Technische Universität München

# Electric dipole moment searches

Peter Fierlinger

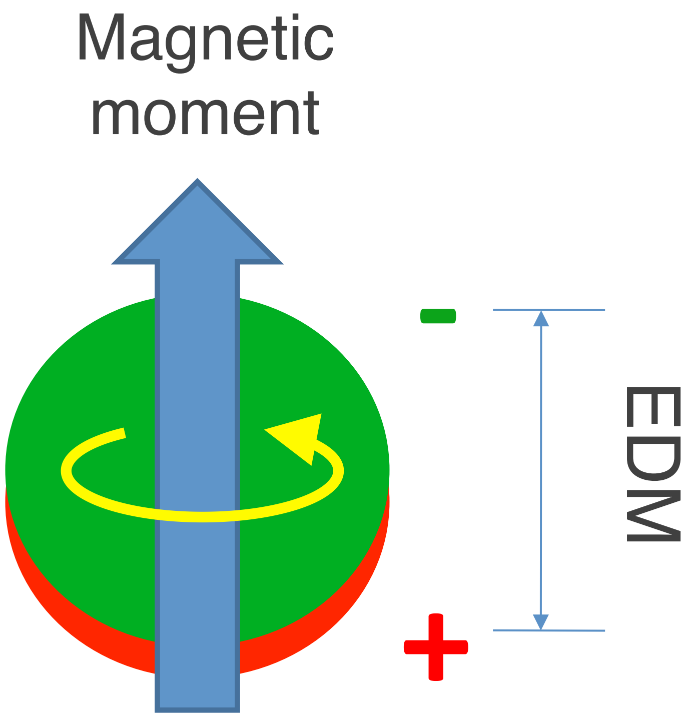
# Outline

Motivation

Different systems to search for electric dipole moments (EDMs)

Examples

# Electric dipole moment



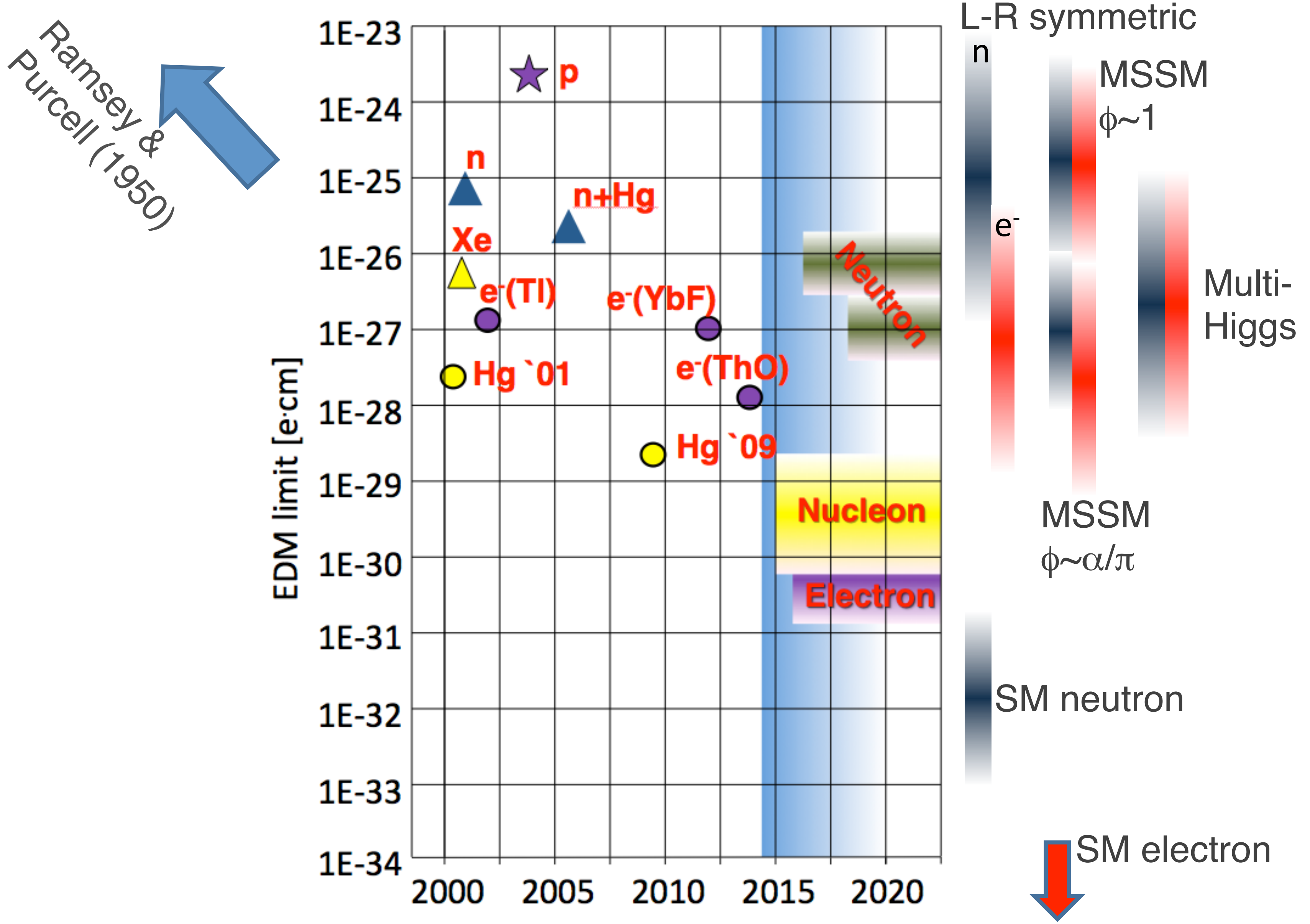

$$H = -\mu \mathbf{B} \cdot \frac{\mathbf{S}}{S} - d\mathbf{E} \cdot \frac{\mathbf{S}}{S}$$

A non-zero particle EDM violates T
(time reversal symmetry)

Purcell and Ramsey, PR78(1950)807

… assuming CPT conservation,
also CP is violated

# History



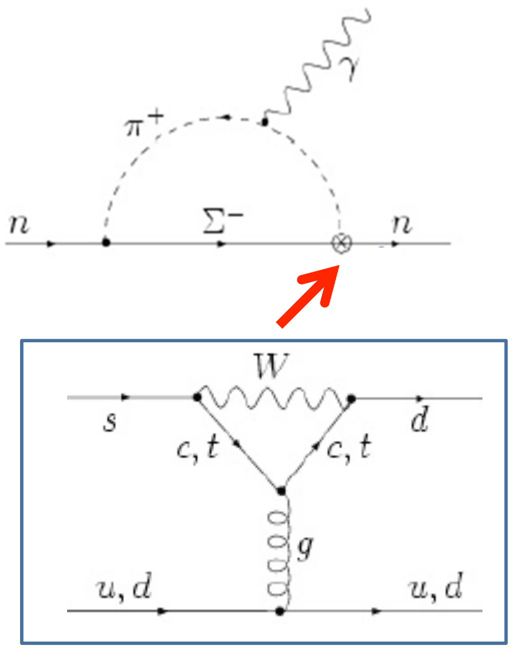
Ramsey & Purcell (1950)
EDM limit [e·cm]
1E-23
1E-24
1E-25
1E-26
1E-27
1E-28
1E-29
1E-30
1E-31
1E-32
1E-33
1E-34
2000
2005
2010
2015
2020
p
n
n+Hg
Xe
e-(Tl)
e-(YbF)
Hg `01
e-(ThO)
Hg `09
Neutron
Nucleon
Electron
L-R symmetric
n
e-
MSSM
φ~1
Multi-Higgs
MSSM
φ~α/π
SM neutron
SM electron

# Neutron EDM and the SM

Khriplovich Zhitnitsky (1986), McKellar et al., (1987)

M. Pospelov, et al., Sov. J. Nucl. Phys. 53, 638 (1991)

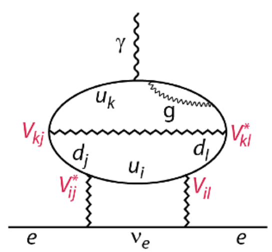
## CP violation from CKM




Neutron EDM $d_n \approx 10^{-32}$ ecm

More complex calcuations may be required:
T. Mannel, N. Uraltsev, Phys.Rev. D85 (2012) 096002

Side note: $d_{electron} < 10^{-38}$ ecm…




## Strong Interaction

CP-odd term in Lagrangian:

$$L_\theta = \bar{\theta} \frac{\alpha_s}{8\pi} G\tilde{G}$$

$$d_n(\bar{\theta}) \sim \bar{\theta} \frac{e}{m_n} \frac{m_*}{\Lambda_{QCD}} \sim 6.10^{-17} \bar{\theta} e \cdot cm$$

$$\bar{\theta} < 10^{-10}$$

Strong CP problem

E.g. Pospelov, Ritz, Ann. Phys. 318(2005)119

# Baryon asymmetry

**Observed:** $n_B / n_\gamma \sim 6 \times 10^{-10}$ **(BBN, CMB)**

e.g. astro-ph/0603451

**Expected:** $n_B / n_\gamma \sim$ **MUCH smaller**

## ‚Ingredients' to model baryogenesis: Sakharov criteria

JETP Lett. 5 (1967) 24

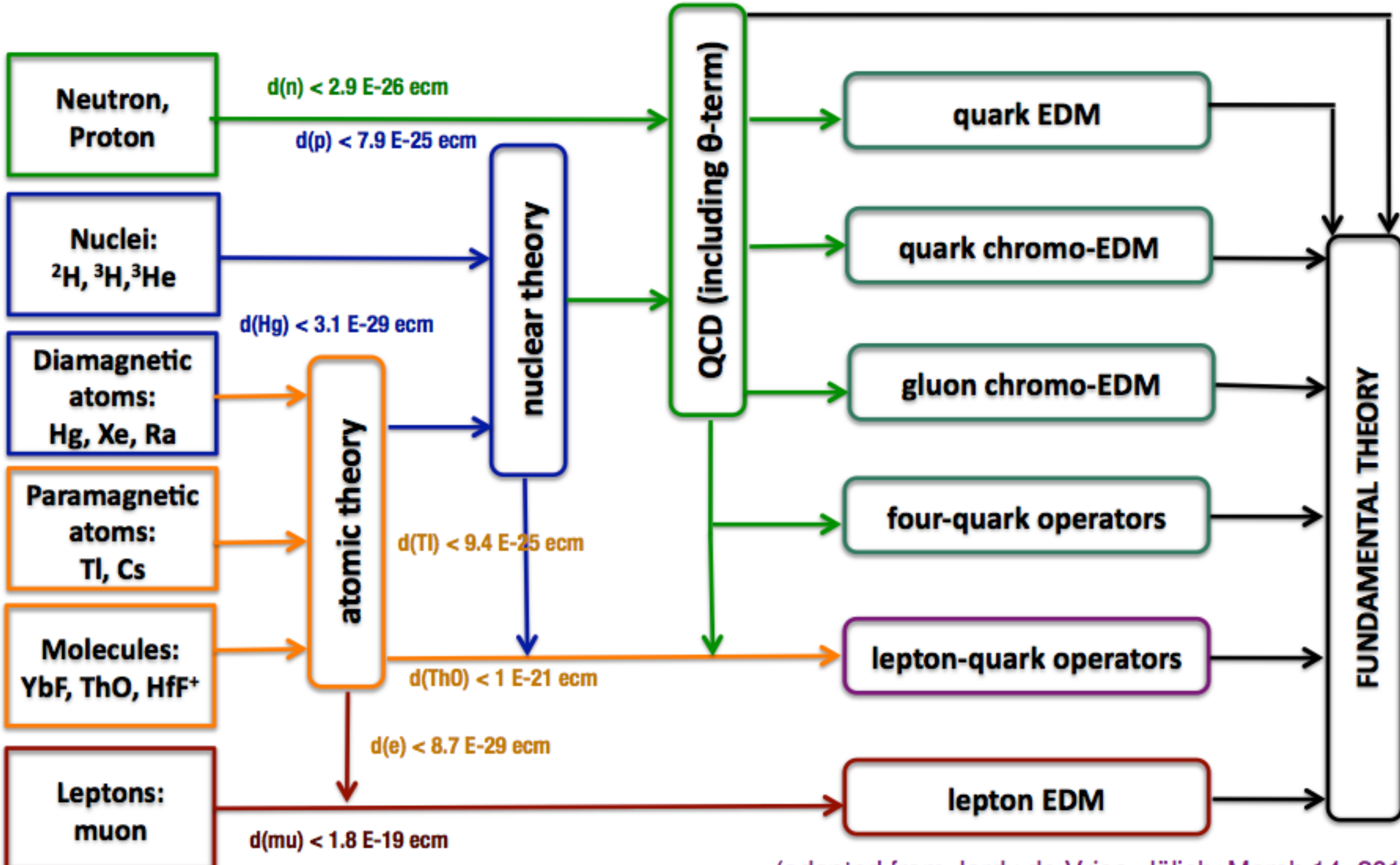
## Remarks:

- Beyond-SM physics usually requires large EDMs
- EDMs and Baryogenesis via Leptogenesis?
- Also other options w/o new CP violation possible (Kostelecky, CPT)
- SUSY: small CPV phases, heavy masses, cancellations?
- What do we learn from an EDM?

Different measurements are needed!

e.g. Cirigliano, Profumo, Ramsey-Musolf JHEP 0607:002 (2006)

# Physics behind EDMs



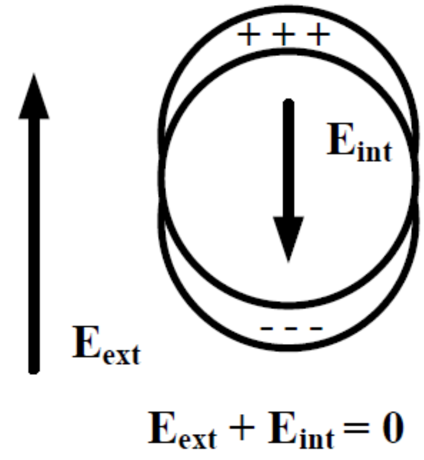

See also e.g. Pospelov, Ritz, Ann. Phys. 318(2005)119

(adapted from Jordy de Vries, Jülich, March 14, 2013)

# Atom EDM

## Schiff moment:

Non-perfect cancellation of $E_{ext}$ in atomic shell

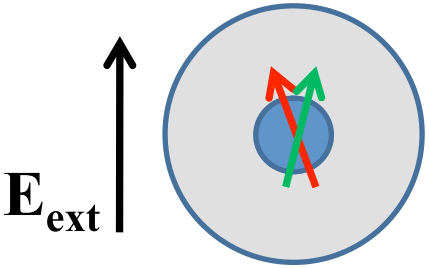



L. Schiff, Phys. Rev. 132, 2194 (1963)

Paramagnetic atoms ~ electron EDM
Relativistic effects

$$d_a \propto d_e Z^3$$ Sandars, 1968

Diamagnetic atoms ~ nuclear EDM
Finite size of nucleus violates Schiff‘s theorem




$$d_a \propto d_{nucl} Z^2$$

Schiff 1963; Sandars, 1968;
Feinberg 1977; ... - 2010


Large enhancements also with deformed nuclei
(Ra, Rn, also Fr, Ac, Pa)

# Atomic effects

## Contributions to atomic EDMs:

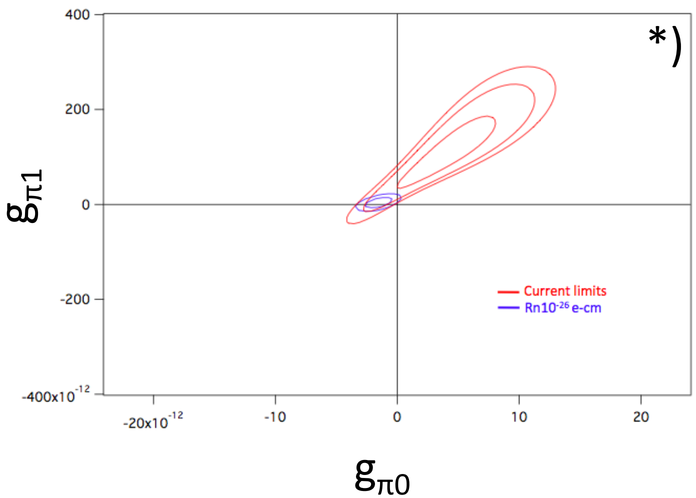
$$d_A = (k_T C_T + k_S C_S) + \eta_e d_e + \kappa_S S + \text{ h.o. (MQM)}$$

- 13 (model-dependent) parameters
  TeV-scale CP odd physics, nucleon level, nucleus-level
- Only 8 types of experiments

Illustration: T. Chupp et al., to be published

| | $\theta_{QCD}$ | $d_n^0$ | $d_n^1$ | $C_T$ | $g_\pi^0$ | $g_\pi^1$ |
|---|---|---|---|---|---|---|
| neutron | x | 1 | -1 | | | |
| Xe, Hg, TlF | x | | | x | x | x |
| Ra, Rn | x | | | x | x | x |
| proton | x | 1 | +1 | | | |
| d, $^3$H, $^3$He | x | | | | x | x |

**Schiff Moment**




$$S = g_{\pi NN}(a_0 \bar{g}^0_{CP} + a_1 \bar{g}^1_{CP} + a_2 \bar{g}^2_{CP})$$

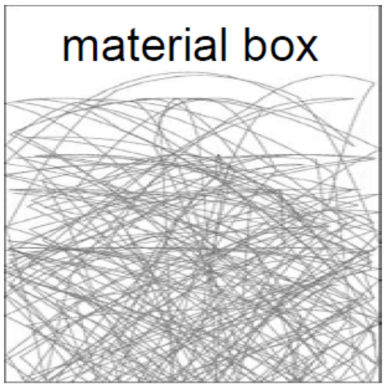
$$d_n \approx \bar{d}_n + (1.44 \times 10^{-14} g_\pi^{(0)} - 8.3 \times 10^{-16} g_\pi^{(1)}) \text{ e} - \text{cm}$$

$$\bar{g}^0_{CP} \approx 0.027\, \theta_{QCD}$$

See also J. Engel, M. J. Ramsey-Musolf, U. van Kolck, Prog. Part. Nucl. Phys. 71, 21 (2013)

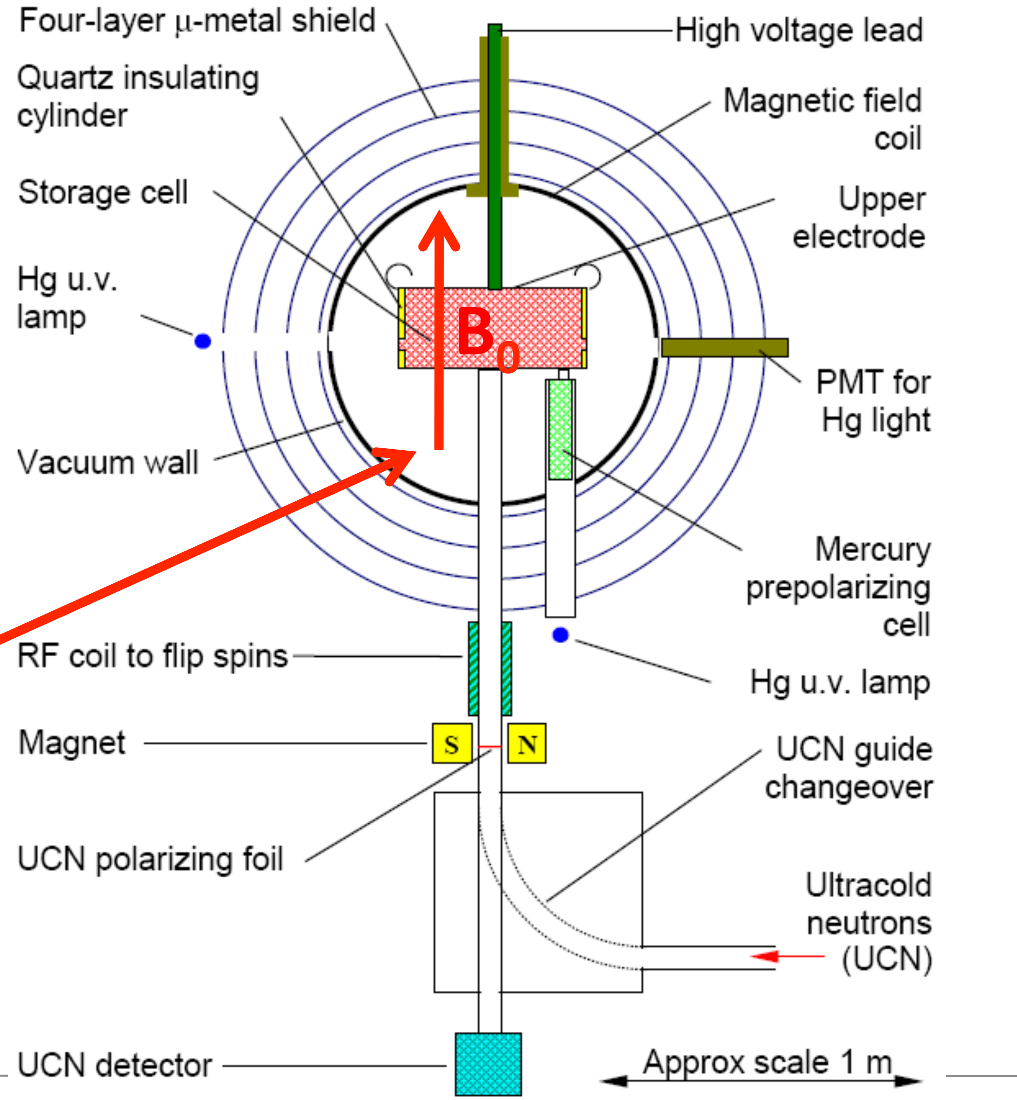
# Measuring the neutron EDM

## Ultra-cold neutrons (UCN) trapped at 300 K in vacuum



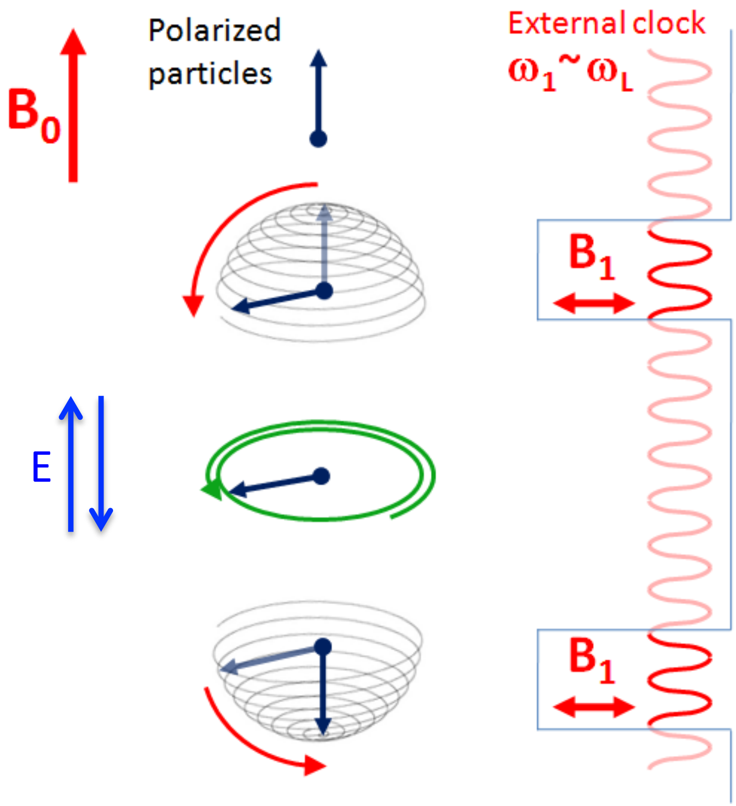

$E_{kin} < 250$ neV
$\lambda > 50$ nm
T ~mK
Storage ~ $10^2$ s

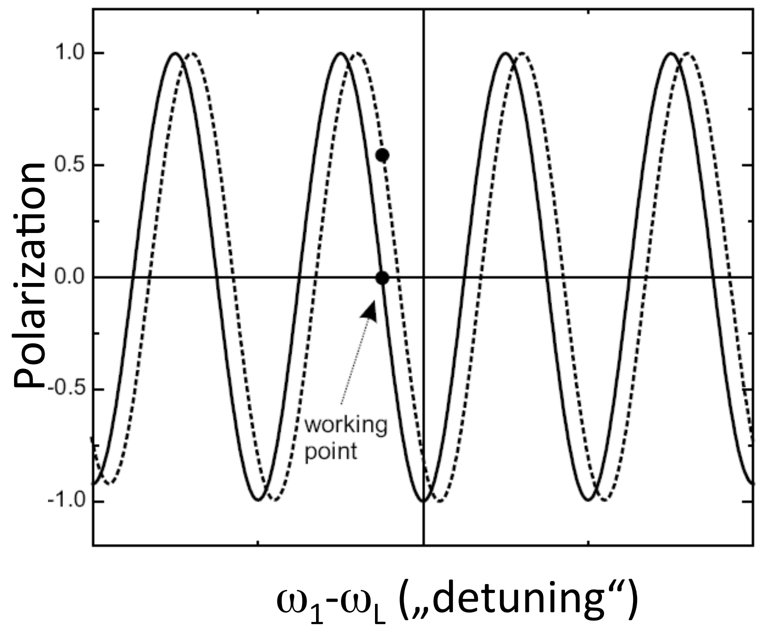

(RAL/SUSSEX/ILL experiment)



# Ramsey's method

Particle beam or trapped particles




$$\sigma_{d_n} = \frac{h}{2\alpha ET\sqrt{N}}$$

EDM changes frequency:

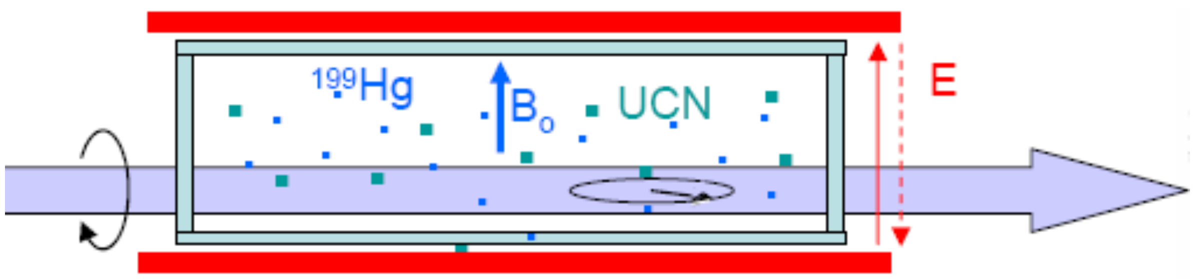
$$\hbar\omega_L \sim \mu B + dE$$

# Clock-comparison experiment

- Neutrons and $^{199}$Hg stored in the same chamber

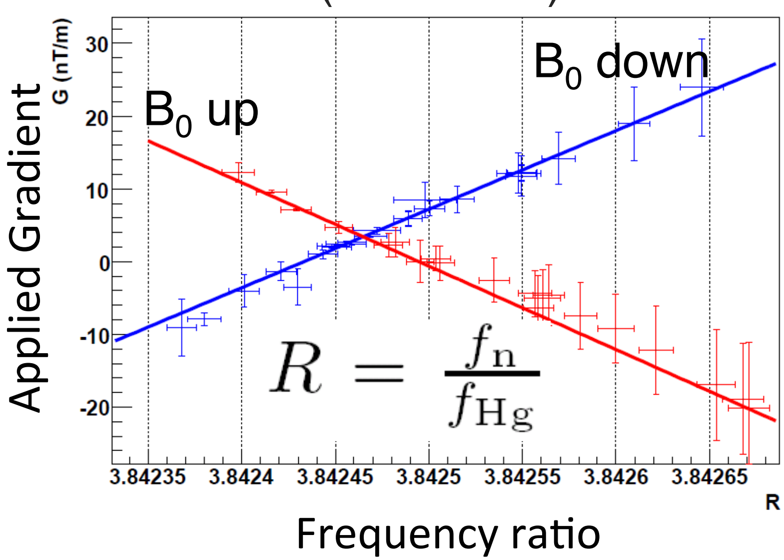
- Gravity changes center of mass!

B =1 μT ( + small vertical gradient)




Physical Review Letters 97 (2006) 131801.

Illustration (2008 data)




**Analysis using the gradient:**

$$d_n < 2.9 \times 10^{-26}\ e\ cm$$

Requirement: $^{199}$Hg-EDM must be small:
(btw., this also limits other parameters, e.g $C_S$, $C_T$...):

$$d_{Hg} < 3.1 \times 10^{-29}\ e\ cm$$

Hg-EDM: W. C. Griffith et al., PRL 102, 101601 (2012)

# Neutron and proton experiments

| nEDM | Method | Goal (x$10^{-28}$ ecm) | Comments |
|---|---|---|---|
| Cryo EDM | 4He | 1. ~ 50; 2. < 5 | CANCELED in 2014 |
| ILL Crystal EDM | Solid | < 100 | Diffraction in crystal: large E |
| FRM-II EDM | sD2 | < 5 | Adjustable UCN velocity |
| JPARC | sD2 | < 10 | Special UCN handling |
| NIST Crystal | Cold beam | < 10 | R&D |
| PNPI/ILL | Turbine | 1. ~ 100; 2. < 10 | E = 0 reference cell |
| PSI EDM | sD2 | 1. ~ 50; 2. < 5 | Phase 1 takes data |
| SNS EDM | 4He | < 5 | Sophisticated technology |
| TRIUMF/RNPC | 4He | < 10 | Phase II at TRIUMF |

| pEDM | | | |
|---|---|---|---|
| Jülich | B and E field ring | 1. R&D; 2. $10^{-24}$; 3. $10^{-29}$ | Stepwise improvements |
| BNL | Electrostatic ring | $10^{-29}$ | Completely novel technology |

# ‚Current generation‘ improvements

PSI (adapted from B. Lauss, K. Kirch, 2013)

UCN density measured in a 25l volume
extrapolated to t=0
at PSI area West-1

| | |
|---|---|
| 2010 | ~0.15 UCN/cm3 |
| 2011 | ~18 UCN/cm3 |
| 2012 | ~23 UCN/cm3 |

⇒ correct for detector foil transmission
status (4/2013) >33 UCN/cm3 in storage experiment (-> this is an extrapolation)

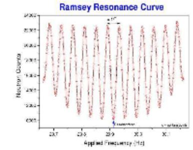
< 2 UCN/cm3 in EDM experiment

## Statistical Sensitivity

projected (and as of Nov. 2012)

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

Ramsey Resonance Curve



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
$d_n = 0$: $|d_n| < 4 \times 10^{-27}$ ecm (95% C.L.)

* 200 nights each

PNPI/ILL (adapted from A. Serebrov, 2013):

**UCN density 3-4 ucn/cm$^3$ (MAM position)**

**Electric field 10 kV/cm**

**T(cycle) = 65 s**

**$\delta D_{edm}$ ~ $5\cdot10^{-25}$ e·cm/day**

**...new electric field 20 kV/cm**

**$\delta D_{edm}$ ~ $2.5\cdot10^{-25}$ e·cm/day**

**~ 2014: EDM position at PF2**

**$1\cdot10^{-26}$ e·cm/100 days**

# ‚Next generation'

Pendlebury et al., Phys. Rev. A **70**, 032102 (2004)

## Most critical systematic effect for next generation experiments:

$$\Delta\omega = \frac{\omega_{xy}^2}{2(\omega_0 - \omega_r)}$$

$$\omega_{xy}^2 = \left(\frac{\partial B_{0z}}{\partial z}\alpha\right)^2 + \left(\frac{E\times v}{c^2}\right)^2 + \boxed{2\frac{\partial B_{0z}}{\partial z}\alpha \cdot \frac{E\times v}{c^2}}$$

Magnetic field requirements for $10^{-28}$ ecm – level accuracy:

~ fT field drift error,

~ < 0.3 nT/m avg. gradients

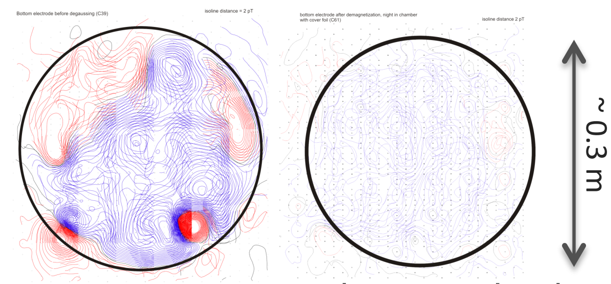
$d_f \sim 4 \cdot 10^{-27}$ ecm ($^{199}$Hg geom. phase)

$d_n \sim 1\text{-}2 \cdot 10^{-28}$ ecm (UCN geom. phase)

**Statistics:** $10^3$ UCN/cm$^3$ ~ 1 year

Example:
Dipole fields in EDM chambers

SQUID measurements of Sussex EDM electrodes @ PTB Berlin




200 pT pp

demagnetized: 20 pT pp

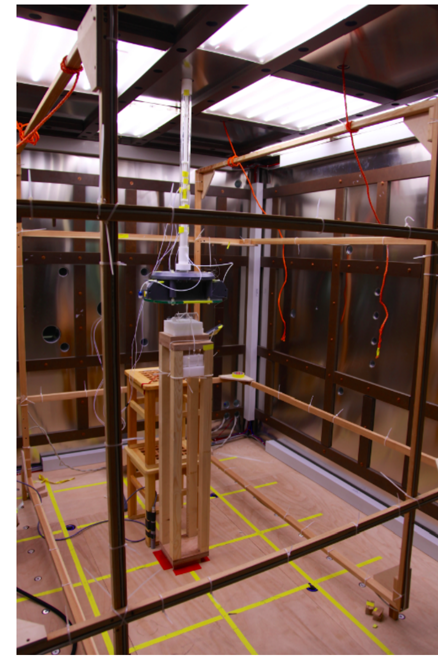
20 pT in 3 cm ~ 5 x error budget!

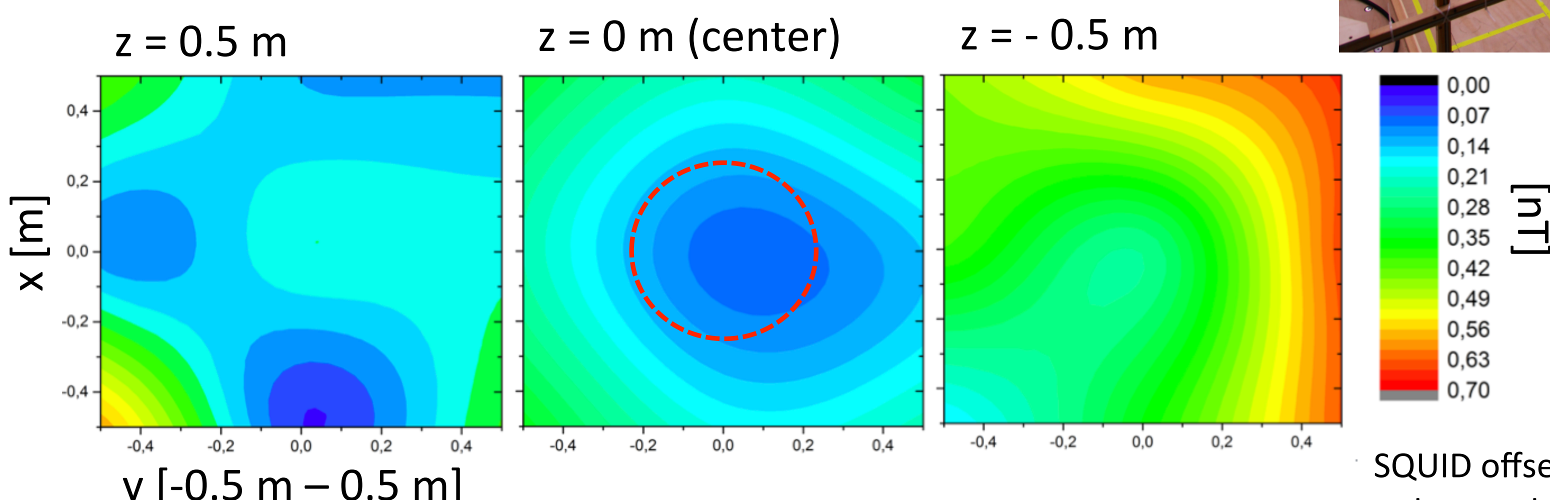
Further: P. G. Harris et al., Phys. Rev. A 73, 014101 (2006); G. Pignol, arXiv:1201.0699 (2012); A. Steyerl, PRA (2014)

# Magnetic fields

## The smallest extended size field and gradient on earth

- < 100 pT/m gradient in 0.5 m$^3$
- At FRM-II EDM setup: fields designed and measured - this technology is ready and available!





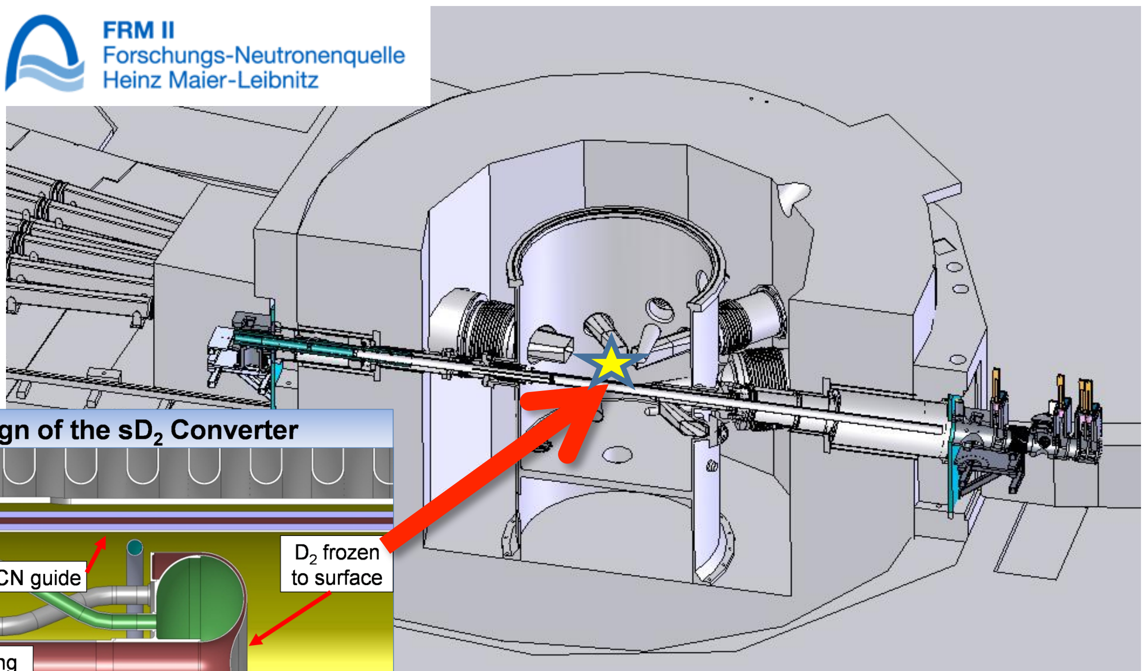

SQUID offset in z not corrected

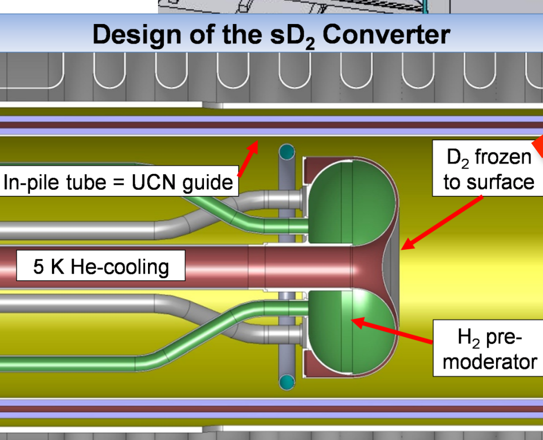
# New sources of UCN

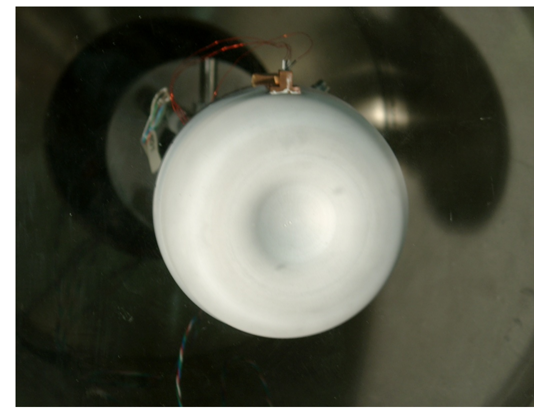
## Superthermal solid $D_2$ or superfluid $^4$He-II

**$sD_2$:** Molceular excitations used to cool neutrons to zero energy - similar: **ILL, LANL, Mainz,** NCSU, PNPI, PSI, TUM …

**$^4$He:** **ILL**, KEK, SNS, TRIUMF, …



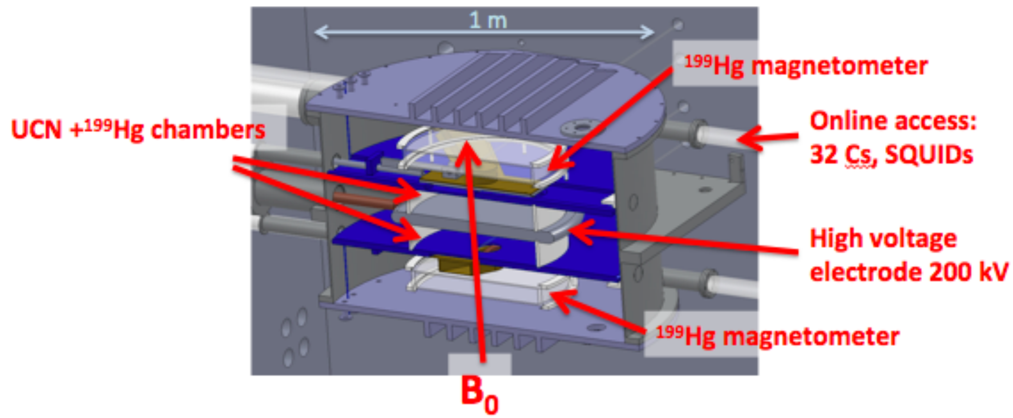
Goal of most sources:

**$10^3$ UCN /cm$^3$ in experiment**

# Next generation experiments

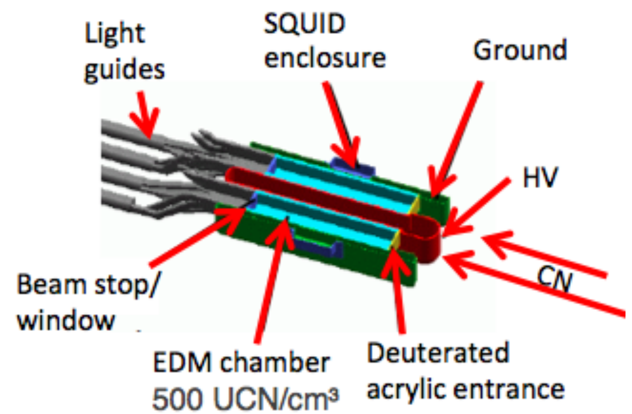
## E.g. at FRM-II (reactor):

- ‚Conventional', double chamber
- UCN velocity tuning
- SQUIDs, Cs, $^{3}He$, $^{199}Hg$, $^{129}Xe$ (co)magnetometers
- Measurements at FRM and ILL




## E.g. at SNS (spallation):

- Cryogenic, double chamber
- Neutron detection via spin dependent $^{3}He$ absorption and scintillation
- $^{3}He$ co-magnetometry




**In the future... again nEDM with a cold beam?**

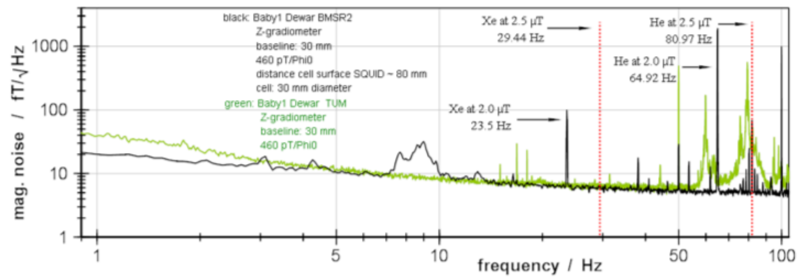
Pulse structure and strong peak flux:

- Cold-beam-EDM at long-pulse-neutron source (ESS) could be competitive? (Piegsa, PRC)
- Re-accelerated polarized UCN with pulse-structure?
- Large-scale neutron interferometer?

# TUM EDM overview

SLOW NEUTRONS
DFG SPP 1491

EDM




3He/129Xe EDM measurements in 'outer' part of the experiment

**Work at FRM-II:**

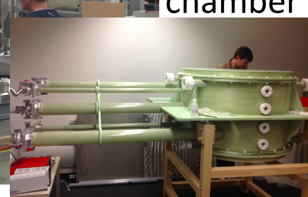
- Ongoing noble gas EDM measurement
- Magnetometry: geometric phases controlled to 1.10$^{-27}$ ecm

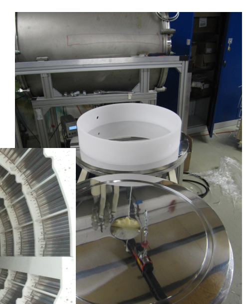
**Work at ILL** starting end of 2014:

- Commissioning and optimization of inner apparatus with UCN (initially 1-10 UCN/cc)
  - < 10$^{-26}$ ecm sensitivity in 2015/16;
  - < 10$^{-27}$ ecm sensitivity in 2017

**Future: possible cryogenic inner module**


'Inner' part of the experiment
UCN optics, B0/1 field, vacuum chamber





# Next generation nucleon EDMs

## Proton, deuteron, ... EDM

- Charged particle EDM searches require the development of a new class of high-precision storage rings

- Projected sensitivity ~ $10^{-29}$ ecm: … tests $\theta$ to < $10^{-13}$!
- Currently 2 approaches:
  - JEDI collab.: starting with COSY ring, development in stages
    E, B fields
  - BNL: completely electrostatic, new design
    all-electric ring

- Requirements:
  - Electric field gradients 17 MV/m (possible)
  - Spin coherence times > 1000 s (200s demonstrated at Jülich)
  - Continuous polarimetry < 1 ppm error (demonstrated at Jülich)
  - Spin tracking simulations of $10^9$ particles over 1000 s

# Proton EDM in ‚magic' ring

## - Frozen horizontal spin precession: p ll s
## - EDM turns s out of plane

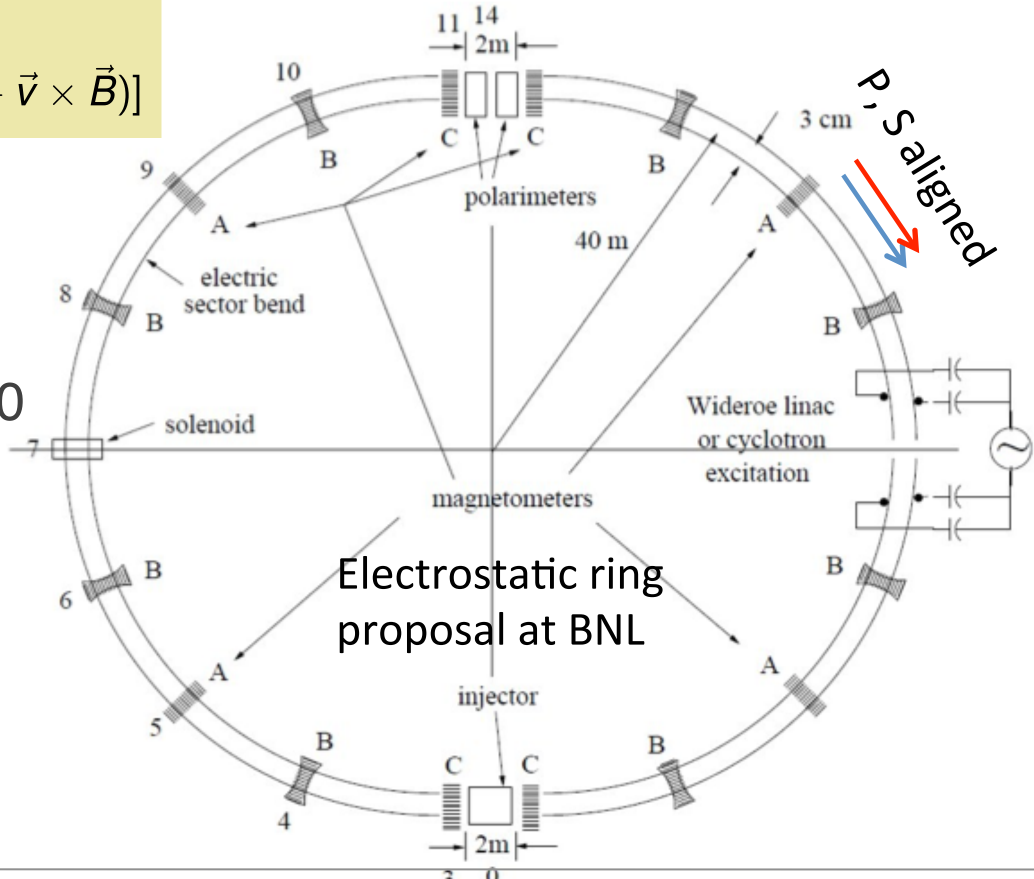
$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}$$

$$\vec{\Omega} = \frac{e\hbar}{mc}\left[G\vec{B} + \left(G - \frac{1}{\gamma^2-1}\right)\vec{v}\times\vec{E} + \frac{1}{2}\eta(\vec{E} + \vec{v}\times\vec{B})\right]$$

$$\vec{d} = \eta\frac{e\hbar}{2mc}\vec{S}, \quad \vec{\mu} = 2(G+1)\frac{e\hbar}{2m}\vec{S}, \quad G = \frac{g-2}{2}$$

Magic ring:
- Purely electric ring only for G > 0
- E and B ring for other isotopes

| | $G=\frac{g-2}{2}$ | p/GeV/c | $E_R$/MV/m | $B_V$/T |
|---|---|---|---|---|
| proton | 1.79 | 0.701 | 10 | 0 |
| deuteron | −0.14 | 1.0 | −4 | 0.16 |
| $^3$He | −4.18 | 1.285 | 17 | -0.05 |




V. Bargmann, L. Michel and V. L. Telegdi, Phys. Rev. Lett. 2 (1959) 435.

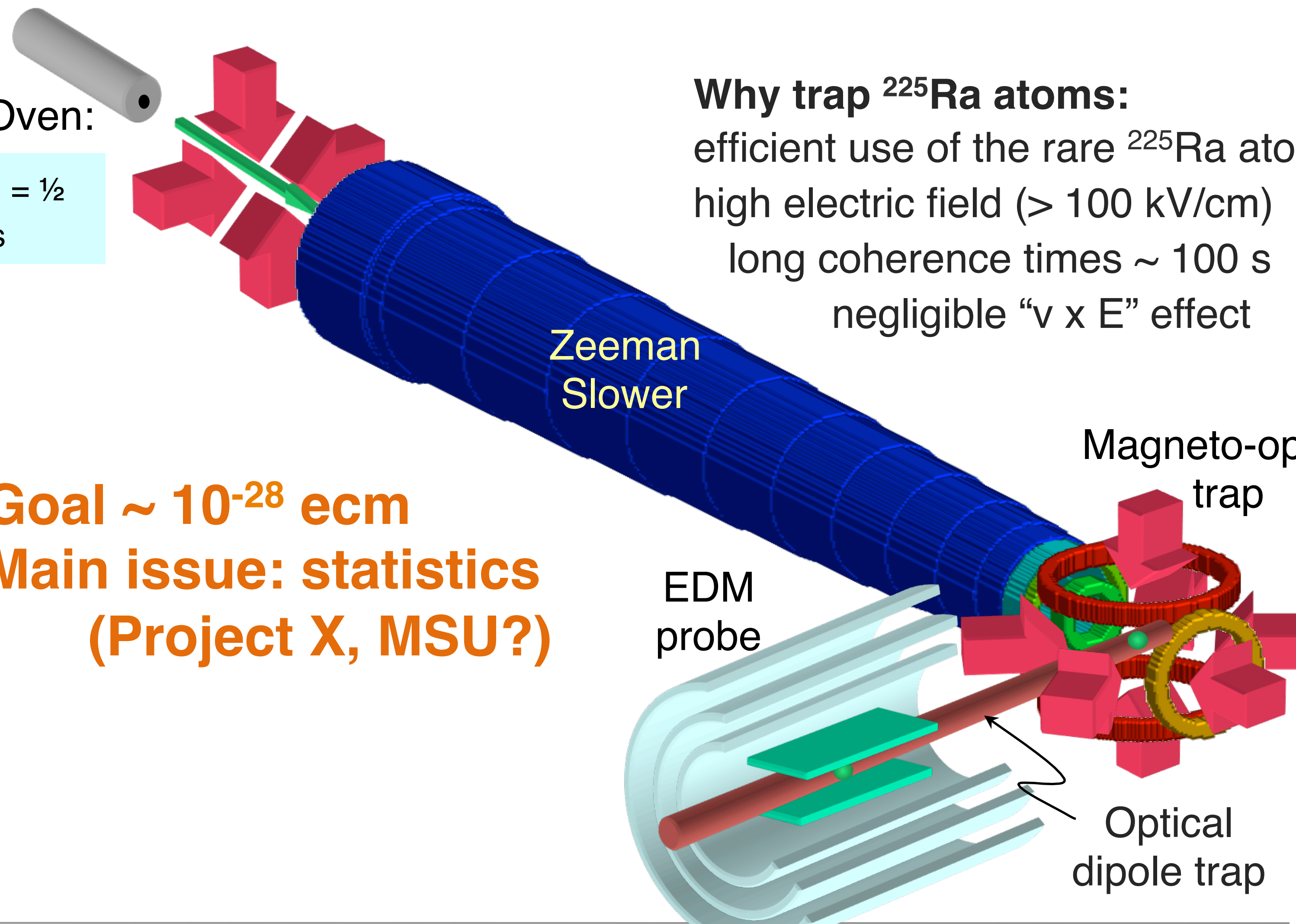


Figures: H. Stroeher

# Octupole deformations: $^{225}$Ra

**Enhancement factors: EDM ($^{225}$Ra) / EDM ($^{199}$Hg) ~ $10^3$**

Nuclear Spin = ½
$t_{1/2}$ = 15 days




**Why trap $^{225}$Ra atoms:**
efficient use of the rare $^{225}$Ra atoms
high electric field (> 100 kV/cm)
long coherence times ~ 100 s
negligible "v x E" effect

- **Goal ~ $10^{-28}$ ecm**
- **Main issue: statistics (Project X, MSU?)**

Dipole trap: Trimble *et al.* (2010)
MOT: Guest et al., PRL (2007)

Schiff moment of $^{225}$Ra, Dobaczewski & Engel, PRL (2005)

Figures: Z.-T. Lu

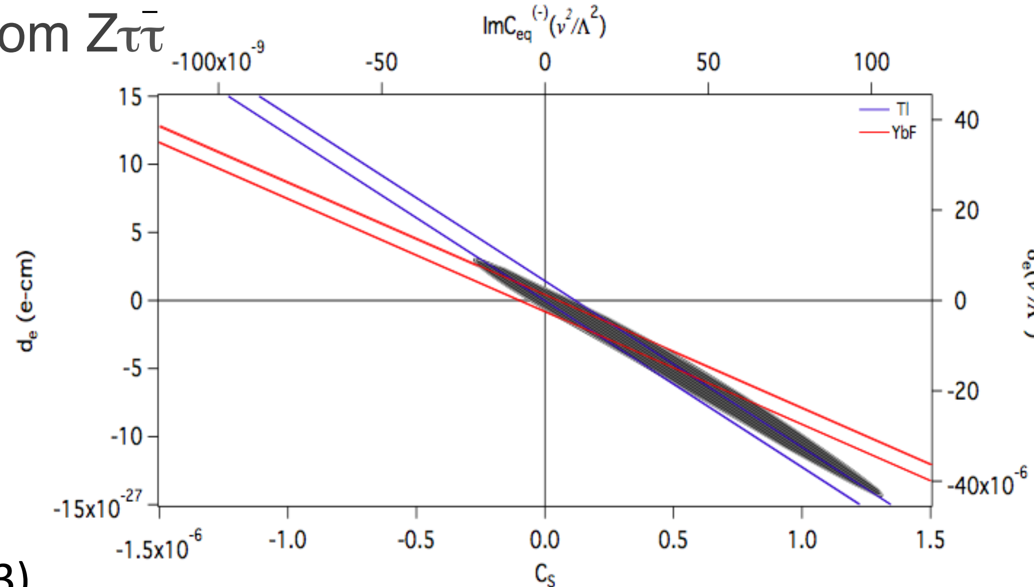
# Lepton EDM measurements

## Best limits:

Mainly paramagnetic systems and polar molecules

- Cs, Tl, YbF: $d_e < 1.05 \cdot 10^{-27}$ ecm (E. Hinds et al.)
- Soon: ThO – currently taking data
- Molecules, molecular ions, solids: PbO, PbF, HBr, BaF, HgF, GGG, $Gd_2Ga_5O_{12}$ etc.
- $d_{GGG} \sim < 10^{-24}$ ecm
- $d_\mu < 1.8 \, . \, 10^{-19}$ (90%) ecm from g-2
- $d_\tau < 1.7 \, . \, 10^{-17}$ (90%) ecm from $Z\tau\bar{\tau}$

Diamagnetic atoms also contribute to such limits!



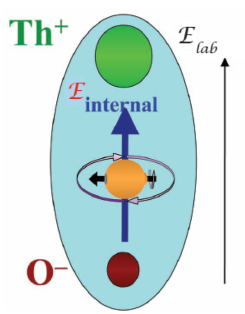

Tl, YbF limits together, courtesy T. Chupp (2013)

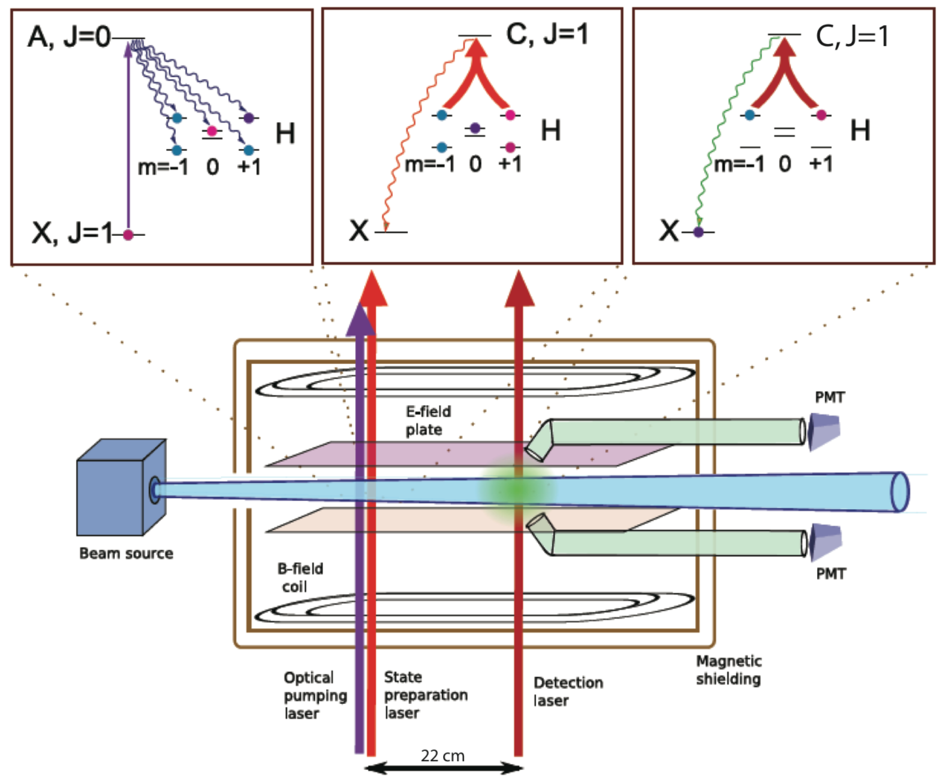
Shapiro, Usp. Fiz. Nauk., **95** 145 (1968)

# The ACME experiment

- ThO molecules:
  100 GV/cm internal electric field due to level structure, polarizable with very small lab-field
- Small magnetic moment, therefore less sensitive to B-field quality
- Ω-doublet: internal co-magnetometer
- High Z: enhancement
- Well understood system
- High statistics:
  strong cold beam

ACME Collab. Science 343, 269 (2014)




**Status: $10^{-28}$ ecm /√day,**
**limit $d_e < 8.7.10^{-29}$ ecm**



Figures: thesis Y. Gurevich

# Summary

New EDM experiments are highly sensitive probes for new physics

Several experiments must be performed to understand the underlying physics.

Experimental techniques span from
table top AMO - solid state - low temperature – accelerators - neutron physics

Next generation precision within next

2 years: nEDM ~ few $10^{-27}$ ecm
atoms ~ < $1.10^{-29}$ ecm (ThO, $^{199}$Hg, $^{129}$Xe)

6 years: nEDM ~ few $10^{-28}$ ecm
atoms - hard to predict

... Note: my nEDM time estimate stayed constant since 2009