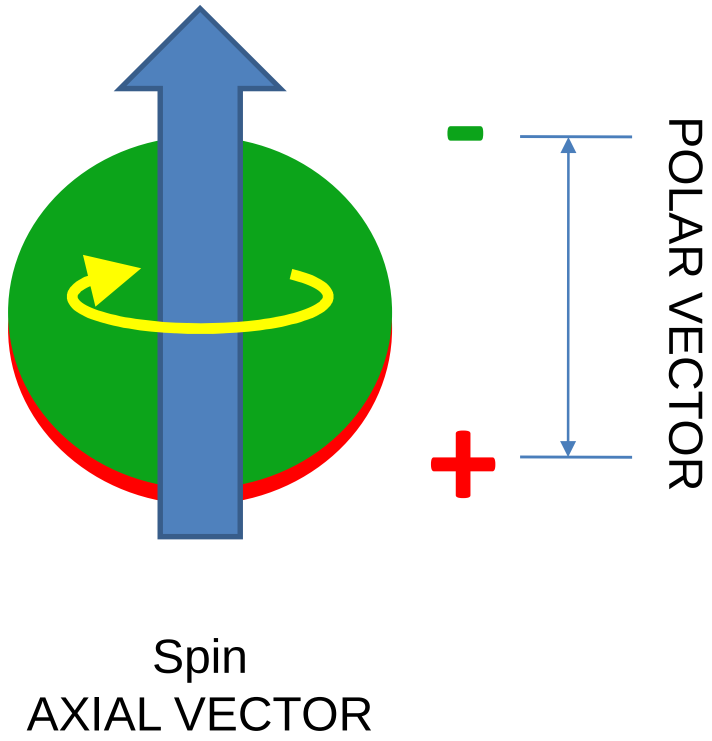
Technische Universität München

Particle electric dipole moments
An overview

Peter Fierlinger

Electric dipole moment



A non-zero particle EDM violates P, T

Purcell and Ramsey, PR78(1950)807

… assuming CPT conservation, also CP

Neutron EDM

Electroweak SM:
CKM matrix contains CP violation

$$d_n \sim 10^{-32}\ \mathrm{ecm}$$

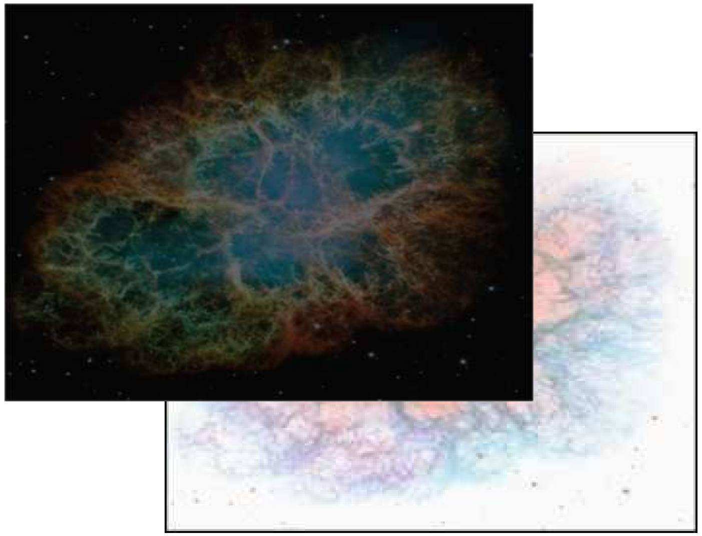
Baryon-asymmetry:

Observed:
$n_B / n_\gamma \sim 6 \times 10^{-10}$
WMAP astro-ph/0603451

Expected (CKM):
$n_B / n_\gamma \sim 10^{-18}$

Sakharov 1967:

- B-violation
- CP-violation
- non-equilibrium



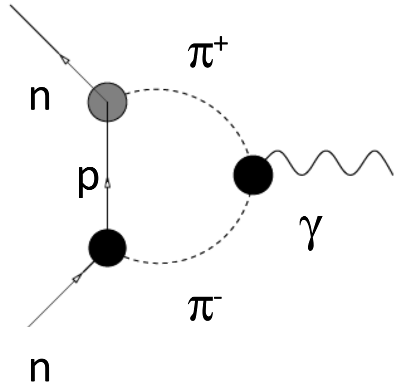
JETP Lett. 5 (1967) 24

Other sources of EDMs

Strong Interaction – ‚Strong CP‘-problem

$$d_n \propto \bar{\theta}\,\frac{1}{\Lambda_{QCD}} \approx 10^{-16}\,\bar{\theta}\,e\cdot cm$$

Experimentally limited to tiny number



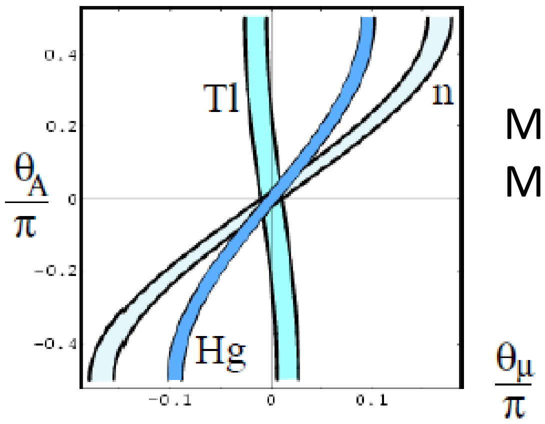
Supersymmetry

Prediction for the neutron EDM

$$d_n \approx 10^{-26} - 10^{-28}\ ecm$$

Hg EDM ~ exp. Limit!

$$d_{Hg} \approx 2\times10^{-27}\left(\frac{1\,\mathrm{TeV}}{M}\right)^2 ecm$$



MSSM for M = 500 GeV

There is an even better Hg result in 2009!

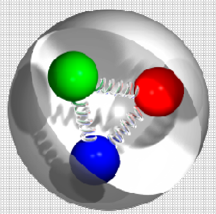
Pospelov, Ritz, Ann. Phys. 318(2005)119

EDM searches

Neutrons, Spin 1/2

- Quark EDM
- Most prominent system

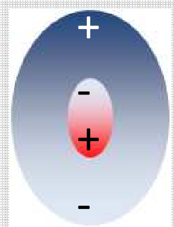
- only few constituents: easier to understand



Diamagnetic atoms: Hg, Xe, Rn, Ra, He

- Nuclear EDM: dominated by πNN couplings

- Electron shell ‚screens' effect
- Schiff moment: EDM ~ Z^2



- Heavy atoms: deformations = enhancement

Paramagnetic Atoms: Tl, Cs, Fr

-Electron EDM: ‚point-like' electron

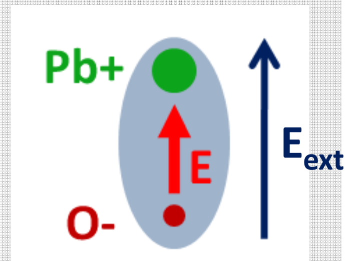
-Electron surrounded by polarizable vacuum, rich structure at short distances

- Enhancement: Z^3

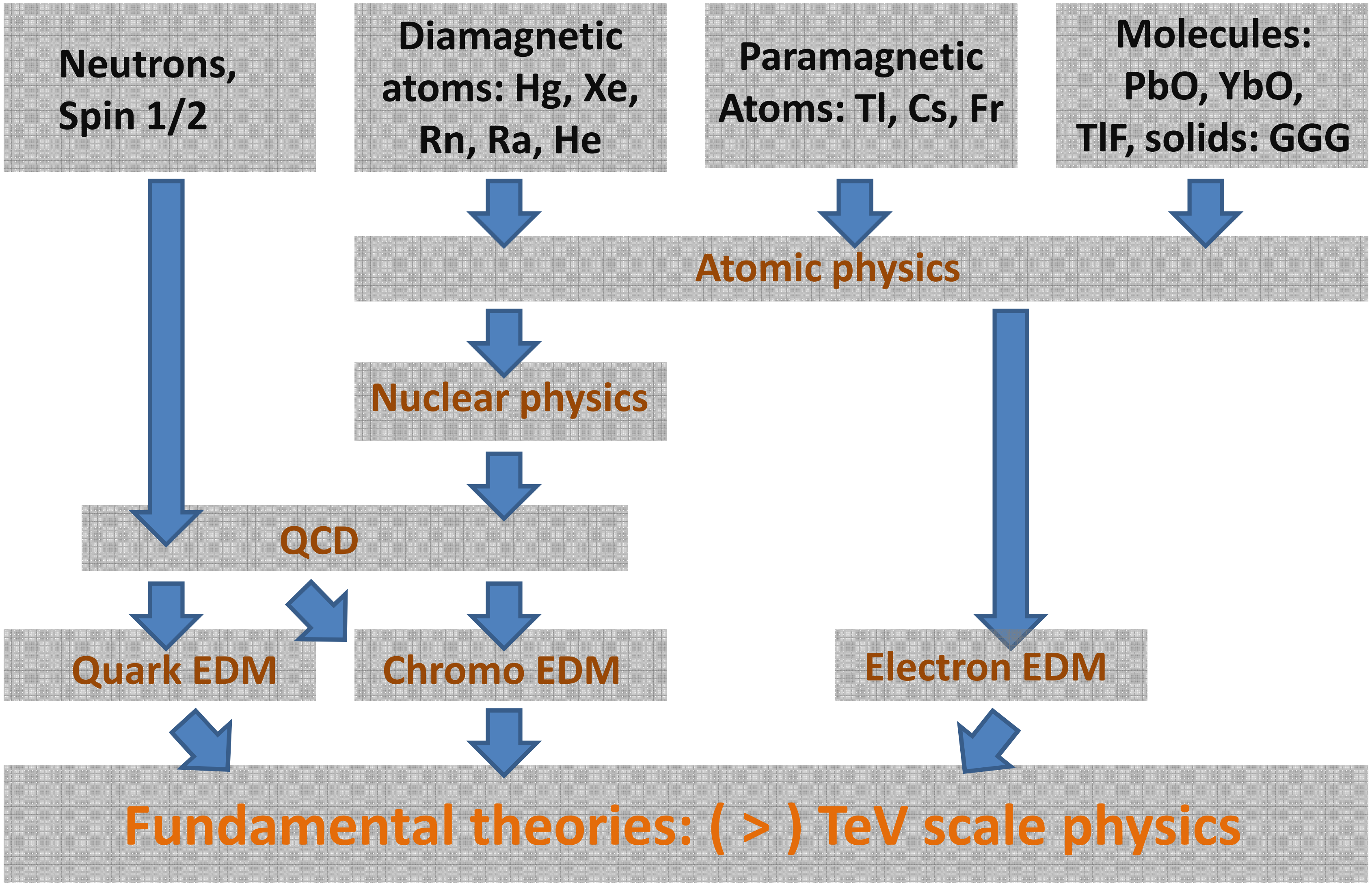
Molecules: PbO, YbO, TlF, soilds: GGG

-Electron EDM

- Molecules or solid can be used to form high electric fields



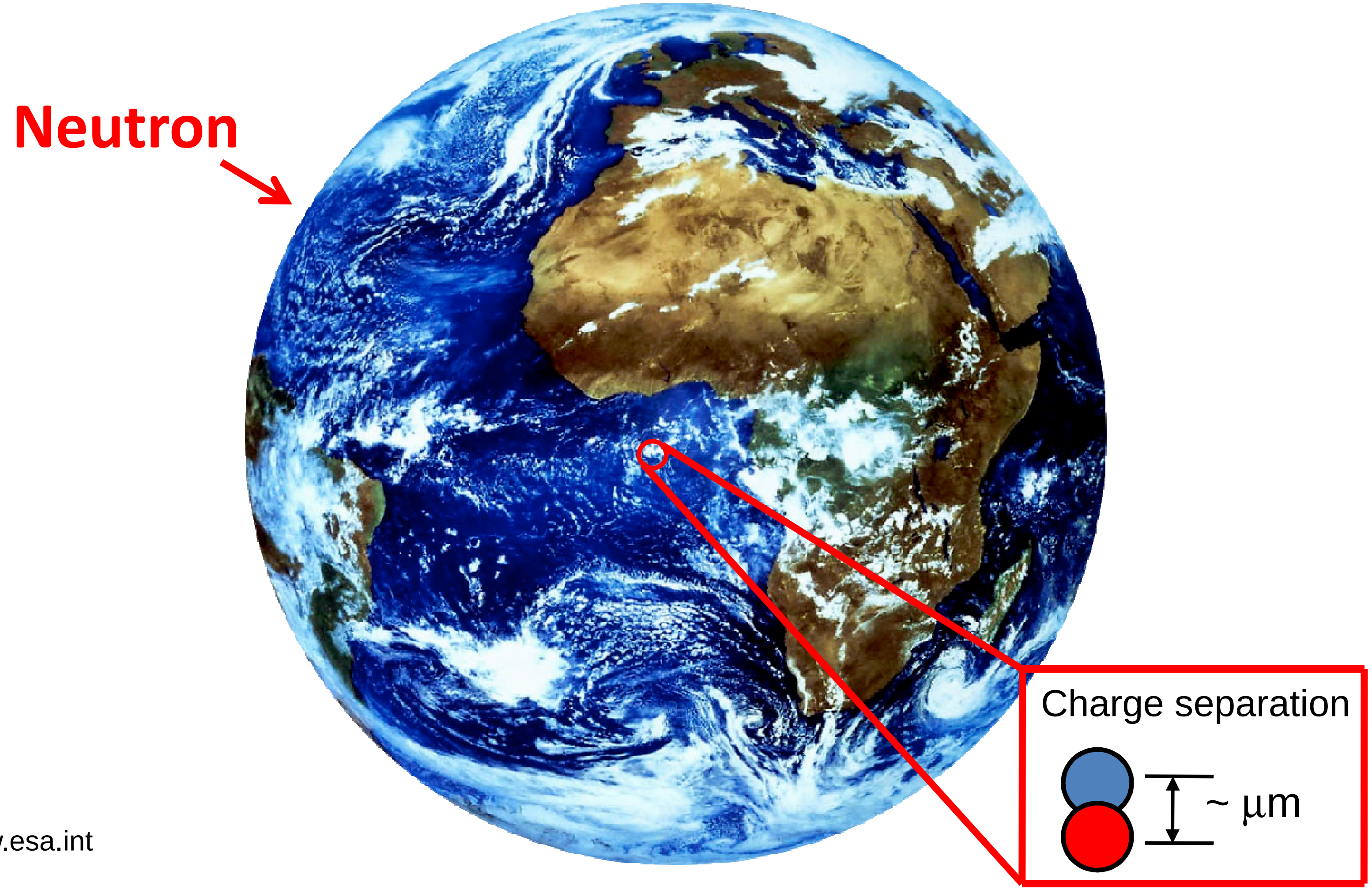
EDM searches



Current experiments (no complete list!)

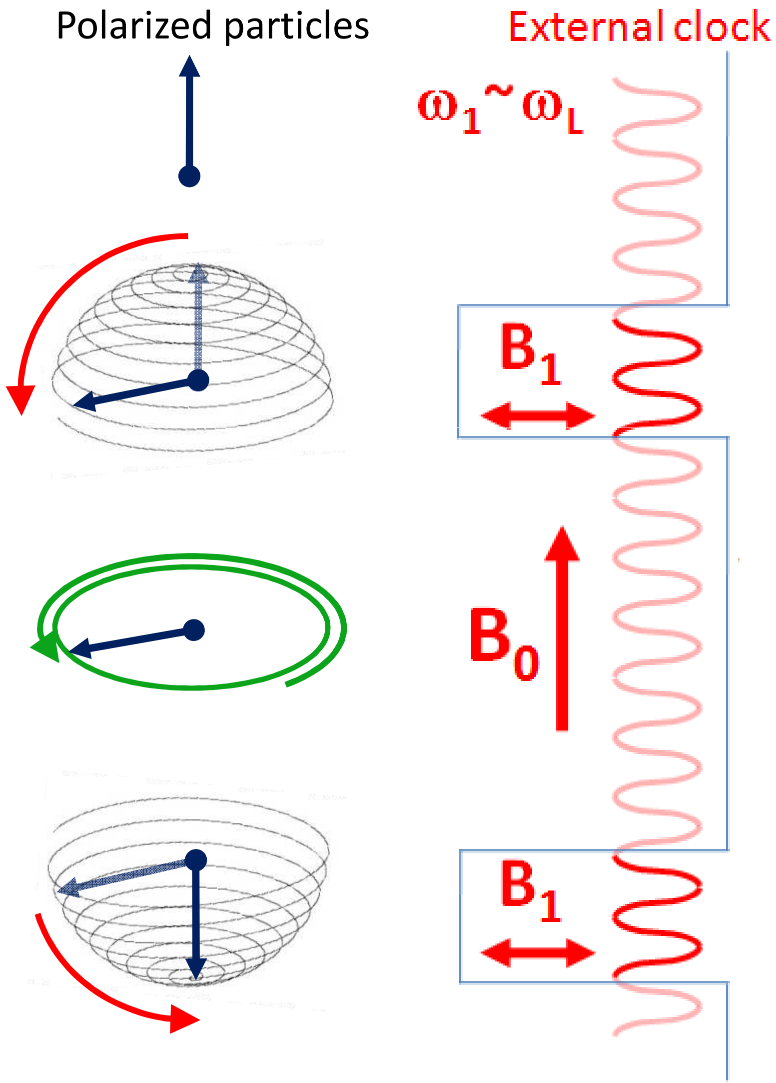
Neutron	$d_n < 2.9.10^{-26}$ (90%), Grenoble, Others: PSI/TUM/… , SNS, SUSSEX/RAL/…, ILL Crystal EDM
199-Hg	$d_A < 3.1.10^{-29}$ (95%), Washington
129-Xe	$d_A < 7 . 10^{-27}$ (90%), Michigan Others: Princeton, Munich
225-Ra	Argonne, KVI
221, 223-Rn	TRIUMF, Stony Brook … $d_A < 4.10^{-27}$, 5.10^{-28} e.cm (projected)
Muon, Deteron	$d_\mu < 1.8 . 10^{-19}$ (90%), Brookhaven
YbF	$d_e < 6.6 . 10^{-26}$ (90%), Imperial
GGG	Indiana/Yale
Cs, **Tl**	$d_e < 1.6 . 10^{-27}$ (90%), combined from Cs (Amhearst), Tl (Berkeley)

How large is 10^{-26} e·cm?



picture: www.esa.int

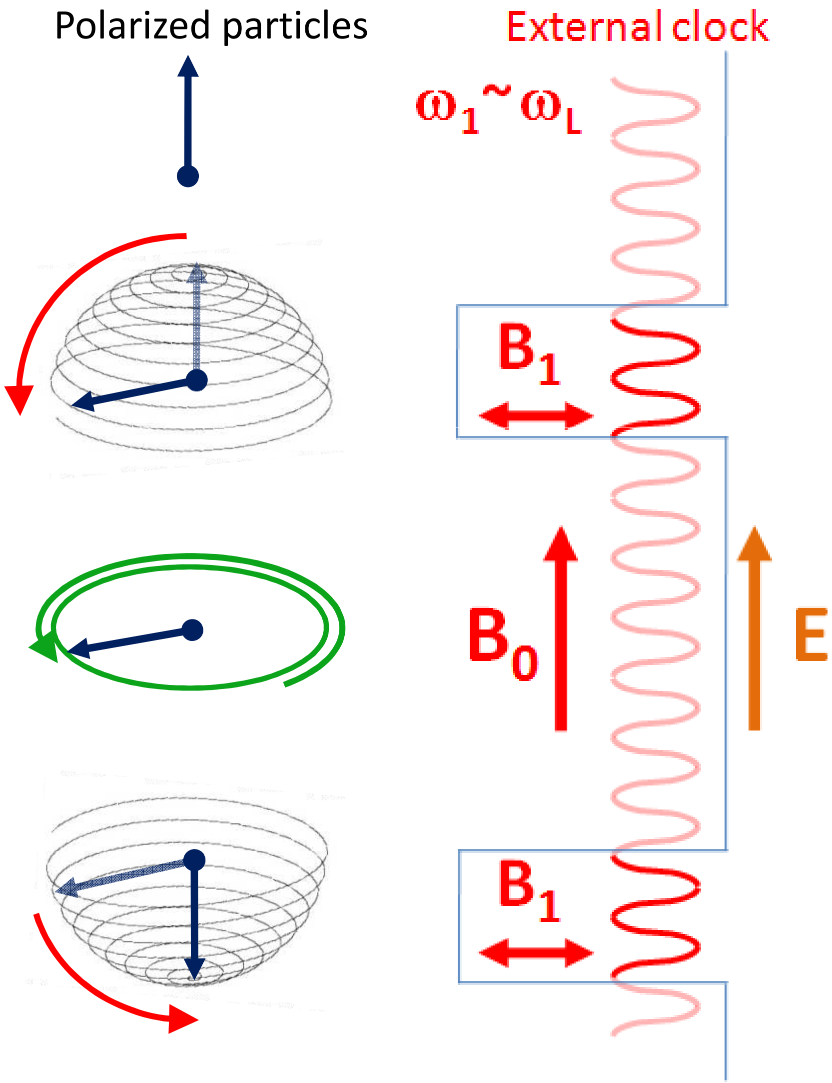
Method



Ramsey‘s method of separated oscillatory fields

$$\hbar\nu \approx \mu B$$

Method



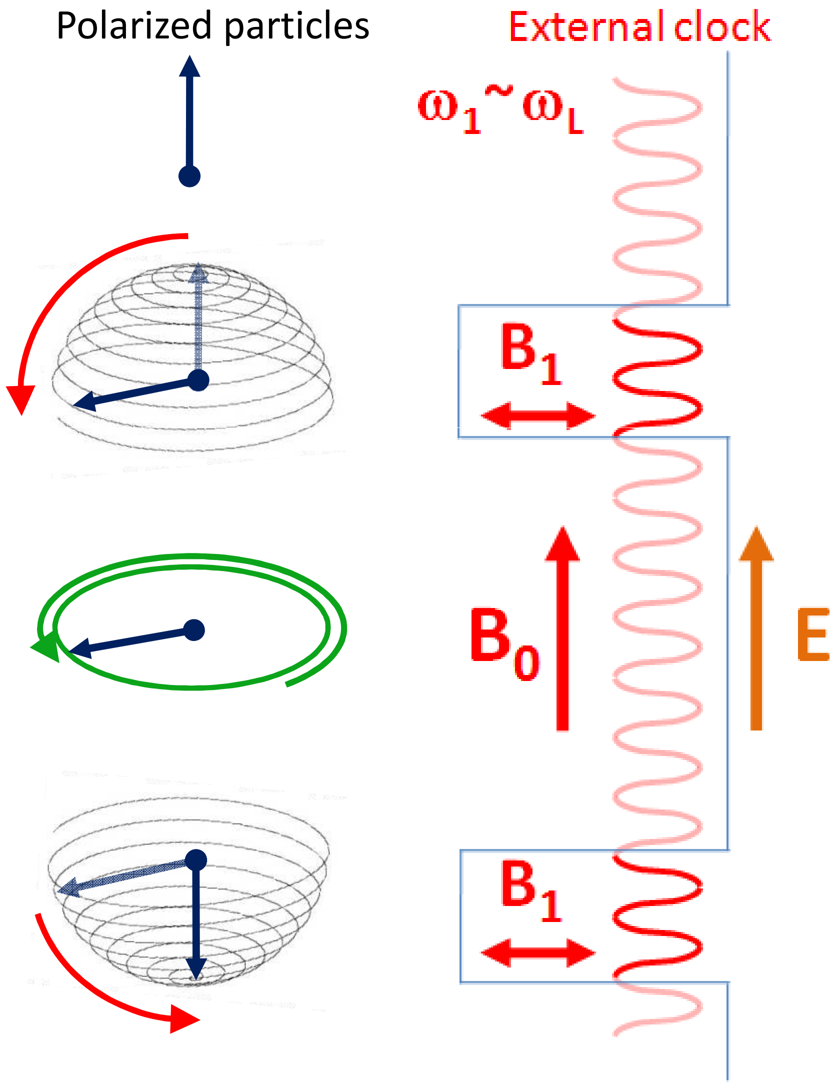
Ramsey's method of separated oscillatory fields

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

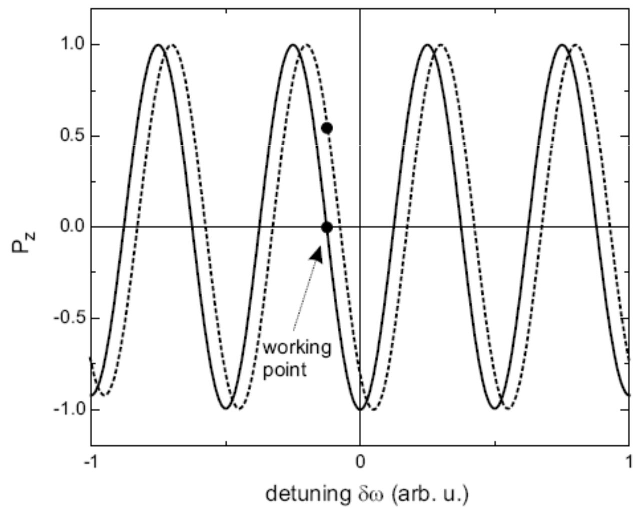
$$\hbar\nu_{\uparrow\downarrow} = 2(\mu B - d_n E)$$

$$\hbar\Delta\nu = 4 d_n E$$

Method



Ramsey's method of separated oscillatory fields



Sensitivity:

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

Outline

Neutron EDMs

Atom EDMs

Outlook

Ultra-cold neutrons (UCN)

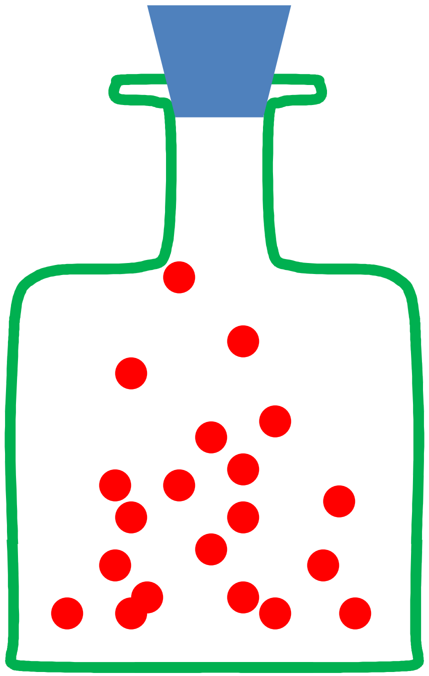
-E_{kin} < 250 neV (< 7 m/s velocity)

-Gravitational potential ~ 100 neV/m
< 3 m height

-Magnetic level splitting
~ 60 neV/T

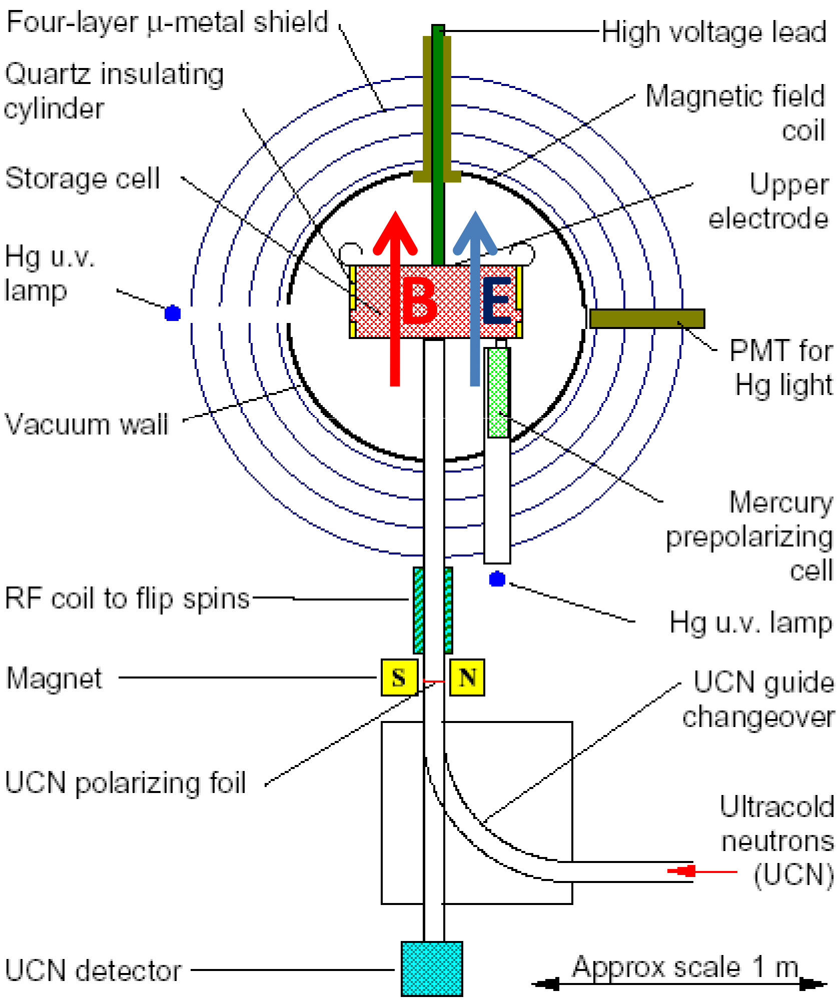
-Strong Interaction:
reflection from many material surfaces

- One can build traps for UCN

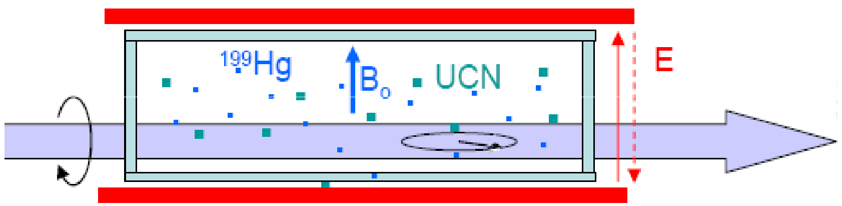


Storage times ~ β-decay life-time (1000 s)
…. long observation time!

Status: RAL/Sussex/ILL



UCN and 199-Hg ‚co-magnetometer' In the same volume



Ratio of ^{199}Hg (8 Hz) & neutron (30 Hz) precession in 1 μT field

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

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

New neutron EDM experiments

Precision goal: 10^{-28} ecm

New experiments:

- Cryogenic EDM @ ILL (ILL/SUSSEX/RAL/KURE/Oxford)
  superfluid helium, first data expected soon
- n2EDM @ PSI or TUM (PSI/TUM/LPSC/…)
  UCN stored in vacuum
- neutron EDM @SNS (LANL/…)
  superfluid helium, very innovative
- Other: neutron EDM (Gatchina), crystal EDM, …

Accuracy goal will be achieved by:

- New UCN sources with $10^{2\text{-}3}$ more neutrons
- Improved magnetic field control
- Stronger electric fields
- Improved control of systematic effects

The nEDM project (PSI/TUM/…)

Strategy:

UCN stored in vacuum at room temperature

Phases:

- Operate enhanced 'old' ILL apparatus at strong PSI UCN source (now being installed). First UCN expected end of 2009.

Goal ~ 5.10^{-27} e·cm (2y data)

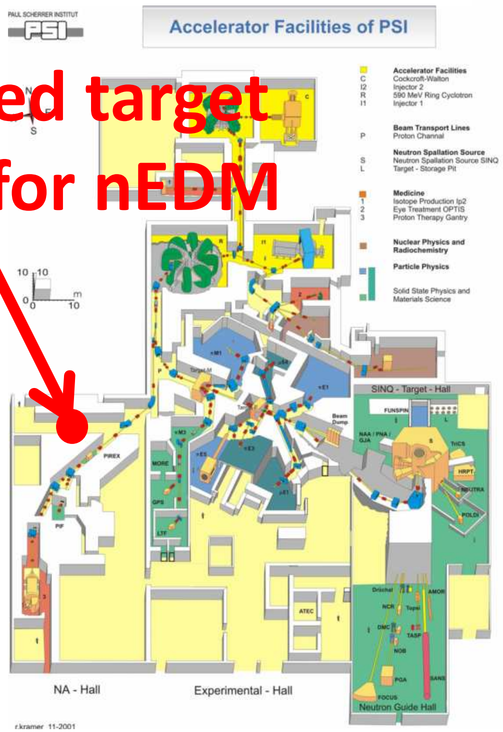
- Set up new apparatus at strongest available UCN source (PSI or TUM)

Goal: few 10^{-28} e·cm (2013)

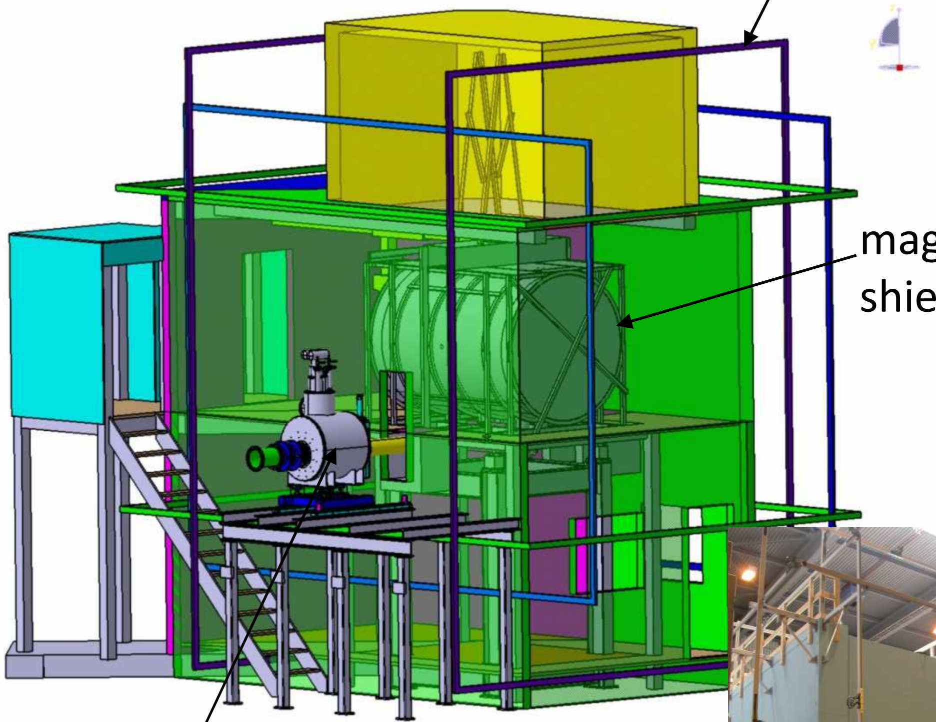
Installation at PSI - ongoing

New strong UCN source being built for us! **First UCN: Dec 2009.**

- ~ few 100 UCN /cm³ in the experiment (now: 1-5 /cm³)
- New detection system, SC polarizer
- Magnetic and thermal stabilization
- dPS coated UCN chamber walls



Dedicated target station for nEDM



Dominating systematic effects

Electrode leakage currents

Create additional magnetic field: precession, small for $I_{Leak} < 1$ nA

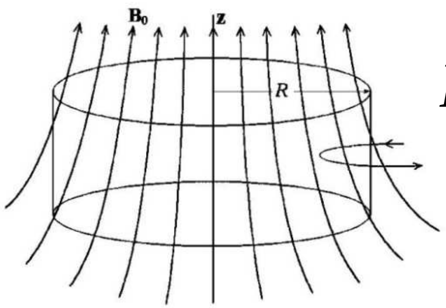
Motional field

B field in the rest frame of the neutron due to its motion

$< 10^{-26}$ ecm

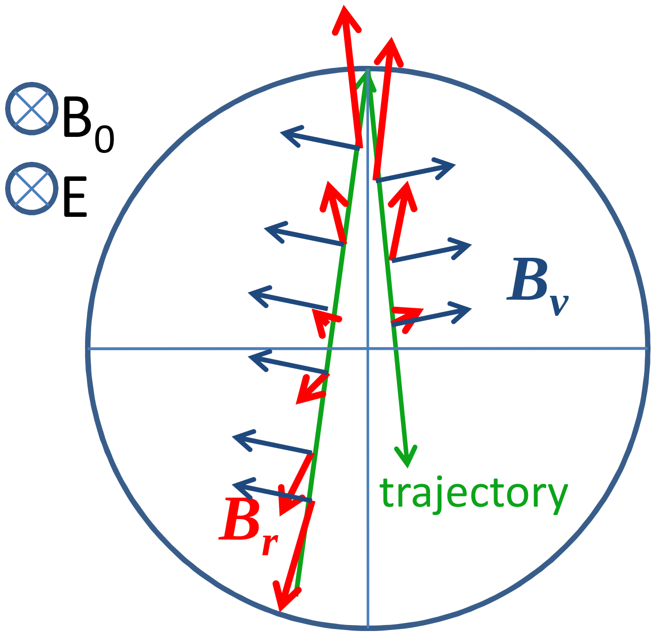
$$B_v = \frac{E \times v}{c^2}$$

Vertical gradient (few nT/m are enough)



$$B_z \rightarrow B_r \propto r$$

Motional field and gradient cause 'geometric phase effect'



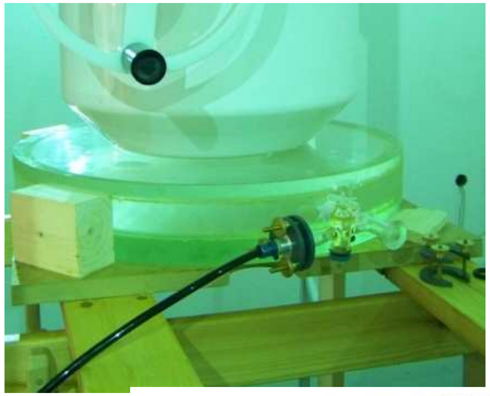
(top view into neutron chamber)

Different for UCN and co-magnetometer:

10^{-26} ecm level

Magnetic fields

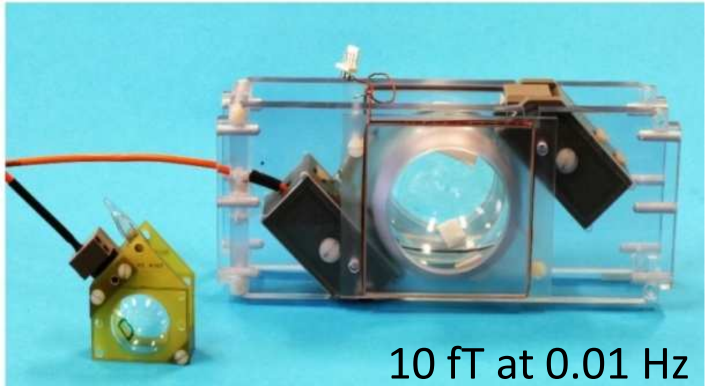
55 cm ^{3}He cell w/ 2fT resolution



- Components magnetically tested at PTB at pT level
- Cs magnetometer arrays
- Large area ^{3}He cell parallel to UCN chamber
- Improved ^{199}Hg co-magnetometer

Optically pumped Cs magnetometers

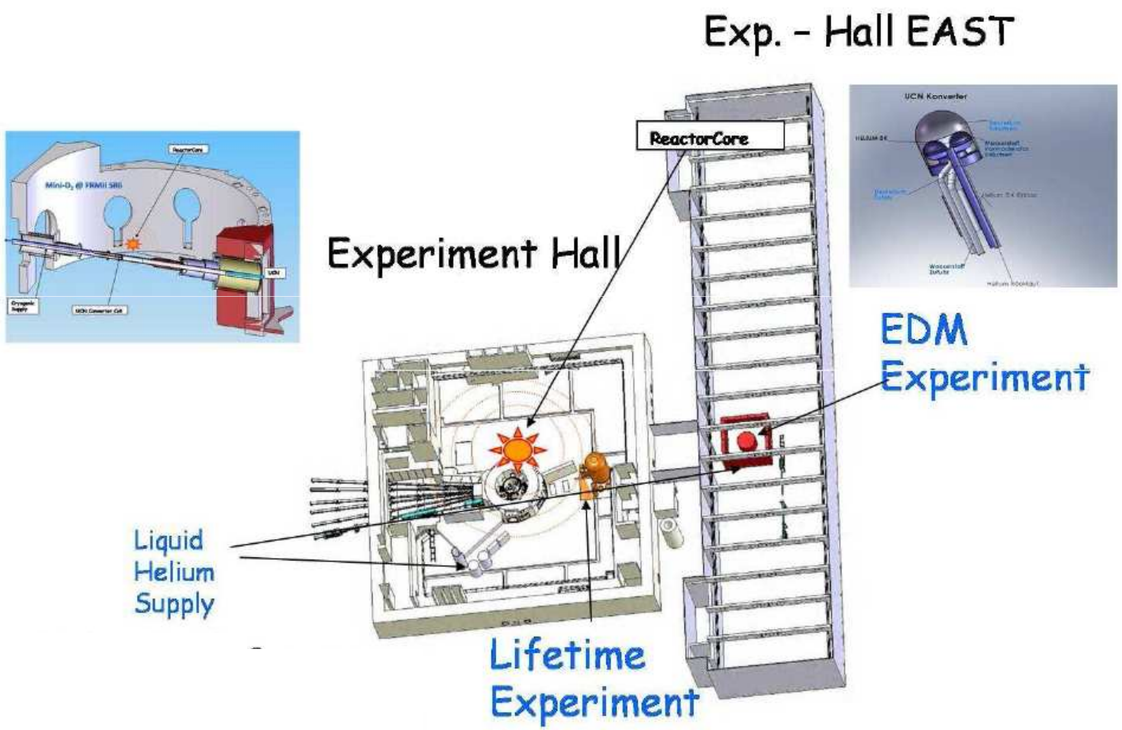
Module Comparison



Magnetically shielded room for testing of Components w/ 300 SQUIDs,~ 1 fT/√Hz

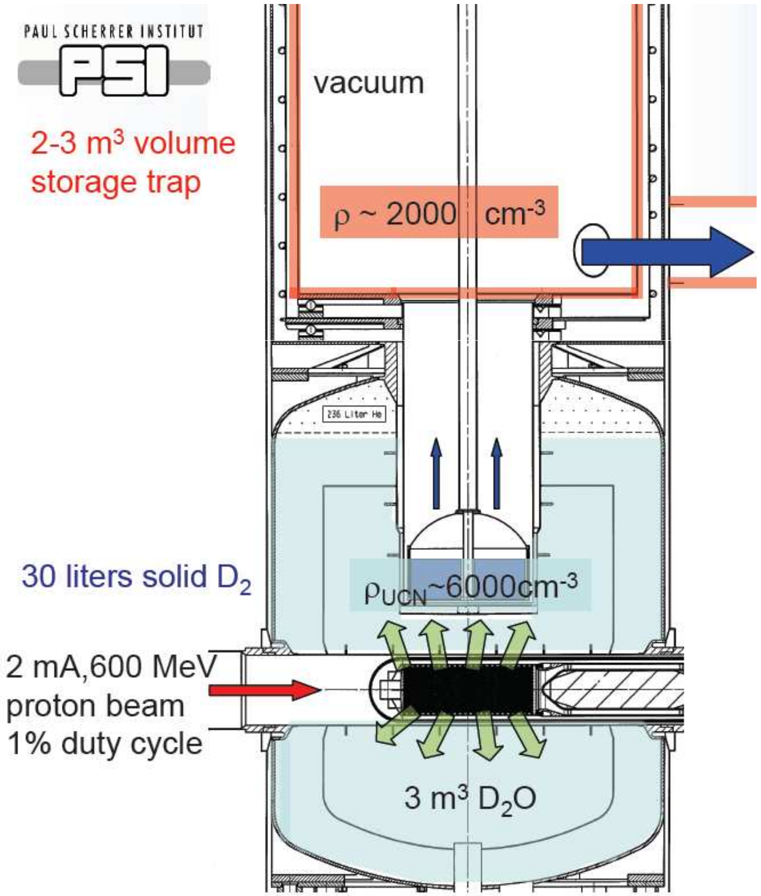
UCN sources for the new EDM

UCN source at TU Munich



FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz

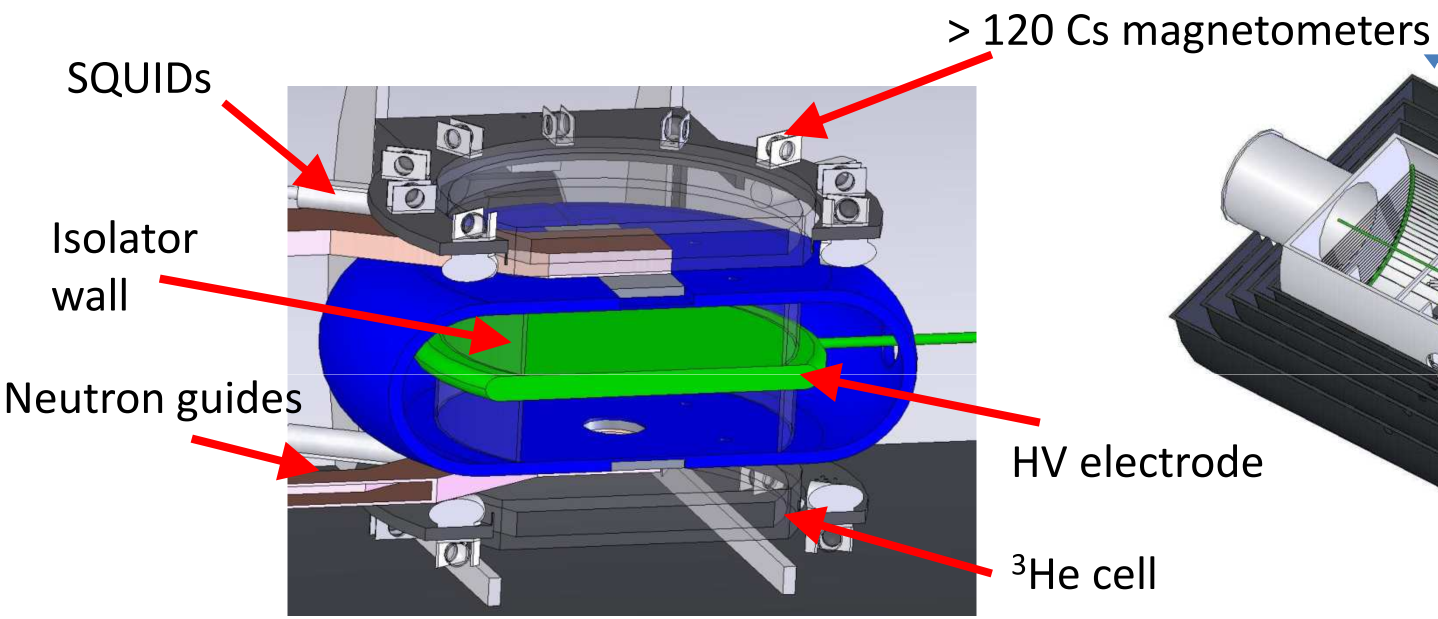
UCN source at PSI

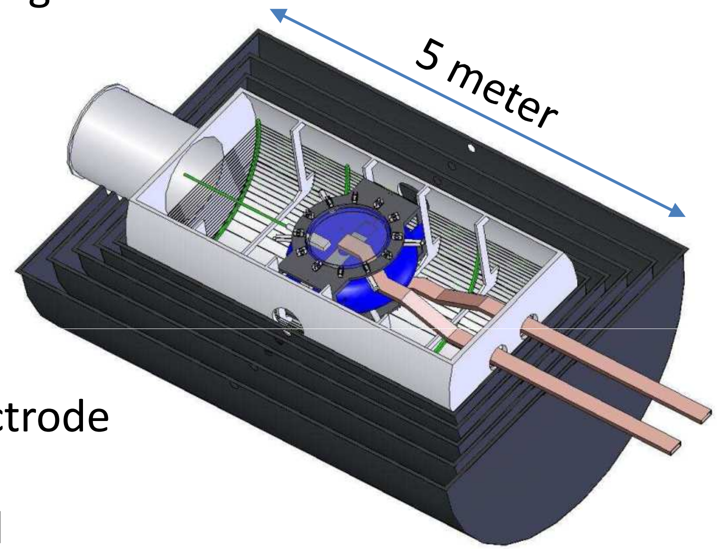


~ 500 UCN /cm³ in the experiment

New nEDM experiment

Double chamber setup:





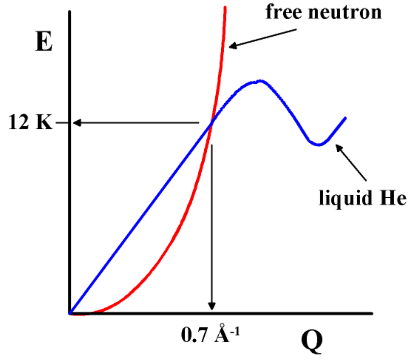
- **Inverted E-field measurements simultaneously**
- **Different magnetometry and co-magnetometry systems**
- **Large scale magnetic shield**

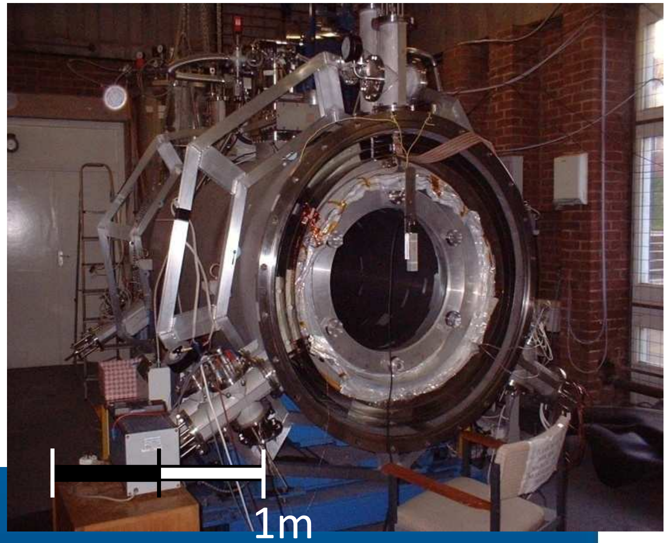
Many R&D projects:

Mu-metal prototyping and field stabilization,
Cs and ^{3}He magnetometry,
^{199}Hg and ^{129}Xe co-magnetometry,
New UCN storage materials

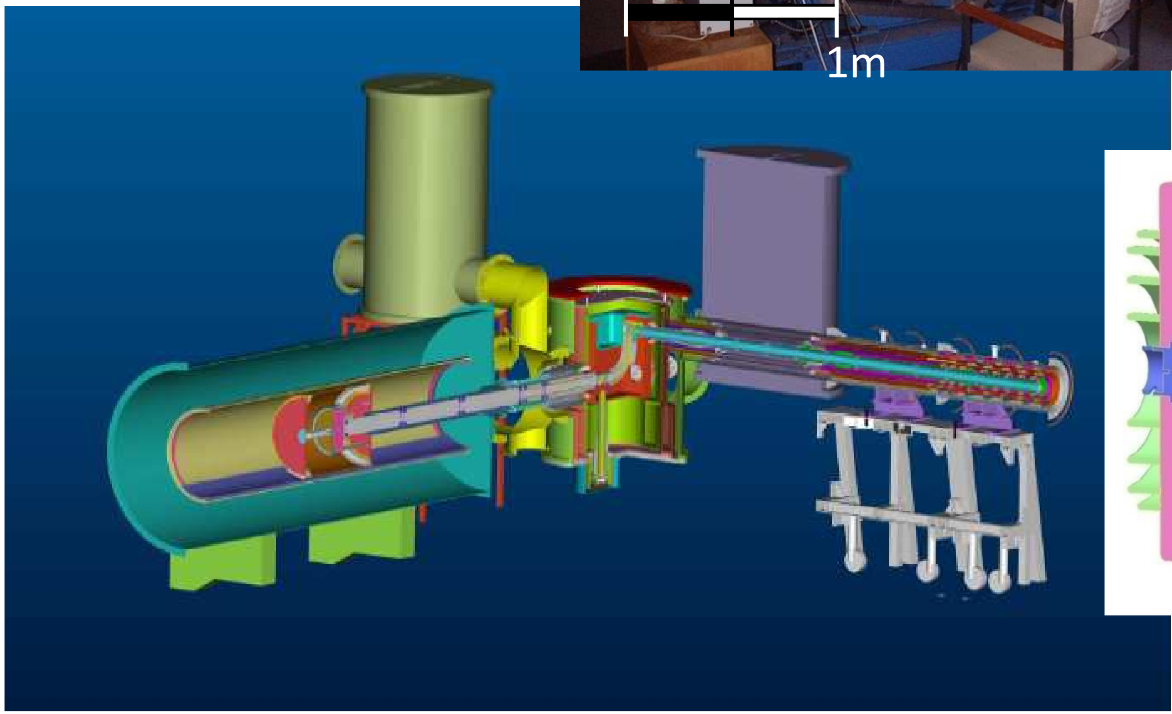
Cryo EDM

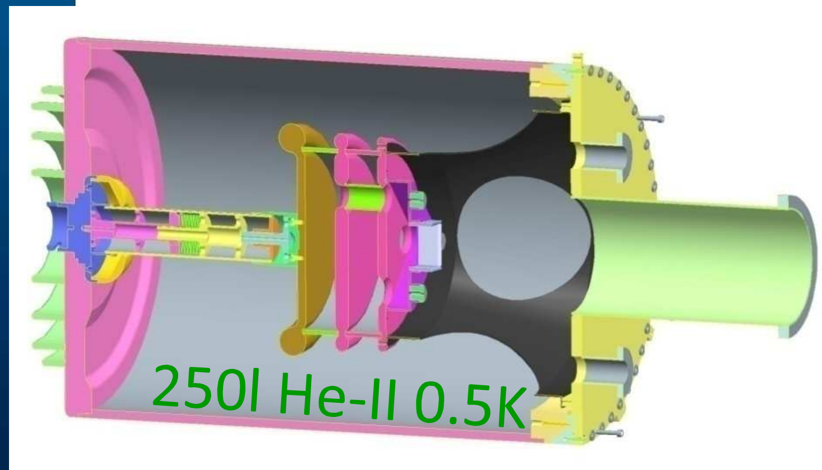
UCN production in super-fluid 4-helium





- Experiment performed in superfluid helium
- high density of UCN
- Long coherence times
- High electric fields
- Superconducting magnetic shield
- Most advanced approach, first data soon.



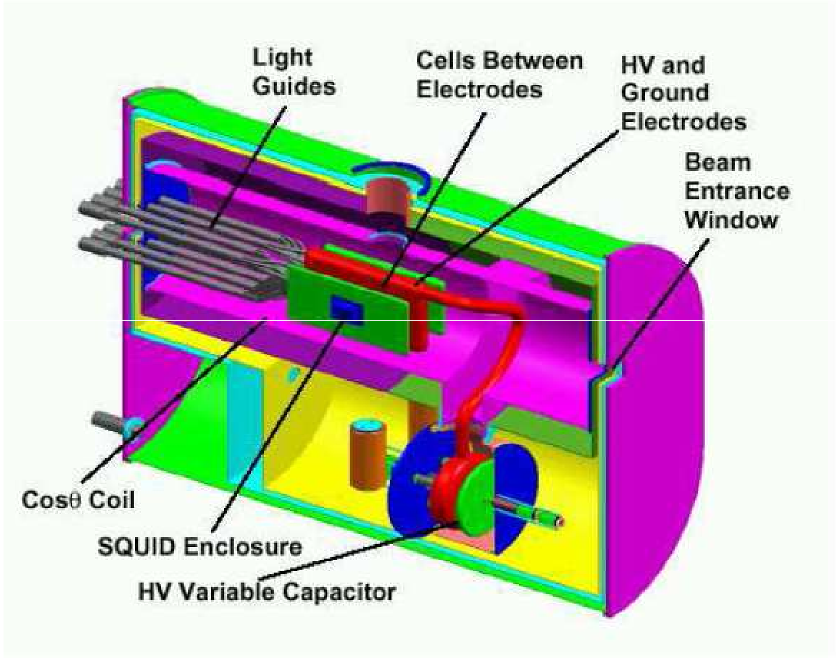


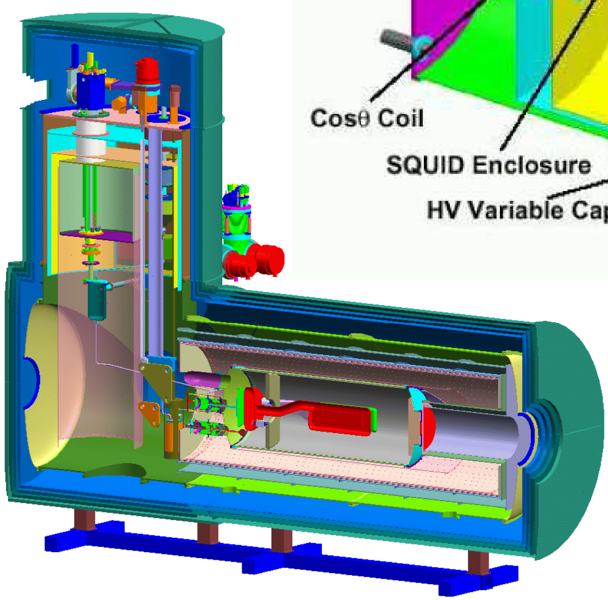
Measurement cell

Pictures: P. Harris

SNS EDM

Experiment is performed in superfluid helium
- UCN are produced in EDM chamber





(Some) basic ideas:

- ^{3}helium and neutron spins precess in the same chamber

- Use spin dependent 3-he neutron absorption and scintillation detection

- ‚Dressed spins‘:
AMO-technique to effectively change magnetic moment

Very innovative, but still has significant time constant.

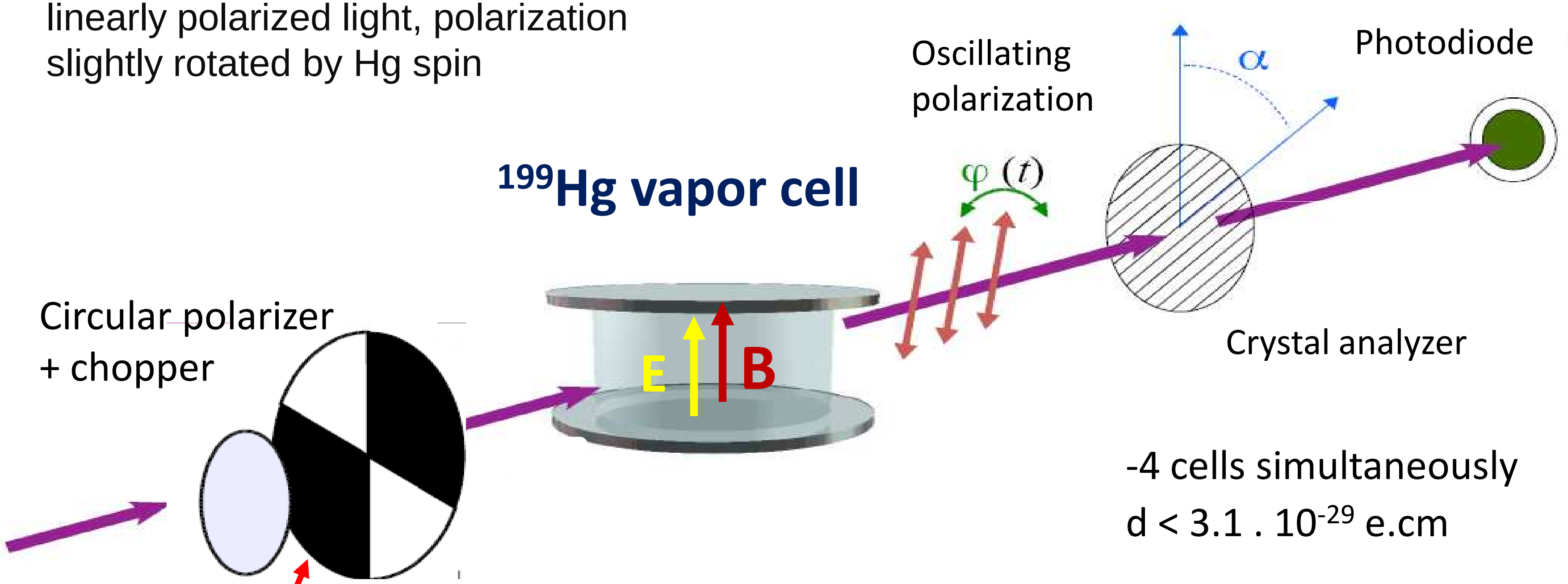
Pictures: M. Cooper

^{199}Hg EDM experiment

Procedure:

1) Transverse optical pumping: periodically chopped laser light

2) Analysis using Faraday effect:
linearly polarized light, polarization
slightly rotated by Hg spin



Running at $\omega_L(B)$ for pumping, circularly polarized light

-4 cells simultaneously
d < 3.1 . 10^{-29} e.cm

SM-prediction

$$d_{\mathrm{Hg}} \approx 6\times10^{-33}\ e\mathrm{cm}$$

O.P. Sushkov et al.,JETP 60 (1984) 873

(Seattle)

W. C. Griffith et al., Phys. Rev. Lett. **102**, 101601 (2009)

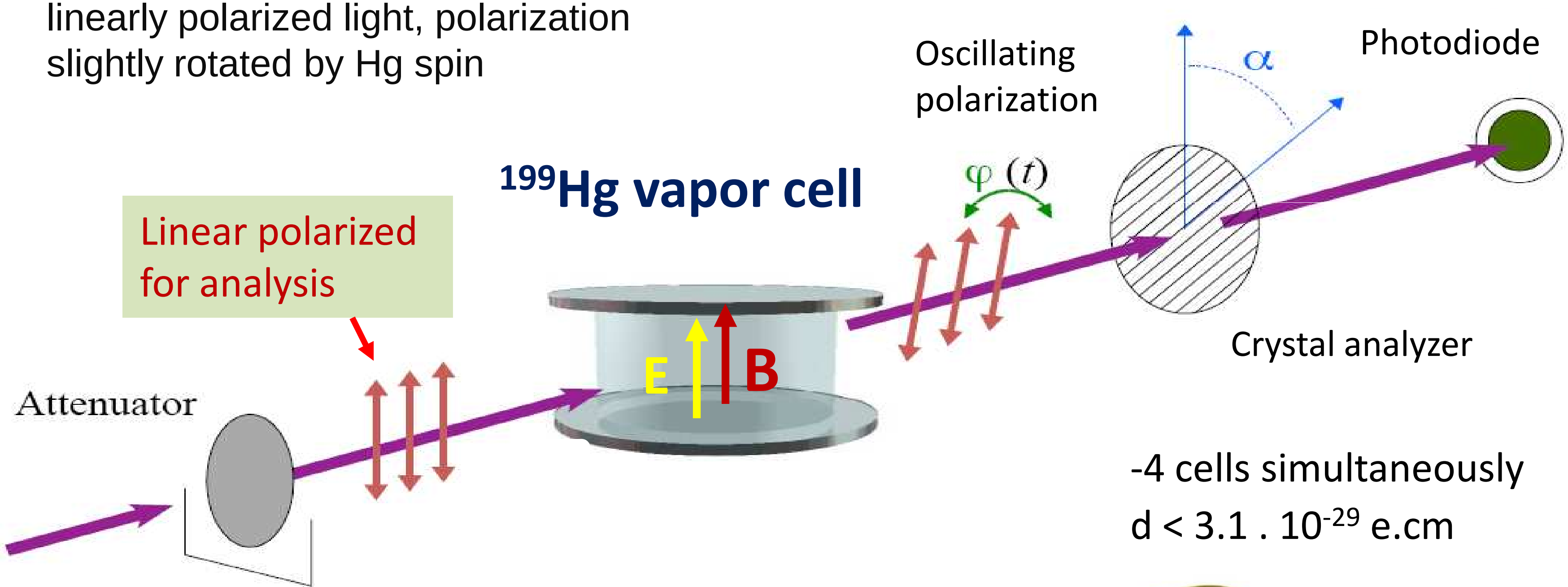
^{199}Hg EDM experiment

Procedure:

1) Transverse optical pumping: periodically chopped laser light

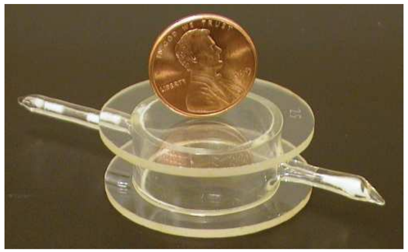
2) Analysis using Faraday effect:

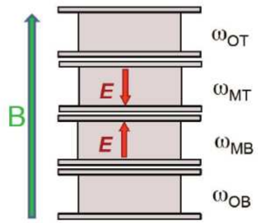
linearly polarized light, polarization slightly rotated by Hg spin

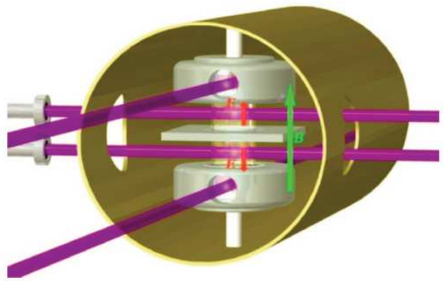


-4 cells simultaneously

d < 3.1 . 10^{-29} e.cm





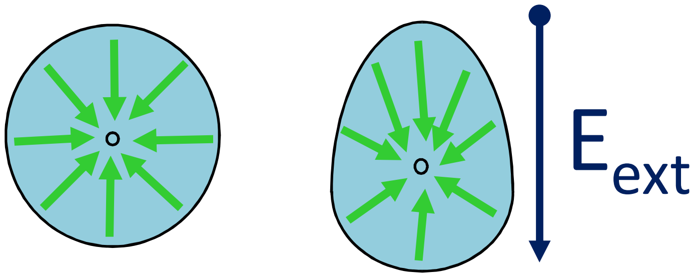


(Seattle)

W. C. Griffith et al., Phys. Rev. Lett. **102**, 101601 (2009)

Electron EDM experiment

$\langle \mathbf{E}_{int} \rangle = 0$



$\langle \mathbf{E}_{int} \rangle \neq 0!$

Classic atomic beam Ramsey experiment

Thermal beam of atomic Tl (Z=81)

E_{ext} =120 kV/cm

E_{int} = 70 MV/cm (!) …

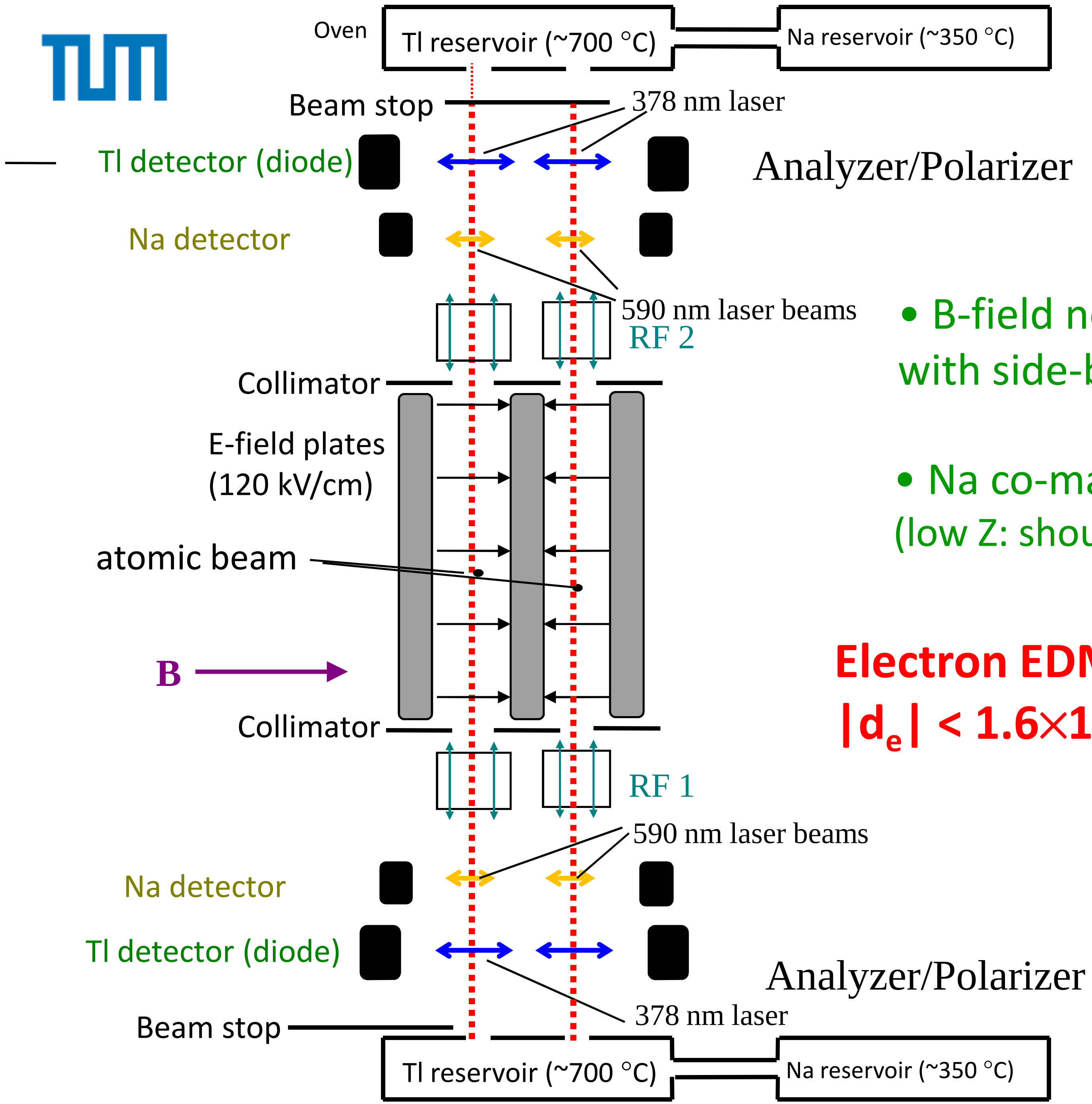
Strong enhancement of EDM

Means for testing systematic effects:

- Counter-propagating vertical beams to cancel systematic effects from $\mathbf{B}_{mot} \sim \mathbf{E} \times \mathbf{v}$

- Second substance as 'co-magnetometer'

(Berkeley)



- B-field noise rejection with side-by-side regions

- Na co-magnetometer
(low Z: should have small EDM)

Electron EDM limit:
$|d_e| < 1.6\times10^{-27}$ e·cm (90% c.l.)

B. Regan, E. Commins, C. Schmidt, D. DeMille
Phys. Rev. Lett. **88**, 071805 (2002)

(Berkeley)

New approaches: ^{129}Xe EDM

Experiment is currently being set up in Munich

^{129}Xe is a diamagnetic atom, nuclear spin ½

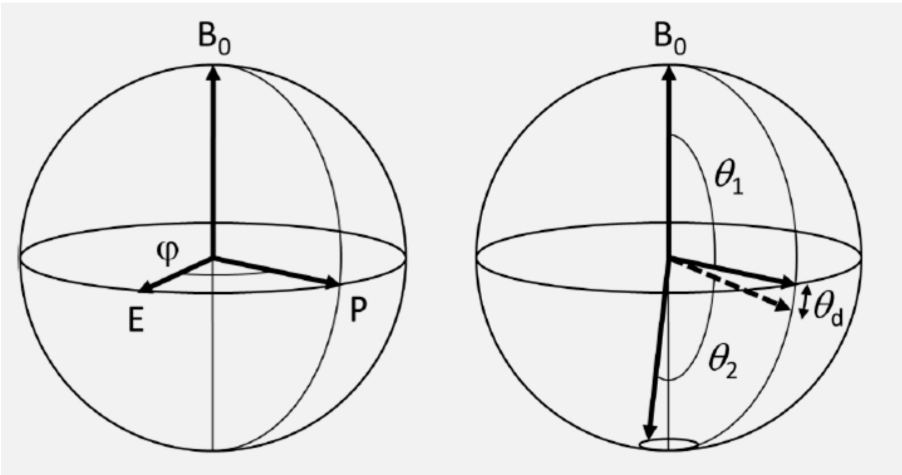
Schiff-moment:

EDM due to CP-odd πNN-coupling:

suppressed and enhanced, scales with Z^2

New method:

- Rotating electric fields
- Different systematics compared to Ramsey's method
- Micro-fabricated arrangement

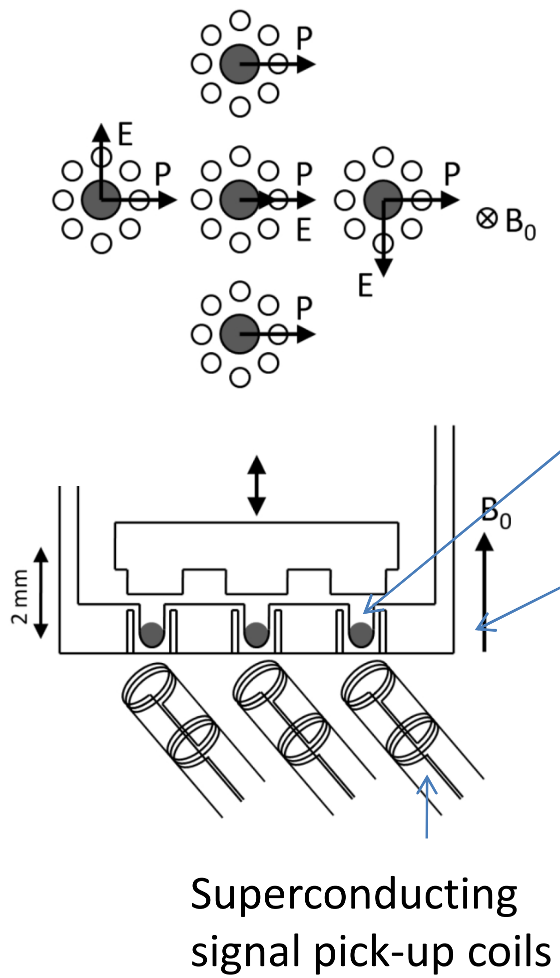


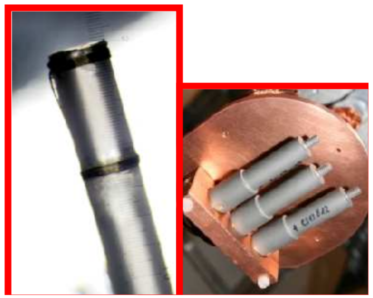
^{129}Xe EDM

Array of many polarized liquid xenon droplets in parallel
~ 10^{18} atoms / droplet

E-field rotates with defined constant phase to P

Checks for systematics are performed in parallel





- Statistical sensitivity in 1000 s ~ 3. 10^{-31} ecm
-Sum of (known) systematics < 10^{-31} ecm

Summary

EDMs are interesting probes to find new CP violation

The next generation neutron EDM experiments are on the way.
An improved limit will still take a while ~2-3 years.
New UCN sources to be online ~ 1 year

Atomic physics can provide valuable complementary data.

The ^{199}Hg experiment raised the bar for all other approaches quite a bit.

New approaches with different systematic effects are very much welcome.