EDM searches

"It may be that the next exciting thing to come along will be the discovery of a neutron or atomic or electron electric dipole moment. These electric dipole moments... seem to me to offer one of the most exciting possibilities for progress in particle physics."

- S. Weinberg

Klaus Kirch, ETHZ - PSI

CIPANP May 30, 2012

EDM Searches

- Why search for permanent electric dipole moments?
- How to measure EDM?
- Which systems are studied experimentally?
- What are the fields involved?
- What are the technologies involved?
- What is the present status?
- What will come next?

EDM Searches

- Why search for permanent electric dipole moments?
  - CP-violating and very small in the Standard Model
  - expect clean signals of New Physics: discovery potential
  - in some BSM scenarios the best or only hope
  - highly sensitive techniques available or being developed
  - multiple complementary systems can help unravelling the underlying theory
  - highly complementary to collider physics
- How to measure EDM?
- Which systems are studied experimentally?
- What are the fields involved?
- What are the technologies involved?
- What is the present status?
- What will come next?

EDM Searches

- Why search for permanent electric dipole moments?
- How to measure EDM?
  - search for an interaction of the spin with the electric field
- Which systems are studied experimentally?
  - many: particles, nucleons, nuclei, atoms, molecules, solids
- What are the fields involved?
  - many: molecular, atomic, neutron, nuclear, particle, solid state, accelerator physics, surface science, chemistry, ...
- What are the technologies involved?
  - many: particle&neutron sources, radioactive ions, exotic molecules, laser, trapping, high voltage, magnetometry, magnetic shields, unprecedented magnetic field control, new materials, ...
- What is the present status?
  - new results further squeeze BSM parameter space
  - many new projects started during the last few years
- What will come next?
  - some results in the next couple of years
  - major improvements within a decade

... ideally, I should now cover everything ☺

(which doesn´t work)

... let´s start at the beginning:

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
$n_B / n_\gamma = (6.1 \pm^{0.3}_{0.2}) \times 10^{-10}$

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

New theories provide the CP-violation to describe Nature

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

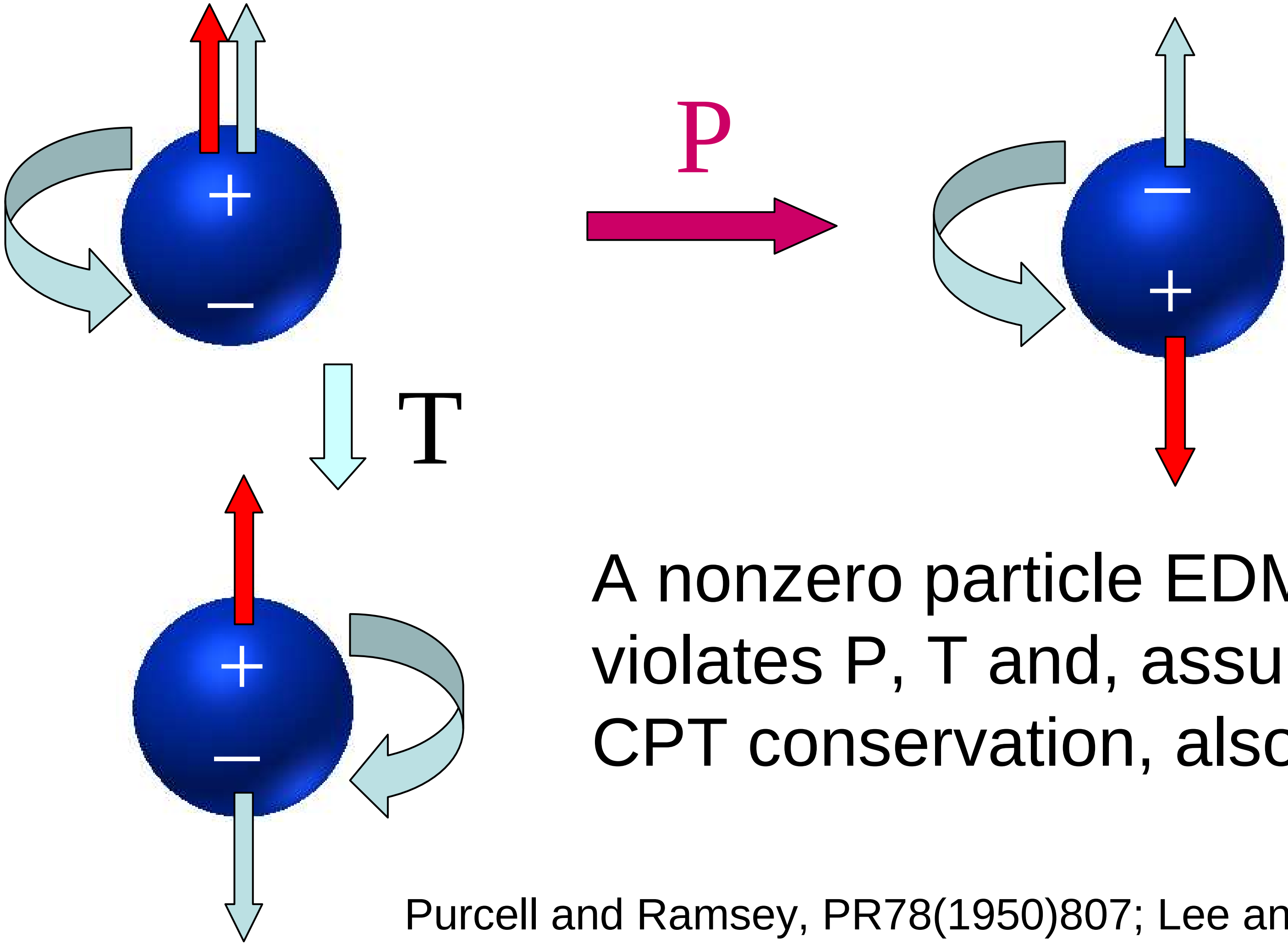
Nature has probably violated CP when generating the Baryon asymmetry !?

New theories provide the CP-violation to describe Nature

Experiments must access with high sensitivity CP-violating observables

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

EDM and symmetries

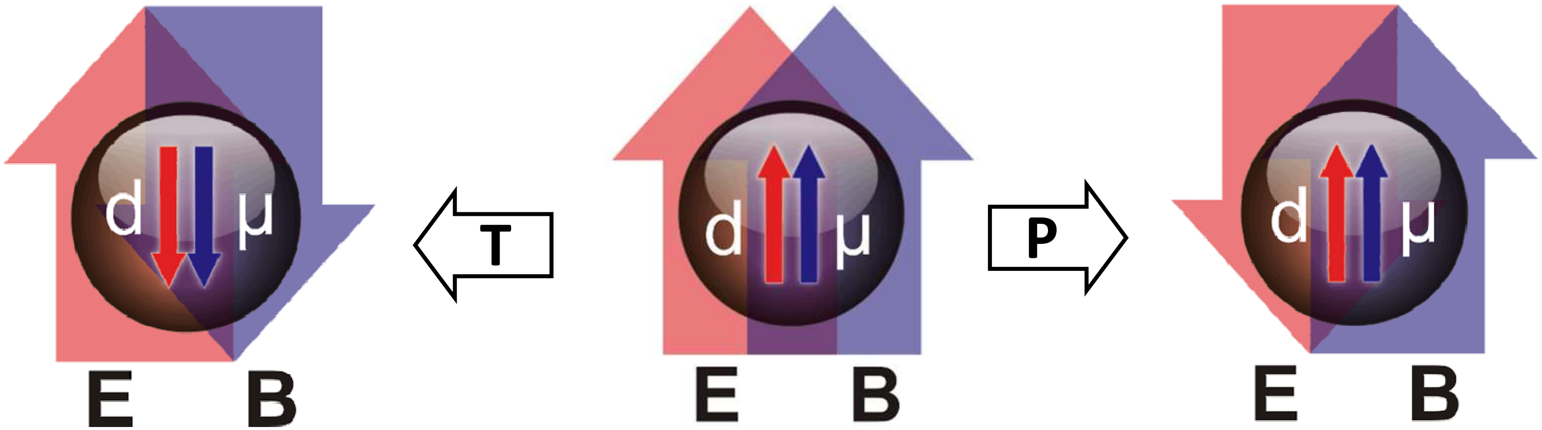


A nonzero particle EDM violates P, T and, assuming CPT conservation, also CP

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

EDM and symmetries

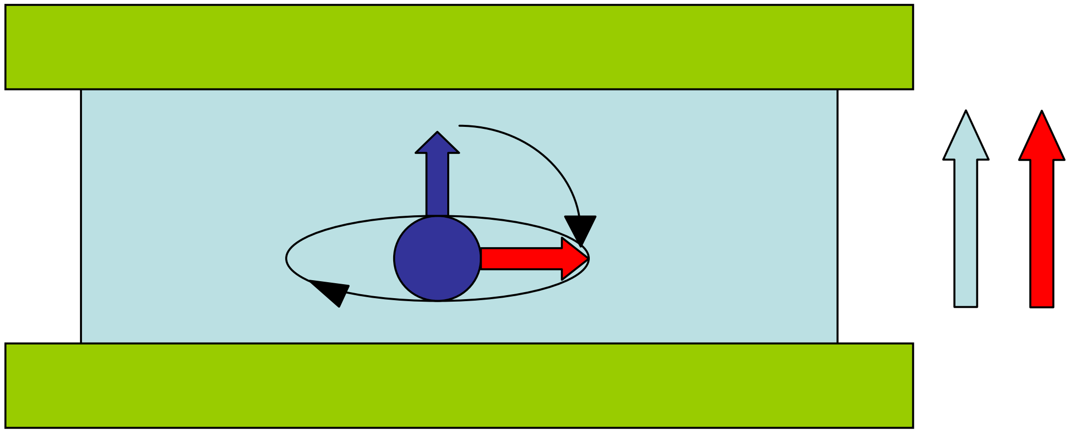
$$H = -\left(d\frac{\vec{\sigma}}{|\vec{\sigma}|}\cdot\vec{E} + \mu\frac{\vec{\sigma}}{|\vec{\sigma}|}\cdot\vec{B} \right)$$



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

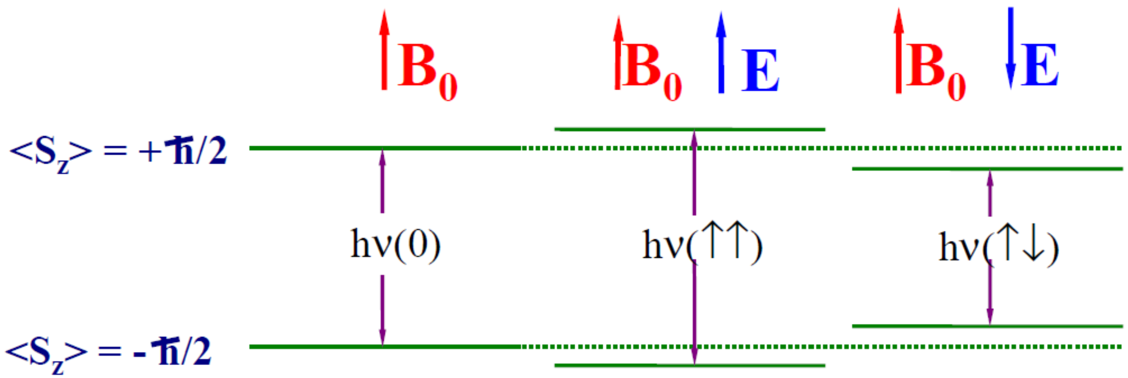
Purcell and Ramsey, PR78(1950)807; Lee and Yang; Landau

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



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

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



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

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

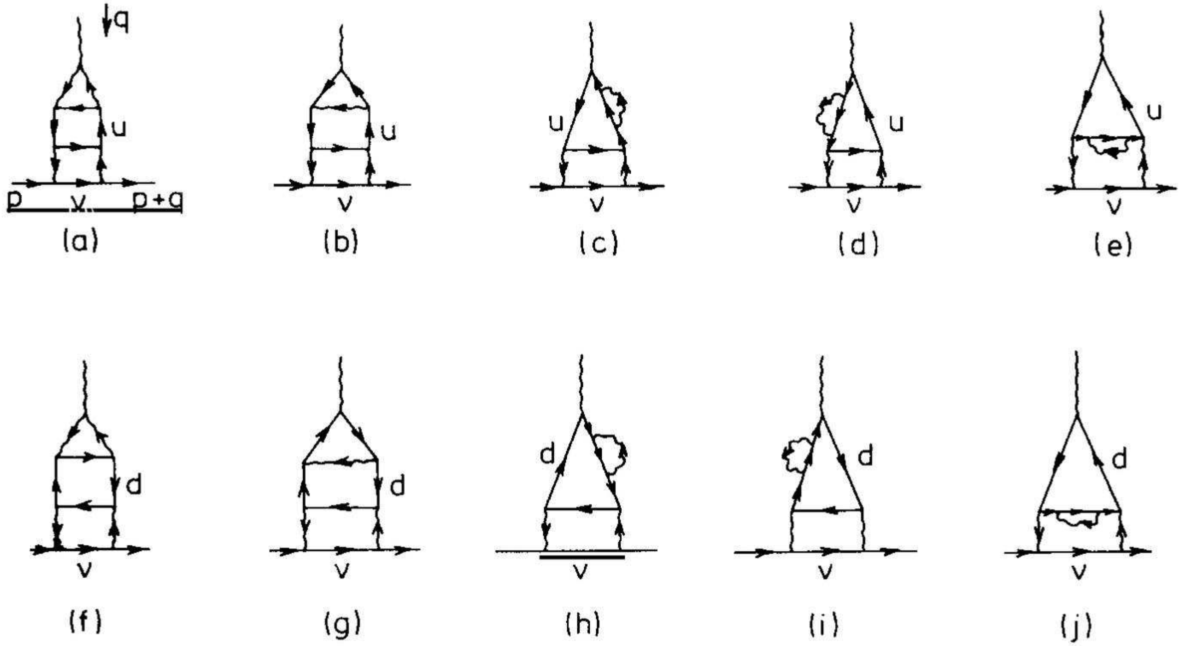


Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

… + new physics?

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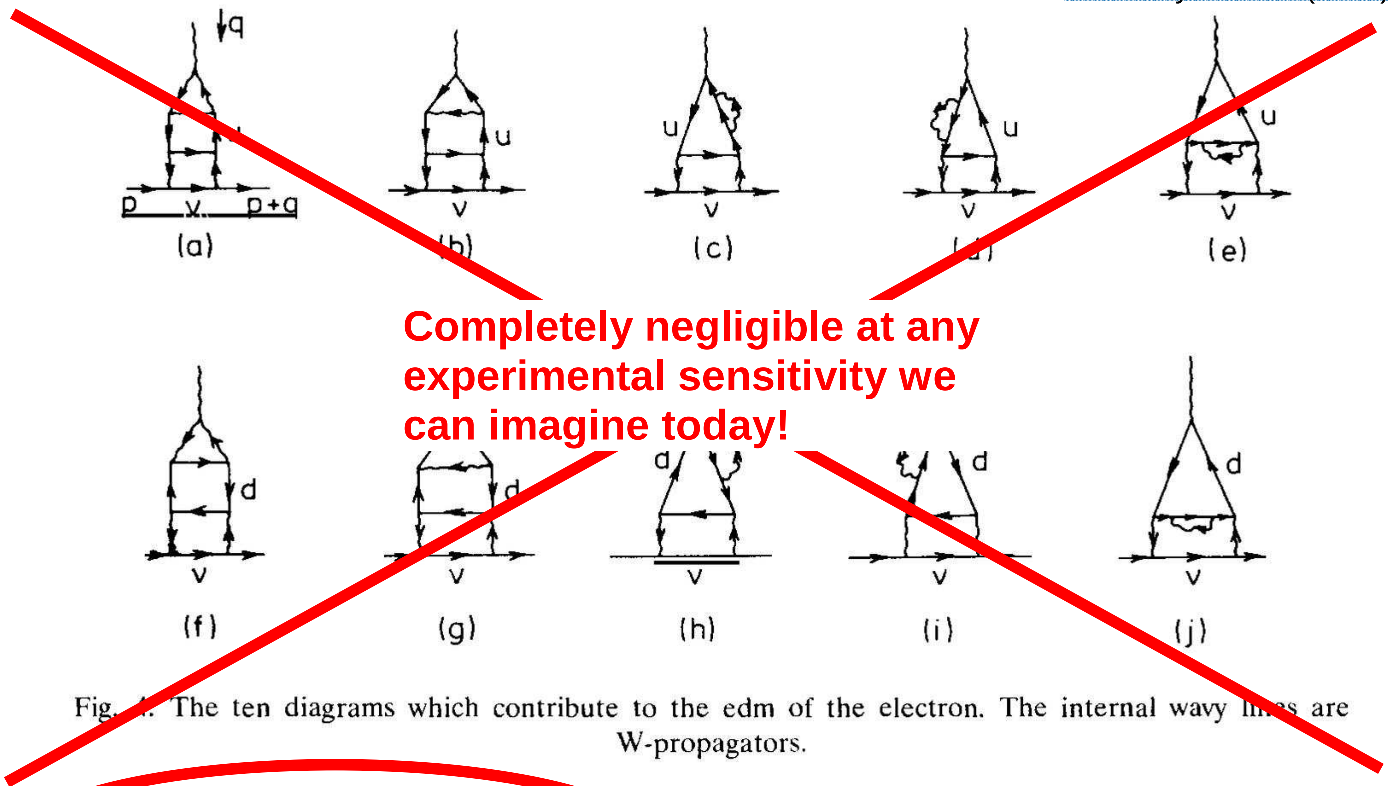

Fig. 4. The ten diagrams which contribute to the edm of the electron. The internal wavy lines are W-propagators.

… + new physics?

Much greater sensitivity to new, CP-violating physics!

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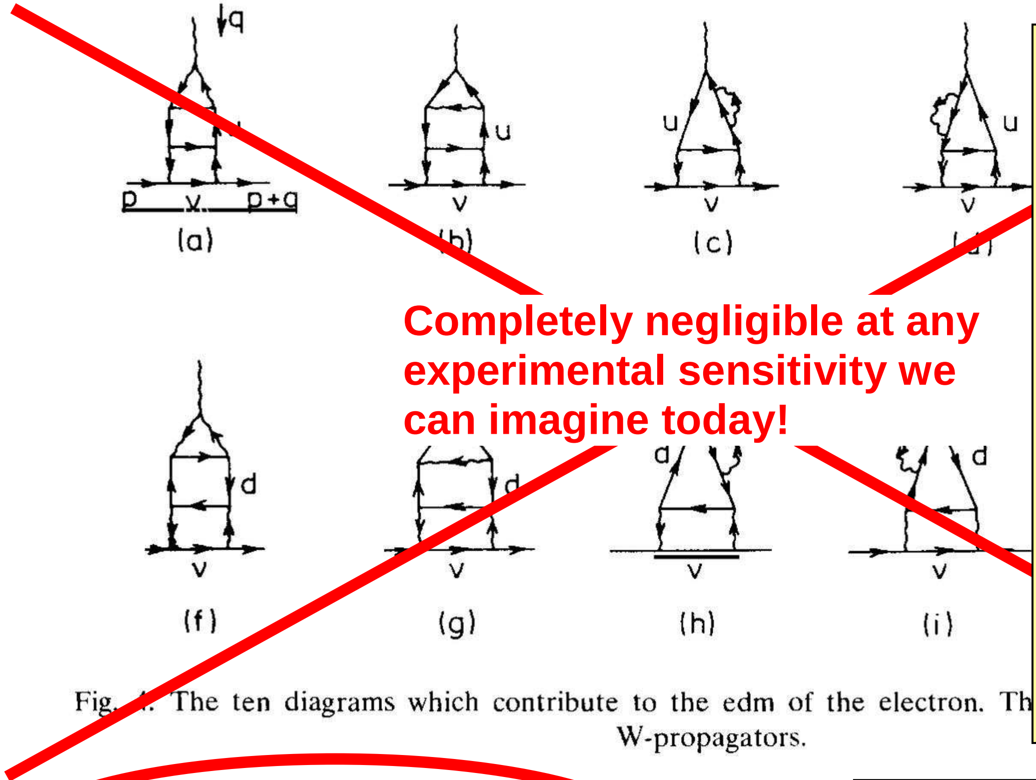


Fig. 4. The ten diagrams which contribute to the edm of the electron. Th... W-propagators.

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

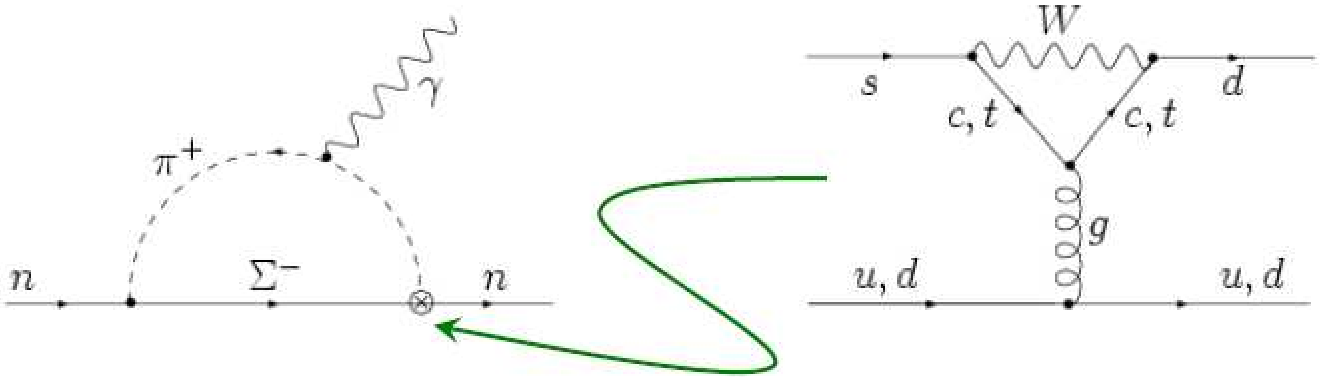
Experimentally so far:

$d_e < 1 \times 10^{-27}$ 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!

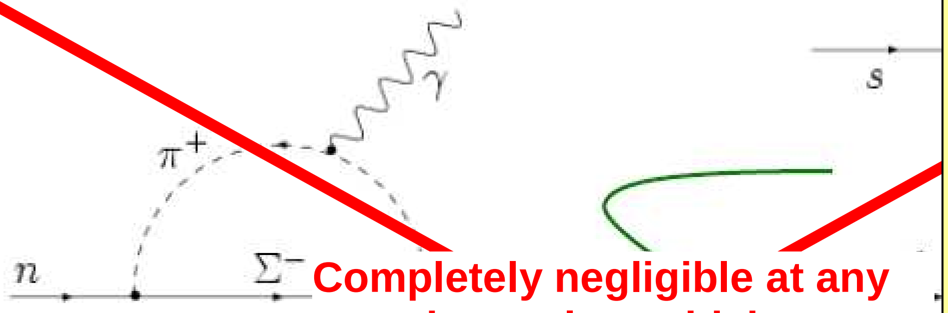
Neutron: Standard Model prediction



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

[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:

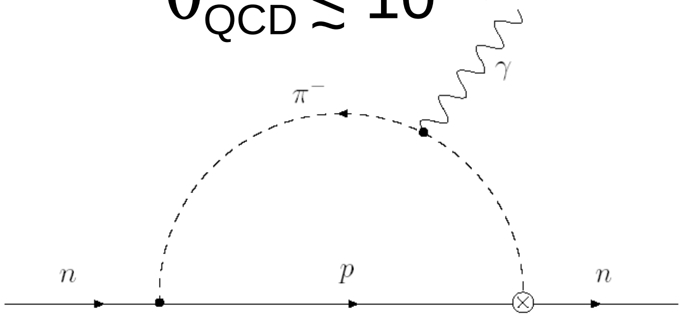
$d_n < 3 \times 10^{-26}$ e•cm

The strong CP problem

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

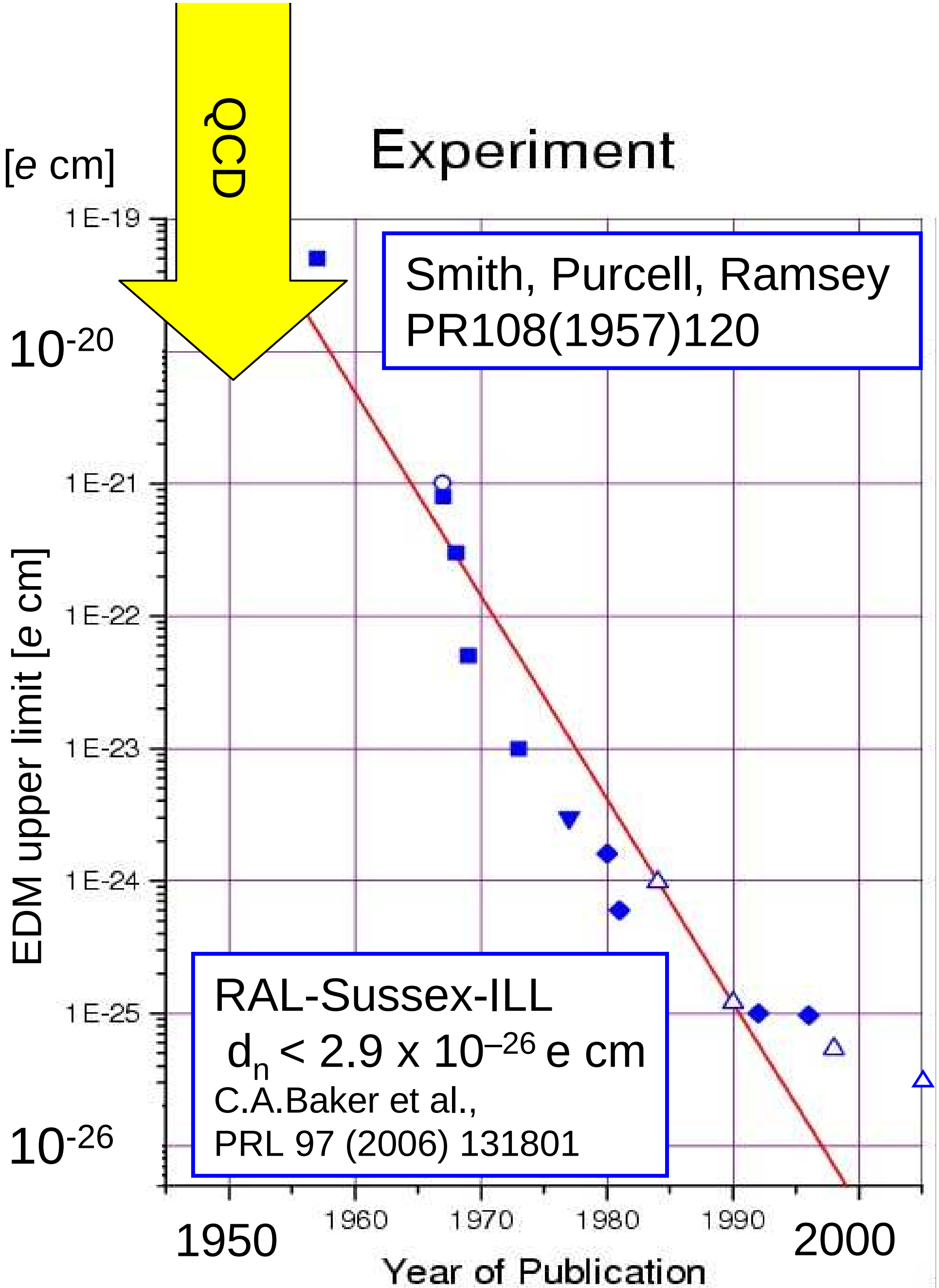
$$d_n \approx 10^{-16}\ e\ \mathrm{cm} \cdot \theta_{QCD}$$

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



Why is θ_{QCD} so small ?

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



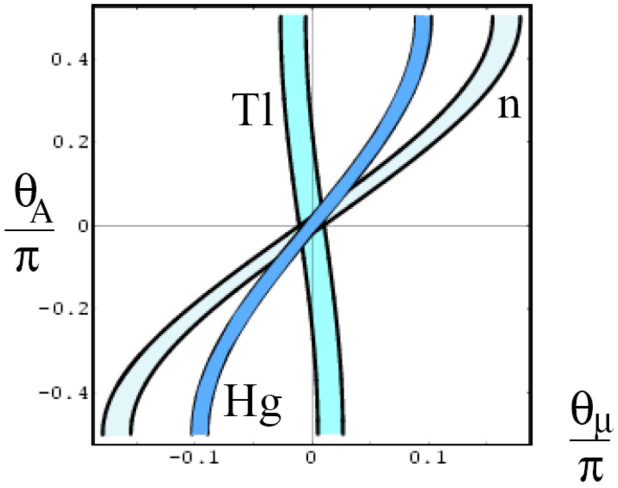
The SUSY CP problem

(for neutron and electron!)

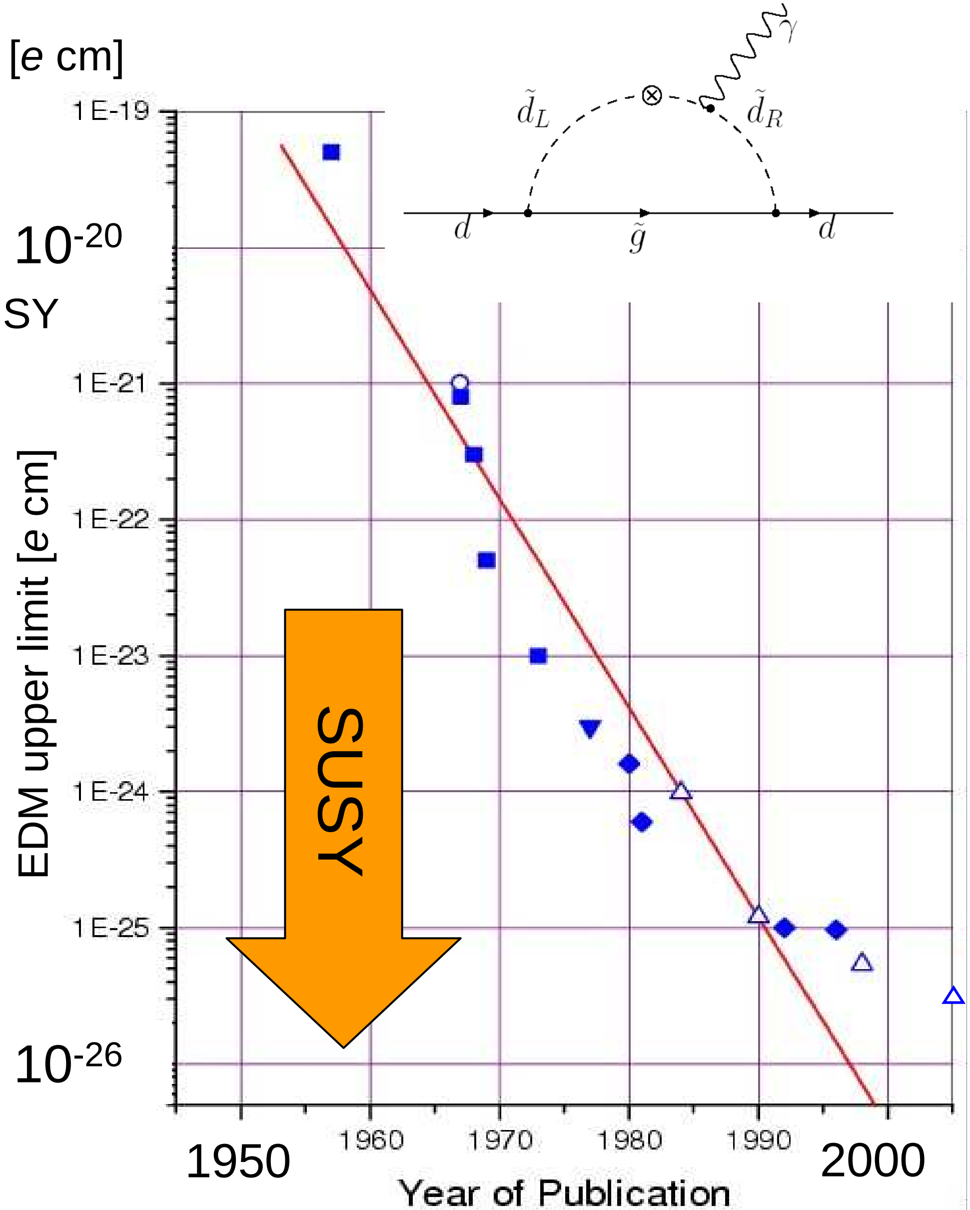
$$d_n \approx 10^{-23}\, e\ \text{cm} \left(\frac{300\ \text{GeV/c}^2}{M_{SUSY}}\right)^2 \sin\phi_{SUSY}$$

Why is ϕ_{SUSY} so small ?

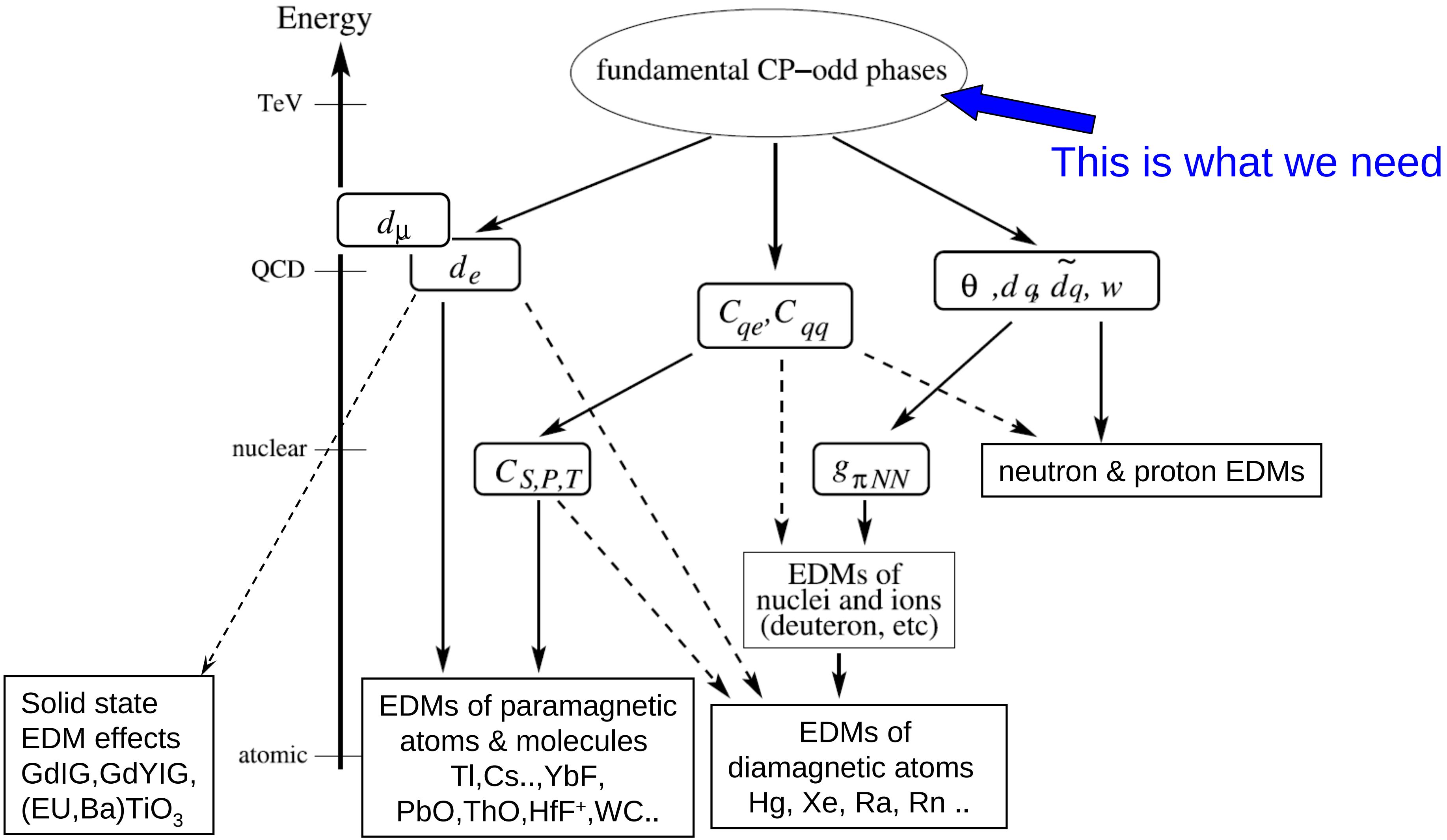
(this is testing M already to 10TeV and you may also ask: why are the masses so huge?)



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

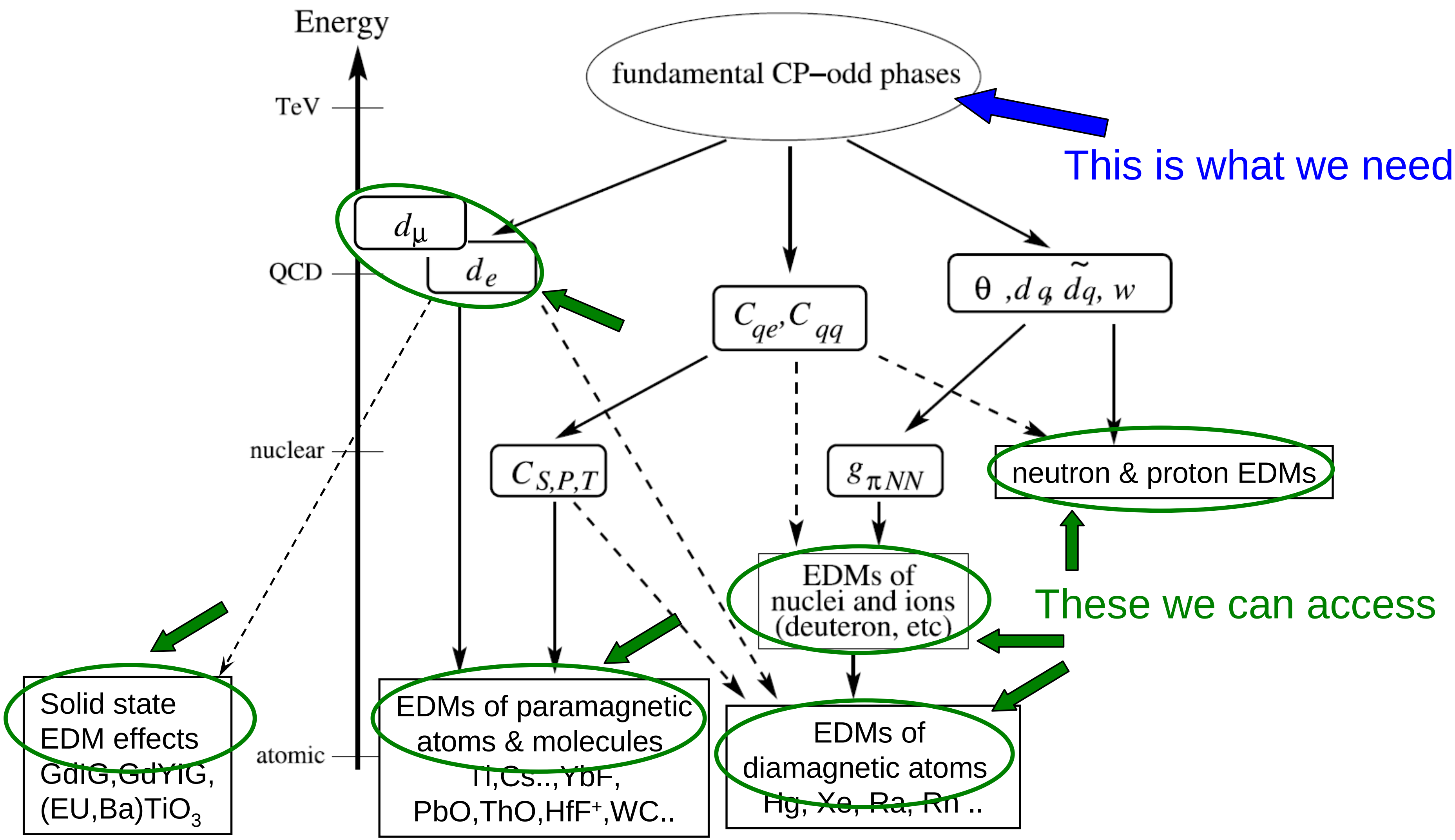


Origin of EDMs



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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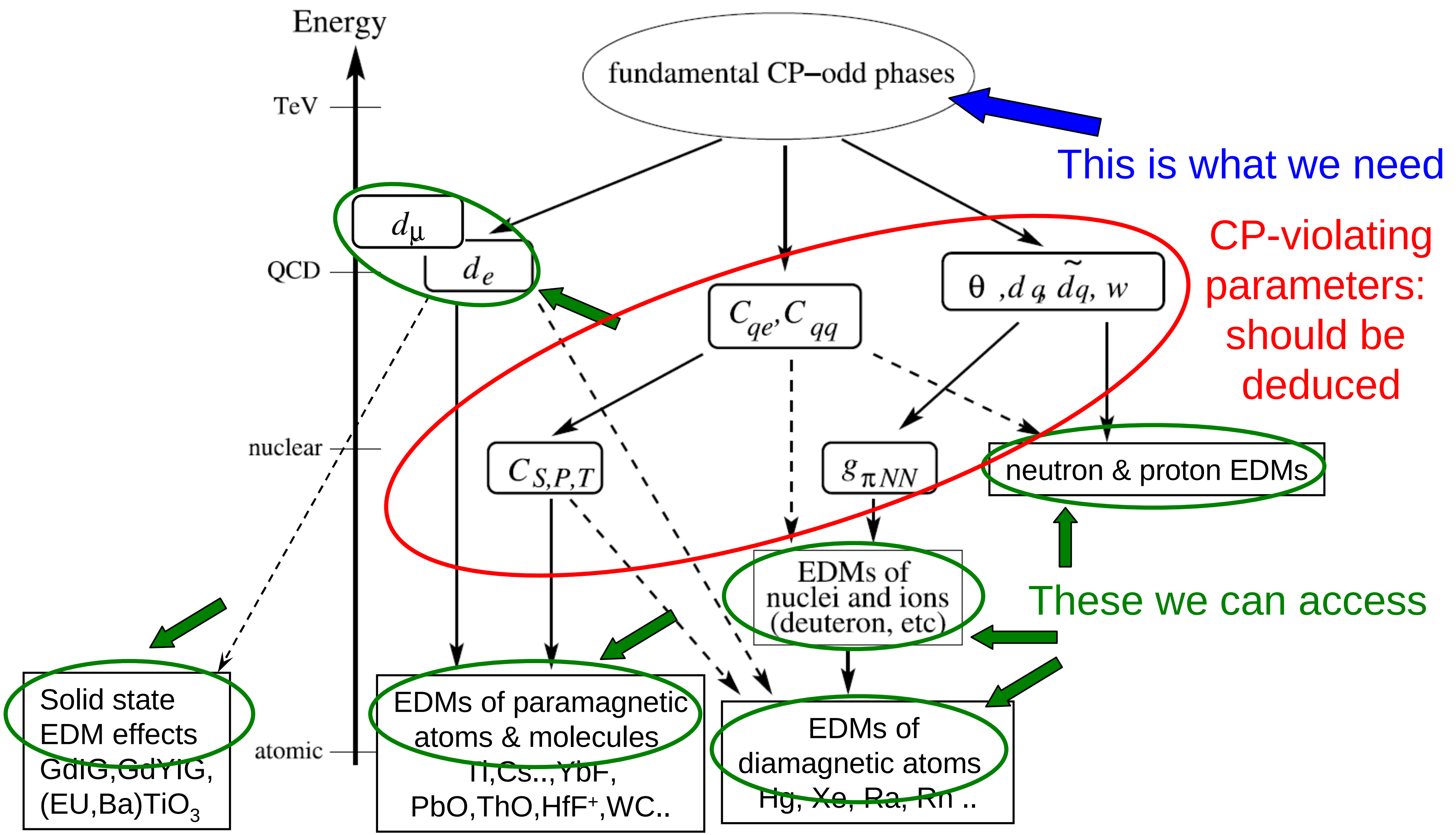

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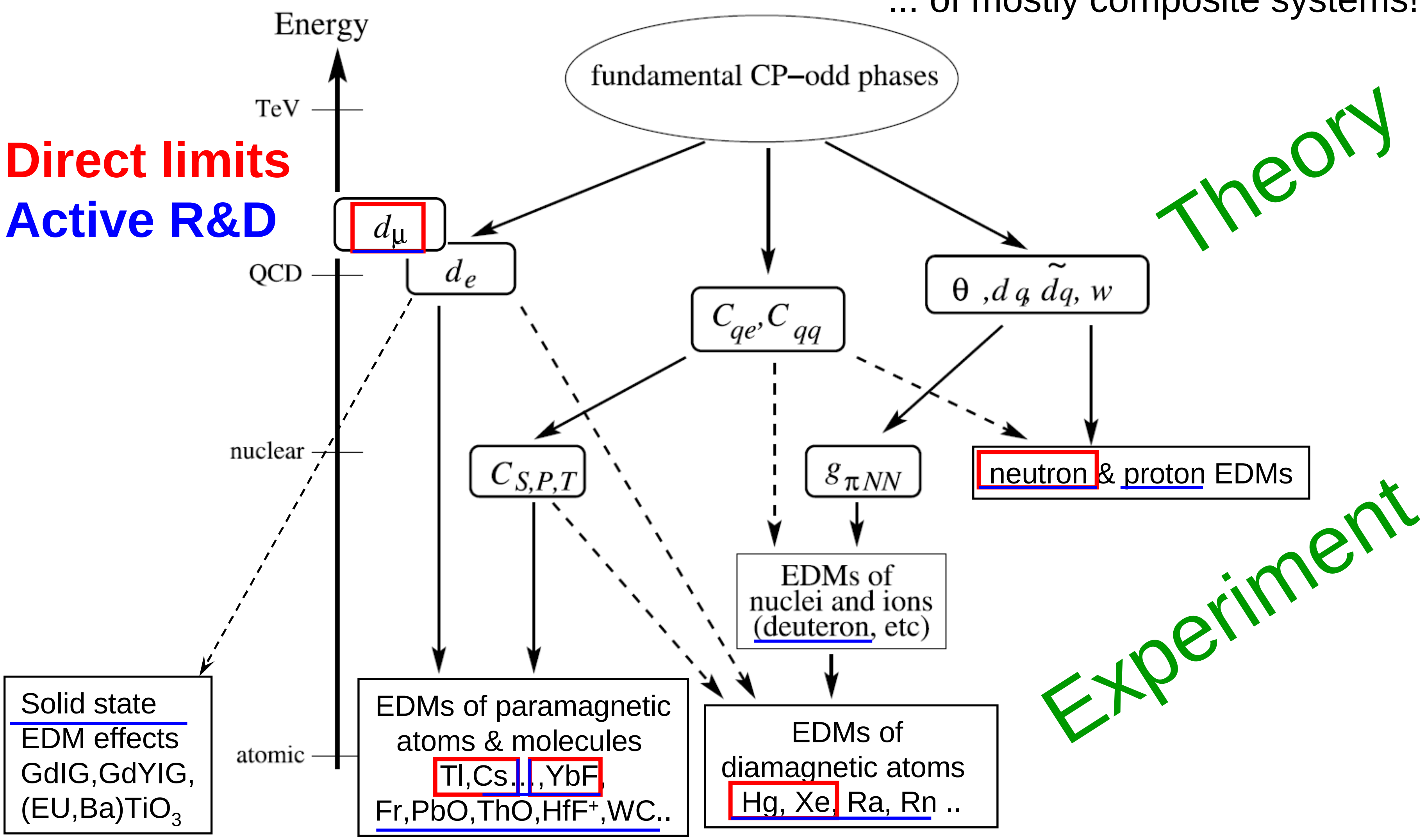
Origin of EDMs

... of mostly composite systems!



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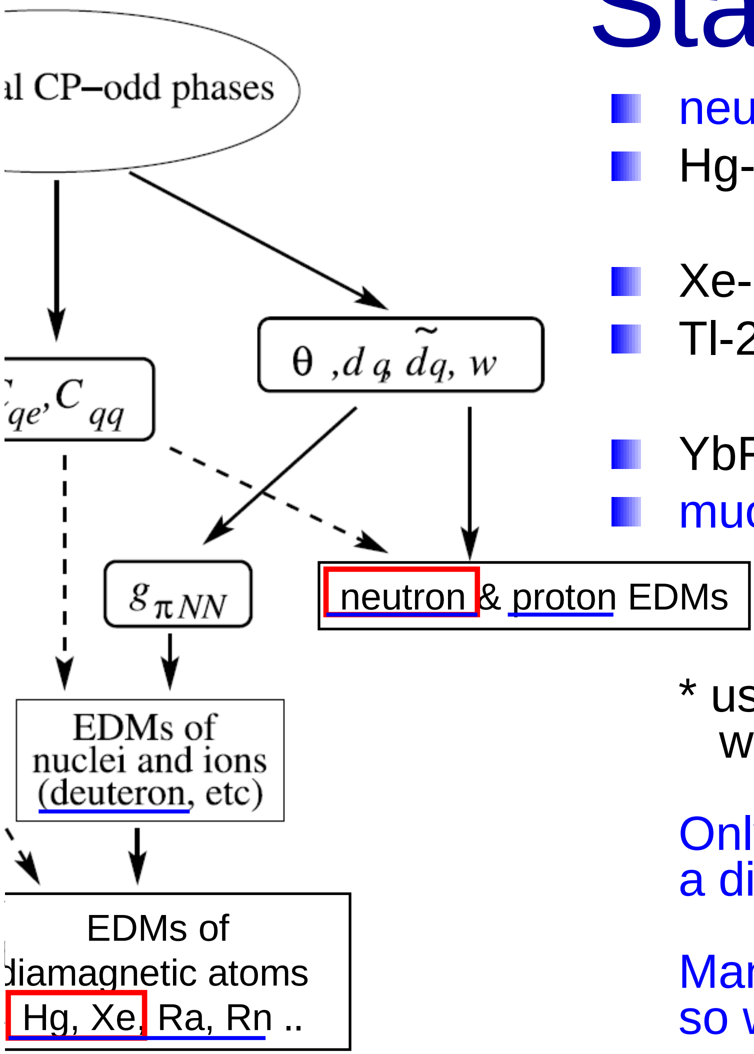
ɡin of EDMs



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.

Many people consider the neutron almost fundamental -- so we may perhaps count two direct basic EDM limits.

Complex composite systems have constituents and interactions

Paramagnetic atoms

$d_{\text{para}}(d_e) \sim 10\alpha^2 Z^3 d_e \Longrightarrow d_{\text{Tl}} = -585 d_e - 43\ \text{GeV} \times e\, C_S^{\text{singlet}}$ enhancement

Paramagnetic molecules

additional enhancement from large internal electric fields of order 10 GV/cm or more, influenced by molecular level structure

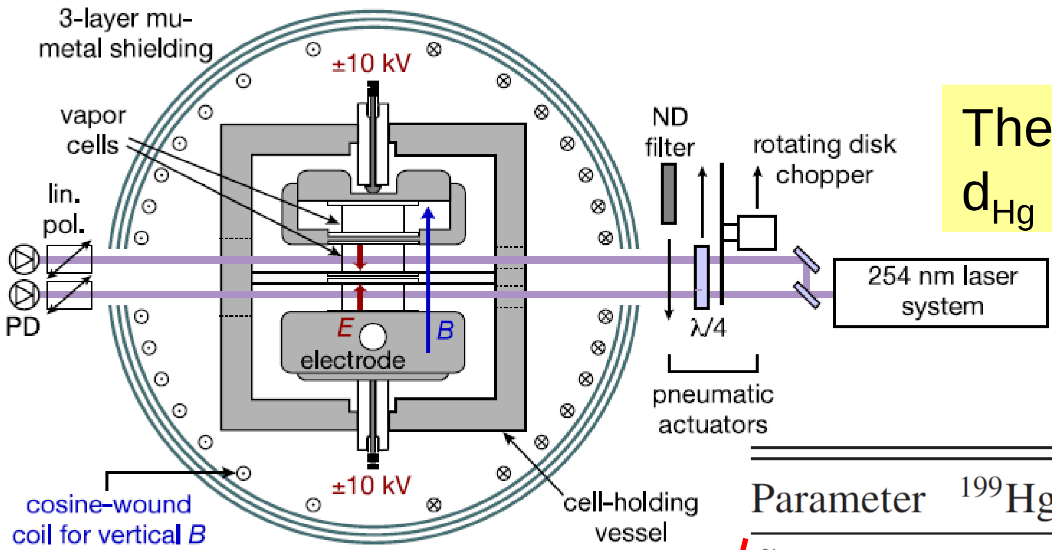
Diamagnetic atoms

$d_{\text{dia}} \sim 10 Z^2 (R_N/R_A)^2 \tilde{d}_q$ suppression of order 10^3

$$\Longrightarrow \quad d_{\text{Hg}} = 7 \times 10^{-3}\, e\,(\tilde{d}_u - \tilde{d}_d) + 10^{-2}\, d_e + \mathcal{O}(C_S, C_{qq})$$

enhancement factors possible due to atomic state mixing and nuclear deformation.

Hg-199 EDM at Seattle



The best EDM limit in absolute terms:
$d_{Hg} < 3.1 \times 10^{-29}$ e cm (95% C.L.)

PRL **102,** 101601 (2009)

Limiting various CP-violating parameters:

Parameter	^{199}Hg bound	Hg theory	Best alternate limit
$\tilde{d}_q$ (cm) [a]	6×10^{-27}	[15]	n: 3×10^{-26} [3]
d_p (e cm)	7.9×10^{-25}	[16]	TlF: 6×10^{-23} [17]
C_S	5.2×10^{-8}	[18]	Tl: 2.4×10^{-7} [19]
C_P	5.1×10^{-7}	[18]	TlF: 3×10^{-4} [1]
C_T	1.5×10^{-9}	[18]	TlF: 4.5×10^{-7} [1]
$\bar{\theta}_{QCD}$	3×10^{-10}	[20]	n: 1×10^{-10} [3]
d_n (e cm)	5.8×10^{-26}	[16]	n: 2.9×10^{-26} [3]
d_e (e cm)	3×10^{-27}	[21,22]	Tl: 1.6×10^{-27} [18]

[a] For ^{199}Hg, $\tilde{d}_q = (\tilde{d}_u - \tilde{d}_d)$, while for n, $\tilde{d}_q = (0.5\tilde{d}_u + \tilde{d}_d)$.

EDM landscape

More than 30 efforts under way world-wide (plus many ideas ...)

- Neutrons
- Ions+Muons
- Atoms
- Molecules
- Solids

collaborations ranging from university groups of 2-3 or 10 to relatively large international collaborations

EDM landscape

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

EDM landscape

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

Essentially all projects aim at sensitivities of a few x 10^{-28}ecm within the next decade. Some promise intermediate results of a few x 10^{-27}ecm within the next 3 years.

EDM landscape

- Ions-Muons
  - @BNL
  - @FZJ
  - @FNAL(g-2)
  - @JPARC(g-2)

EDM landscape

- Ions-Muons
  - @BNL
  - @FZJ
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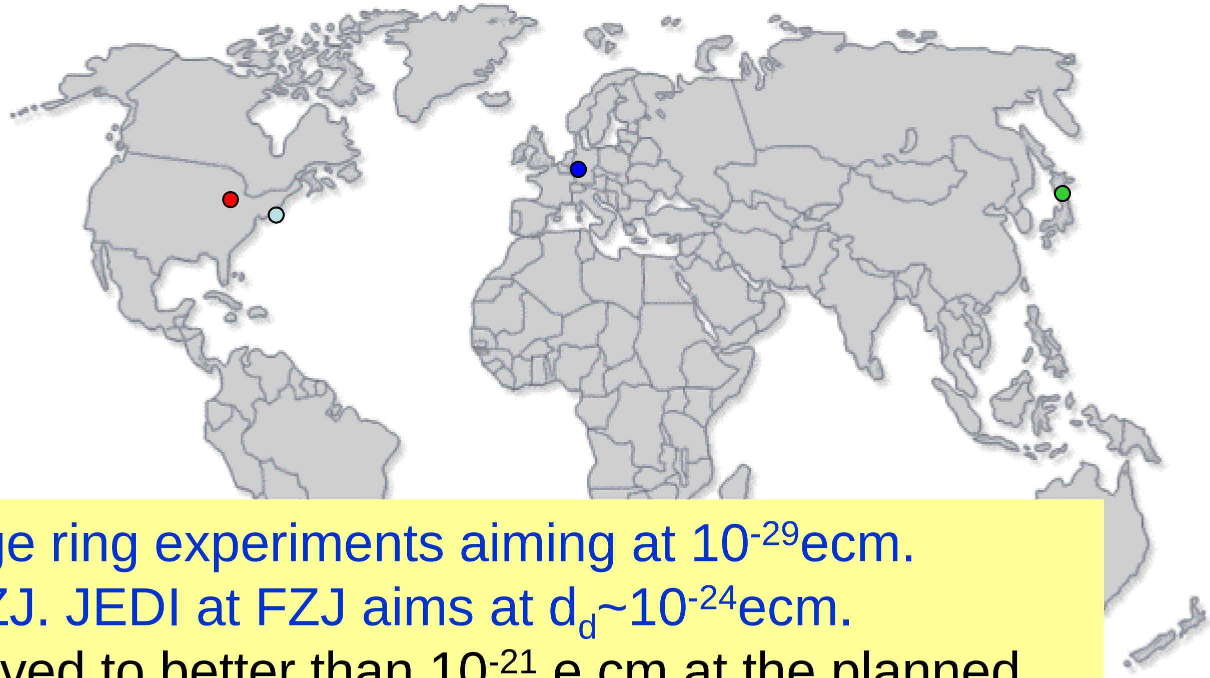
  - @JPARC(g-2)



Dedicated p and d storage ring experiments aiming at 10^{-29}ecm. Proposals at BNL and FZJ. JEDI at FZJ aims at $d_d \sim 10^{-24}$ecm.
Muon EDM can be improved to better than 10^{-21} e cm at the planned new g-2 experiments within the next decade. Dedicated muon EDM experiments at PSI (5×10^{-23}ecm) and J-PARC (10^{-24}ecm) presently not pushed further. Variants of frozen spin technique PRL93(2004)052001.

EDM landscape

- Atoms
  - 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

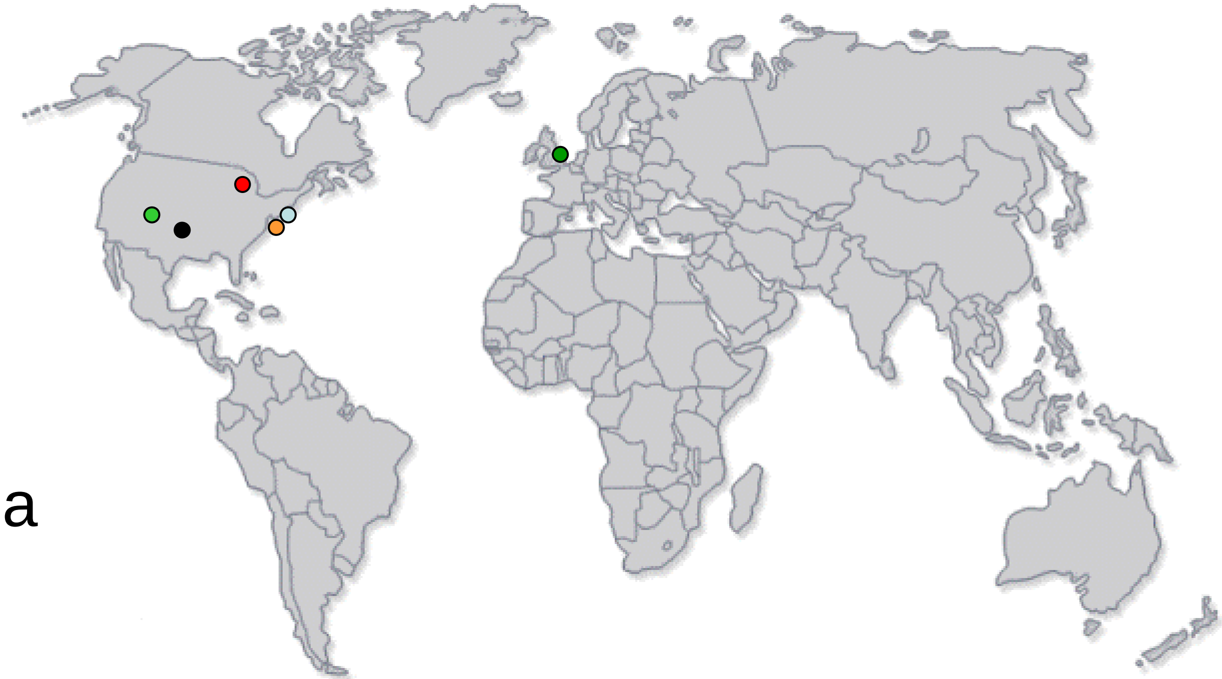
EDM landscape

- Atoms
  - 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

Hg-199 EDM plans to improve to few x 10^{-30}ecm by 2014.
Xe-129 efforts aim at 10^{-28}ecm as a first/next step.
Cs exps. aim at 10^{-29} - few x 10^{-30}ecm for d_e around 2014.
Fr aims at 10^{-29} - few x 10^{-30}ecm for d_e after 2014.
Ra at KVI aims at 10^{-30}ecm (and 10^{-28}ecm for d_e)

EDM landscape

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



EDM landscape

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

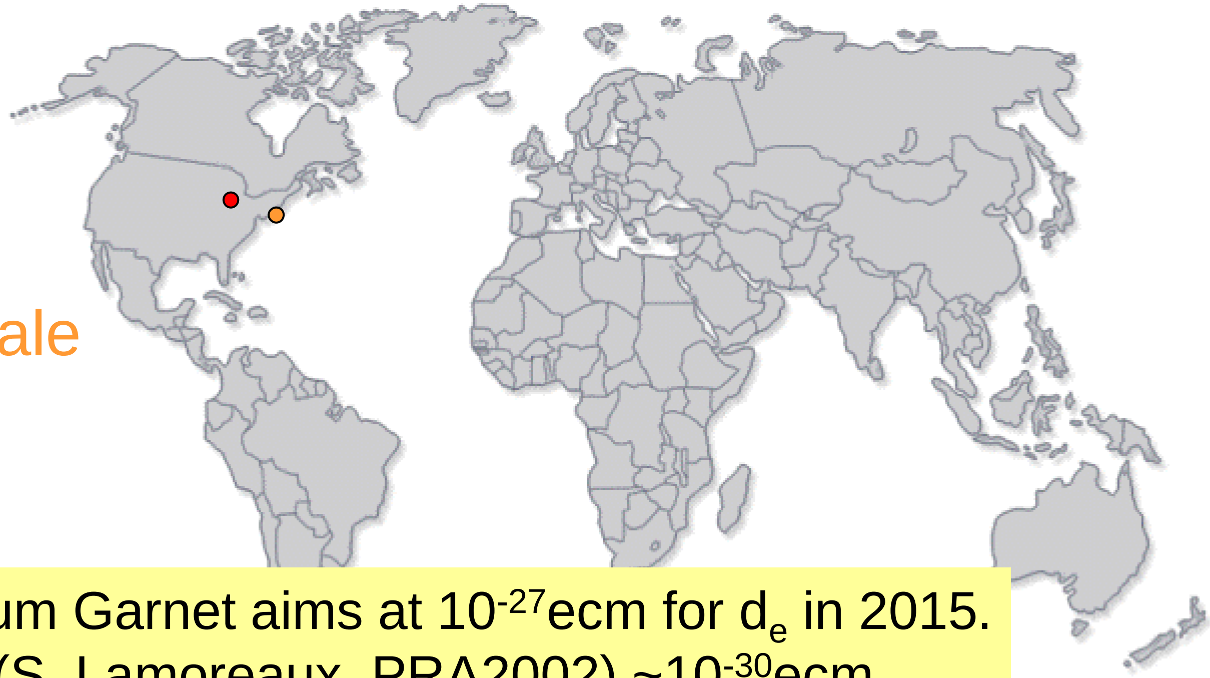
YbF works on improvement by factor 3 in 2012 3-4x10^{-28}ecm and aims at sensitivity for de of 4x10^{-29}ecm by 2016.
ThO presently taking data, "to either soon discover the electron edm or to significantly reduce the current limit."
HfF+ and WC aiming at 10^{-29}ecm in a few years.

EDM landscape

- Solids
  - GGG@Indiana
  - ferroelectrics@Yale

EDM landscape

- Solids
  - GGG@Indiana
  - ferroelectrics@Yale



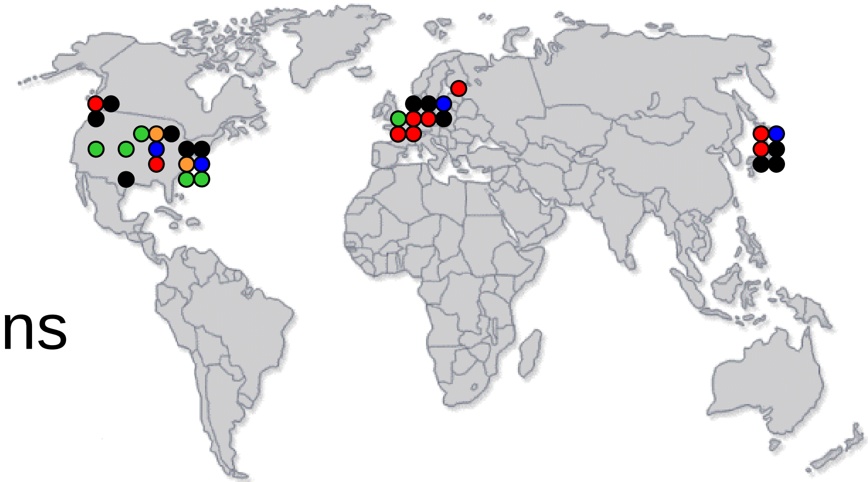
Gadolinium Gallium Garnet aims at 10^{-27}ecm for d_e in 2015.
Estimated reach (S. Lamoreaux, PRA2002) ~10^{-30}ecm.
Studies on various ferro-electric substances.

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

Technology & Fields

- particle and neutron sources
- atom and molecular beam sources
- radioactive ion beams
- exotic molecules
- laser, trapping
- high voltage
- magnetometry & shields
- magnetic field control
- new materials
- ...

- Experiment&Theory of:
- particle physics
- neutron physics
- atomic physics
- nuclear physics
- molecular physics
- accelerator and beam physics
- solid state physics
- surface science
- chemistry
- ...

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- Experiment&Theory of:
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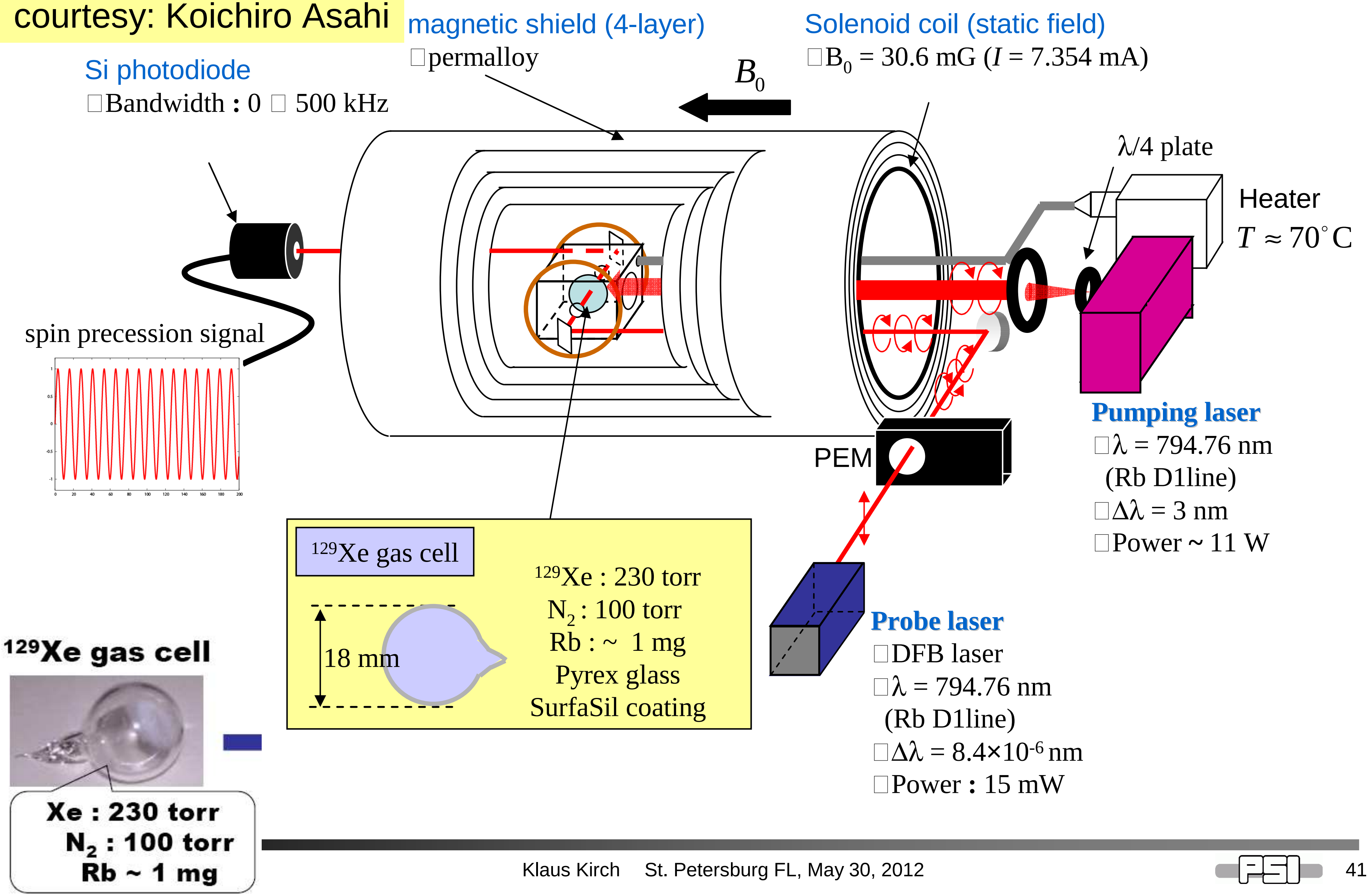
- nuclear physics
- molecular physics
- accelerator and beam physics
- solid state physics
- surface science
- chemistry
- ...

Major common issues (for different subsets):
- statistics and (cold) sources
- magnetic field homogeneity, gradients and stability
- state preparation and spin coherence times
- control of HV, noise, reversal, leakage currents
- stability of lasers, trapping, pumping
- motional fields, geometric phases, ...

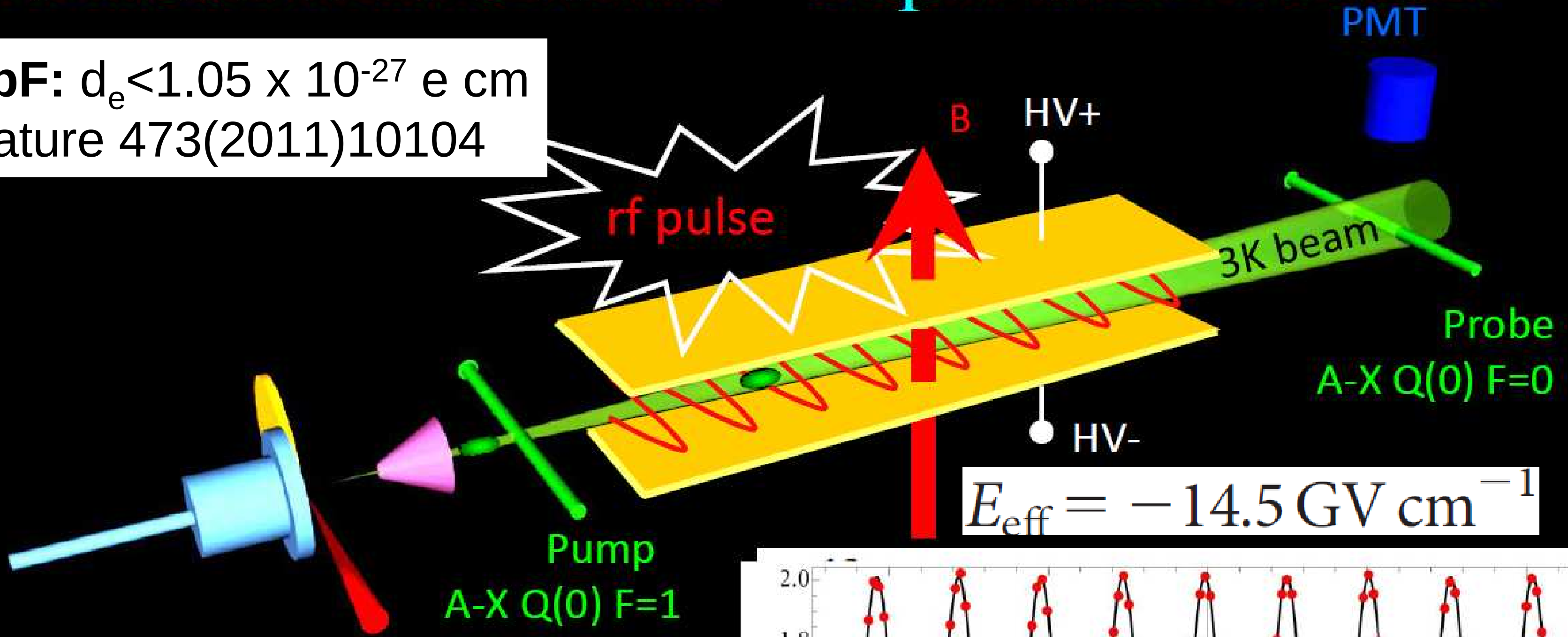
Setup for the spin oscillator experiment

Xe-EDM@TIT
courtesy: Koichiro Asahi

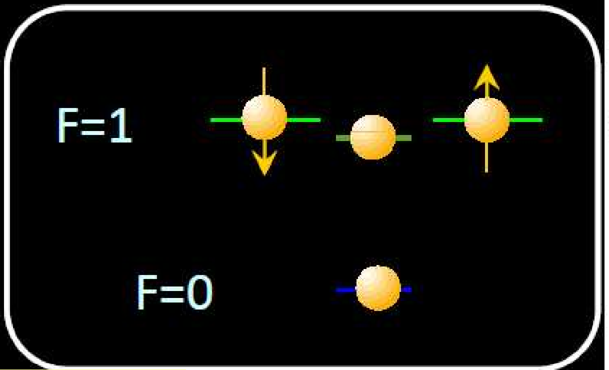


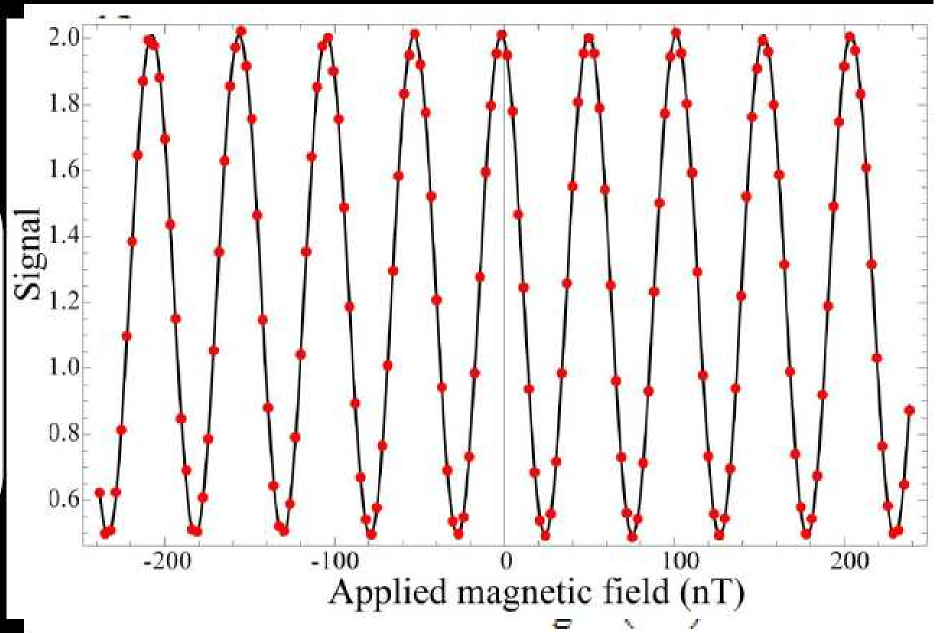
Measurement scheme – a spin interferometer

YbF: $d_e<1.05 \times 10^{-27}$ e cm
Nature 473(2011)10104



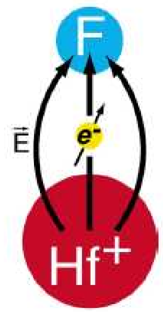
$$E_{eff} = -14.5\,\mathrm{GV\,cm}^{-1}$$





YbF-EDM@Imperial
courtesy: Ben Sauer

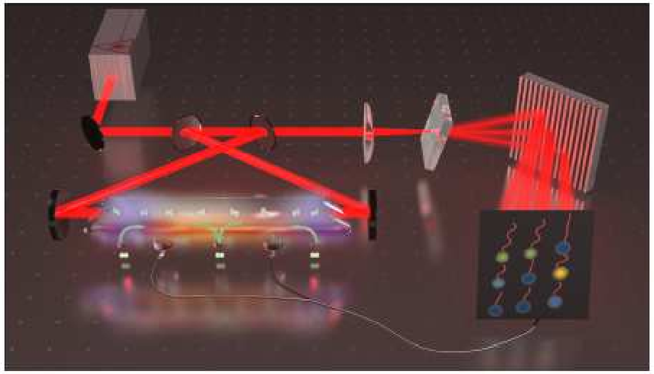
Trapped HfF^+ for a JILA eEDM search[1]



To reach current limit of $10.5*10^{-28}$ e-cm in 1 hour:

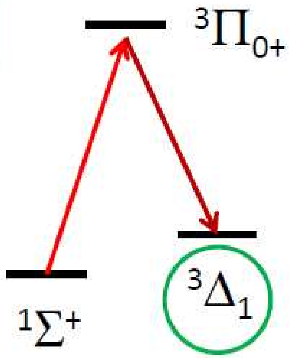
ε_{eff} ~ 24 GV/cm; $\tau_{coherence}$ = 0.25s; N = 2/shot

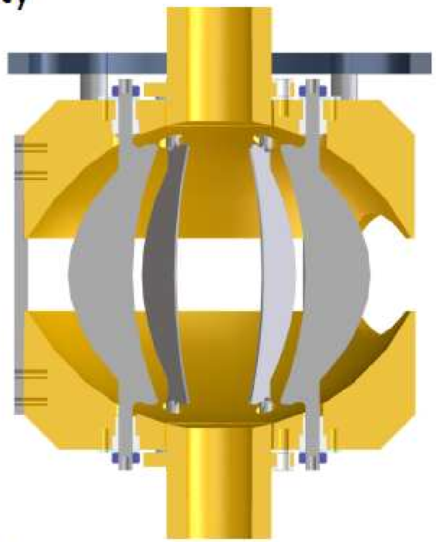
Current status:



- Prepared 300 ions in a single Zeeman, rovibronic level
- Trapped HfF^+ in RF Paul trap designed for fluorescence photon collection + field uniformity

- Mapped out HfF^+ energy levels up to 15000 cm^{-1}
- Identified promising transitions for population transfer to $^3\Delta_1$

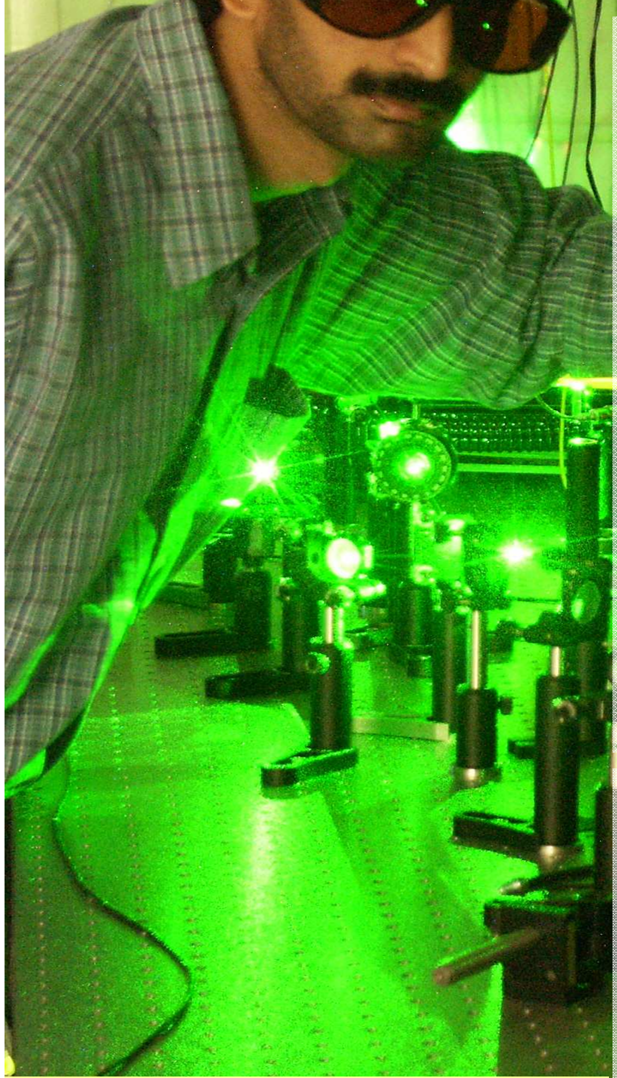


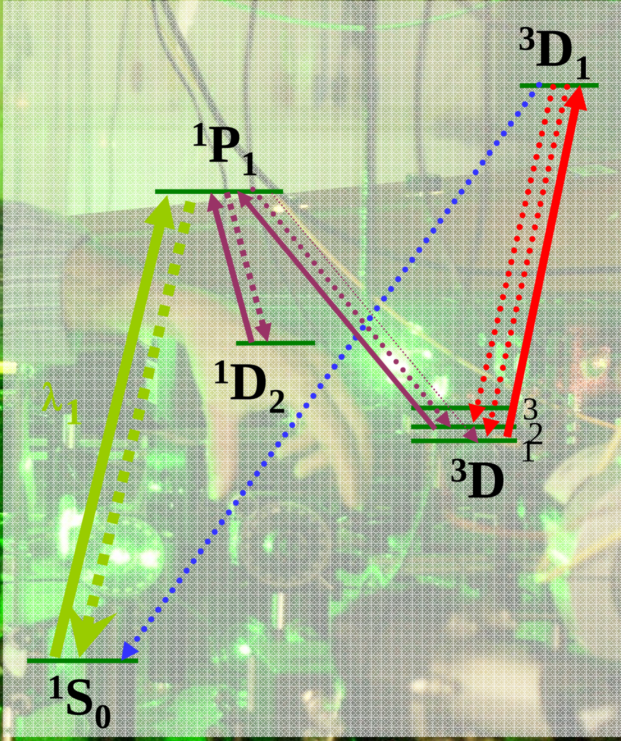


[1] JILA eEDM team, J Mol Spectrosc, 270, 1 (2011) and references therein

courtesy: Huanqian Loh, Eric Cornell

Laser cooling leaky systems: Barium

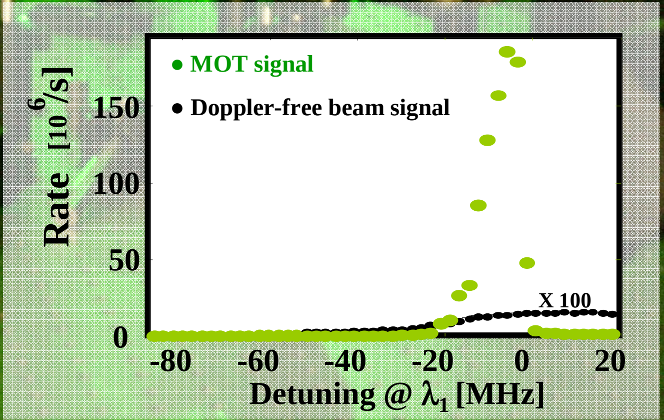


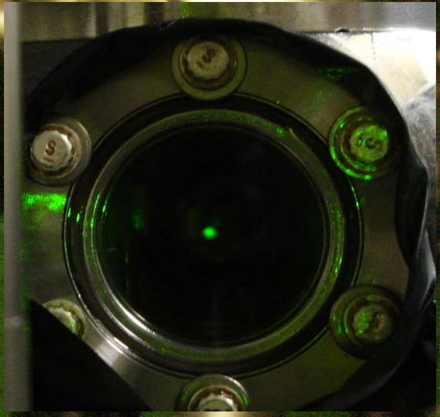


Multiple repump transitions

Efficient capture from atomic beam (>1%)

Radium similar level scheme. Laser cooling approach transferable





Ra-EDM@KVI
courtesy: Lorenz Willmann

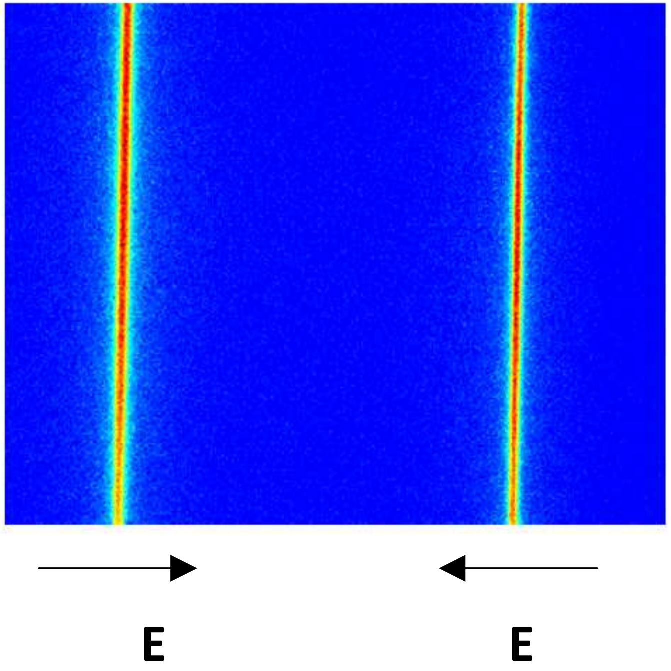
S. De et al., Phys. Rev. A 79 , 041402(R) (2009)

Search for the electron-EDM with cold Cs and Rb atoms in optical lattices

PENNSTATE

NSF

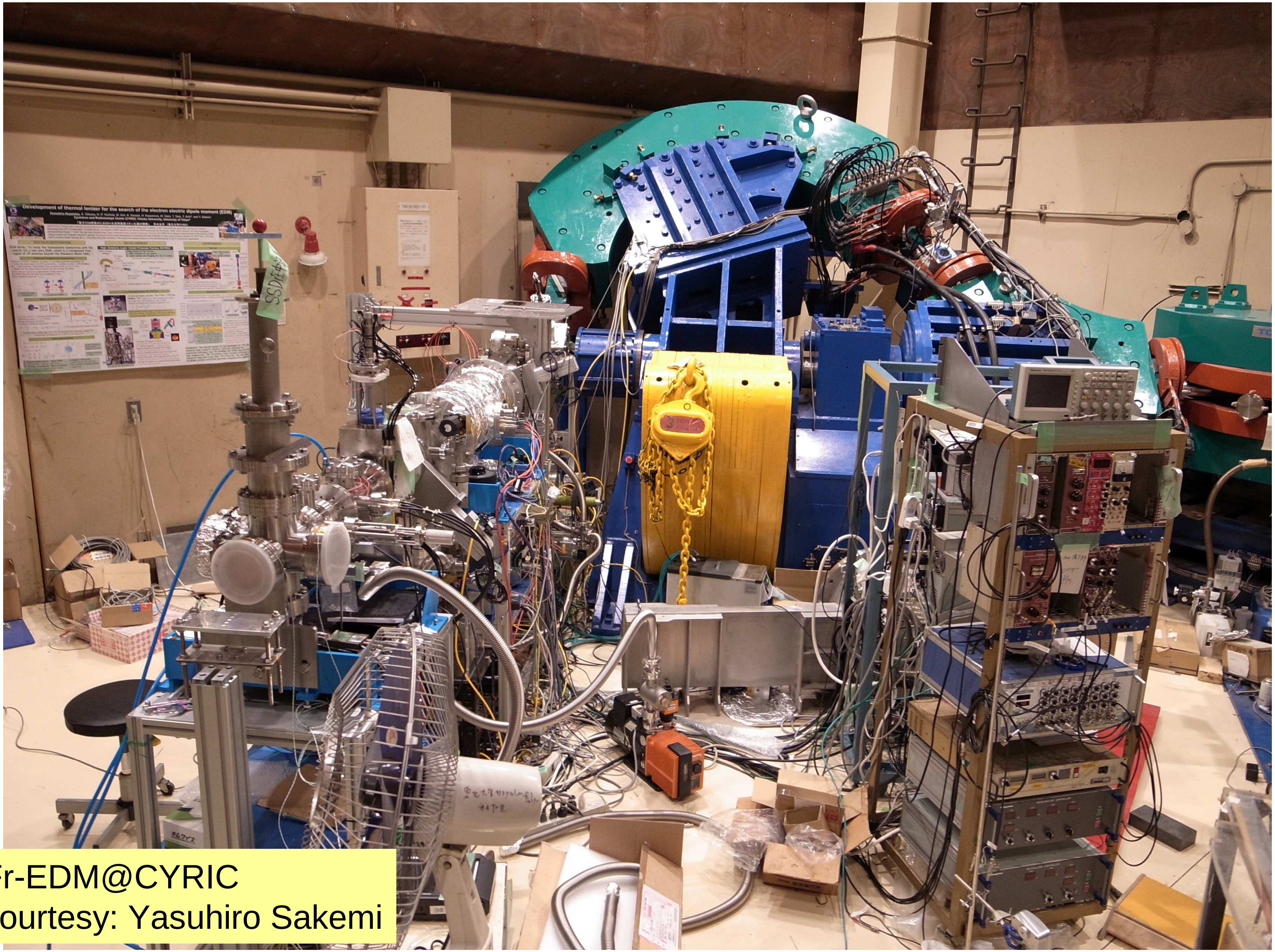
Kunyan Zhu, Neal Solmeyer, Cheng Tang and David Weiss



- Simultaneously measure with two opposite E-fields and minimal bias B-field.
- Use in situ measurements of 5 to 10 cm long linear arrays of atoms to cancel magnetic field gradients and monitor potential systematic errors.
- The atomic physics can be unraveled from a measurement with ~1% accuracy.
- Rb atoms provide an ultimate check on any Cs result.

We expect >200x improved sensitivity.

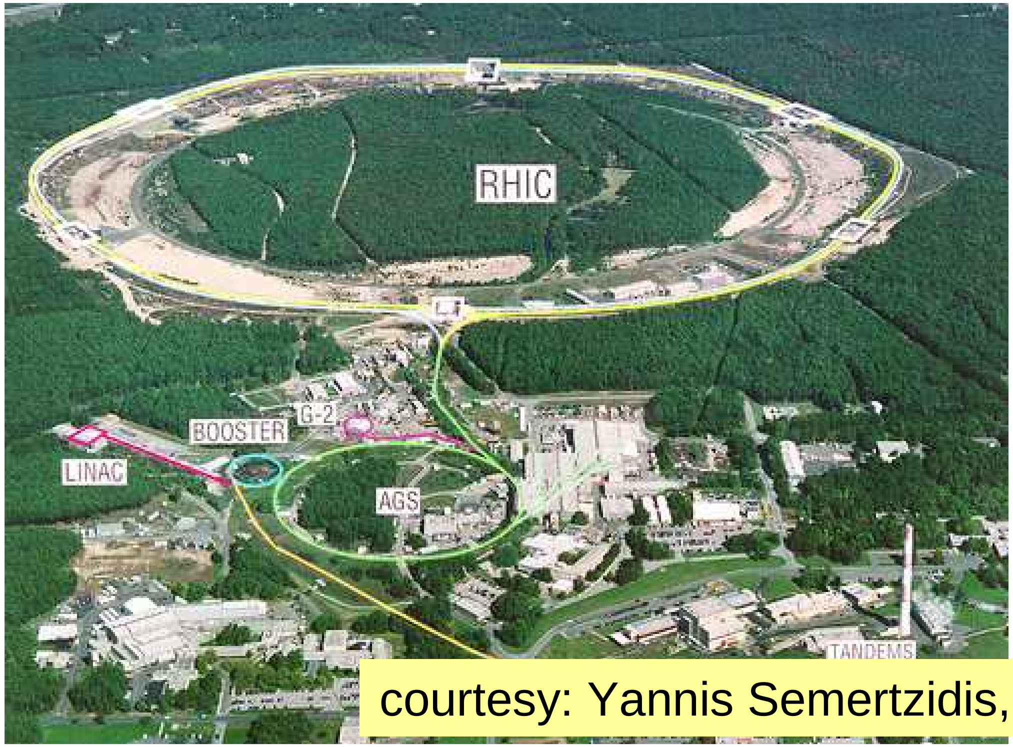
courtesy: David Weiss



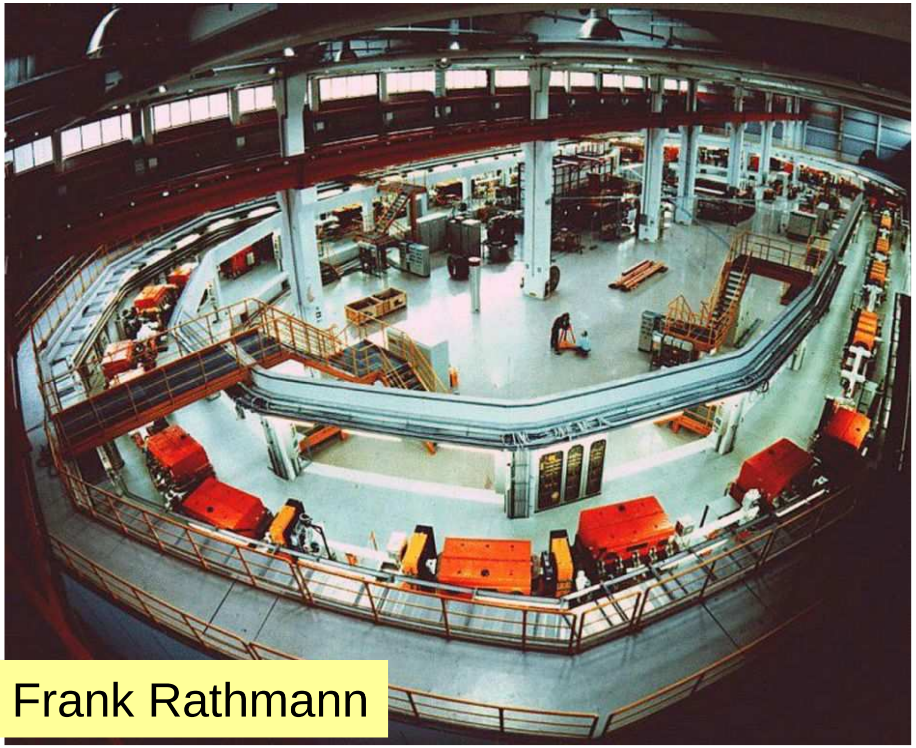
Fr-EDM@CYRIC
courtesy: Yasuhiro Sakemi

Labs to host S.R. EDM experiments

- BNL, USA:
  proton “magic” ring



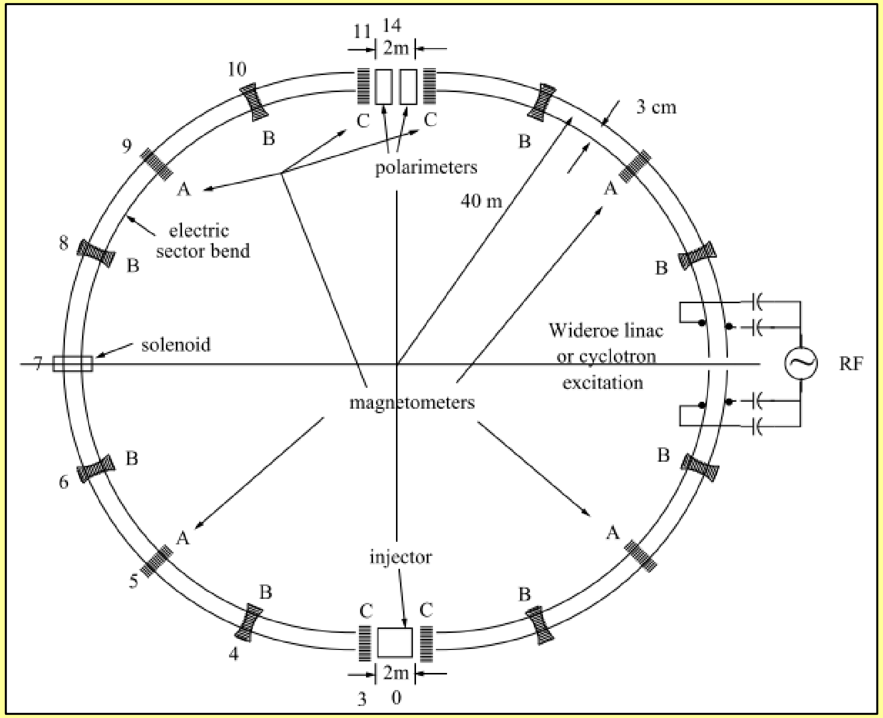
- COSY, Jülich/Germany
  deuteron ring: JEDI



courtesy: Yannis Semertzidis, Frank Rathmann

Two storage ring projects being pursued

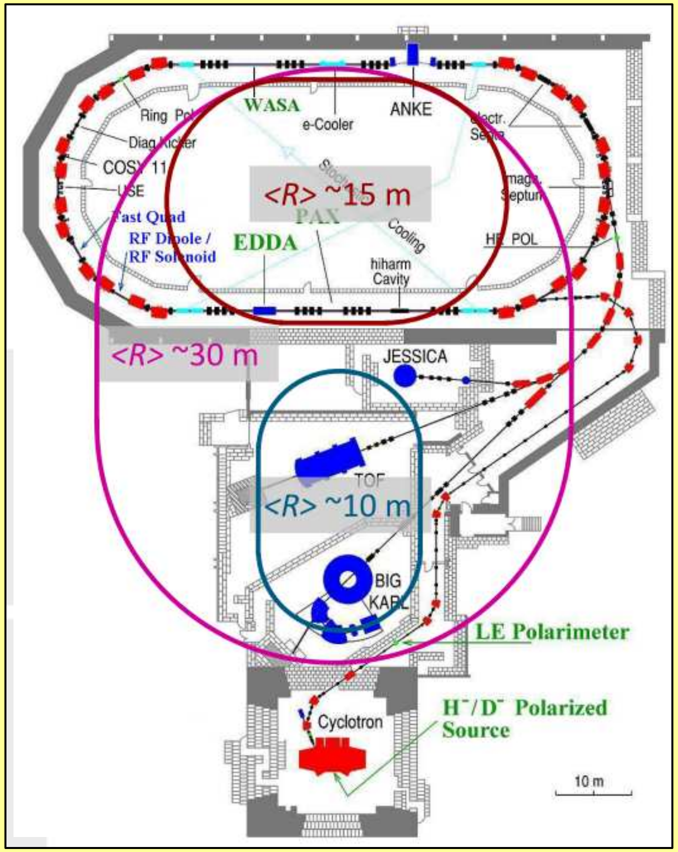
BNL for protons all electric machine



CW and CCW propagating beams

(from R. Talman)

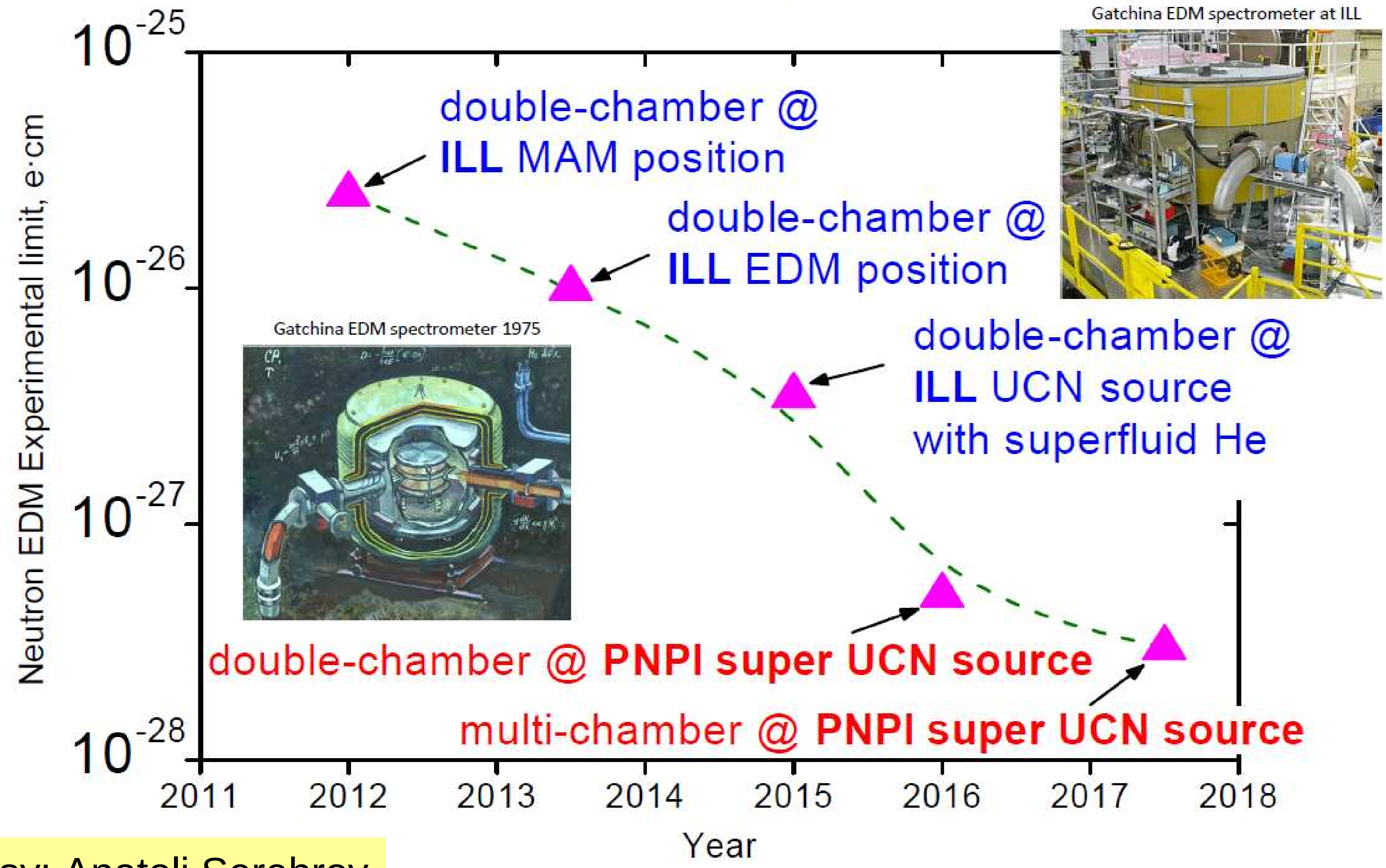
Jülich, focus on deuterons, or a combined machine



(from A. Lehrach)

PNPI-ILL-PTI collaboration

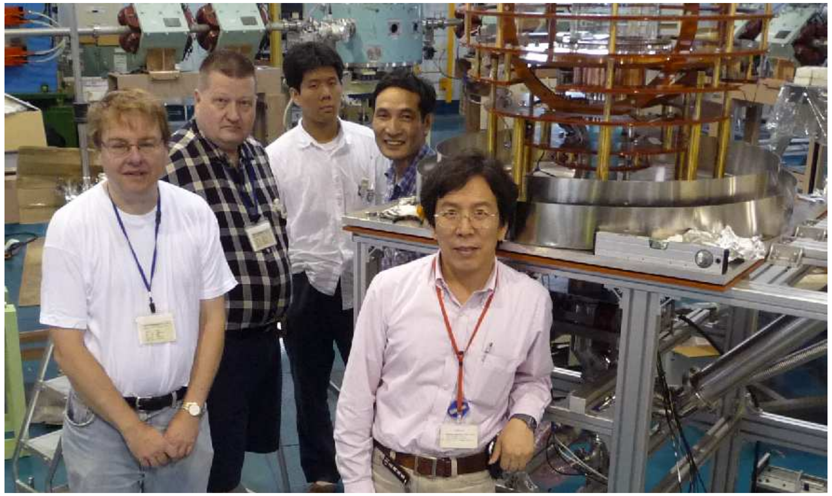
Prospects to increase sensitivity of EDM measurements

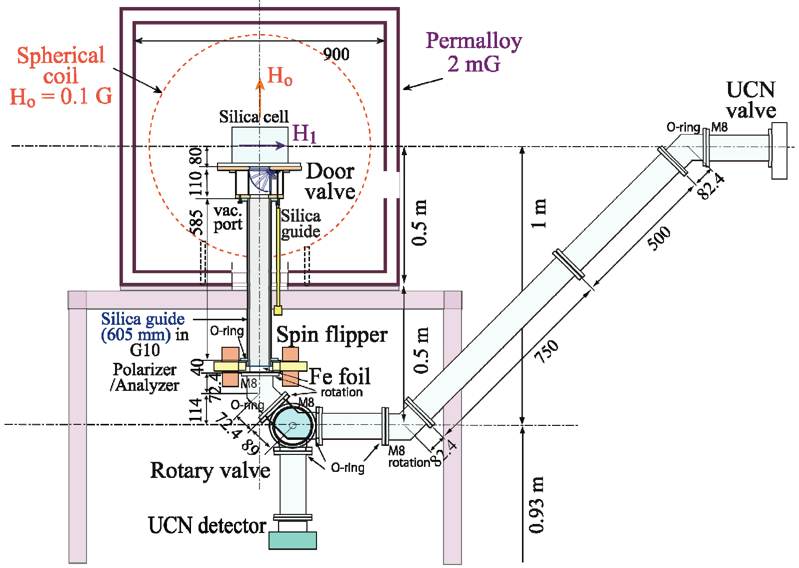


courtesy: Anatoli Serebrov

Japan-Canada nEDM experiment

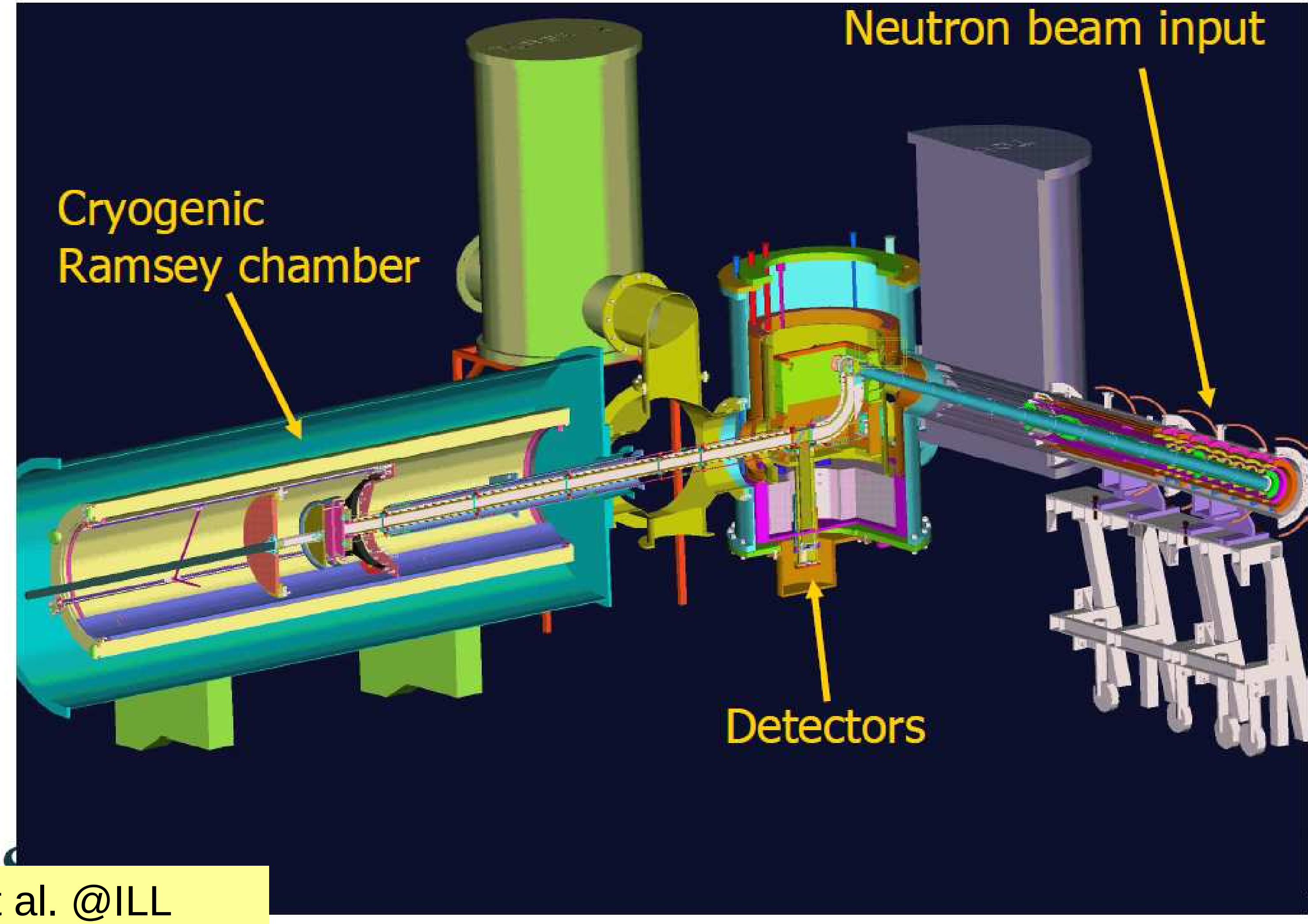
- Spherical coil for DC field
- Xe-129 nuclear-spin buffer-gas comagnetometer
- Room-temp experiment, keeping EDM cell size small, anticipating gains in UCN density
- Modern magnetic shielding, cost reduced with cell size
- Superfluid He-4 UCN source
- Basic prototype in operation





courtesy: Yasuhiro Masuda, Jeff Martin

CryoEDM overview

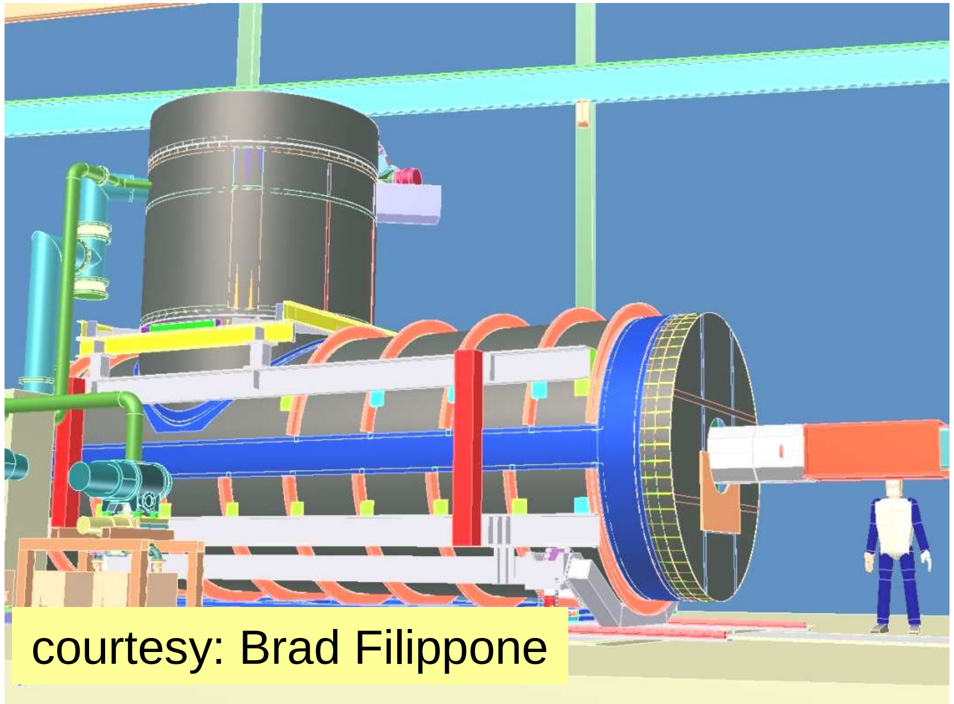


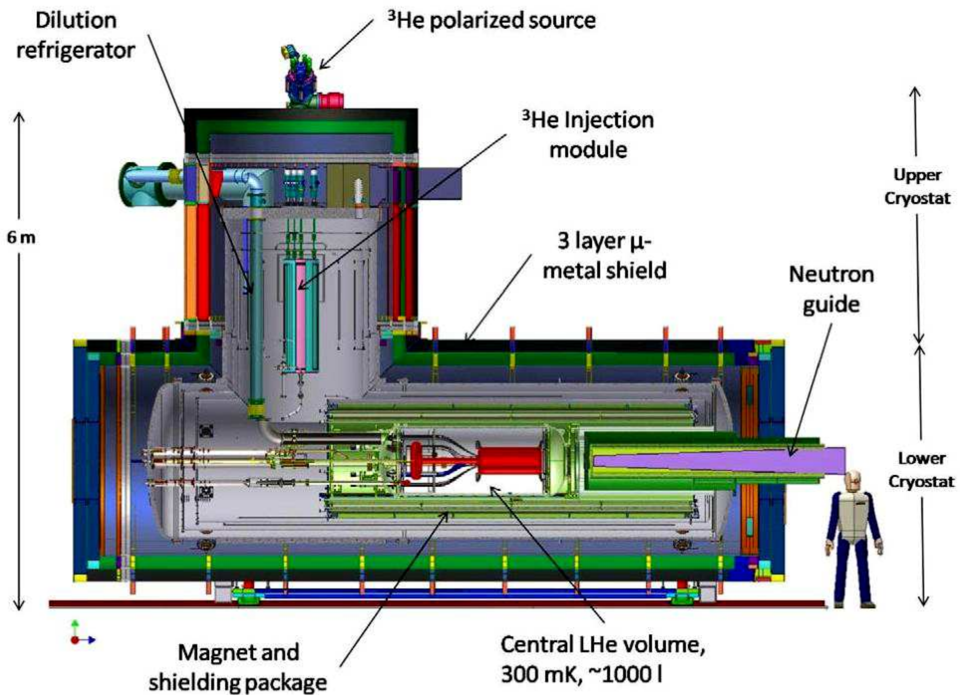
Sussex et al. @ILL
courtesy: Philipp Harris

Neutron EDM @ SNS

1 Arizona State University
2 Brown University
3 Boston University
4 University of California, Berkeley
5 California Institute of Technology
6 Duke University
7 Harvard University
8 Indiana University
9 University of Illinois, Urbana-Champaign
10 University of Kentucky
11 Los Alamos National Laboratory
12 Massachusetts Institute of Technology
13 Mississippi State University
14 North Carolina State University
15 Oak Ridge National Laboratory
16 Simon Fraser University
17 University of Tennessee
18 Valparaiso University
19 University of Virginia

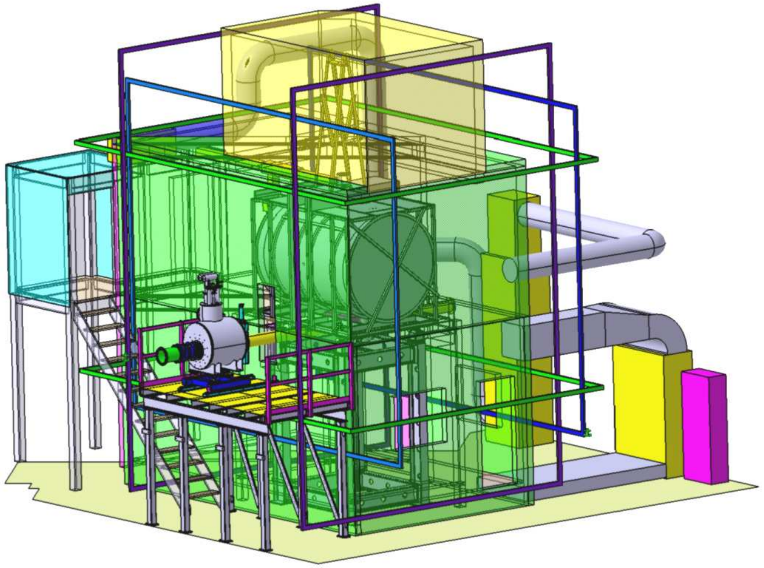
Aiming at sensitivity of 3×10^{-28} e cm, construction ends 2018

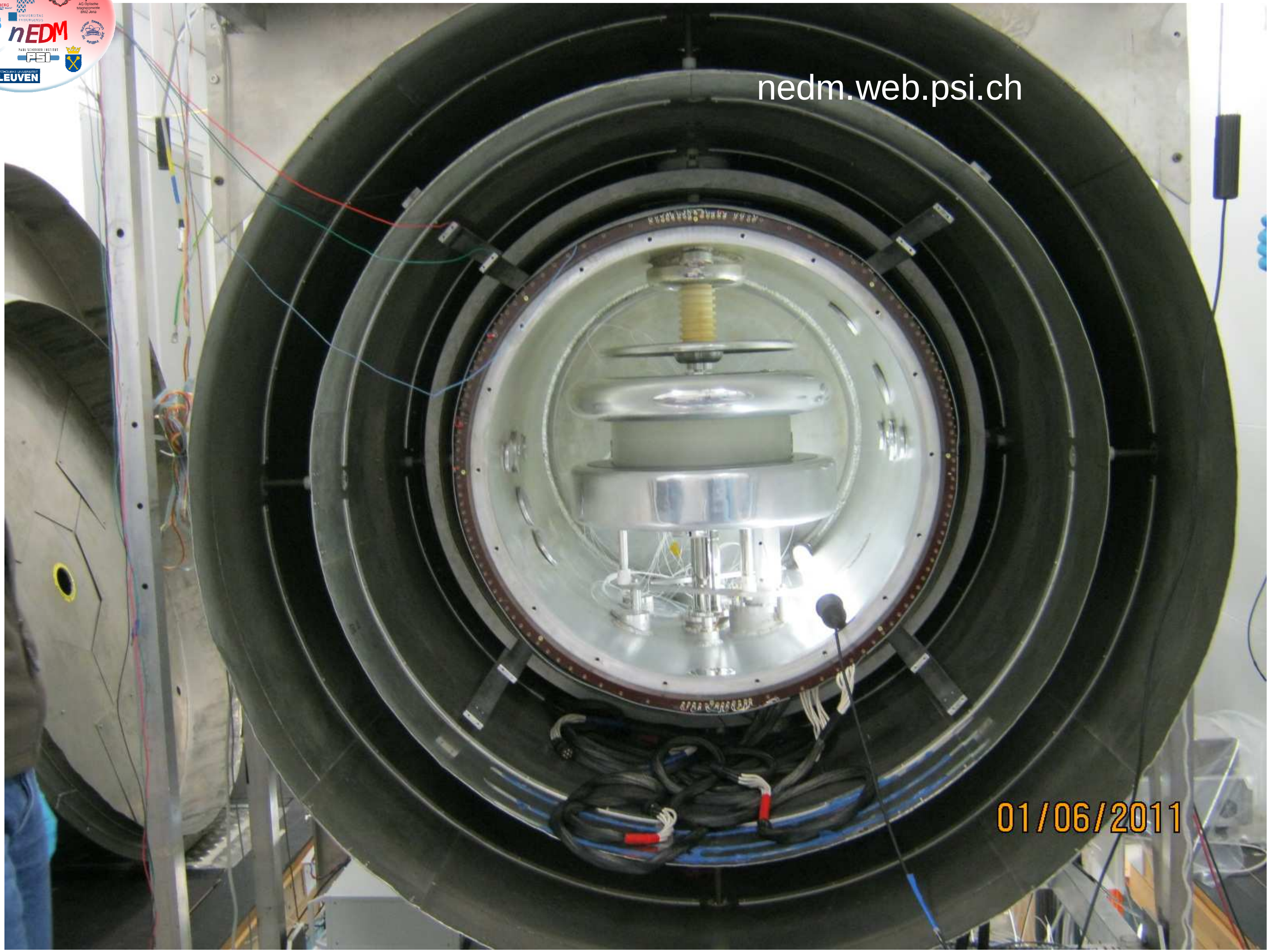




Installing nEDM at PSI in 2009

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

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01/06/2011