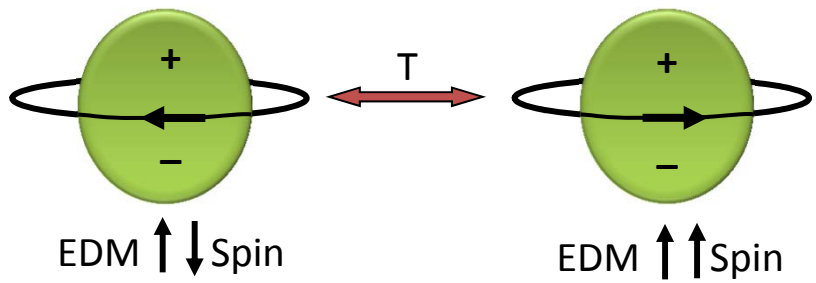
EDM Overview



- Motivation for EDM searches
  - Physics reach has been discussed
  - Why so many systems to study?
- EDMs and Nuclear Physics
  - Radioactive atom EDMs
  - Proton EDM in storage ring
  - Neutron EDM in worldwide context

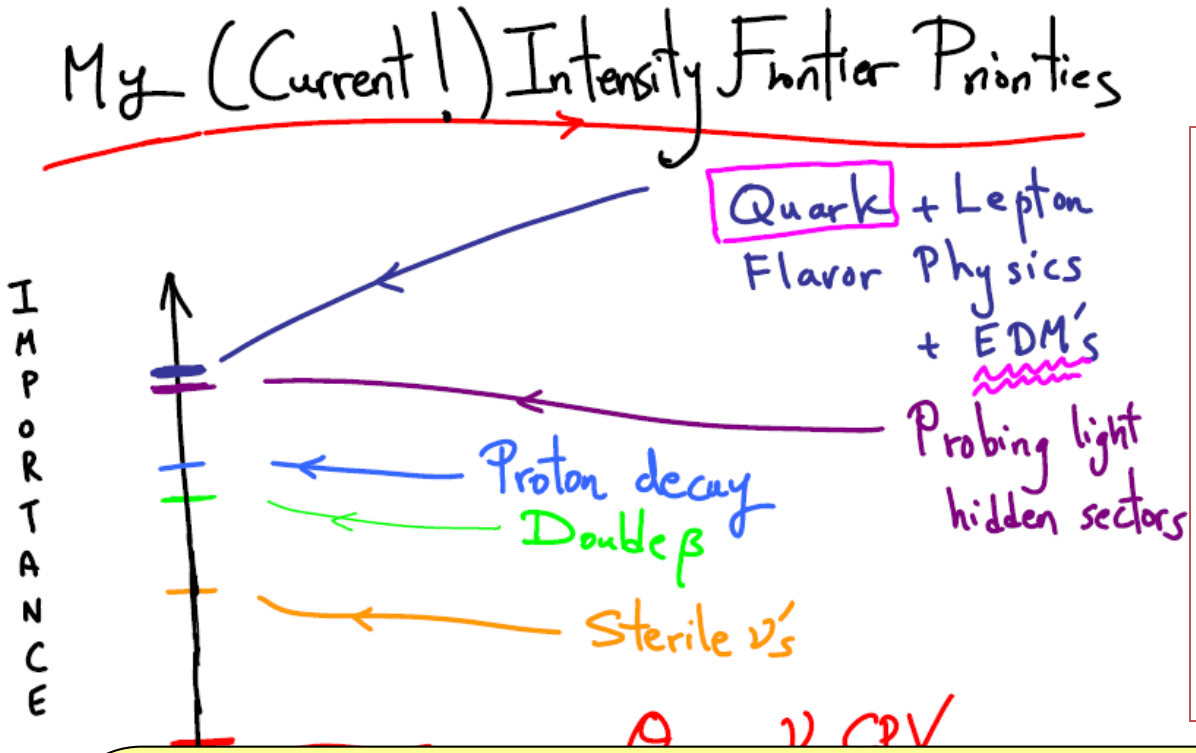
Thanks to:
Z-T Lu (ANL)
Y Semertzidis (BNL)
T Chupp (U Michigan)

(Potentially biggest budget impact over next 5 years

B. Filippone
NSAC Subcommittee
9/7/12

EDMs continue to have strong discovery potential

$$d_f \propto e \cdot \sin\phi_{CP} \cdot \frac{m_f}{\Lambda^2}$$



"… the existence of an EDM can provide the "missing link" for explaining why the universe contains more matter than antimatter."

"A nonzero EDM would constitute a truly revolutionary discovery."

-- Nuclear Science Advisory Committee (NSAC) Long Range Plan (2007)

"The non-observation of EDMs to-date, thus provides tight restrictions to building theories beyond the Standard Model."

-- P5 report : The Particle Physics Roadmap (2006)

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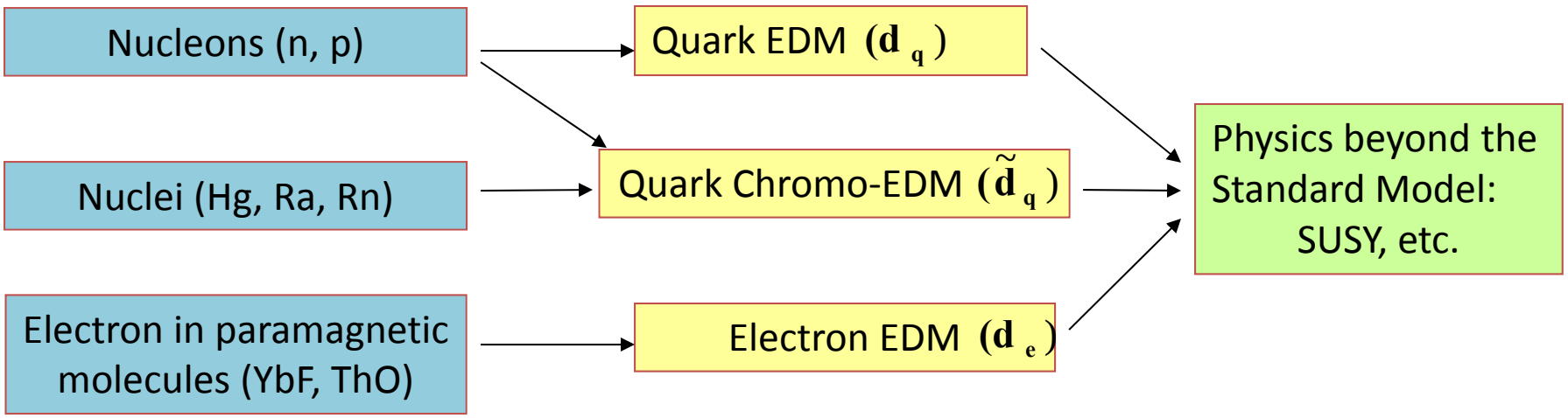
What is the Origin of an EDM?



Sector	Exp Limit (e-cm)	Method	Standard Model
Electron	1×10^{-27}	YbF in a beam	10^{-38}
Neutron	3×10^{-26}	UCN in a bottle	10^{-31}
^{199}Hg	3×10^{-29}	Hg atoms in a cell	10^{-33}

M. Ramsey-Musolf (2009)

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Future Hadronic EDM Searches

- Atoms -
  - Suppressed by electron screening (Schiff Moment) ☹
  - Enhanced by octupole deformations ☺
- Protons - New Concept - Electric Field Storage Ring
- Neutrons - new cryogenic superthermal Ultra-Cold Neutron Sources

Different/Complementary Sensitivities to Origins of New CP Violation

System	Dependence of (& model dependent)	Present Limit (10^{-28} e-cm)
n	$d_n \sim 3x10^{-16}\theta_{QCD} + 0.7(d_d - \frac{1}{4}d_u) + 0.6e(\tilde{d}_d + \frac{1}{2}\tilde{d}_u)$	< 300
^{199}Hg	$d_{Hg} \sim 1x10^{-20}\theta_{QCD} + 0.006e(\tilde{d}_d - \tilde{d}_u)$	< 0.3
p	$d_p \sim 3x10^{-16}\theta_{QCD} + 0.7(d_u - \frac{1}{4}d_d) + 0.6e(\tilde{d}_u + \frac{1}{2}\tilde{d}_d)$	< 8000

Enhancement of EDM for Deformed Nuclei

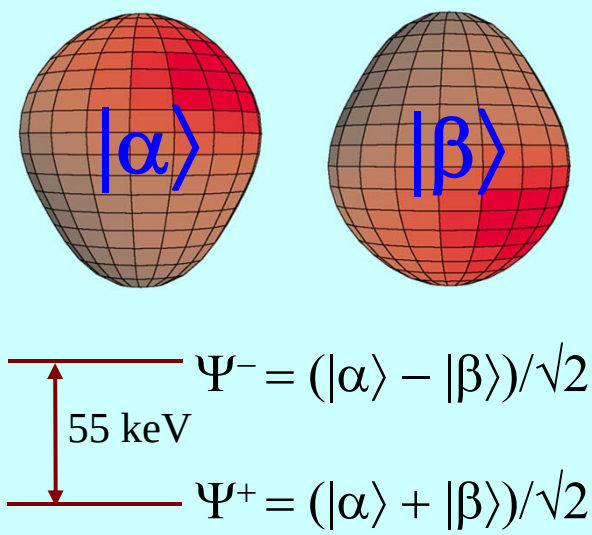
^{225}Ra:
I = ½
$t_{1/2}$ = 15 d

- Closely spaced parity doublet – *Haxton & Henley (1983)*
- Large intrinsic Schiff moment due to octupole deformation

  – *Auerbach, Flambaum & Spevak (1996)*
- Relativistic atomic structure (^{225}Ra / ^{199}Hg ~ 3)

  – *Dzuba, Flambaum, Ginges, Kozlov (2002)*

Parity doublet



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

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

Skyrme Model	Isoscalar	Isovector	Isotensor
SIII	300	4000	700
SkM*	300	2000	500
SLy4	700	8000	1000

Schiff moment of ^{225}Ra, Dobaczewski, Engel (2005)
Schiff moment of ^{199}Hg, Ban, Dobaczewski, Engel, Shukla (2010)

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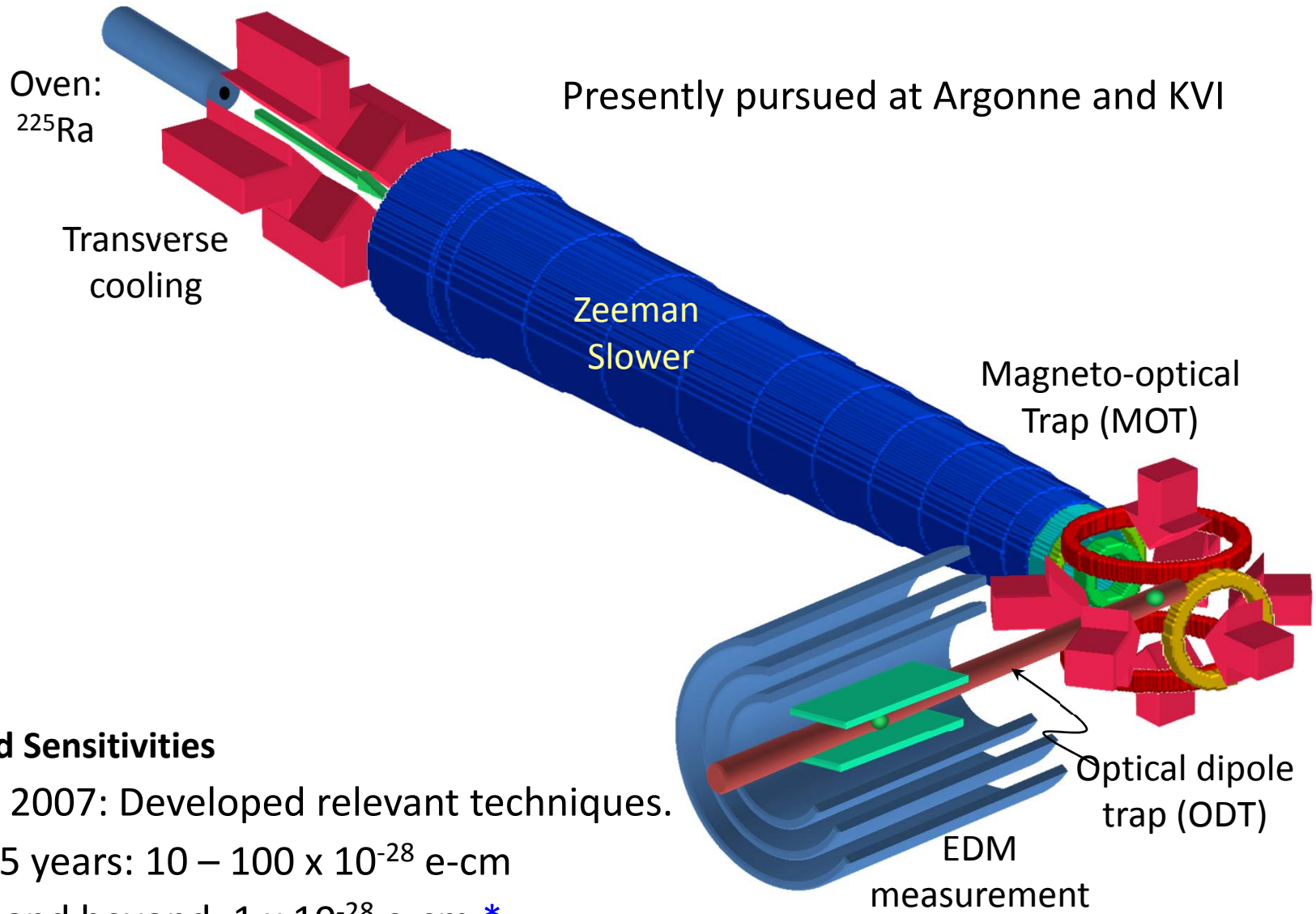
EDM measurement on ^{225}Ra



Presently pursued at Argonne and KVI

Limits and Sensitivities

- Since 2007: Developed relevant techniques.
- Next 5 years: 10 – 100 x 10^{-28} e-cm
- 2020 and beyond: 1 x 10^{-28} e-cm *

* at an accelerator-based isotope production facility

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Enhancements also Possible in ^{223}Rn

TRIUMF E929

Spokesmen: Timothy Chupp & Carl Svensson

E-929 Collaboration (Guelph, Michigan, SFU, TRIUMF)

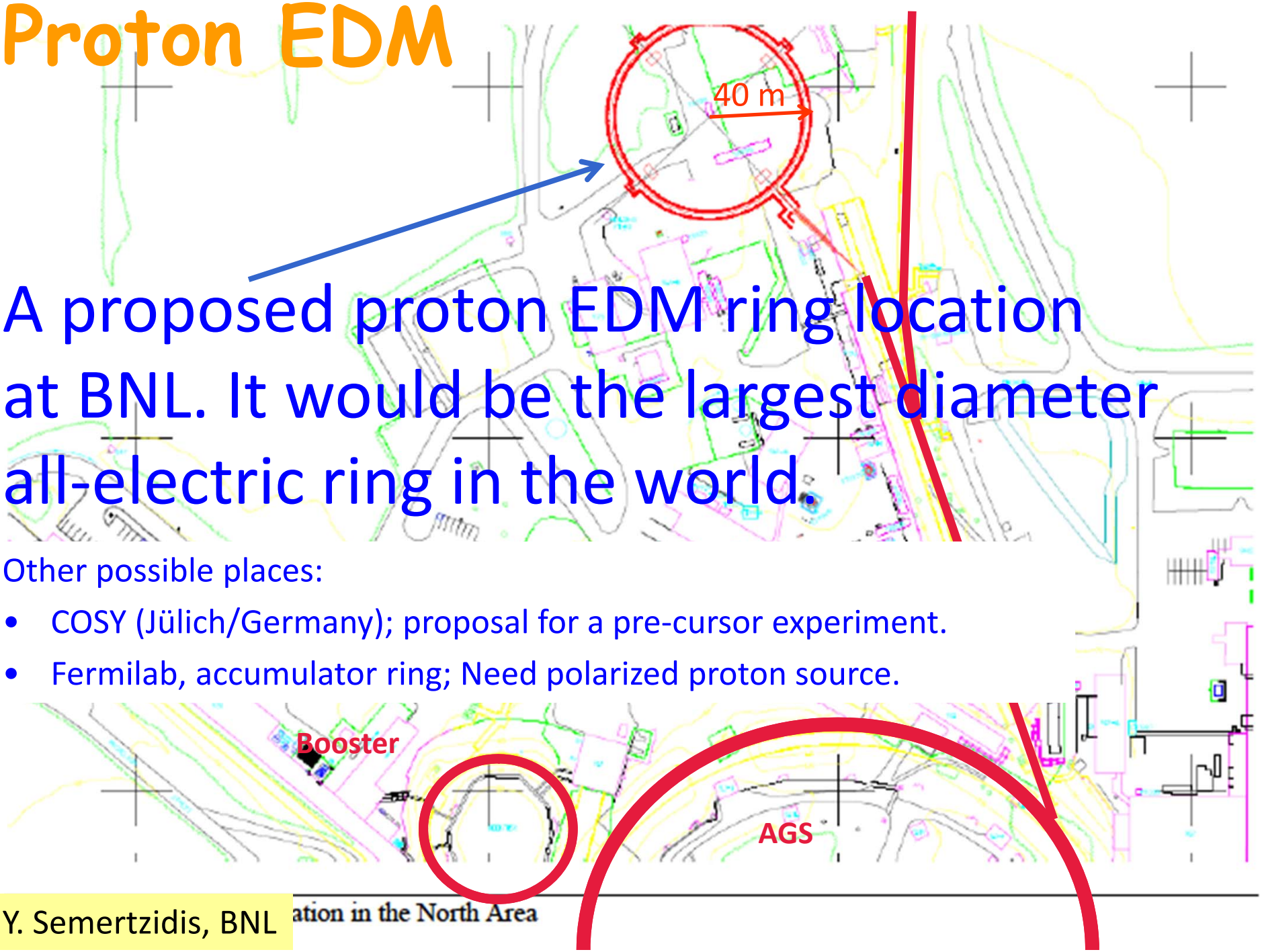
TRIUMF

Canada's National Laboratory for Particle and Nuclear Physics

Funding: NSF-Focus Center, DOE, NRC (TRIUMF), NSERC

Both ^{225}Ra and ^{223}Rn intensities can be greatly improved at FRIB

Proton EDM



A proposed proton EDM ring location at BNL. It would be the largest diameter all-electric ring in the world.

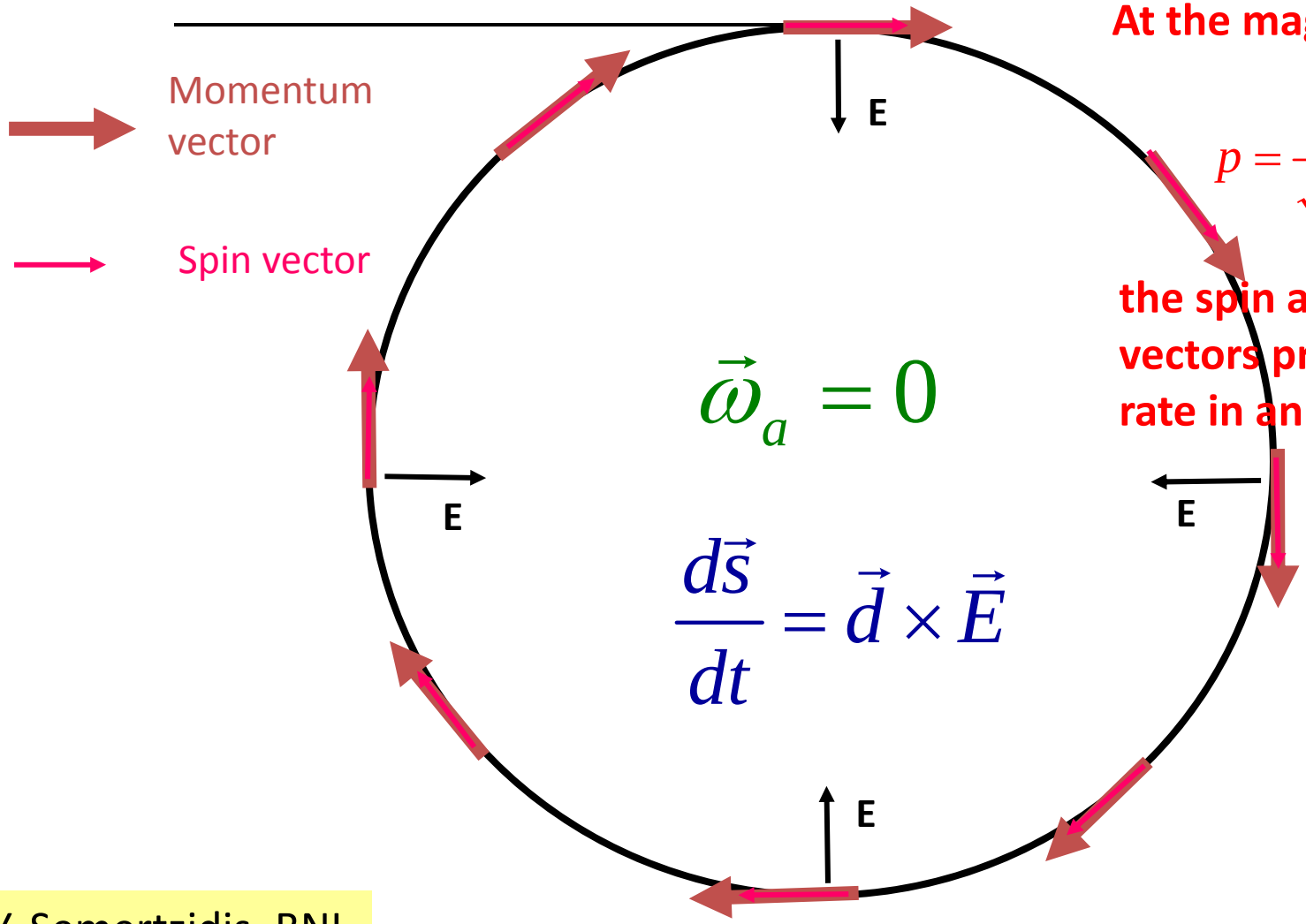
Other possible places:

- COSY (Jülich/Germany); proposal for a pre-cursor experiment.
- Fermilab, accumulator ring; Need polarized proton source.

Y. Semertzidis, BNL

Proton EDM

The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector



At the magic momentum

$$p = \frac{m}{\sqrt{a}} = 0.7 GeV / c$$

the spin and momentum vectors precess at same rate in an E-field

$$\vec{\omega}_a = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

Y. Semertzidis, BNL

Components of Storage Ring pEDM

1. Magic momentum (MM): **high intensity (10^{11})** pol. protons in an all-electric storage ring

2. High analyzing power: A>50% at the MM - p-C scattering

3. Weak vertical focusing in an all-electric ring: Spin Coherence Time allows for 10^3s beneficial storage; prospects for much longer SCT

4. Co-magnetometer: Counter-rotating beams. The beams vertical splitting tells the average radial B-field; the main systematic error source

Limits and Sensitivities

- 2020: 0.1 x 10^{-28} e-cm
- Ultimate: 0.01 x 10^{-28} e-cm

Estimated Cost ~ 100M$

Y. Semertzidis, BNL

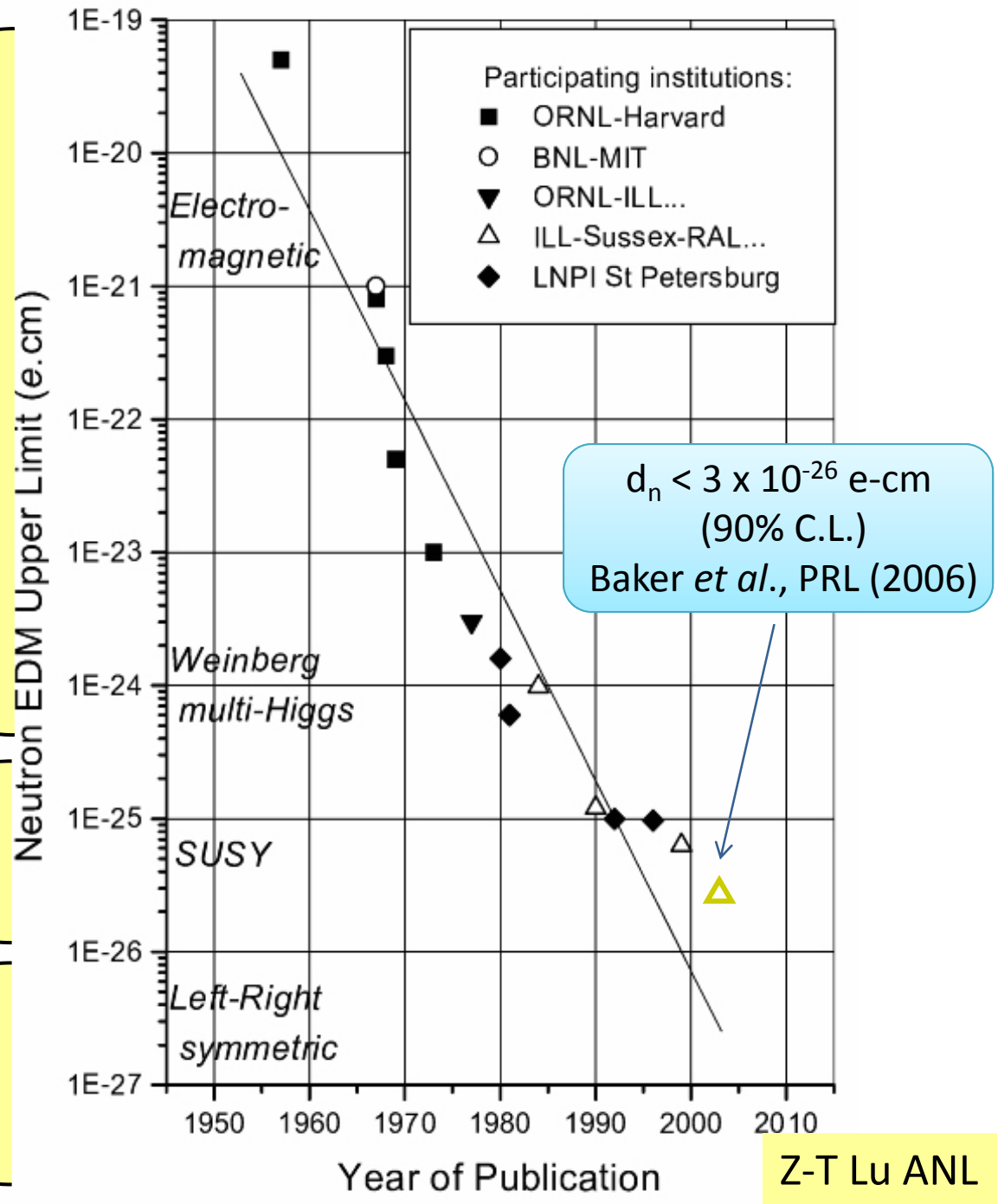
History of nEDM searches

Beam

$\Delta \mathbf{B} \approx \mathbf{v} \times \mathbf{E} / c^2$ limited

Stored UCN (ultra-cold neutrons)

Cryogenic UCN sources



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Next Generation nEDM Experiments

Cryogenic UCN source &
room temperature storage cells

- Intitut Laue-Langevin/PNPI
- Paul Scherrer Institute
- Munich reactor
- TRIUMF-Japan collaboration

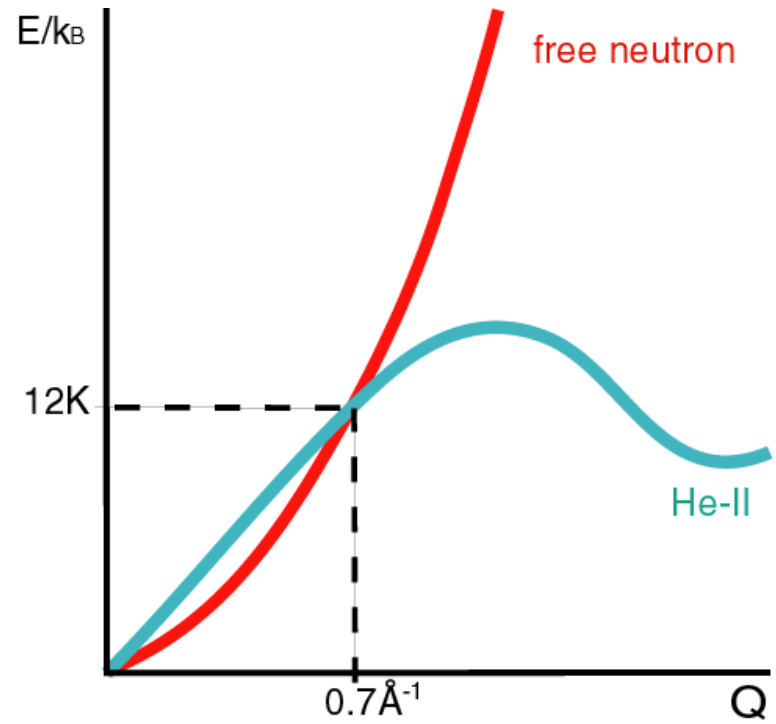
Super-fluid He source/storage cell

- Intitut Laue-Langevin, CyroEDM
- Spallation Neutron Source, nEDM

Limits and Sensitivities

- Current: 300 x 10^{-28} e-cm
- Next 5 years: 50 – 100 x 10^{-28} e-cm
- 2020 and beyond: 3 – 5 x 10^{-28} e-cm

Dispersion curves for He-II and free neutrons



Golub & Pendlebury, Phys. Lett. (1977)

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Worldwide nEDM experiments

Exp	UCN source	cell	Measurement techniques	σ_d (10^{-28} e-cm)
ILL CryoEDM	**Superfluid ^{4}He**	**^{4}He**	Ramsey technique for ω External SQUID magnetometers	**Phase1 ~ 50** **Phase 2 < 5**
PNPI – ILL	**ILL turbine** **PNPI/Solid D_2**	**Vac.**	Ramsey technique for ω $\vec{E}$=0 cell for magnetometer	**Phase1<100** **< 10**
ILL Crystal	**Cold n Beam**	**solid**	Crystal Diffraction	**< 100**
PSI EDM	**Solid D_2**	**Vac.**	Ramsey for ω, external Cs & $^3\vec{He}$ magnetom.Possible Xe or Hg comagnetometer	**Phase1 ~ 50** **Phase 2 < 5**
Munich FRMII	**Solid D_2**	**Vac.**	Under Construction (similar to PSI	**< 5**
SNS EDM	**Superfluid ^{4}He**	**^{4}He**	$^3\vec{He}$ capture for ω $^3\vec{He}$ comagnetometer SQUIDS & Dressed spins	**< 5**
TRIUMF	**Superfluid ^{4}He**	**Vac.**	Phase I @ RCNP	**< 10**
JPARC	**Solid D_2**	**Vac.**	Under Development	**< 5**
NIST	**Crystal**	**Solid**	R & D	**~ 5 ?**

The nEDM@SNS Collaboration

M. Ahmed[6], R. Alarcon[1], R. Allen[15], S. Baeßler[19], S. Balascuta[1,A], L. Bartoszek, D. Beck[9], J. Boissevain, D. Budker[4], M. Busch[6], R. Carr[5], P. Chu[6,C], V. Cianciolo[15], S. Clayton[11], M. Cooper[11,B], C. Crawford[10], C. Daurer, K. Dow[12], D. Dutta[13], M. Espy[11], B. Filippone[5,B], N. Fomin[11,C], H. Gao[6], G. Greene[17], C. Griffith[11,C], R. Golub[14,D], T. Gorringe[10], C. Gould[14], D. Haase[14], D. Hasell[12], A. Hawari[14], M. Hayden[16], E. Hazen[3], P. Huffman[14], E. Ihloff[12], T. Ito[11], M. Karcz[8,A], J. Kelsey[12], D. Kendellen[14,A], A. Kolarkar[3], E. Korobkina[14], W. Korsch[10], E. Leggett[13,A], C.-Y. Liu[8], I. Logashenko, J. Long[8], M. Makela[11], S. Malkowski[10,A], E. Martin[10,A], A. Matlashov[11], M. Mendenhall[5,A], H.O. Meyer[8], J. Miller[3], R. Milner[12], P. Mueller[15], E. Olivas[11], B.K. Park[4,A], C. Pena[5,A], J.-C. Peng[9], S. Penttila[15], A. Perez Galvan[5,C], G. Phelps[10,A], R. Picker[5,C], B. Plaster[10], S. Rahaman[11,C], J. Ramsey[11], R. Redwine[12], L. Roberts[3], R. Schmid[5,A], J. Seele[12,C], G. Seidel[2], I. Silvera[7], M. Snow[8], W. Sondheim[11], S. Stanislaus[18], C. Swank[14,A], G. Swift[6], E. Tsentalovich[12], C. Vidal[12], P. Volegov[11], D. Wagner[10,A], S. Williamson[9], W. Yao[15], Q. Ye[15,C], J. Yoder[11,C], A. Young[14], Y. Zhang[6,A], W.Z. Zheng[6,A]

Manpower is significant and probably sufficient (NSAC subcommittee)

[1] Arizona State University
[2] Brown University
[3] Boston University
[4] University of California, Berkeley
[5] California Institute of Technology
[6] Duke University
[7] Harvard University
[8] Indiana University
[9] University of Illinois, Urbana-Champaign
[10] University of Kentucky
[11] Los Alamos National Laboratory
[12] Massachusetts Institute of Technology
[13] Mississippi State University
[14] North Carolina State University
[15] Oak Ridge National Laboratory
[16] Simon Fraser University
[17] University of Tennessee
[18] Valparaiso University
[19] University of Virginia

[A] Graduate Student
[B] Co-spokesperson
[C] Postdoc
[D] Chief Scientist

Office of Nuclear Physics

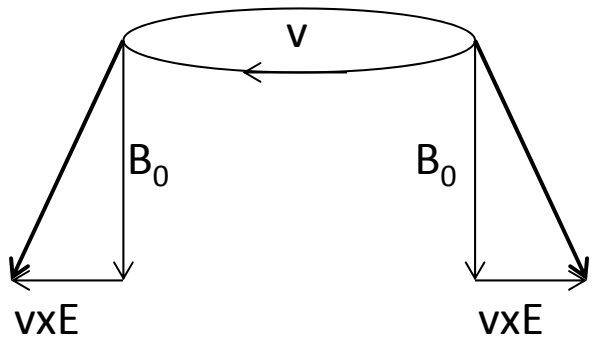
Key Features of SNS experiment

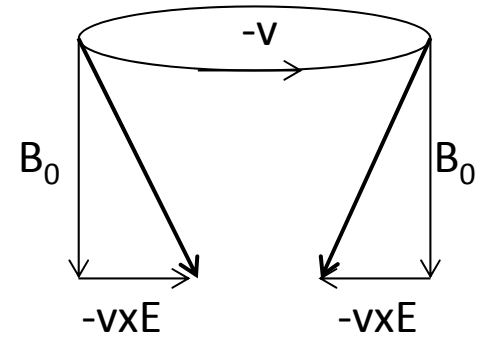
- Sensitivity: ~10^{-28} e-cm, 100 times better than existing limit
- Production of UCN in superfluid helium (no UCN transport)
- Polarized ^{3}He co-magnetometer
  - Also functions as neutron spin precession monitor via spin-dependent n-^{3}He capture cross section using wavelength-shifted scintillation light in the LHe
  - Ability to vary influence of external B-fields via "dressed spins"
    - Extra RF field allows control of n & ^{3}He relative precession frequency
  - Can study dependence on B-field, B-gradients & ^{3}He density
- Highly uniform E and B fields
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Control of central-volume temperature
  - Can vary ^{3}He diffusion (mfp) which greatly changes geometric phase effect on ^{3}He

Arguably the most ambitious of all neutron EDM experiments

Key Systematic Effect:

Geometric Phase Effect

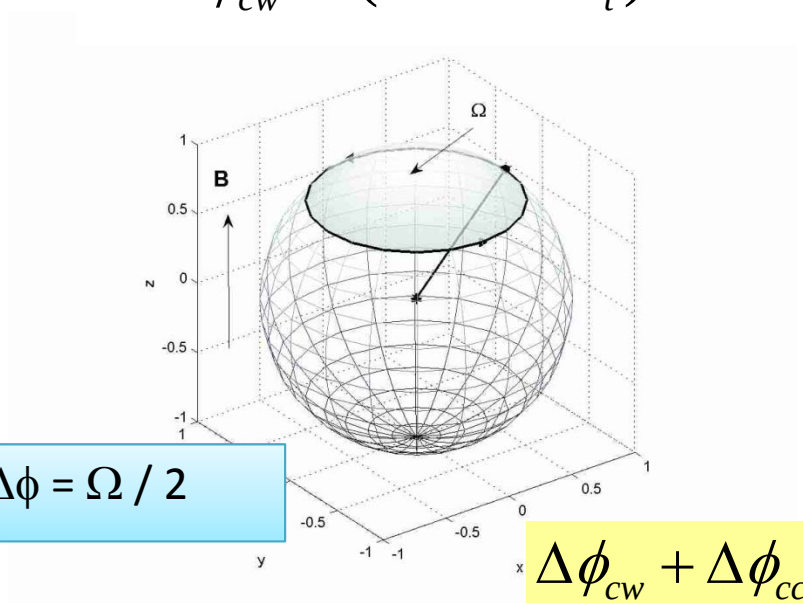




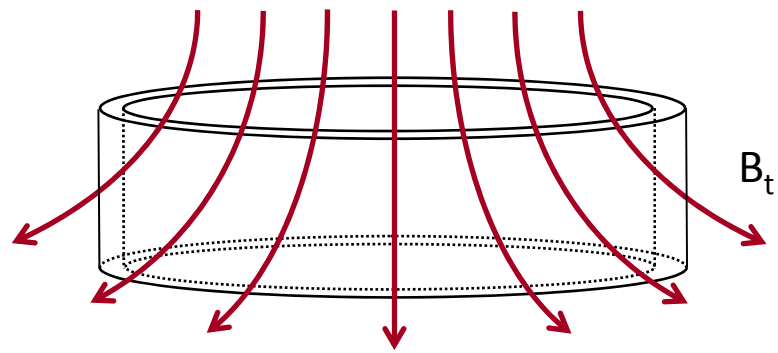
Pendlebury et al., PRA (2004)

$$\Delta\phi_{cw} \propto (\mathrm{v}\times E + B_t)^2$$

$$\Delta\phi_{ccw} \propto -(-\mathrm{v}\times E + B_t)^2$$



$\Delta\phi = \Omega / 2$



$$\Delta\phi_{cw} + \Delta\phi_{ccw} \propto 2\cdot \mathrm{v}\times E\cdot B_t$$

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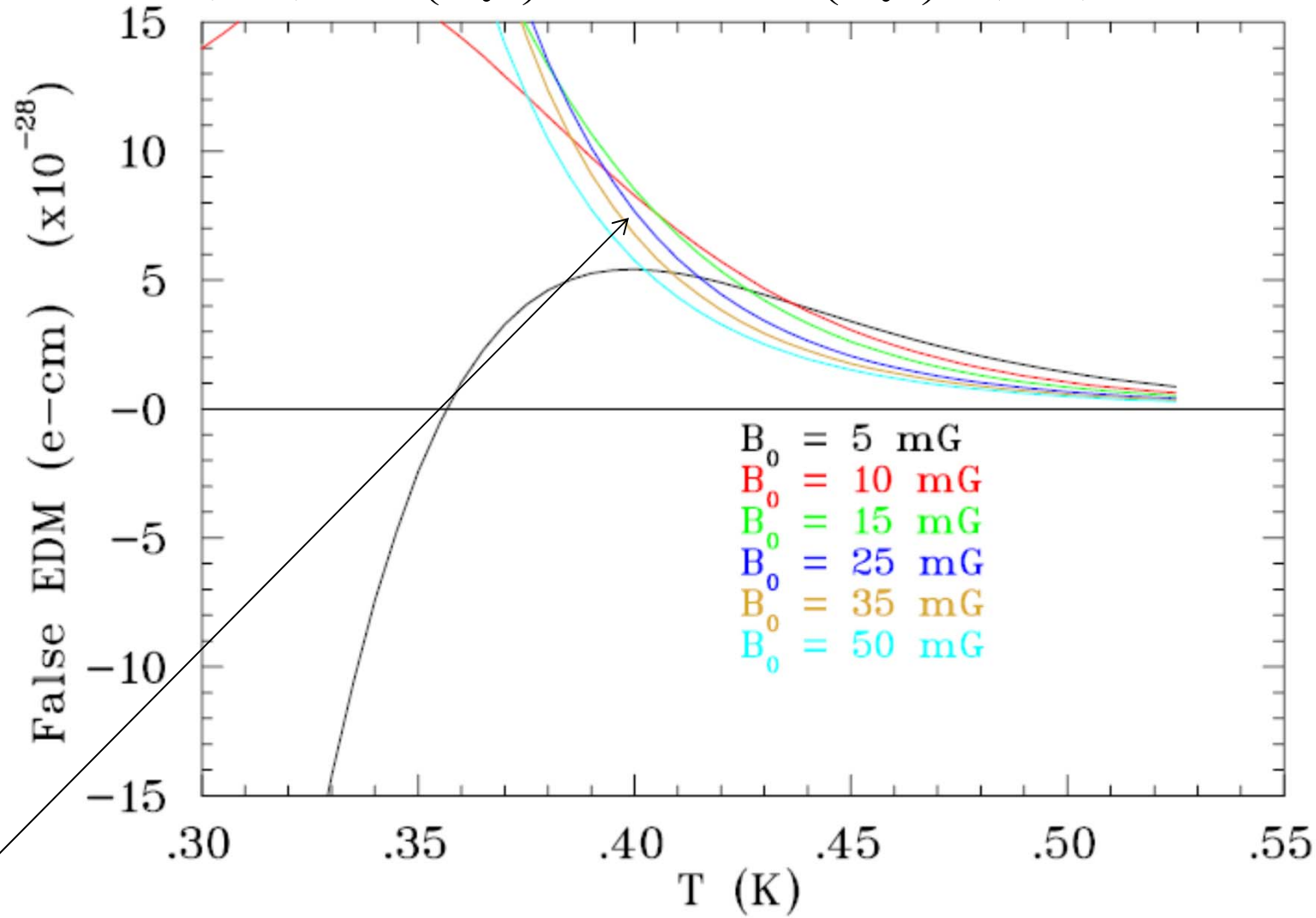
e.g. - Geometric phase effect for ^{3}He

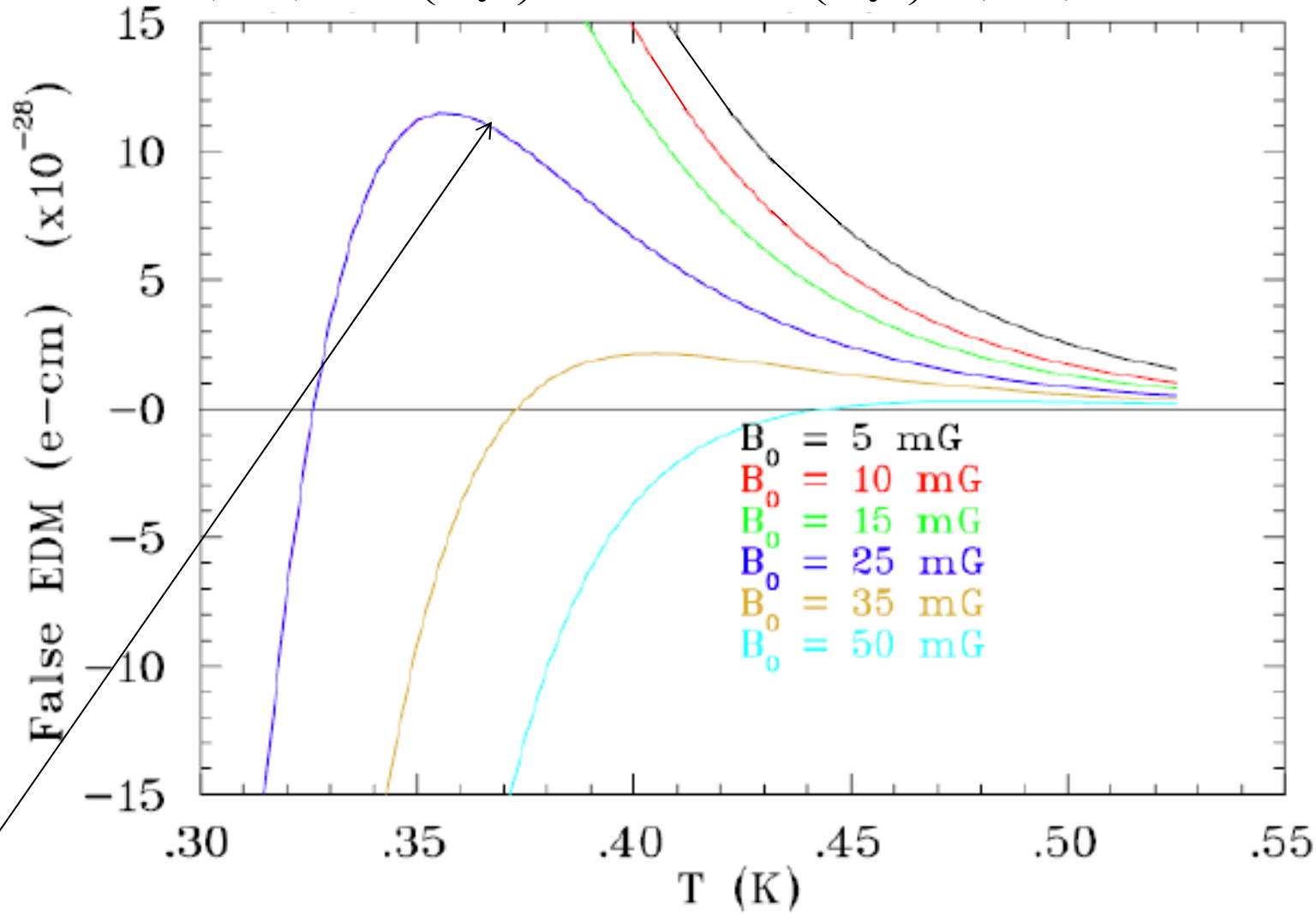
$$\left(\frac{\partial \mathbf{B}_z}{\mathbf{dz}}\right) = -\left(\frac{\partial \mathbf{B}_y}{\mathbf{dy}}\right) \; ; \; \textit{Assuming} \; \left(\frac{\partial \mathbf{B}_y}{\mathbf{dy}}\right), \left(\frac{\partial \mathbf{B}_z}{\mathbf{dz}}\right) \propto \mathbf{B}_0$$



Strong temperature dependence!

e.g. - Geometric phase effect for ^{3}He

$$\left(\frac{\partial \mathbf{B}_z}{\mathbf{dz}}\right) = +\left(\frac{\partial \mathbf{B}_y}{\mathbf{dy}}\right) \; ; \; \textit{Assuming} \; \left(\frac{\partial \mathbf{B}_y}{\mathbf{dy}}\right), \left(\frac{\partial \mathbf{B}_z}{\mathbf{dz}}\right) \propto \mathbf{B}_0$$



Strong temperature dependence!

Status & Timeline

Recent NSAC (Nuclear Science Advisory Committee) Subcommittee on Fundamental Nuclear Physics with Neutrons (report 11/11)

Motivation remains Strong

"The successful completion of an nEDM experiment, the initiative with the highest scientific priority in US neutron science, would represent an impressive scientific and technical achievement for all of nuclear physics, with ramifications that extend far beyond the field."

Sensitivity Remains Compelling

- **nEDM conceptual design is novel**
  - *large active volume: gain statistical sensitivity to* $1\text{-}10 \times 10^{-28}$ *e-cm*
  - *several novel techniques to explore unknown new systematics*
  - *only concept aimed directly at exploring a new regime of sensitivity*
- **nEDM reach is nominally estimated at** 4×10^{-28} **e-cm**
  - *such reach would have profound impact beyond subfield even if negative*

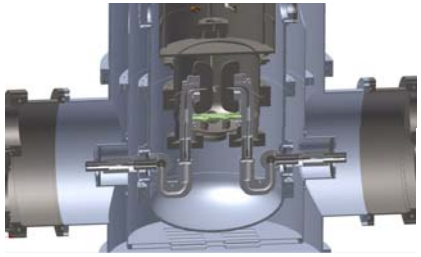
But …

A 2-year window is proposed to allow collaboration to complete critical R&D prior to starting construction (main focus is HV studies)

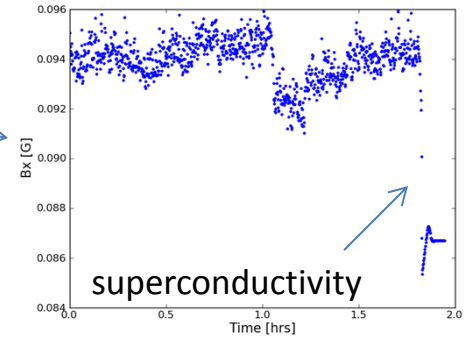
Construction can then begin (~ 4-5 years required)

"A Singular focus on Outstanding R&D Issues"

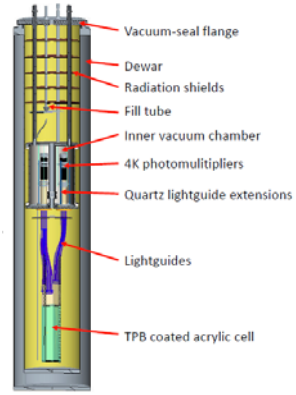
- HV strength & electrode materials



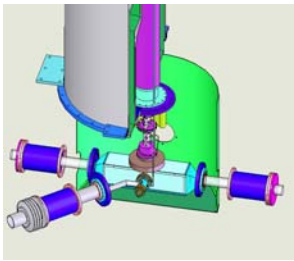
- Magnetic field uniformity & Superconducting shielding studies



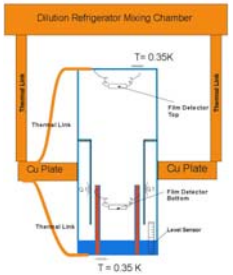
- Light collection from scintillation



- Development of polarized UCN & ^{3}He test facility



- ^{3}He transport studies



- & SQUID development & UCN storage studies

Have completed 3 reviews by external review commitee

Overall Cost Estimate for nEDM@SNS

nEDM Estimated Construction Profile ($M)										
	< FY14	FY14	FY15	FY16	FY17	FY18	FY19	FY20	FY21	Total
Estimated Spending Profile (DOE+NSF)	13.5	3.9	11.7	7.4	6.0	3.6	2.1	1.9	0.3	50.0
Funding (Flat-flat at FY13 levels)	13.5	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	23.5
Difference	0.0	-2.6	-10.4	-6.1	-4.7	-2.3	-0.8	-0.6	1.0	-26.5
Cumulative Difference	0.0	-2.6	-13.0	-19.1	-23.8	-26.1	-26.9	-27.5	-26.5	

- R&D funded for next 18 months via capital $$, program funds & carry-over
- Construction costs to complete hardware:

  ~ 40M$ → this is ~ 30M$ above flat-flat $$

Comparison of Capabilities

	CRYOEDM1	CRYOEDM2	PSIEDM1	PSIEDM2	SNSEDM	
$\Delta\omega$ via accumulated phase in n polarization	■	■	■	■	■	
$\Delta\omega$ via light oscillation in ^{3}He capture	■	■	■	■	■	
Co-magnetometer	■	■	■	■	■	★
Superconducting B-shield	■	■	■	■	■	★
Dressed Spin Technique	■	■	■	■	■	★
Horizontal B-field	■	■	■	■	■	
Multiple EDM cells	■	■	■	■	■	★
Temperature Dependence of Geo-phase effect	■	■	■	■	■	★

■ = included ■ = not included ★ = systematics advantage

Longer term Prospects (>2020):

- Fermilab Project X may be an upgrade path for higher neutron density $\delta d_n \propto 1/\sqrt{N_n}$
- Once systematics have been studied at ORNL pushing statistics to $\delta d_n < 1 \cdot 10^{-28}$ e-cm may be possible

Summary of Hadronic EDM Searches via Nucleons and Nuclei

EDM units: 1 x 10^{-28} e-cm

Sector	Experiment	Current Limit	5-year goal	Beyond 2020	Standard Model	d_n Equivalent (x 10^{-28} e-cm)
Neutron	UCN general	300	50 – 100	<3 – 5	0.001	< 3
Neutron	SNS nEDM			<3	0.001	< 3
Proton	BNL Storage ring	8,000*		0.01 – 0.1	0.001	< .1 - < .01
Nucleus	Seattle ^{199}Hg cell	0.3	0.03	0.006	0.000,01	< 6
Nucleus	ANL ^{225}Ra trap		10 – 100	1	0.01	< 1
Nucleus	Michigan ^{223}Rn cell			2	0.01	< 2

* Indirect limit derived from the ^{199}Hg measurement.

Model Dependent!

Z-T Lu ANL

Take Away Message …

- Importance of greatly improving EDM sensitivity is recognized worldwide
- A number of exciting technologies are being developed to extend the EDM sensitivity by at least two orders-of-magnitude as well as characterize its origins (should it be found)
- US is poised to be a world-leader in high-sensitivity searches for EDMs