# *Neutron Physics Status*

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*NIST*

***NSAC***
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National Institute
of Standards
and Technology

Thanks to the following for their help:

Stefan Baessler
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Ken Nollet
Andy Saunders
Mike Snow
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## *n.b., "Neutron Physics" vs. "Neutron Physics"*

- *To most physicists "neutron physics" concerns the study of condensed matter by neutron scattering.*

- *All major US neutron facilities are funded by agencies whose primary mission is not nuclear physics (DOE BES, DOC, NNSA). Our efforts represent < 5% of the overall US neutron science enterprise.*

# US Neutron Sources

NIST Center for Neutron Research
Continuous Beams

ORNL Spallation Neutron Source
Pulsed Beams

LANSCE Spallation Source
Ultracold Neutrons

High Flux Isotope Reactor
Continuous Beams

# *US Neutron Sources*

- *Facilities are operated by other agencies (DOE-BES, DOC, NNSA) at no cost to the US Nuclear Physics Program.*

- *This represents a significant in-kind contribution to the NP program*

- *When costs are integrated over all expenditures (including operations), neutron physics is extremely cost effective.*

*<u>HOWEVER</u>*

- *While neutron physics experiments incur no facility costs, they do not benefit from the institutional support that may be available at other facilities.*

## *Low Energy Neutrons*

*"Cold Neutrons" (Beams) (e.g. NIST, SNS)*

- *Energies of a few meV ( $v \sim 100's\ ms^{-1}$ )*
- *Intense beams ( $10^{10}\ s^{-1}$ )*
- *High in-beam densities ( $\rho \sim 10^4\ \mathrm{c}m^{-1}$ )*
- *Easy to Polarize and Analyze*
- *Available at NIST and SNS*

*"Ultracold Neutrons" (Bottles) (e.g. LANL)*

- *Energies below 1 $\mu$eV ( $v < 5\ ms^{-1}$ )*
- *Can be contained in "bottles"*
- *Long observation times ( $t \geq 1000\ s$ )*
- *Available at LANL*

## ***The Neutron Physics program has three* major themes***

*1. Neutron Beta Decay*

*2. The Neutron Electric Dipole Moment*

*3. Hadronic Parity Violation*

**Also includes a suite of "opportunistic" smaller scale activities that include the search for NS short range interactions, measurements of scattering lengths, measurement of the neutron charge radius, and a variety of novel neutron interferometry experiments.*

# Neutron Beta Decay

# Big Bang Nucleosynthesis

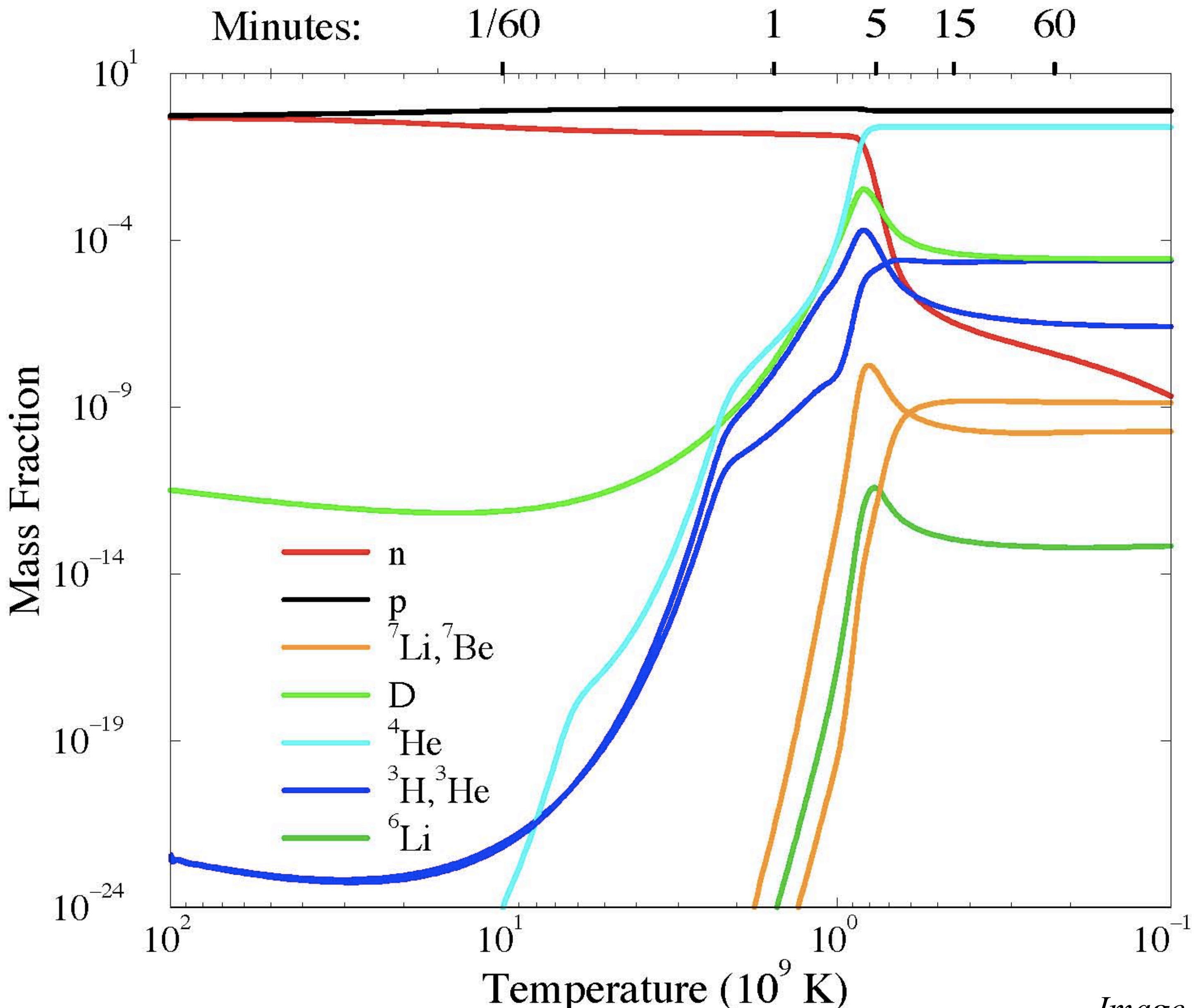
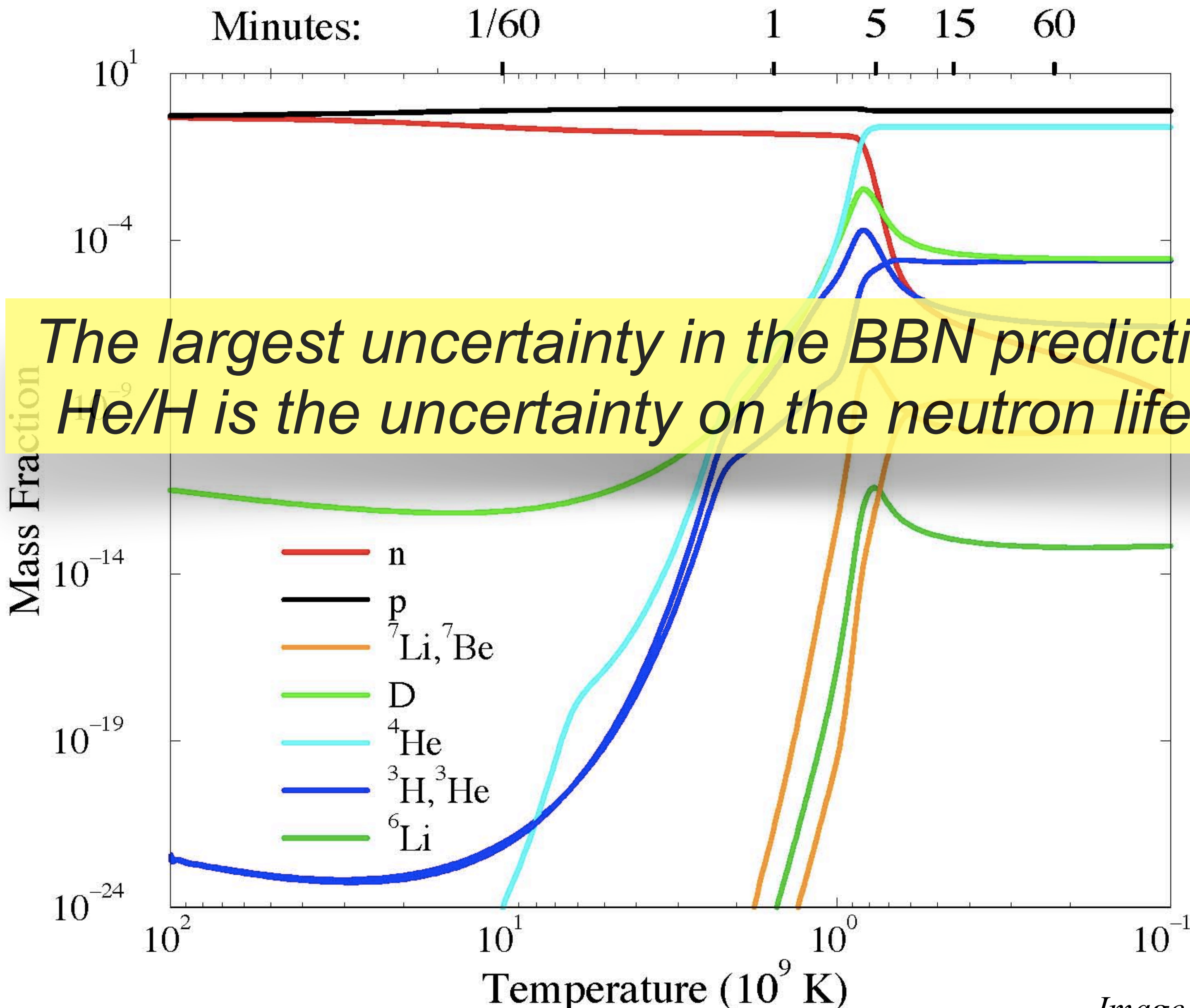



*Image courtesy Ken Nollet*

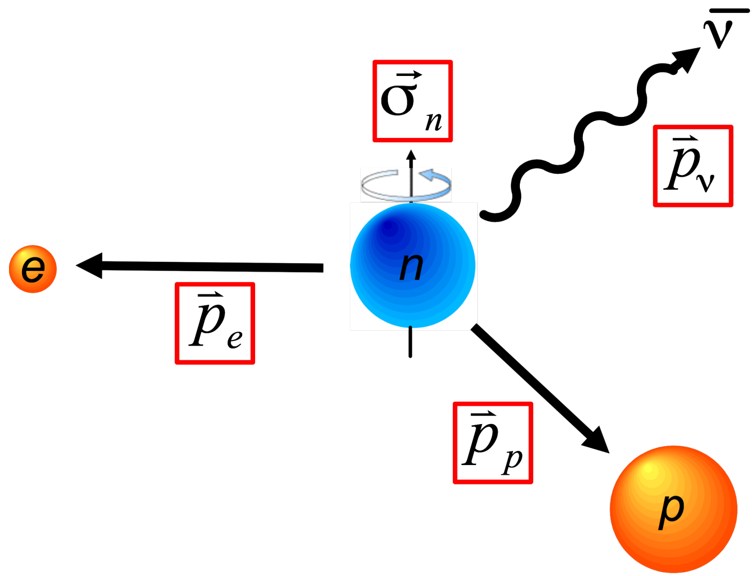
# Big Bang Nucleosynthesis




*The largest uncertainty in the BBN prediction for He/H is the uncertainty on the neutron lifetime.*

*Image courtesy Ken Nollet*

# Observables in Neutron Decay




In the Standard Model (V-A), free neutron decay is described by two parameters $G_V$ and $G_A$.

$G_V$ may be determined independently via $0^+ - 0^+$ nuclear decays and/or Kaon decay via CKM unitarity.

$$dW \propto \frac{1}{\tau_n} F(E_e)\left[1 + a\frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\upsilon}{E_e \cdot E_\upsilon} + b\frac{m_e}{E_e} + A\frac{\sigma_n \cdot \boldsymbol{p}_e}{E_e} + B\frac{\sigma_n \cdot \boldsymbol{p}_\upsilon}{E_\upsilon} + \ldots\right]$$

$$\frac{1}{\tau_n}: \quad \frac{1}{\left(G_V^2 + 3G_A^2\right)}$$

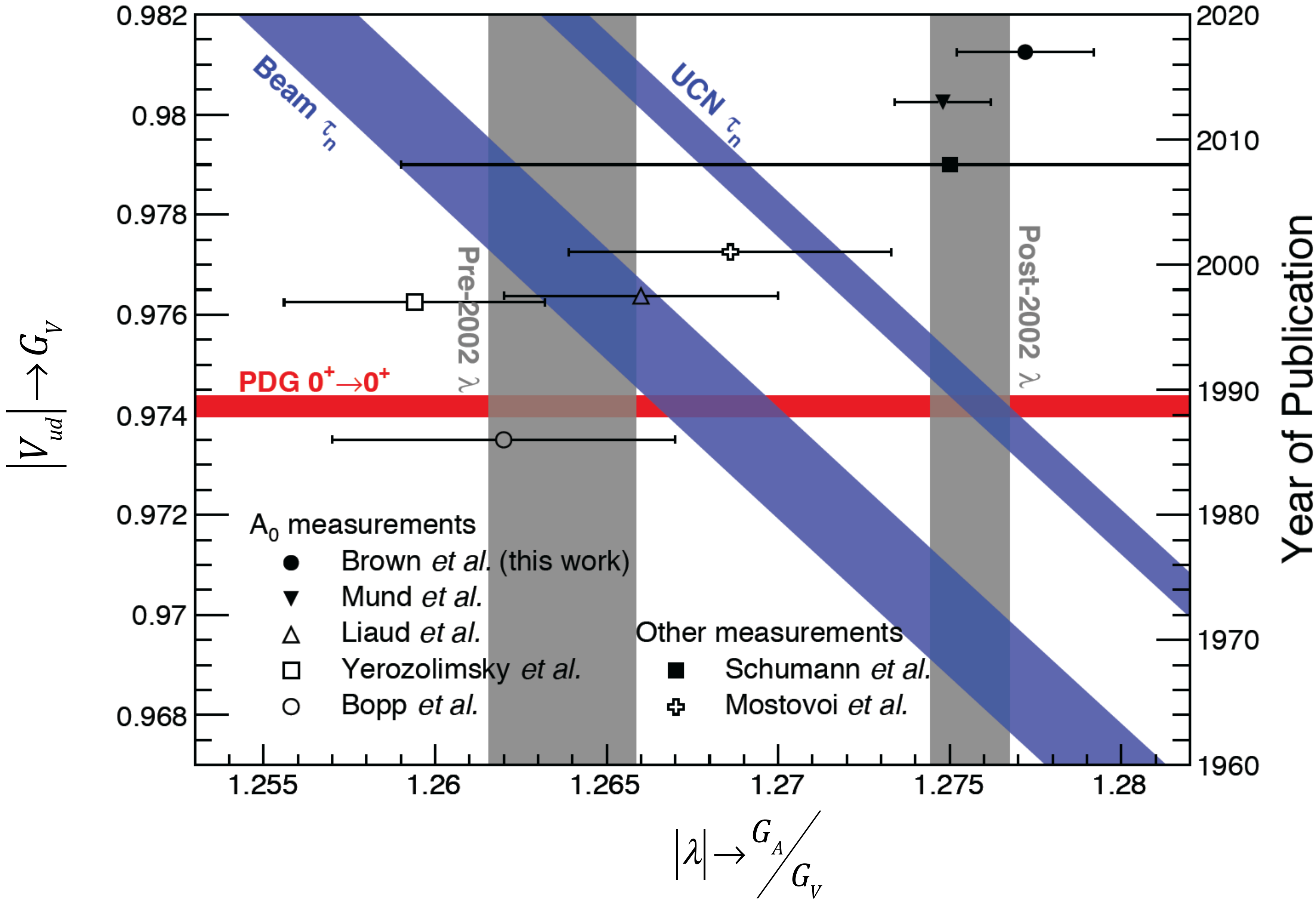
$$a: \quad \frac{1-\left(\frac{G_A}{G_V}\right)^2}{1-3\left(\frac{G_A}{G_V}\right)^2}$$

$$b = 0$$

$$A: \quad -2\frac{\left(\frac{G_A}{G_V}\right)^2 + \left(\frac{G_A}{G_V}\right)}{1-3\left(\frac{G_A}{G_V}\right)^2}$$

$$B: \quad -2\frac{\left(\frac{G_A}{G_V}\right)^2 - \left(\frac{G_A}{G_V}\right)}{1-3\left(\frac{G_A}{G_V}\right)^2}$$

# Data is Discrepant




*See Czarnecki, Marciano, Sirlin, arXiv:1802.01804

*Image courtesy T. Ito*

# Two Approaches to Measuring a Lifetime

1. Observation time is longer than (or comparable to) the lifetime.

STEP 1: Determine $N(0)$ number unstable nuclei in a sample at $t=0$, and
STEP 2: Determine $N(t)$ number unstable nuclei in a sample at $t=t$.

$$N(t) = N(0)e^{-t/\tau}$$

**Bottle Method**

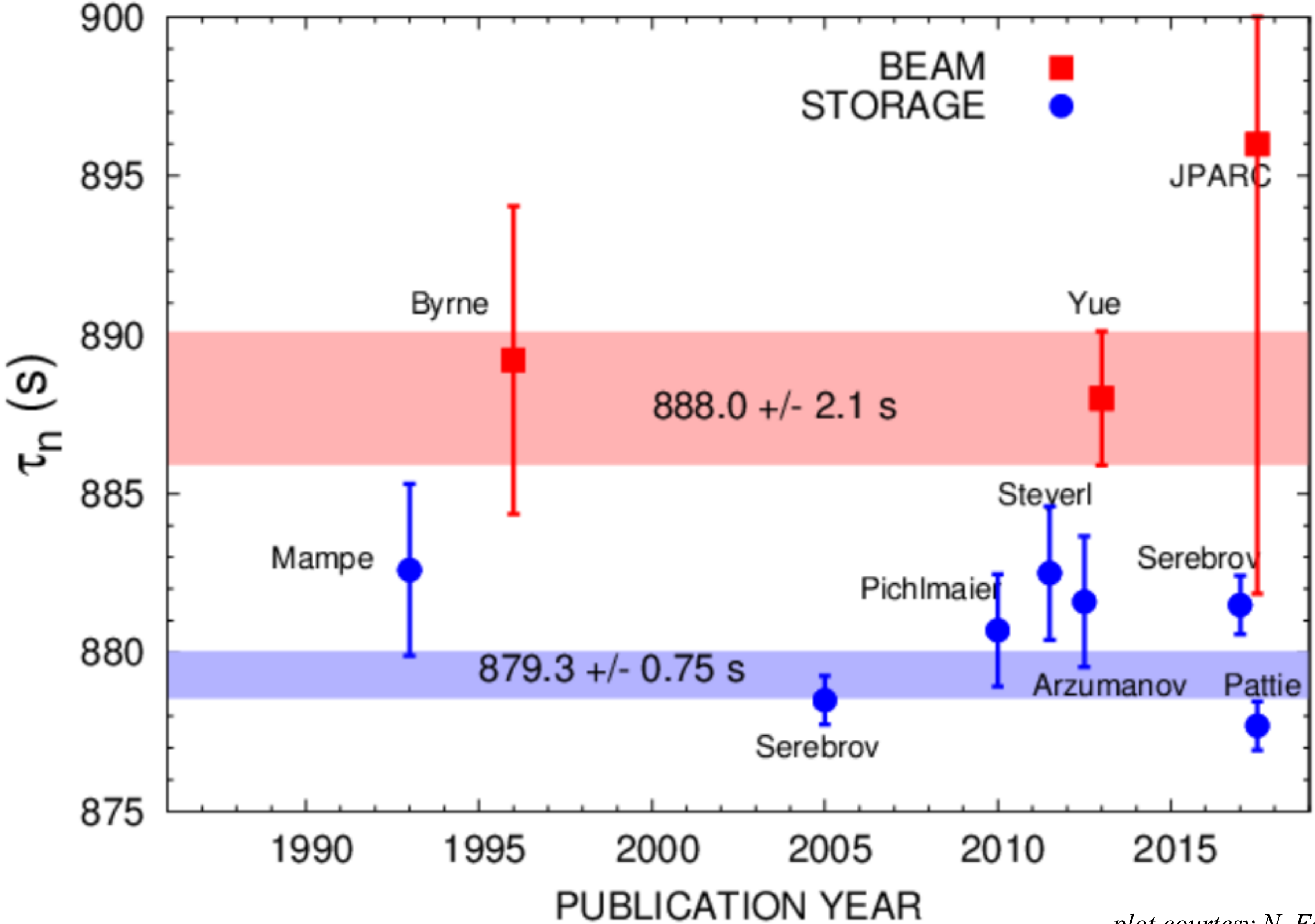
2. Observation time is much shorter than the lifetime.

STEP 1: Determine $N$, the number of unstable nuclei in a sample, and
STEP 2: Determine the rate of decays $\dot{N}$.

$$\dot{N} = \frac{N}{\tau}$$

**Beam Method**

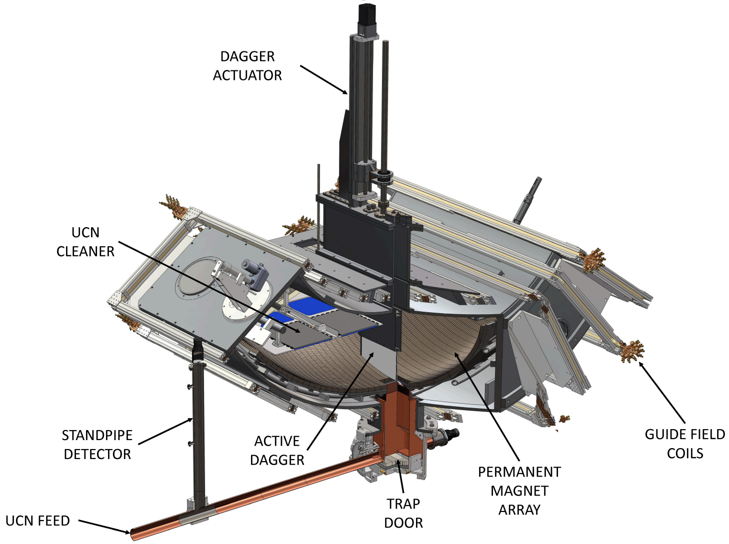
# *The Current Situation*




*plot courtesy N. Fomin*

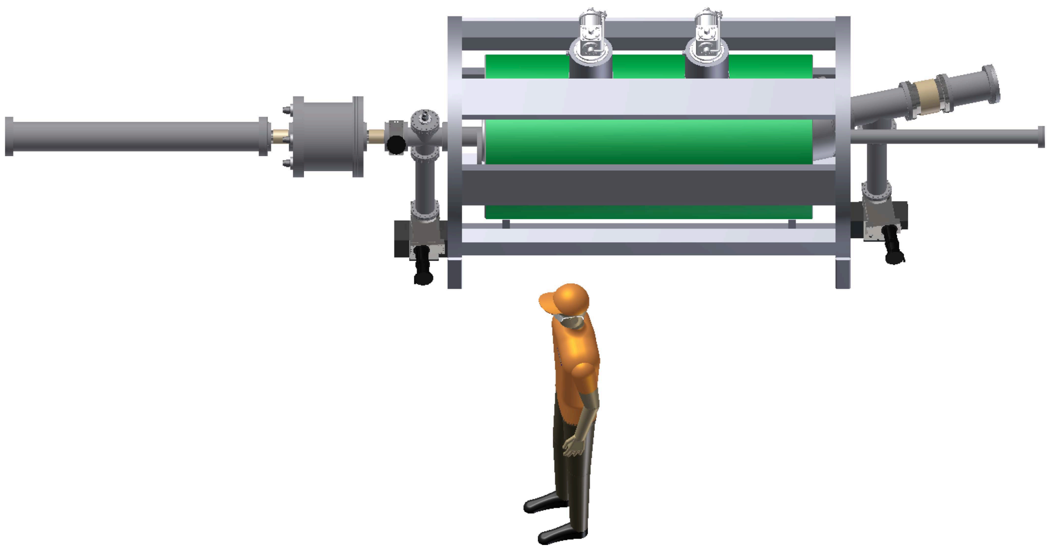
# US Neutron Lifetime Experiments

*UCN$\tau$ Experiment*



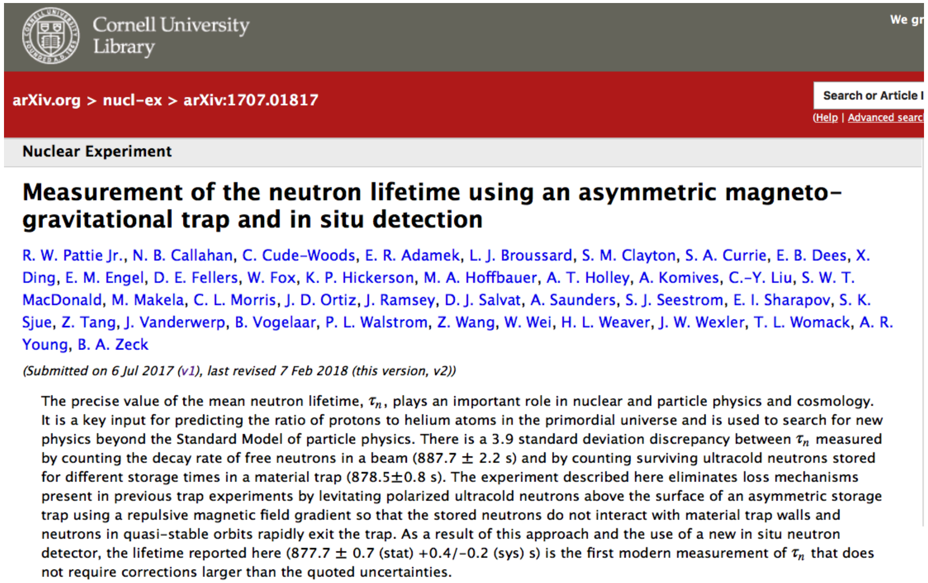

UCN$\tau$, LANL (continuing)


BL2, NIST (data production)



BL3, NIST (proposed)

# *Recent News*


Cornell University Library

arXiv.org > nucl-ex > arXiv:1707.01817

Nuclear Experiment

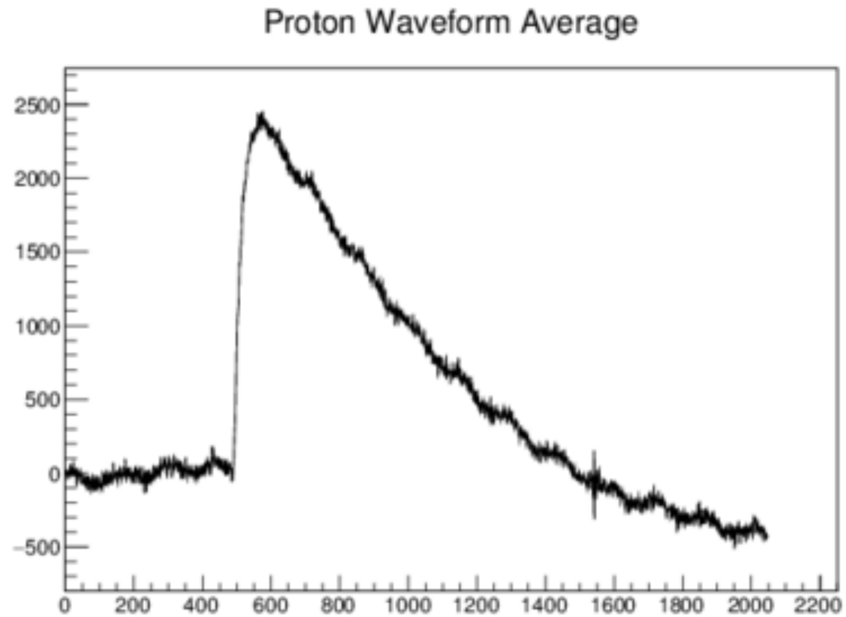
**Measurement of the neutron lifetime using an asymmetric magneto-gravitational trap and in situ detection**

R. W. Pattie Jr., N. B. Callahan, C. Cude-Woods, E. R. Adamek, L. J. Broussard, S. M. Clayton, S. A. Currie, E. B. Dees, X. Ding, E. M. Engel, D. E. Fellers, W. Fox, K. P. Hickerson, M. A. Hoffbauer, A. T. Holley, A. Komives, C.-Y. Liu, S. W. T. MacDonald, M. Makela, C. L. Morris, J. D. Ortiz, J. Ramsey, D. J. Salvat, A. Saunders, S. J. Seestrom, E. I. Sharapov, S. K. Sjue, Z. Tang, J. Vanderwerp, B. Vogelaar, P. L. Walstrom, Z. Wang, W. Wei, H. L. Weaver, J. W. Wexler, T. L. Womack, A. R. Young, B. A. Zeck

*(Submitted on 6 Jul 2017 (v1), last revised 7 Feb 2018 (this version, v2))*

The precise value of the mean neutron lifetime, $\tau_n$, plays an important role in nuclear and particle physics and cosmology. It is a key input for predicting the ratio of protons to helium atoms in the primordial universe and is used to search for new physics beyond the Standard Model of particle physics. There is a 3.9 standard deviation discrepancy between $\tau_n$ measured by counting the decay rate of free neutrons in a beam (887.7 ± 2.2 s) and by counting surviving ultracold neutrons stored for different storage times in a material trap (878.5±0.8 s). The experiment described here eliminates loss mechanisms present in previous trap experiments by levitating polarized ultracold neutrons above the surface of an asymmetric storage trap using a repulsive magnetic field gradient so that the stored neutrons do not interact with material trap walls and neutrons in quasi-stable orbits rapidly exit the trap. As a result of this approach and the use of a new in situ neutron detector, the lifetime reported here (877.7 ± 0.7 (stat) +0.4/−0.2 (sys) s) is the first modern measurement of $\tau_n$ that does not require corrections larger than the quoted uncertainties.

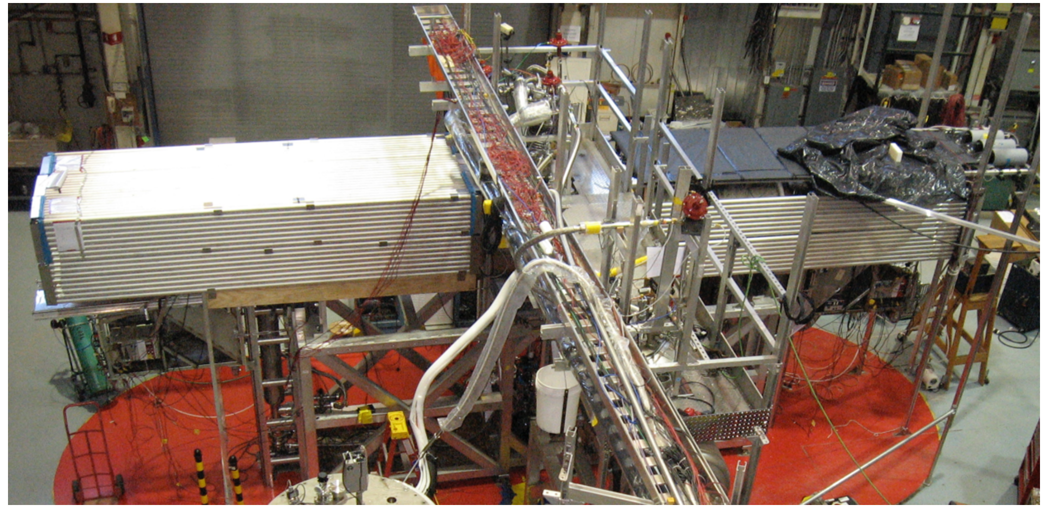
UCN $\tau$ result 2/18



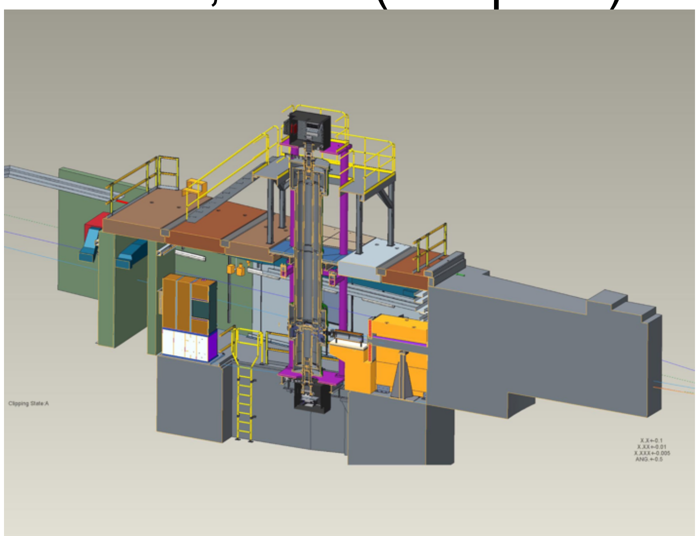

NIST Lifetime data runs *NOW*

# US Correlation Coefficient Experiments

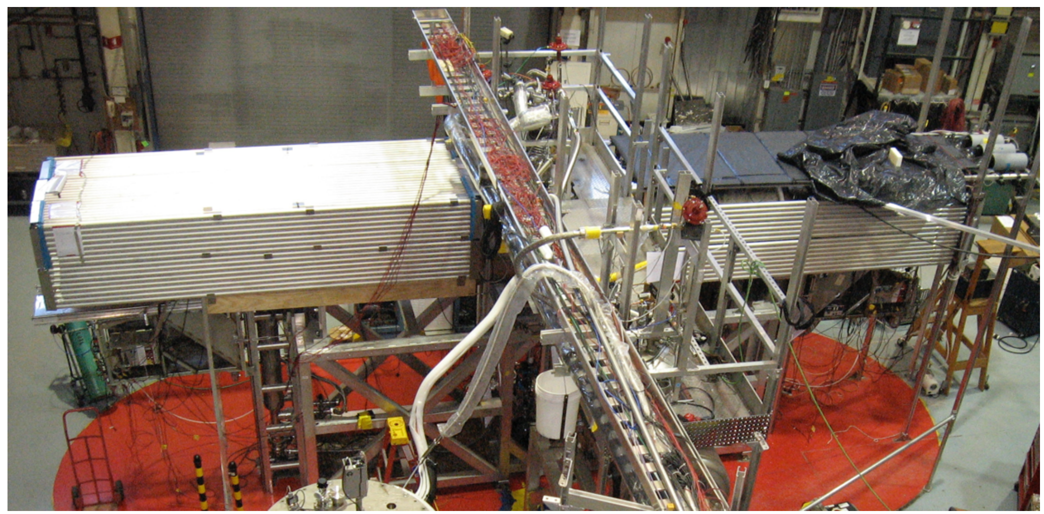
aCORN, NIST (complete)



UCNA, LANL (complete)



Nab, ORNL (under construction)



UCNA2, LANL (proposed)

# *Recent News*

Delivery of Nab Cryomagnet to SNS, 2/18

## *Beta Decay Summary*

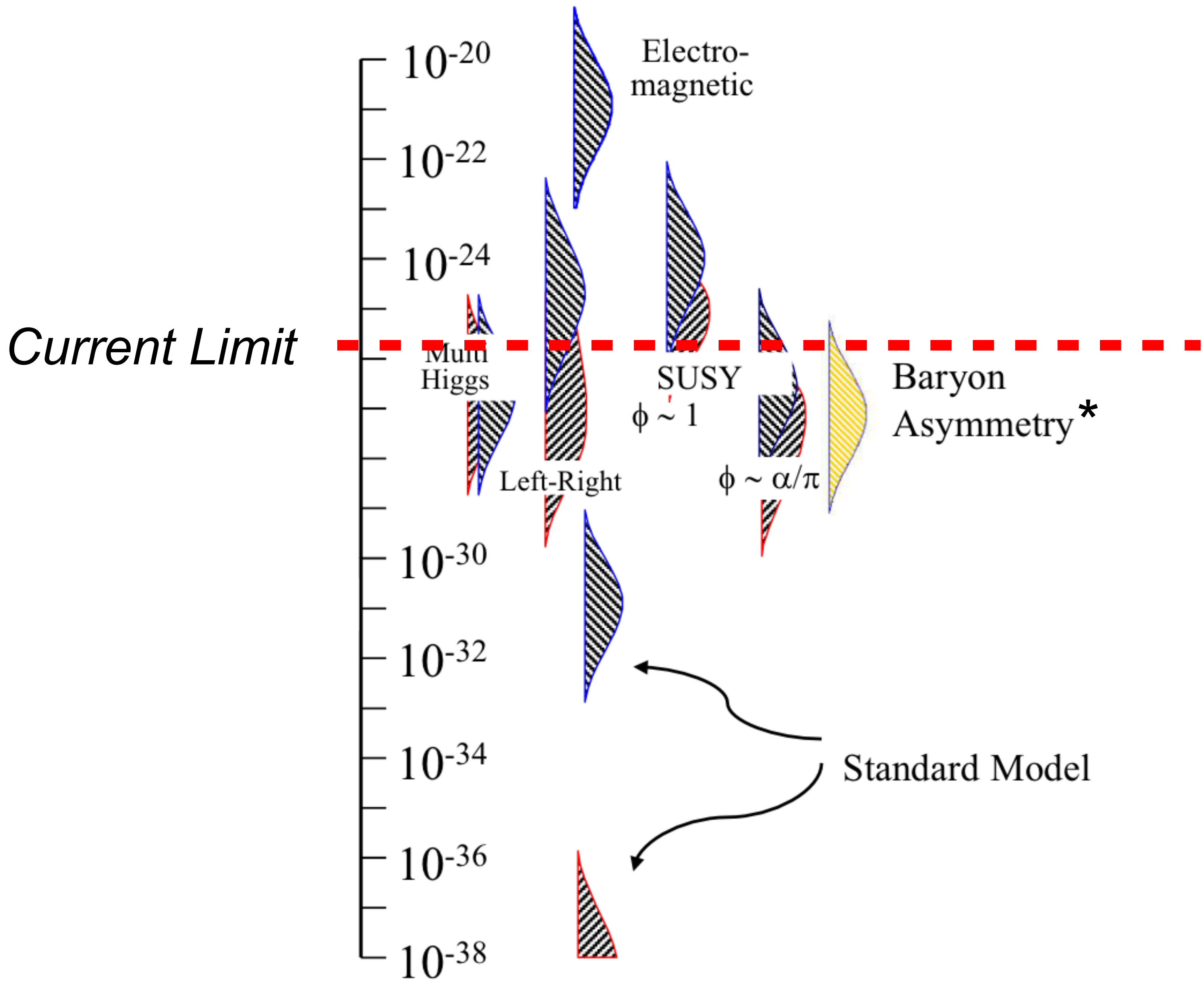
- *US Neutron Decay Program is vigorous and world leading*
- *Both Beam and Bottle experiments poised for <<1s sensitivity*
- *UCNA and Nab offer independent, high accuracy values for* $G_A / G_V$

# Neutron Electric Dipole Moment

# *Motivation*

- *We do not understand the origin of observed CP violation*
- *Standard Model CP violation appears to be too small to explain the Cosmic Baryon Asymmetry*
- *We expect a non-zero neutron EDM and its observation would likely be a window on New Physics*
- *The neutron EDM search is highly complementary to searches in atoms and diatomic molecules.*

# *Neutron EDM Predicted Values*

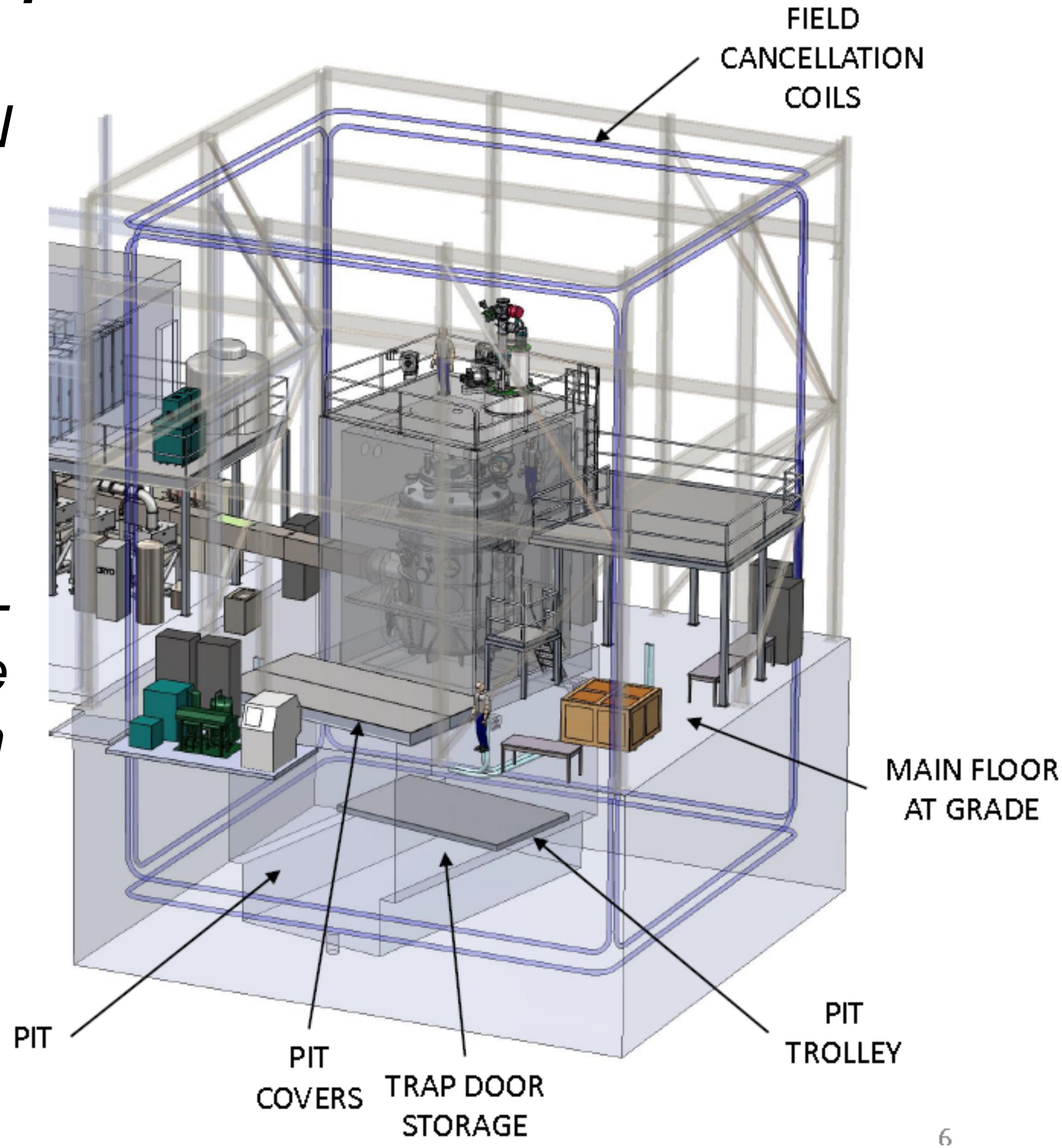


# *nEDM at the Spallation Neutron Source*

*Cold neutrons from the SNS are down-converted into UCN within the detector volume.*

*The experiment is performed at mK temperature within a volume of superfluid Helium that is is "spiked" with polarized $^3$He to provide a co-magnetometer to average the magnetic over the precession volume.*

***This large cryogenic experiment offers significant advantages but is complex.***



# *nEDM has completed a Critical Component Demonstration Project*

**Technical Review Committee (2017):**

Charge Element #1: Has the nEDM@SNS collaboration made significant and sufficient Other Neutron EDM effortstechnical progress on all aspects of the Critical Component Demonstration (CCD), as envisioned and presented to the TRC previously?

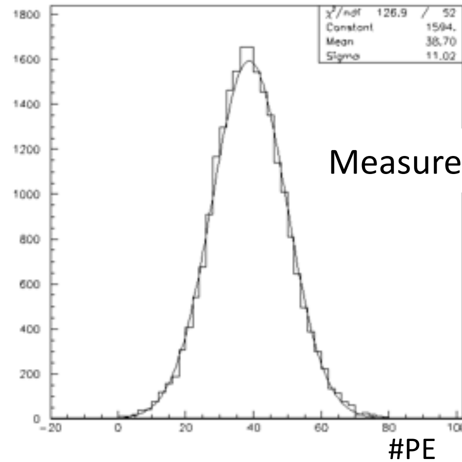
*"The TRC finds the answer to be yes. The collaboration has made significant and sufficient technical progress on all aspects of CCD. The committee commends the collaboration for judicious changes to the design of the nEDM instrument and for its steady R&D progress. From the TRC perspective, the collaboration has more than met the challenges it has faced."*

## Technical Review Committee

Dave DeMille (Yale)
Blayne Heckel (U. Washington)
Chris Keith (TJNAF)
Dan McKinsey (Yale)

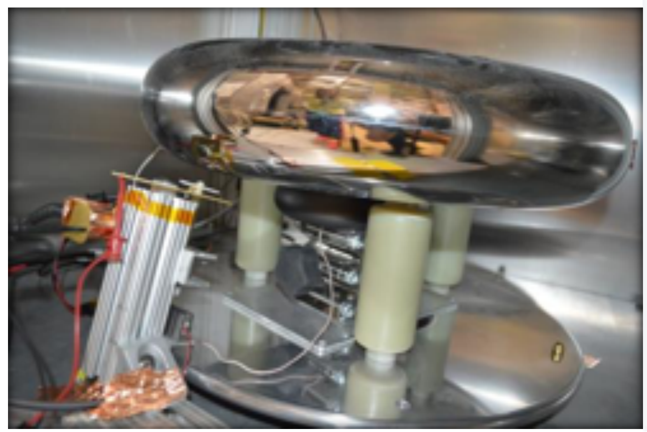
# *High Voltage Electrodes and Light Collection were Key Issues*

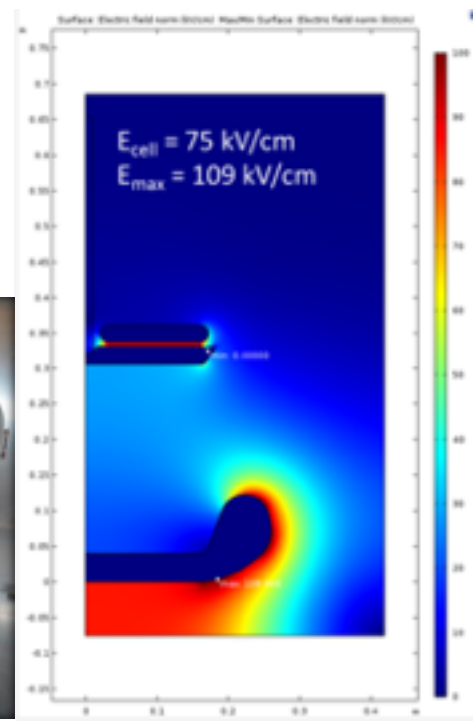

High-voltage Test Cryostat




Measured LHe scintillation yield (WLS fibers + SiPM)

Cavallo HV multiplier, room-temp demonstrator, cryogenic design



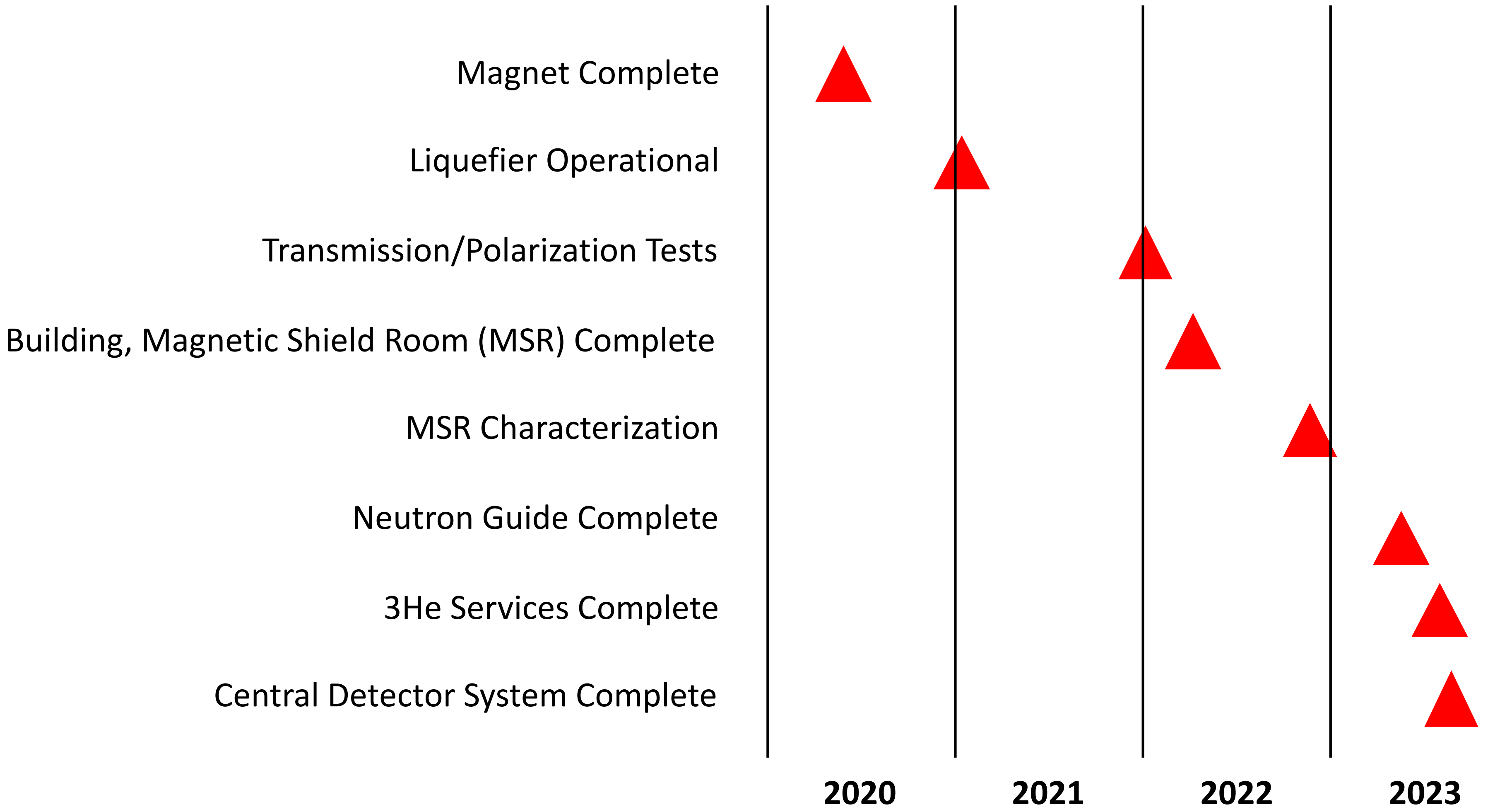


# *Procurement of Major Components has Begun*

Cryovessel: all vendor tests passed.

Magnetic Field Test Setup at Cal Tech

# *High Level nEDM Schedule*



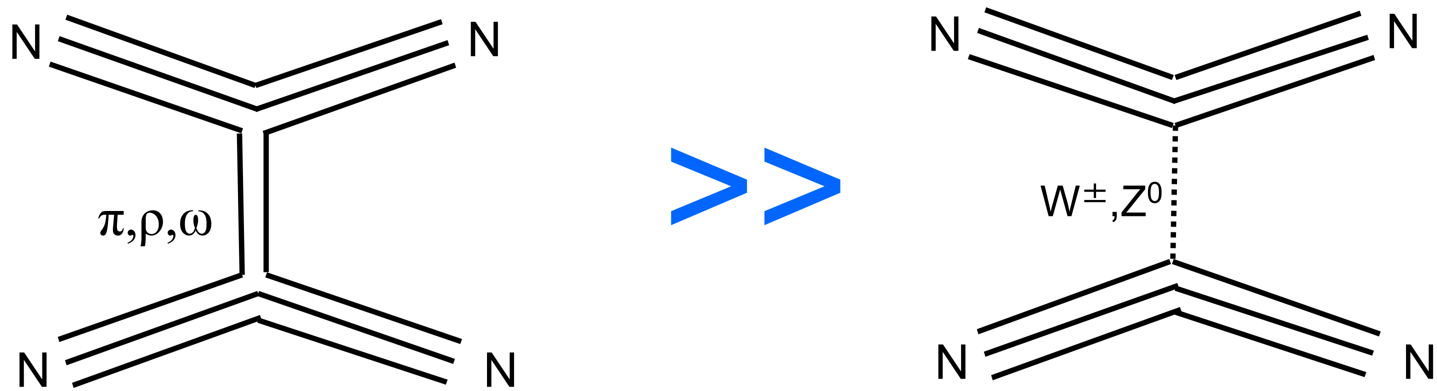
# *Other Neutron EDM efforts*

- ***Paul Scherrer Institut***
- *TRIUMF*
- *Institut Laue Langevin*
- *Los Alamos*
- *Petersburg Nuclear Physics Institute*
- *European Spallation Source*

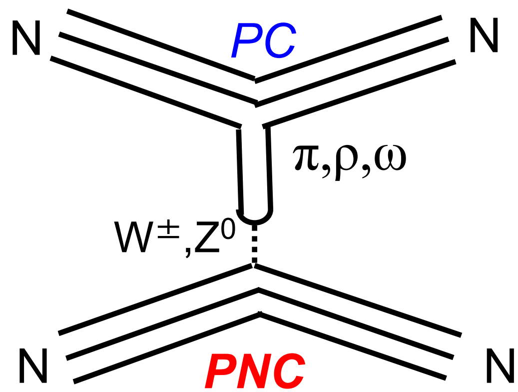
# Hadronic Parity Violation

# The Weak Interaction Between Nucleons

# *The Weak Interaction between Nucleons is "Overwhelmed" by the Strong Interaction*




In the meson exchange model we can consider the interference between a Strong and an "effective" Weak vertex




***Parity Violation provides a "Tag" for the Weak Interaction***

## *Theoretical Approaches to NN Weak Interaction*

Kinematic: 5 S→P transition amplitudes in elastic NN scattering (*Danilov*)

Dynamical: meson exchange model for NN weak interaction (6 couplings), QCD sum rules, Skyrme models, chiral quark model… (*Desplanques, Donoghue, Holstein, Meissner, Hwang, Gazit,…)*

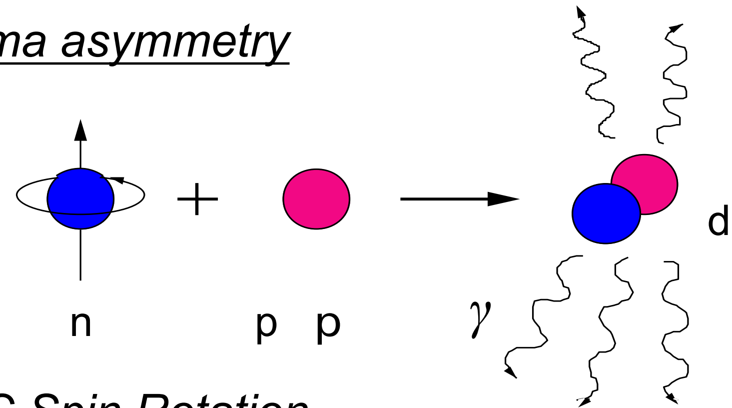
Effective field theory: $\chi$ perturbation theory, incorporates low energy symmetries of QCD
(Kaplan, Savage, Wise, *Liu, Holstein, Musolf, Zhu, Phillips,Springer, Schindler,…)*

Standard Model; lattice gauge theory:
*A target for exoscale computing?*
(*Wasem, Beane & Savage, Walker-Loud,…* )

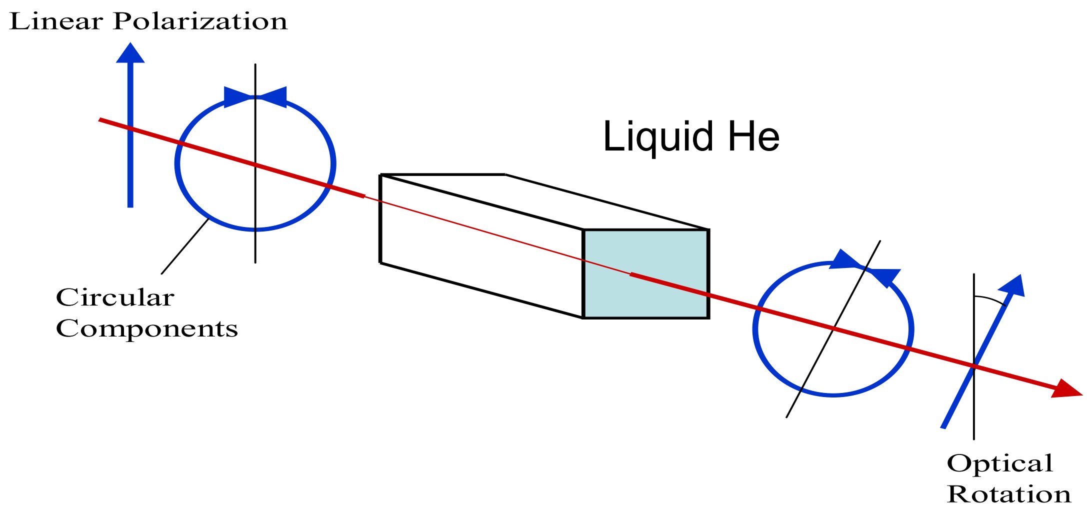
*courtesy Mike Snow*

# For Intepretability we wish to study few nucleon systems that are uncomplicated by nuclear structure effects.

PNC Capture Gamma asymmetry




Weak Nuclear PNC Spin Rotation



**DDH model** – uses valence quarks to calculate effective PV meson-nucleon coupling directly from SM via 6 weak meson coupling constants

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

P-odd observables can be written as linear combinations of these couplings

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

| | np $A_\gamma$ | nD $A_\gamma$ | $n^3He$ $A_p$ | np $\phi$ | n$\alpha$ $\phi$ | pp $A_z$ | p$\alpha$ $A_z$ |
|---|---|---|---|---|---|---|---|
| $f_\pi$ | -0.11 | 0.92 | -0.18 | -3.12 | -0.97 | | -0.34 |
| $h_r^0$ | | -0.50 | -0.14 | -0. 23 | -0.32 | 0.08 | 0.14 |
| $h_r^1$ | -0.001 | 0.10 | 0.027 | | 0.11 | 0.08 | 0.05 |
| $h_\rho^2$ | | 0.05 | 0.0012 | -0.25 | | 0.03 | |
| $h_\omega^0$ | | -0.16 | -0.13 | -0. 23 | -0.22 | -0.07 | 0.06 |
| $h_\omega^1$ | -0.003 | -0.002 | 0.05 | | 0.22 | 0.07 | 0.06 |

*courtesy Mike Snow*

*Recent / Current Experiments*

| | |
|---|---|
| $n+p \rightarrow d+\gamma$ | *Gamma emission asymmetry (SNS)*<br>*Complete - <u>Manuscript submitted to PRL</u>* |
| $n+{}^{3}He \rightarrow p+{}^{3}H$ | *Fragmentation Asymmetry (SNS)*<br>*Data Collection Complete, Analysis in Progress* |
| $n+{}^{4}He \rightarrow n+{}^{4}He$ | *Coherent PNC Spin Rotation (NIST)*<br>*Initial Run Complete,*<br>*New Apparatus Under Construction* |

# Future Opportunities Under Discussion Later this week

# “Other”

## *Additional Experiments*

- *“Radiative” neutron decay*
- *Determination of scattering lengths of light nuclei (neutron interferometry)*
- *Search for non-SM interactions and short range forces*
- *Determination of neutron charge radius (neutron interferometry)*

*….*

# Manpower

## *Who is involved*

- *~100* PhD’s are “seriously” engaged in Neutron Physics Research*
- *~50 PhD students are working on Neutron Physics Experiments*
- *DOE & NSF directly support 16 research groups*
- *Many other NP groups participate at significant levels*

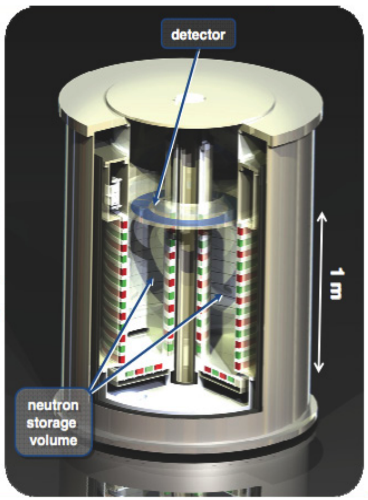
**Rough estimate based on data from facilities. Efforts were made to avoid double counting but error bar on estimate is high.*

# *SUMMARY*

- *“Fundamental” neutron physics is alive and well in the US*
- *There is significant recent progress in all parts of the the program*
- *The US neutron beta decay effort is now the world leader*
- *There is a significant involvement among the US NP Community*
- *The work is highly cost effective with NO major facility expenses.*

END OF PRESENTATION

# *Neutron Lifetime Experiments Worldwide*




PENELOPE, Munich
Magnetic Bottle

“Big” Gravitational Trap, St. Petersburg
Material Bottle

HOPE, Grenoble
Magnetic Bottle