Baryogenesis

- **Plausibility Argument** (GUTS Baryogenesis)
  - Consider very heavy boson X ($M_X \sim 10^{19}$ GeV)
    - Baryon number violation:

$$\begin{array}{ll} X \to qq & X \to ql \\ \overline{X} \to \overline{q}\,\overline{q} & \overline{X} \to \overline{q}\,\overline{l} \end{array}$$

    - C & CP violation

$$\Gamma_{X\to qq} = (1+\Delta_q)\Gamma_q; \quad \Gamma_{X\to ql} = (1-\Delta_l)\Gamma_l$$

$$\Gamma_{\overline{X}\to\overline{q}\,\overline{q}} = (1-\Delta_q)\Gamma_q; \quad \Gamma_{\overline{X}\to\overline{q}\,\overline{l}} = (1+\Delta_l)\Gamma_l$$

$$\textbf{but} \quad \Gamma_X^{Tot} = \Gamma_{\overline{X}}^{Tot} \quad \textbf{(CPT conservation)}$$

    - Out of Thermal Equilibrium

If in Equilibrium then the reverse reactions (e.g. $qq \to X,\quad \overline{q}\,\overline{q} \to \overline{X}$) will smooth out any matter/antimatter excess

Origin of 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 at first order
  - Need at least two "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 $\sim 10^{-32}$ e-cm (=10^{-19} e-fm)

Electron EDM in Standard Model is $< 10^{-40}$ e-cm

Origin of EDMs

- Quark EDMs lead to hadronic EDMs (neutrons or diamagnetic atoms)

↳ All e^- paired-up

- Electron EDMs lead to atomic EDMs in paramagnetic atoms

↳ One unpaired e^-

- Nuclear searches are in hadrons

Origin of Hadronic EDMs

- **Hadronic (strongly interacting particles) EDMs are from**
  - θ_{QCD} (a special parameter in Quantum Chromodynamics – QCD)

  - or from the quarks themselves

EDM from θ_{QCD}

- θ_{QCD} **results from CP-odd term is** L_{QCD}

$$L_{QCD} = -\theta\left(\frac{\alpha_s}{8\pi}\right)\tilde{G}^{\mu\nu}_{a}G^{a}_{\mu\nu}$$

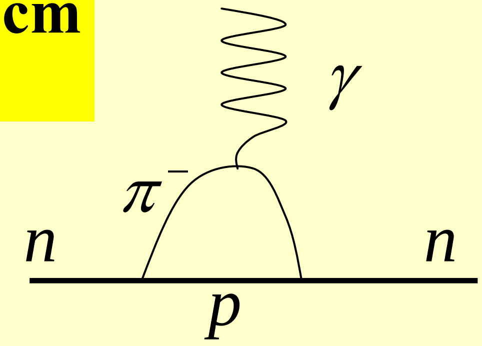
  - θ_{QCD} should be naturally about ~ 1
- **This gives an "effective" neutron EDM of**

$$d_n = \frac{g_{\pi NN}}{4\pi^2}\left(\frac{e}{m_p f_\pi}\right)\ln\left(\frac{m_\rho}{m_\pi}\right)\left(\frac{m_u m_d}{m_u + m_d}\right)\theta \approx (-10^{-15})\theta\ \mathrm{e\text{-}cm}$$

but $d_n^{\mathrm{exp}} < 10^{-25}$ e-cm

$\therefore\ \theta < 10^{-10}$

Why so small??



EDM from θ_{QCD}

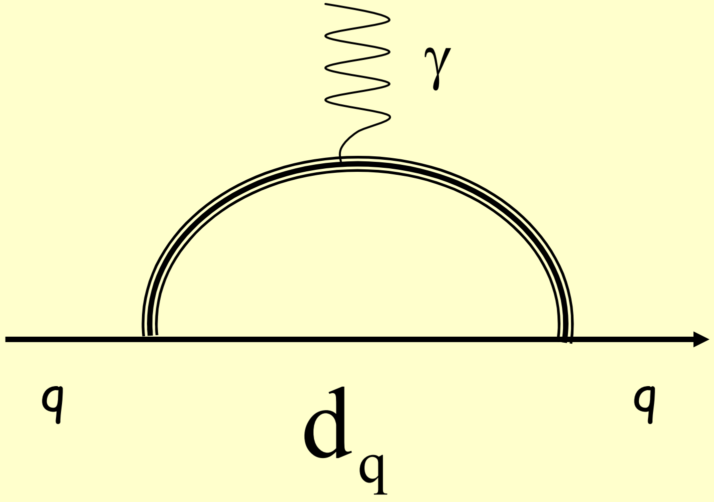
- **This is the Strong CP problem in QCD**

- **Small θ_{QCD} does not provide any new symmetry for L_{QCD}**
  - – Popular solution is "axions" (Peccei-Quinn symmetry) – new term in L_{QCD}
    - No Axions observed yet
  - – Extra dimensions might suppress θ_{QCD}

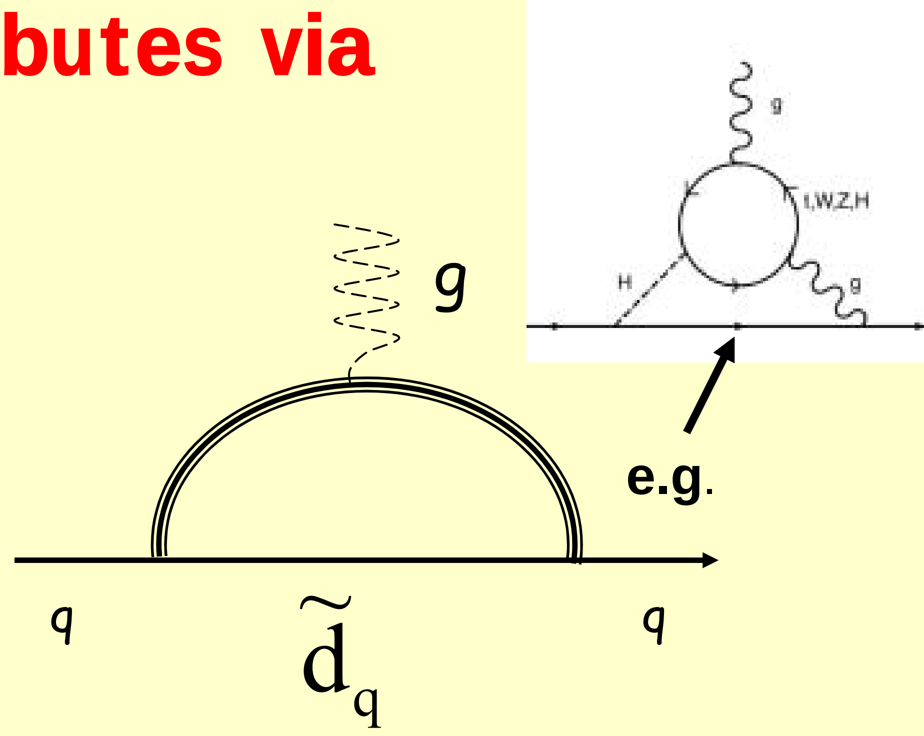
    (Harnik et al arXiv:hep-ph/0411132)
  - – Remains an unsolved theoretical "problem"

Hadronic EDM from Quarks

- Quark EDM contributes via



Quark EDM



Quark ChromoEDM

but $d_n^{\text{Standard Model}} < 10^{-31}$ e-cm
recall $d_n^{\exp} < 10^{-25}$ e – cm

Note: $d_n \cong 0.7(d_d - \frac{1}{4}d_u) + 0.6(\tilde{d}_d + \frac{1}{2}\tilde{d}_u)$
$d_{{}^{199}\text{Hg}} \cong 0.007(\tilde{d}_d - \tilde{d}_u)$

Physics Beyond the Standard Model

- **New physics (e.g. SuperSymmety = SUSY) has additional CP violating phases in added couplings**
  - New phases: (ϕ_{CP}) should be ~ 1 (why not?)
- **Contributions to EDMs depends on masses of new particles** $d_n \propto \frac{\sin\phi_{CP}}{M_{SUSY}^2}$
  - In MSSM (Minimal Supersymmetric Standard Model)

$$\mathbf{d_n \sim \left(\frac{200\,GeV}{M_{SUSY}}\right)^2 \times 10^{-25}\ e-cm}$$

Possible impacts of non-zero EDMs

- **Must be new Physics**

  (at proposed sensitivities)

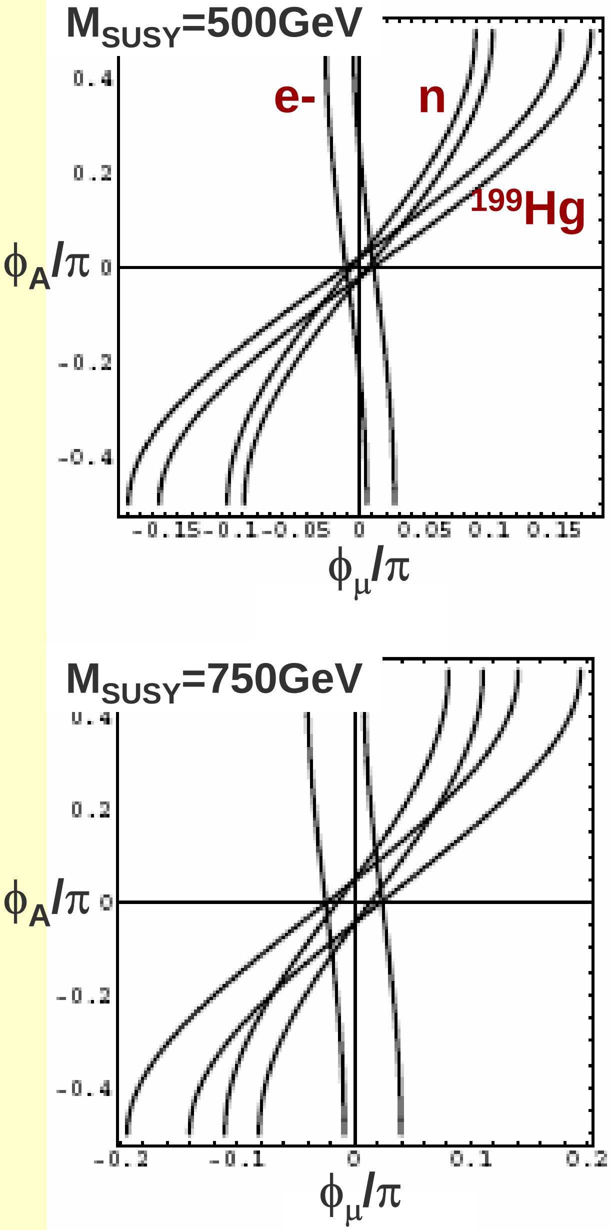
- **Sharply constrains models beyond the Standard Model**

  (especially *with* LHC data)

  Large Hadron Collider

- **May account for matter-antimatter asymmetry of the universe**

  (via ElectroWeak Baryogenesis)



From Pospelov et al for CMSSM

EDM Measurements

particle	Present Limit (90% CL) (e-cm)	Laboratory	Possible Sensitivity (e-cm)	Standard Model (e-cm)
e^- (Tl)	**1.6×10^{-27}**	**Berkeley**		
e^- (PbO)		**Yale**	**10^{-29}**	**$<10^{-40}$**
e^- (YbF)		**Sussex**	**10^{-29}**	
e^- (GGG)		**LANL/Indiana**	**10^{-30}**	
μ	**9.3×10^{-19}**	**CERN**		**$<10^{-36}$**
μ		**BNL**	**$<10^{-24}$**	
n	**6.3×10^{-26}**	**ILL**	**1.5×10^{-26}**	
n		**ILL**	**$\sim 2 \times 10^{-28}$**	**$\sim 10^{-32}$**
n		**PSI**	**$\sim 7 \times 10^{-28}$**	
n		**SNS**	**$< 1 \times 10^{-28}$**	
^{199}Hg	**1.9×10^{-27}**	**Seattle**	**5×10^{-28}**	**$\sim 10^{-33}$**
^{129}Xe		**Princeton**	**10^{-31}**	**$\sim 10^{-34}$**
^{225}Ra		**Argonne**	**10^{-28}**	
^{223}Rn		**TRIUMF**	**1×10^{-28}**	
d		**COSY/JPARC?**	**$<10^{-27}$**	

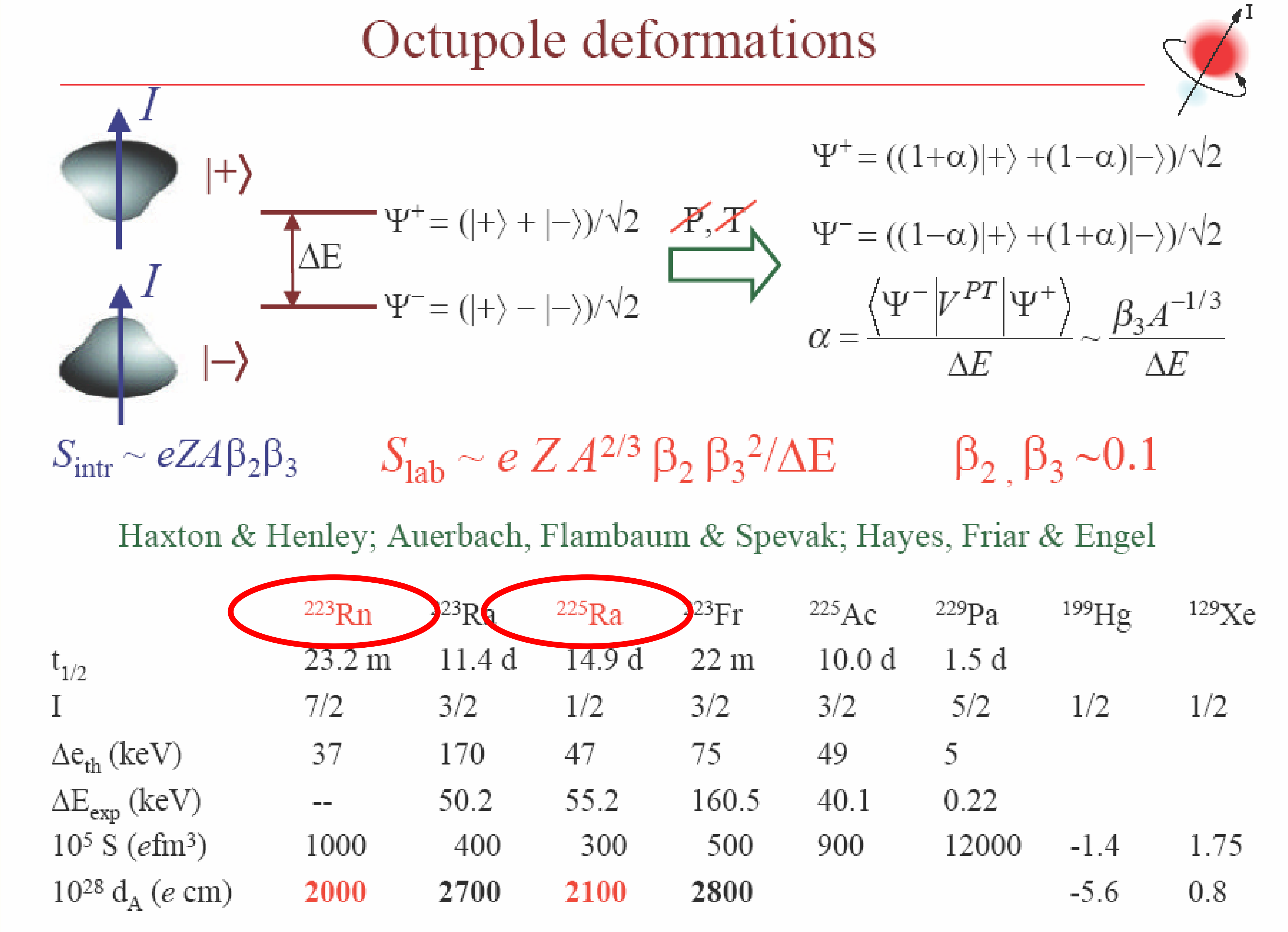
New Nuclear EDM Techniques

- Accelerator production of radioactive diamagnetic atoms
  (probes hadronic EDMs)

- Charged particles in storage rings

- Superthermal sources of Ultra-Cold Neutrons

Enhanced Atomic EDM via Octupole deformations



Octupole deformations

I

$|+\rangle$

I

$|-\rangle$

ΔE

$$\Psi^{+} = (|+\rangle + |-\rangle)/\sqrt{2}$$

$$\Psi^{-} = (|+\rangle - |-\rangle)/\sqrt{2}$$

$$\cancel{P}, \cancel{T} \Rightarrow$$

$$\Psi^{+} = ((1+\alpha)|+\rangle + (1-\alpha)|-\rangle)/\sqrt{2}$$

$$\Psi^{-} = ((1-\alpha)|+\rangle + (1+\alpha)|-\rangle)/\sqrt{2}$$

$$\alpha = \frac{\langle \Psi^{-} | V^{PT} | \Psi^{+} \rangle}{\Delta E} \sim \frac{\beta_3 A^{-1/3}}{\Delta E}$$

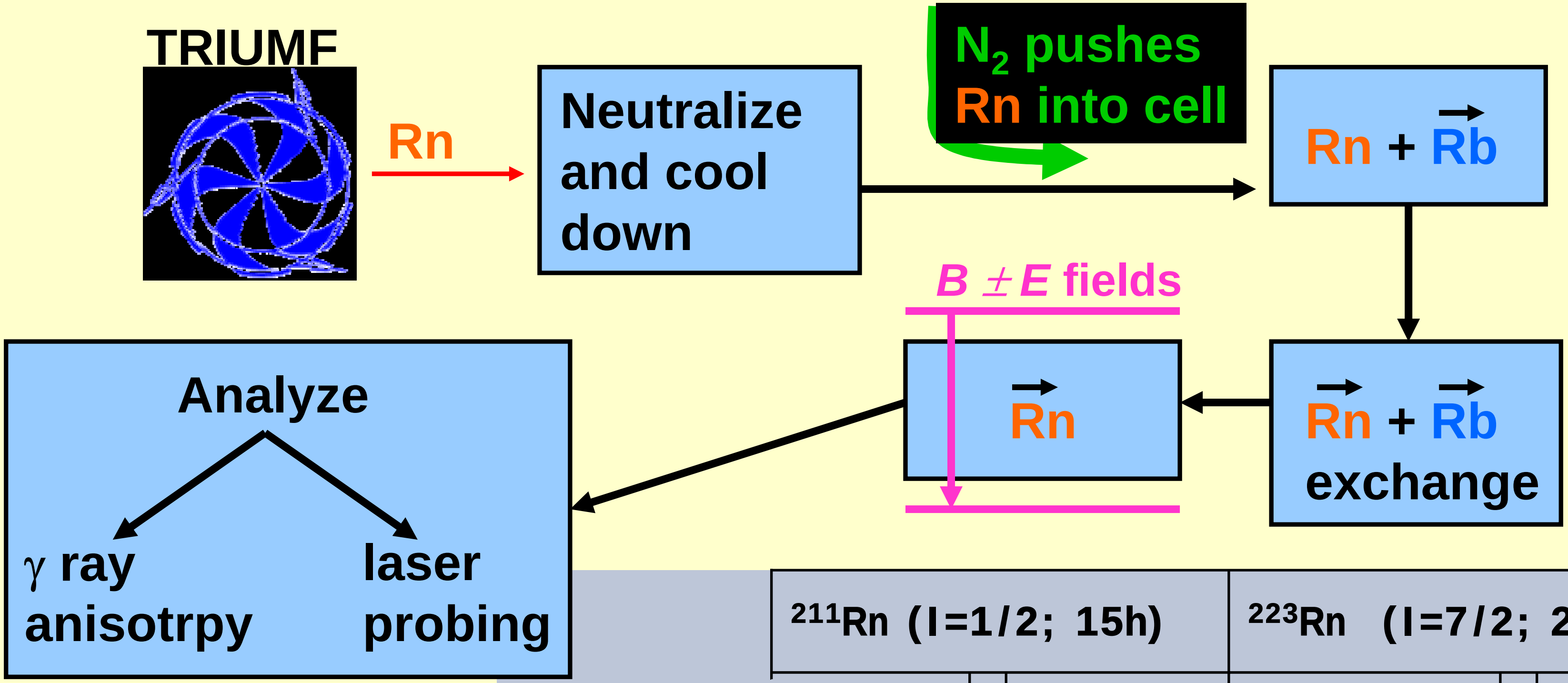
$S_{\text{intr}} \sim eZA\beta_2\beta_3$ $\quad S_{\text{lab}} \sim e\,Z\,A^{2/3}\,\beta_2\,\beta_3^{2}/\Delta E$ $\quad \beta_2, \beta_3 \sim 0.1$

Haxton & Henley; Auerbach, Flambaum & Spevak; Hayes, Friar & Engel

	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{225}Ac	^{229}Pa	^{199}Hg	^{129}Xe
$t_{1/2}$	23.2 m	11.4 d	14.9 d	22 m	10.0 d	1.5 d		
I	7/2	3/2	1/2	3/2	3/2	5/2	1/2	1/2
Δe_{th} (keV)	37	170	47	75	49	5		
ΔE_{exp} (keV)	--	50.2	55.2	160.5	40.1	0.22		
10^5 S ($e$fm^3)	1000	400	300	500	900	12000	-1.4	1.75
10^{28} d_A (e cm)	**2000**	**2700**	**2100**	**2800**			-5.6	0.8

EDM in Rn

Spokesmen: Timothy Chupp[2] and Carl Svensson[1]
Sarah Nuss-Warren[2], Eric Tardiff[2], Kevin Coulter[2], Wolfgang Lorenzon[2], Timothy Chupp[2]
John Behr[4], Matt Pearson[4], Peter Jackson[4], Mike Hayden[3], Carl Svensson[1]
University of Guelph[1], University of Michigan[2], Simon Fraser University[3], TRIUMF[4]



TRIUMF

Rn

Neutralize and cool down

N_2 pushes Rn into cell

Rn + $\overrightarrow{\text{Rb}}$

$B \pm E$ fields

$\overrightarrow{\text{Rn}}$

$\overrightarrow{\text{Rn}}$ + $\overrightarrow{\text{Rb}}$ exchange

Analyze

γ ray anisotrpy

laser probing

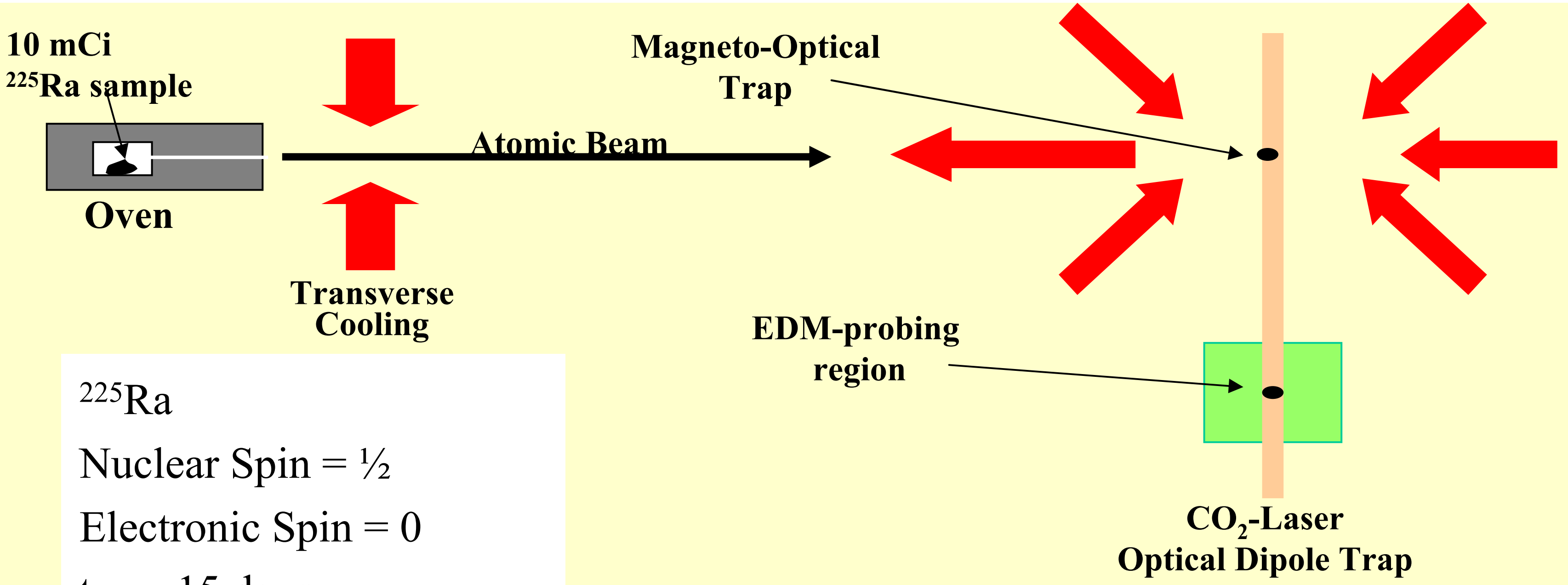
	^{211}Rn (I=1/2; 15h)			^{223}Rn (I=7/2; 23 m)		
						σ_d (√day)
TRIUMF	$2\text{x}10^{9}$		$6\text{x}10^{-29}$	$1\text{x}10^{7}$		$2\text{x}10^{-27}$
RIA	$1\text{x}10^{10}$	1	$3\text{x}10^{-29}$	$5\text{x}10^{8}$		$1\text{x}10^{-28}$

EDM with Trapped Radium Atoms

Irshad Ahmad, Roy J. Holt, Zheng-Tian Lu, Elaine C. Schulte, Physics Division, Argonne National Laboratory

Advantages of an EDM measurement on ^{225}Ra atoms in a trap

- In ^{225}Ra the EDM effect is enhanced by two orders of magnitude due to nuclear quadrupole and octupole deformation.
- Trap allows a long coherence time (~ 300 s).
- Cold atoms result in a negligible "v x E" systematic effect.
- Trap allows the efficient use of the rare and radioactive ^{225}Ra atoms.
- Small sample in an UHV allows a high electric field (> 100 kV/cm).



10 mCi ^{225}Ra sample

Oven

Transverse Cooling

Atomic Beam

Magneto-Optical Trap

EDM-probing region

CO_2-Laser Optical Dipole Trap

^{225}Ra

Nuclear Spin = ½

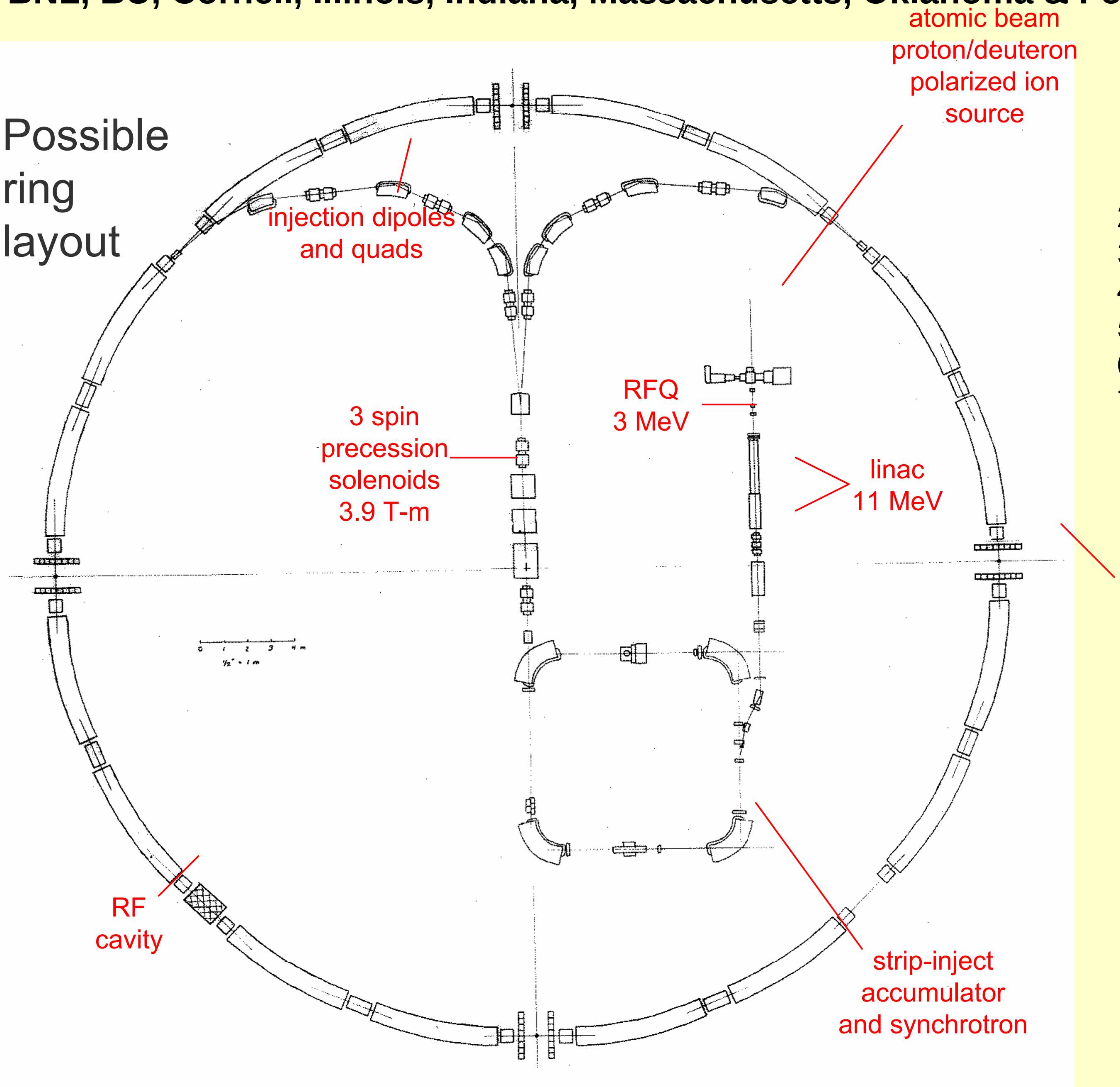
Electronic Spin = 0

$t_{1/2}$ = 15 days

Deuteron (and Muon) EDM in Storage Ring

BNL, BU, Cornell, Illinois, Indiana, Massachusetts, Oklahoma & Foreign Institutions

Possible ring layout



Example
for ring:

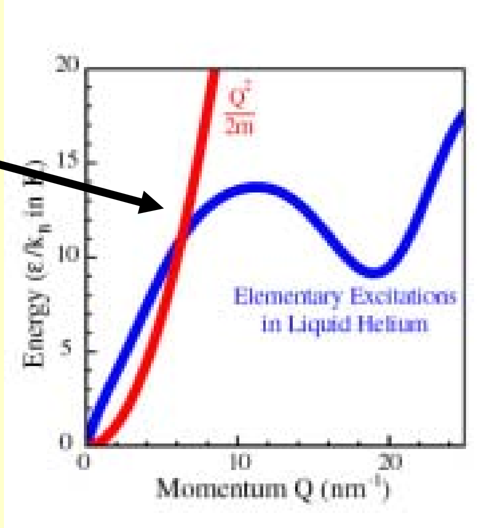
1. polarized ion source
2. pre-accelerator
3. accumulator
4. accelerator
5. spin preparation
6. injection
7. EDM ring

Ring Properties:

E = 3.5 MV/m
B = 2.1 kG
T(d) = 126 MeV
p = 0.7 GeV/c
β = 0.35
γ = 1.07
dipole radius
= 13.3 m

New Techniques for n-EDM:

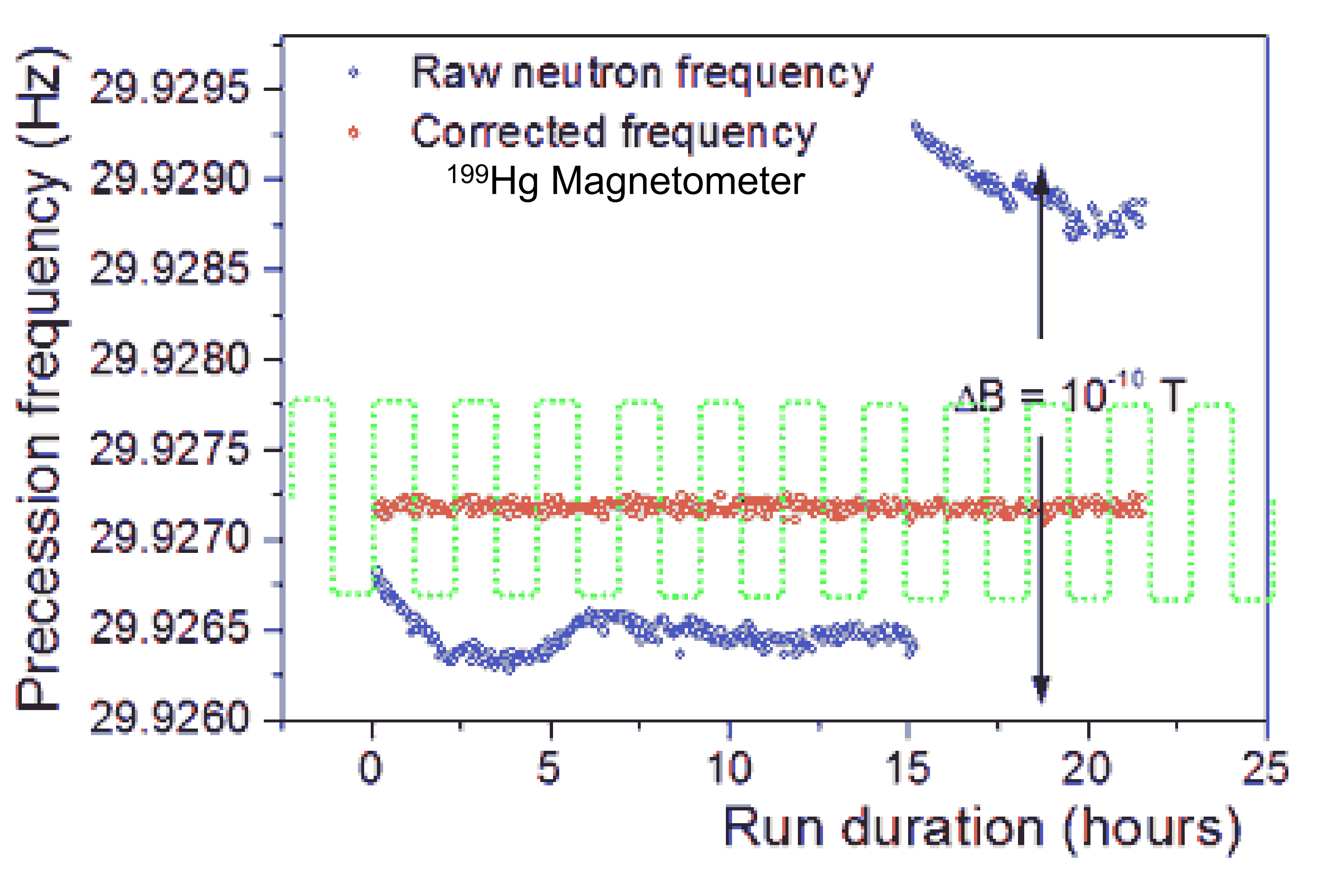
- Use Superthermal (non-equilibrium) system to produce UCN
  - Superfluid 4He can yield ~1000 more UCN than conventional UCN source



8.9$\overset{0}{\mathrm{A}}$ incident n produces roton & becomes UCN

- Higher Electric fields in ^{4}He
  - Breakdown voltage may be 10x vacuum breakdown
- ^{3}He comagnetometer measures B-field at same location as neutrons
  - *Very* small amount of ^{3}He in ^{4}He
  - Use SQUIDs to measure ^{3}He precession – calibrates B-field since $\omega_3 \propto |\vec{B}|$
- $\vec{n} + {}^3\vec{\mathrm{He}} \Rightarrow t + p$ has $\sigma_{\uparrow\downarrow} >> \sigma_{\uparrow\uparrow}$
  - Detect capture via scintillation of ^{4}He
    - Same technique as NIST LHe τ_n measurement
      (UV photons converted to visible in tetraphenyl butadiene - TPB)
    - Measures difference of ω_n and ω_3
- "Dressed" spin technique suppresses sensitivity to fluctuations in B-field

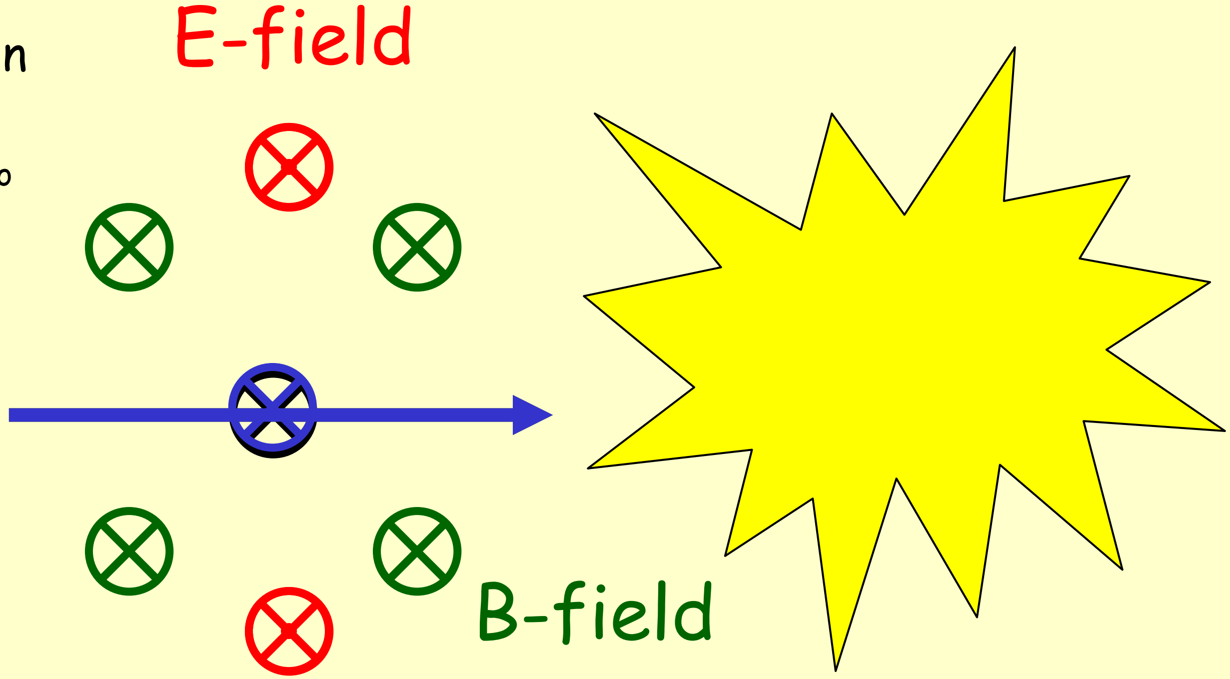
Careful magnetometry is essential !



New Technique for n-EDM

1. Inject polarized neutron & polarized ^{3}He
2. Rotate both spins by 90°
3. Measure n+^{3}He capture vs. time

   (note: $\sigma_{\downarrow\uparrow} >> \sigma_{\uparrow\uparrow}$)
4. Flip E-field direction



^{3}He functions as “co-magnetometer”

EDM Statistical Sensitivity

	EDM @ ILL	**EDM @ SNS**
N_{UCN}	1.3×10^4	2×10^6
$\lvert\vec{E}\rvert$	10 kV/cm	50 kV/cm
T_m	130 s	500 s
m (cycles/day)	270	50
σ_d **(e-cm)/day**	3×10^{-25}	3×10^{-27}
SNR (signal noise ratio)	1	1

$$\sigma_d \cong \frac{(1 + 1/SNR)\hbar}{2\,|\vec{E}|\,T_m\sqrt{mN_{UCN}}}$$

Systematic Effects in EDM

- **Nonuniformity of B-field and E-field**
  - Comagnetometer monitors B-field variations
- **Leakage currents from Electric Field**
  - These produce B-fields that change with E-field (must be less than picoAmps)
- **Gravitational offset of n and ^{3}He** (~ 10^{-29} e-cm)
- $\vec{v} \times \vec{E}$ **effects are the largest sources of systematic error in present ILL exp.**
  - $\vec{B}_E = \vec{v} \times \vec{E}$ → changes $\vec{\mu}$ precession frequency
  - Geometric phase due to $\vec{B}$ gradients

Systematic Controls in new EDM experiment

- Highly uniform E and B fields
  - Cosθ coil in Ferromagnetic shield
  - Kerr effect measurement of E-field
- Two cells with opposite E-field
- Ability to vary influence of B_0 field
  - via dressed spins
- Control of central temperature
  - Can vary ^{3}He diffusion

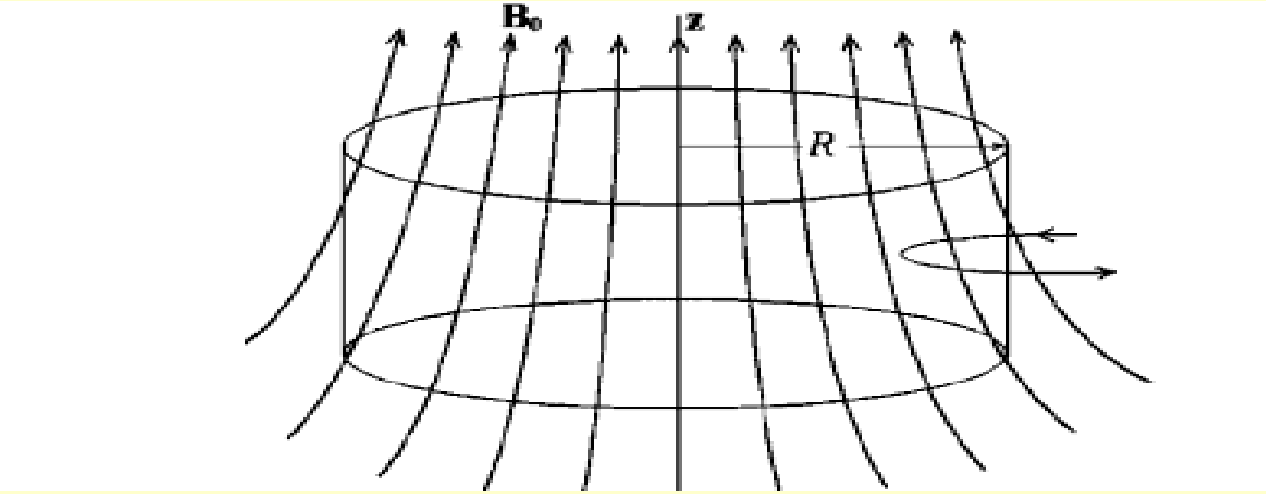
Geometric Phase

- **Path-dependent phase (no $\hbar$)**
  - E.g. Parallel transport of vector on sphere

- **In Quantum Mechanics often called Berry's phase**

False EDM from Geometric phase

- Pendlebury et al PRA 70 032102 (04)
- Lamoreaux and Golub nucl-ex/0407005
- Geometric phase gives false EDM's that depend strongly on radial B fields perpendicular to B_0
  - These result from dB_0/dz

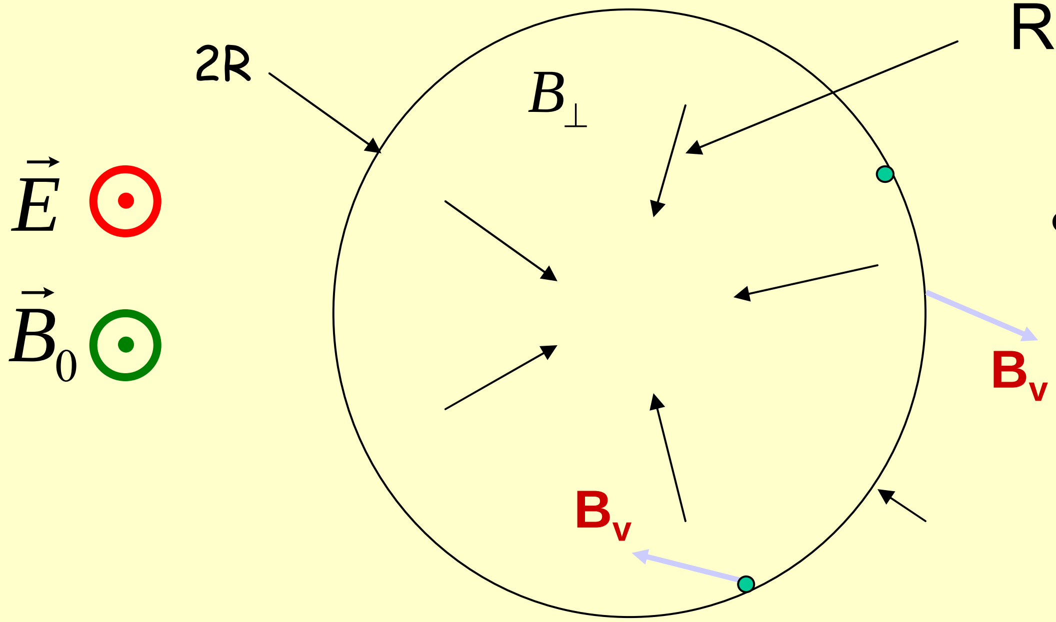


Geometric phase contributions

- Gradients and **vxE** field gives d^{false}
- Impacts neutron and ^{3}He
- Magnetometers (^{199}Hg & ^{3}He) pick up phase at different rate due to higher velocities
  - Can be reduced by frequent collisions with buffer gas or phonons
    - if collision rate $\dfrac{\mathbf{v}_{\mathbf{rms}}}{\lambda_{\mathbf{mfp}}} >> \omega_{\mathrm{L}}$

Then GP doesn't have time to build up

Geometric phase with B_E = v x E field



Radial B-field due to gradient

- Motion in B – field shifts the precession frequency - ω_0 :

$$\Delta\omega \cong \frac{\gamma_n^2\left(B_\perp \mp (\vec{v}_n \times \vec{E})/c^2\right)^2}{4\left(\omega_0 \mp v_n/R\right)}$$

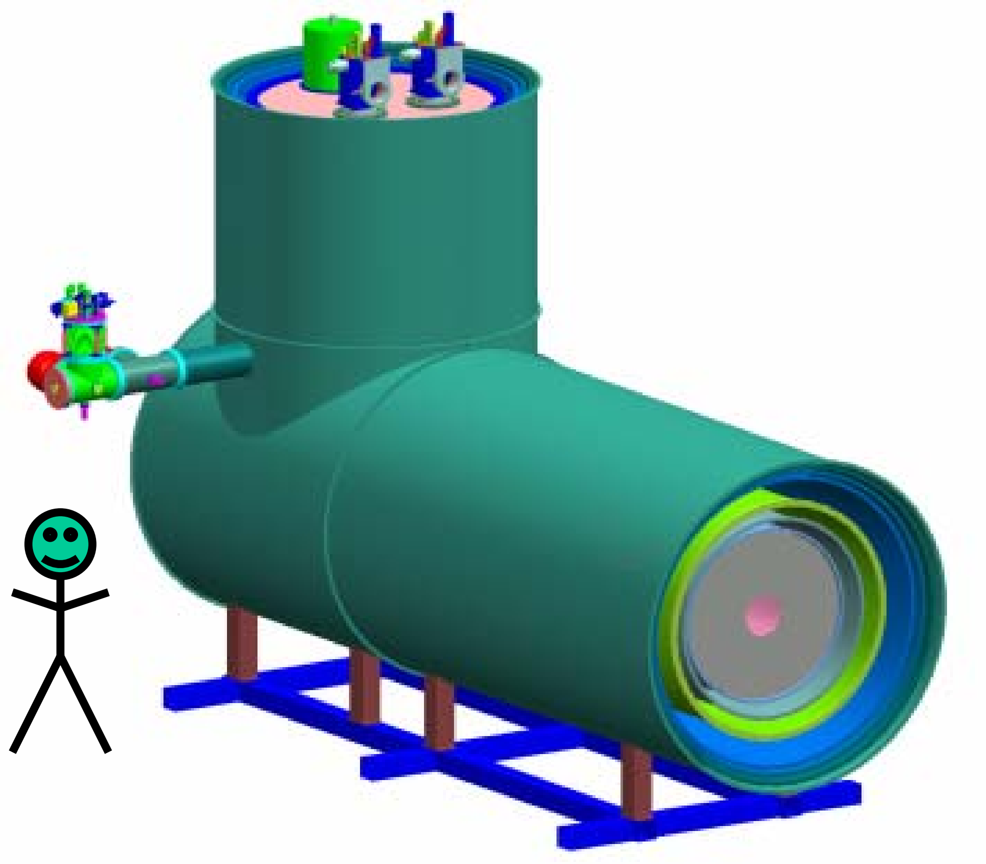
- $\mp$ due to different trajectories
- Does NOT average to 0
- Gives $\Delta\omega$ that depends on direction of $\vec{E} \Rightarrow$ false EDM

v x E field
changes sign with
neutron direction

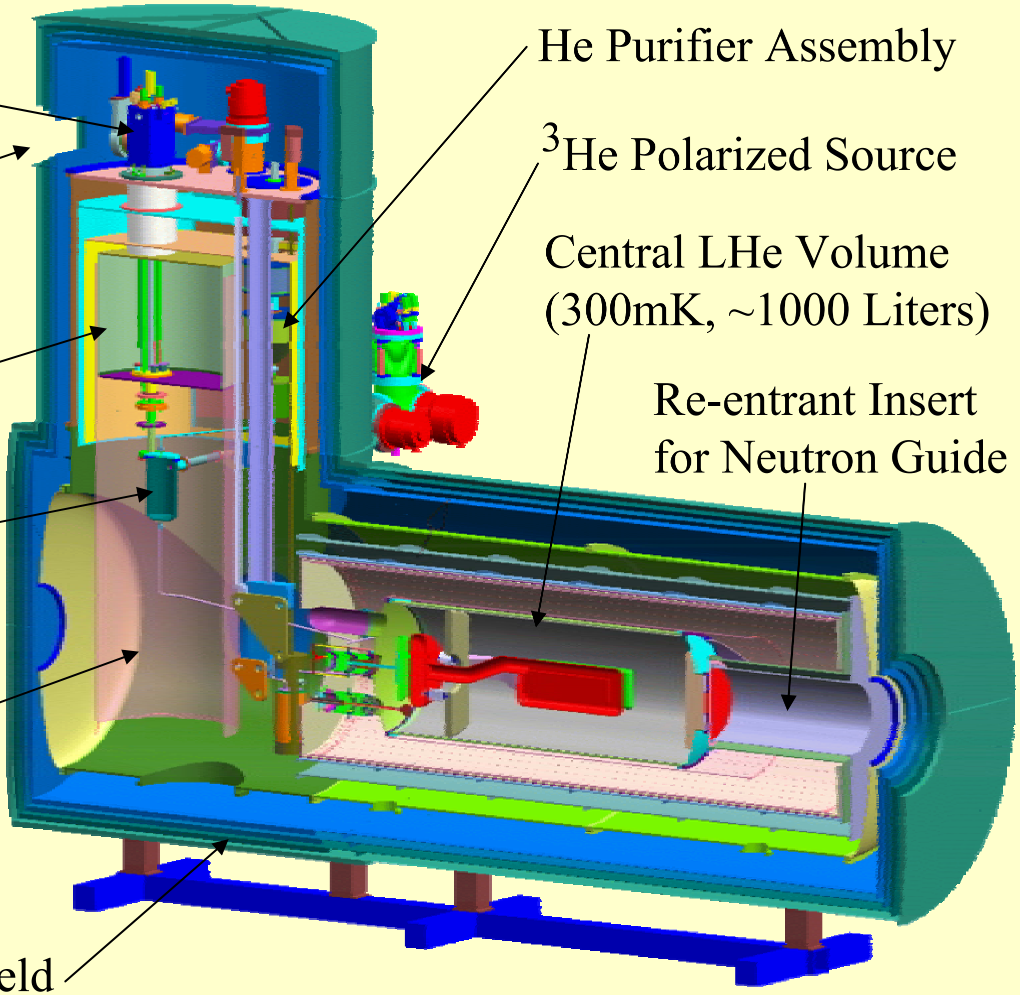
Dressed Spins

- By applying a strong non-resonant RF field, the gyromagnetic ratios can be modified or “dressed” $\gamma' = \gamma J_o(\gamma B_{rf}/\omega_{rf})$
- For a particular value of the dressing field, the neutron and ^{3}He magnetic moments are equal
- Can tune the dressing parameter until the relative precession is zero. Measure this parameter vs. direction of $\vec{E}$

n-EDM Design Concept



EDM Experiment Section View



Dilution Refrigerator
(DR: 1 of 2)

Upper Cryostat
Services Port

DR LHe Volume
450 Liters

^{3}He Injection
Volume

3He Injection
Volume cosθ
Magnet

4 Layer μmetal Shield

He Purifier Assembly

^{3}He Polarized Source

Central LHe Volume
(300mK, ~1000 Liters)

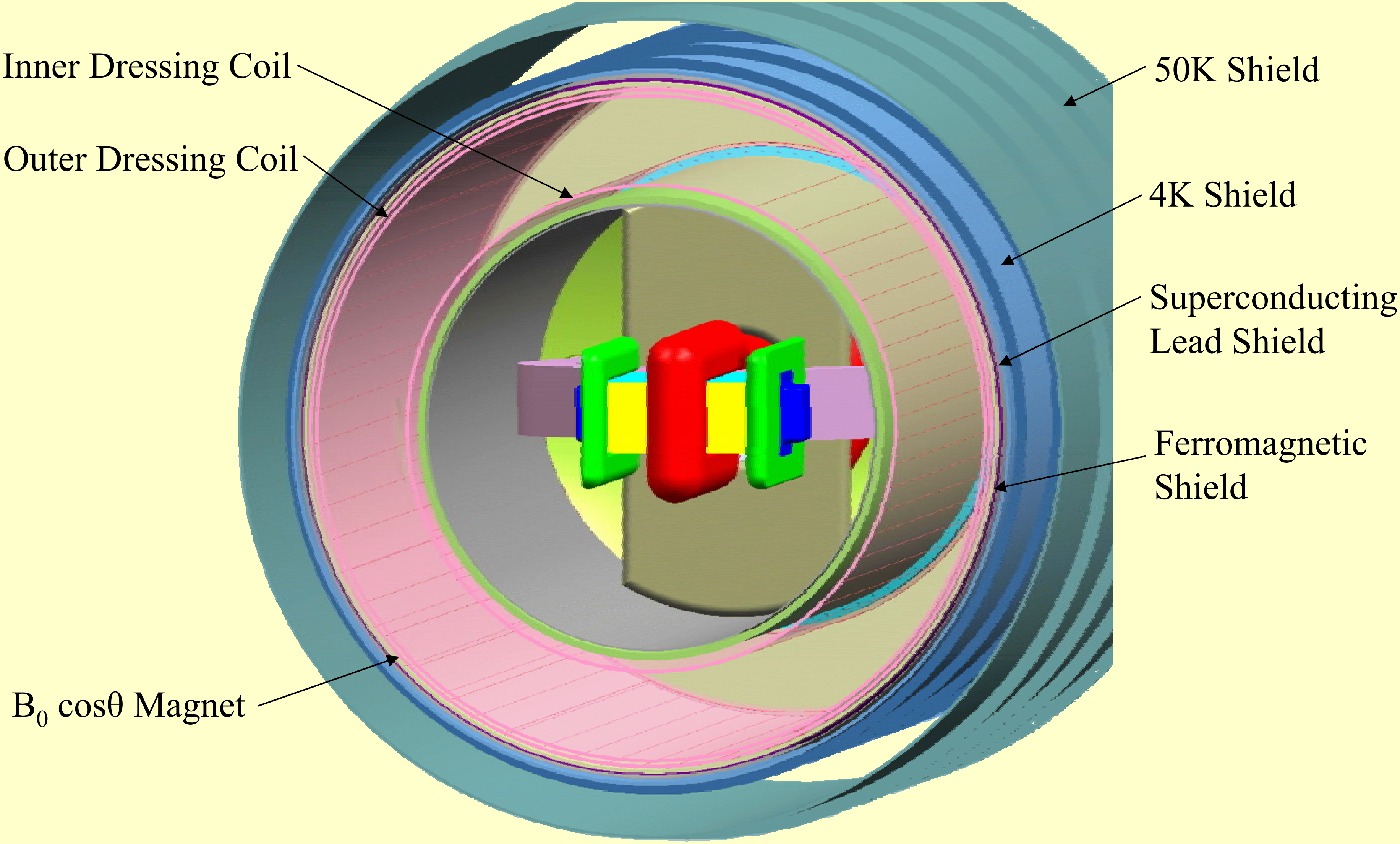
Re-entrant Insert
for Neutron Guide

Upper
Cryostat

Lower
Cryostat

5.6m

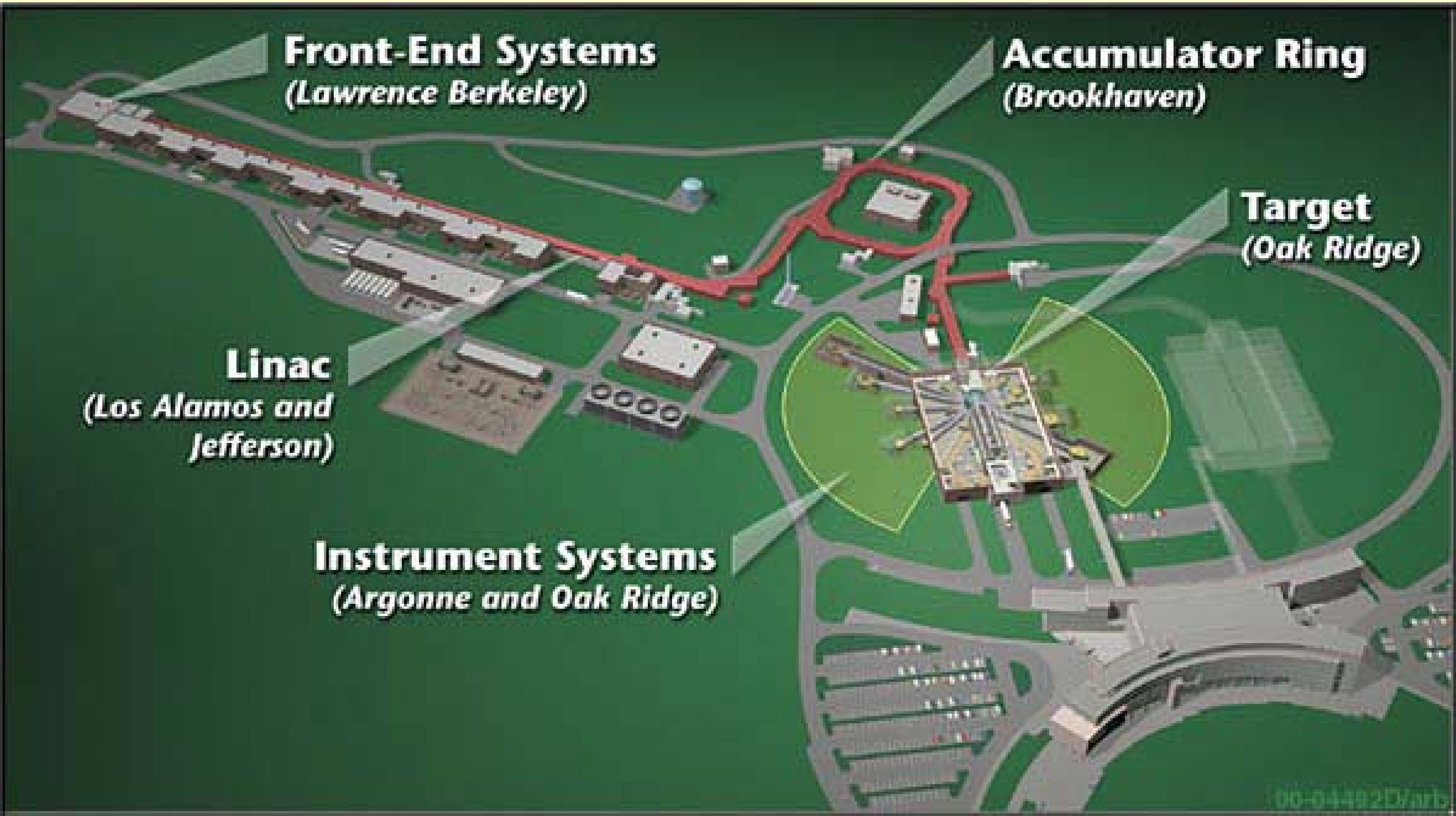
Measurement Cell

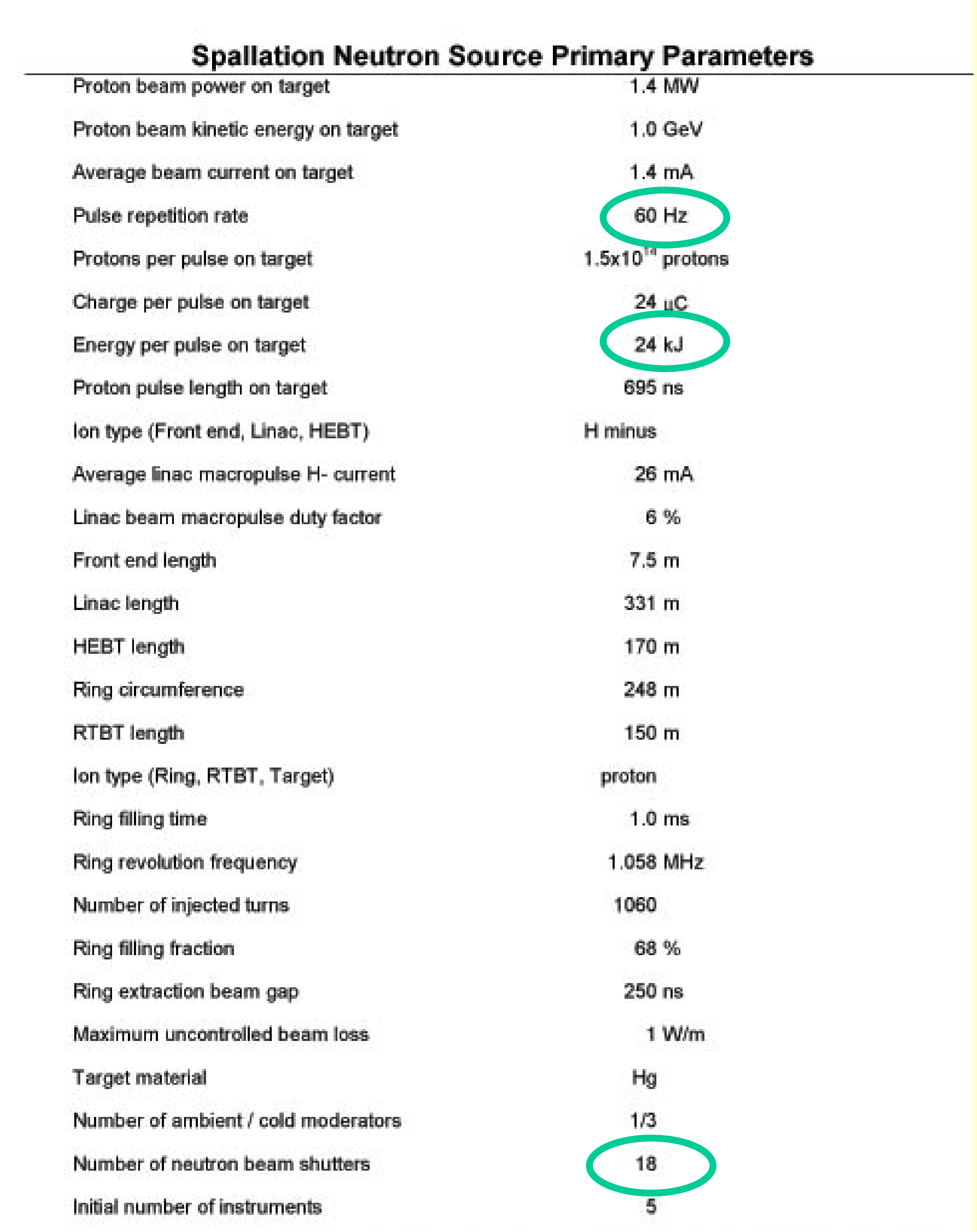


Neutrons come from at Oak Ridge National Laboratory

Spallation Neutron Source (SNS) at ORNL

1 GeV proton beam with 1.4 MW on spallation target





Spallation Neutron Source Primary Parameters

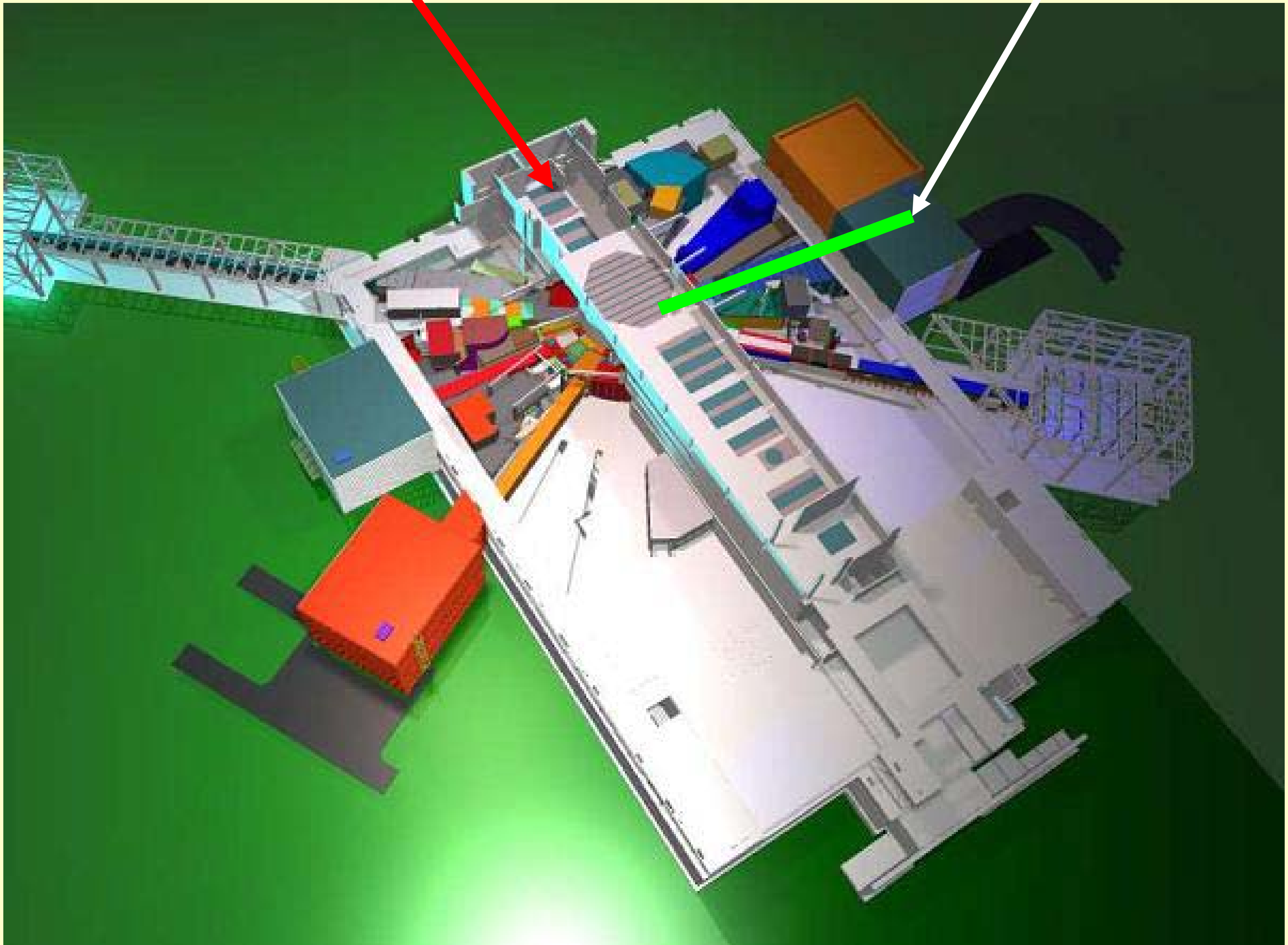
Proton beam power on target	1.4 MW
Proton beam kinetic energy on target	1.0 GeV
Average beam current on target	1.4 mA
Pulse repetition rate	60 Hz
Protons per pulse on target	1.5x10^{14} protons
Charge per pulse on target	24 µC
Energy per pulse on target	24 kJ
Proton pulse length on target	695 ns
Ion type (Front end, Linac, HEBT)	H minus
Average linac macropulse H- current	26 mA
Linac beam macropulse duty factor	6 %
Front end length	7.5 m
Linac length	331 m
HEBT length	170 m
Ring circumference	248 m
RTBT length	150 m
Ion type (Ring, RTBT, Target)	proton
Ring filling time	1.0 ms
Ring revolution frequency	1.058 MHz
Number of injected turns	1060
Ring filling fraction	68 %
Ring extraction beam gap	250 ns
Maximum uncontrolled beam loss	1 W/m
Target material	Hg
Number of ambient / cold moderators	1/3
Number of neutron beam shutters	18
Initial number of instruments	5

SNS Status

Photo courtesy of ORNL

- **SNS completed: 2006**
- **FNPB Beam line completed: 2007**
- **Full design flux: 2008**
- **SNS Total Project Cost: 1.411B$**

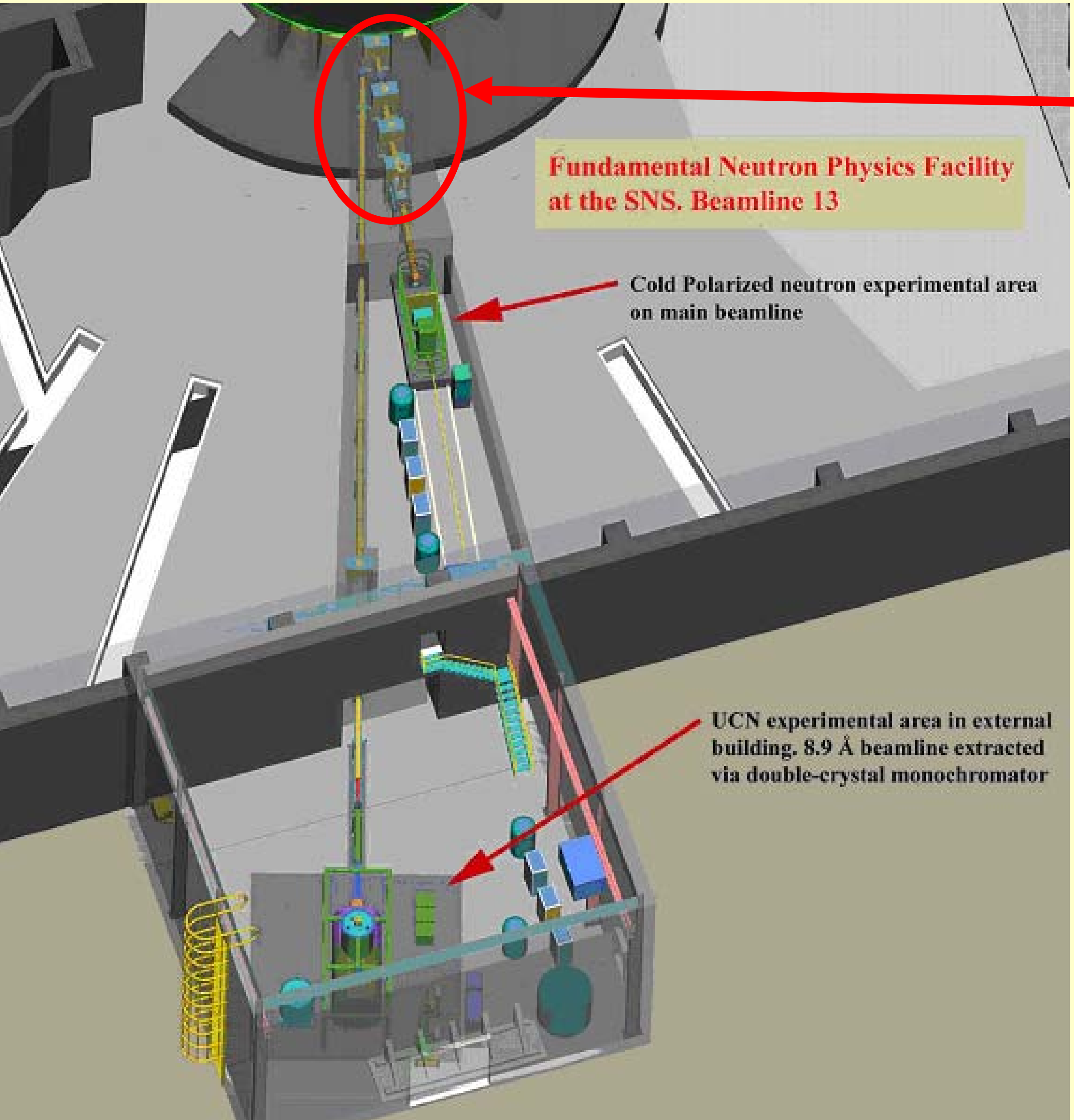
SNS Target Hall



p beam

18 neutron beam ports with 1 for Nuclear Physics

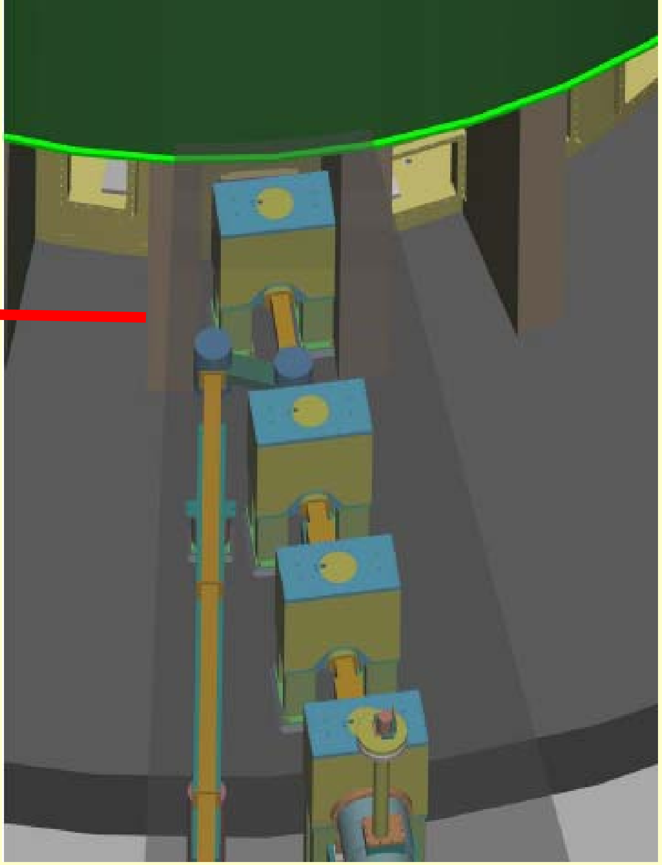
Fundamental Neutron Physics Beamline



Fundamental Neutron Physics Facility at the SNS. Beamline 13

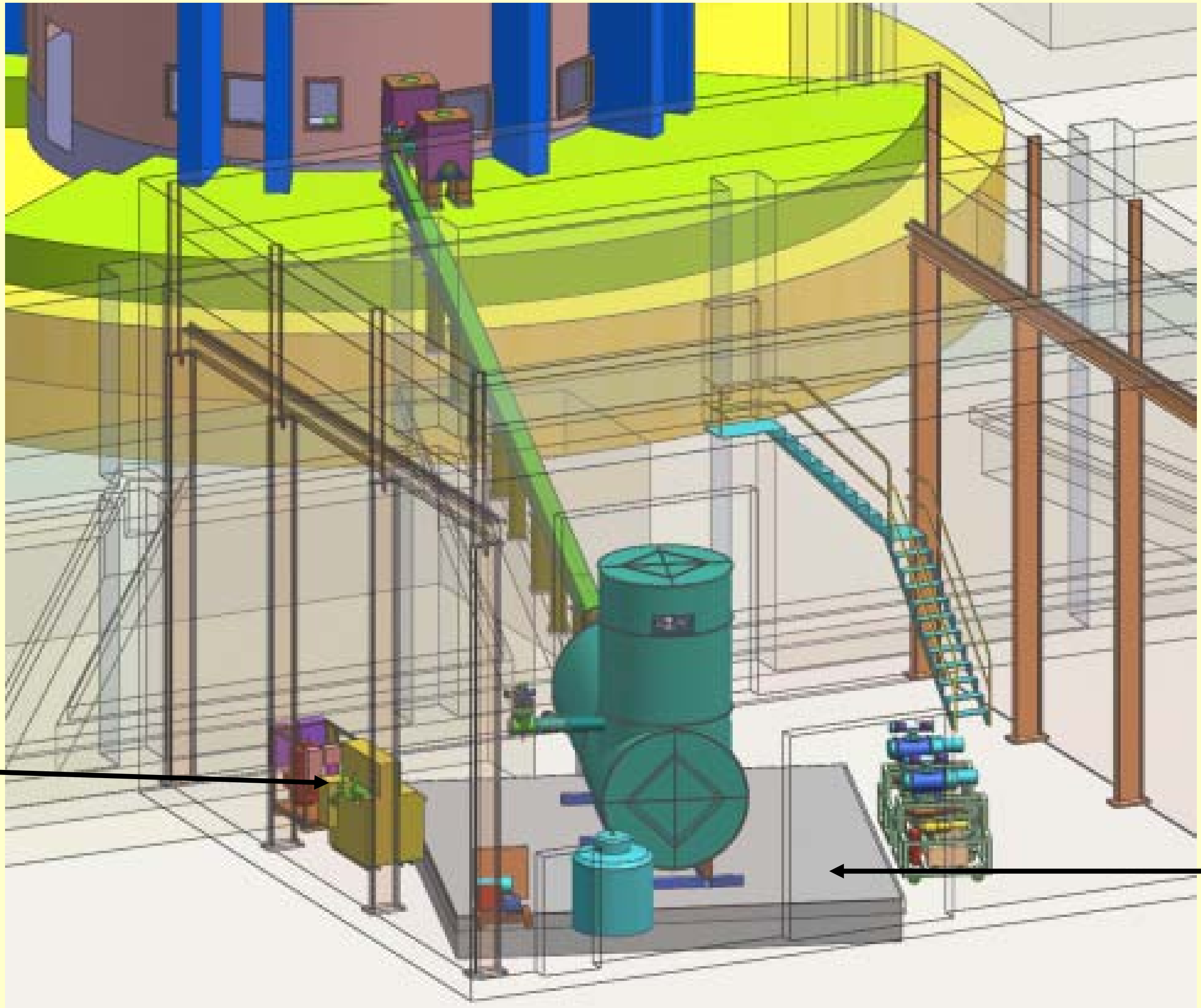
Cold Polarized neutron experimental area on main beamline

UCN experimental area in external building. 8.9 Å beamline extracted via double-crystal monochromator



Double monochrometer selects 8.9 Å neutrons

EDM Experiment at SNS



He Liquifier

Isolated floor

Funding Status of US n-EDM

- 2002: Preproposal submitted to DOE: 2003 DOE/NSF subcommittee review
  - Established DOE "mission need"

Department of Energy

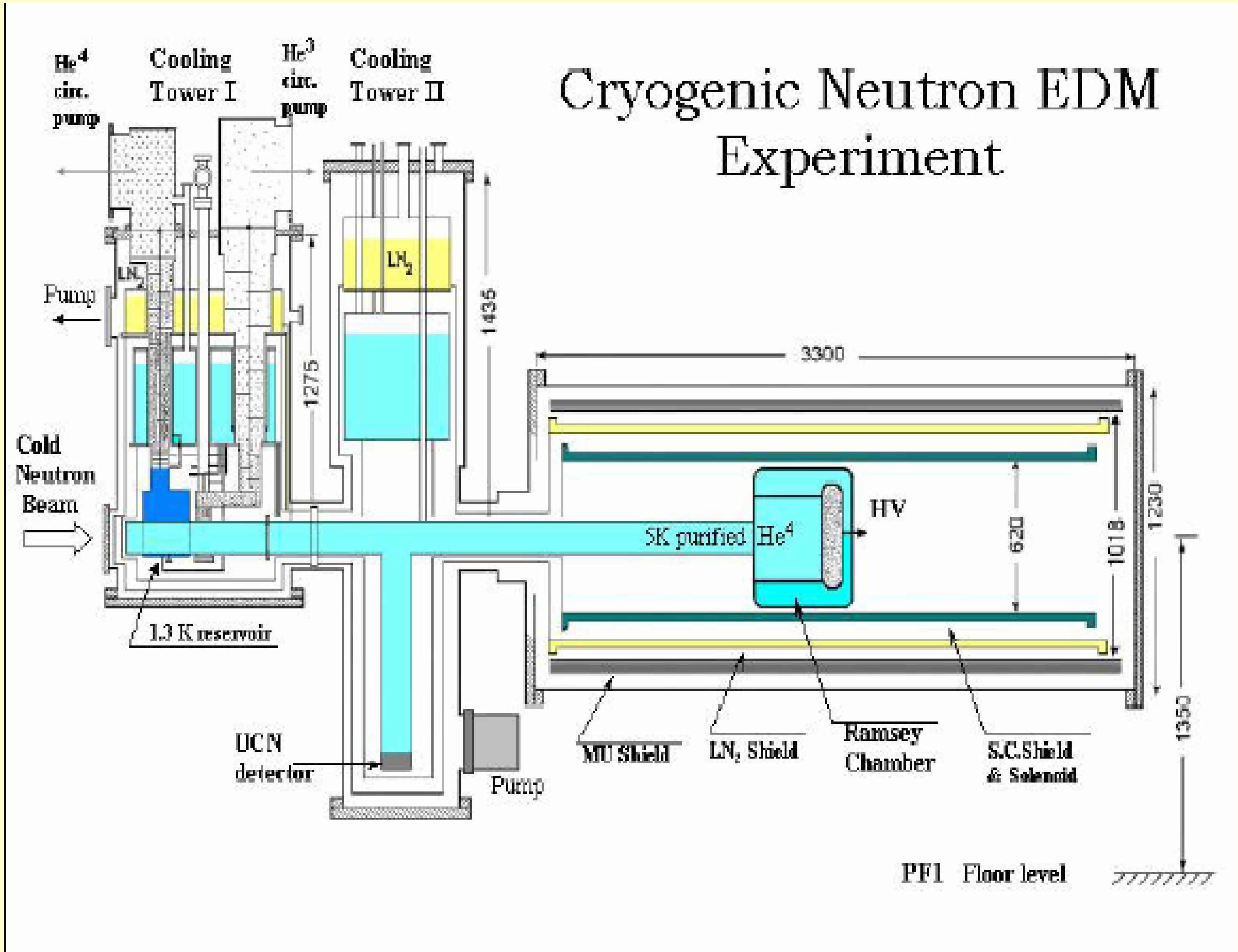
- 2003: Requested R&D funding for FY03-04
  - Received 650k$ - resolved key feasibility issues
- 2004: Requested R&D funds for FY05-06
  - Request = 1.65M$ - "... we'll get back to you"
- 2005: "Internal" Cost and Schedule review
  - Total Cost of experiment = 16+/-2 M$ (~5M$ NSF)
  - Schedule of experiment: commissioning in 2012
- 11/05: n-EDM receives "Critical Decision 0" (CD0)

Other New EDM experiments

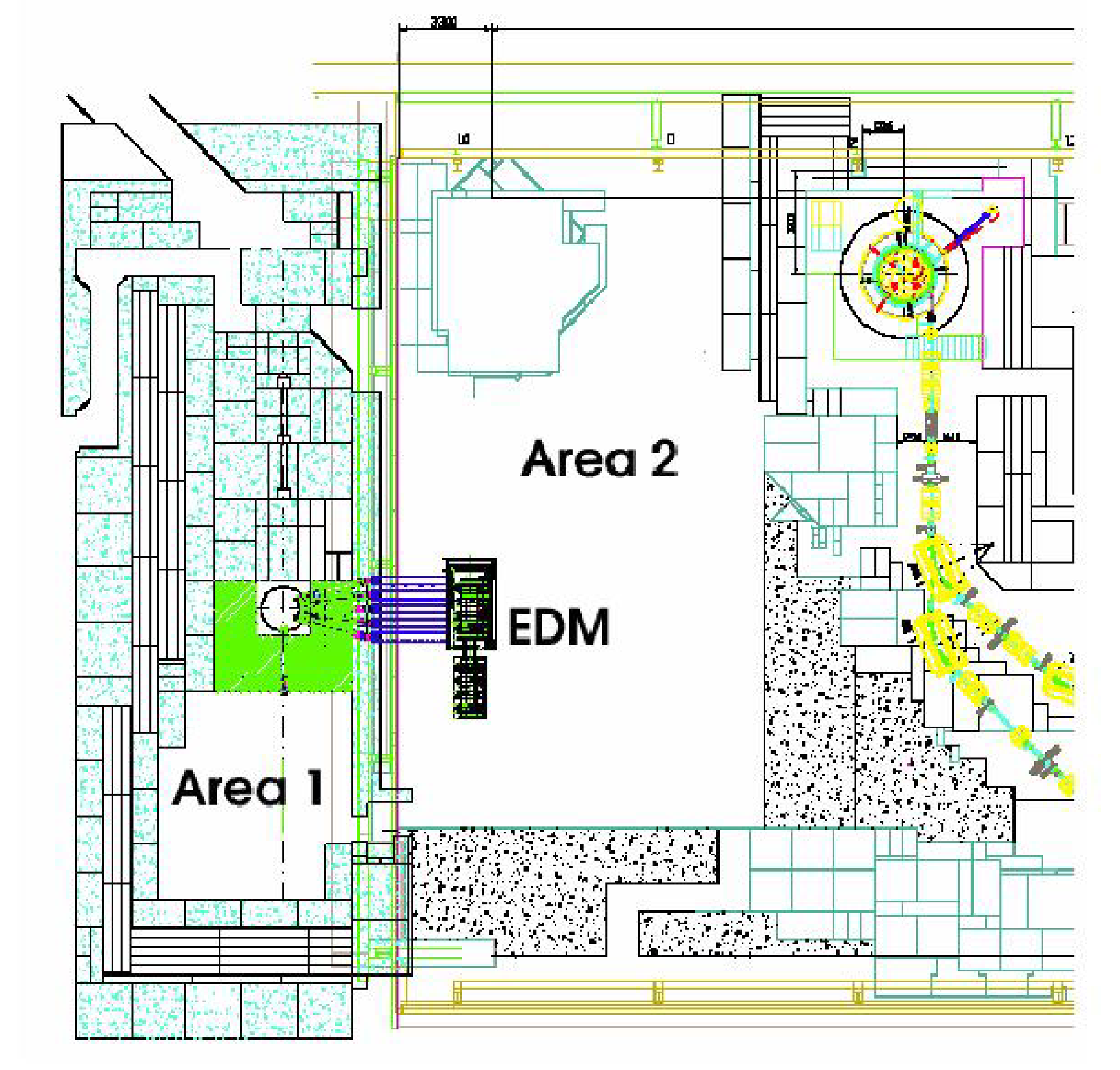
- **CryoEDM at ILL**
  - Similar to new US experiment
  - Does not use polarized 3He
  - Sensitivity of 2×10^{-28} e-cm
  - First phase of experiment underway
- **EDM at PSI based on SD_2**
  - Similar technique to present ILL exp.
    - But no comagnetometer
  - Sensitivity of 7×10^{-28} e-cm
  - SD2 source being constructed

New ILL EDM Experiment

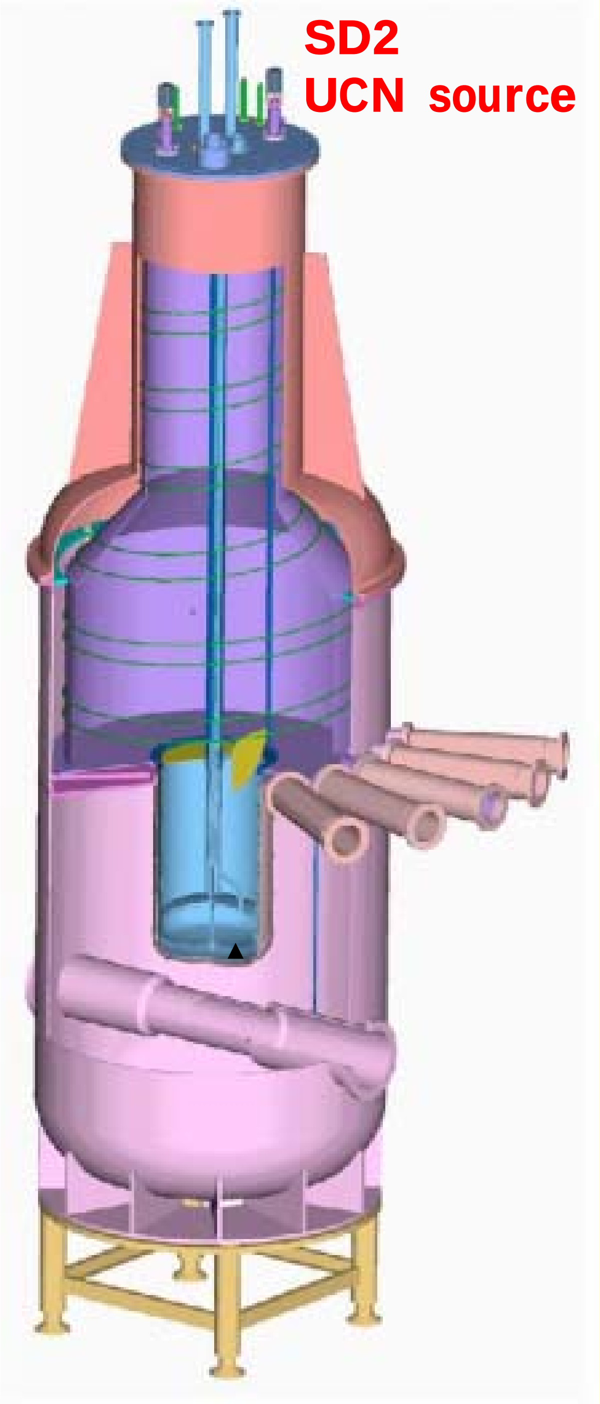
- Similar to new US experiment
- No ^{3}He (only SQUIDs)



New EDM experiment at PSI

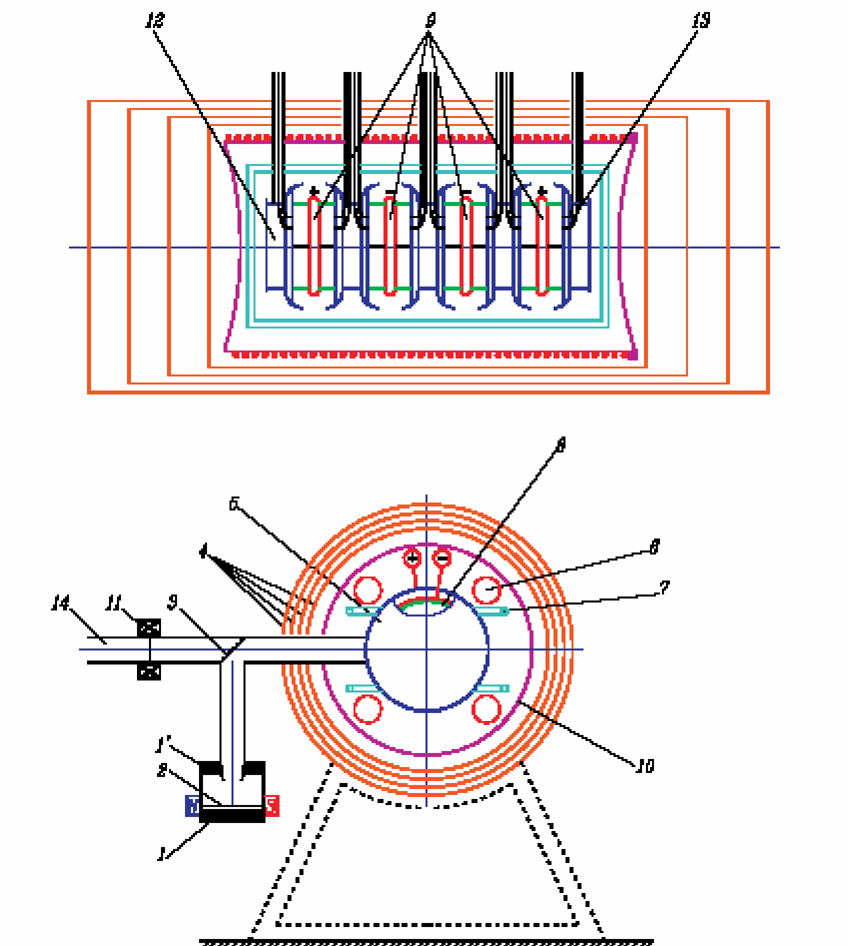


PSI UCN Facility (using Solid D_2 from Los Alamos-Caltech-... collaboration)

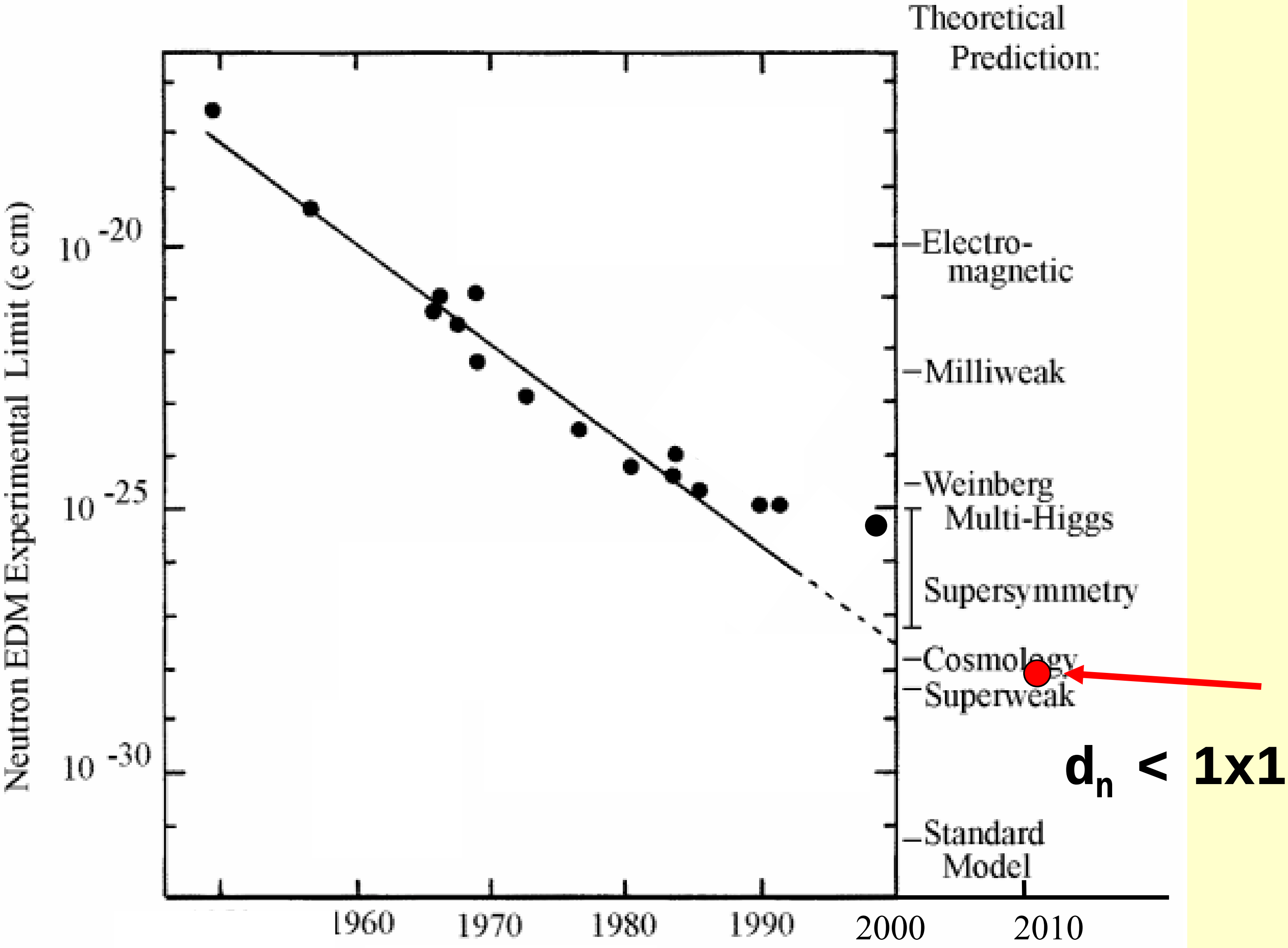


PSI EDM

- Based on present ILL experiment
- No "Comagnetometer"
- Uses UCN in adjacent cell with $\left|\vec{\mathrm{E}}\right| = 0$



New n-EDM Sensitivity



$d_n < 1 \times 10^{-28}$ e-cm

Summary

- Thanks for Invite!
- Searches for physics beyond the standard model are key part of Nuclear Physics
- Precision measurements at low energy can access very high energy physics
- Physics reach of EDM measurements remains strong (even after Large Hadron Collider)
  - New sources of CP violation possible in SUSY