Recent Results from UCNtau and implication for V_{ud}

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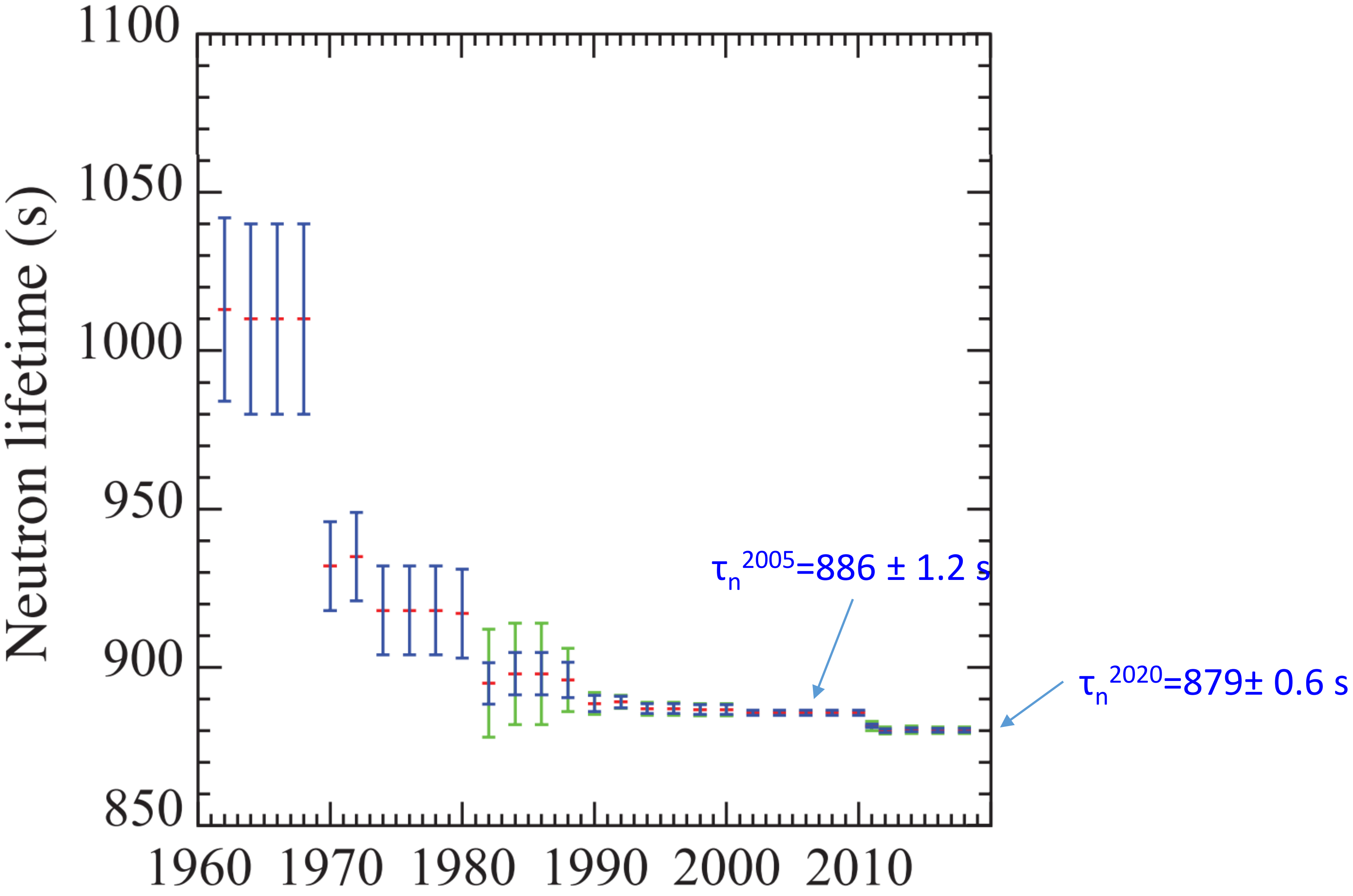
Indiana University

11/23/2021

11th International Workshop on the CKM Unitarity Triangle (CKM2021)

The Particle Data Group (PDG) average of the neutron lifetime:

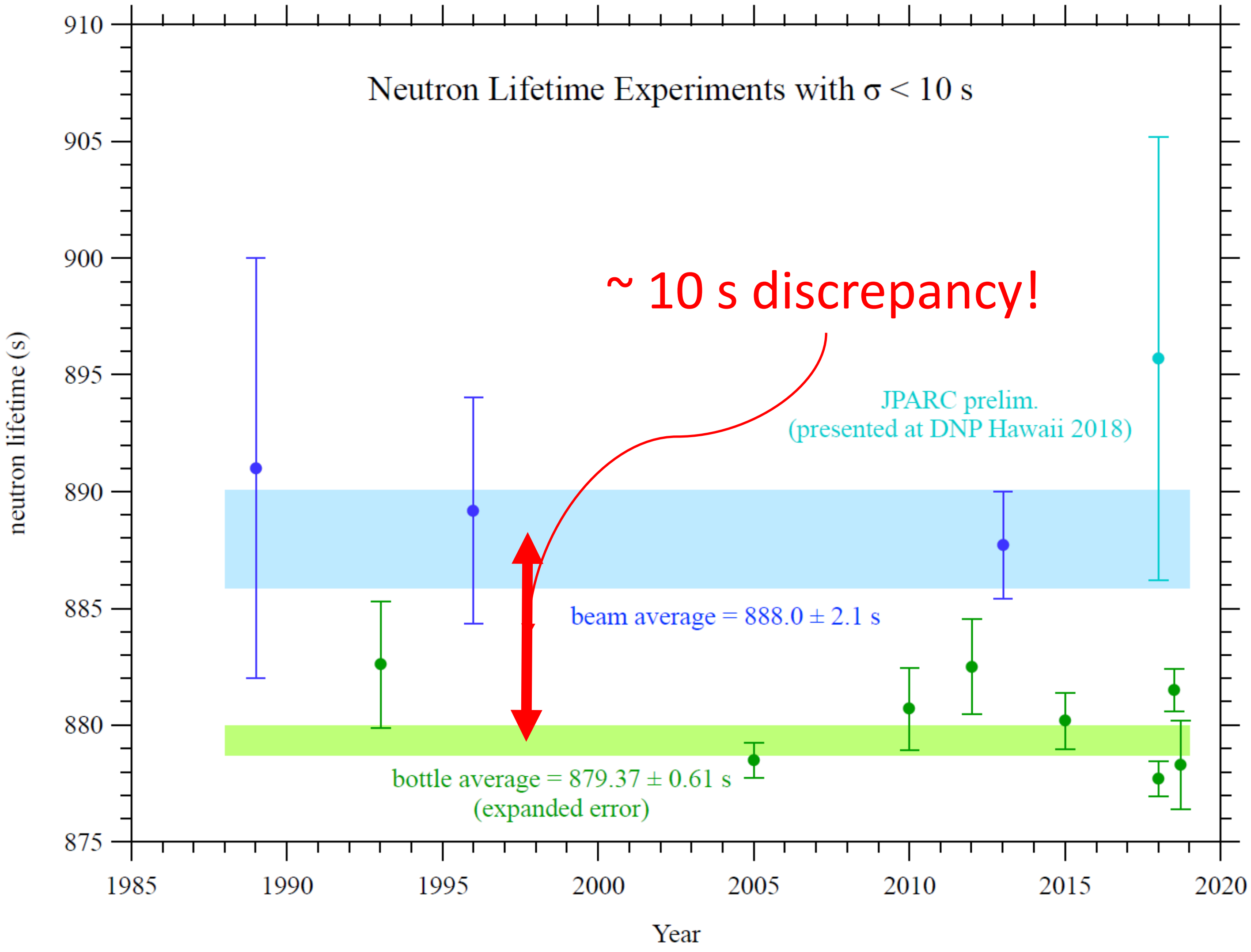


τ_n^{2005}=886 ± 1.2 s

τ_n^{2020}=879± 0.6 s

There is an unresolved discrepancy between two leading methods to measure the neutron lifetime: neutrons in a bottle seem to disappear faster.

The Situation Today - 2019

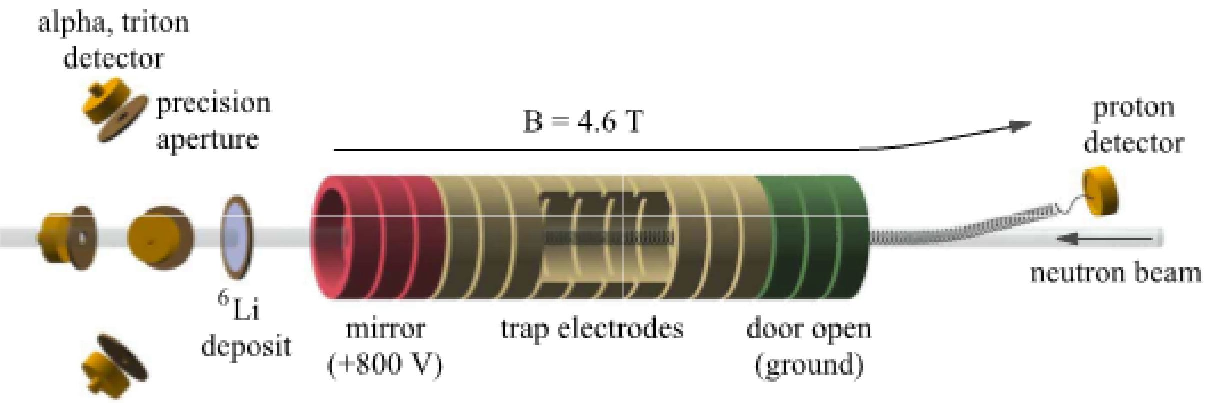


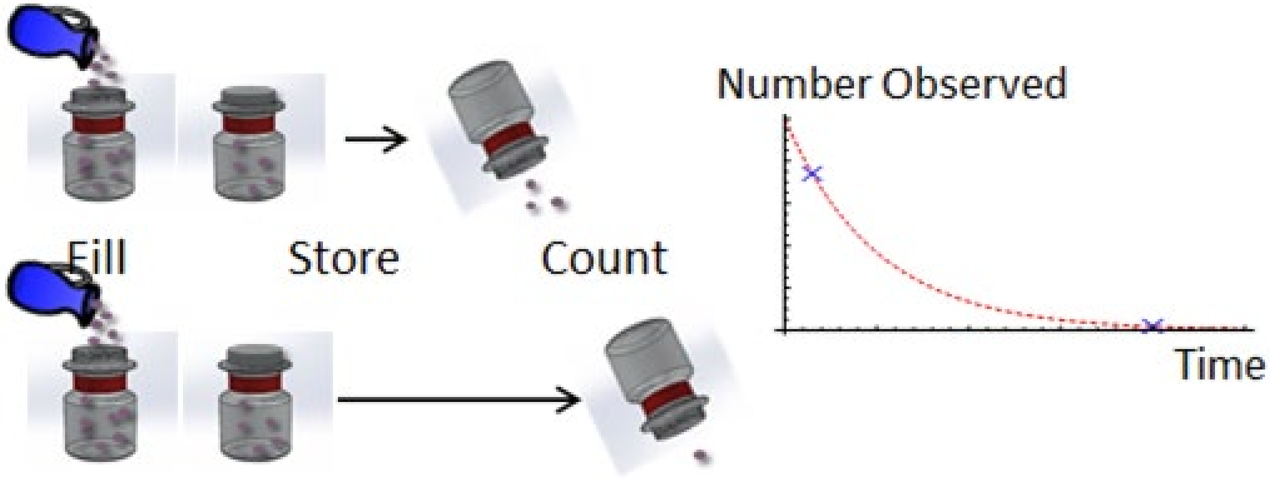
The “beam” and “bottle” techniques

$$\tau_n = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$

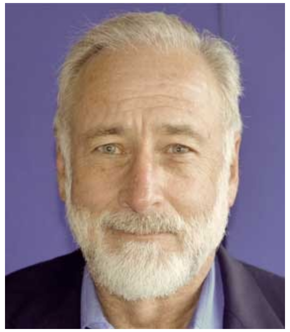
$$Y(t) = Y_0 e^{-t\,/\,\tau_{meas}}$$

$$\tau_{meas}^{-1} = \tau_n^{-1} + \tau_{loss}^{-1}$$



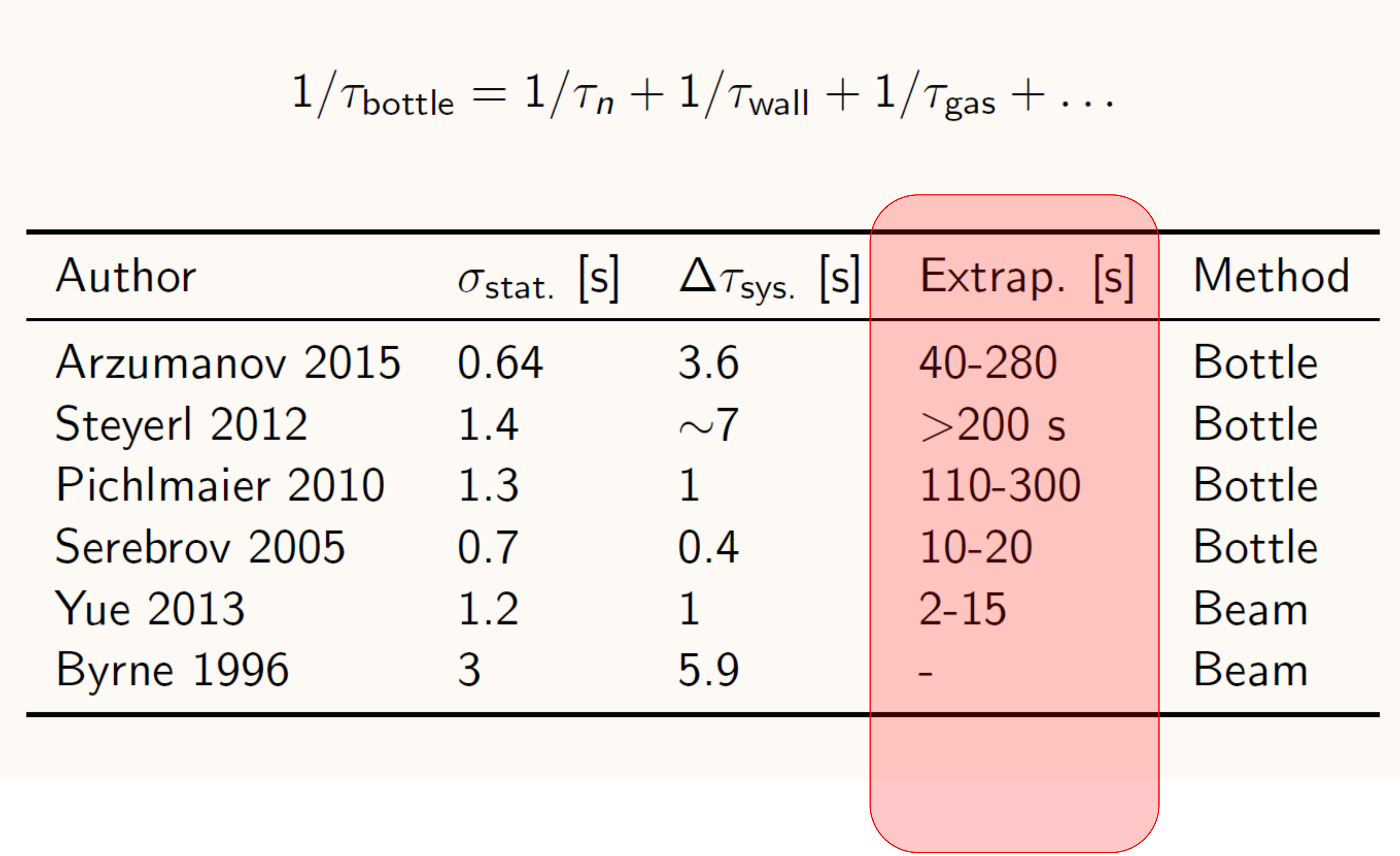


“It sounds hard, and it is hard”
said Geoff Greene.
(2021 Bonner Prize Recipient)



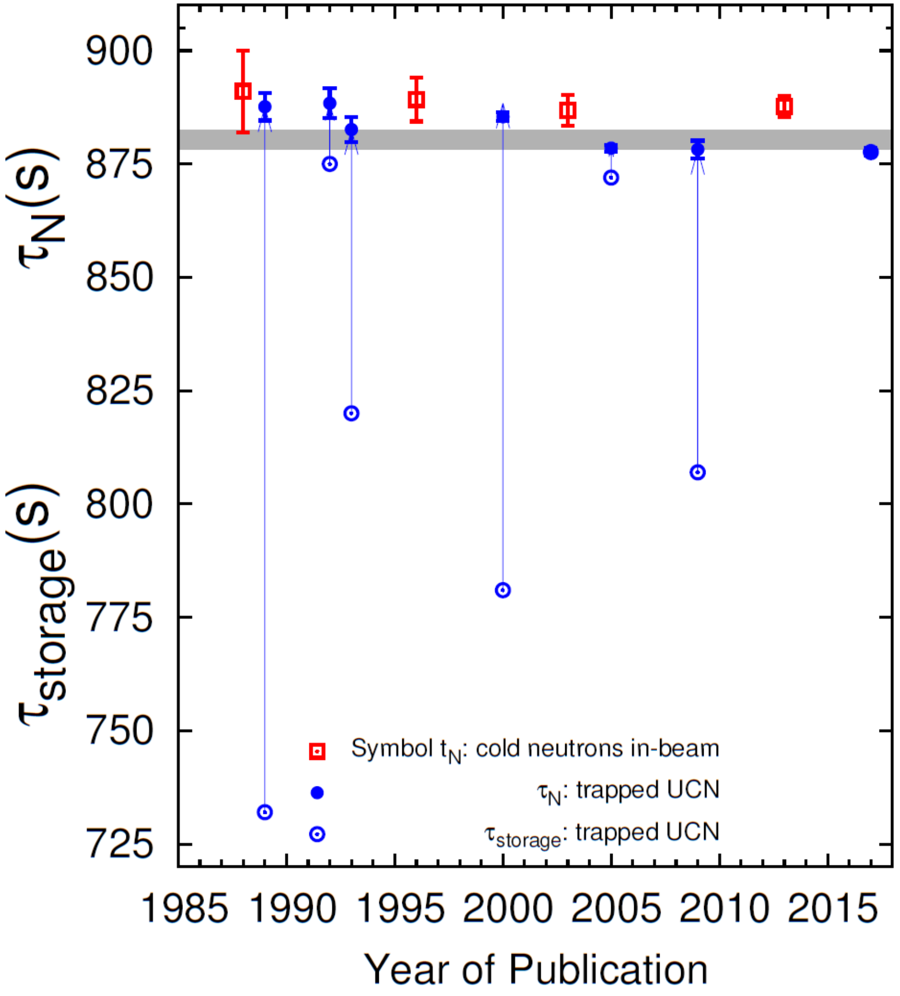
“It sounds easy, and it is hard”
said Geoff Greene.

Many experiments need to correct for the systematic effects and extrapolate from the measured lifetime to report the Neutron Lifetime



$$1/\tau_{\text{bottle}} = 1/\tau_n + 1/\tau_{\text{wall}} + 1/\tau_{\text{gas}} + \ldots$$

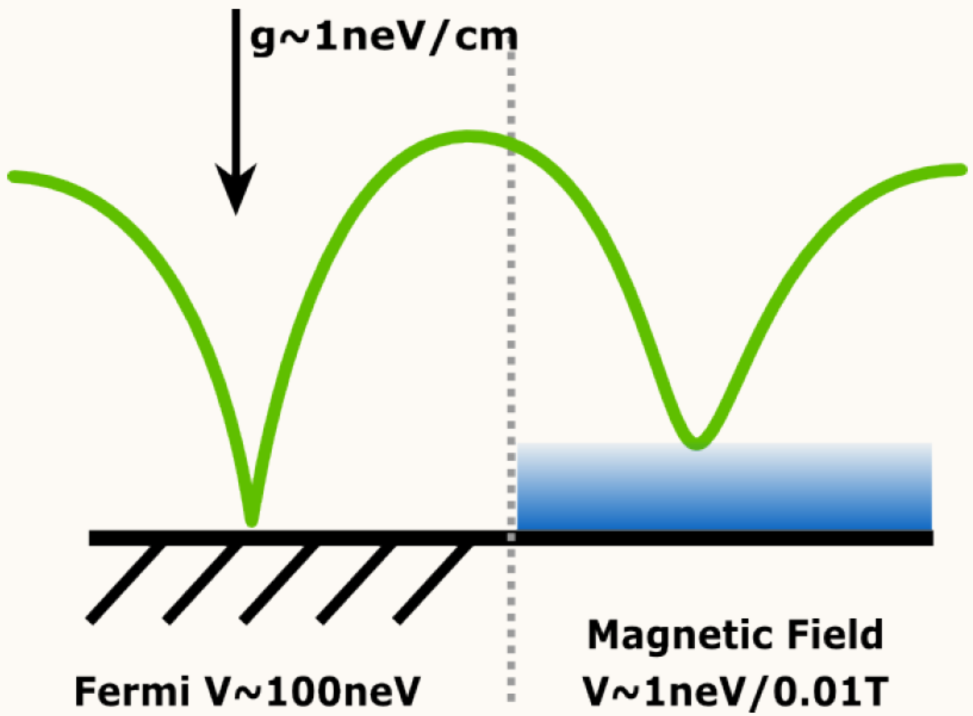
Author	$\sigma_{\text{stat.}}$ [s]	$\Delta\tau_{\text{sys.}}$ [s]	Extrap. [s]	Method
Arzumanov 2015	0.64	3.6	40-280	Bottle
Steyerl 2012	1.4	$\sim$7	$>$200 s	Bottle
Pichlmaier 2010	1.3	1	110-300	Bottle
Serebrov 2005	0.7	0.4	10-20	Bottle
Yue 2013	1.2	1	2-15	Beam
Byrne 1996	3	5.9	-	Beam



Neutron-wall interactions

Material bottle

Magnetic bottle

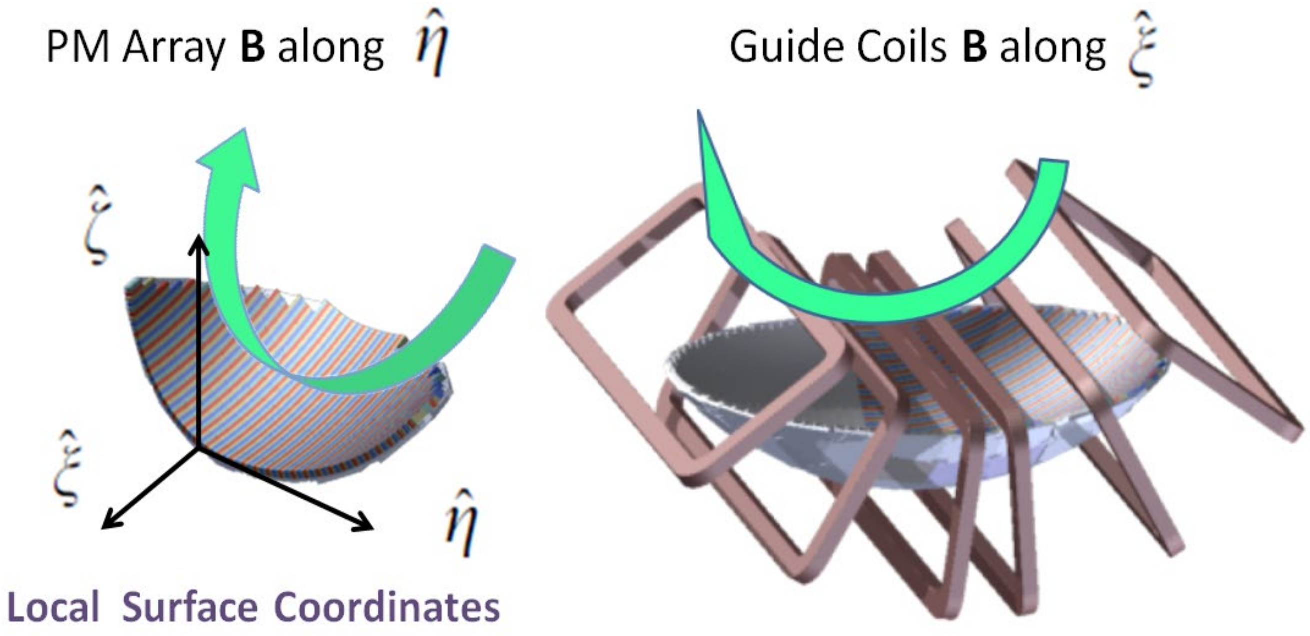


- Material - $V_f \sim \mathcal{O}(100\text{s neV})$
- Magnetic Field - $V_B \sim 1\text{neV}/1000\ \text{Gauss}$
- Gravity - $V_g \sim 1\ \text{neV}/\text{cm}$

A magneto-gravitational trap eliminates neutron losses on the walls

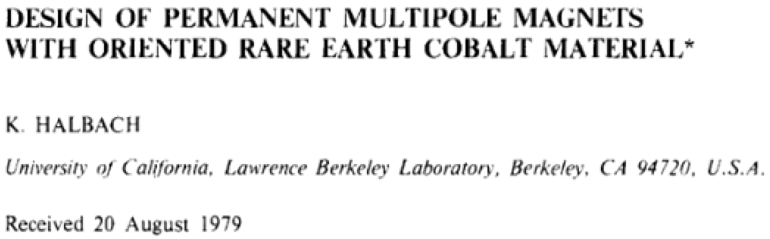
- **Magnetic trapping**: Halbach array of permanent magnets along trap floor repels spin polarized neutrons.

- **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 “Halbach” array



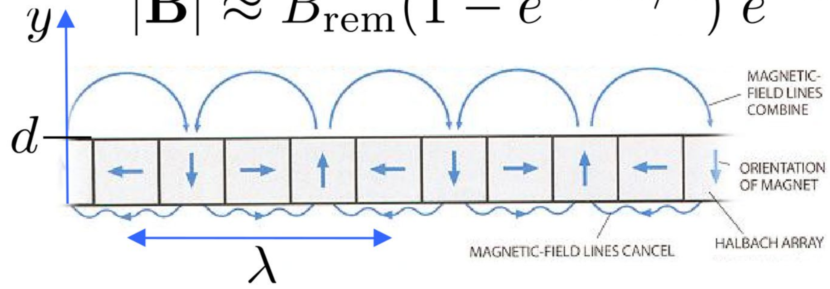
DESIGN OF PERMANENT MULTIPOLE MAGNETS
WITH ORIENTED RARE EARTH COBALT MATERIAL*

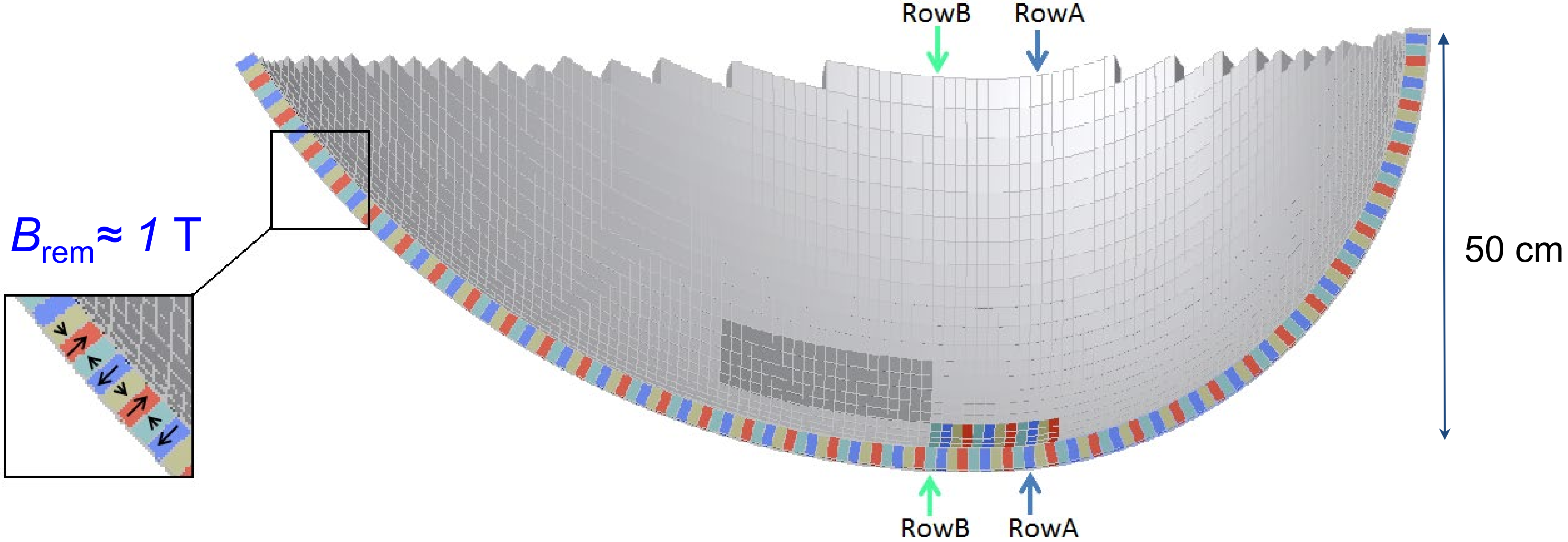
K. HALBACH

University of California, Lawrence Berkeley Laboratory, Berkeley, CA 94720, U.S.A.

Received 20 August 1979

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





$B_{\rm rem} \approx 1$ T

Bailey inside the Halbach array performing field mapping (before Christmas 2012)

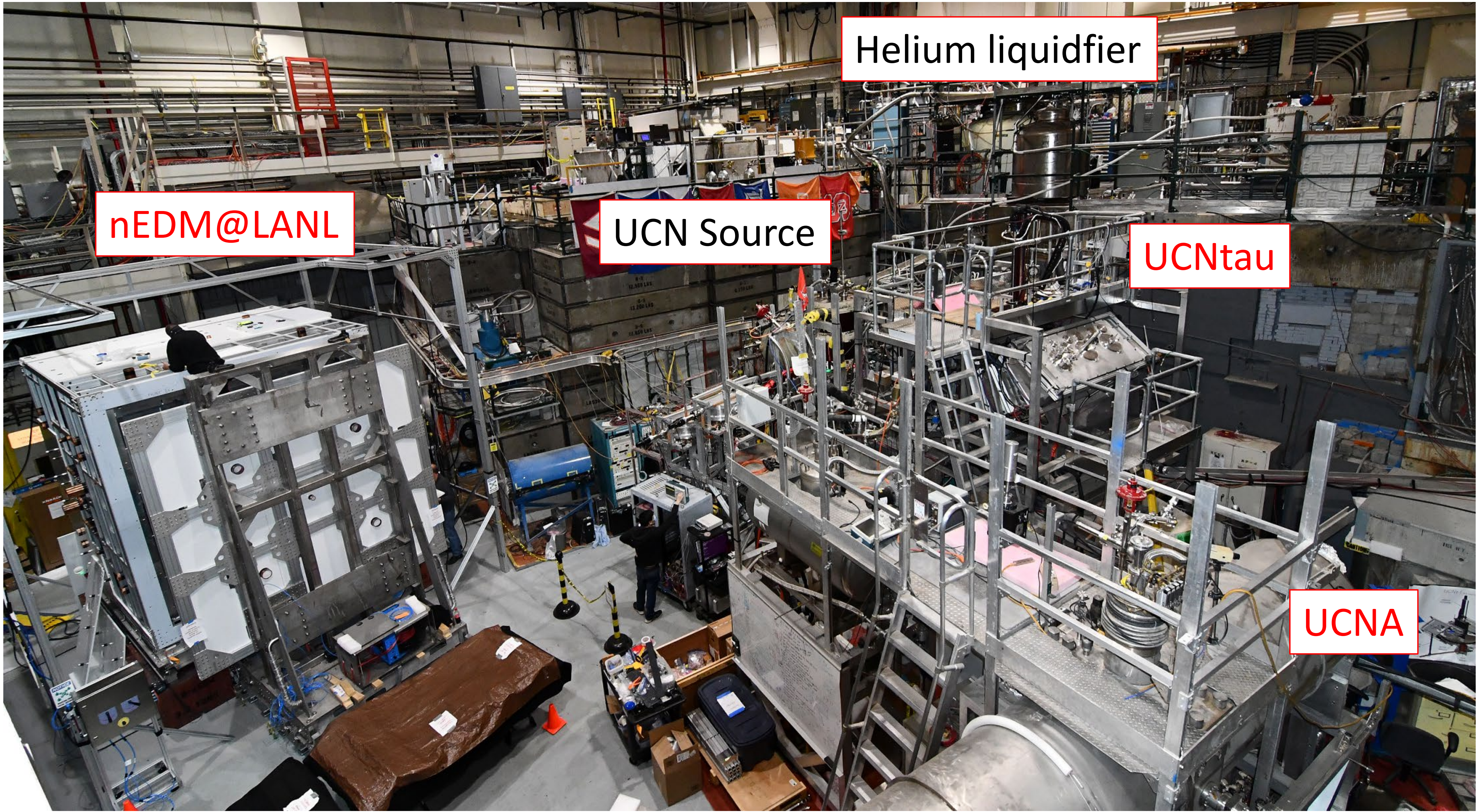
Chris Hadfield
@Cmdr_Hadfield

That's Bailey in a neutron bottle. She helped discover that neutrons in the wild last 14.629 minutes (in an atom they can last billions of years).
@LosAlamosNatLab
The details: bit.ly/3mBp5Tm

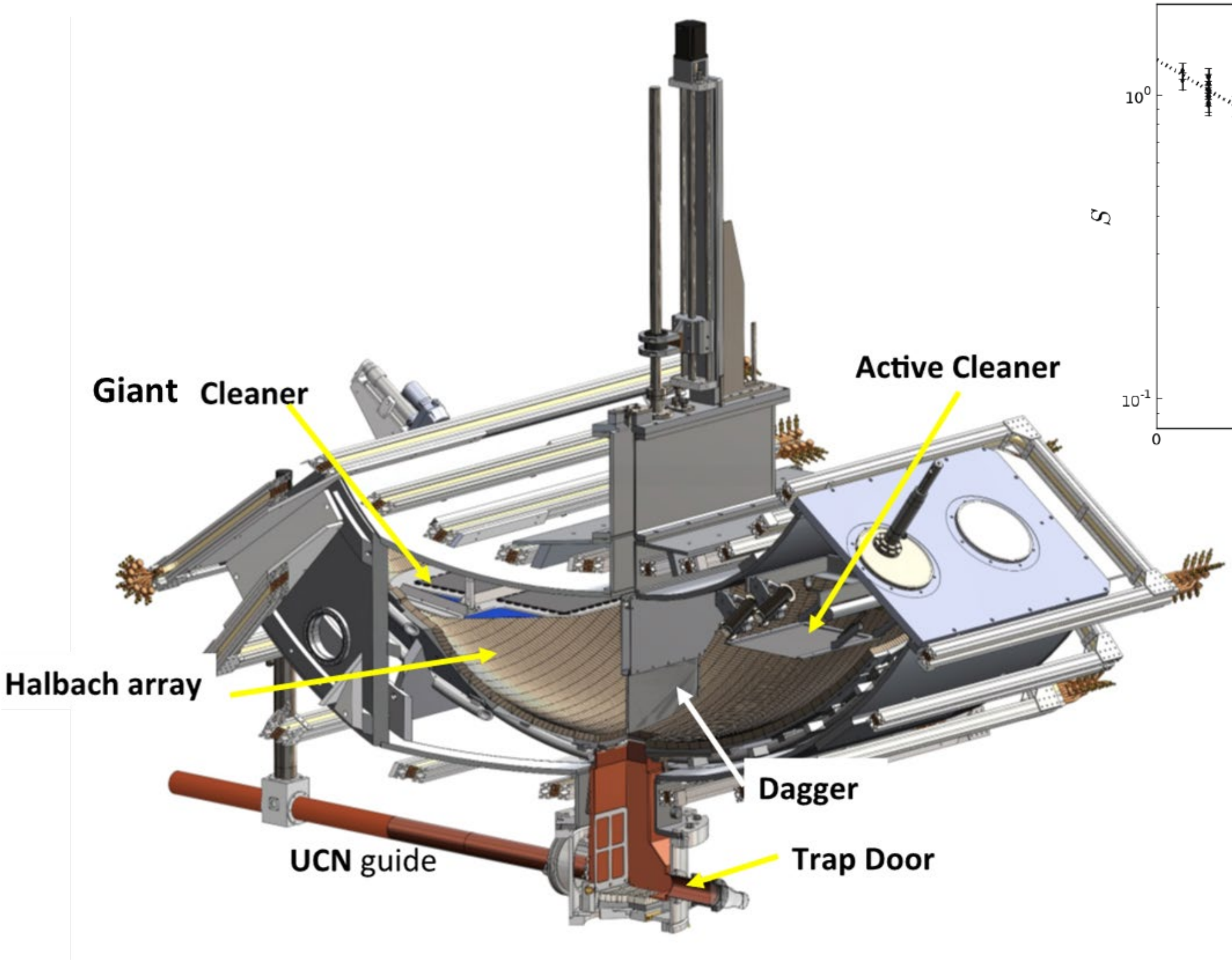
9:20 AM · Nov 2, 2021 · Twitter Web App

Los Alamos Neutron Science Center (LANSCE)

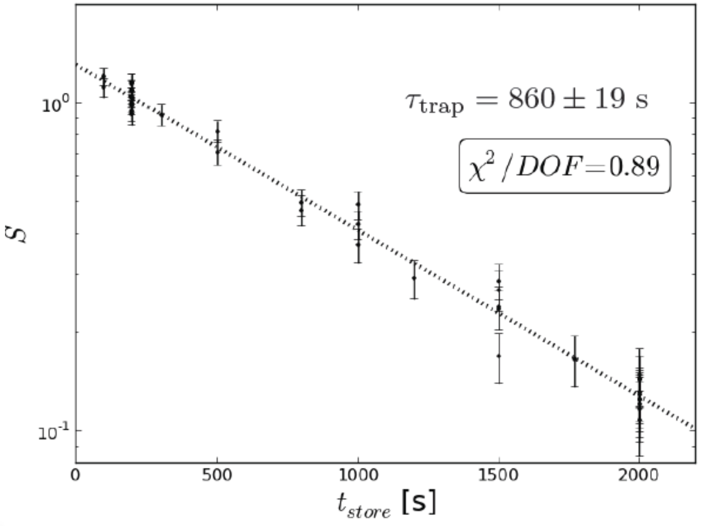
UCN Experimental Area (2021)



The UCNτ Apparatus

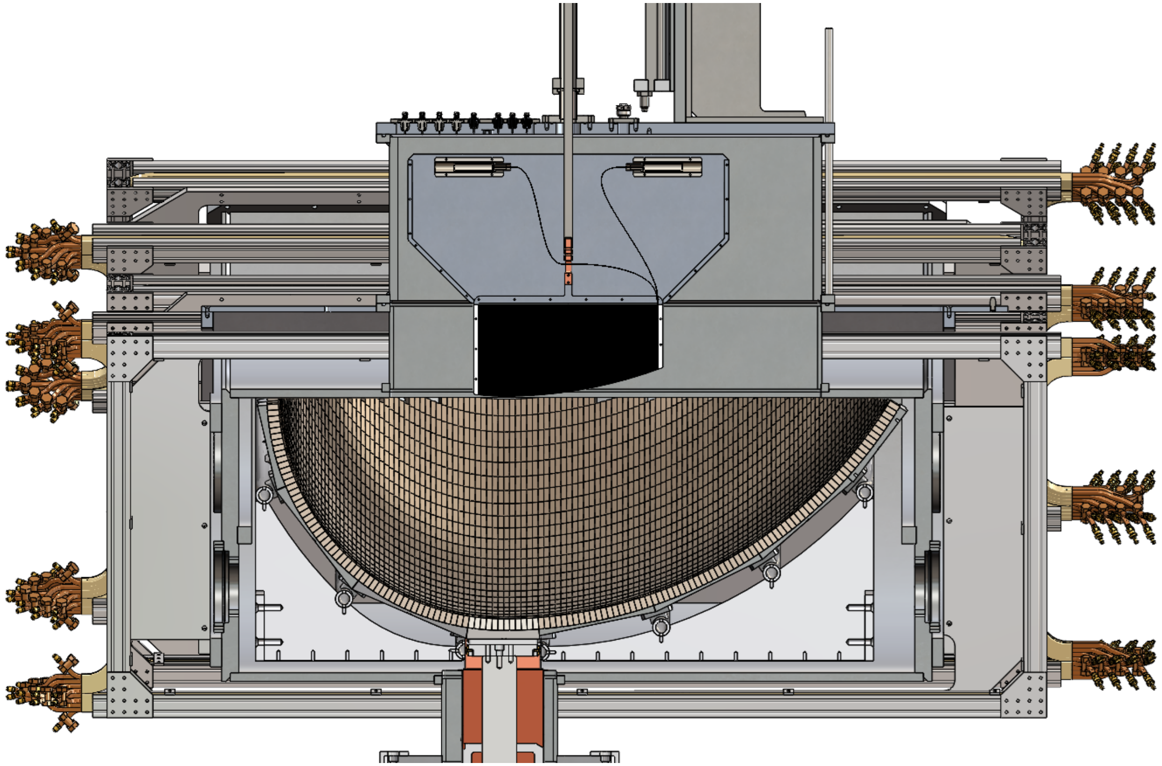


First Physics Data: 2013

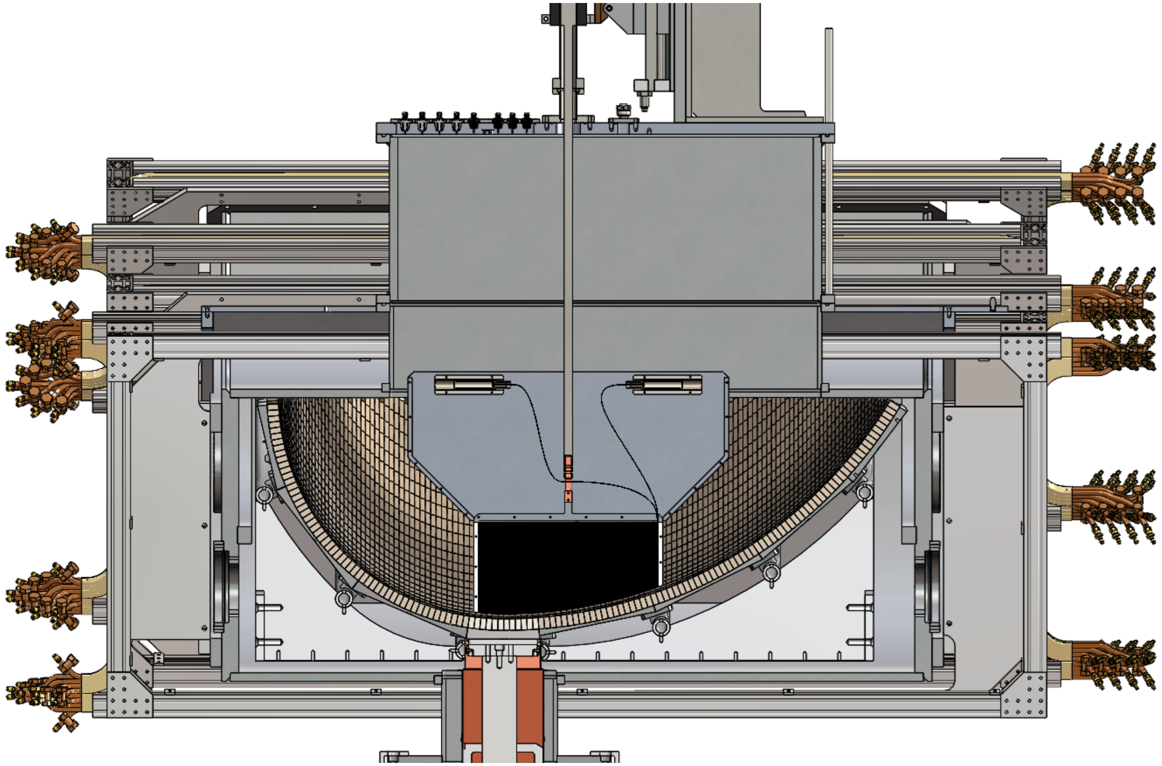


D. Salvat, PRC 89, 052501 (2014)

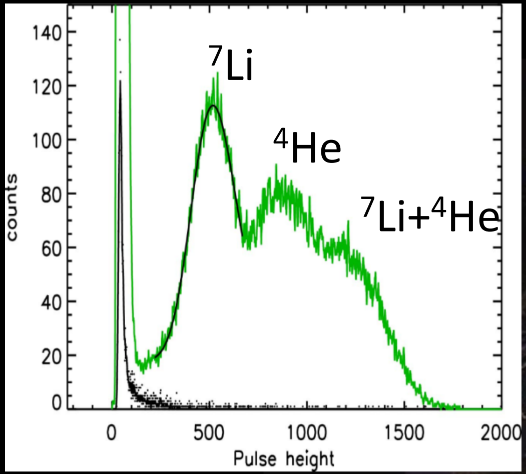
We also implemented a new way to count the trapped neutrons:



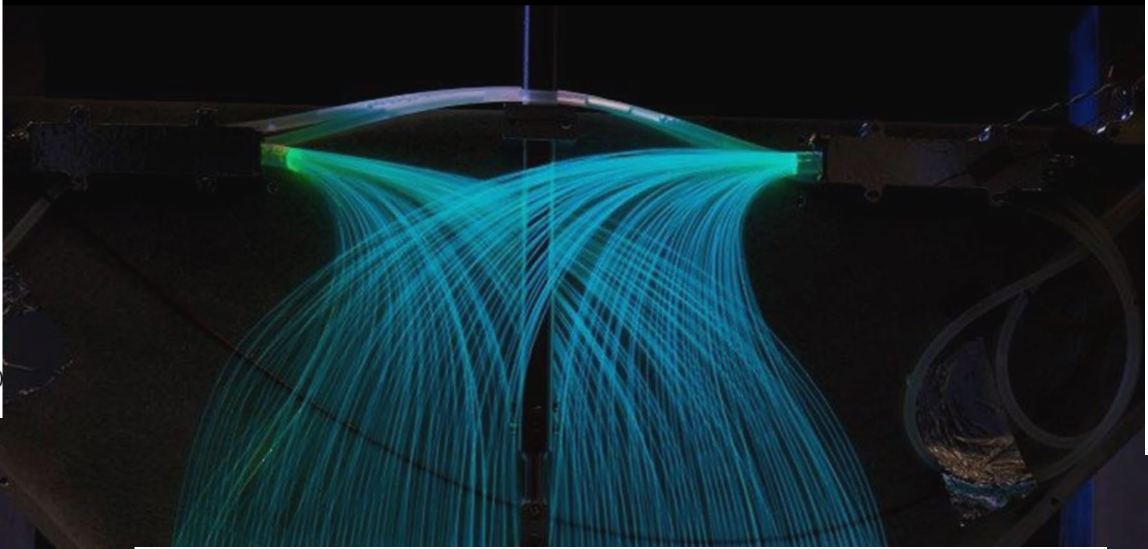
In-situ UCN detection using a “dagger” detector: detection time ~ 8 s

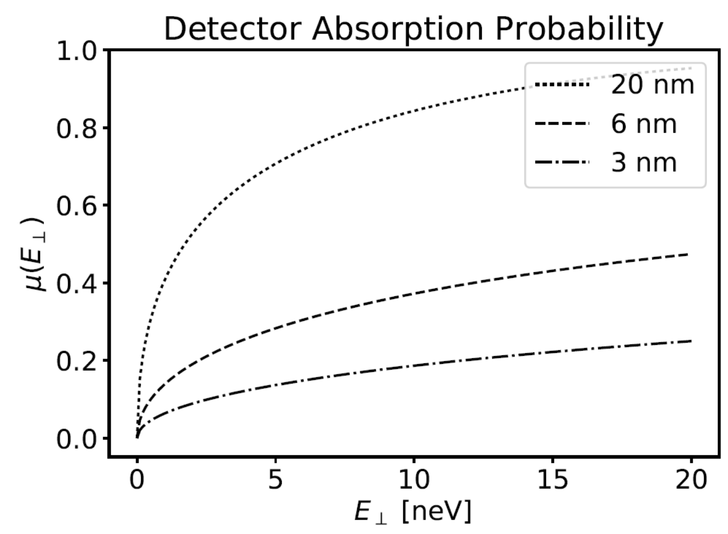


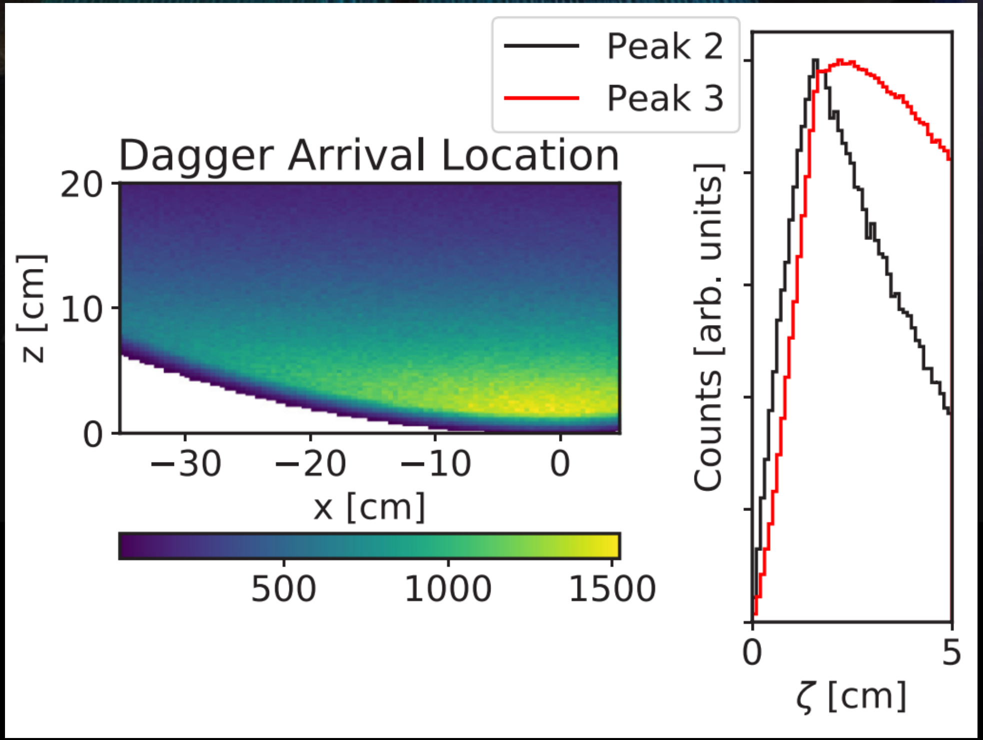
Z. Wang *et al.*, NIMA **798**, 30 (2015).



$n + {}^{10}\mathrm{B} \rightarrow {}^{7}\mathrm{Li} + \alpha$





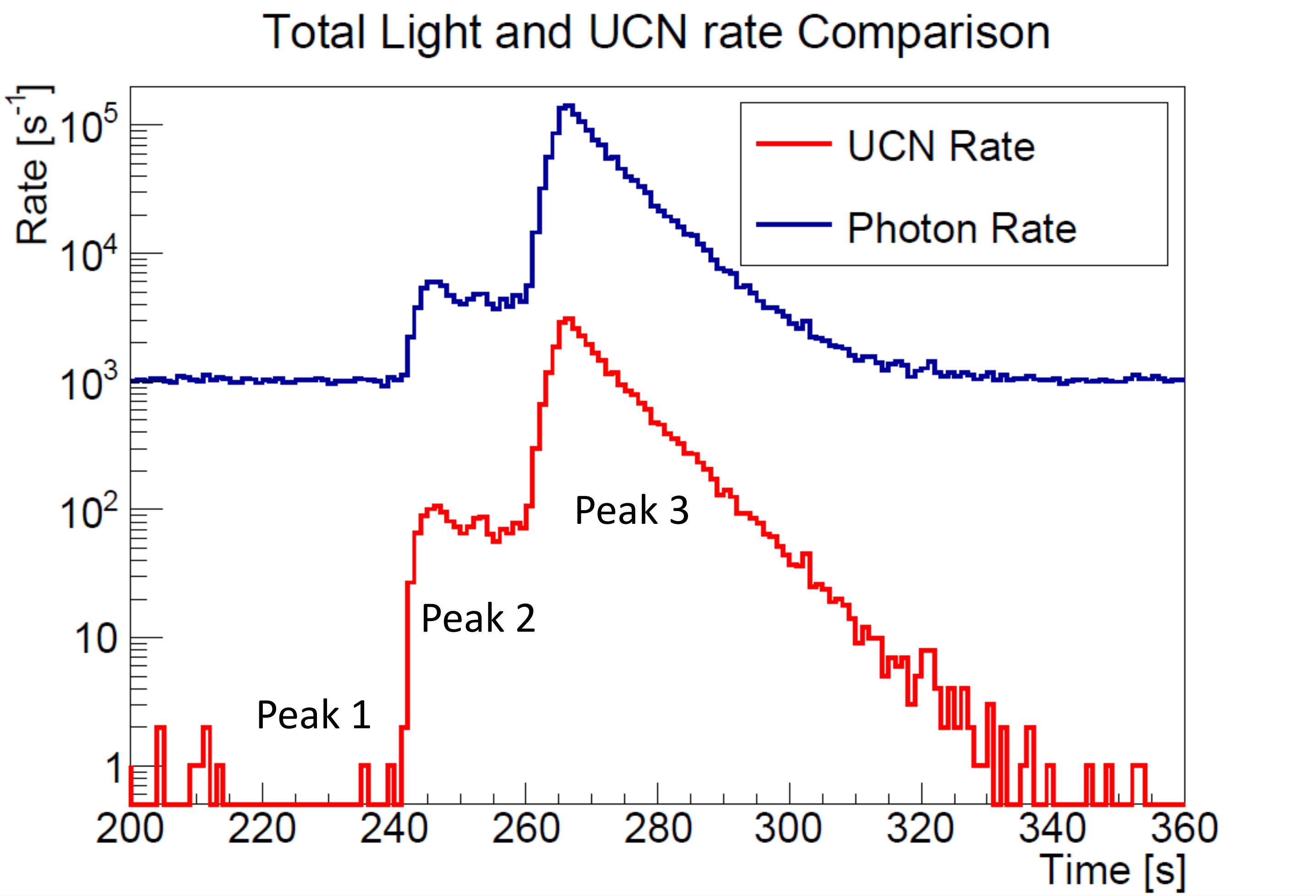


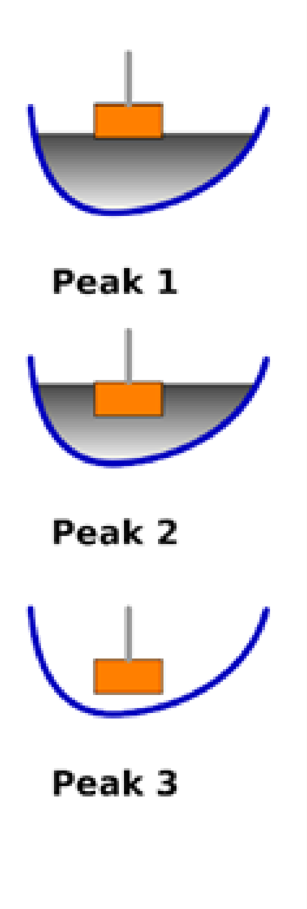
The response function (single collision) of the in-situ detector is highly non-uniform.

It takes ~ 5 collisions before a UCN is detected.

Singles vs Coincidence

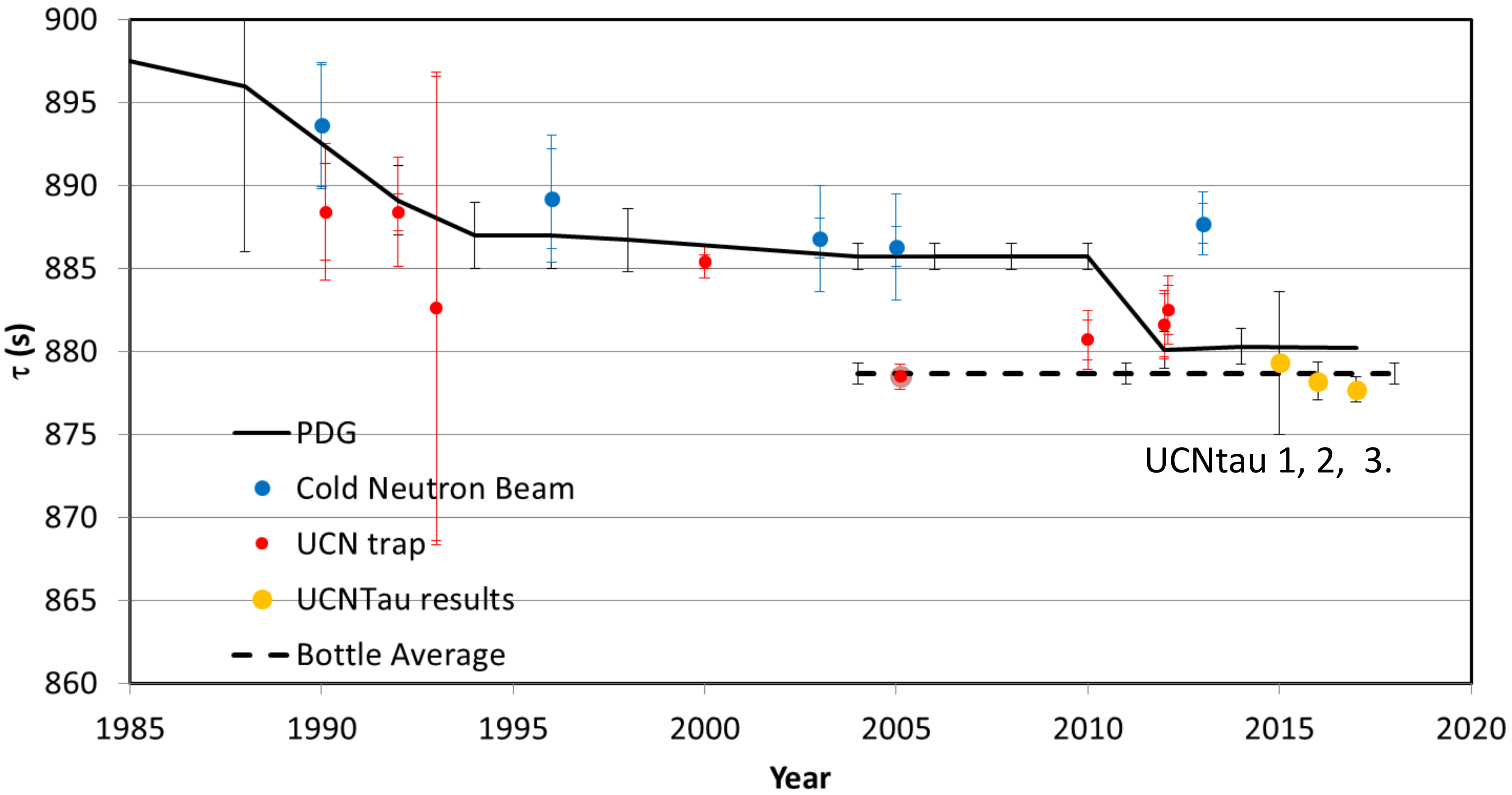
- Singles - High Background (100-400 s correction)
- Coincidence - Pileup/Deadtime (as high as 3 s)





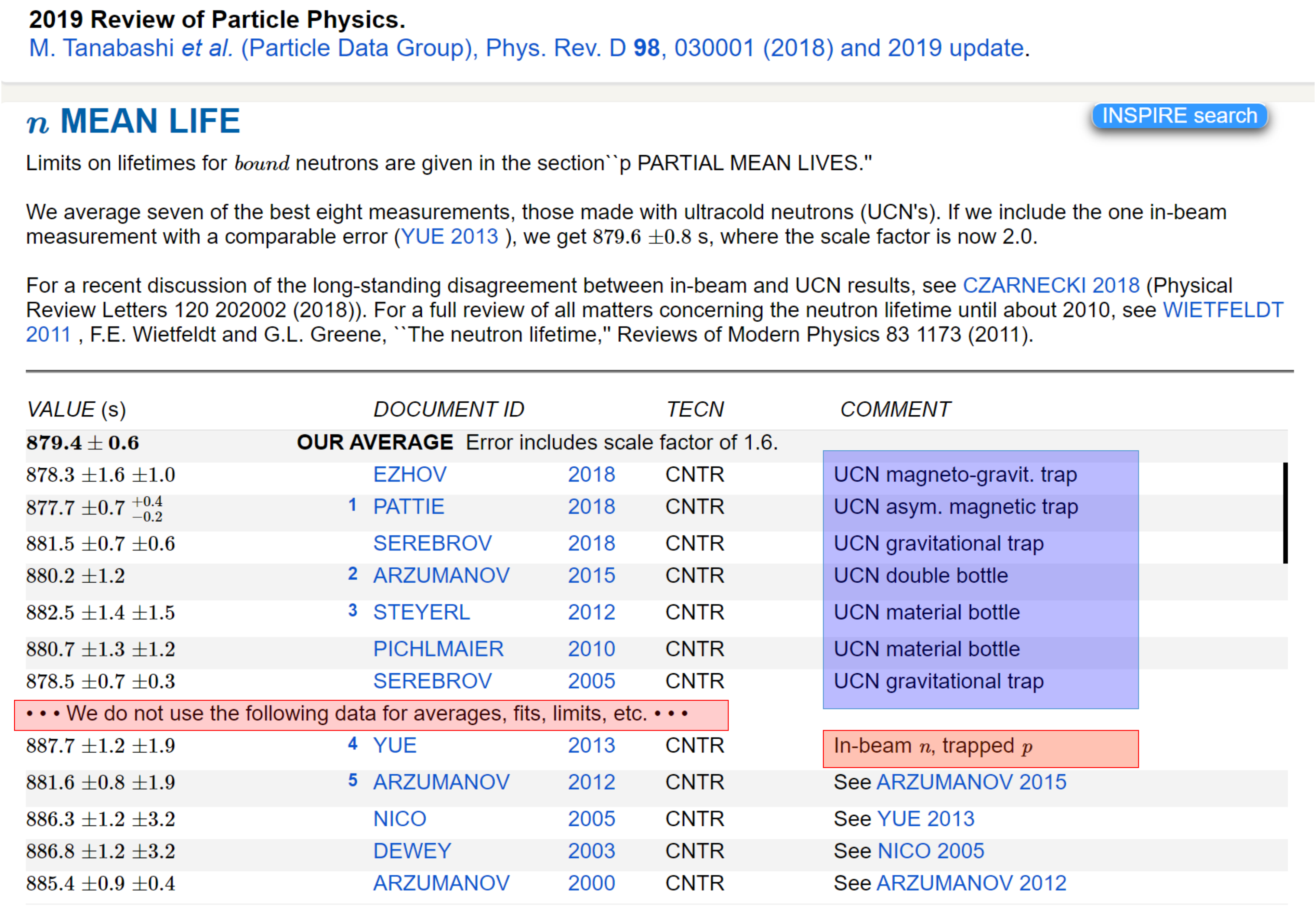
UCNtau results (2018)

1. 2015 commission data (RSI)
2. 2015-2016 data
3. 2016-2017 data (Science, 2018)



With UCNtau, we have made a measurement of τ_n for the first time with **no extrapolation**: 877.7 ± 0.7 (stat) +0.3/-0.1 (sys) s.

This gives confidence in previous bottle lifetime experiments



2019 Review of Particle Physics.
M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

INSPIRE search

n MEAN LIFE

Limits on lifetimes for *bound* neutrons are given in the section``p PARTIAL MEAN LIVES."

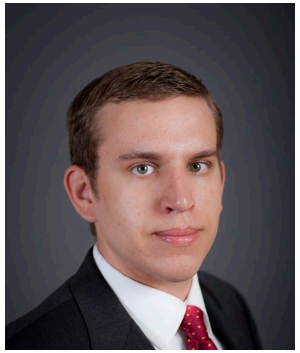
We average seven of the best eight measurements, those made with ultracold neutrons (UCN's). If we include the one in-beam measurement with a comparable error (YUE 2013), we get 879.6 ± 0.8 s, where the scale factor is now 2.0.

For a recent discussion of the long-standing disagreement between in-beam and UCN results, see CZARNECKI 2018 (Physical Review Letters 120 202002 (2018)). For a full review of all matters concerning the neutron lifetime until about 2010, see WIETFELDT 2011 , F.E. Wietfeldt and G.L. Greene, ``The neutron lifetime," Reviews of Modern Physics 83 1173 (2011).

VALUE (s)	*DOCUMENT ID*		*TECN*	*COMMENT*
$\mathbf{879.4 \pm 0.6}$	**OUR AVERAGE** Error includes scale factor of 1.6.			
$878.3 \pm 1.6 \pm 1.0$	EZHOV	2018	CNTR	UCN magneto-gravit. trap
$877.7 \pm 0.7\ ^{+0.4}_{-0.2}$	[1] PATTIE	2018	CNTR	UCN asym. magnetic trap
$881.5 \pm 0.7 \pm 0.6$	SEREBROV	2018	CNTR	UCN gravitational trap
880.2 ± 1.2	[2] ARZUMANOV	2015	CNTR	UCN double bottle
$882.5 \pm 1.4 \pm 1.5$	[3] STEYERL	2012	CNTR	UCN material bottle
$880.7 \pm 1.3 \pm 1.2$	PICHLMAIER	2010	CNTR	UCN material bottle
$878.5 \pm 0.7 \pm 0.3$	SEREBROV	2005	CNTR	UCN gravitational trap
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$887.7 \pm 1.2 \pm 1.9$	[4] YUE	2013	CNTR	In-beam n, trapped p
$881.6 \pm 0.8 \pm 1.9$	[5] ARZUMANOV	2012	CNTR	See ARZUMANOV 2015
$886.3 \pm 1.2 \pm 3.2$	NICO	2005	CNTR	See YUE 2013
$886.8 \pm 1.2 \pm 3.2$	DEWEY	2003	CNTR	See NICO 2005
$885.4 \pm 0.9 \pm 0.4$	ARZUMANOV	2000	CNTR	See ARZUMANOV 2012

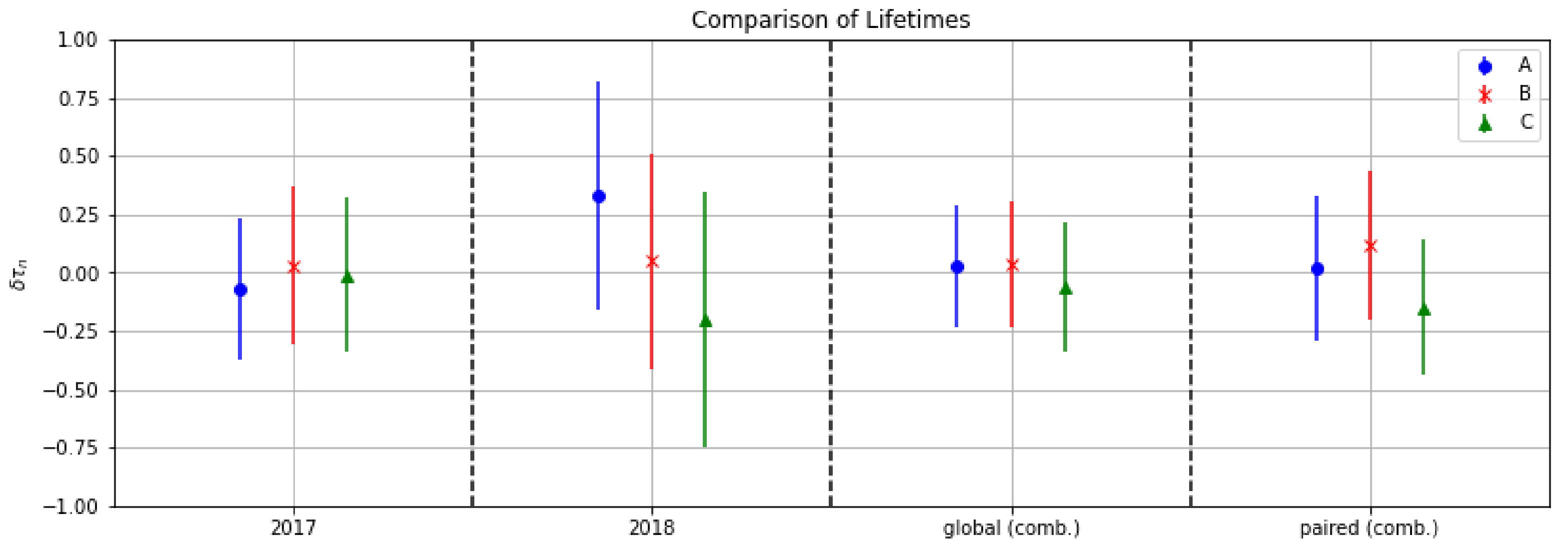
New data 2017-2018 data sets, 3 Independent Analyses


Frank Gonzalez (Indiana)


Eric Fries (Caltech)


Chris Morris (LANL)

- Blinded data:
  - Holding time is modified
  - Measured lifetime blinded by up to ±15 s
- Unblinding Criteria:
  - Three complete (statistical and systematic) analyses
  - After cross-checking analyses, lifetimes combined via unweighted average, using largest uncertainties

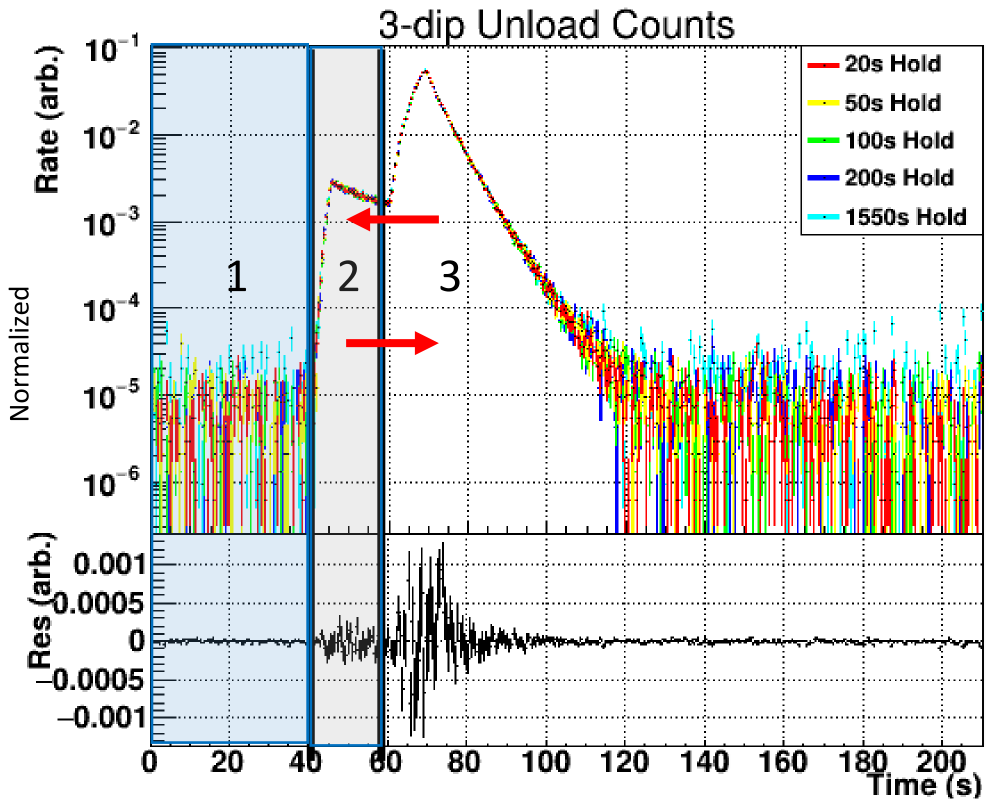


New Result: $\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}$ s

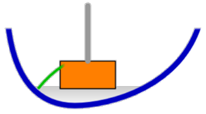
Effect	Previous Reported Value (s)	New Reported Value (s)	Notes
τ_{meas}	877.5 ± 0.7	877.58 ± 0.28	Uncorrected Value!
UCN Event Definition	0 ± 0.04	0 ± 0.13	Single photon analysis vs. Coincidence analysis
Normalization Weighting	--	0 ± 0.06	Previously unable to estimate
Depolarization	$0 + 0.07$	$0 + 0.07$	
Uncleaned UCN	$0 + 0.07$	$0 + 0.11$	
Heated UCN	$0 + 0.24$	$0 + 0.08$	
Phase Space Evolution	0 ± 0.10	--	Now included in stat. uncertainty
Al Block	--	0.06 ± 0.05	Accidentally dropped into trap…
Residual Gas Scattering	0.16 ± 0.03	0.11 ± 0.06	
Sys. Total	$\mathbf{0.16^{+0.4}_{-0.2}}$	$\mathbf{0.17^{+0.22}_{-0.16}}$	
TOTAL	$\mathbf{877.7 \pm 0.7^{+0.4}_{-0.2}}$	$\mathbf{877.75 \pm 0.28^{+0.22}_{-0.16}}$	

F. M. Gonzalez et al. Phys. Rev. Lett. 127 162501 (October 13, 2021)

Quantify the systematic effects using the 3-Step unload scheme



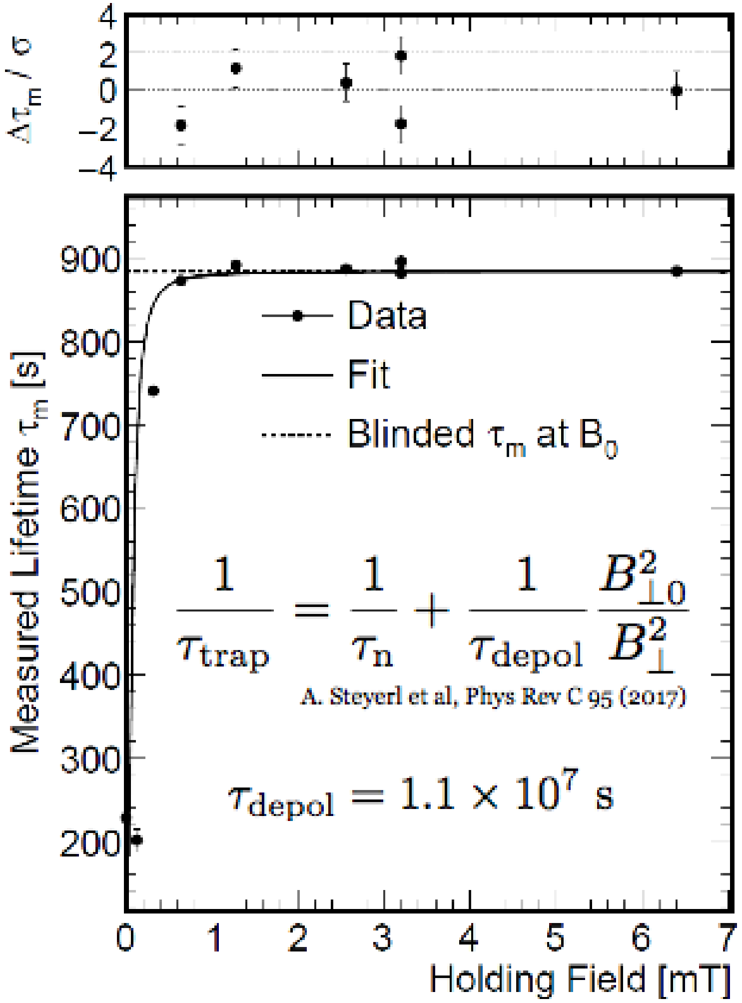
- Overthreshold UCN above cleaning height
  - “Heated” UCN (at long times): $\Delta\tau_{heat} = 0 + 0.08$ s
  - “Uncleaned” UCN (at short times): $\Delta\tau_{unc} = 0 + 0.11$ s
- Overthreshold neutrons $< 2 \times 10^{-5}$!
- Require constant detection efficiency
  - Phase space evolution couples to counting time
  - Use mean arrival time during unload
  - $\Delta\tau_{PSE} = 0.02 \pm 0.01$ s



4) Detect

$$\tau_n^{-1} = \tau_{meas}^{-1} - \tau_{loss}^{-1}$$

UCN Depolarization



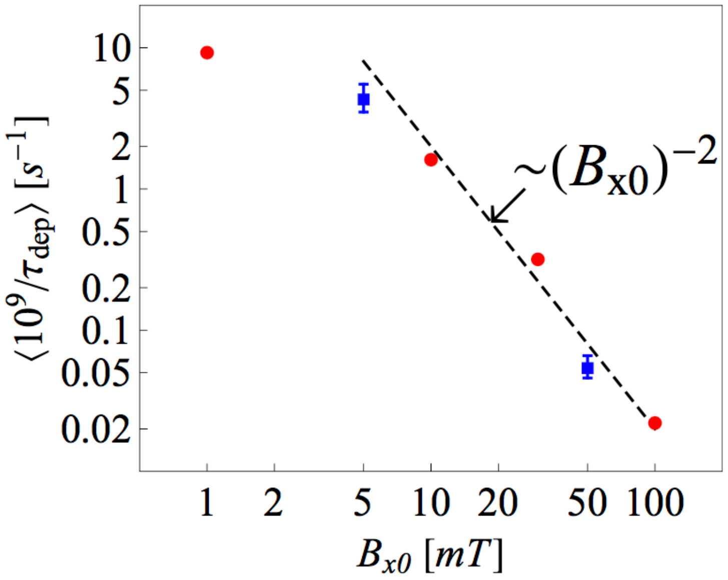
$$\frac{1}{\tau_{\rm trap}} = \frac{1}{\tau_{\rm n}} + \frac{1}{\tau_{\rm depol}} \frac{B_{\perp 0}^2}{B_\perp^2}$$

A. Steyerl et al, Phys Rev C 95 (2017)

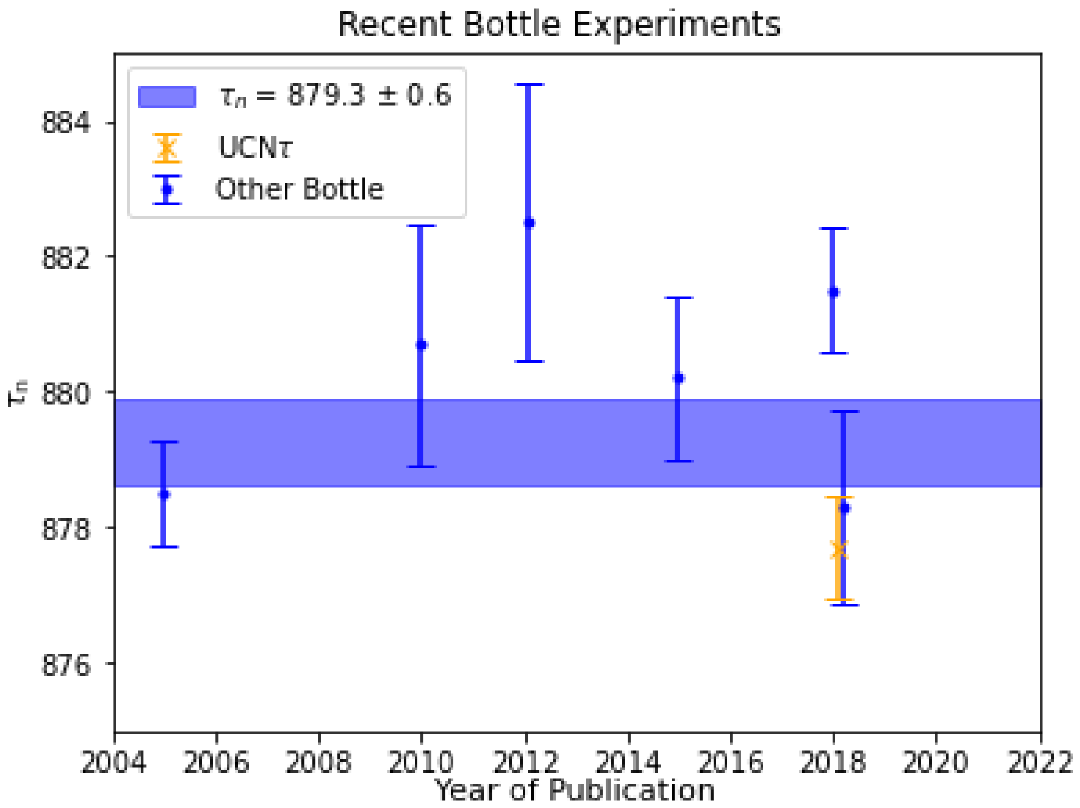
$$\tau_{\rm depol} = 1.1 \times 10^7 \text{ s}$$

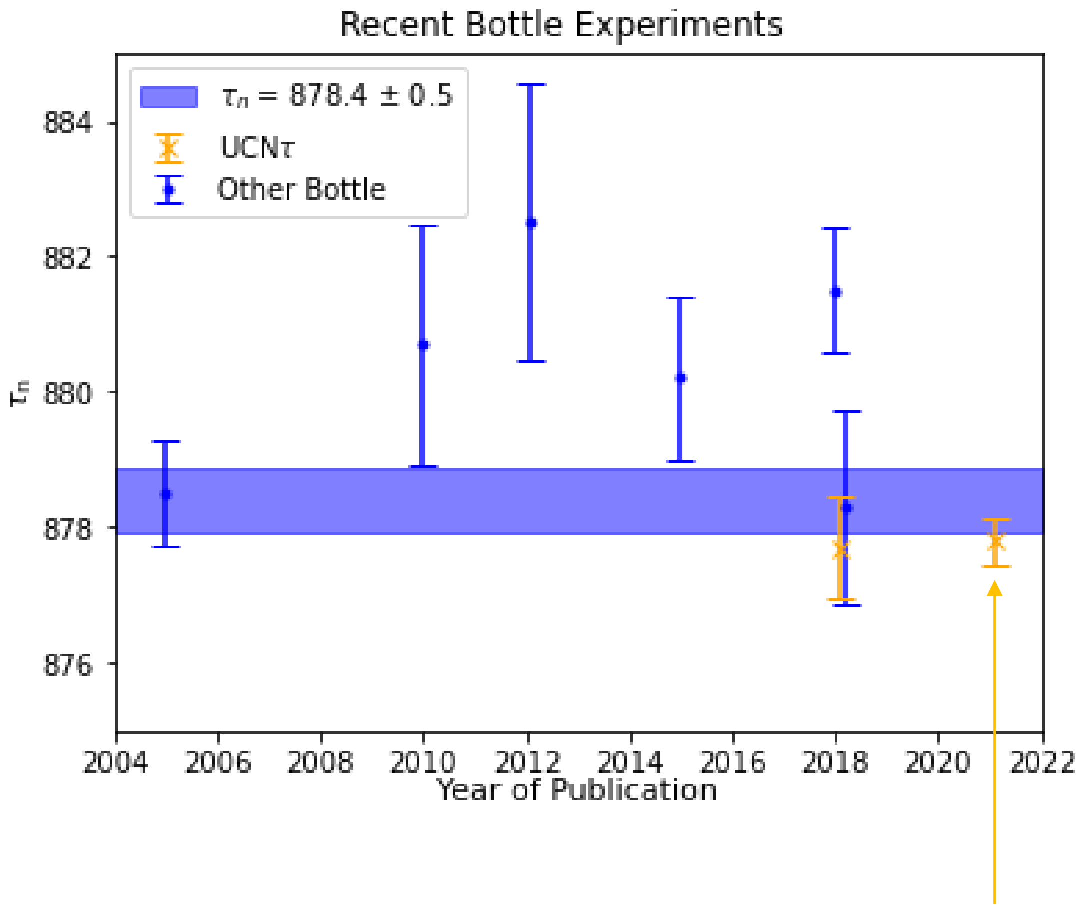
Three things to check:

1. Scaling behavior at low holding field.
2. Ideal vs. actual magnetic field.
3. Where to assess spin flip probability.



A new lifetime result (2021):





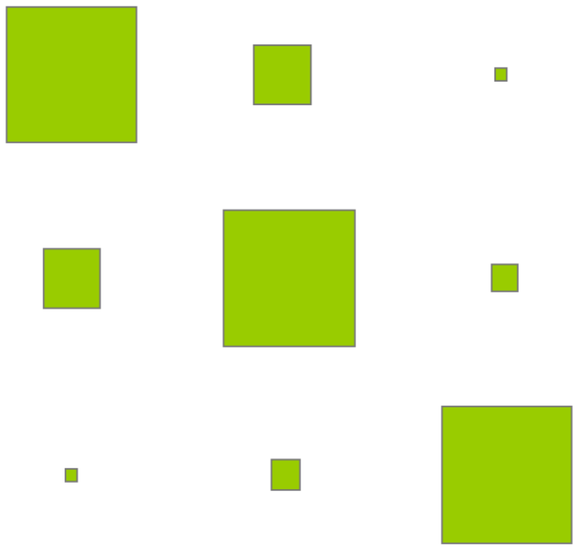
$$\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}\ \text{s}$$

The CKM matrix quantifies the quark flavor mixing.

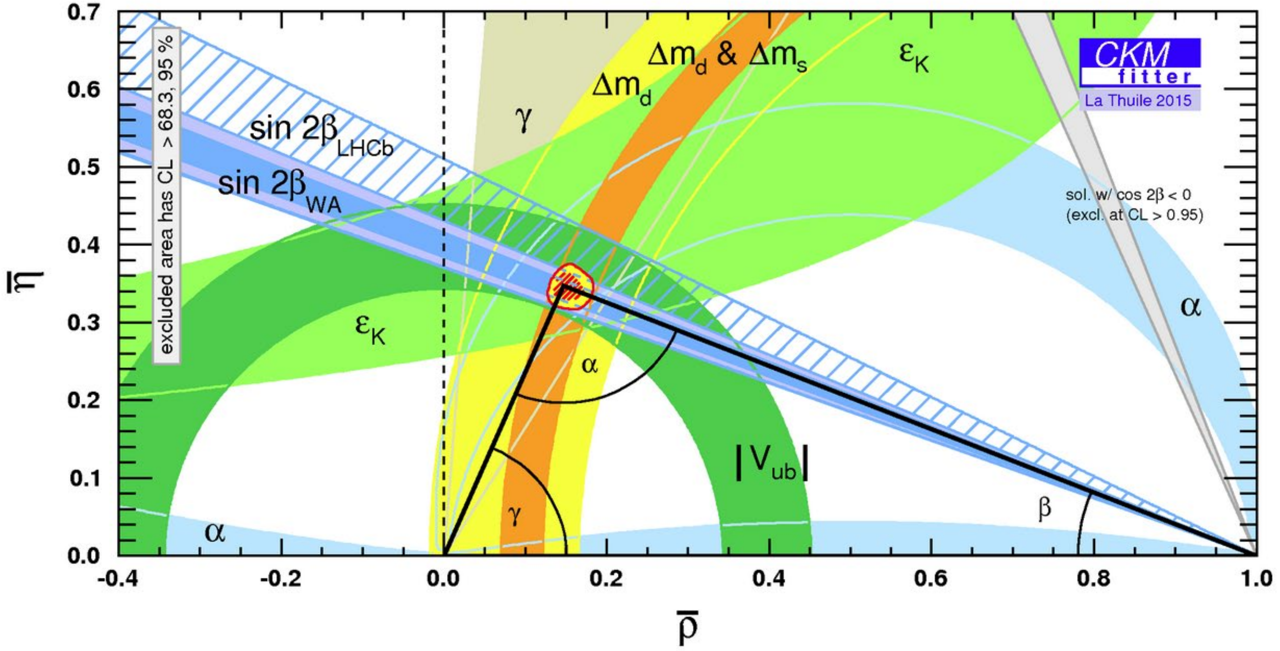
$$\begin{pmatrix} d \\ s \\ b \end{pmatrix}_f = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_m$$

Wolfenstein parameterization – expansion in λ = sin θ_C ~0.22

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$



V_{us}=λ=sin Θ_c



Area of the triangle → CP-violating phase

Precision Test on the CKM Unitarity

First Row: $|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1 + \Delta_{BSM}$

$V_{ub} \ll V_{ud}$ and V_{us}, so negligible contribution

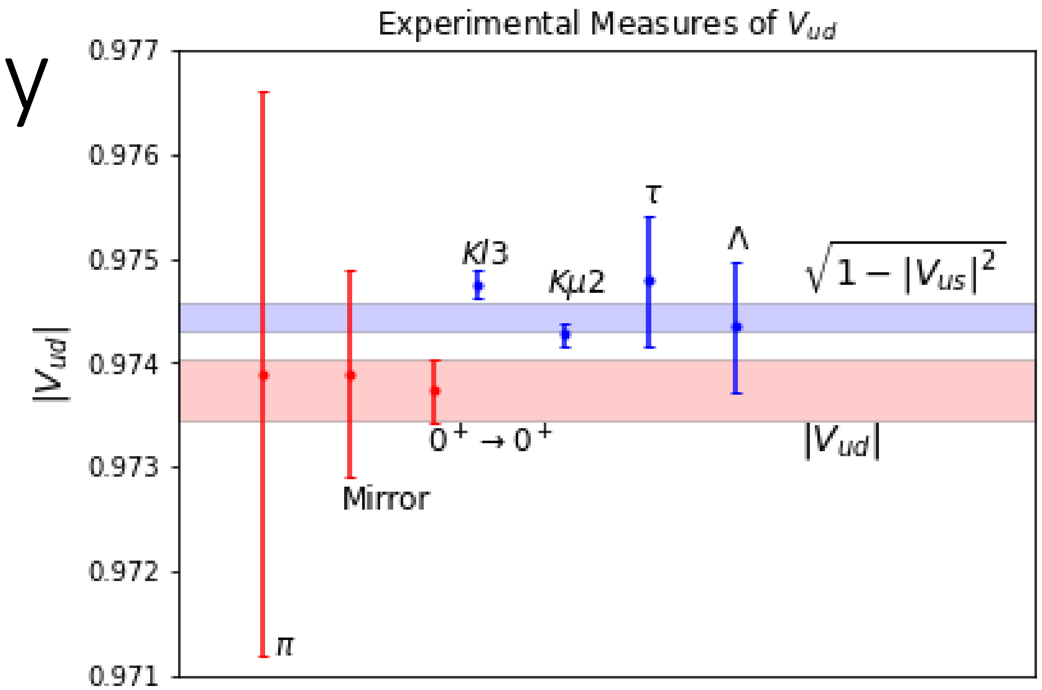
Measurements of V_{ud}:

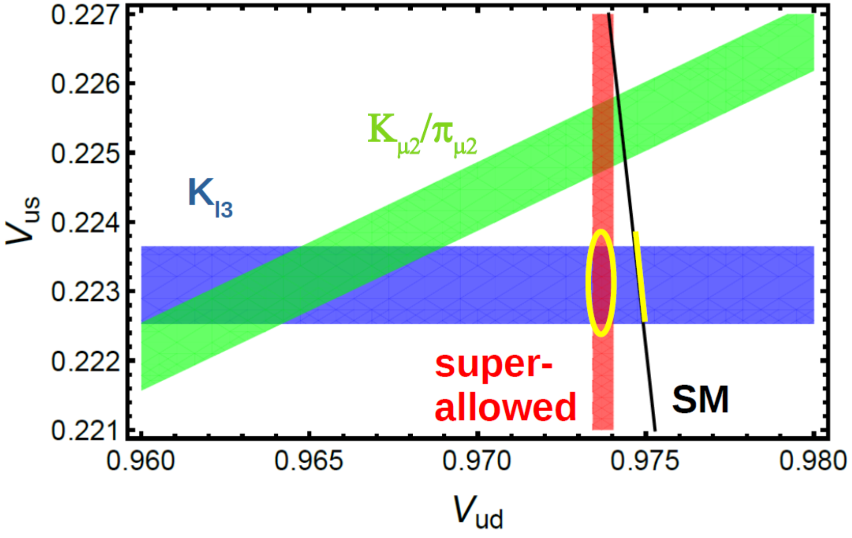
- Most precise “Superallowed” $0^+ \rightarrow 0^+$ decays
- Mirror nuclei and Pions less precise
- Large theoretical uncertainties from radiative corrections and nuclear structure

Measurements of V_{us}:

- Most precise from Kaon decays
- Cabibbo angle anomaly (V_{us}=λ=sin Θ_c) between different decay channels
- Also limits from τ and Λ hyperons

Most precise measurements disagree (up to 3σ)!





“Cabibbo Angle Anomaly (CAA)” ~ 3σ

Discovery potential of the beta decay anomalies

A concrete example: First-row CKM unitarity with $|V_{ud}|$ from 0^+ beta decay and $|V_{us}|$ from K_{l3} decay

$$\boxed{|V_{ud}|^2_{0^+} + |V_{us}|^2_{K_{\ell 3}} + \cancel{|V_{ub}|}^2 - 1 = -0.0021(7)}$$

SOURCES OF UNCERTAINTY:

$\delta|V_{ud}|^2_{0^+}$, **RC:**

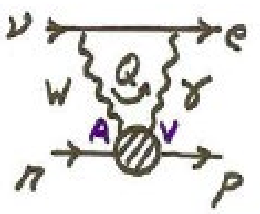
Theory uncertainties in the single-nucleon radiative corrections (RC)

$\lvert V_{ud}\rvert^2_{0^+} + \lvert V_{us}\rvert^2_{K_{\ell 3}} - 1$	-2.1×10^{-3}
$\delta\lvert V_{ud}\rvert^2_{0^+}$, **exp**	2.1×10^{-4}
$\delta\lvert V_{ud}\rvert^2_{0^+}$, **RC**	1.8×10^{-4}
$\delta\lvert V_{ud}\rvert^2_{0^+}$, **NS**	5.3×10^{-4}
$\delta\lvert V_{us}\rvert^2_{K_{\ell 3}}$, **exp+th**	1.8×10^{-4}
$\delta\lvert V_{us}\rvert^2_{K_{\ell 3}}$, **lat**	1.7×10^{-4}
Total uncertainty	6.5×10^{-4}
Significance level	3.2σ

Chien-Yeah Seng's talk DNP 2021

CYS, Galviz, Marciano and Meißner, 2107.14708

Extracting V_{ud} with neutron decays



f: Phase space factor=1.6886
(Fermi function, nuclear mass, size,
recoil)

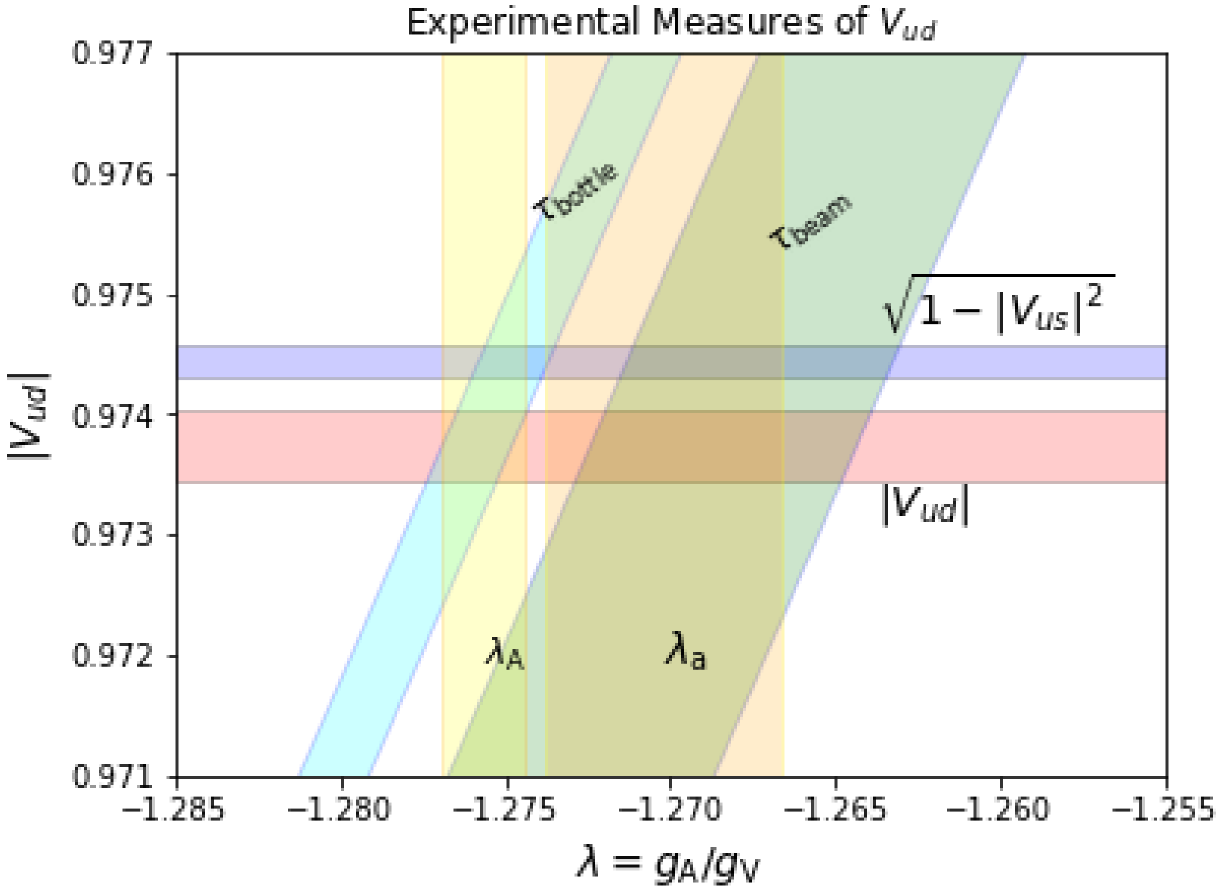
$$1/\tau_n = f G_F^2 |V_{ud}|^2 m_e^5 (1+3g_A^2)(\underline{1+RC})/2\pi^3$$

From μ-decay: 0.6 ppm (MuLan 2011)

$$|V_{ud}|^2 = \frac{4905.7 \pm 1.7\ s}{\tau_n (g_V + 3g_A^2)}$$

Marciano & Sirlin, PRL 96, 032002 (2006)
Seng et al, PRL 121 (2018); Seng et al, PRD 100 (2019);
Czarnecki, Marciano & Sirlin, PRD 100 (2019)

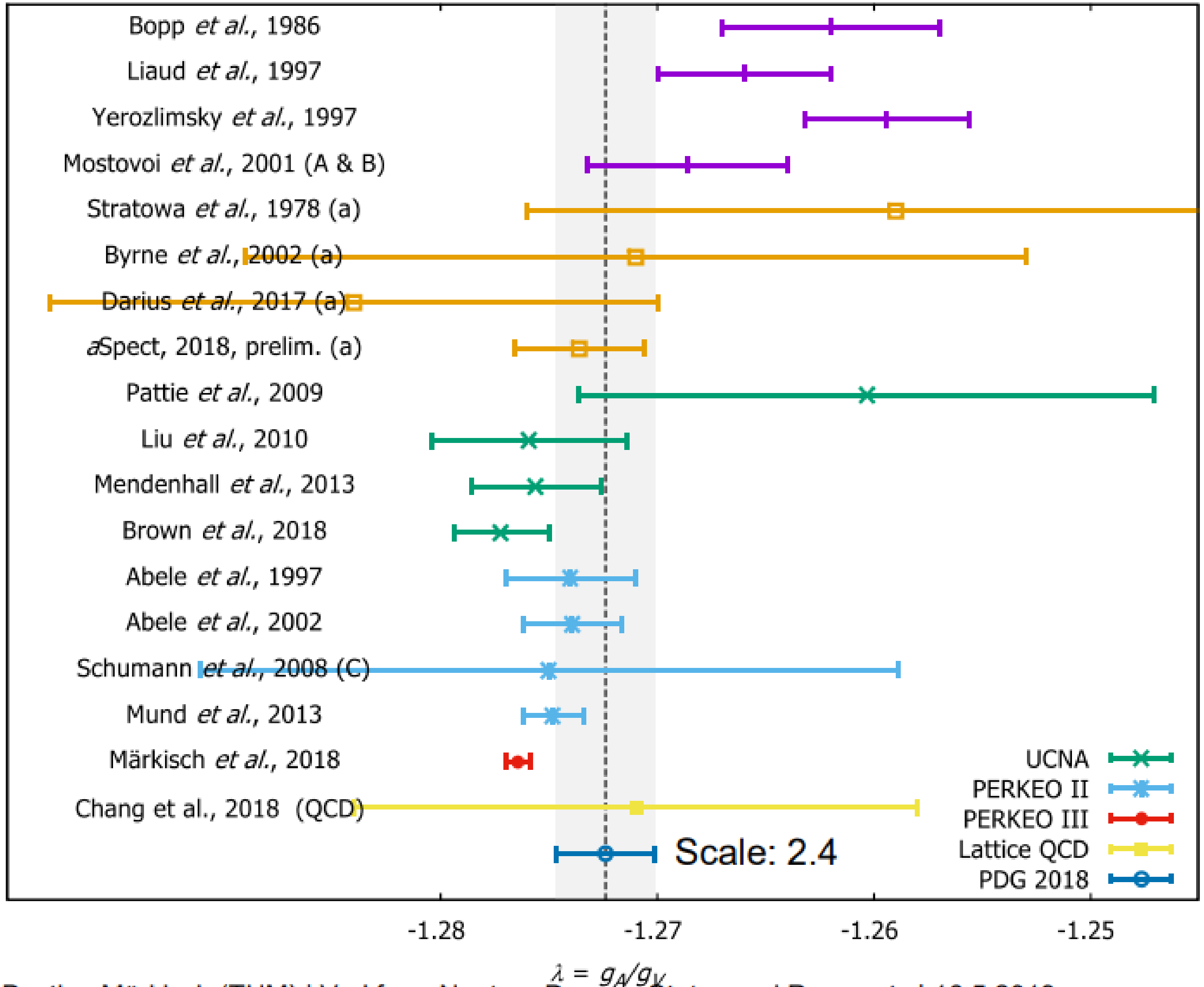
To match the theoretical uncertainty: 3.5×10^{-4}, it requires experimental uncertainties of: $\Delta A/A = 4\Delta\lambda/\lambda < 2 \times 10^{-3}$ and $\Delta\tau/\tau = 3.5 \times 10^{-4}$.



To be consistent with CKM unitarity, it requires a smaller $|g_A|$, or a shorter τ_n.

Axial Coupling: Status

Results from beta asymmetry A, unless where noted otherwise



PERKEO I

electron-neutrino correlation *a*

UCNA

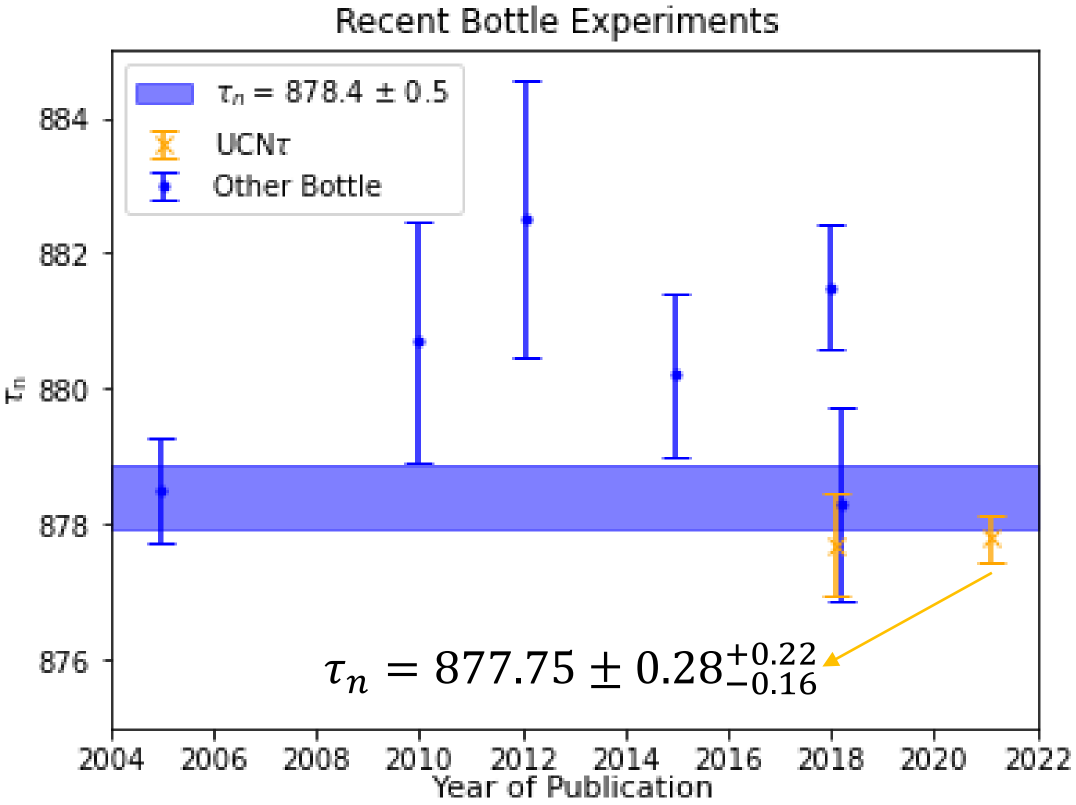
(newer results mostly include older data)

PERKEO II

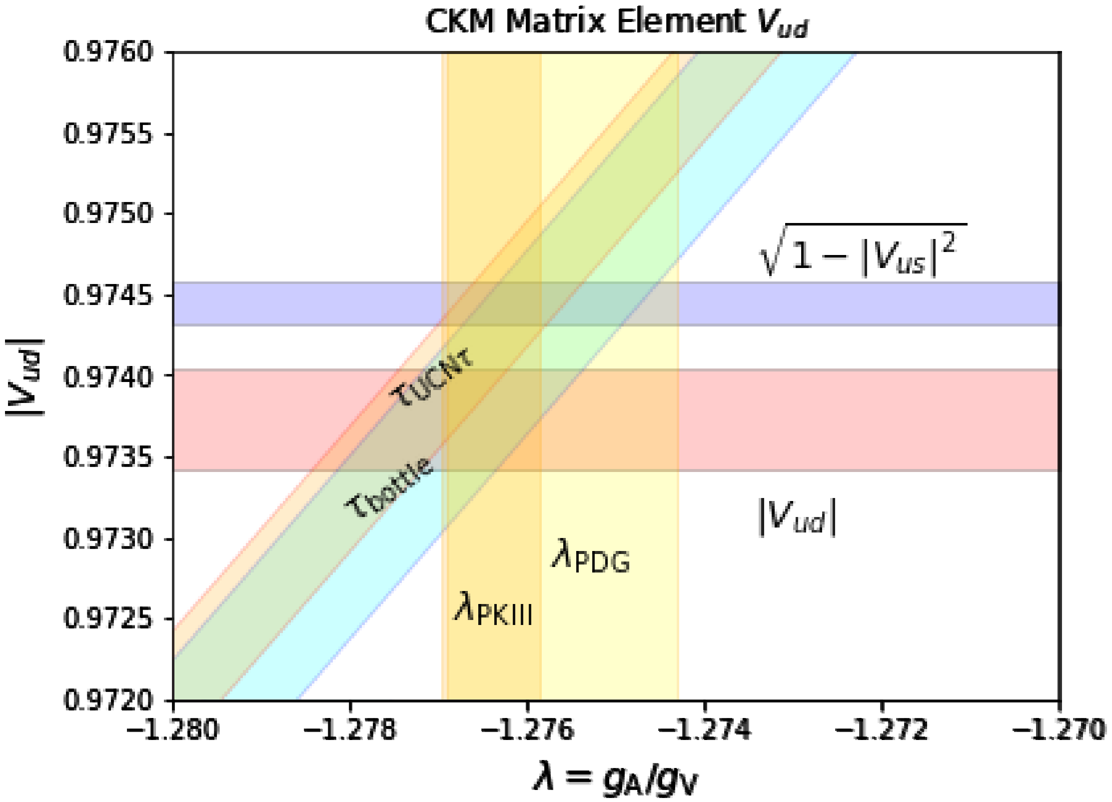
(newer A results include older data)

PERKEO III

With new UCNtau lifetime result (+ Perkeo III), the extracted V_{ud} agrees with the CKM unitarity.



$\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}$



We report a measurement of τ_n with 0.34 s (0.039%) uncertainty, improving upon our past results by a factor of 2.25 using two blinded datasets from 2017 and 2018. The new result incorporates improved experimental and analysis techniques over our previous result [Science **360**, 627 (2018)].

This is the first neutron lifetime measurement precise enough to confront SM theoretical uncertainties.

Summary

Low-energy neutrons are useful in testing the Standard Model of particle physics. Storage of UCN allows for the long observation times needed for precision measurement of many neutron observables. High-precision measurements, confronted with theoretical predictions, probe high-energy physics.

Precision measurements on the neutron lifetime (δt< 0.1s), combined with the beta-decay asymmetry (δA/A< 0.1%), test the unitarity of the CKM matrix (to 1e-4 level of precision) and probe physics beyond the Standard Model. With UCNτ, all systematic uncertainties have been quantified by measurements.

- $\tau_n = 877.7 \;\pm 0.7\; {}^{+0.3}_{-0.1}$ s (Science 2018)
- $\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}$ s (PRL 2021)

To be consistent with CKM unitarity, it requires a smaller $|g_A|$*, or a shorter* τ_n .

Discrepancy with CKM unitarity is an opportunity for new physics.

Moving forward:

- UCNτ + (immediate future): elevator loading, reaching δt=0.1 s
- UCNτ 2 (future): superconducting coils (conceptual design), reaching δt=0.01 s

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