V_{ud} from neutron experiments: τ and λ

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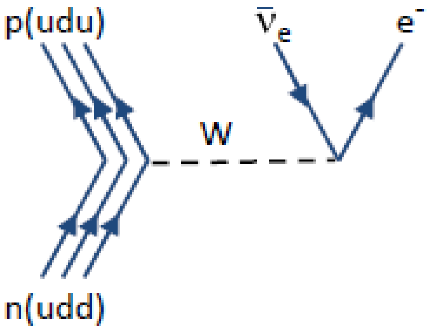
for the UCNA and UCNτ collaborations

20 September 2018
CKM Workshop

Outline

- Using neutron measurements to extract V_{ud} and test CKM Unitarity
  - Decay correlations and neutron lifetime
- Decay correlation experiments and path forward
- Lifetime experiments present and future

Neutron Decay Parameters



- Semi-leptonic decay
  - Lifetime ~880 s
  - Endpoint energy 782 keV

- Just two free parameters in SM
  - CKM mixing matrix element
  - Ratio of weak coupling constants
  - Uncertainty comes from radiative corrections

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\tau_n = \frac{4908.7 \pm 1.9\ s}{|V_{ud}|^2 (1 + 3\lambda^2)}$$

$$\lambda = g_A / g_V$$

Neutron β decay and V_{ud}

Angular correlations in polarized neutron decay (Jackson *et al* ‘57)

$$d\Gamma = d\Gamma_0 \times \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \left\langle \vec{\sigma}_n \right\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e}{E_e} \times \frac{\vec{p}_\nu}{E_\nu} \right) \right]$$

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2}, \qquad A = -2\frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1+3|\lambda|^2}, \qquad B = 2\frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1+3|\lambda|^2}, \qquad b_n = \frac{|b_F| - 3\lambda|b_{GT}|}{1+3\lambda^2}$$

$$\tau^{-1} = Kf^R(G_V{}^2 + 3G_A{}^2) \qquad\qquad B = B_0 + B_1\frac{m_e}{E_e}$$

$$\lambda \equiv \frac{G_A}{G_V}$$

$$\tau_n = \frac{4908.7 \pm 1.9\ s}{|V_{ud}|^2\left(1+3\lambda^2\right)}$$

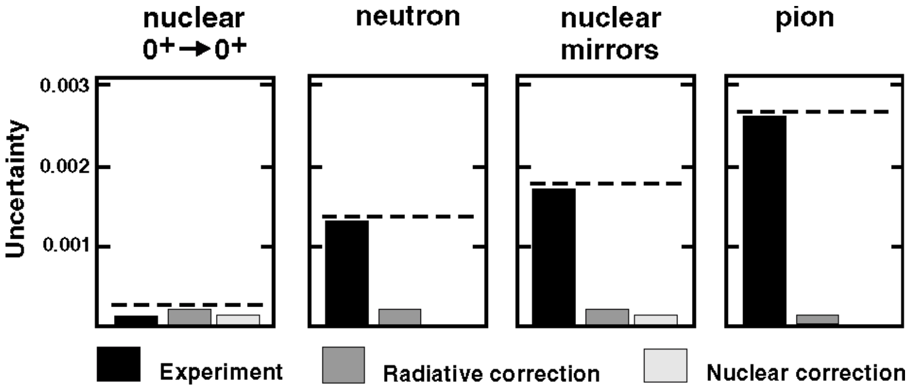
Neutron Decay and Unitarity

$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cd} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

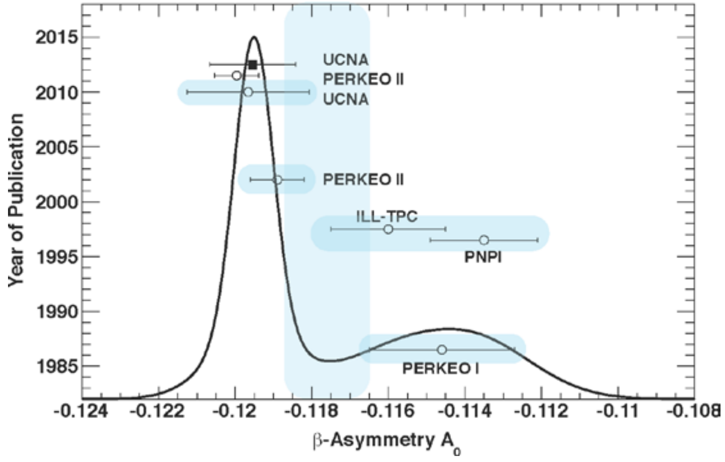
$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} 0.975 & 0.22 & 0.005 \\ 0.22 & 0.97 & 0.04 \\ 0.005 & 0.04 & 0.99 \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

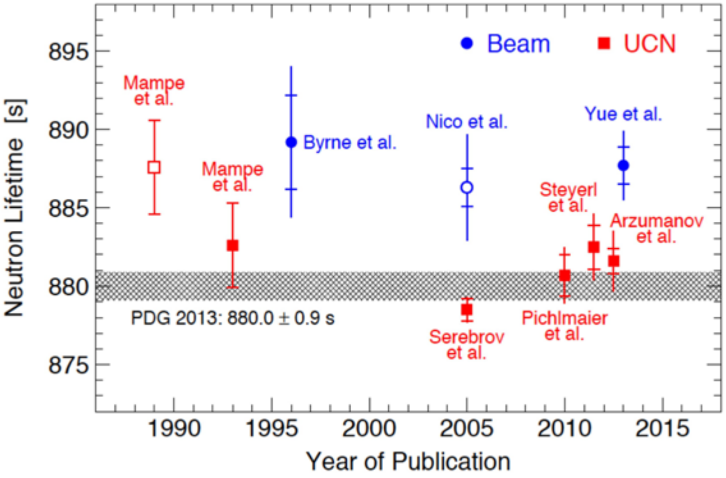
Unitarity, eg. $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$, (or lack thereof) of CKM matrix tests existence of further quark generations and possible new physics (eg. Supersymmetry)

V_{ud} from Beta Decay



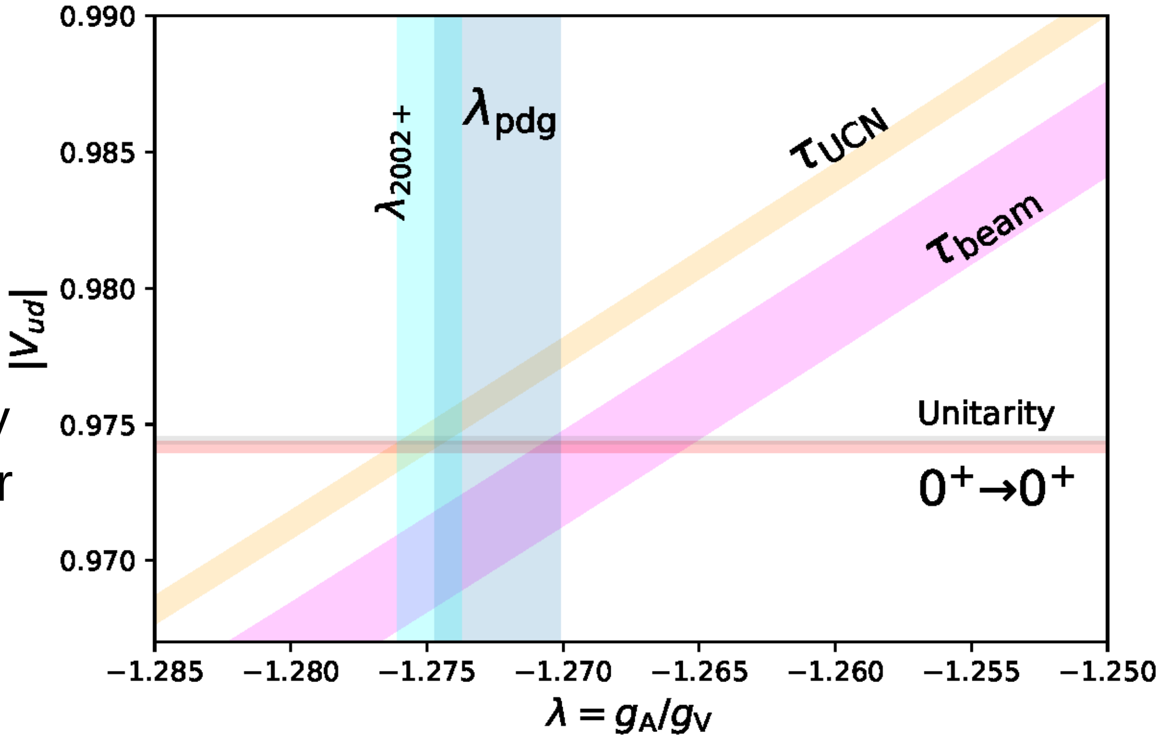
- Superallowed Fermi $0^+ \rightarrow 0^+$ decays: V_{ud} at 0.02% level
- To reach same level from neutron decay, $\delta\lambda/\lambda$ = 3e-4 and $\delta\tau$ = 0.3 s are both necessary





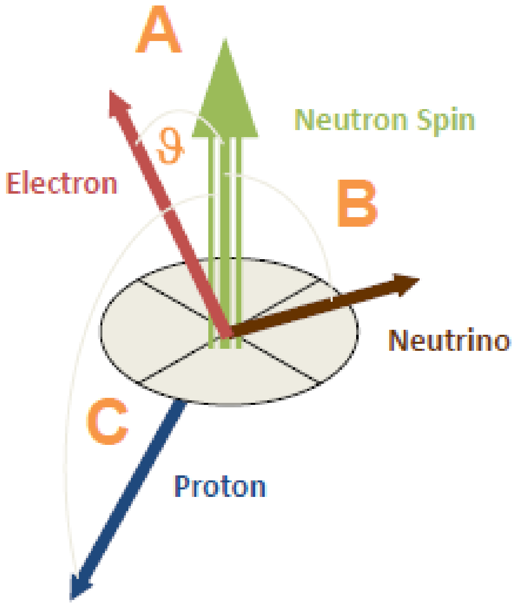
Tension between beam and bottle lifetime measurements, old and new λ measurements

- This is the situation as of six months ago
- Recent developments:
  - UCNA final result confirms newer values
  - Perkeo III preliminary result confirms newer values
  - UCNτ lifetime confirms bottle value



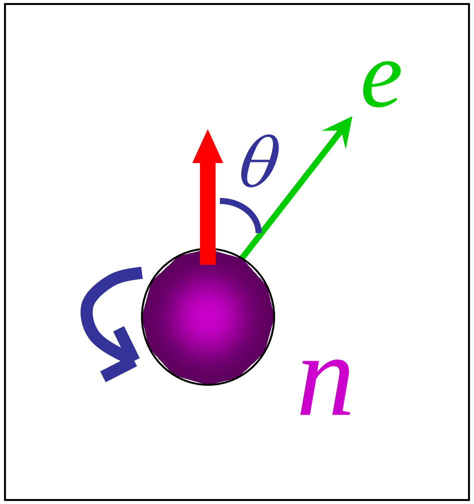
Decay Correlations

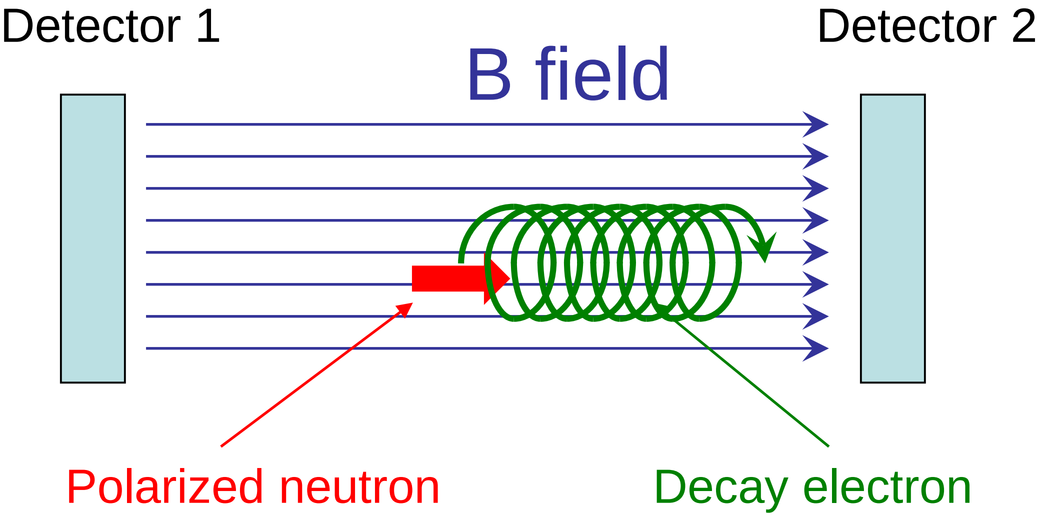
- A: electron asymmetry
  - Perkeo II, Perkeo III, UCNA
- B: neutrino asymmetry
  - Perkeo II
- C: proton asymmetry
  - Perkeo II
- D: triple correlation
  - TRINE, emiT
- a: electron-neutrino correlation
  - aSpect, aCORN, Nab



Plus Fierz interference *b*, helicity correlations, etc.

Principle of the *A*-coefficient Measurement (and other correlations)





$$dW=[1+\beta P A\cos\theta]d\Gamma(E)$$

$$A_{\exp}(E)=\frac{N_1(E)-N_2(E)}{N_1(E)+N_2(E)}\approx\langle P\rangle A\beta\langle\cos\theta\rangle$$

Systematics:

- Polarization
- Backgrounds
- Energy reconstruction

(End point energy = 782 keV)

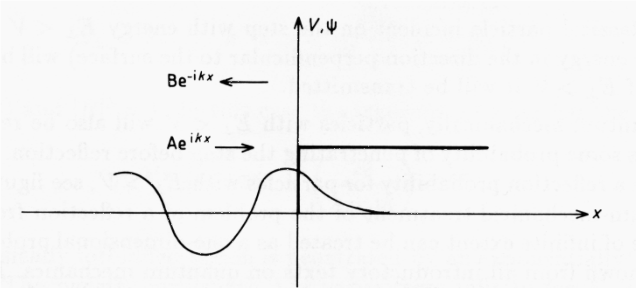
Interlude: Ultra-Cold Neutrons (UCN)

“Man is the Measure of All Things” Protagoras, 480-411 BC

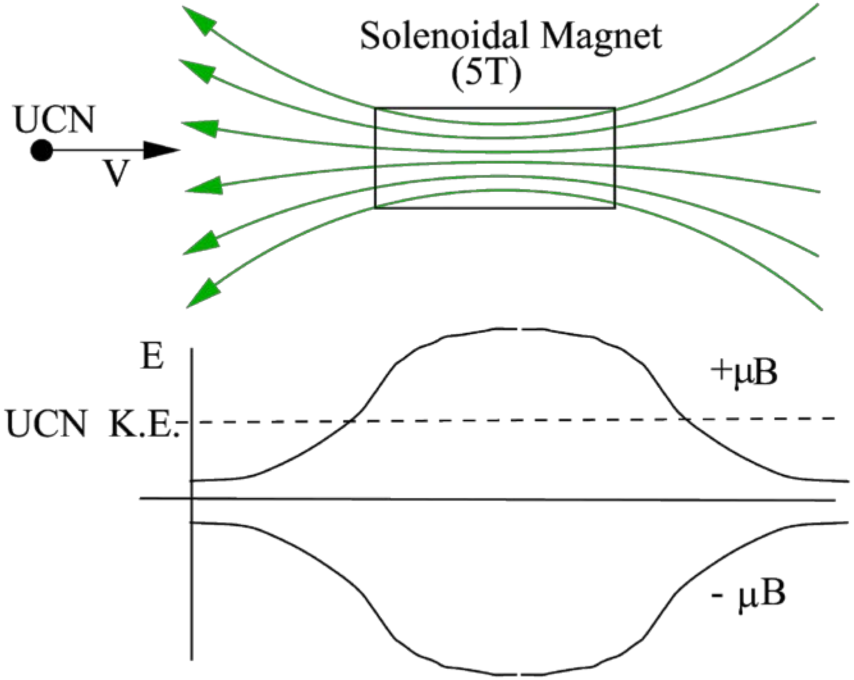
- 300 neV = Potential Energy in wall

300 neV = Potential Energy in wall		External reflection
$= \frac{1}{2} m_n v^2$	$= \frac{1}{2} m_n (8\ \mathrm{m/s})^2$	Running speed
$= m_n g h$	$= m_n g\ (3\ \mathrm{m})$	Human scale equipment
$= h^2/\ (2\ m_n\ \lambda^2)$	$= h^2/\ (2\ m_n\ (50\ \mathrm{nm})^2)$	Ultraviolet
$= \mu_n B$	$= \mu_n\ (3.5\ \mathrm{T})$	100% polarization
$= k T$	$= k\ (3\ \mathrm{mK})$	Ultra-cold!

- Total external reflection allows arbitrary guides and bottles; long lifetime
- Speed implies easy timing
- Installations: centimeters to meters in size
- UCN wavelength: about 0.1 μm
  - *close to visible light*
  - *mirrors for people can be mirrors for UCN*
- 100% polarization is easy to achieve (for a time)



UCN can also be essentially 100 percent polarized



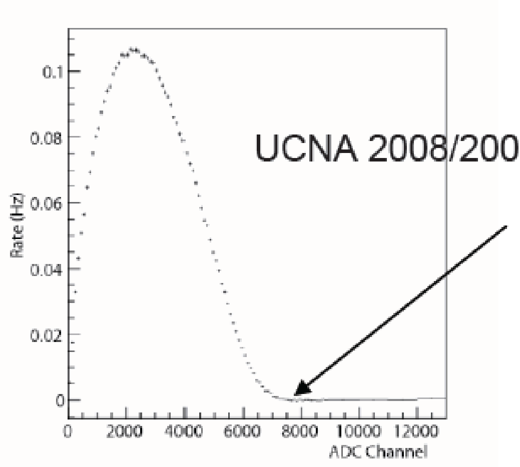
spin parallel to B
can not penetrate
magnetic barrier

spin antiparallel to B
passes unhindered

(note: neutron magnetic moment is negative

→ ~100% polarization, provided v_{UCN} is low enough

Backgrounds can be reduced relative to cold neutron experiments

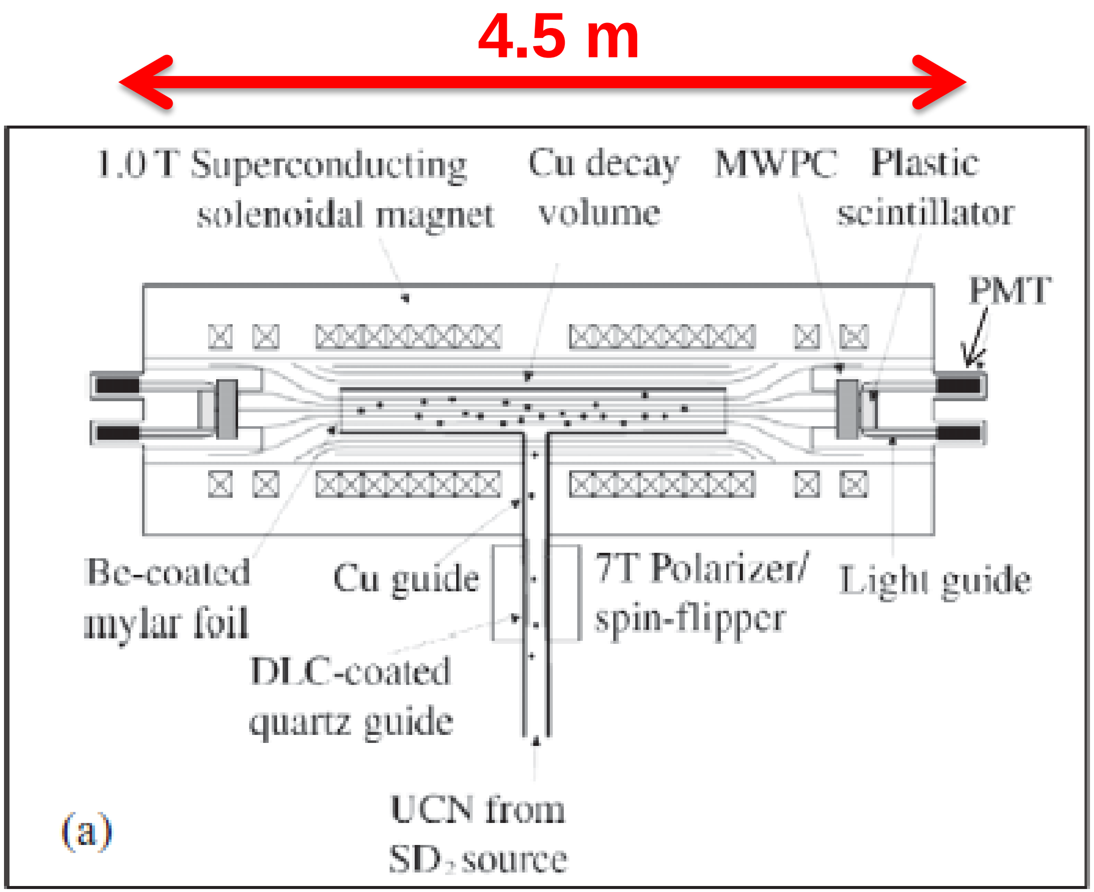


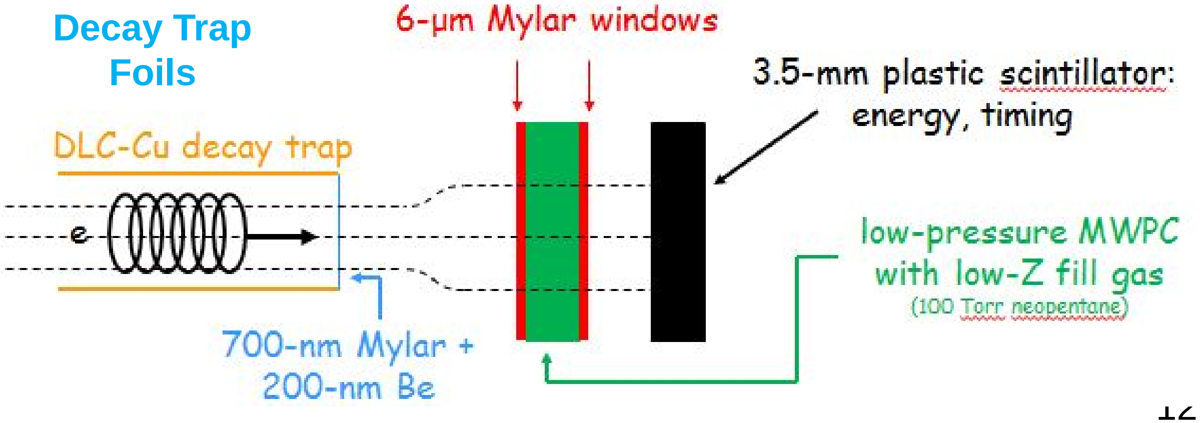
UCNA 2008/2009 data

< 0.015%
(negligible)

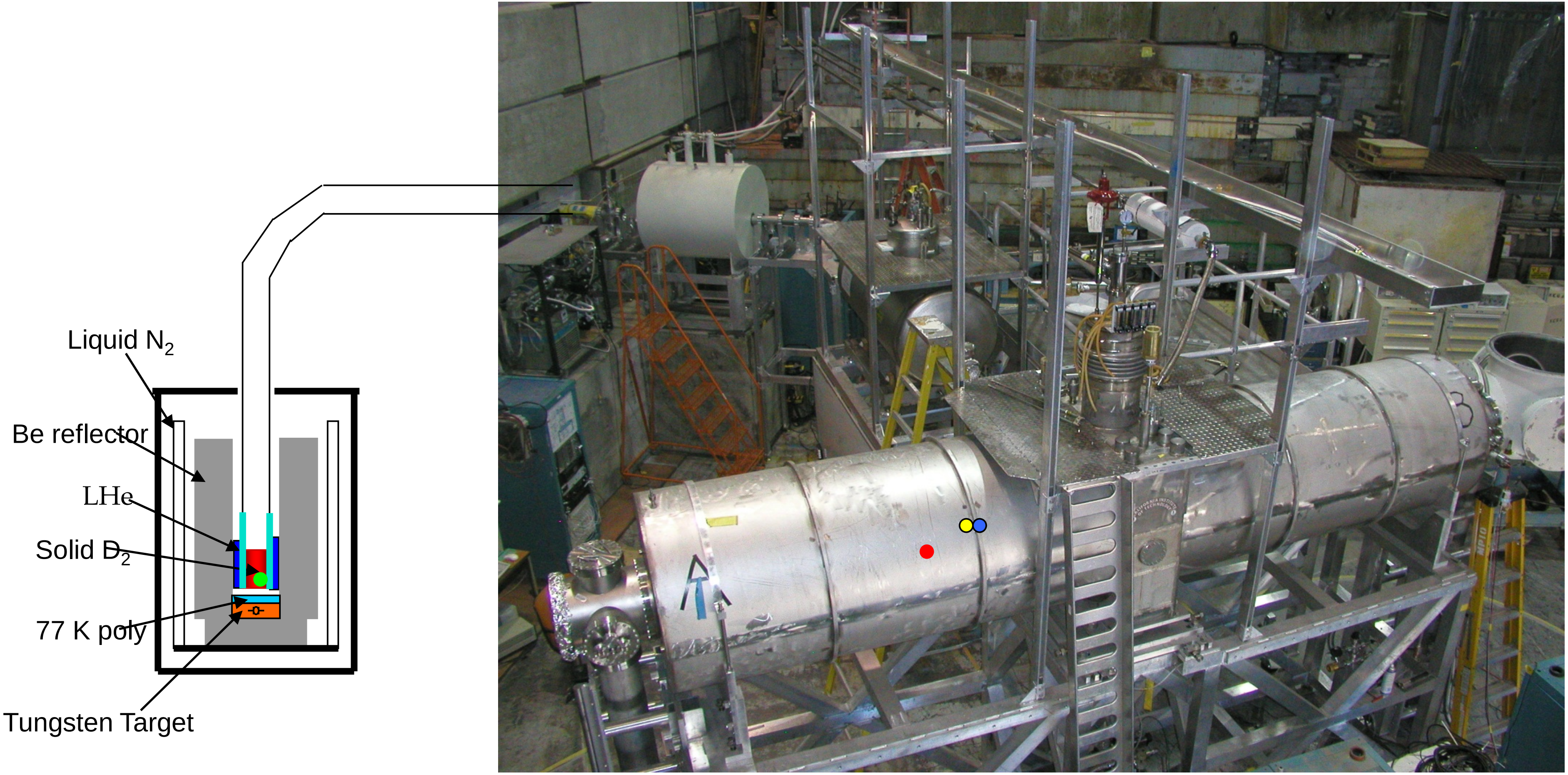
UCNA Detector

- The UCNA experiment ran from 2007 to 2013 at Los Alamos
- Results published incrementally, with independent statistics and correlated systematics
- Final results published 2018: $\delta\lambda/\lambda = 1.5e-3$
- Proposed UCNA+ upgrade



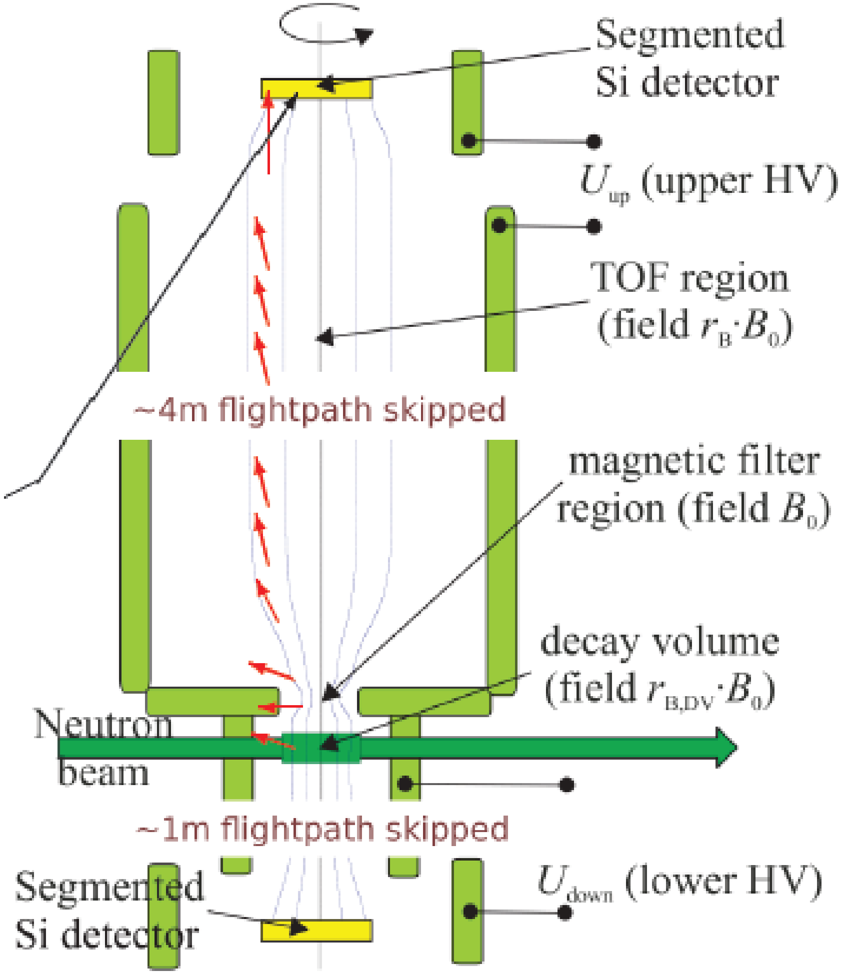


UCNA Experiment



Nab experiment in final construction

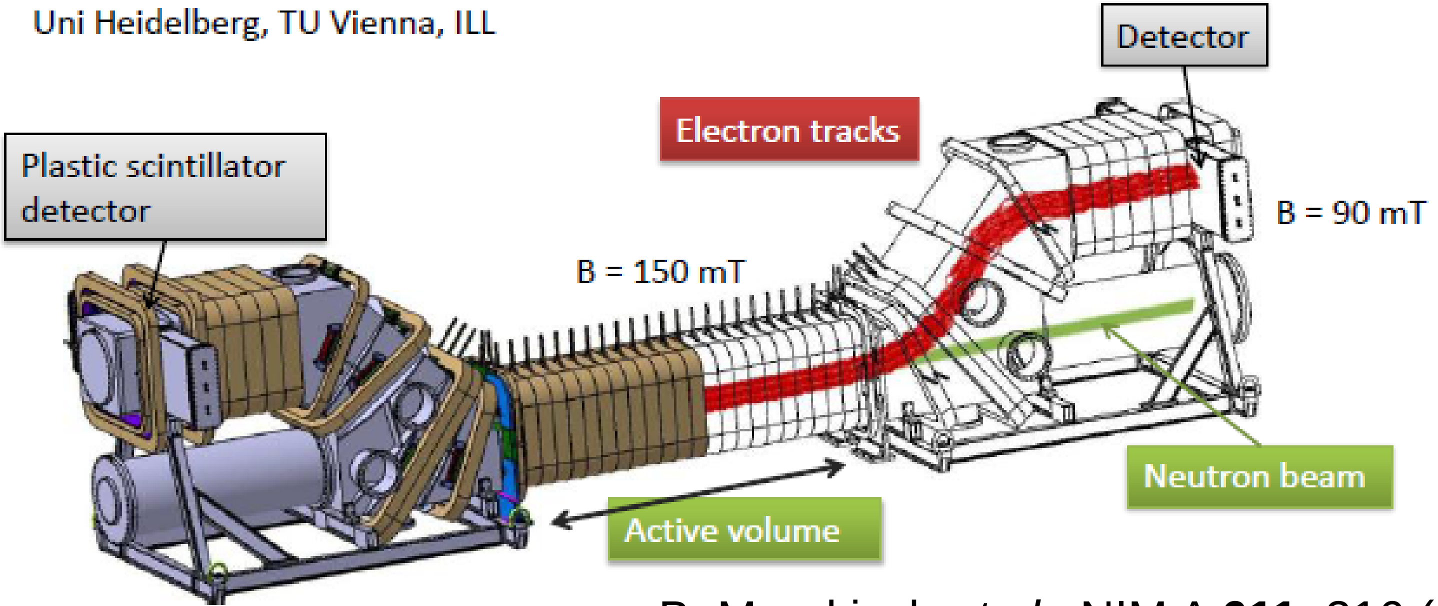
- Nab will measure a,b at SNS in Oak Ridge
  - Recall a=electron-neutrino correlation
  - Reconstruct opening angle from E_p, E_e
  - E_e from Si detectors, E_p from TOF
- Goal: $\Delta a/a$ = 2e-3, $\delta\lambda/\lambda$ = 5e-4



Perkeo III is state of art of CN beta decay

- Backgrounds eliminated using pulsed beam
- Up to 50 kHz decay rate
- Total uncertainty expected to be $\Delta A/A$=2.1e-3, $\delta\lambda/\lambda$=5e-4
- Results very soon!

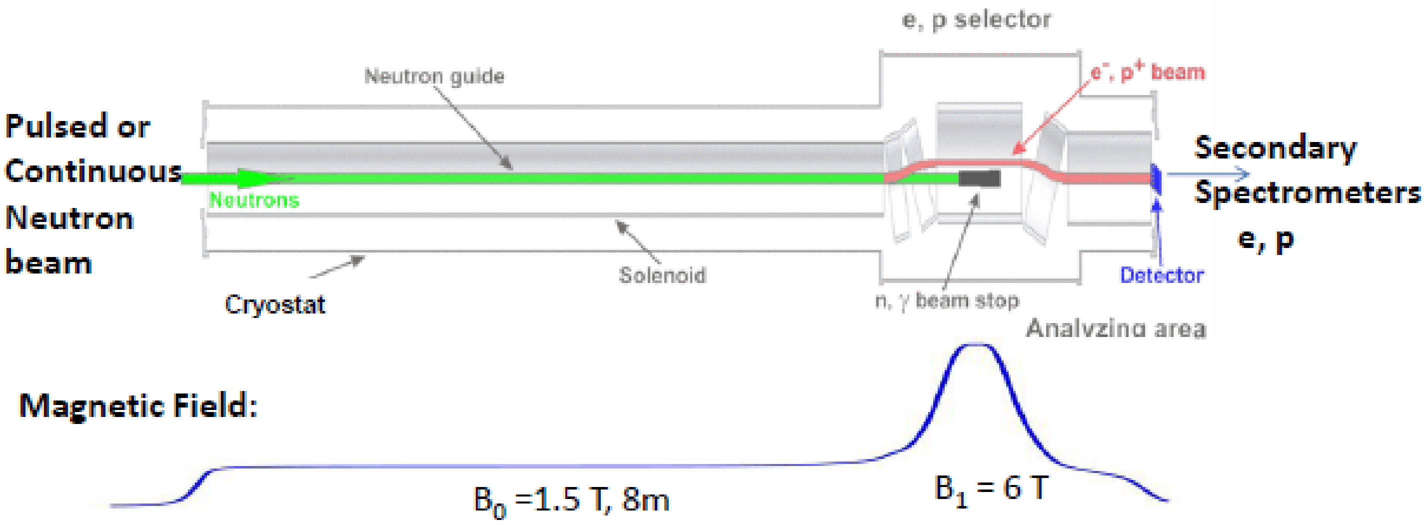
Uni Heidelberg, TU Vienna, ILL



B. Maerkisch *et al.*, NIM A **611**, 216 (2009)

PERC is the next generation

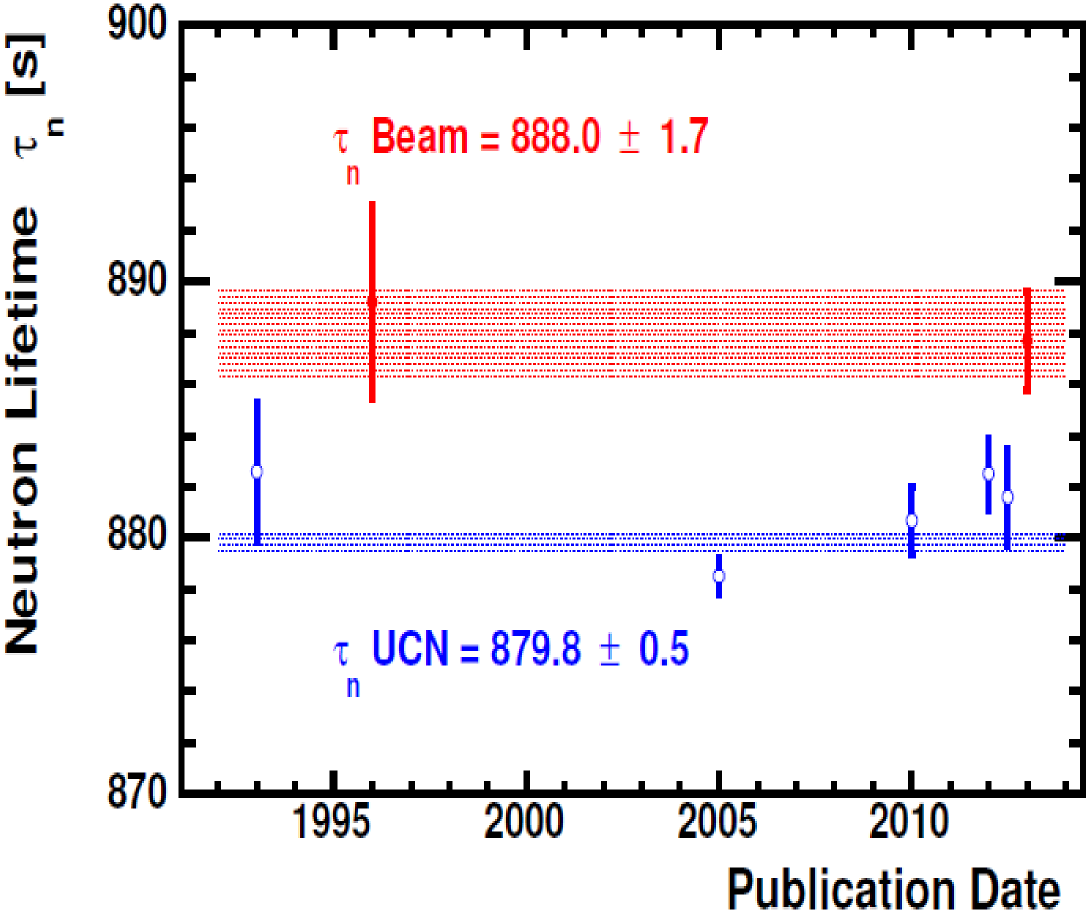
- **P**roton **E**lectron **R**adiation **C**hannel
- 8 m flight path maximizes statistics
- 6 T field pinch minimizes backscatter, field inhomogeneity effects
- To be installed in flight path at FRM-2
- All systematics expected to be O(10^{-4})



D. Dubbers *et al.*, NIM A **596**, 238 (2008)

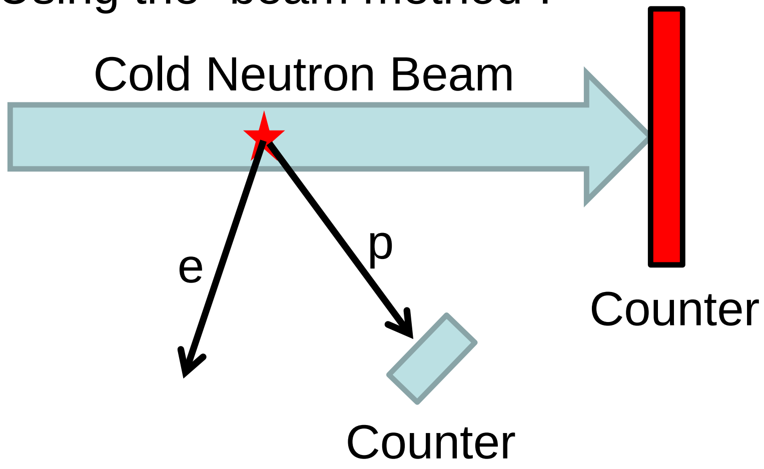
The neutron lifetime puzzle

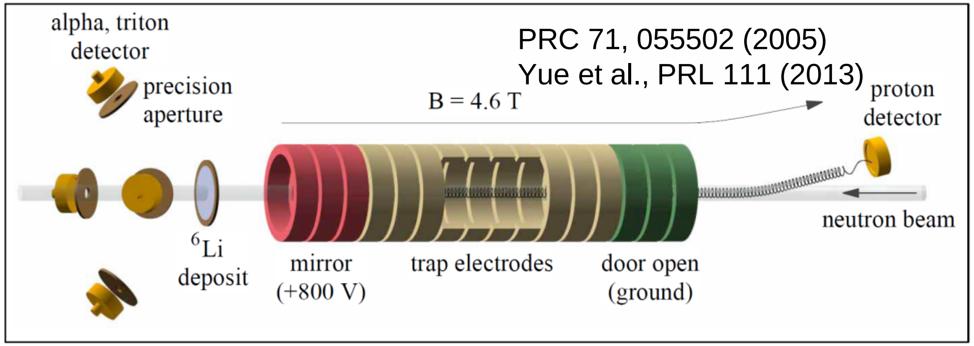
- Two methods of measuring neutror lifetime:
  - beam (appearance of decay products)
  - Bottle (disappearance of UCN)
- PDG experiments disagree by over four σ



How to measure neutron lifetime

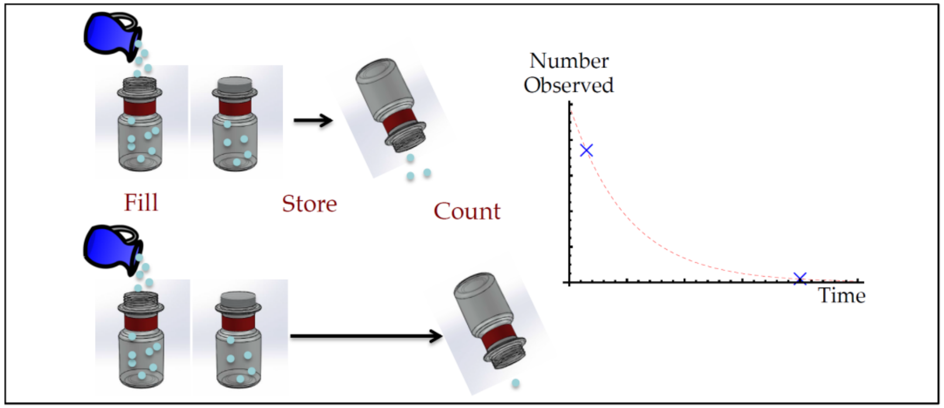
Using the “beam method”:

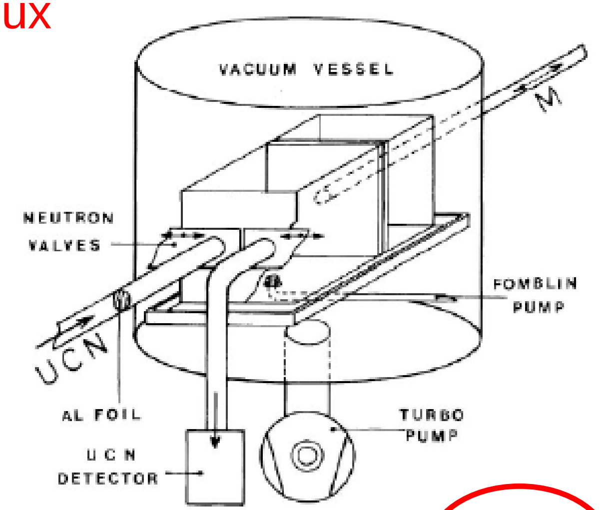



PRC 71, 055502 (2005)
Yue et al., PRL 111 (2013)

BL2 experiment in progress right now, with higher flux

Using the Ultra-cold neutron “bottle” method:



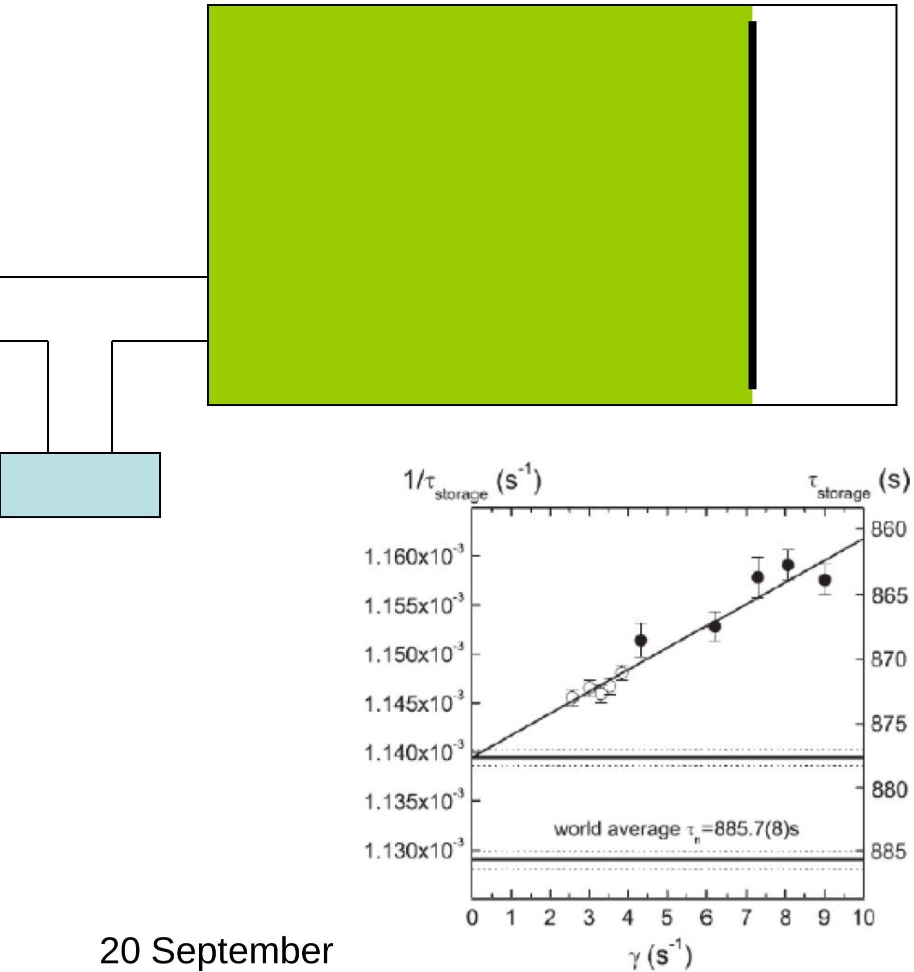


$$1/\tau_{\text{storage}} = 1/\tau_n + 1/\tau_{\text{loss}}$$

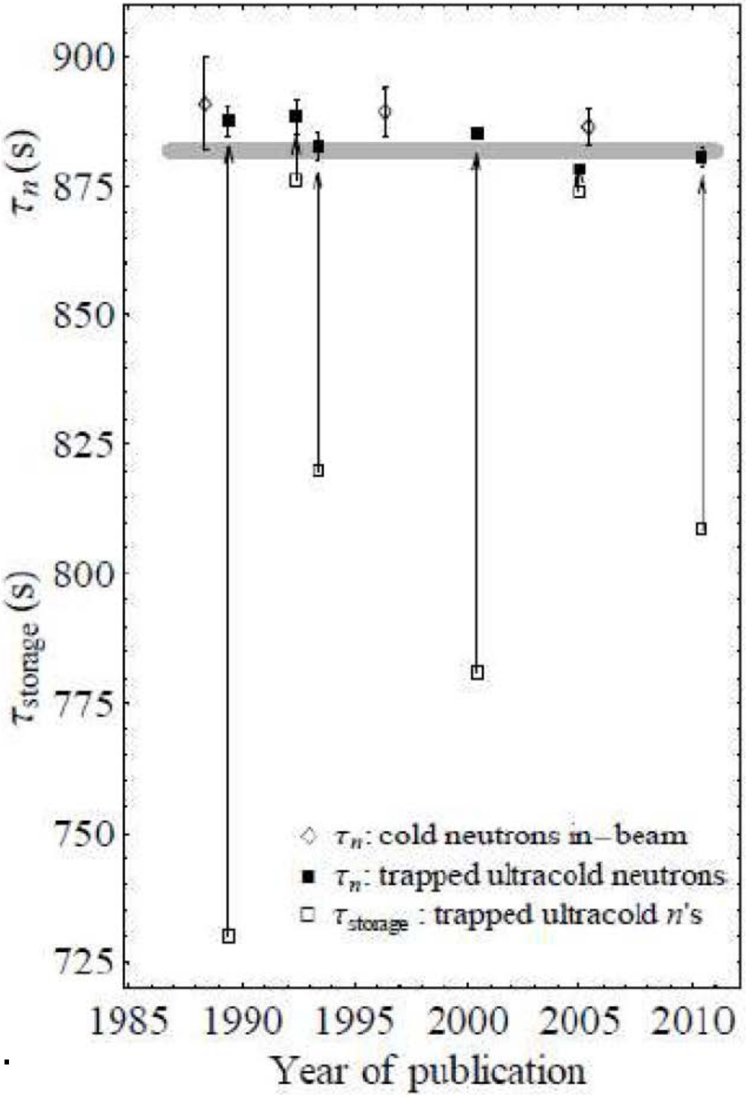
Rev. Mod. Phys. **83**, 1173 (2011)

Material bottle experiments involved 100 s extrapolations due to wall losses

Typical bottle experiment



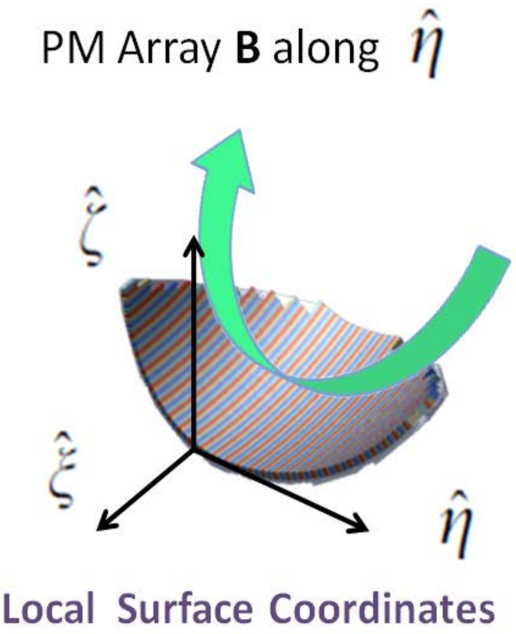
Serebrov et al., PRC 78 (2008).

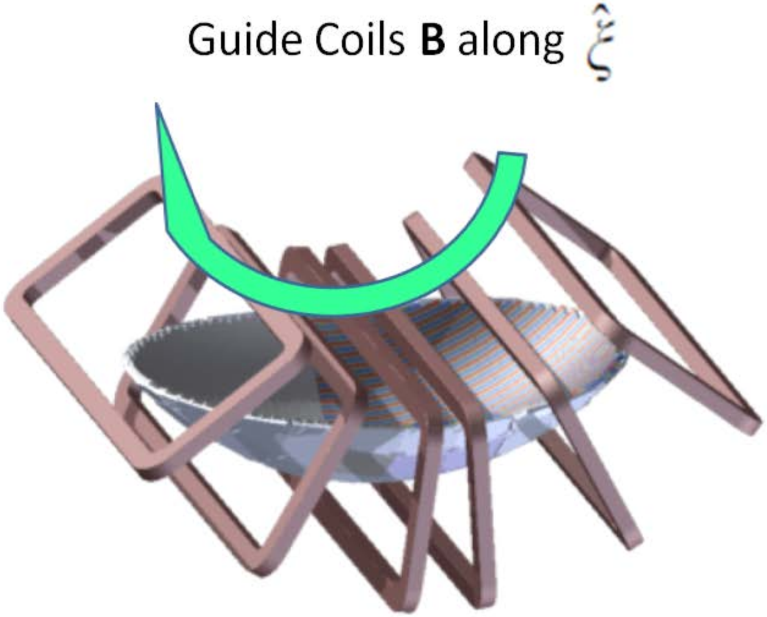


UCNτ: Magneto-Gravitational Trap (proposed in 2006)

- **Magnetic trapping**: Halbach array of permanent magnets along trap floor repels spin polarized neutrons: no material contact during holding period

- **Minimize UCN spin-depolarization loss**: EM Coils arranged on the toroidal axis generates holding **B** field throughout the trap (perpendicular to the Halbach array field).

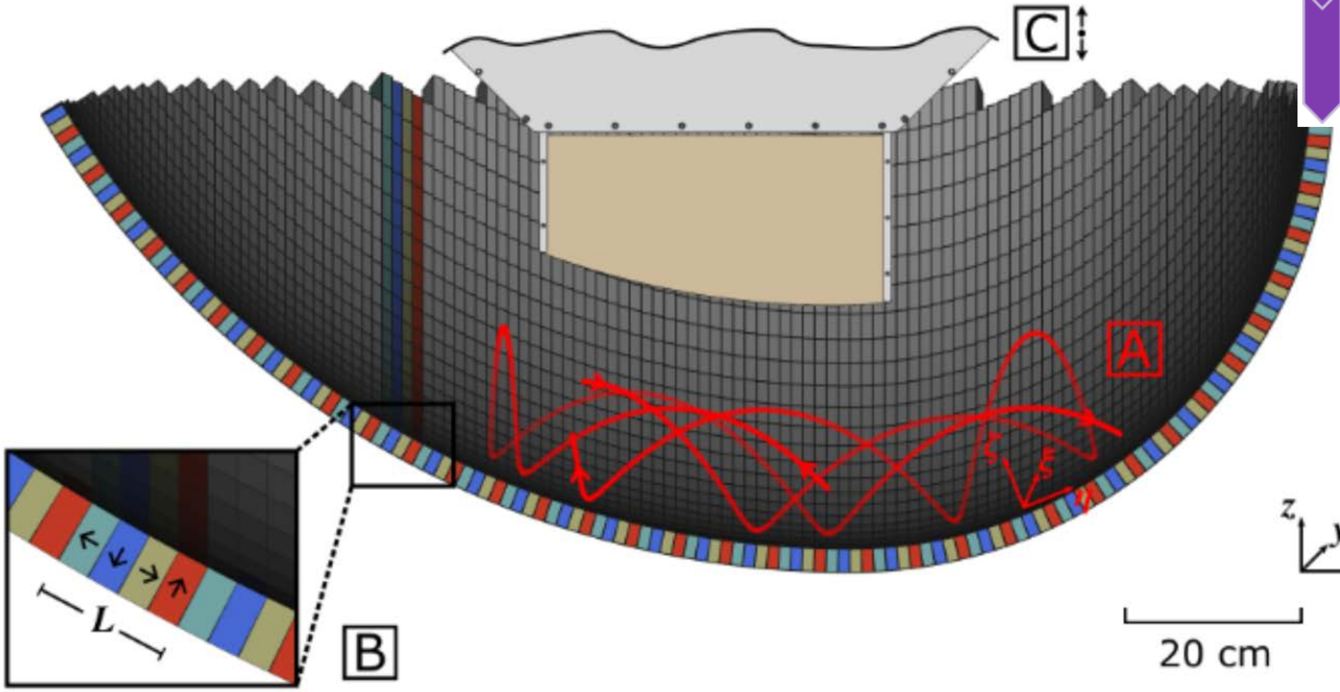




Walstrom et al, NIMA, 599, 82 (2009)

The UCNτ Magneto-Gravitational Trap

- Rows: 141
- PMs: 5310



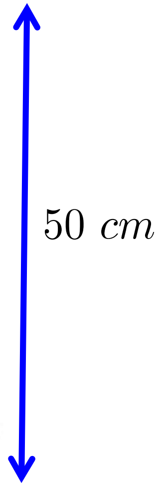
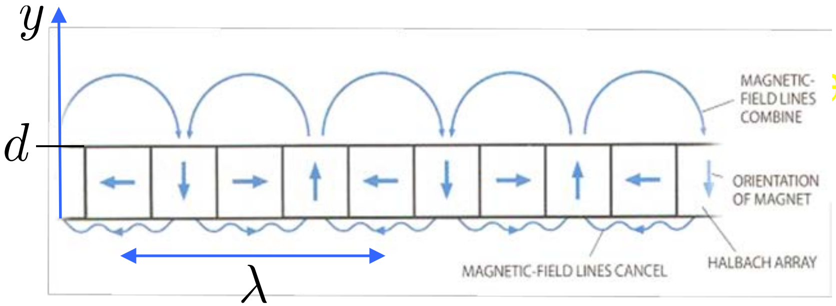


Figure 1: The UCNτ apparatus. **A** UCN trajectory inside the trap which enters and leaves the page as indicated. **B** Arrows indicating the magnetization direction for the Halbach Array. Colored strips show rows of identical magnetization. **C** The *in-situ* detector which can be raised out of the trap and lowered to the bottom. The khaki color is the active area of ^{10}B.

$$|\mathbf{B}| \approx B_{\rm rem}(1 - e^{-2\pi d/\lambda})\, e^{-2\pi y/\lambda}$$



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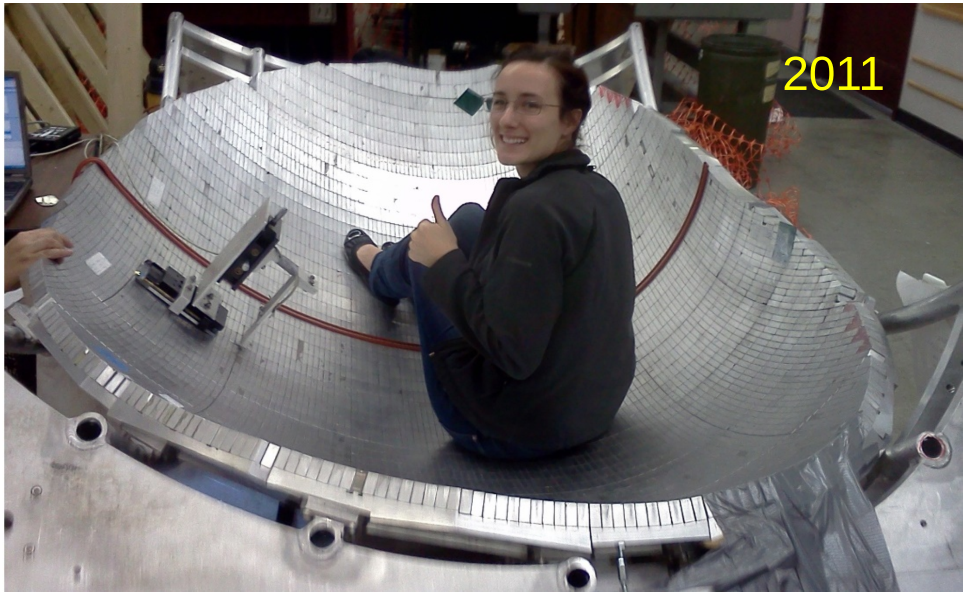
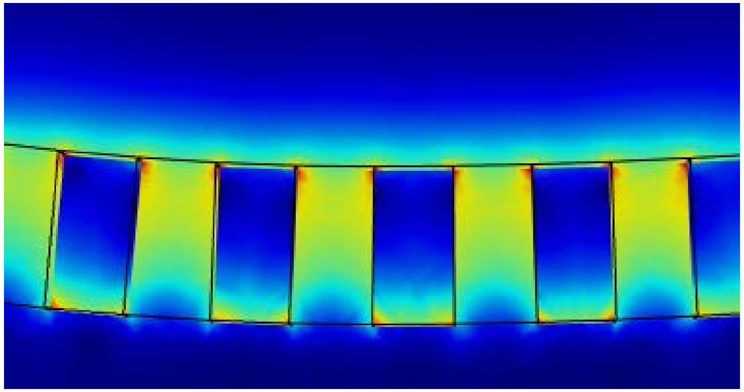
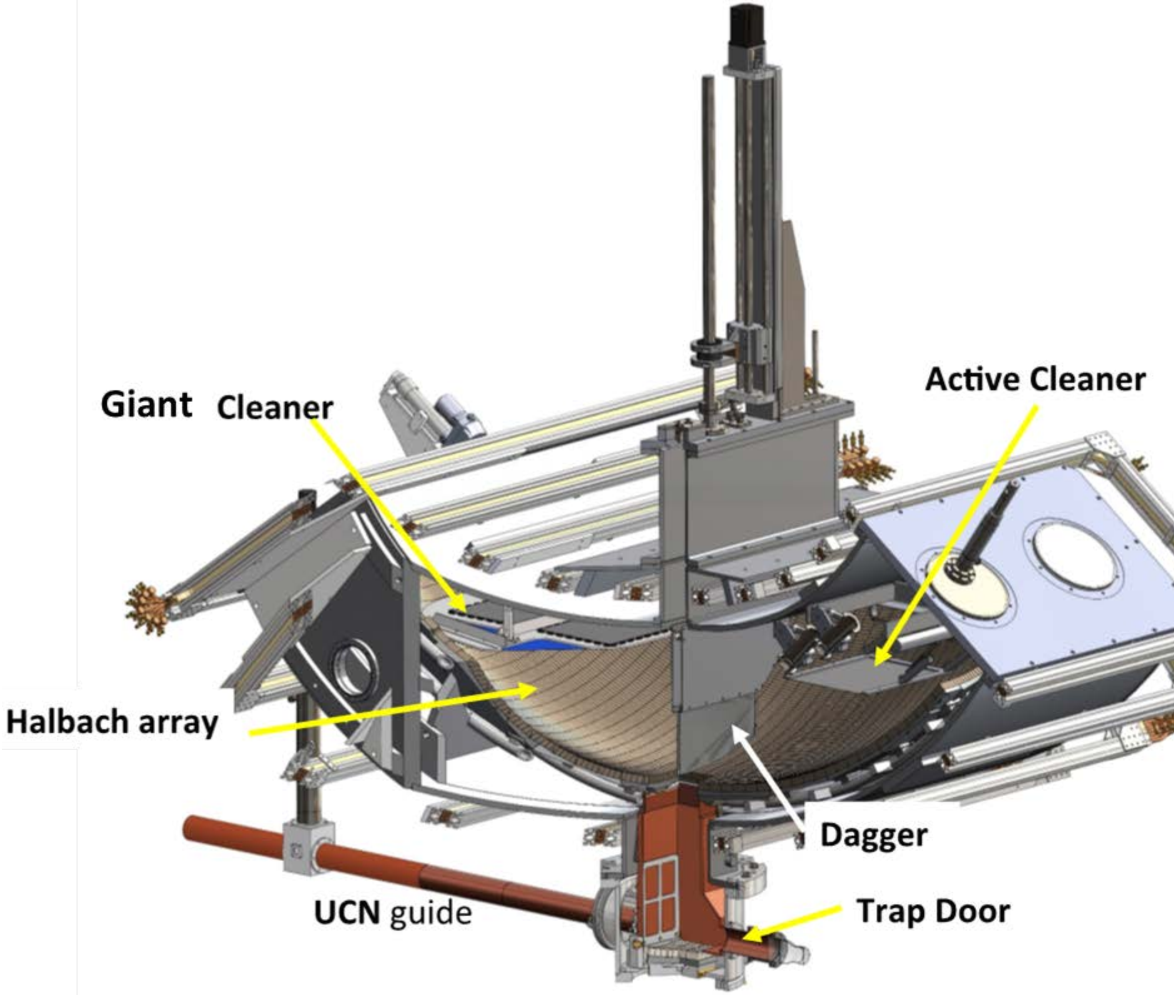


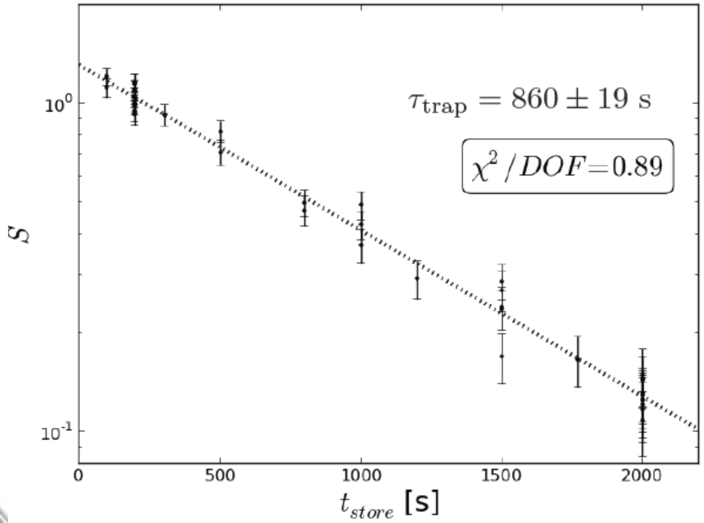
Top: UCNτ Magnetic Trap (IU undergrad, Bailey Slaughter, inside mapping the field)

Bottom: Magnetic Field Mapping (developed by A. Holley, TTU)



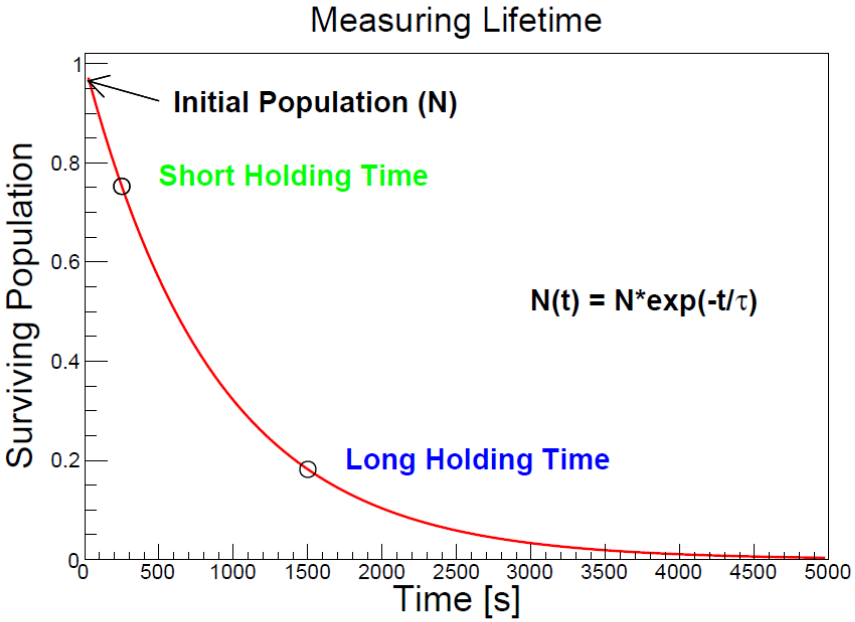
The UCNτ apparatus

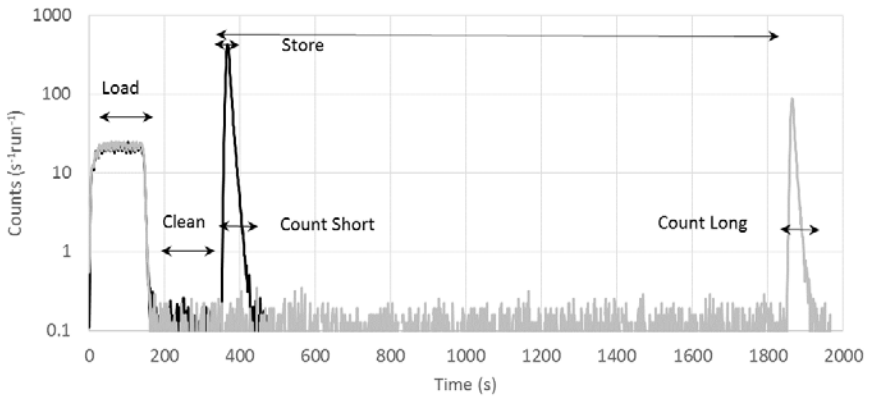




D. Salvat, PRC 89, 052501 (2014)

Pairs of short-long storage times





$$\tau_{trap} = \frac{\Delta t}{\log\left(\frac{N_{short}}{N_{long}}\right) - \log\left(\frac{M_{short}}{M_{long}}\right)}$$

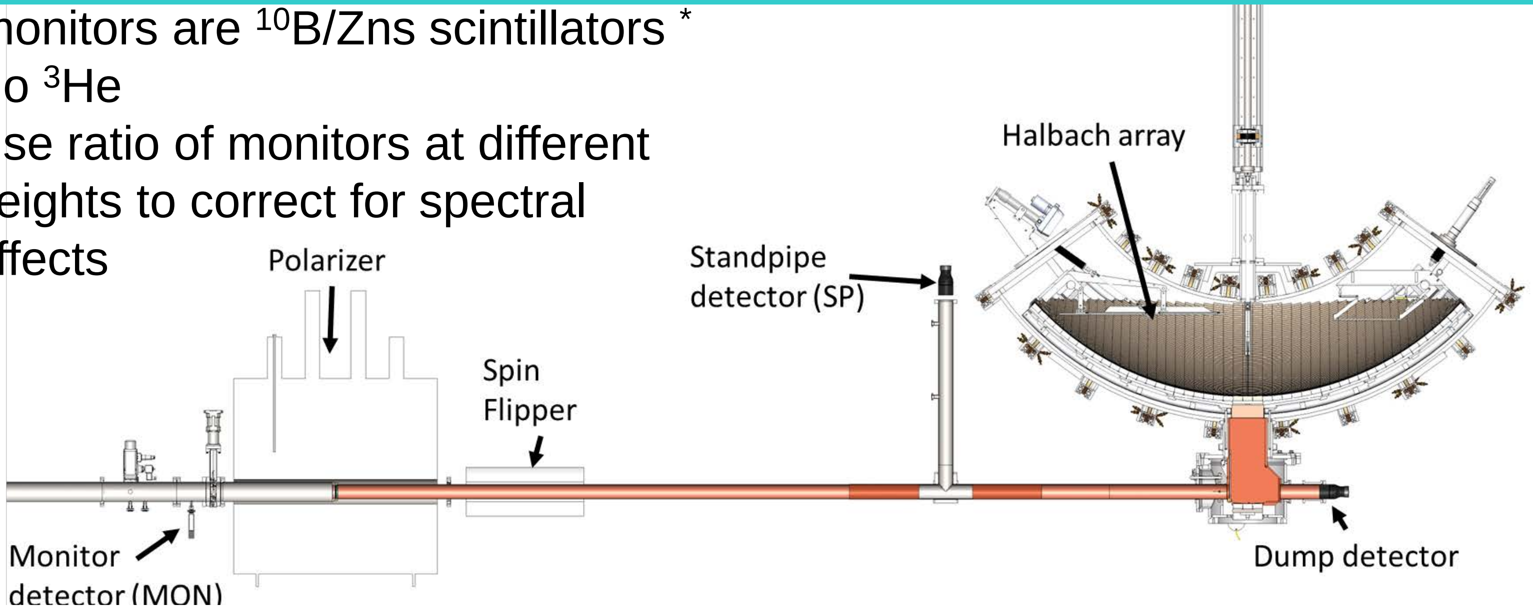
N: UCN counts
M: Monitor counts

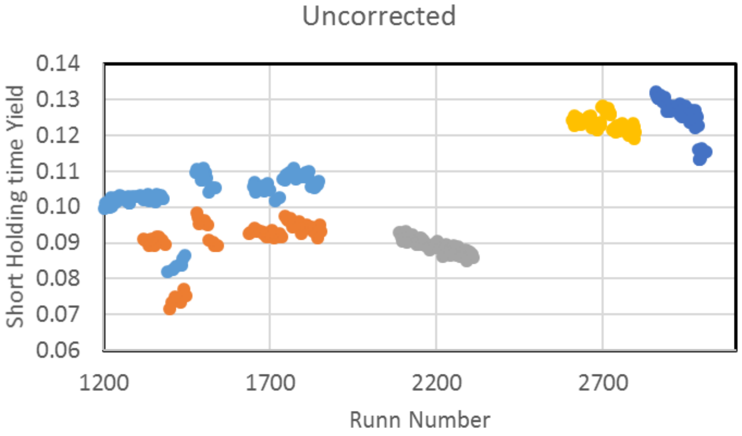
$$\frac{1}{\tau_{\text{trap}}} = \frac{1}{\tau_{\text{n}}} + \frac{1}{\tau_{\text{escape}}} + \frac{1}{\tau_{\text{heating}}} + \frac{1}{\tau_{\text{depol}}} + \ldots$$

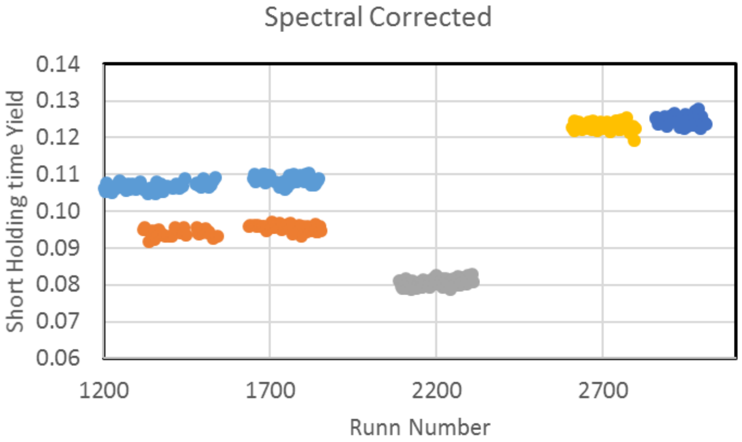
Flux Monitoring

All monitors are ^{10}B/Zns scintillators *

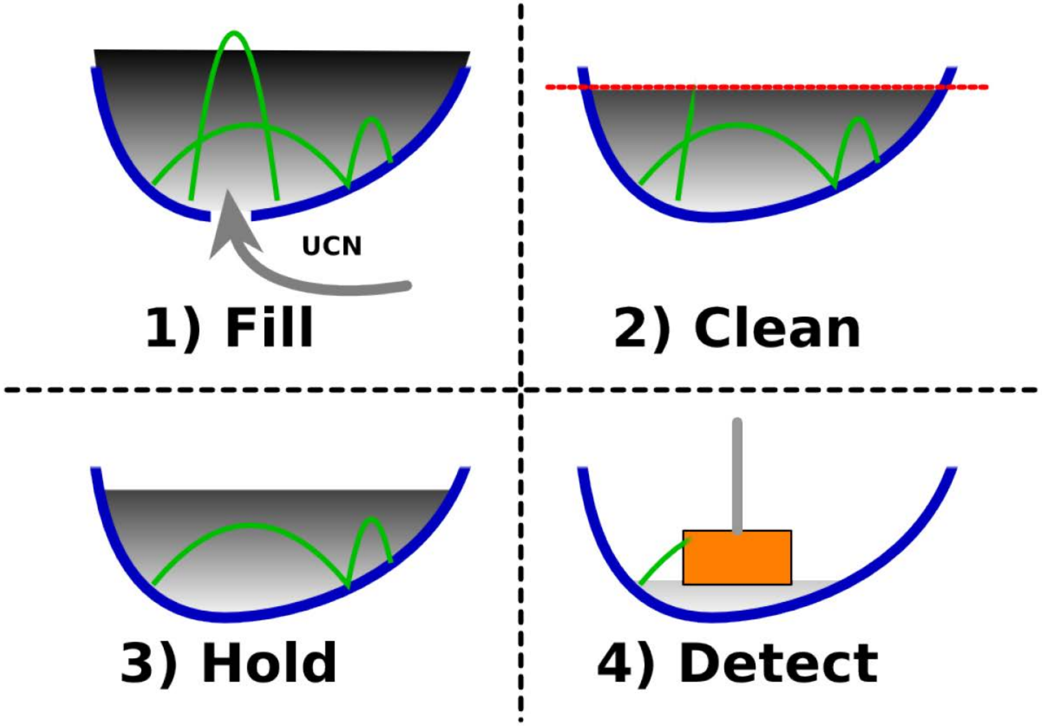
- No ^{3}He
- Use ratio of monitors at different heights to correct for spectral effects

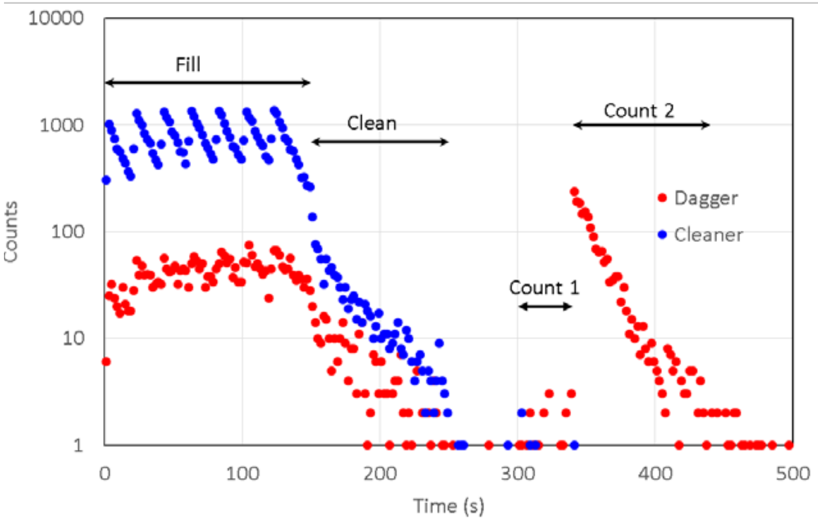




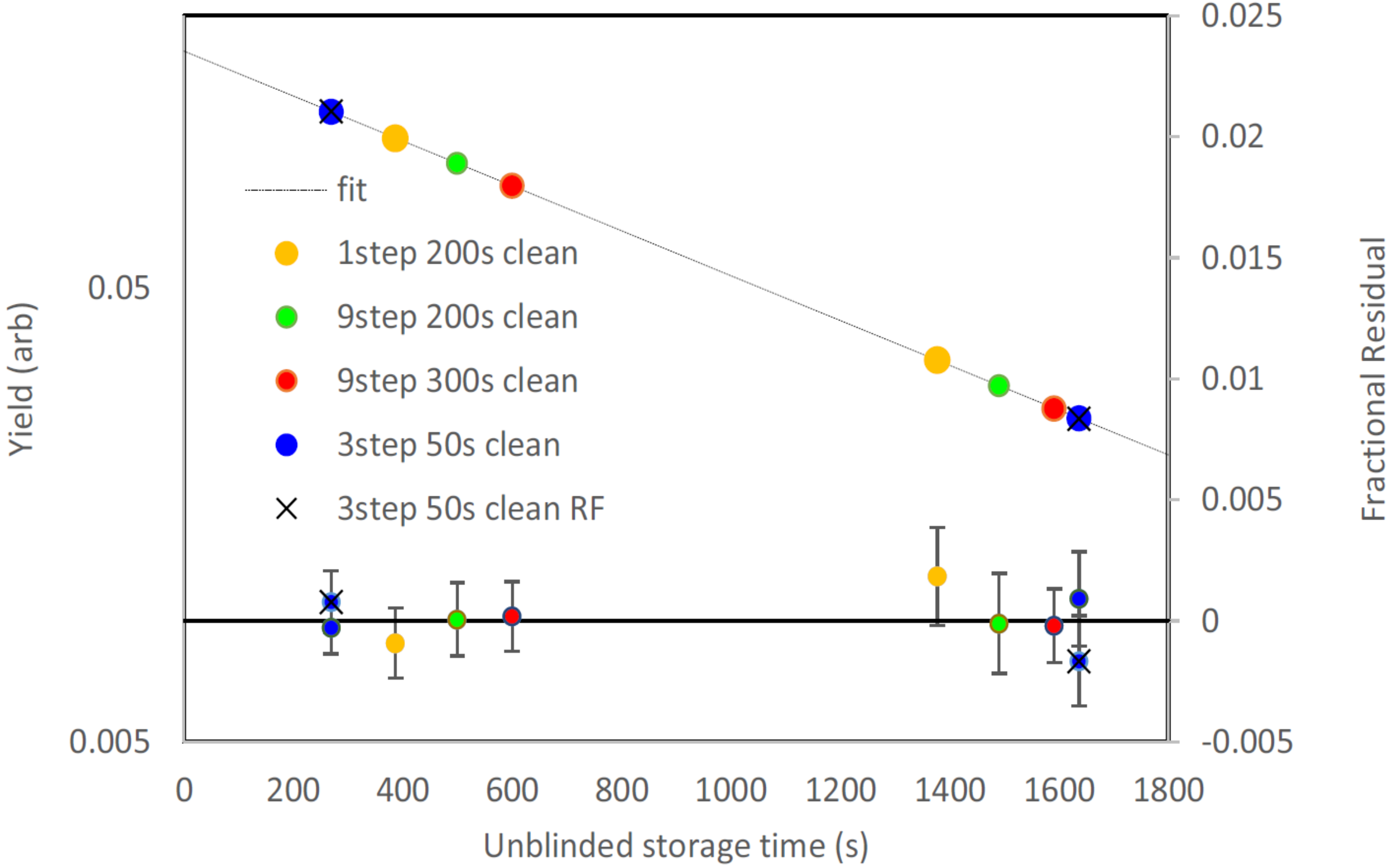


A typical lifetime run:



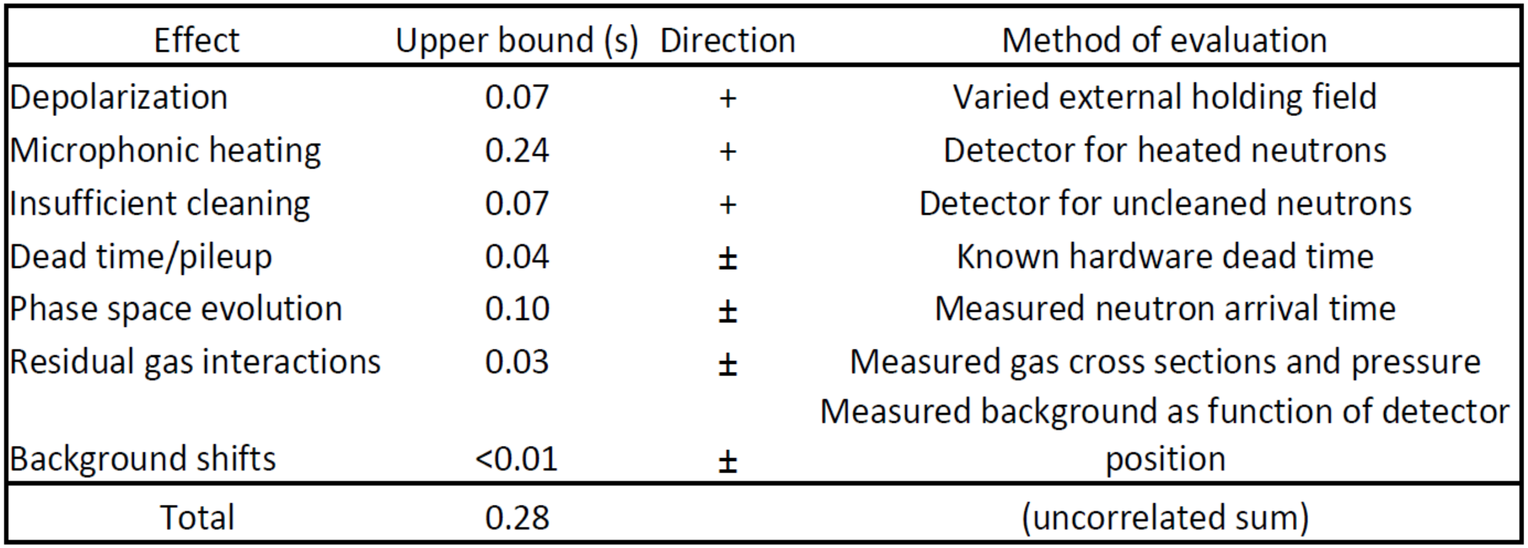


First science run published 2018



Pattie et al., Science 360, p. 627 (2018).

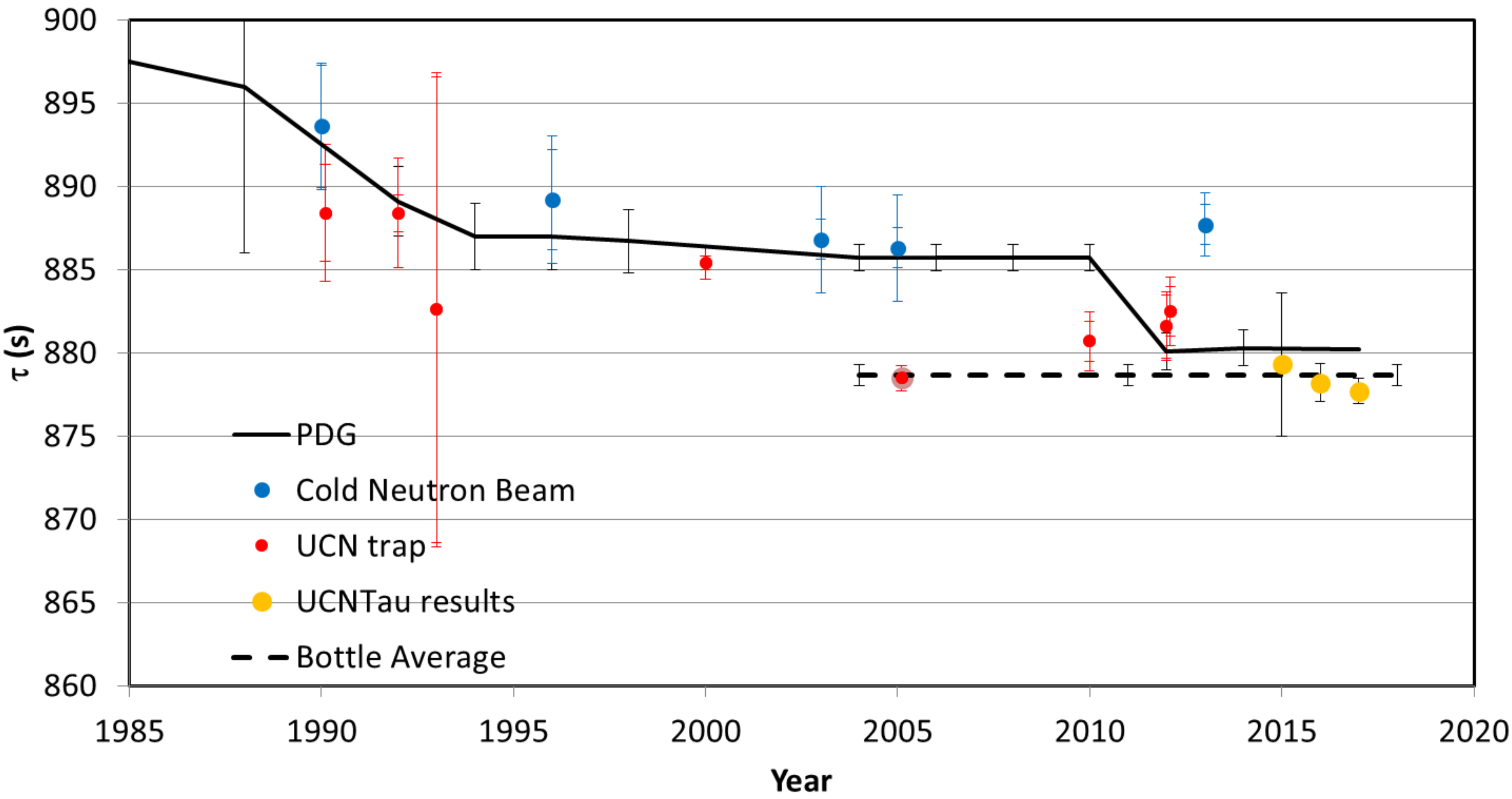
UCNτ path forward



Effect	Upper bound (s)	Direction	Method of evaluation
Depolarization	0.07	+	Varied external holding field
Microphonic heating	0.24	+	Detector for heated neutrons
Insufficient cleaning	0.07	+	Detector for uncleaned neutrons
Dead time/pileup	0.04	±	Known hardware dead time
Phase space evolution	0.10	±	Measured neutron arrival time
Residual gas interactions	0.03	±	Measured gas cross sections and pressure
Background shifts	<0.01	±	Measured background as function of detector position
Total	0.28		(uncorrelated sum)

- Only correction, for residual gas interactions, is smaller than statistical and systematic uncertainties: no extrapolation!
- All major systematics appear to scale with statistics
- Data on tape for 0.4 s total uncertainty, acquisition continues

UCNτ results confirm material trap results with independent systematics



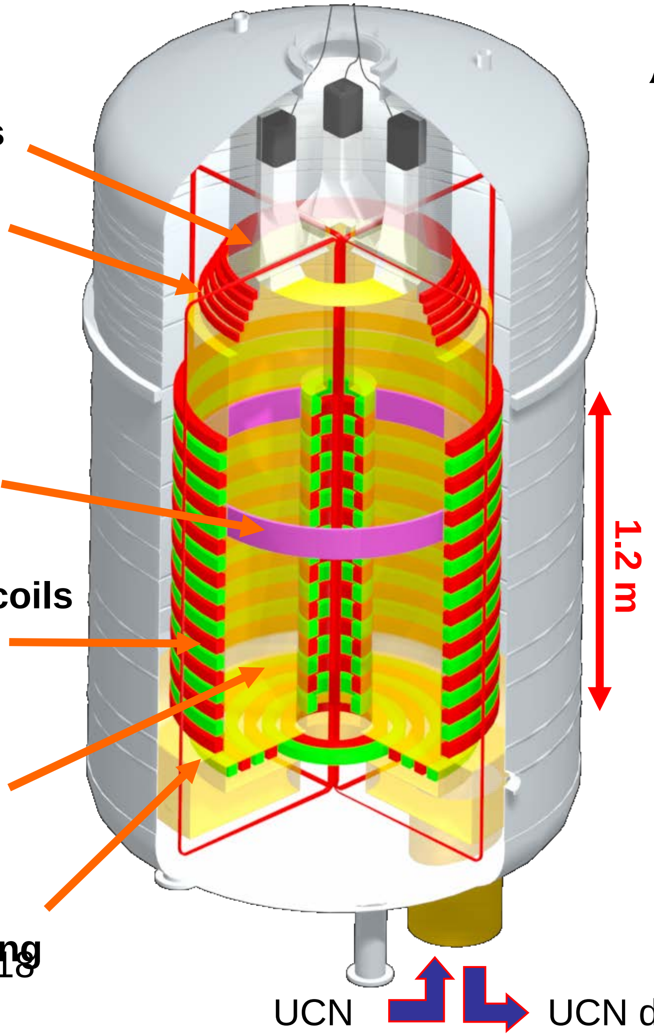
Proposed large volume magnetic storage experiment

$$N(t) = N(t_0)\exp\left(-\frac{t}{\tau_{\mathrm{n}}}\right)$$

PENeLOPE

Magnetic storage of UCN & proton extraction

S. Paul et al.



$\rho_{\mathrm{UCN}} = 10^3 – 10^4$ cm^{-3} (PSI /FRM II):

$N_{\mathrm{stored}} = 10^7 – 10^8$

- **Statistical accuracy:**

  $\delta\tau_{\mathrm{n}}$ ~ 0.1 s in 2-4 days

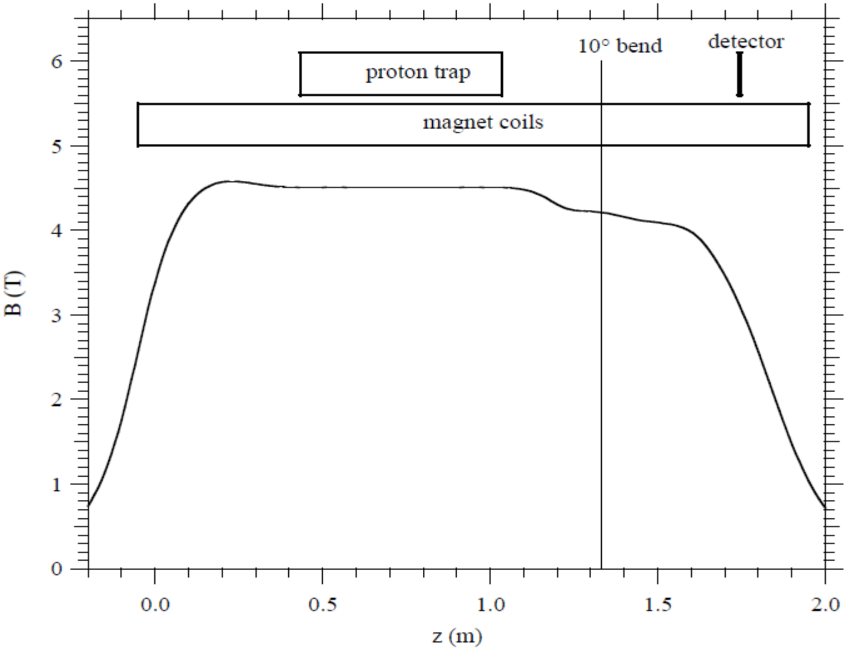
- **Systematics:**
  - **Spin flips negligible (simulation)**
  - **use different values B_{max} to check expected E_{UCN} independence of τ**

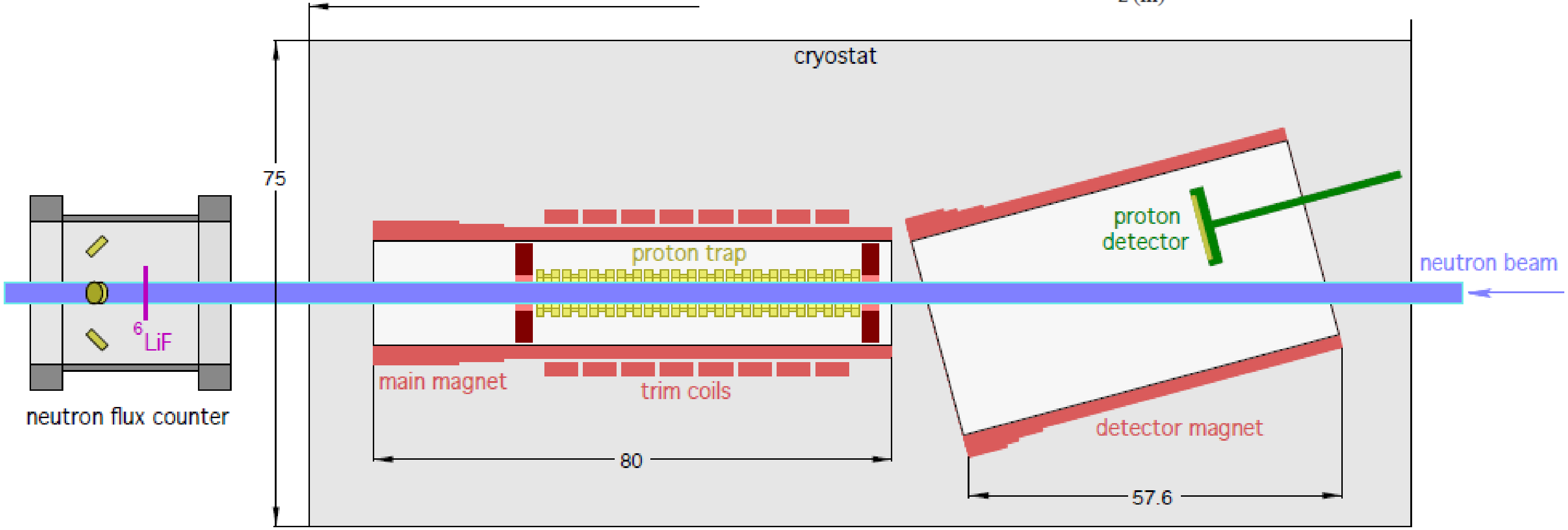
R. Picker et al., J. Res. NIST 110 (2005) 357

- Source not yet ready.
- Cryogenic experiment adds challenges.
- Symmetric trap.

BL3 Experiment
(proposal considered by the NSF Mid-scale program)

- Increased neutron beam diameter
  7 mm → 30 mm
- Uniformity requirements:
  $\Delta B/B < 10^{-3}$ (in proton trap)
- 50x increase in trapping volume

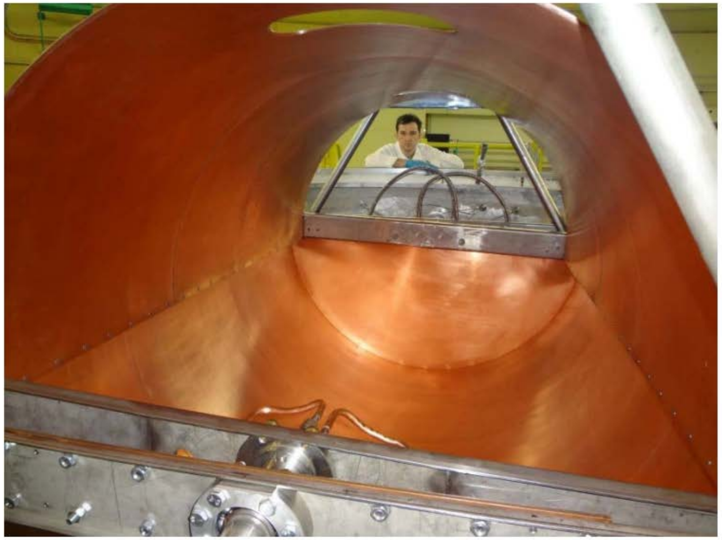


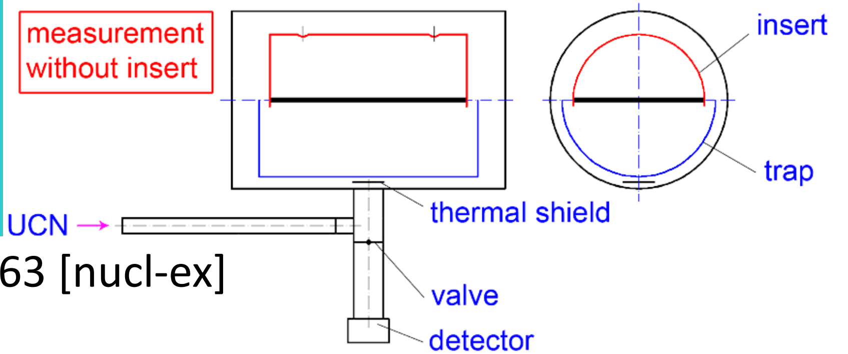


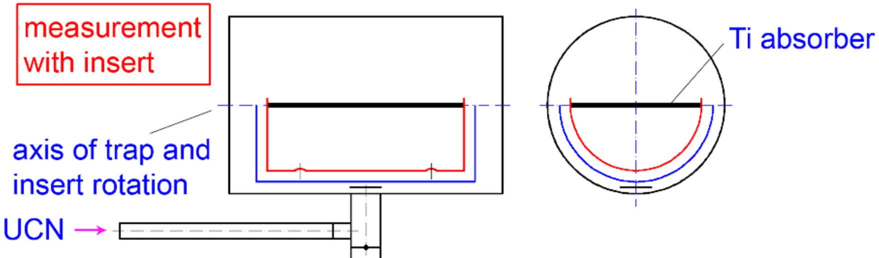
Information provided by N. Fomin

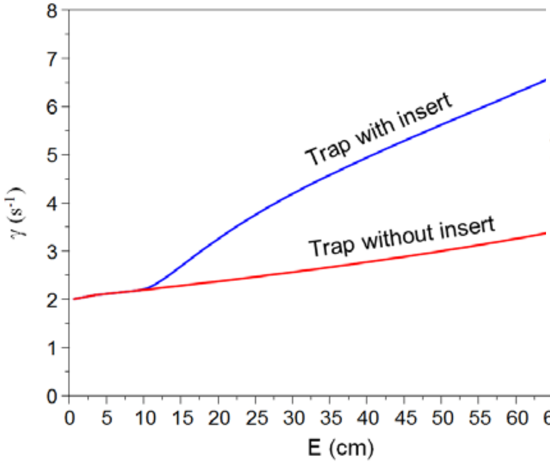
New GraviTrap

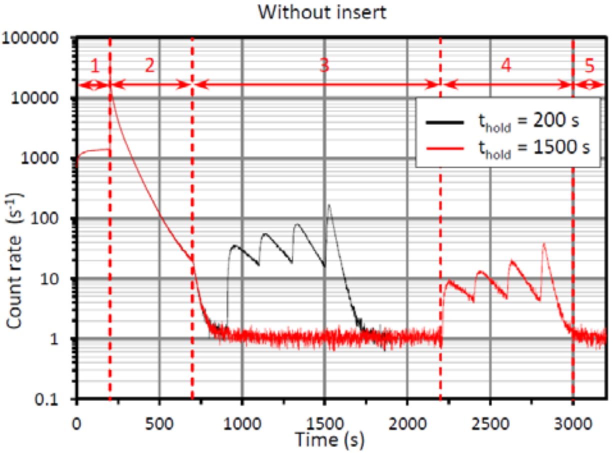
A. Serebrov et al.,(2017) arXiv:1712.05663 [nucl-ex]











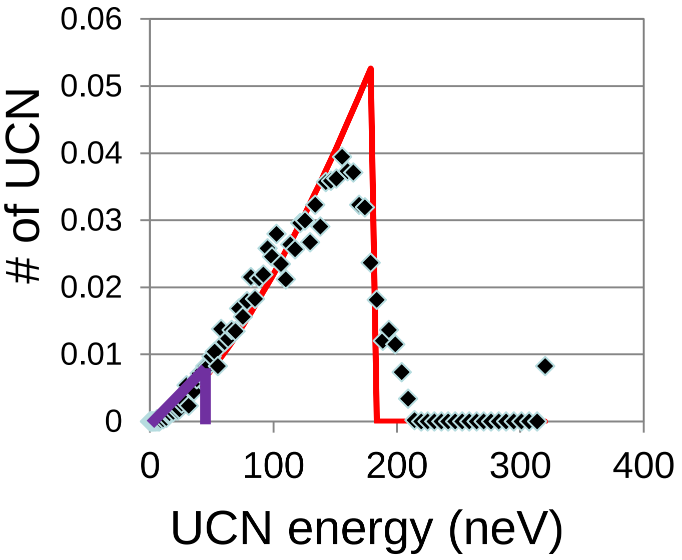
$$\tau_{loss}^{-1} = \eta(T)\gamma(E)$$

Preliminary result: τ=881.5 +/- 0.7 +/- 0.6 s
(between beam and previous bottle)

Tau2: A UCNτ-style experiment optimized to use the UCNs from the LANSCE source

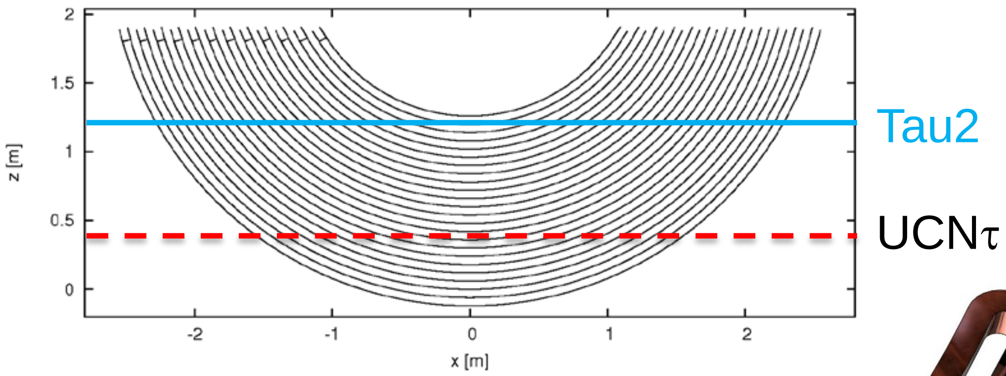
UCNτ's precision is limited not by systematic effects, but by the UCN density and spectrum produced by the LANSCE UCN source, the brightest in the world.

Tau2 can achieve a factor of four better precision than UCNτ by matching its trapping potential to the spectrum produced by the LANSCE source.



UCN spectrum produced by LANL source
UCN spectrum counted by UCNτ (38 cm)
UCN spectrum available to be counted by Tau2

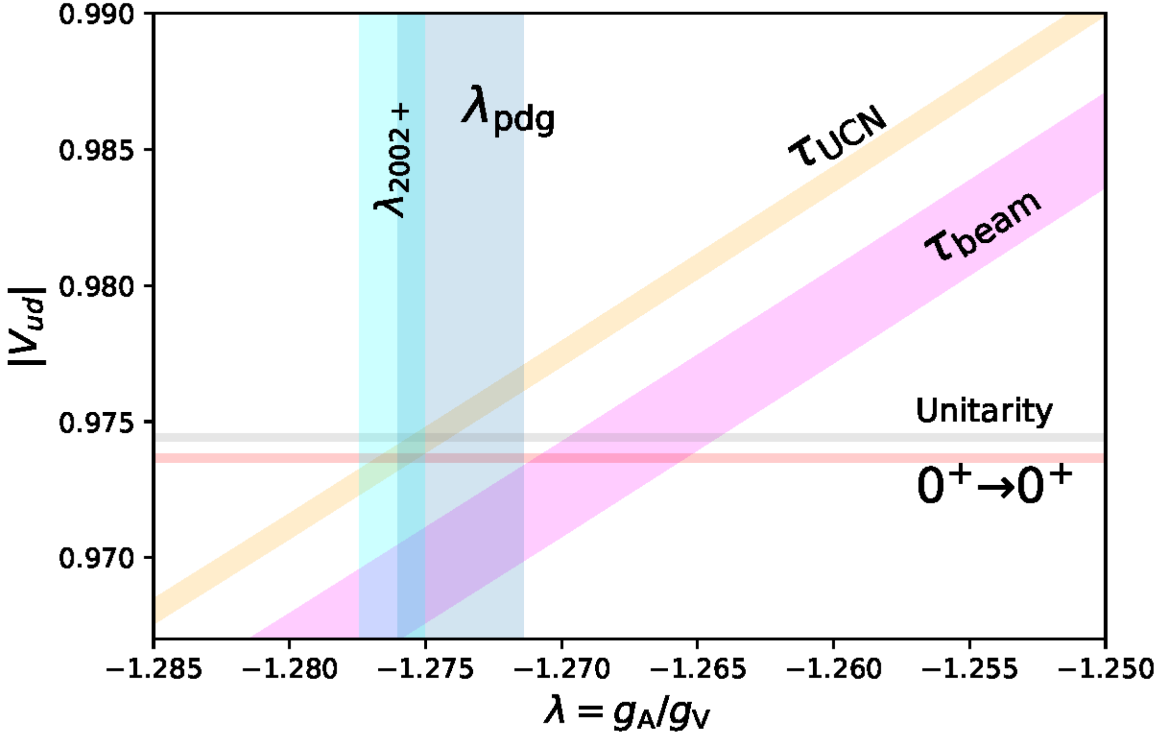
By replacing UCNτ's permanent magnet trap with one made of superconducting magnets.



A multi-year R&D effort will be needed to design the trap and ancillary systems

Recent (two weeks) shift in radiative corrections: 4 σ tension between nuclear beta decay and V_{us}

- This is the situation today
- Next generation of λ experiments, plus resolution of lifetime puzzle, needed to distinguish between nuclear beta decay value and unitarity value of V_{ud}



Seng, Gorchtein, Patel, and Ramsey-Musolf, 9/2018 (arXiv:1807.10197).

Conclusions

- Neutron experiments give independent measurement of V_{ud} with insufficient precision as yet
- Proposed lifetime and correlation experiments can reach precisions competitive with nuclear beta decay
- Neutron lifetime puzzle must be solved, ideally with systematically independent appearance measurement!