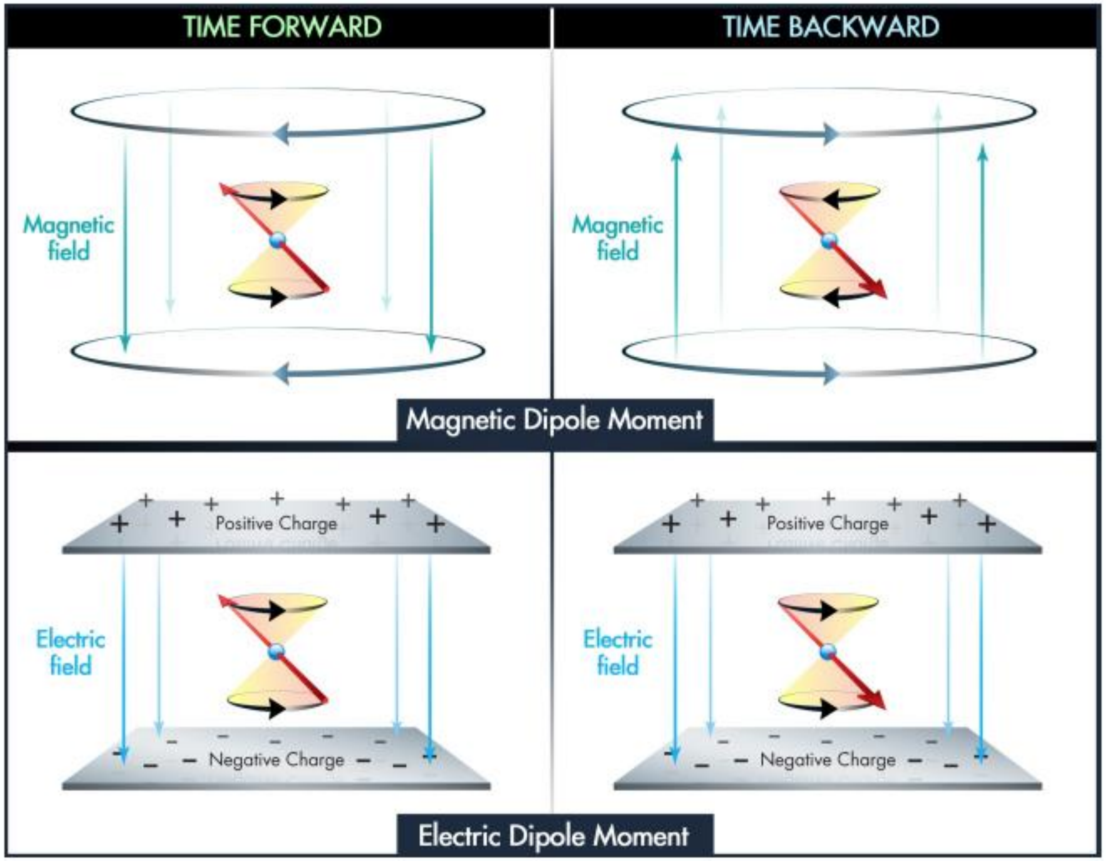
# Searches for Electric Dipole Moments - EDMs




From NSAC 2012 Implementation Report

- Why are they important (even after LHC)?
- Which EDMs are important?
- What is the future of EDMs and how do we get there?

Brad Filippone
(Caltech)
Spin2014

# EDMs violate Time Reversal & Parity Symmetry

## Quantum Picture - Discrete Symmetries

Assume $\vec{\mu} = \mu \frac{\vec{J}}{J}$ and $\vec{d} = d \frac{\vec{J}}{J}$

no spin → no EDM

Then non-relativistic Hamiltonian is

$$H = \underbrace{\vec{\mu} \cdot \vec{B}}_{\text{P-even, T-even}} + \underbrace{\vec{d} \cdot \vec{E}}_{\text{P-odd, T-odd}}$$

P-even
T-even

P-odd
T-odd

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

**Non-zero EDM violates both T and P**

**& assuming CPT invariance it also violates CP**

# Note: Nucleon EDM also appears in Electron Scattering

- Nucleon EM current:

$$< n | J_\mu^{EM} | n >= \bar{u}_N \left[ \underbrace{F_1(q^2)\gamma_\mu + \frac{F_2(q^2)}{2M_N}\sigma_{\mu\nu}q_\nu}_{\text{P\&T even}} + \underbrace{F_A(q^2)(iq^2\gamma_\mu\gamma_5 - 2M_N q_\mu\gamma_5)}_{\text{P odd}} + \underbrace{\frac{F_3(q^2)}{2M_N}\gamma_5\sigma_{\mu\nu}q_\nu}_{\text{P\&T odd}} \right] u_N$$

- $F_3$ related to nucleon EDM: $d_n = \lim_{q^2 \to 0} \frac{F_3(q^2)}{2M_N}$
- Also related to Transversity!

$$\delta q = \int_0^1 dx \left[ h_1(x) - \bar{h}_1(x) \right]$$ Tensor Charge

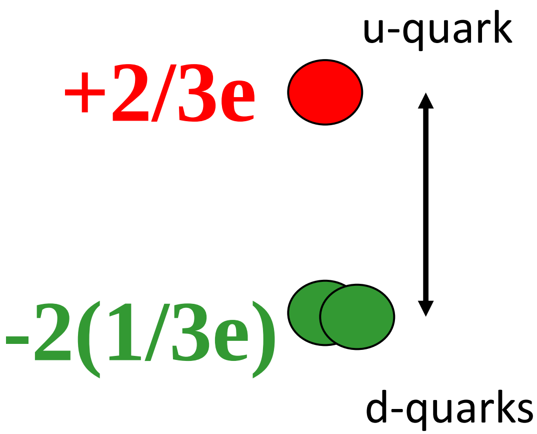
$$d_n = \sum_q d_q \delta q$$ Relates neutron EDM to quark EDM $d_q$

# New CP Violation May Help Resolve Matter/Antimatter Asymmetry of the Universe

- **Sakharov Criteria**
  - **Particle Physics can produce matter/antimatter asymmetry in the early universe *IF* there is:**
    - Baryon Number Violation (need only very small amount)
    - CP & C violation (need much bigger CP violation than in Standard Model)
    - Departure from Thermal Equilibrium

# How big is the are EDMs?

# e.g. neutron:




if $\ell \sim 0.1\ r_n$

$d_n \sim 5 \times 10^{-14}$ e-cm

**But Experiment says**
**$d_n < 3 \times 10^{-26}$ e-cm !!**

# Origin of elementary EDMs

- **Standard Model EDMs are due to CP violation in the quark weak mixing matrix CKM (e.g. the $K^0/B^0$-system) but…**
  - $e^-$ and quark EDM's are zero at 1 and 2 loops
  - Need at least three loops to get EDM's (electron actually requires 4 loops!)
    - Thus EDM's are VERY small in standard model

**e.g. neutron EDM in Standard Model is $\sim 10^{-32}$ e-cm ($\sim 10^{-19}$ e-fm)**


**Experimental neutron limit: $< 3 \times 10^{-26}$ e-cm**

# Is there a "natural" source for new CP violation & EDMs?

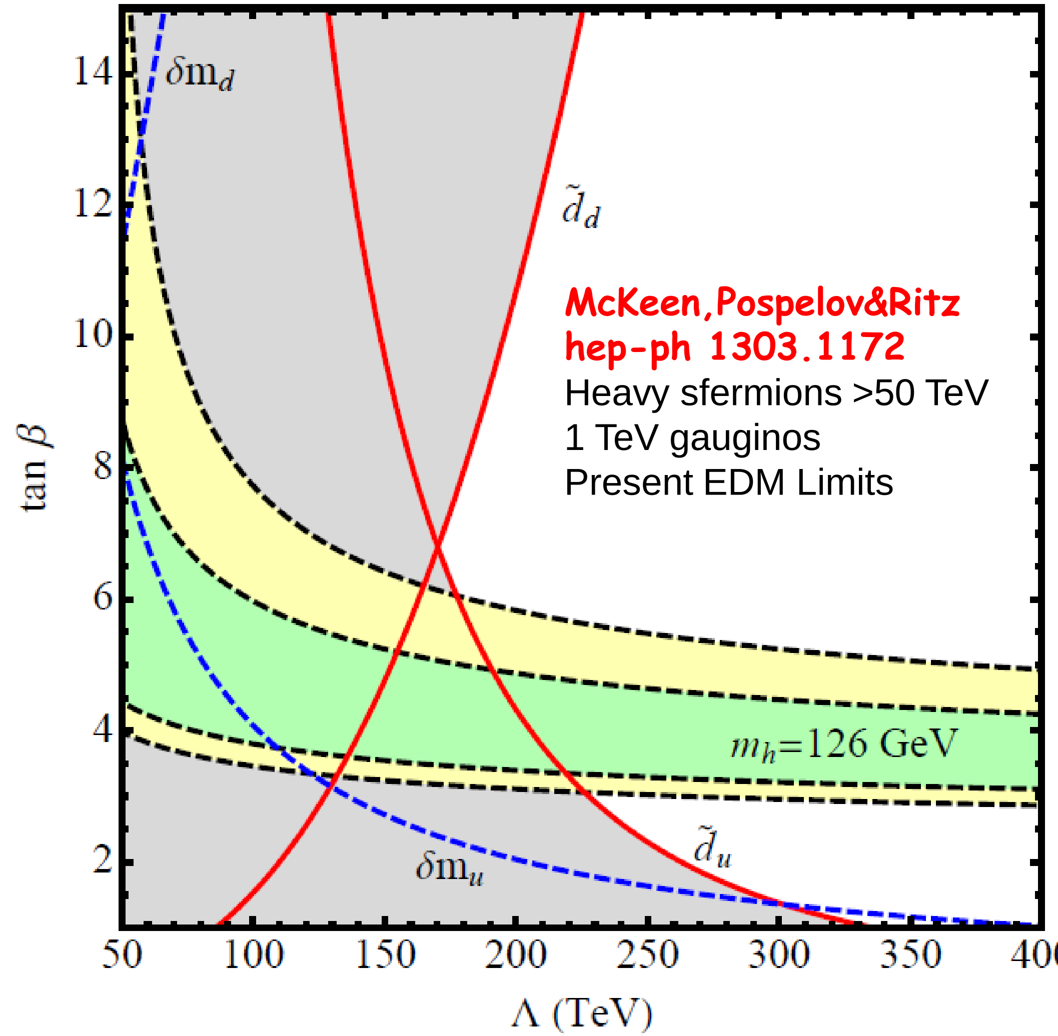
- New physics (e.g. SUSY/other) often has additional CP violating phases in added couplings
  - New phases: ($\phi_{CP}$) should be ~ 1 (why not?)
- Contribution to EDMs depends on masses of new particles

$$d_n \sim 10^{-24}\ \text{e-cm} \times \sin\varphi_{CP}(1\ \text{TeV}/M_{SUSY})^2$$

**Note: experimental limit: $d_n < 0.03 \times 10^{-24}$ e-cm**

# Impact of non-zero EDM

- Must be new Physics
- Sharply constrains models beyond the Standard Model (especially *with* LHC data)




Example for Chromo-EDMs

# Particle EDM Zoo (where to look)

- Paramagnetic atoms and polar molecules are very sensitive to $d_e$

- Diamagnetic atoms are sensitive to quark "chromo-"EDM (gluon+photon) = $\tilde{d}_q$ and $\Theta_{QCD}$

- Neutron and proton sensitive to $d_q$, $\tilde{d}_q$ & $\Theta_{QCD}$

**Observation or lack thereof in one system *does not* predict results for other systems**

# Note: $d_e$ and storage ring EDMs discussed earlier …

- D. Kawall
  - Recent Results and Progress on Leptonic and Storage Ring EDM Searches
- A. Lehrach
  - Storage Ring Based EDM Search
- A. Saleev
  - Studies of Systematic Limitations in EDM Searches in Storage Rings
- **Here we will focus on hadronic EDMs**

# Origin of Hadronic EDMs

- Hadronic (strongly interacting particles) EDMs are from
  - $\theta_{QCD}$ (an allowed term in QCD)
  - or from the quarks and gluons themselves

$\theta_{QCD}$

Weinberg 3-gluon term

$$\mathcal{L}^{\not{CP}}_{eff} = \frac{g_s^2}{32\pi^2}\,\bar{\theta}\, G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{1}{3} w\, f^{abc} G^a_{\mu\nu}\tilde{G}^{\nu\beta,b} G_{\beta}{}^{\mu,c}$$
$$- \frac{i}{2}\sum_{i=e,u,d,s} d_i\, \overline{\psi}_i (F\cdot\sigma)\gamma_5\psi - \frac{i}{2}\sum_{i=u,d,s} \tilde{d}_i\, \overline{\psi}_i g_s (G\cdot\sigma)\gamma_5\psi + \cdots$$

$e^-$, quark EDM

quark color EDM (chromo-EDM)

# Relative EDM Sensitivities

| System | Dependence (simple quark model) | Present Limit (e-cm) | Future (e-cm) |
|---|---|---|---|
| | | | |
| n | $d_n \sim (3\times10^{-16})\theta_{QCD}$ + $0.7(d_d - \frac{1}{4}d_u) + 0.6(\tilde{d}_d + \frac{1}{2}\tilde{d}_u)$ | $<3\times10^{-26}$ | $10^{-28}$ |
| $^{199}$Hg | $d_{Hg} \sim (0.001\times10^{-16})\theta_{QCD}$ - $0.006(\tilde{d}_d - \tilde{d}_u)$ | $<3\times10^{-29}$ | $10^{-30}$ |

# What is the precision for an EDM measurement?

$$\mathcal{E} = \hbar\omega = \vec{\mathbf{d}} \cdot \vec{\mathbf{E}}$$ → Uncertainty in d: $$\sigma_d \sim \frac{\Delta\mathcal{E}}{|\vec{E}|}$$

$$\Delta\mathcal{E}\Delta t \sim \hbar$$

Precise energy measurement requires long individual measurement time, giving

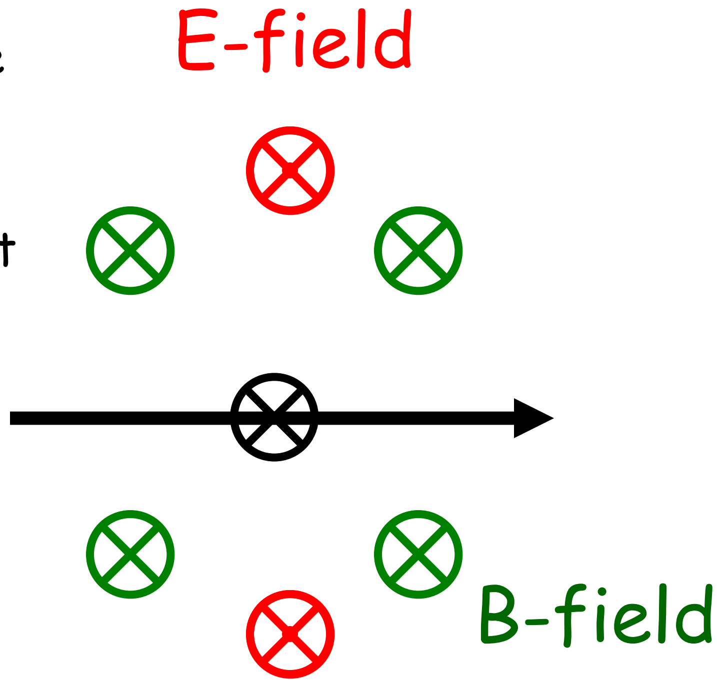
$$\sigma_d^1 \sim \frac{\Delta\mathcal{E}}{|\vec{E}|} \sim \frac{\hbar}{|\vec{E}|T_m}$$

Coherence effect

Can improve with counting statistics $\propto \frac{1}{\sqrt{\mathbf{N}}}$

# Simplified Measurement of EDM

1. Inject polarized particle
2. Rotate spin by $\pi/2$
3. Flip E-field direction
4. Measure frequency shift




$$\nu = \frac{2\vec{\mu}\cdot\vec{B} \pm 2\vec{d}\cdot\vec{E}}{h}$$

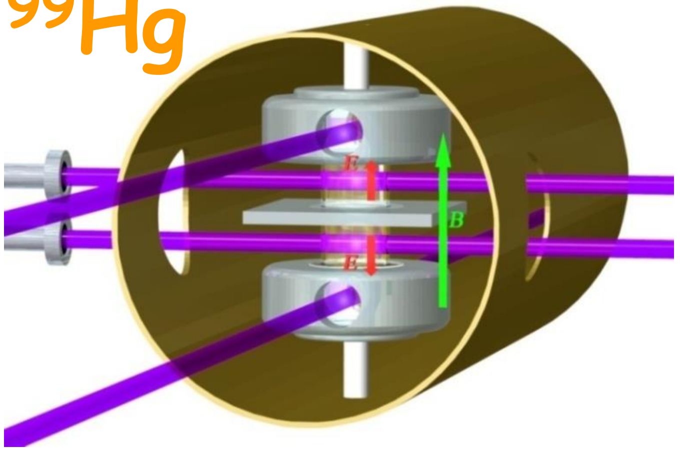
Must know B very well

# Hadronic EDM experiments & plans

- Heavy Atoms increase sensitivity to EDM
  - Atomic electrons shield external E-field
  - Need to compensate for this via finite size
- $^{199}$Hg – lowest measured EDM limit
- Deformed heavy-nuclei
  - Deformation can enhance further
  - several radioactive species appear best
- Improvements in Neutron technology
  - Vigorous world-wide effort underway

# Electric Dipole Moment of $^{199}$Hg

## University of Washington




2009: Last reported result

$d(^{199}Hg) = (0.49 \pm 1.29 \pm 0.76) \times 10^{-29}$ e-cm;

PRL 102, 101601 (2009)

$| d(^{199}Hg) | < 3.1 \times 10^{-29}$ e-cm

2014: EDM data-taking is underway.

We anticipate a reportable result by the end of 2014 with a statistical uncertainty of $\sim 3.5 \times 10^{-30}$ e-cm.

2017: They believe another factor of 3 increase in sensitivity is achievable

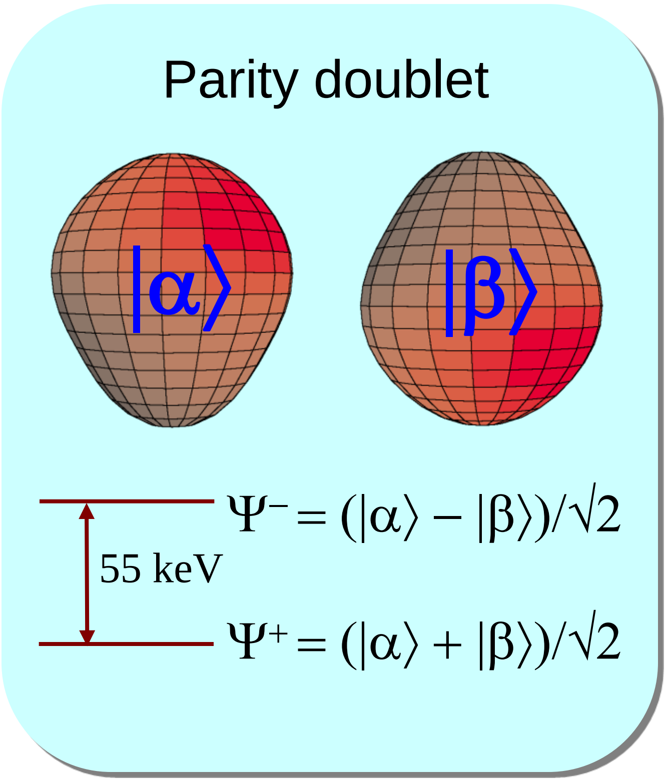
- With a larger electric field, longer spin coherence times, and better control of the uv beam paths, the current apparatus could reach a statistical sensitivity of $\sim 1 \times 10^{-30}$ e-cm.



**Thanks to B. Heckel (UW)**

# EDM of $^{225}$Ra is Significantly Enhanced

- Closely spaced parity doublet – Haxton & Henley, PRL (1983)
- Large Schiff moment due to octupole deformation – Auerbach, Flambaum & Spevak, PRL (1996)
- Relativistic atomic structure ($^{225}$Ra / $^{199}$Hg ~ 3) – Dzuba, Flambaum, Ginges, Kozlov, PRA (2002)




$$Schiff\_moment = \sum_{i \neq 0} \frac{\langle \psi_0 | \hat{S}_z | \psi_i \rangle \langle \psi_i | \hat{H}_{PT} | \psi_0 \rangle}{E_0 - E_i} + c.c.$$

**Enhancement Factor: EDM ($^{225}$Ra) / EDM ($^{199}$Hg)**

| Skyrme Model | Isoscalar | Isovector |
|---|---|---|
| SIII | 300 | 4000 |
| SkM* | 300 | 2000 |
| SLy4 | 700 | 8000 |

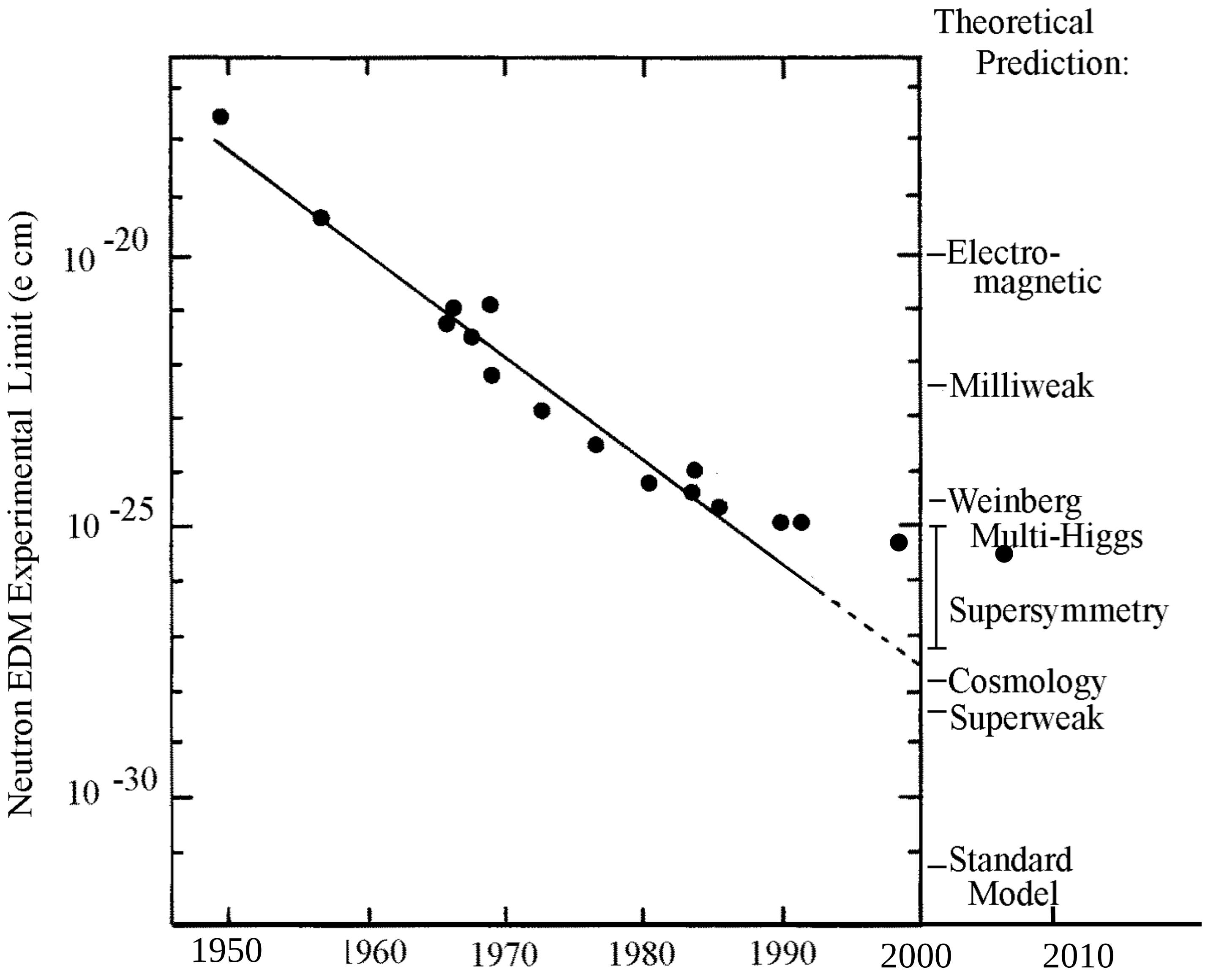
*Schiff moment of $^{225}$Ra*, Dobaczewski, Engel, PRL (2005)
*Schiff moment of $^{199}$Hg*, Dobaczewski, Engel *et al.*, PRC (2010)

- Near goal: $10^{-26}$ e cm
- 5-10 years: $10^{-28}$ e cm
- $10^{-30}$ e cm may be ultimate limit

**Thanks to Z-T Lu (ANL)**

→ Deformation enhanced $^{223}$Rn experiment also under development at TRIUMF

# History of nEDM Sensitivity



# Best Existing Neutron Limit:

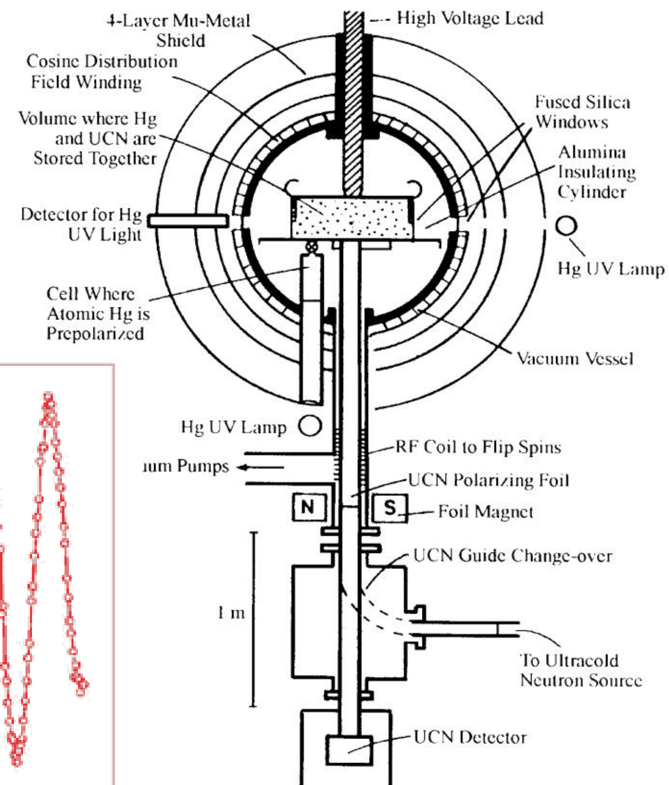
# ILL-Grenoble neutron EDM Experiment

Harris et al. Phys. Rev. Lett. 82, 904 (1999)

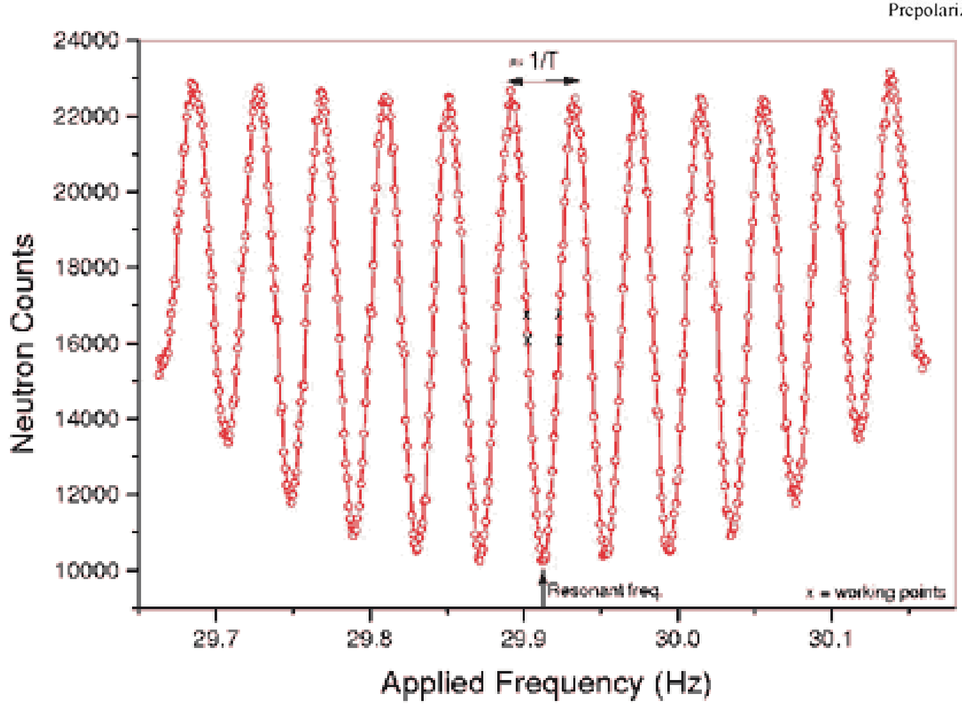
Baker et al. Phys. Rev. Lett. 97, 131801 (2006)

- Trapped Ultra-Cold Neutrons (UCN)
- $N_{UCN}$ = 0.5 UCN/cc
- |E| = 5 - 10 kV/cm
- 100 sec storage time

**→ $\sigma_d$ < 3 x $10^{-26}$ e-cm**




tic of the ILL UCN EDM experiment incorporating a $^{199}$Hg comagnetometer



# Technologies for new neutron EDM

- UCN (or beam for crystal exps)
  - $SD_2$ , Superfluid $^4He$
- HV - the bigger the better
  - Vacuum, LHe, Crystal
- Magnetic Shielding
  - Room temperature and Cryogenic Shields
- Magnetometers
  - Atomic & others: 199Hg, $^3He$, $^{129}Xe$, $^{133}Cs$, SQUIDs, neutrons
  - Co-magnetometers most effective

# Worldwide neutron EDM Searches

# Worldwide neutron EDM Searches

| Experiment | UCN source | cell | Measurement techniques | $\sigma_d$ Goal ($10^{-28}$ e-cm) |
|---|---|---|---|---|
| | | | | Present neutron EDM limit < 300 |
| ILL-PNPI | ILL turbine<br>PNPI/Solid $D_2$ | Vac. | Ramsey technique for $\omega$<br>E=0 cell for magnetometer | Phase1<100<br>< 10 |
| ILL Crystal | Cold n Beam | solid | Crystal Diffraction<br>Non-Centrosymmetric crystal | < 100 |
| PSI EDM | Solid $D_2$ | Vac. | Ramsey for $\omega$, external Cs & $^3$He, Hg co-magnetom. Xe or Hg comagnetometer | Phase1 ~ 50<br>Phase 2 < 5 |
| Munich FRMII | Solid $D_2$ | Vac. | Room Temp. , Hg Co-mag., also external Cs mag. | < 5 |
| RCNP/TRIUMF | Superfluid $^4$He | Vac. | Small vol., Xe co-mag. @ RCNP<br>Then move to TRIUMF | < 50<br>< 5 |
| SNS nEDM | Superfluid $^4$He | $^4$He | Cryo-HV, $^3$He capture for $\omega$, $^3$He co-mag. with SQUIDS & dressed spins, supercond. | < 5 |
| JPARC | Solid $D_2$ | Vac. | Under Development | < 5 |
| JPARC | Solid $D_2$ | Solid | Crystal Diffraction<br>Non-Centrosymmetric crystal | < 10? |
| LANL | Solid $D_2$ | Vac. | R & D | ~ 30 |

[shaded box] = sensitivity < 5 x $10^{-28}$ e-cm

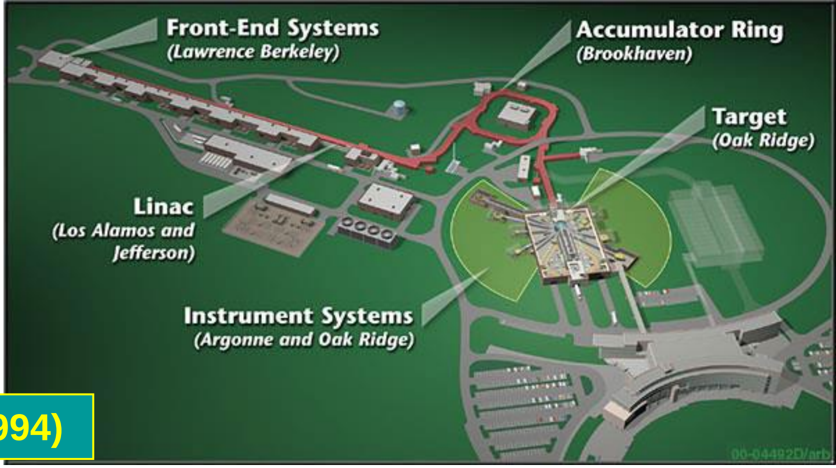
# Comparison of Capabilities for High Sensitivity experiments

| Capability | Cryo | FRM | PSI1 | PSI2 | SNS |
|---|---|---|---|---|---|
| $\Delta\omega$ via accumulated phase in n polarization | Y | Y | Y | Y | N |
| $\Delta\omega$ via light oscillation in $^3$He capture | N | N | N | N | Y |
| Horizontal B-field | Y | N | N | N | Y |
| *Comagnetometer | N | Y | Y | Y | Y |
| *Superconducting B-shield | Y | N | N | N | Y |
| *Dressed Spin Technique | N | N | N | N | Y |
| *Multiple EDM cells | N | Y | N | Y | Y |
| *Temperature Dependence of Geometric phase effect | N | N | N | N | Y |

Last five items (marked with *) denote a systematics advantage

- **SNS is arguably the most ambitious of the new experiments**
- **Will probe for systematic effects < 1 x $10^{-28}$ e-cm**

# US nEDM Experiment at Oak Ridge Lab-SNS




**Based on: R. Golub & S. K. Lamoreaux, Phys. Rep. 237, 1 (1994)**

- Production of ultracold neutrons (UCN) within the apparatus
  – *high UCN density and long storage times*

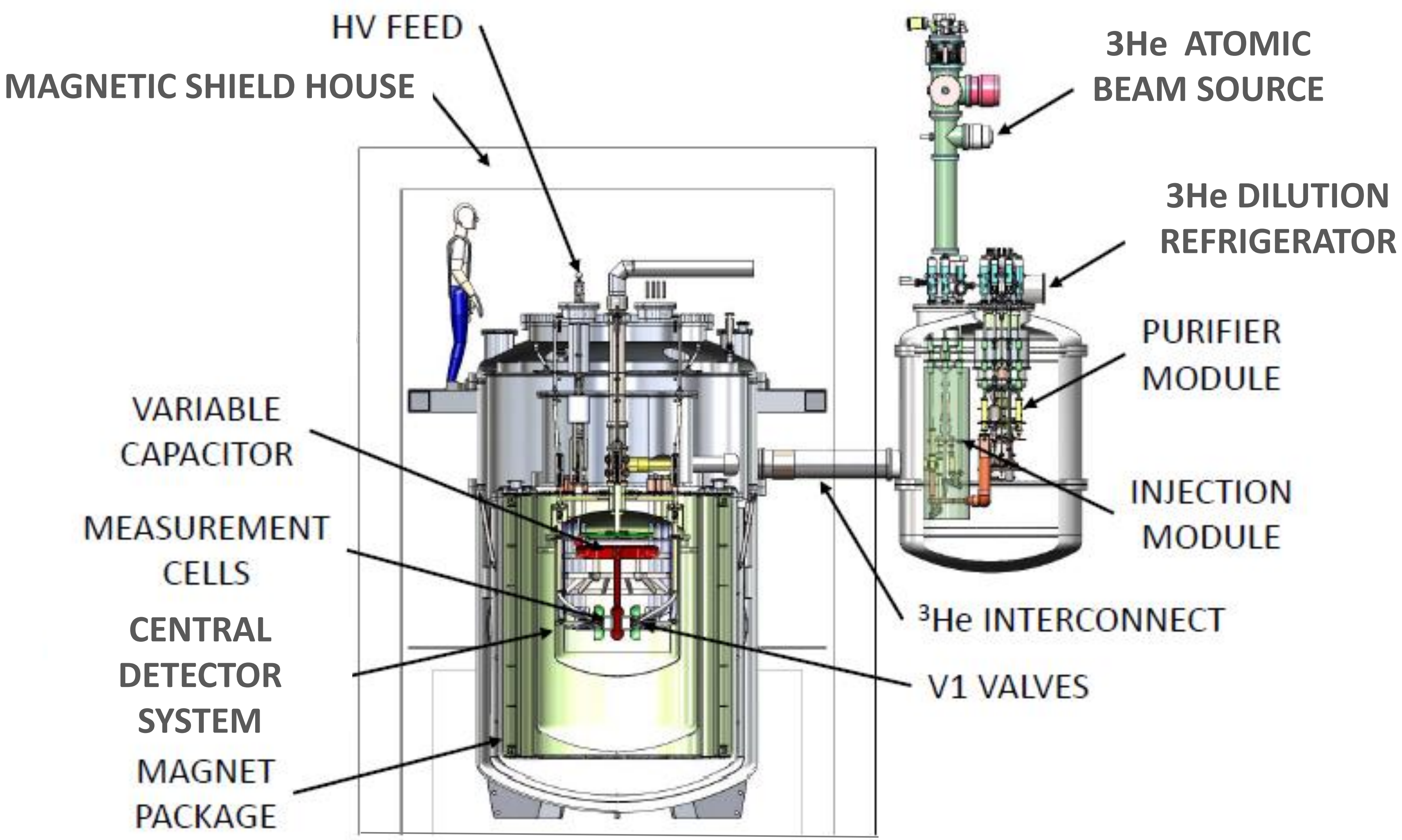
- Liquid He as a high voltage insulator
  – *high electric fields*

- Use of a $^3\vec{He}$ co-magnetometer and superconducting shield
  – *Control of magnetic field systematics*

- Use $\vec{n}$-$^3\vec{He}$ capture → Scintillation light variation allows neutron precession frequency measurement via two techniques:
  - *free precession*
  - *dressed spin techniques*

- Sensitivity estimate: $d_n \sim 3\text{-}5 \times 10^{-28}$ e•cm (90% CL after 3 yrs)

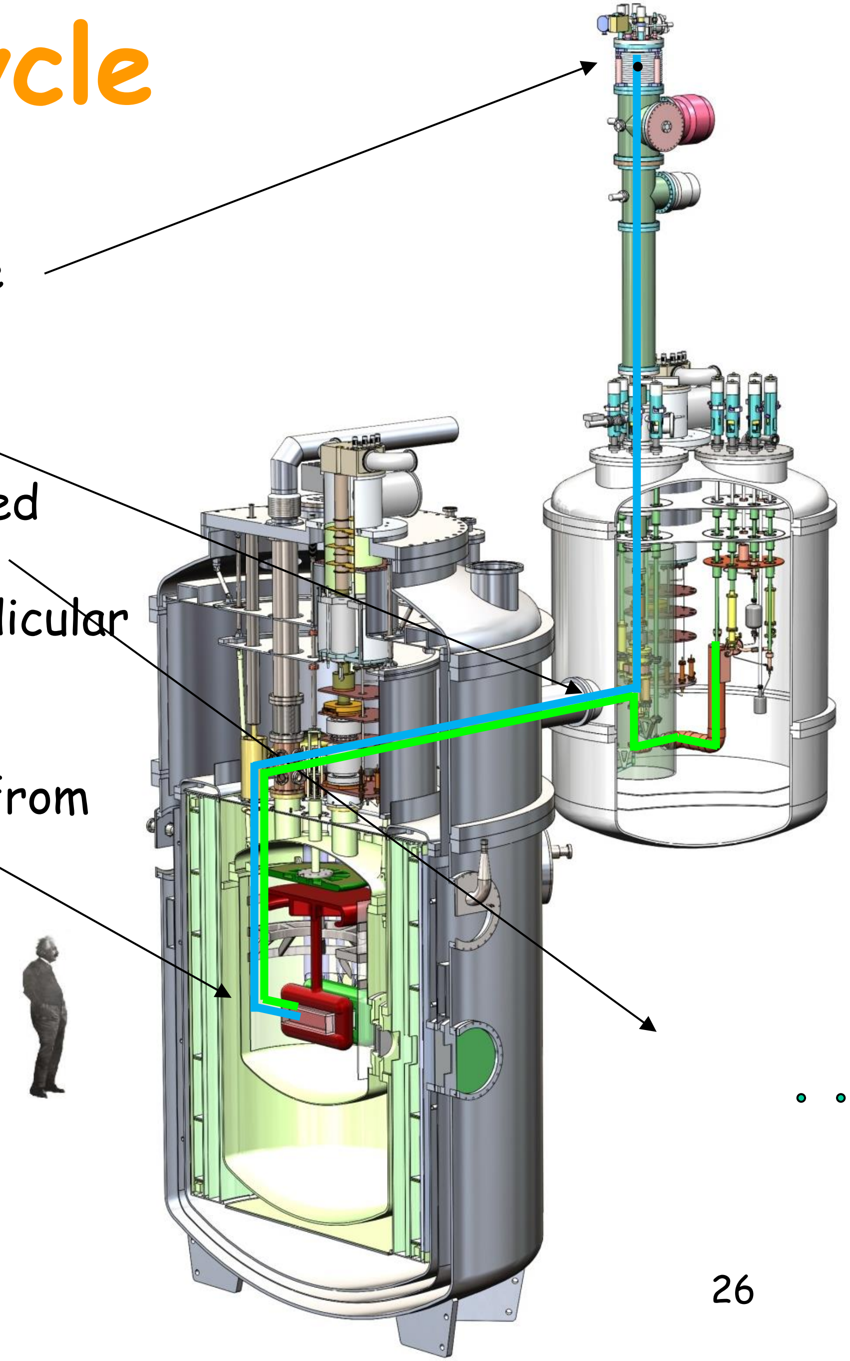
# SNS-nEDM Experiment

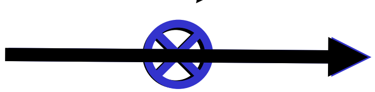



Neutron beam is into page

# Measurement Cycle

1. Load collection volume with polarized $^3$He atoms
2. Transfer polarized $^3$He atoms into measurement cell
3. Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
4. Apply a $\pi/2$ pulse to rotate spins perpendicular to $B_0$
5. Measure precession frequency
6. Remove reduced polarization $^3$He atoms from measurement cell
7. Flip E-field & Go to 1.





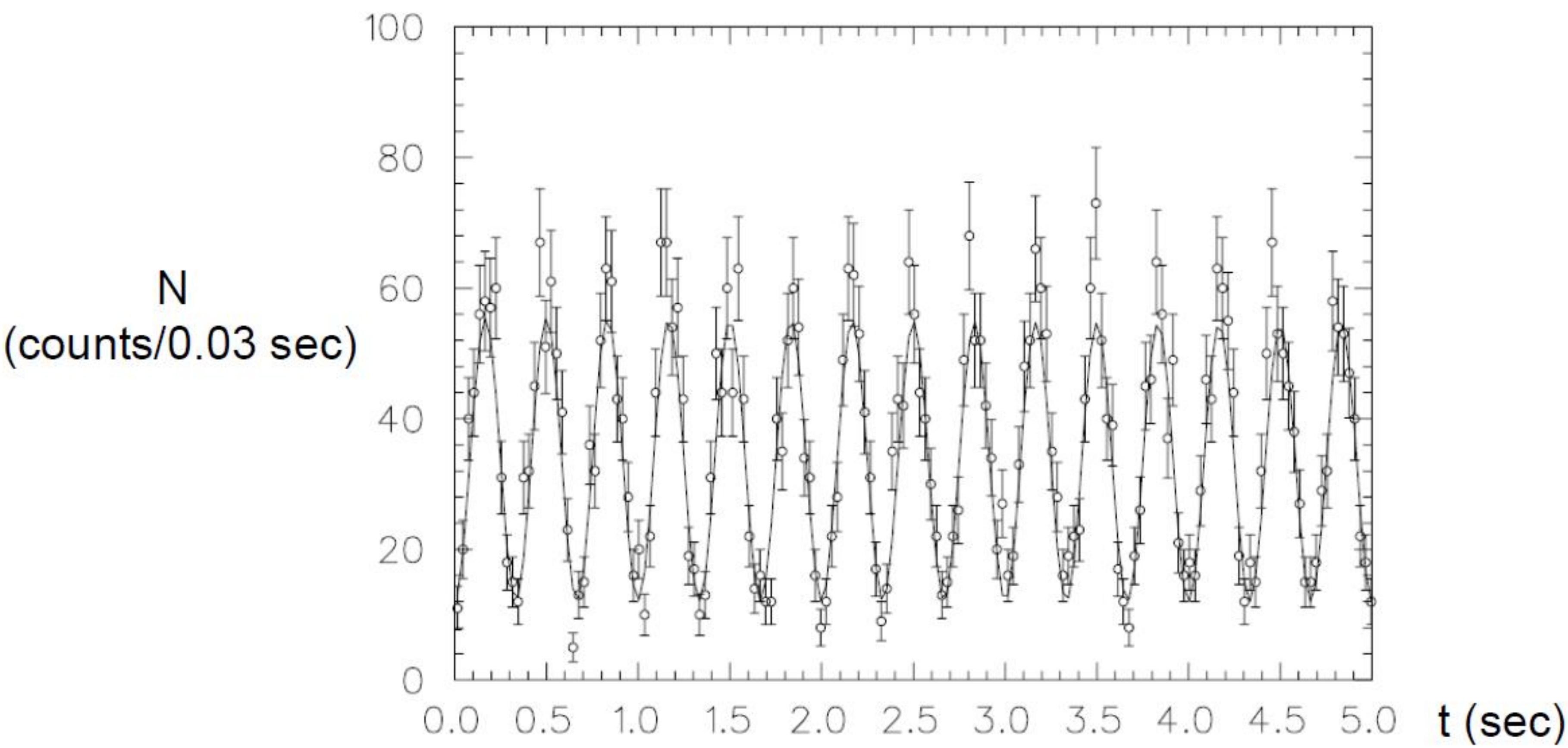
$^3$He functions as "co-magnetometer"
Since $d_{3He} << d_n$ due to $e^-$-screening

# Two ways to measure nEDM

via direct frequency measurement

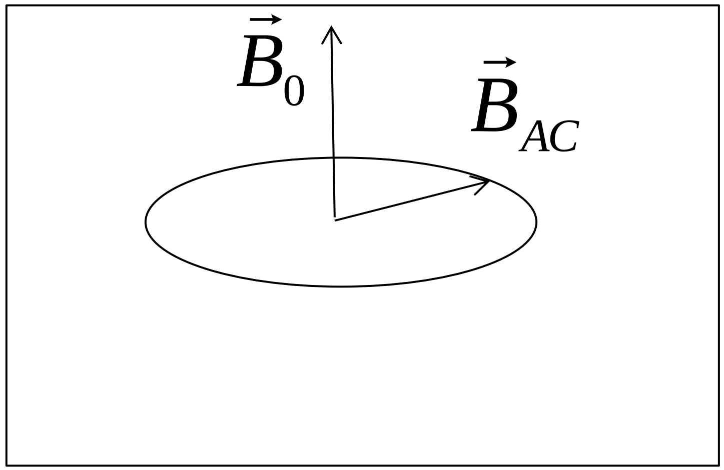
e.g. via spin-dependent neutron capture on polarized $^3$He

Signal oscillates at n-$^3$He beat frequency

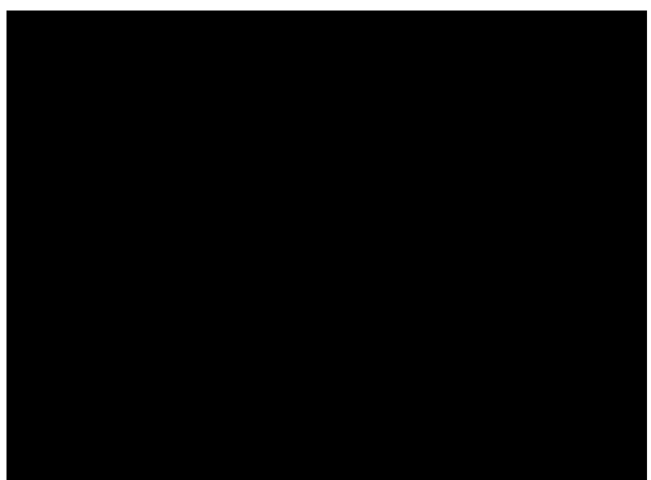


# Can also take advantage of "Dressed" Spins

Add a non-resonant AC B-Field




**Use of two measurement techniques provides critical cross-check of EDM result with different systematics**



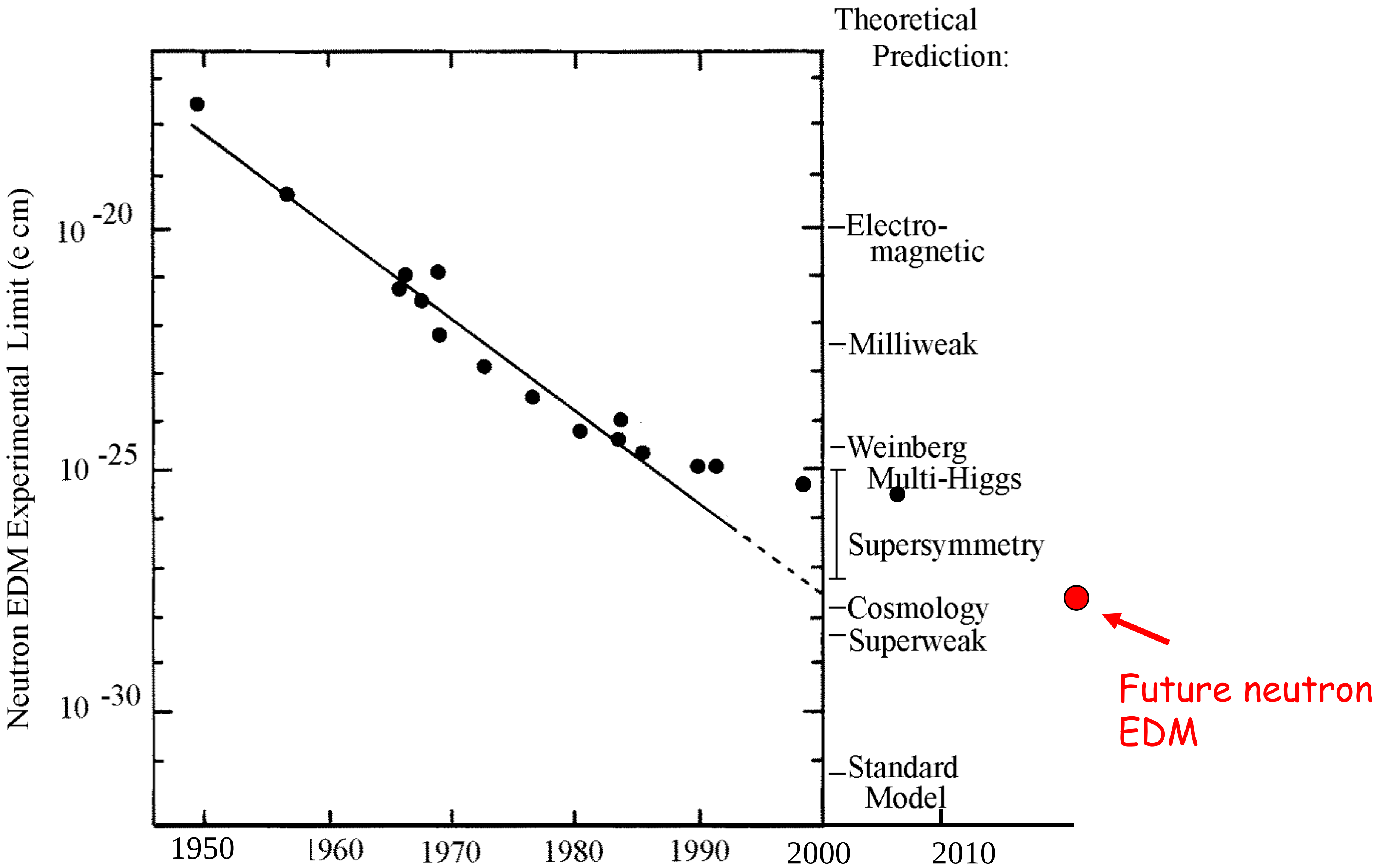
Can match effective precession frequency of n & $^3$He about $B_0$

Video from Pinghan Chu (Duke)

# SNS nEDM Construction

- Four year "Critical Component Demonstration" construction underway
  - Construction of the most challenging components 2014-2017
  - Build from the inside to the outside
- Followed by two year Conventional Construction
  - Begin data taking by 2020

# Future nEDM Sensitivity



# Summary

- Greatly improved EDM sensitivity can probe Beyond-Standard-Model physics at very high mass scales
- A number of exciting technologies are being developed to extend the EDM sensitivity by more than two orders-of-magnitudes
- We look forward to the **discovery** of an EDM in the next decade

# Extra Slides

# nEDM @ SNS COLLABORATION


R. Alarcon, R. Dipert

*Arizona State University*

G. Seidel

*Brown University*

E. Hazen, A. Kolarkar, J. Miller, L. Roberts

*Boston University*

D. Budker, B.K. Park

*UC Berkeley*

R. Carr, B. Filippone, M. Mendenhall, C. Osthelder, S. Slutsky,

C. Swank

*California Institute of Technology*

M. Ahmed, M. Busch, P. –H. Chu, H. Gao

*Duke University*

I. Silvera

*Harvard University*

M. Karcz, C.-Y. Liu, J. Long, H.O. Meyer, M. Snow

*Indiana University*

L. Bartoszek, D. Beck, C. Daurer, J.-C. Peng, T. Rao, S. Williamson, L. Yang

*University of Illinois Urbana-Champaign*

C. Crawford, T. Gorringe, W. Korsch,

E. Martin, N. Nouri, B. Plaster

*University of Kentucky*

S. Clayton, M. Cooper, S. Currie, T. Ito, Y, Kim, M. Makela, J. Ramsey,

A. Roberts, W.Sondheim

*Los Alamos National Lab*

K. Dow, D. Hasell, E. Ihloff, J. Kelsey, J. Maxwell, R. Milner, R. Redwine, E. Tsentalovich, C. Vidal

*Massachusetts Institute of Technology*

D. Dutta, E. Leggett

*Mississippi State University*

R. Golub, C. Gould, D. Haase, A. Hawari, P. Huffman, E. Korobkina,

K. Leung, A. Reid, A. Young

*North Carolina State University*

R. Allen, V. Cianciolo, Y. Efremenko, P. Mueller,

S. Penttila, W. Yao

*Oak Ridge National Lab*

M. Hayden

*Simon Fraser University*

G. Greene, N. Fomin

*University of Tennessee*

S. Stanislaus

*Valparaiso University*

S. Baeßler

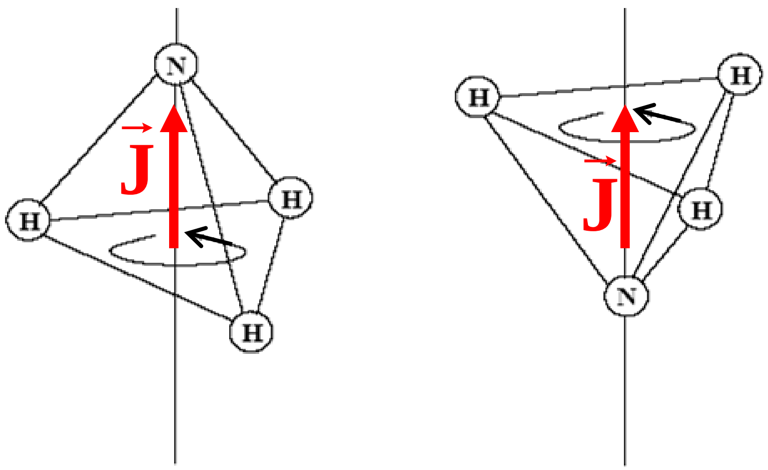
*University of Virginia*

S. Lamoreaux

*Yale University*

# Note: Some molecules have HUGE EDMs!

$H_2O$: $d = 0.4 \times 10^{-8}$ e-cm
NaCl: $d = 1.8 \times 10^{-8}$ e-cm
$NH_3$: $d = 0.3 \times 10^{-8}$ e-cm




But $NH_3$ EDM is not T-odd or CP-odd since

$$\vec{d} \neq d\frac{\vec{J}}{J}$$

$$\left(\text{both } \vec{d} = +d\frac{\vec{J}}{J} \quad \text{and} \quad \vec{d} = -d\frac{\vec{J}}{J} \text{ exist!}\right)$$

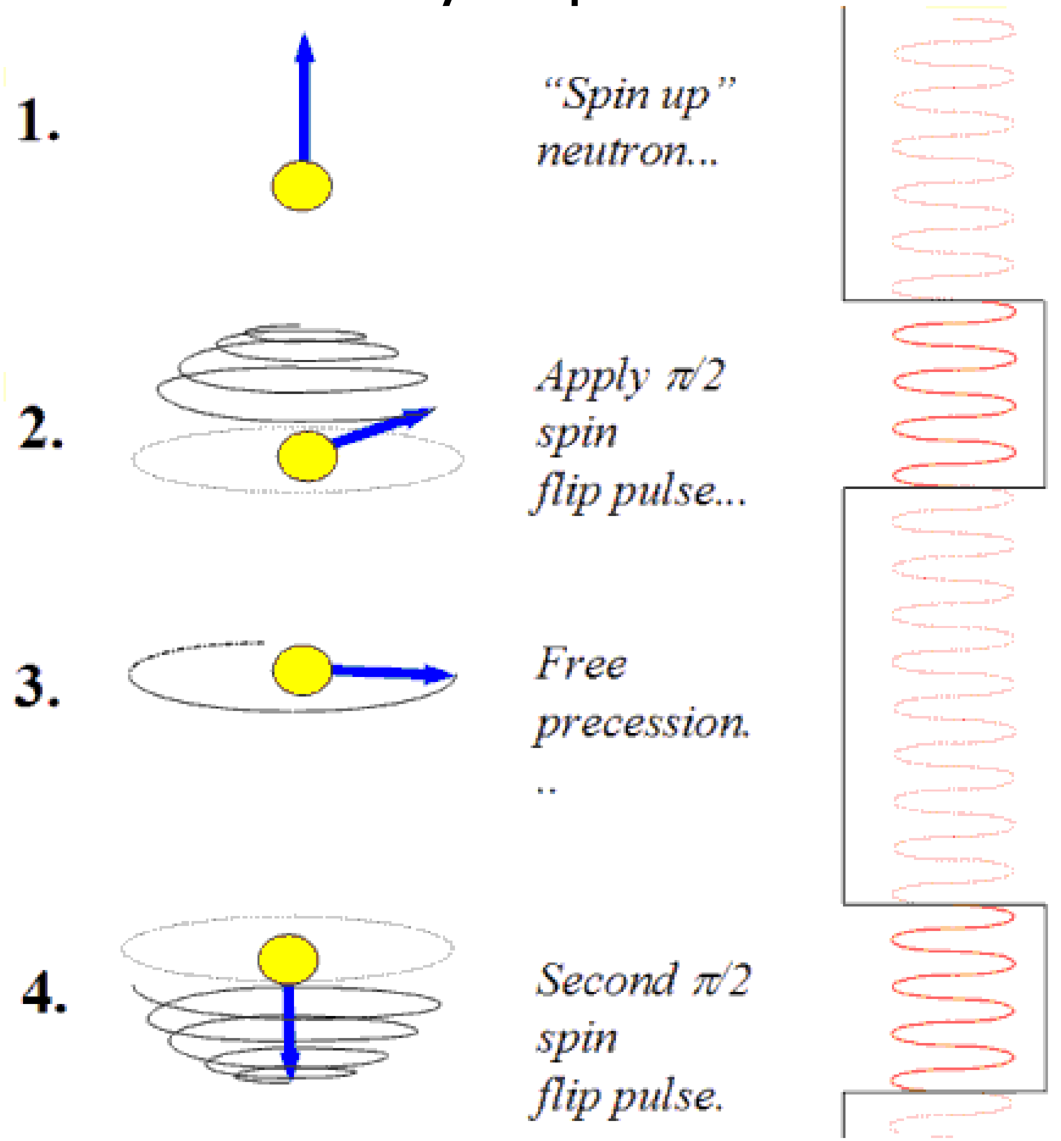
If Neutron had degenerate state


it would not violate T or CP

Ground state is actually a superposition

# How to Measure an EDM

## Ramsey Separated Oscillatory Field Technique




If small angle (phase) is added after ~ 1000s of oscillations (e.g. from EDM) then final spin doesn't point *exactly* down