Tests of Fundamental Symmetries with Neutrons

- The Science
  - Violation of Parity Symmetry in NN Force
  - Search for new Symmetries in n β-decay
    - (eg. SUperSYmmetry aka SUSY)
  - New Sources of CP Violation (n EDM)
- Neutron Technology
- Facilities & Experiments
  - (focus on US effort – relatively new)
- Outlook

B. Filippone
PANIC 05
10/25/05

Related PANIC05 Talks

Section XII.2: New Accelerator Facilities II

Parallel Session 2, Monday, October 24, 4:30 - 6:00PM, room: Hilton - Ortiz

Manfred Daum	The ultracold neutron facility at PSI, a status report
Peter Fierlinger	Deuterium for Ultra-cold Neutron Sources
Peter Fierlinger	Diamond-like Carbon for Ultra-cold Neutrons

Section VII.1: EDM of electrons, muons, neutrons, atoms

Parallel Session 3, Tuesday, October 25, 2:30 - 4:00PM, room: Sweeney - Meeting 3

Section VII.2: Fundamental Measurements in Atomic and Molecular Physics

Parallel Session 4, Thursday, October 27, 2:30 - 4:00PM, room: Sweeney - Meeting 3

Bernhard Lauss	Precision Measurement of Parity Violation in Polarized Neutron Capture on the Proton: the NPDgamma Experiment.
Anna Micherdzinska	Measurement of the Parity-Violating Neutron Spin Rotation in 4He

Section VII.3: Neutron lifetime and beta decay

Parallel Session 5, Thursday, October 27, 4:30 - 6:00PM, room: Sweeney - Meeting 3

Alexey Barabanov	Testing T invariance in the interaction of slow neutrons with aligned nuclei
Maurits van der Grinten	Search for the Electric Dipole Moment of the Neutron
Kazimierz Bodek	Search for Time Reversal Violation in Neutron Decay – A Measurement of the Transverse Polarization of Electrons
Mark Makela	Precision measurement of the neutron's beta asymmetry using ultra-cold neutrons
Pil-Neyo Seo	Measuring the Neutron Lifetime Using Magnetically Trapped Ultracold Neutrons

Overview of the Science

- **Hadronic Weak Interaction**
  - Should be interpretable via QCD
  - May play role in nucleon structure and neutrinoless $\beta\beta$-decay
- **Decay Correlations and Neutron Lifetime**
  - Decay parameters sensitive to non-SM phys.
  - τ_n important for Big-Bang Nucleosynthesis
- **Neutron EDM**
  - New sources of CP violation (complements LHC)
  - May contribute to Baryon-Antibaryon asymmetry of Universe

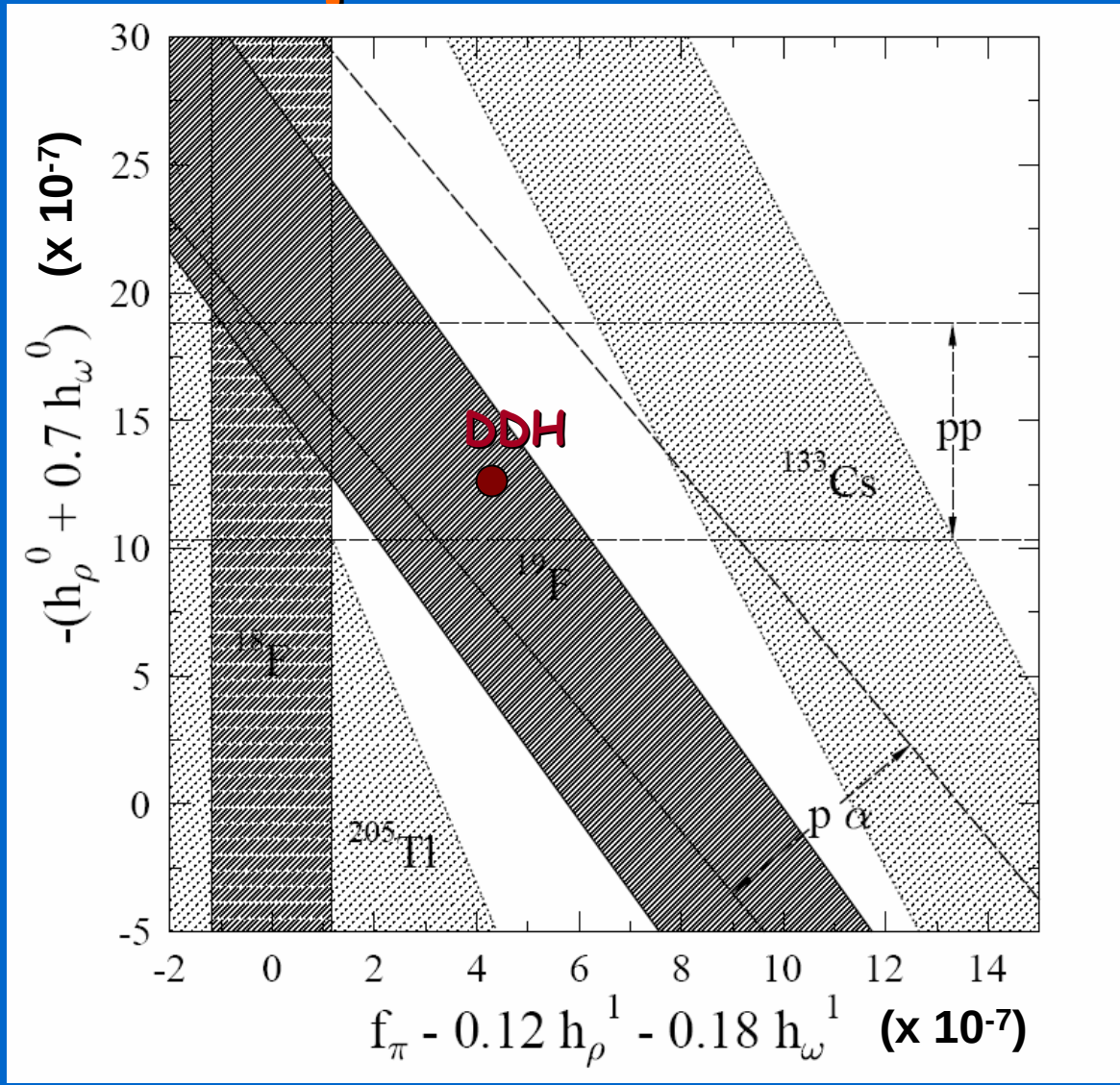
N-N Weak Interaction

- Purely hadronic weak interaction influenced by QCD
- Plays role in Atomic and Nuclear Parity Violation
- Desplanques, Donahue and Holstein estimated NN weak interaction via a quark model
  - 6 parameters in meson exchange model

$$f_\pi,\ h_\rho^0,\ h_\rho^1,\ h_\rho^2,\ h_\omega^0,\ h_\omega^1$$

Status of N-N Weak Interaction experiments

Experimental constraints on combinations of the couplings are *not consistent*



From Haxton & Wieman 01

Sensitivity to NN Weak Meson Couplings in few-nucleon observables

	np A_γ	np ϕ	nD A_γ	nα ϕ	pp A_z	pα A_z
f_π	-0.11	-3.12	0.92	-0.97		-0.34
h_ρ^0		-0.23	-0.50	-0.32	0.08	0.14
h_ρ^1	-0.001		0.10	0.11	0.08	0.05
h_ρ^2		-0.25	0.05		0.03	
h_ω^0		-0.23	-0.16	-0.22	0.07	0.06
h_ω^1	-0.003		-0.002	0.22	0.07	0.06

Table from J. D. Bowman

Role of Neutrons

- n + p → d + γ (NPDγ) spin asymmetry can isolate f_π
- n + α Spin rotation provides unique constraints
- also n + p spin rotation and n + d → t + γ

Neutron Decay and Unitarity

Weak eigenstates

Mass eigenstates

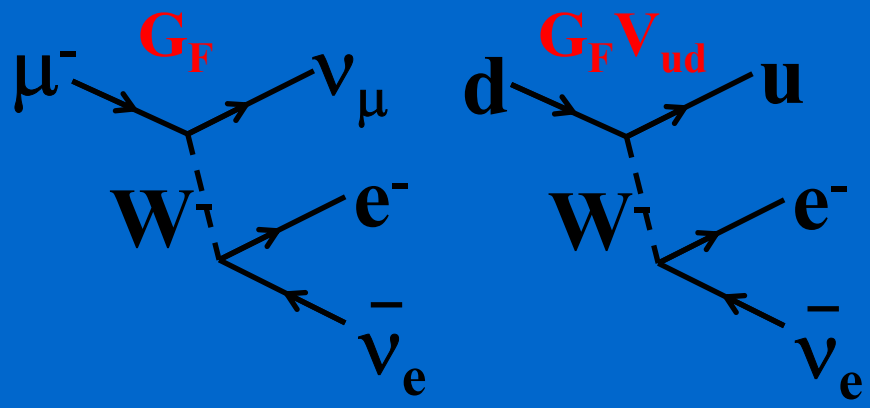
$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} 0.975 & 0.22 & 0.005 \\ 0.22 & 0.97 & 0.04 \\ 0.005 & 0.04 & 0.99 \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitarity, eg. $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$, (or lack thereof) of CKM matrix tests existence of possible new physics (eg. Supersymmetry)

V_{ud} from β-decay

- G_V is related to Fermi coupling G_F via V_{ud}



- G_V measured in β-decay (u→d)
  - 0^+-0^+ nuclear decay (must include nuclear corrections)
  - neutron decay (must extract G_V and G_A)

Polarized Neutron decay

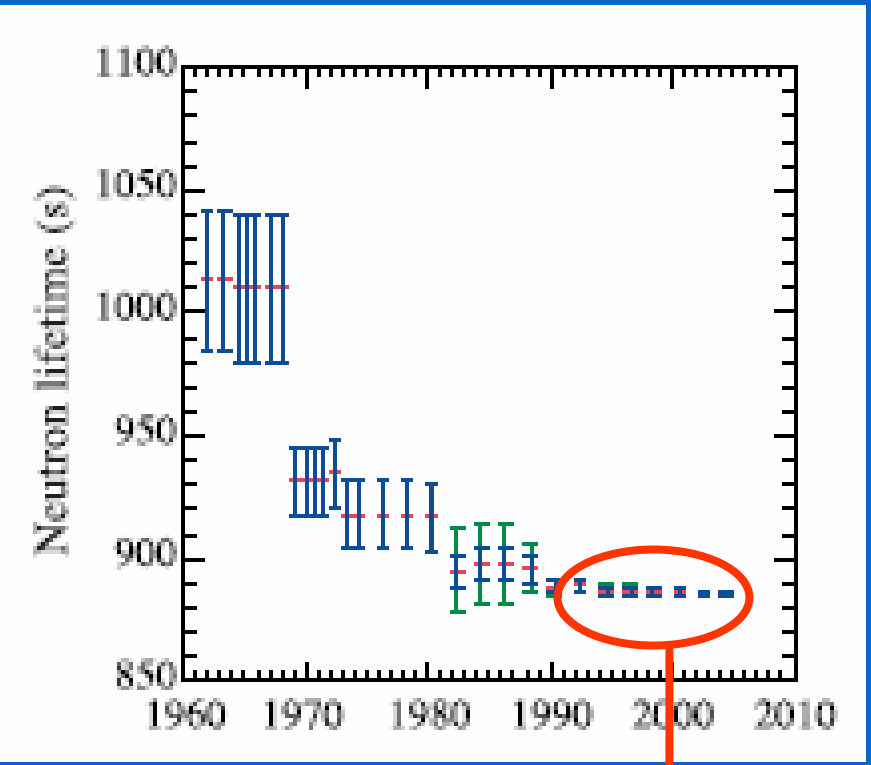
Summing over final-state polarization

$$d\Gamma = \Gamma_n \left(1 + b\frac{m_e}{E_e} + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + A\frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + B\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + D\,\vec{\sigma}_n \cdot \frac{\vec{p}_e \times \vec{p}_\nu}{E_e}\right)$$

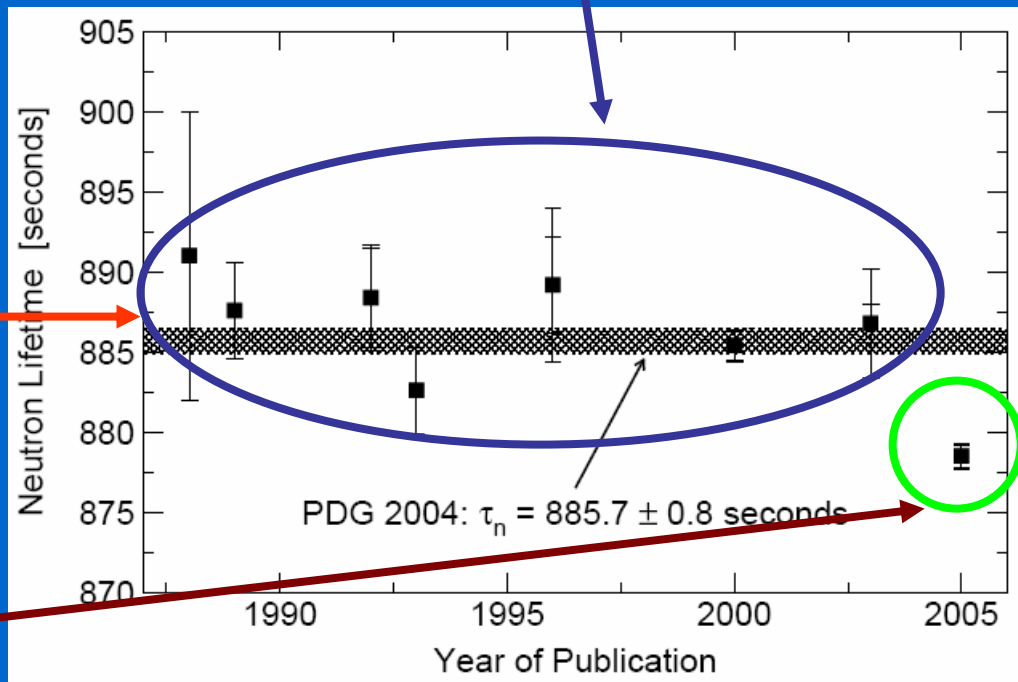
- $\Gamma_n = 1/\tau_n$ total decay rate (depends on G_A and G_V)
- Correlations a, A and B depend on G_A and G_V
- Coefficient b requires S and T interaction
- Correlation D violates Time Reversal Invariance

Must measure two observables to extract G_A and G_V (eg. τ_n and A)

Neutron Lifetime versus Year

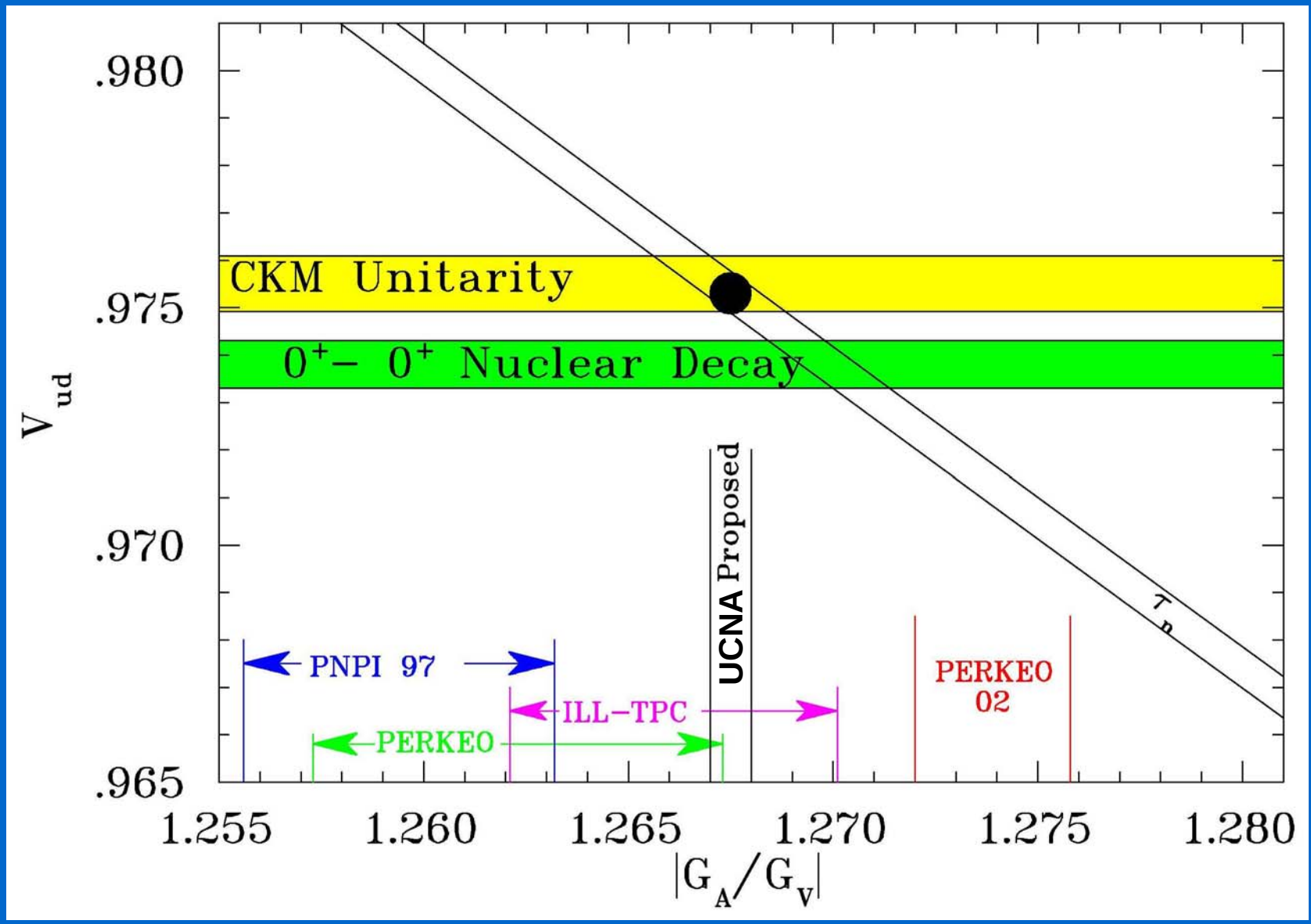


Data points used by Particle Data Group (PDG) 2004 for averaging

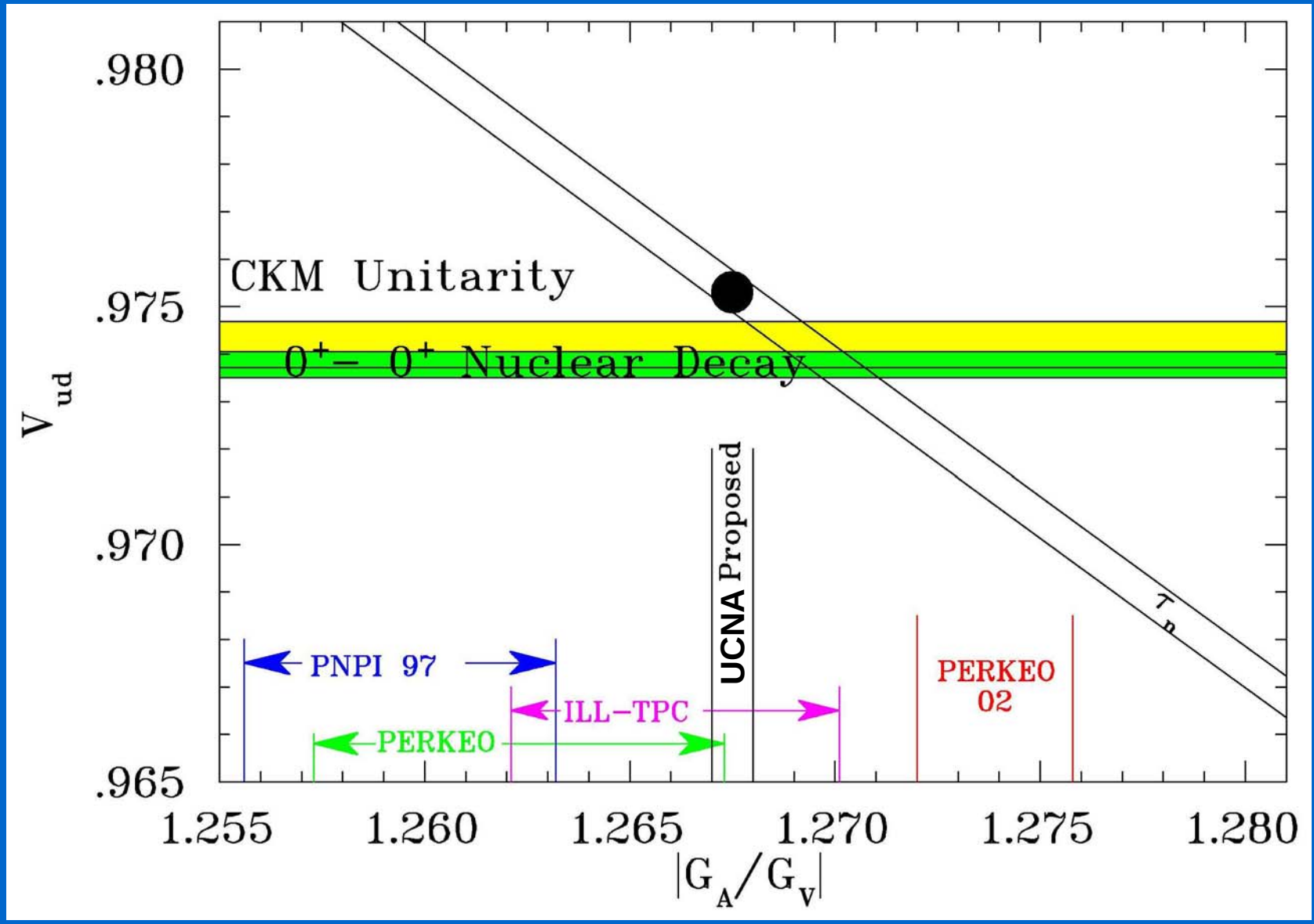


Serebrov *et al.*,
Phys. Lett. B 605, 72 (2005)
(878.5 ± 0.7 ± 0.3) seconds

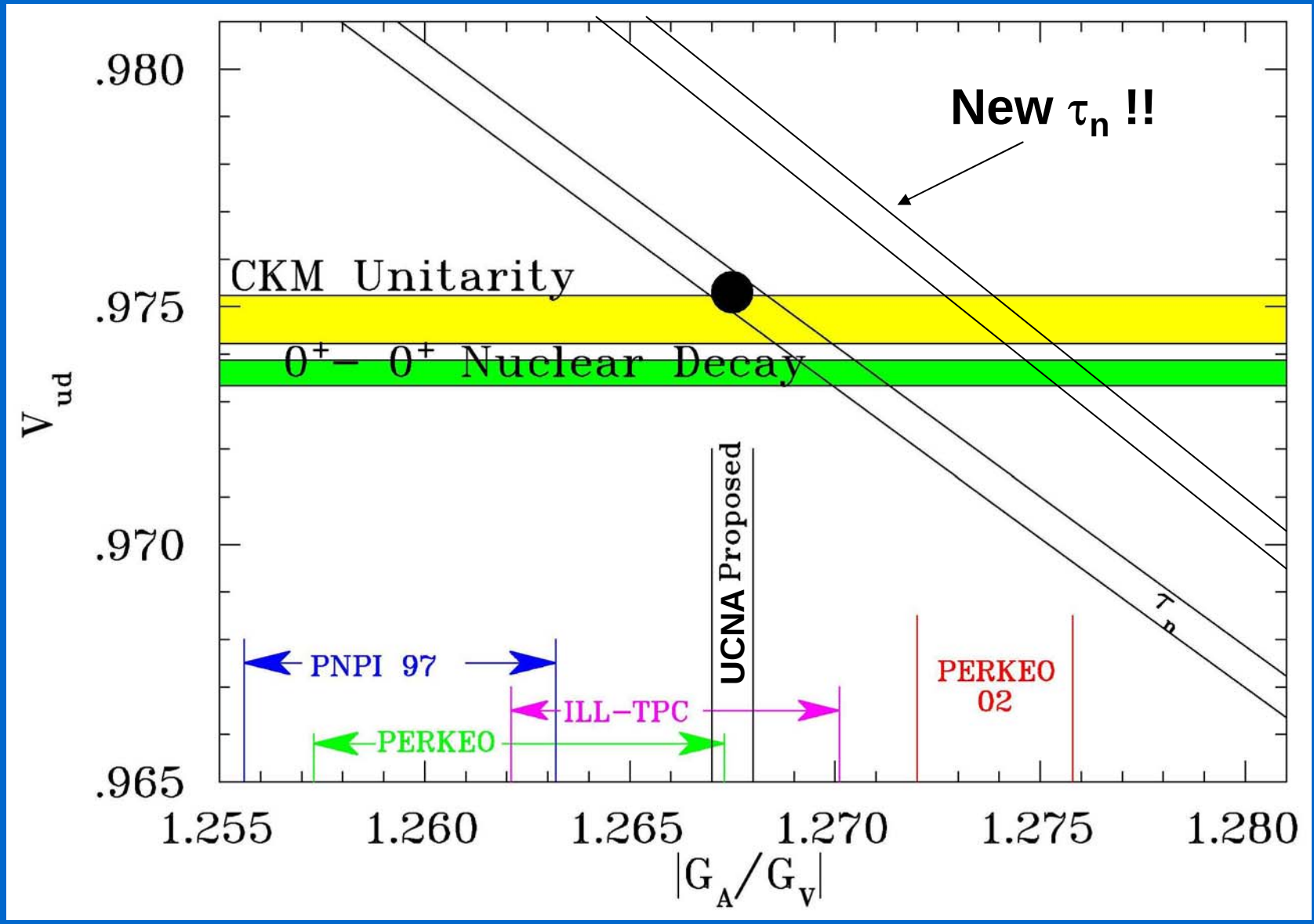
CKM Summary: PDG04



CKM Summary: PDG06?



CKM Summary: Other?



Neutron EDM beyond the Standard Model

- New physics (e.g. SUSY) should have additional CP violating phases in couplings
  - $\sin\theta_{CP}$ should be ~ 1

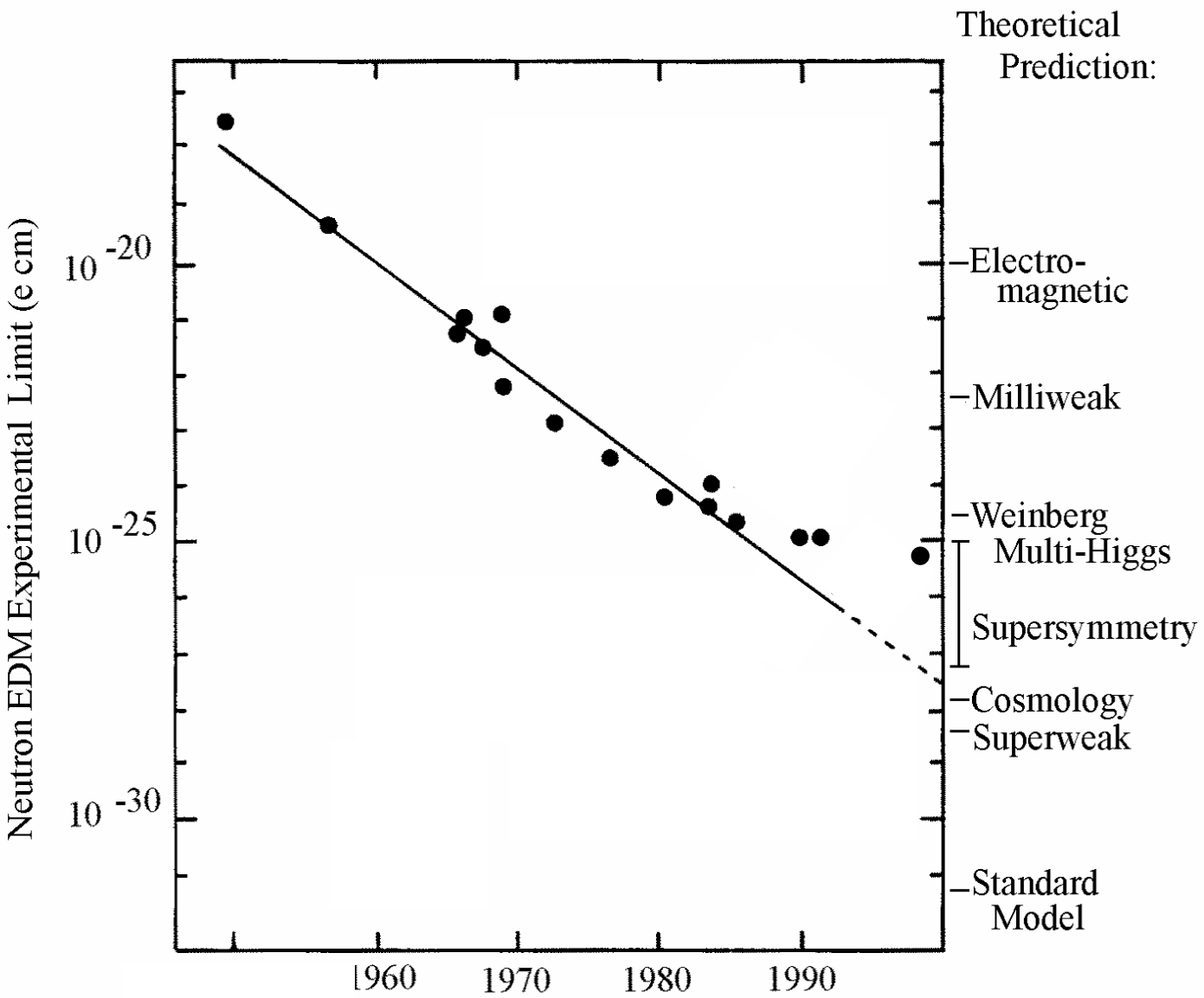
- Contributions to EDMs depends on masses of new particles

$$d_n \propto \frac{\sin\theta_{CP}}{M^2_{SUSY}}$$

  - In MSSM (Minimal Supersymmetric Standard Model)
    - $d_n \sim 10^{-25}$ e-cm x (200 GeV)/M^2_{SUSY}

experiment: $d_n < 6 \times 10^{-26}$ e-cm

n-EDM vs Time


Theoretical Prediction:
Neutron EDM Experimental Limit (e cm)
10 -20
10 -25
10 -30
1960
1970
1980
1990
Electro-magnetic
Milliweak
Weinberg
Multi-Higgs
Supersymmetry
Cosmology
Superweak
Standard Model

Neutron Technology

- Cold neutrons ~ 4 Å
  - Produced from Cold Moderator (20K)

Cold Neutron Advantages
- High Flux
- Improved polarization with pulsed source

- Ultra-Cold Neutrons (UCN) ~ 500 Å
  - Boltzmann tail from Reactor cold moderator
  - Superthermal Converters
    - LHe, SD_2

UCN Advantages
- Can be trapped in certain materials
- Can be easily polarized (B = 6T)

Worldwide Neutron source comparison

Facility	Status	Op days per year Note 1	Guide Area (cm^2)	$\left(\frac{\text{Guide}}{\text{m}}\right)^2$ Note 2	Cold source Brightness at ~4Å (10^{10} n/cm^2/s/sr/Å)	Relative Brightness *Area*Year Note 3	Relative Yearly Fluence Note 3
Pulsed Sources							
Lujan (FP12)	Op	104 85%	90	9	2.5	1	1
SNS (FP13)	*Prop*	*208*	*120*	*12*	*71*	*76*	*101*
Continuous Sources							
NIST (NG6)	Op	266 100%	36 Note 4	1.4	150	61	10
HFIR (HB4)	*Prop*	*261* *93%*	*22* Note 5	*4*	*450*	*110*	*50* Note 5
PSI	Op	245	120	9	60	75	75
ILL (PF1b)	Op	200	120	4	450	460	205

Adapted from NSAC Subcommittee Report on Fundamental Physics with Neutrons (03)

US Facilities for Fundamental Physics with Neutrons

- NIST
  - NG6 - Cold Neutron Lines
- LANSCE
  - Flight Path 12 (FP12) - Pulsed Cold Neutrons
  - Area B - UCN
- SNS
  - Fundamental Neutron Physics Beamline (FNPB)
- Other Initiatives
  - PULSTAR Reactor @ NCSU
  - LENS Cold neutrons @ IUCF

Non-US Facilities for Fundamental Neutron Physics

- ILL – Cold & Ultra-Cold lines
  - Improved EDM experiment (Cryo-EDM)
  - Improved correlation experiments
- PSI – Spallation SD_2 UCN source
  - EDM experiment under development
  - Correlation experiments possible
- Germany - FRM-II 20MW research reactor
  - Work underway for SD_2 UCN source
- Japan
  - Osaka UCN, JPARC?

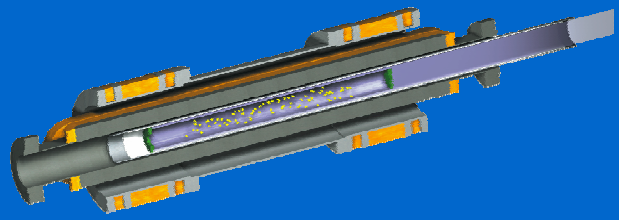
The Fundamental Neutron Physics Program at NIST

- 20 MW research reactor with a LH_2 cold source
- Operates ~210 days/year
- 5 Fundamental neutron physics facilities

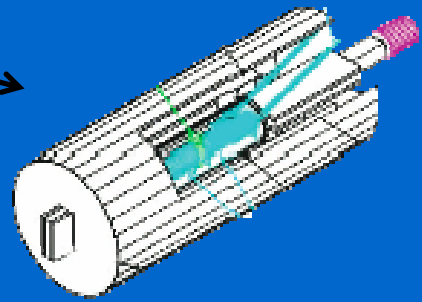
NIST

Upcoming Experiments at NIST

- Neutron lifetime using magnetically trapped UCN
  (Underway - 0.9 nm Monochromatic neutron line)



- Neutron spin rotation in liquid helium
  (05-06)



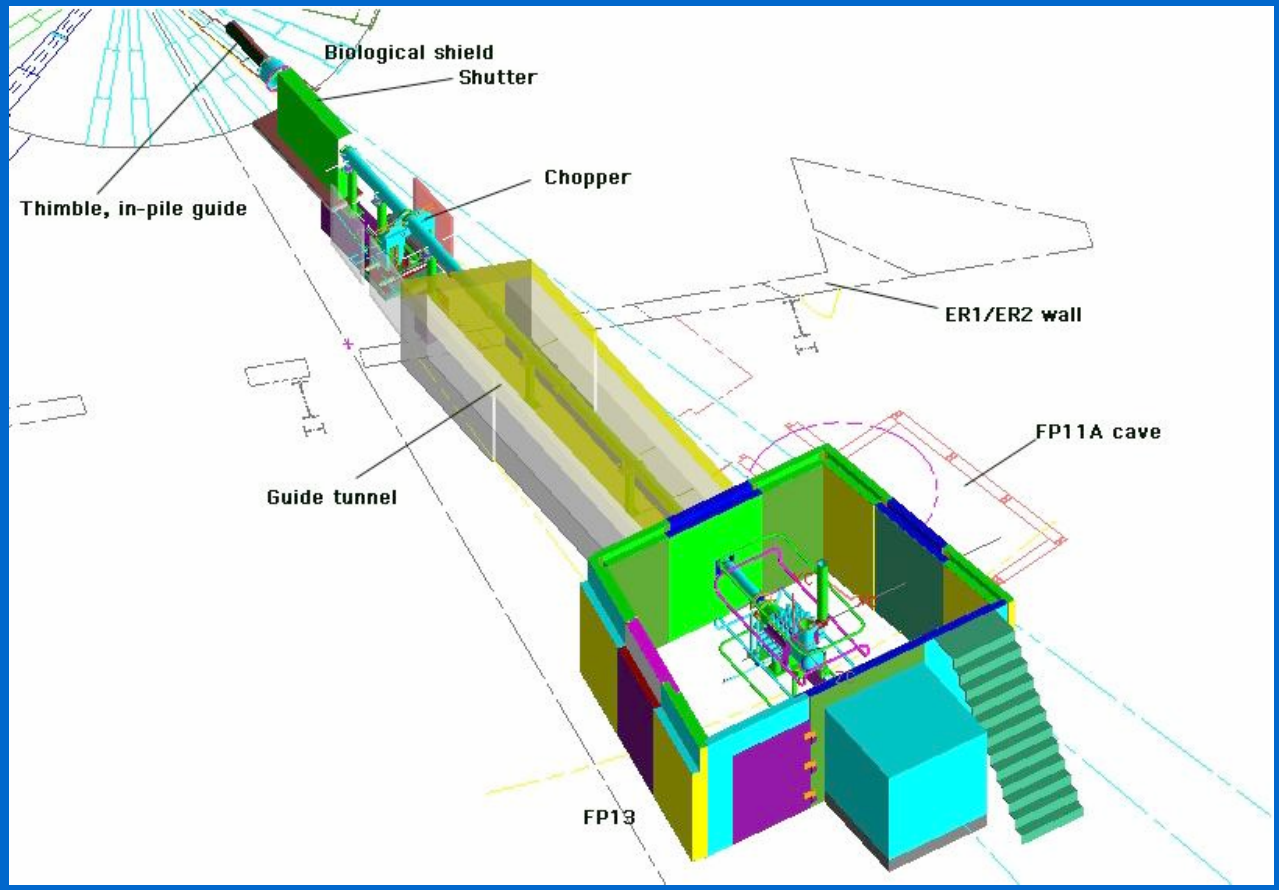
- Electron-neutrino asymmetry - "a"

- Proton asymmetry - "A" + "B"

LANSCE

(Los Alamos Neutron Science CEnter)

FP12 at LANSCE



LH2 moderator

2 x 10^9 polarized cold n/sec

Available for nuclear physics experiments and staging SNS experiments after 2007

NPDγ experiment - measure f_π

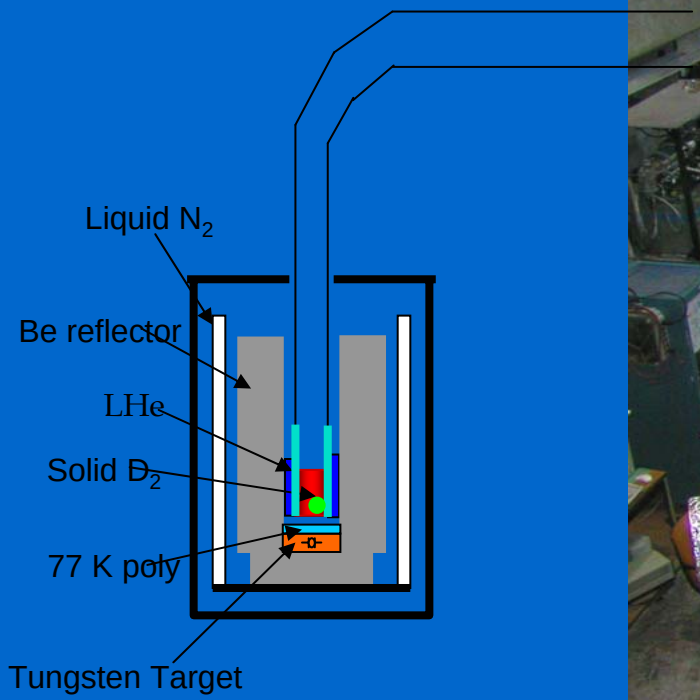
From S. Penttila

$\Delta f_\pi = 5 \times 10^{-7}$
2005-6 at LANSCE

$\Delta f_\pi = 5 \times 10^{-8}$
2007-8 at SNS

LANSCE Area B

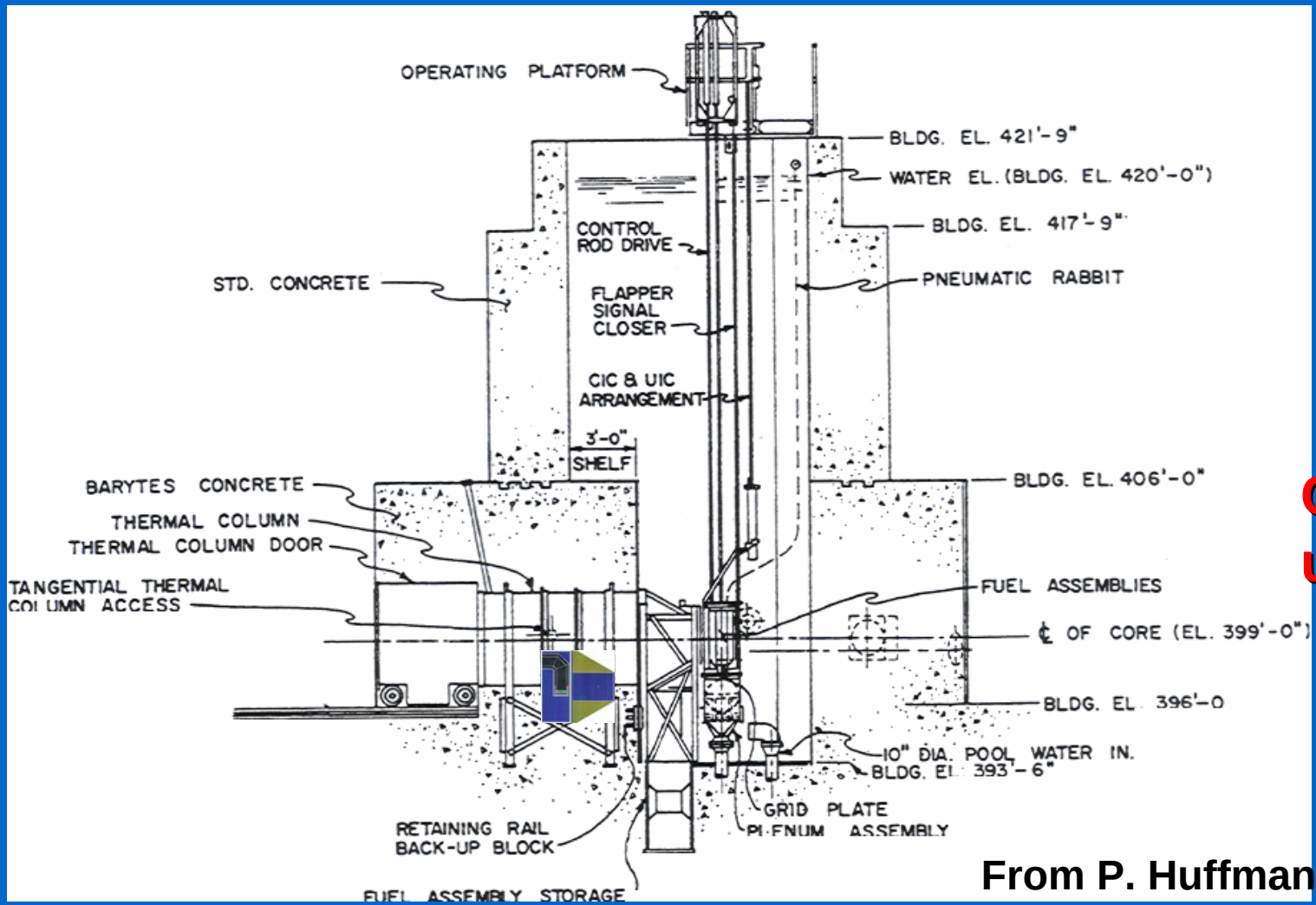
Experiment commissioning Underway
Initial goal is 0.2% measurement of A-correlation



UCNA

NCSU PULSTAR UCN Source

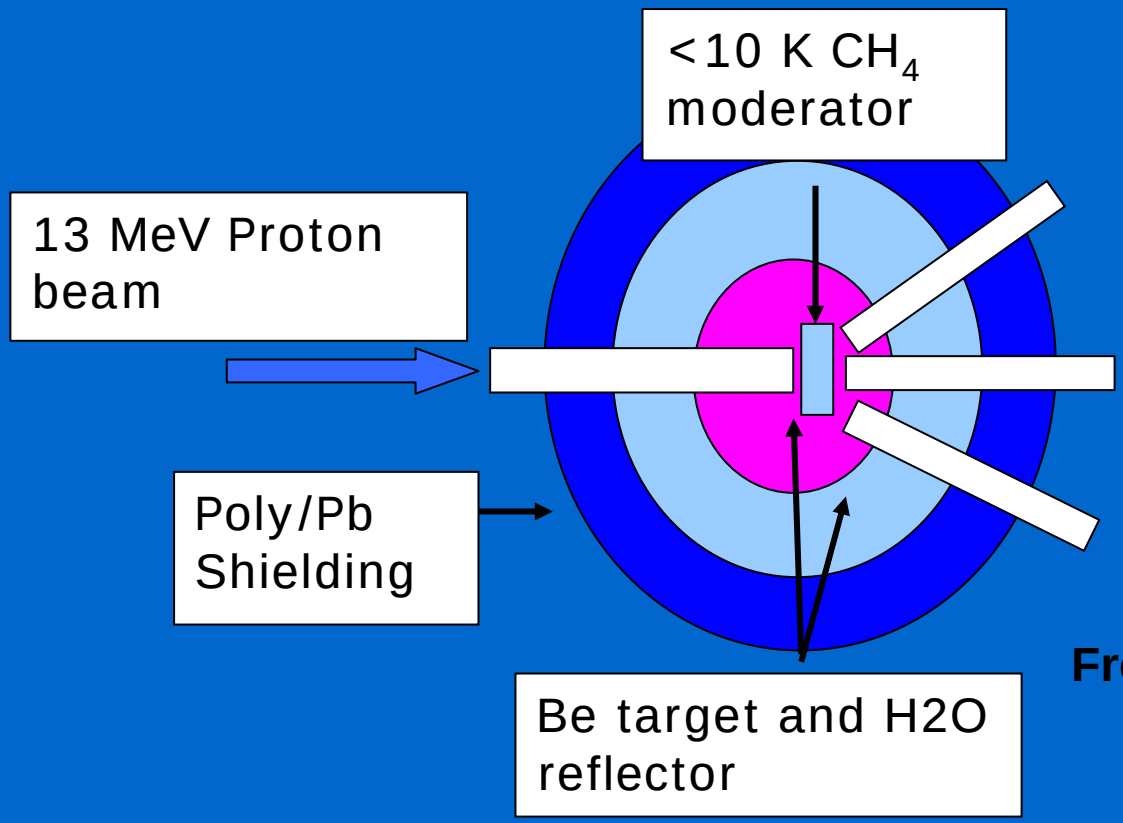
- 1MW research reactor
- Possible UCN source could provide densities > 1,000/cm^3



Construction underway

From P. Huffman

Low Energy Neutron Source (LENS) at Indiana Univ.

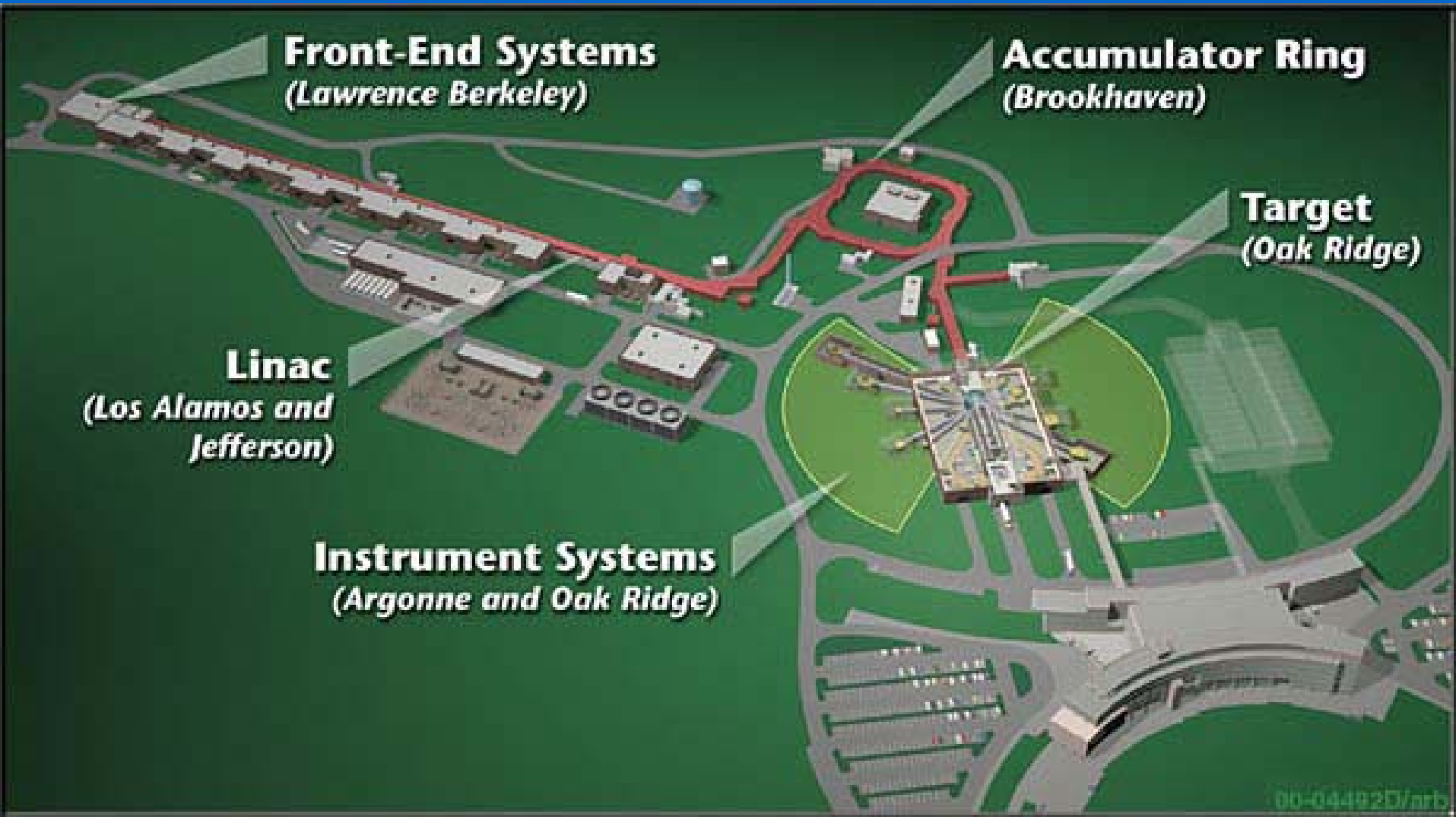


From M. Snow

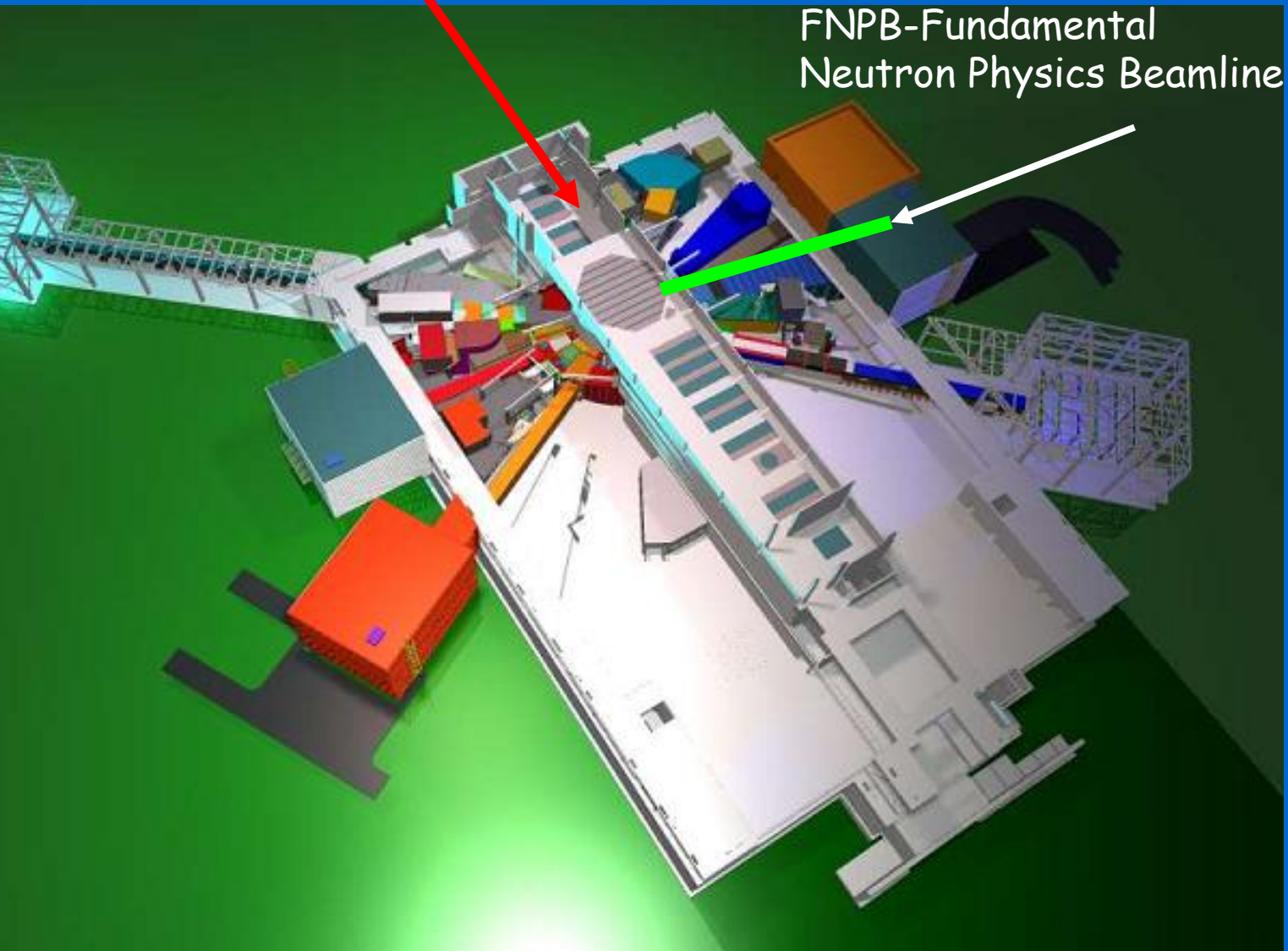
Ideal for development of new moderators and neutron scattering instruments

SNS at ORNL

1.4 MW Spallation Source



SNS Target Hall

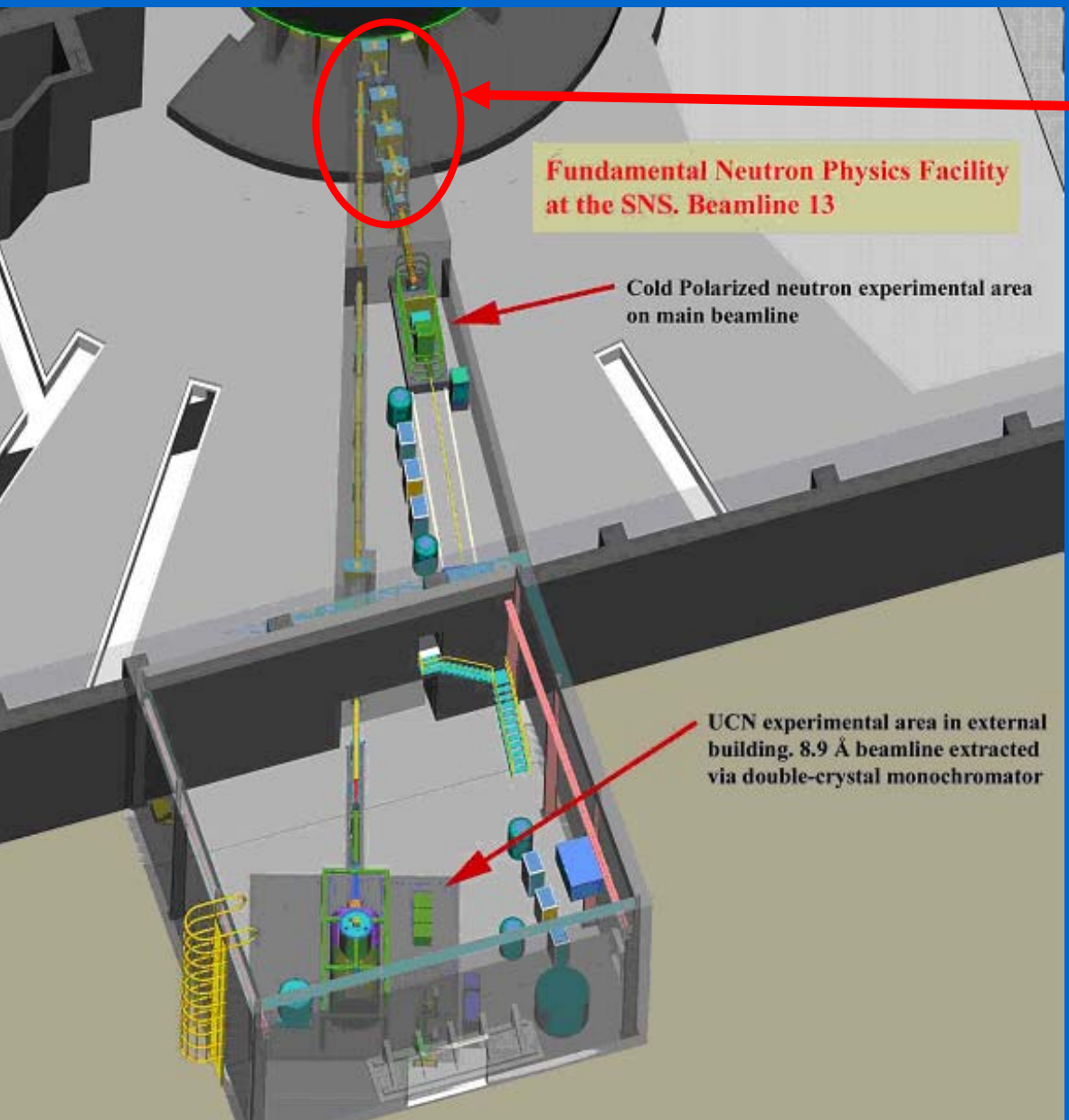


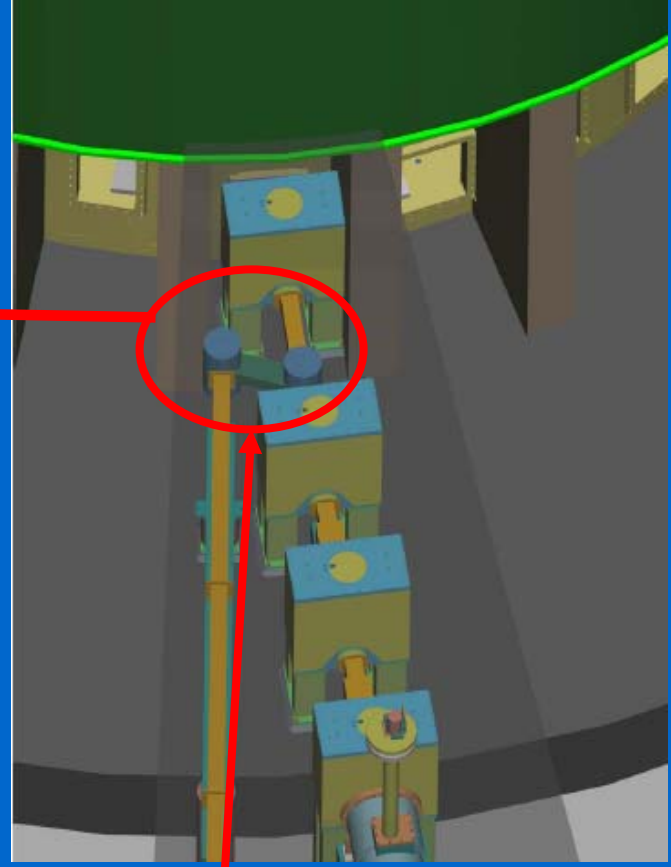
FNPB construction underway

Cold beam available ~2007

UCN line via LHe ~2009

FNPB Beamline





Double monochrometer

Selects 8.9 Å neutrons for UCN via LHe

SNS EDM Experiment

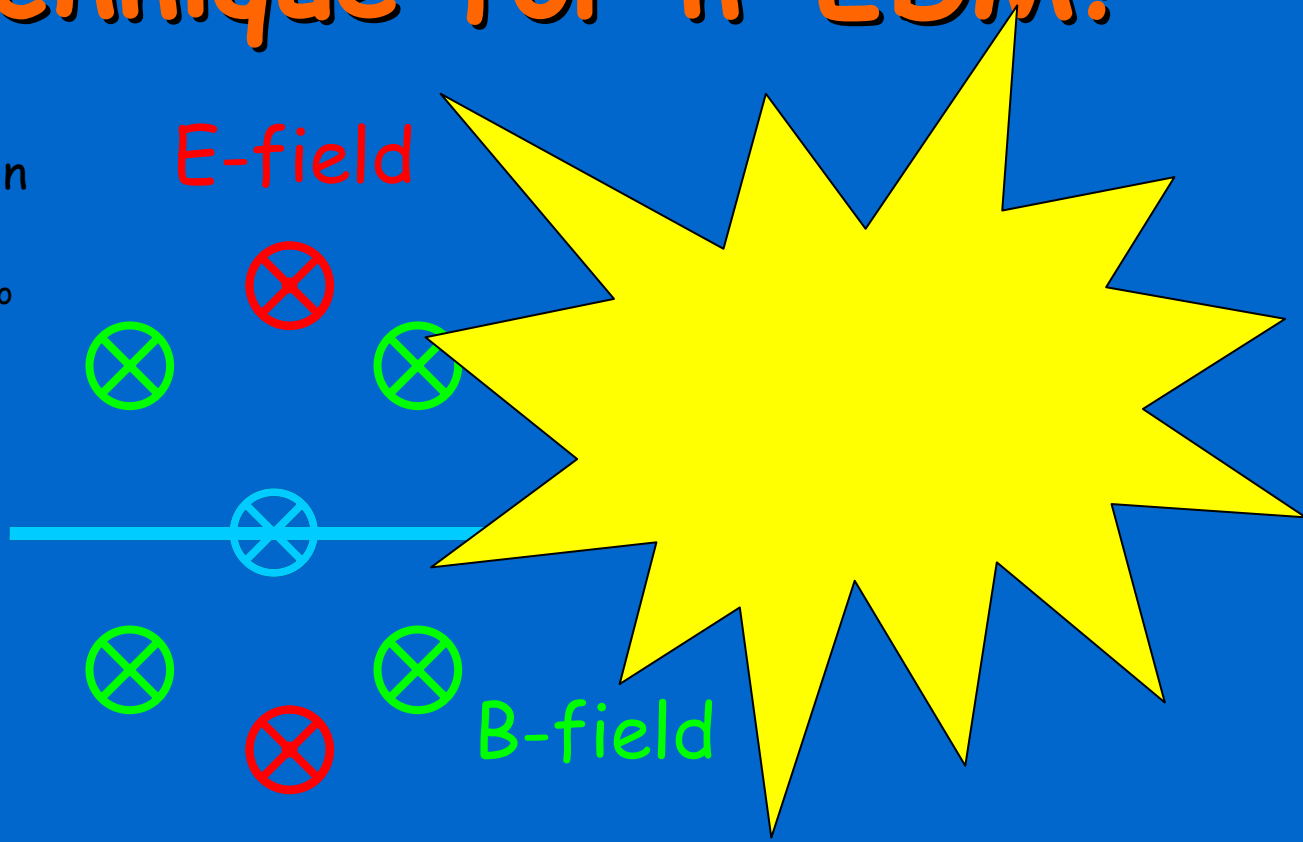
Based on Golub & Lamoreaux (94) concept:

- Produce UCN in superfluid ^{4}He
- Use higher $|\vec{E}|$ field in ^{4}He
- Use polarized $^3\vec{H}e$ as comagnetometer
- Measure precession frequency via n-capture on $^3\vec{H}e$
- Can also "dress" the 3He and neutron spin
  - Extra RF field gives $\omega_{^3\mathrm{He}} = \omega_{\mathrm{n}}$

New Technique for n-EDM?

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

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

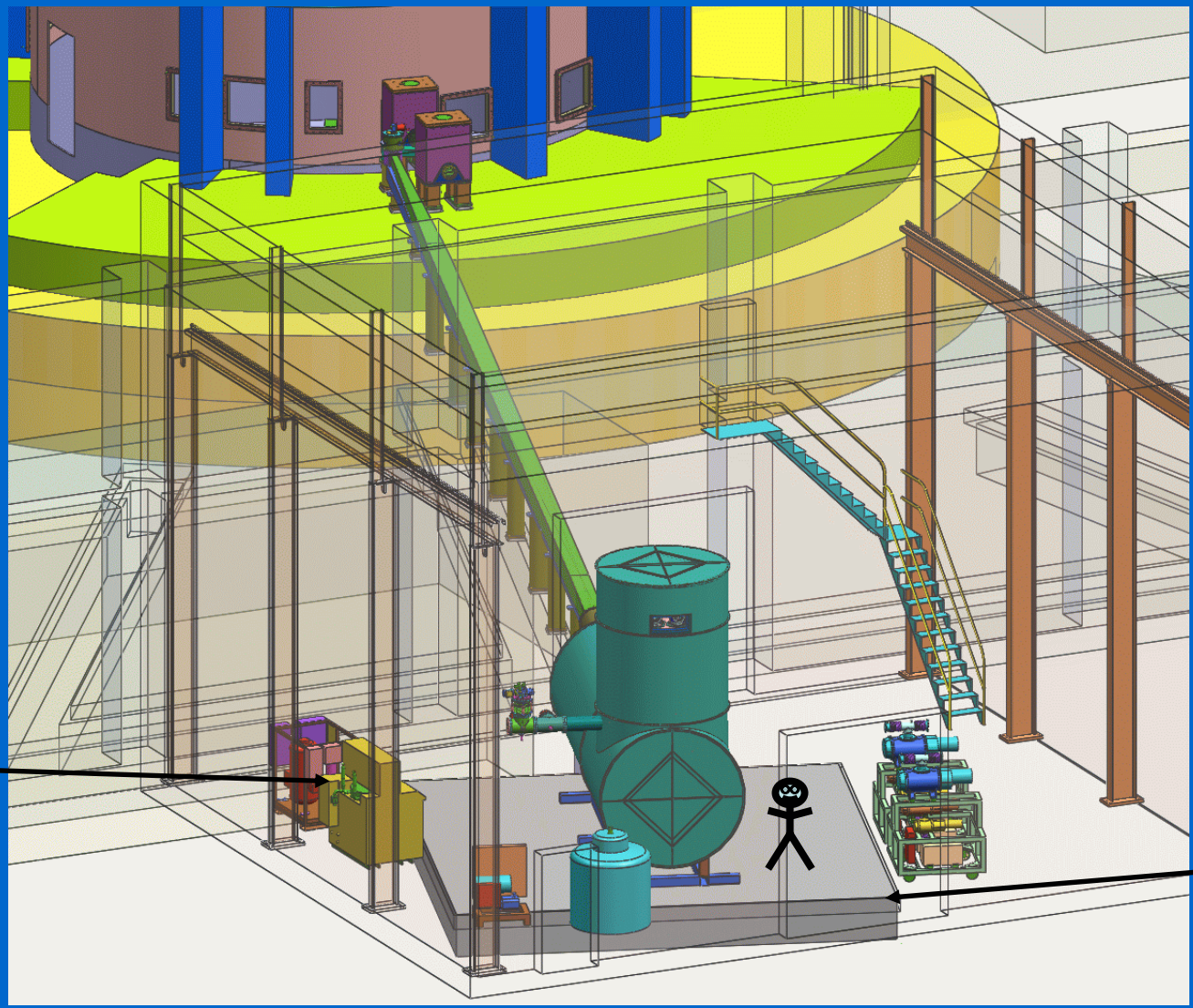


EDM Sensitivity

Paramter	EDM @ ILL (1999)	EDM @ SNS
N_{UCN}	1.3×10^4	2×10^7
$\vec{E}$	4.5 kV/cm	50 kV/cm
T_m	140 s	500 s
m (cycles/day)	270	50
σ_d (e-cm)/day	6×10^{-25}	1.5×10^{-27}

$$\sigma_d \cong \frac{\hbar}{4 |\vec{E}| T_m \sqrt{m N_{UCN}}}$$

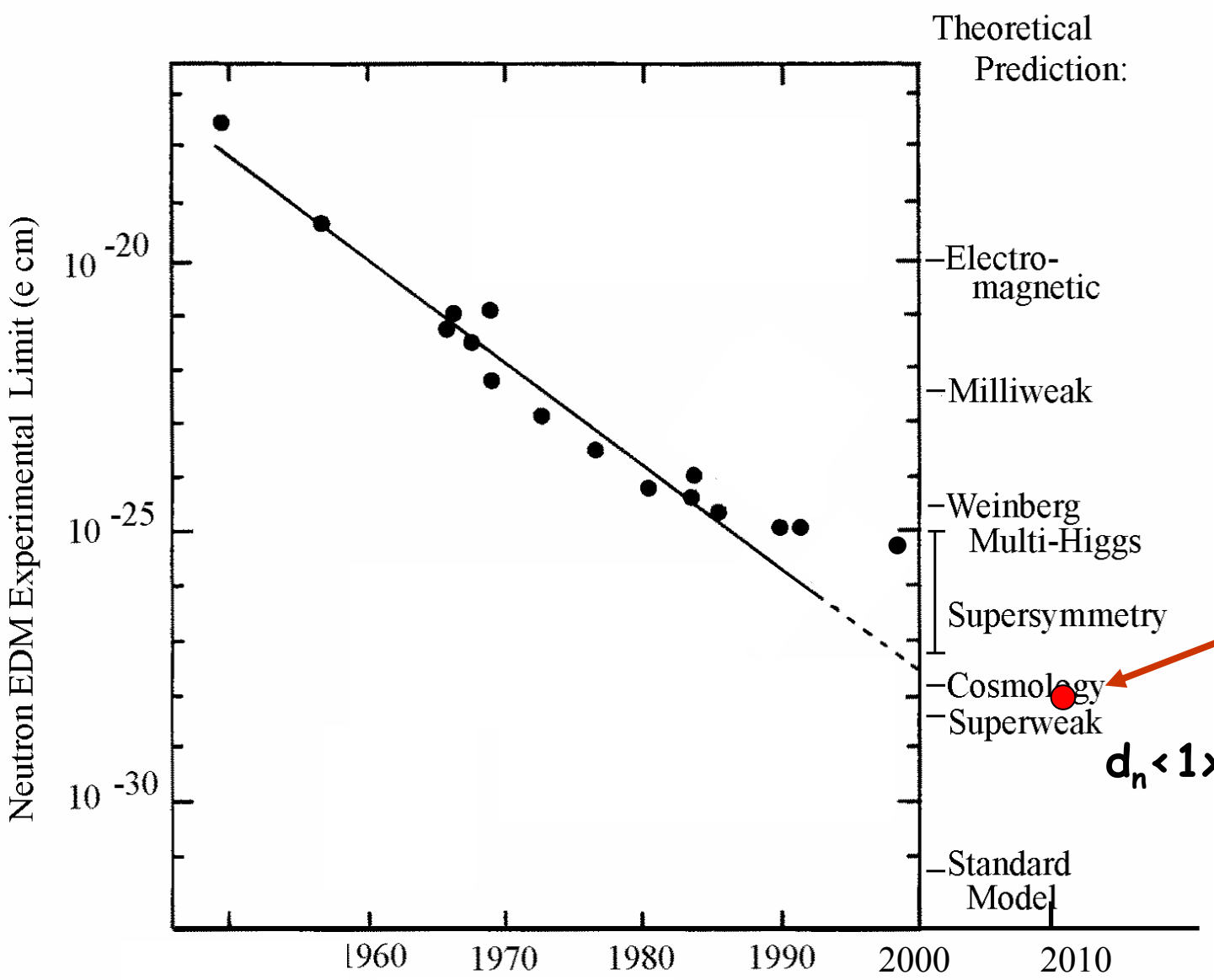
n EDM Experiment at SNS



Status of SNS neutron EDM

- Feasibility of <1x10-28 e-cm demonstrated (2003-2005 R&D)
- Internal Review 2/05
  - Construction Possible: FY07-FY10
  - Cost: 15-18 M$
- Collaboration prepared to begin construction in FY07

n-EDM Sensitivity vs Time



Worldwide n-EDM Sensitivity

Facility	Limit (e-cm)	Date	Technique	Status
ILL (ILL-99)	7.5×10^{-26}	1999	20-ℓ cell Hg magnetometer	Latest publication
ILL	3.4×10^{-26}	2003	20-ℓ cell Hg magnetometer	(ILL-99) Now running
ILL	$8\text{-}20 \times 10^{-27}$	2004-6	20-ℓ cells Hg magnetometer	(ILL-99) Possible continuation
PSI	2×10^{-27}	2006-8	Eight 3-ℓ cells neutron/Cs magnetometer	Proposal funded
ILL	$1\text{-}20 \times 10^{-28}$	2006-9	Superfluid He trap, neutron magnetometer	Phase 1 underway
SNS	$3\text{-}12 \times 10^{-29}$	2010-12	Superfluid He trap, ^{3}He magnetometer	Proposal under review

Adapted from NSAC Subcommittee Report on Fundamental Physics with Neutrons (03)

Outlook

- Program to Test Fundamental Symmetries with neutrons is developing in the US
- There exists an active program worldwide
- Compelling science is anticipated within the next 5-10 years
  - NN weak current
  - n β-decay (correlations & lifetime)
  - n EDM