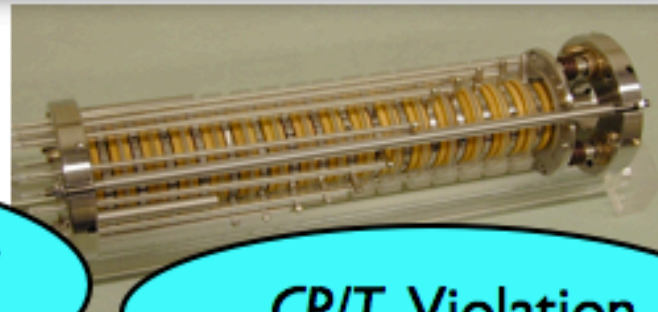
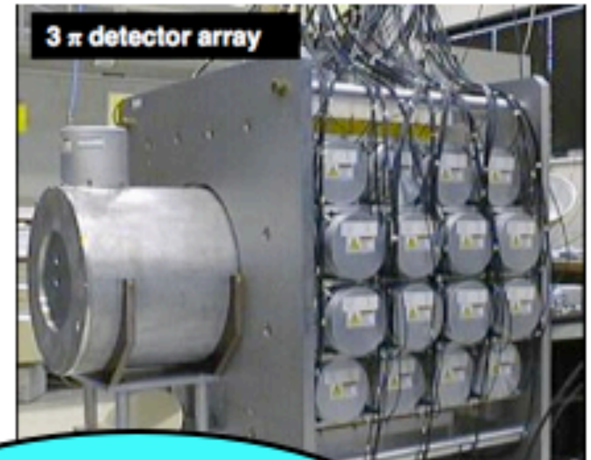
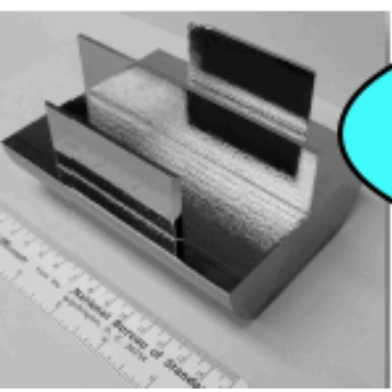
# Physics with Cold Neutrons






- Hadronic Parity Violation
- *CP/T* Violation
- Beta Decay
- Few-body Interactions
- n
- n-$\bar{n}$ Oscillations
- Gravity
- Neutron Interferometry
- Quantum Information

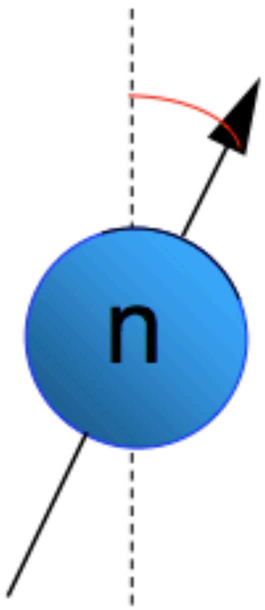


NIST

J. Nico, NIST Physics Laboratory
Workshop on Fundamental Symmetries and Neutrinos
Chicago, August 10, 2012

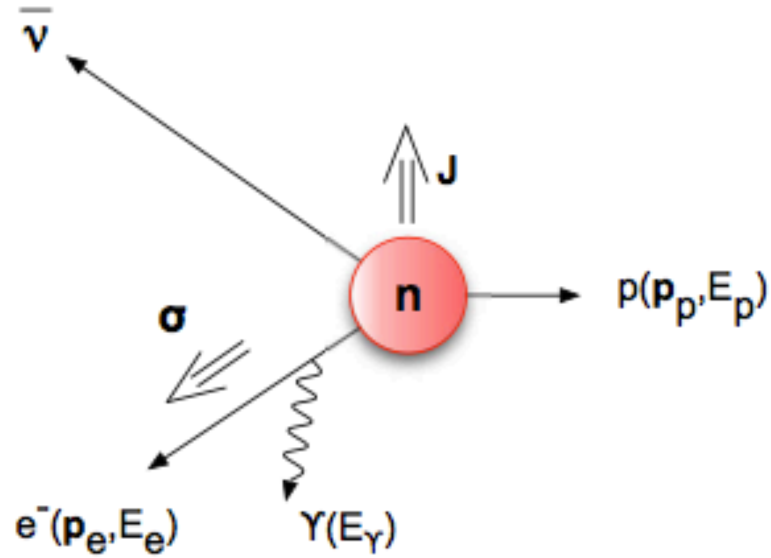
# Cold Neutrons for Nuclear Physics

## Neutron as a probe




- Hadronic parity violation - QCD
- Few-body nuclear physics
- Cross sections
- Scattering lengths
- Neutron charge radius

## Neutron itself




- Neutron lifetime
- Angular correlations (*a, A, b, B, D, ...*)
- n-$\bar{n}$ oscillations

# U.S. Cold Neutron Facilities

**ORNL:** Spallation Neutron Source (SNS)
- FNPB pulsed high-flux cold beam
- Beam time advised by PRAC

**NIST:** Center for Neutron Research
- NG-6 (and NG-C) high-flux beams and neutron interferometry facility
- Beam time advised by BTAC

**LANL:** LANSCE
- FP-12 pulsed cold beam

***Operating costs of these facilities are not borne by DOE or NSF Nuclear Physics***

# Recent Accomplishments

**Hadronic Parity Violation:**

➢ Limit on parity-violating gamma ray asymmetry

- *PRC* (2011)

➢ Limit on parity-violating neutron spin rotation

- *PRC* (2012)

**Beta Decay:**

➢ Observation of neutron radiative decay

- *Nature* (2006)

➢ Limit on *T*-violation in neutron beta decay (emiT)

- *PRL* (2011)

**Interferometry:**

➢ Demonstration of vertical coherence in neutron interferomery

- *PRL* (2008)

➢ Precision measurement of $n$-$^3He$ incoherent scattering length

- *PRL* (2009)

➢ Decoherence-free neutron interferometry

- *PRL* (2011)

# NSAC Subcommittee Report on Neutrons

**Major scientific priorities:**

I. The search for a neutron electric dipole moment with the nEDM experiment.

II. Continuation of the UCNA experiment to obtain improved precision on **λ**, the ratio of the weak axial-vector to vector coupling constants of the neutron.

→ III. Completion of the NPDGamma experiment to obtain a precision measurement of the weak isovector nucleon-nucleon-pion coupling constant.

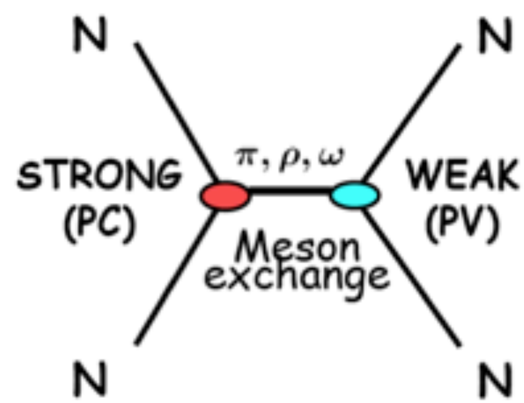
→ IV. Investment in the Nab apparatus with the main goal to determine **λ** to unprecedented precision, using a complementary observable to that of UCNA.

→ V. Continuation of the NIST experiment to perform the most precise cold beam-based measurement of the neutron lifetime.

# Hadronic Parity Violation

➢ The weak interaction among quarks is a fundamental part of the Standard Model, but the hadronic weak interaction between nucleons remains one of the most poorly-understood areas.

➢ If the quarks are close, the weak interaction can produce non-negligible, parity-violating observables. Use hadronic parity violation as a probe of QCD in low energy, non-perturbative regime.




$$\frac{e^2}{M_W^2} / \frac{g^2}{m_\pi^2} \approx 10^{-7}$$

➢ For light quarks and low-Z nuclei, nucleon-nucleon interactions are one of the (calculable) places to study the hadronic weak interaction. Much theoretical work being done with EFT and lattice QCD.

➢ Currrently there are about 10 precise experiments (pp scattering, F-18, p-$\alpha$ asymmetries, Cs anapole moment) for 4 couplings.

# Hadronic Weak Interaction Models

1. ***DDH model*** – uses valence quarks to calculate effective PV meson-nucleon coupling directly from SM via 7 weak meson coupling constants

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

$f_\pi \sim 4.5\text{x}10^{-7}$

$A_\gamma \approx -0.11\, f_\pi^1$

- Observables can be written as their combinations

$$A = a_\pi^1 f_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1$$

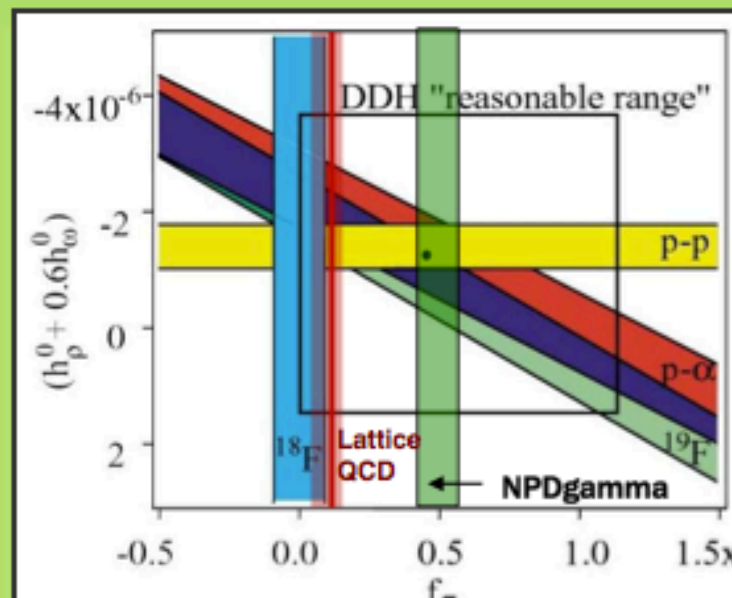
2. ***Lattice QCD***
– J. Wasem, PRC C85 (2012)

$$f_\pi = 1.099 \pm 0.505 \,{}^{+0.058}_{-0.064} \; [\text{x}10^{-7}] \;\; (m_\pi \sim 589\text{MeV})$$

3. ***Effective Field Theory*** (hybrid and pure)
– model-independent

- NN potentials are expressed in terms of 12 parameters, whose linear combinations give us 5 low energy coupling constants
  - connect to 5 parity-odd S-P NN amplitudes

$$A_\gamma^{np} \approx -0.27\, \tilde{C}_6^\pi - 0.09\, m_N \rho_t$$

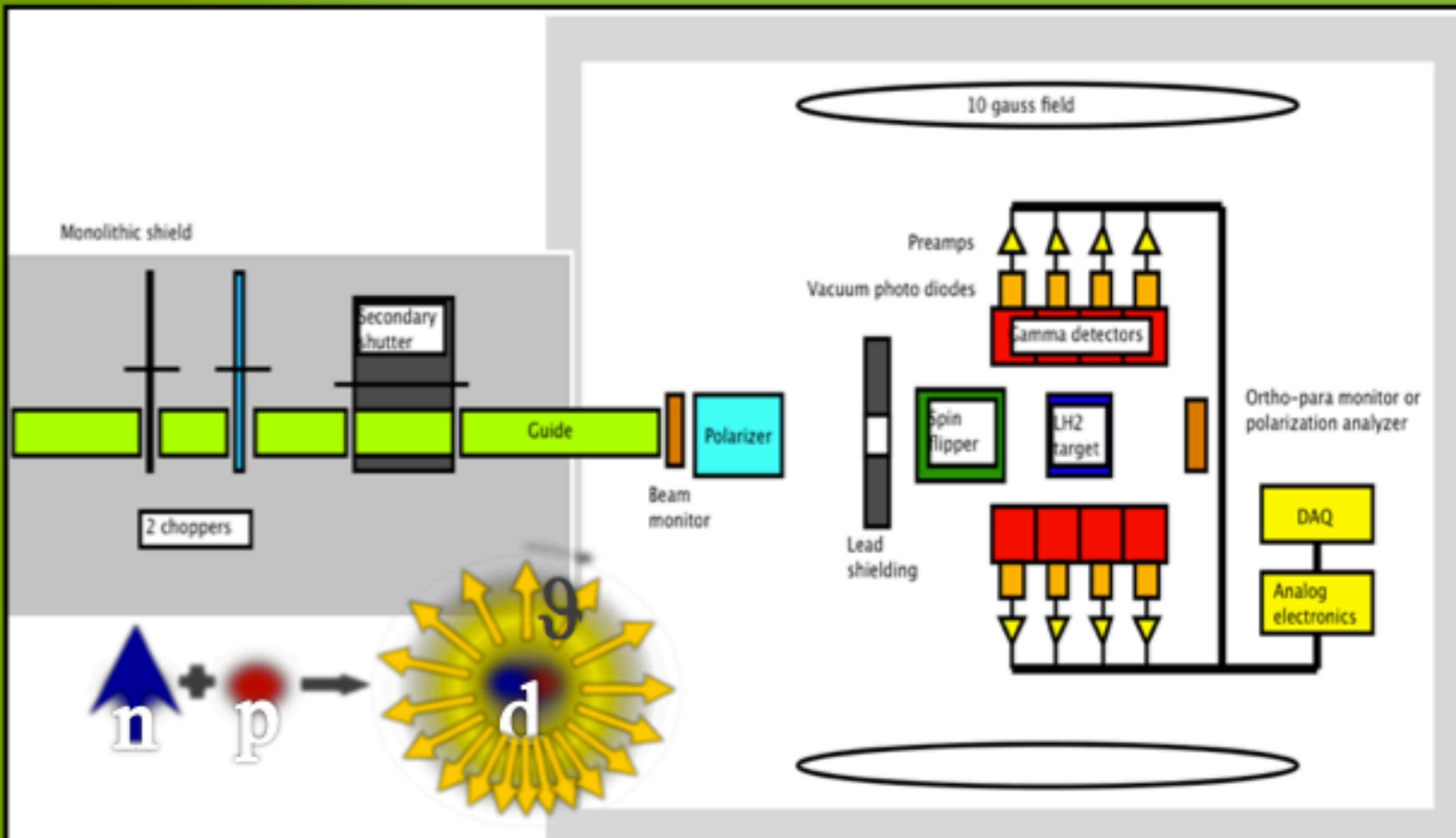



courtesy G. Greene

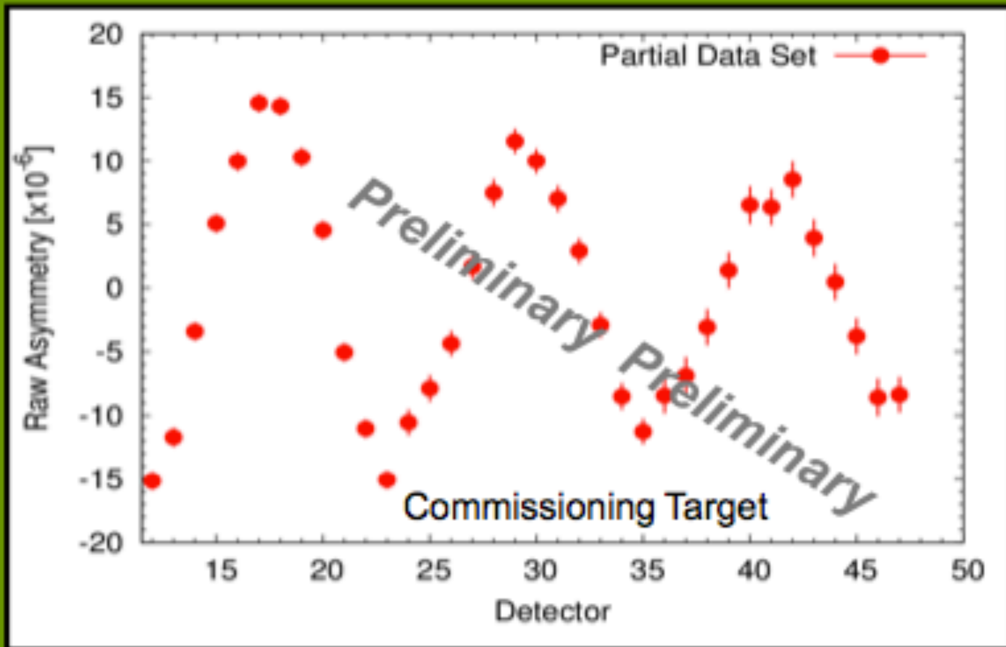
# The NPDGamma experiment at the SNS

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_\gamma \cos\theta\right)$$

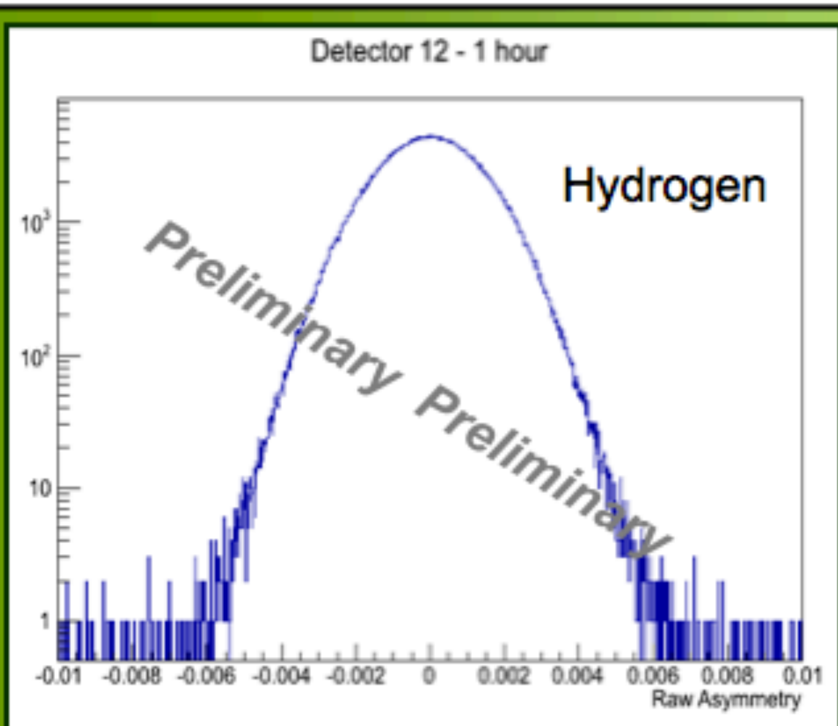
*$A_\gamma$ – directional asymmetry in the gammas emitted from cold neutron capture on protons*

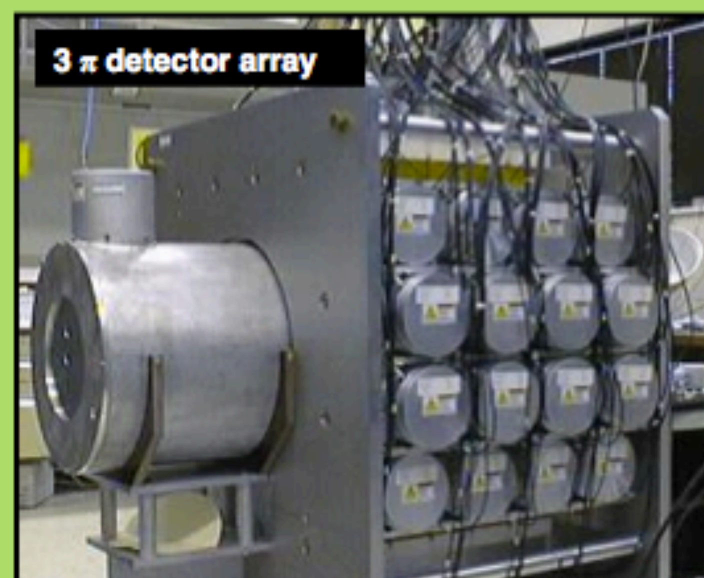



courtesy G. Greene








courtesy G. Greene

# The NPDGamma collaboration

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[22]Duke University
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*DOE and NSF (USA)*
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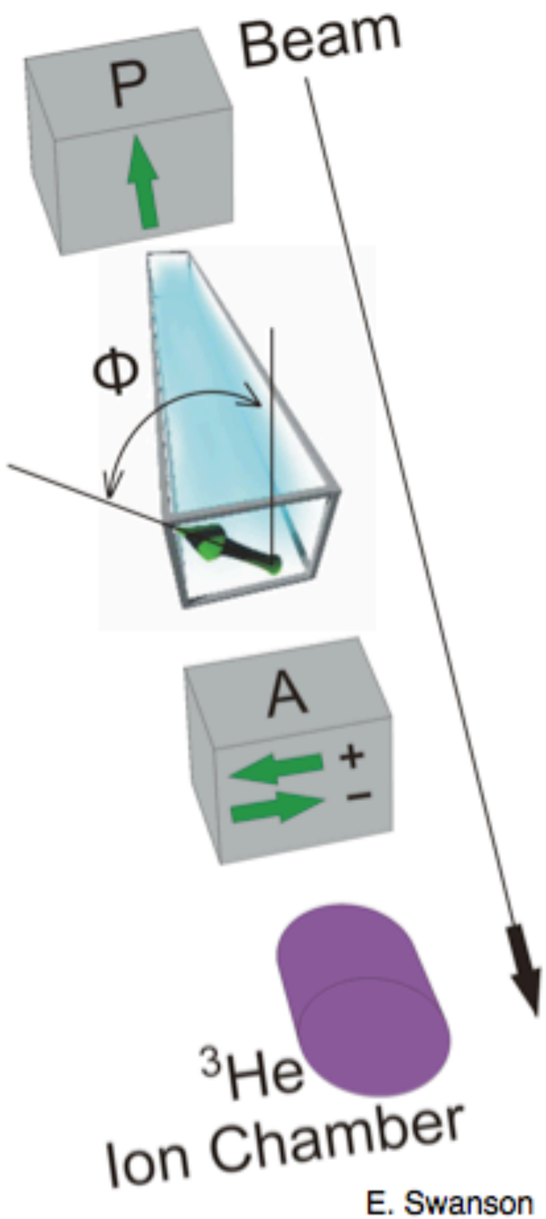
*CONACYT (MEXICO)*
*BARC (INDIA)*

courtesy G. Greene

# Neutron Spin Rotation (NSR) in LHe




➢ It's a *very* small angle measurement O($10^{-7}$) rad.

$$\frac{d\phi_{PNC}}{dz} = (0.1 \pm 1.5) \times 10^{-6}\,\mathrm{rad/m}$$ Dmitriev et al 1983

➢ Target is placed between a crossed (supermirror) polarizer-analyzer pair (analyzing power *PA*).

➢ Output field is rotated every second, and neutrons are counted in a $^3$He ion chamber.

$$sin\phi = \frac{1}{PA}\frac{N_+ - N_-}{N_+ + N_-}$$

***Two critical issues:***

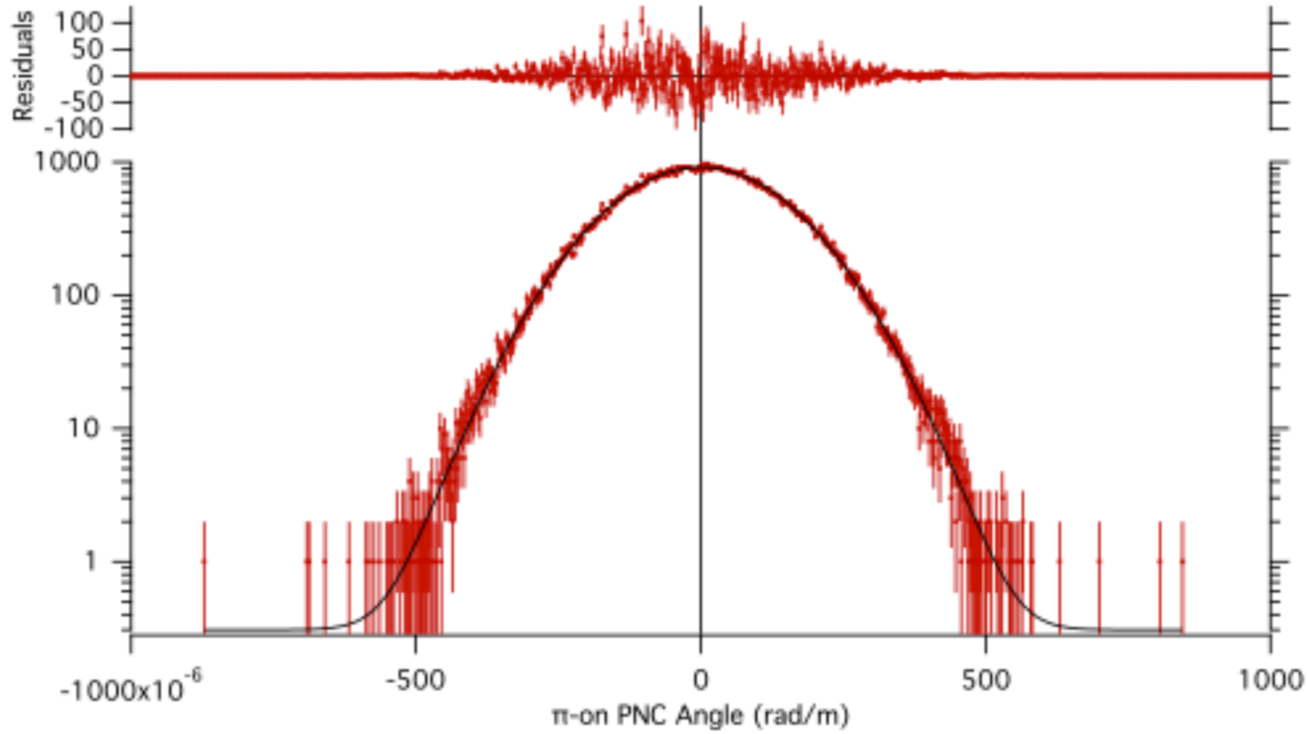
➢ Beam fluctuations exist at O(1%).

➢ Difficult to shield below 100 $\mu$G. Rotation angle from this field is about 3 orders of magnetic greater than $\phi_{PCN}$.

# Systematics and Result

➢ Apparatus acquired data on NG-6 January through May 2008.

➢ Result was published in 2011 and is statistics limited.




$$\frac{d\phi_{PNC}}{dz} = [+1.7 \pm 9.1(stat) \pm 1.4(sys)] \times 10^{-7}\,\mathrm{rad/m}$$

**Collaboration:** Indiana, NIST, Gettysburg, George Washington, Washington, N. Carolina Central, JNIR- Dubna, and Al-Farabi Kazakh National

# Toward an improved NSR measurement

## Statistical Improvement

Expect x40 more polarized neutron flux through apparatus from
1) NIST NCNR expansion and NG-C
2) Increasing apparatus acceptance

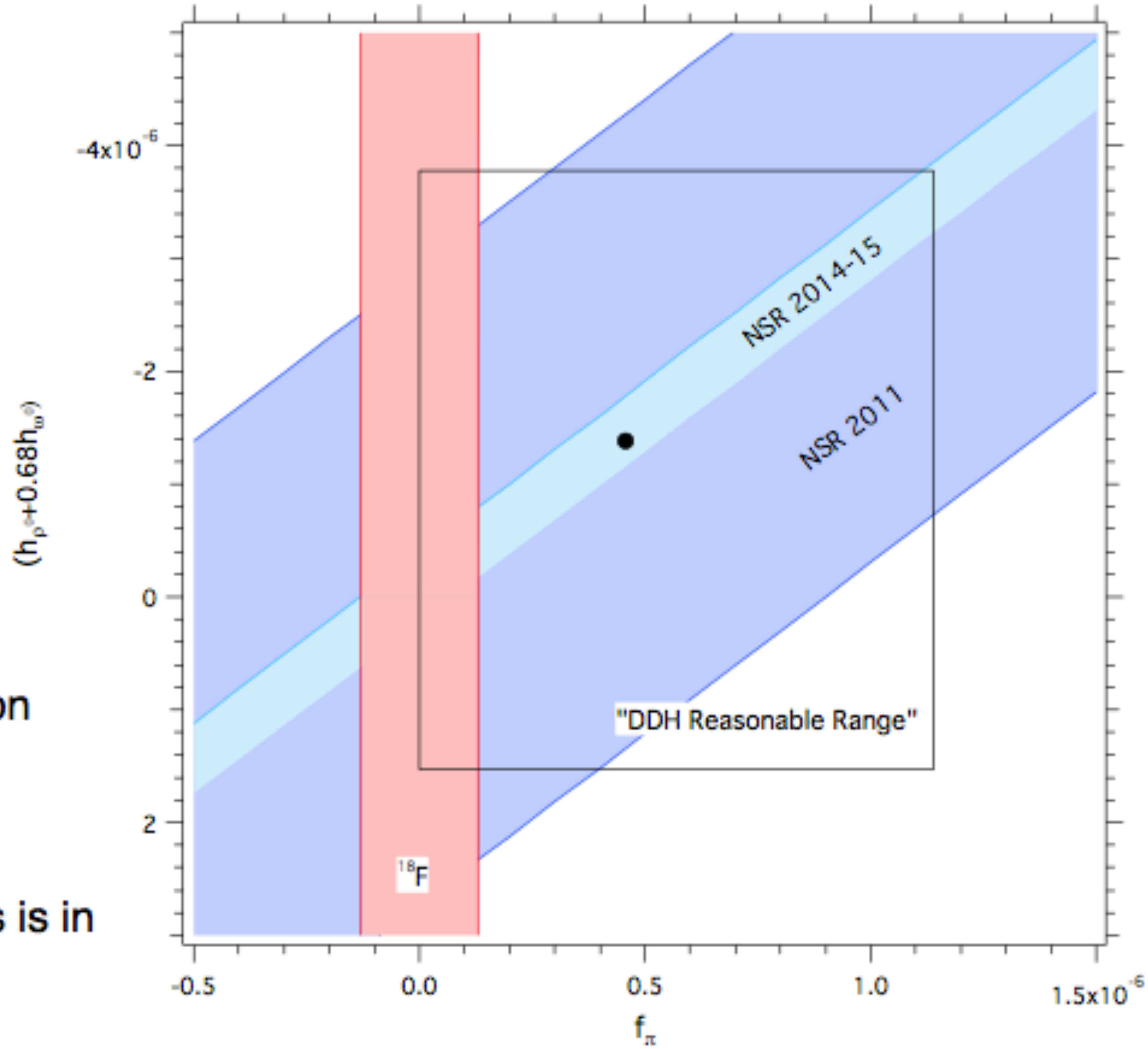
1) Reduce heat load
2) Reduce fill/drain times

## NSR Status

- Redesign in progress: cryogenics, ion chamber, and magnetics.

- Purchase of large area supermirror polarizer and analyzer pair and guides is in progress

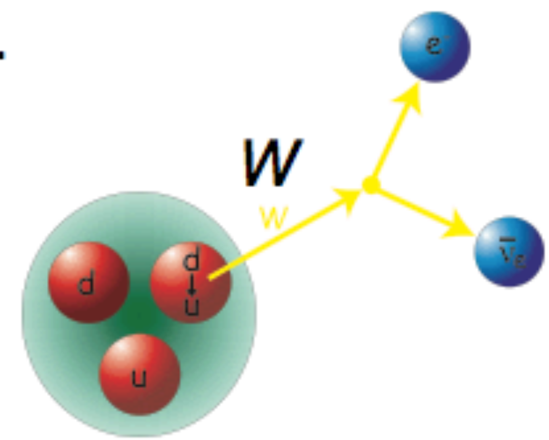
- Mounting of new experiment on NG-C in approximately 2 years.




Goal: $\frac{d\phi_{PNC}}{dz} \leq 2 \times 10^{-7}\,\mathrm{rad/m}$

# Physics from Neutron Decay

- Solar physics: $p + p \rightarrow {}^2H + e^+ + \nu_e$
- Big Bang Nucleosynthesis and light element abundance.
- Test of CKM unitarity; determination of $V_{ud}$.
- Over-constrained measurements give model-independent SM checks.
- Look for scalar, tensor forces, non-SM physics.
- Measurement of radiative corrections.
- New source of time-reversal (*CP*) violation?



# Neutron Decay

$$dW \propto (g_V^2 + 3g_A^2)F(E_e)[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_eE_\nu} + b\frac{m}{E_e} + \vec{\sigma_n}\cdot(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e}\times\vec{p_\nu}}{E_eE_\nu})]$$

---

## Electron-antineutrino correlation

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2} = (-0.103 \pm 0.004)$$

## Lifetime

$$\tau = \frac{1}{f(1+\delta_R)}\frac{K/ln2}{(1+\Delta_R^V)(g_V^2+3g_A^2)} = (880.1 \pm 1.1)\,\mathrm{s}$$

## Spin-electron asymmetry

$$A = -2\frac{|\lambda|^2 + |\lambda|cos\phi}{1+3|\lambda|^2} = (-0.1176 \pm 0.0011)$$

## Coupling ratio

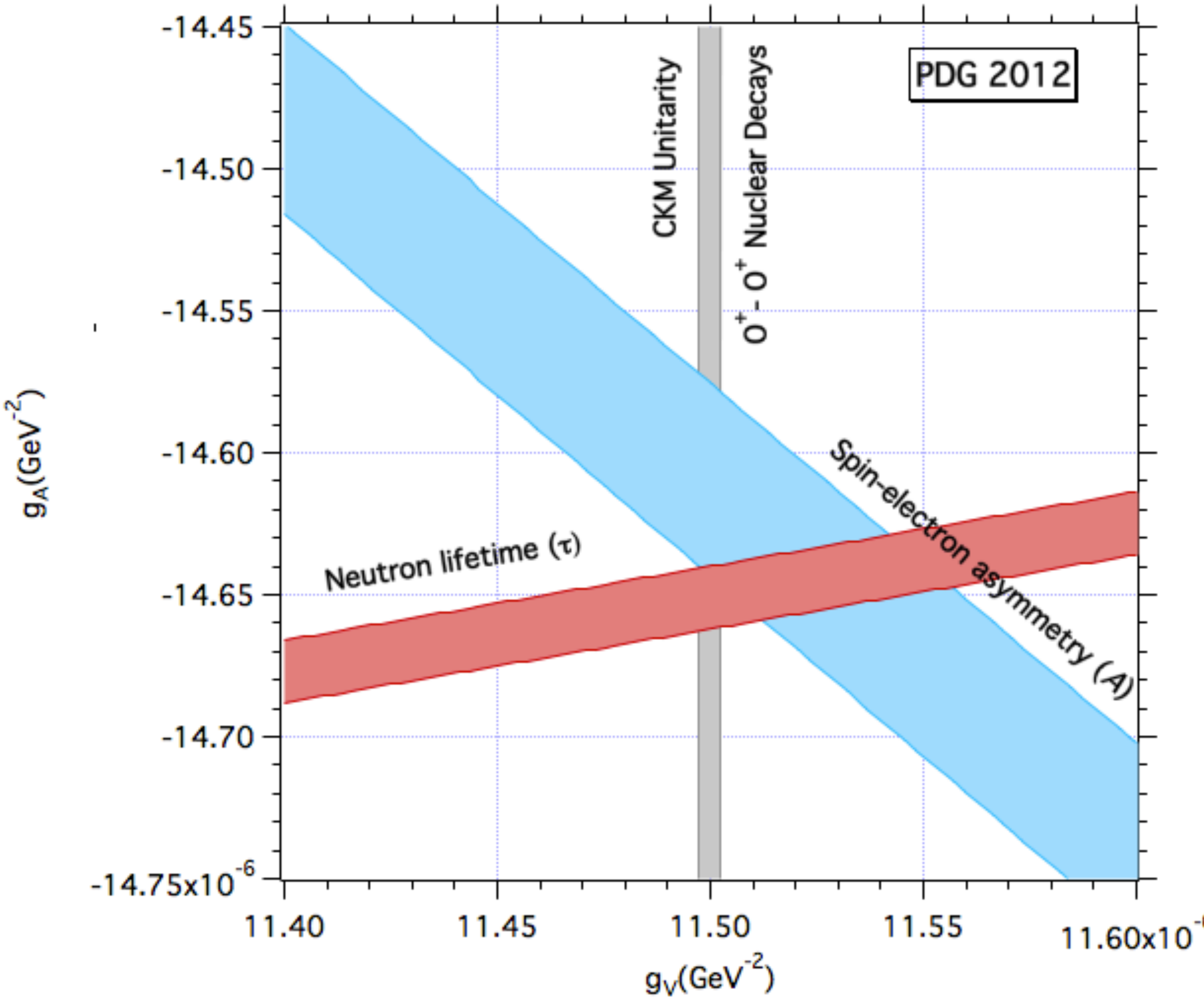
$$\lambda = \frac{|g_A|}{|g_V|}e^{i\phi} = (-1.2701 \pm 0.0025)$$

## Spin-antineutrino asymmetry

$$B = 2\frac{|\lambda|^2 - |\lambda|cos\phi}{1+3|\lambda|^2} = (0.9807 \pm 0.0030)$$

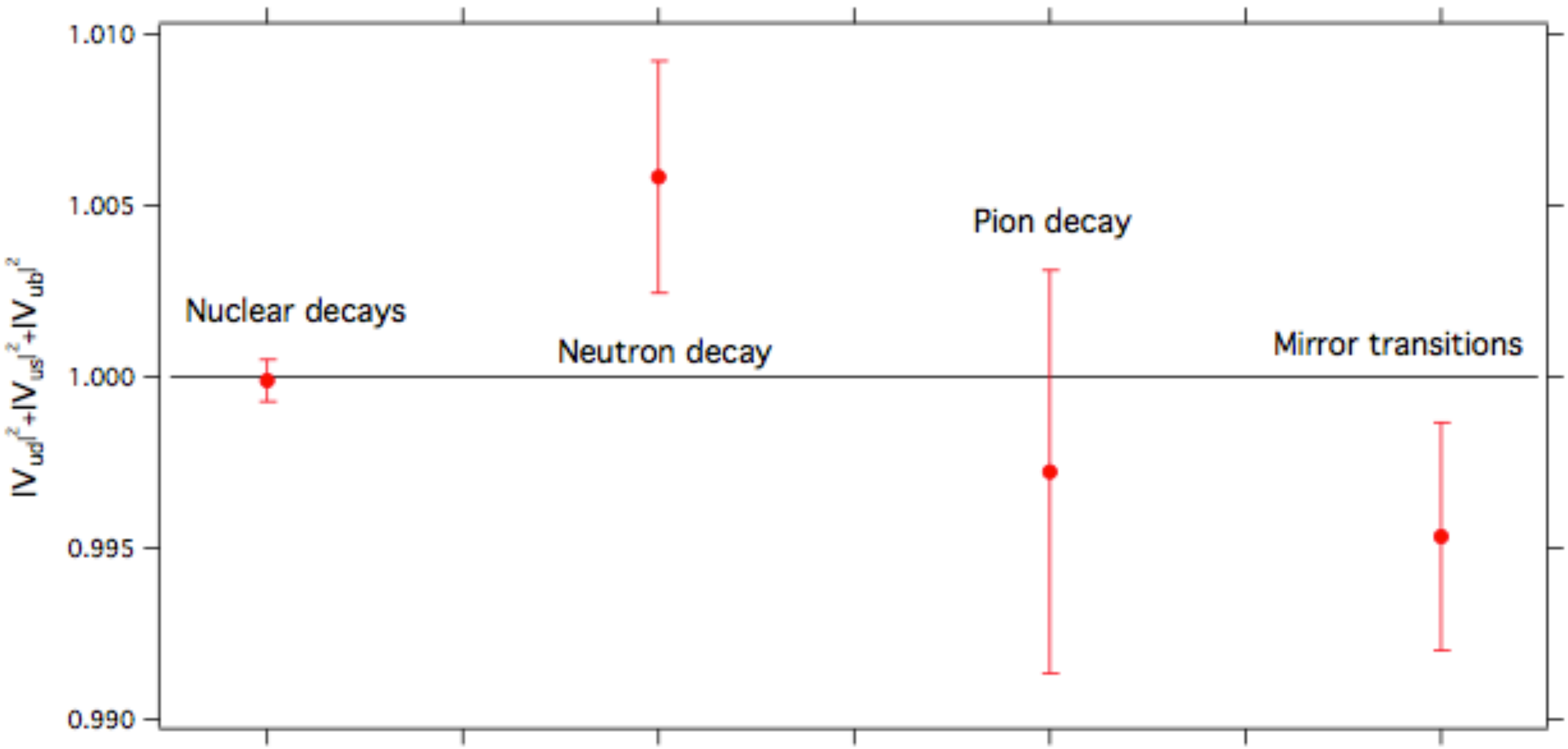
J. Beringer et al. (PDG) Phys. Rev. D **86** 010001 (2012)

Jackson, Treiman, Wyld, *Nucl. Phys.* **4**, 206 (1957)



PDG 2012
CKM Unitarity
0+ - 0+ Nuclear Decays
Spin-electron asymmetry (A)
Neutron lifetime (τ)
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75x10-6
gA(GeV-2)
11.40
11.45
11.50
11.55
11.60x10-6
gV(GeV-2)

# Status of First Row CKM Unitarity



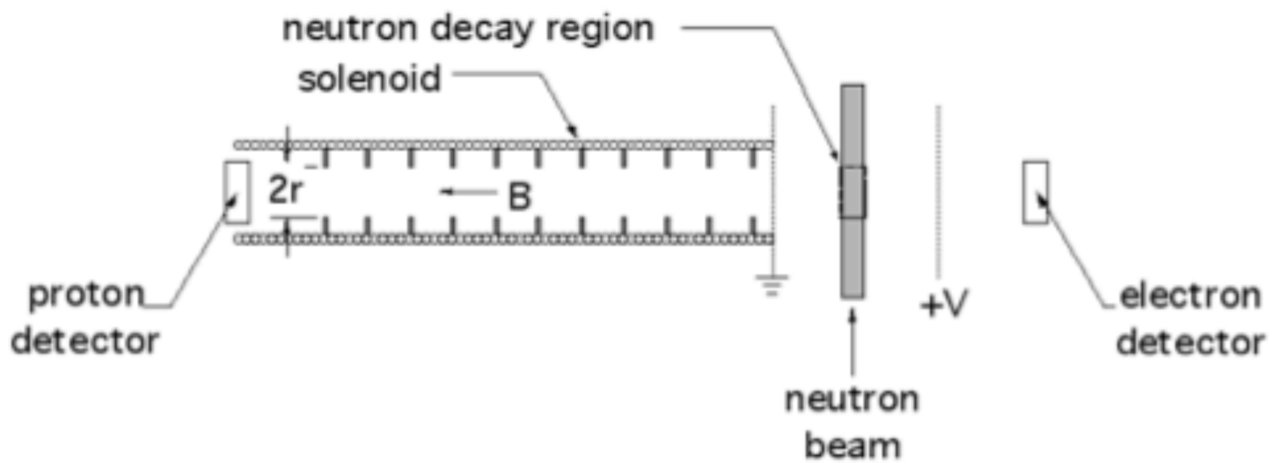

Caveats:

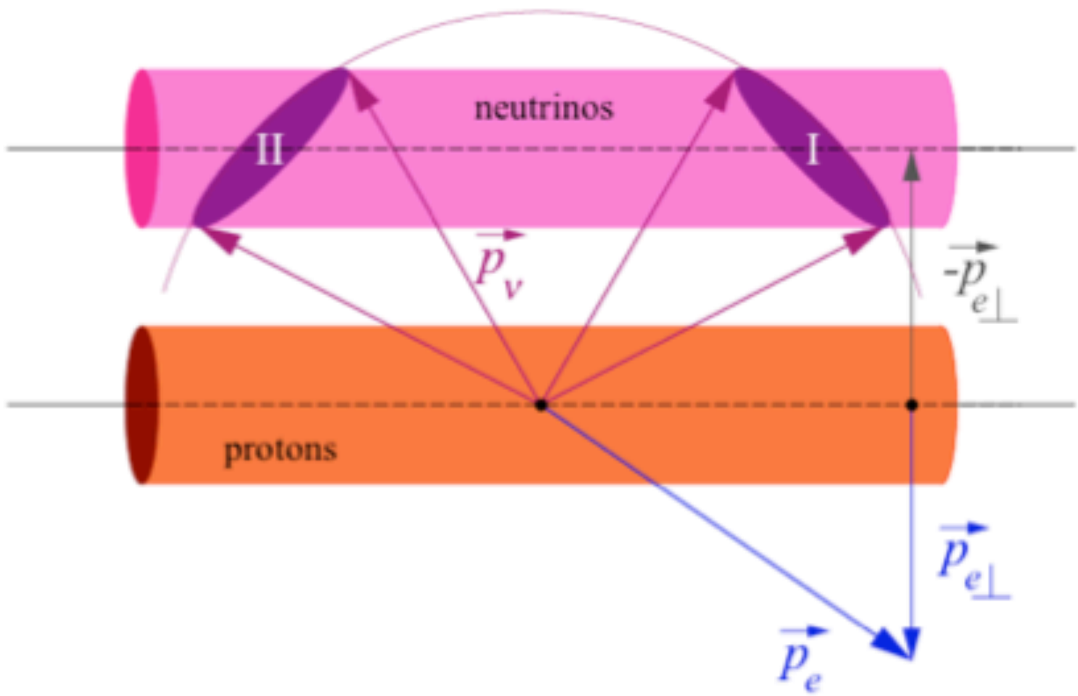
- PDG scaling factors for both *A* and lifetime.
- PDG 2012 only. Does not include final UCNA or PERKEO results.

# aCORN

## A Novel Method to Measure *a*

(Yerozolimsky and Mostovoy, 1996)

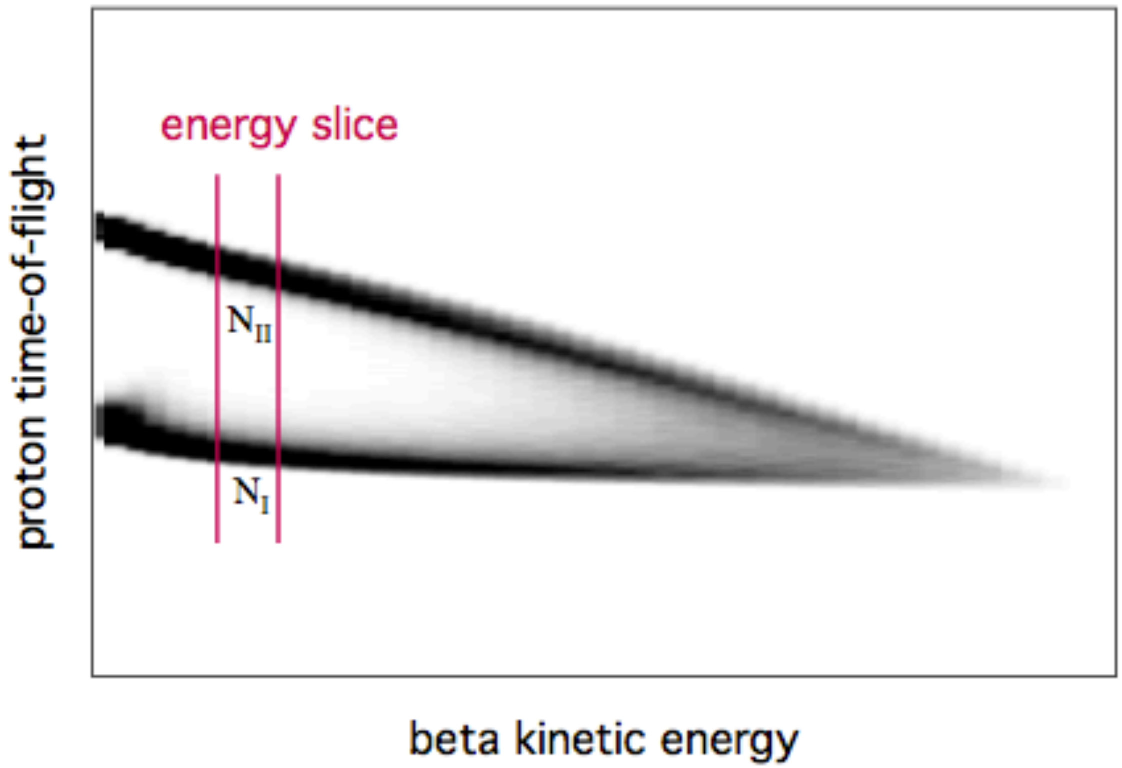



courtesy F. Wietfeldt

# aCORN

We separate groups I and II by the beta energy and time-of-flight between beta and proton detection.

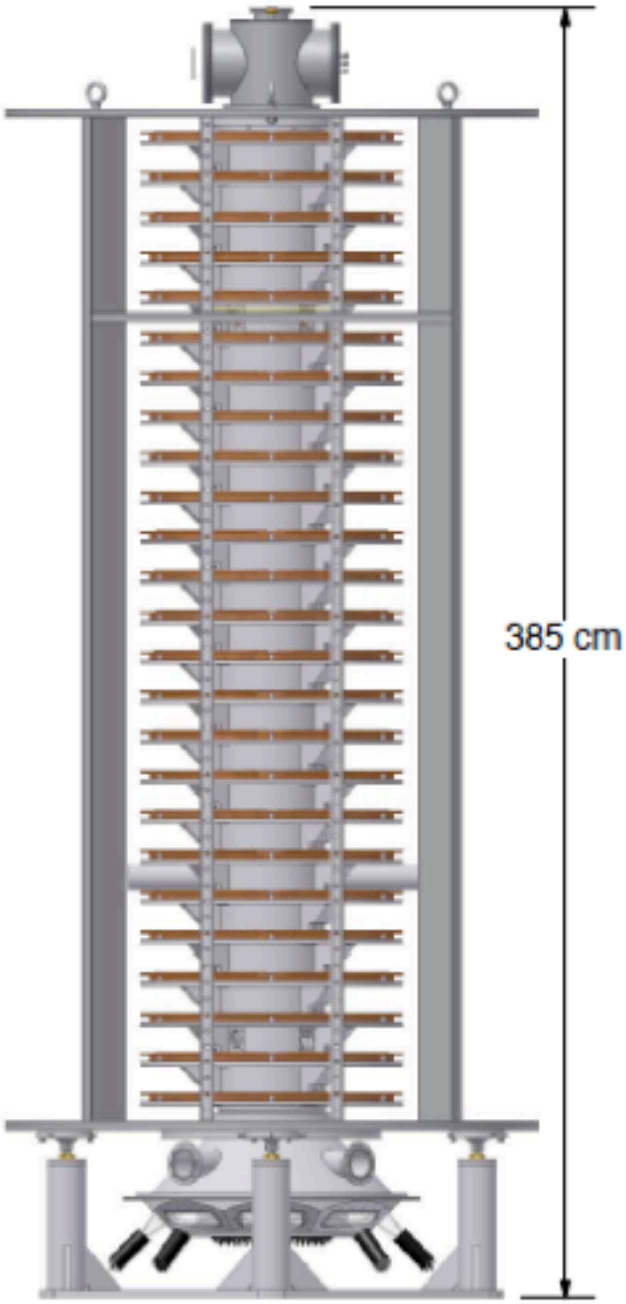


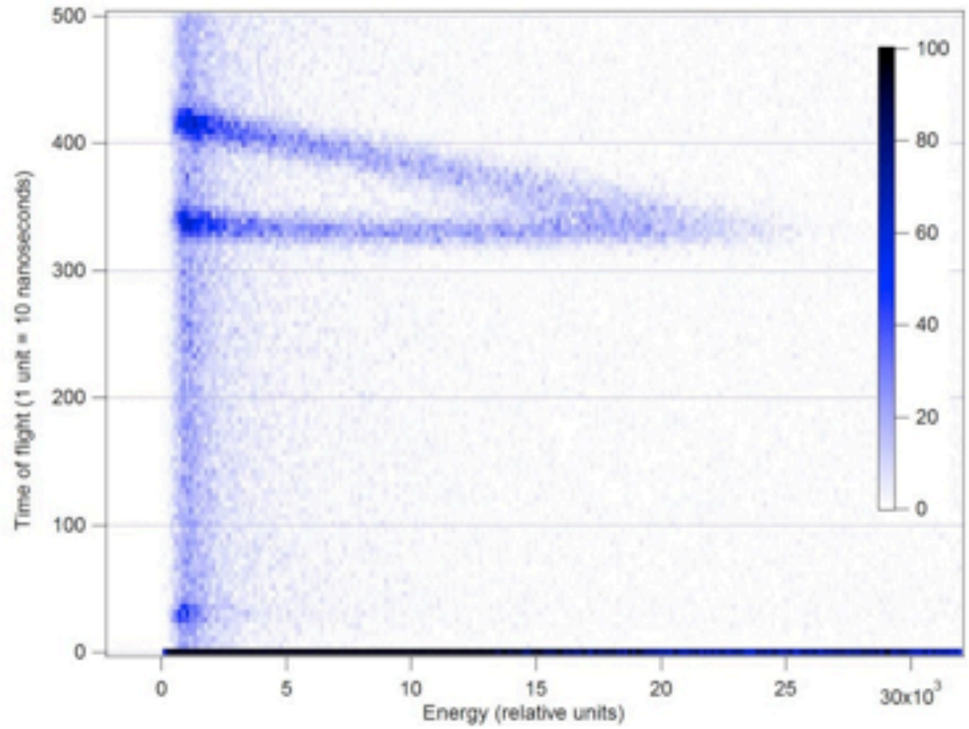

$$a\left(E_\beta\right) = \frac{1}{v_\beta} K\left(E_\beta\right)\left(\frac{N_I - N_{II}}{N_I + N_{II}}\right)$$

Our goal is a 0.5% measurement (10x improvement)

courtesy F. Wietfeldt

# aCORN




- ➢ Currently online on NG-6.
- ➢ Acquiring data until early 2013 until statistics limited at about 2%.
- ➢ Move to NG-C in 2013; acquire precision data for 5 x $10^{-3}$ measurement of *a.*
- ➢ **Collaboration:** Tulane, Indiana, Hamilton, NIST, DePauw, Harvard, and Sussex

# Nab Experiment

- Measure the electron-neutrino parameter **a** in neutron decay

  with accuracy of $\boxed{\frac{\Delta a}{a} \simeq 10^{-3}}$ or $\sim 50\times$ better than:

| | | |
|---|---|---|
| | $-0.1054 \pm 0.0055$ | Byrne et al '02 |
| current results: | $-0.1017 \pm 0.0051$ | Stratowa et al '78 |
| | $-0.091 \pm 0.039$ | Grigorev et al '68 |

- Measure the Fierz interference term **b** in neutron decay

  with accuracy of $\boxed{\Delta b \simeq 3 \times 10^{-3}}$

  current results: **none** (not yet measured in n decay)

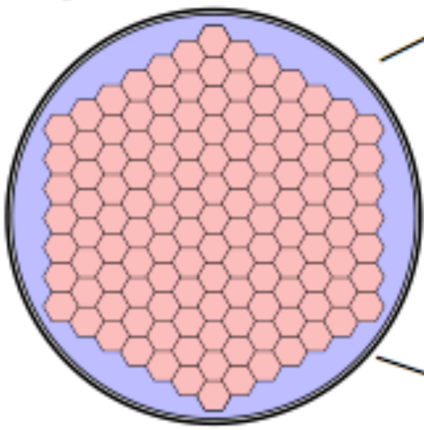
- **Nab** will be followed by the **abBA/PANDA** polarized program to measure **A**, electron, and **B/C**, neutrino/proton, asymmetries with $\simeq 10^{-3}$ relative precision, an independent measurement of $\lambda$.

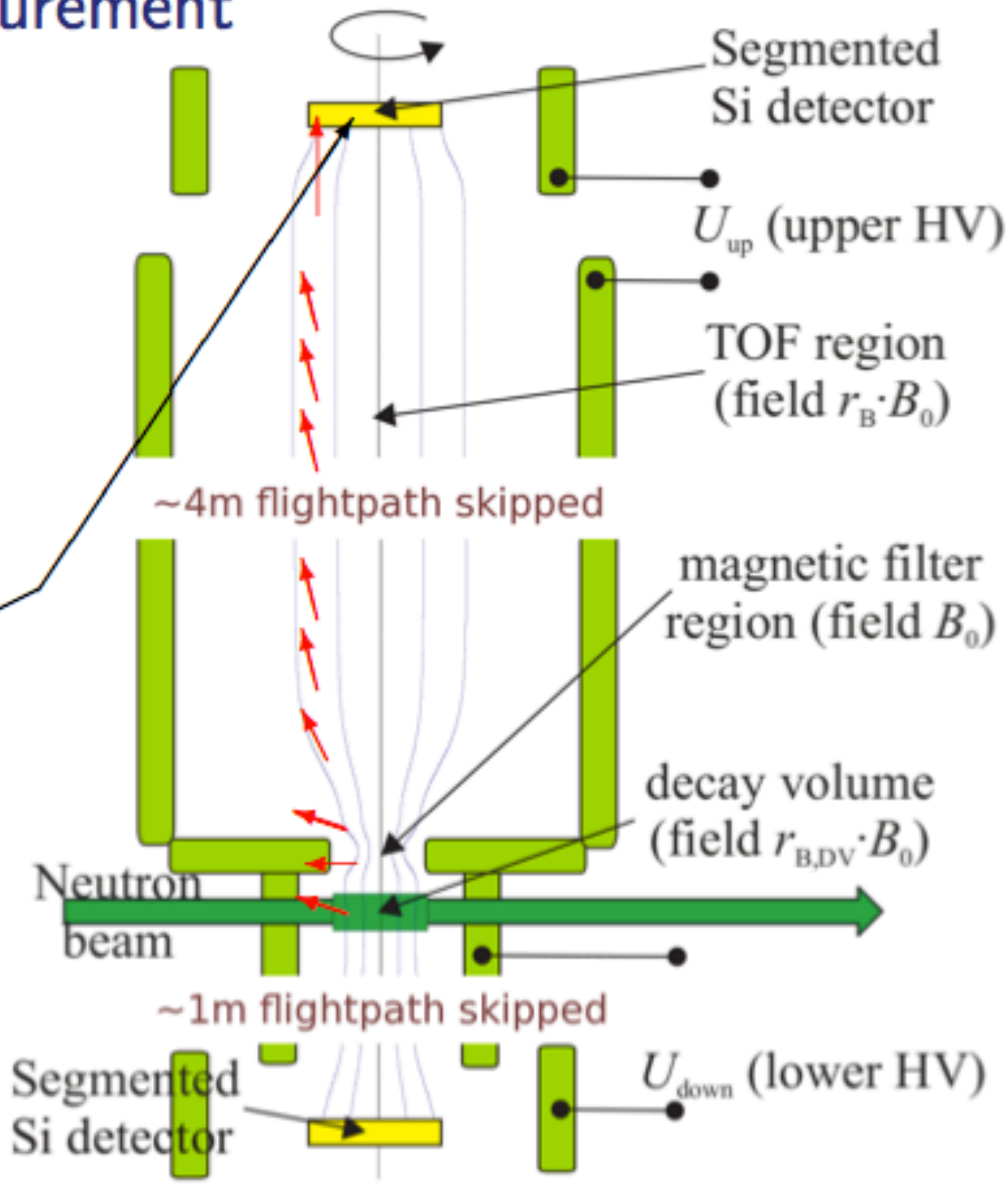
courtesy D. Počanić

# Measurement Principle

## Nab principles of measurement

- Collect and detect both electron and proton from neutron beta decay.
- Measure $E_e$ and $TOF_p$ and reconstruct decay kinematics
- Segmented Si det's:






**Collaboration:** Virginia, Michigan, Tennessee, ORNL, LANL, Arizona State, Kentucky, N. Carolina State, New Hampshire, and UNAM



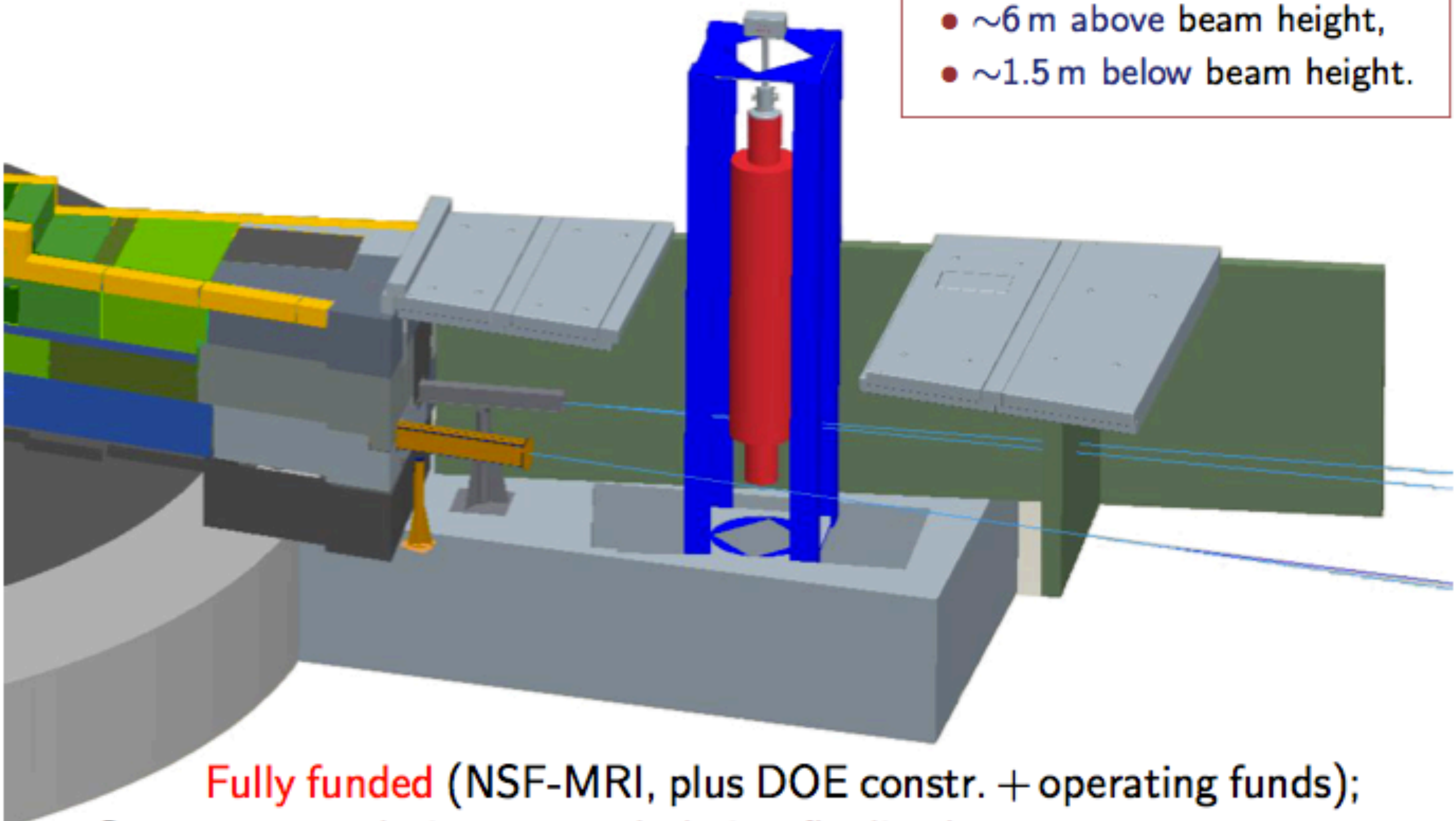
courtesy D. Počanić

# Nab at the SNS

## Nab apparatus in FnPB

Apparatus extends:

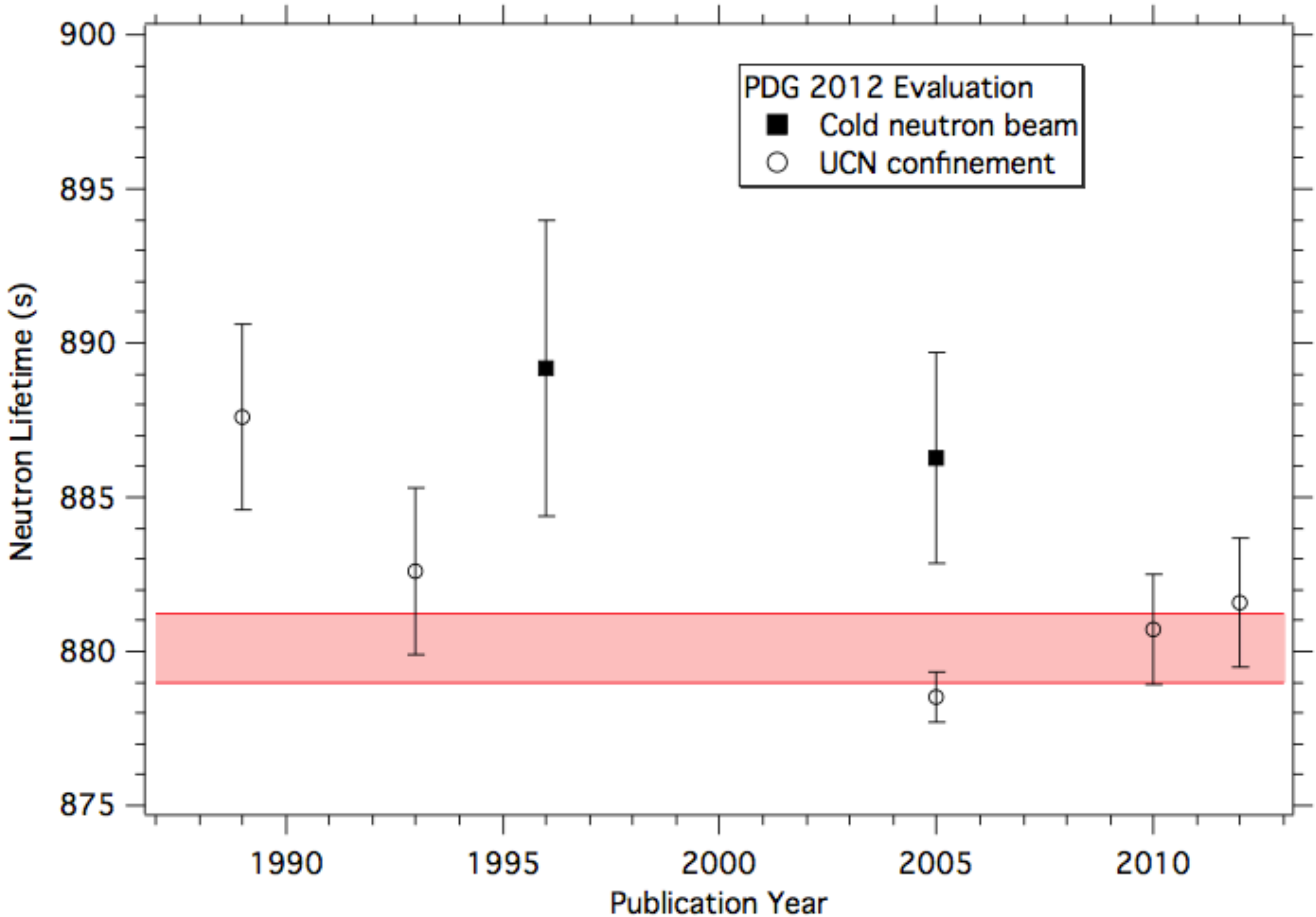
- ~6 m above beam height,
- ~1.5 m below beam height.



Fully funded (NSF-MRI, plus DOE constr. + operating funds);
Spectrometer design currently being finalized;
Experiment projected to be ready for beam sometime in 2015.

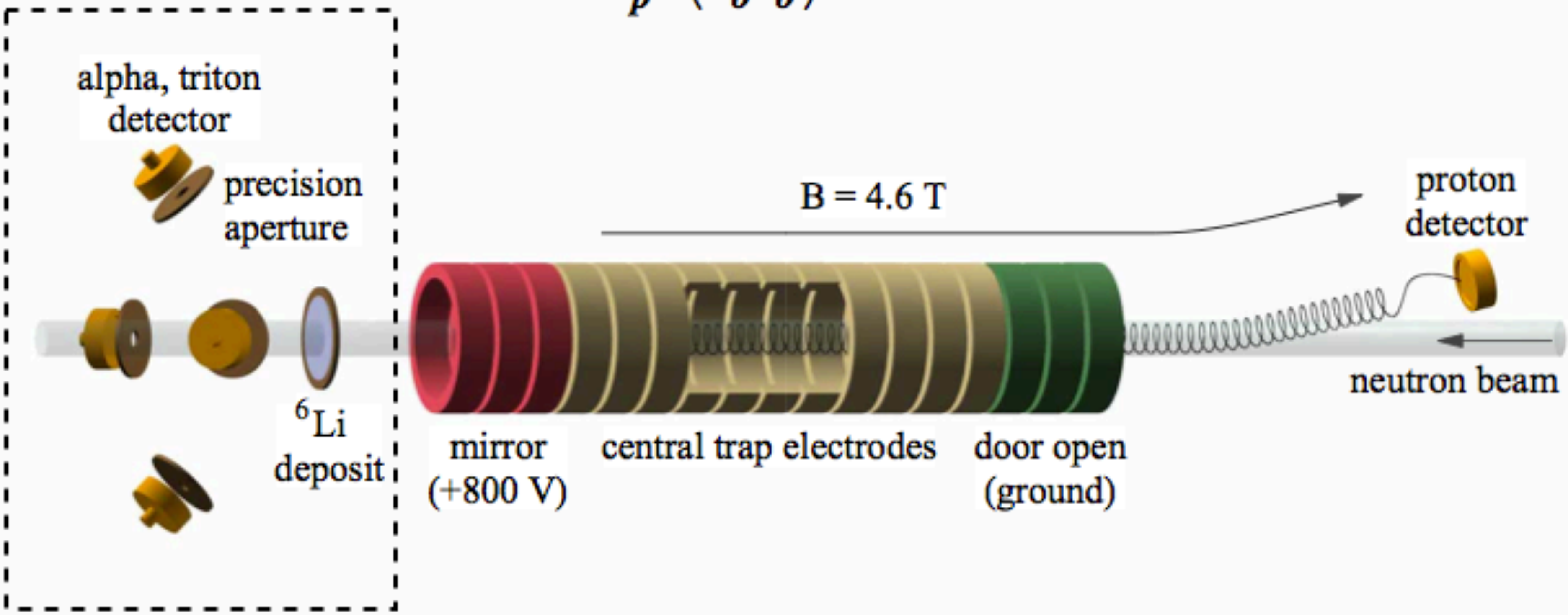
courtesy D. Počanić

# Status of the Neutron Lifetime - 2012



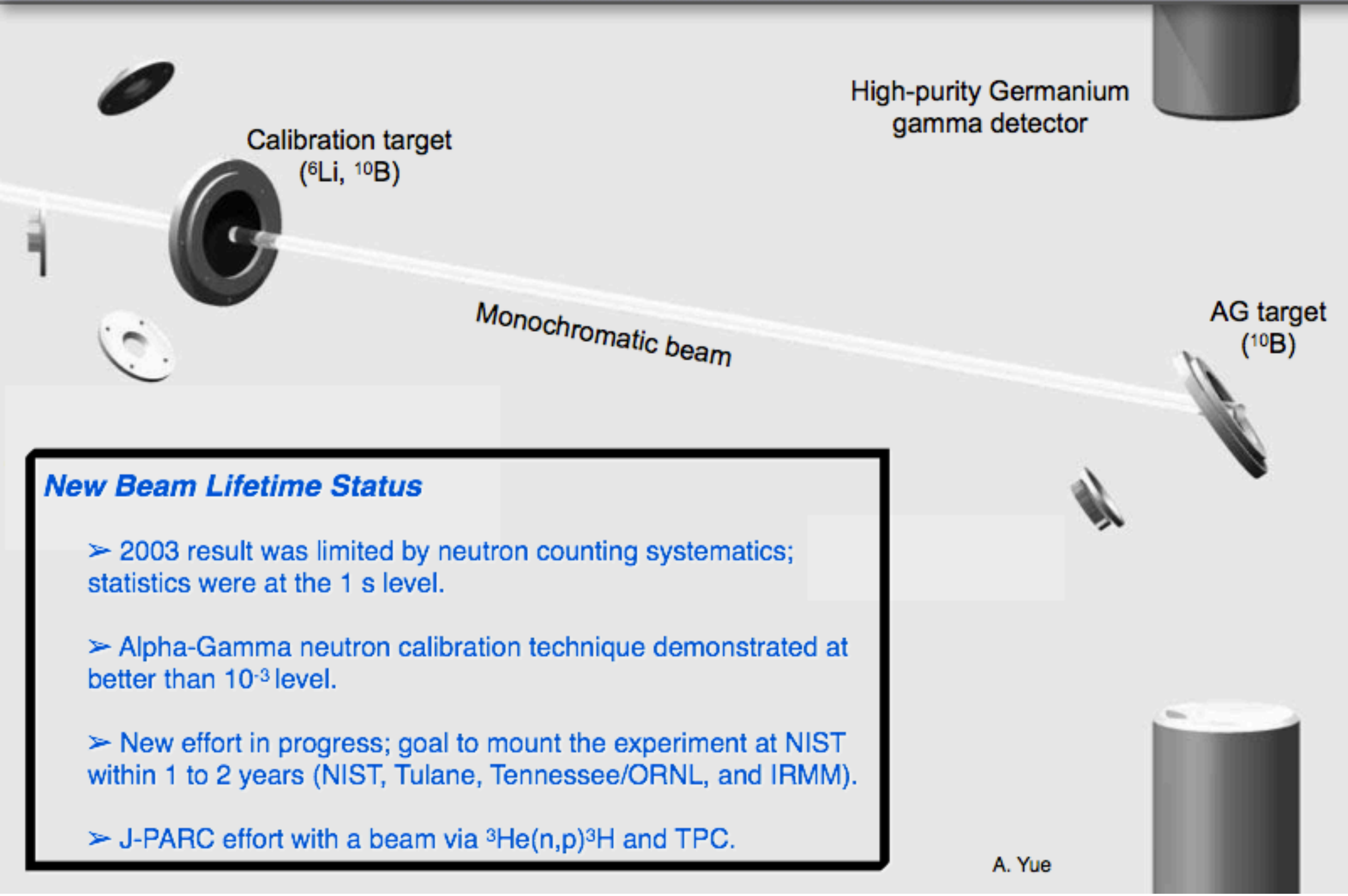
# 2003 Measurement in Cold Beam

$$\tau = \frac{\dot{N}_{\alpha+t}}{\dot{N}_p}\left(\frac{\varepsilon_p}{\varepsilon_o v_o}\right)(nl + L_{end})$$




Requires absolute knowledge of neutron and proton counting.
Fit for lifetime and end effects.

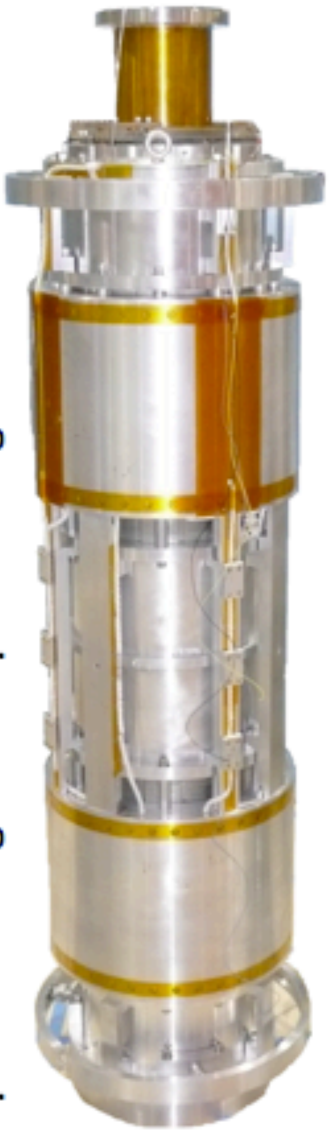
# Alpha-Gamma Apparatus




***New Beam Lifetime Status***

- 2003 result was limited by neutron counting systematics; statistics were at the 1 s level.
- Alpha-Gamma neutron calibration technique demonstrated at better than $10^{-3}$ level.
- New effort in progress; goal to mount the experiment at NIST within 1 to 2 years (NIST, Tulane, Tennessee/ORNL, and IRMM).
- J-PARC effort with a beam via $^{3}$He(n,p)$^{3}$H and TPC.

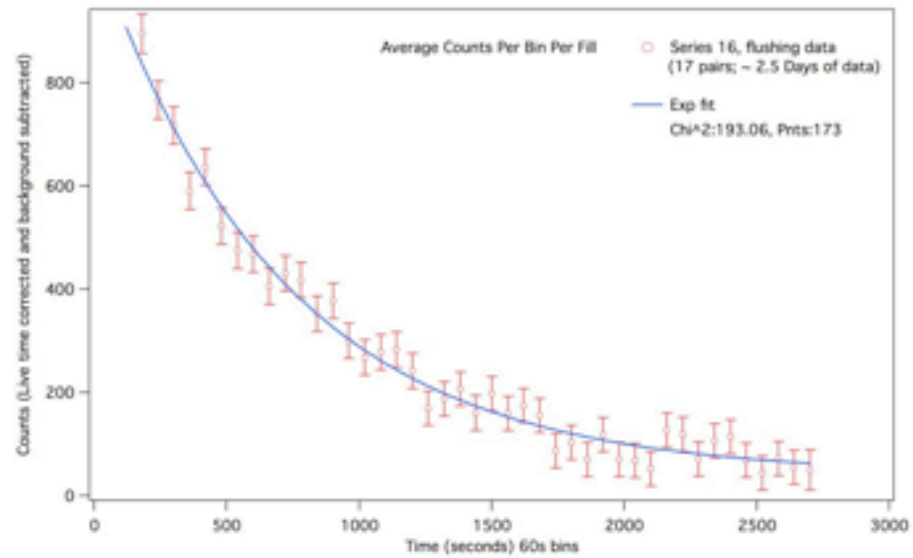
# Lifetime via Magnetic Trapping



Superconducting Ioffe Trap containing a helium filled cell

**Magnetic Trapping of Neutrons**

- Neutrons lose energy in liquid helium
- Electrons from decay excite helium
- De-excited helium gives off photons
- Light is detected by outside PMTs



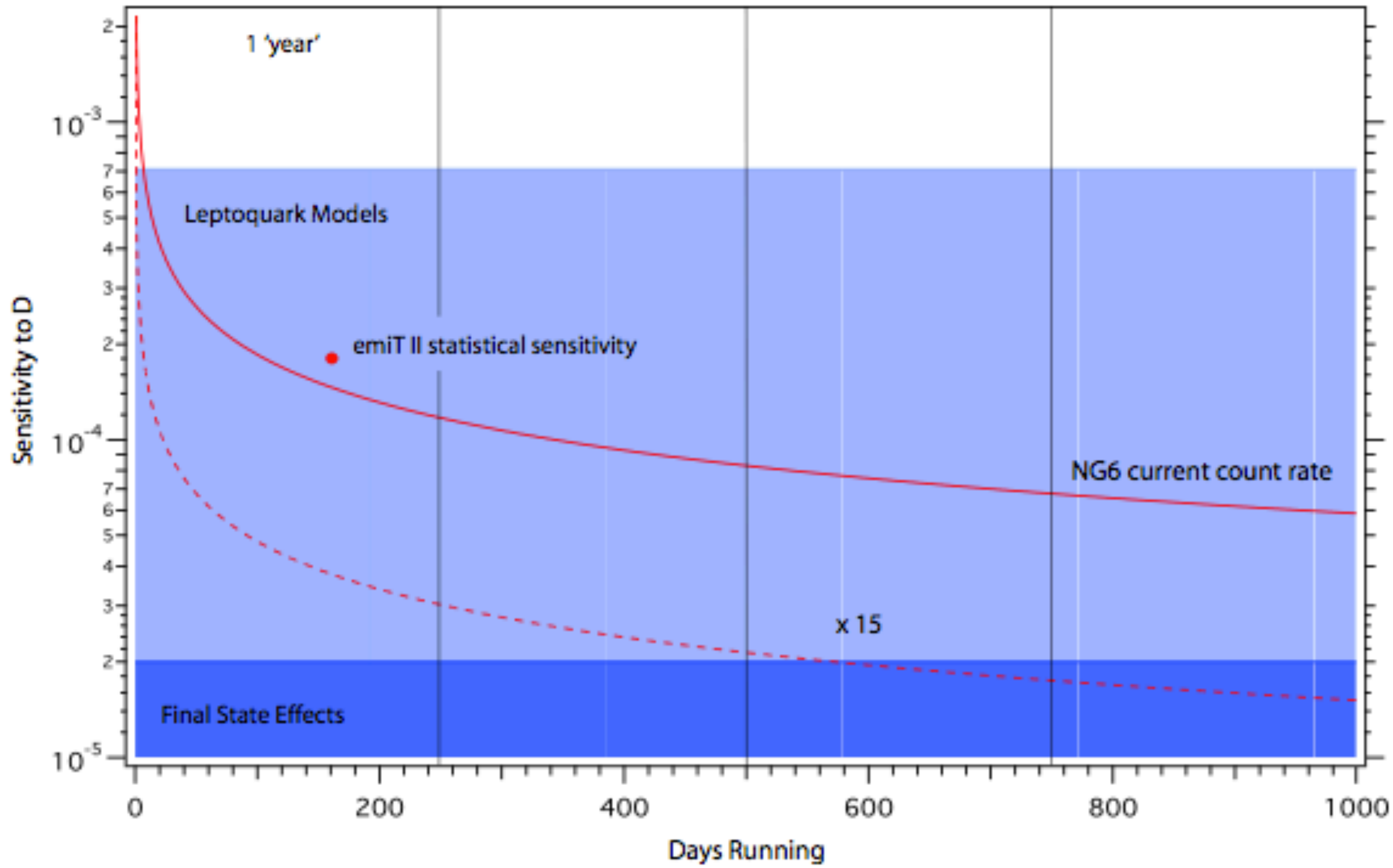

***Status***

- ➢ 2004 -10 construction of new apparatus.
- ➢ 2011 six month data run. Data analysis nearing completion.
- ➢ He-3 purity runs at ANL completed.
- ➢ Any future runs pending result of this analysis.

Collaboration: NIST, N. Carolina State, Maryland, and Illinois

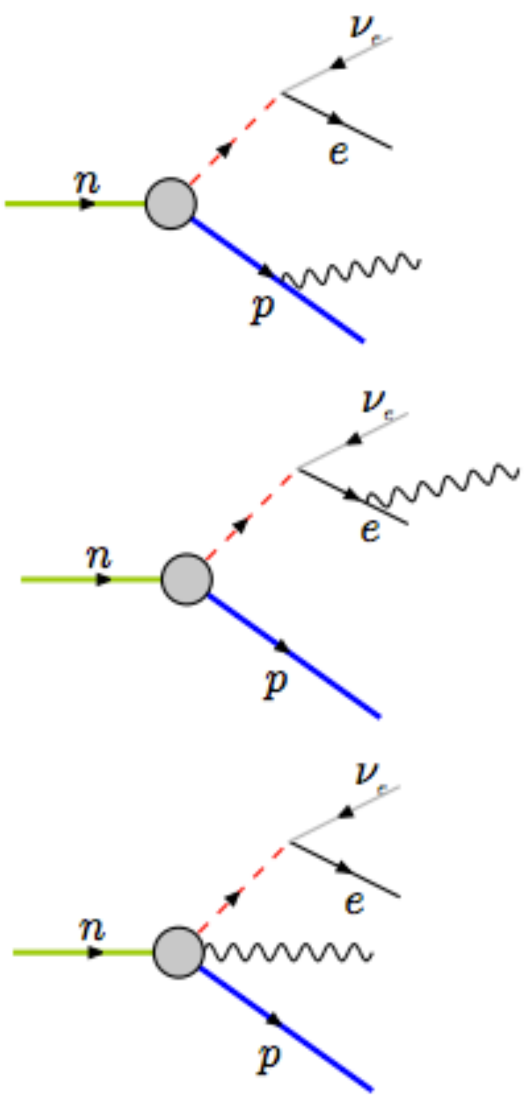
# emiT: T-Violation Search in Neutron Decay

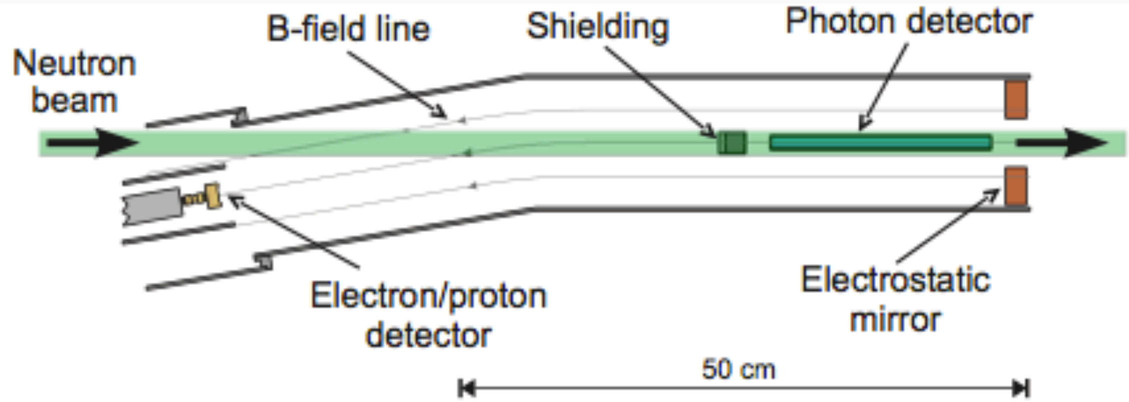
- Completed emiT II analysis in 2011 yielding best limit on *D* in nuclear beta decay.
- NG-C beam line could provide a factor of 10 increase in neutron flux and approach final state effects with an upgraded emiT apparatus.
- No definite plan at this time.




**Collaboration:** UC-Berkeley, LBNL, Hamilton, Tulane, Michigan, NIST, N. Carolina/ORNL, Washington

# Radiative Neutron Decay




***Status:***

➢ Second run completed on NG-6. Analysis to extract branching ratio and energy spectrum at 1% level in progress.

➢ Examining possibility of extracting Fierz term *b*.

➢ Physics beyond 1% level:

- Non-leading order: proton bremsstrahlung, recoil terms, vertex contribution.
- Polarization
- New classes of angular correlations with photon, e.g. $A(\mathbf{J_n} \cdot \mathbf{k}), \mathrm{D}[\mathbf{J_n} \cdot (\mathbf{k} \times \mathbf{p}_\nu)]$

➢ No new efforts planned within 5-year time frame.

# A New Avenue for Neutron Radiative $\beta$-Decay

**Gardner and He, PRD 86, 016003 (2012) [arXiv:1202.5239]...**

Radiative $\beta$-decay admits a T-odd correlation in momenta alone, $\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\nu)$. Under CPT this probes new spin-independent sources of CP violation.

**How can a $\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\nu)$ correlation emerge at low energy?**

Enter Harvey, Hill, and Hill (2007, 2008): Gauging the axial anomaly of QCD under $SU(2)_L \times U(1)_Y$ gives rise to interactions containing $\varepsilon^{\mu\nu\rho\sigma}$ at low energy.

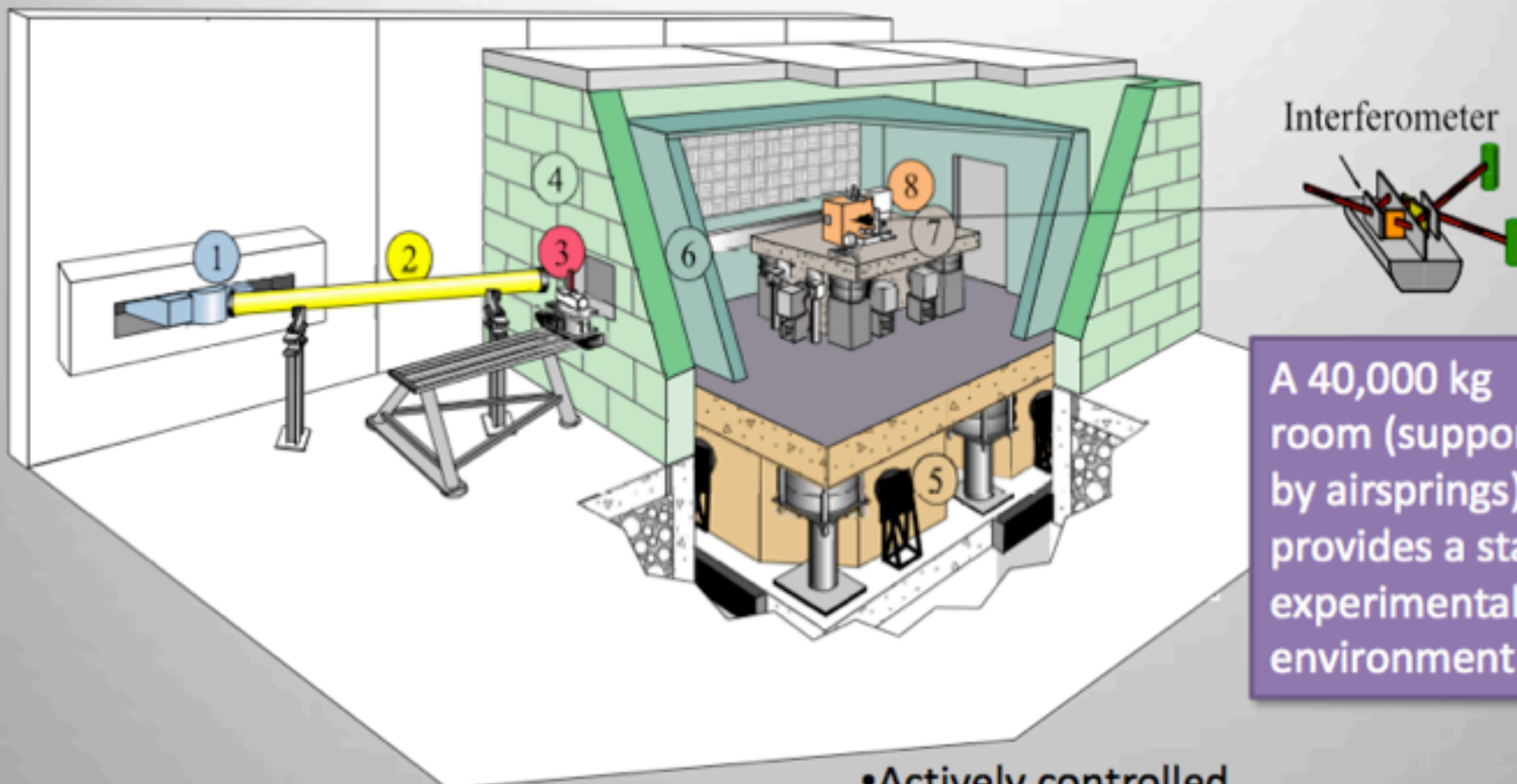
**This means the weak vector current can mediate parity violation on its own.**

Such terms appear at $N^2LO$ in the chiral effective theory gauged under $SU(2)_L \times U(1)_Y$ [Hill (2010)]

The decay correlation probes the Im part of the interference with the leading vector amplitude. An experiment could set limits on the imaginary part of the low-energy constant.

Such would give a window on new CP phases arising from hidden fermionic matter. Existing constraints are poor.

# Neutron Interferometry

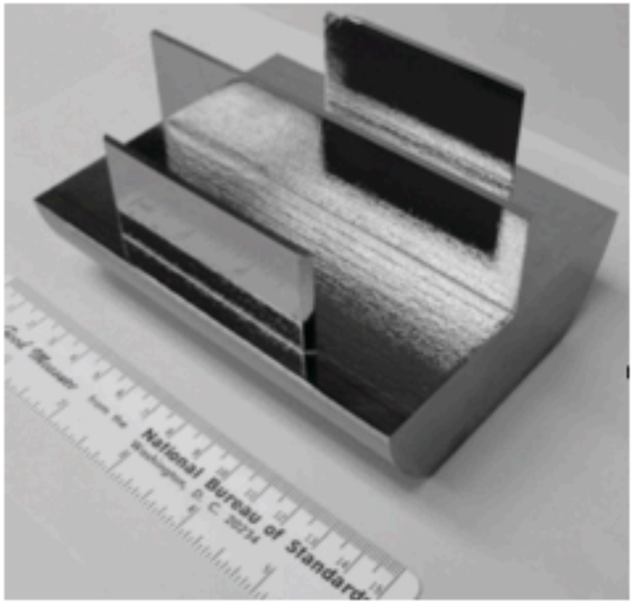


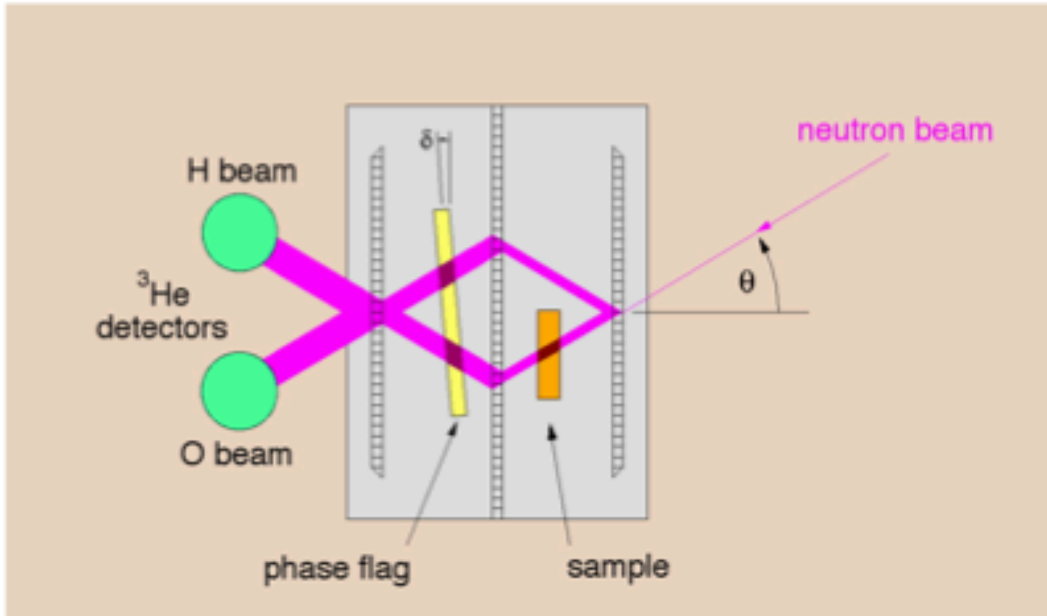

A 40,000 kg room (supported by airsprings) provides a stable experimental environment.

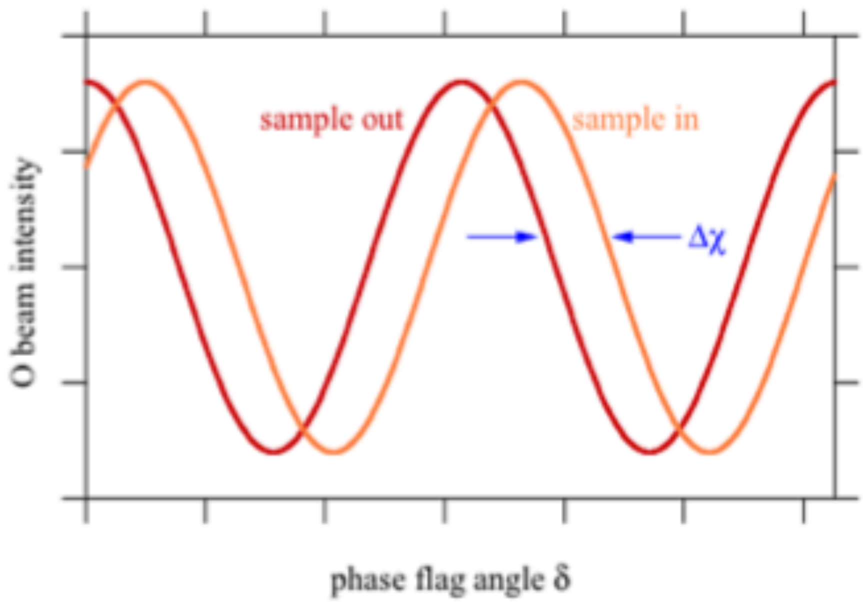
- Interferometer Contrast ~ 90%
- Acceptable wavelengths: 0.2 to 0.47 nm
- Extremely Low Backgrounds: < 0.1 /s
- Highly efficient detectors

- Actively controlled
- Phase stability 0.25 deg/day
- Position Stability (actively controlled):
  - better than 0.1 micron
  - better than 0.1 μrad
- Temperature controlled to +/-5 mK

# Precision Phase Shift Measurement






$$\Delta\chi = Nb\lambda\frac{D}{\cos\theta}$$

Example:

aluminum sample, $\lambda =$ 2.70 Å,

<111> reflection

$$D = 100\ \mu m \rightarrow \Delta\chi = 2\pi$$

# Interferometry Program

- Few-body neutron scattering length measurements. Motivated to provide input for few body theory in both quantum MC and EFT methods.

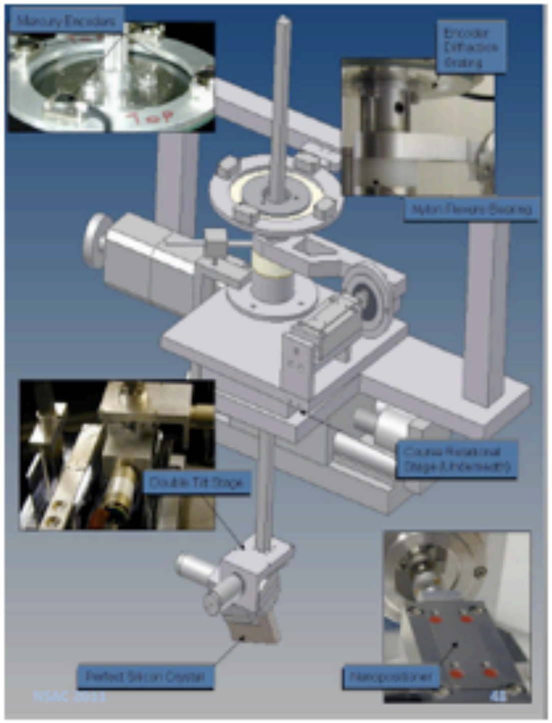
done {
  n-H
  n-D
  n-$^{3}$He (unpolarized)
  n-$^{3}$He (polarized)
}

n-$^{4}$He
n-T
n-Xe

- Search for “long-range” nuclear forces using ultracold neutrons and noble gases, specifically Ar and Ne (A. Serebrov).

- Neutron mean square charge radius.

- Collaborators: Tulane, NIST, UNC-Wilmington, Waterloo, and Indiana



Neutron charge radius apparatus

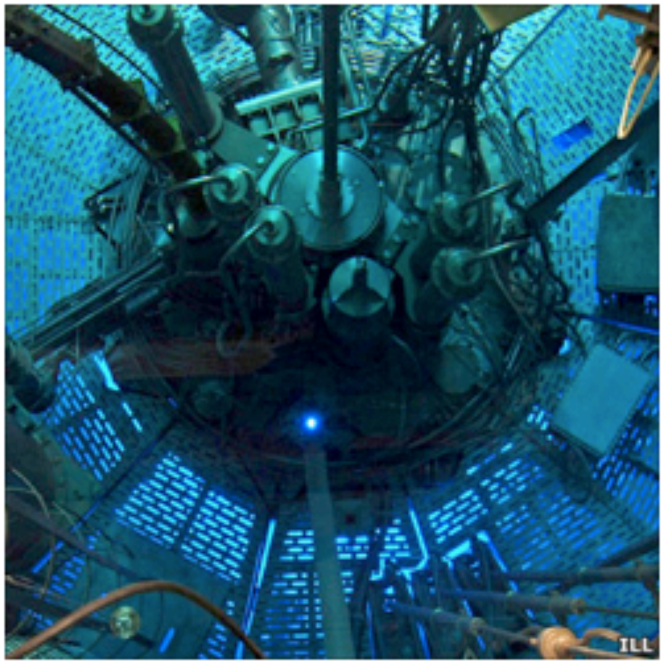
# International Context

*Cold Neutron Facilities:*

➢ Institut Laue-Langevin (France)
  • aSPECT
  • PERKEO III

➢ FRM-II (Germany)
  • PERC

➢ J-PARC (Japan)
  • Beam lifetime in He-3.




ILL core

FRM-II

# Summary

In the next 5 years ...

**SNS - FNPB**

- ➢ NPDGamma - in progress
- ➢ n- $^3$He
- ➢ Nab
- ➢ nEDM

**NIST - NG-6/C**

- ➢ aCORN - in progress
- ➢ Neutron spin rotation
- ➢ Neutron lifetime

**NIST - Interferometer**

- ➢ Few-body systems ($^4$He,T, Xe)
- ➢ Neutron charge radius
- ➢ Long-range forces (Ar, Ne)

- Precision measurements in neutron physics still play an important role in searching for new physics and provide complementary information to HEP as well as important questions in QCD.
- New high-flux facilities coming online world-wide for fundamental neutron physics: PSI, FRM-II, SNS, LANL, JSNS, NIST, TRIUMF, ESS ...
- Theoretical work and new ideas are critical for progress.
- Experiments supported by DOE, NSF, DoC, and internationally by NSERC (Canada), CONACYT (Mexico), and BARC (India).
- *Facility and operations costs borne by other sources and agencies.*

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