Progress of the SNS Neutron EDM Experiment

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SNS nEDM Collaboration and Indiana University

Motivation

Expected Sensitivity

Experiment Overview

Systematics

nEDM Research and Development

Readout system: scintillation

Electric Field Generator

Outlook

Office of Science
U.S. DEPARTMENT OF ENERGY

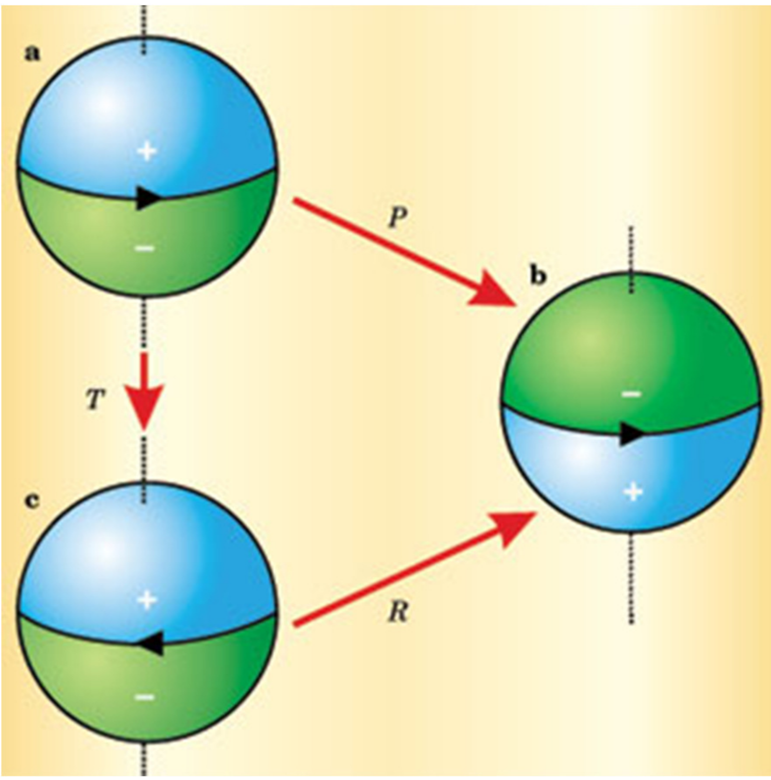
Office of Nuclear Physics

NSF

Test of Discrete Spacetime Symmetries

$$H = -\left(\mu\vec{B} + d_n\vec{E}\right)\cdot\frac{\vec{S}}{|S|}$$

EDM: violates P and T



CPT theorem → also CP

Figure: E. N. Fortson,
Physics Today 56 6 (2003) 33

$Y_B = n_B/\gamma \sim 10^{-10}$

WMAP, PDB (2010)

Sakharov's criteria

- Baryon number violation

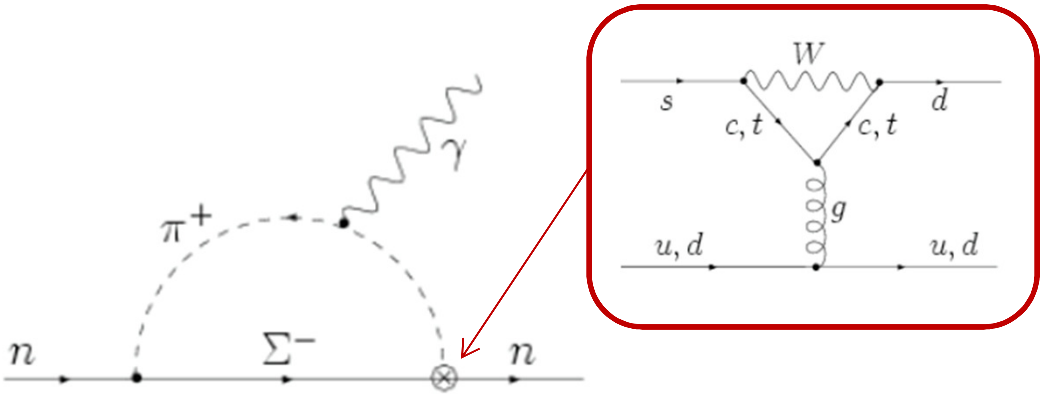
  $\phi \to B;\ \phi \to \overline{B}$ $\Delta B \neq 0$
- CP violation and C violation

  $R(\phi \to B) > R(\phi \to \overline{B})$
- Departure from thermal equilibrium

  $R(\phi \to B) > R(B \to \phi)$

EDMs in SM and SUSY

- Suppressed multi-loop effect in the Standard Model



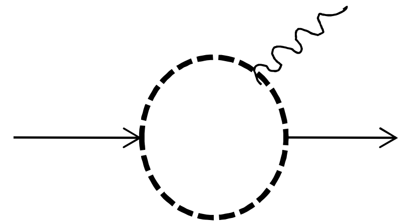
$\rightarrow d_n \sim 10^{-32}$ e-cm [1]

Current limit: $d_n < 2.9 \times 10^{-26}$ e-cm [2]

$$\mathcal{L} \supset \frac{\alpha_s}{4\pi}\theta_{QCD} tr\, G\tilde{G}$$

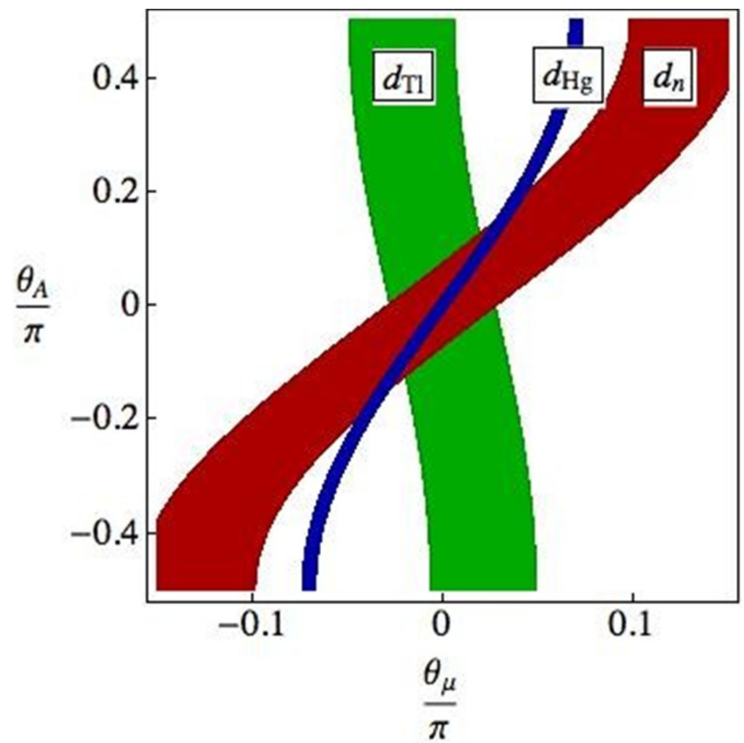
$\theta_{QCD} \lesssim 3 \times 10^{15}\, d_n$ (e-cm) $\lesssim 10^{-10}$

- Large effect in more comprehensive theories



$d_n \sim 10^{-26}$ e-cm

Constraints on SUSY phases [3]

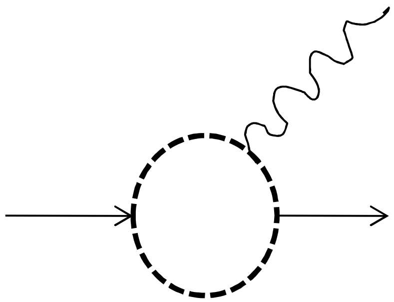


[1] Khriplovich, Zhitnitsky , Sov. J. Nucl. Phys 34 (1981) 95

[2] C. Baker, et al., PRL 97 (2006) 131801

[3] M. Pospelov and A. Ritz, Ann. Phys. 318 (2005)119; CIPANP 2009

EDMs and SUSY

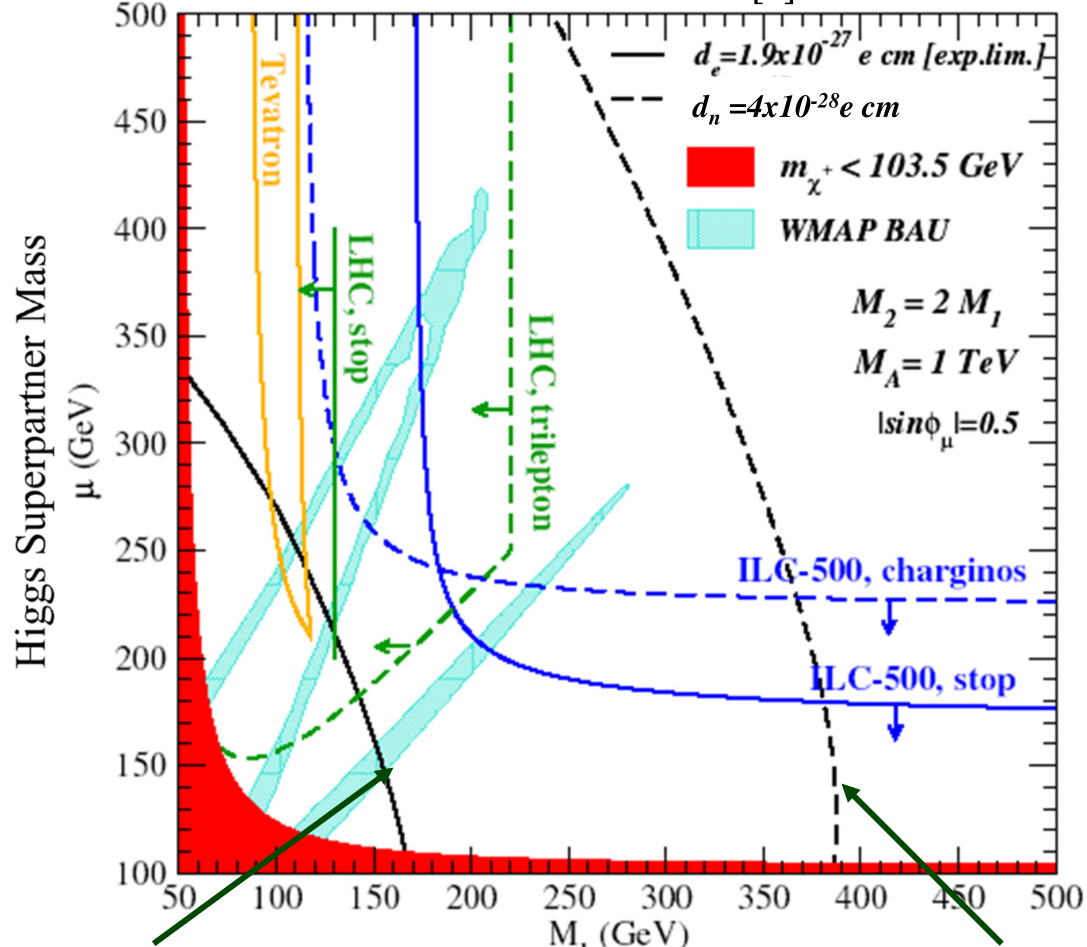


$$d \sim \frac{m_f}{\Lambda_{cp}^{\;2}}$$

$d_n < 10^{-28}$ e-cm$\rightarrow \Lambda_{cp} = 10$ TeV

LHC reach

Collider and EDM reaches in the SUSY mass plane,
MSSM with EWBG [1]

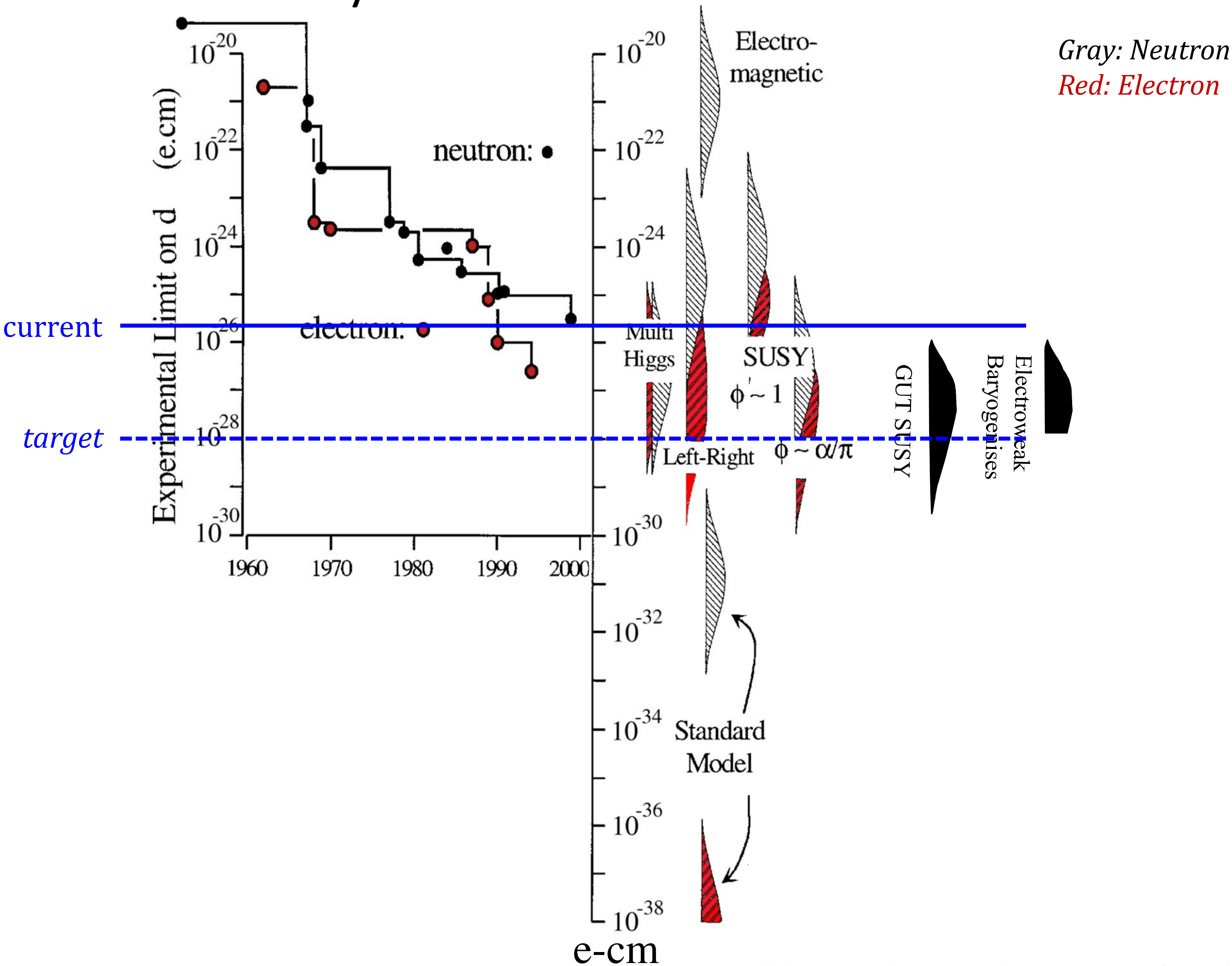


Present d_e

Prospective d_n

[1] V. Cirigliano, S. Profumo, M. Ramsey-Musolf,
JHEP 07 (2006) 002; ECT* (Nov. 2010)

Sensitivity to Rule on Several New Models



J.M.Pendlebury and E.A. Hinds, NIMA 440 (2000) 471

nEDM Technique: Nuclear Magnetic Resonance

$$H = -\left(\mu \vec{B} + d_n \vec{E}\right) \cdot \frac{\vec{S}}{|S|}$$

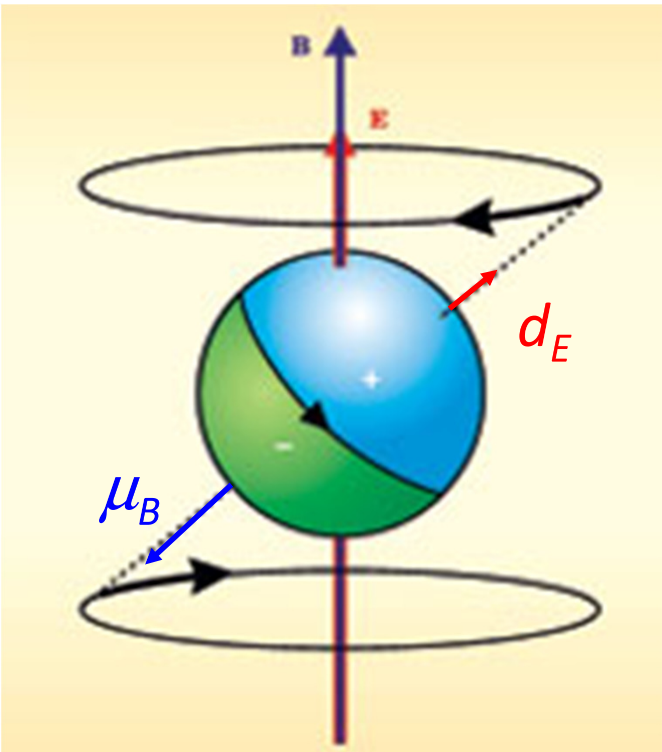


Figure: Physics Today 56 6 (2003) 33

- Larmor frequency: $\omega_B = -\frac{2\mu_B B}{\hbar}$

(~ 29.2 Hz for B ~ 0.1G)

- d_n: additional precession: $\omega_E = \frac{2 d_n E}{\hbar}$

$$\omega_{E\|B} - \omega_{E\,anti-\|B} \equiv \boxed{\Delta\omega = \frac{4 d_E E}{\hbar}}$$

- Apply static B, $E || B$
- Look for $\Delta\omega$ on reversal of E

If $d_n = 5\times10^{-28}$ e cm, $\Delta\omega$ =12 nHz.

SNS nEDM Experiment Expects Record Figure of Merit

EDM Energy shift: $\Delta U = \hbar\, \Delta\omega_E = 4\, d_E\, E$

Uncertainty principle: $\Delta U \Delta t > \hbar$

(Δt = measurement time)

$$d_E \sim \frac{\hbar}{4\Delta t E}$$

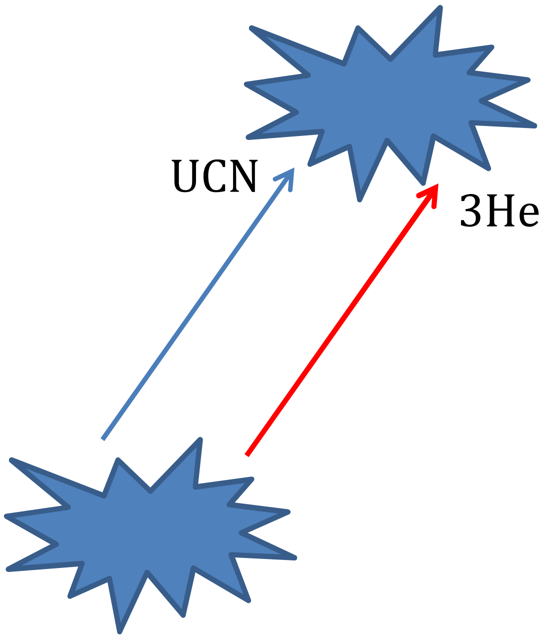
Repeat with *N* neutrons: $$d_E \sim \frac{\hbar}{4\Delta t E\sqrt{N}}$$

	N	Δt	E	d_E
Previous (ILL)	$\sim 10^8$ (UCN from reactor)	130 s (UCN in vacuum)	5 kV/cm (across vacuum)	$< 3\text{x}10^{-26}$ e-cm
SF LHe	$\sim 3\ \text{x}10^{10}$ (spallation, superthermal UCN)	~ 500 s (UCN in LHe)	75 kV/cm (across LHe)	$\sim 10^{-28}$ e-cm*

Experiment Uses ^{3}He as Detector

R. Golub and S. K. Lamoreaux, Phys. Rep. 237 (1994) 1

- UCN too dilute to detect with magnetometer (SQUID)
- Inject small concentration (~ 10^{-11}) of polarized ^{3}He
- Look for reaction: n + ^{3}He → t + p + 764 keV
  - t, p scintillate in ^{4}He
  - Pipe through light guides and detect with PMT



- n + ^{3}He → t + p:

  σ (^{3}He, n: ↑↓singlet) ~ 10^7 b

  σ (^{3}He, n: ↑↑ triplet) < 10^4 b

- $\mu_{He}/\mu_n = 1.11$

  ^{3}He spins will rotate ahead of n spins in same B

  Scintillation light according to $\Phi \sim 1\text{-}P_n P_3 \cos(\omega_{He} - \omega_n)t$

- Independent monitor of ^{3}He spins with SQUIDs

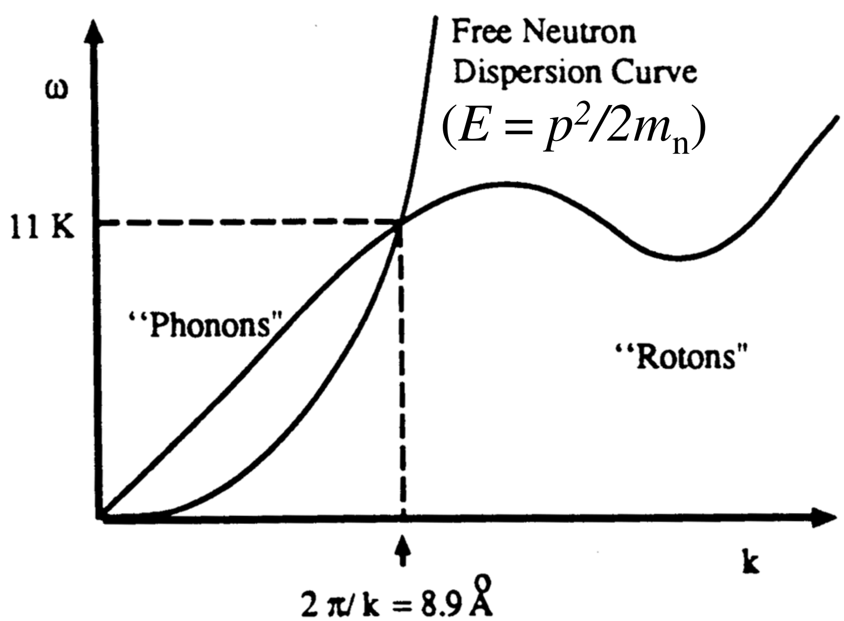
Improved Statistics with Superthermal UCN Source

Ultra-cold neutrons (UCN): E < 300 neV, trapped in material bottles

Previous (ILL): Reactor neutrons (~ meV) slowed in g-field, turbine → 5 UCN/cc

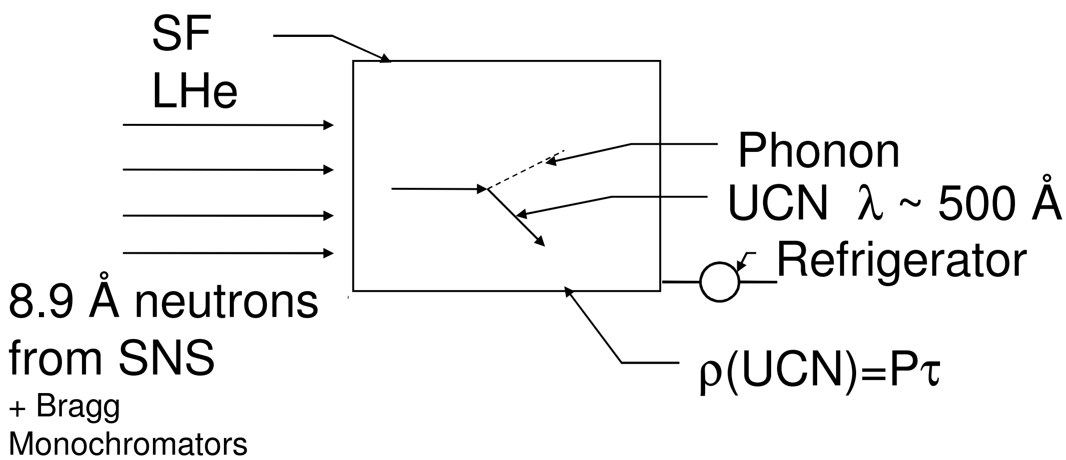
Superthermal source: defeating thermal equilibrium

Inelastic scattering off superfluid ^{4}He atoms



8.9 Å(~1 meV) incident n transfers all p, E to phonon, "downscatters" to UCN

Improved Statistics with Superthermal UCN Source



UCN density = (Flux × LHe density × cross-section) × storage time

~ 0.3/cc/s × 500s = 150/cc (30 × previous)

^{4}He nucleus does not absorb neutrons

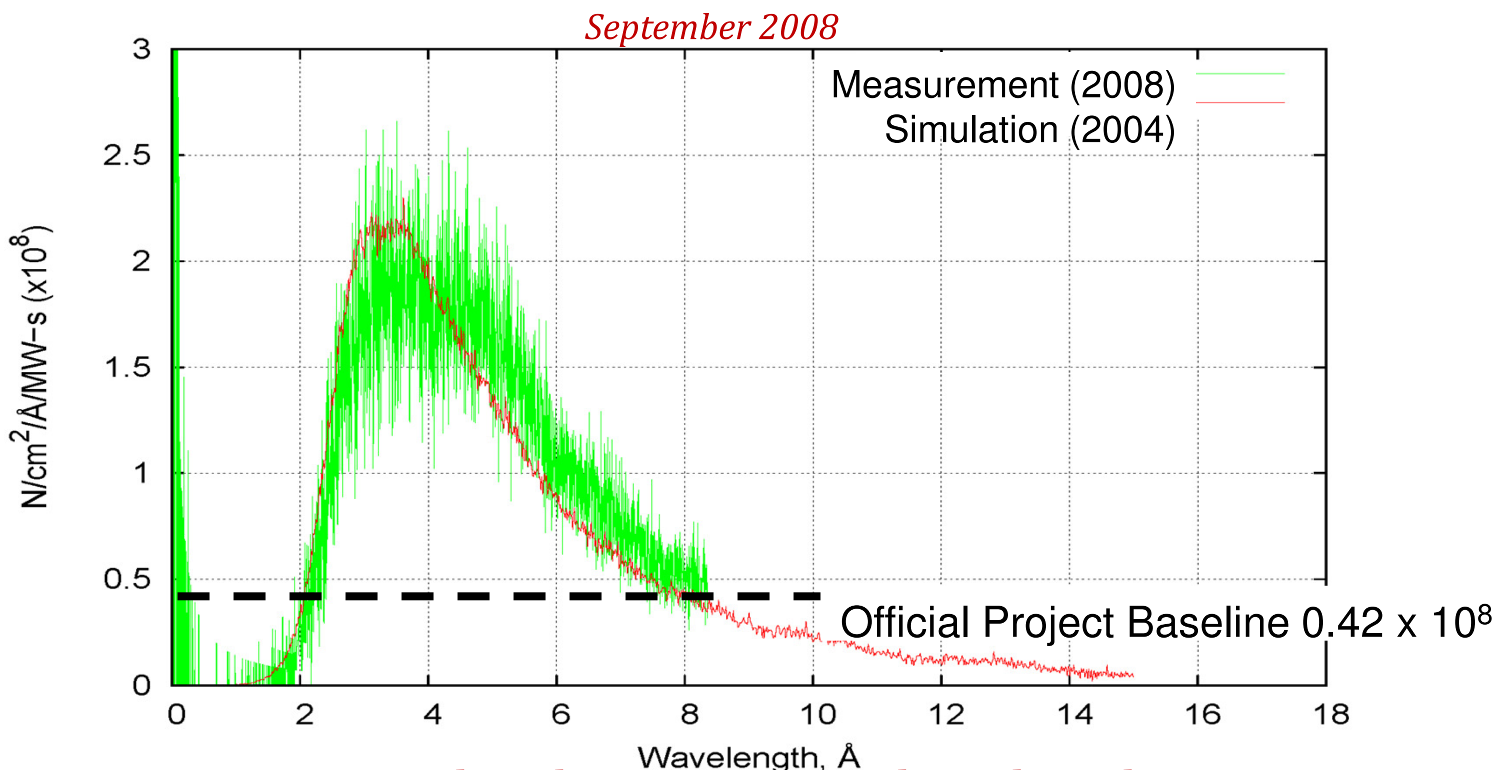
500 s storage time dominated by wall losses and β - decay (886 s)

Improved Statistics with Superthermal UCN Source

SNS:
1 GeV proton beam on Hg target, eventually 1.4 MW

Fundamental Nuclear Physics Beamline (FNPB): LH_2 moderator, first beam 2008

First FNPB Cold Beam Flux Measurements



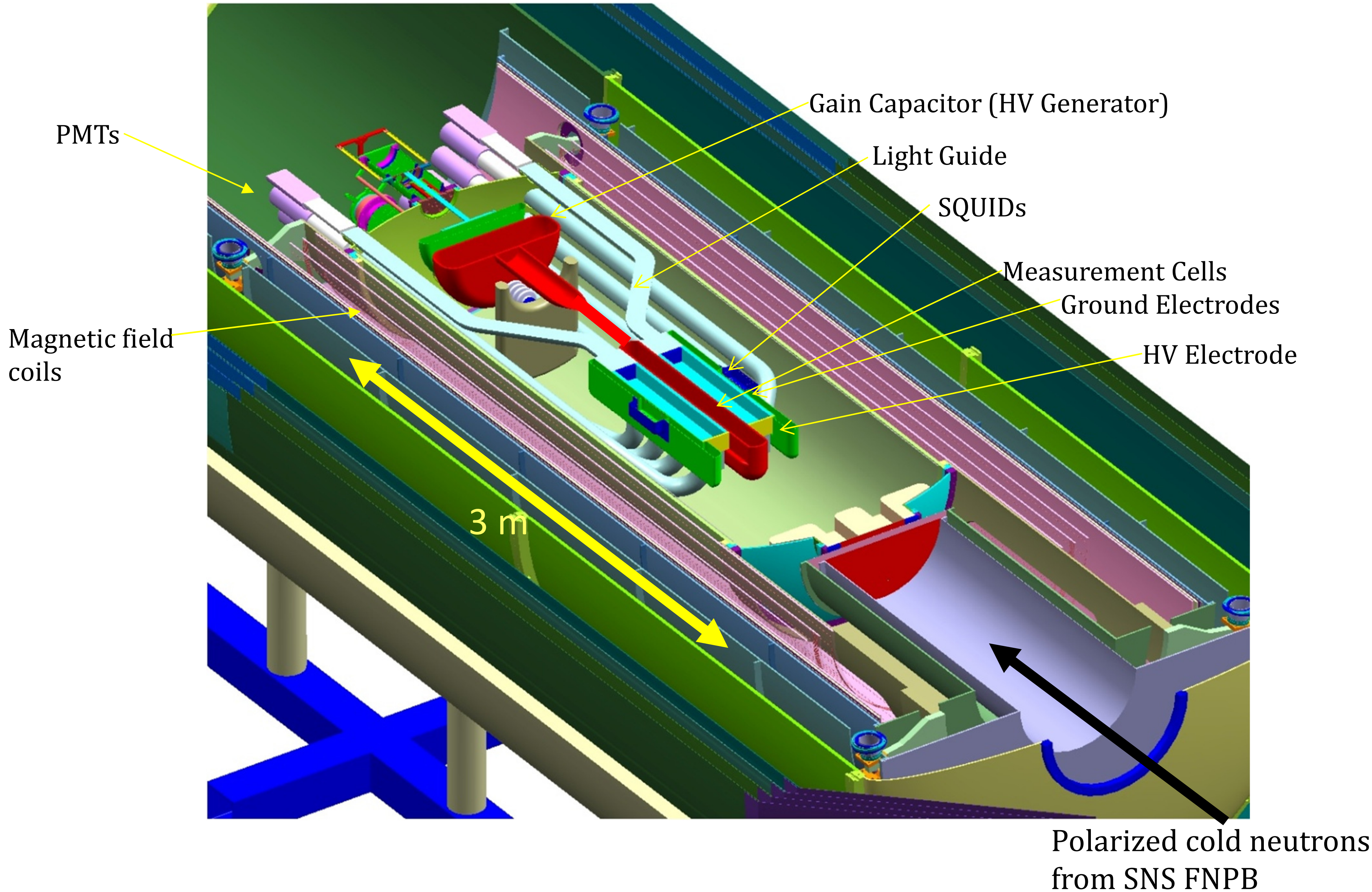
Simulated spectrum was based on the initial "physics" model for moderator.

(No fitted parameters for either plot)

$\frac{\Delta N}{N}$ ~ -.75 (monochromators) $\frac{\Delta N}{N}$ ~ 0 (directly in FNPB, backgrounds…)

Activation, beta decays, cosmic rays, $\Delta E/E = 0.5 \rightarrow d_n = 3\text{-}6 \times 10^{-28}$ ecm

Central Detector System



nEDM Collaboration:
~ 100 Scientists from 21 Institutes

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N. Fomin, G. Greene (*University of Tennessee)*
S. Stanislaus *(Valparaiso University)*

Projected Systematic Errors

Error Source	Systematic error (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

Motional *B* Systematic

Ramsey & Purcell
First beam experiment (1950).

v × E motional magnetic field, $\vec{B}_{mot} = \vec{E} \times \frac{\vec{v}}{c}$

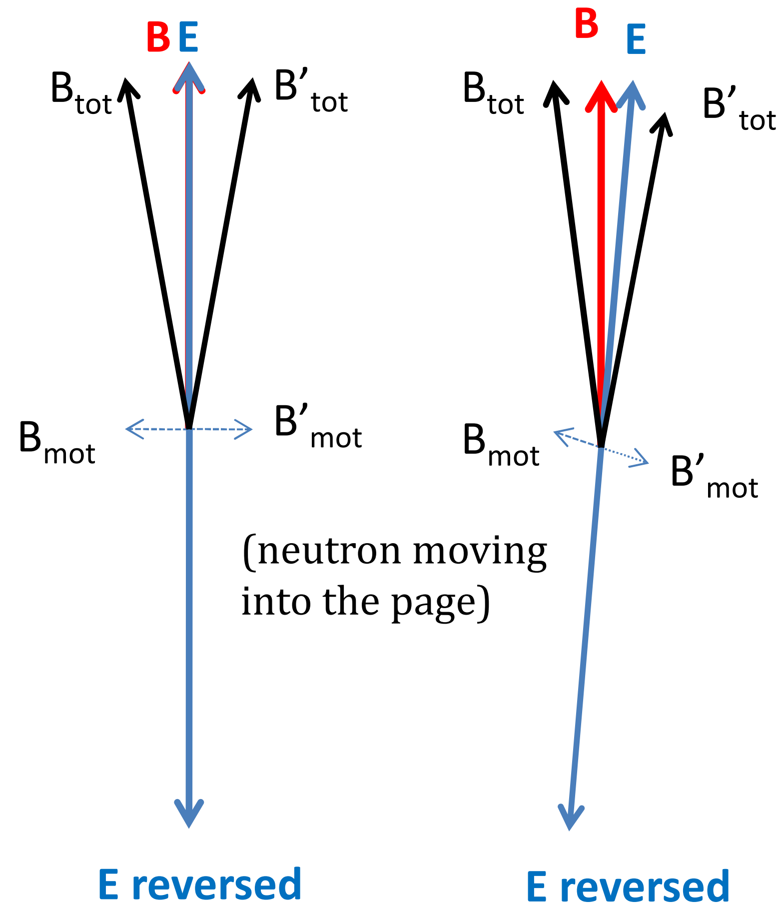
Thermal neutron beam: v $=10^3$ m/s, E$=10^2$kV/cm,
B_{mot}=1mG

$$B = B_0 + \theta_{\rm EB} B_{\rm m} + \frac{1}{2}\frac{B_{\rm m}^2}{B_0}$$

$$\Delta\omega = \frac{\gamma \theta_{\rm EB} v}{c} E + \frac{\gamma v^2}{2c^2}\frac{E^2}{B_0}$$

$\theta_{EB} < 10^{-5}$ radians for 10^{-24} e-cm measurement

Ideally,   In reality,



$|B_{tot}| = |B'_{tot}|$
upon field reversal

$|B_{tot}| \neq |B'_{tot}|$
$\Delta\omega \neq 0$

This led to UCN storage cell experiment
v_{ucn}=5m/s,
$\langle v \rangle = 0$ in a cell

θ_{EB} =0.5° for SNS nEDM,
E-reversal to 10% accuracy.

^{3}He Co-magnetometer

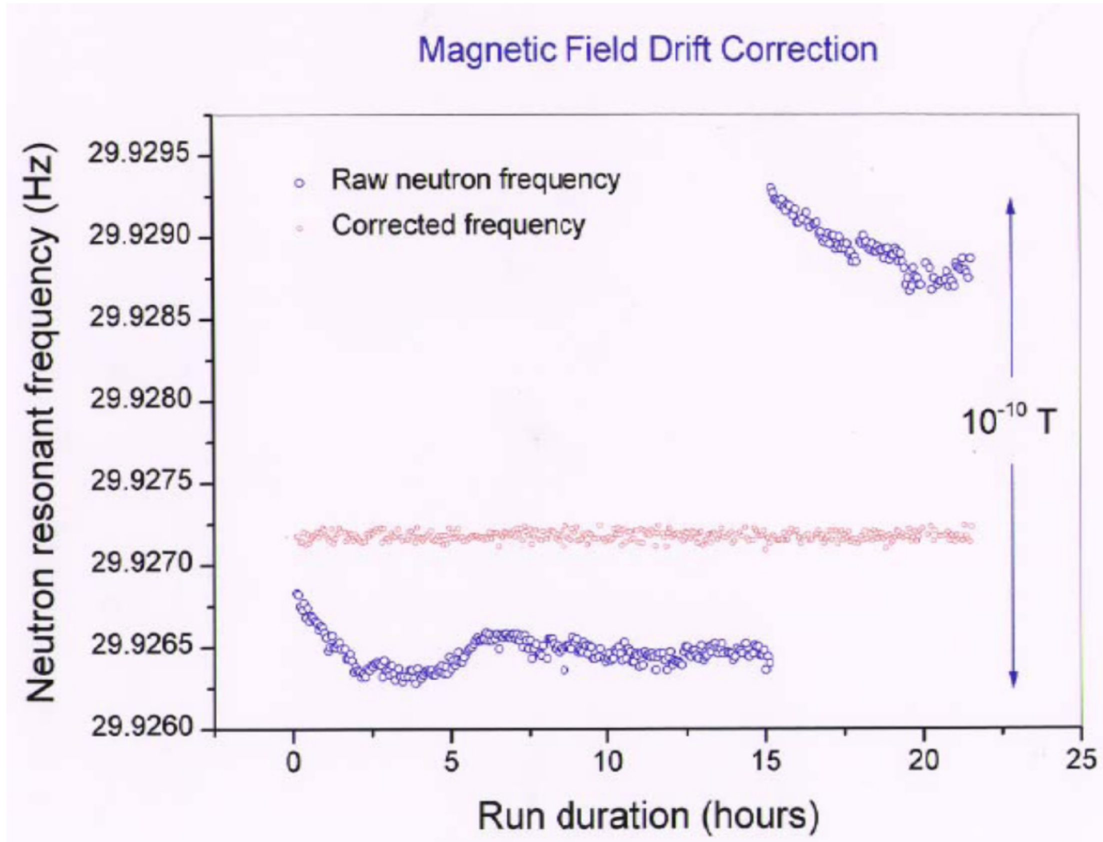
If nEDM = 10^{-26} e·cm,

10 kV/cm $\rightarrow$ 0.1 μHz shift

$\cong$ B field of 2×10^{-15} T.

Co-magnetometer :

Uniformly samples the B Field faster than the relaxation time.



Data: ILL nEDM experiment with ^{199}Hg co-magnetometer

EDM of ^{199}Hg < 10^{-28} e-cm (measured); atomic EDM ~ $Z^2 \rightarrow {}^3$He EDM << 10^{-30} e-cm

Under gravity, the center of mass of He-3 is higher than UCN by $\Delta h \approx 0.13$ cm, sets ΔB = 30 pGauss (1 nA of leakage current). $\Delta B/B = 10^{-3}$.

Geometric Phase

In a rotating frame (ω_r)

$$\delta\omega = -\frac{{\omega_\perp}^2}{\gamma B_0 - \omega_r}$$

- UCNs "rotate" due to specular reflection

$$\omega_r \approx \frac{v}{R}$$

- Gradient adds radial field

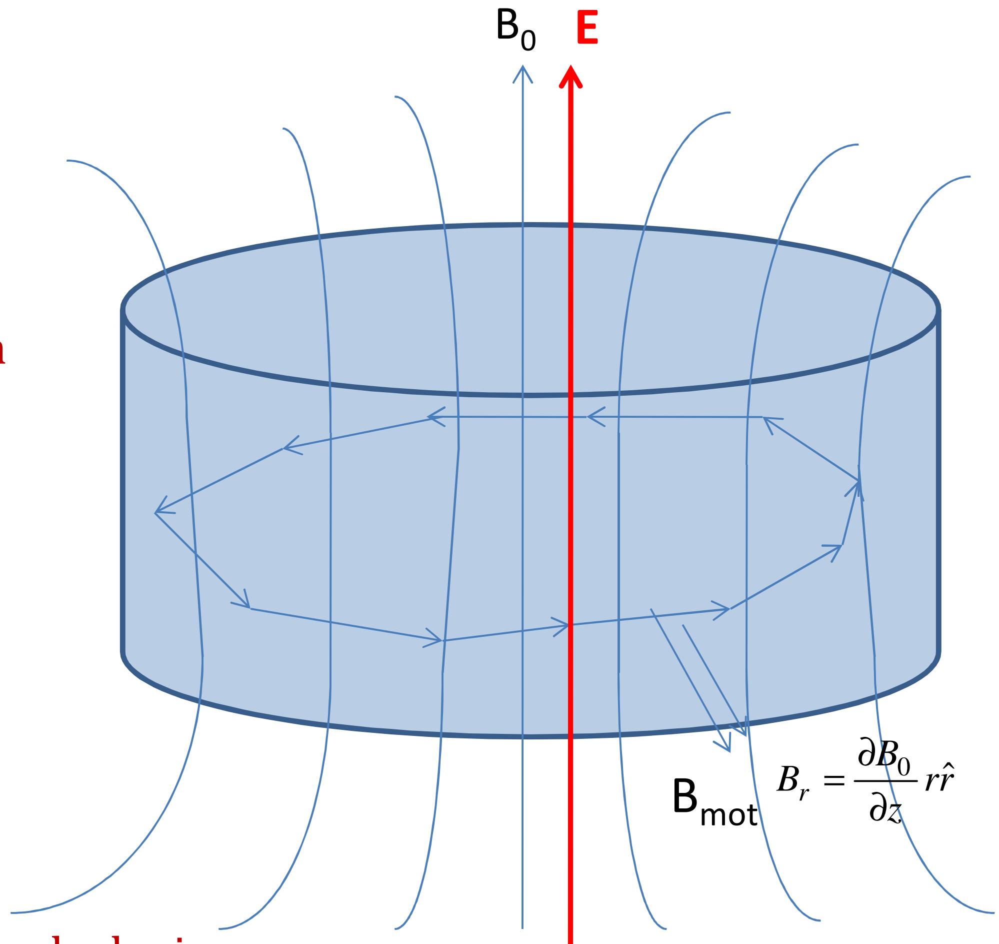
$$\omega_\perp = \gamma\left(B_{mot} + B_r\right)$$

$$\frac{\delta\omega}{\gamma^2} = -\frac{B_m B_r}{\omega_o - \omega_r} = -\frac{B_r v E}{c\,(\omega_o - v/R)}$$

- Sum for UCNs moving clockwise, counterclockwise:

$$\delta\omega = -\frac{\gamma^2}{2}\frac{(\partial B_o/\partial z)\,E}{c}\frac{v^2}{\omega_o^2 - \omega_r^2}$$

- Effect is significant at level of 10^{-28} e·cm



$\frac{\partial B_0}{\partial z}$ < 0.1 μG/cm

T > 0.4 K
(increase ^{3}He collisions)

Some recent nEDM R&D activities

- Measure 3He relaxation time (Duke, UIUC)
- Build light system prototype, measure geometry dependent factors, attenuation lengths, transmission from cells to PMTs (Boston, LANL)
- Investigate PMT operation at 4K (IU)
- Observe 3He S/N with SQUIDs (LANL, Duke, IU)
- Measure neutron storage time in coated acrylic cell (LANL)
- Prototype and test valves for 3He transport (UIUC)
- Test evaporative purification of 4He (NCSU)
- Measure 3He polarization after injection into SF 4He (Duke)
- Compatibility study of SQUIDs to HV operations (IU)
- Re-optimize experiment specification to reduce geometric phase background (NCSU, Yale, Caltech)
- Build magnet coil prototypes and verify uniformity requirements (Caltech, ASU)
- Measure LHe dielectric strength at large volumes below 1K (LANL, IU)
- Measure LHe scintillation at 40kV/cm and at 0.4K (LANL, IU)

2012-2014 Focus

(NSAC and Tech. Review Committee recommendations, Summer 2011):

Suitable electrodes and cell materials, test at 75 kV/cm at T < 1K

Light collection efficiency

Magnetic design and shielding

SQUIDS

PULSTAR UCN facility (simultaneous UCN+3He precession, monitoring, dressed spin…)

R&D: Light Collection Efficiency

Requirement: ~20 PE/ 3He capture

	Factor	Value	% Error
✓ (Indirectly measured)	N_{XUV}	4800	15
✓ (Directly measured)	ε_{HV}	0.76	5
	$\Omega_{TPB}/4\pi$	0.90	1
✓ (Indirectly measured)	ε_{conv}	0.33	19
✓ (Indirectly measured)	$\varepsilon_{collect}$	0.21	5
✓ (Directly measured)	ε_{coated}	0.92	5
	$\varepsilon_{endcaps}$	0.87	1
	ε_{holes}	0.97	10
	ε_{gaps}	0.78	5
✓ (Directly measured)	g_{AR}	1.05	4
✓ (Directly measured)	$\varepsilon_{straight\text{-}guide}$	0.64	3
✓ (Indirectly measured)	ε_{bend}	0.88	10
✓ (Directly measured)	ε_{PMT}	0.18	10
	#PE	**14.8**	**32**

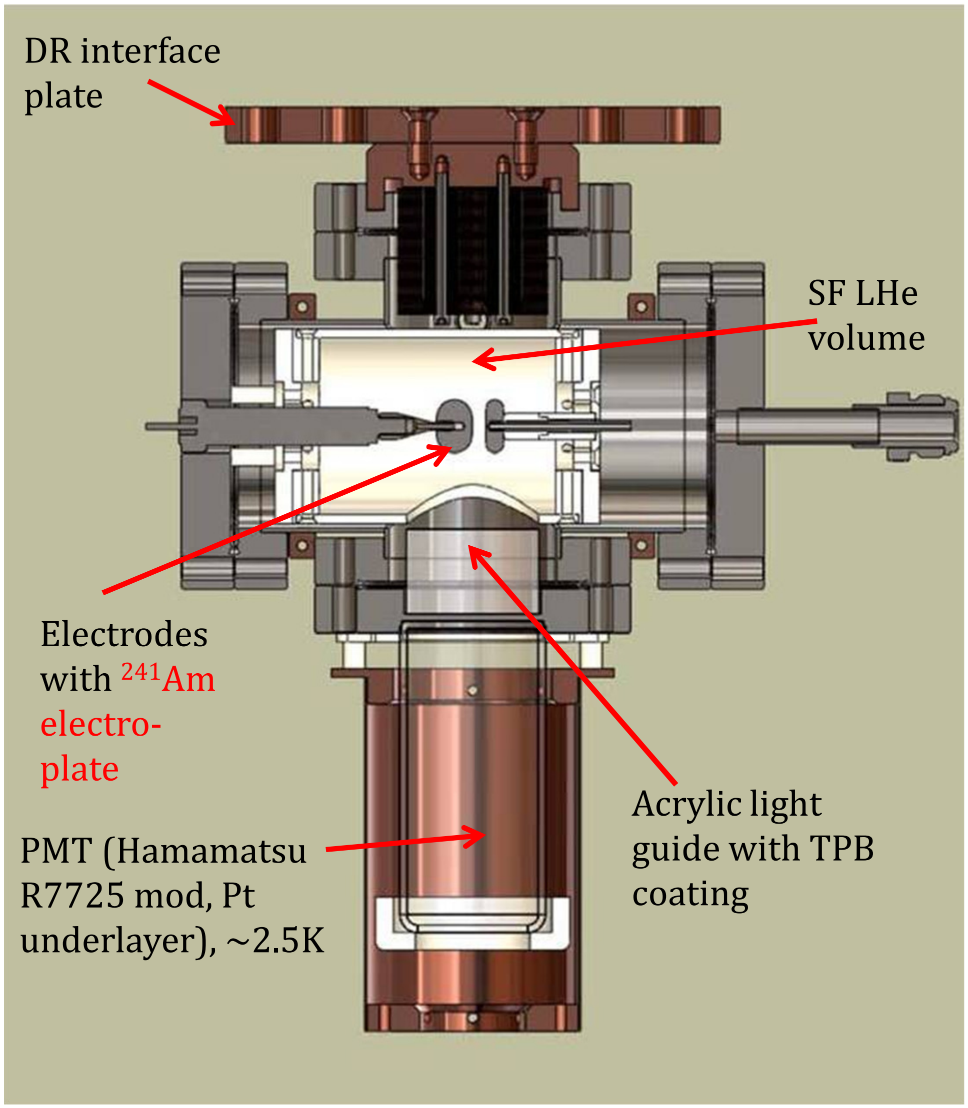
✓ Directly measured

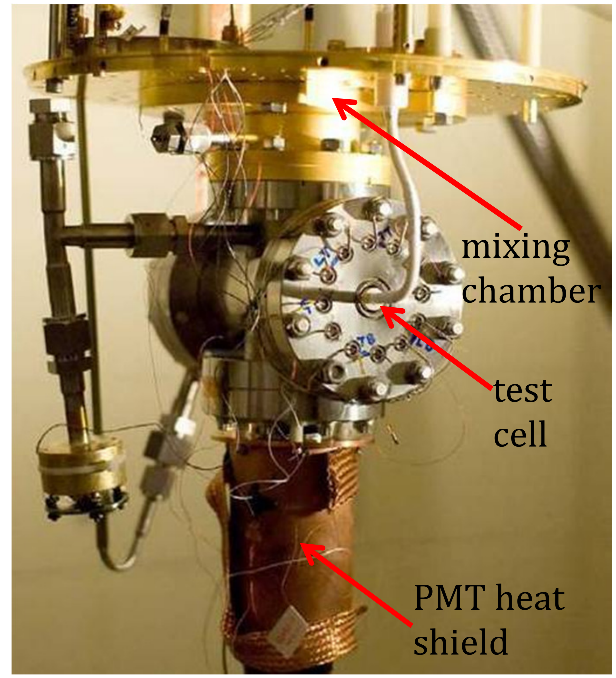
✓ Indirectly measured

R&D: LHe Scintillation Dependence on Electric Fields

T. Ito, et al., PRA 85 (2012) 042718

- At IU: measure scintillation from alpha particles (similar to p, ^{3}H) in SF at 0.4 K and 0–45 kV/cm





- Prompt scintillation: 40% from α, 60% from ionization-recombination.

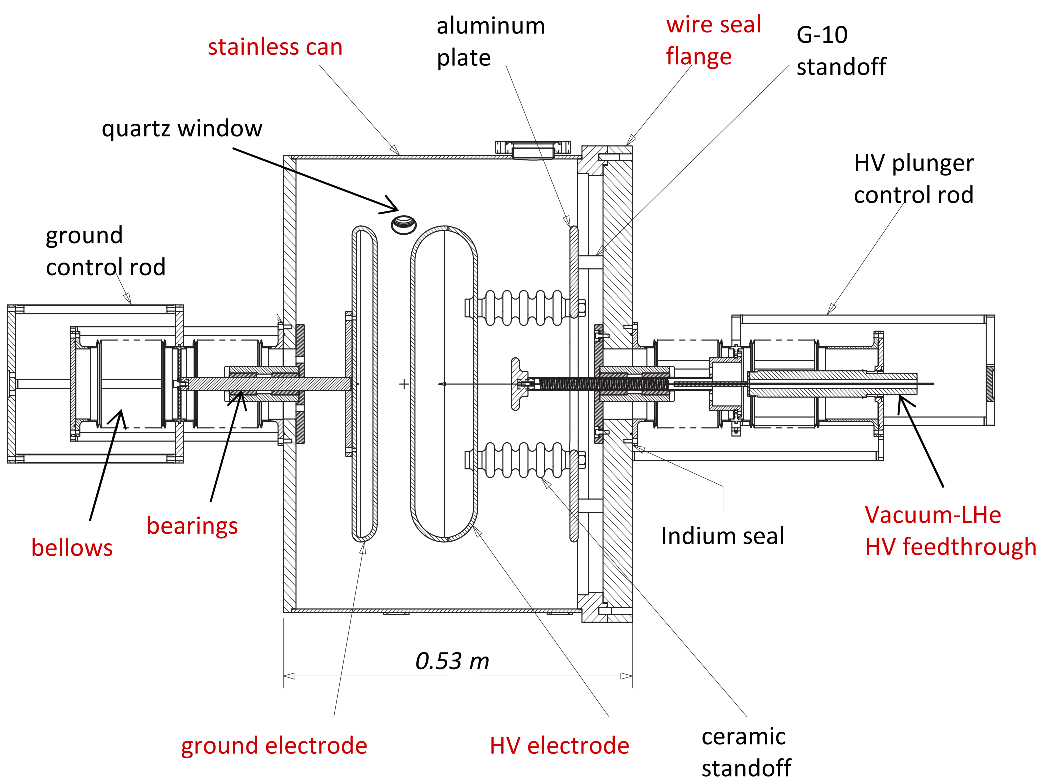
- 15% overall reduction (little concern)

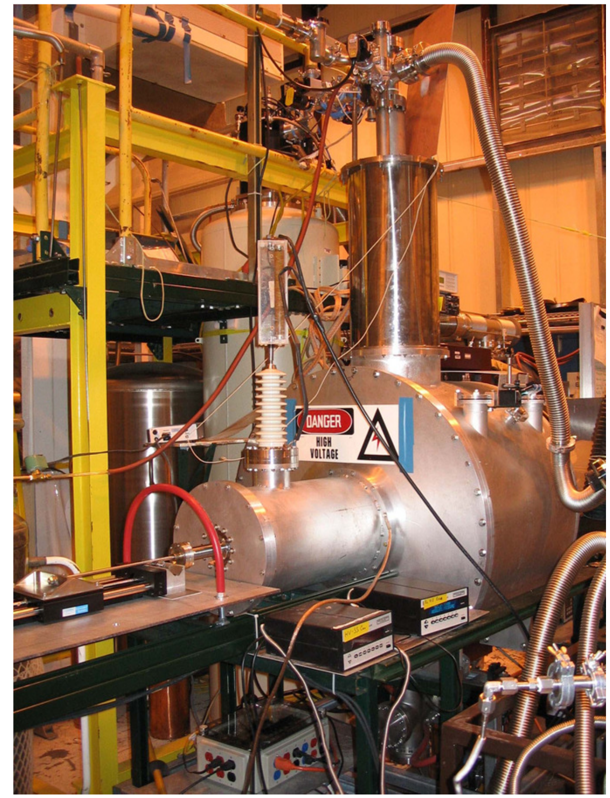
- Dielectric strength of LHe at 400 mK (and vapor pressure) at least 45 kV/cm

R&D: High Voltage System Prototype Tested at LANL

- Measure breakdown properties of large volumes of LHe

Target: 75 kV/cm at 0.4 K, 7cm gap



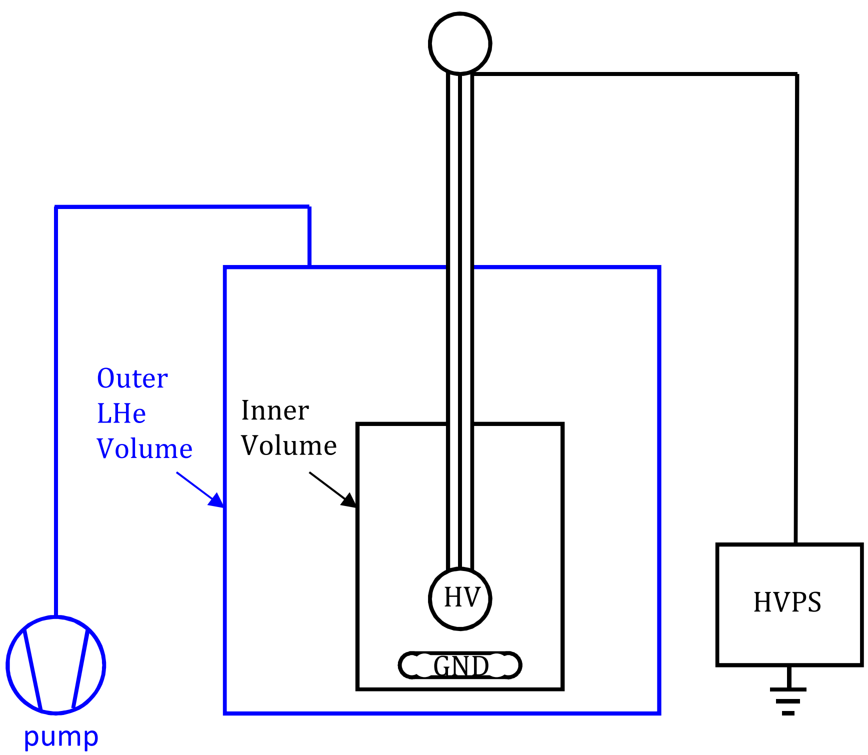


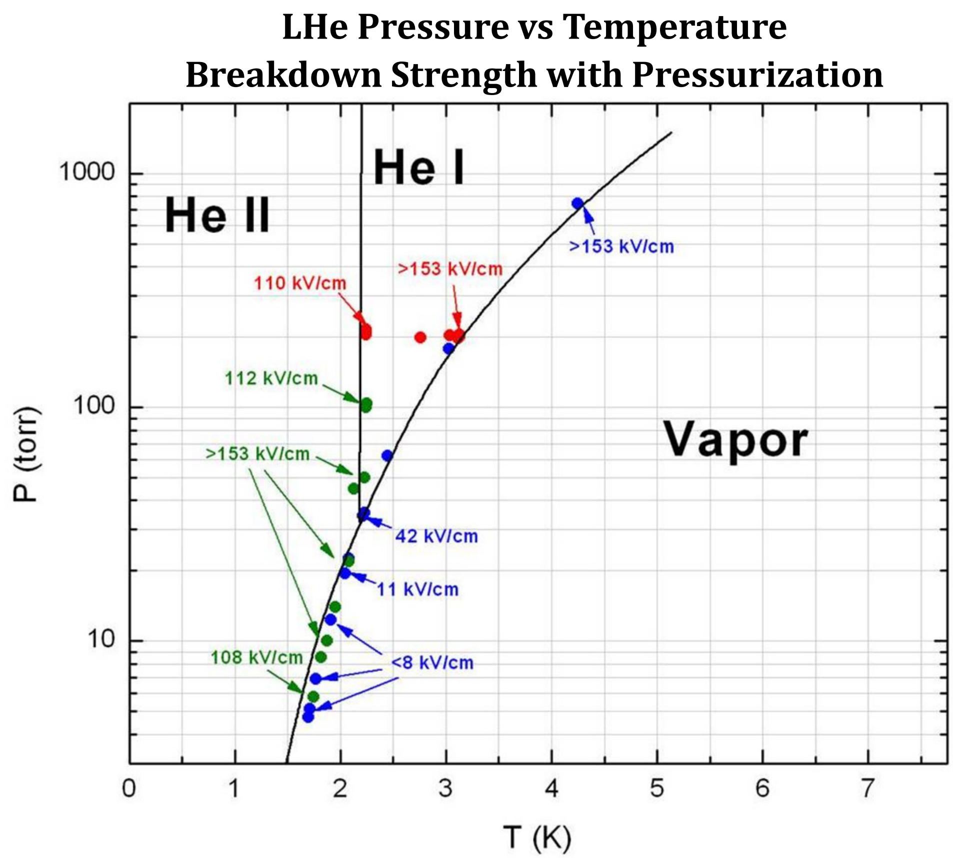
Maximum potentials sustained:
Normal State (4.38 K):
(119 ± 11) kV/cm

SF (2.14 K, cooled by pumping):
(58 ± 8) kV/cm
Worse at 0.4 K?
Pressure or Temperature effect?

R&D: Adjustable-Pressure HV Cryostat (IU)

- Small sealed inner LHe volume with ~ $1cm^3$ HV electrodes, immersed in larger bath
- Small volume pressurized with cold He gas at top; outer bath cooled by pumping (1.5 K)



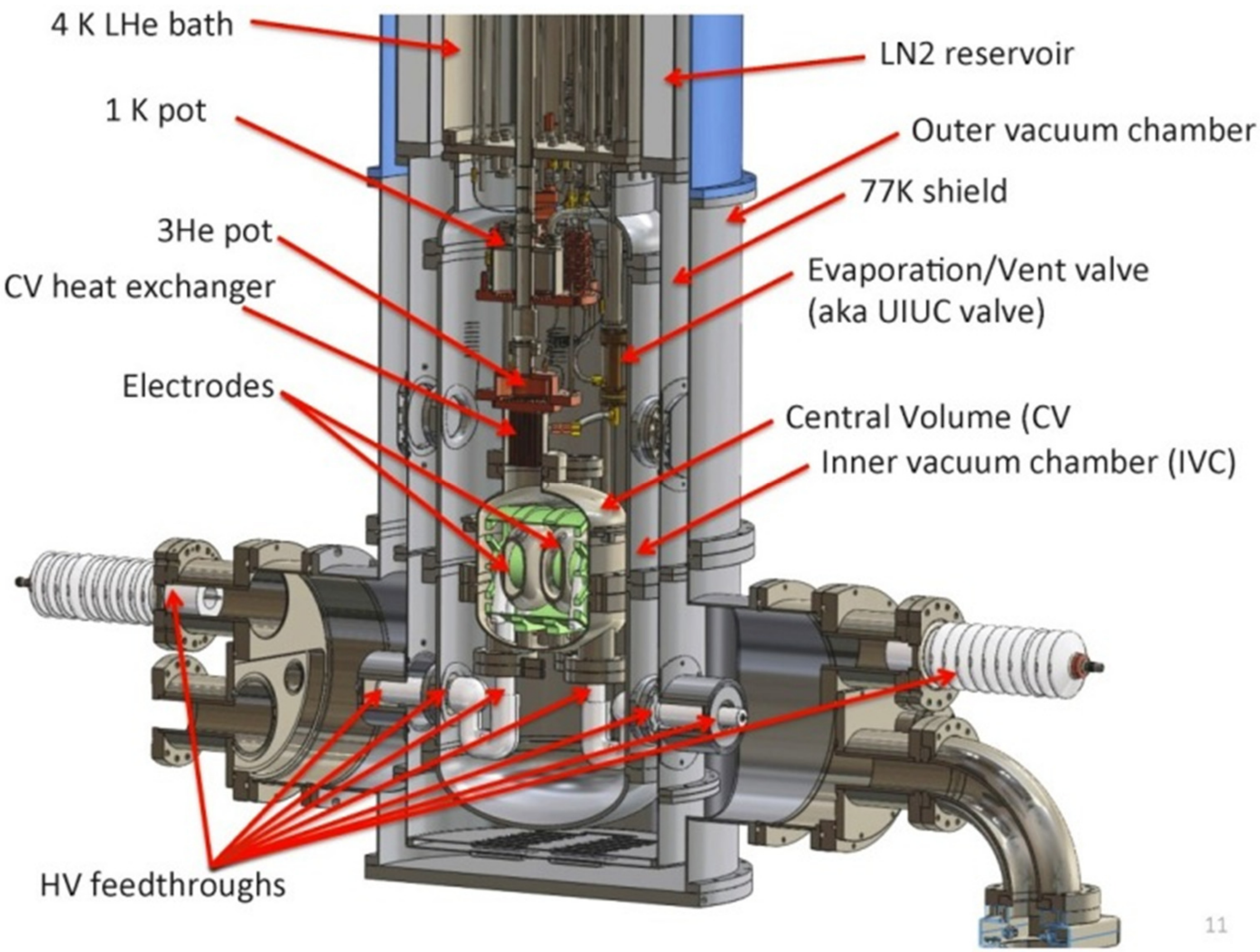


High breakdown strength preserved if system pressurized (even temporarily at 200 torr)

No pressurization needed with electropolished electrodes

R&D: Medium-Scale HV Test Cryostat (LANL)

- Test electrodes and cell materials in more realistic (~ ¼ scale) geometry: 150 kV
- Test at more realistic temperature (0.6 K)



- System assembled except for CV
- Cold leak check with LN2 (now)
- Install CV (week of July 30)
- Fill with LHe (mid-August)
- First HV tests (fall 2012)

Schedule – US DOE

Project funded jointly – NSF and DOE

Decision	Funding Profile
CD-0 Approve Mission Need	2006
CD-1 Approve Preliminary Baseline Range	2007
Evaluation of critical R&D (technical committees, agencies)	~ Winter 2014
CD-2 Engineering design review	Review + few months
CD-3 Approve Start of Construction	CD-2 + few months
CD-4 Approve Start of Operations	CD-3 + ~5 yr (2018)

Summary

SNS nEDM experiment expects sensitivity of 10^{-28} e-cm

Superthermal UCN in LHe: greater statistics, longer integration times, higher E-fields

Covers much of remaining parameter space of SUSY predictions (*all* of MSSM)

Critical R&D must have conclusions in next ~ 2 years

Estimated construction at SNS: 2014 - 2018

Worldwide neutron EDM program

	Magnetometer	Sensitivity [e-cm]
ILL / "CryoEDM"	Ext SQUID, E=0	5×10^{-27} / 5×10^{-28}
PNPI / ILL	E=0	$< 1 \times 10^{-26}$ / $< 1 \times 10^{-27}$
PSI	Ext Cs + ^{199}Hg	5×10^{-27} / 5×10^{-28}
SNS	^{3}He	$\sim 7 \times 10^{-28}$
KEK/TRIUMF	^{129}Xe	$< 10^{-27}$

Plus… Broad array of searches for EDMs of electron, proton, deuteron, nuclei, atoms, …