The Search for a Neutron Electric Dipole Moment

- Science of Electric Dipole Moments (EDM)
- Status of neutron EDM searches
- nEDM experiment at SNS
  - Technical challenges & progress
  - Construction/Funding challenges & status
- Worldwide efforts for neutron EDM

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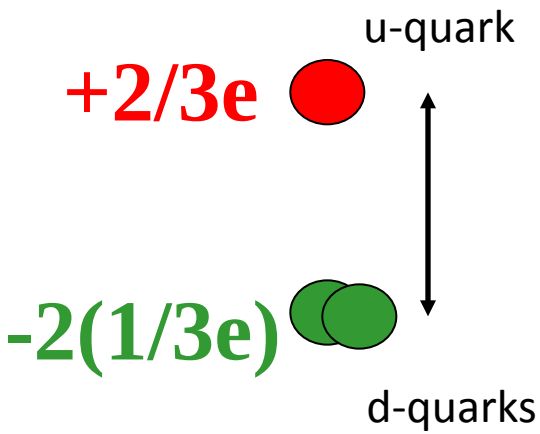
JLAB User Group Mtg
6/4/14

How big is the neutron EDM?



if $\ell \sim 0.1\ r_n$

$d_n \sim 1\times10^{-14}$ e-cm

But experiment says $d_n < 3\times10^{-26}$ e-cm

Neutron EDM & Electron Scattering

- Neutron EM current:

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

P&T even P odd P&T odd

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

- Also related to Transversity! $\delta q = \int_0^1 dx \left[h_1(x) - \bar{h}_1(x) \right]$

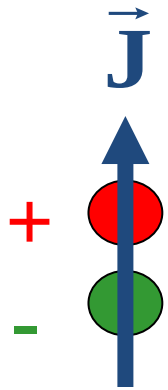
$$d_n = \sum_q d_q \delta q$$

Transversity distribution = spin distribution of quarks carrying momentum fraction - x - of the total momentum of a transversely polarized nucleon

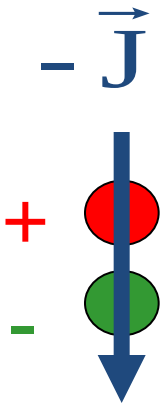
nEDM Violates Time-Reversal Symmetry

Neutron

Distinguishable Neutron !



$$t \Rightarrow -t$$
$$\vec{J} \Rightarrow -\vec{J}$$
$$\vec{d} \Rightarrow \vec{d}$$



- Since neutron has no distinguishable partner, EDM violates Time-Reversal Symmetry

Primary Motivation for EDM Searches

- Particle EDMs violate Time-Reversal Symmetry and Charge-Parity (CP) Symmetry
- Can be a window to new physics beyond the Standard Model (even beyond Large Hadron Collider)
  - Since they are *Very* small in Standard Model
- May shed light on why the Universe is not symmetric in amount of Matter vs Antimatter
  - **Sakharov Criteria: Proton decay, non-equilibrium phase & new CP violation**

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 in 1st & 2nd order
  - Need at least three loops to get EDM's (electron actually requires 4 loops!)
    - Thus EDM's are VERY small in standard model

Neutron EDM in Standard Model is ~ 10^{-32} e-cm (~10^{-19} e-fm)

Experimental neutron limit: < 3 x 10^{-26} e-cm

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

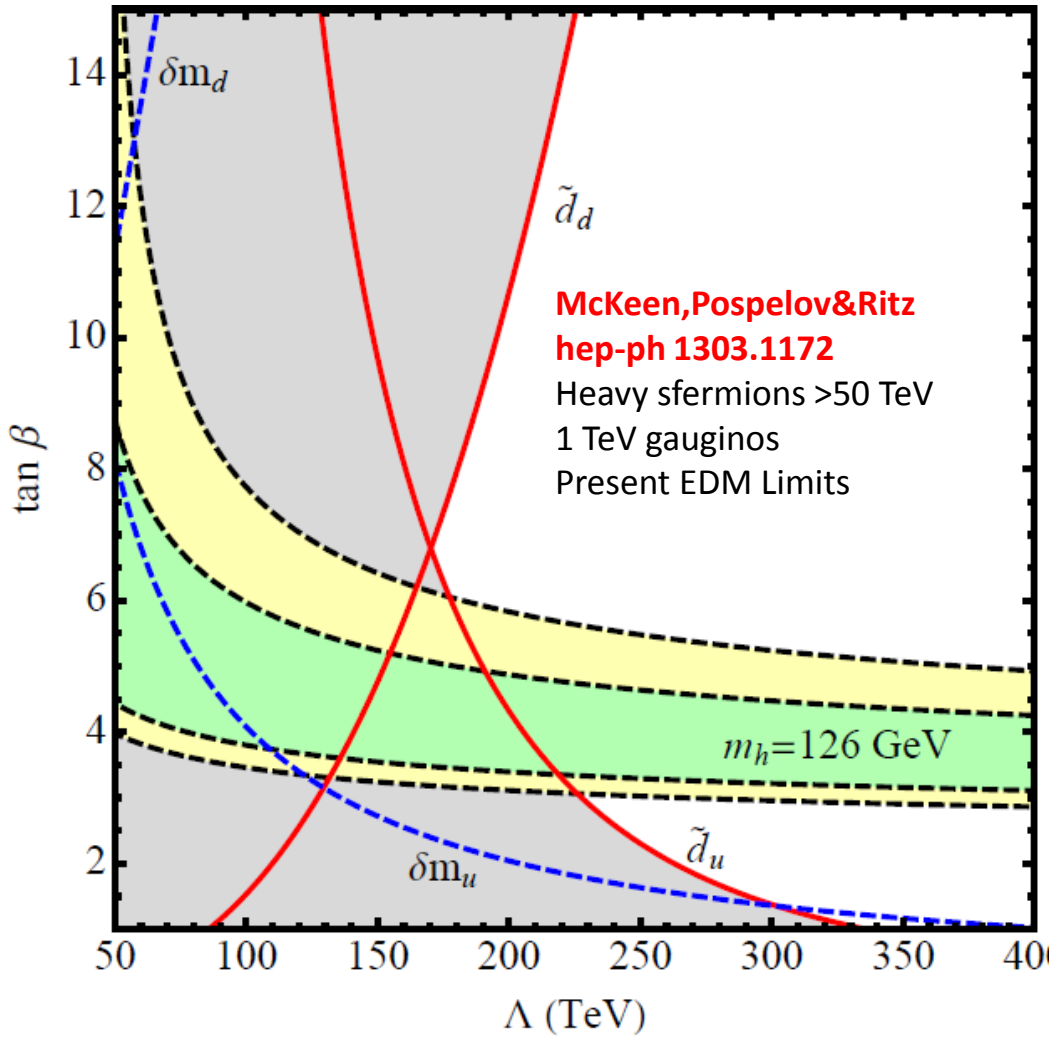
- New physics (e.g. SuperSymmety = SUSY) often has additional CP violating phases in added couplings
  - New phases: (ϕ_{CP}) should be ~ 1 **(why not?)**
- Contribution to EDMs depends on masses of new particles

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

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)



New nEDM at 3×10^{-28} e-cm moves limits off graph

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

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

e^-,quark EDM

quark color EDM (chromo-EDM)

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

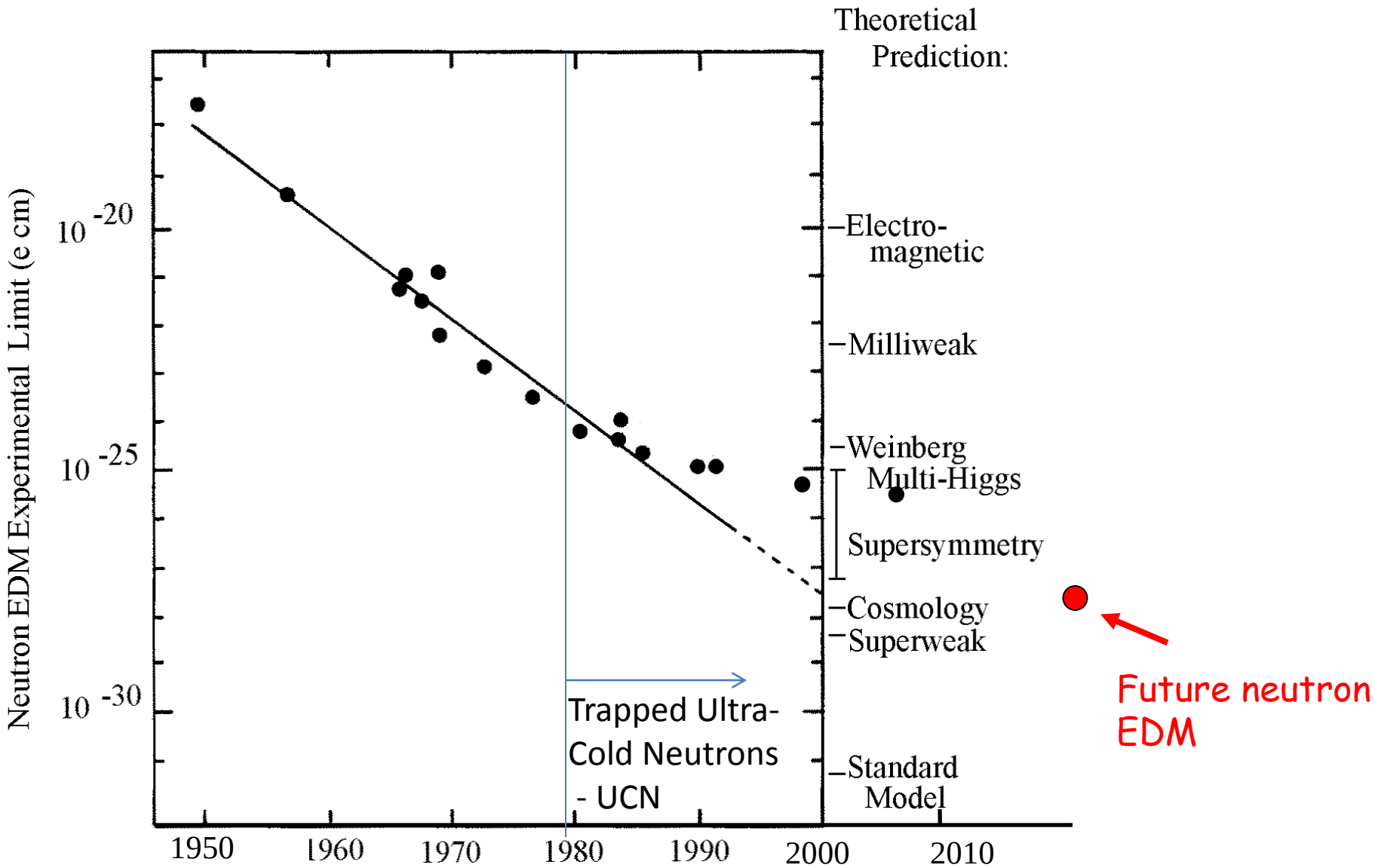
Relative EDM Sensitivities

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"



What is the precision in an EDM measurement?

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

Using Uncertainty Principle:

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

Precise energy measurement requires long individual measurement time, giving

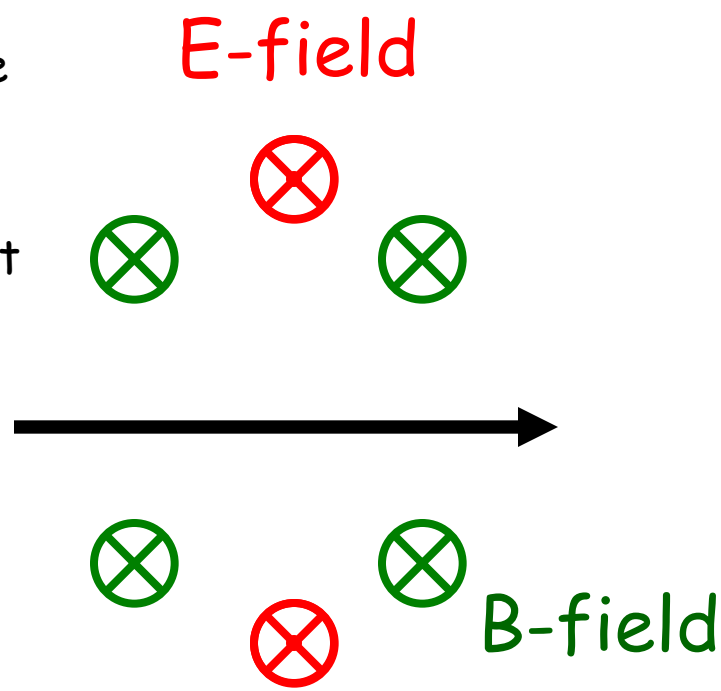
Coherence effect

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

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

How to Measure an 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

- Small change in B obscures measurement of d
  - thus larger B requires smaller fractional control of B
  - large $\langle \Delta B^2 \rangle$ can give short spin-coherence time T_2
  - but smaller B leads to larger geometric phase systematics

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)

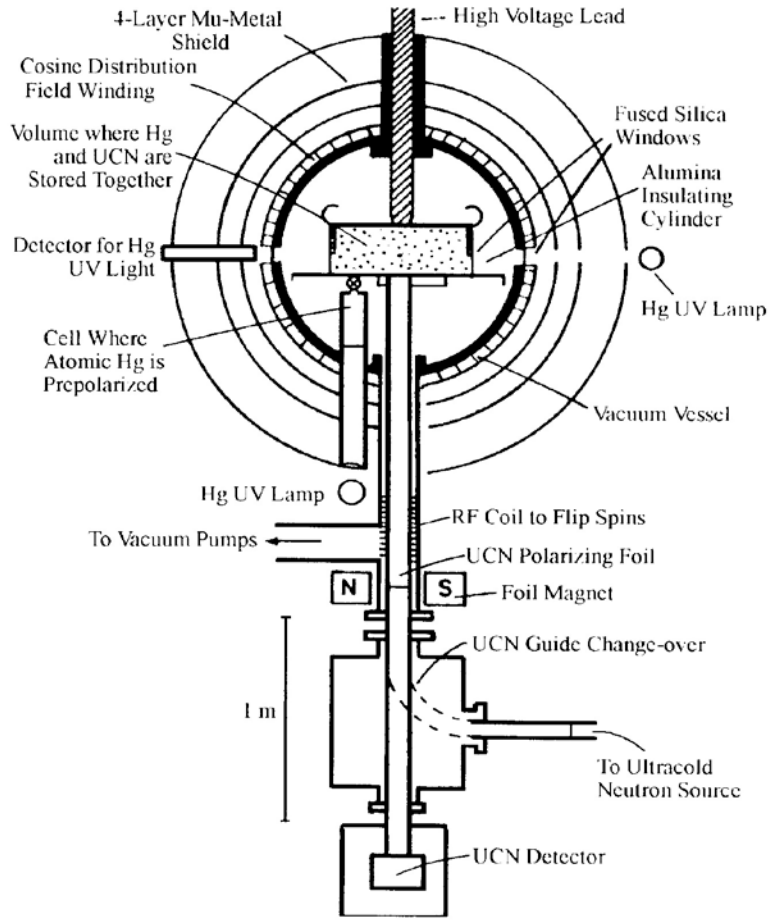
Trapped Ultra-Cold Neutrons (UCN) with N_{UCN} = 0.5 UCN/cc

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

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

Technologies for nEDM (new, SNS)

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

nEDM COLLABORATION

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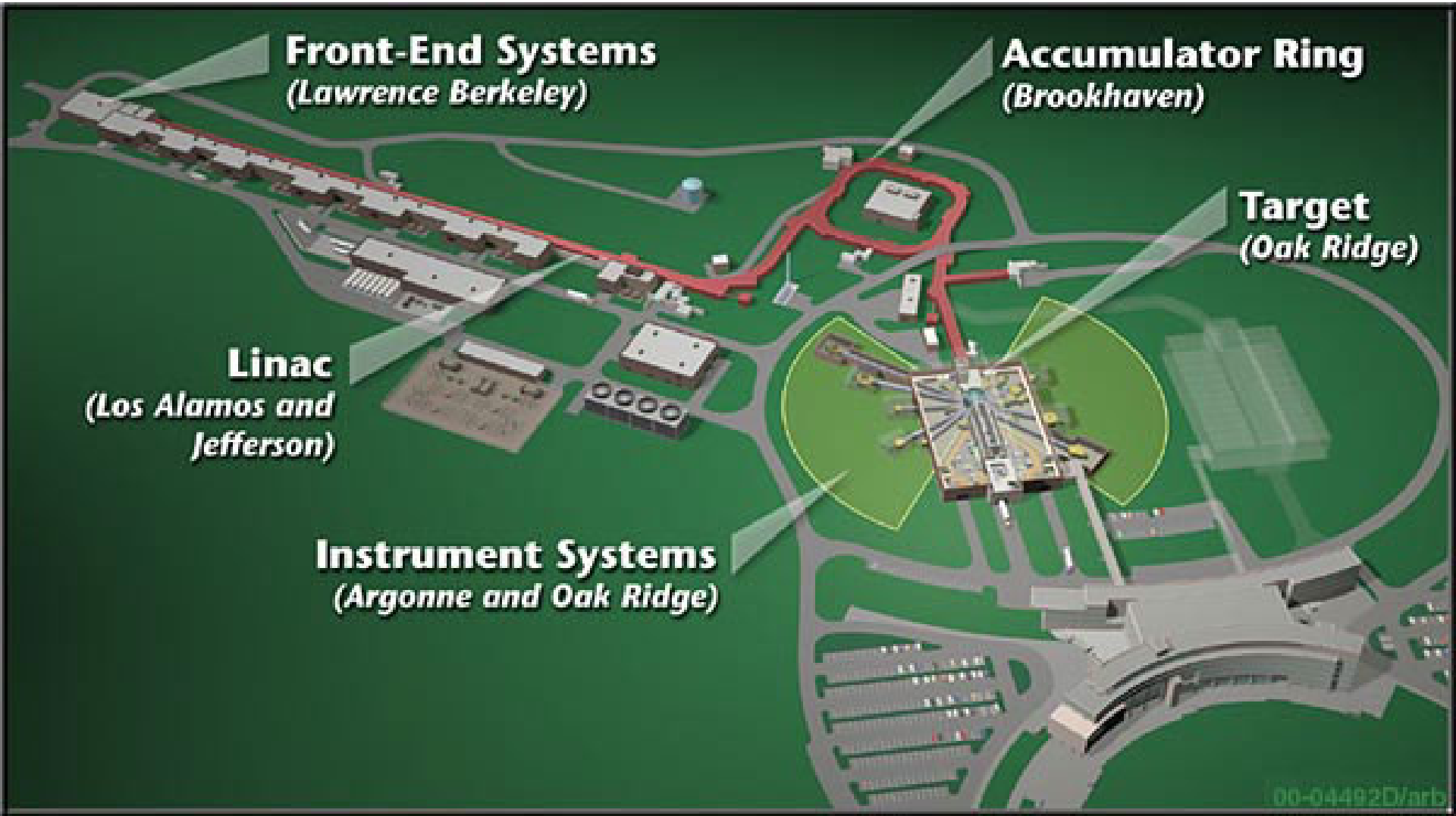
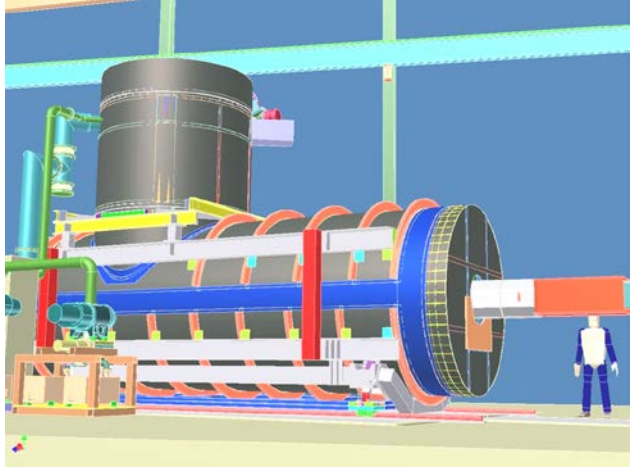
Spallation Neutron Source (SNS) at ORNL

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

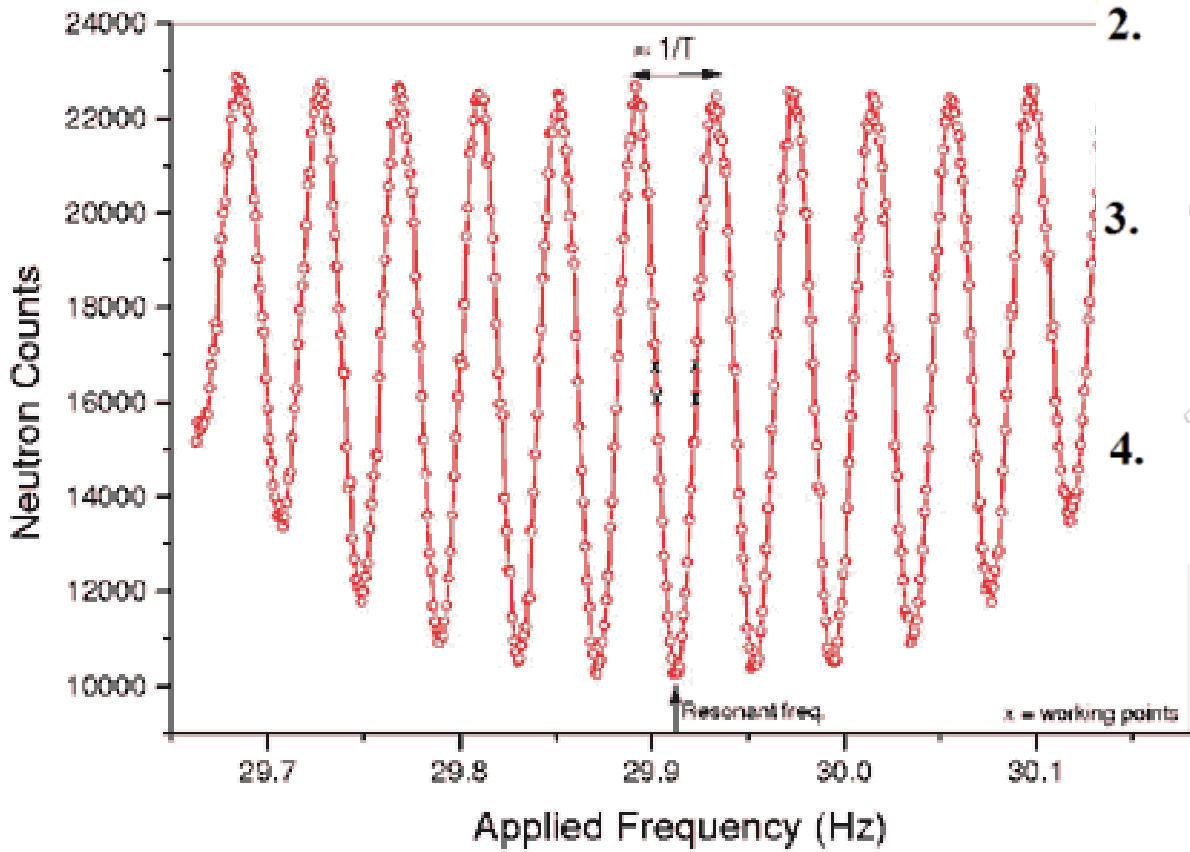
- Use $\vec{n}$-$^3\vec{He}$ capture → light to measure neutron precession frequency
  – two techniques:
    - *free precession*
    - *dressed spin techniques*

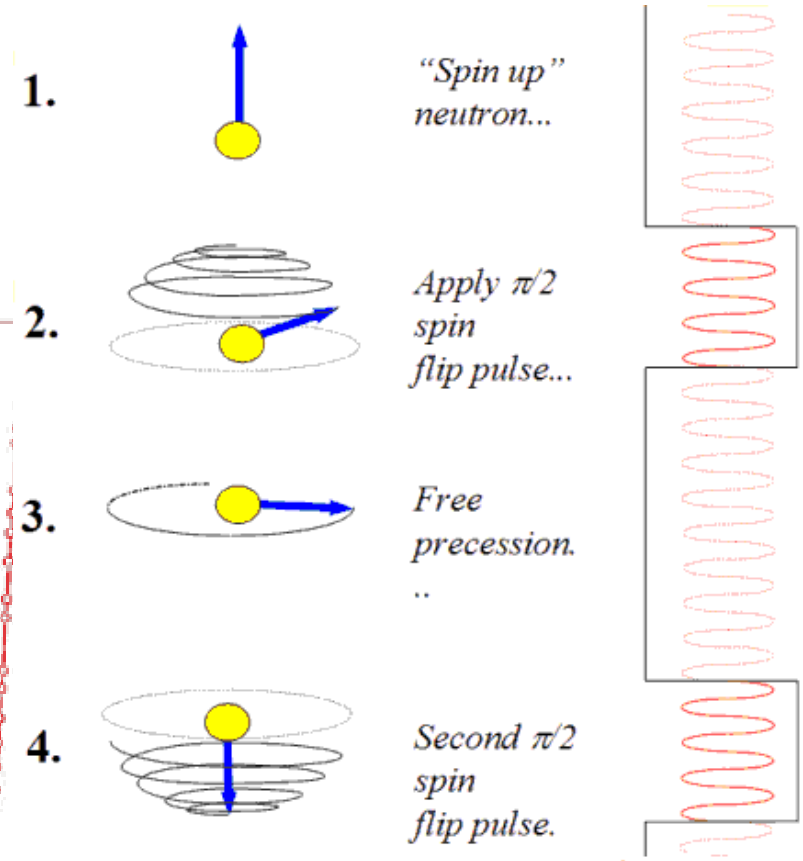
100x improvement over existing limit

- 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↓



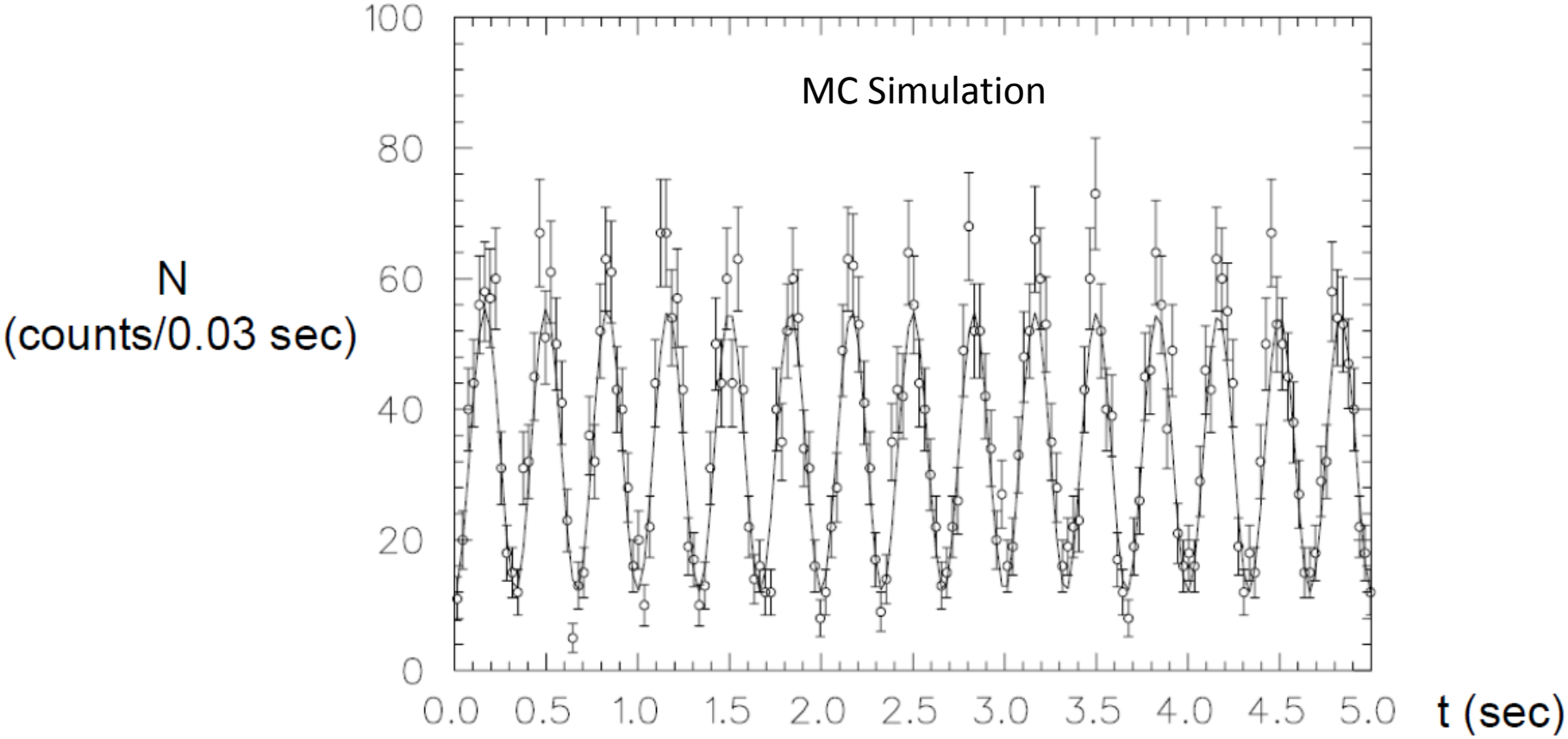


Alternative to Ramsey technique is direct measurement of frequency

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

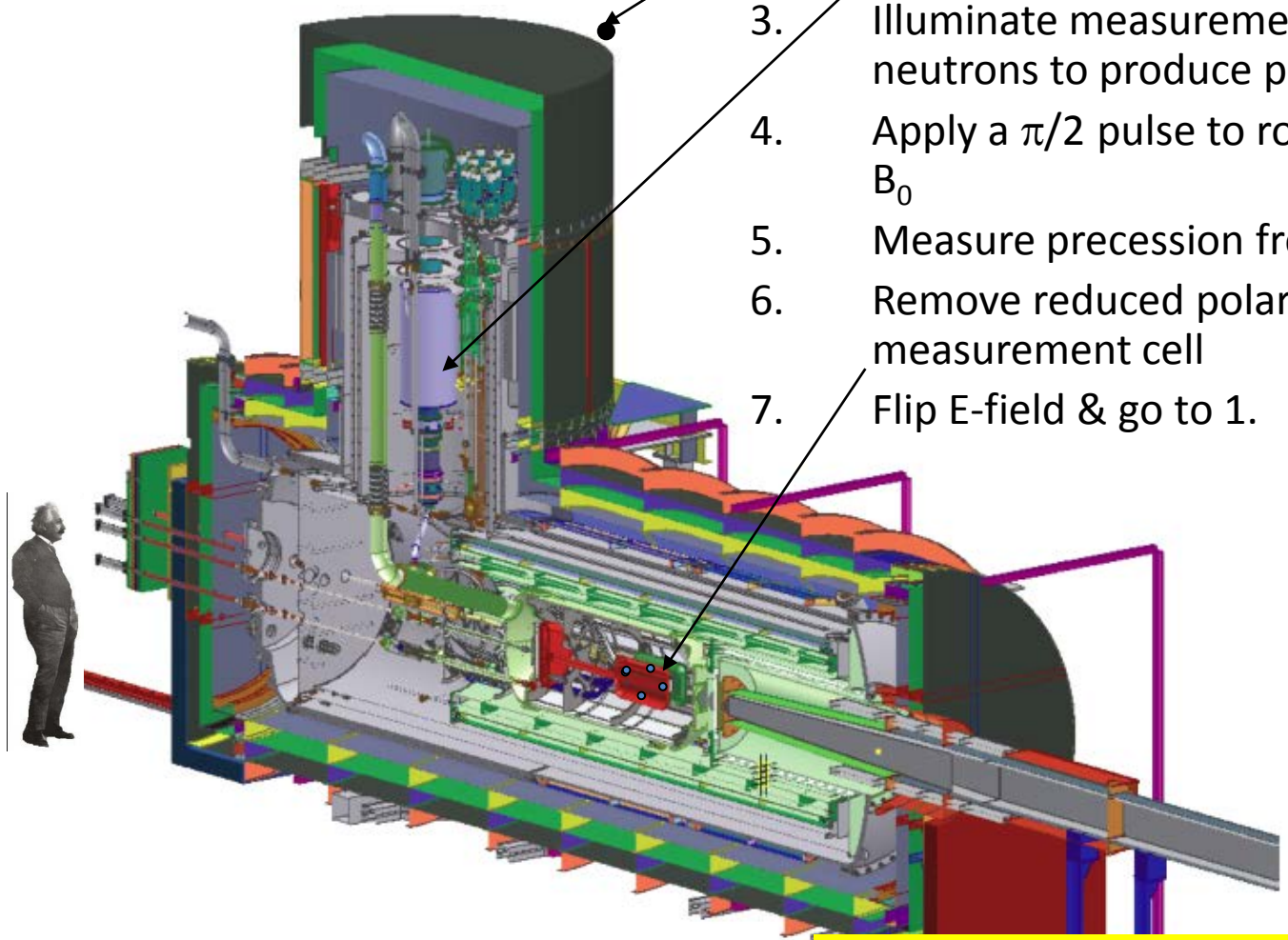
capture rate, measured via scintillation in LHe, oscillates at n-^{3}He beat frequency

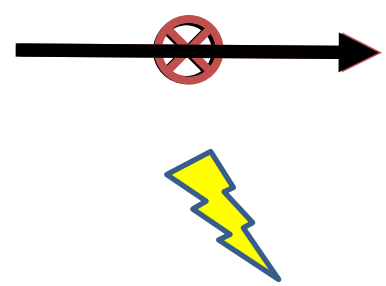
Measure neutron "casualties"



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.

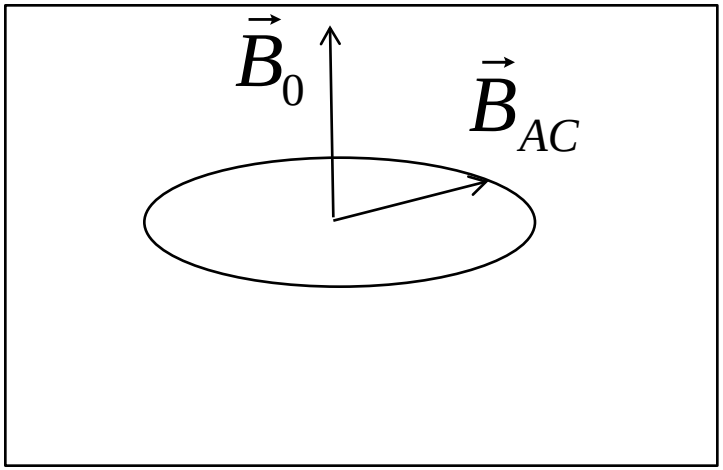




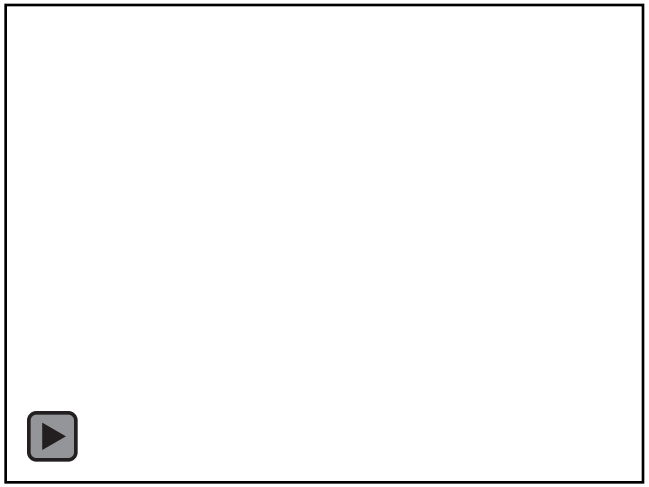
^{3}He functions as "co-magnetometer"
Since $d_{3He} << d_n$ due to e^--screening

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

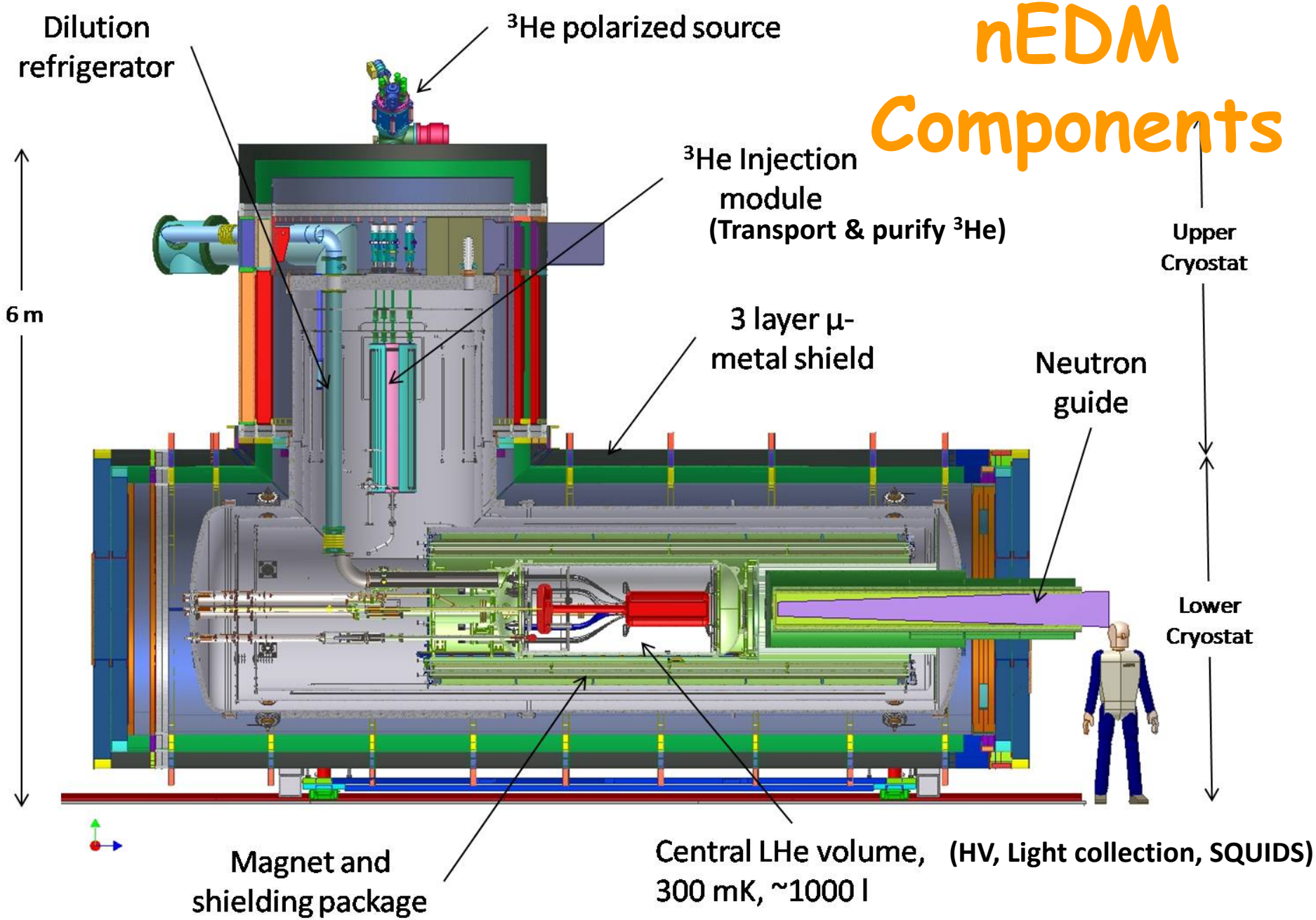
Video = Ping-Han Chu

Example of future Neutron EDM Sensitivity

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

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

nEDM Components



+ offline test facility at NCSU research reactor

Some Technical Challenges:
("it's just engineering" ☺)

- 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 4He: ppt compared to ppm (natural)
- 1200L SF LHe at 0.3 K: no leaks
- High E-field: ~ 80 kV/cm
- No E-breakdown: SQUID survivial
- Ambient B-field suppression: 10-5 for SQUIDS & systematics
- Uniform B-fields: ppm level
- All above approved for Ops at National Lab !

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	$< 1 \times 10^{-28}$	$\pi/2$ 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	$< 1 \times 10^{-28}$	$\Delta E/E < 0.1\%$
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

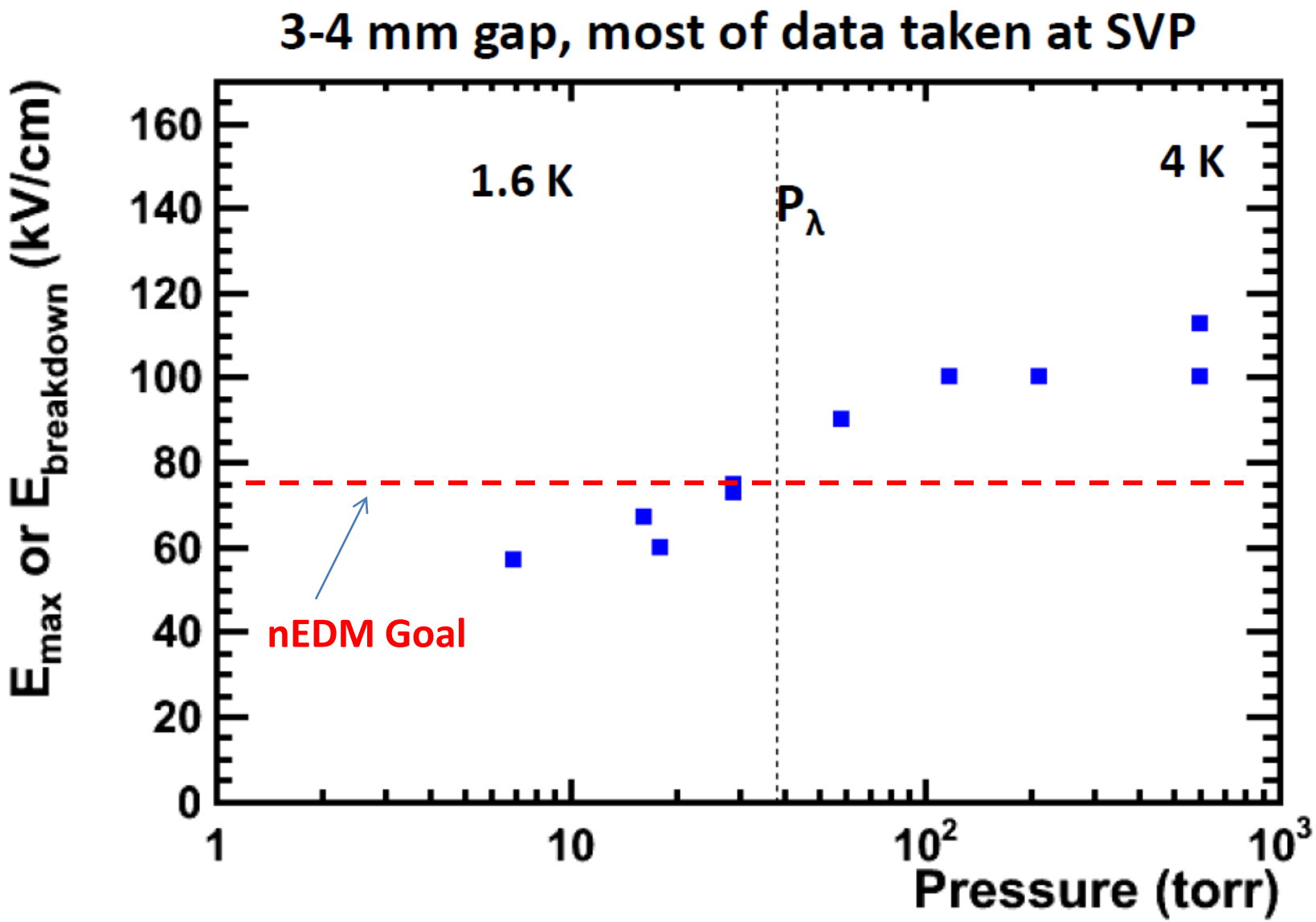
- NSAC Review of Fundamental Physics with Neutrons (1/12)
  - nEDM is highest priority of sub-field
  - nEDM should focus on Critical R&D for 2 yrs
    - Several key elements need to be demonstrated
  - "Equipment Project" (MIE) stopped 3/12
  - Funded via R&D (2012/2013)
    - Reviewed every 4 months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

Thanks Chris Keith/JLAB!!

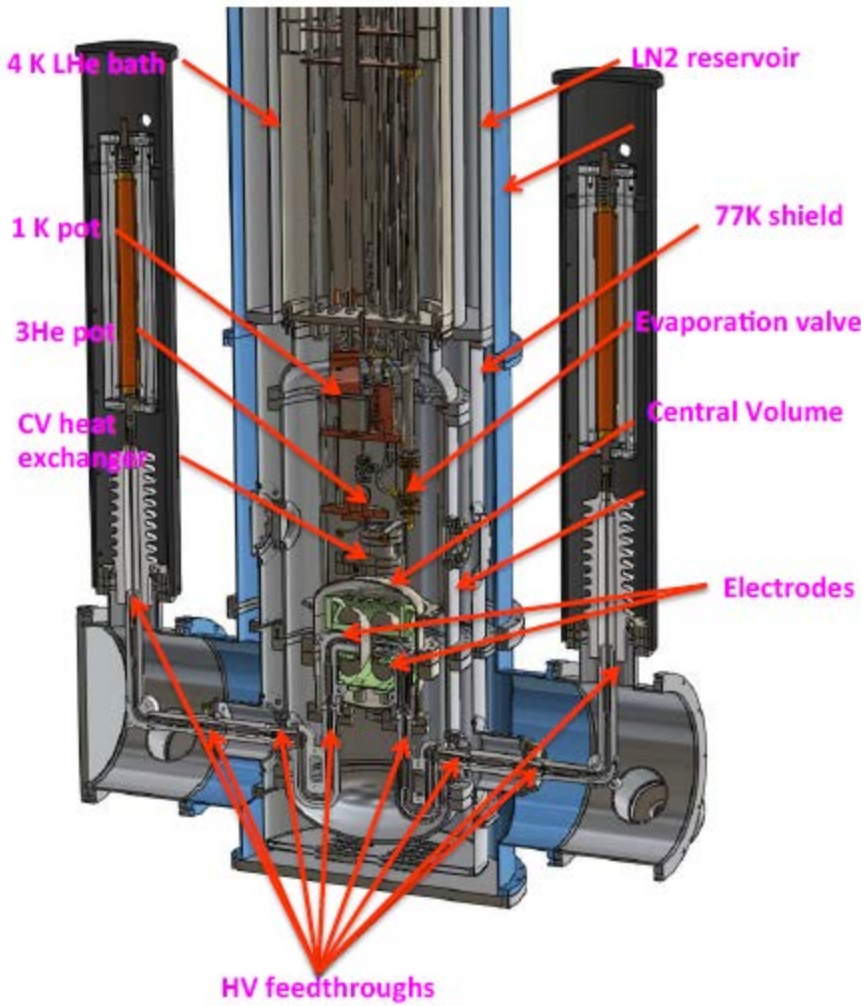
DOE Review (12/13)

- Key Technical milestones largely met
  - High Electric Fields
  - Uniform Magnetic Fields
  - ^{3}He transport uncertainties reduced
  - Other advances

HV in Nov. 2011

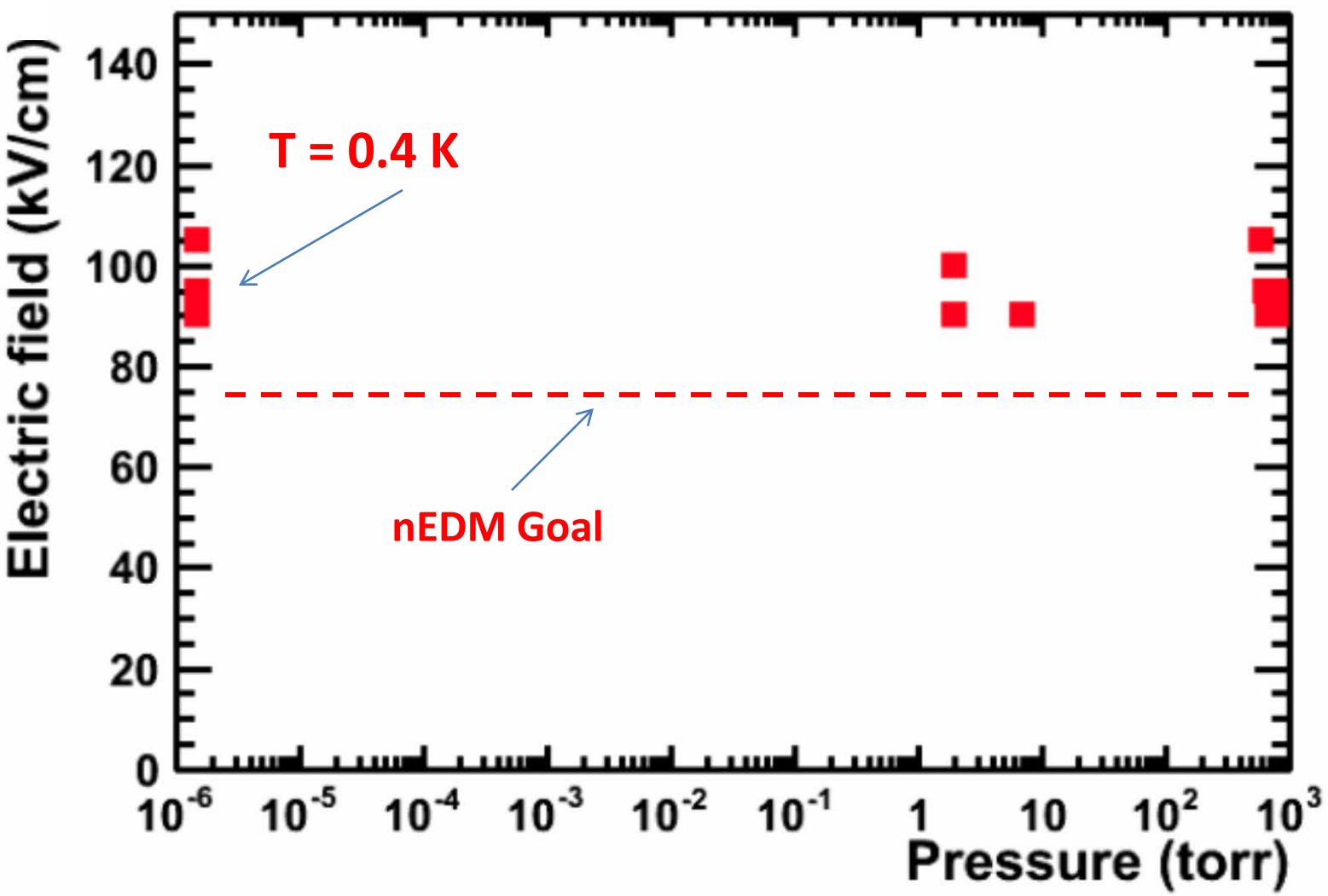


Medium-scale HV system



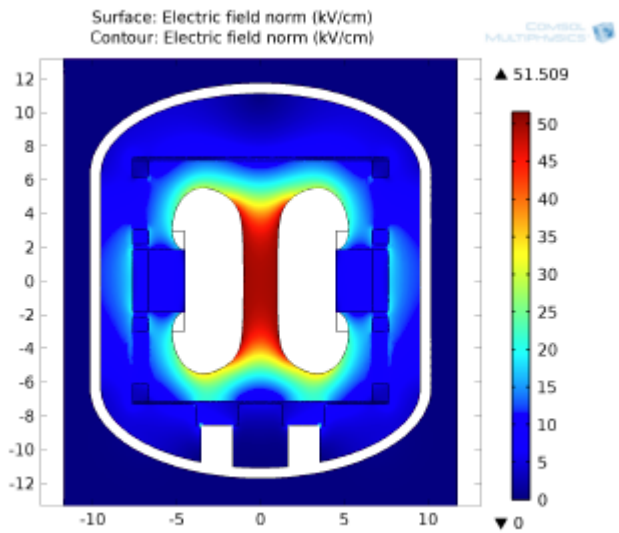
MSHV Central Volume

HV in Nov. 2013



Next Steps for HV

- Previous studies used electropolished SS
- Will soon test coated PMMA electrodes



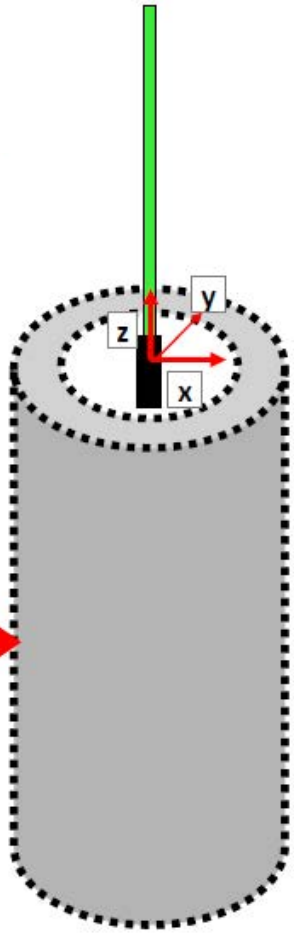
Carbon nano-particle coating on PMMA

Cryogenic Magnets and Magnetic Shielding

½ - Scale
Cosθ Coil

Superconducting
Pb B-Shield

Cryostat



Automated B-mapping system

Recent Magnetic Performance

- With Pb Shield in Superconducting state:
  - Can reproducibly measure gradients < 0.2 μG/cm (< 2 nT/m)
  - Pb Shield increases B-shielding > x 100
  - Present gradients limit false EDM effect (uncorrected) to < 4×10^{-28} e-cm
    - comparable to statistical sensitivity goal

DOE Review (12/13)

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

Recent Status & Future

- 4-yr NSF proposal for CCD approved ~6.5M$
- Anticipate 4-yr DOE Funding for CCD ~7M$
- Continuation of external Technical Review Committee
- Developing "inch-pebbles" (i.e. NOT "mile-stones") to monitor progress over CCD
- Would complete construction "after" CCD over ~ 2 yrs with more conventional systems
- Commissioning underway by 2019-2020

CCD Goal:
Reduce Risk and Uncertainty
"Do the Hard Stuff First"

Status of Components Now

Component	Current TRL	Cost Risk	Schedule Risk	Technical Risk
2.01. Neutronics: Neutron Guide Vacuum Window Material (DOE)	3	Low	Low	Low
2.02. Neutronics / He3 Services: Spin Transport Magnets (DOE, NSF)	4	Medium	Low	Low
2.03. Cryogenics: Helium Insulation Volume and Seals (DOE)	3-4	Medium	Low	Low
2.04. He3 Services: Dilution Refrigerator (NSF)	3	Medium	Medium	Low
2.05. He3 Services: Injection System (NSF)	3	Medium	Medium	Low
2.06. He3 Services: Purification System (NSF)	3	Low	Low	Low
2.07. Magnets and Magnetic Shielding: Coil Package (NSF)	3-4	Medium	Low	Medium
2.08. Magnets & Magnetic Shielding: B-field Monitor (NSF)	3	Medium	Low	Low
2.09. Central Detector System: Light Collection, E-field Monitor (DOE)	5	Low	Low	Low
2.10. Central Detector System: UCN Storage (DOE)	4	Medium	Low	Low
2.11. Central Detector System: High Voltage (DOE)	2-4	High	High	Medium
2.12. Central Detector System: V1 Valve (DOE)	2	Medium	Low	Medium
2.13. Central Detector System: SQUIDs, Grounding and Shielding (DOE)	5	Low	Low	Low
2.14. PULSTAR Systematic Error and Spin Dressing Test Cryostat (DOE)	3	Medium	Low	Low
2.15. Assembly and Commissioning (DOE, NSF)	3	Medium	Medium	Low

Technical Readiness Level

CCD Goal:
Reduce Risk and Uncertainty
"Do the Hard Stuff First"

Status of Components after CCD

Component	Current TRL	Cost Risk	Schedule Risk	Technical Risk
2.01. Neutronics: Neutron Guide Vacuum Window Material (DOE)	6	Low	Low	Low
2.02. Neutronics / He3 Services: Spin Transport Magnets (DOE, NSF)	6	Low	Low	Low
2.03. Cryogenics: Helium Insulation Volume and Seals (DOE)	6	Low	Low	Low
2.04. He3 Services: Dilution Refrigerator (NSF)	6	Low	Low	Low
2.05. He3 Services: Injection System (NSF)	6	Low	Low	Low
2.06. He3 Services: Purification System (NSF)	6	Low	Low	Low
2.07. Magnets and Magnetic Shielding: Coil Package (NSF)	6	Low	Low	Low
2.08. Magnets & Magnetic Shielding: B-field Monitor (NSF)	6	Low	Low	Low
2.09. Central Detector System: Light Collection, E-field Monitor (DOE)	6	Low	Low	Low
2.10. Central Detector System: UCN Storage (DOE)	6	Low	Low	Low
2.11. Central Detector System: High Voltage (DOE)	5	Medium	Medium	Low
2.12. Central Detector System: V1 Valve (DOE)	6	Low	Low	Low
2.13. Central Detector System: SQUIDs, Grounding and Shielding (DOE)	6	Low	Low	Low
2.14. PULSTAR Systematic Error and Spin Dressing Test Cryostat (DOE)	6	Low	Low	Low
2.15. Assembly and Commissioning (DOE, NSF)	5	Medium	Medium	Low

Yes, we have an Org. Chart

Internal Technical Committee
Bob Golub, co-chair
Paul Huffman, co-chair

R&D Manager
Vince Cianciolo
Paul Huffman (deputy)

Spokesperson
Brad Filippone

Collaboration Board
Bob Redwine, chair

Executive Committee

NSF Co-Pi's
Brad Filippone
Doug Beck

CCD Activity Leaders

2.01 Neutron Guide Vacuum Window Material, *Vince Cianciolo*
2.02 Spin Transport Magnets, *Chris Crawford*
2.03 Helium Insulation Volume and Seals, *David Haase*
2.04 Dilution Refrigerator, *Weijun Yao*
2.05 Injection System, *Steve Williamson*
2.06 Purification System, *Steve Williamson*
2.07 Coil Package, *Brad Filippone*
2.08 B-field Monitor, *Brad Plaster*
2.09 Light Collection, E-field Monitor, *Vince Cianciolo*
2.10 UCN Storage, *Kent Leung*
2.11 High Voltage, *Takeyasu Ito*
2.12 V1 Valve, *Takeyasu Ito*
2.13 SQUIDs, Grounding and Shielding, *Steve Clayton*
2.14 PULSTAR Systematic Error and Spin Dressing Test Cryostat, *Katerina Korobkina*
2.15 Assembly and Commissioning, *Vince Cianciolo*

Worldwide nEDM Searches

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

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**, construction of detectors for the PVES program at Jefferson Lab

NSAC LRP 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.

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- Exciting opportunities for new/existing facilities
  - New = FRMII,JPARC,SNS; Existing = ILL,PSI,TRIUMF

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.

Capability	Cryo1	Cryo2	PSI1	PSI2	FRMII 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