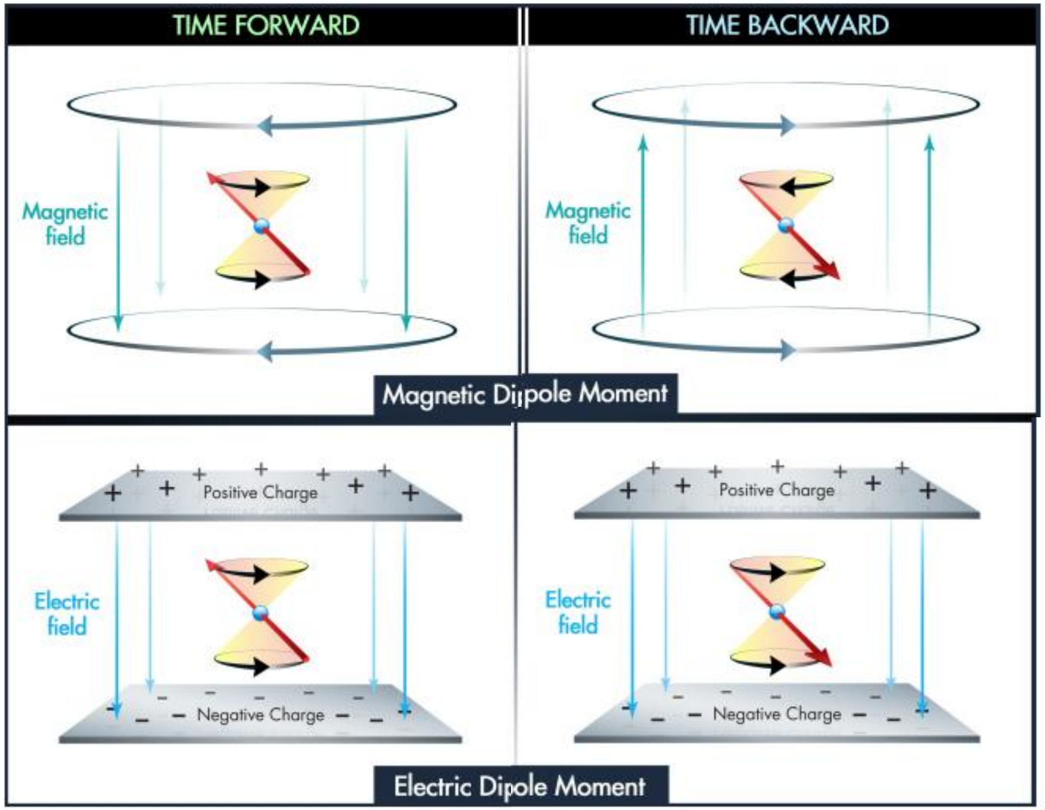
Status of Neutron Electric Dipole Moment (EDM) Searches

- ~~Motivation for EDM searches~~
- How to measure neutron's EDM
- Present limit and how to improve it
- nEDM experiment at SNS
  - Technical challenges & progress
  - Construction/Funding challenges & status
- Worldwide efforts for neutron EDM

B. Filippone
Particlegenesis 2014
6/24/14

Why Look for EDMs?

- Existence of unique EDM implies violation of Time Reversal Invariance



- Time Reversal Violation seen in K^0–$\overline{K^0}$ system
- May also be seen in early Universe
  - Matter-Antimatter asymmetry

but the Standard Model effect is too small !

Particle EDM Zoo

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

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

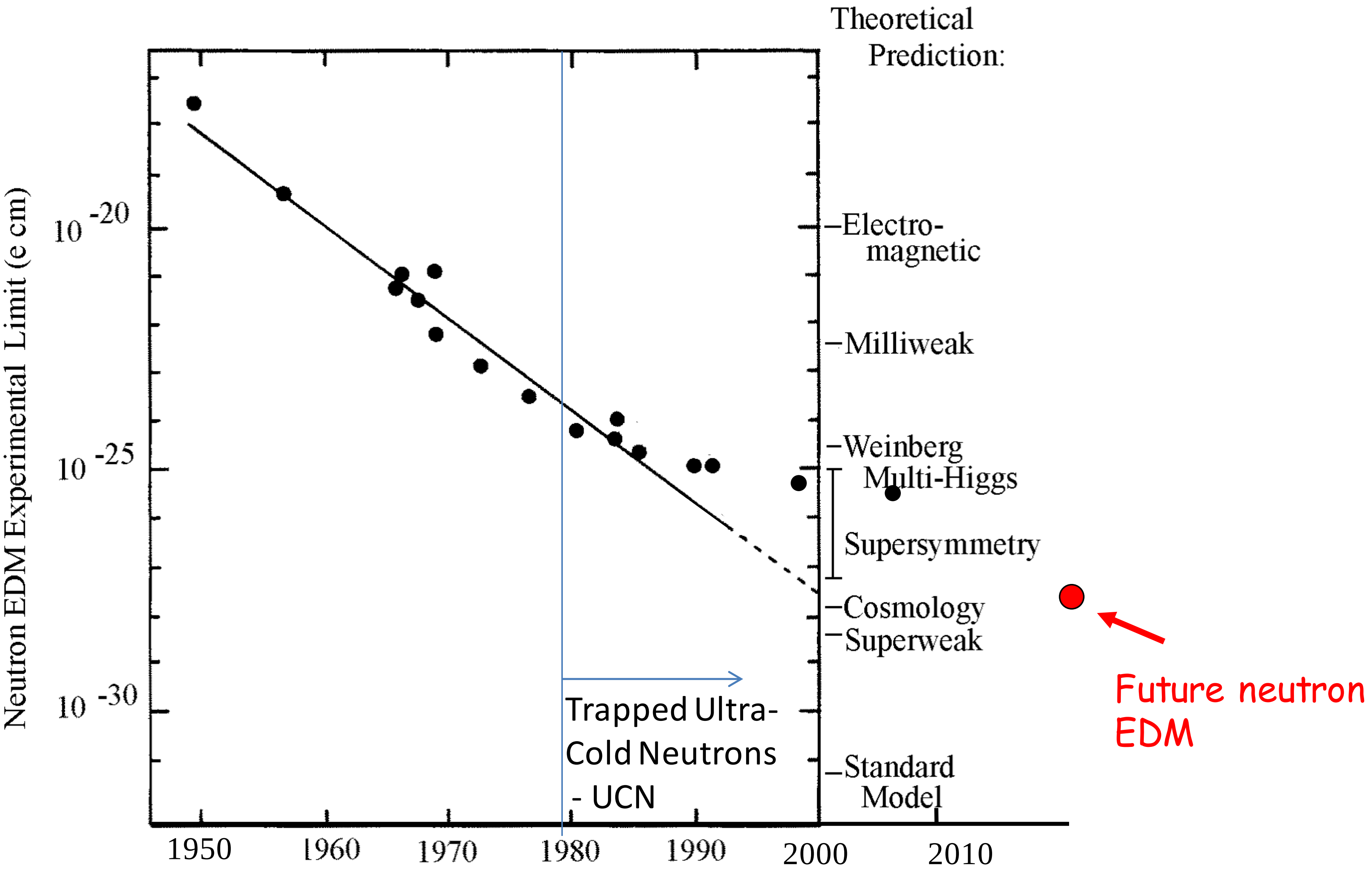
Relative EDM Sensitivities

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

Searches for a Neutron EDM

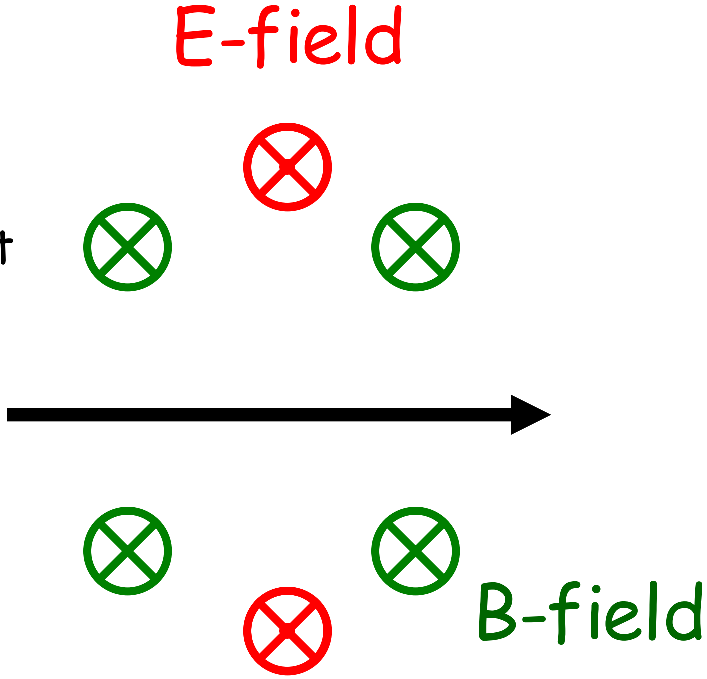
- E.M. Purcell and N.F. Ramsey, *Phys. Rev.* **78**, 807 (1950)
  - **Neutron Scattering**
  - **Searching for Parity Violation**
  - **Pioneered Neutron Beam Magnetic Resonance**

nEDM Sensitivity "Moore's Law"



How to Measure an EDM

1. Inject polarized particle
2. Rotate spin by π/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

With E = 50 kV/cm, B = 3 μT

Neutron EDM of 1 x 10^{-28} e-cm gives

$\Delta\nu = 5$ nHz, $\nu = 90$ Hz

Best 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)

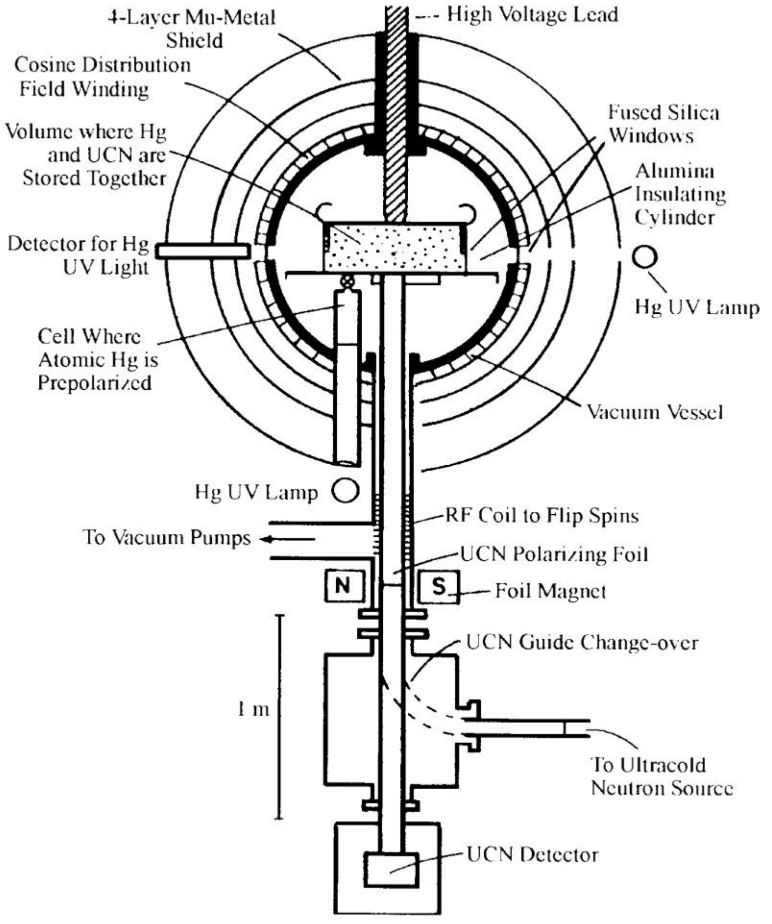
Trapped Ultra-Cold Neutrons (UCN) with N_{UCN} = 0.5 UCN/cc

4-layer Magnetic Shield

|E| = 5 - 10 kV/cm

100 sec storage time

$\sigma_d < 3 \times 10^{-26}$ e cm



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

What is the precision in an EDM measurement?

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

Using Uncertainty Principle:

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

Precise energy measurement requires long individual measurement time, giving

$$\sigma_d \sim \frac{\Delta \mathrm{E}}{|\vec{E}|} \sim \frac{\hbar}{|\vec{E}| T_m}$$

Can improve with multiple measurements $\propto \frac{1}{\sqrt{N_n}}, \propto \frac{1}{\sqrt{m}}$

To further improve sensitivity need new techniques

- Enhance number of stored neutrons
  - $\sqrt{N}$ improvement - LHe at < 1K can do this
- Increase Electric field
  - Linear improvement – LHe as dielectric could help
- Minimize key systematic effects
  - Highly uniform B-field to minimize systematics
  - Can try superconducting B-shield
  - Co-magnetometer could be essential
    - Measure B-field averaged over neutron volume

Why is it so hard to measure?

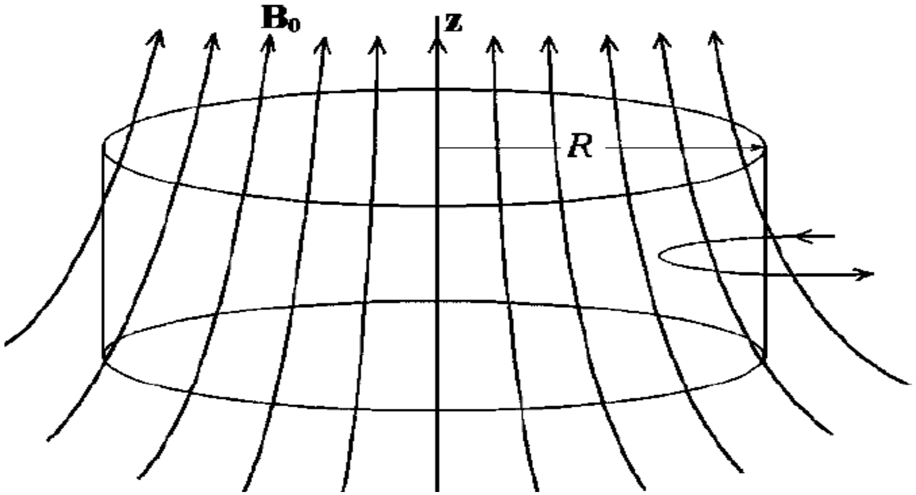
- To increase sensitivity by 100 need to measure a frequecy shift of 5 nHz for 100 Hz neutron precession
- Severe technical challenges – kind of like non-perturbative QCD
  - "Boring" experimental issues actually pushing technology past state-of-the-art
- Subtle systematic problems exist
  - Relativistic effect of 5 m/s neutrons
    - "Geometric" phase

“Geometric Phase” Systematic Effect

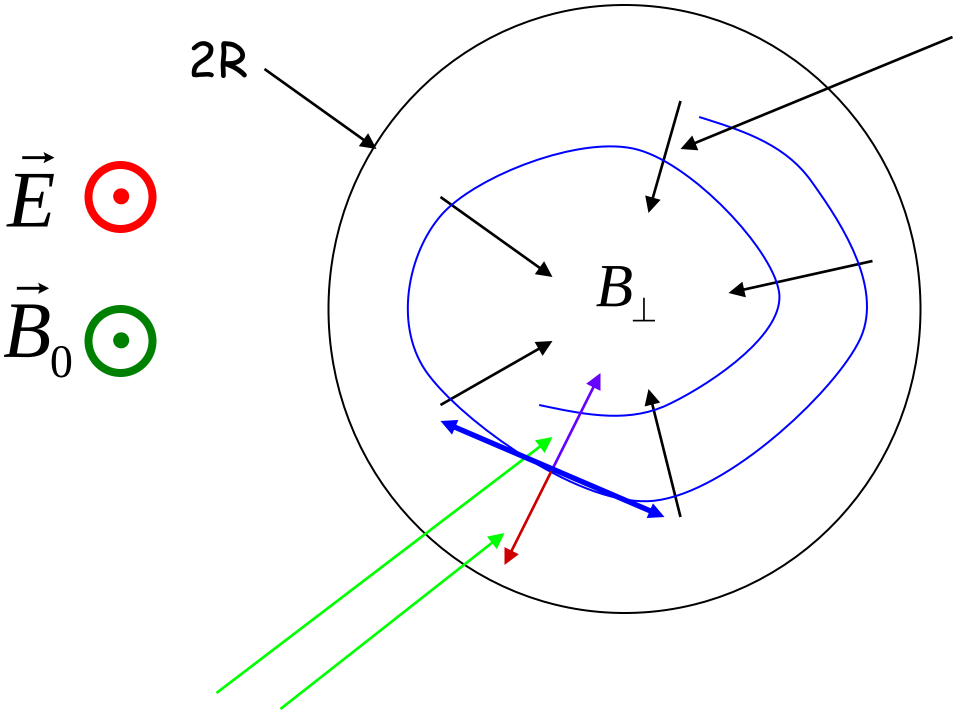
- For slow particles:
  - Path-dependent phase
  - In Quantum Mechanics often called Berry’s phase
  - Actually a *relativistic* effect for neutrons!

False EDM from motional B-field

- Commins Am J Phys 59, 1077 (91)
- Pendlebury et al PRA 70 032102 (04)
- Lamoreaux and Golub PRA 71 032104 (05)
- Motional (vxE) B-fields can add to radial B fields perpendicular to B_0 **(These can result e.g. from dB_0/dz) giving a false EDM**
- Gives rotating B-field in frame of moving neutron



Geometric phase with B_E = v x E field



Radial B-field → rotating field

v x E field
changes sign with
neutron direction

- Motion in rotating B-field shifts the precession frequency (away from ω_0)

$$\Delta\omega \cong \frac{\gamma^2 B_{Rot}^2}{2(\omega_0 - \omega_{Rot})}, \quad B_{Rot} = B_\perp + \frac{\vec{v}x\vec{E}}{c^2}$$

- Does not average to zero over trajectories

- Is proportional to direction of E-field

$$d_n \approx \frac{v_\perp^2 \left|\frac{\partial B}{\partial z}\right|}{B_0^2} \quad \rightarrow \text{False EDM}$$

Some Technical Challenges:

- Non-conducting central volume: RF heating & magnetic Johnson noise
- Polarized ^{3}He friendly: maximize T_2
- Polarized n friendly: maximize T_2
- UCN friendly: maximize T_m
- Purify ^{4}He: ppt compared to ppm (natural)
- 1200 liters of Superfluid LHe at 0.3 K: no leaks
- High E-field: ~ 80 kV/cm
- No E-field breakdown: SQUID survivial
- Ambient B-field suppression: 10^{-5} for SQUIDS & systematics
- Uniform B-fields: ppm level
- All above approved to run at a National Lab !

nEDM COLLABORATION

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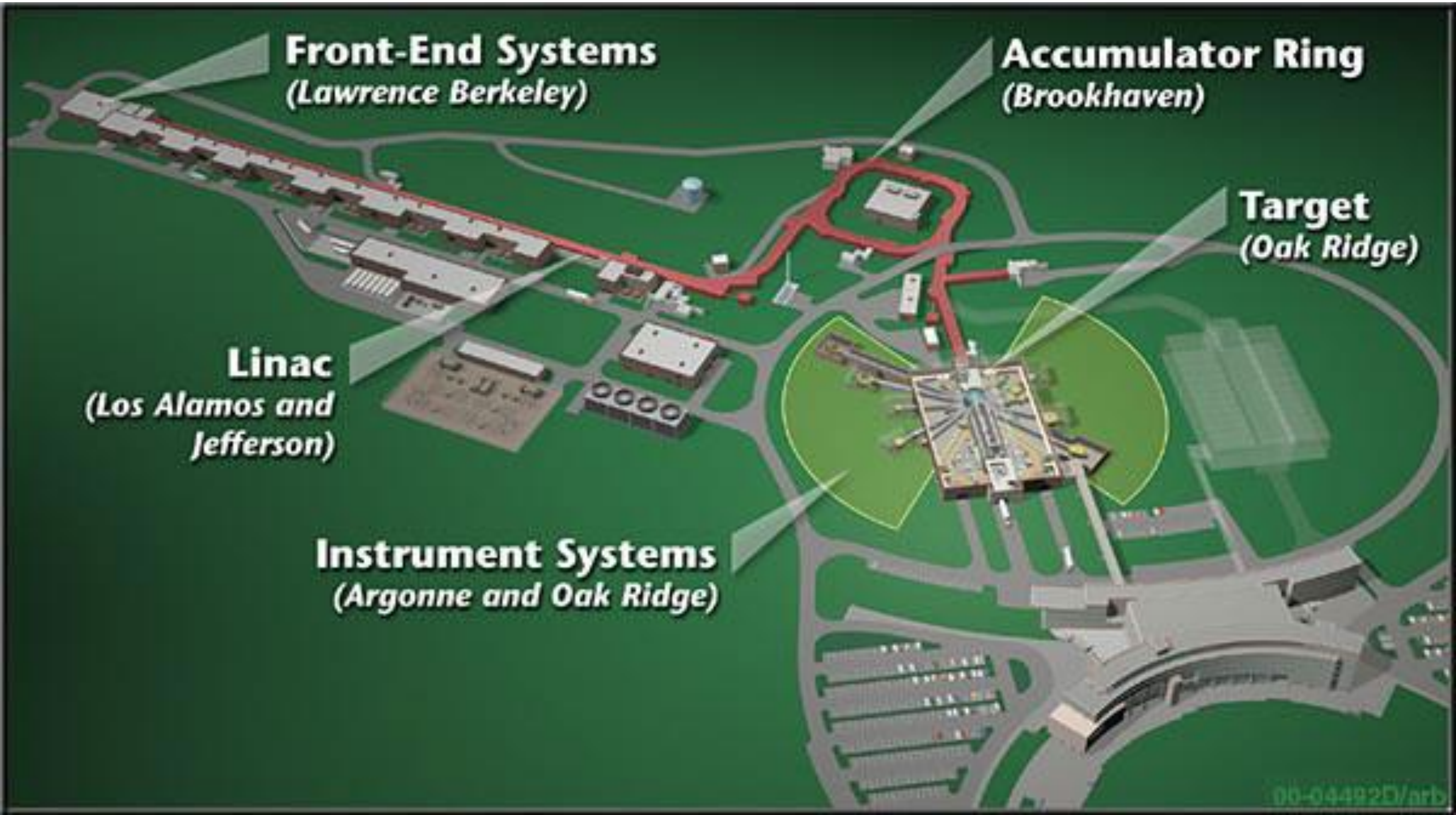
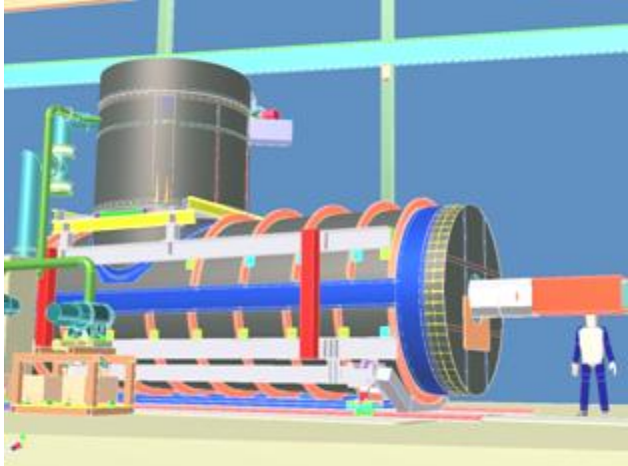
Spallation Neutron Source (SNS) at ORNL

1 GeV proton beam with 1.4 MW on spallation target



SNS nEDM Experiment



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 (along with CryoEDM)
  – *high electric fields*

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

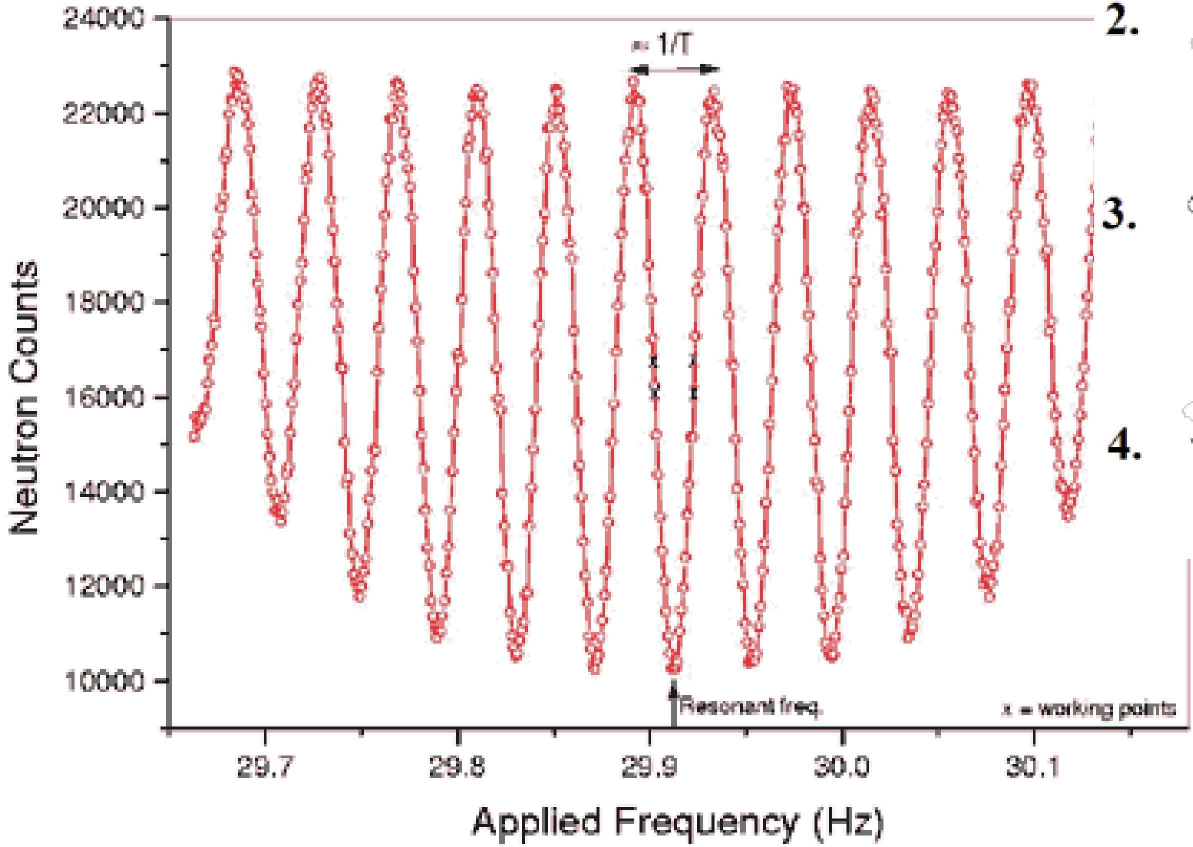
- Use $\vec{n}$-$^{3}\overrightarrow{\mathrm{He}}$ capture → light to measure neutron precession frequency
  - two techniques:
    - *free precession*
    - *dressed spin techniques*

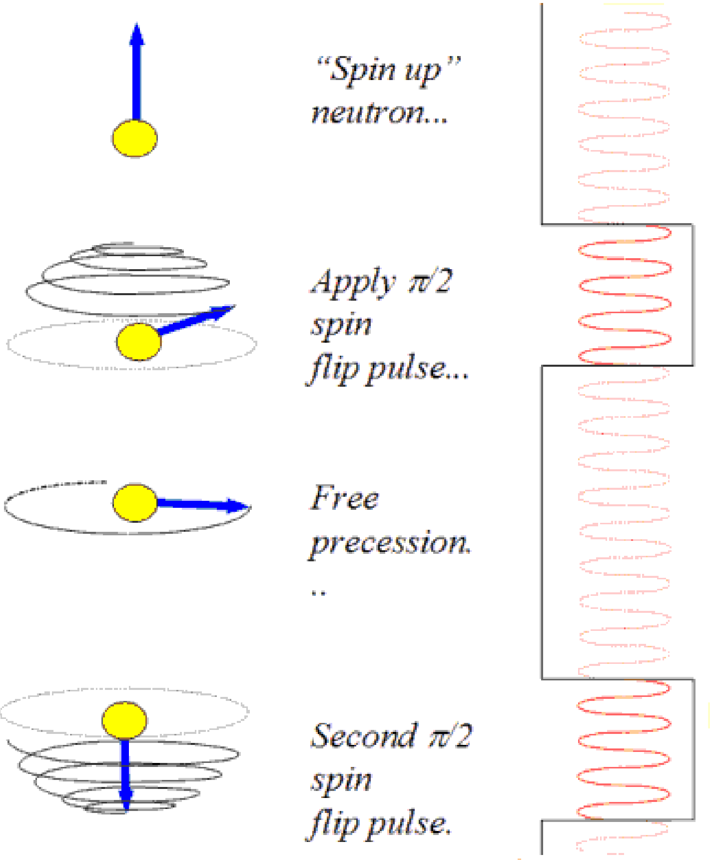
100x improvement over existing limit

- Sensitivity estimate: **d_n ~ 3-5 x 10^{-28} e•cm (90% CL after 3 yrs)**

Previous experiments used Ramsey Technique

- So-called separated-oscillatory field technique
  - Measure neutron "survivors" how many n↑ vs. n↓





1. *"Spin up" neutron...*

2. *Apply π/2 spin flip pulse...*

3. *Free precession...*

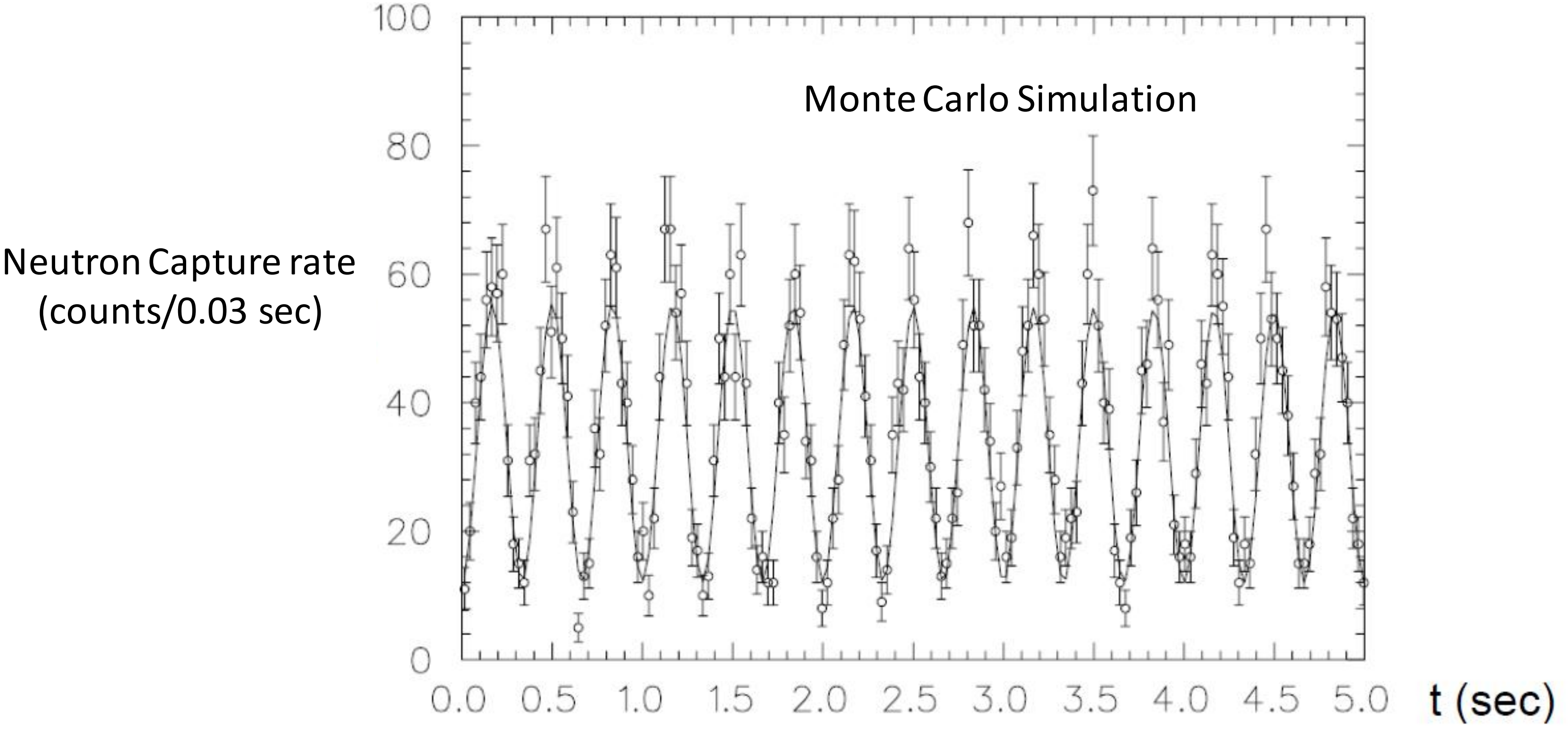
4. *Second π/2 spin flip pulse.*

Alternative to Ramsey technique is direct measurement of frequency

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

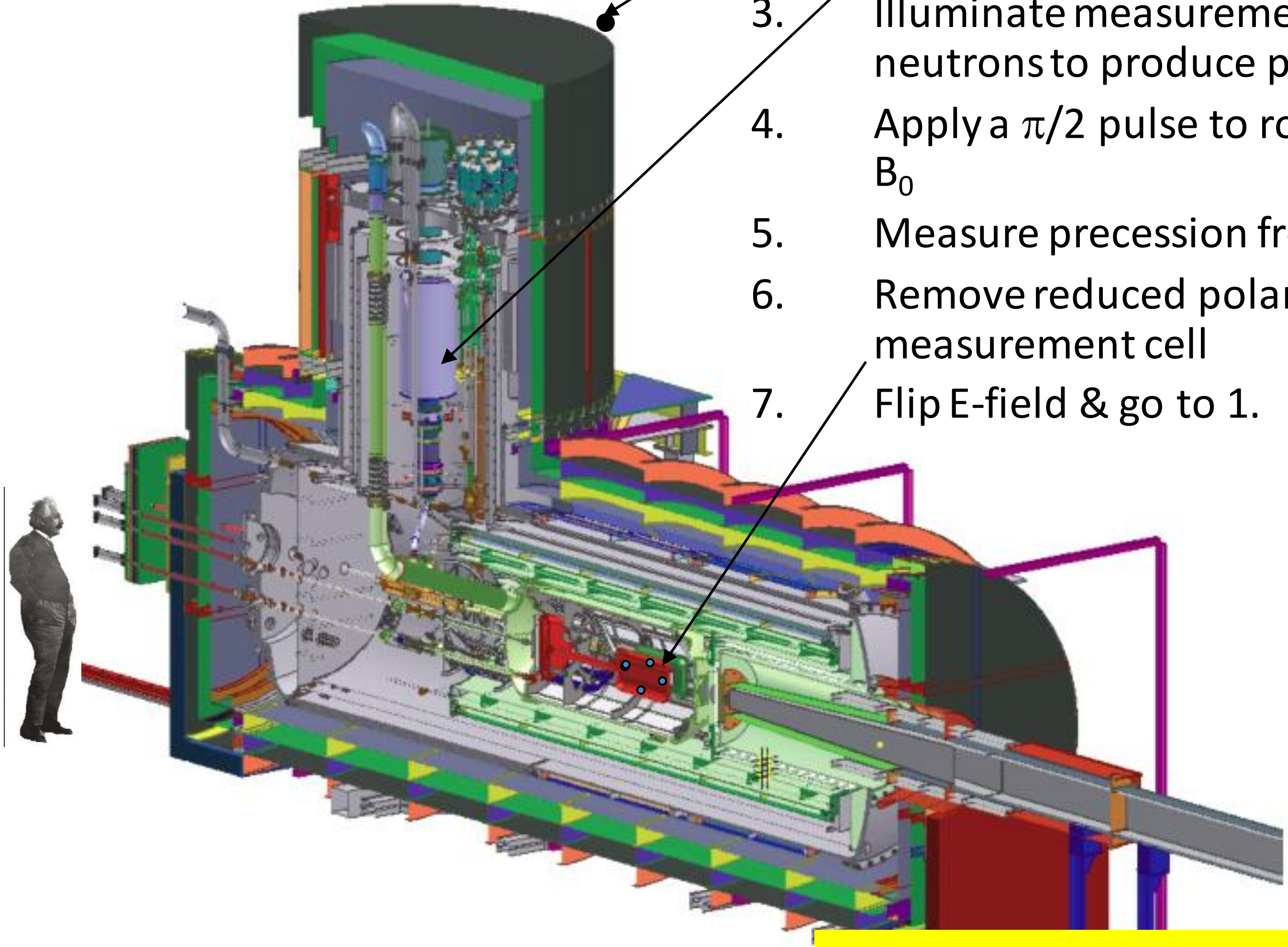
capture rate, measured via scintillation in LHe, oscillates at n-^{3}He beat frequency

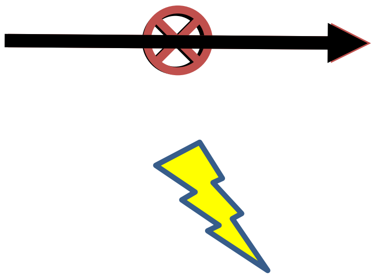
Measure neutron "casualties"



SNS Measurement cycle

1. Load collection volume with polarized ^{3}He atoms
2. Transfer polarized ^{3}He atoms into the 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.

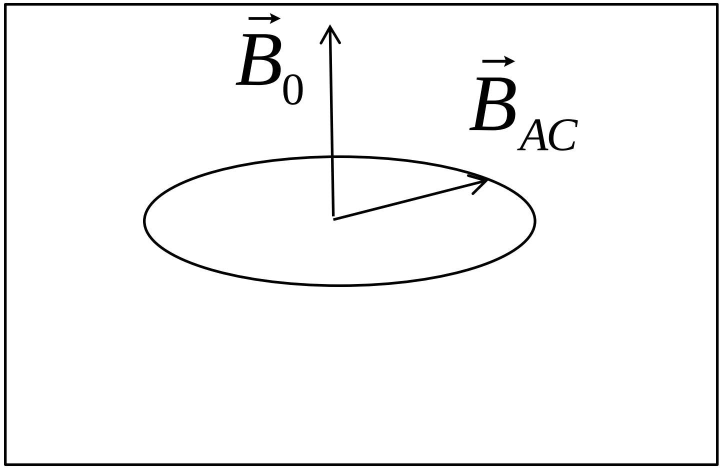




^{3}He functions as "co-magnetometer"
Since $d_{3He} << d_n$ due to e^--screening

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 = Ping-Han Chu

Example of future Neutron EDM Sensitivity

	ILL published	**EDM @ SNS**	Improve Sens.
$\mathbf{N_{UCN}}$	1.3×10^4	4×10^5	x 5.5
$\mathbf{|\vec{E}|}$	10 kV/cm	70 kV/cm	x 7
$\mathbf{T_m}$	130 s	1000 s	x 2.3
m (cycles/day)	270	25	
$\mathbf{\sigma_d}$ **(e-cm)/day**	3×10^{-25}	3.5×10^{-27}	x ~ 90

$$\sigma_d \cong \frac{\hbar}{|\vec{E}|\, T_m \sqrt{m N_{UCN}}}$$

Projected systematic uncertainties

Error Source	Systematic uncertainty (e-cm)	Comments
Linear vxE (geometric phase)	$< 2 \times 10^{-28}$	Uniformity of B_0 field
Quadratic vxE	$< 0.5 \times 10^{-28}$	E-field reversal to <1%
Pseudomagnetic Field Effects	$< 1 \times 10^{-28}$	π/2 pulse, comparing 2 cells
Gravitational offset	$< 0.2 \times 10^{-28}$	With E-field dependent gradients < 0.3nG/cm
Heat from leakage currents	$< 1.5 \times 10^{-28}$	< 1 pA
vxE rotational n flow	$< 1 \times 10^{-28}$	E-field uniformity < 0.5%
E-field stability	$< 1 \times 10^{-28}$	ΔE/E < 0.1%
Miscellaneous	$< 1 \times 10^{-28}$	Other vxE, wall losses

Statistical sensitivity: 3 - 5 x 10^{-28} e-cm @ 90% CL in 3 calendar years

Status of nEDM @ SNS

- Nuclear Science Advisory Committee (NSAC) Review of Fundamental Physics with Neutrons (1/12)
  - nEDM is highest priority of sub-field
  - nEDM should focus on Critical R&D for 2 yrs
    - Several key elements need to be demonstrated
- "Equipment Project" stopped 3/12
- Funded as R&D project (2012/2013)
    - Reviewed every 4 months via external Technical Review Committee
- Full NSF/DOE review 12/13

NSF/DOE Review (12/13)

- Key Technical milestones largely met
  - High Electric Fields
  - Uniform Magnetic Fields
  - Polarized ^{3}He transport demonstrated
  - Progress on Neutron storage/SQUIDS/Light Collection

Path to Construct experiment

- Collaboration proposes a 4-yr "Demonstration" phase (Critical Component Demonstration – CCD)
  - Continue as an R&D project to build high-fidelity, full-scale "prototypes" of most difficult subsystems
  - Working prototypes are then part of the experiment

Funding & Schedule for SNS

- 4-yr NSF proposal for CCD approved ~6.5M$
- Anticipate 4-yr DOE Funding for CCD ~7M$
- Continuation of external Technical Review Committee
- Need additional ~ 25M$ after CCD
- Could complete construction over ~ 2 yrs with more conventional systems
- Commissioning underway by 2019-2020

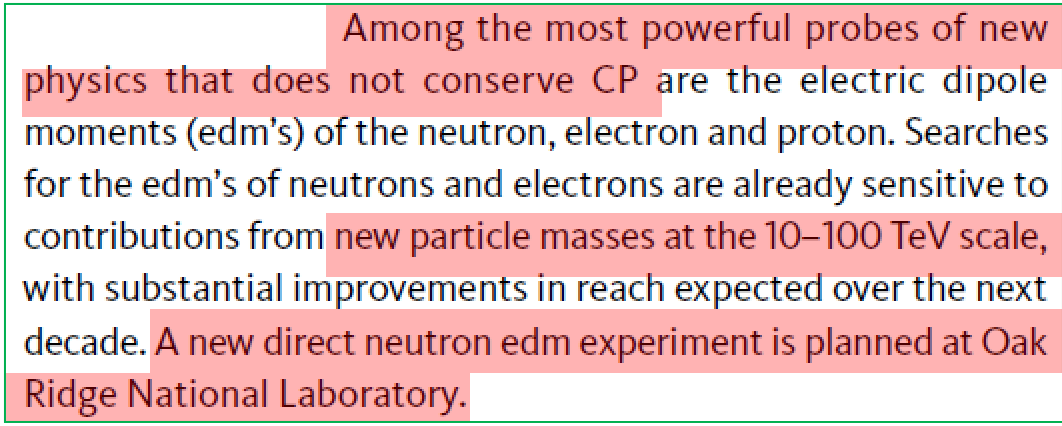
Worldwide nEDM Searches

Why so many exps ??

- Science remains compelling even with LHC data

If the U.S. is to remain a leader, additional new investments by the nuclear science funding agencies will be necessary over the next 5-10 years aimed at realizing the program outlined in Table II-1. **These investments include** construction of at least one tonne scale neutrinoless double beta decay detector, **construction of a high sensitivity neutron EDM experiment**,

NSAC Long Range Plan Implementation 2013



Among the most powerful probes of new physics that does not conserve CP are the electric dipole moments (edm's) of the neutron, electron and proton. Searches for the edm's of neutrons and electrons are already sensitive to contributions from new particle masses at the 10–100 TeV scale, with substantial improvements in reach expected over the next decade. A new direct neutron edm experiment is planned at Oak Ridge National Laboratory.

P5 – Report 2014

- Opportunities at new & existing facilities
  - New = FRMII,JPARC,SNS;   Existing = ILL,PSI,TRIUMF

Worldwide nEDM Searches

Experiment	UCN source	cell	Measurement techniques	σ_d Goal (10^{-28} e-cm)
ILL - CryoEDM	Superfluid ^{4}He	^{4}He	Cryo HV, SuperCond., Ramsey technique, external SQUID mag.	< 5
ILL-PNPI	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for ω E=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam	solid	Crystal Diffraction Non-Centrosymmetric crystal	< 100
PSI EDM	Solid D_2	Vac.	Ramsey for ω, external Cs & ^{3}He, Hg co-magnetom. Xe or Hg comagnetometer	Phase1 ~ 50 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 Then move to TRIUMF	< 50 < 5
SNS EDM	Superfluid ^{4}He	^{4}He	Cryo-HV, ^{3}He capture for ω, ^{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 Non-Centrosymmetric crystal	< 10?
LANL	Solid D_2	Vac.	R & D	~ 30

🟥 = sensitivity < 5 x 10^{-28} e-cm

Status of high sensitivity experiments

- CryoEDM at ILL – phasing out ("under-resourced")
- PSI – reduced number of UCN
- FRMII – safety concerns slow UCN
- SNS – see earlier slides
- RCNP/TRIUMF – under development
- JPARC – under discussion

Comparison of advanced, high sensitivity experiments

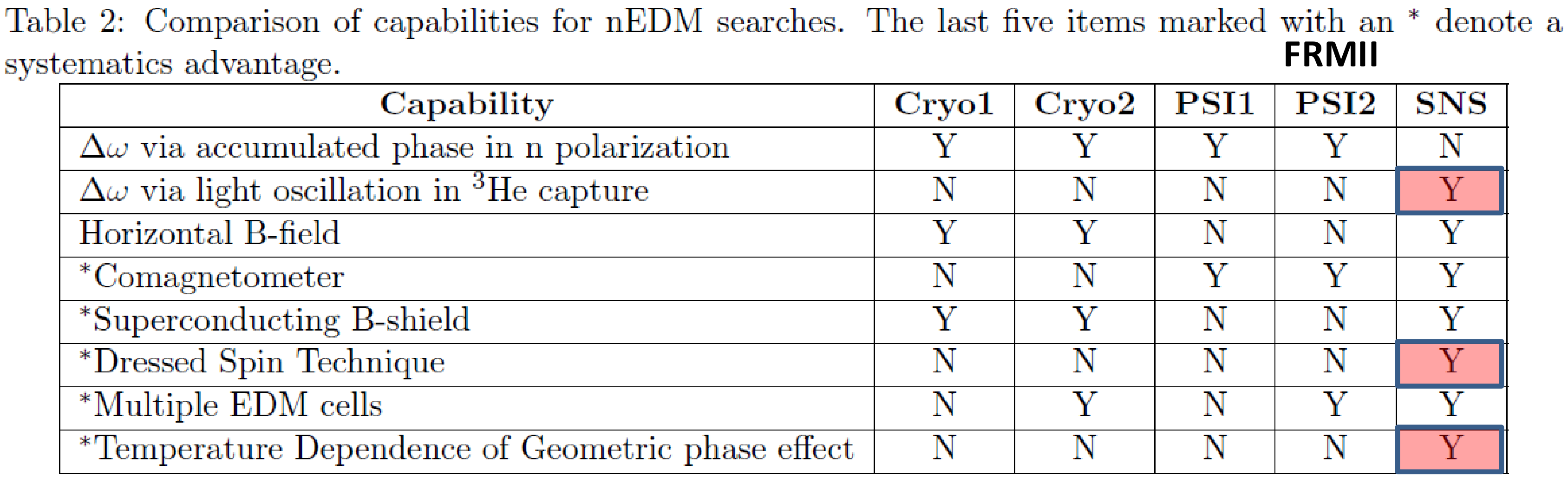


Table 2: Comparison of capabilities for nEDM searches. The last five items marked with an * denote a systematics advantage.

FRMII

Capability	Cryo1	Cryo2	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	Y	N	N	Y
*Comagnetometer	N	N	Y	Y	Y
*Superconducting B-shield	Y	Y	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

nEDM @ SNS has unique systematics advantages

Summary

- Importance of greatly improved neutron EDM sensitivity is recognized worldwide
- A number of exciting technologies are being developed to extend the neutron EDM sensitivity by two orders-of-magnitude
- nEDM @ SNS is world leading in sensitivity and systematic error control

Origin of Hadronic EDMs

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

θ_{QCD}

Weinberg 3-gluon term

$$\begin{aligned}\mathcal{L}_{eff}^{\cancel{CP}} \;=\;& \frac{g_s^2}{32\pi^2}\,\bar{\theta}\, G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{1}{3} w\; f^{abc} G^a_{\mu\nu}\tilde{G}^{\nu\beta,b} G_{\beta}{}^{\mu,c} \\ & -\frac{i}{2}\sum_{i=e,u,d,s} d_i\; \overline{\psi}_i (F\cdot\sigma)\gamma_5\psi - \frac{i}{2}\sum_{i=u,d,s} \tilde{d}_i\; \overline{\psi}_i g_s (G\cdot\sigma)\gamma_5\psi + \cdots\end{aligned}$$

e^-, quark EDM

quark color EDM (chromo-EDM)