Electric dipole moments: theory and experiment

EA Hinds

Blois June 2002

Two motivations to measure EDMs

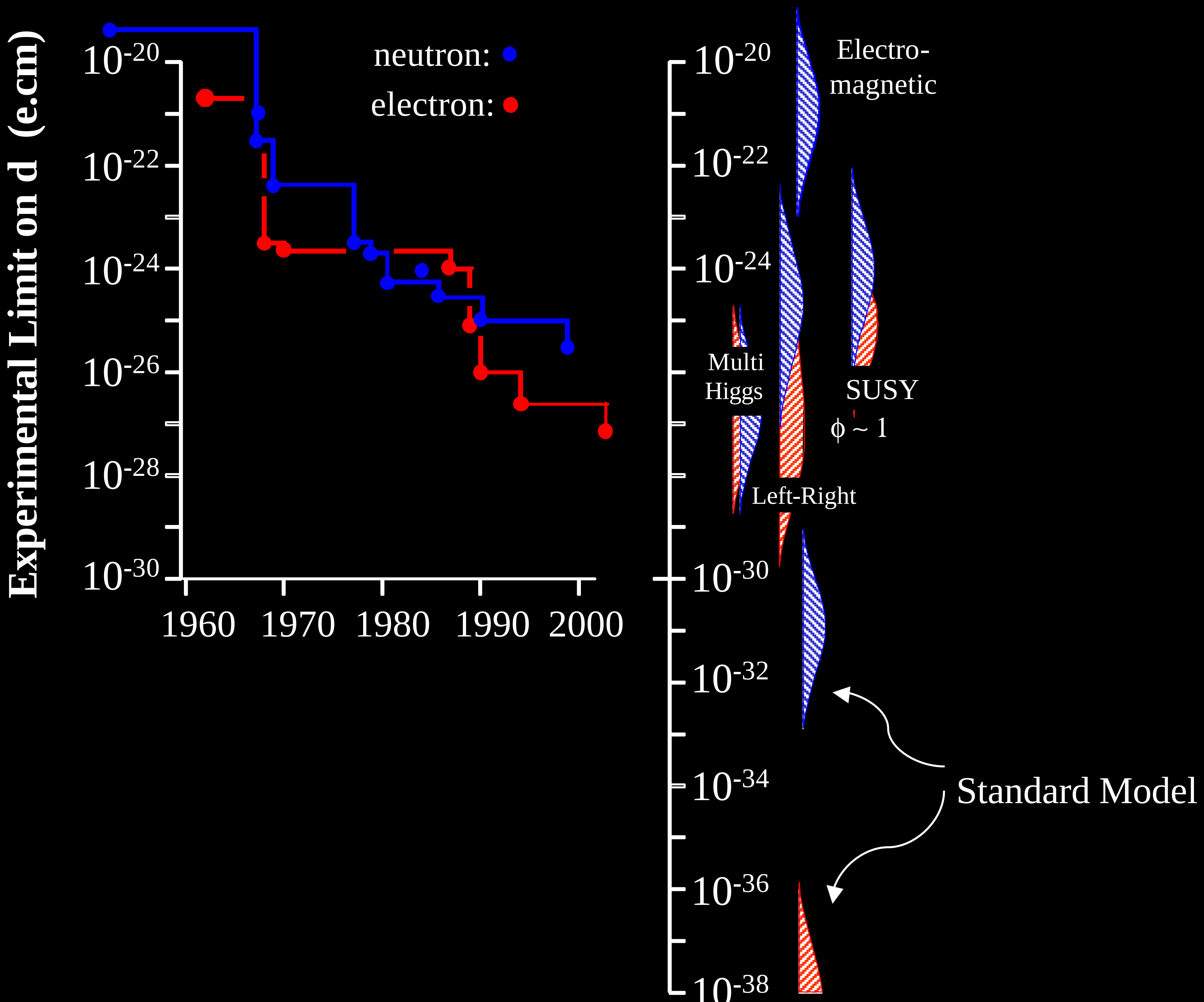
EDM violates T symmetry

➡ **Deeply connected to CP violation and the matter-antimatter asymmetry of the universe**

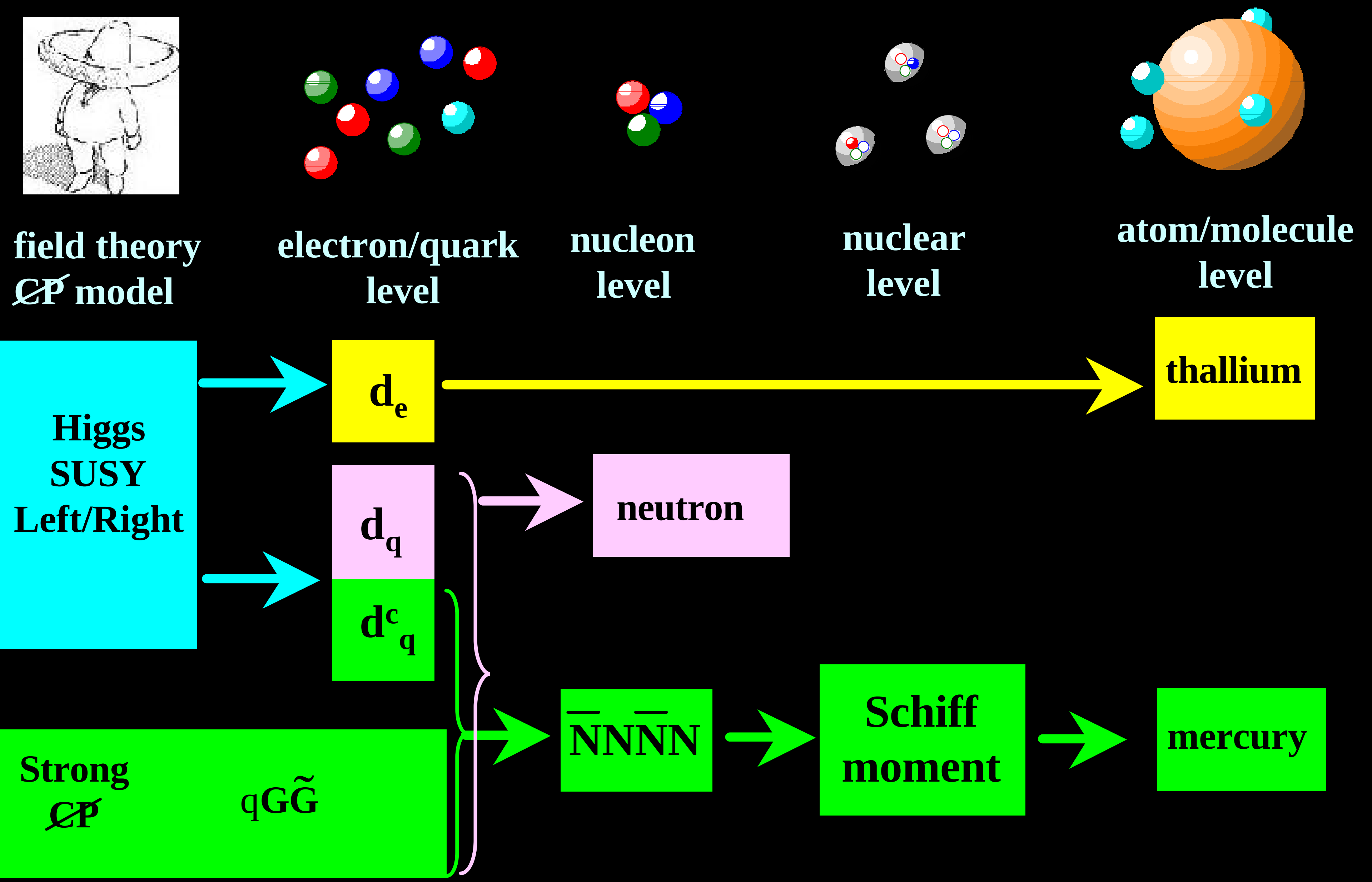
EDM is effectively zero in standard model
but
big enough to measure in non-standard models

➡ **direct test of physics beyond the standard model**

A bit of history



$\not{CP}$ from particles to atoms (main connections)



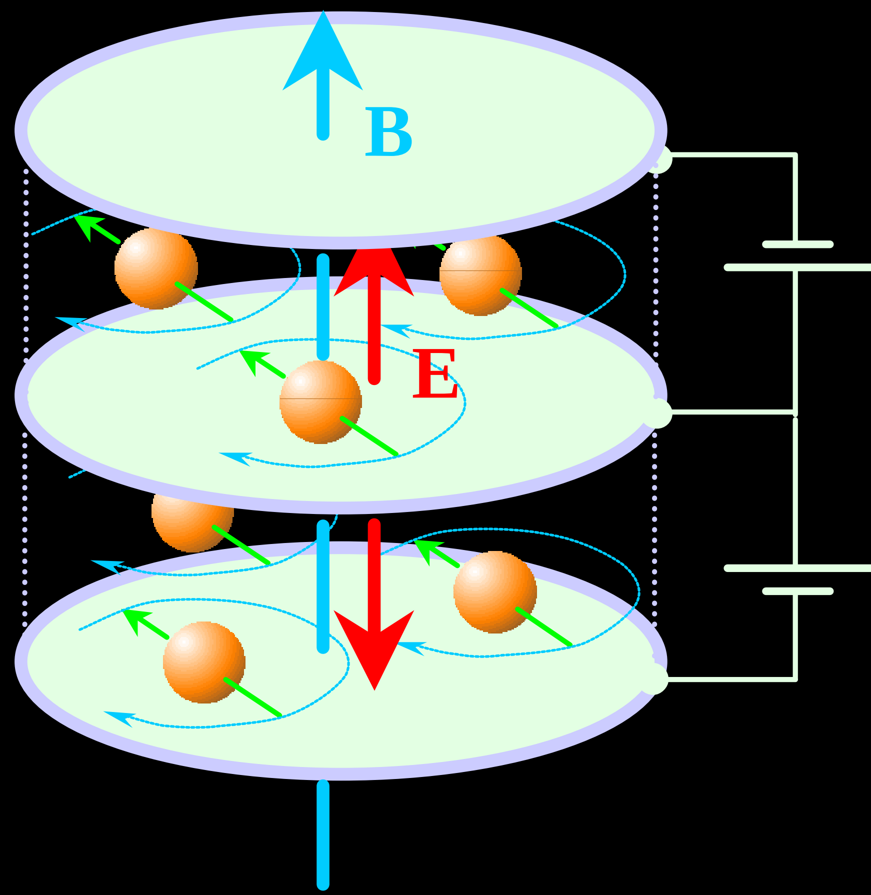
The Mercury EDM experiment

University of Washington, Seattle
M.V. Romalis, W.C. Griffith, J.P. Jacobs, E.N. Fortson

Nuclear spin polarised ^{199}Hg vapor in a double cell

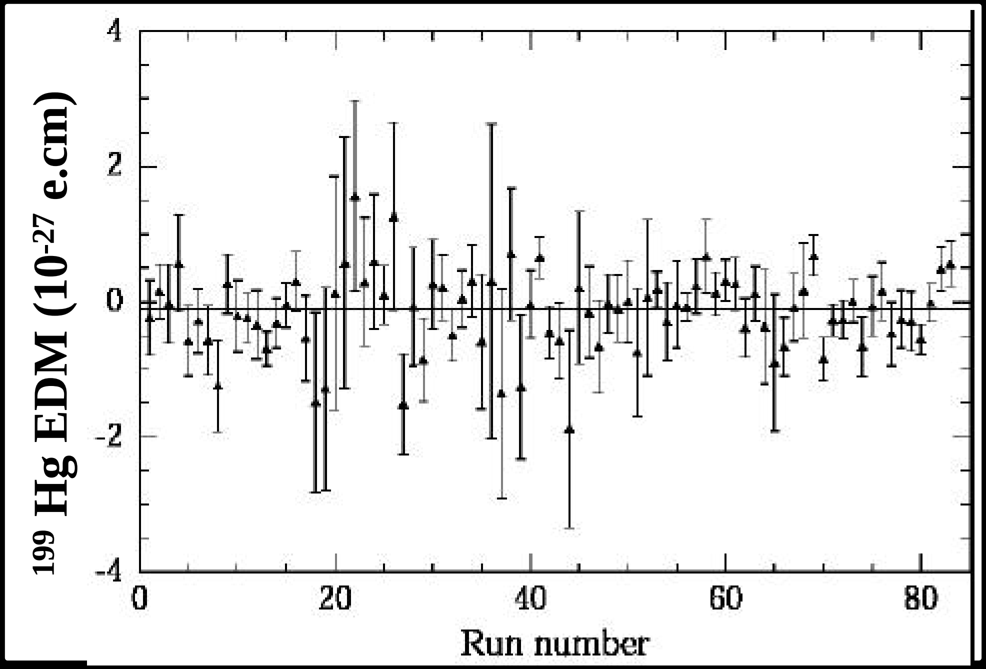
$\hbar w_{\pm} = m\mathbf{B}$ + dE

$\hbar w_{\pm} = m\mathbf{B}$ - dE



$w_{\pm}$ measured optically

Difference of precession frequencies gives ^{199}Hg EDM



E = 9 kV/cm

B = 15 μT stable to 0.4 pT

$T_{coherence}$ ~ 100 s

Hg edm result:

Phys. Rev. Lett. **86,** 2505 (2001)

$$|d_{Hg}| < 2.1\times10^{-28}\ e\ \mathrm{cm}$$

The Neutron EDM

Rutherford-Appleton Laboratory

CA Baker, K Green, P Iaydjiev, S Ivanov

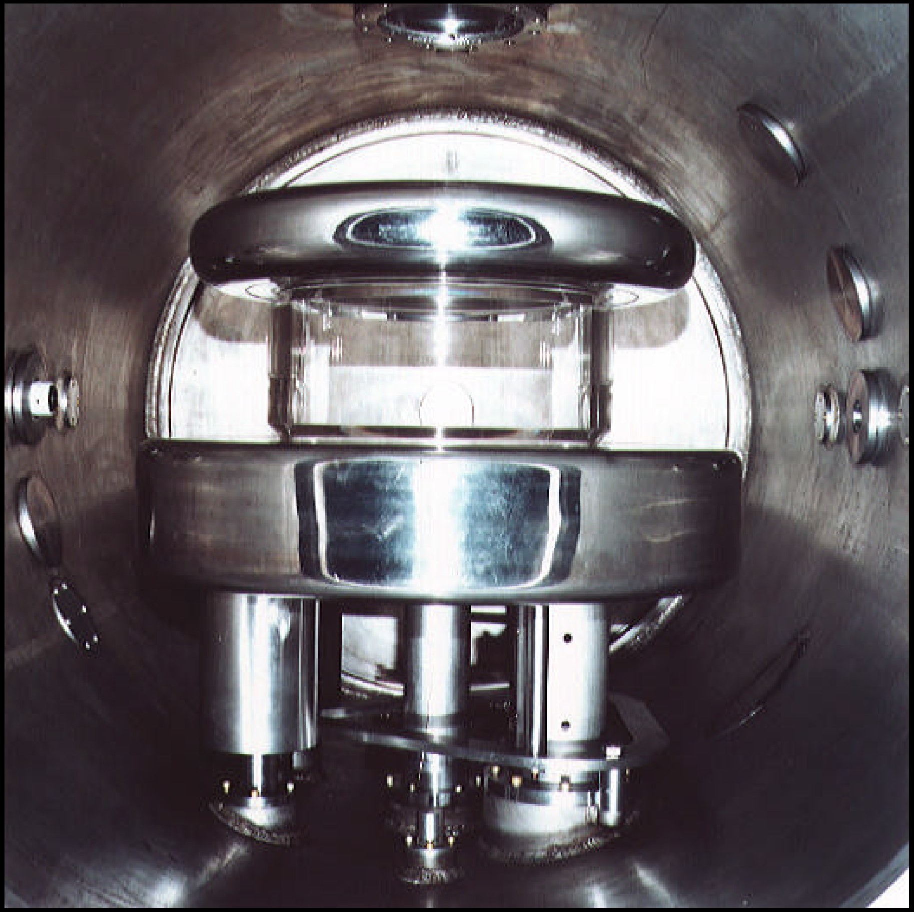
Sussex University

S Al-Ayoubi, PG Harris, JM Pendlebury, JD Richardson, D Shiers, K F Smith, M van der Grinten

ILL

P Geltenbort

- **Ultracold neutrons in a bottle precess at frequency $(m_n B \pm d_n E)/\hbar$**
- **Reverse E to measure d_n**



$E = 4.5$ kV/cm

$B = 1\ \mu T$

$T_{coherence} \sim 130$ s

Hg co-magnetometer

(B is measured to 1 pT rms)

Neutron edm result:

Phys. Rev. Lett. **82,** 904 (1999)

$|d_n| < 6.3\times10^{-26}\ e$ cm

Neutron: longer range plans

New moderators using liquid helium or solid deuterium

- **Helium (ILL, LANL)**
  - ***Inside the helium***
  - ***Higher neutron density***
  - ***Higher E field***

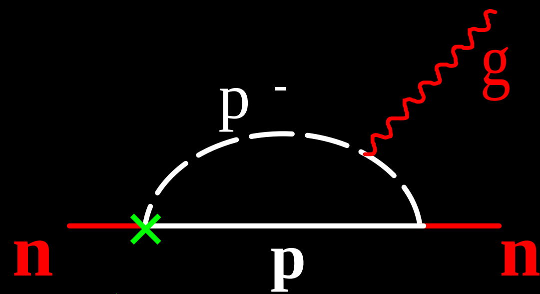
- **Deuterium (PSI, TU-Munich)**
  - ***Outside the deuterium***
  - ***Higher neutron density***
  - ***Bigger volume (fast moderation)***

Aiming at 10^{-27} e.cm over next decade

Implications of n and Hg for the theta parameter

~~CP~~ strong interaction

induces neutron EDM { Baluni, Crewther, Pospelov



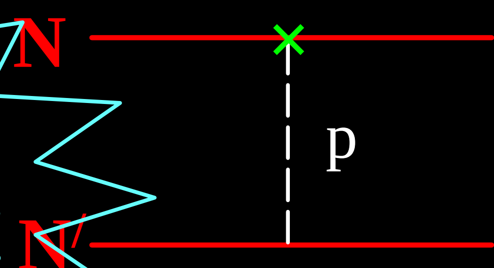
$d_n \approx 10^{-16}\,\theta$

$\Rightarrow \theta < 6\times10^{-10}$

$$\theta \frac{g_s^2}{32\pi^2} \tilde{G}G$$

induces mercury Schiff moment

{ Henley & Haxton, Pospelov

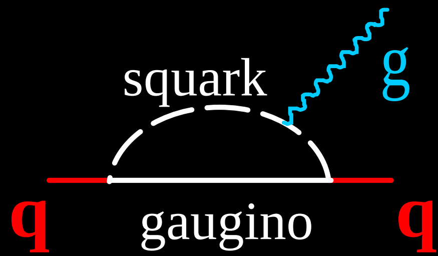


$d_{Hg} \approx 3\ 10^{-19}\ \theta$

$\Rightarrow \theta < 6\times10^{-10}$

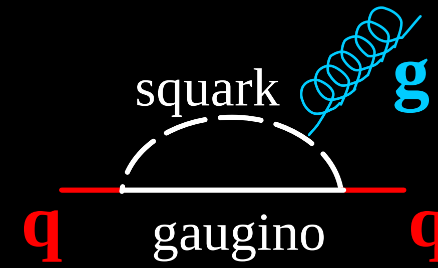
Something (Peccei-Quinn?) makes θ very small!

Implications of Hg and n for SUSY



quark electric dipole moments

$\frac{1}{2}\, d_q\, \bar{q}\, (F_{\mu\nu}\, \sigma_{\mu\nu} i\gamma_5)\, q$



quark color dipole moments

$\frac{1}{2}\, d_q^c\, \bar{q}\, (g_s\, G_{\mu\nu} \sigma_{\mu\nu} i\gamma_5)\, q$

$d_q, d_q^c \sim (\text{loop factor})\ ´\ \frac{m_q}{L^2} \sin j_{CP}$

naturally ~ α/π

$\not{CP}$ phase from soft breaking

naturally O(1)

scale of SUSY breaking naturally ~200 GeV

$d_{u,d}, d_{u,d}^c \sim 1\times10^{-23}$ cm naturally

n and Hg experiments give

$d_u < 2 \times 10^{-25}$

$d_d < 5 \times 10^{-26}$

$d_u^c < 3 \times 10^{-26}$

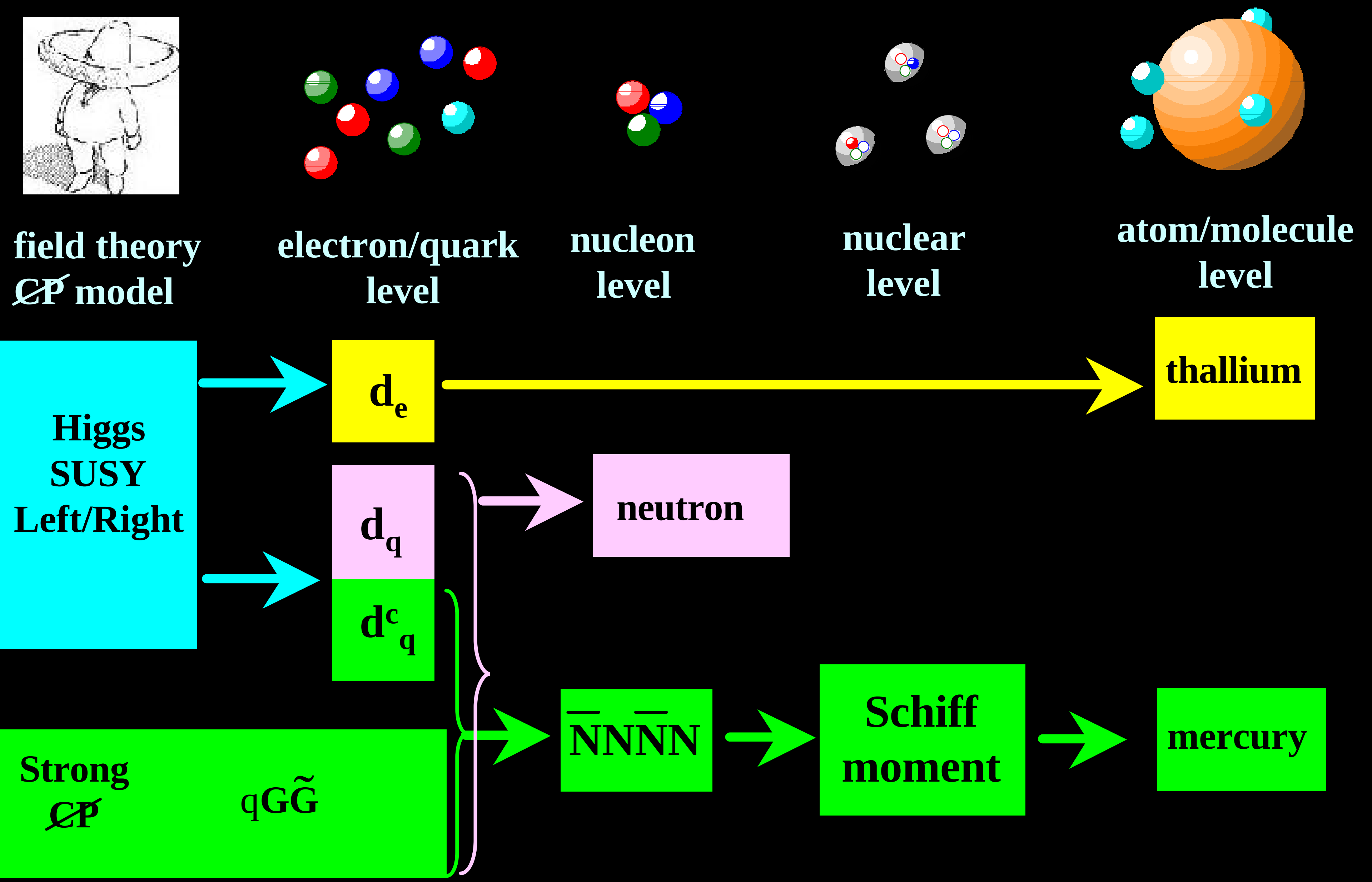
$d_d^c < 3 \times 10^{-26}$

~ 300 times less!

$\varphi_{CP} < 3\times10^{-3}$??

$\Lambda > 5$ TeV ??

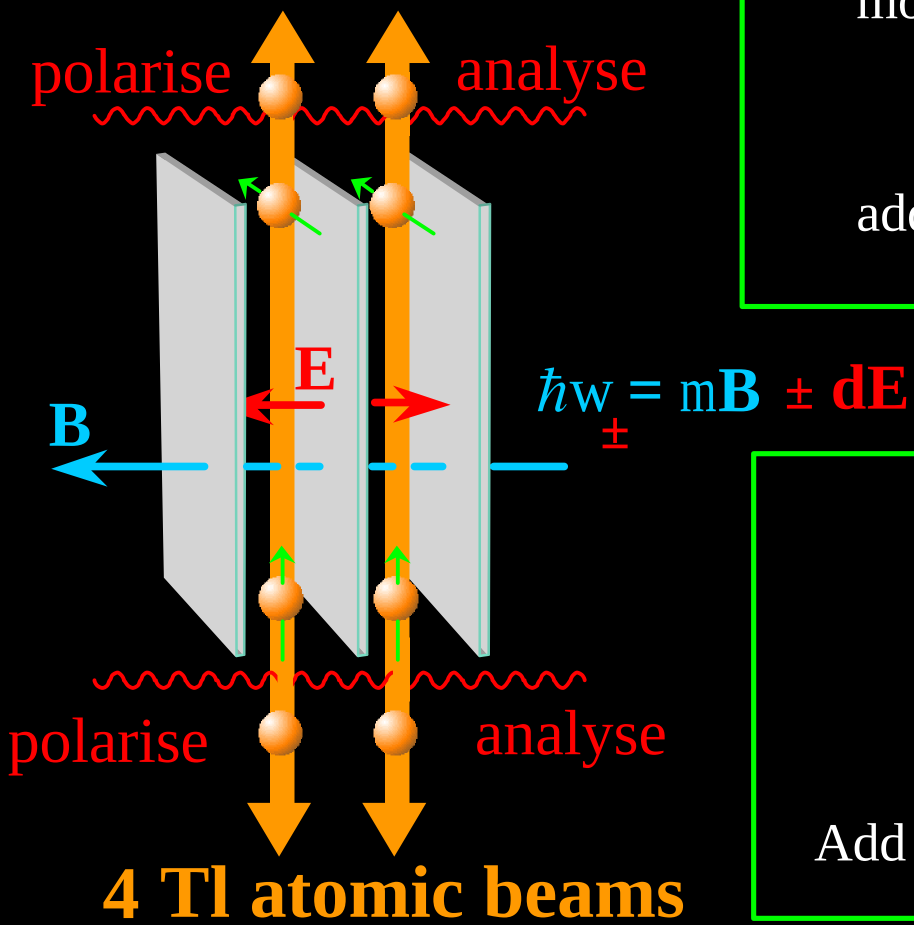
$\not{CP}$ from particles to atoms (main connections)



And now for the electron………..

The Thallium EDM experiment

Berkeley B.C. Regan, E.D. Commins, C.J. Schmidt and D. DeMille



1st huge problem:

motional interaction μ . **v** ´ **E**

The solution:

add 2 more Tl beams going down

2nd huge problem:

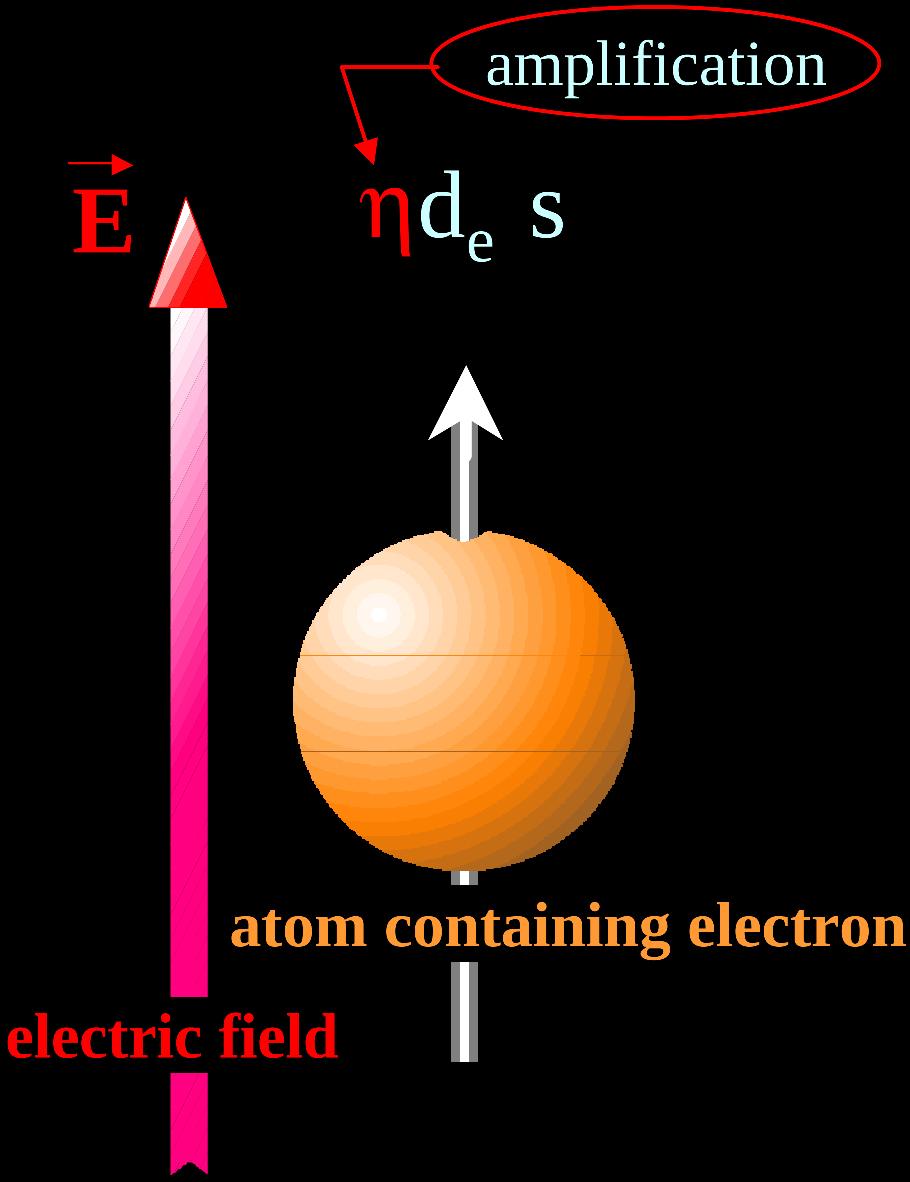
stray static magnetic fields

The solution:

Add 4 Na beams for magnetometry

A beautiful feature of the method

(Sandars)



Interaction energy

$$-d_e \eta \vec{E} \cdot s$$

-585 for Tl

Final Tl result: PRL **88,** 071805 (2002)

$E = 123$ kV/cm $\xrightarrow{\times 585}$ Effective field = 72 MV/cm

$B = 38\ \mu T$

$T_{coherence} = 2.4$ ms

Na co-magnetometer

$|d_{Tl}| < 9.4 \times 10^{-25}$ e.cm $\xrightarrow{\div 585}$

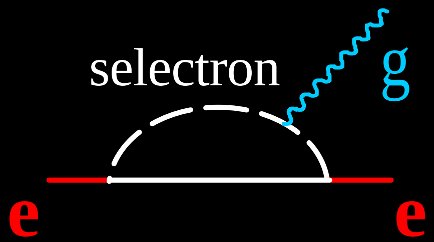
electron edm result:

$|d_e| < 1.6 \times 10^{-27}$ e.cm

Theoretical consequences of electron EDM

No direct contamination from θ problem

- a pure new physics search



SUSY electron edm

$$d_e \sim (\text{loop}) \times \frac{m_e}{\Lambda^2} \sin \varphi_{CP}$$

$$\sim 5 \times 10^{-24}\ \text{cm}$$

Once again, natural SUSY is too big by 300

$\varphi_{CP} < 3\times10^{-3}$??

$\Lambda > 5$ TeV ??

The future for electron EDM experiments

polar molecules

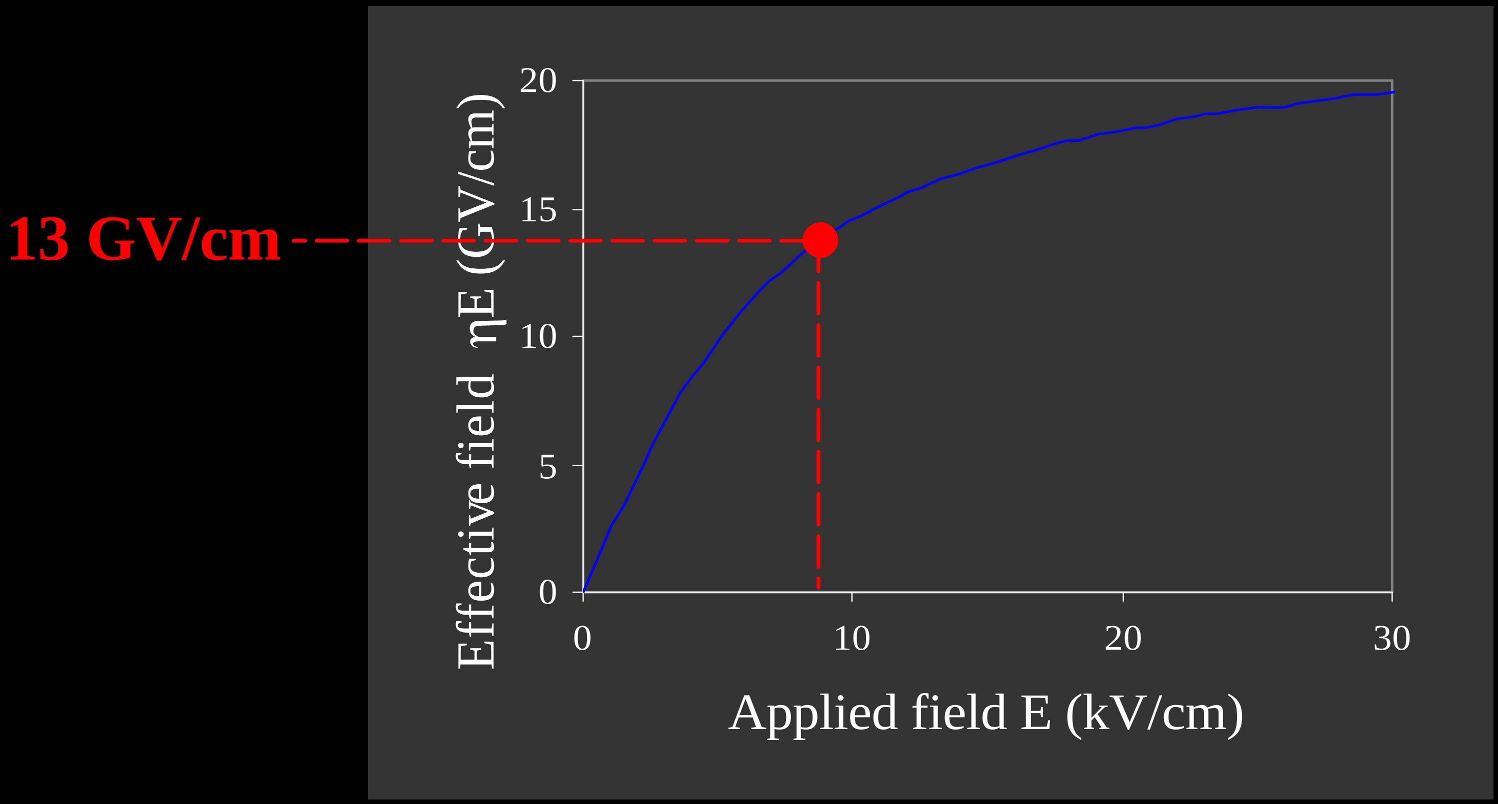
potentially 1000 ´ more sensitive

The Sussex experiment uses ytterbium fluoride molecules

JJ Hudson, BE Sauer, MR Tarbutt and EA Hinds,
arXiv hep-ex0202014 (2002)

First advantage of YbF: Huge effective field ηE

Parpia
Quiney
Kozlov
Titov



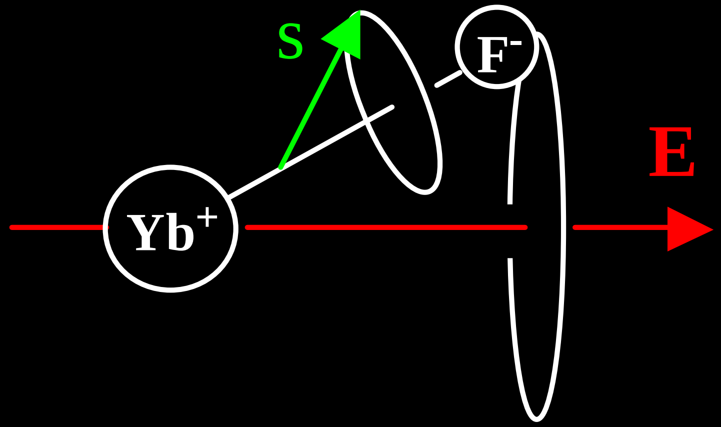
(in Tl experiment ηE was 72 MV/cm)

2nd advantage of YbF:

No coupling $\mathbf{s} \times \mathbf{E} \cdot \mathbf{v}$ to motional magnetic field

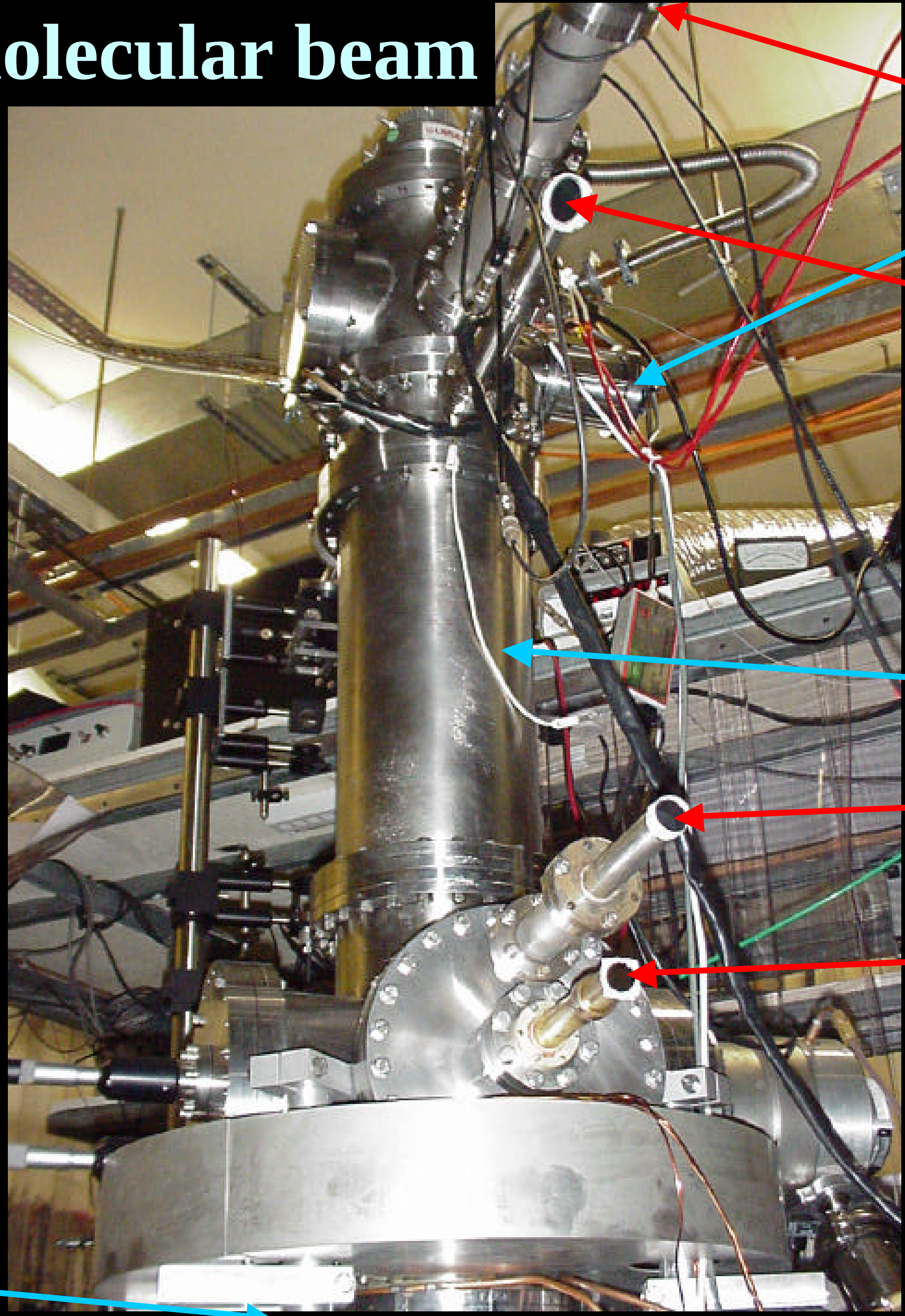
electron spin s is coupled to internuclear axis

and internuclear axis is coupled to E

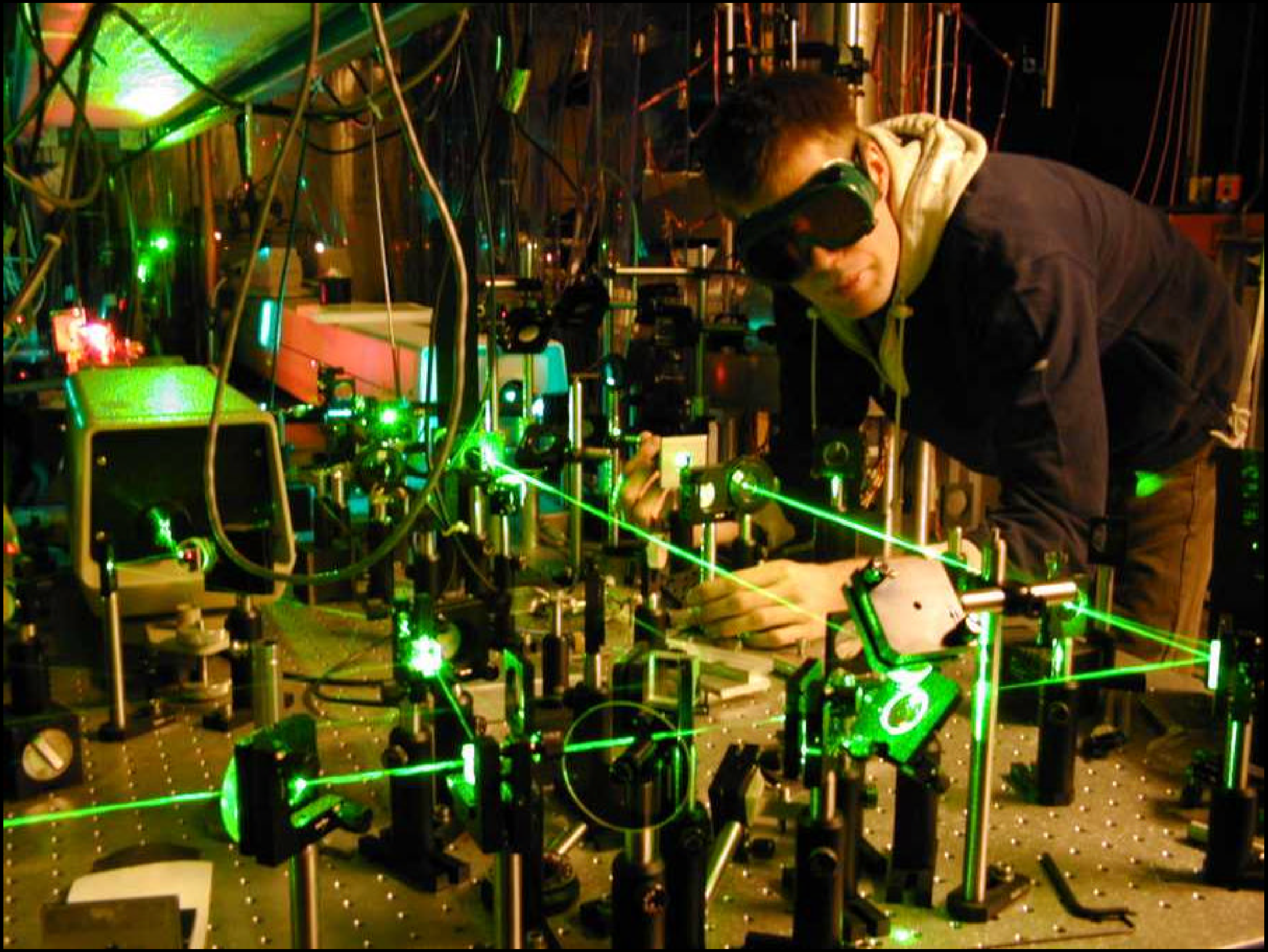


$\backslash < \mathbf{s} \times \mathbf{E} > = 0$ → **no motional systematic error**

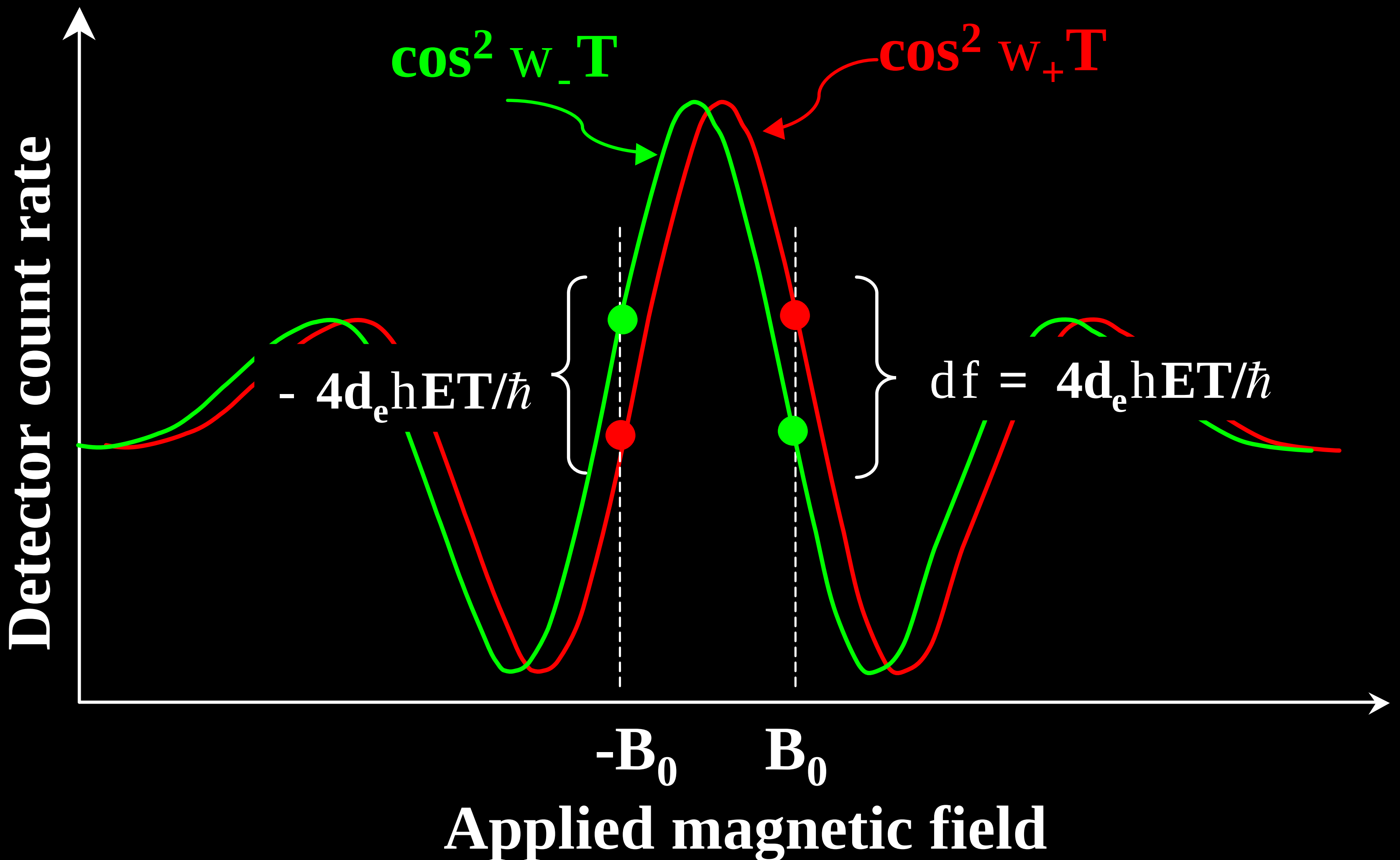
The Sussex molecular beam



Part of the optical setup



Measuring the edm



Projections for the future

	2002 result	cold YbF beam	trapped molecules
background	150kHz	640kHz	40kHz
fringe height	1.5 kHz	160 kHz	10 kHz
coherence time	1.5 ms	1 ms	1 s
d_e in 1 day	$3\ 10^{-26}$ e cm	$6\ 10^{-28}$ e cm	$3\ 10^{-30}$ e cm

long time = narrow fringes

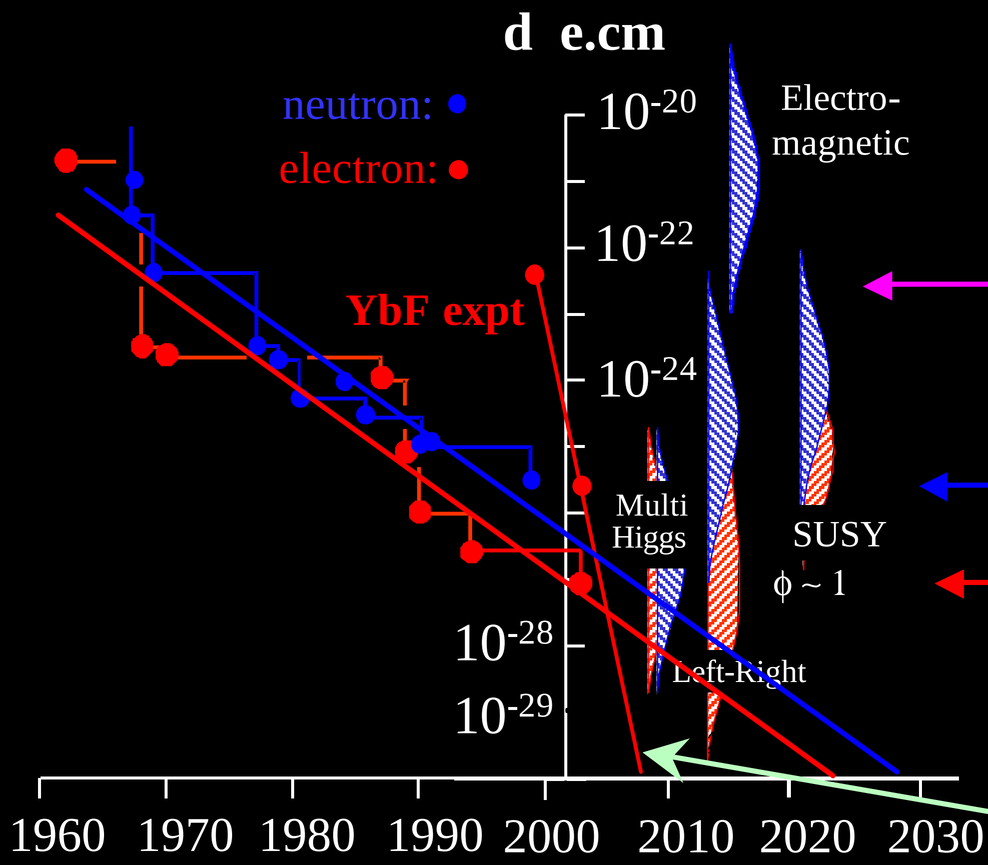
Current status of EDMs

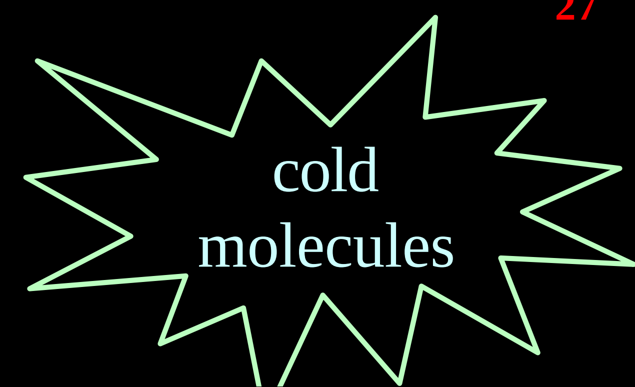
d(muon) 🖫 7⑨10^{-19}

d(proton) 🖫 6⑨10^{-23}

d(neutron) 🖫 6⑨10^{-}

d(electron) 🖫 1.6⑨10^{-27}





Conclusion

EDM measurements (especially cold moleules) have great potential to elucidate

- **CP violation**
- **particle physics beyond the standard model**
- **matter/antimatter asymmetry of the universe**

some of the most fundamental issues in physics