# The Neutron Electric Dipole Moment

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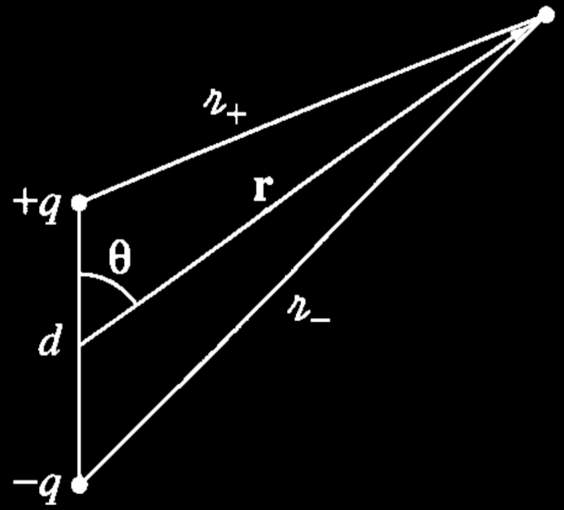
# Electric Dipole Moments (EDMs)

- Quantify the charge separation
- Neutron is composed of charged particles, so classically an EDM could be expected



From Griffiths, *Introduction to Electrodynamics*

- If we suppose the separation of charges is about a 10th of the neutron radius, we get [1]

$$d_n \sim 1 \times 10^{-14}\ e{\cdot}\mathrm{cm}$$

but the experimental upper limit is

$$d_n < 3 \times 10^{-26}\ e{\cdot}\mathrm{cm}$$

# Discrete Symmetries in Quantum Mechanics

- Discrete symmetries are charge (*C*), parity (*P*), and time (*T*)
- Discrete symmetry violation of general interest
  - There are known amounts of *CP* violation in weak interactions
- *CPT* theorem says violation of one implies violation of other two, so total symmetry is preserved

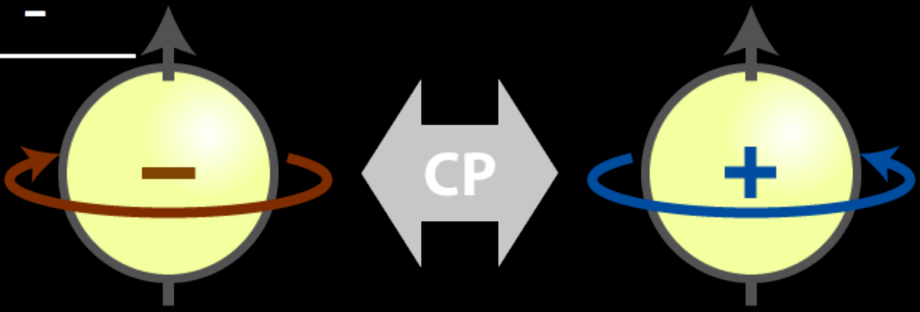
# *CP* Violation from *n*EDM

E&M interaction Hamiltonian: $\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$

Symmetry transformations of terms [2]:

| | $\vec{E}$ | $\vec{B}$ | $\vec{\mu}$ or $\vec{d}$ |
|---|---|---|---|
| $P$ | - | $+$ | $+$ |
| $C$ | - | - | - |
| $T$ | $+$ | - | - |

Conclusion: *n*EDM violates *CP* symmetry



www.quantumdiaries.org

# Matter-antimatter asymmetry

- We observe more matter than antimatter in the universe
  - Unexpected from discrete symmetries
  - Can be explained with *CP* violation (+non-equilibrium conditions and baryon number nonconservation)
  - $K_0$- and *B*-meson decays do not provide enough *CP* violation for this explanation
- Conclusion: look for more sources of *CP* violation

# Possible Sources of *CP* Violation [3]

$\theta_{QCD}$ term

$$\delta\mathcal{L} = -\sum_{q=u,d,s} \bar{q}(m_q + i\,\theta_q\gamma_5)q + \theta_G\frac{\alpha_s}{8\pi}G\tilde{G}$$

$$-\frac{i}{2}\sum_{q=u,d,s} d_q\bar{q}F\sigma\gamma_5 q - \frac{i}{2}\sum_{q=u,d,s}\tilde{d}_q\bar{q}g_s G\sigma\gamma_5 q$$

quark EDM

quark chromo-EDM

# Calculation of $d_n$

- Use non-relativistic SU(6) wavefunctions to relate EDMs $d_{u,d}$ or chromo-EDMS $f_{u,d}$ to find the contributions [4]

$$d_n^{(v)} = \frac{1}{3}(4d_d - d_u) \qquad d_n^{(c)} = \frac{1}{3}e\left(\frac{4}{3}f_d + \frac{2}{3}f_u\right)$$

- Effective field theory [4]
- QCD sum rules [3]
- Lattice QCD [5]

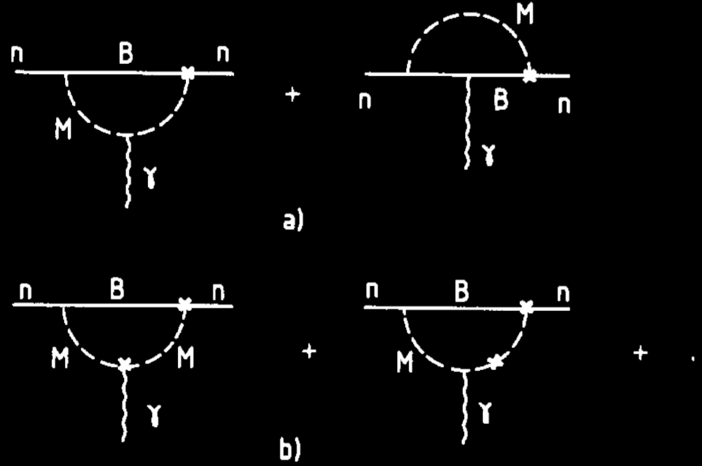
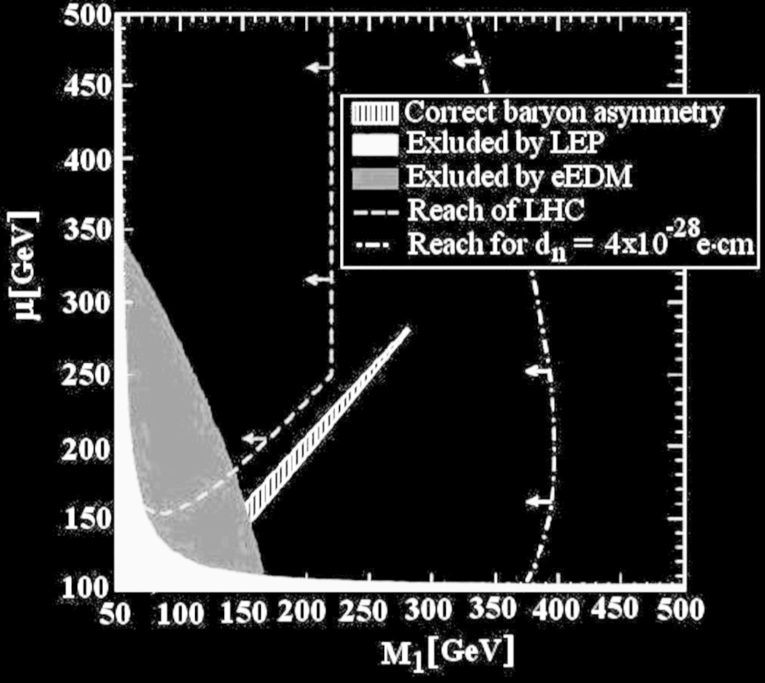


Fig. 1. Classes of loop diagrams contributing to $d_n$: (a) with one weak vertex, (b) with two weak vertices

# Constraints on New Physics

- Standard model calculation gives $d_n < 1 \times 10^{-33}\ e{\cdot}\mathrm{cm}$
- Extensions to the standard model all provide new (usually larger) estimates for $d_n$.



"Sensitivity of present and future EDM measurements to the mass parameters of an exemplary supersymmetric model relevant for discussion of the electroweak baryon genesis." [6]

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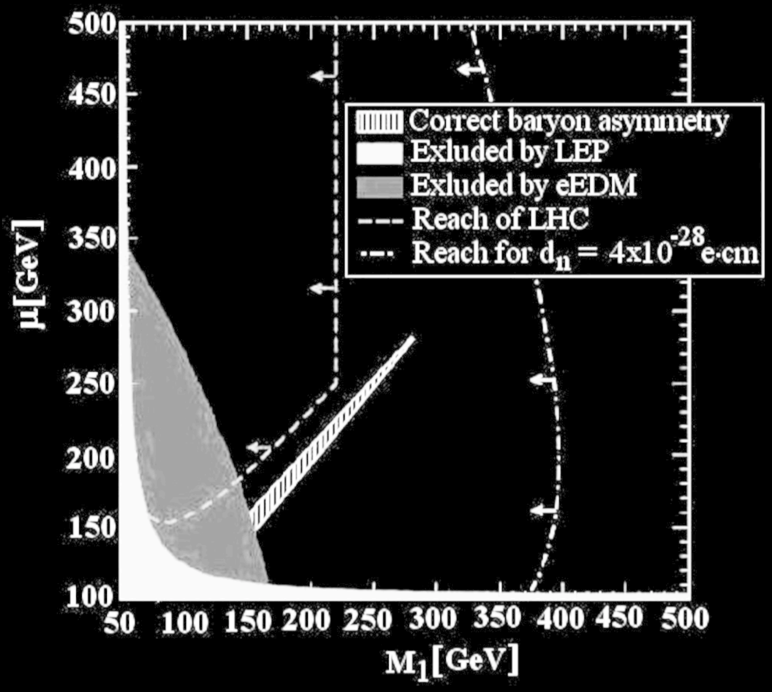
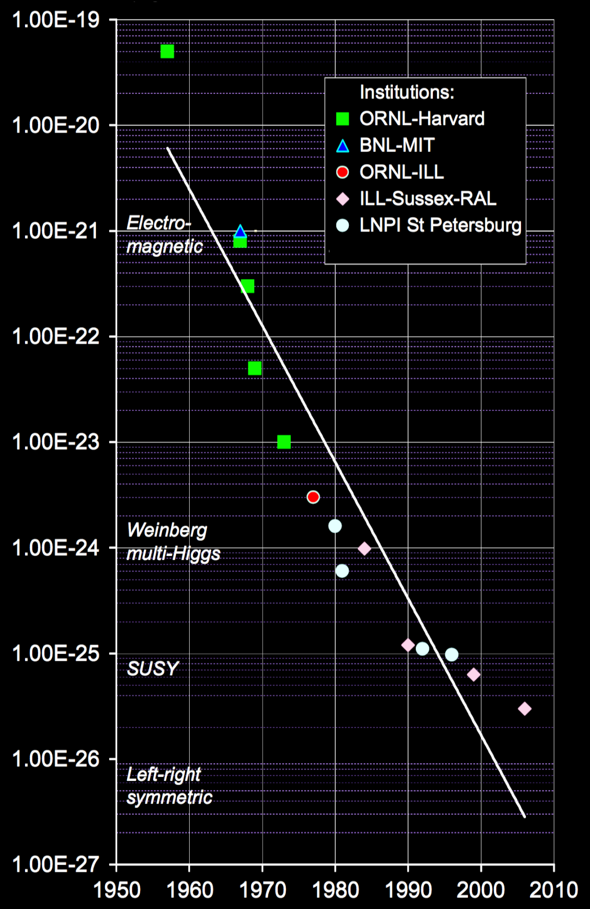




[7]

# An Aside on $\theta_{QCD}$

- The $\theta_{QCD}$ term is $\mathscr{L}_\theta = -\theta_{\mathrm{QCD}} \frac{g^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}; \quad \tilde{G}^{\mu\nu} \equiv \epsilon^{\mu\nu\alpha\beta} G_{\alpha\beta}$
- Calculating *n*EDM with this term yields [4]

$$d_n \simeq 10^{-16} \times \Theta_{QCD} \ e{\cdot}\mathrm{cm}$$

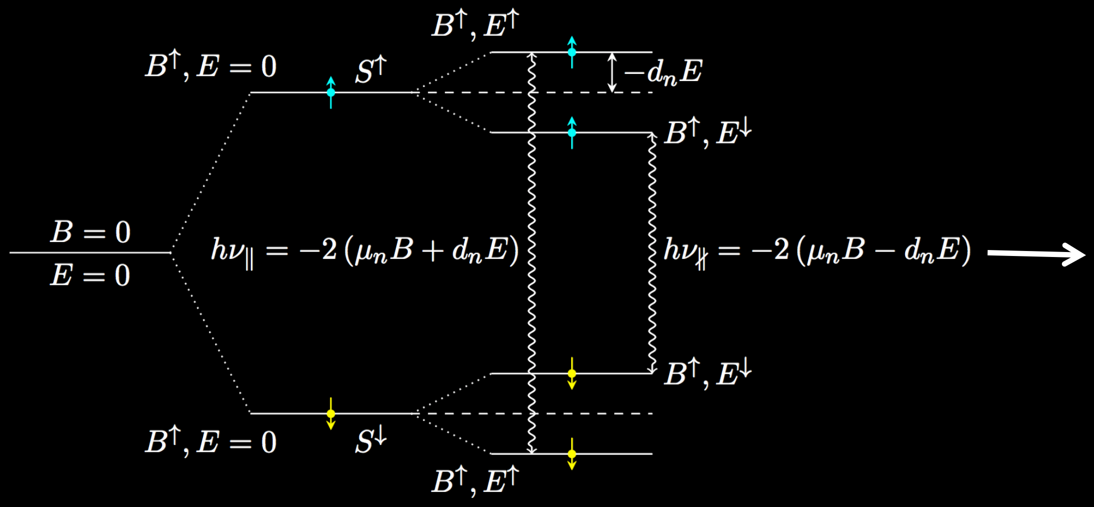
- Combined with experimental limit gives

$$\Theta_{QCD} < 10^{-10}$$

- Axionic dark matter an alternative explanation for the tuning of this term

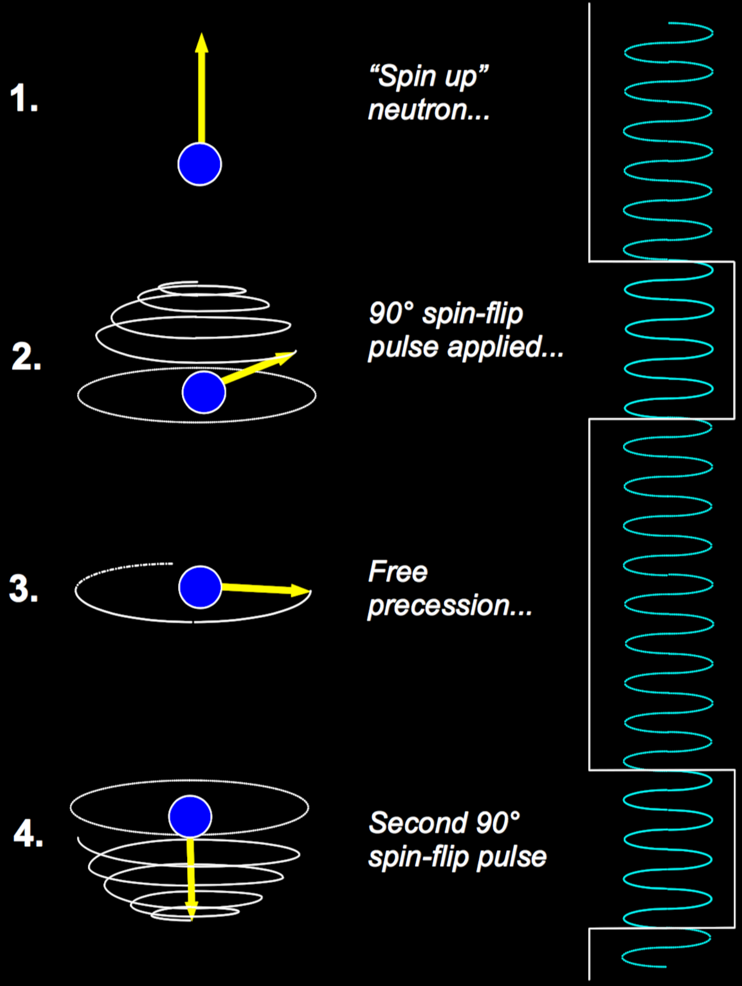
# Experimental Approach

- Return to the Hamiltonian $\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$
- Basic approach is magnetic resonance experiment [8]



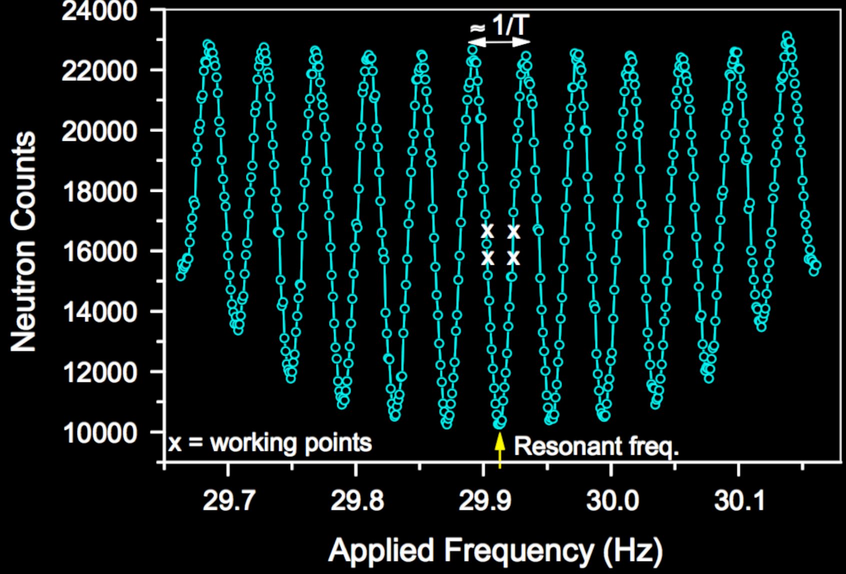
$$\delta\nu_0 = -\frac{4 d_n E_0}{h}$$

# Neutron Precession Readout [7]



1. *"Spin up" neutron...*
2. *90° spin-flip pulse applied...*
3. *Free precession...*
4. *Second 90° spin-flip pulse*

- When magnetic field slightly off resonance, final polarization strongly dependent on accumulated phase of neutron.
  - x's mark data taking points



# First Attempt

- Smith, Purcell, and Ramsey used neutron beams to make the first measurement in 1957 [8]: $d_n < 5 \times 10^{-20}\ e{\cdot}\mathrm{cm}$
- Motional magnetic field effect limited the sensitivity
  - Extra magnetic field in neutron reference frame that mimics EDM signal

$$\vec{B}_{\mathrm{m}} = \vec{E} \times \frac{\vec{v}}{c}$$

# Ultracold Neutron Approach

- To limit motional magnetic field contribution, the next generation of experiments used ultracold neutrons (UCNs):

$$v \approx 100\ \mathrm{m/s} \rightarrow v \approx 7\ \mathrm{m/s}$$

- Neutrons at this temperature are effectively "bottled," reflecting diffusely off of hard container walls.
  - Leads to an isotropic speed distribution, canceling motional effects on average

# Nonzero Measurement!

- In the mid-80s, two UCN experiments declared nonzero measurements [9]
  - Institut Laue-Langevin (ILL) in Grenoble, France and Petersburg Nuclear Physics Institute (PNPI) in Gatchina, Russia.
  - They agreed in sign and magnitude.
- Case closed!

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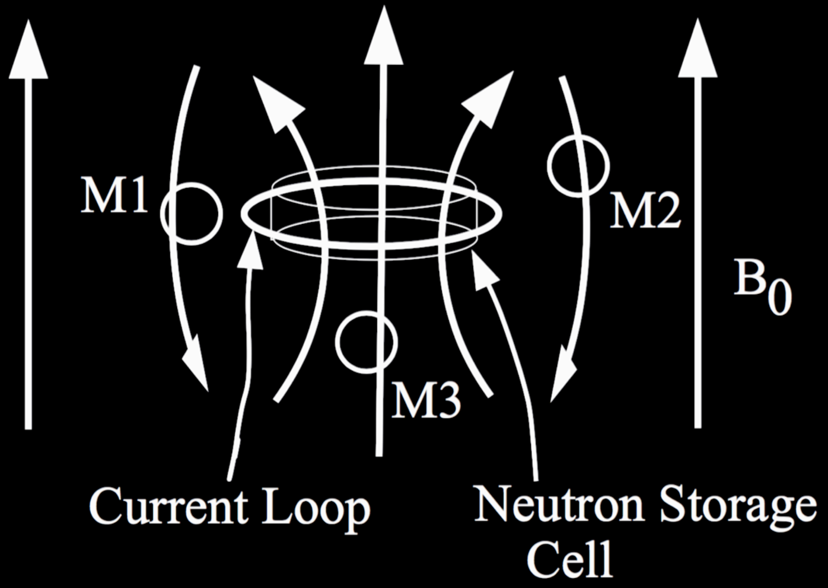
# “The External Magnetometer Problem” [9]

- Stray magnetic fields inside the storage cell are really hard to control.
  - Leakage currents, etc.
  - Measuring the field outside not precise enough

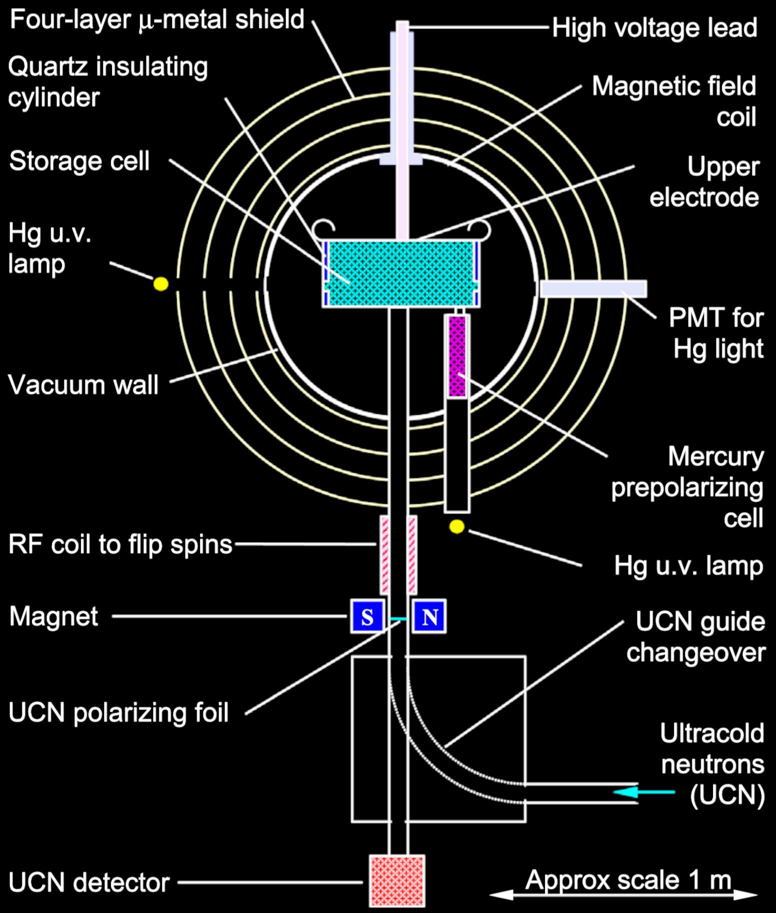


# Record Holder – ILL Experiment

- In 2006, the ILL Grenoble experiment published the world's current upper limit on the *n*EDM [10]:

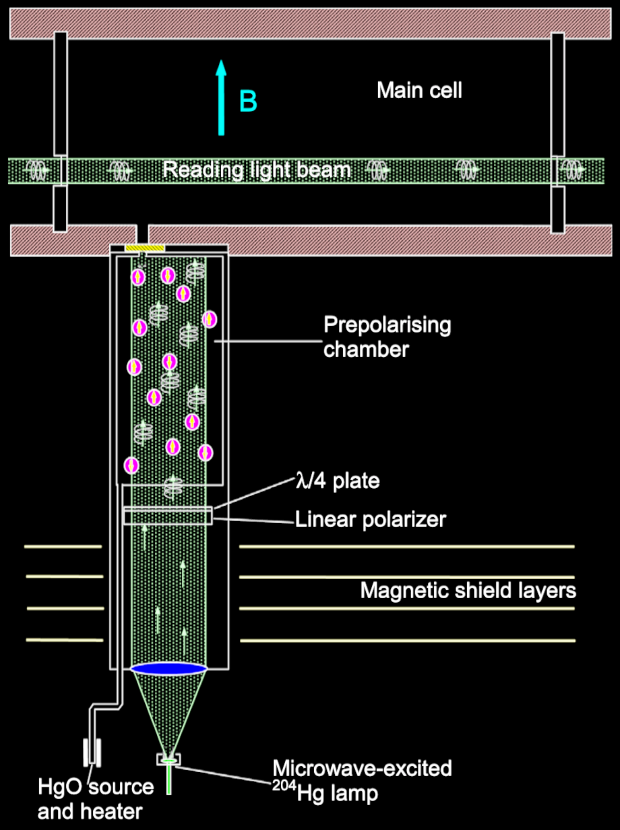
  $$d_n < 3 \times 10^{-26}\ e{\cdot}\mathrm{cm}$$

  - Data taken between 1998 and 2002
  - Analysis revised to account for more systematics in 2014 [11]; yielded similar results.



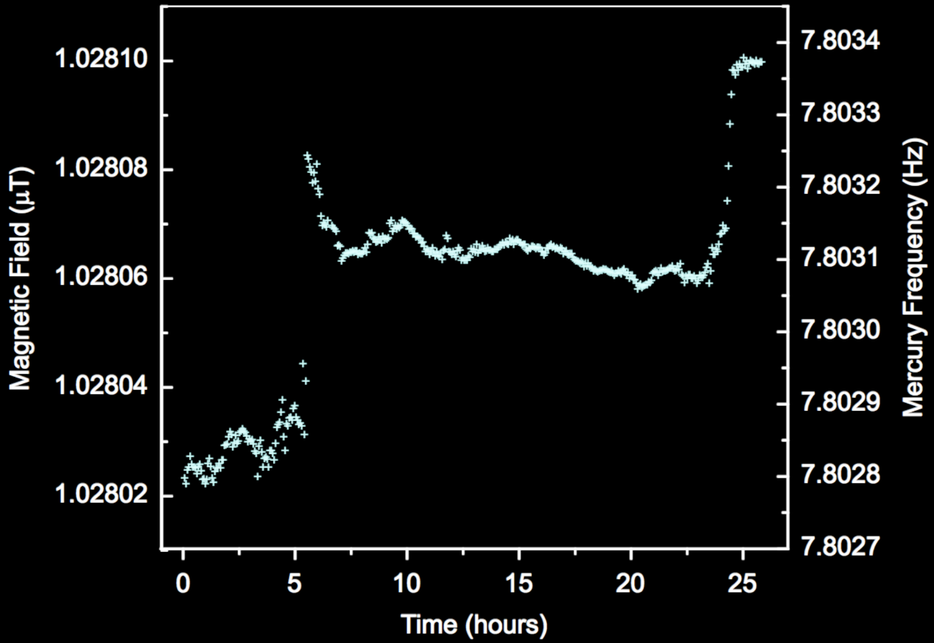
# Mercury Comagnetometer

- Spin polarized $^{199}$Hg subjected to rotating magnetic field at resonant frequency.
- EDM of the mercury atom is known to be small
- Gives volume- and time-averaged magnetic field during measurement interval

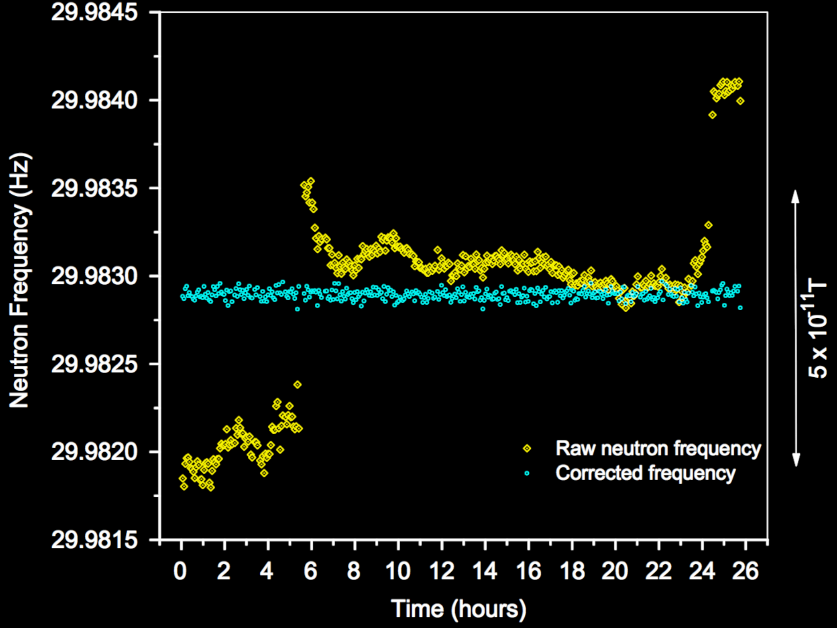


# Comagnetometer results [7]

Magnetic field strength measured by mercury resonant frequency



Neutron resonant frequency (uncorrected and corrected)



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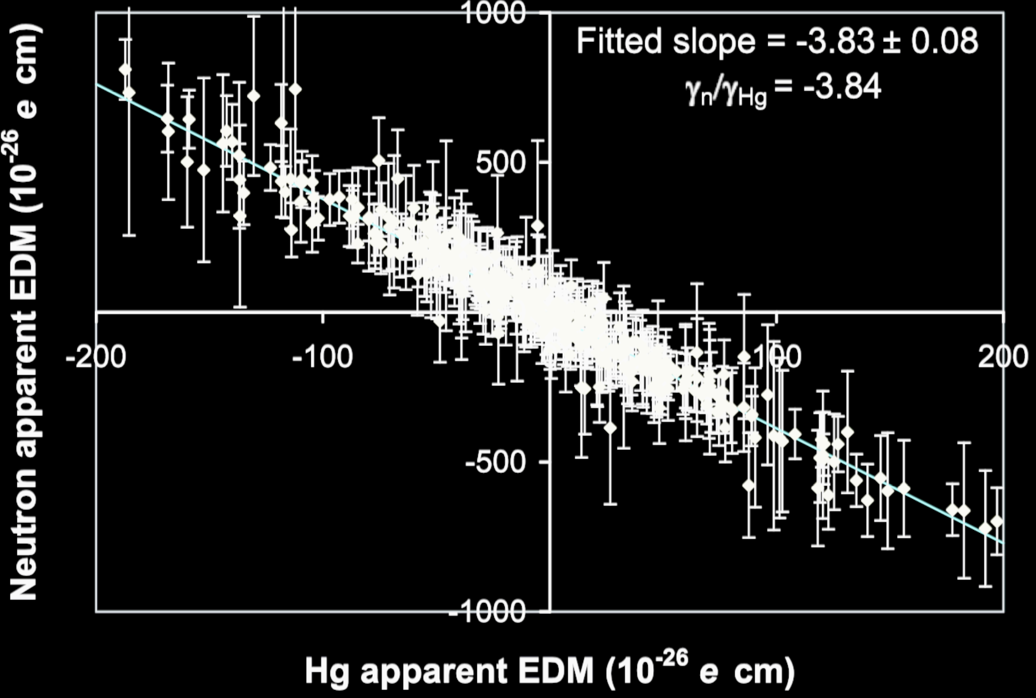
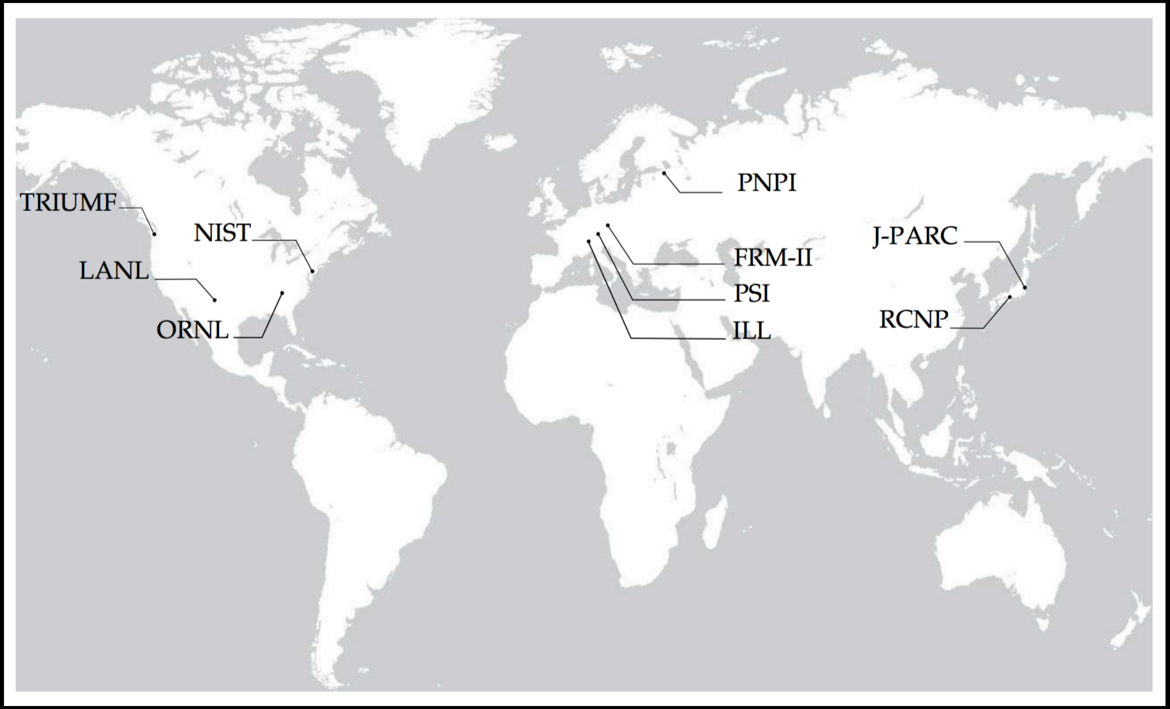


**Fig. 18.** Apparent neutron EDM signals (due to uncompensated random magnetic field fluctuations) as a function of the corresponding apparent mercury EDM signals.

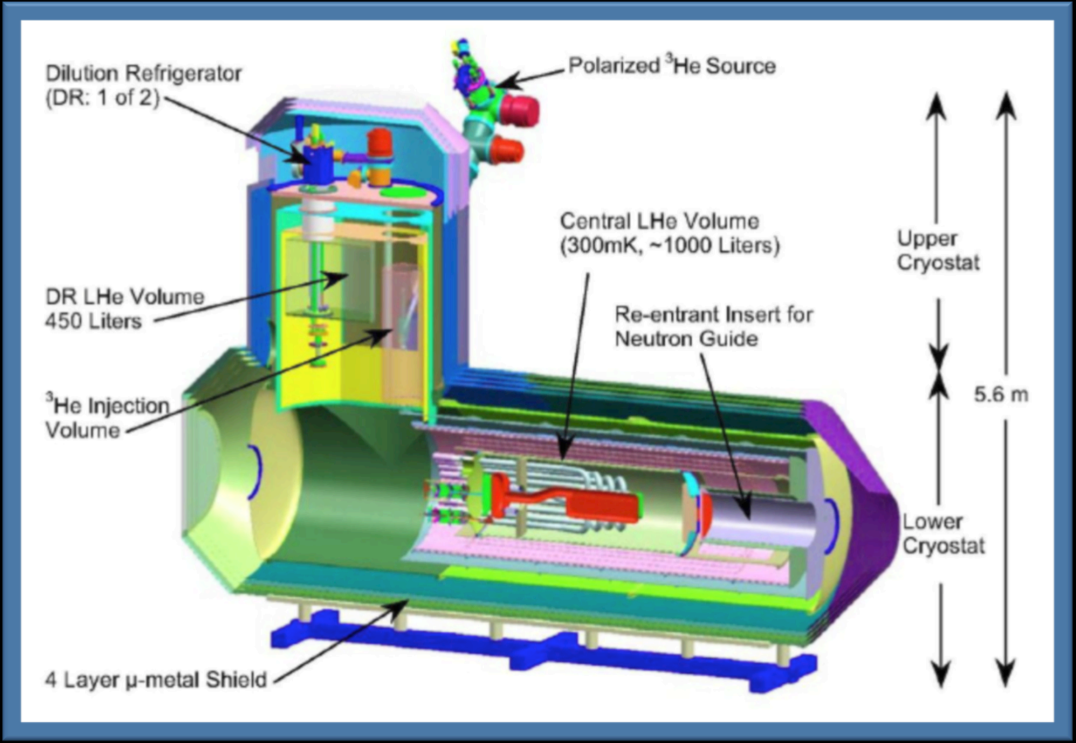
# Current and Future Efforts

- The Paul-Scherrer Institut (PSI) and PNPI experiment at ILL have produced results recently
- Next gen: superfluid helium storage at Oak Ridge National Lab



# Superfluid Helium Approach

- Inelastically scattering neutrons into superfluid helium improves density significantly
- $^4$He can support larger electric fields



- $^3$He serves as comagnetometer and readout system
- Improve sensitivity by ~100

# Alternative Methods?

- Crystal diffraction methods [9]
  - Use effective electric field of scatterer
  - Difficult to know angle and effective field well
  - R&D Phase
- Cold molecular beams [12]
  - Spin precession measurement on diatomic molecules
  - Similar to *e*EDM measurement techniques
  - Some papers have been written

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[12] V. V. Flambaum, *et al*. Time-reversal symmetry violation in molecules induced by nuclear magnetic quadrupole moments. Physical Review Letters, 113(103003), September 2014.