Overview of EDM Expt's

Workshop on dipole moments in storage rings

Gerco Onderwater

KVI/Rijksuniversiteit Groningen, The Netherlands

KVI RIJKSUNIVERSITEIT GRONINGEN

RuG

NWO Netherlands Organisation for Scientific Research

FOM

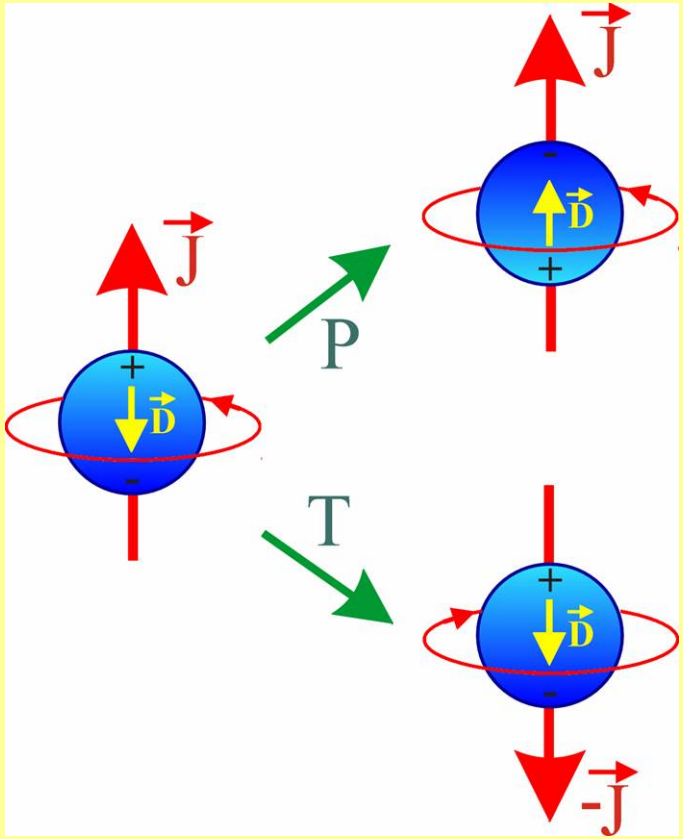
Motivation

Cosmology (WMAP)

Cosmological matter-antimatter asymmetry explainable with *e.g.* Sakharov-conditions

$\neq$

- baryon number violation
- C & CP violation ← δ_{CKM} from K- and B-physics
- thermal non-equilibrium



Direct measurements:

K, B, D (η,η')

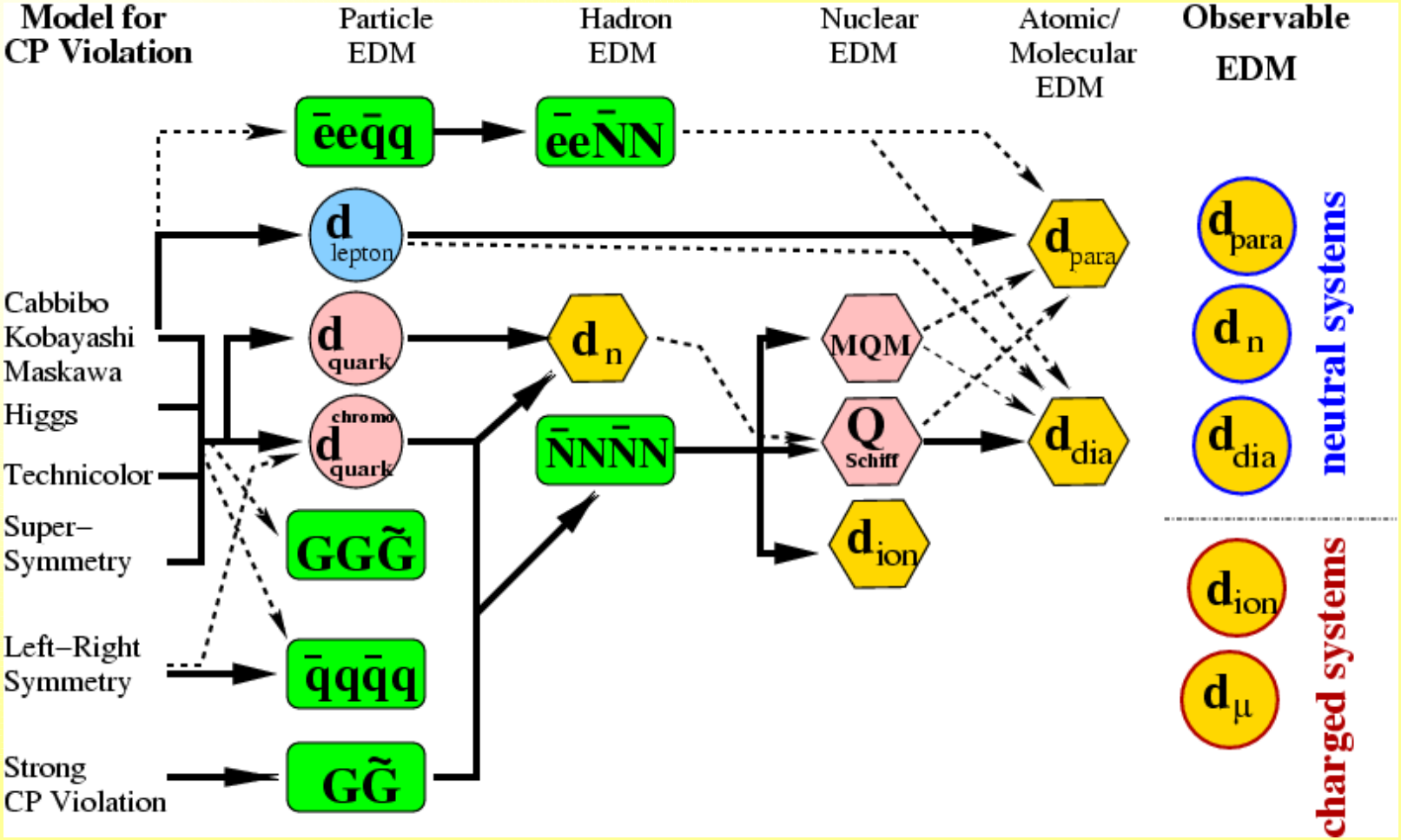
Indirect:

- **Permanent electric dipole moments**
- Correlations in (super-allowed) β-decay

SM values are beyond experimental reach, so **sensitive probe for new physics!**

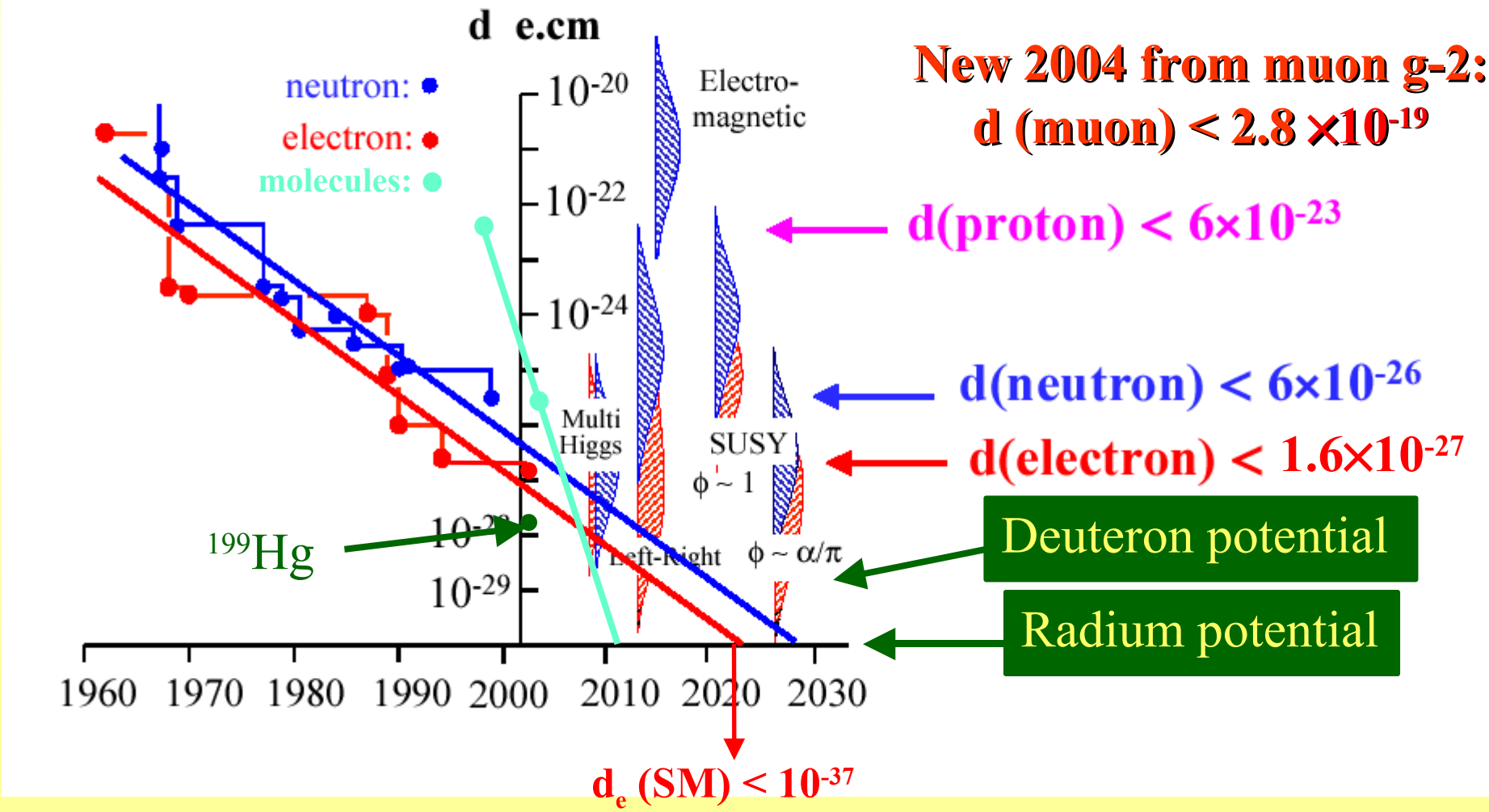
Alternative routes: PMNS, ~~CPT~~, ...

EDM genealogy



Once we found EDM≠0, we need *several* experiments to sort out origin of new sources of ~~CP~~

EDM Experiments Compared



New techniques: radioactive atoms, cryoEDM, liqXe, GGG, storage ring, ...

EM Interaction

$$H_{EM} = \frac{1}{2m}\left(\vec{p} + \frac{e}{c}\vec{A}\right)^2 - e\phi - \vec{\mu}\cdot(\vec{\nabla}\times\vec{A}) + \vec{d}\cdot(\vec{\nabla}\phi - \frac{\partial \vec{A}}{\partial t})$$

Lorentz $\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{v}\times\vec{B}\right)$

"Stern-Gerlach" $\frac{d\vec{p}}{dt} = -\vec{\nabla}\left(\vec{\mu}\cdot\vec{B} + \vec{d}\cdot\vec{E}\right)$

"Larmor" $\frac{d\vec{S}}{dt} = \left(\mu\vec{B} + d\vec{E}\right)\times\hat{S}$

"(Hyper)fine structure" $\Delta E_m \propto -\mu B m_z$

Generic EDM Experiment

1. Prepare of spin polarized ensemble

2. Interaction with electric field

$$\frac{d\langle \vec{S} \rangle}{dt} = \left(\mu \vec{B} + d \vec{E}\right) \times \langle \hat{S} \rangle$$

3. Measure of spin evolution

Uncertainty

The general expression for the uncertainty of an EDM experiment looks like

$$\sigma_d \propto \frac{1}{P\,E\sqrt{N}\,T\,A}$$

N: number of particles in full experiment

P: initial polarization of sample

A: analyzing power of polarimeter

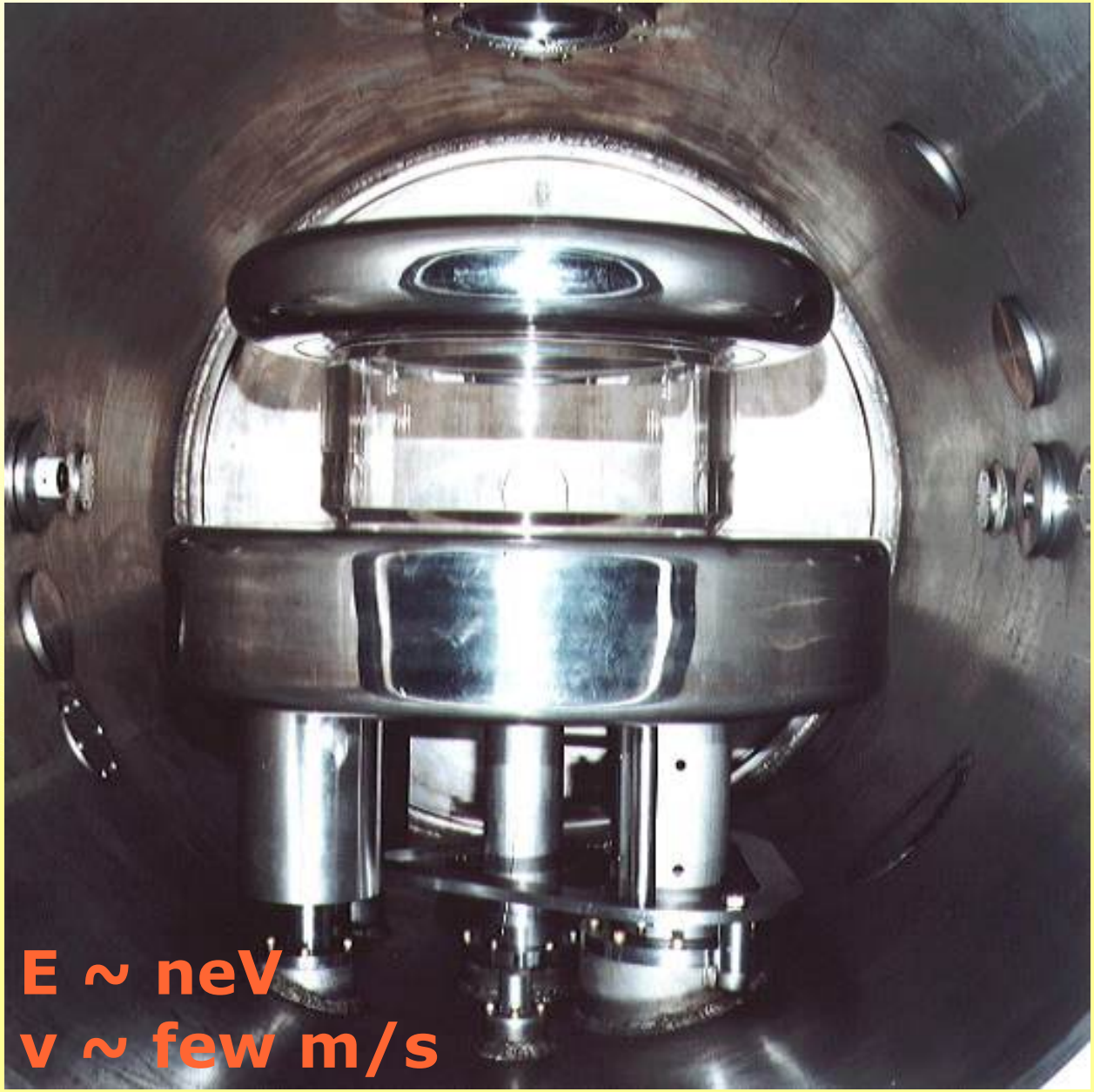
E: electric field strength in particle rest frame

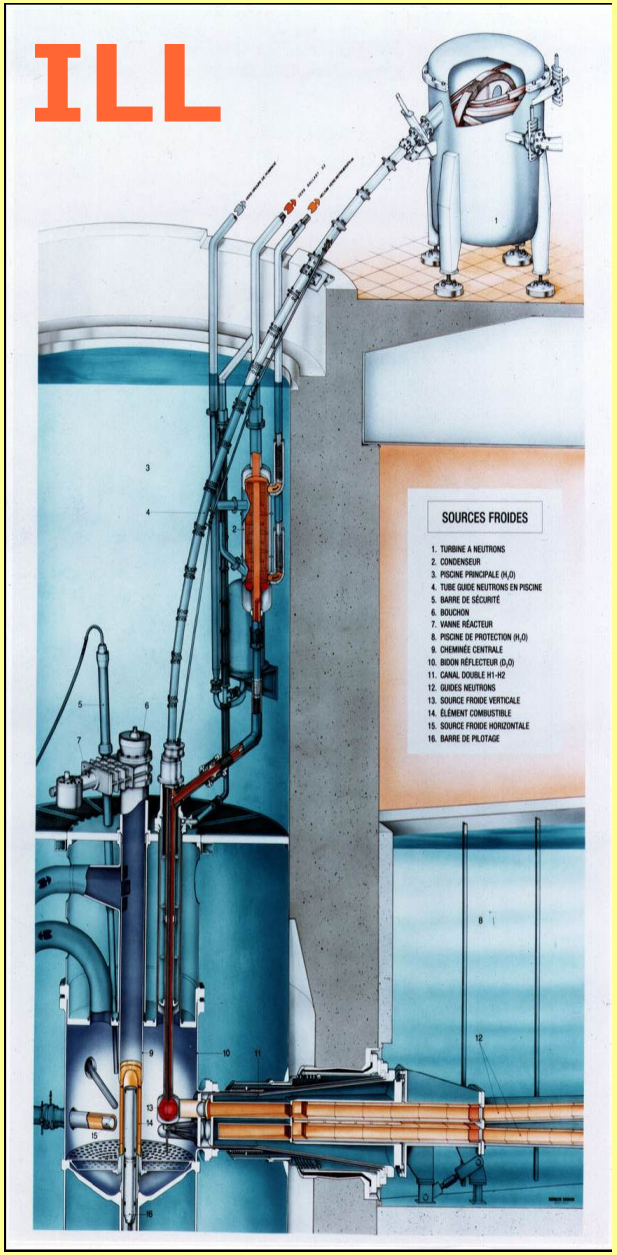
T: characteristic time of a single measurement

The Neutron

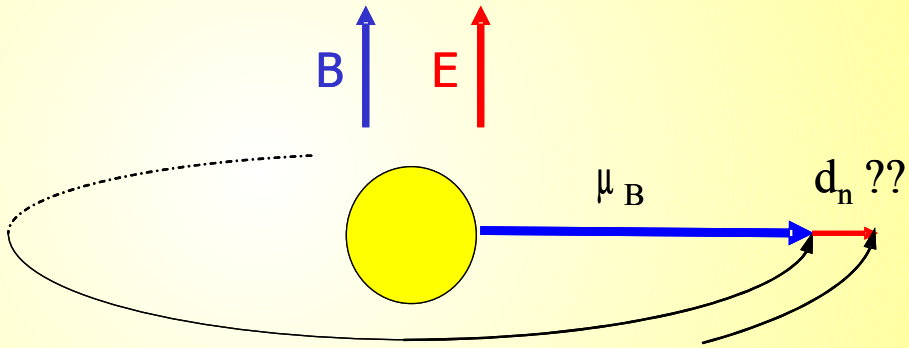
Conceptually the simplest experiment

Ultra Cold Neutrons

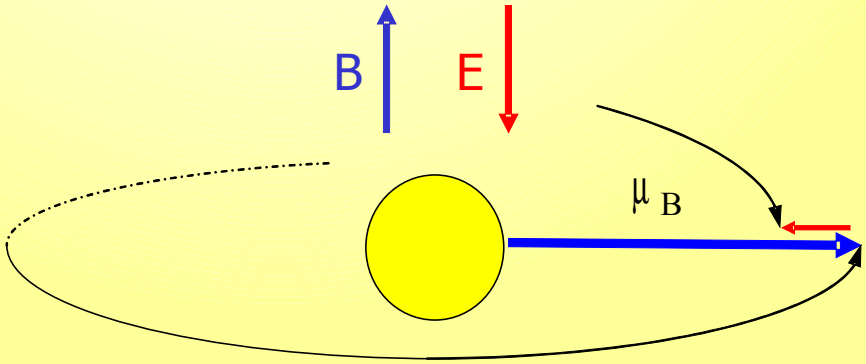




Larmor Precession



$$\nu_{\uparrow\uparrow} = \Delta E_{\uparrow\uparrow}/h = \left[-2B\mu_n - 2Ed_n\right]/h$$



$$\nu_{\uparrow\downarrow} = \Delta E_{\uparrow\downarrow}/h = \left[-2B\mu_n + 2Ed_n\right]/h$$

$$h\left(\nu_{\uparrow\uparrow} - \nu_{\uparrow\downarrow}\right) = 4Ed_n$$

$$\frac{d\langle\vec{S}\rangle}{dt} = \left(\mu\vec{B} + d\vec{E}\right)\times\langle\hat{S}\rangle$$

Ramsey's Oscillatory Fields

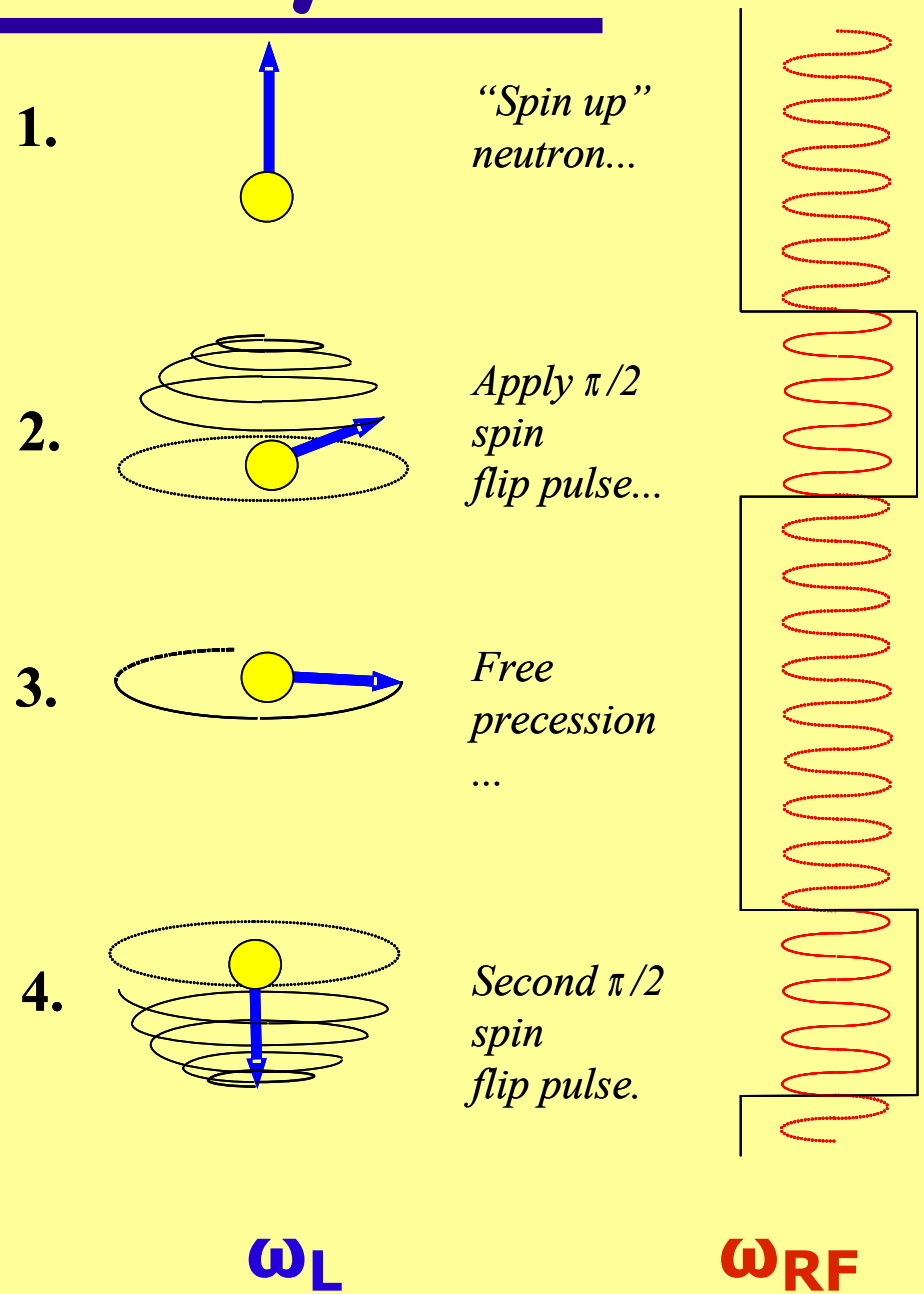
1. Start with neutrons polarized along B

2. Apply oscillating magnetic field to flip polarization sideways

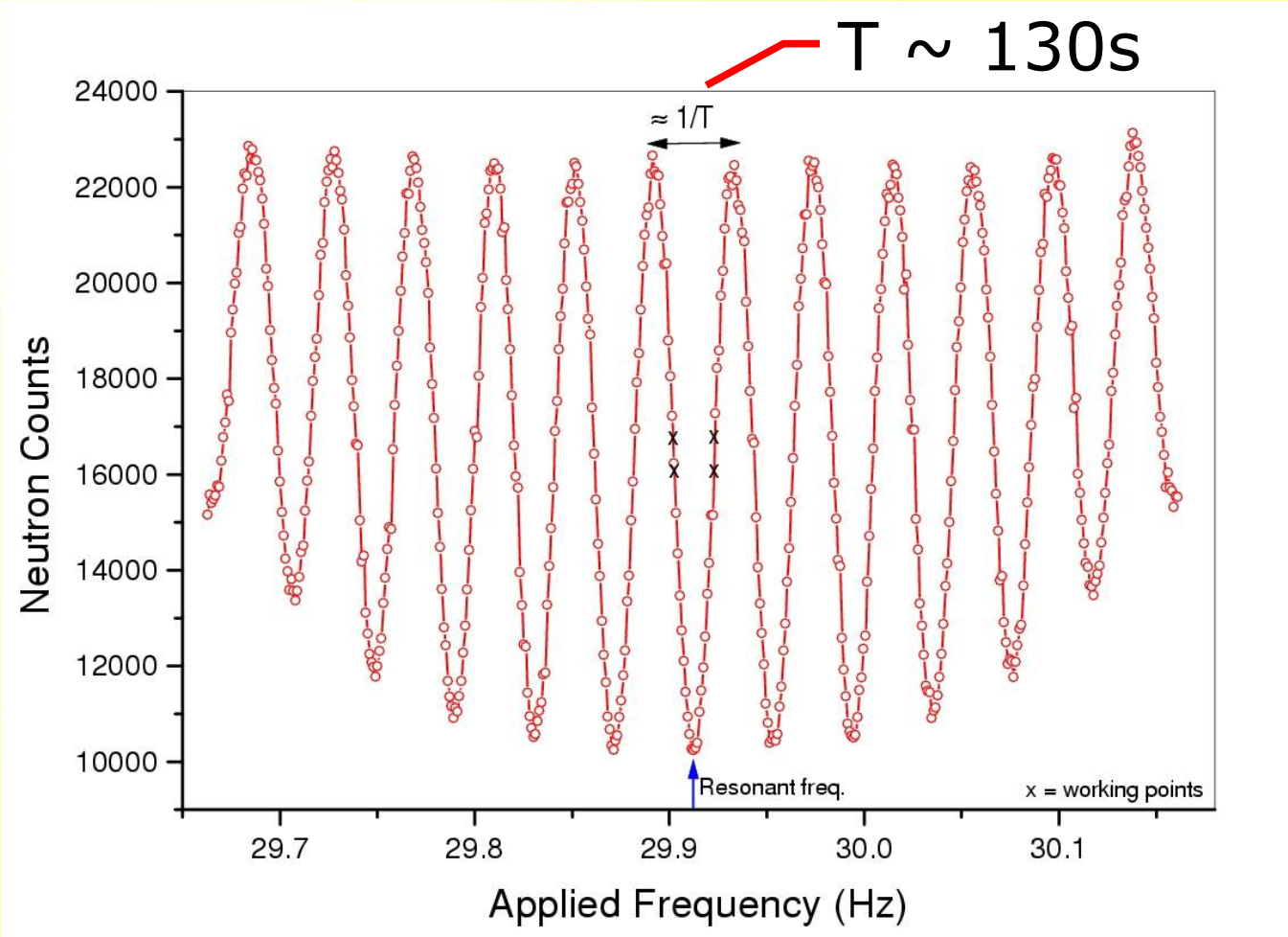
3. Allow free precession

4. Apply second flip and analyze spin

If polarization orientation in phase with oscillating field, polarization ends up anti-parallel to B.



Resonance Curve

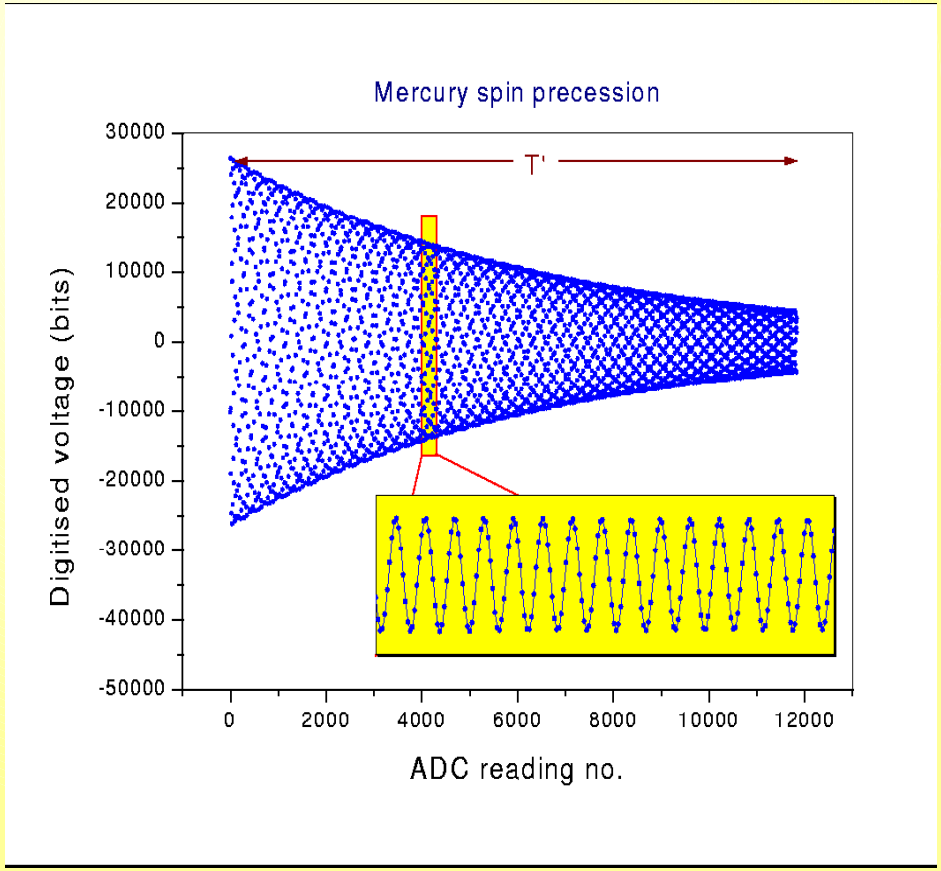


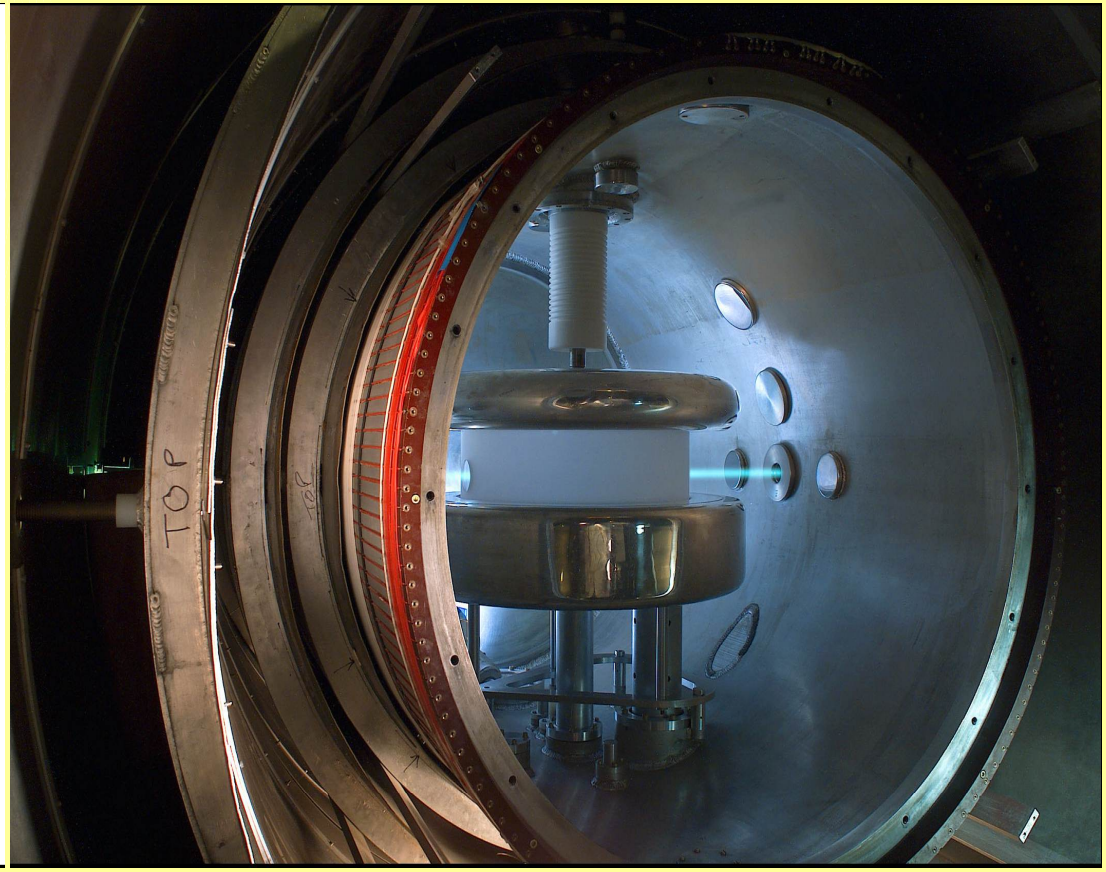
Asymmetry from polarization and polarimeter ~ 0.5

$$\frac{d\langle\vec{S}\rangle}{dt}=\left(\mu\vec{B}+d\vec{E}\right)\times\langle\hat{S}\rangle$$

Sensitivity to ω_{RF}

^{199}Hg Co-Magnetometer

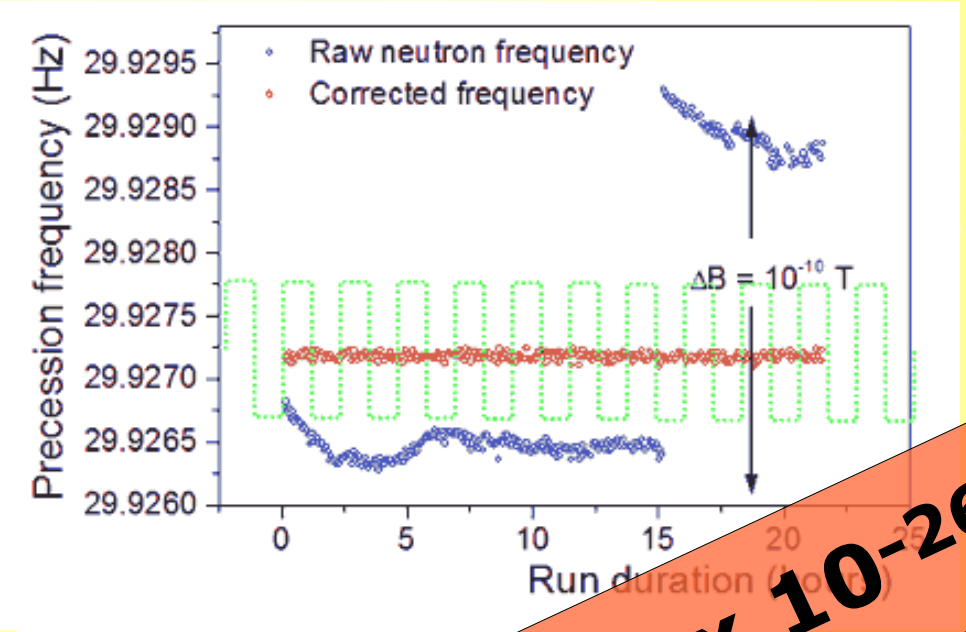


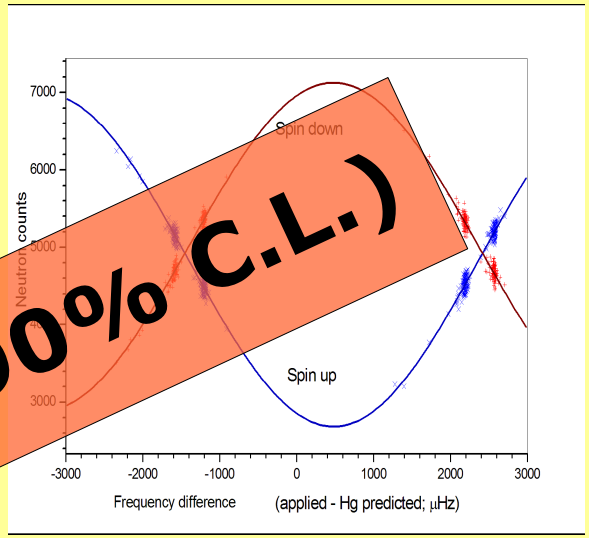


$$\frac{d\langle\vec{S}\rangle}{dt}=\left(\mu\vec{B}+d\vec{E}\right)\times\langle\hat{S}\rangle$$

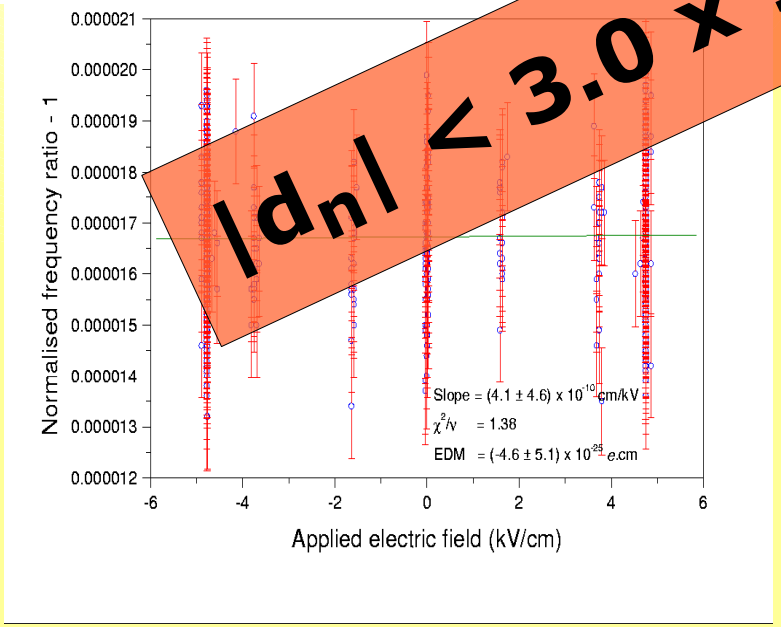
Variation of ω_L and B (~1μT)

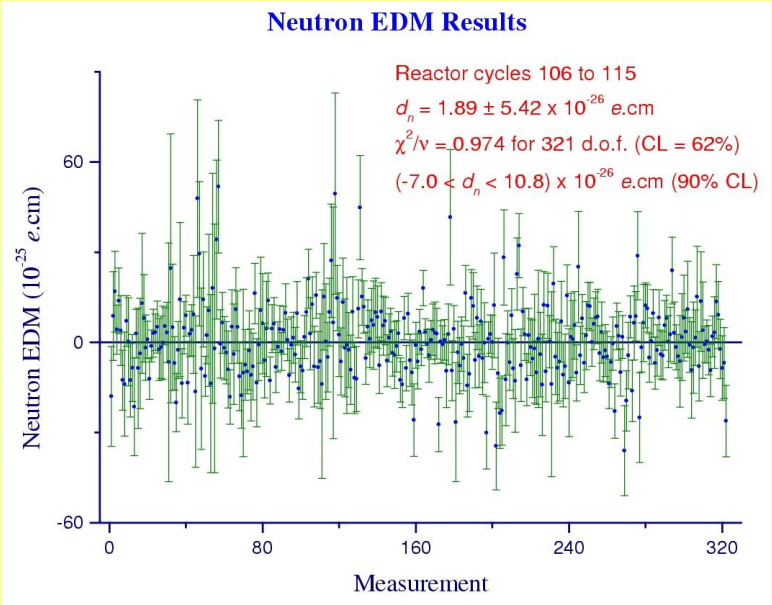
Putting Things Together





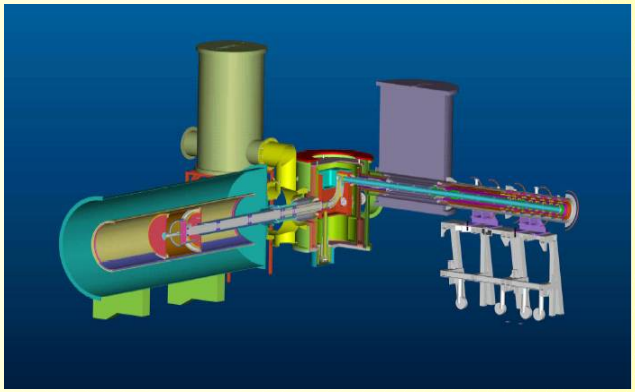
$|d_n| < 3.0 \times 10^{-26}$ e·cm (90% C.L.)

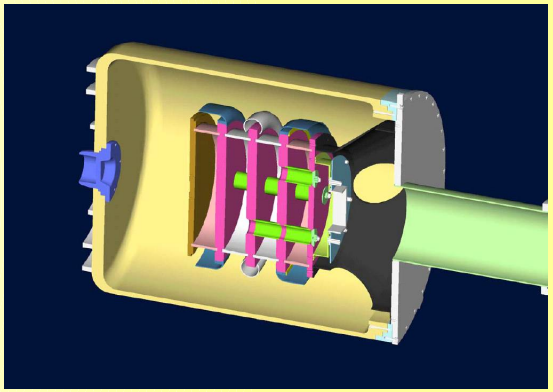




P.G. Harris et al., PRL 82, 904 (1999)
C.A. Baker et al., submitted to PRL (2006)

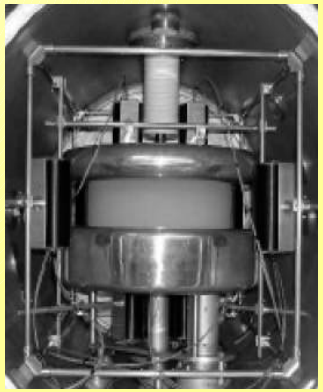
Future Experiments



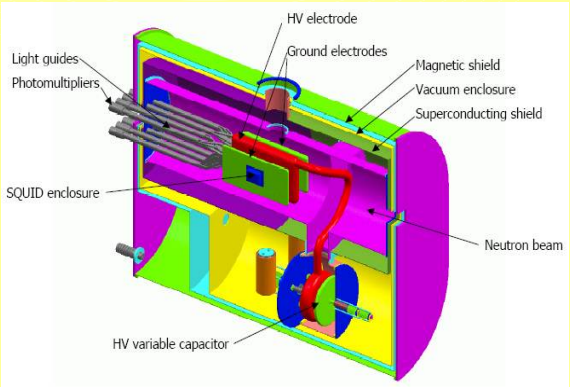


CryoEDM @ ILL
liqHe UCN production
Improve 100x?
Start Oct. 2006

nEDM @ PSI
solid^{2}H UCN production
High intensity expected
Use ILL device



Ultra Cold Neutron Source



nEDM @ SNS
Improve 100x?
3He comagnetometer?
SQUID readout
~2011

Nuclei

Diamagnetic Atoms

Schiff Screening

Measurability of Nuclear Electric Dipole Moments

"It is shown that for a quantum system of point, charged, electric dipoles, in an external electrostatic potential of arbitrary form, there is complete shielding; there is no term that is of first order in the EDMs [...] This is true even if the particles are of finite size provided that the charge and dipole moment [...] have the same spatial distribution. Relativistic and second order effects are uninterestingly small."

"There is, however, a first-order interaction if the charge and moment distribution are different, and also for a point dipole if it also carries a magnetic dipole moment."

L.I. Schiff, PR 132, 2194 (1963)

Schiff Moment

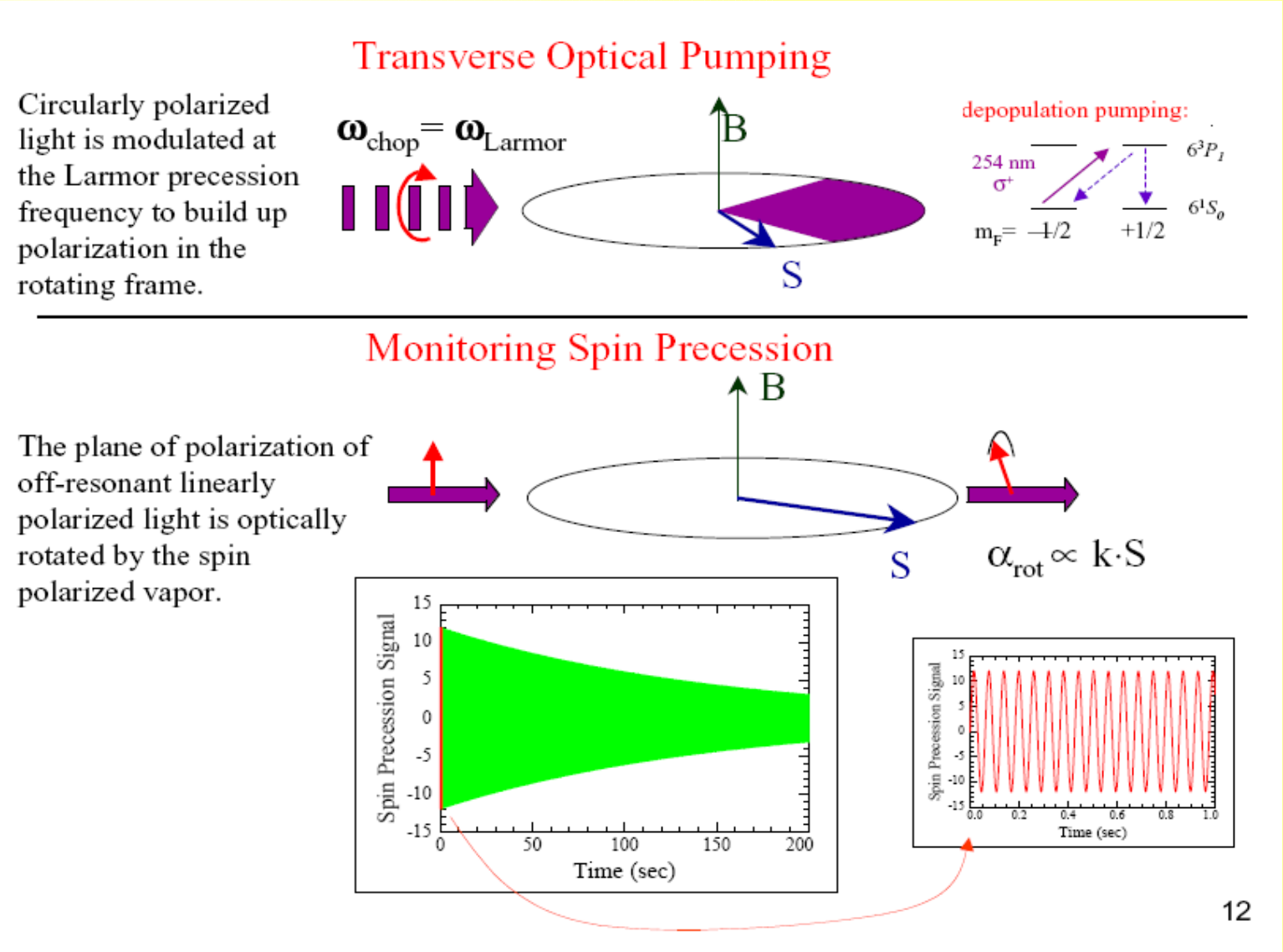
From average interaction between electrons and nucleus, atom acquires a so-called Schiff moment

$$\vec{S} = \frac{1}{10} \int d\vec{r}\, \rho_{ch}(\vec{r}) \left(r^2 - \frac{5}{3} \langle r_{ch}^2 \rangle \vec{r} \right)$$

With relativistic effects

$$\frac{S}{D} \propto 10\, Z^2 \left(\frac{R_N}{R_A} \right)^2 \sim 10^{-3}$$

^{199}Hg Principle

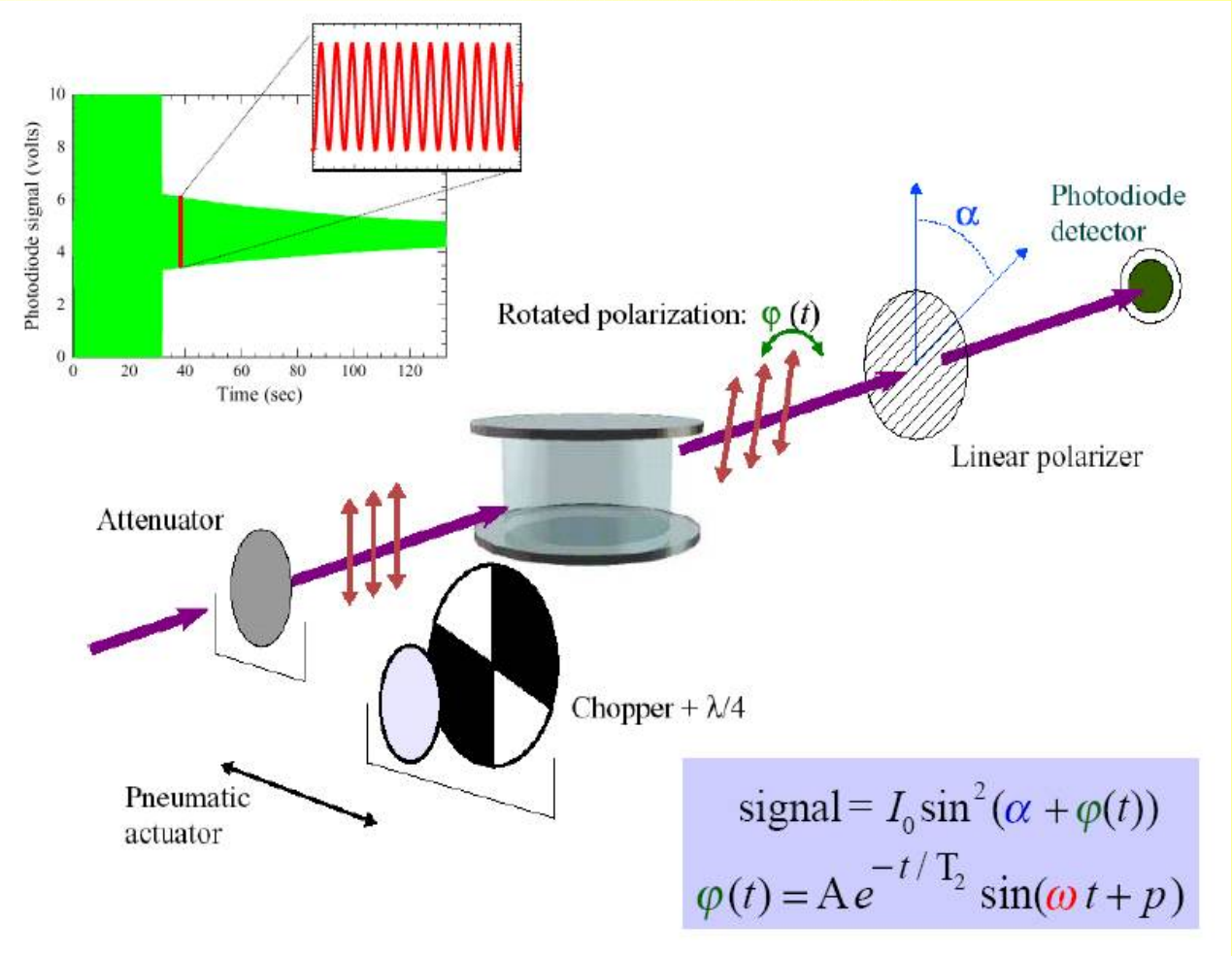


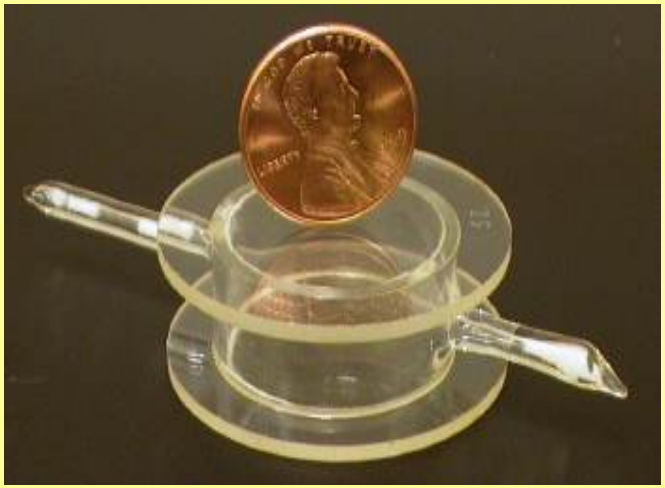
Optical pumping

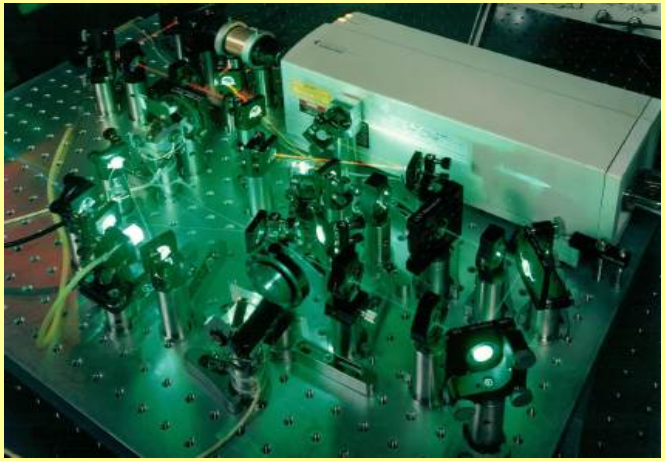
Optical readout

Romalis, Griffith, Jacobs, Fortson, PRL 86, 2505 (2001)

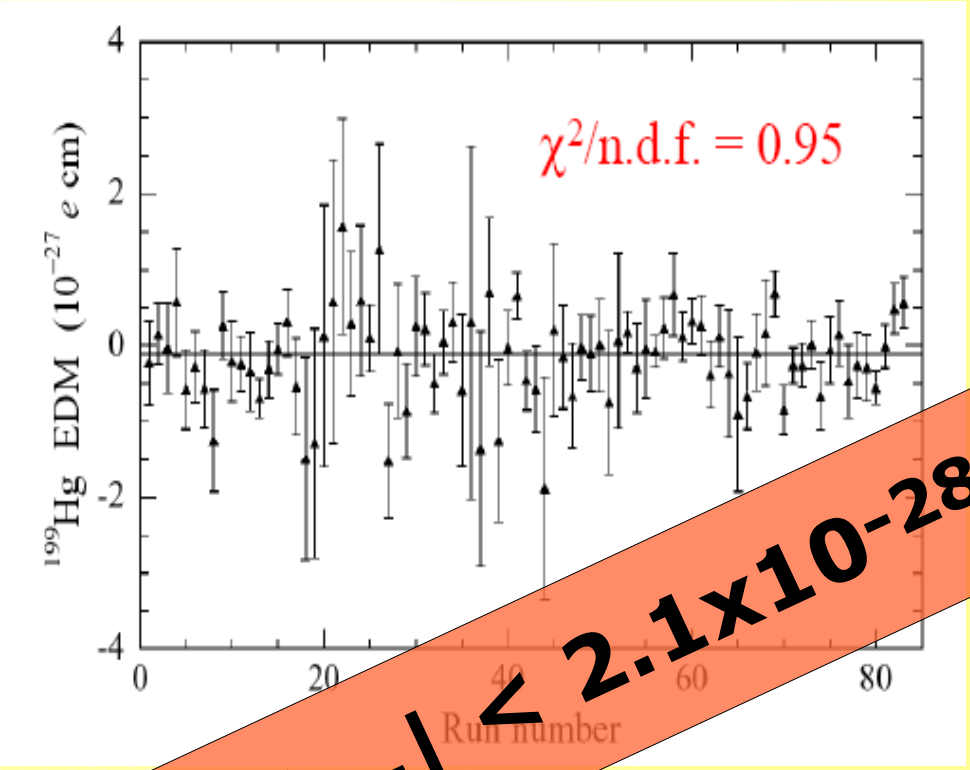
Setup

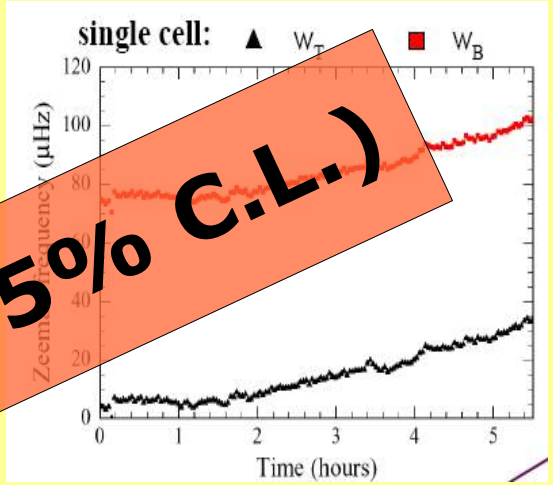

Photodiode signal (volts)
Time (sec)
Rotated polarization: φ (t)
α
Photodiode detector
Linear polarizer
Attenuator
Chopper + λ/4
Pneumatic actuator
$\text{signal} = I_0 \sin^2(\alpha + \varphi(t))$
$\varphi(t) = A e^{-t/T_2} \sin(\omega t + p)$

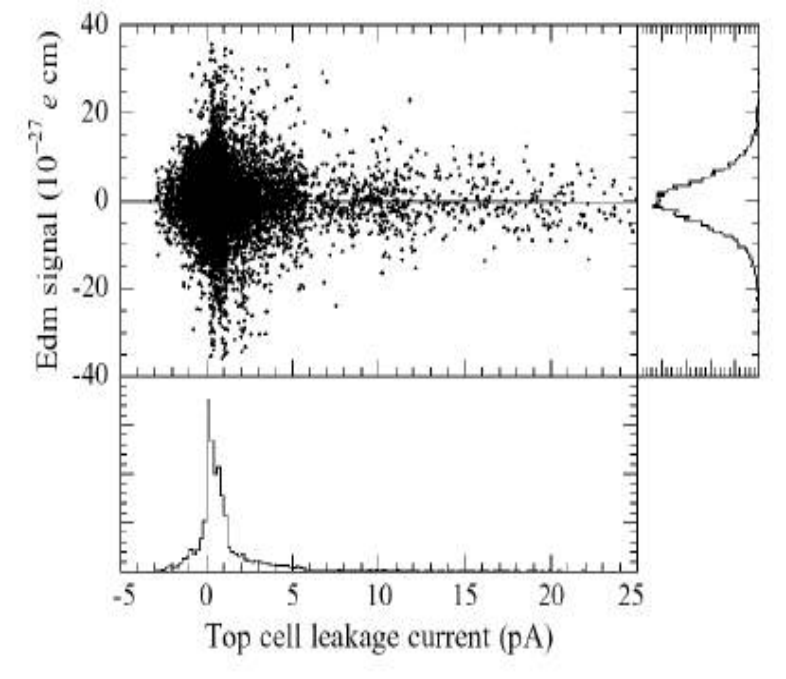




Result

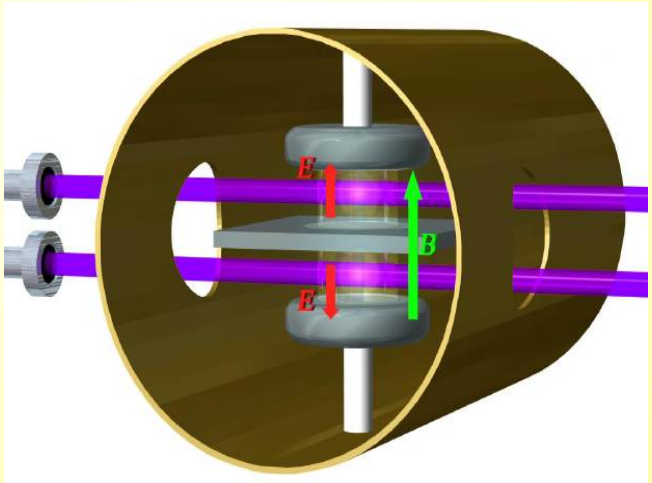


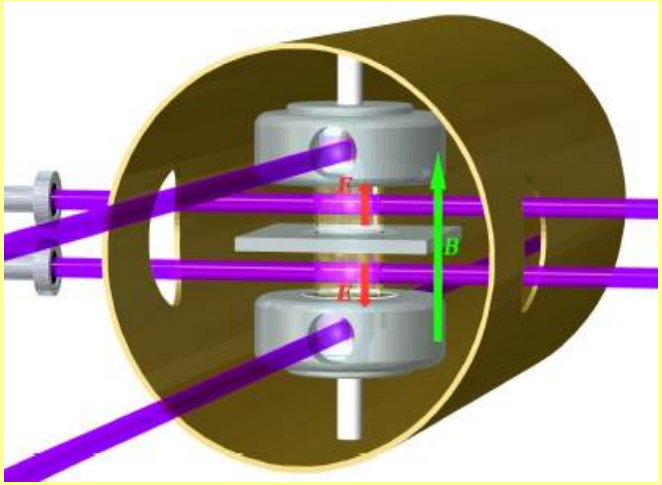




$|d_{Hg}| < 2.1\times10^{-28}$ e·cm (95% C.L.)

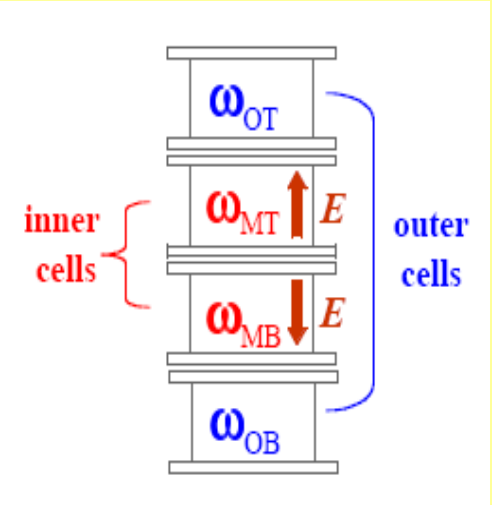
Upgrades





Upgrade to quad-cell setup

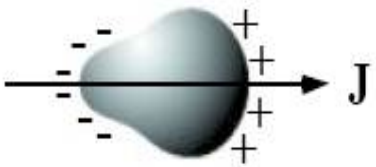
Hope for factor 5 improvement



Octupole Deformation

Expect large enhancement of Schiff Moment for octupole deformed nuclei (200x ^{199}Hg)

$$S \sim \frac{\langle +|\eta r^3 \cos\theta|- \rangle}{E_+ - E_-} \sim \frac{\eta \beta_2 \beta^2{}_3 Z A^{2/3} r_0{}^3}{E_+ - E_-}$$



	223Rn	223Ra	225Ra	223Fr	225Ac	229Pa	199Hg	129Xe
t_{1/2}	23.2 m	11.4 d	14.9 d	22 m	10.0 d	1.5 d		
I	7/2	3/2	1/2	3/2	3/2	5/2	1/2	1/2
ΔE_{th}* (keV)	37†	170	47	75	49	5		
ΔE_{exp} (keV)	--	50.2	55.2	160.5	40.1	0.22		
10^5 S (efm^3)	1000	400	300	500	900	12000	-1.4	1.75
10^{28} d_A (e-cm)	**3300**	**3300**	**2500**	**2800**			-5.6	0.8

Ref: Dzuba PRA66, 012111 (2002) - Uncertainties of 50%

Experiments planned on Ra (KVI, ANL), Rn (TRIUMF)

Electron

Paramagnetic Atoms and Molecules

Electron EDM in Alkali

Static: $\Sigma F = ma = 0$

$$\Sigma F = eE_{ext} + eE_{int} + \nabla U_{spin\text{-}orbit}$$

$$\boxed{\nabla U_{spin\text{-}orbit} = -\mu\cdot(v \times E) \qquad \textbf{non-electrical force}}$$

$$E_{int}/E_{ext} \approx p/m = (Z\alpha)^2\, r_N^3$$

Nucl	Z	E_{int}/E_{ext}
Li	3	0.0294
Na	11	0.240
K	19	1.99
Rb	37	19.5
Cs	55	94.0
Ag	79	327.5
Tl	81	-419.5
Fr	87	~600

Single unpaired electron

^{205}Tl Experiment

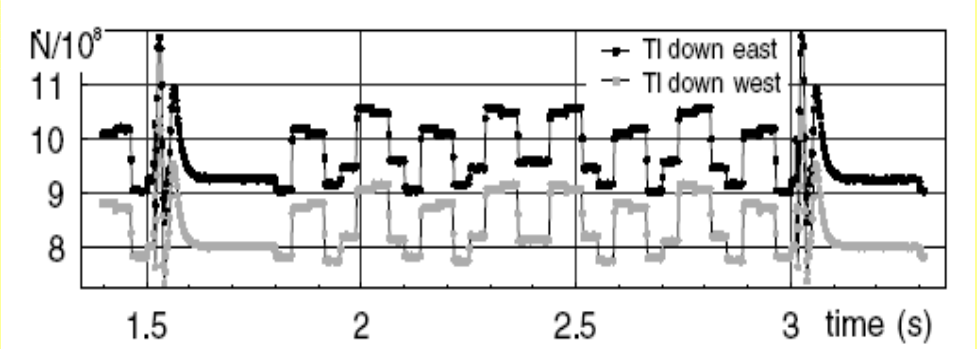
Polarization (pump)/
Polarimetry (fluorescence)

RF $\pi/2$ flipper

256 Independent measurements

E/B field

φ_{RF} : $\pm(90° \pm 45° \pm 1°)$
field : $\pm E$, $\pm B$
beam : up/down/east/west
HV cable : $\pm$polarity



Atomic Beam Sources

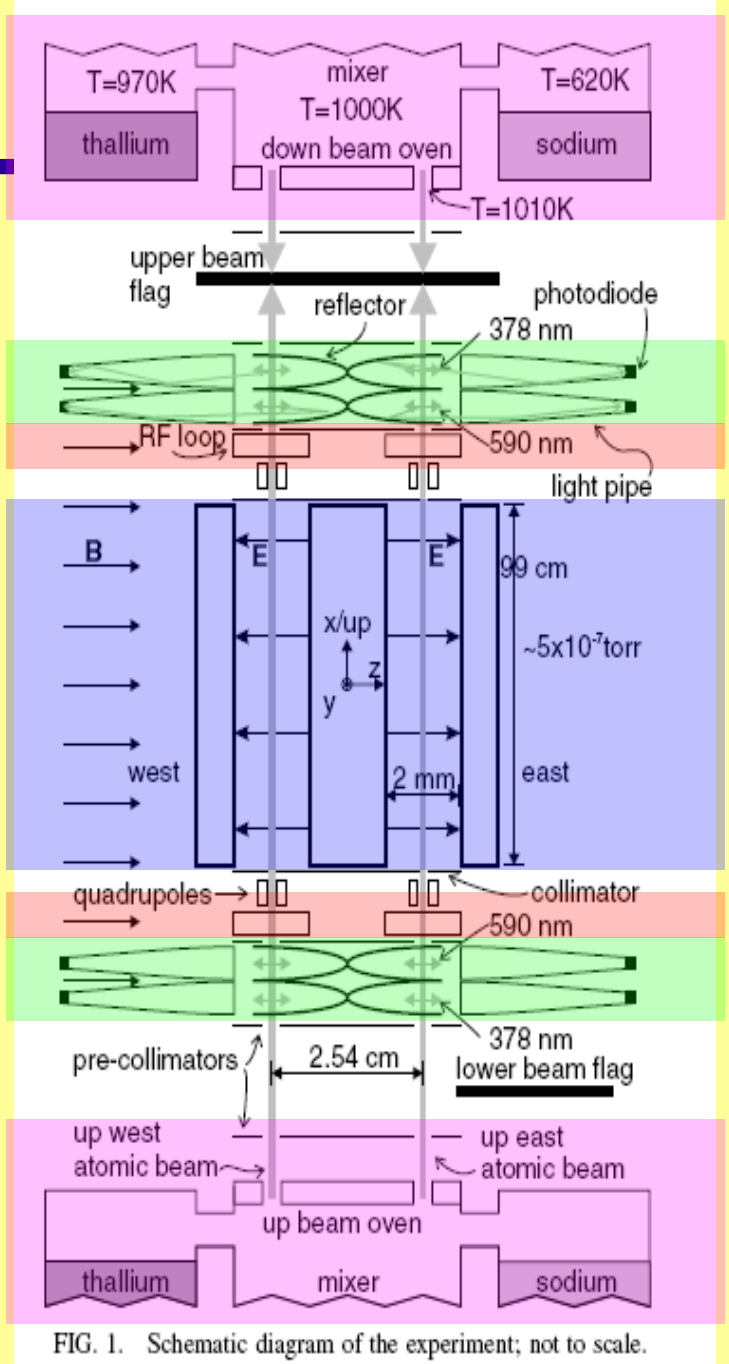


FIG. 1. Schematic diagram of the experiment; not to scale.

Regan, Commins, Schmidt, and DeMille, PRL 88, 071805 (2002)

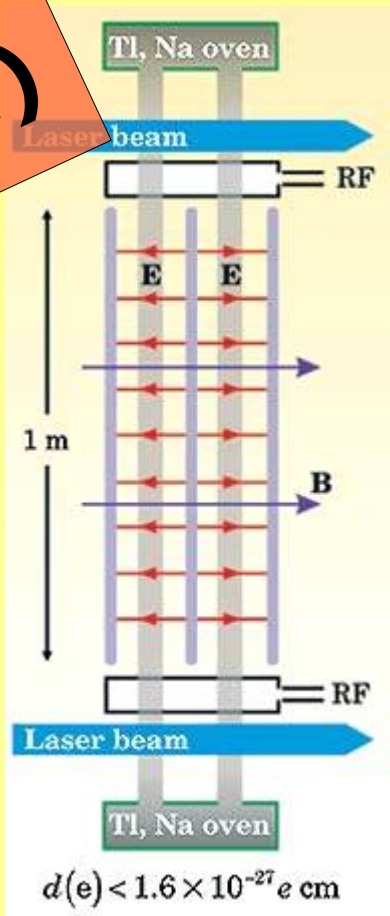
From atom to electron

In heavy atoms, $d_{atom} = R \cdot d_e$; for ^{205}Tl, R=-585

Experiment systematics limited

Need to cancel $B_{motional}=vxE$ effect to 1:10^8
Control B to 1fT level
Further improvement unlikely

$|d_e| < 1.6 \times 10^{-27}$ e·cm (90% C.L.)



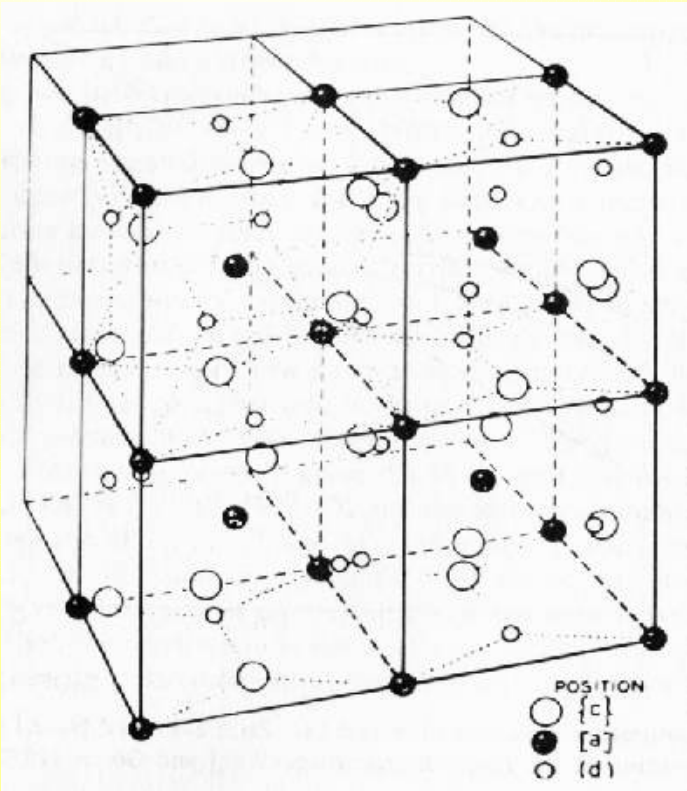
Other eEDM

Group	System	Advantages	Projected gain
D. Weiss (Penn St.)	Trapped Cs	Long coherence	~100!
D. Heinzen (Texas)	Trapped Cs	Long coherence	~100!
H. Gould (LBL)	Cs fountain	Long coherence	?
L. Hunter (Amherst)	GdIG solid	Huge S/N	100?
S. Lamoreaux (LANL) C.-Y. Liu (Indiana)	GGG solid	Huge S/N	100?-100,000?
E. Hinds (Imperial)	YbF beam	Large Internal E	2-3
D. DeMille (Yale)	**PbO* cell**	**Int.E+good S/N**	**30!-1,000?**
E. Cornell (JILA)	trapped HBr^+	Int. E + long T	??
N. Shafer-Ray (Okla.)	trapped PbF	Int. E + long T	??

From deMille

Solids

GdIG – $Gd_3^{3+}Fe_2^{3+}Fe_3^{3+}O_{12}$



When μ's aligned, also d's aligned

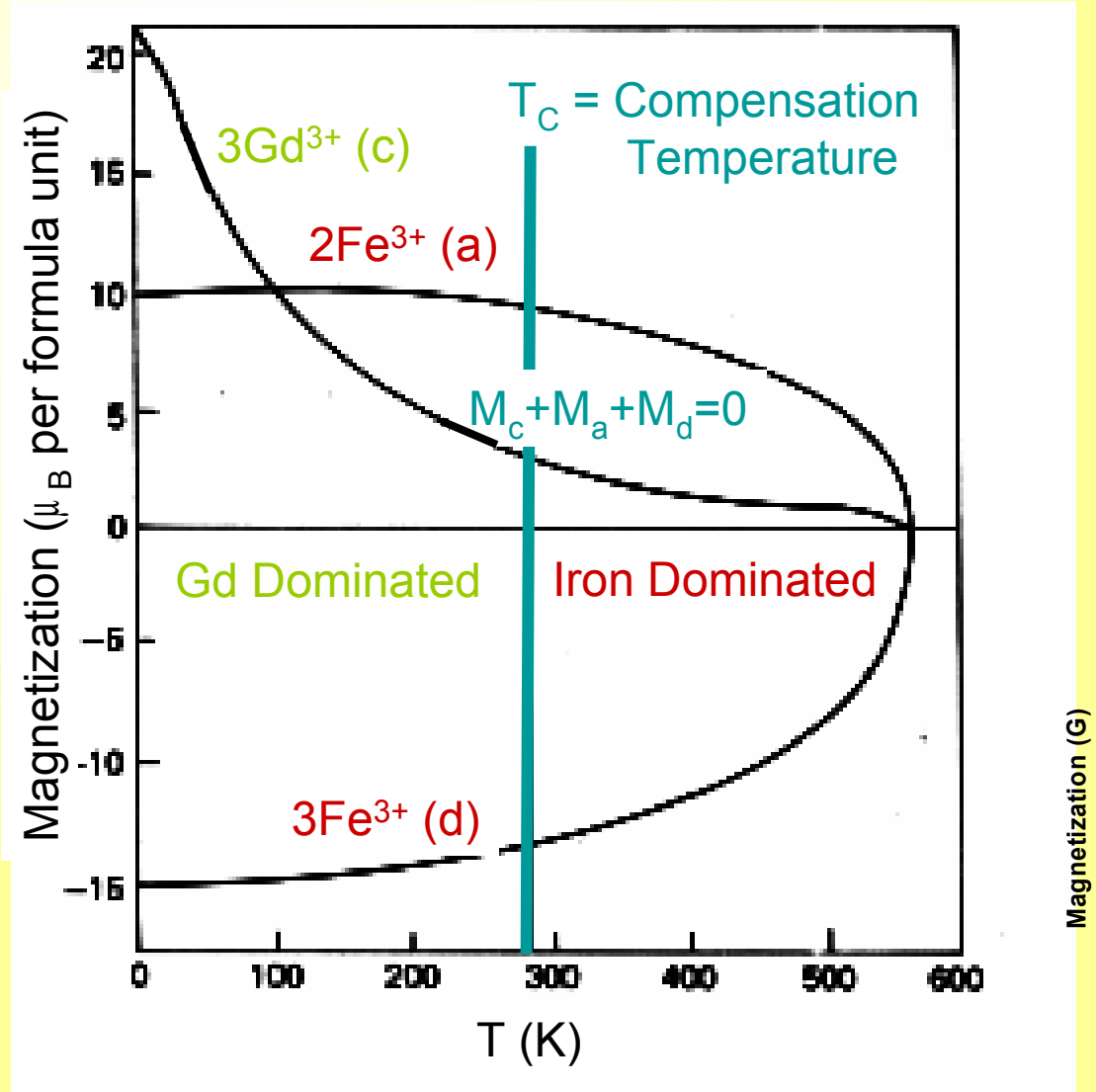
apply electric field and measure magnetization (GdGG at LANL)

apply magnetic field and measure voltage (GdIG at Amherst)

Present limit: 1.1nV/10cm @ 0K
In a few 100s, 1-2 orders better (stat).

B. J. Heidenreich, et al. PRL 95 (2005) 253004

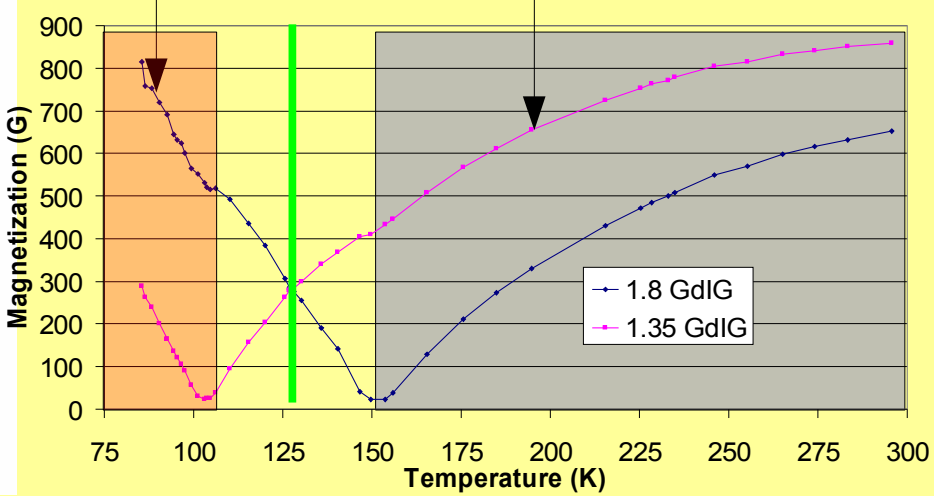
Alignment of Gd^{3+}



By replacing Gd with Y T_C can be adjusted

Gd parallel to B

Gd antiparallel to B



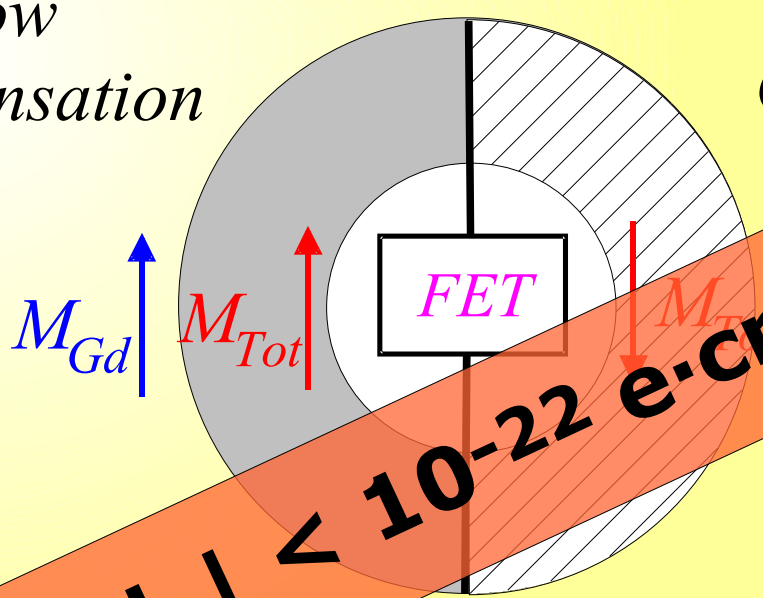
Experimental Setup

((1.8Gd, 1.2Y)IG

Below Compensation T

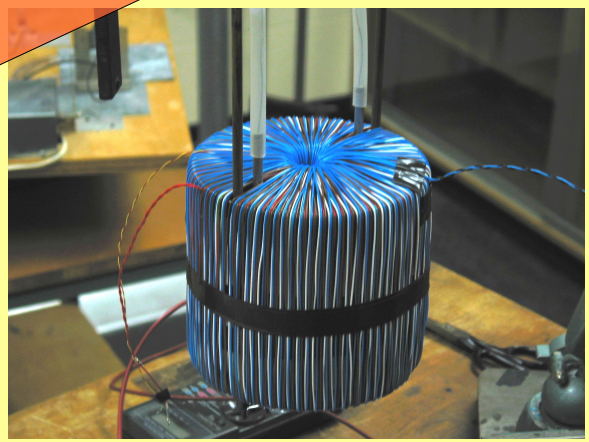
((1.35Gd, 1.65Y)IG

Above Compensation T

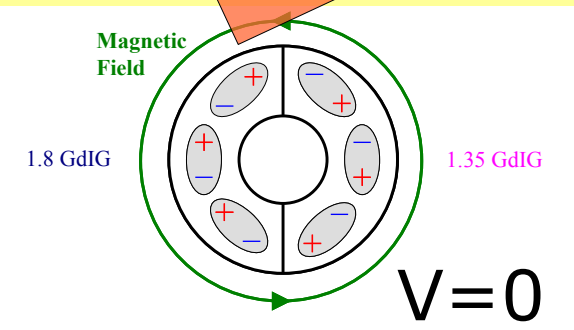


|dₑ| < 10-22 e·cm (90% C.L.)

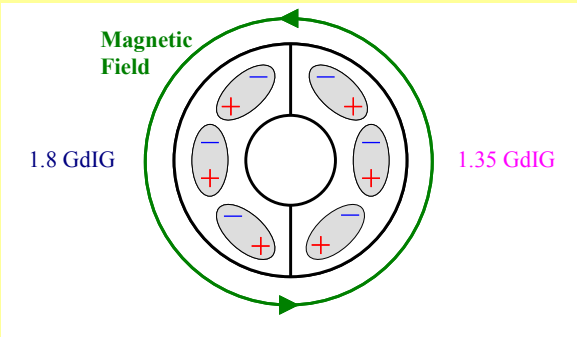
2″ x 4″



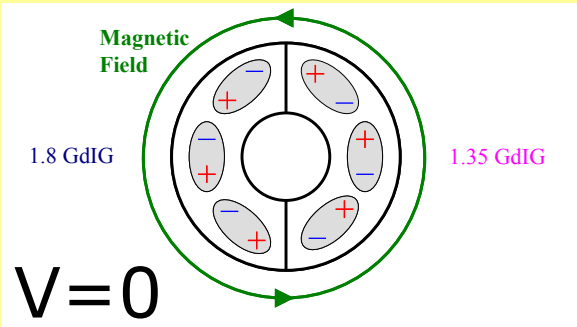
170K



127K

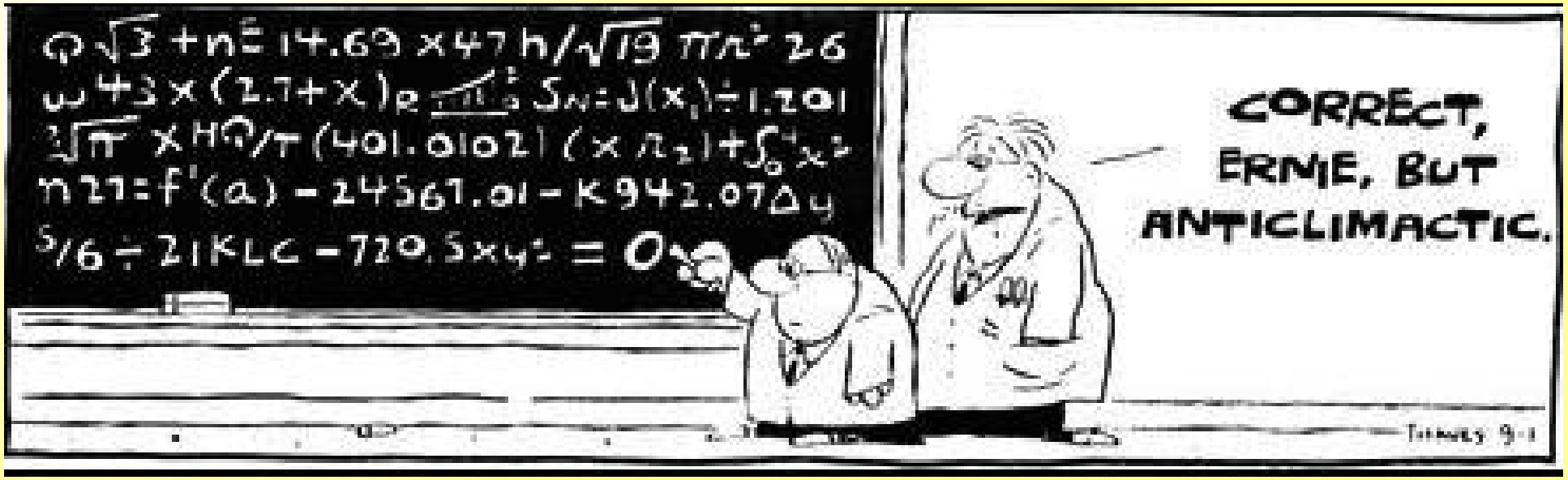


80K



Now let's go for something positive ...

Proton, deuteron, muon, ...



Courtesy Maurits v.d. Grinten