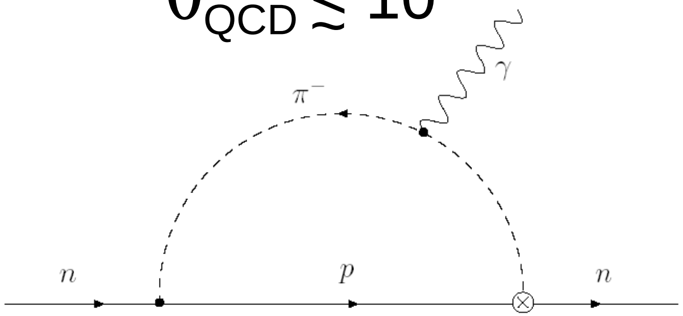
$d_n < 3 \times 10^{-26}$ e•cm

The strong CP problem

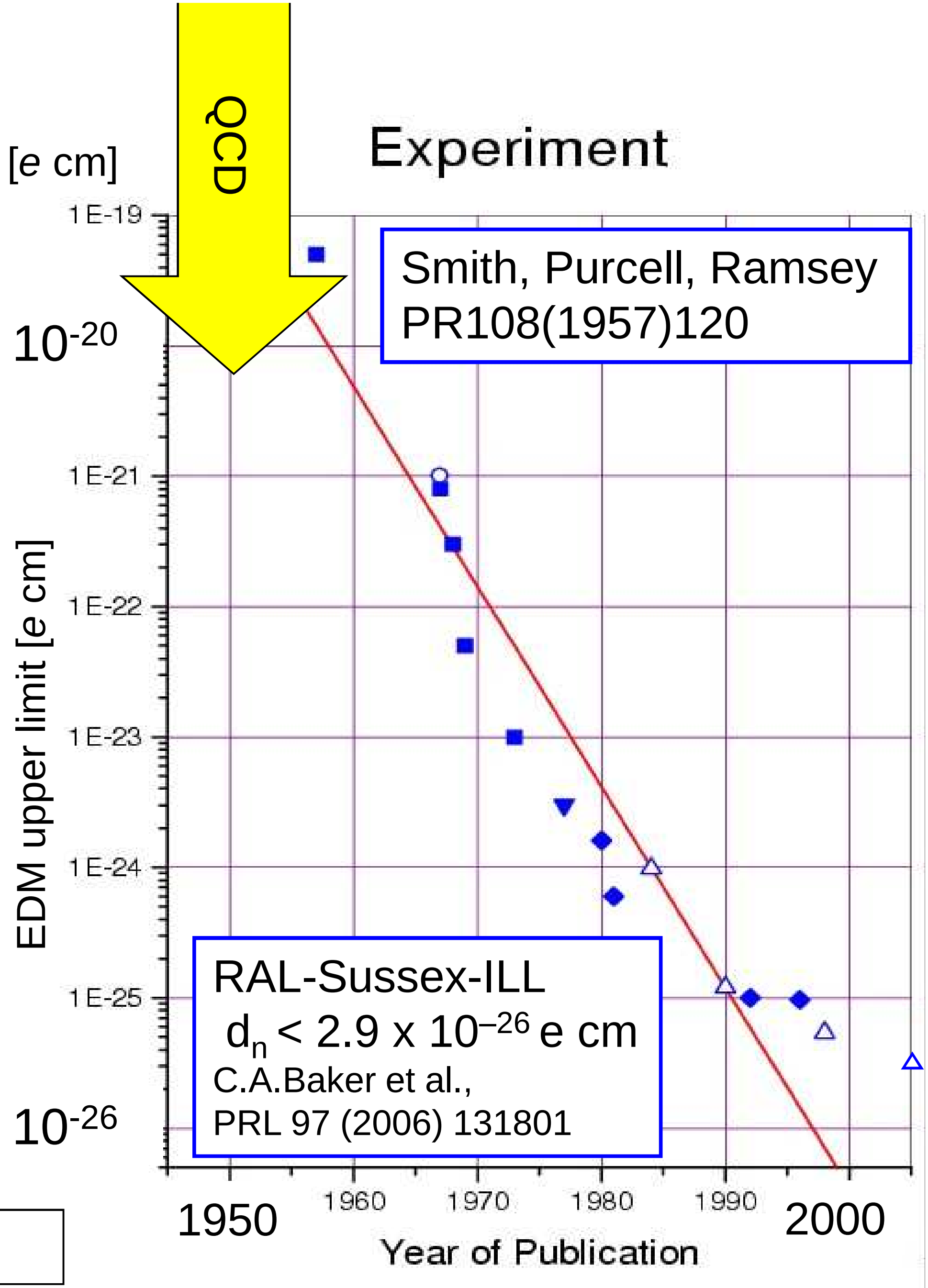
$L_{QCD} \approx L_{QCD}^{\theta_{QCD}=0} + g^2/(32\pi^2)\ \theta_{QCD} G\tilde{G}$

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

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



Why is θ_{QCD} so small ?



here, e.g., $d_p \sim -4/3\ d_n$ and $d_D \sim d_n + d_p + d_D^{\pi NN}$

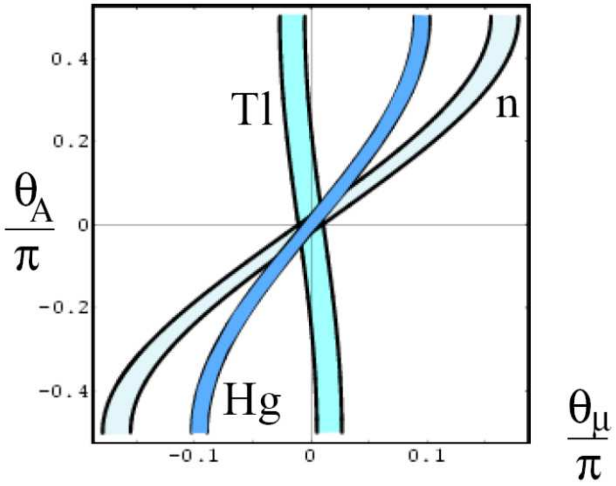
The SUSY CP problem

(for neutron and electron!)

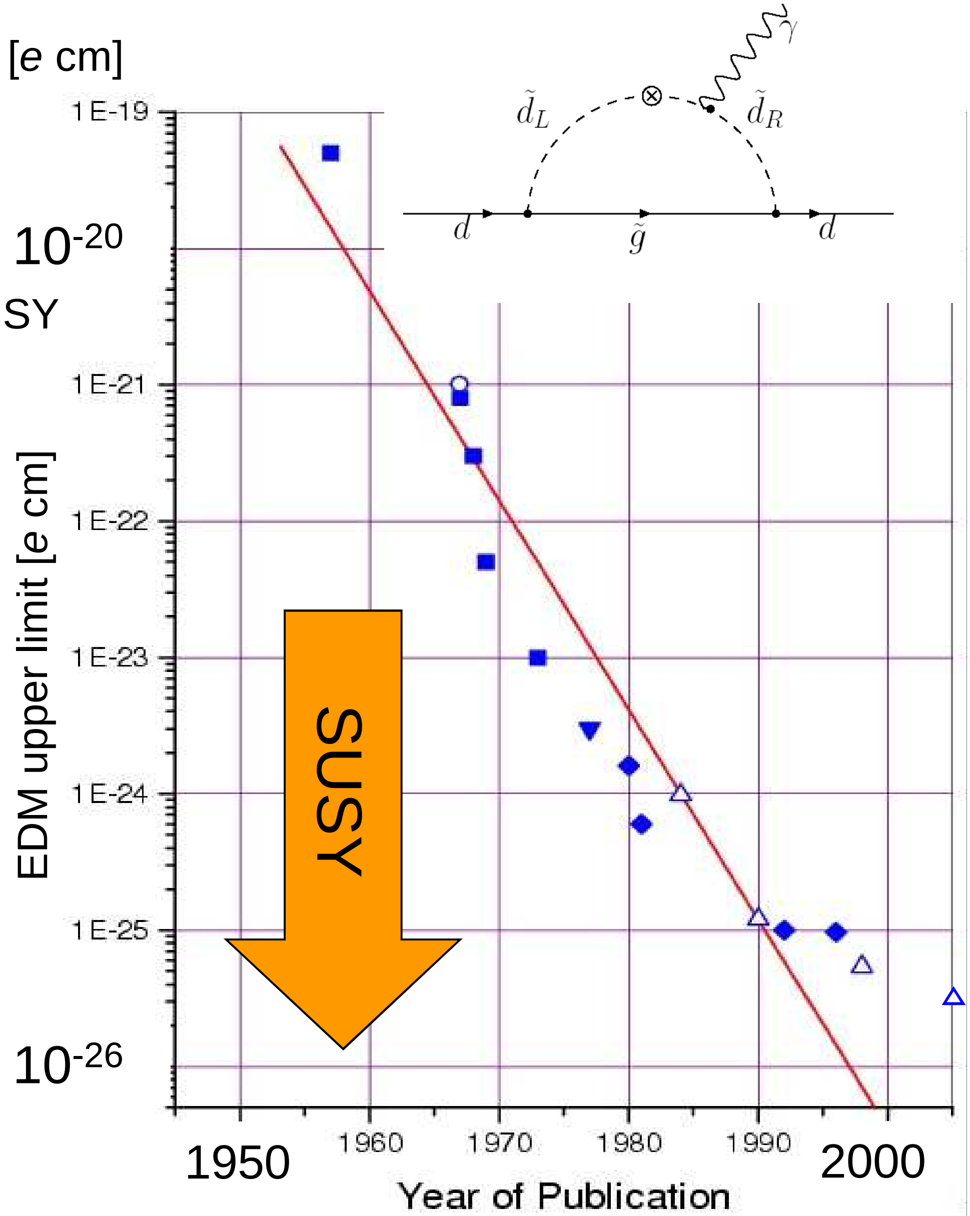
$$d_n \approx 10^{-23}\, e\ \text{cm} \left(\frac{300\ \text{GeV}/c^2}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

Why is ϕ_{SUSY} so small ?

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



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



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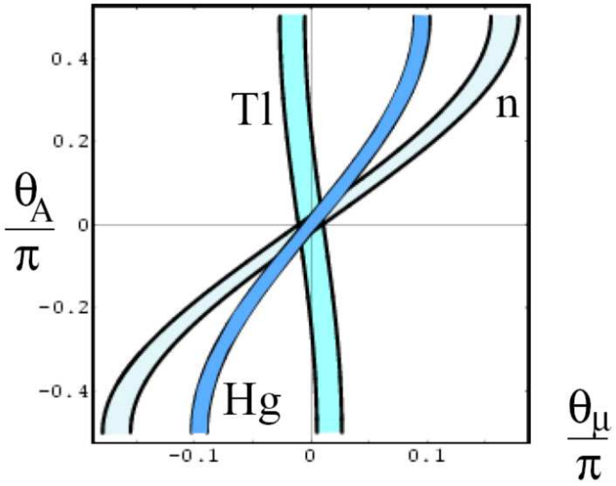

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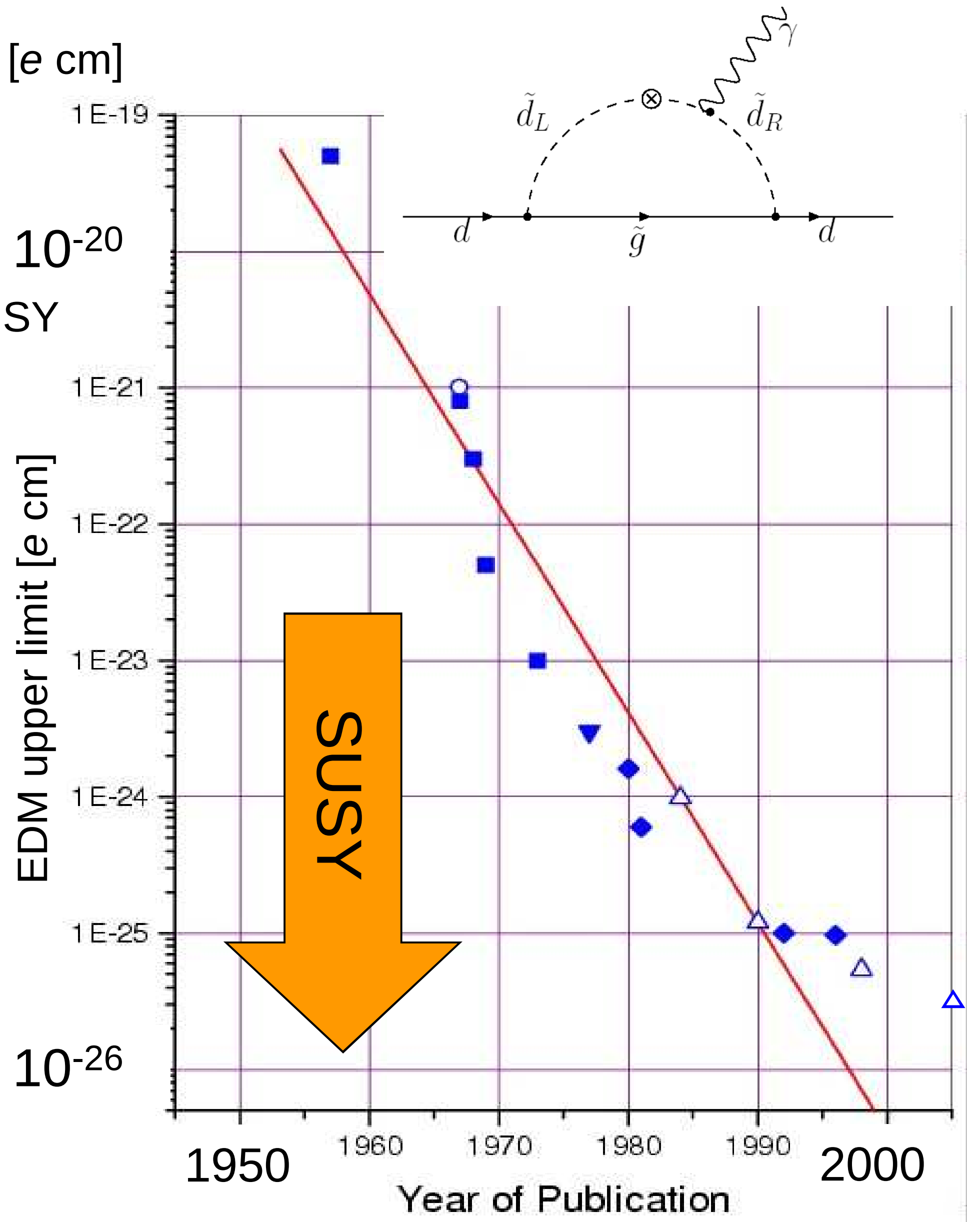


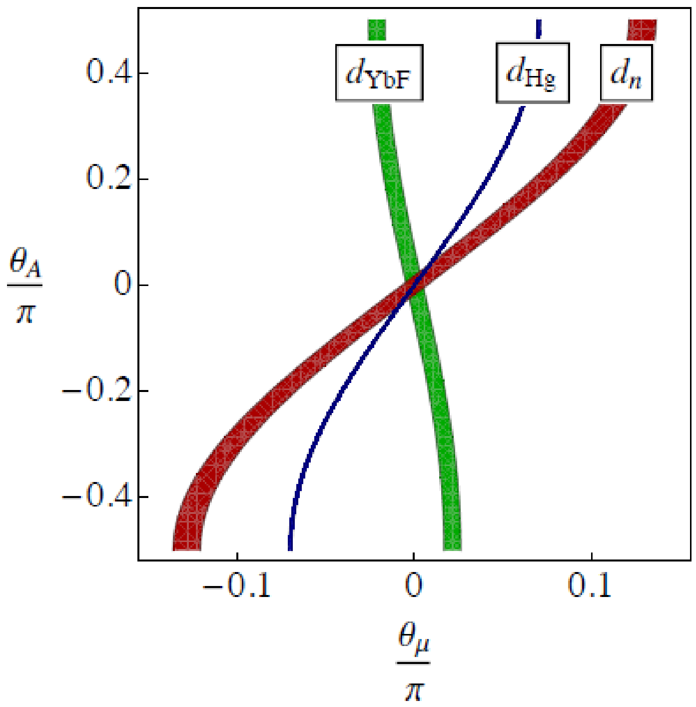
E.g. - SUSY CP Problem (given LHC constraints)

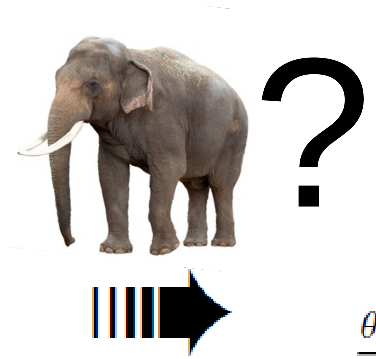
(pre-LHC)

See: Adam Ritz, PSI2013
www.psi.ch/psi2013

(now)

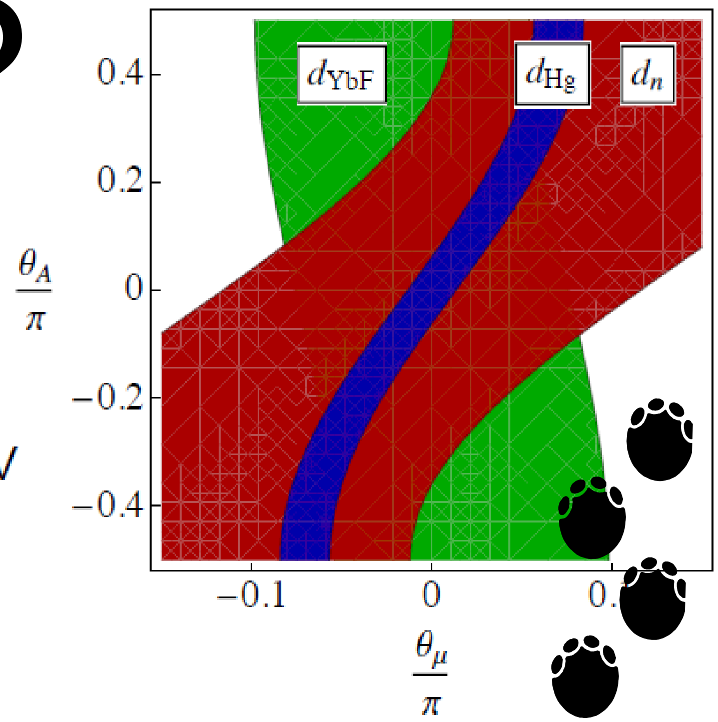
M_{susy} = 500 GeV





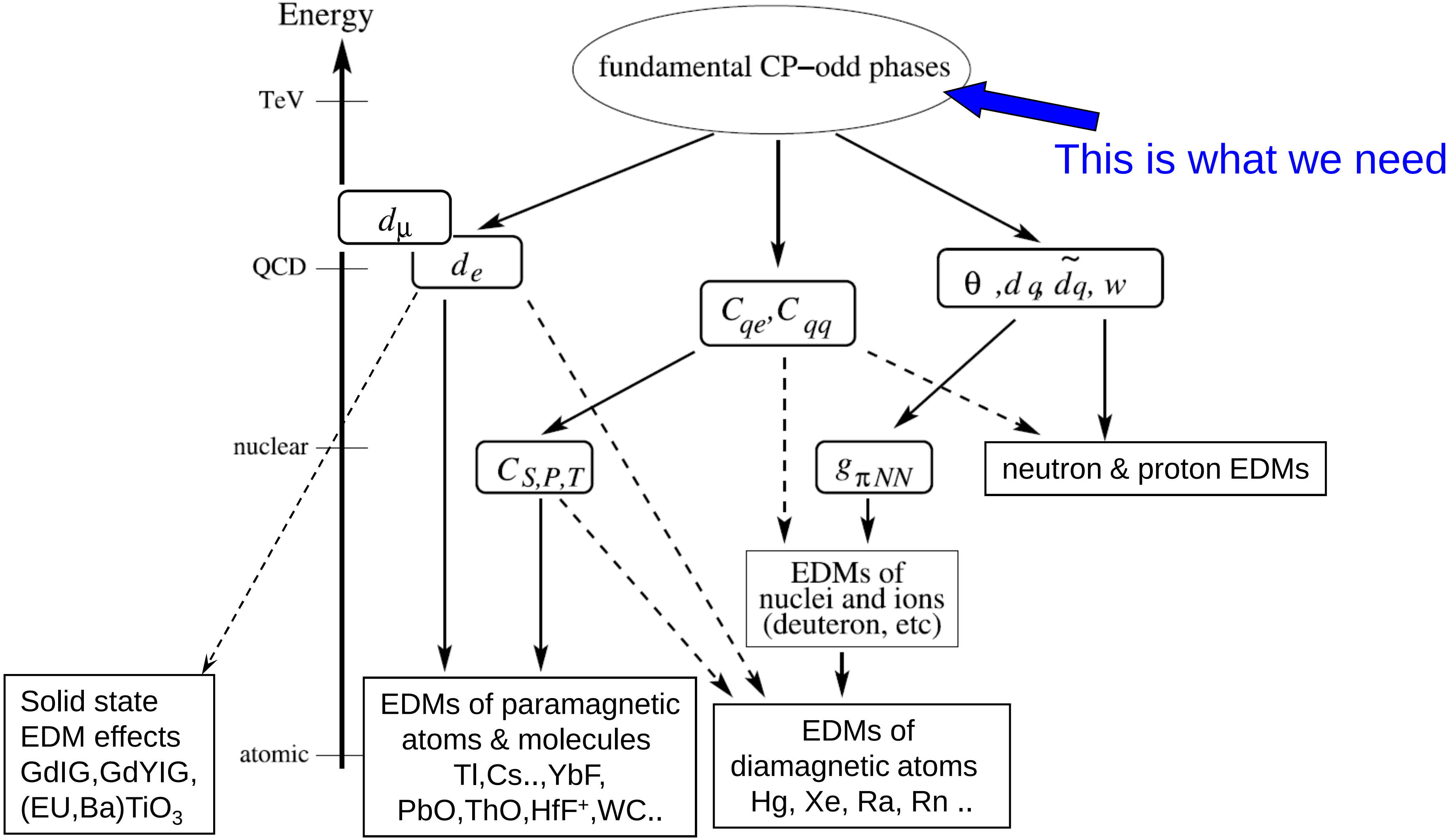
1st gen squarks excluded by direct searches at ~1 TeV

M_{susy} = 2 TeV



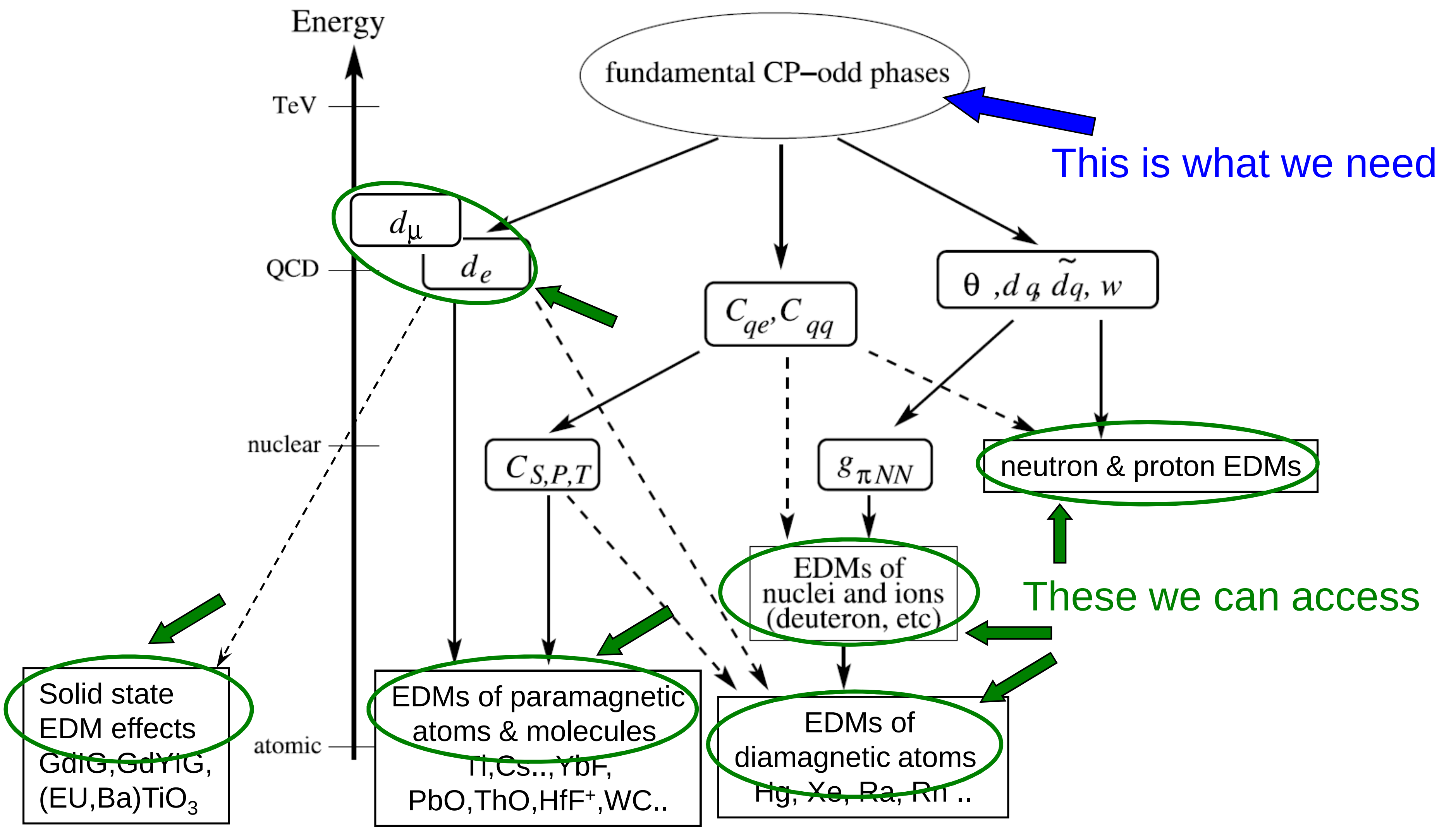
EDMs have for many years required (tuned) O(10^{-3}) CP-odd phases for generic weak-scale SUSY. The LHC appears to have “resolved” this by pushing mass limits on 1st generation sfermions above a TeV

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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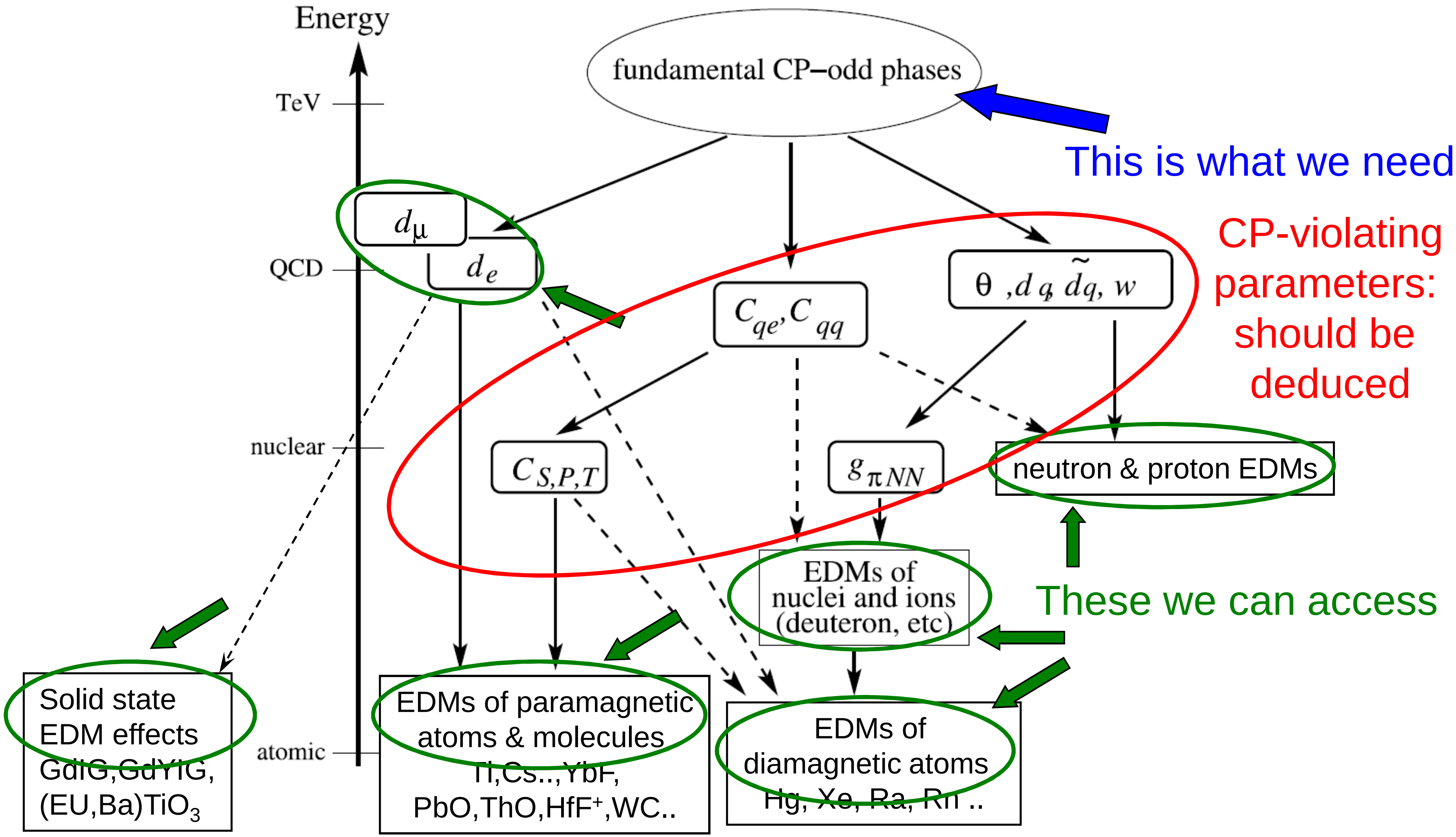

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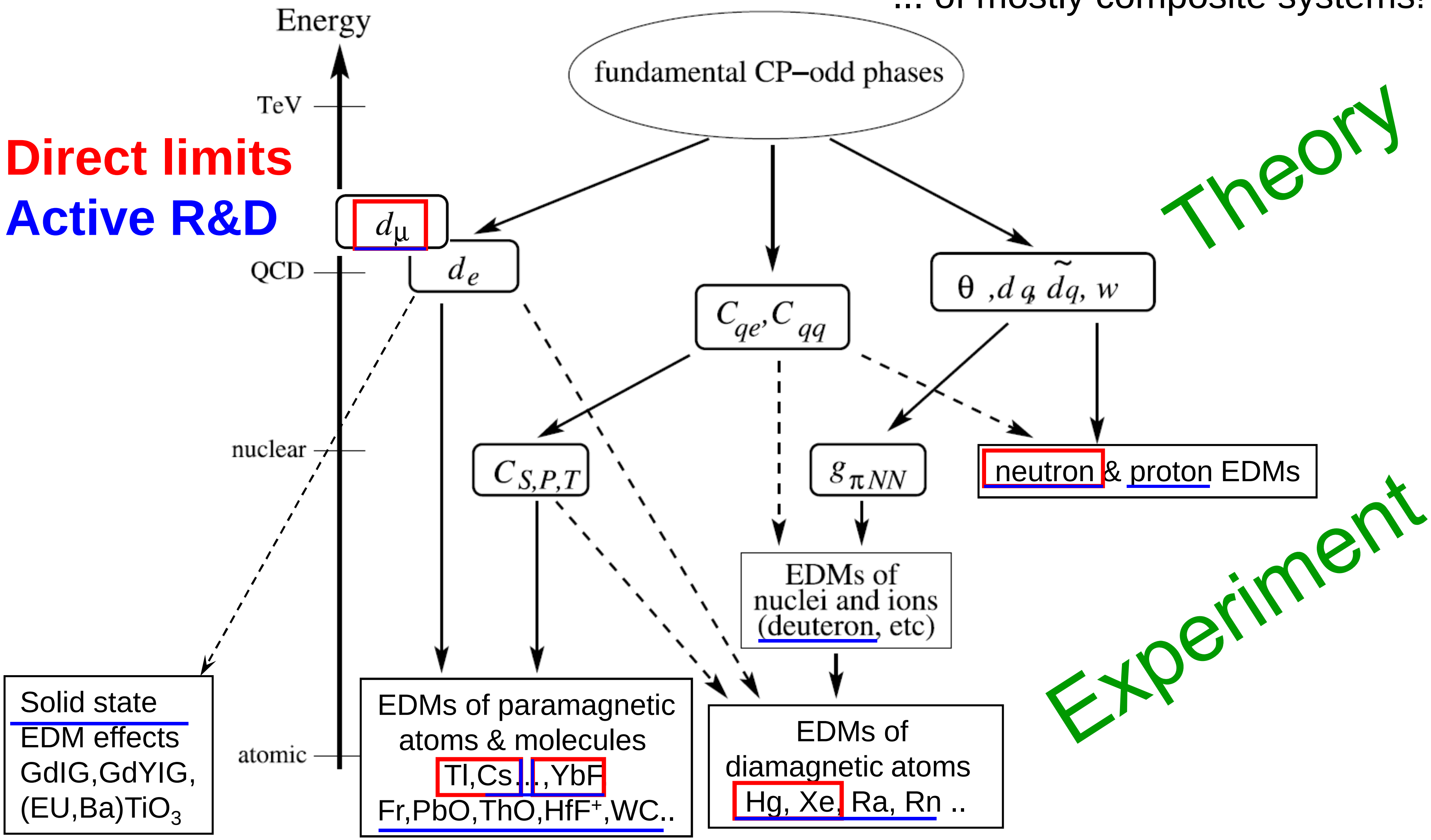
M. Raidal et al., Eur. Phys. J. C 57 (2008) 13

Origin of EDMs

... of mostly composite systems!



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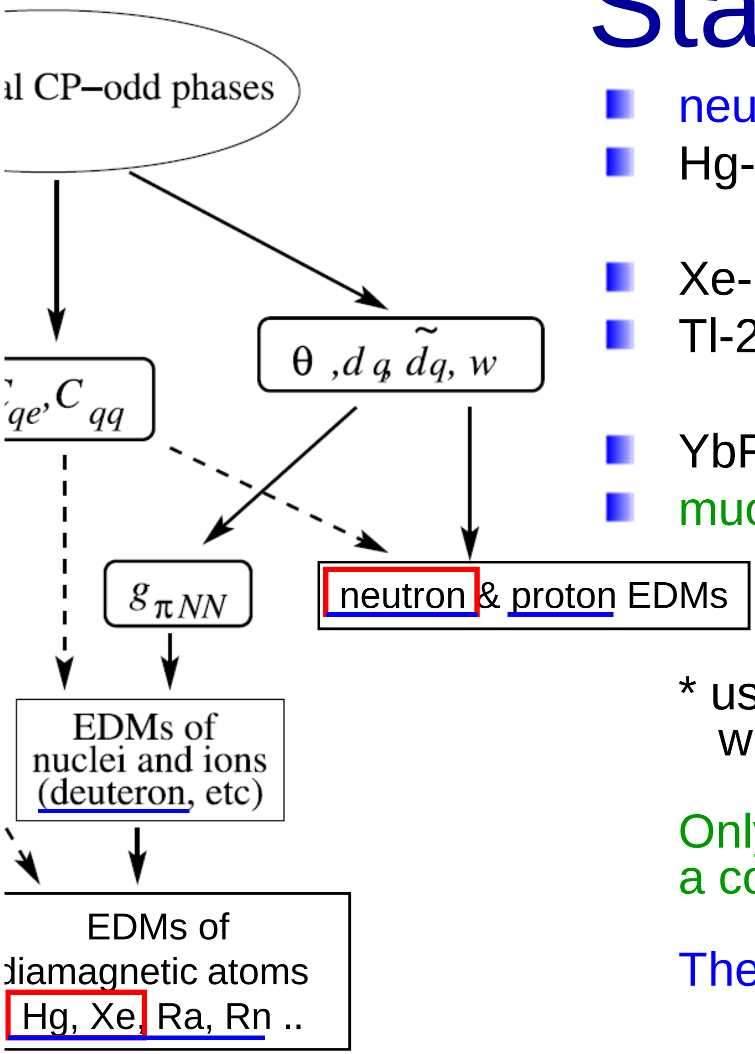
M. Raidal et al., Eur. Phys. J. C 57 (2008) 13

gin of EDMs



State of the art

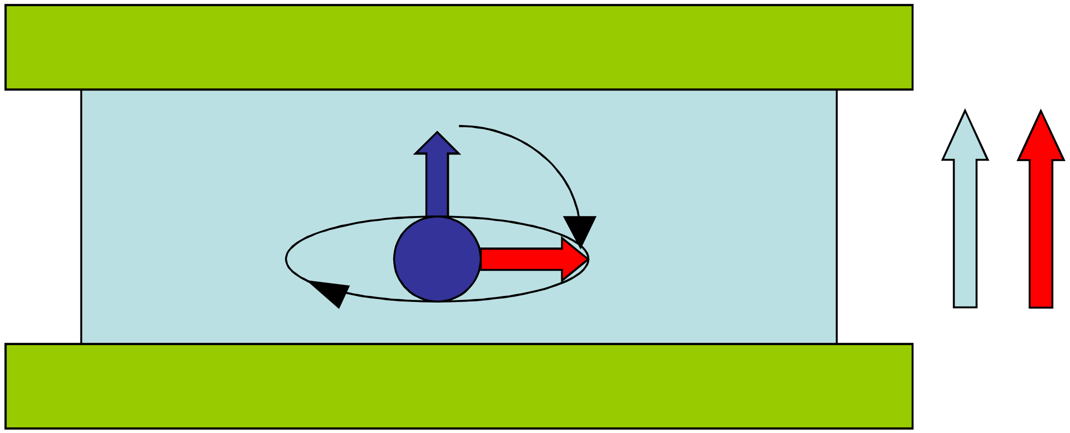
neutron	$d_n < 2.9 \times 10^{-26}$ e cm		PRL97(2006)131801
Hg-199	$d_{Hg} < 3.1 \times 10^{-29}$ e cm		PRL102(2009)101601
	→	$d_p < 8 \times 10^{-25}$ e cm*	
Xe-129	$d_{Xe} < 6 \times 10^{-27}$ e cm		PRL86(2001)22
Tl-205	$d_{Tl} < 9 \times 10^{-25}$ e cm		
	→	$d_e < 1.6 \times 10^{-27}$ e cm*	PRL88(2002)071805
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 competitive direct EDM-limits exist.

The next ‚simple‘ system is arguably the neutron.

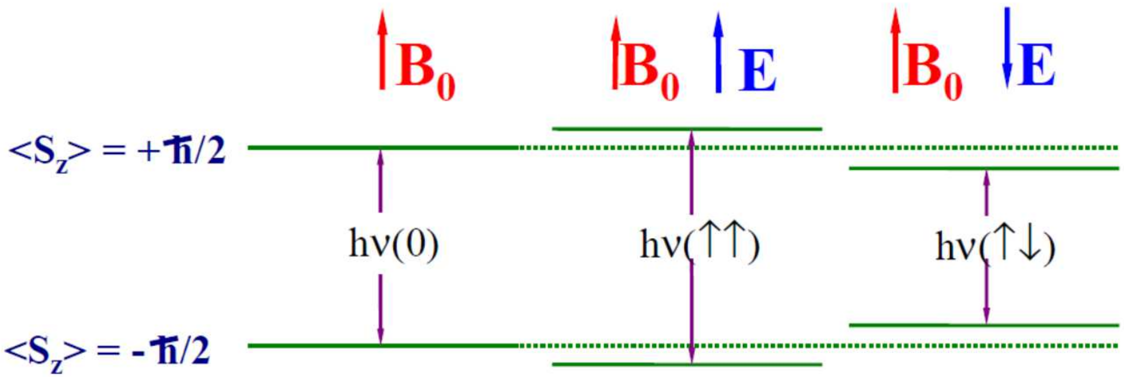
How to measure the neutron (or other) electric dipole moment ?



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

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

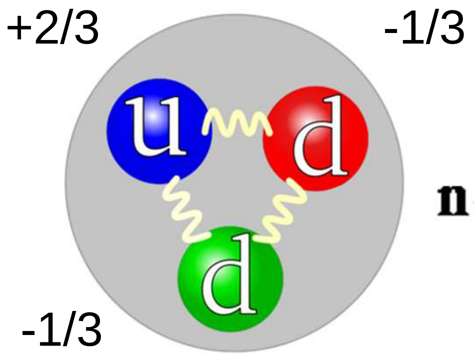
$$h\Delta\nu = 4\, d_n E$$

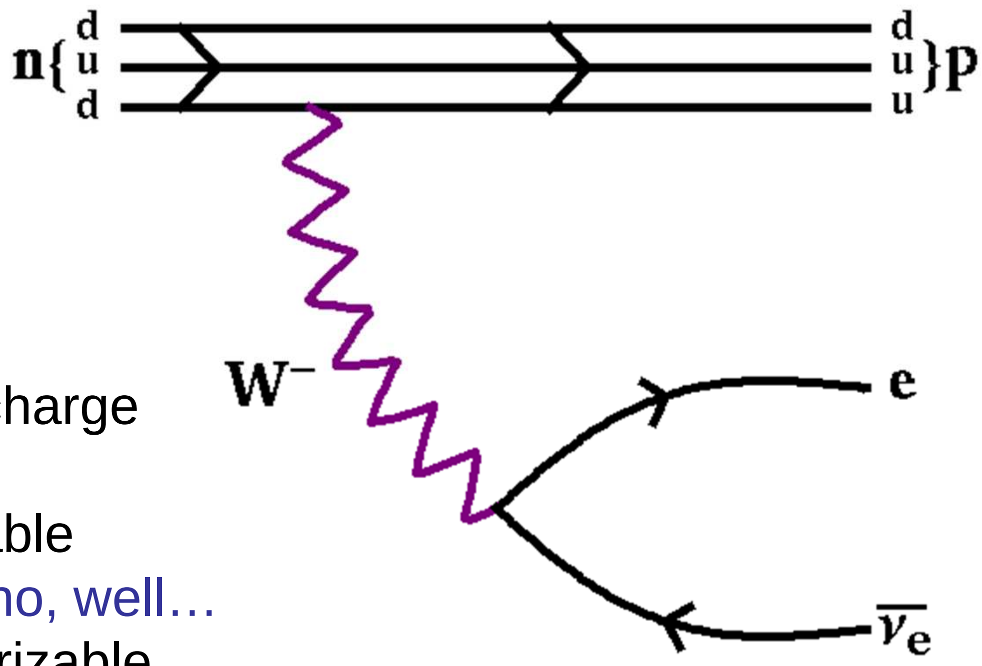


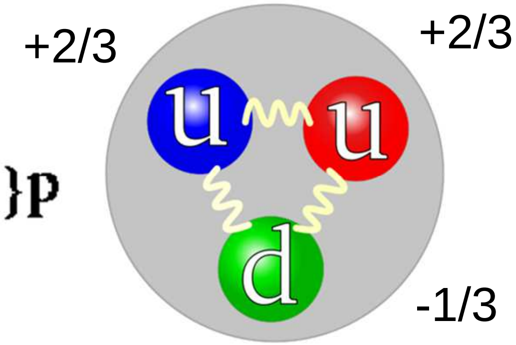
$$\sigma(d_n) = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

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

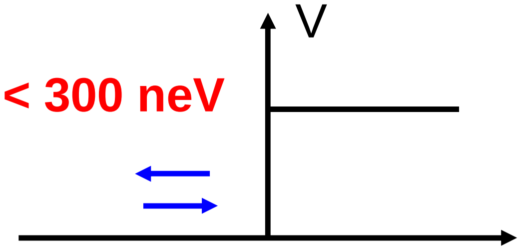
strong

Fermi potential V_F

↓

300 neV

$E_n < 300$ neV



magnetic

$V_m = -\mu B$

↓

60 neV T^{-1}

↓

5 T field -> 300 neV

gravitation

$V_g = m_n g h$

↓

100 neV m^{-1}

↓

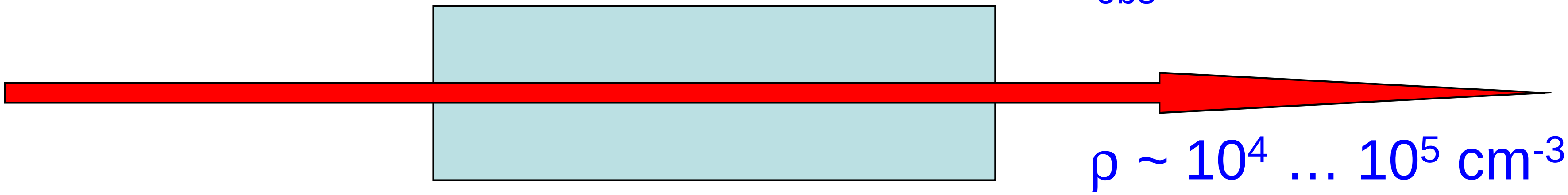
3 m up -> 300 neV

Typical neutron experiments

CN Beam

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

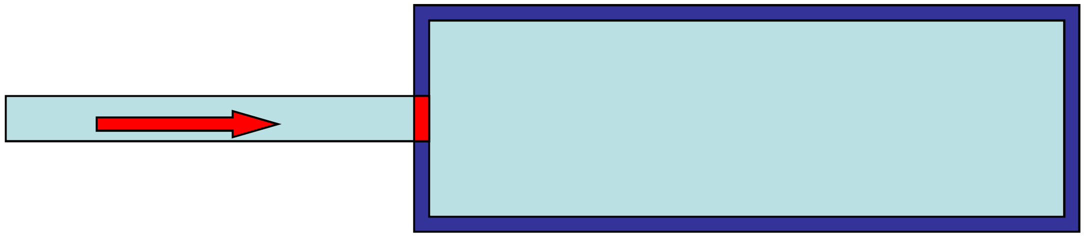
$t_{obs} \sim 10^{-3}$ s



$\rho \sim 10^4 \ldots 10^5$ 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}

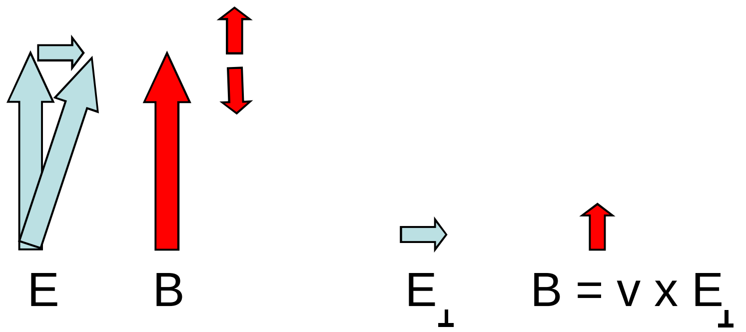
improved density at new UCN sources

Use UCN for nEDM search

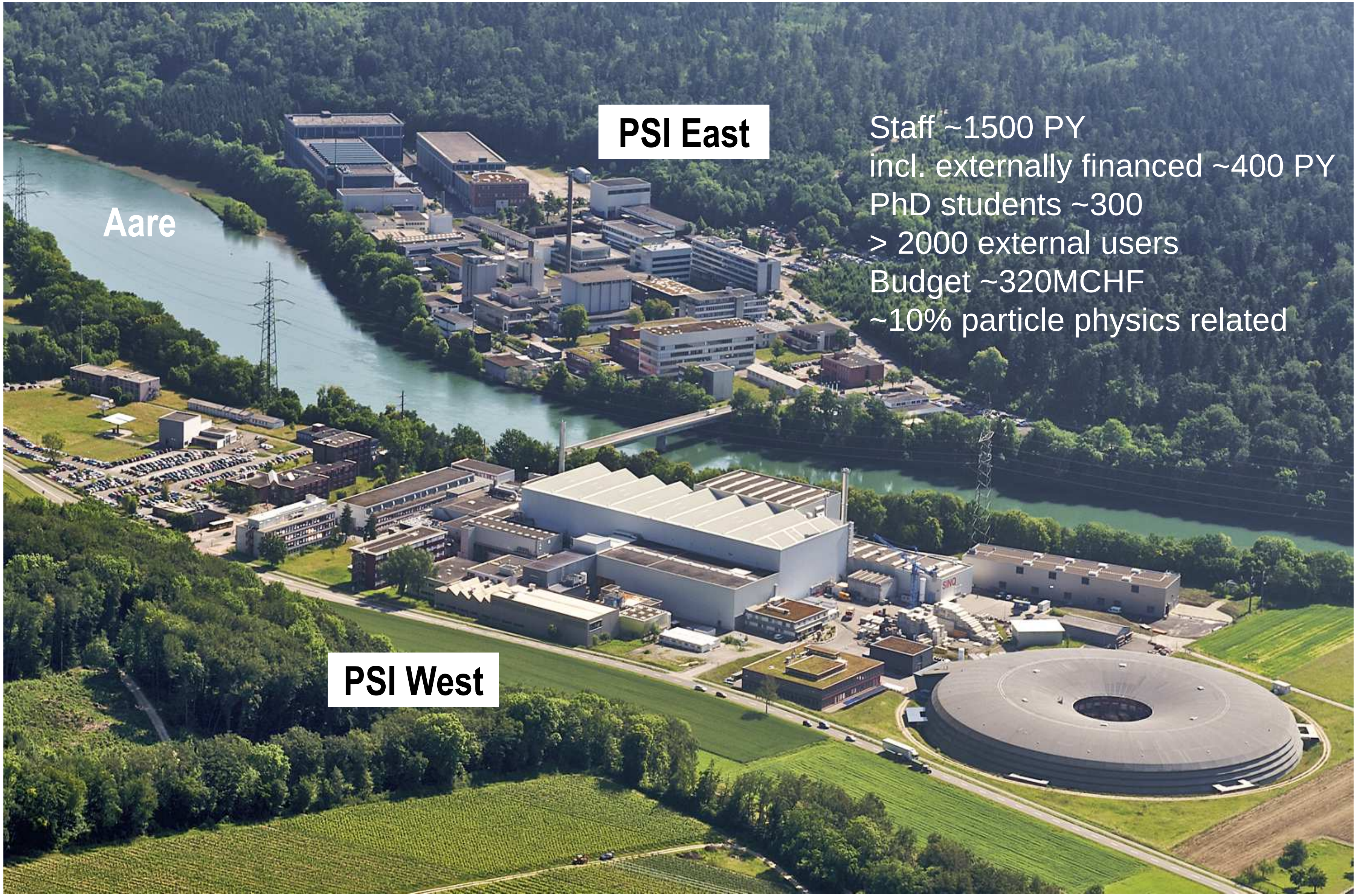
- Statistics:

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

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



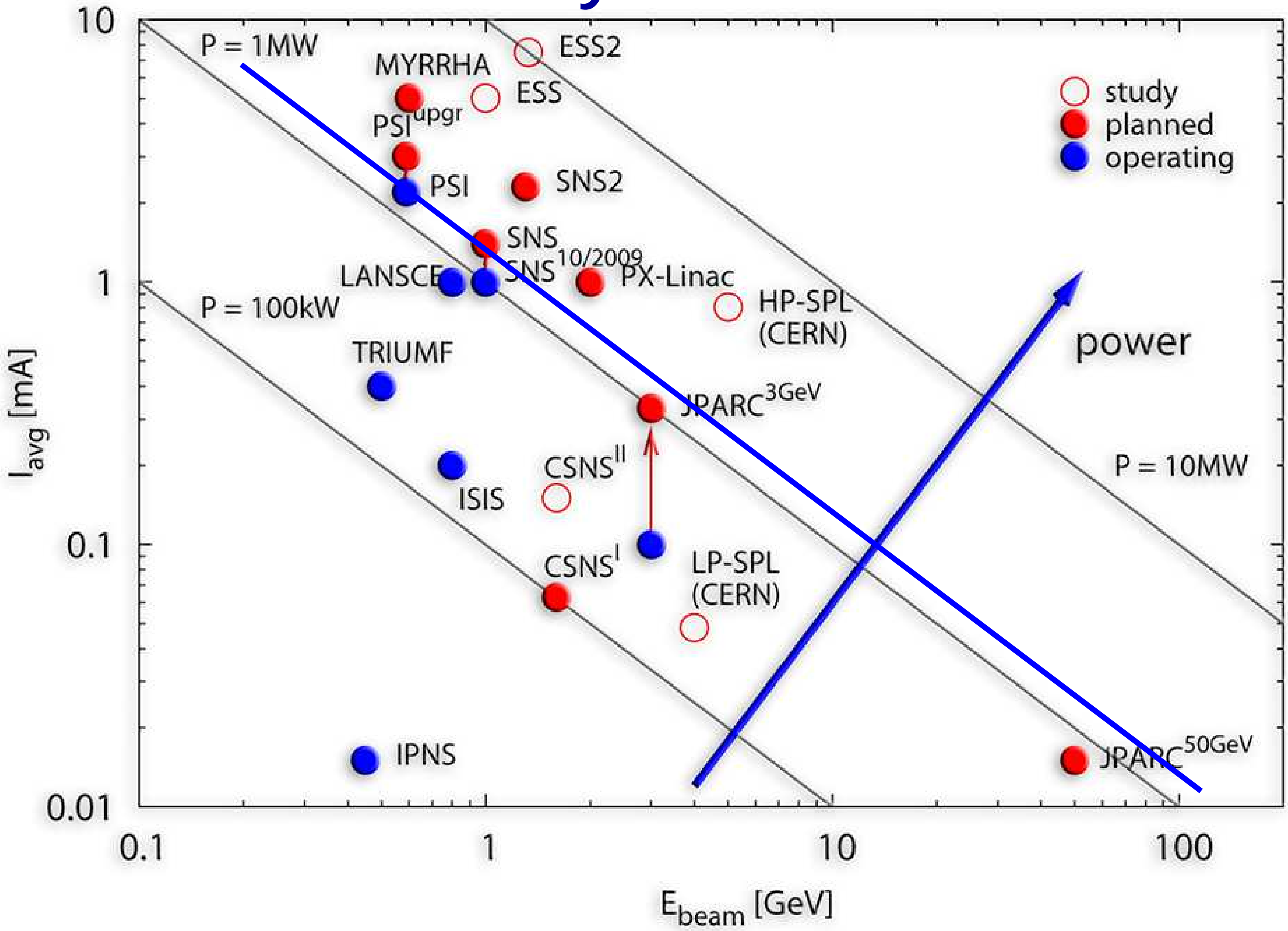
The high intensity&precision frontier at PSI



The 590 MeV Ringcyclotron at PSI

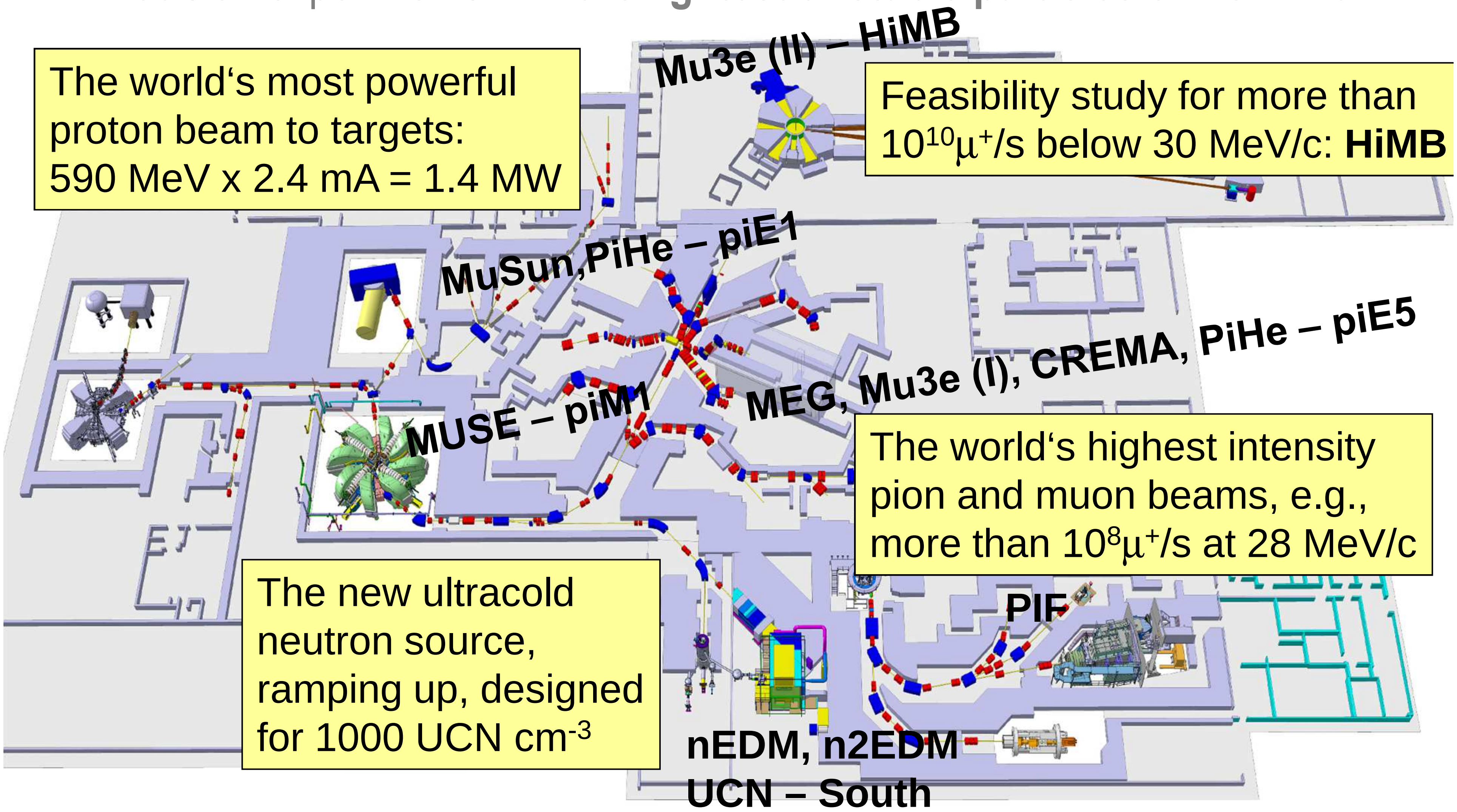
2.2 ... 2.4 mA
1.3 ... 1.4 MW

Intensity machines



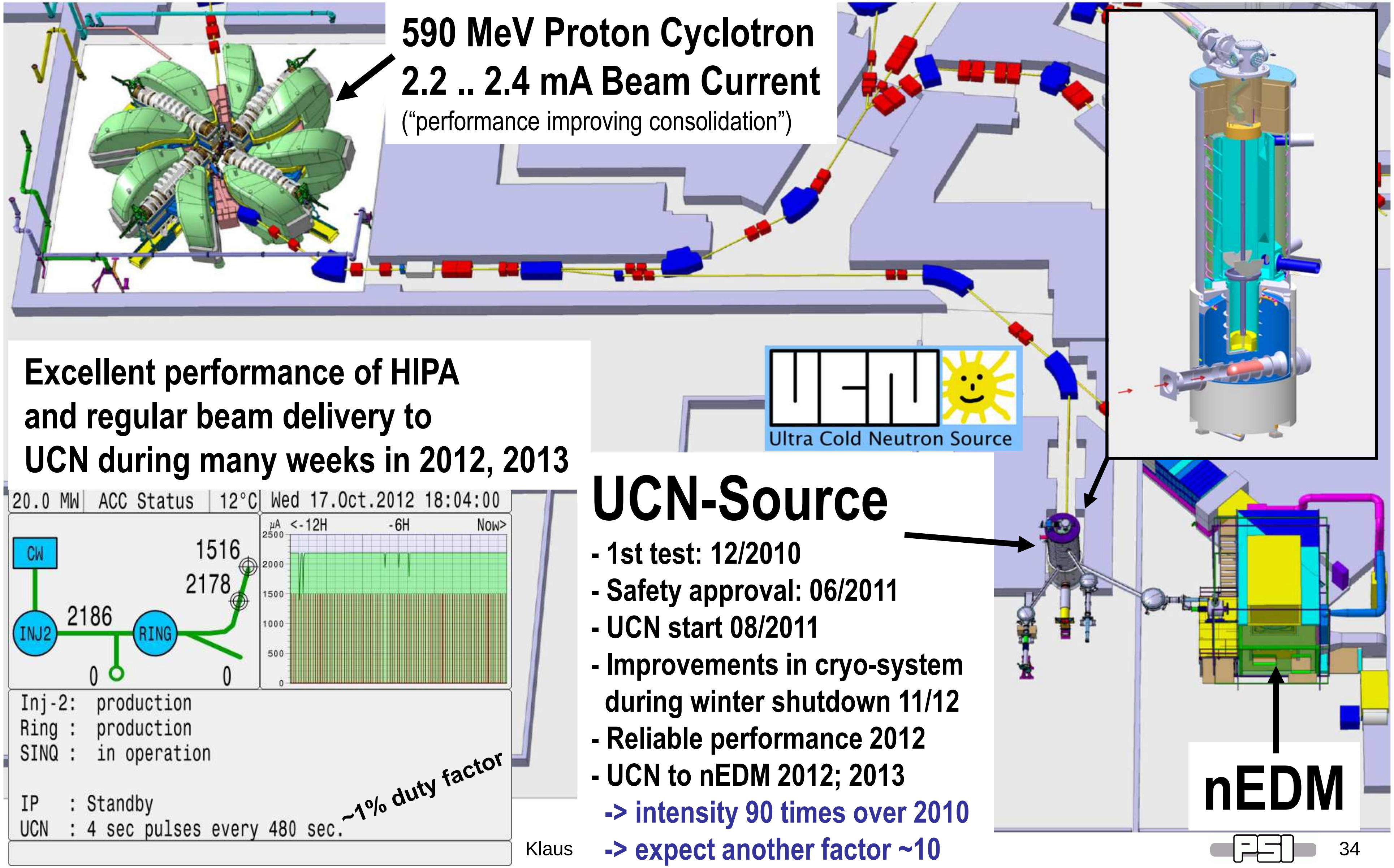
The intensity frontier at PSI: π, μ, UCN

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, 2013

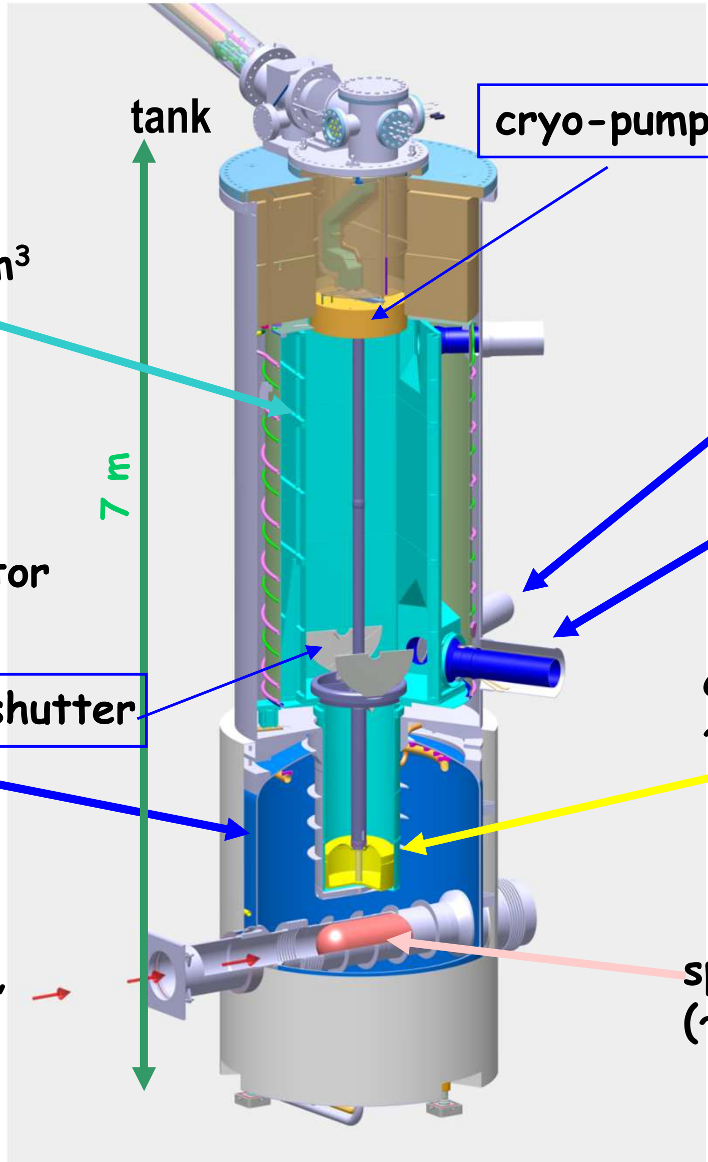
~1% duty factor

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 2012; 2013
  -> intensity 90 times over 2010
  -> expect another factor ~10

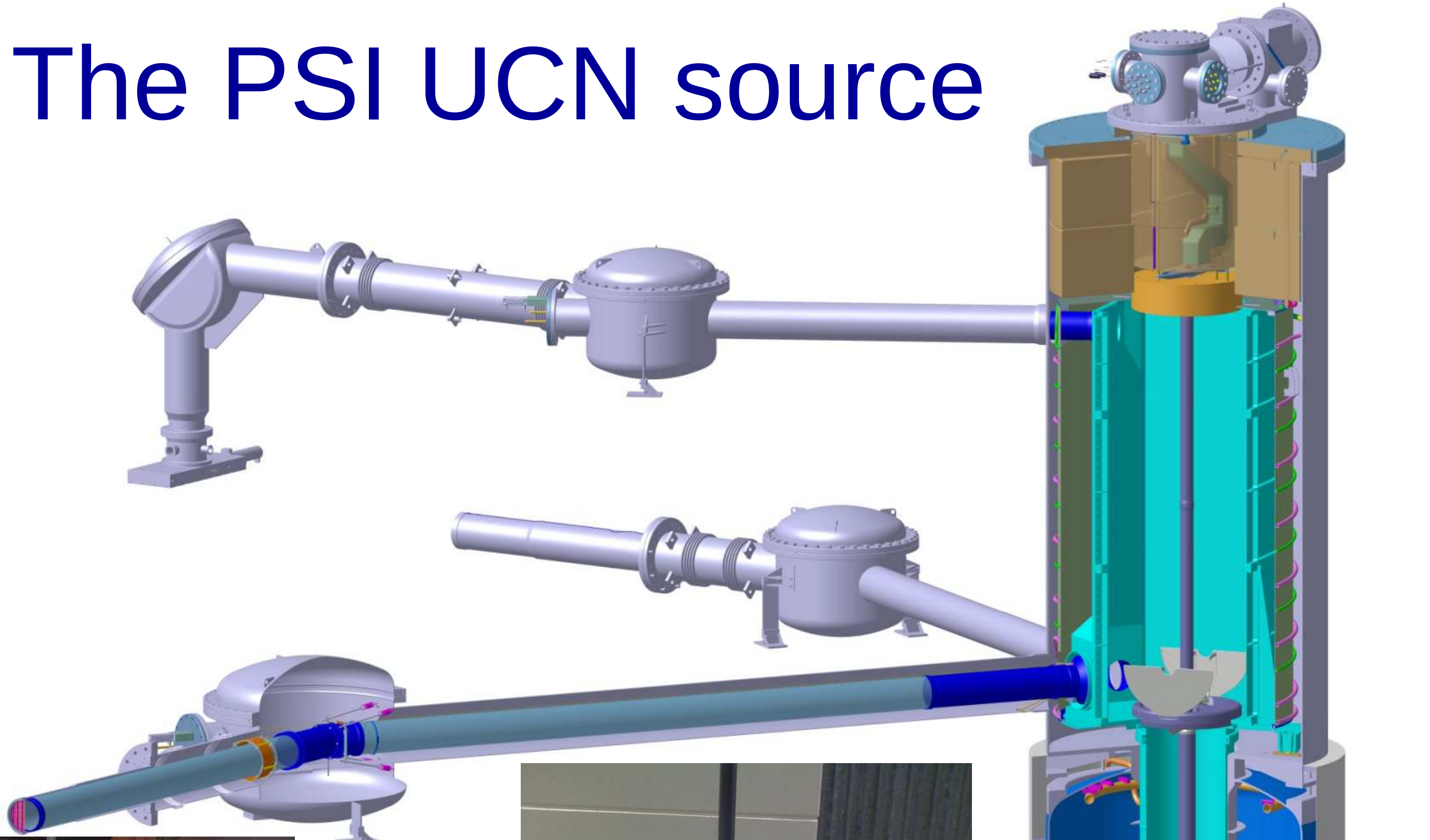
The PSI UCN source

Ultra Cold Neutron Source



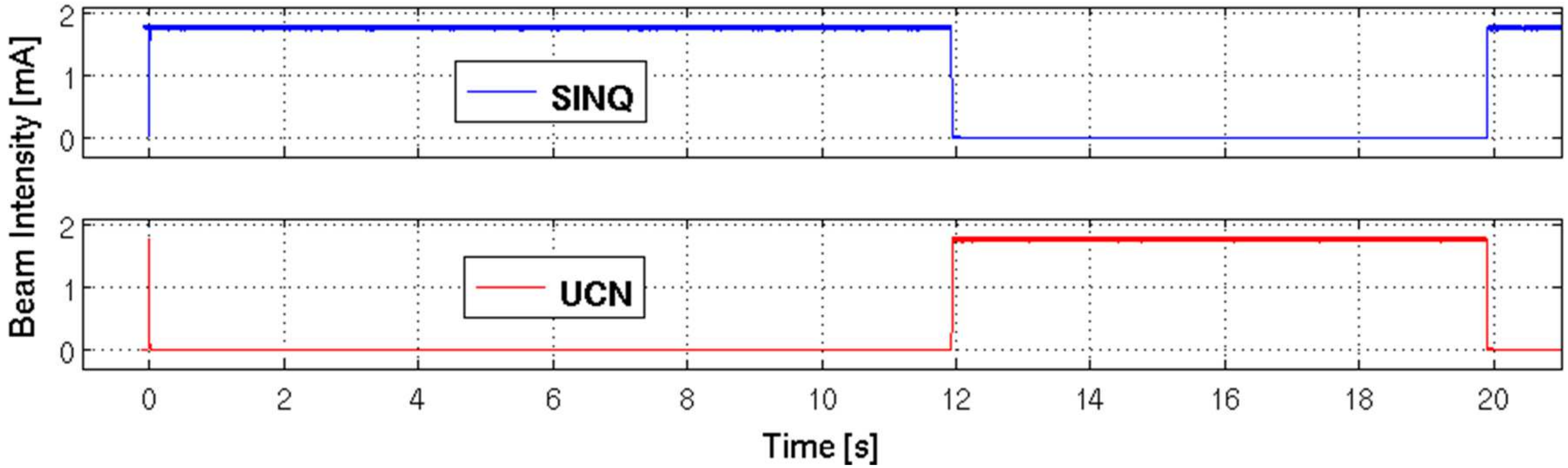
The PSI UCN source

Ultra Cold Neutron Source



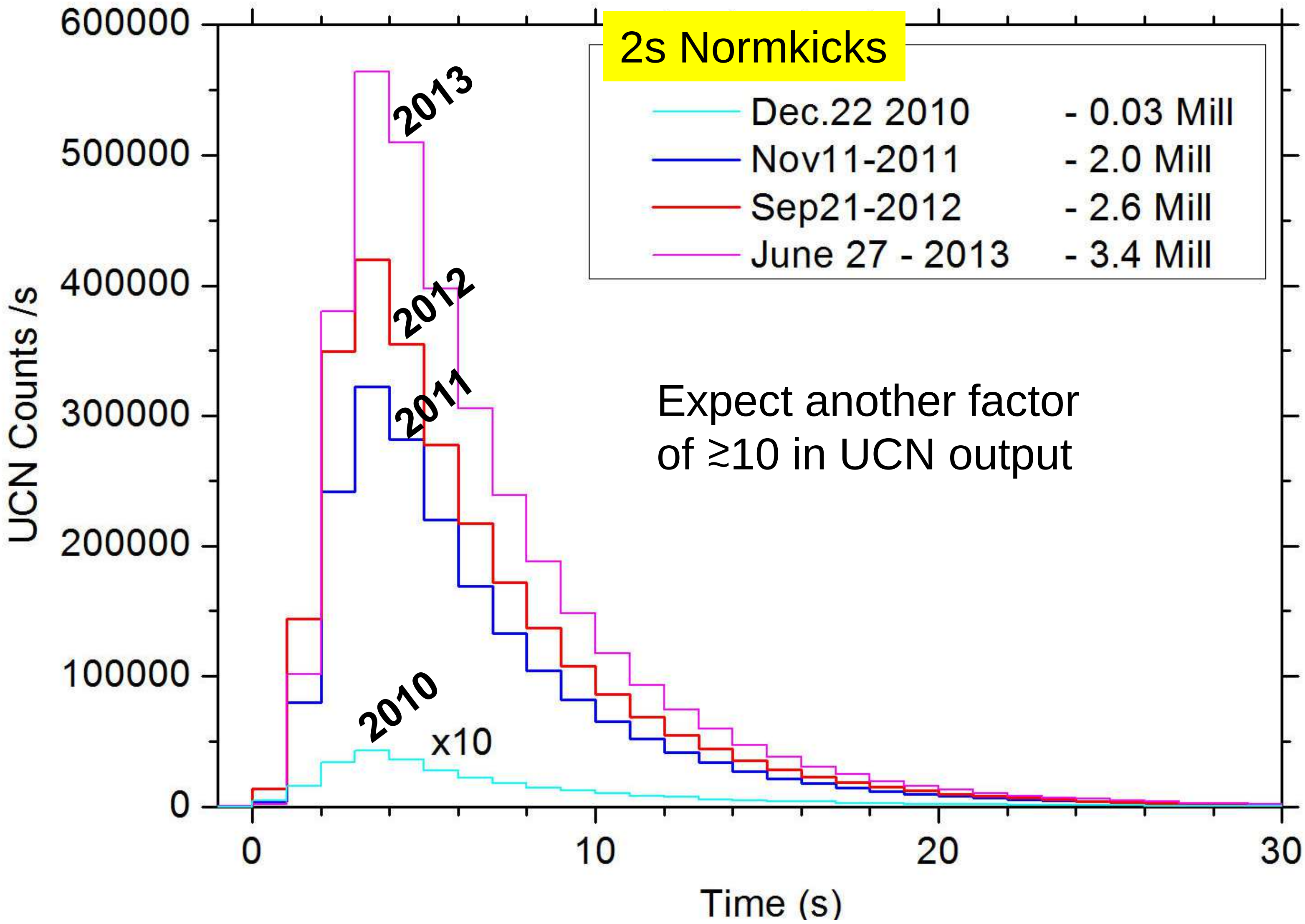
UCN-Start Dec.16/17/22, 2010

1 MW UCN pulse

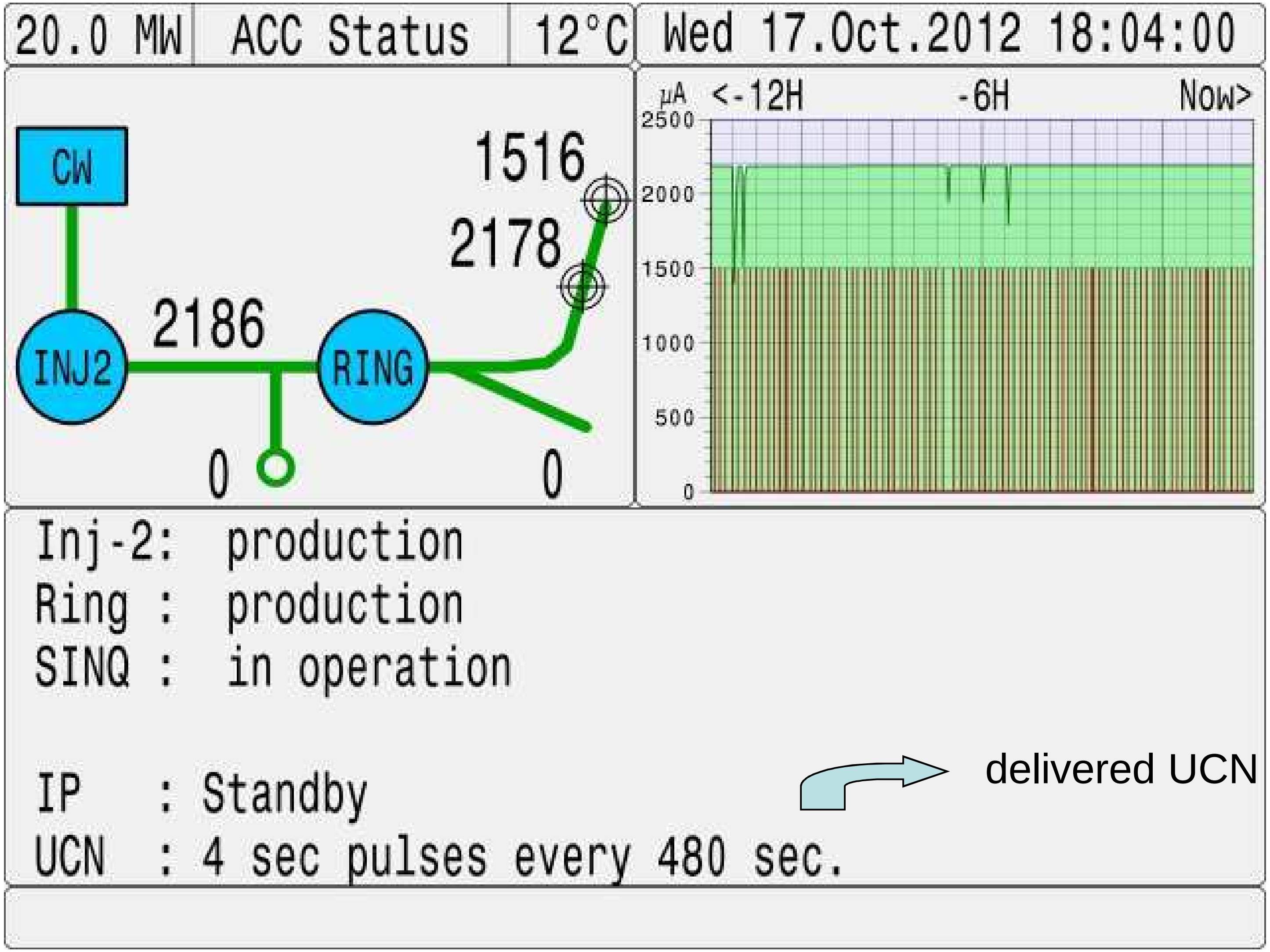


BL2011

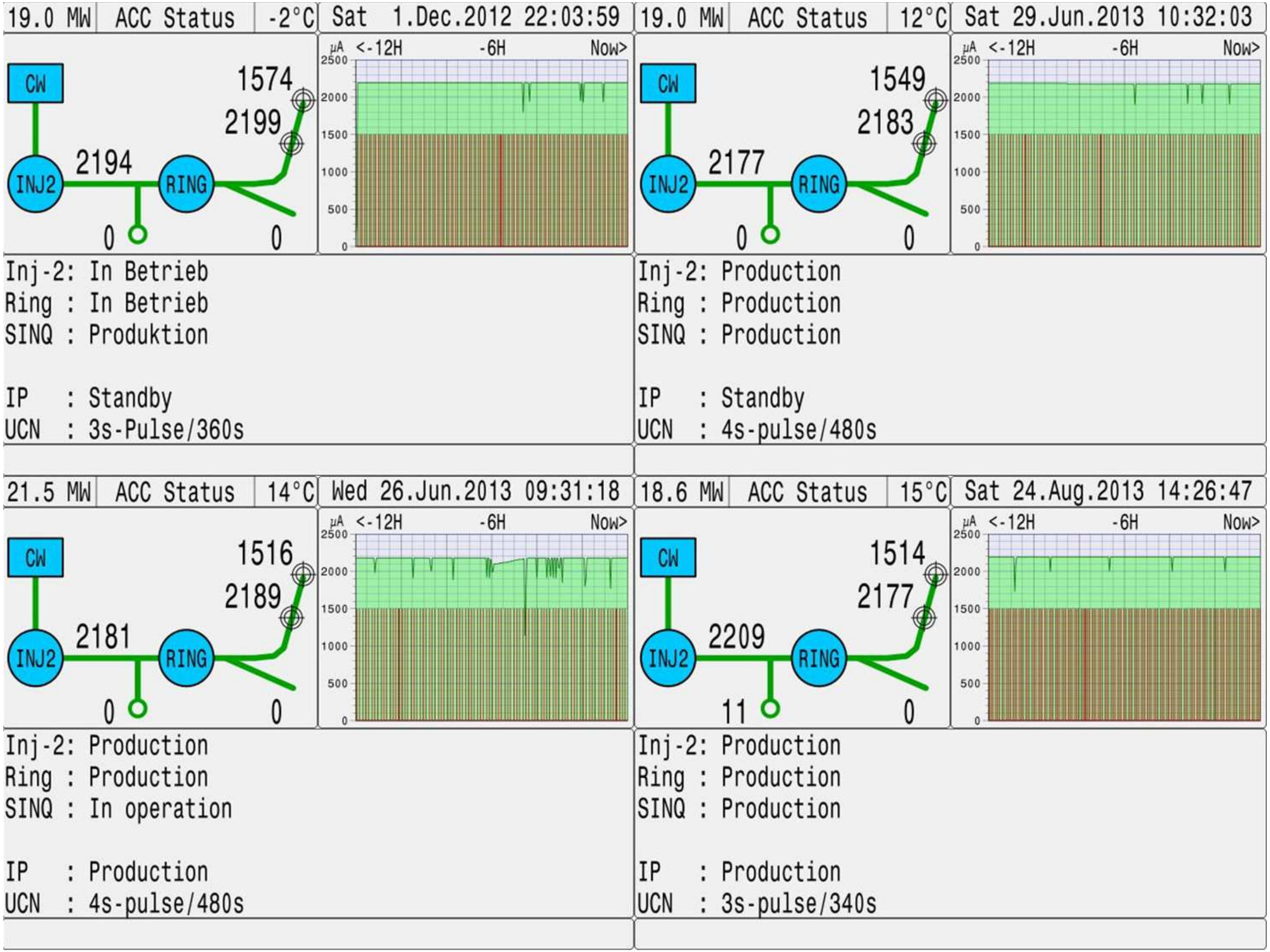
Continuous improvement under way



Routine operation since 2012

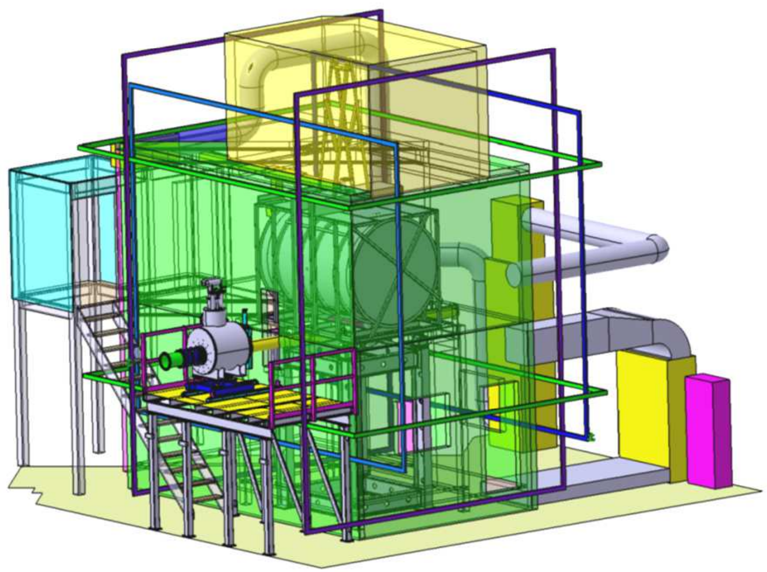


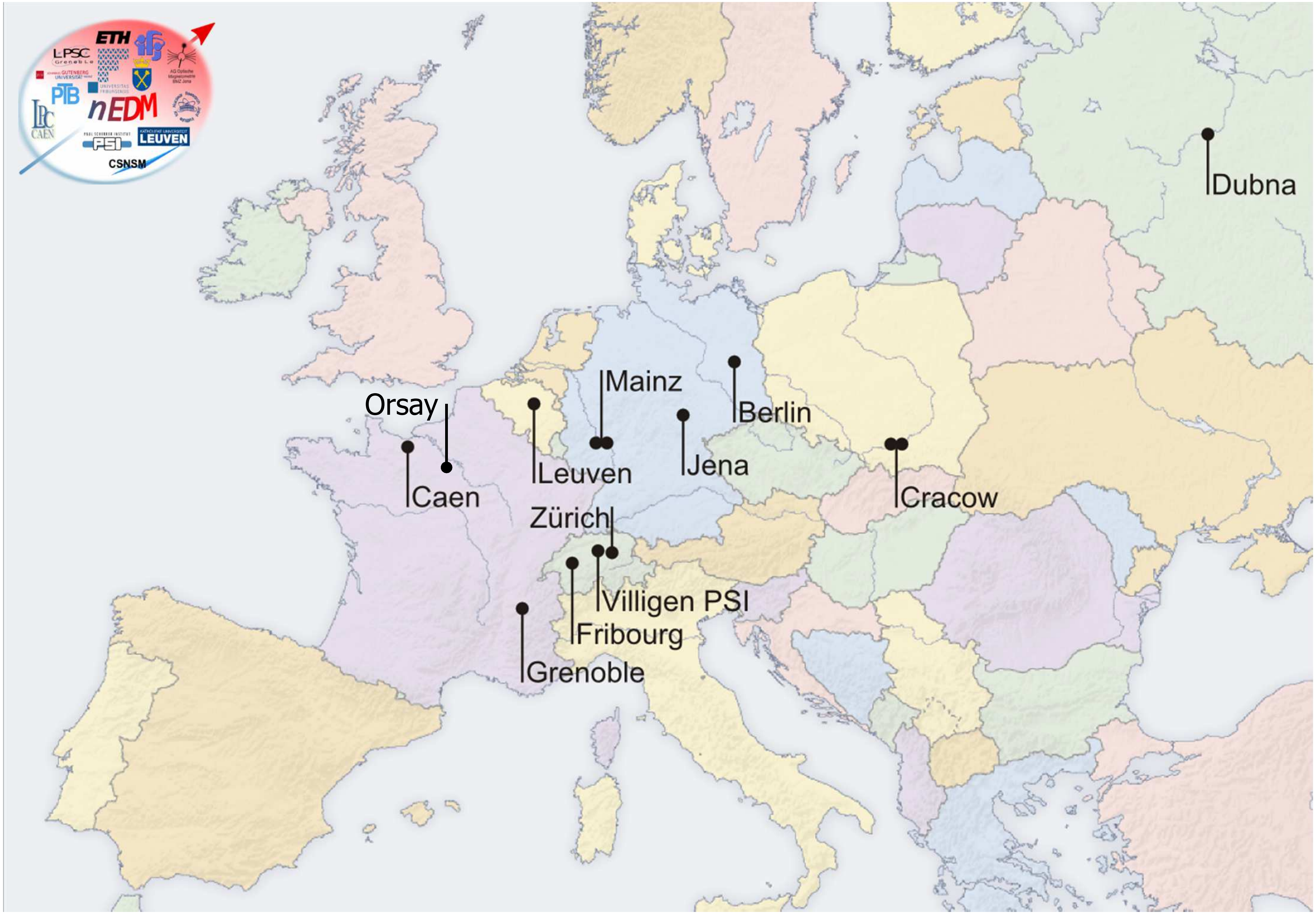
delivered UCN to nEDM


19.0 MW ACC Status -2°C Sat 1.Dec.2012 22:03:59
CW
1574
2199
2194
INJ2
RING
0
0
µA <-12H -6H Now>
2500
2000
1500
1000
500
0
Inj-2: In Betrieb
Ring : In Betrieb
SINQ : Produktion
IP : Standby
UCN : 3s-Pulse/360s
19.0 MW ACC Status 12°C Sat 29.Jun.2013 10:32:03
CW
1549
2183
2177
INJ2
RING
0
0
µA <-12H -6H Now>
Inj-2: Production
Ring : Production
SINQ : Production
IP : Standby
UCN : 4s-pulse/480s
21.5 MW ACC Status 14°C Wed 26.Jun.2013 09:31:18
CW
1516
2189
2181
INJ2
RING
0
0
µA <-12H -6H Now>
Inj-2: Production
Ring : Production
SINQ : In operation
IP : Production
UCN : 4s-pulse/480s
18.6 MW ACC Status 15°C Sat 24.Aug.2013 14:26:47
CW
1514
2177
2209
INJ2
RING
11
0
µA <-12H -6H Now>
Inj-2: Production
Ring : Production
SINQ : Production
IP : Production
UCN : 3s-pulse/340s

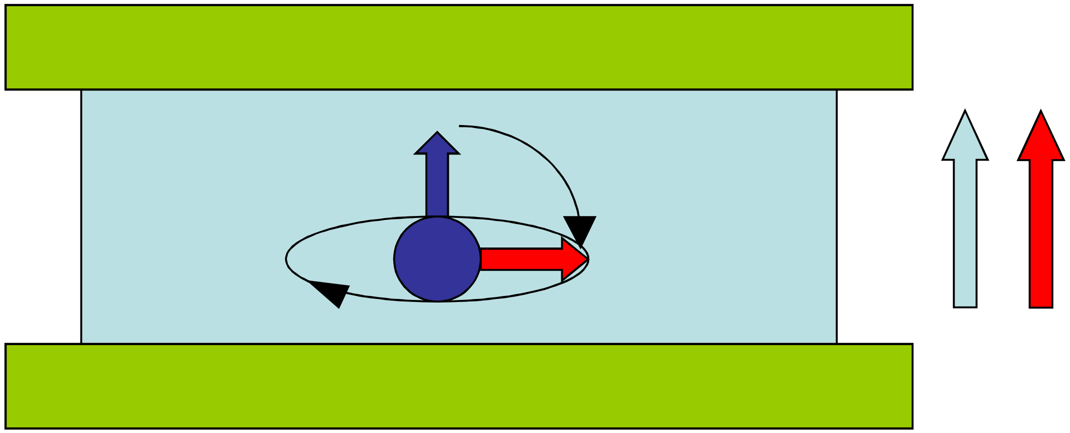
Installing nEDM at PSI in 2009

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



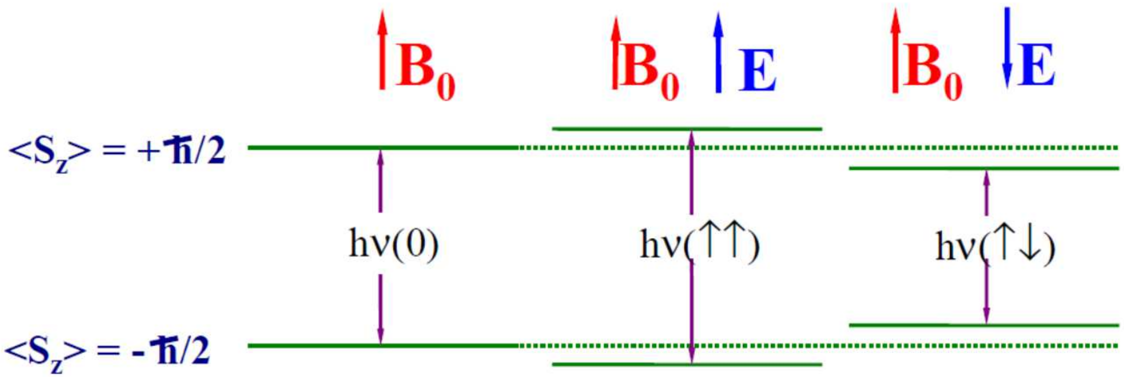

Dubna
Mainz
Orsay
Berlin
Leuven
Jena
Caen
Cracow
Zürich
Villigen PSI
Fribourg
Grenoble

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



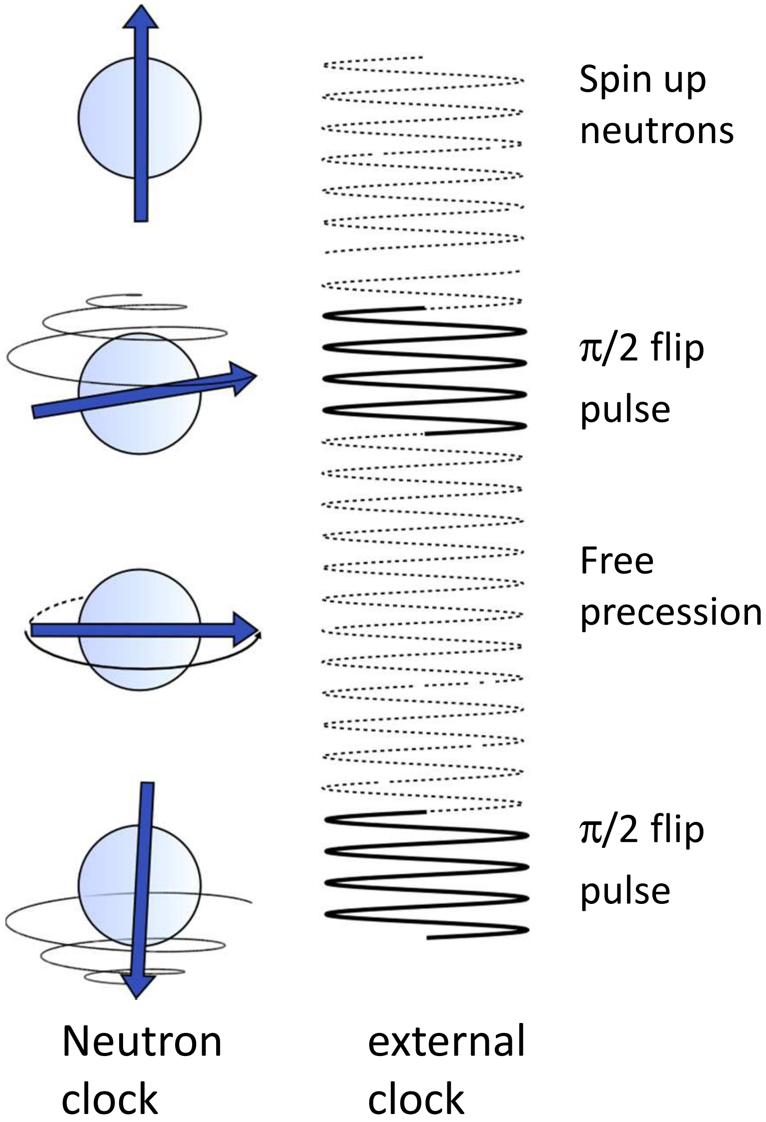
$$h\nu_{\uparrow\uparrow} = 2\,(\mu B + d_n E)$$
$$h\nu_{\uparrow\downarrow} = 2\,(\mu B - d_n E)$$

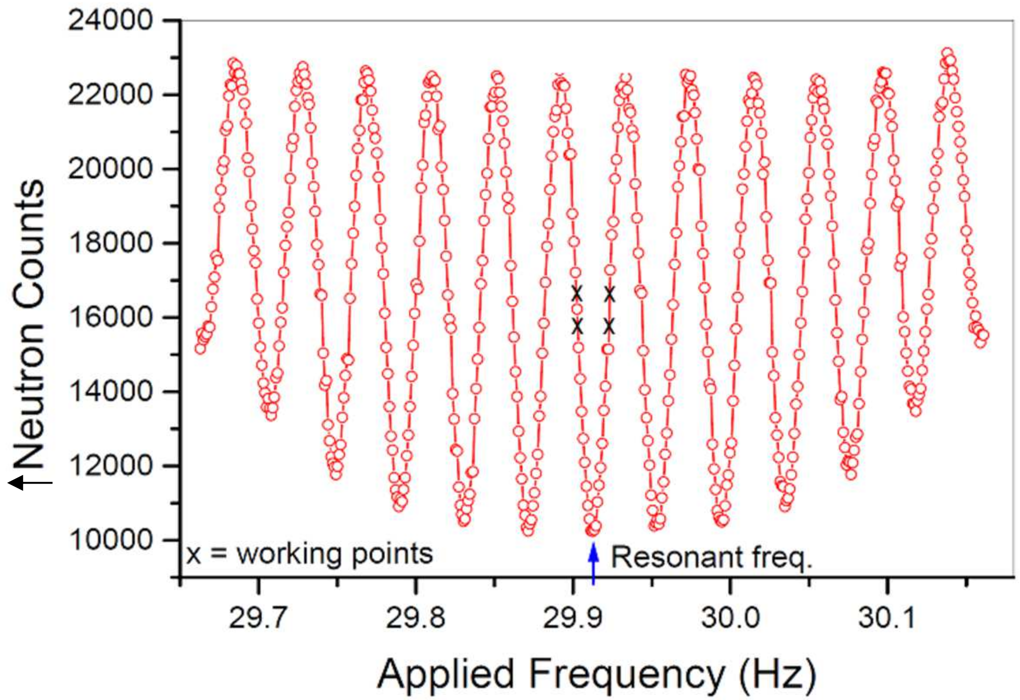
$$h\Delta\nu = 4\, d_n E$$



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

The Ramsey method





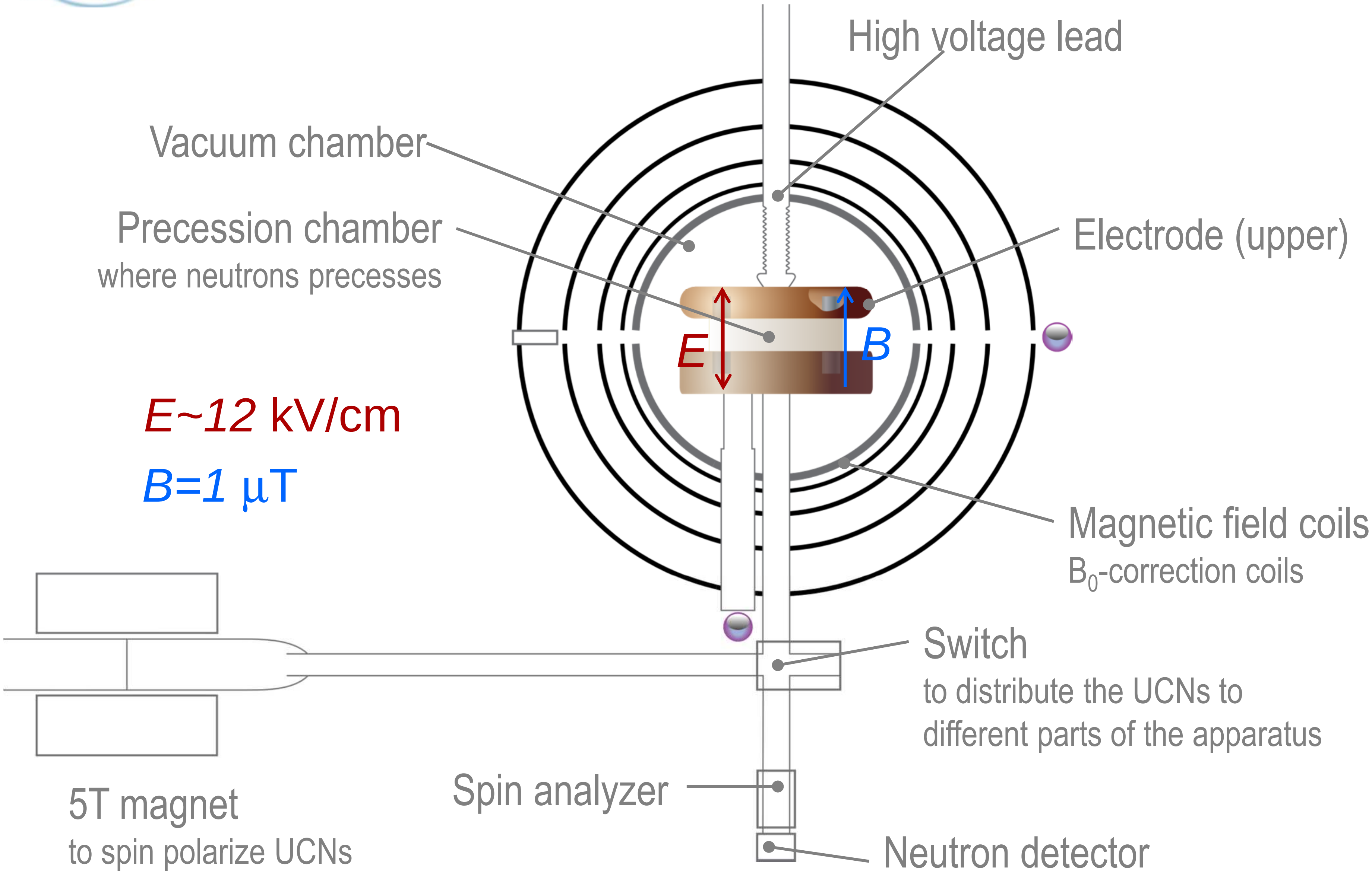
[K. Green et al, Nucl. Instr. Meth. A 404, 381 (1998)]

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

Apparatus



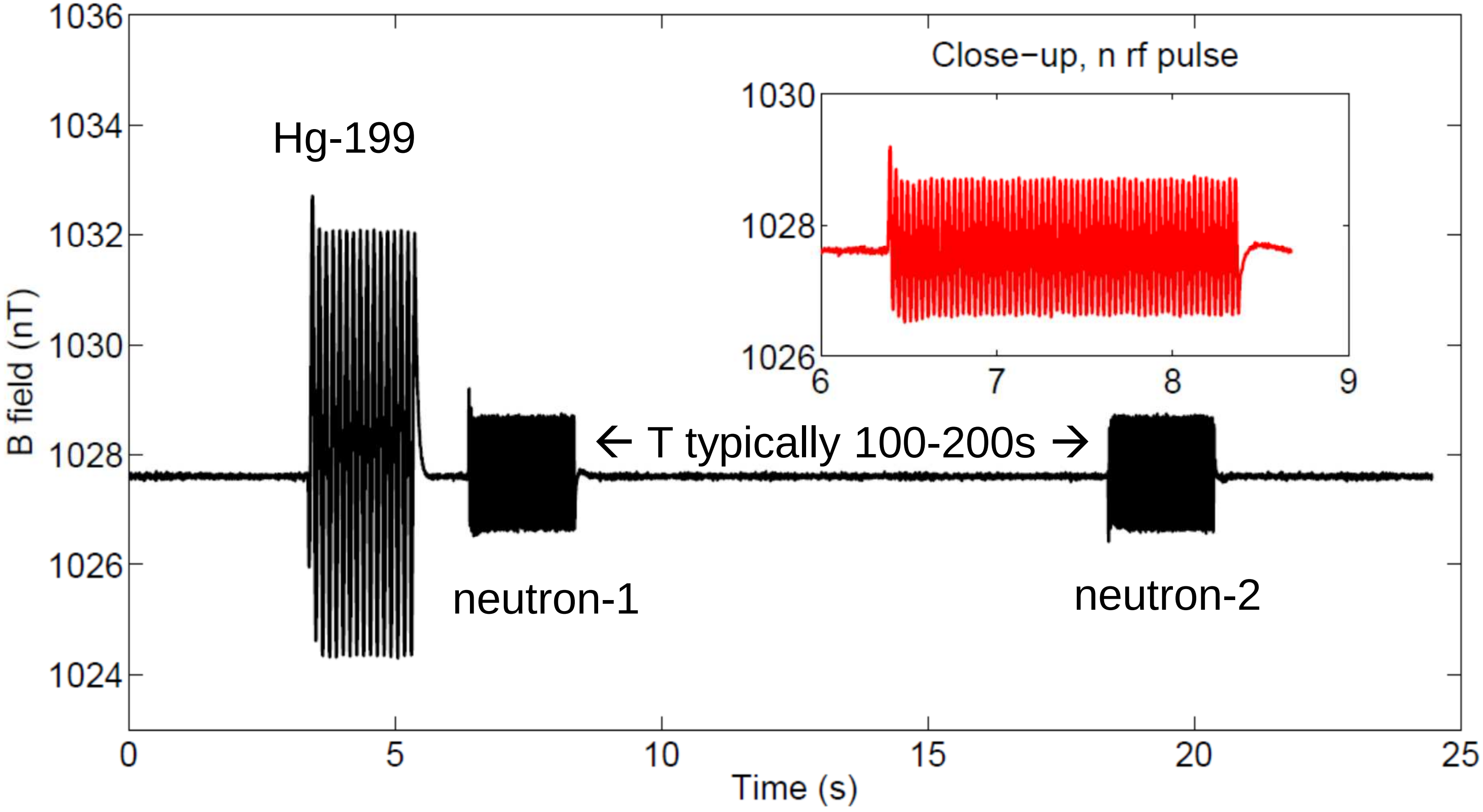
E~12 kV/cm

B=1 μT

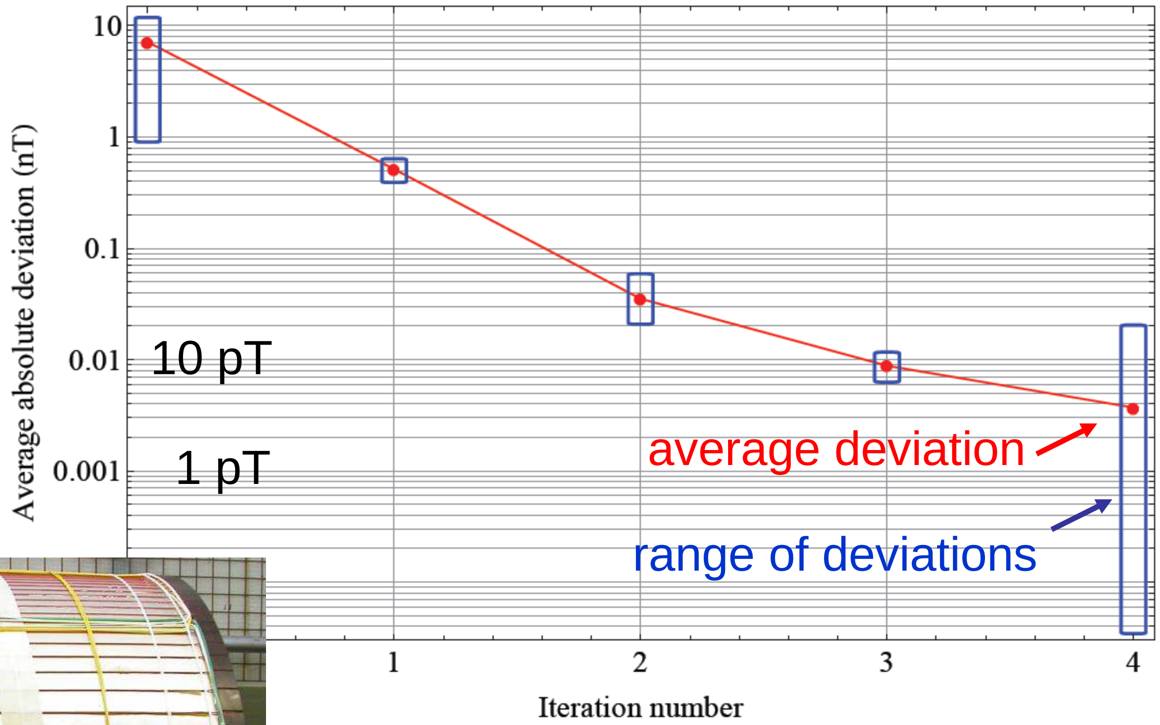

01/06/2011

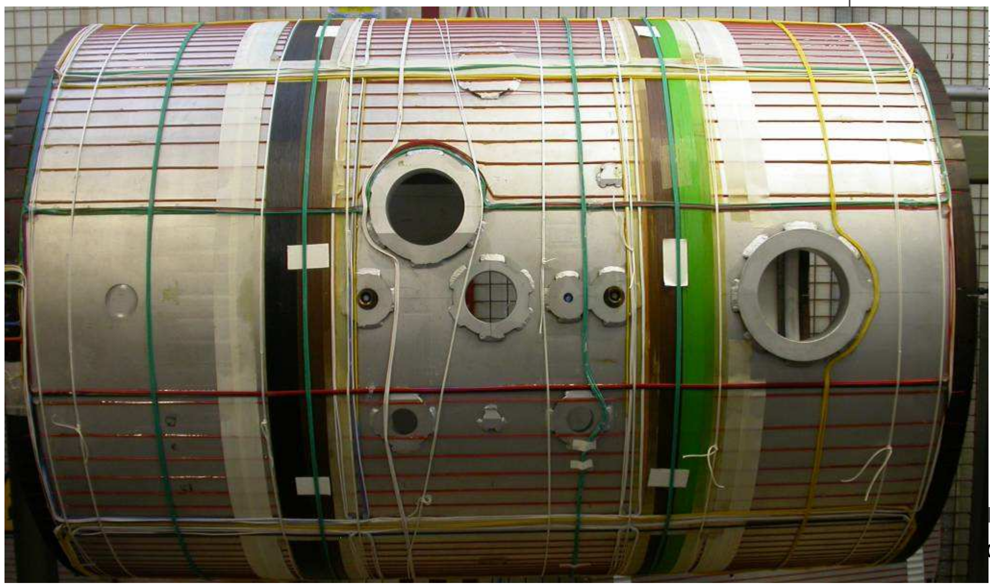

01/06/2011

The π/2-pulses seen by CsM

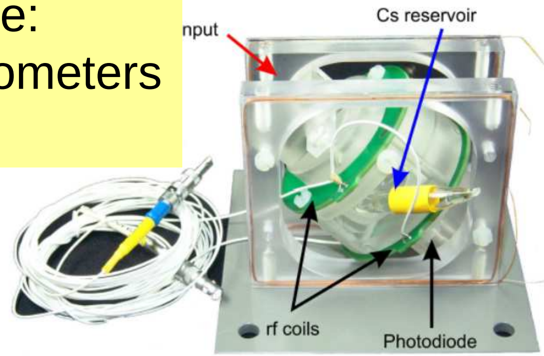


Optimizing the magnetic field homogeneity

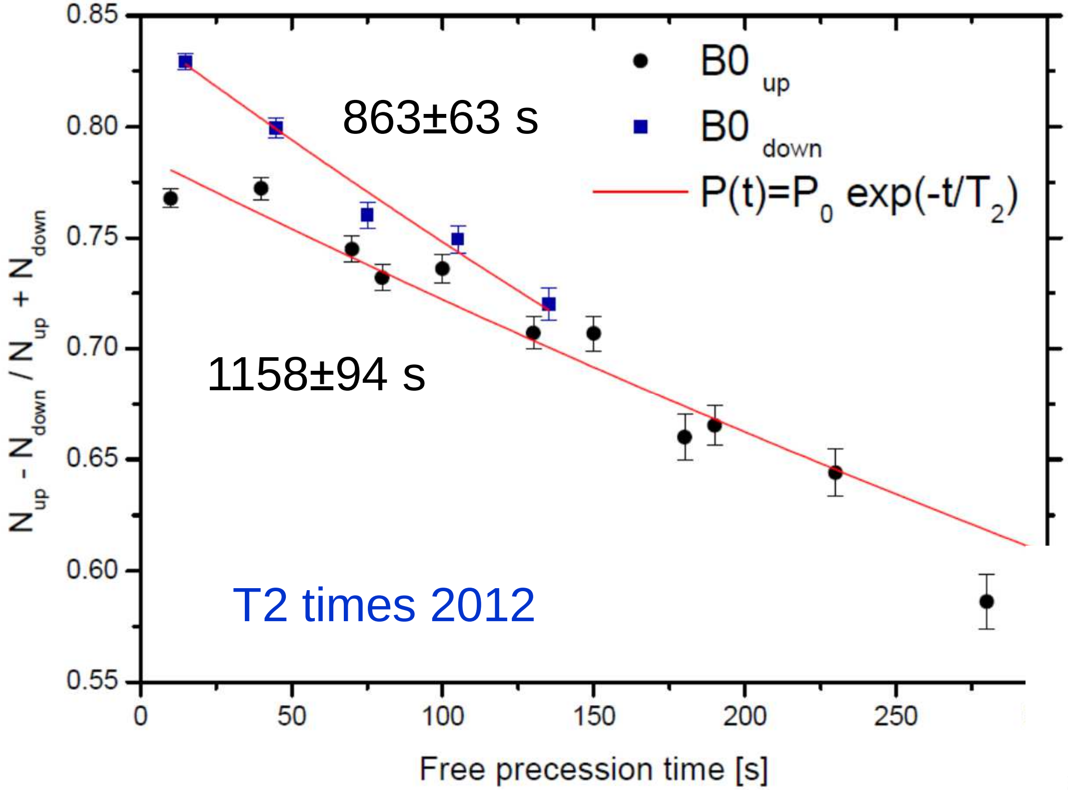


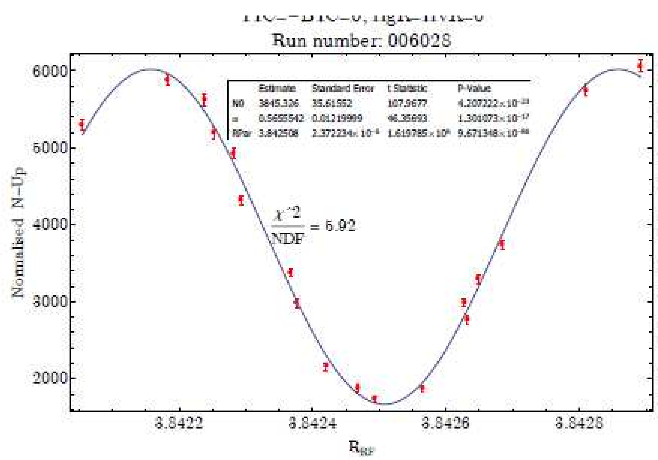


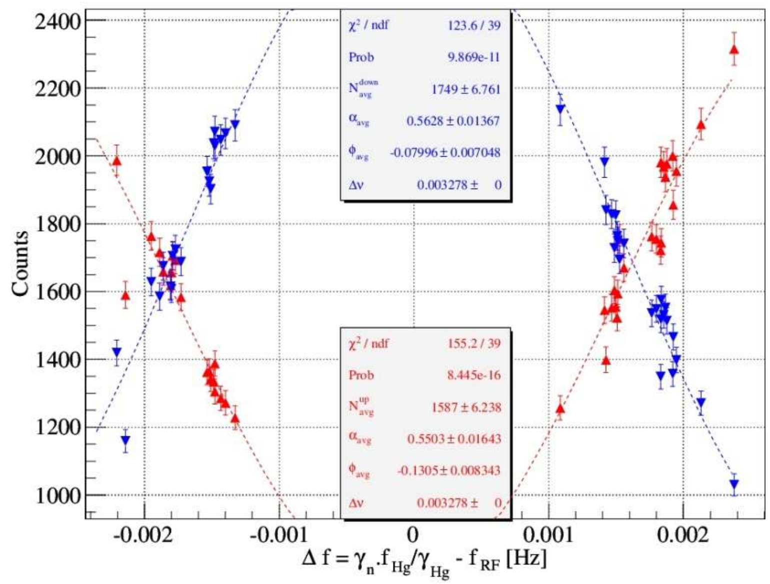
presently in use:
12 Cs magnetometers
33 trim coils



nEDM – performance 2012



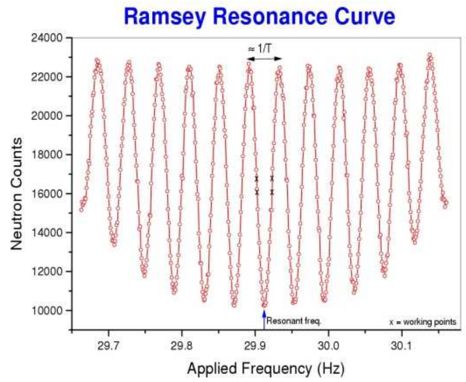




Statistical Sensitivity

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)

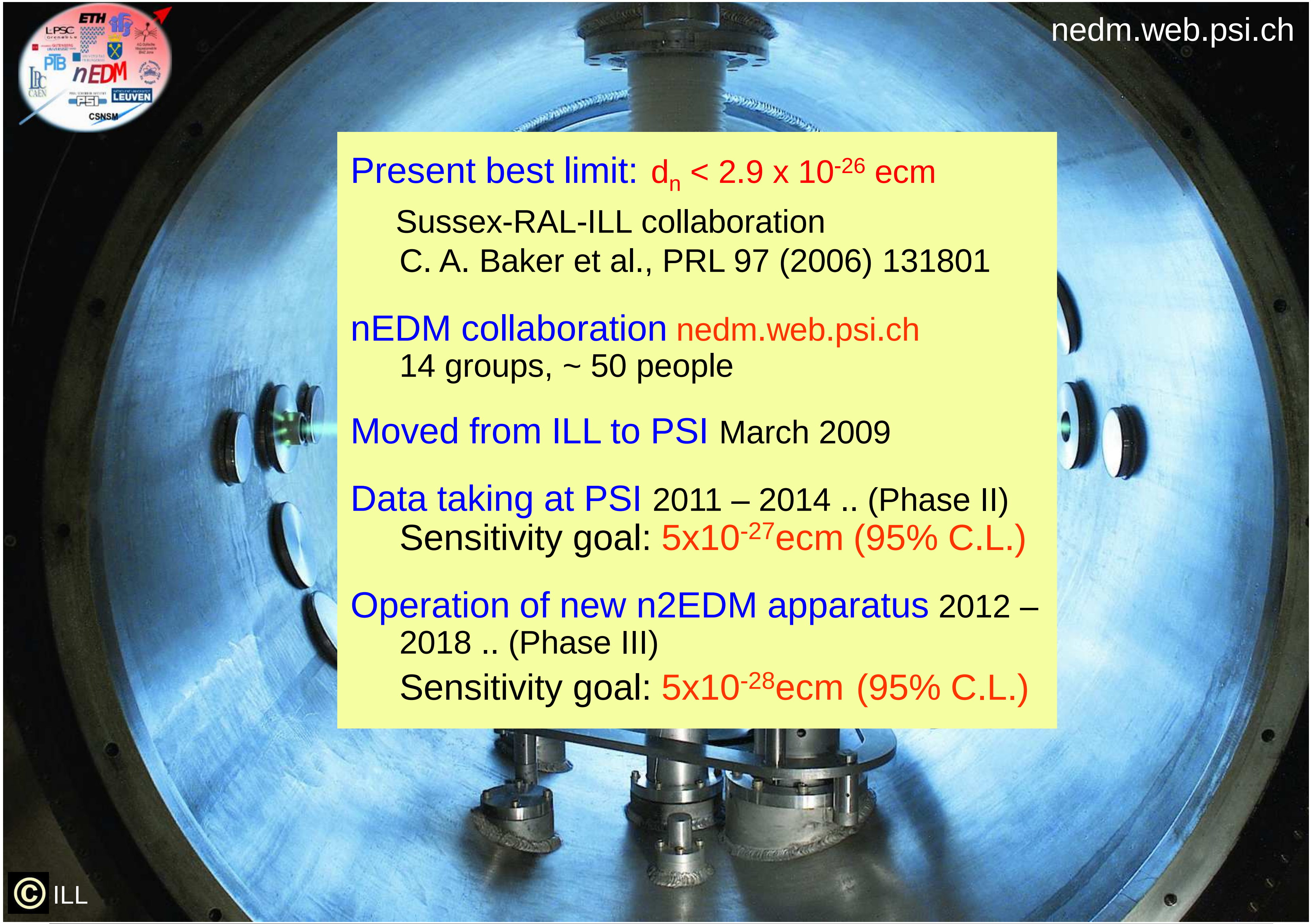
= 3 x 10^{-26} ecm / day

= 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.)

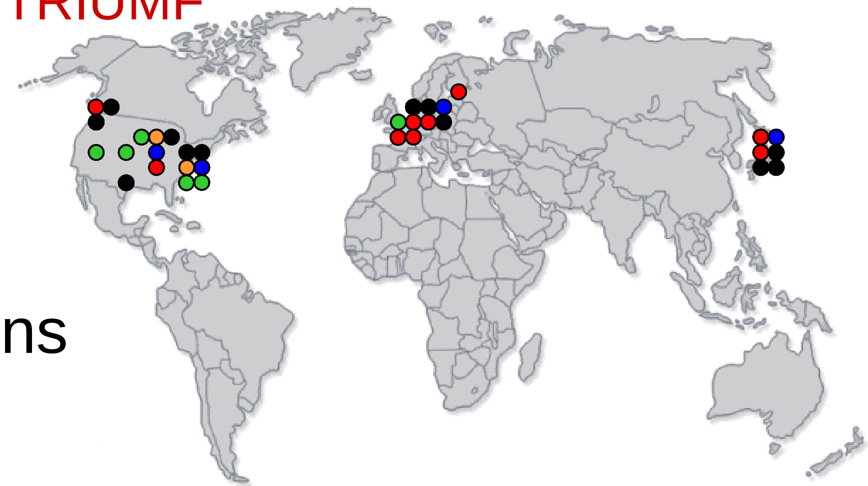
International context (nEDMs)

Project	Goal (en *e*.cm)	Result expected
nEDM@PSI n2EDM@PSI	$\sim 5 \times 10^{-27}$ $\sim 5 \times 10^{-28}$	2014 2020
PNPI@ILL	$\sim 5 \times 10^{-26}$	2013
CryoEDM@ILL	$\sim 3 \times 10^{-27}$	2016
nEDM@SNS	$\sim 3 \times 10^{-28}$	2020
nEDM@TRIUMF	$\sim 3 \times 10^{-27}$ $\sim 1 \times 10^{-28}$	2017 2020
nEDM@TUM	$\sim 5 \times 10^{-28}$	2018

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

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