Electric Dipole Moment (EDM) Searches

- Motivation in post-LHC turn-on era - MJRM
- Complementary role of different systems
  - Atom, Molecule, Proton, Neutron, …
- Status & future of on-going searches in NP
  - ^{199}Hg at UW
  - Radioactive atoms
  - Storage Ring proton
  - nEDM

B. Filippone
9/28/14
FSN Twn Mtg

Primary Motivation

- Particle EDMs violate Time-Reversal Symmetry and Charge-Parity (CP) Symmetry
- Can be a window to new physics beyond the Standard Model (& beyond Large Hadron Collider)
  - Since they are *Very* small in Standard Model of Fundamental Interactions
- May shed light on why the Universe is not symmetric in amount of Matter vs Antimatter

Connections beyond NP

P5 (Particle Physics Project Prioritization Panel) Report 6/14

Many extensions of the Standard Model, including Supersymmetry, have additional sources of CP non-conservation. 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. At Fermilab, a direct measurement of the electric dipole moment of the proton, with sensitivity three orders of magnitude better than the present limit, may be possible. The experiment would be sensitive to contributions from new particles with masses well in excess of 100 TeV.

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}

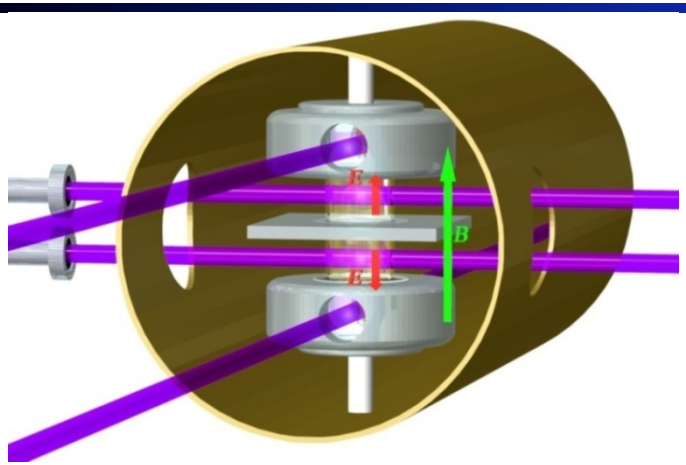
Observation or lack thereof in one system *does not* predict results for other systems

Relative EDM Sensitivities

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

Search for an Electric Dipole Moment of ^{199}Hg

University of Washington



Provides the tightest bounds on:

- Chromo-EDM's of quarks
- The EDM of the proton
- Semi-leptonic CP-odd couplings

And competitive bounds on:

- θ_{QCD}
- The EDM of the neutron

<u>Personnel</u>

Faculty: Blayne Heckel

Graduate students: Jennie Chen, Brent Graner

Scientific glassblower: Eric Lindahl

Support: NSF and DOE Low Energy Nuclear Physics (total $190k/yr)

B. Heckel

Status and Plans

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.

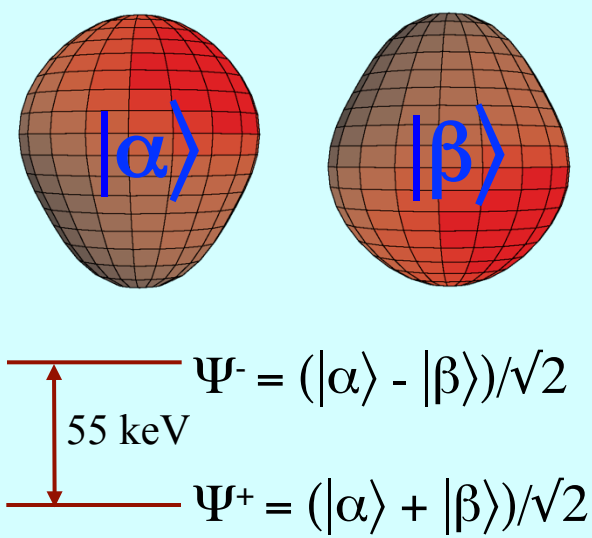
2017: We believe another factor of 3 increase in sensitivity is achievable.

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

EDM of ^{225}Ra enhanced and more reliably calculated

- 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)

Parity doublet



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

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)

"[Nuclear structure] calculations in Ra are almost certainly more reliable than those in Hg."
– Engel, Ramsey-Musolf, van Kolck, Prog. Part. Nucl. Phys. (2013)

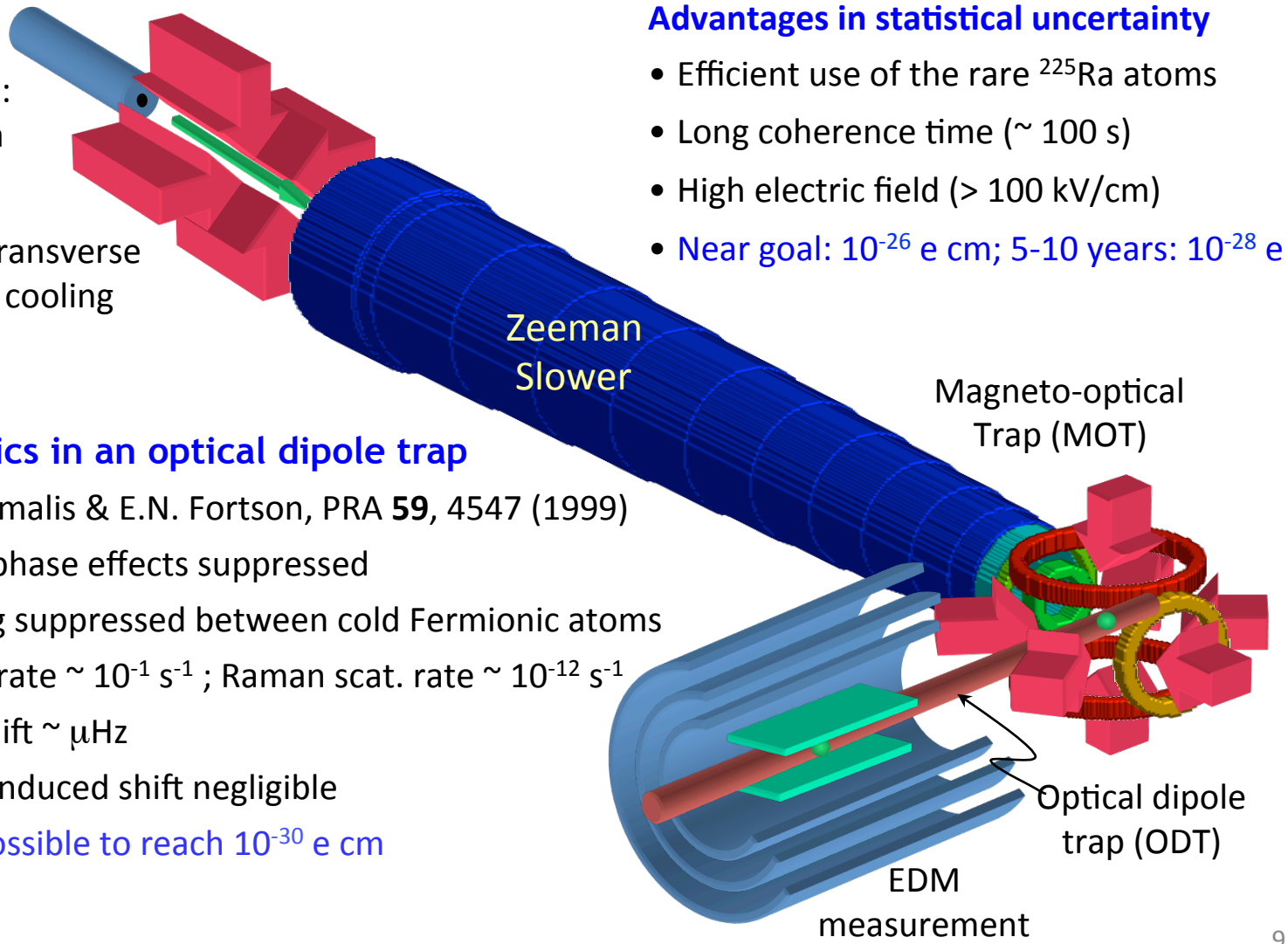
Z-T Lu

(Deformation enhanced ^{223}Rn experiment also under development at TRIUMF- BWF)

^{225}Ra:
I = ½
$t_{1/2}$ = 15 d

EDM measurement on ^{225}Ra in a trap

Collaboration of Argonne, U Kentucky, Michigan State U



Advantages in statistical uncertainty

- Efficient use of the rare ^{225}Ra atoms
- Long coherence time (~ 100 s)
- High electric field (> 100 kV/cm)
- Near goal: 10^{-26} e cm; 5-10 years: 10^{-28} e cm

EDM systematics in an optical dipole trap

- M.V. Romalis & E.N. Fortson, PRA **59**, 4547 (1999)

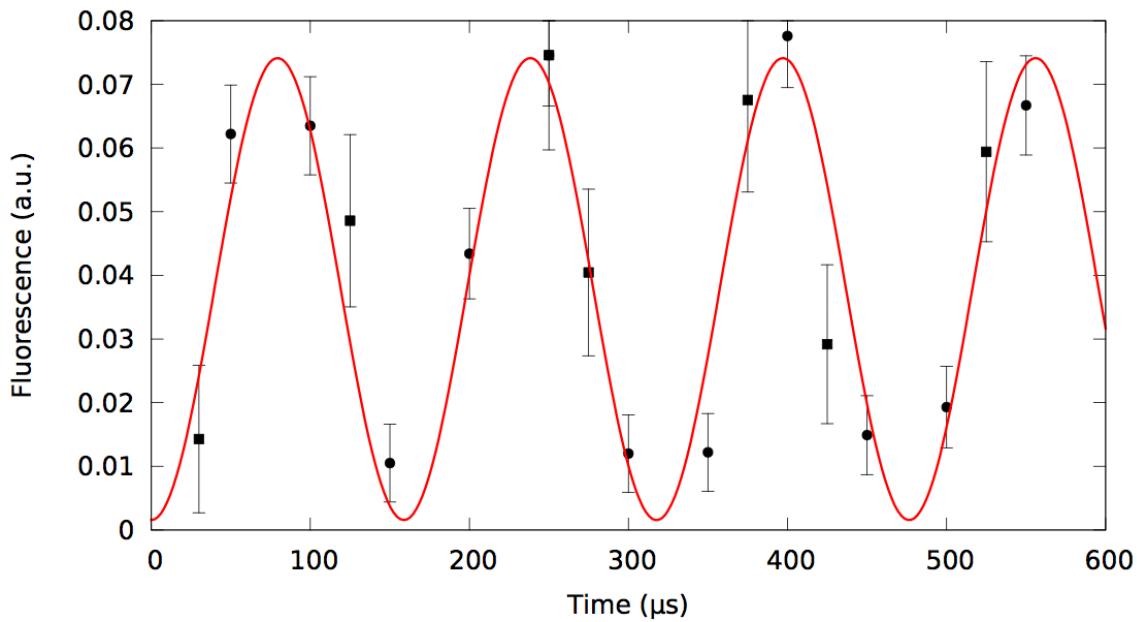
- v x E , Berry's phase effects suppressed
- Cold scattering suppressed between cold Fermionic atoms
- Rayleigh scat. rate ~ 10^{-1} s^{-1} ; Raman scat. rate ~ 10^{-12} s^{-1}
- Vector light shift ~ μHz
- Parity mixing induced shift negligible
- Conclusion: possible to reach 10^{-30} e cm

Z-T Lu

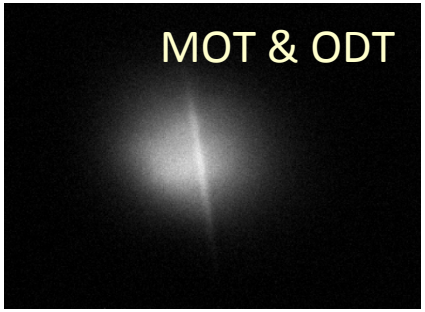
Preparation of Cold Radium Atoms for EDM

- 2006 – Atomic transitions identified and studied; N.D. Scielzo *et al.*, PRA Rapid **73**, 010501 (2006)
- 2007 – Magneto-optical trap (MOT) of radium realized; J.R. Guest *et al.*, PRL **98**, 093001 (2007)
- 2010 – Optical dipole trap (ODT) of radium realized;
- 2011 – Atoms transferred to the measurement trap; R.H. Parker *et al.*, PRC **86**, 065503 (2012)
- 2012 – Spin precession of Ra-225 in ODT observed;
- 2014 – Attempt to measure EDM of Ra-225.

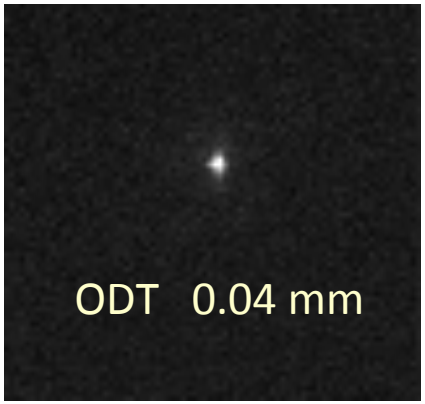
Precession frequency: $\varpi = 2\mu B$



Sideview

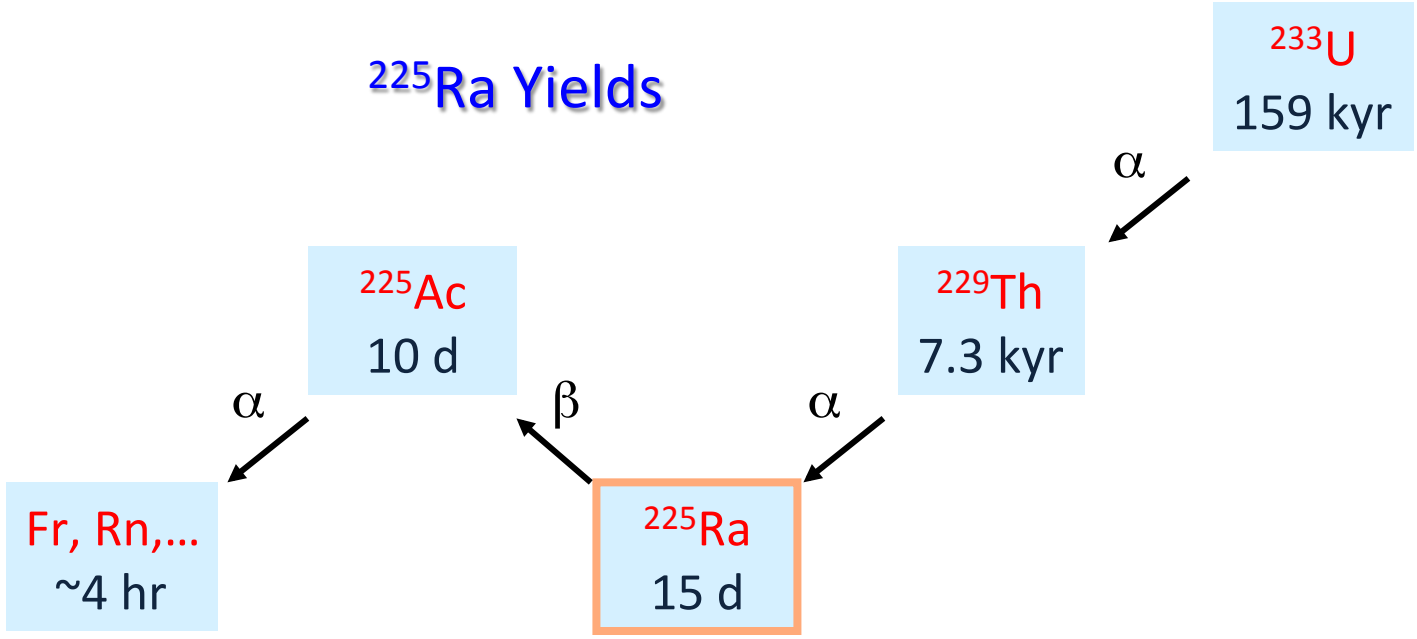


Head-on view



Z-T Lu

^{225}Ra Yields



Presently available

- National Isotope Development Center, ORNL
  - Decay daughters of ^{229}Th ---------- ^{225}Ra: 10^8 /s

Projected

- FRIB (B. Sherrill, MSU)
  - Beam dump recovery with a ^{238}U beam ---------- ^{225}Ra: 6×10^9 /s
  - Dedicated running with a ^{232}Th beam ---------- ^{225}Ra: 5×10^{10} /s

- ISOL@FRIB (I.C. Gomes and J. Nolen, Argonne)
  - Protons on thorium target, 1 mA x 1 GeV = 1 MW ^{225}Ra: 10^{13} /s

Z-T Lu

Storage Ring Electric Dipole Moment Experiment for the Proton

- Revolution in statistics: 1×10^{11} polarized protons per 1000 s
- Strong endorsement from P5
- Discussion with DOE-HEP office to plan a successful experiment

✓ An experiment to probe proton EDM to 10^{-29}e-cm
✓ Most sensitive, flavor-conserving CP-violation
✓ Complementary to LHC and the neutron EDM; probes New Physics ~1000 TeV
✓ Based on "g-2" experience using the magic momentum technique with electric fields

Y. Semertzidis

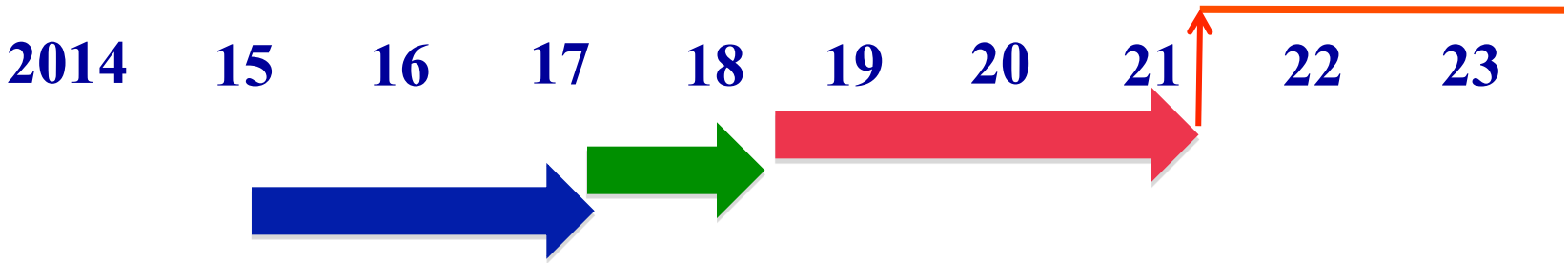
Feasibility of an all-electric ring

- First all-electric ring (AGS-analog) proposed/built 1953-57. It worked!
- Two encouraging technical reviews performed at BNL: Dec. 2009, March 2011.
- Fermilab comprehensive review: Fall 2013. Val Lebedev considers the concept to be sound.
- Major progress on R&D.
  - Polarimeter stat. & syst. (COSY,IU,KVI,…)
  - Spin Coherence Time understanding (BNL, CAPP, Cornell, COSY…)
  - Electric field strength & fringe-field effects (BNL, J-LAB,…)
- Ongoing R&D: SQUID-based beam position monitors (CAPP/IBS, KAIST, KRISS/Korea, Garching/Germany)

Our proton EDM plan

- Develop the following systems (funded by IBS/ Korea, COSY/Germany, applying for NSF support, and seek support from DOE-HEP/NP):
  - SQUID-based BPM prototype, includes B-field shielding (UMass, CAPP/Korea, BNL,…)
  - Polarimeter development (Ind. Univ., CAPP, COSY,…)
  - Electric field prototype (Old Dom. Un. (NSF), JLab,…)
  - Study of systematic errors (BNL, FNAL, Cornell,…)
  - Precision beam and spin dynamics simulation (BNL, CAPP, Cornell, COSY,…)
  - Lattice optimization, beam diagnostics (MSU (NSF),…)

Technically driven pEDM timeline



- Two years' system development (R&D); Ring design; Installation.
- Cost (2011, 2012 engineering cost): $70M + tunnel.
- Proposed cost-sharing if existing tunnel is used:
  - DOE-HEP $35M; DOE-NP $20M (+ running costs).
- Foreign contributions: electric field plates, vacuum chambers, SQUID-based magnetometers

Y. Semertzidis

R&D Toward a new neutron EDM Experiment at LANL

S. Clayton, S. Currie, T. Ito, M. Makela, C. Morris, R. Pattie,
J. Ramsey, A. Saunders, Z.Tang, F. Trouw, T. Womack
Los Alamos National Laboratory

C.-Y. Liu, J. Long, W. Snow
Indiana University

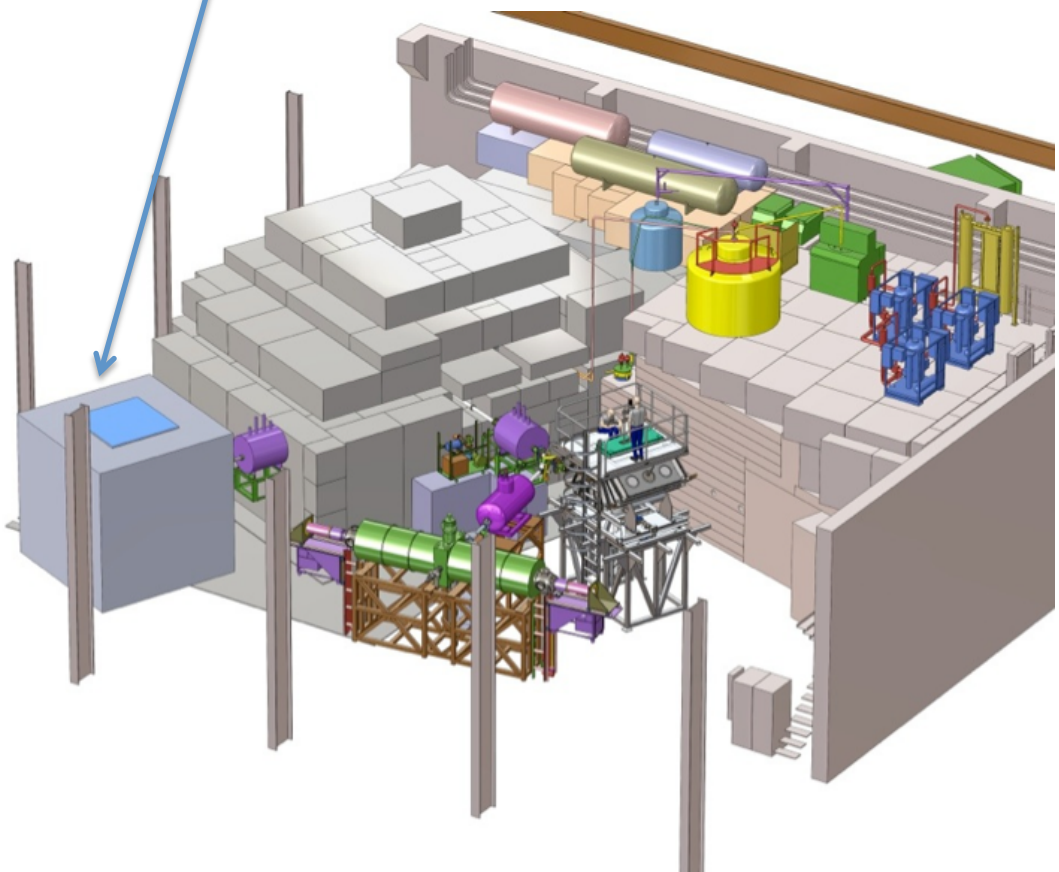
B. Plaster
University of Kentucky

S. Lamoreaux
Yale University

E. Sharapov
Joint Institute of Nuclear Research

LANL UCN Experimental Area

Location of the envisioned nEDM experiment



T. Ito

Concept for neutron EDM experiment at LANL

- A neutron EDM experiment with a sensitivity of $\delta d_n \sim O(10^{-27})$ e-cm based on already proven room temperature Ramsey's separated oscillatory field method could take advantage of the existing LANL SD_2 UCN source
  - nEDM measurement technology for $\delta d_n \sim O(10^{-27})$ e-cm exists. What is holding up the progress is the lack of UCN density.
  - The LANL UCN source currently provides a UCN density of ~ 60 UCN/cc at the exit of the biological shield
  - A 10 fold improvement in the delivered UCN density is required for an nEDM experiment with $\delta d_n \sim O(10^{-27})$ e-cm
- Such an experiment could provide a venue for the US nEDM community to obtain physics results, albeit less sensitive, in a shorter time scale with much less cost while development for the SNS nEDM experiment continues.

T. Ito

Current status and future needs

- This effort currently funded by LANL internal funds (FY14-16). The current activities include:
  - UCN source upgrade
    - New source insert with more optimized source geometry
    - Increased proton beam current with more optimized pulsed beam delivery
    - Improved UCN transport
  - Prototyping of an nEDM apparatus
- Short term goal (3 years)
  - Demonstration of stored UCN in a prototype nEDM apparatus with a sufficient number of UCN for an nEDM experiment with a sensitivity of $\delta d_n \sim O(10^{-27})$ e-cm
- Funding needs after LDRD
  - Approximately $5M to complete the construction of the experiment (a large fraction of it is for the magnetic shielding)
  - If we could attract foreign collaborators with existing apparatus, the cost would be substantially lower.

T. Ito

Worldwide neutron EDM Searches

Worldwide neutron EDM Searches

Experiment	UCN source	cell	Measurement techniques	σ_d Goal (10^{-28} e-cm)
				Present neutron EDM limit < 300
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 nEDM	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

Comparison of Capabilities for High Sensitivity experiments

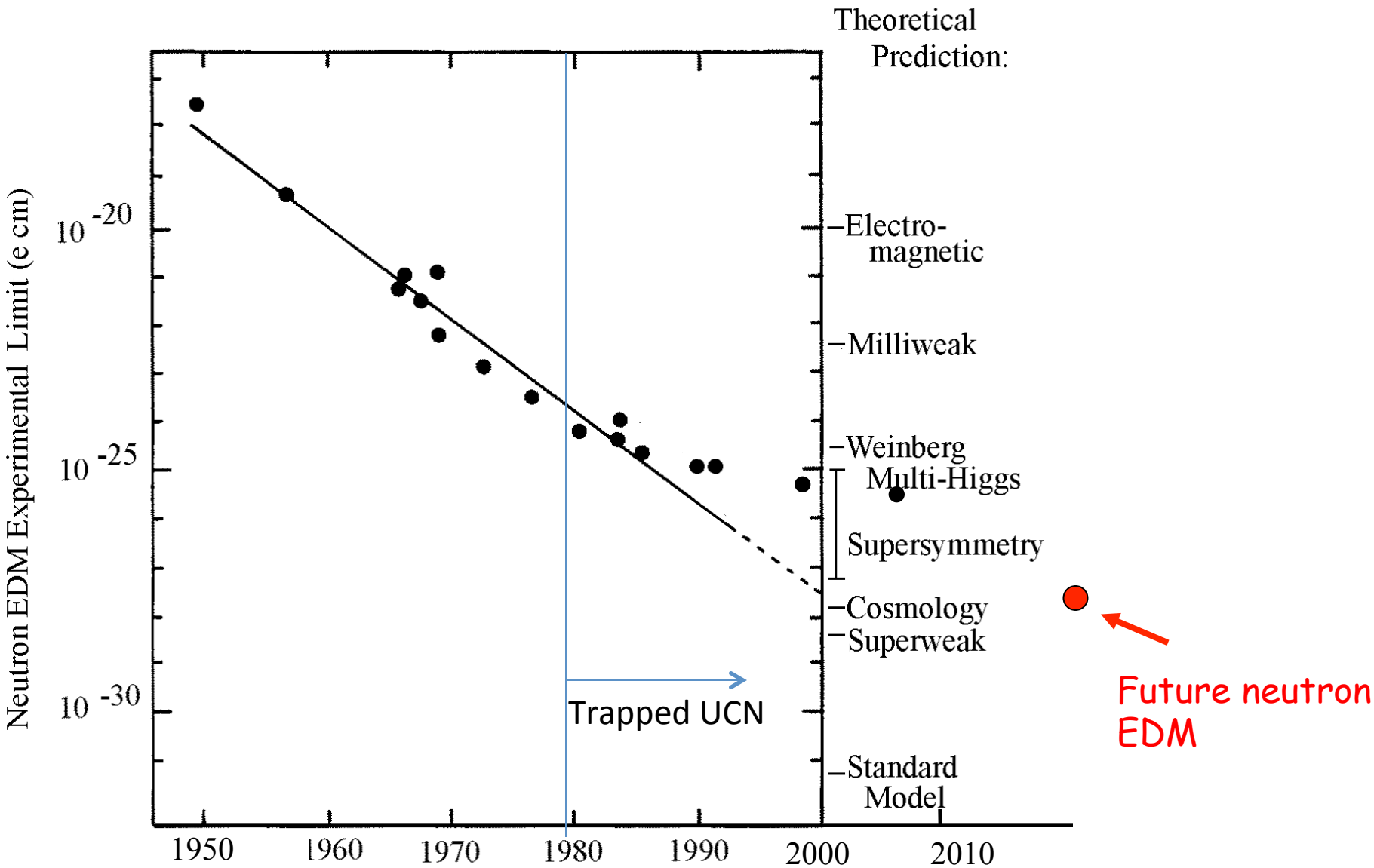
Capability	Cryo	FRM	PSI1	PSI2	SNS
$\Delta\omega$ via accumulated phase in n polarization	Y	Y	Y	Y	N
$\Delta\omega$ via light oscillation in ^{3}He capture	N	N	N	N	Y
Horizontal B-field	Y	N	N	N	Y
*Comagnetometer	N	Y	Y	Y	Y
*Superconducting B-shield	Y	N	N	N	Y
*Dressed Spin Technique	N	N	N	N	Y
*Multiple EDM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

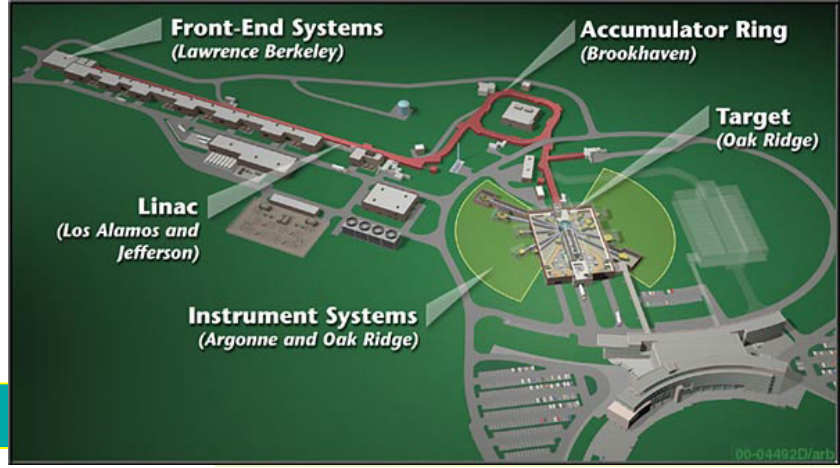
"No other EDM effort currently has as comprehensive a set of diagnostics as the US nEDM experiment."

Report to NSAC of the Subcommittee on Fundamental Physics with Neutrons (December 2011)

Neutron EDM Sensitivity



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
  – *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*

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

nEDM 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

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I. Silvera

Harvard University

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

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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

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

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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. Baeβler

University of Virginia

S. Lamoreaux

Yale University

Systematic Controls in SNS experiment

- Highly uniform E and B fields
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Ability to vary influence of B_0 field
  - via "dressed spins"
- Study dependence on $|\vec{B}|$, $\vec{B}$, B-gradients & $^3\vec{He}$ density
- Variation of ^{3}He m.f.p. with LHe temperature
  - Can vary ^{3}He diffusion which changes geometric phase effect on ^{3}He

Status of nEDM @ SNS

- Nuclear Science Advisory Committee (NSAC) Review of Fundamental Physics with Neutrons (12/11)
  - nEDM is highest priority of sub-field
  - nEDM should focus on Critical R&D for 2 yrs
    - Several key elements need to be demonstrated
- Funded as R&D project (2012/2013)
    - Reviewed every 4 months via external Technical Review Committee
- NSF/DOE review 12/13 = "Do or Die"

NSF/DOE Review (12/13)

- Status of Critical R&D presented
- 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 build the experiment

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

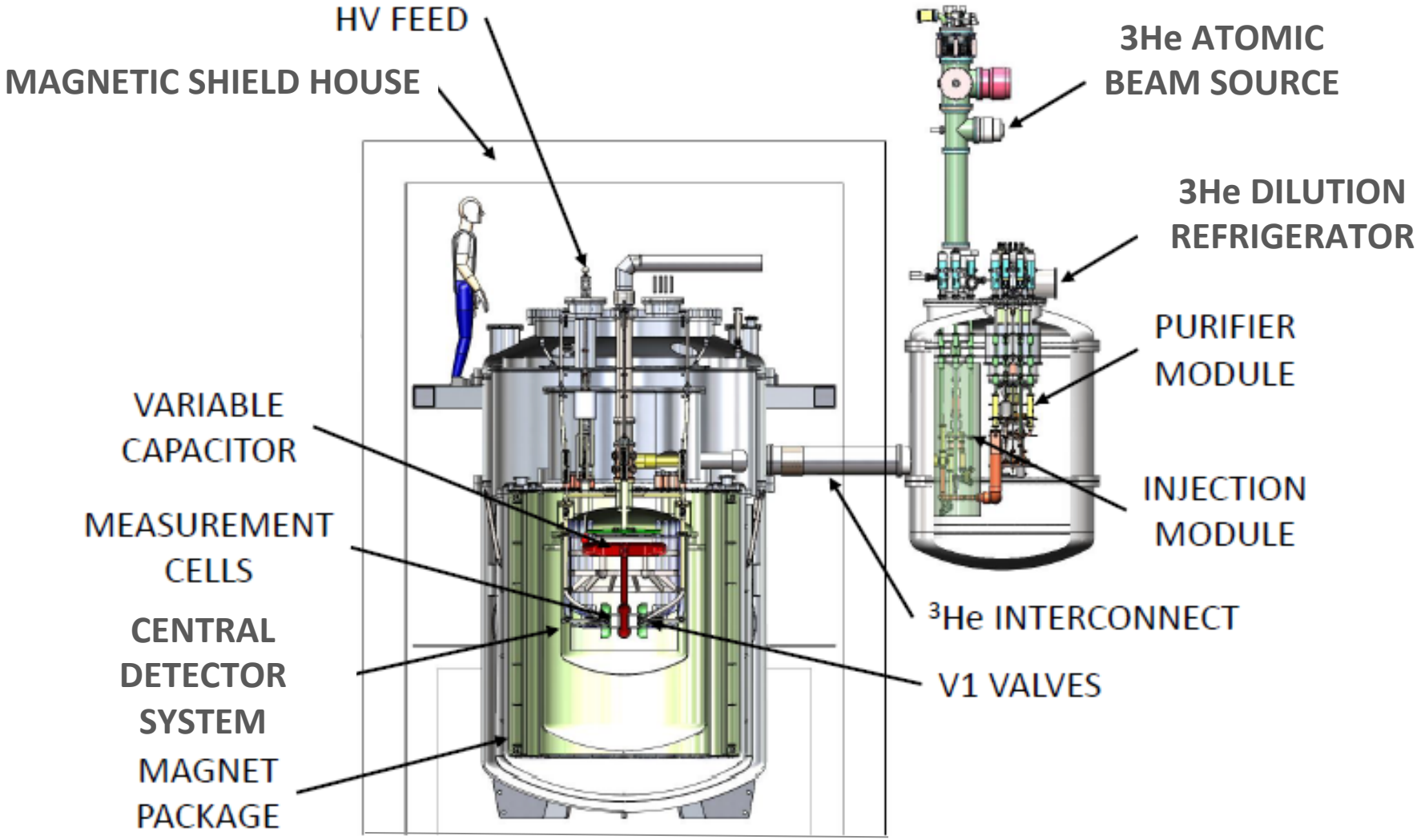
Funding & Schedule for nEDM

- 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 of more conventional systems after additional ~ 2 yrs
- Commissioning underway by 2019-2020

Very Recently: Alternatives Analysis Completed

- Based on experience with focused R&D coupled with developments in the field
- Alternatives analysis modifies design to simplify access & reduce risk
- External Technical Review Committee met 9/13/2014 & endorsed design modifications

- Key Changes in Alternatives Analysis:
  - Central Detector System & Magnets mounted Vertically
  - Separate function into modules (Cells/HV, Magnet, ^{3}He)
  - Use Magnetically Shielded House rather than custom "skin"



Summary

- Large scientific reach of EDM searches remains (100-1000 TeV)
  - One of the few experimental probes of this scale
- US-NP funding continues to support hadronic EDM experiments
- Future funding and commitment is needed through the upcoming LRP period to achieve the next level of sensitivity
  - Funding needs are ~ 5-10 M$/yr

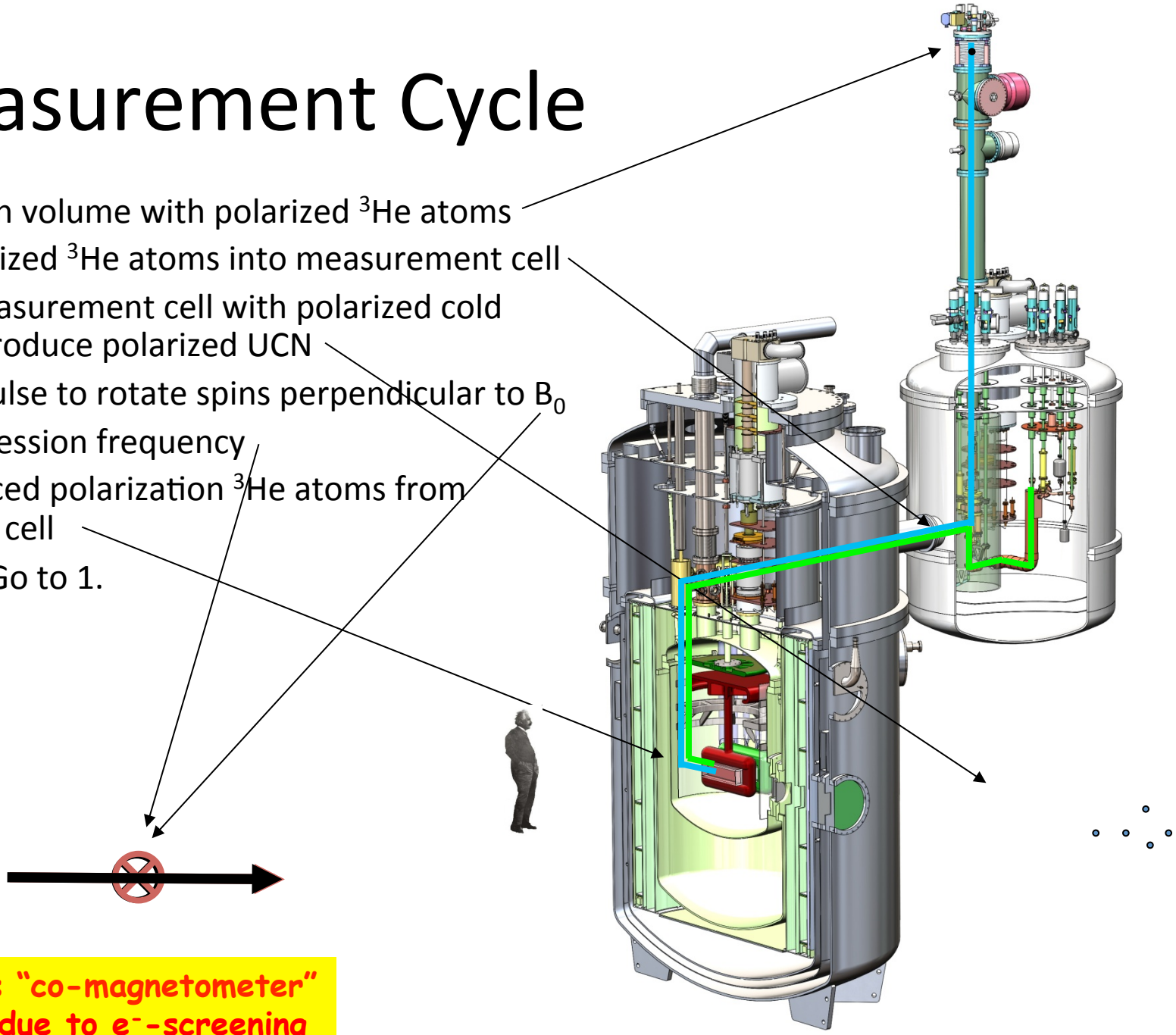
Extra Slides

Opportunities at FNAL or BNL

Ring location	Ring circum-ference Shape	Max E-field Average E-field	Max B-field allowed in storage region	Sensitivity	Ring availability
FNAL (Former Anti-proton Accumulator)	500m Triangle shape (Tentative)	11 MV/m 5 MV/m	0.01nT Strict req., need R&D	1.5×10^{-29} *e*cm/year	Restricted: g-2, mu2e experiments co-habit the ring
BNL (AGS)	807m Circular shape	5 MV/m 3.3 MV/m	0.3-1nT Possible with present technology	2×10^{-29} *e*cm/ year	Available (RHIC refilling ~1/2 hour per 12 hours)

Measurement Cycle

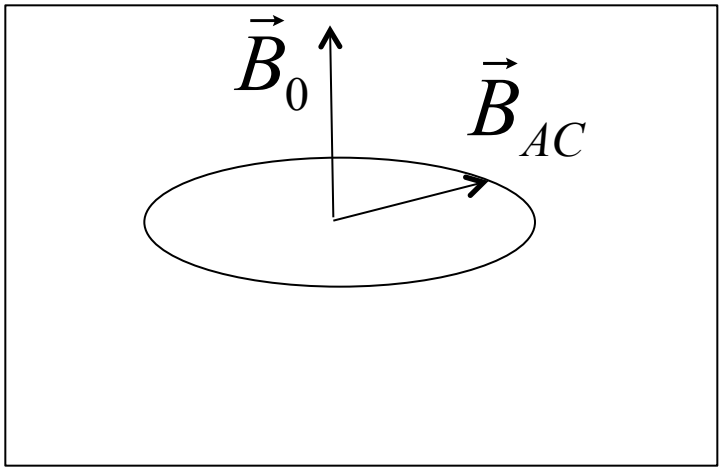
1. Load collection volume with polarized ^{3}He atoms
2. Transfer polarized ^{3}He atoms into measurement cell
3. Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
4. Apply a $\pi/2$ pulse to rotate spins perpendicular to B_0
5. Measure precession frequency
6. Remove reduced 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

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

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