Los Alamos Beta Decay Experimental Program

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Los Alamos National Lab

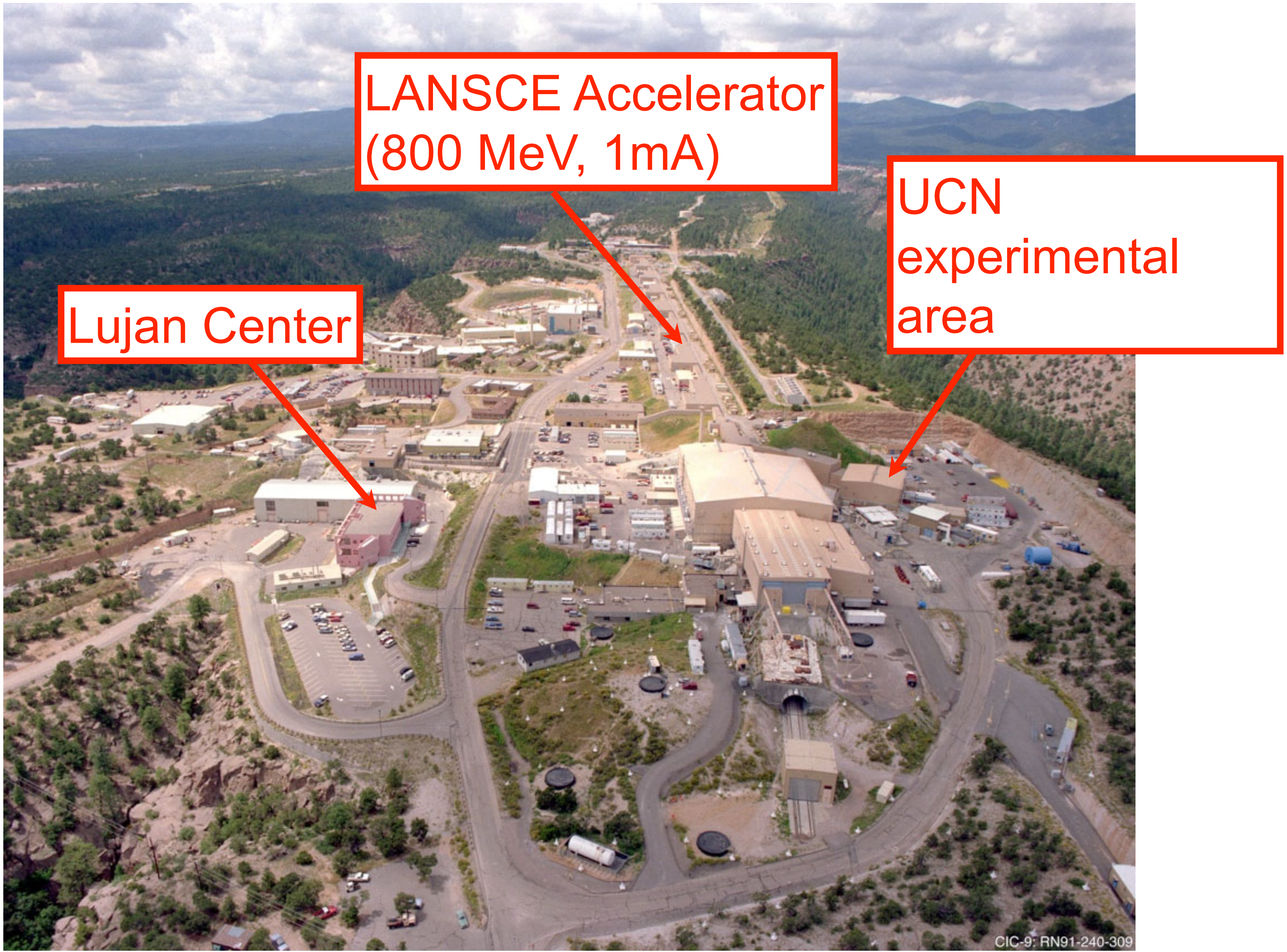
2 November 2018
Amherst Beta Workshop

'LA-UR-18-29113'

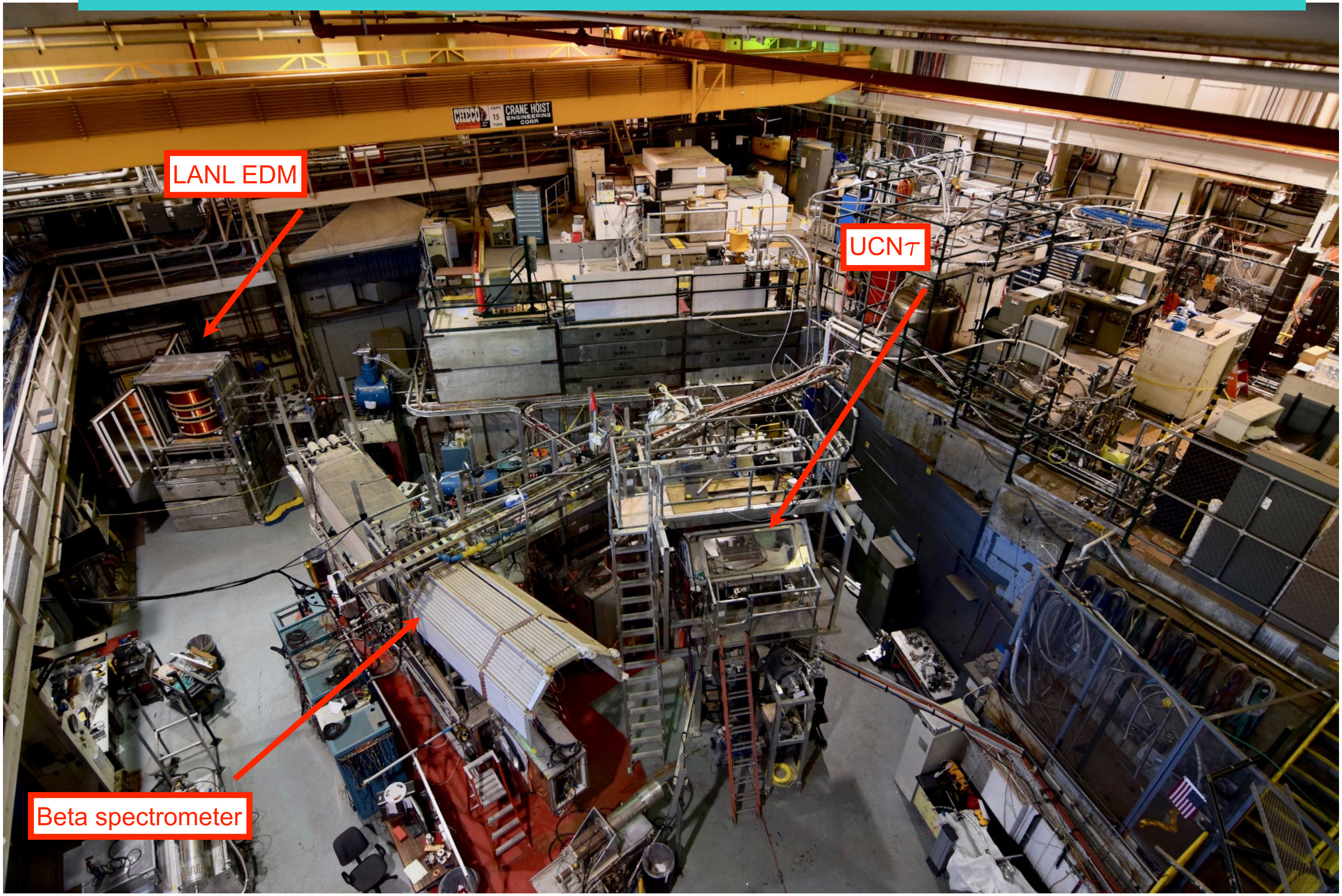
Outline

- Neutron Lifetime Experiments
    - UCNτ, Tau2, UCNProbe
    - Goal: Sub 0.1 s (1e-4)
- Beta Decay Correlations
    - UCNA, UCNA+, ^{45}Ca, Fierz, DM
    - Goal: 1e-4 on λ

Los Alamos Neutron Science Center (LANSCE)



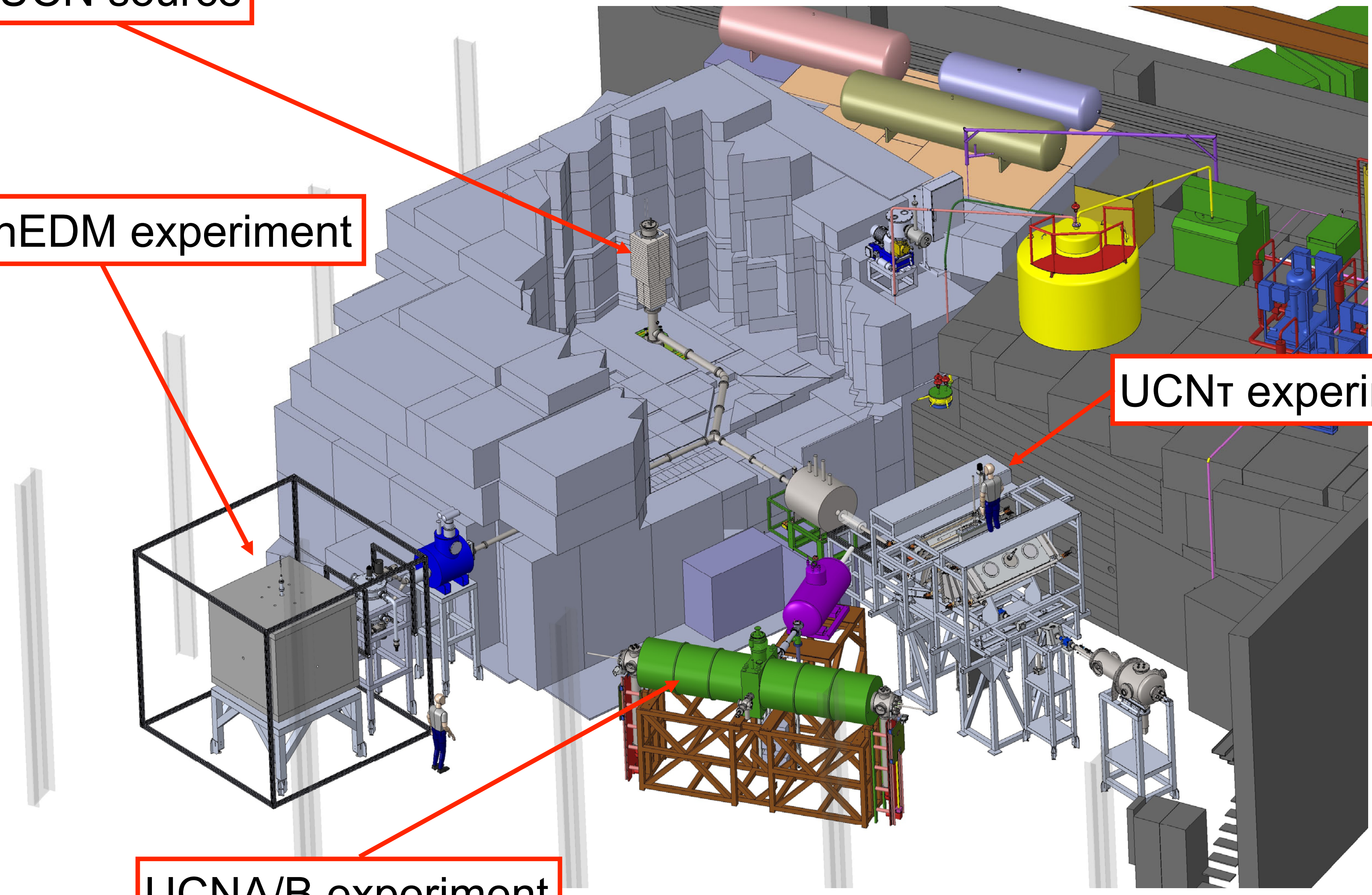
LANL UCN Experimental Area


LANL EDM

UCNτ

Beta spectrometer

LANL UCN Facility



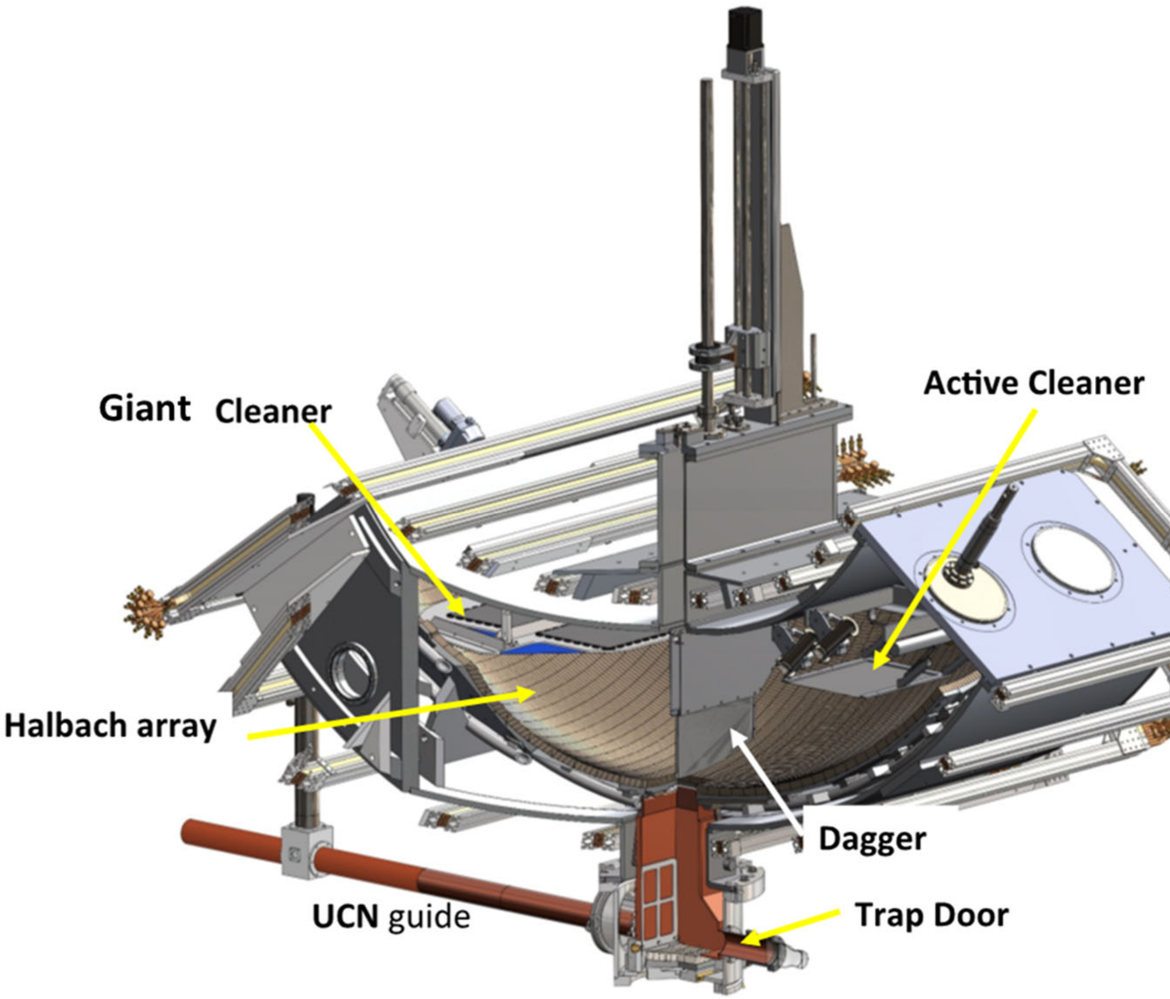
UCN source

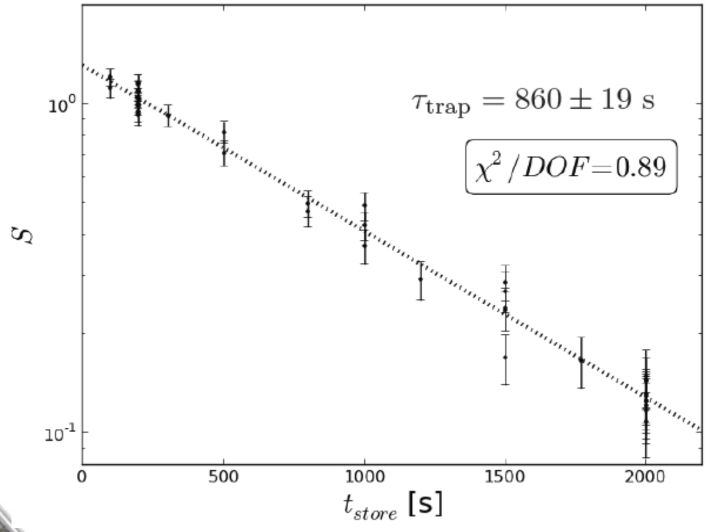
New nEDM experiment

UCNτ experiment

UCNA/B experiment

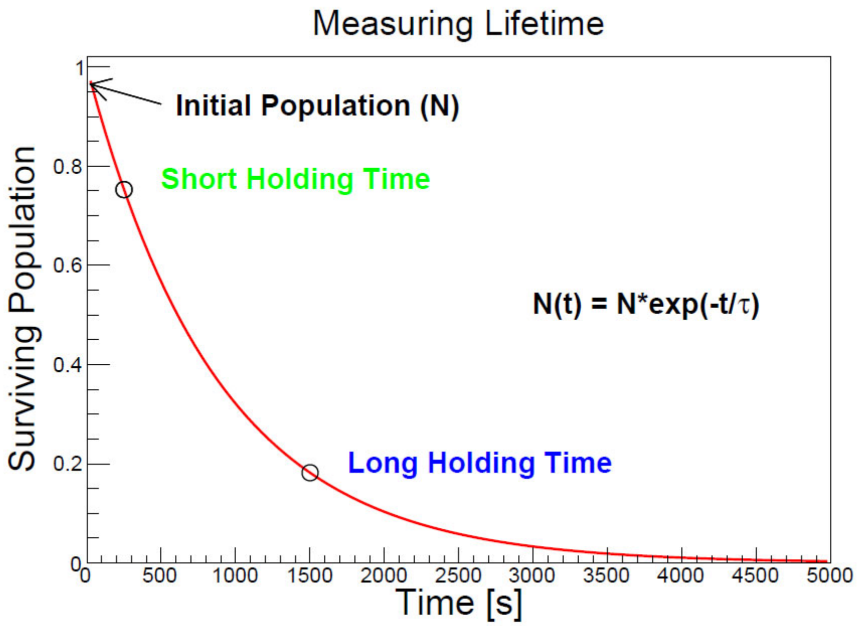
The UCNτ apparatus

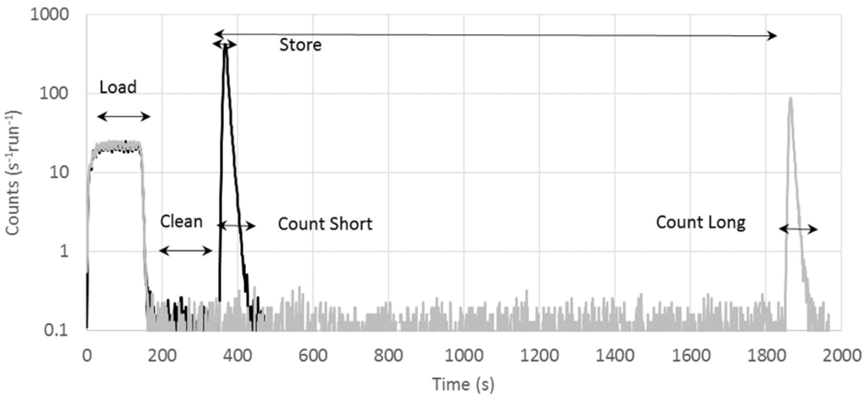




D. Salvat, PRC 89, 052501 (2014)

Pairs of short-long storage times





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

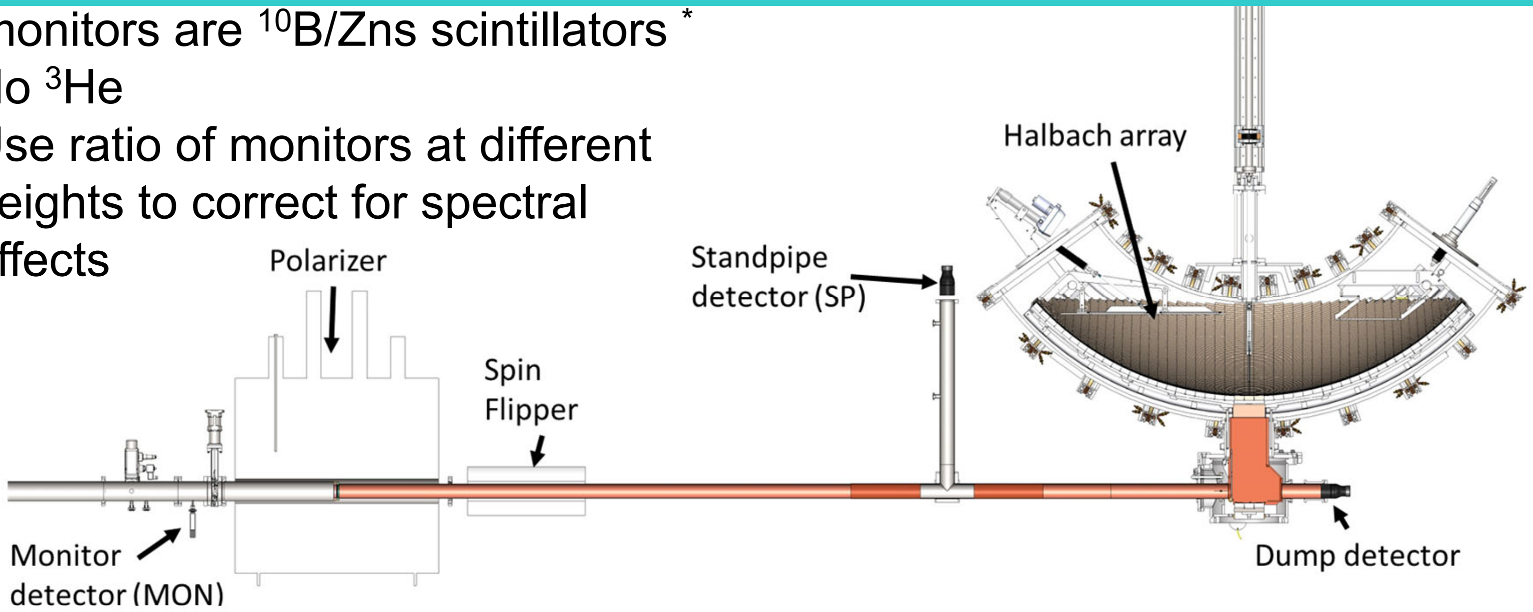
N: UCN counts
M: Monitor counts

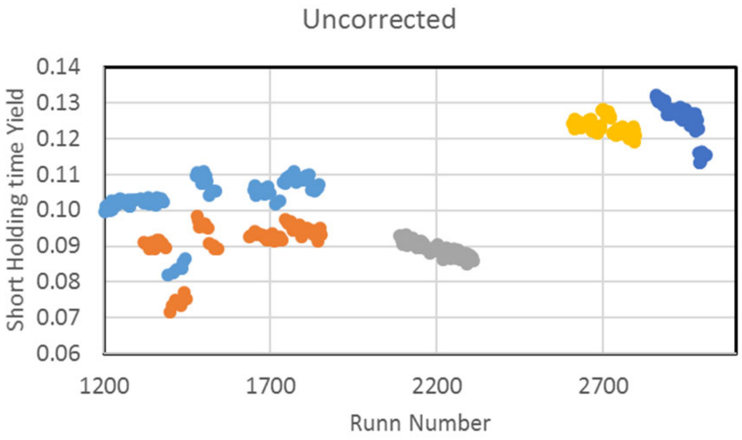
$$\frac{1}{\tau_{\text{trap}}} = \frac{1}{\tau_{\text{n}}} + \frac{1}{\tau_{\text{escape}}} + \frac{1}{\tau_{\text{heating}}} + \frac{1}{\tau_{\text{depol}}} + \dots$$

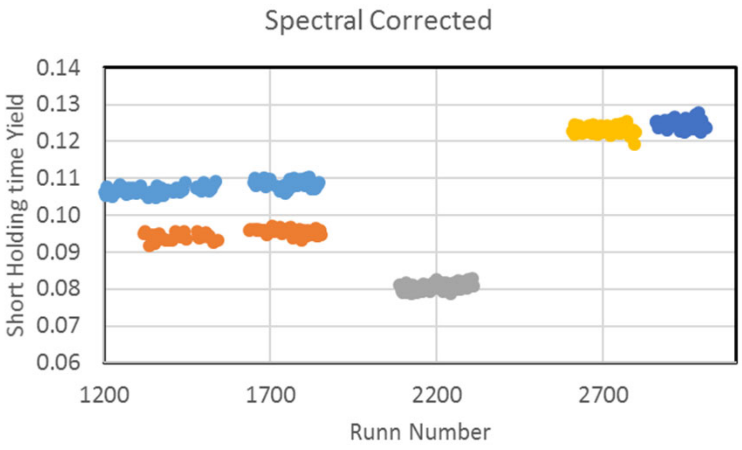
Flux Monitoring

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

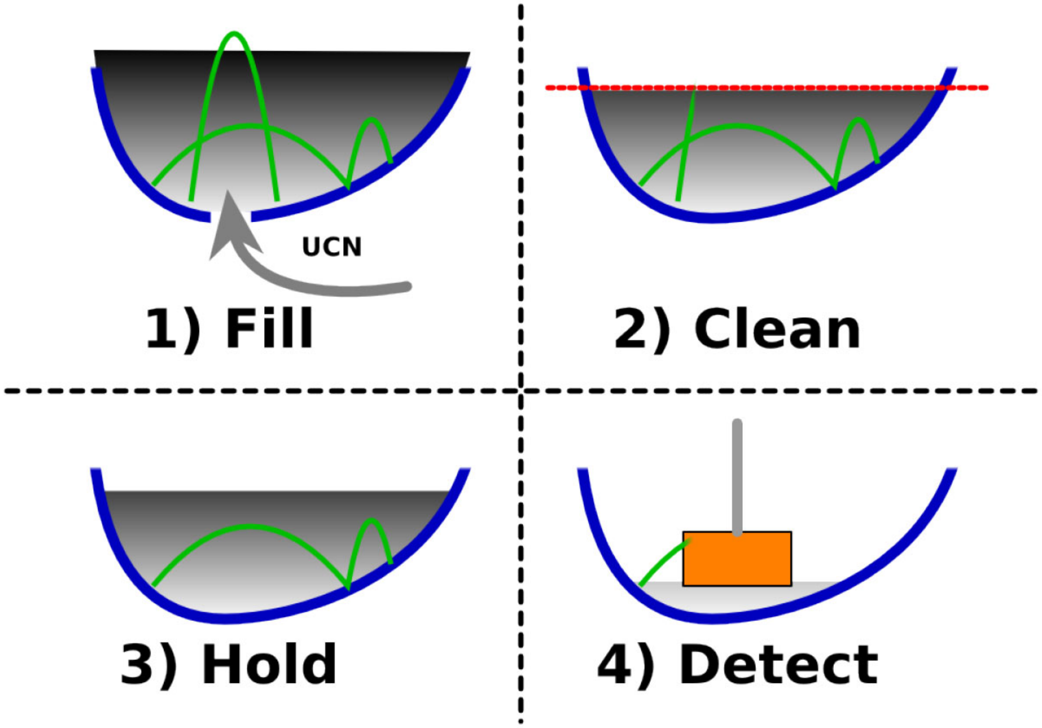
- No ^{3}He
- Use ratio of monitors at different heights to correct for spectral effects

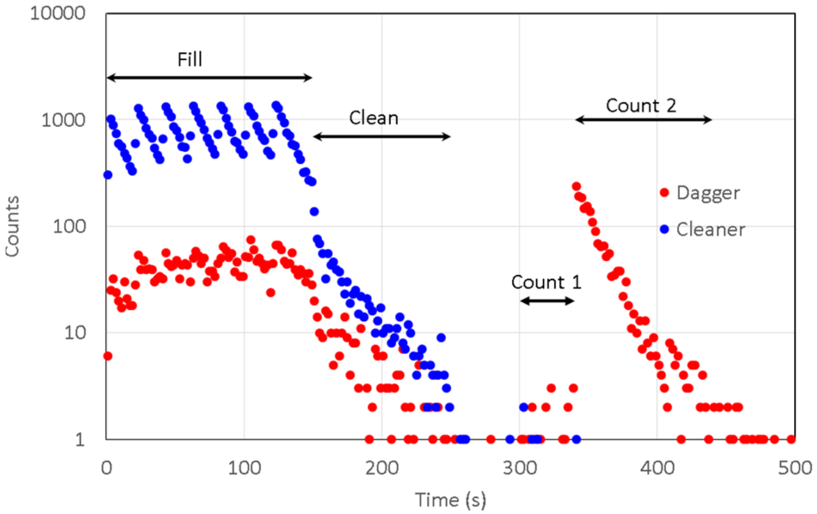




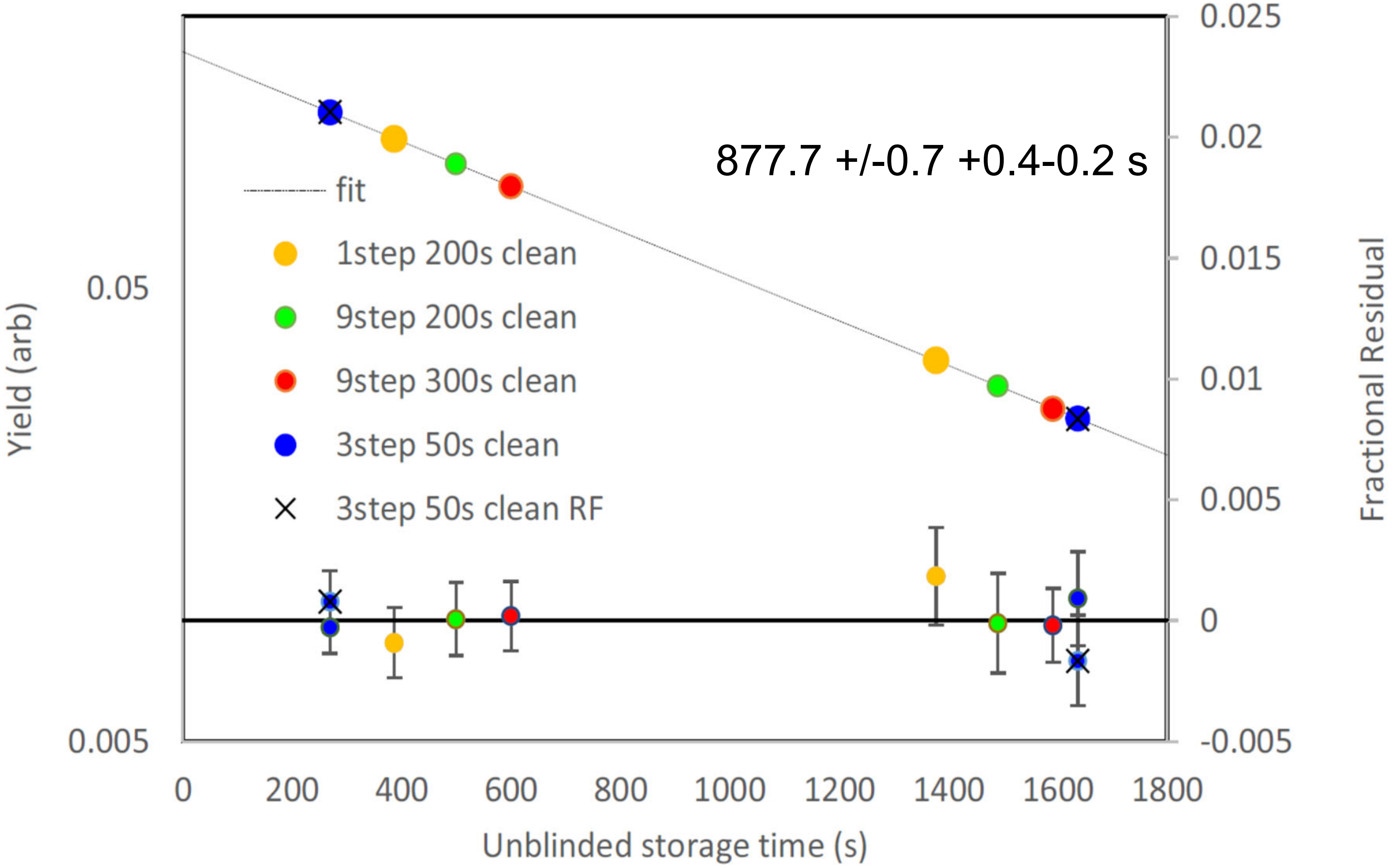


A typical lifetime run:



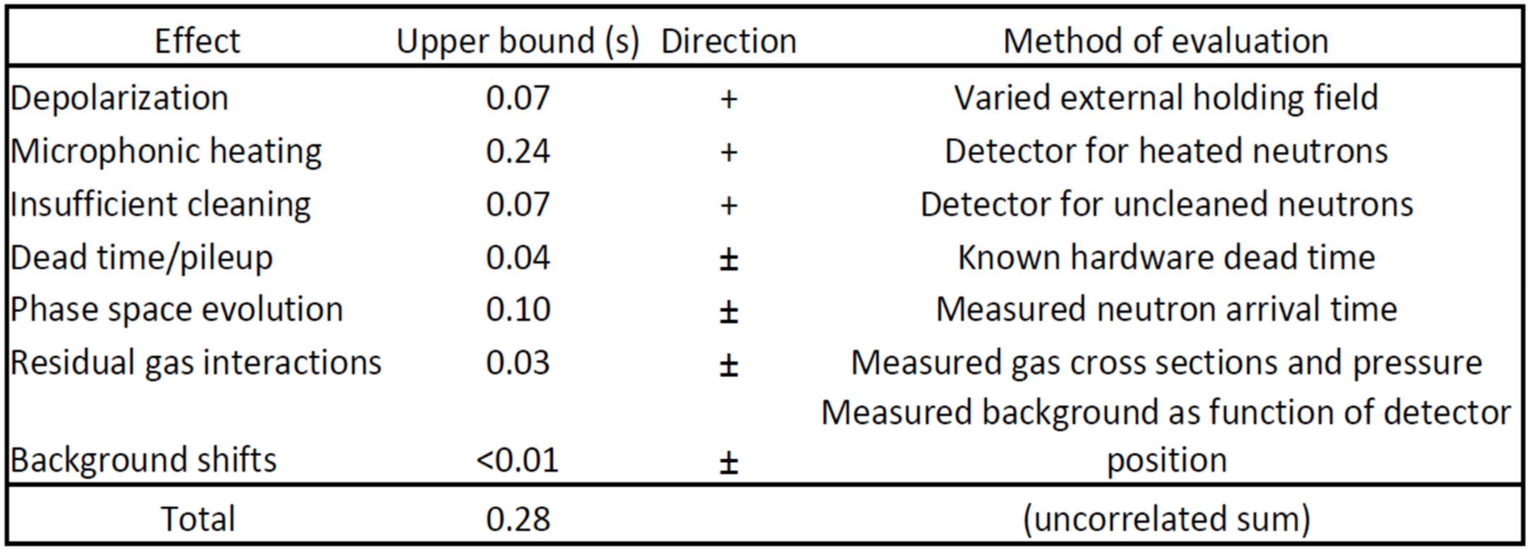


First science run published 2018



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

UCNτ path forward

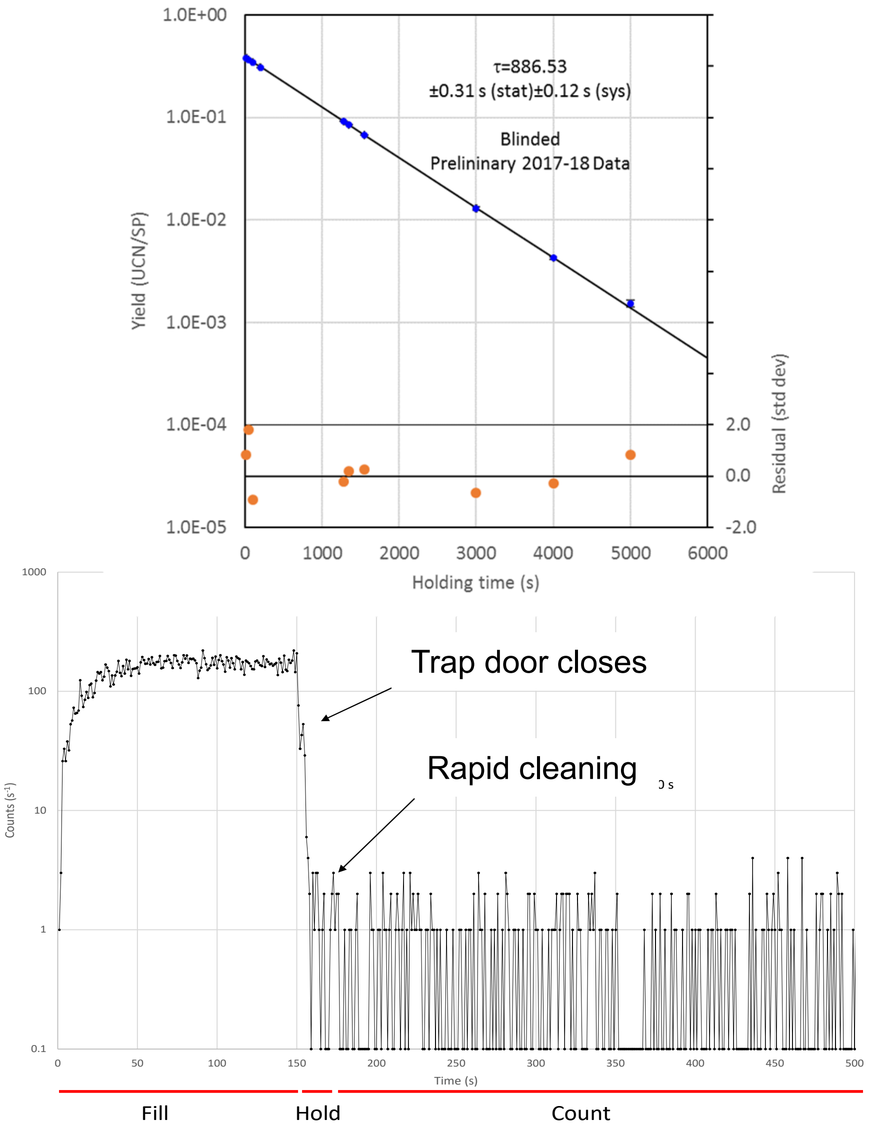


Effect	Upper bound (s)	Direction	Method of evaluation
Depolarization	0.07	+	Varied external holding field
Microphonic heating	0.24	+	Detector for heated neutrons
Insufficient cleaning	0.07	+	Detector for uncleaned neutrons
Dead time/pileup	0.04	±	Known hardware dead time
Phase space evolution	0.10	±	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
- Goal for UCNτ is 0.2 s

Key strengths of UCNτ experiment

- Magnetic+gravity trap: no material interactions during holding period
- Asymmetric rippled trap: near- or superbarrier neutrons cleaned rapidly
- Very long storage time: “other losses” have greater than three weeks characteristic time
  - ~1e-7 Torr vacuum
  - ~zero depolarization
  - No neutron heating observed (yet!)
- *In situ* survivor detection: detector efficiency almost independent of phase space distribution
- Active time-resolved detection: neutrons can be detected as function of time and height, including heated or uncleaned neutrons



UCNs in active cleaner, lowered position

And one major limitation

- UCNτ experiment is, as far as we know, statistically limited: ultimate reach, 0.2 s total uncertainty

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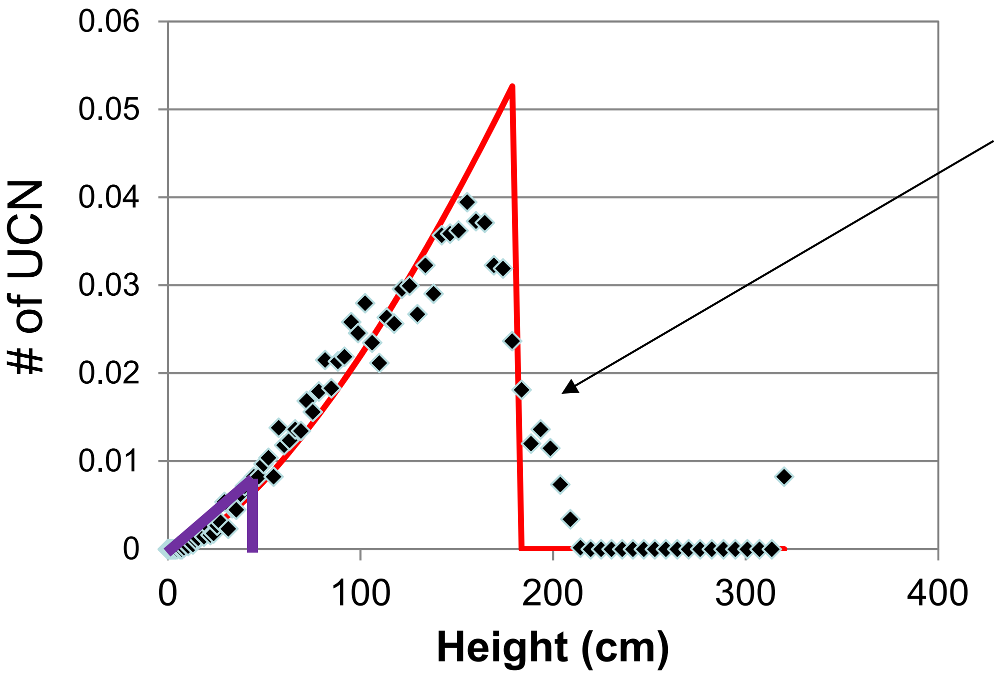
Set by statistics of systematic measurements taken during production: these uncertainties will automatically reduce as statistics improve

Statistical uncertainty on this data set (2016-2017) was 0.7 s, much larger (worse) than systematic uncertainties, and limits total uncertainty

(*Science* 2018, arxiv https://arxiv.org/abs/1707.01817)

The UCNτ experiment uses only a small fraction of the UCNs produced by the LANSCE source



Spectrum cut off by
180 neV potential of
stainless steel UCN
guides

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

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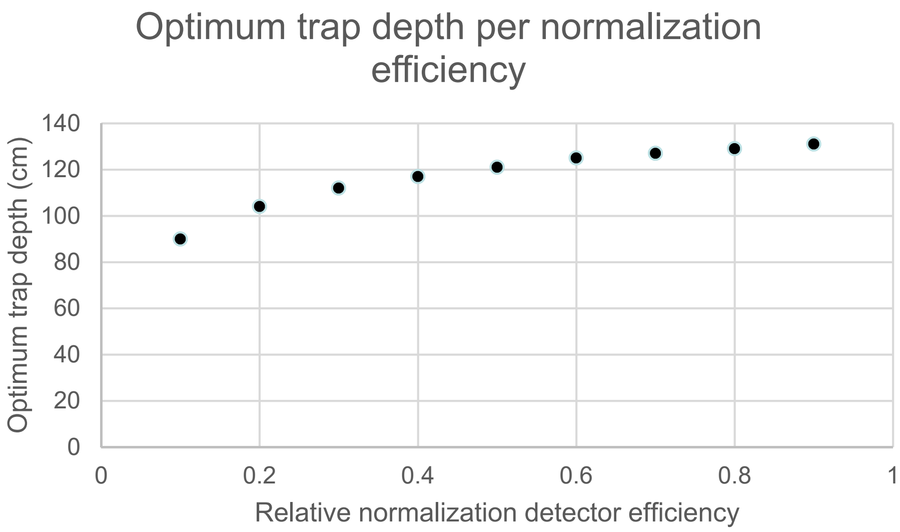
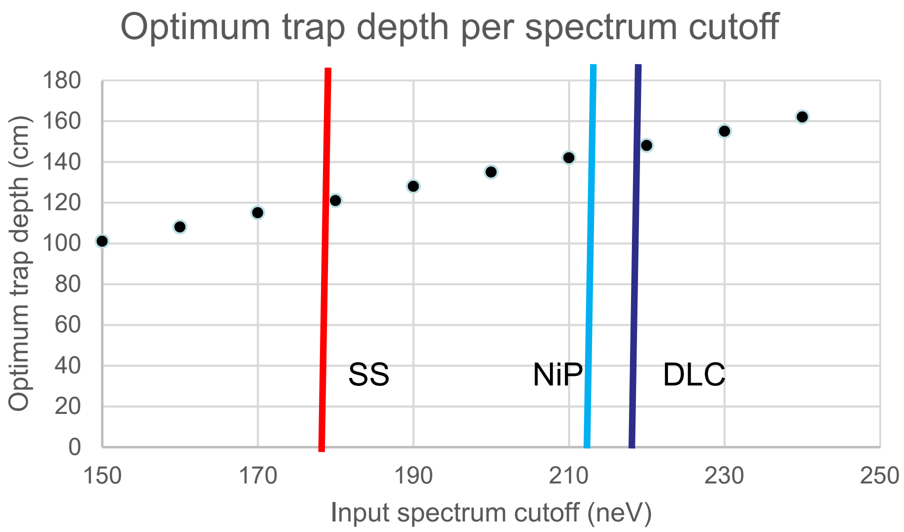
Optimizing the trap depth

- UCNτ has trap depth of 38 cm (~38 neV UCN energy)
- Arriving neutrons must be split between three destinations:
    - Stored in trap for counting
    - Counted in superbarrier normalization detector
    - Lost over rim of trap
- Can vary trap depth to minimize overall statistical uncertainty as function of relative normalization detector efficiency and guide cutoff energy
- Answer: ~120 neV (cm) trap optimizes use of UCNs

$$1/\tau_s = \frac{1}{t_2 - t_1} \ln\left(\frac{N_1 M_2}{N_2 M_1}\right)$$



180 neV



50% efficiency

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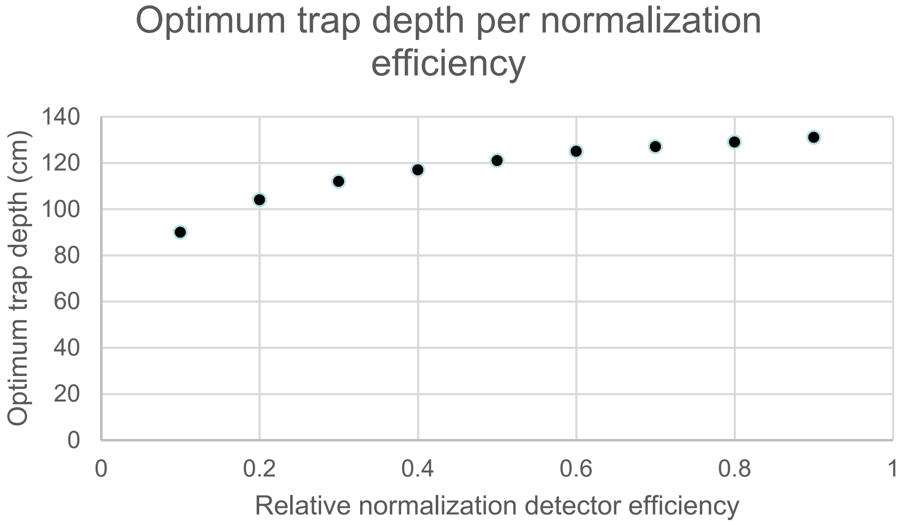
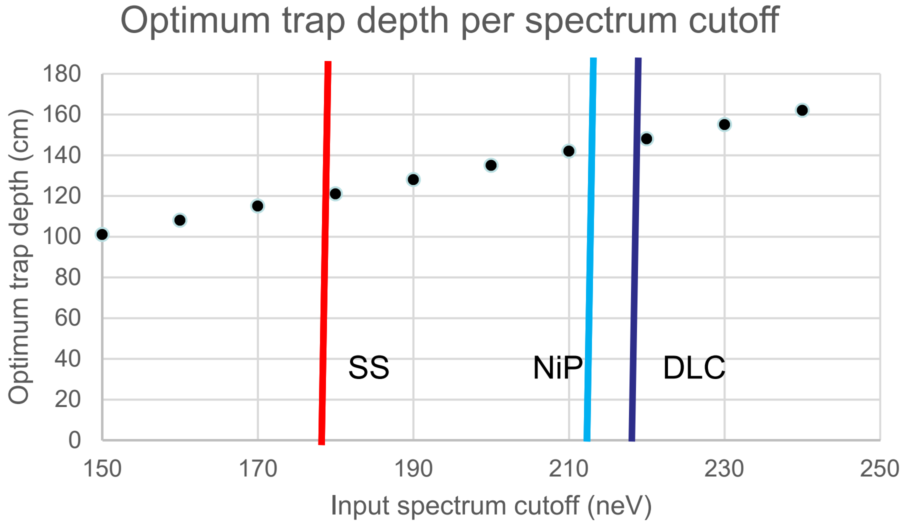
- Answer: ~120 neV (cm) trap optimizes use of UCNs
- But requires superconducting magnets to achieve required >2 T field strength

$$ {}^{1}\!/_{\tau_s} = \frac{1}{t_2 - t_1}\ln\left(\frac{N_1 M_2}{N_2 M_1}\right) $$



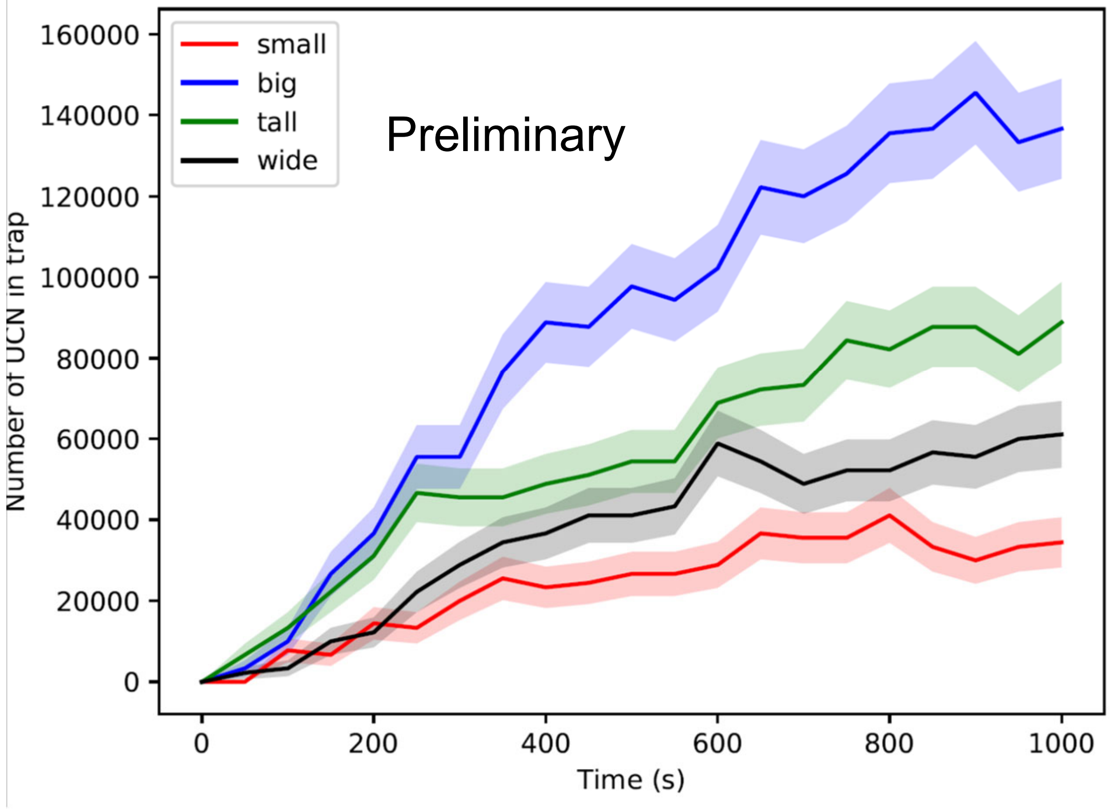
180 neV



50% efficiency

Monte Carlo simulation of trap loading in expanded geometries

- As a first look, we tried expanding a simplified trap in MC
- Simulation includes UCN source and transport all the way from production
- "Small" = UCNτ
- "Wide" = 1.5x wider and longer
- "Tall" = 1.5x deeper
- "Big" = both
- Note the conceptual Tau2 geometry would be another factor of 2 larger in all directions

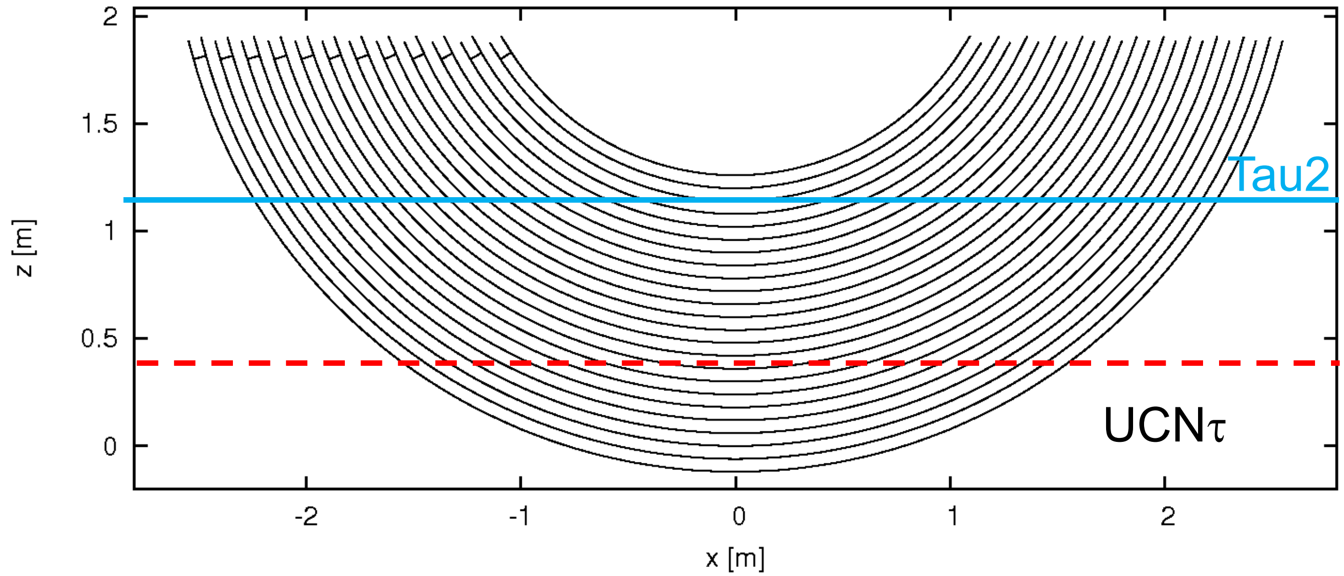


Thanx to S. Clayton, E. M. Fries and V. Su

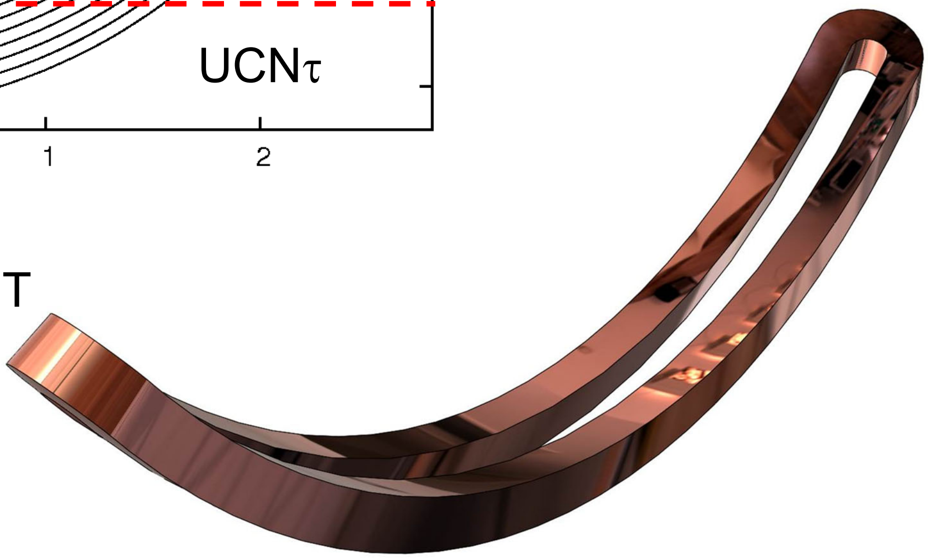
A 120 cm trap with the features of UCNτ

Side view of square coil array:

- Trim height not optimized

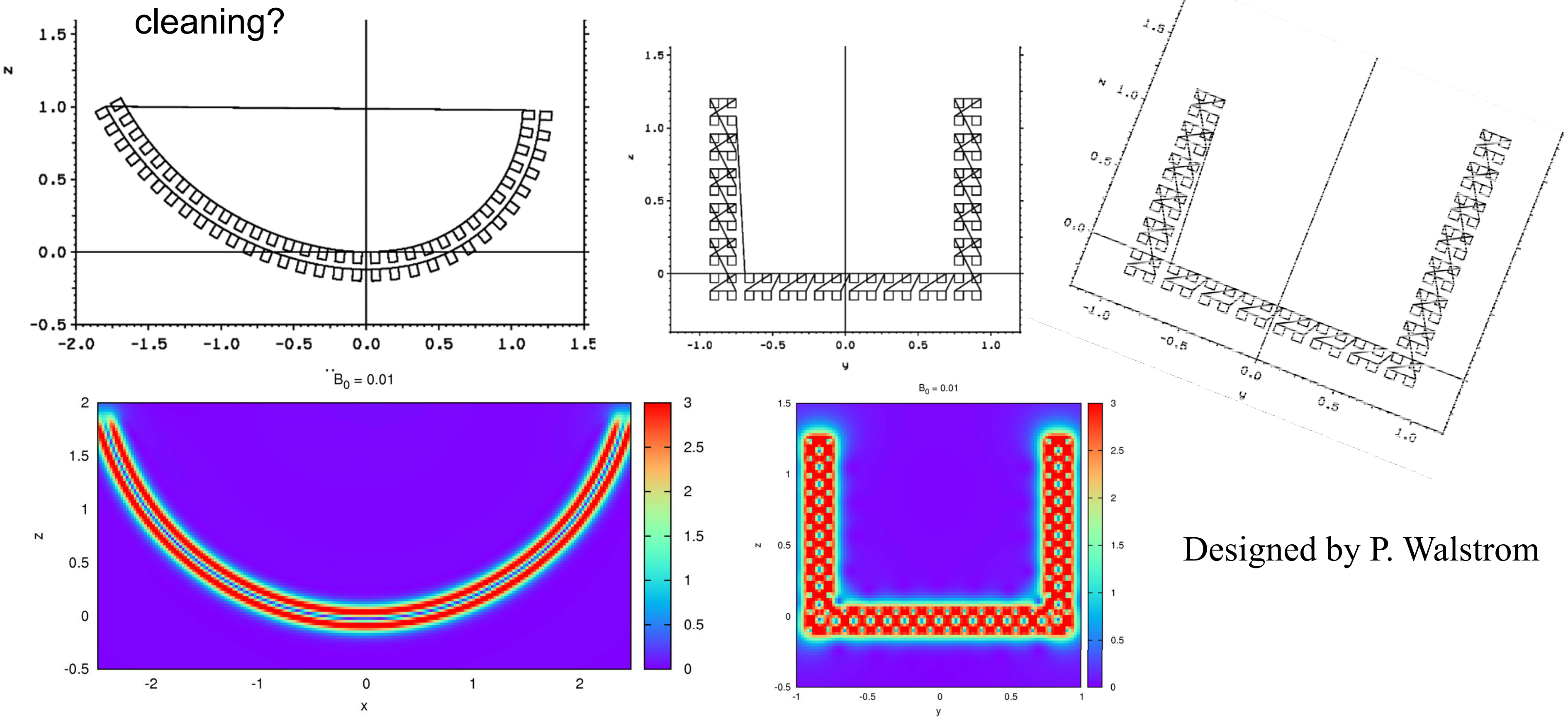


Superconducting coils with 3 T surface field (~180 neV)



Possible Configurations of the Superconducting Trap: Square vs. bowl-type coil arrays

- Trap with square corners and vertical sides was not feasible with permanent magnets due to low fields at corners. This leads to the two-arc y-z cross section configuration of the present UCNτ trap
- Trap with square corners *is* feasible when using superconducting coils
- With square array can use simpler banana coils- easier to wind
- Tilt square array (rotate in y-z plane) to make orbits less symmetric, get faster cleaning?



Designed by P. Walstrom

Schedule, budget, reach

- Approximately 10x improved neutron utilization versus UCNτ
- So approximately 3x better sensitivity in same running period (nominally 4 years), or ~0.06 s
- Leading unresolved systematic uncertainties:
  - residual gas upscattering will be improved by cold bore superconductors
  - Depolarization will be improved by stronger holding field
  - Dead time/pileup can be managed by detector design and insertion rate

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|2019| | |2022| | |2025| | |2028| | | |

Pre-conceptual design Conceptual Design Design and construction Commissioning and DAQ

- Cost dominated by magnet: of order 1e7 $

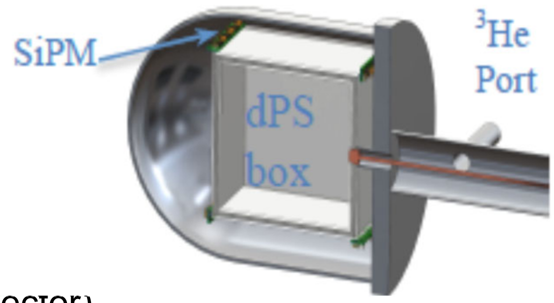
UCNProbe Experimental Concept

Measure τ_β using UCNs

- if $\tau_\beta = \tau_n$(from Bottle), then unaccounted systematic error in beam method
- $\tau_\beta > \tau_n$, then possible new physics

Requires absolute measurements of two quantities

- Number of neutrons in the trap
- Number of neutrons that decayed (measurement of charged particle



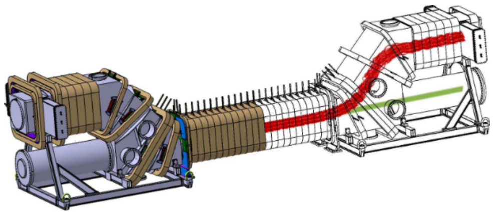
Charged particle detection

- Electron (Using deuterated polystyrene (dPS) as a UCN trap and detector)
- dPS scintillator (Eljen 299-2D) potential measured at 168 neV

Neutron detection

- UCN capture on ^{3}He gas

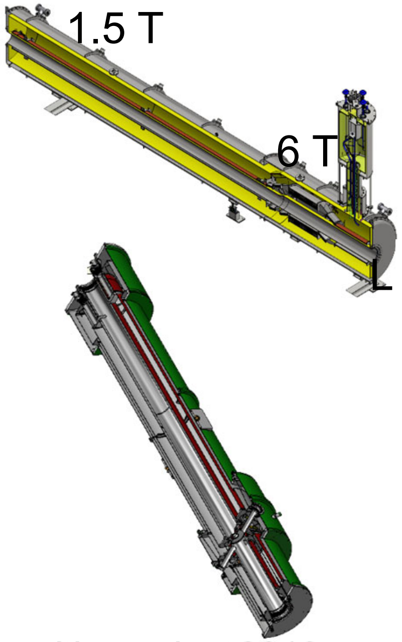
Angular Correlations Exps with precision targets at or below 0.2% (g_A < ~0.05%)



Perkeo III at ILL

Beta Asymmetry, δA/A = 0.17%
Symmetric, longitudinal
spectrometer, chopped beam

complete



Perc at MLZ

Beta Asymmetry, δA/A = 0.05%
asymmetric, longitudinal
spectrometer, chopped beam

Nab at SNS

Electron-neutrino asymmetry,
Δa/a = 0.1%
asymmetric, transverse
spectrometer, pulsed beam

Pluses: different observables (conv. beta spectroscopy vs. proton TOF measurements)

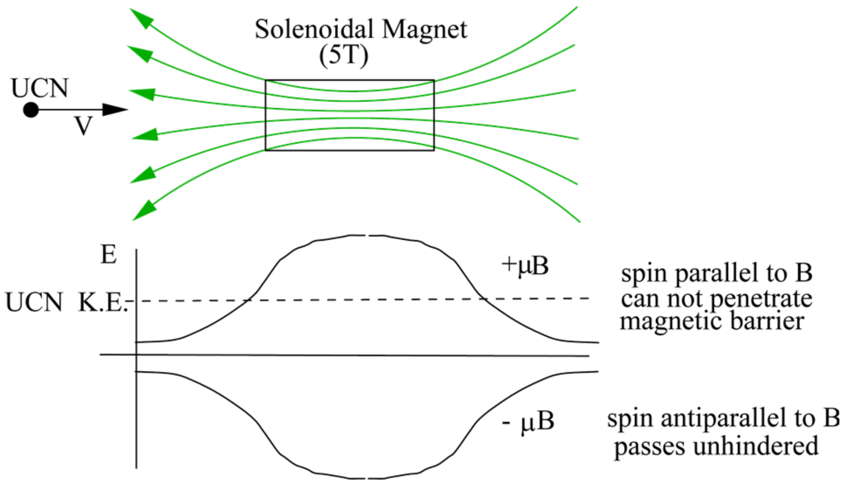
Concerns: both involve CN beams in asymmetric spectrometers, both are very new and will only start full commissioning in 2019, and rather few candidate expts compared to τ

Motivation for Angular Correlations Measurements with UCN

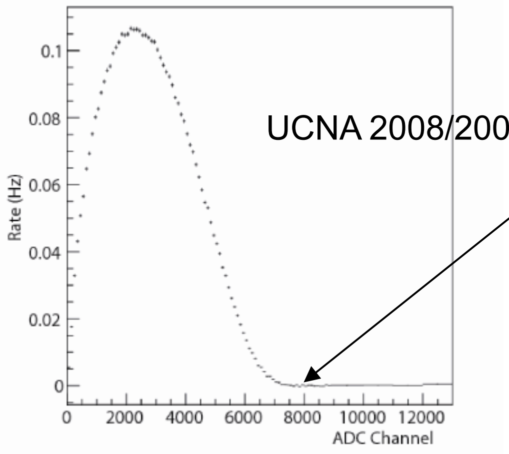
We use UCN to establish a different approach to the key neutron-related systematic errors

Polarization: “Potential barrier” polarization demonstrated effective alternative to supermirror/^{3}He cell technology with P ≥ 99.5% and ultimate uncertainties at or below 0.1% level

Neutron generated backgrounds: small number of neutrons and low capture probability (long residency time) lead to order of magnitude improvement relative to (then) current cold neutron beams experiments

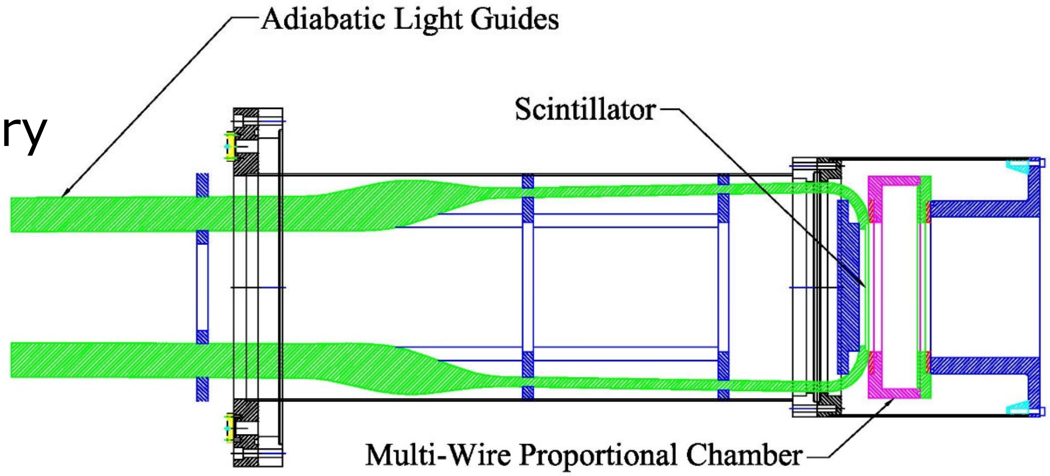


(note: neutron magnetic moment is negative)



UCNA was the first experiment to utilize UCN for angular correlations measurements. The approach to the detectors systems also provided a unique balance of advantages and concerns

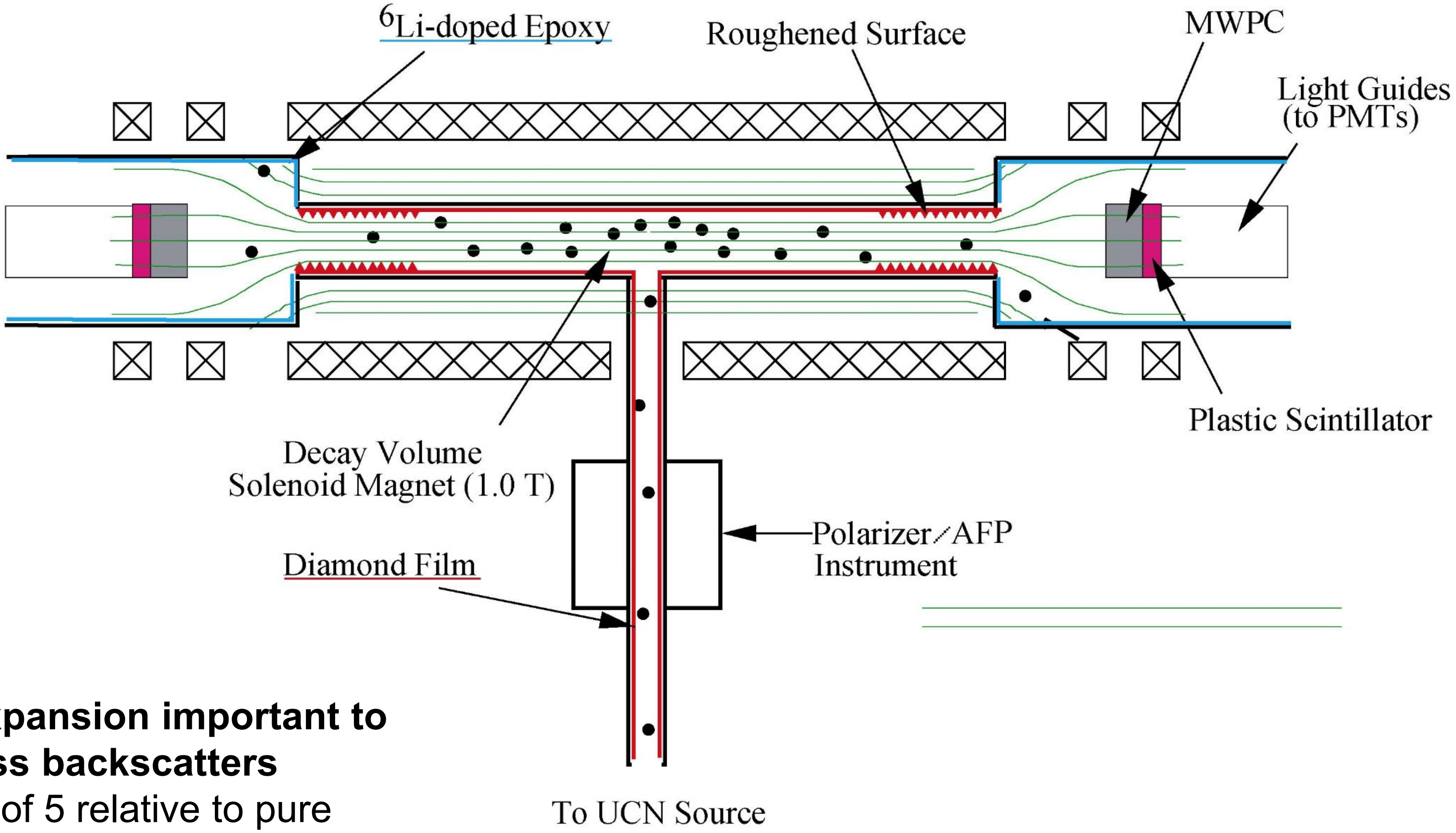
Minimize backscatters
- "Inverse"-pinch geometry
- Low Z detectors



MWPC-scintillator coincidence
- Provide position sensitivity
  - Map position sensitive detection efficiency effects
  - Eliminate effect of apertures
  - Explore fiducial volume cuts
- Suppress ambient and neutron-generated backgrounds
- Assist in backscatter reconstruction

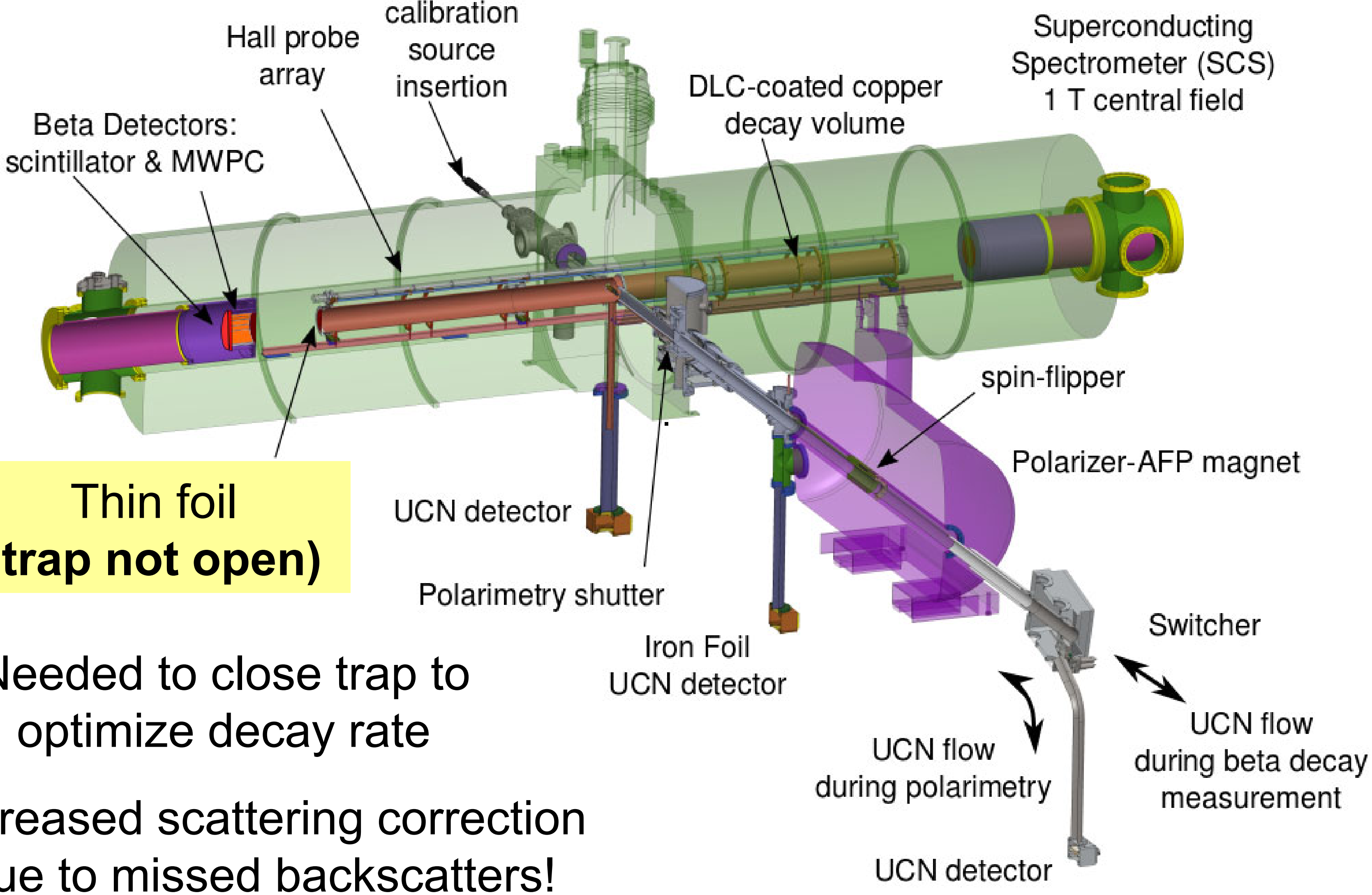
A price to pay for the MWPC: additional dead-layer energy loss and scattering on MWPC foils relative to bare scintillator

The Original Concept for UCNA



Field expansion important to suppress backscatters
(~factor of 5 relative to pure isotropic distribution)

“As Run” UCNA

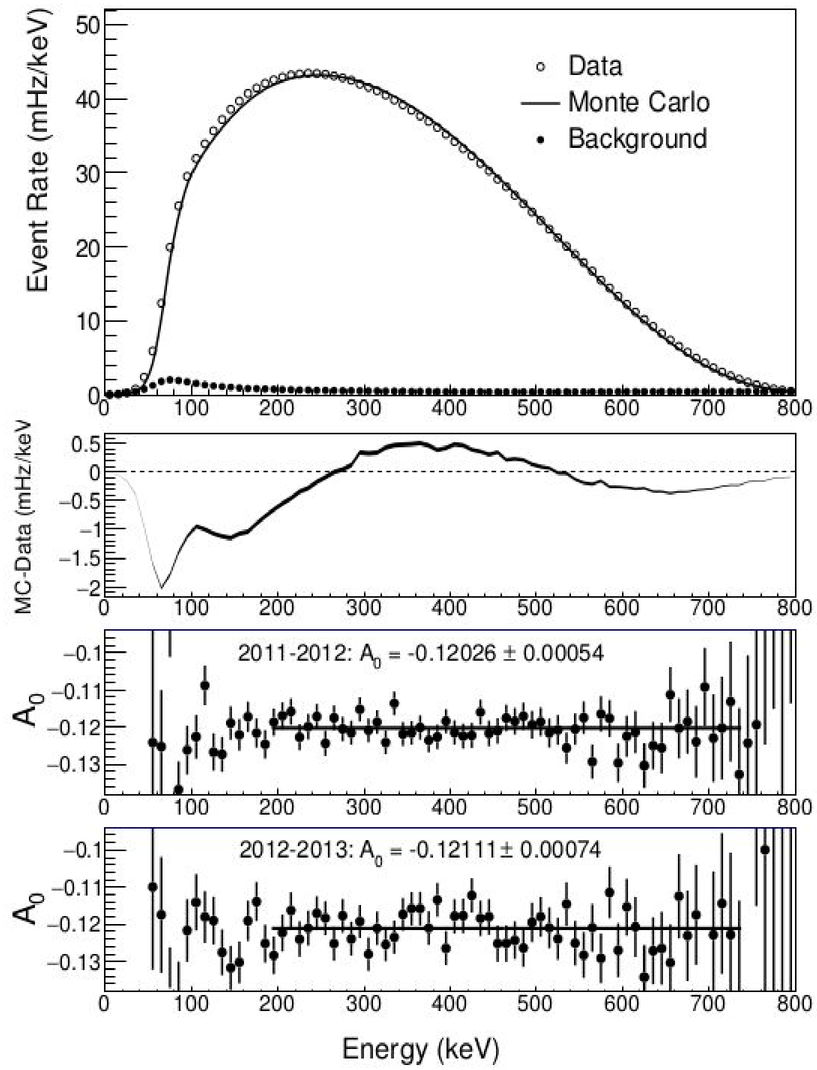


Thin foil
(trap not open)

Needed to close trap to optimize decay rate

Increased scattering correction due to missed backscatters!

Final Results (2017)



$$A_0 = -0.12054(44)_{\mathrm{stat}}(68)_{\mathrm{syst}}$$

$$\lambda \equiv \frac{g_A}{g_V} = -1.2783(22)$$

2011-2012

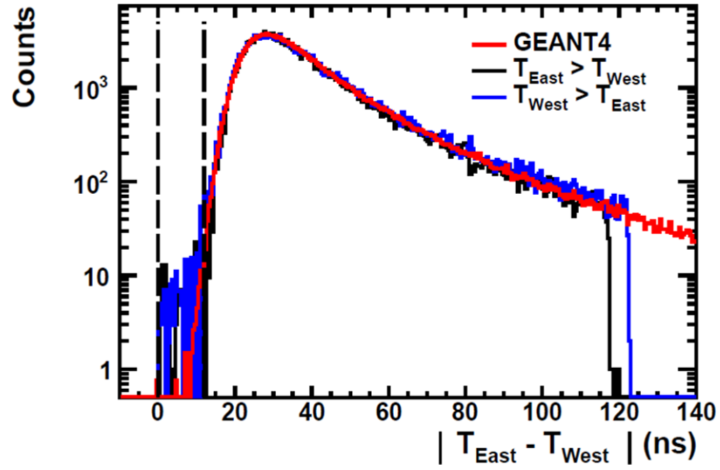
$$A_0 = -0.12026(54)_{\mathrm{stat}}(67)_{\mathrm{syst}}$$

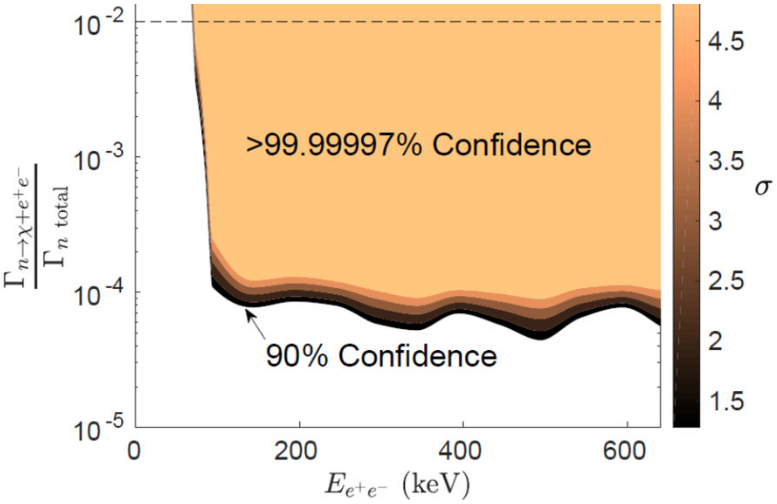
2012-2013

$$A_0 = -0.12111(74)_{\mathrm{stat}}(69)_{\mathrm{syst}}$$

Searches for DM inspired by Fornal and Grinstein hypotheses

- Neutron lifetime discrepancy could be caused by hidden n decay to DM
- Three hypotheses:n->χ+γ, n->χ+e$^+$+e$^-$, n->χ+χ
- F. and G., hep-ph 1801.01124
- First two can be tested at LANL UCN source
- UCNA data set contained test of n->χ+e$^+$+e$^-$
- Coincident e arrival in both detectors could only be caused by DM channel





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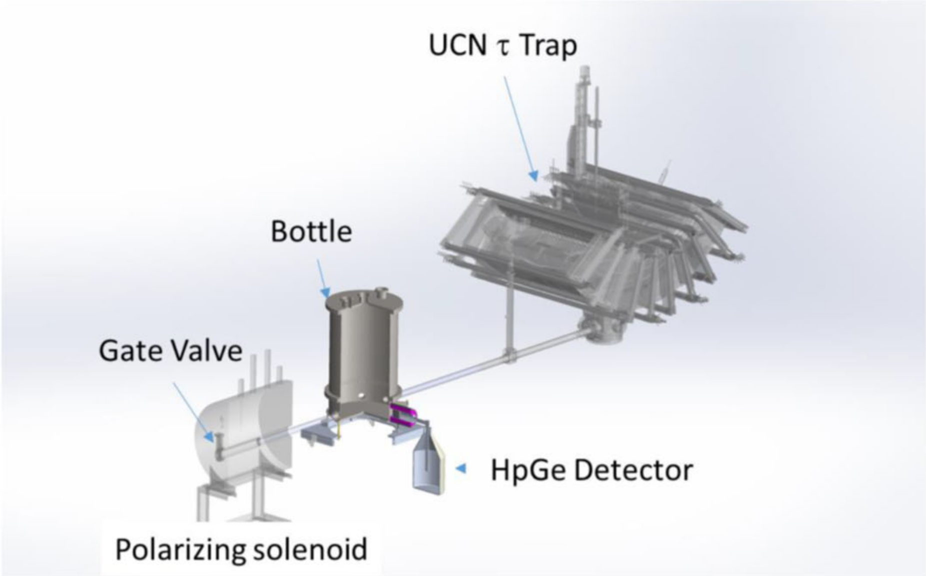
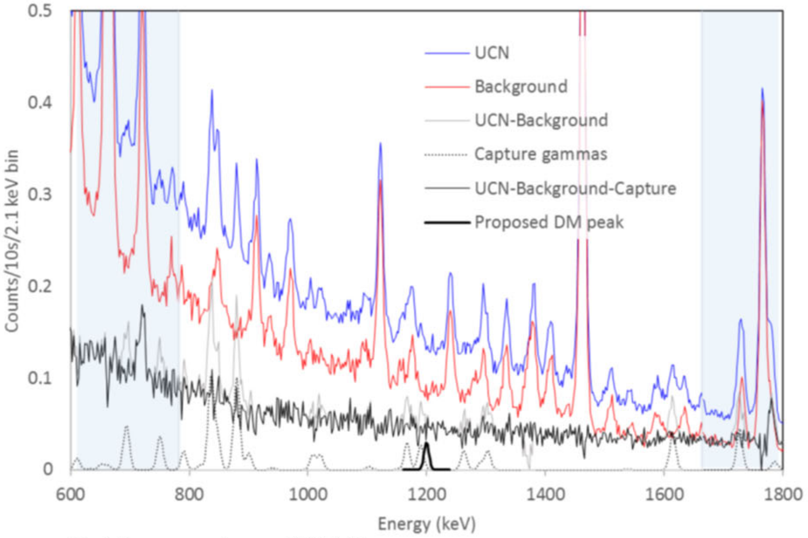
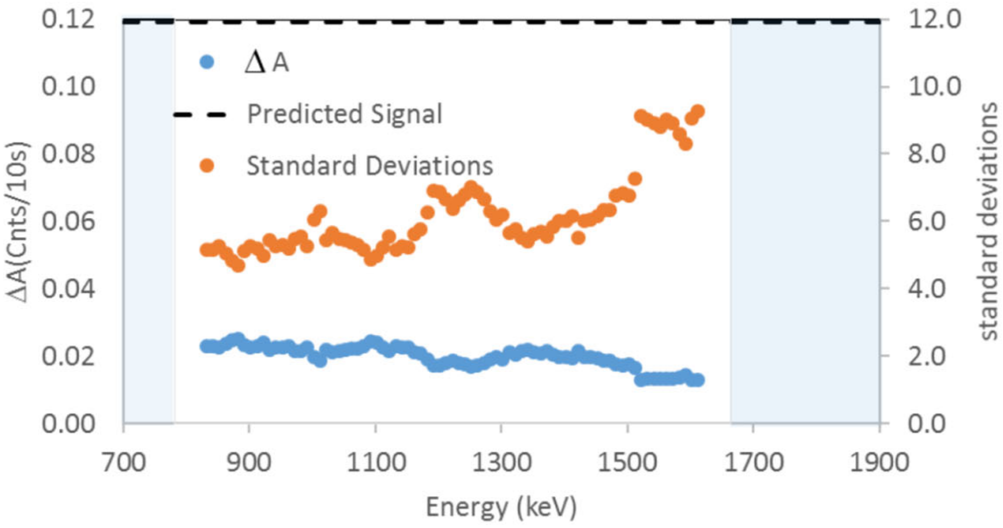
X. Sun et al., nucl-ex 1803.10890

Search for neutron decay to DM + gamma

- Search for a gamma peak in predicted region, location unknown
- Presence of peak (capable of explaining lifetime discrepancy) eliminated at 4 sigma level
- Z. Tang et al., nucl-ex 1802.01595
- Ran parasitically on UCNτ production







^{45}Ca Motivation

- Measurement of Fierz Interference ‘b’
  - Simple nuclear structure of ^{45}Ca
    - 99.998% pure ground state → ground state Fermi transition
    - Low endpoint energy → low sensitivity to Weak Magnetism effects
  - Nonzero → BSM physics
  - Linear in scalar and tensor coupling const.
    - More sensitivity than other correlation parameters

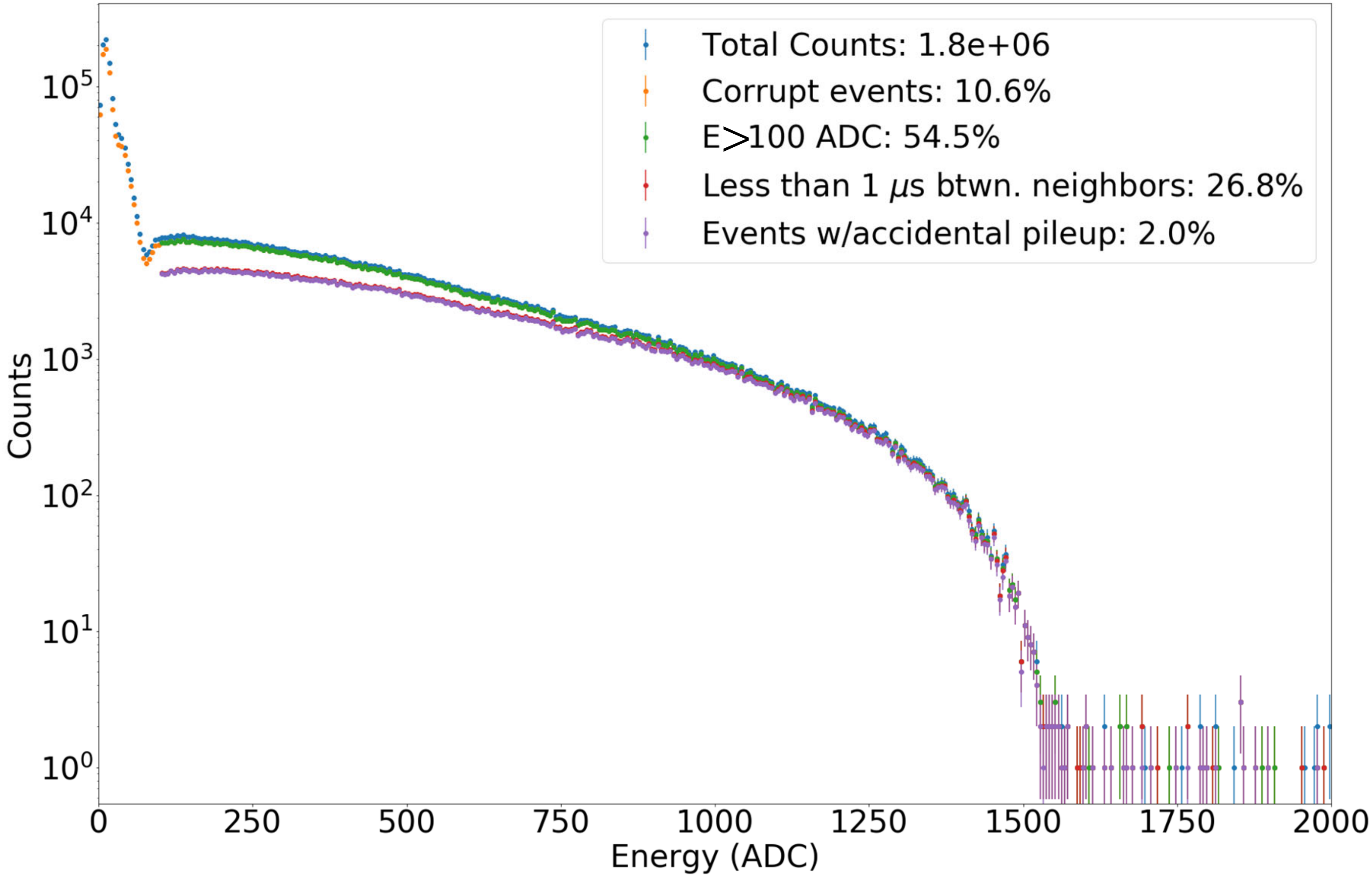
$$b = \pm \frac{1}{1+\rho^2}\left[\mathrm{Re}\left(\frac{C_s + C_S'}{C_V}\right) + \rho^2\,\mathrm{Re}\left(\frac{C_T + C_T'}{C_A}\right)\right]^*$$

  - Straight forward extraction
    - Fit spectrum to $\frac{1}{E_e}$

$$\omega\, dE_e \propto p_e E_e (E_e - E_0)^2 \left\{\mathrm{Const.} + b\,\frac{m_e}{E_e}\right\} dE_e$$

* [M. González-Alonso, *New Physics searches in nuclear and neutron β decay,* Prog. Part. Nucl. Phys., 2018]

Single Pixel Spectrum



Future Work

- Measurement of ^{114}In β spectrum
  - Gammow-Teller $1^+ \rightarrow 0^+$ transition w/ branching ratio of 99.36%
  - High enpoint energy → measurement of weak magnetism (WM) contribution
    - 1st measurement of WM in such a heavy isotope
- Pulser studies for improved linearity determination
  - Currently, conversion electron source data are used for linearity
  - Pulser data provides a much simpler analysis & is not limited by simulation
  - In progress by NCSU graduate student at Area B of LANSCE

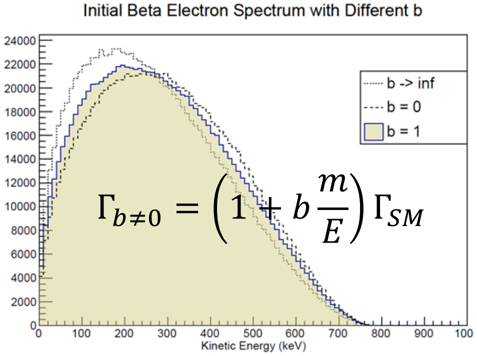
Summary: Preliminary results on Fierz interference from the most-recent UCNA data

Jackson, Treiman, Wyld (1957)

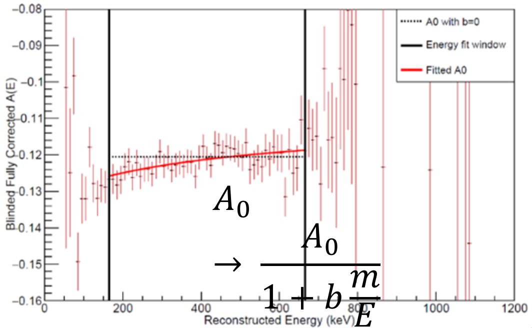
$$\frac{dW}{d\Omega_e d\Omega_\nu dE_e} \propto p_e E_e (E_0 - E_e)^2 \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \left\langle \frac{\vec{J}_n}{J_n} \right\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right)\right]$$

Fierz interference term.

Beta asymmetry term.


Initial Beta Electron Spectrum with Different b

$$\Gamma_{b\neq 0} = \left(1 + b\frac{m}{E}\right)\Gamma_{SM}$$



$$A_0 \rightarrow \frac{A_0}{1 + b\frac{m}{E}}$$

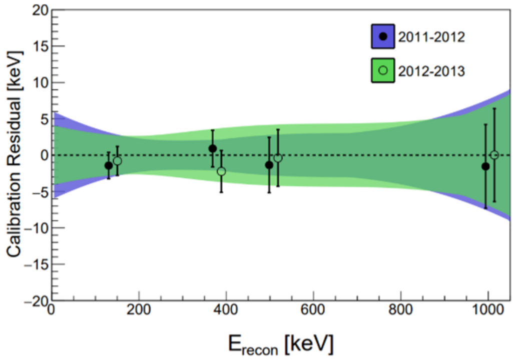
Note: the above shows asymmetry data which has been blinded by $b \neq 0$.

The super-sum cancels out asymmetry effects.

$$\Sigma = \frac{1}{2}\sqrt{\Gamma^E_{up}\Gamma^W_{down}} + \frac{1}{2}\sqrt{\Gamma^E_{down}\Gamma^W_{up}}$$

Super-ratio cancels out energy non-linearities (to 1st order).

$$R = \frac{\Gamma^E_{up}\Gamma^W_{down}}{\Gamma^E_{down}\Gamma^W_{up}}, \quad A = \frac{1-\sqrt{R}}{1+\sqrt{R}}$$



4 independent fit methods	Fitted b value	b error on fit method
2011-2012 super-sum	-0.14 BLINDED	0.055 (statistical error ~0.004)
2012-2013 super-sum	-0.03 BLINDED	0.141 (statistical error ~0.008)
2011-2012 super-ratio	-0.16 BLINDED	0.044
2012-2013 super-ratio	-0.17 BLINDED	0.059

$$b = -0.15 \pm 0.03$$

BLINDED

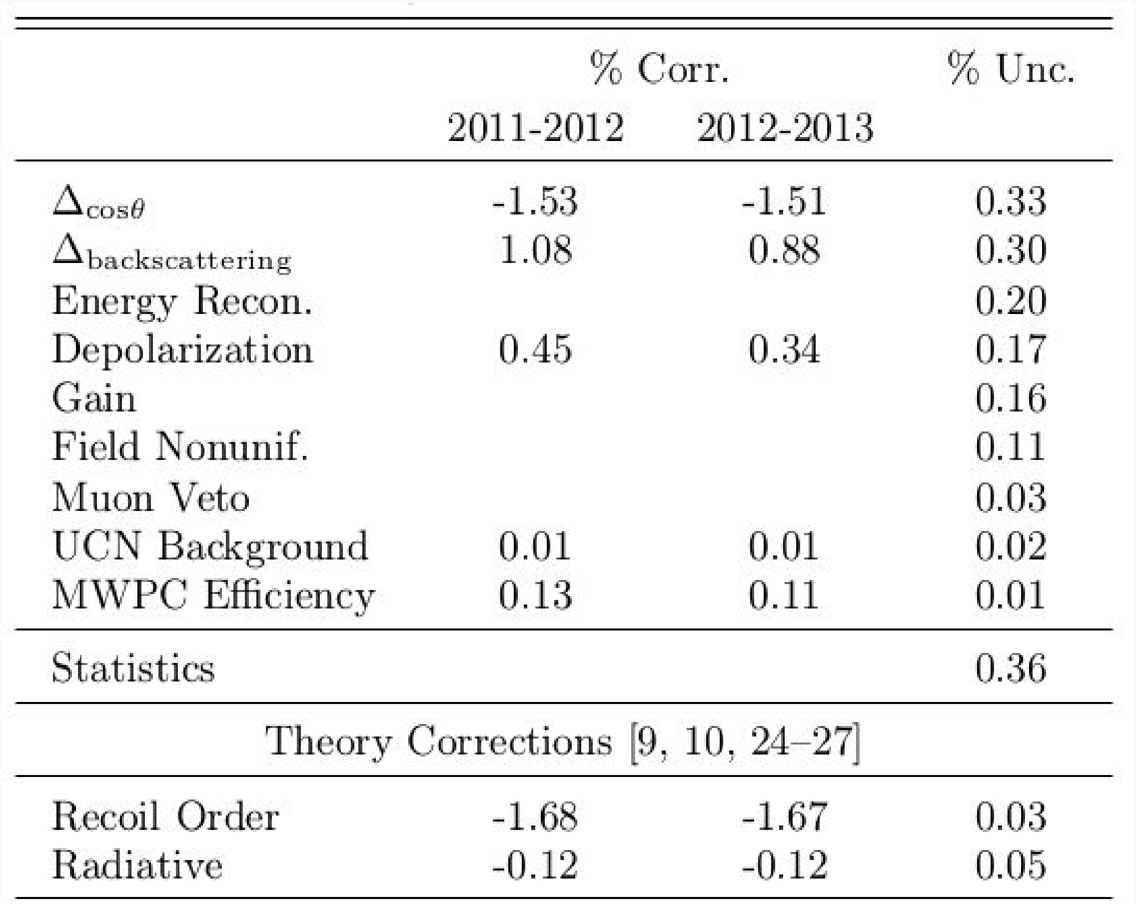
Final Results (2017)

$$A_0 = -0.12054(44)_{\mathrm{stat}}(68)_{\mathrm{syst}}$$

0.67%

$$\lambda \equiv \frac{g_A}{g_V} = -1.2783(22)$$

0.17%

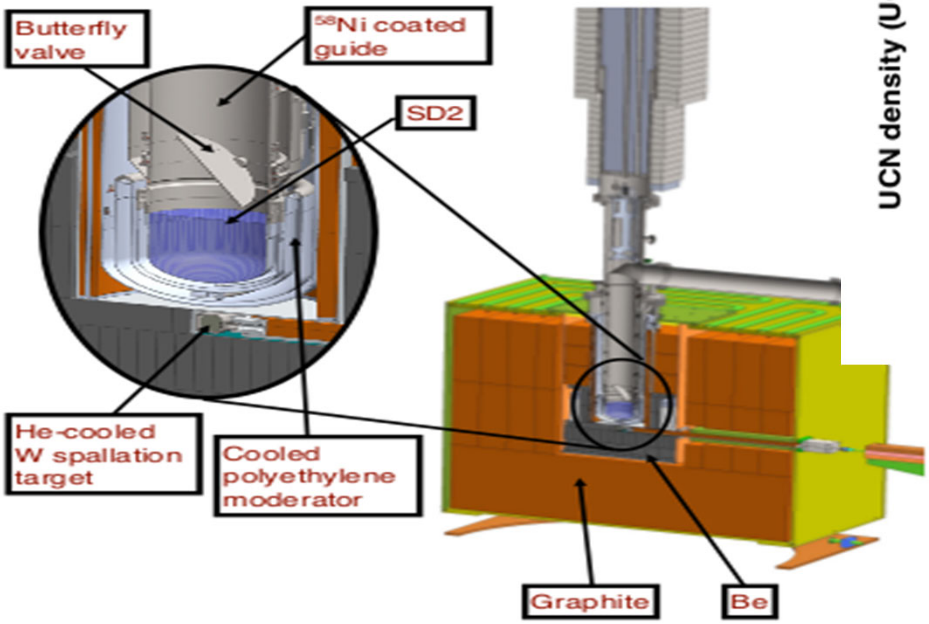


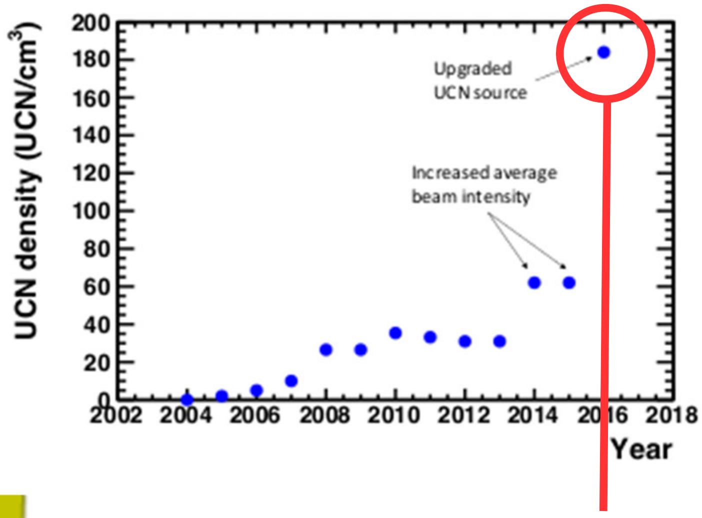
	% Corr.		% Unc.
	2011-2012	2012-2013	
$\Delta_{\cos\theta}$	-1.53	-1.51	0.33
$\Delta_{\mathrm{backscattering}}$	1.08	0.88	0.30
Energy Recon.			0.20
Depolarization	0.45	0.34	0.17
Gain			0.16
Field Nonunif.			0.11
Muon Veto			0.03
UCN Background	0.01	0.01	0.02
MWPC Efficiency	0.13	0.11	0.01
Statistics			0.36
Theory Corrections [9, 10, 24–27]			
Recoil Order	-1.68	-1.67	0.03
Radiative	-0.12	-0.12	0.05

Final PERKEO II
run had precision 0.54%

Opportunities for Progress

LANSCE Area B Source Upgrade!





Corresponds to
5x 2010 decay rate!

New shield wall: Round the clock running! – **~40% more available running time!**

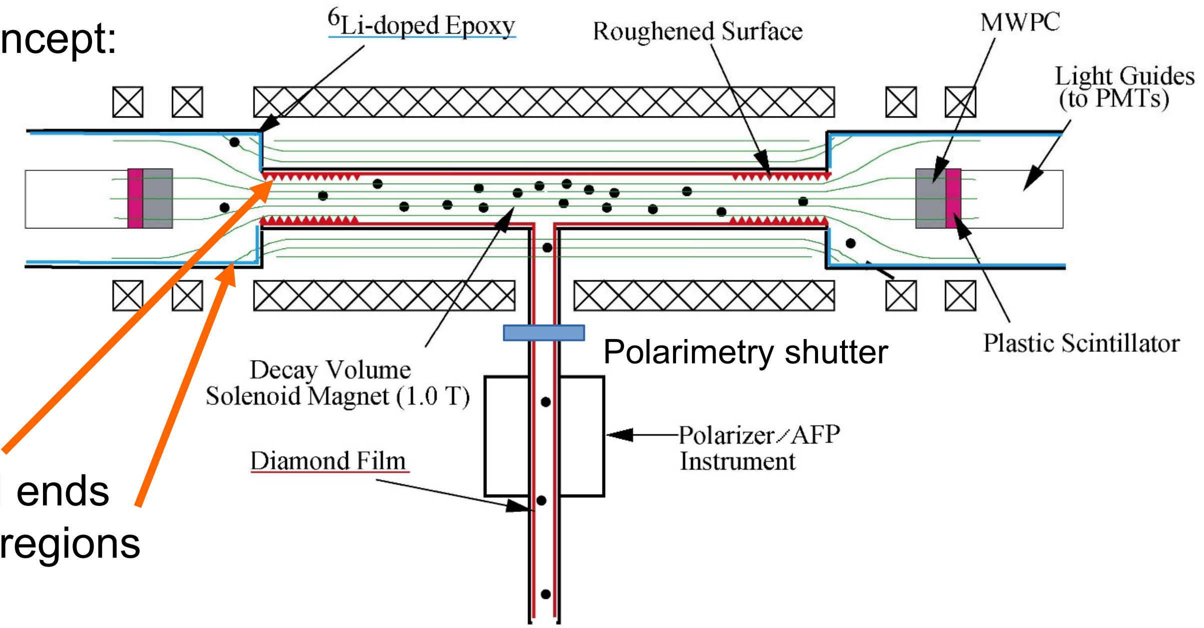
Confirmed ~180 s^{-1} decay rate in spectrometer in 2017
(could be more now, but also some ambiguity because of depol)

Reach: 0.12%/calendar year (stat)

A Strategy for UCN transport in a UCNA+ spectrometer:

Some preliminary thinking to mitigate ~1% correction due to missed backscatter...

Original UCNA concept:



- Shorten guides
- Add roughened ends
- Add absorbing regions
  - will strongly reduce (by factor of > ~3.5) missed backscatter corr.
  - will also result in reduced (x ~0.5) residency time in trap

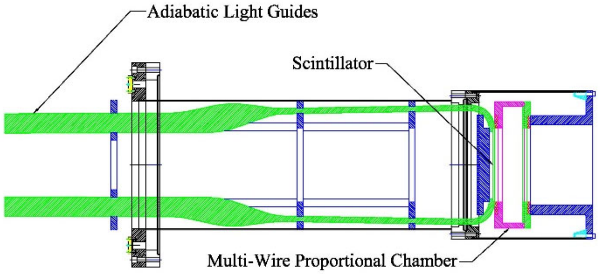
From preliminary simulations...

Should also result in I) reduced decay rate (~ x 0.5)
ii) reduced average depolarization (up to about ~x0.5)
iii) new, < 0.1% correction for decay in field exp. region
iv) still expect negligible neutron-induced bkgs*

R&D Target: confirm expected decay rate!

Detector R&D

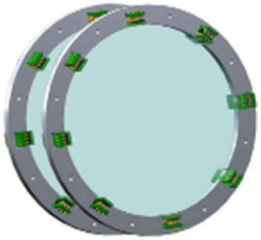
Some interesting choices...



UCNA Detectors
(MWPC +plastic scint}

Existing detectors

Ongoing research program to characterize sources of energy reconstruction uncertainty for UCNA expt (Fierz limits)

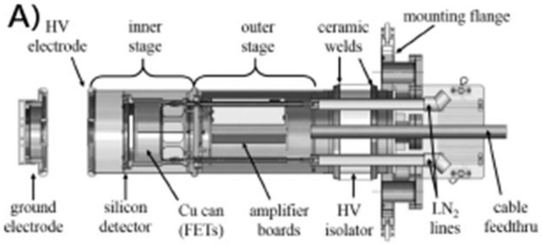


Paired, plastic
scintillators with
SiPM readut

Synergistic development with
PROBE experiment

Each side has front and back detector pair (front measures decay betas, back provides) real time background monitor)

Compact geometry shieldable! SiPM intensities provides position sensitivity



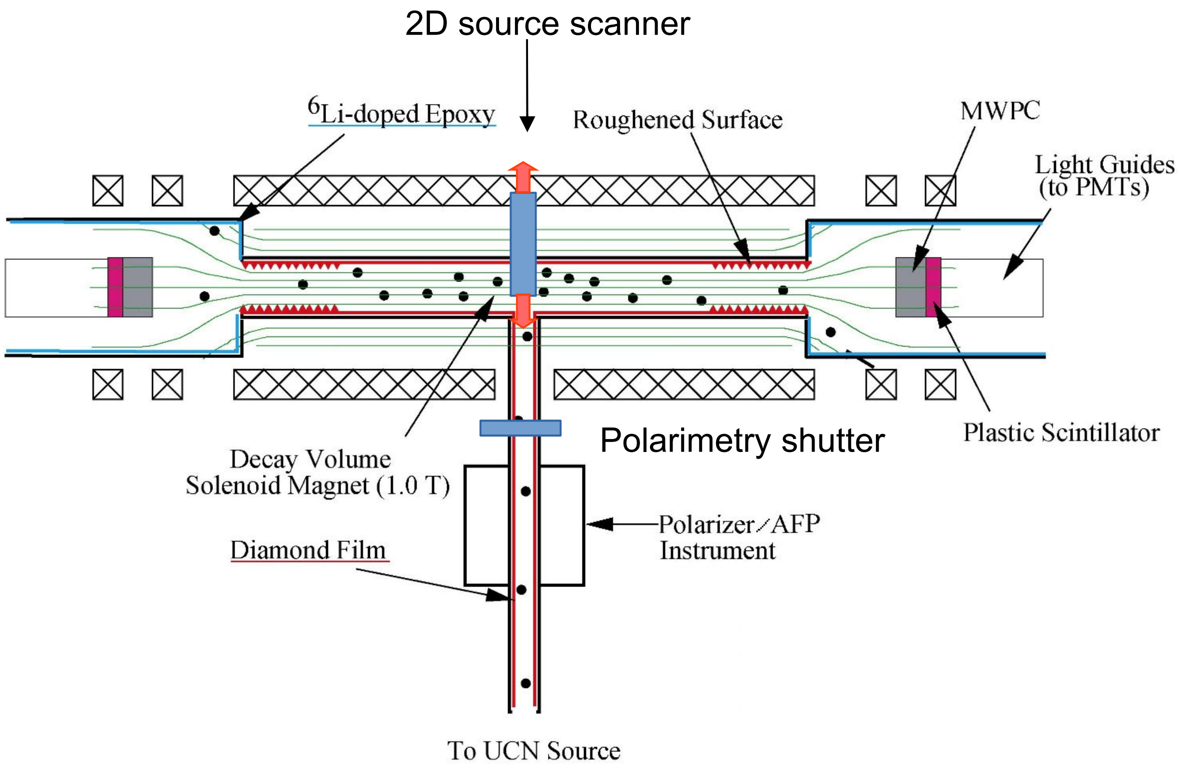
Nab/UCNB highly
segmented Si Detectors

Synergistic development with
Nab/UCNB

Performance measured already benchmarked, DAQ, cooling, etc… established

May require proton coincidence for backgrounds

Improved Mono-energetic Source Scanning



Add full 2D electron source scanning – cover full decay trap guide cross-sectional area with multiple conversion electron sources

R&D target: Detector Performance

- Confirm magnitude of beam generated backgrounds still very small (< 0.1%) – use front/back geometry
- Model expected scattering performance in detail – benchmark
- Confirm calibration variability addressed

The UCNA Collaboration

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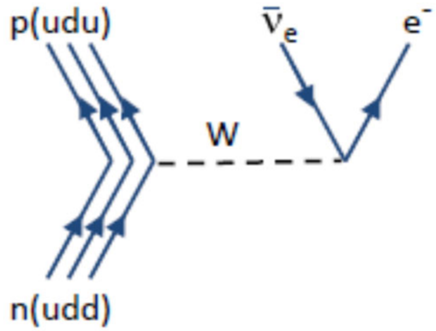
Conclusions

- UCNτ expects to reach 0.2 s total uncertainty on lifetime
- Tau2 should have a factor of three further reach
- UCNA achieved a final precision of 0.67% on A
- UCNA+ hopes to achieve 0.12% stat. precision per year and < 0.1% systematics, competitive with Nab and PERC
- UCN facility also used for smaller scale efforts such as DM searches and nuclear beta decay

- Thanks to Albert, Zhaowen, Noah, Jared, and many others for these slides

BACKUP

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

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

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

$$\lambda = g_A / g_V$$

Neutron β decay and V_{ud}

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

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

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

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

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

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

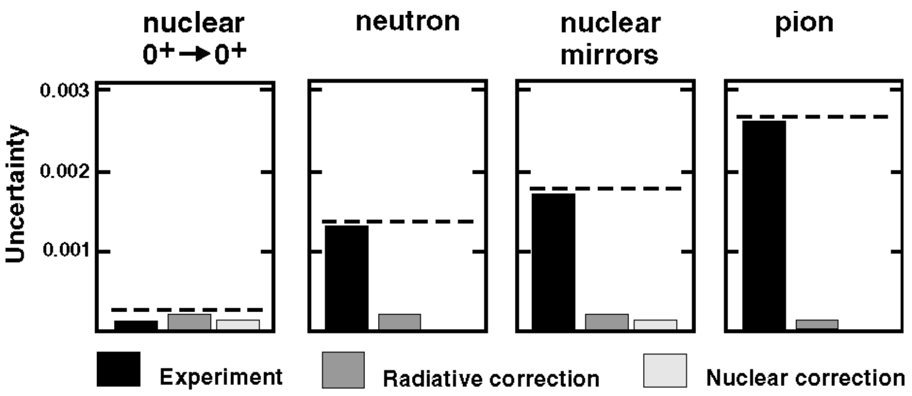
Neutron Decay and Unitarity

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

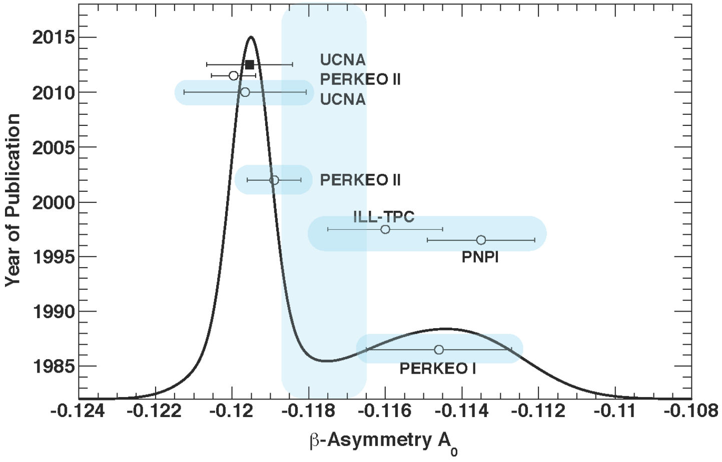
$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} 0.975 & 0.22 & 0.005 \\ 0.22 & 0.97 & 0.04 \\ 0.005 & 0.04 & 0.99 \end{pmatrix} \begin{pmatrix} d_m \\ s_m \\ b_m \end{pmatrix}$$

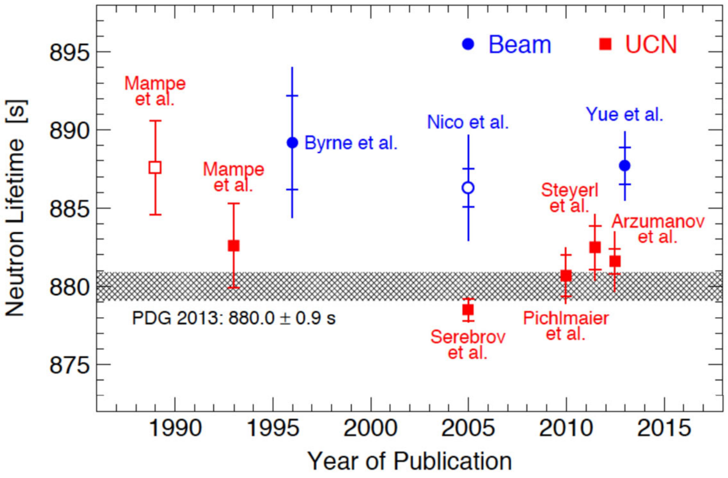
Unitarity, eg. $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$, (or lack thereof) of CKM matrix tests existence of further quark generations and possible new physics (eg. Supersymmetry)

V_{ud} from Beta Decay



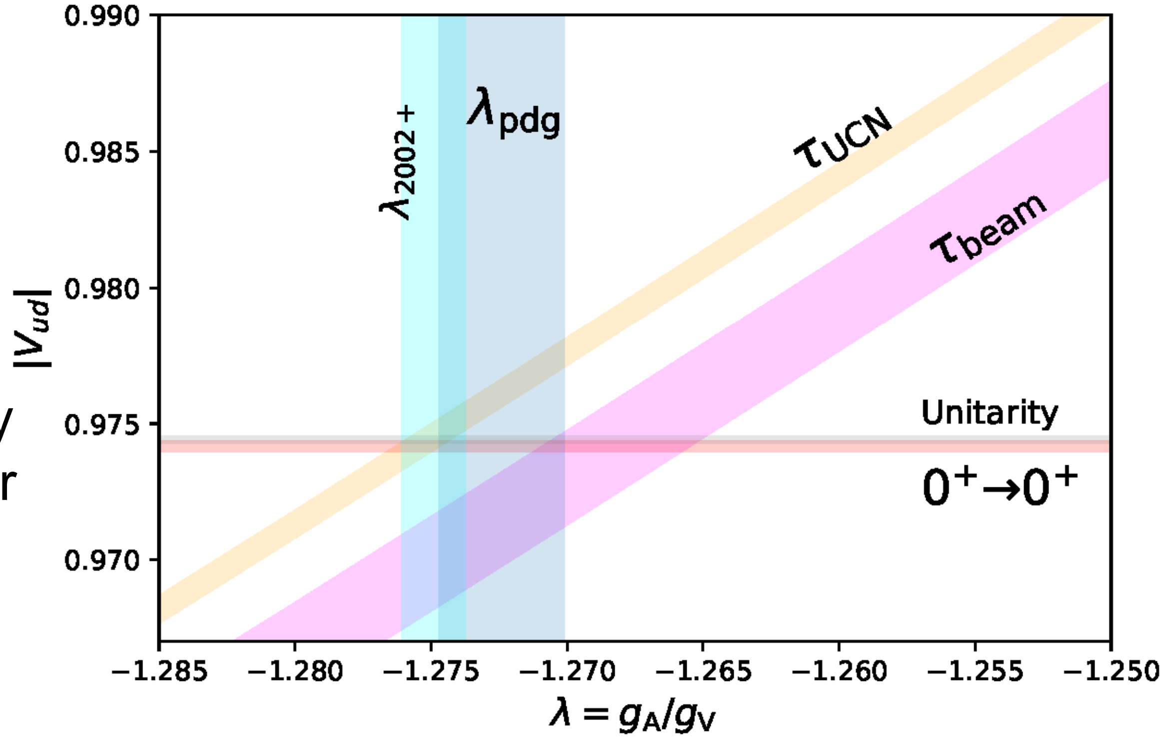
- Superallowed Fermi $0^+ \rightarrow 0^+$ decays: V_{ud} at 0.02% level
- To reach same level from neutron decay, $\delta\lambda/\lambda$ = 3e-4 and $\delta\tau$ = 0.3 s are both necessary





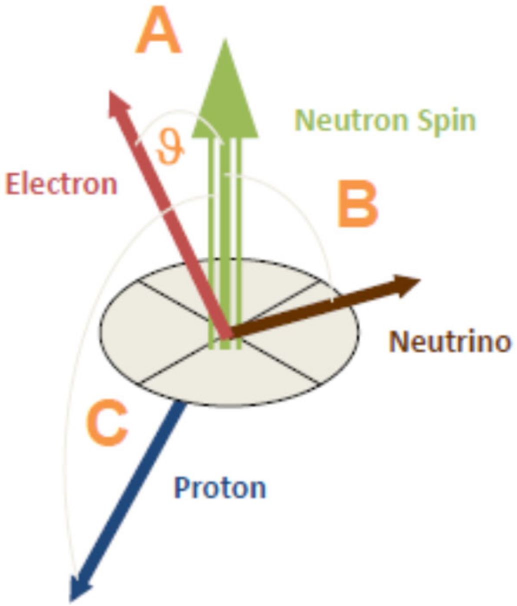
Tension between beam and bottle lifetime measurements, old and new λ measurements

- 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



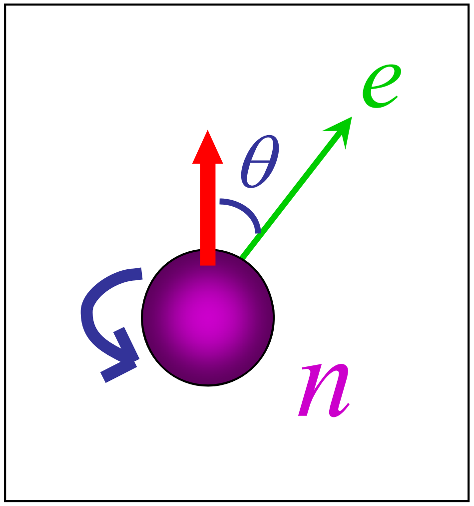
Decay Correlations

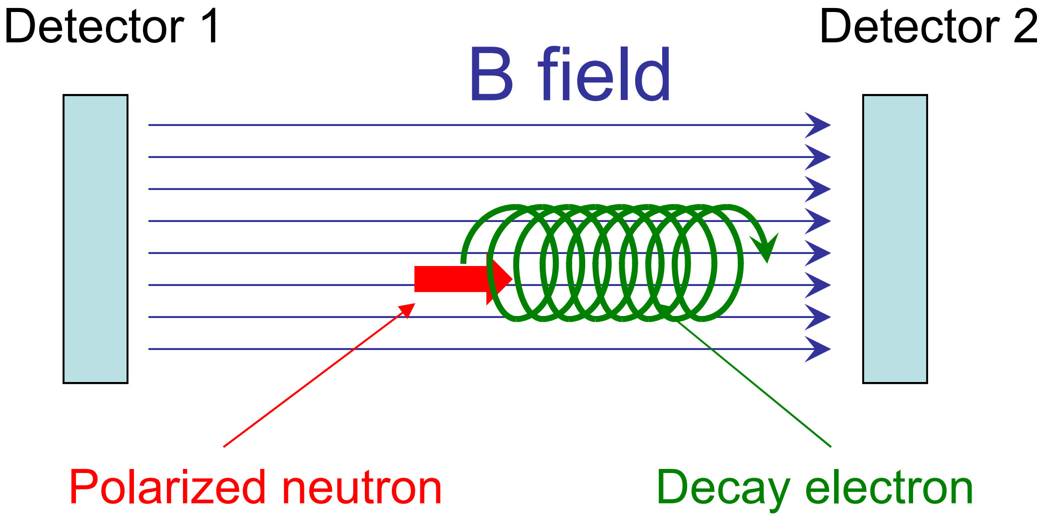
- A: electron asymmetry
  - Perkeo II, Perkeo III, UCNA
- B: neutrino asymmetry
  - Perkeo II
- C: proton asymmetry
  - Perkeo II
- D: triple correlation
  - TRINE, emiT
- a: electron-neutrino correlation
  - aSpect, aCORN, Nab



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

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





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

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

Systematics:

- Polarization
- Backgrounds
- Energy reconstruction

(End point energy = 782 keV)

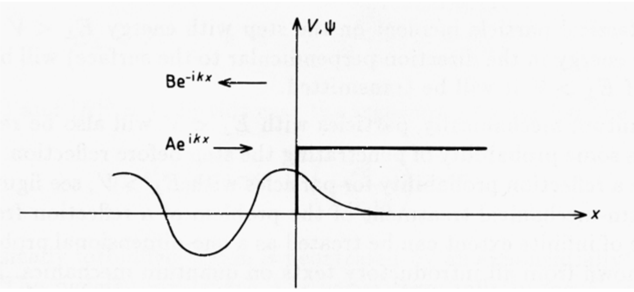
Interlude: Ultra-Cold Neutrons (UCN)

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

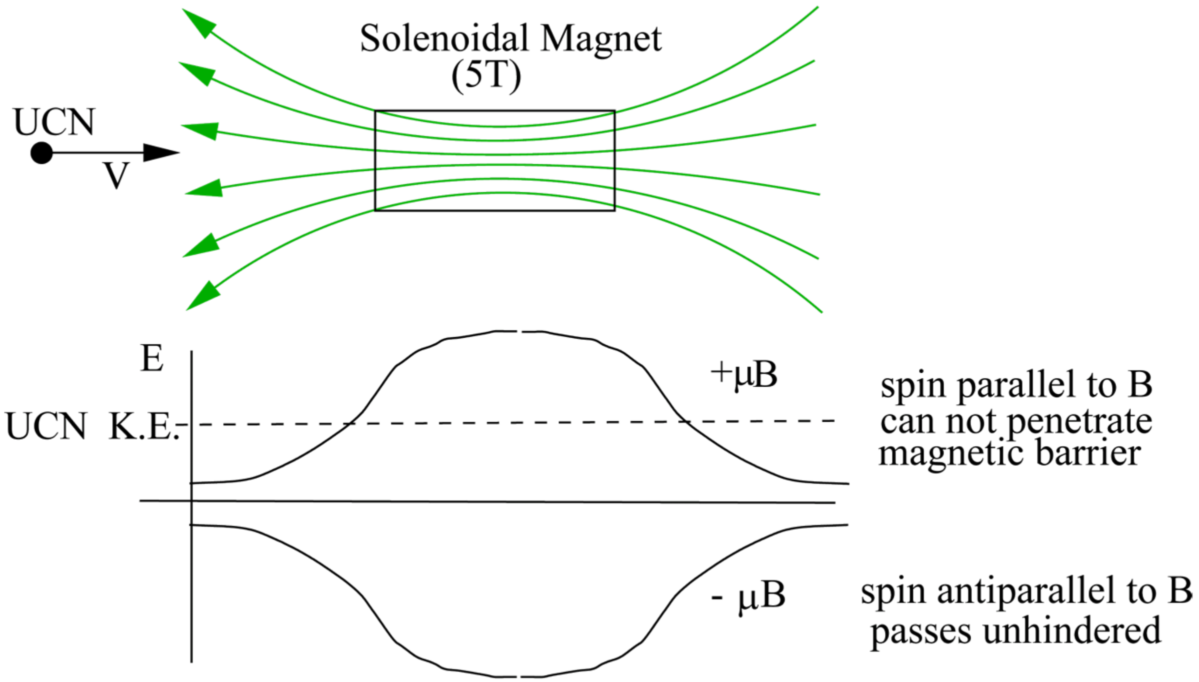
- 300 neV = Potential Energy in wall

		External reflection
$= \frac{1}{2} m_n v^2$	$= \frac{1}{2} m_n (8\ \text{m/s})^2$	Running speed
$= m_n g h$	$= m_n g (3\ \text{m})$	Human scale equipment
$= h^2/(2 m_n \lambda^2)$	$= h^2/(2 m_n (50\ \text{nm})^2)$	Ultraviolet
$= \mu_n B$	$= \mu_n (3.5\ \text{T})$	100% polarization
$= k T$	$= k (3\ \text{mK})$	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)

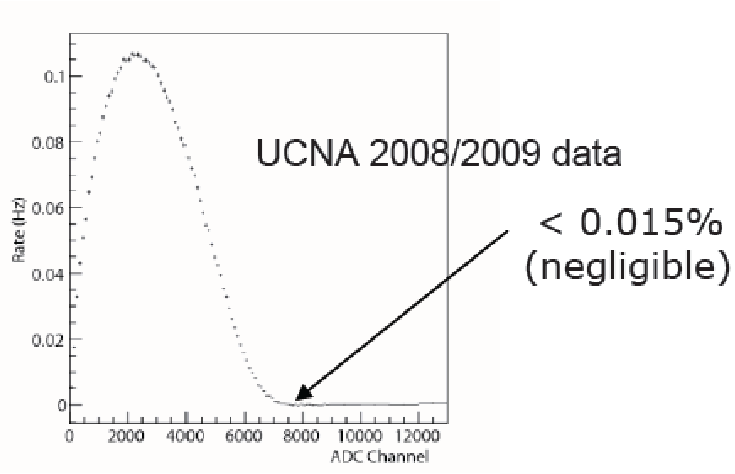


UCN can also be essentially 100 percent polarized



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

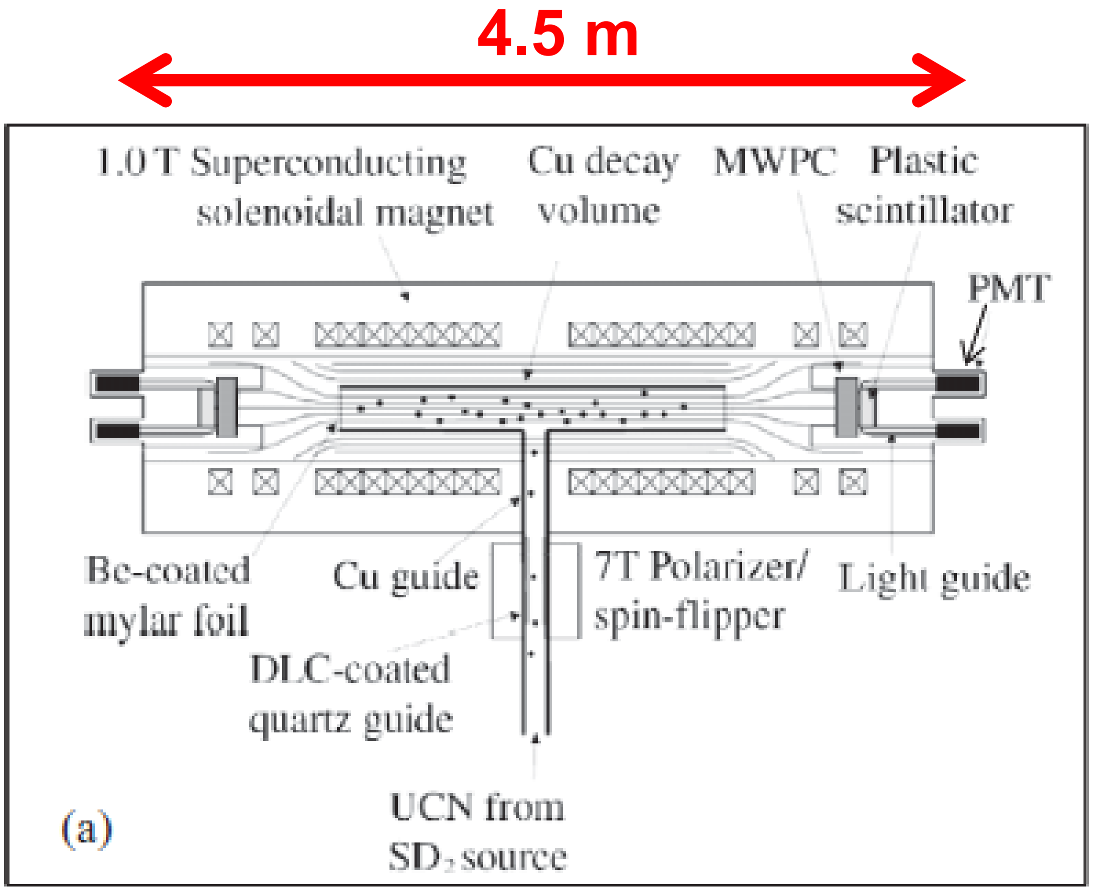
(note: neutron magnetic moment is negative

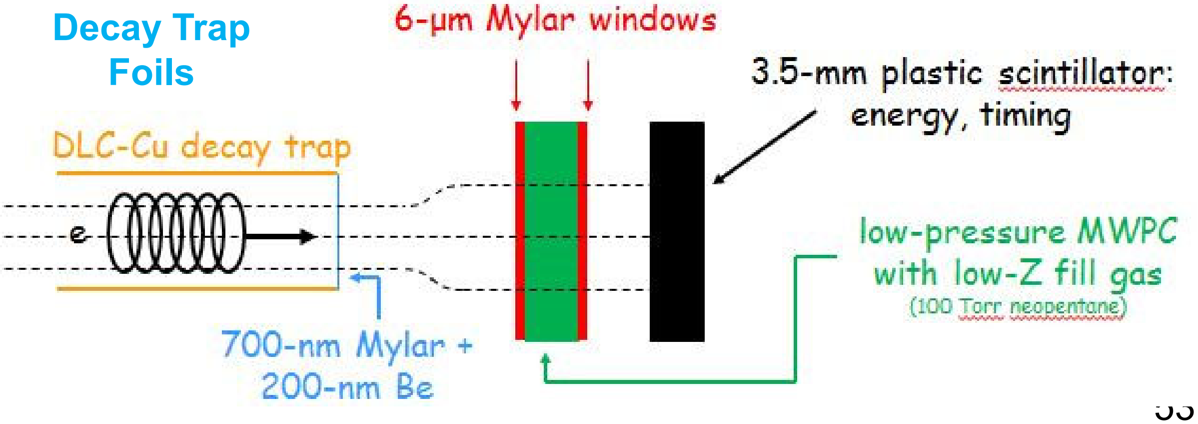


Backgrounds can be reduced relative to cold neutron experiments

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: $\delta\lambda/\lambda = 1.5\text{e-}3$
- Proposed UCNA+ upgrade





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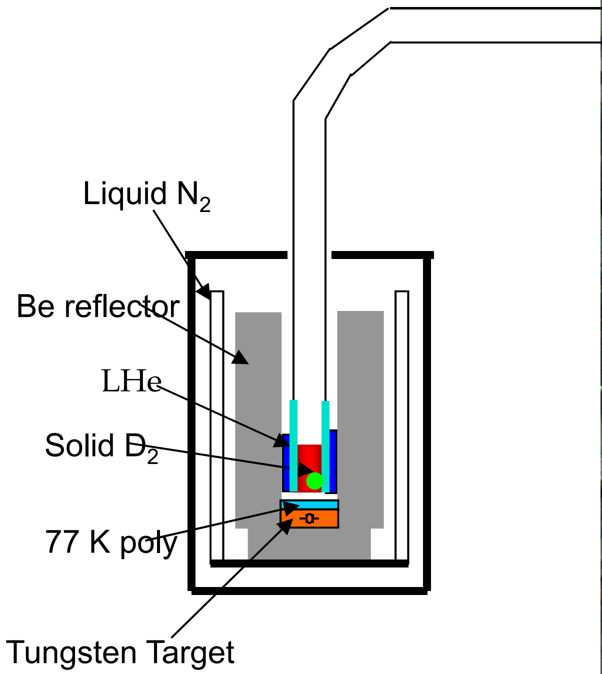
UCNA Experiment



Liquid N_2

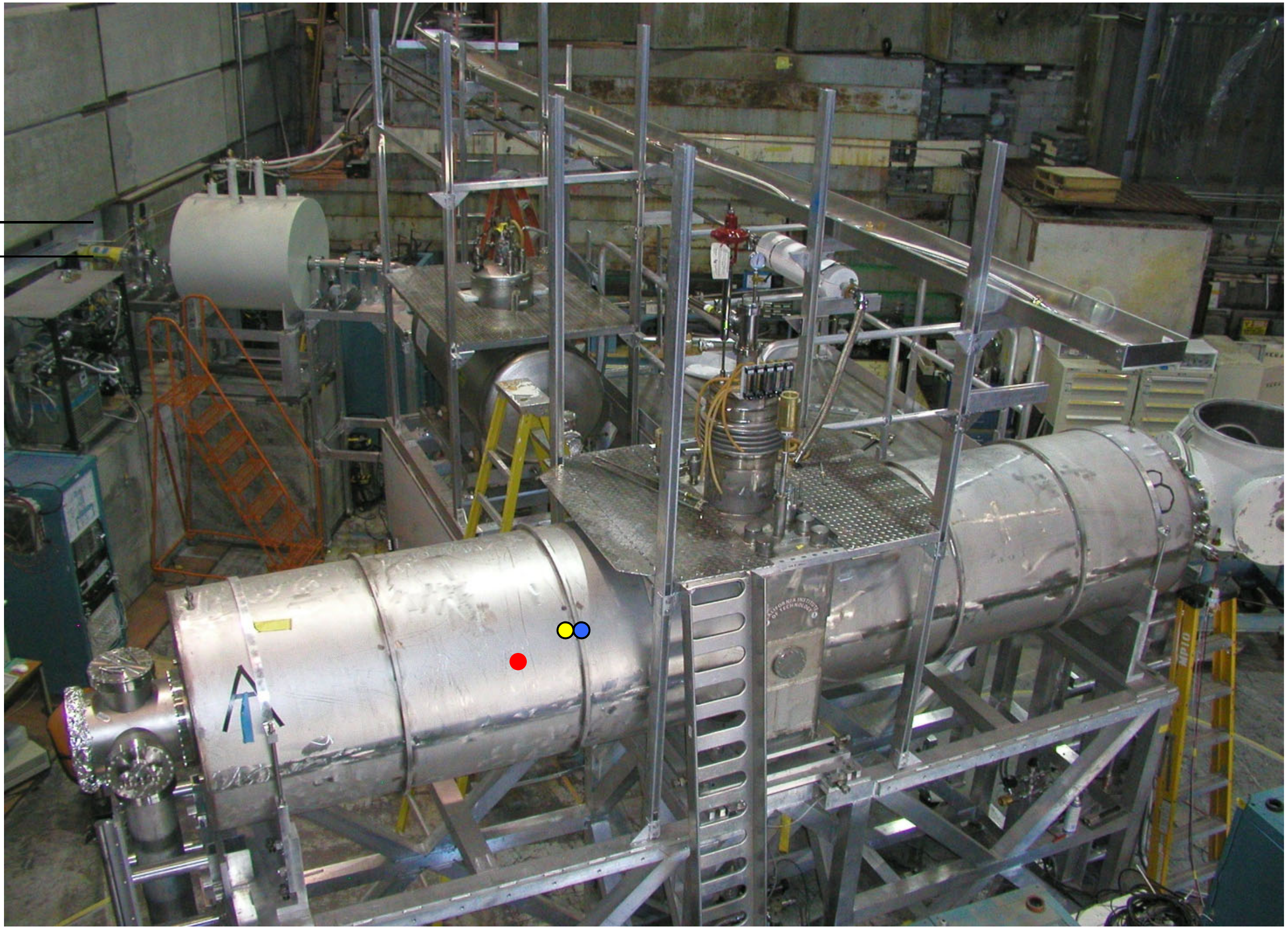
Be reflector

LHe

Solid D_2

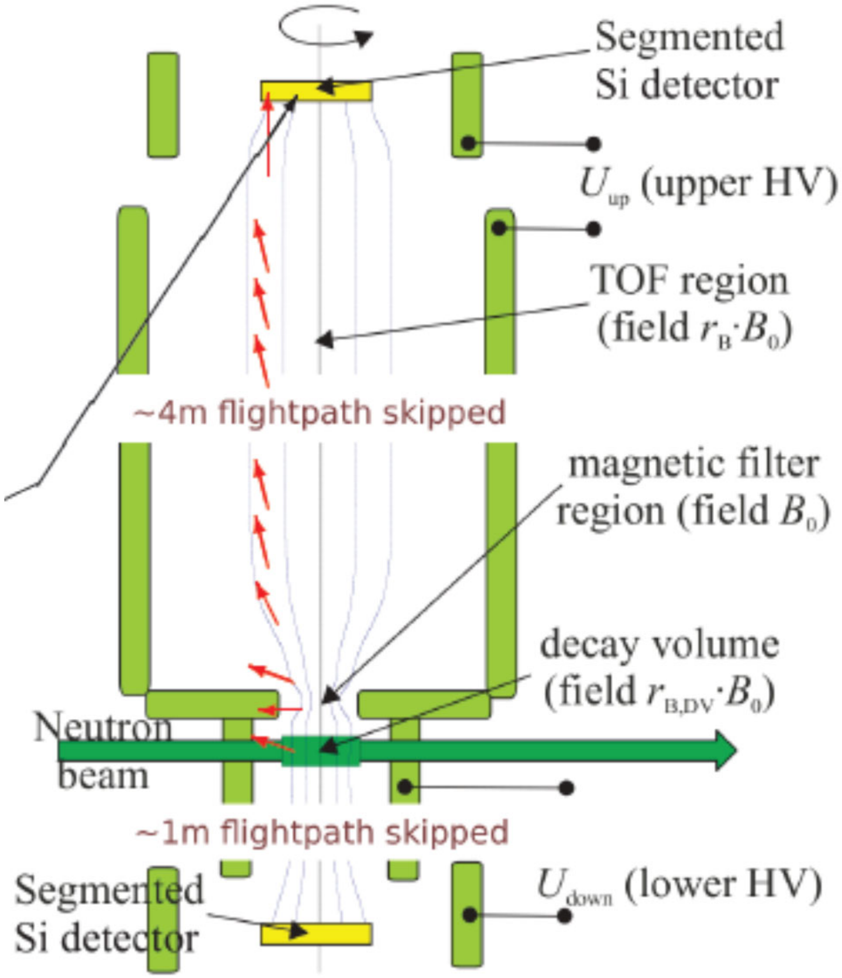
77 K poly

Tungsten Target



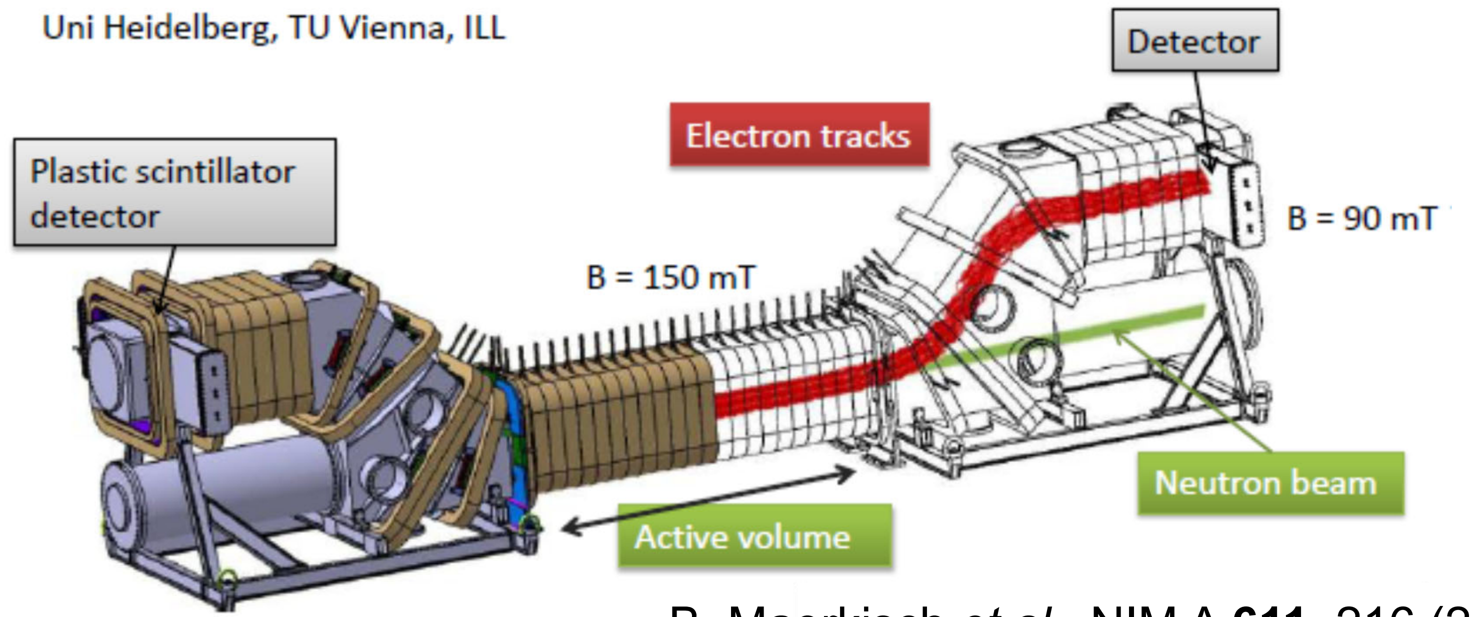
Nab experiment in final construction

- 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: $\Delta a/a = 2e\text{-}3$, $\delta\lambda/\lambda = 5e\text{-}4$



Perkeo III is state of art of CN beta decay

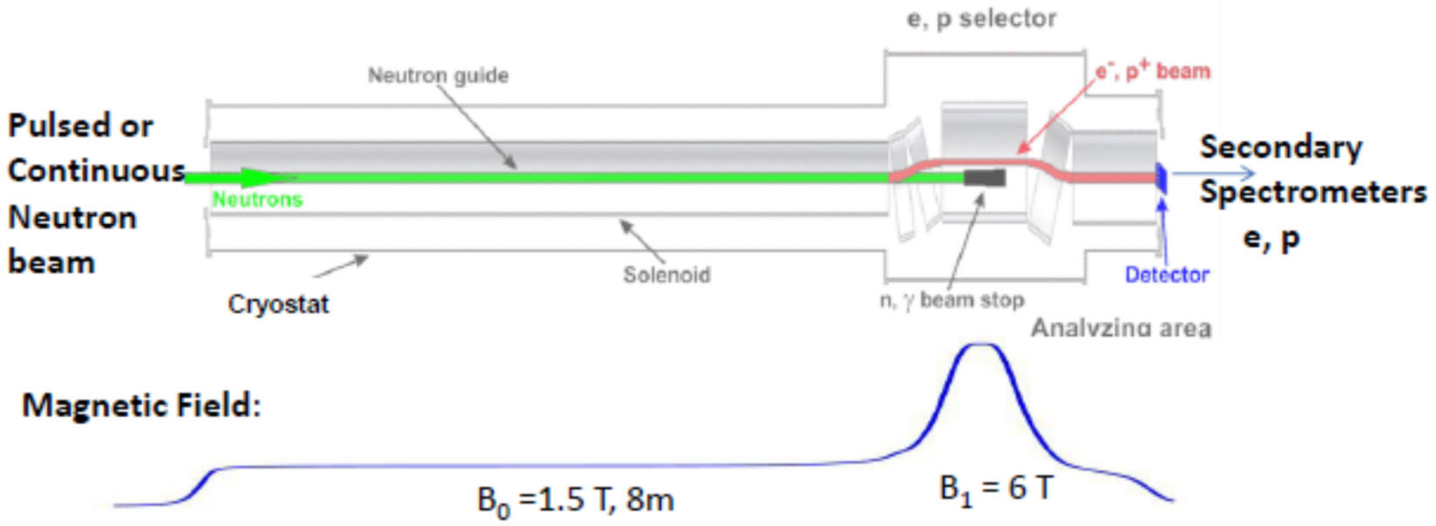
- Backgrounds eliminated using pulsed beam
- Up to 50 kHz decay rate
- Total uncertainty expected to be $\Delta A/A$=2.1e-3, $\delta\lambda/\lambda$=5e-4
- Results very soon!



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

PERC is the next generation

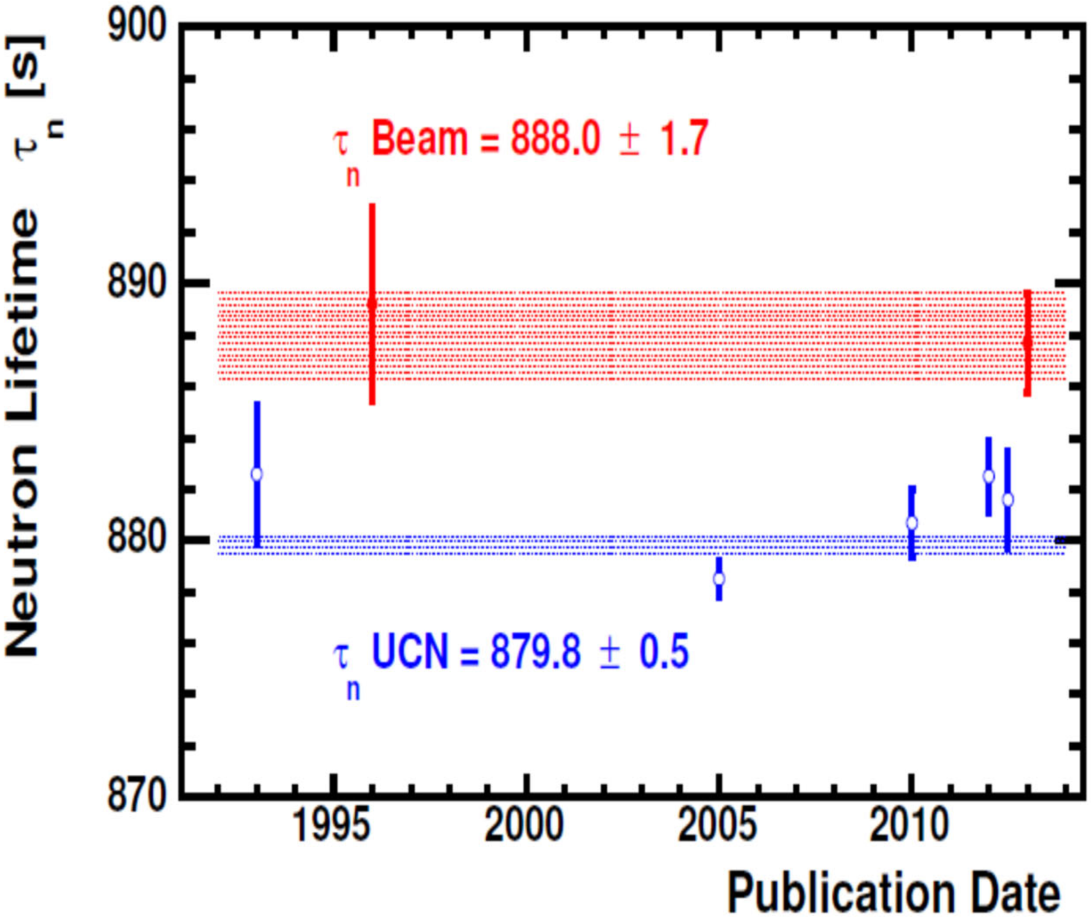
- **P**roton **E**lectron **R**adiation **C**hannel
- 8 m flight path maximizes statistics
- 6 T field pinch minimizes backscatter, field inhomogeneity effects
- To be installed in flight path at FRM-2
- All systematics expected to be O(10^{-4})



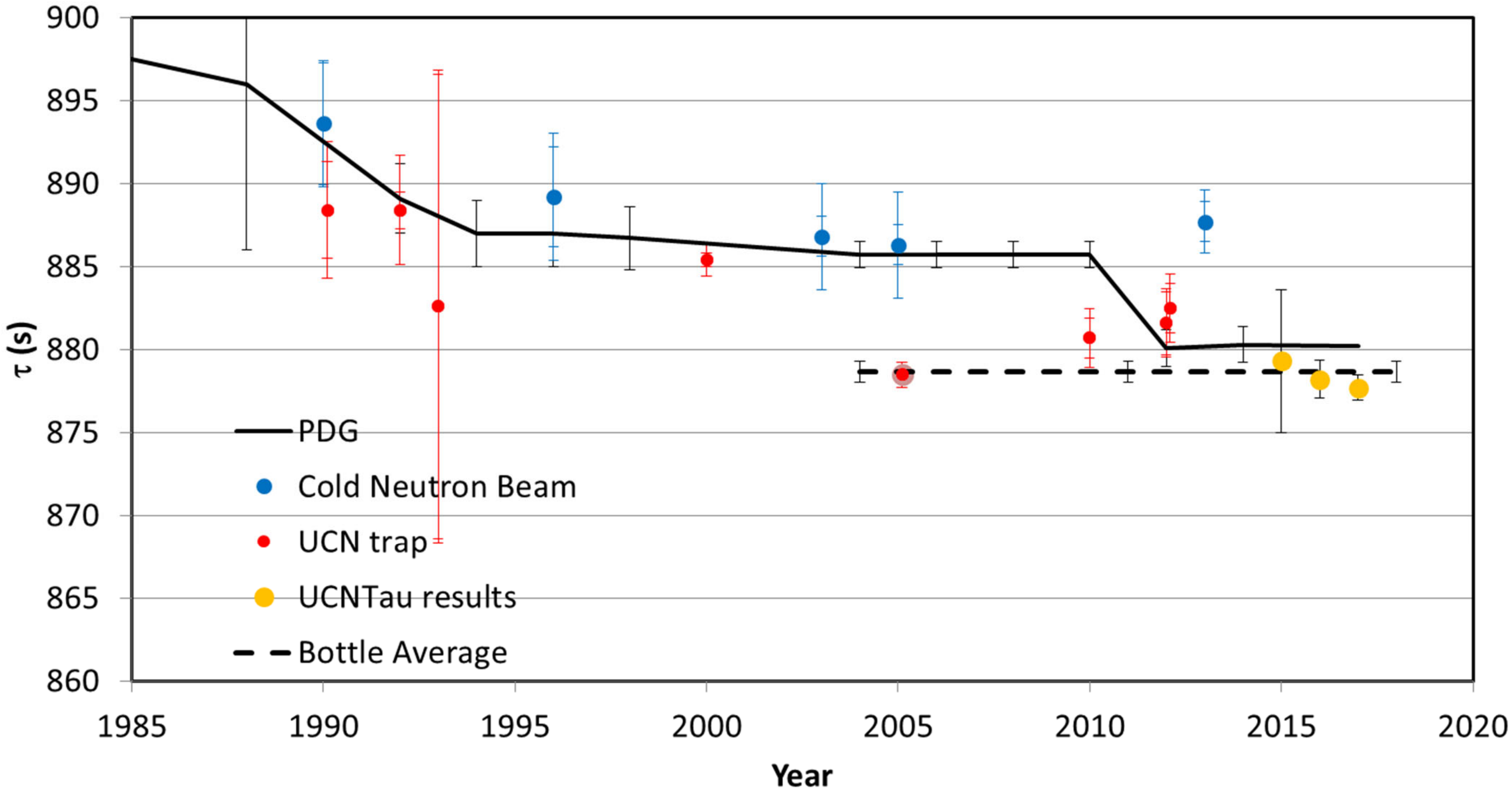
D. Dubbers *et al*., NIM A **596**, 238 (2008)

The neutron lifetime puzzle

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



UCNτ results confirm material trap results with independent systematics



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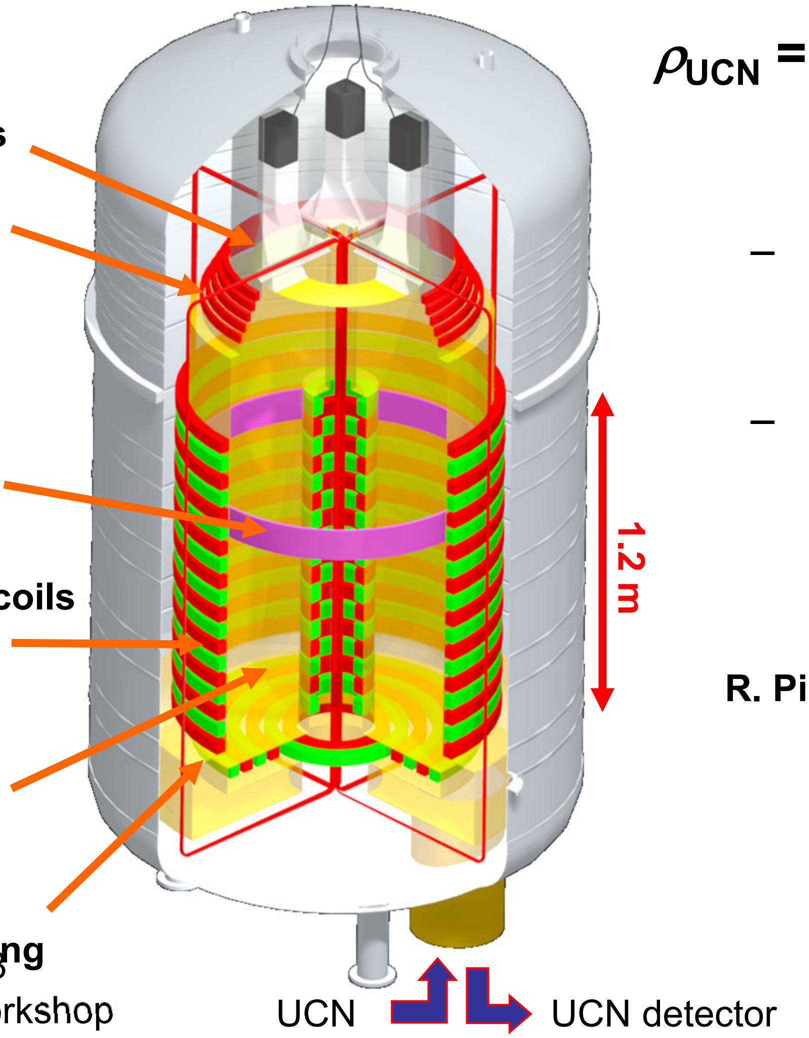
Proposed large volume magnetic storage experiment

PENeLOPE

Magnetic storage of UCN & proton extraction

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

S. Paul et al.



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

$N_\mathrm{stored} = 10^7 - 10^8$

- **Statistical accuracy:**

  $\delta\tau_\mathrm{n} \sim 0.1$ **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)

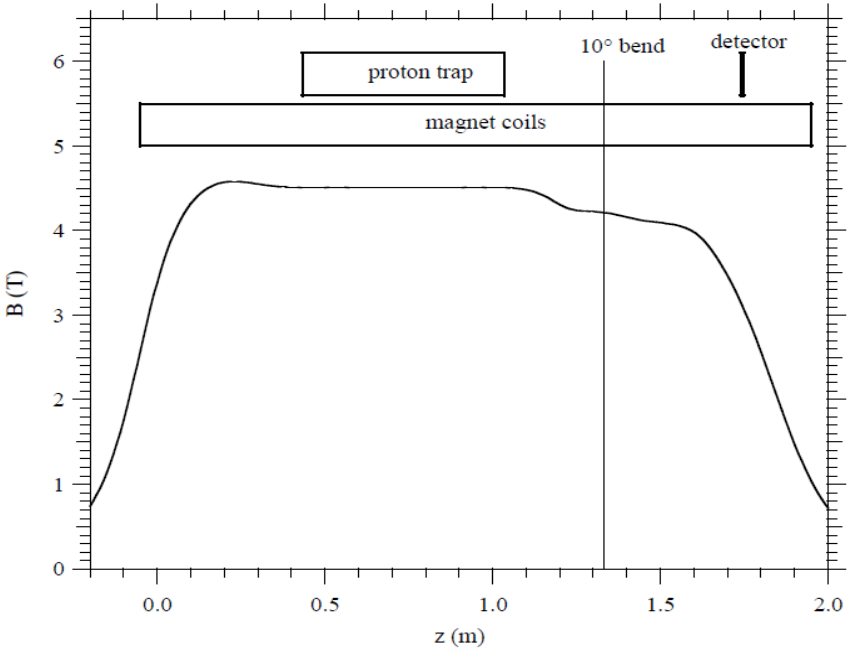
- Increased neutron beam diameter

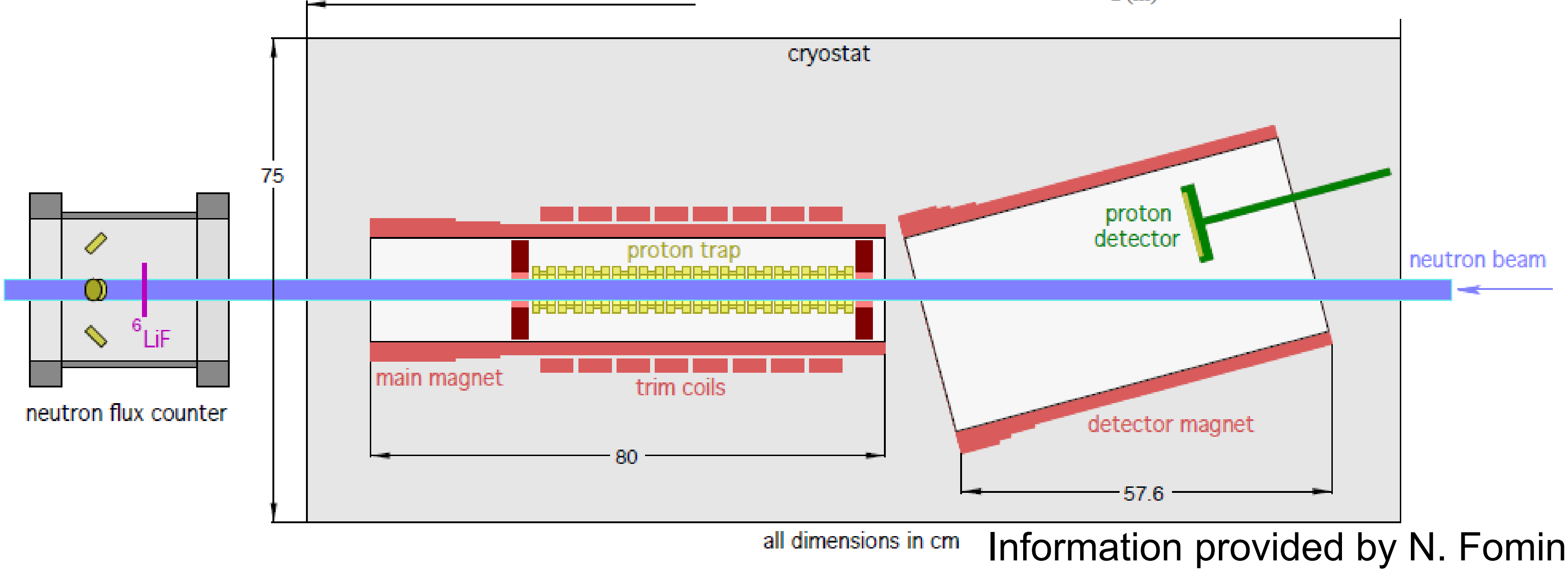
  7 mm → 30 mm

- Uniformity requirements:

  $\Delta B/B < 10^{-3}$ (in proton trap)

- 50x increase in trapping volume

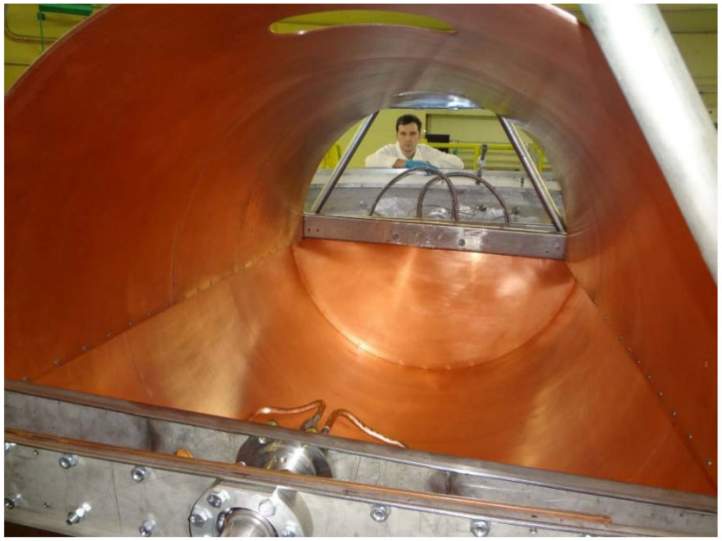


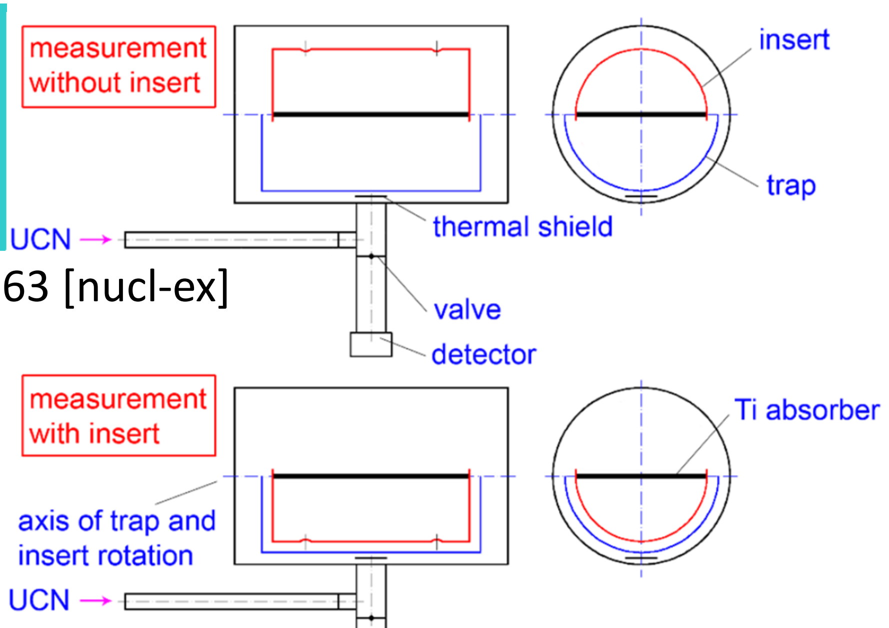


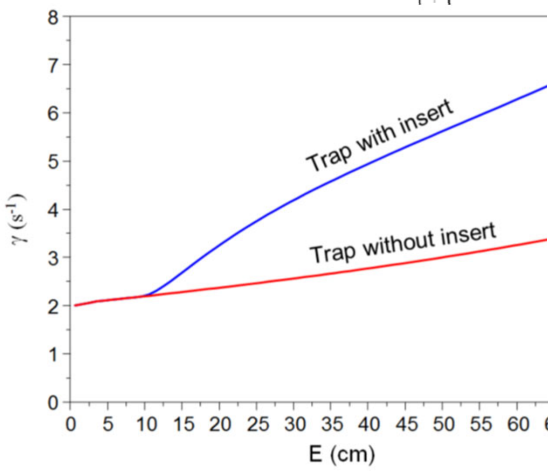
Information provided by N. Fomin

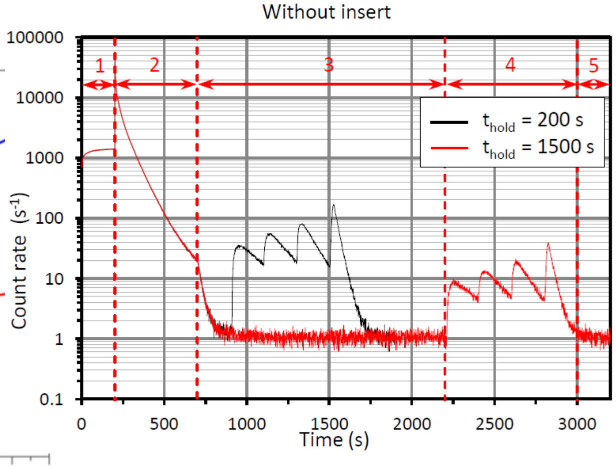
New GraviTrap

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









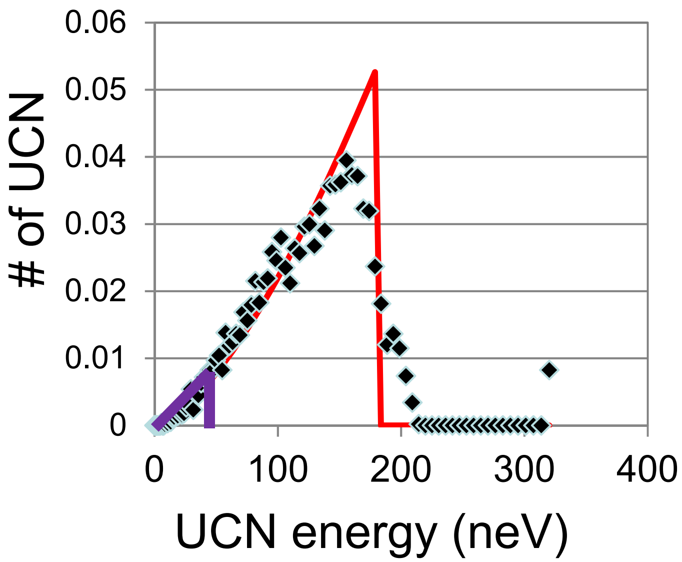
$$\tau_{loss}^{-1} = \eta(T)\gamma(E)$$

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

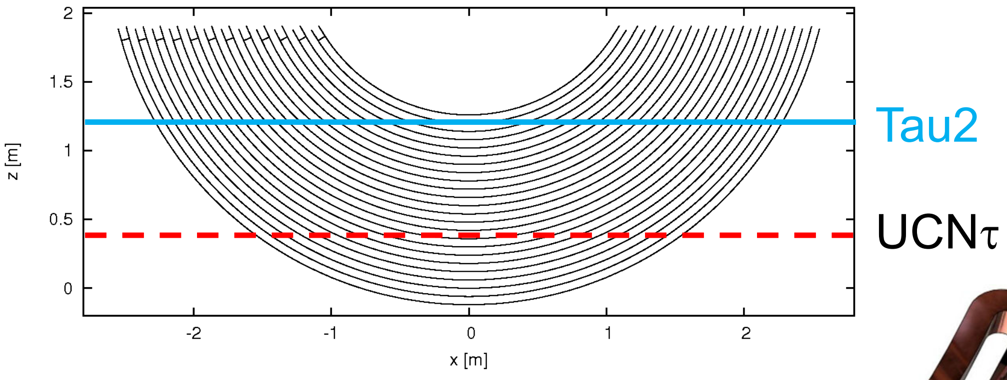
UCNτ’s precision is limited not by systematic effects, but by the UCN density and spectrum produced by the LANSCE UCN source, the brightest in the world.

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

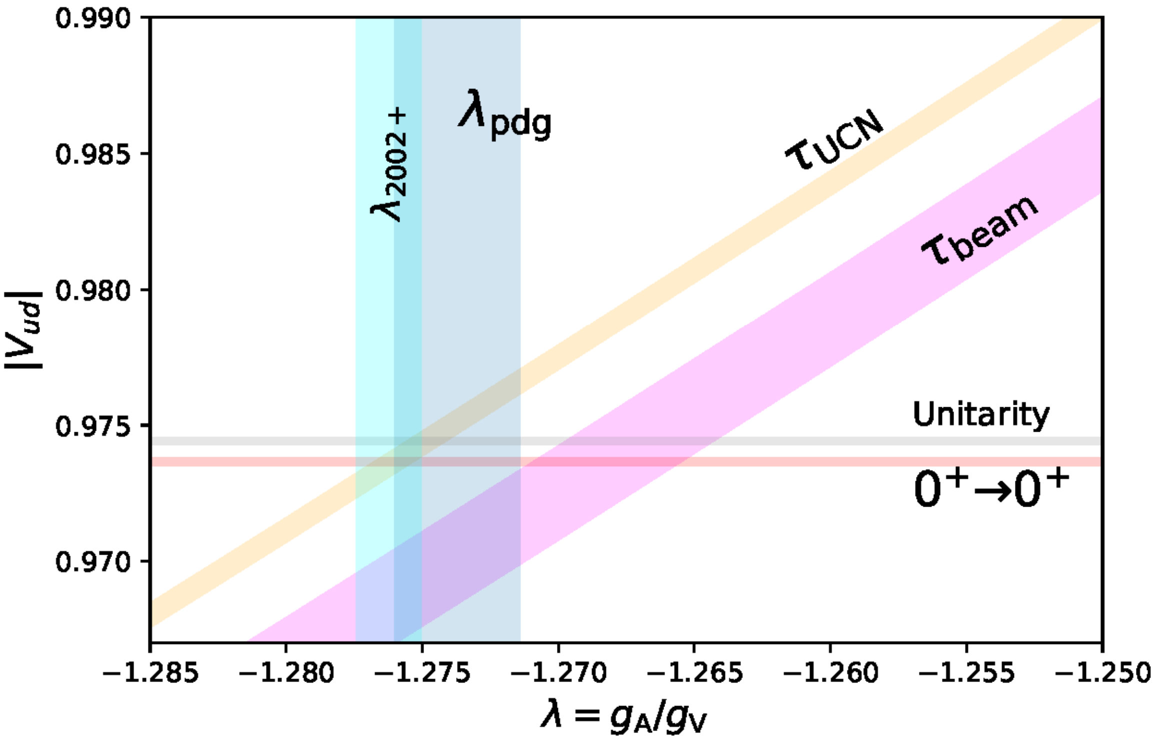
By replacing UCNτ’s permanent magnet trap with one made of superconducting magnets.



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).