

Measurement of Free Neutron Decay: Status and Prospects

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8/31/2022

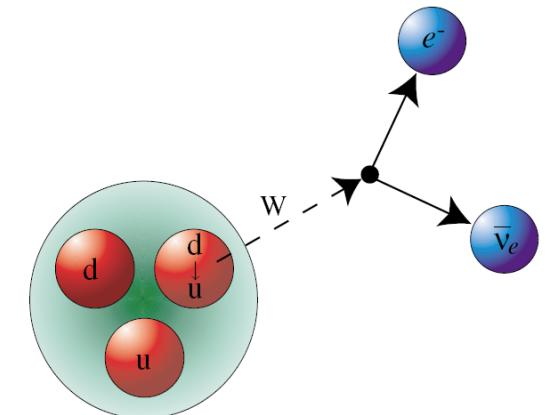
8th International Symposium on Symmetries
in Subatomic Physics, SSP2022, Vienna



Theory of Nuclear Beta-decay

- W. Pauli summarized the decay process into 5 possible Lorentz-invariant (CPT-preserving) forms:

$$(\bar{\phi}_p \hat{O}_i \phi_n)(\bar{\phi}_e \hat{O}_i \phi_\nu)$$



$$n \rightarrow p^+ + e^- + \bar{\nu}_e + 782 \text{ keV}$$

Table 1.2. Elementary fermion transition operators

\hat{O}_i	Transformation property of $\bar{\Psi} \hat{O}_i \Psi$	Number of matrices
1	Scalar (S)	1
γ^μ	Vector (V)	4
$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$	Tensor (T)	6
$\gamma^\mu \gamma_5$	Axial vector (A)	4
$\gamma_5 = -i\gamma_0\gamma_1\gamma_2\gamma_3$ $= i\gamma^0\gamma^1\gamma^2\gamma^3$	Pseudoscalar (P)	1

For non-relativistic fermions in nuclear beta decay

$$\phi_p^\dagger \phi_n$$

Fermi (spin-preserving)

$$\phi_p^\dagger \sigma \phi_n$$

Gamow-Teller
(spin-changing, $\Delta l = \pm 1, 0$)

$$0$$

Spectral measurements (pre-1950)

$$\begin{aligned} H_{\text{int}} = & (\bar{\psi}_p \psi_n) (C_S \bar{\psi}_e \psi_\nu + C_{S'} \bar{\psi}_e \gamma_5 \psi_\nu) \\ & + (\bar{\psi}_p \gamma_\mu \psi_n) (C_V \bar{\psi}_e \gamma_\mu \psi_\nu + C_{V'} \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu) \\ & + \frac{1}{2} (\bar{\psi}_p \sigma_{\lambda\mu} \psi_n) (C_T \bar{\psi}_e \sigma_{\lambda\mu} \psi_\nu + C_{T'} \bar{\psi}_e \sigma_{\lambda\mu} \gamma_5 \psi_\nu) \\ & - (\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n) (C_A \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu + C_{A'} \bar{\psi}_e \gamma_\mu \psi_\nu) \\ & + (\bar{\psi}_p \gamma_5 \psi_n) (C_P \bar{\psi}_e \gamma_5 \psi_\nu + C_{P'} \bar{\psi}_e \psi_\nu) \\ & + \text{Hermitian conjugate,} \end{aligned}$$

5x 2(helicities) x 2 (complex) = 20 coupling constants

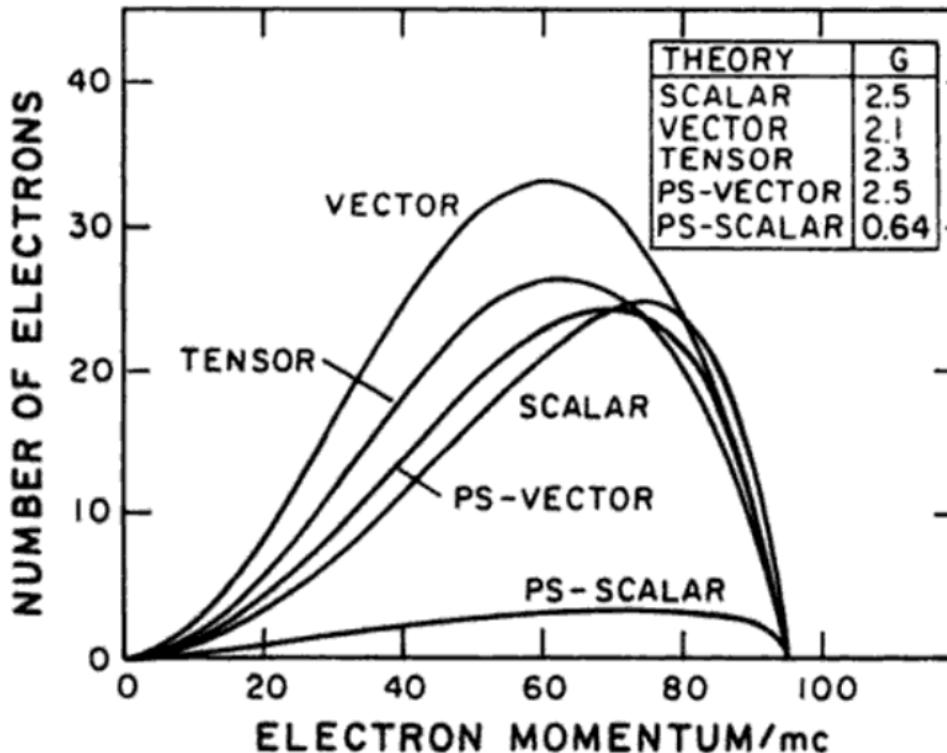
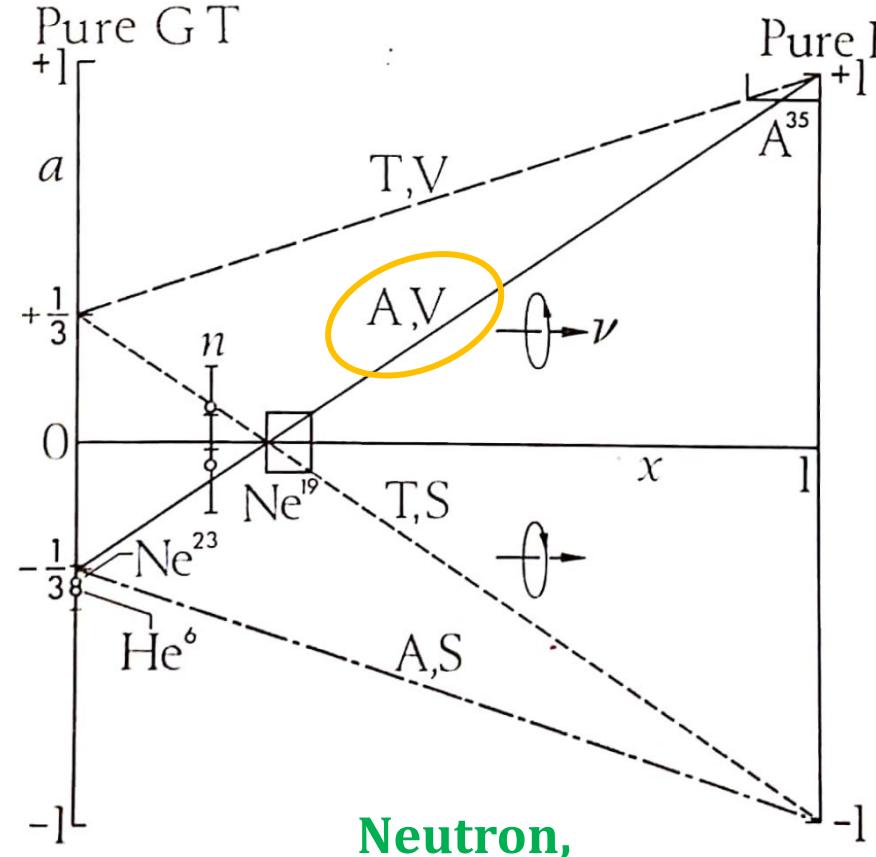


Figure 2.4. "Influence of form of coupling on shape of spectrum for fixed values of the mass of the μ -and μ_0 meson. Contrast this result with the case of ordinary beta-decay, where the atomic nucleus has negligible velocity and the decay curves have the same shape in all five cases" (Tiomno and Wheeler 1949a, p. 148).

Experimental supports for V—A (nuclear data)

beta-neutrino
correlation, “a”
 ${}^6\text{He}, {}^8\text{Li}, \dots$



Neutron,
Mirror Nuclei:
 ${}^{37}\text{K}, {}^{19}\text{Ne}, {}^{21}\text{Na}, {}^{35}\text{Ar}$

Superallowed $0^+ \rightarrow 0^+$
 ${}^{10}\text{C}, {}^{14}\text{O}, \text{etc.}$

$$x = \frac{g_A M_{GT}}{g_V M_F}$$

Measurements of Asymmetries in the Decay of Polarized Neutrons*

M. T. BURGY, V. E. KROHN, T. B. NOVEY, AND G. R. RINGO,
Argonne National Laboratory, Lemont, Illinois

AND

V. L. TELELDI, *University of Chicago, Chicago, Illinois*
 (Received April 17, 1958)

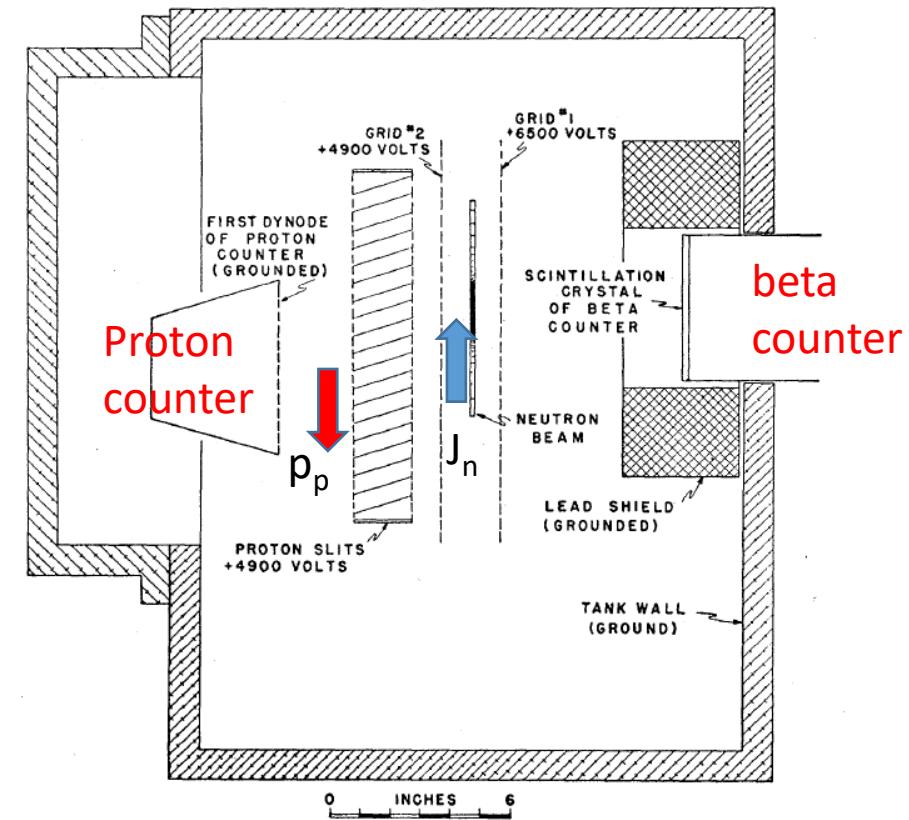


FIG. 1. Vertical cross section (normal to the neutron beam) through the detector system of the experiment measuring the correlation of the neutrino momentum and the neutron spin.

a (beta-neutrino correlation)
 B (neutrino asymmetry)

TABLE II. Predicted values for α and β .

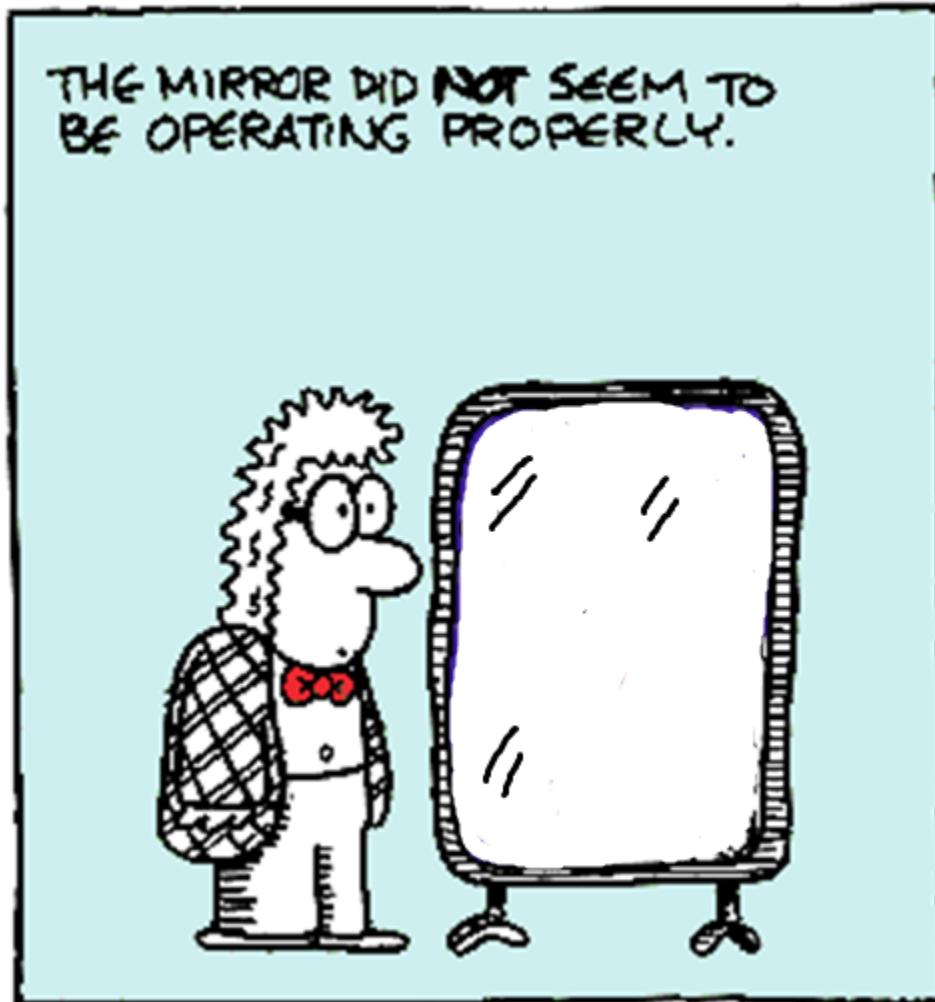
	$S+T^a$	$\bar{\nu}_R$	$S-T$	$\bar{\nu}_L$	$\bar{\nu}_R$	$V+A$	$\bar{\nu}_L$	$\bar{\nu}_R$	$V-A^a$	$\bar{\nu}_R$	Exp.
α	-1	+1		-0.07 ^c	0.07		+1	-1	0.07	-0.07	-0.09
β	-0.07	0.07		-1	+1		-0.07	0.07	-1	+1	+0.88

^a The relative signs in this row are those of the couplings present; i.e., $V-A$ means $C_A/C_V = -1.14$.

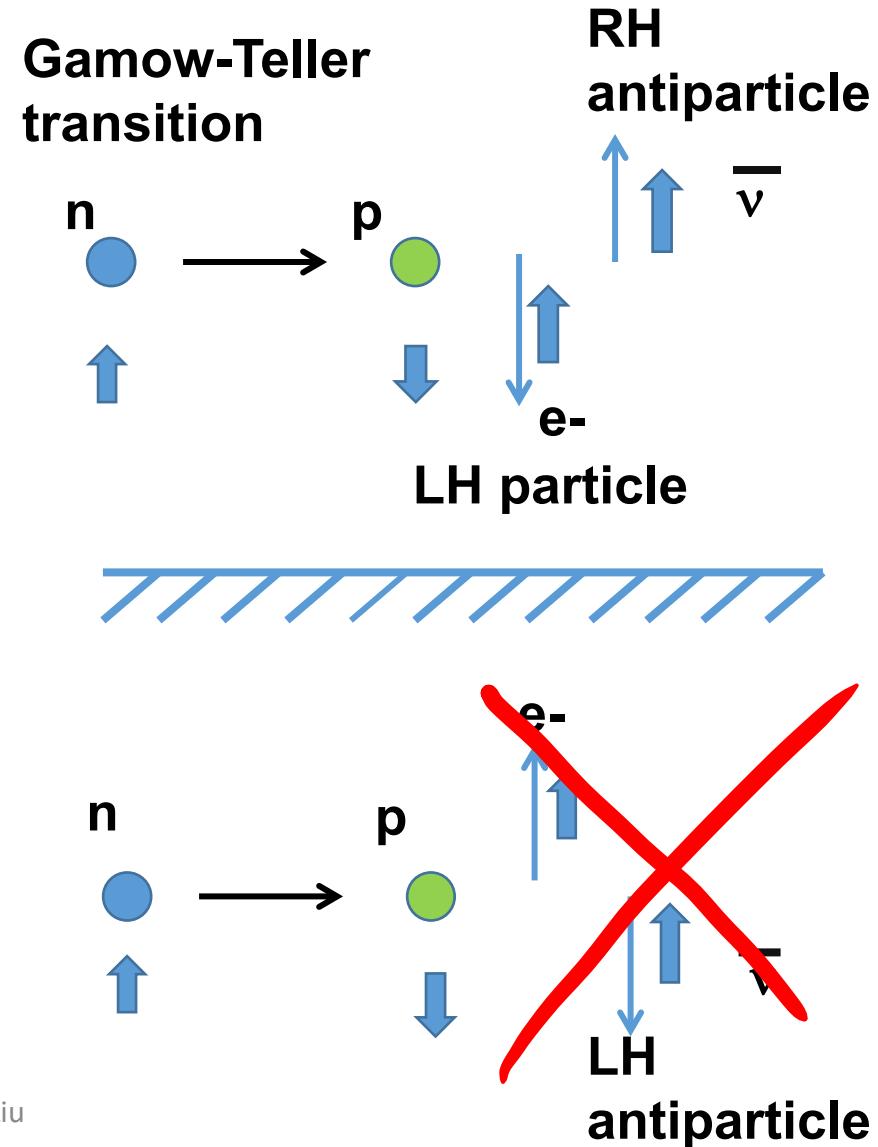
^b $\bar{\nu}_{L(R)}$ means left (right) handed antineutrino; i.e., $\bar{\nu}_{L(R)}$ corresponds to $C_L/C_R = -1(+1)$.

^c The uncertainty of ± 0.05 in x introduces an uncertainty of ± 0.02 in this number, 0.07, wherever it appears.

The Spatial Inversion Symmetry (or Parity) is Broken!



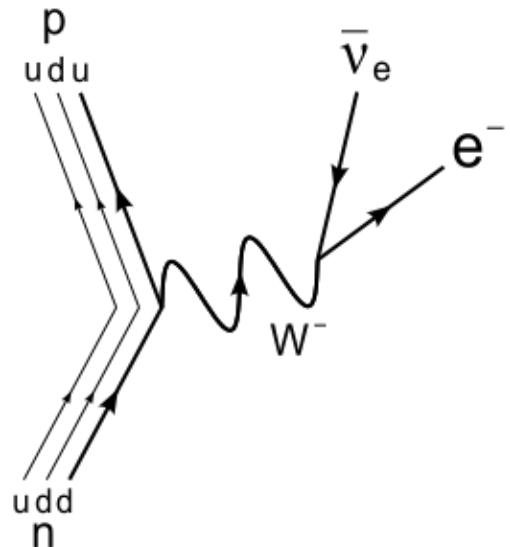
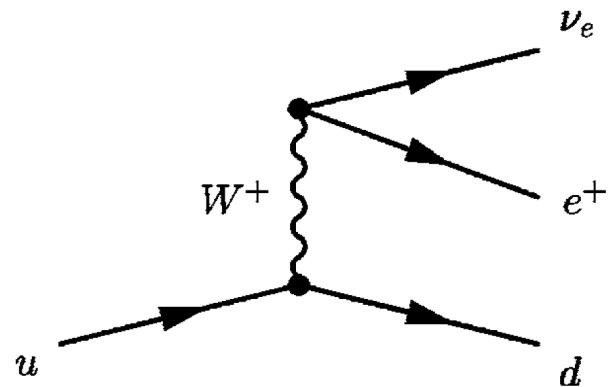
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Girl before a mirror,
Pablo Picasso (1932)

Neutron beta-decay (minimal V—A)



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

Cabbibo-Kobayashi-Maskawa (CKM) matrix

$$H_{V,A} = \frac{G_F V_{ud}}{\sqrt{2}} \left[(\bar{e} \gamma_\mu (1 + \gamma_5) \nu) (\bar{u} \gamma^\mu d) - (\bar{e} \gamma_\mu \gamma_5 (1 + \gamma_5) \nu) (\bar{u} \gamma^\mu \gamma_5 d) \right] + \text{h.c.}$$

$$\begin{aligned} H_\beta &= H_{V,A} \\ &= \frac{G_F V_{ud}}{\sqrt{2}} \bar{\phi}_e \gamma_i (1 - \gamma^5) \phi_{\nu_e} \bar{\phi}_p (g_V + g_A \gamma^5) \gamma^i \phi_n \end{aligned}$$

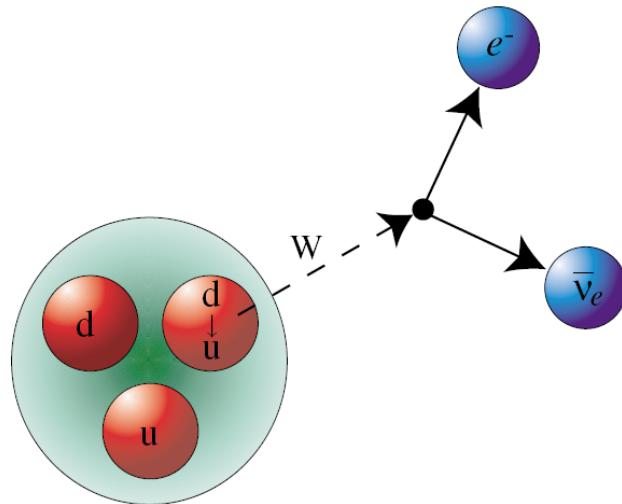
$\boxed{g_V}(\bar{p} \gamma_\mu n) = \langle p | \bar{u} \gamma_\mu d | n \rangle$

$\boxed{g_A}(\bar{p} \gamma_\mu \gamma_5 n) = \langle p | \bar{u} \gamma_\mu \gamma_5 d | n \rangle$

g_A has to be determined by measurements or calculated using Lattice QCD.

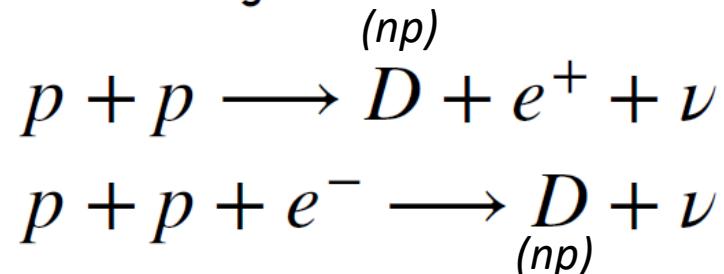
The neutron lifetime has broader impacts in other fields of research:

Neutron beta decay

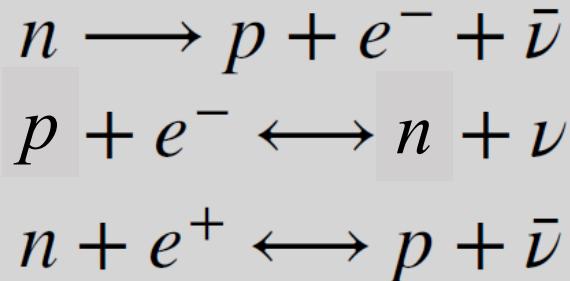


$$n \rightarrow p^+ + e^- + \bar{\nu}_e + 782 \text{ keV}$$

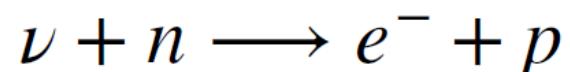
Neutron lifetime gives us weak interaction rates, e.g.



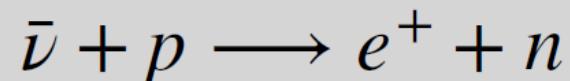
Solar cycle



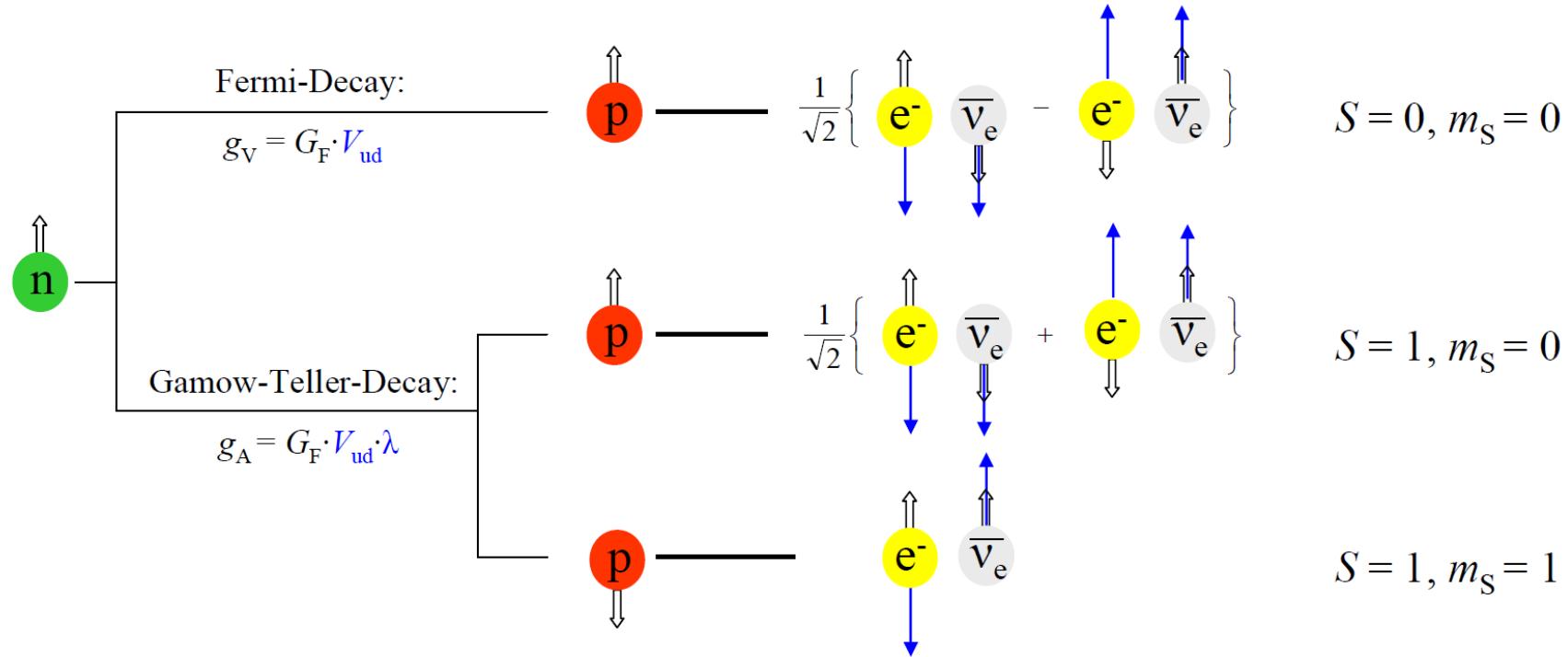
BBN and neutron stars



(anti)neutrino detection



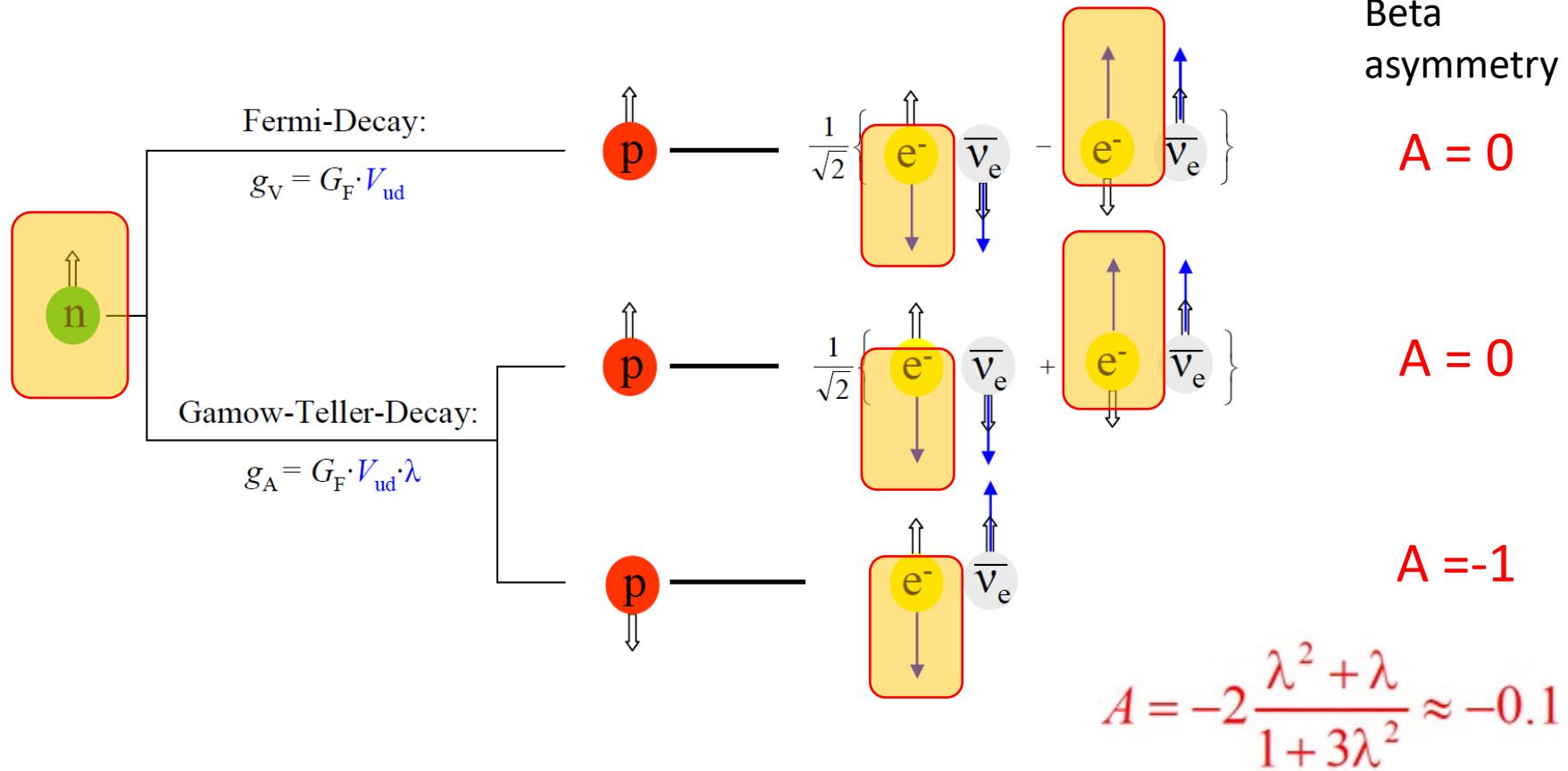
Neutron beta-decay



Two unknown parameters, g_A and g_V , need to be determined in 2 experiments

1. Neutron-Lifetime: $\tau_n^{-1} \propto (g_V^2 + 3g_A^2)$ $\tau_n \approx 885$ s

Neutron beta-decay & angular correlations

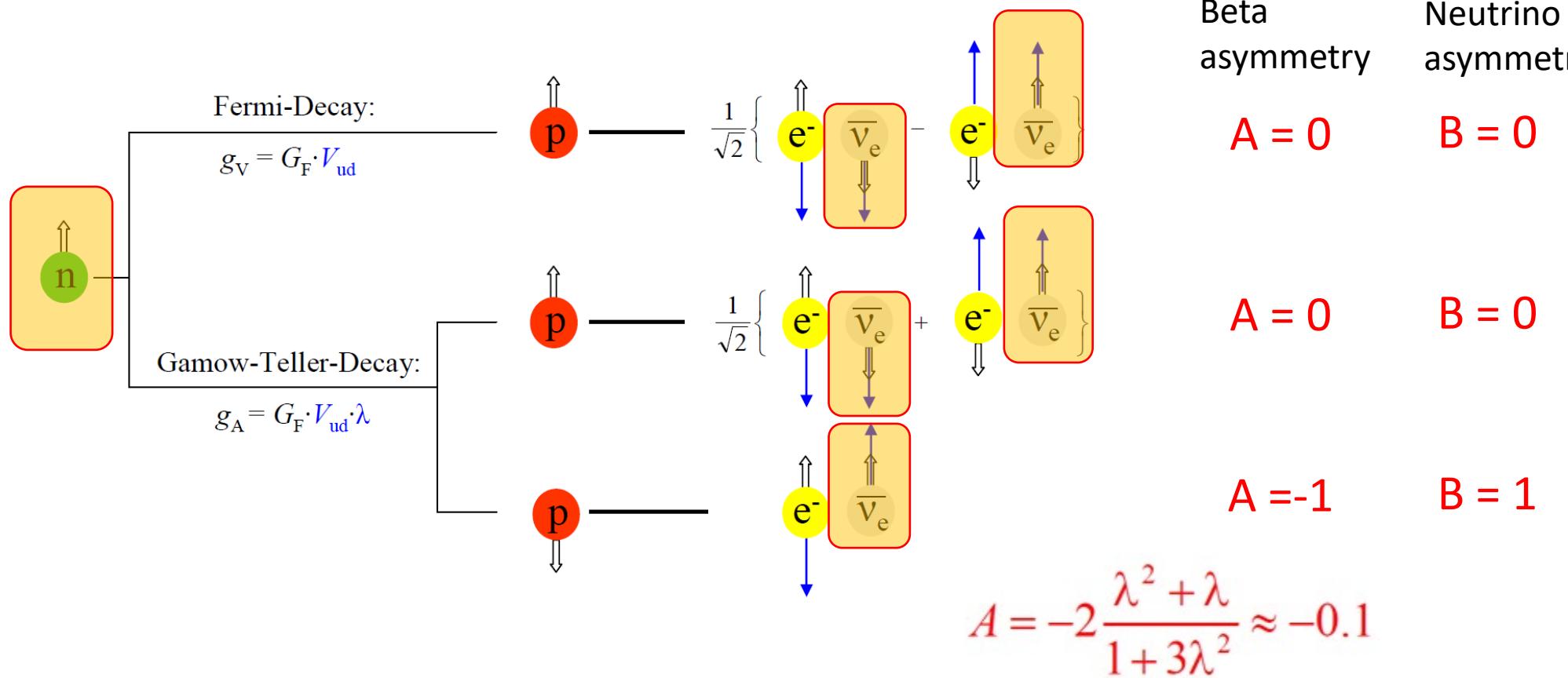


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$$\lambda = \frac{g_A}{g_V}$$

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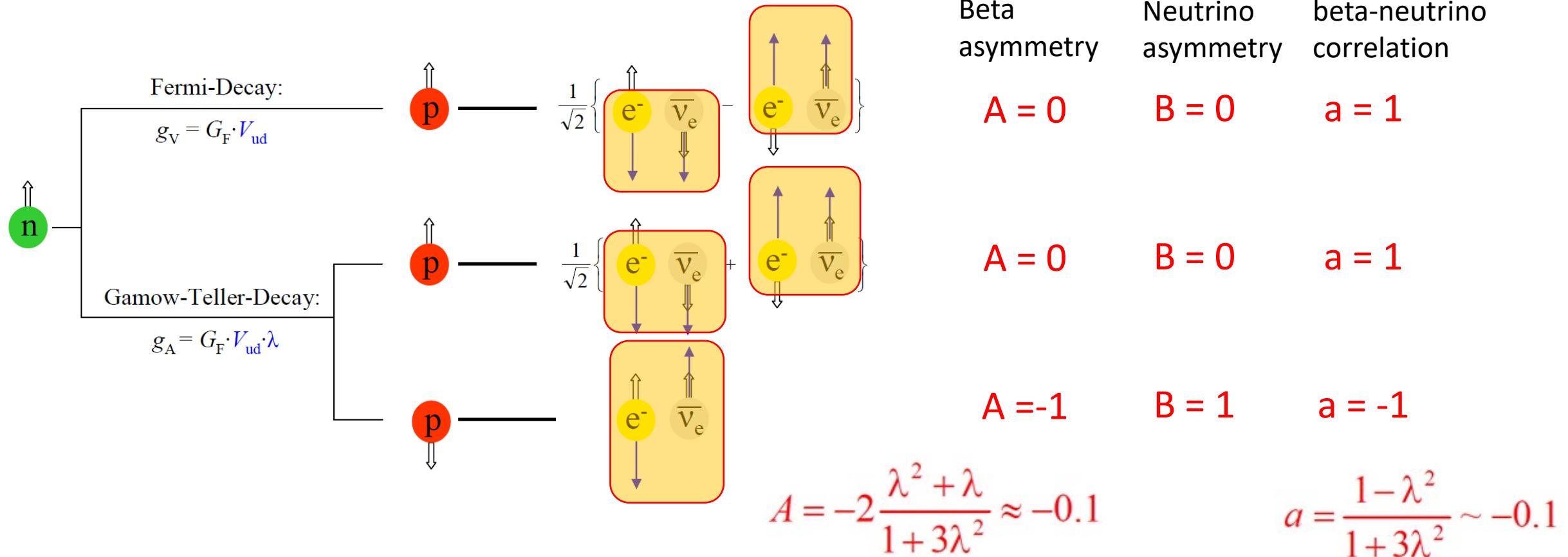
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$$1. \text{ Neutron-Lifetime: } \tau_n^{-1} \propto (g_V^2 + 3g_A^2) \quad \tau_n \approx 885 \text{ s}$$

$$B = 2 \frac{\lambda^2 - \lambda}{1 + 3\lambda^2} \approx 0.98$$

$$\lambda = \frac{g_A}{g_V}$$

Neutron beta-decay & angular correlations



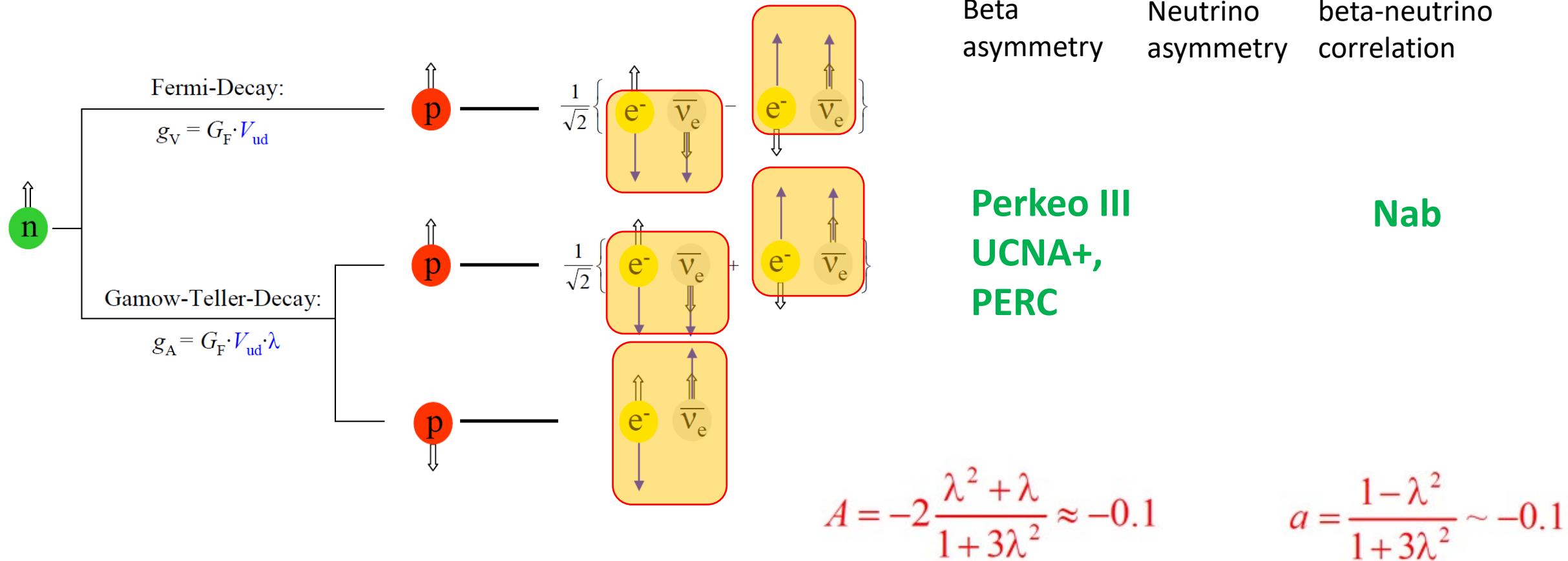
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Neutron beta-decay & angular correlations



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UCNtau, BL2, BL3, J-PARC lifetime, ...

Beta decays and new physics models

- Model → set overall size and pattern of effective couplings
- Beta decays can play very useful diagnosing role
- Qualitative picture:

Can be made quantitative

	ε_L	ε_R	ε_P	ε_S	ε_T
LRSM	x	✓	x	x	x
LQ	✓	x	✓	✓	✓
2HDM	x	x	✓	✓	x
MSSM	✓	✓	✓	✓	✓

YOUR FAVORITE MODEL

The diagram illustrates several particle interactions:

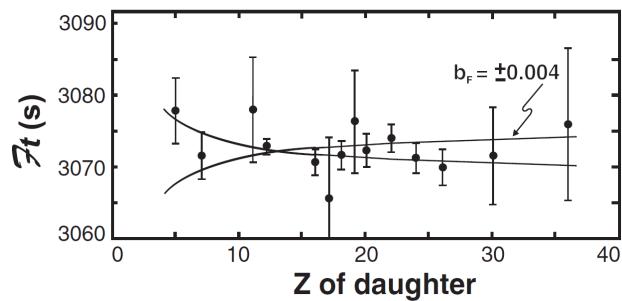
- A vertex labeled W_R is shown with a solid line and a dashed line meeting at a point.
- A vertex labeled LQ is shown with a solid line (u) and a dashed line (d) meeting at a point, with an electron (e) and neutrino (v) line emerging from the same point.
- A vertex labeled H^+ is shown with a solid line and a dashed line meeting at a point.
- Below these, a horizontal line represents a quark (u) interacting with a lepton (e). A dashed line labeled \tilde{d}_i^- enters from the left, and a dashed line labeled \tilde{L}_j^- exits to the right. Above the line, a dashed line labeled χ_k^+ enters from the left, and a dashed line labeled ν_I exits to the right.
- Below the previous line, another horizontal line represents a quark (d) interacting with a lepton (e). A dashed line labeled \tilde{u}_i^0 enters from the left, and a dashed line labeled ℓ_I exits to the right. Above the line, a dashed line labeled χ_m^0 enters from the left, and a dashed line labeled ν_I exits to the right.
- At the bottom, a vertex labeled W^+ is shown with a solid line and a dashed line meeting at a point. A dashed line labeled χ_j^- enters from the left, and a dashed line labeled ℓ_I exits to the right. Above the vertex, a dashed line labeled χ_i^0 enters from the left, and a dashed line labeled $\tilde{\nu}_J$ exits to the right.

Scalar and Tensor Couplings - beyond the Standard Model

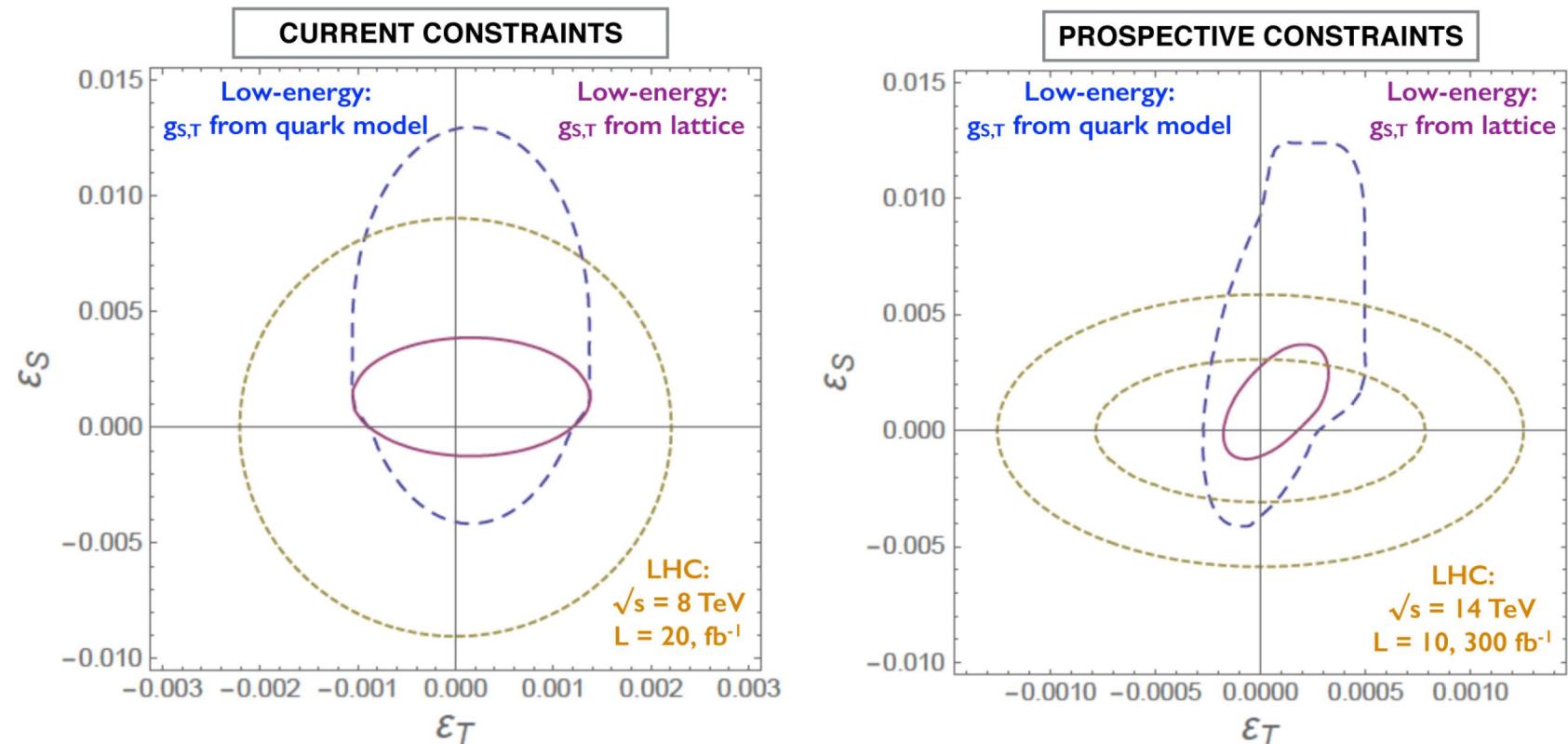
Scalar Currents: b_F

$$f \propto 1 + \langle b_F \gamma_1 m_e / E_e \rangle \quad \gamma_1 = \sqrt{1 - \alpha^2 Z^2}$$

$$C_S / C_V = -b_F / 2 = 0.0014(13)$$



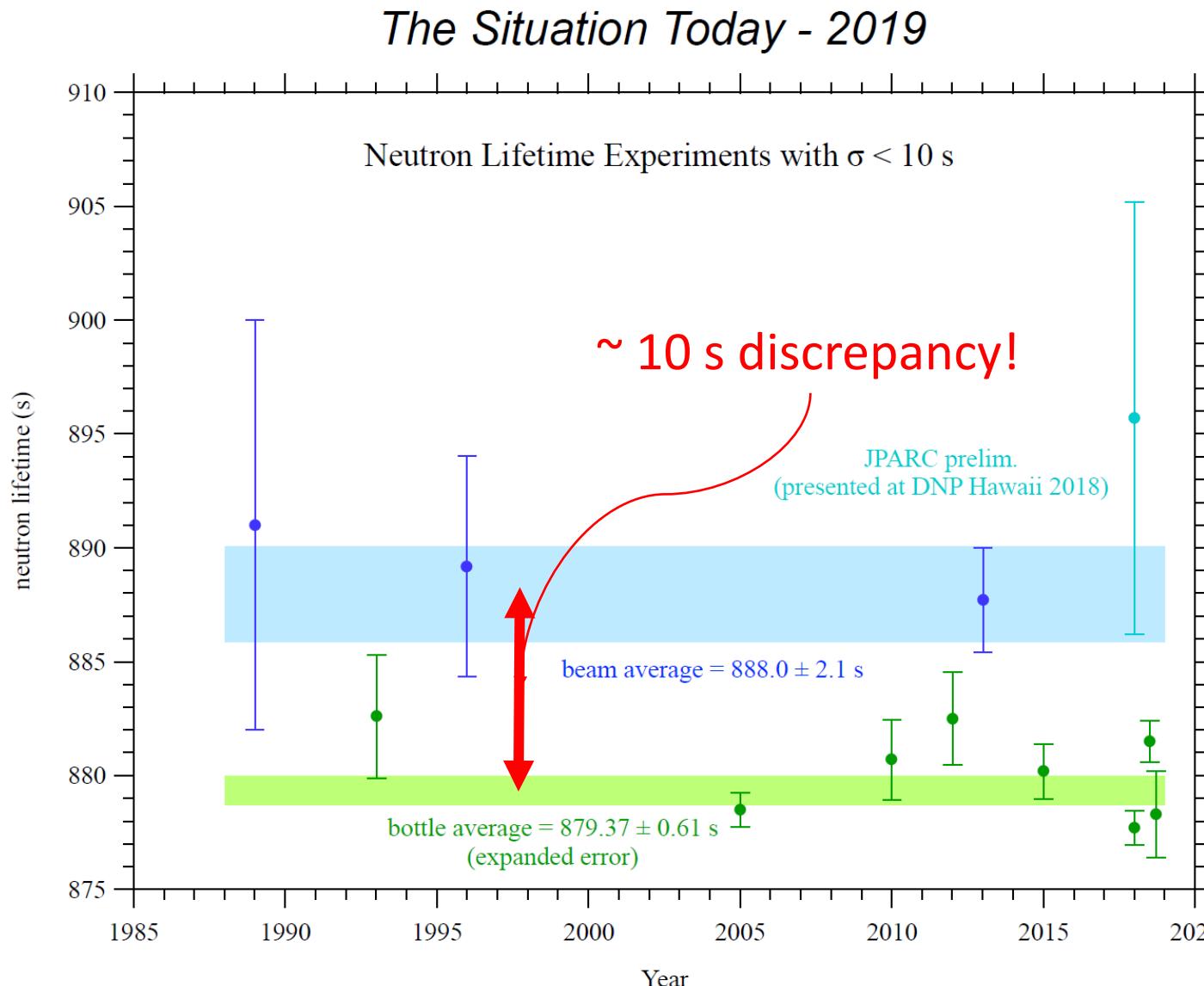
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$$\left. \begin{array}{l} \text{LHC: } pp \rightarrow e\nu + X \\ \epsilon_S: 0^+ \rightarrow 0^+ \text{ Fierz } b_F \\ \epsilon_T: \pi \rightarrow e\nu\gamma \end{array} \right\} \begin{array}{l} \Lambda_S > 7 \text{ TeV} \\ \Lambda_T > 13 \text{ TeV} \end{array}$$

Future ϵ_S, ϵ_T : Neutron b, b_ν
Future ϵ_T : ${}^6\text{He } b$

Neutron Lifetime Puzzle: an unresolved discrepancy between two leading methods to measure the neutron lifetime:



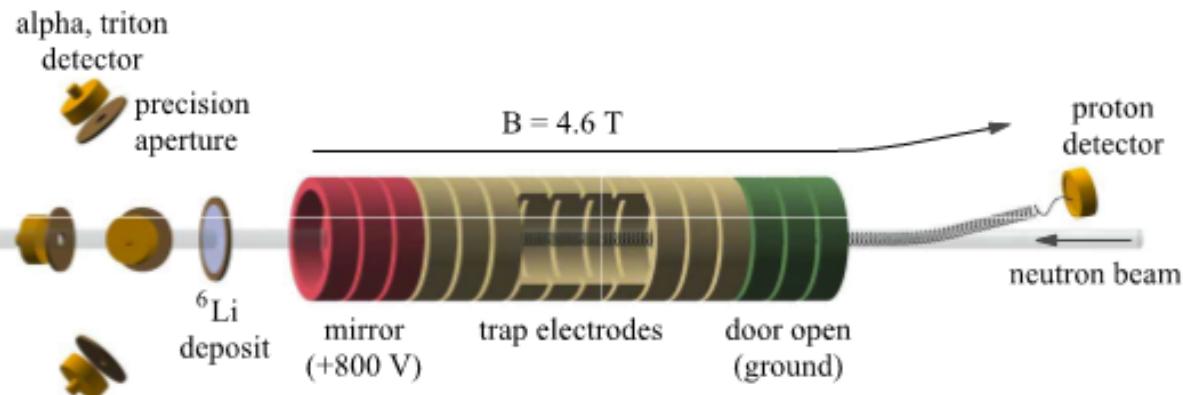
Neutrons in a bottle seem to disappear faster ???

“beam”

VS

“bottle”

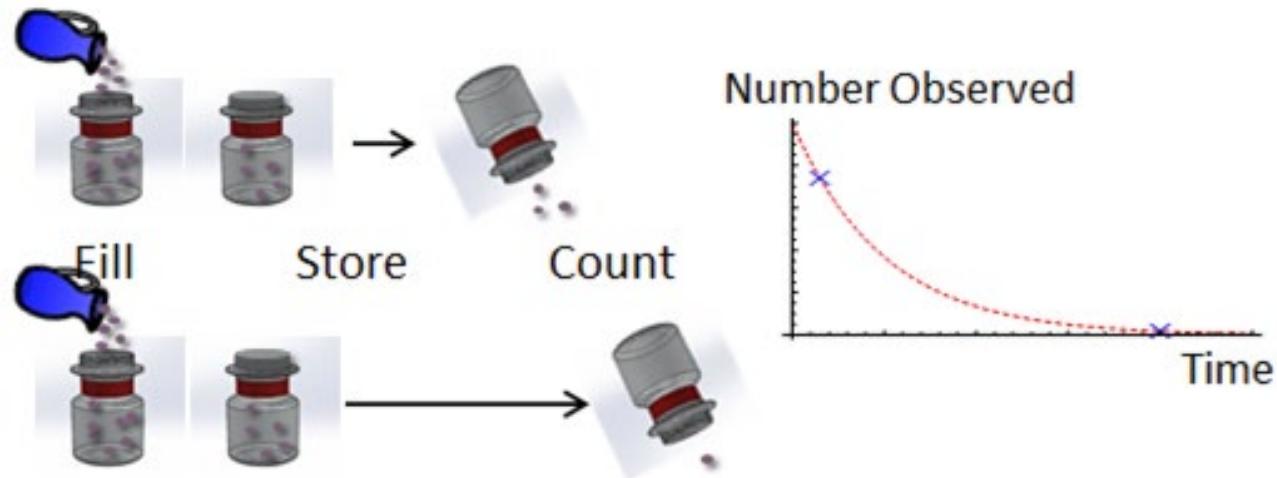
$$\tau_n = \frac{L}{v_n} \frac{\dot{N}_n / \epsilon_n}{\dot{N}_p / \epsilon_p}$$



count the dead
(appearance)

\neq
?????

$$Y(t) = Y_0 e^{-t / \tau_{meas}}$$
$$\tau_{meas}^{-1} = \tau_n^{-1} + \tau_{loss}^{-1}$$

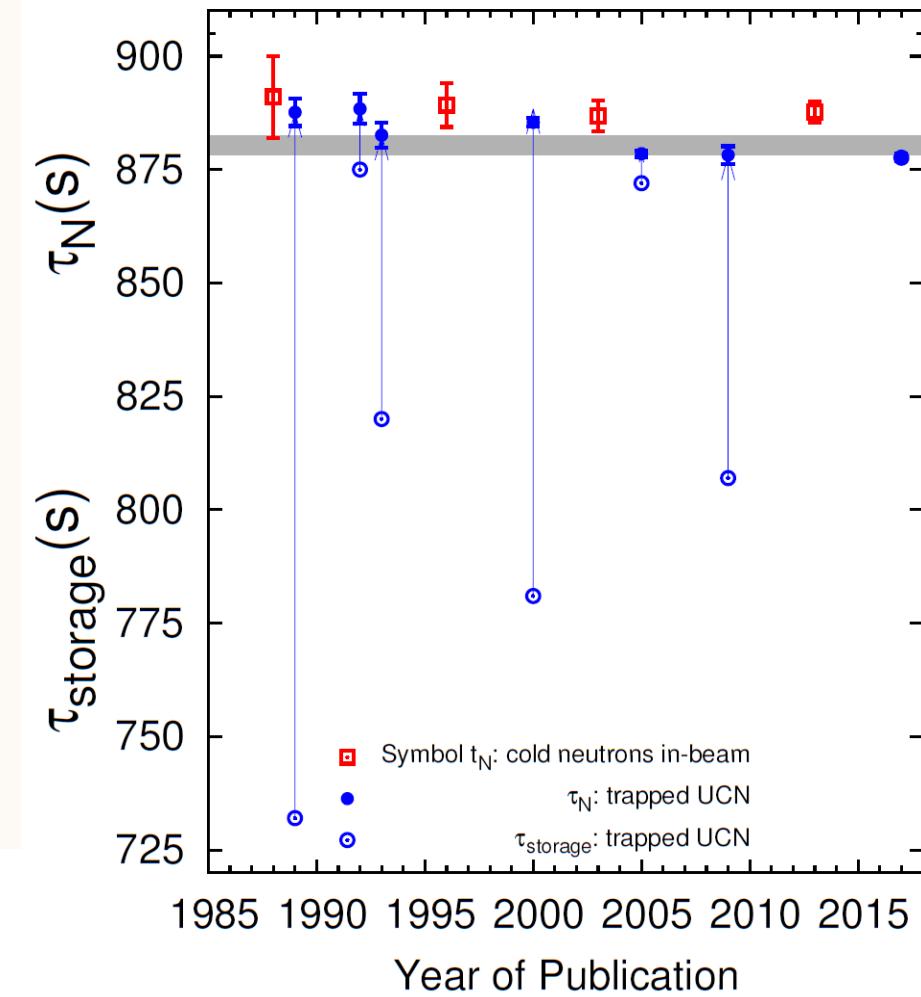


count the living
(disappearance)

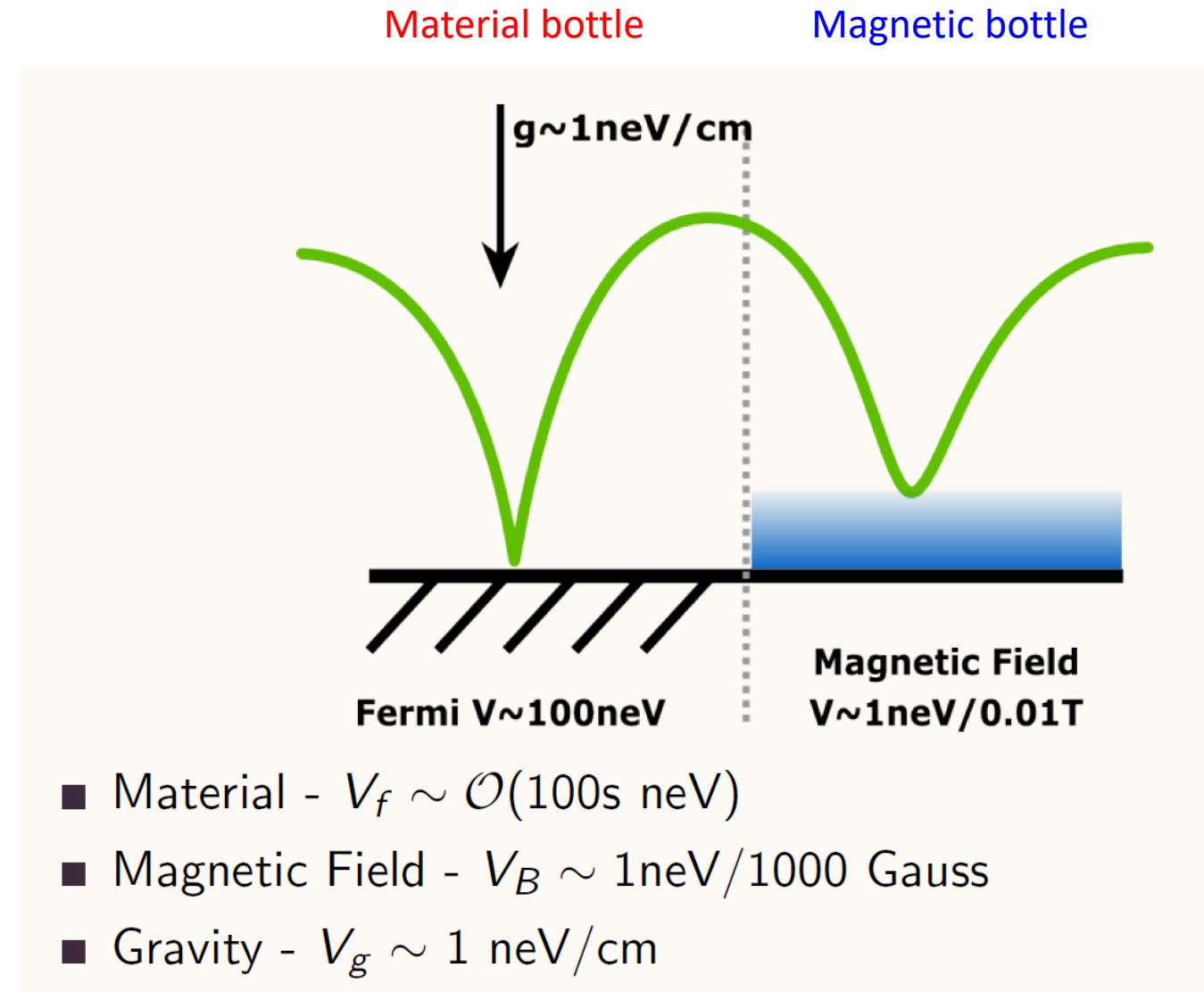
Many experiments need to correct for the systematic effects and extrapolate from the measured lifetime to report the Neutron Lifetime

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

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	~ 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



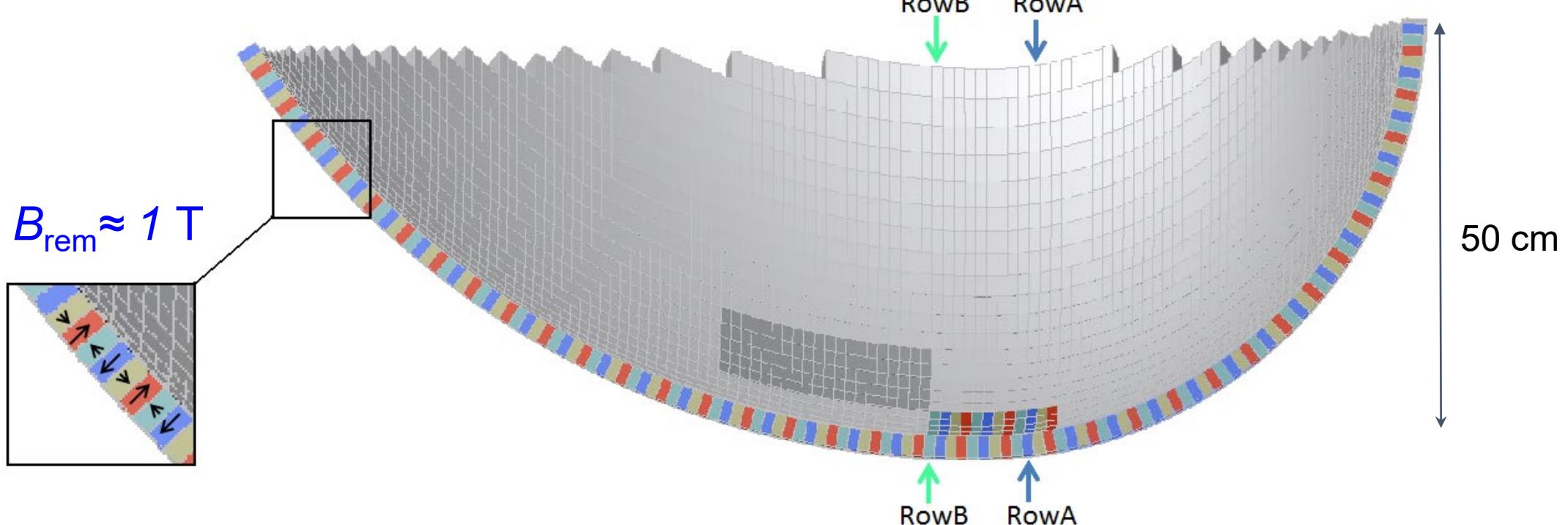
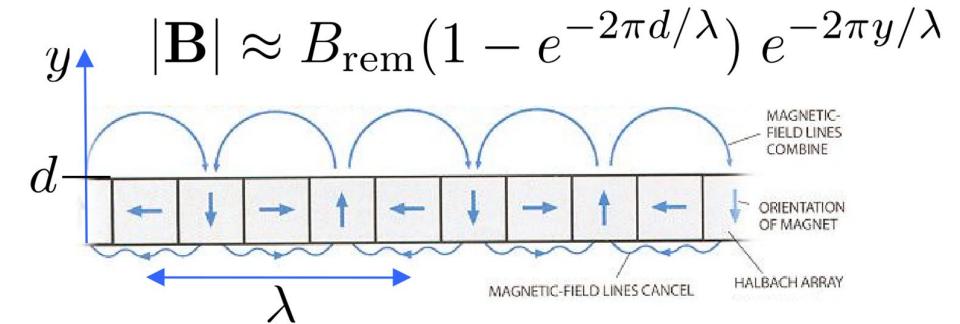
The UCN τ Magneto-Gravitational Trap using a “Halbach” array

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





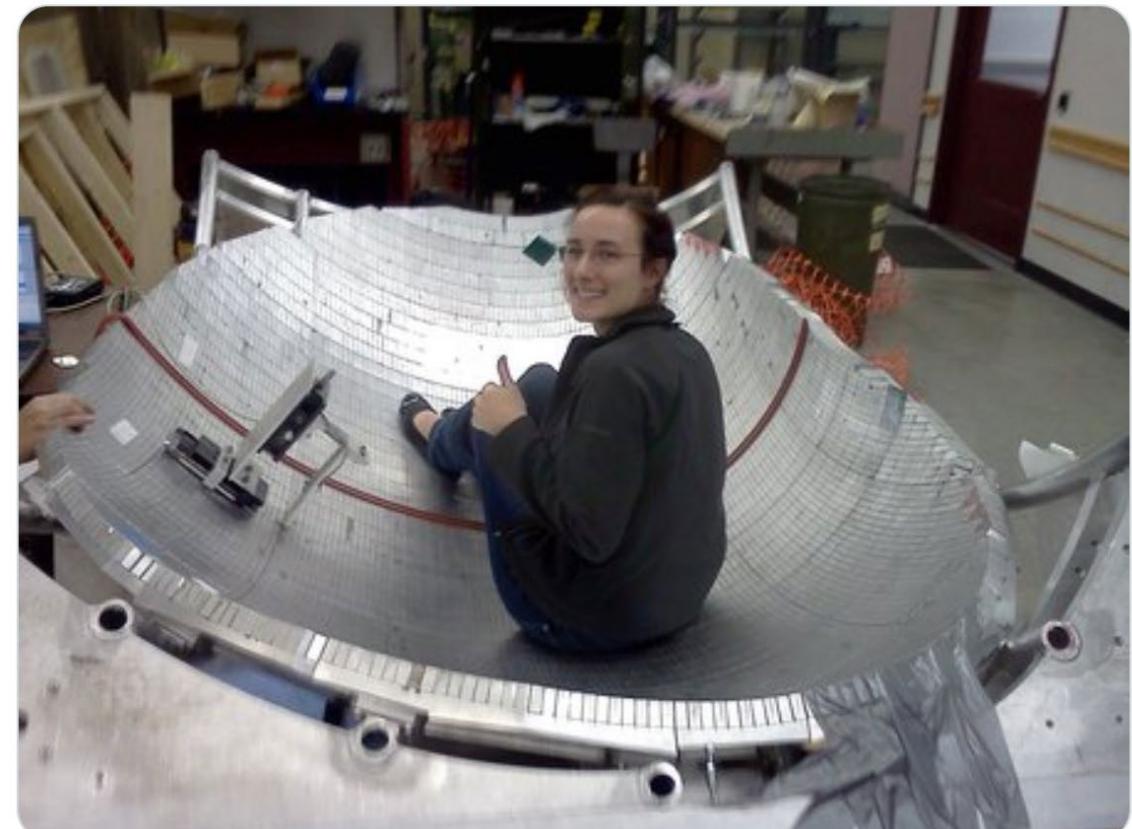
Chris Hadfield
@Cmdr_Hadfield

...

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).

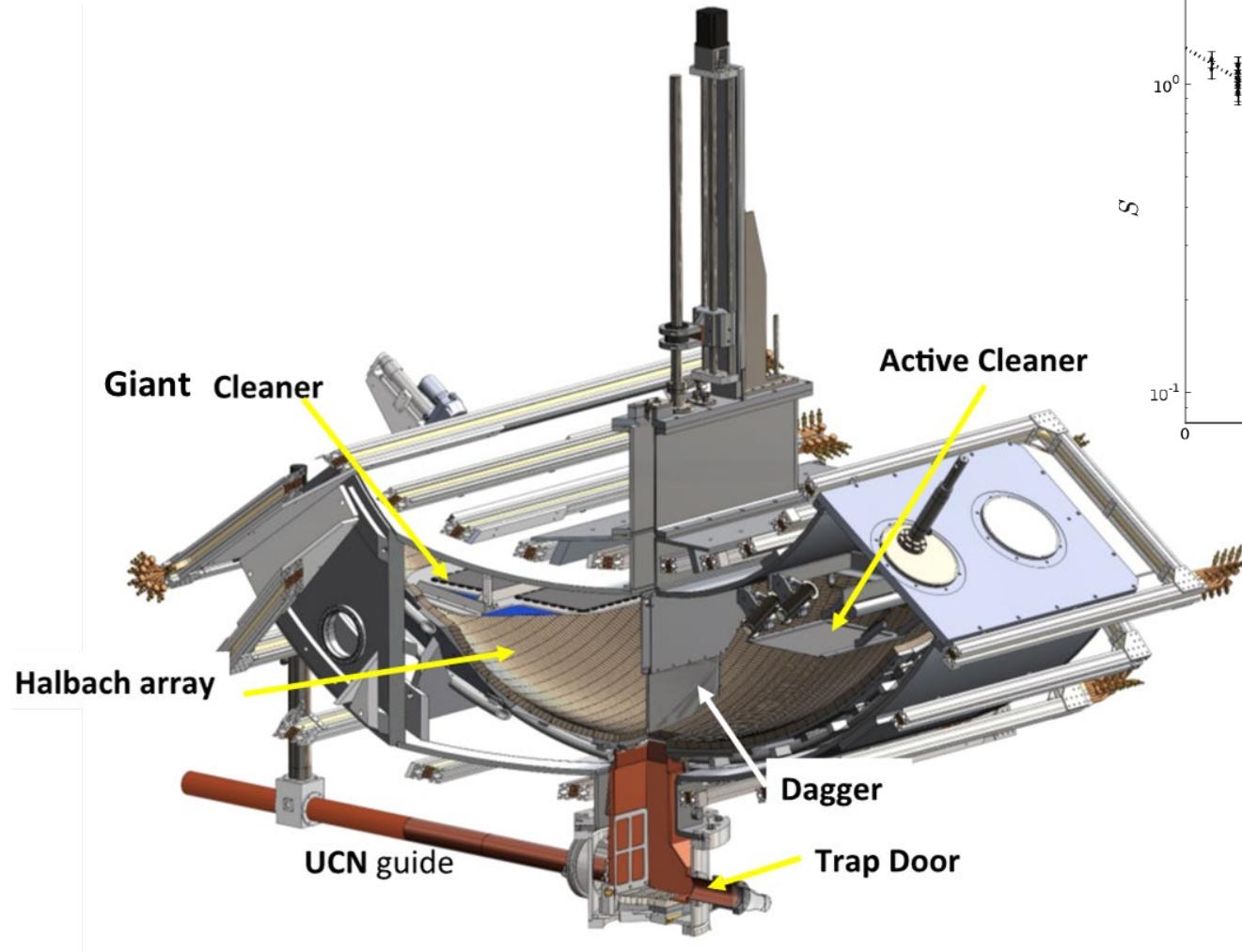
@LosAlamosNatLab

The details: bit.ly/3mBp5Tm

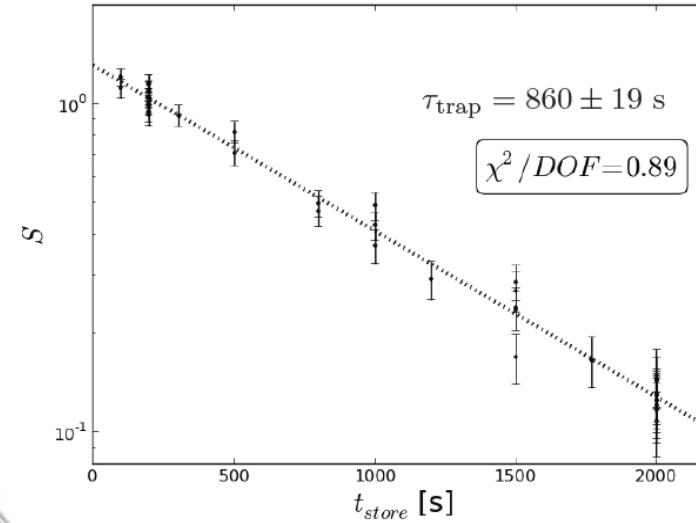


Bailey inside the Halbach array performing field mapping (before Christmas 2012)

The UCN τ Apparatus



First Physics Data: 2013

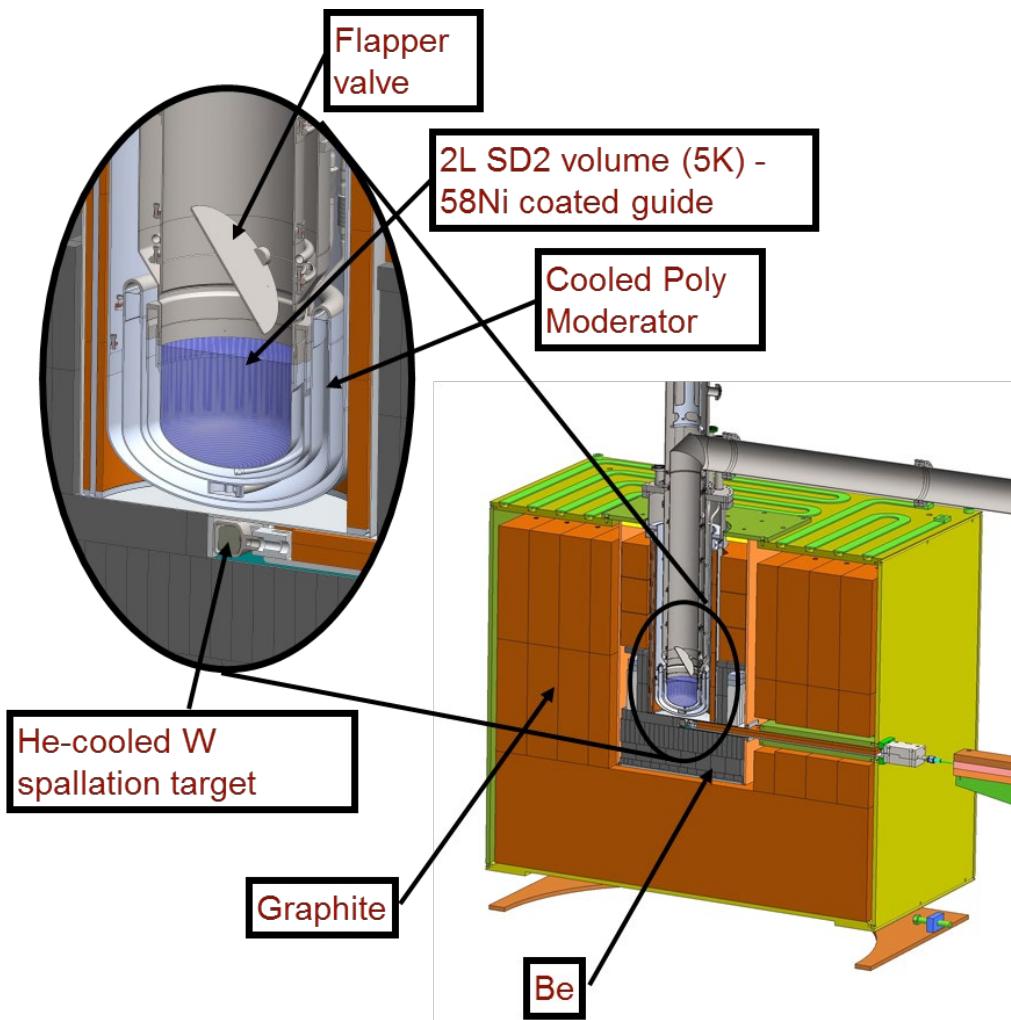


D. Salvat, PRC 89, 052501 (2014)

Los Alamos Neutron Science Center (LANSCE)



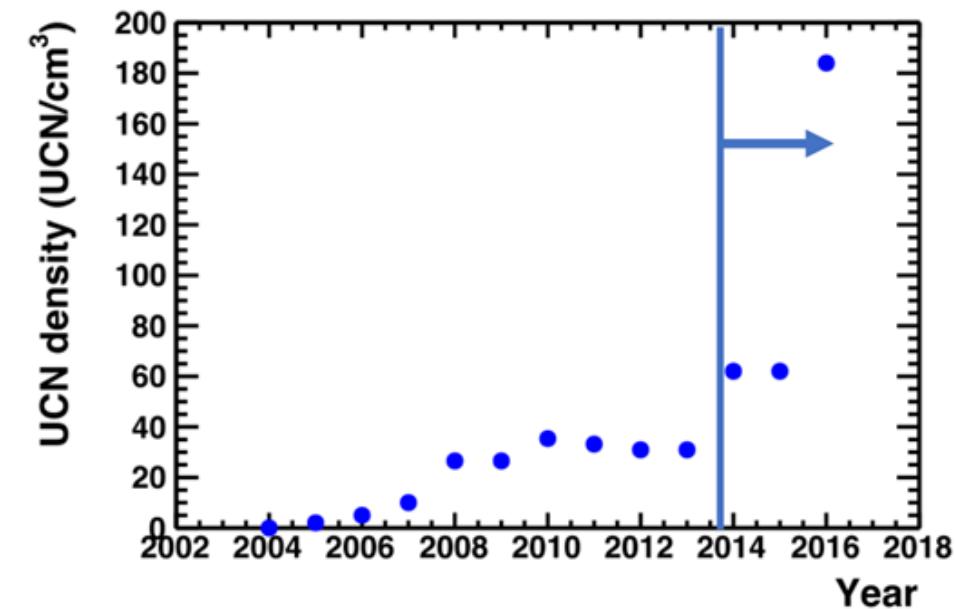
UCN “Pokotilovsky” source operating at the Los Alamos Neutron Science Center (LANSCE)



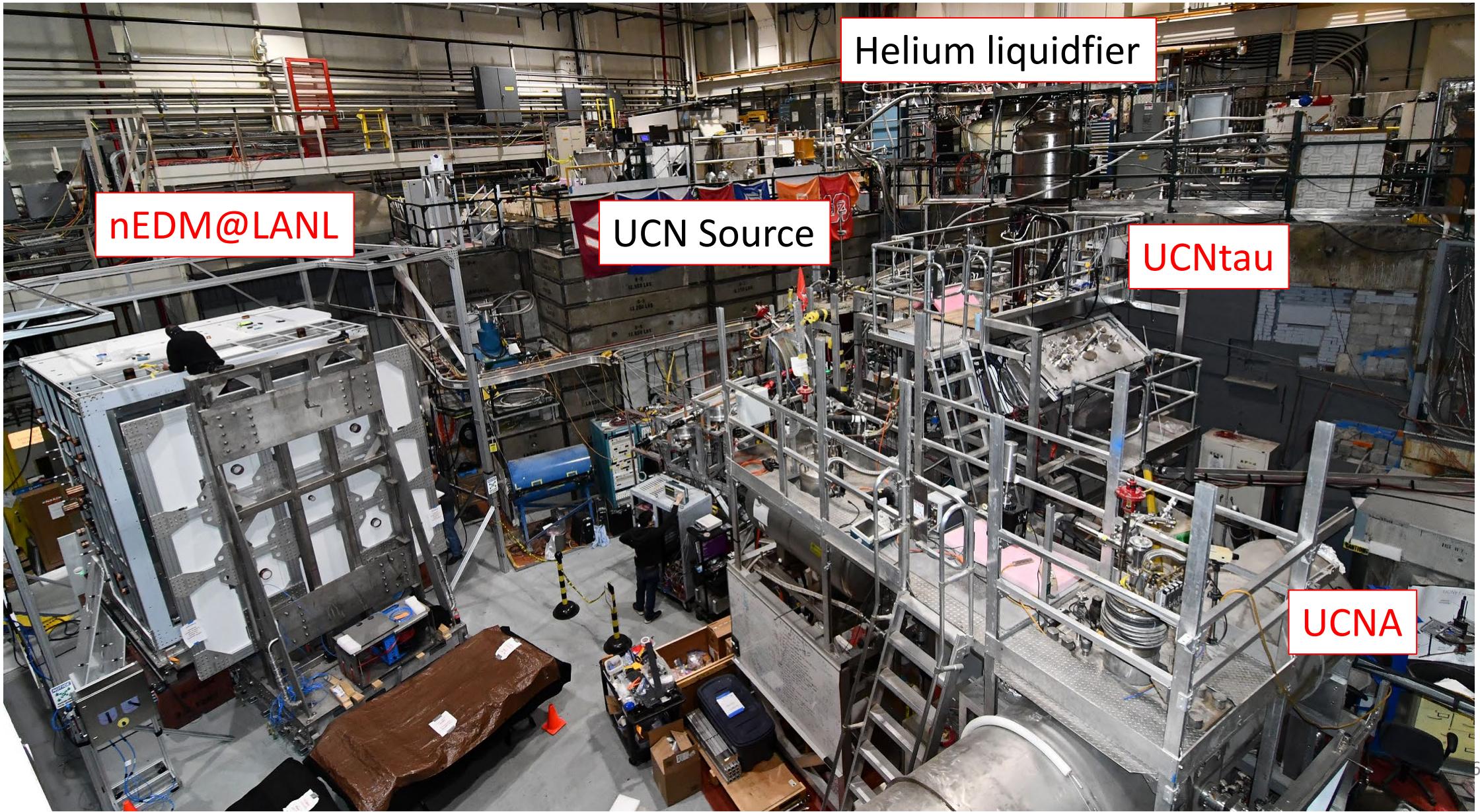
Source upgrade (2016):

- Better moderator cooling
- NiP guides
- Optimized geometry

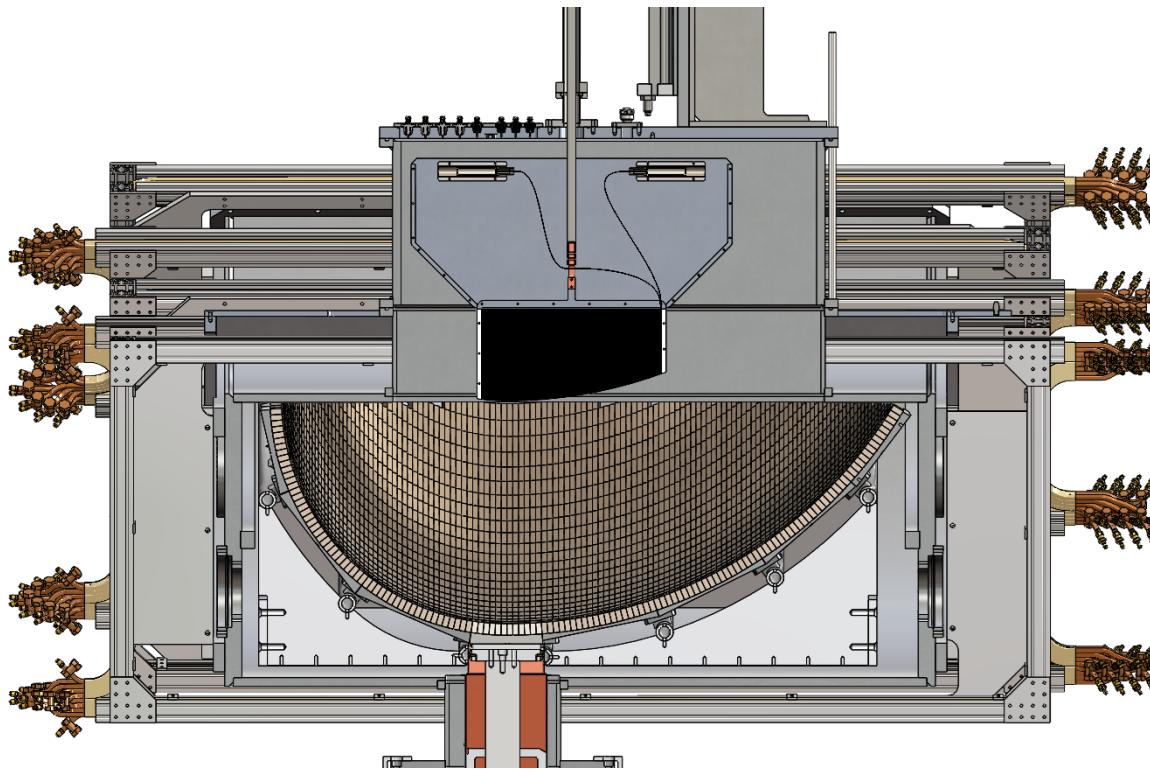
UCN density measured by Vanadium activation: **184 UCN/cc.**



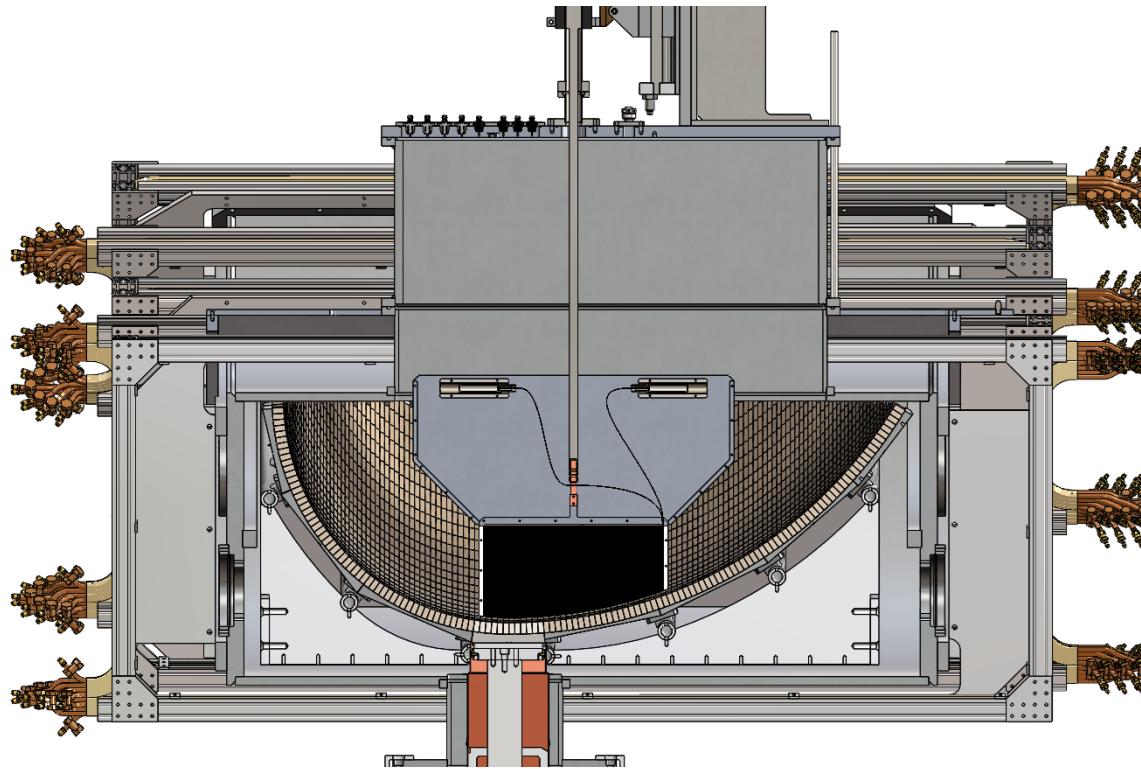
LANSCE UCN Experimental Area (2021)

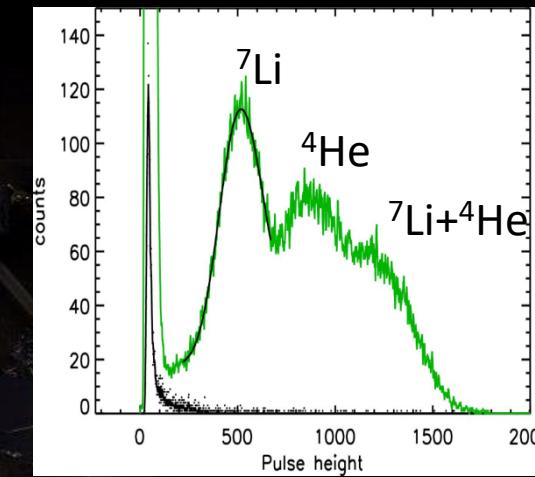
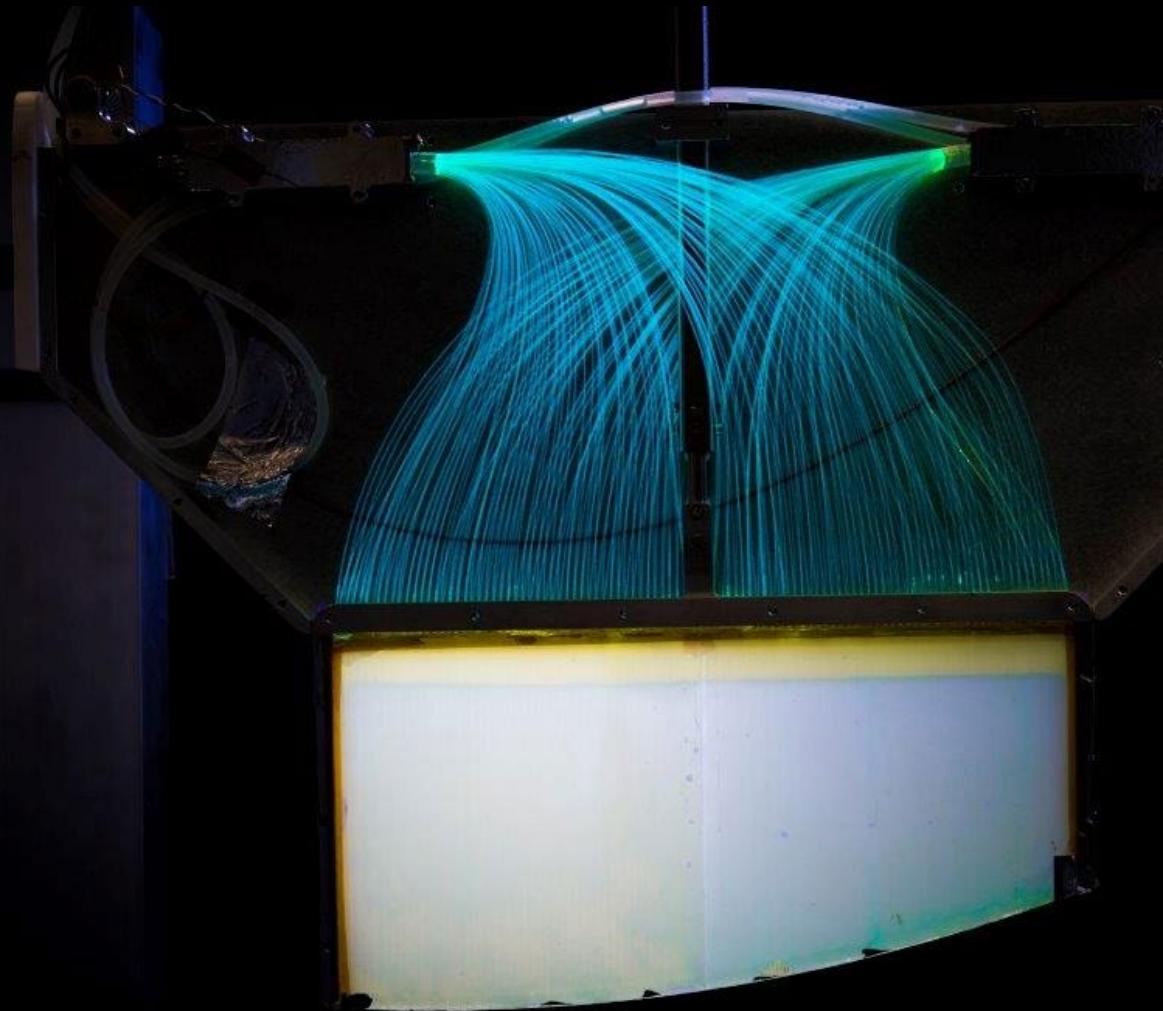


We also implemented a new way to count the trapped neutrons:

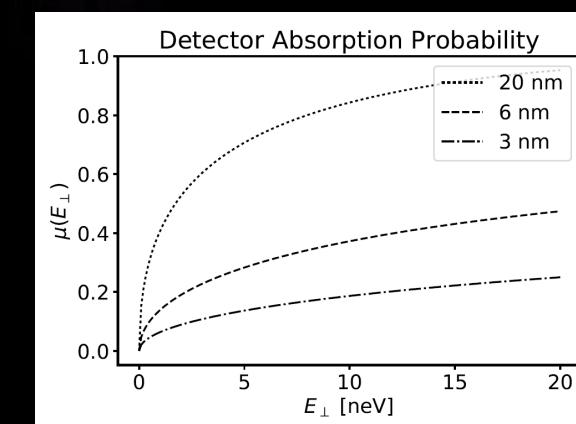
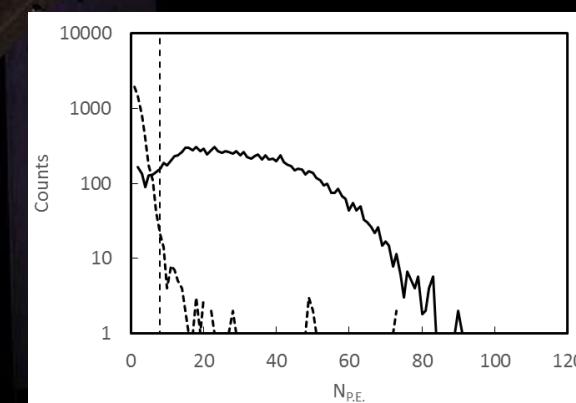


In-situ UCN detection using a “dagger” detector:
detection time ~ 8 s

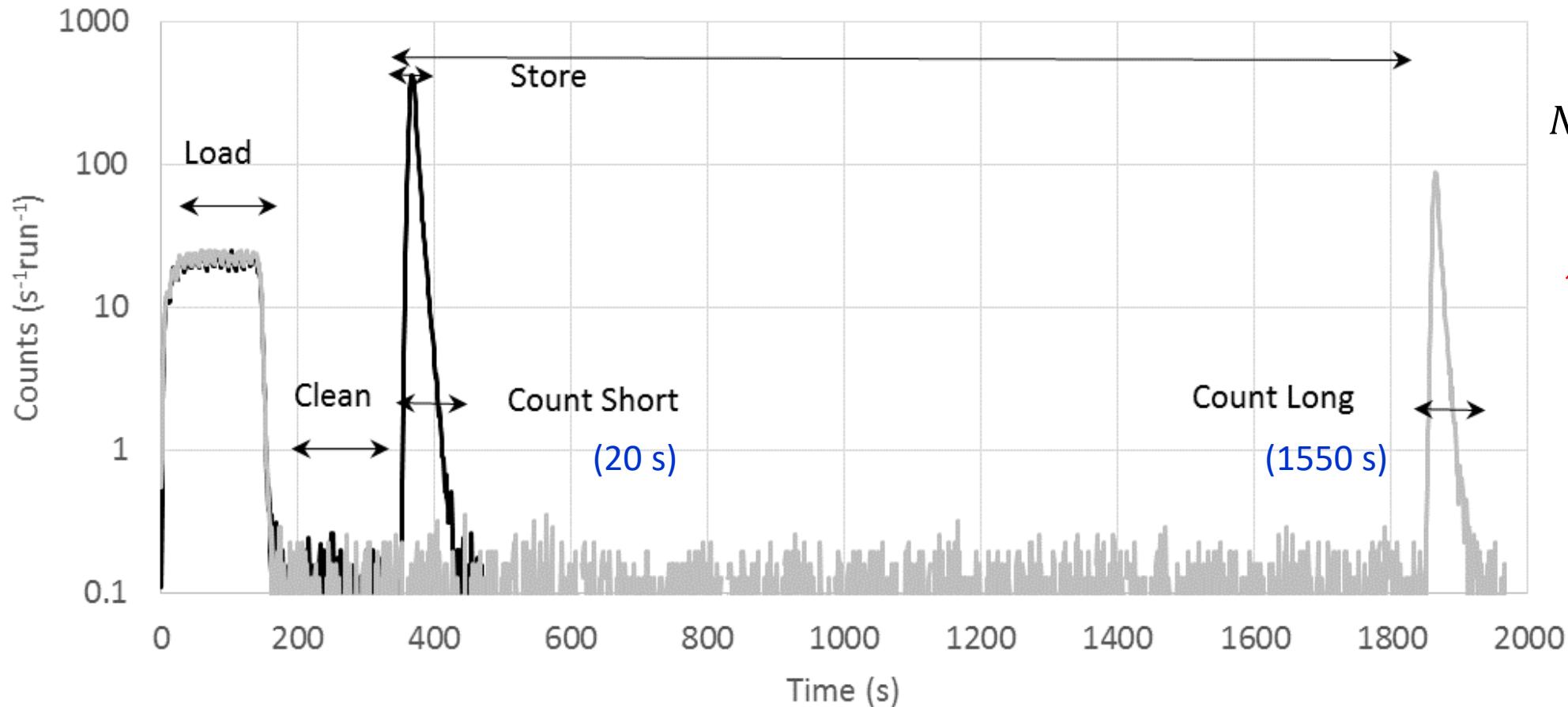




Light Output

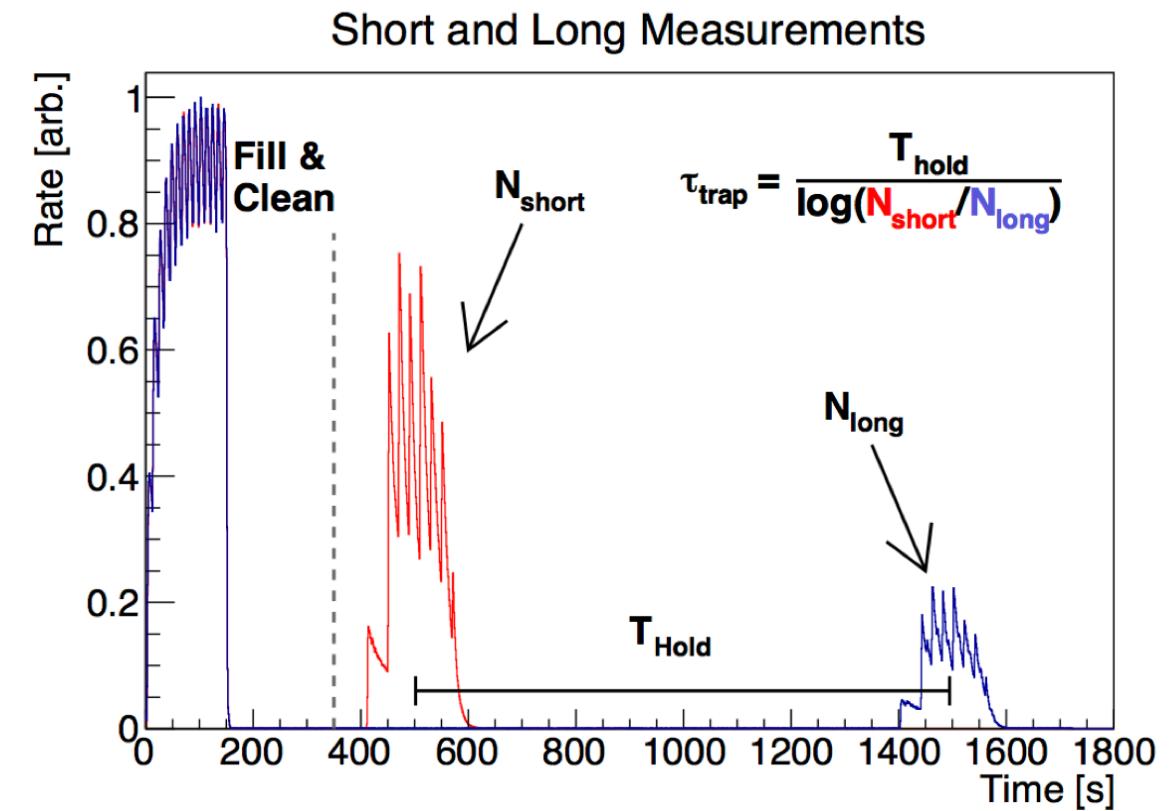
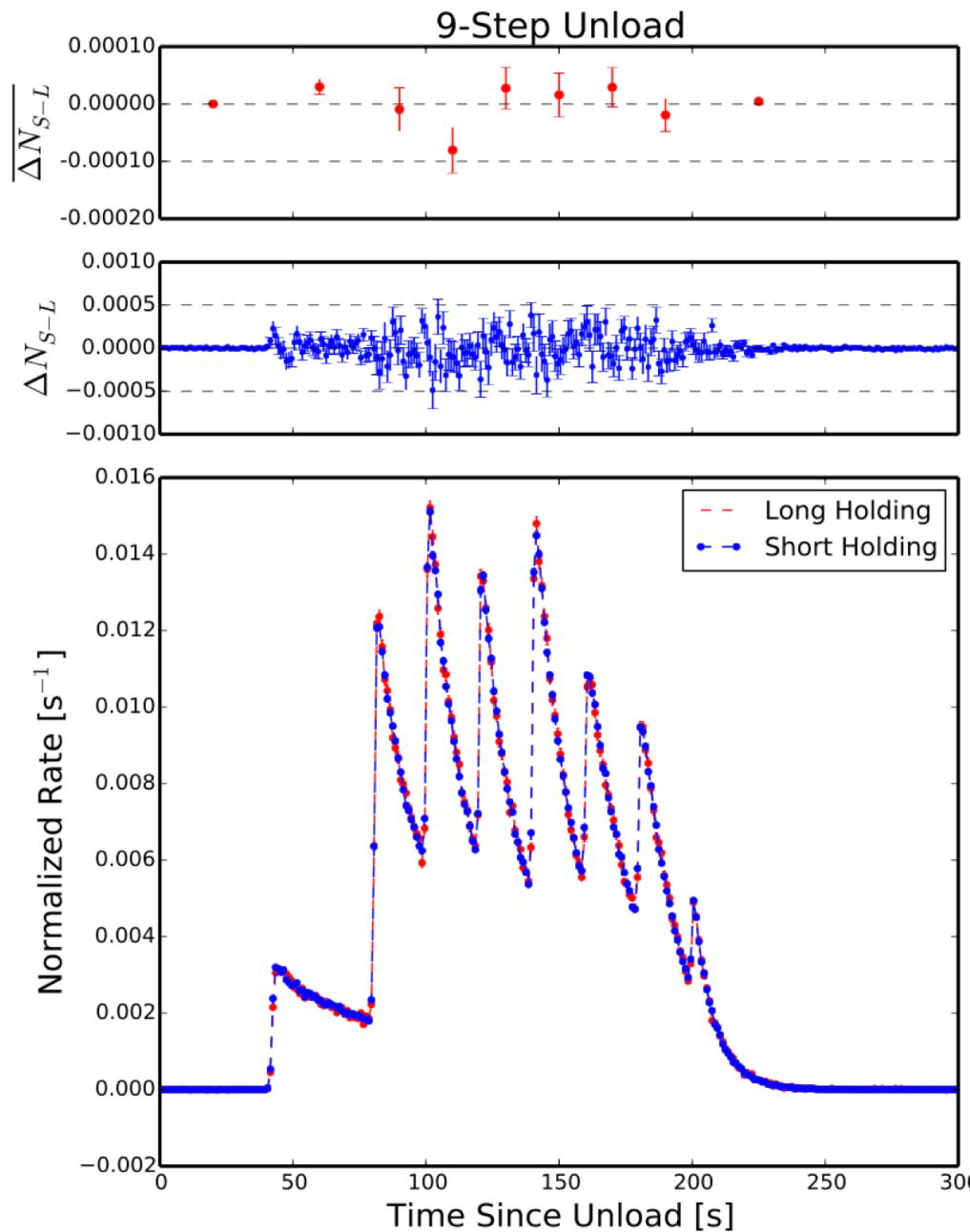


Paired runs: a short-storage followed by a long-storage:



$$N(t) = N_0 e^{-t/\tau}$$

$$\tau = \frac{\Delta t}{\ln \frac{N_1}{N_2}}$$



Use difference between mean arrival times

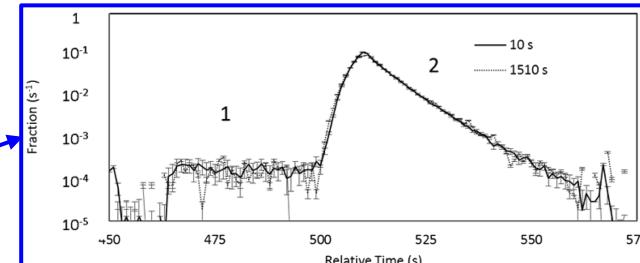
$$\bar{T} = \frac{\sum N_i t_i}{\sum N_i}$$

as T_{hold} . Difference between this and the programmed holding time sets the phase space evolution bound.

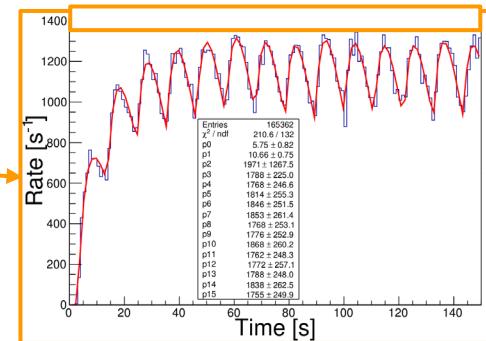
Analyzing data...

Single p.e.
dagger
counts

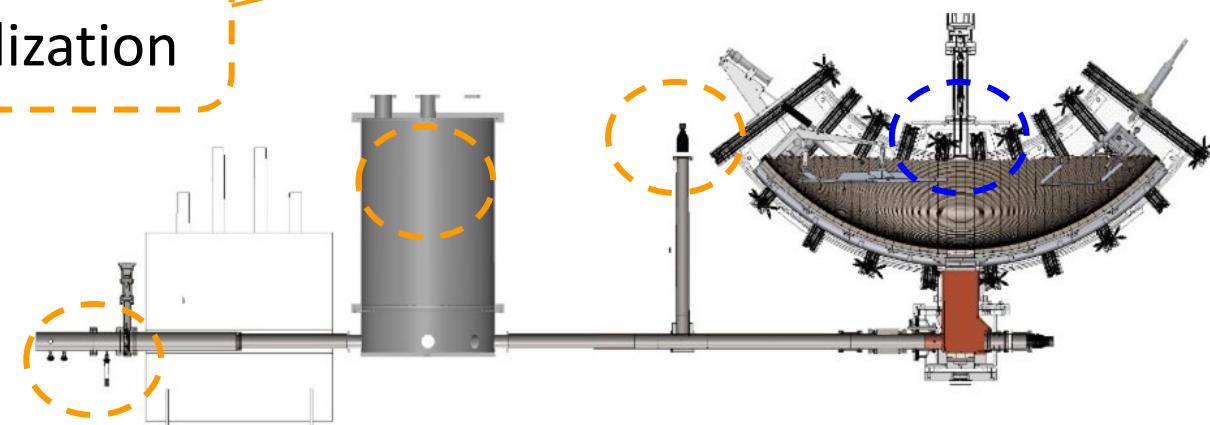
UCN
events
passing
cuts



“Monitor”
detector
counts



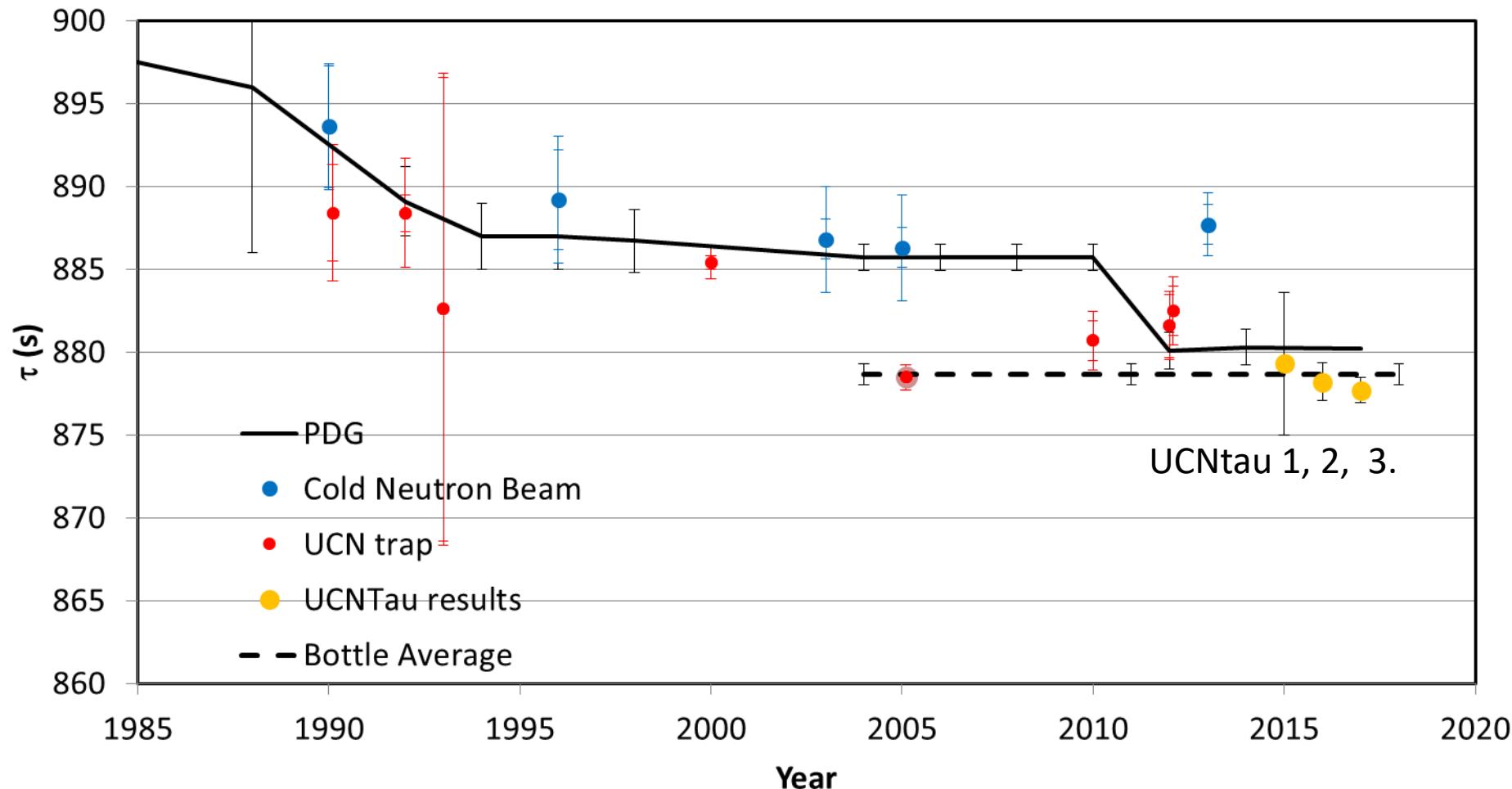
“Monitor”
normalization



$$Y_t = \frac{D_t - B}{M}$$

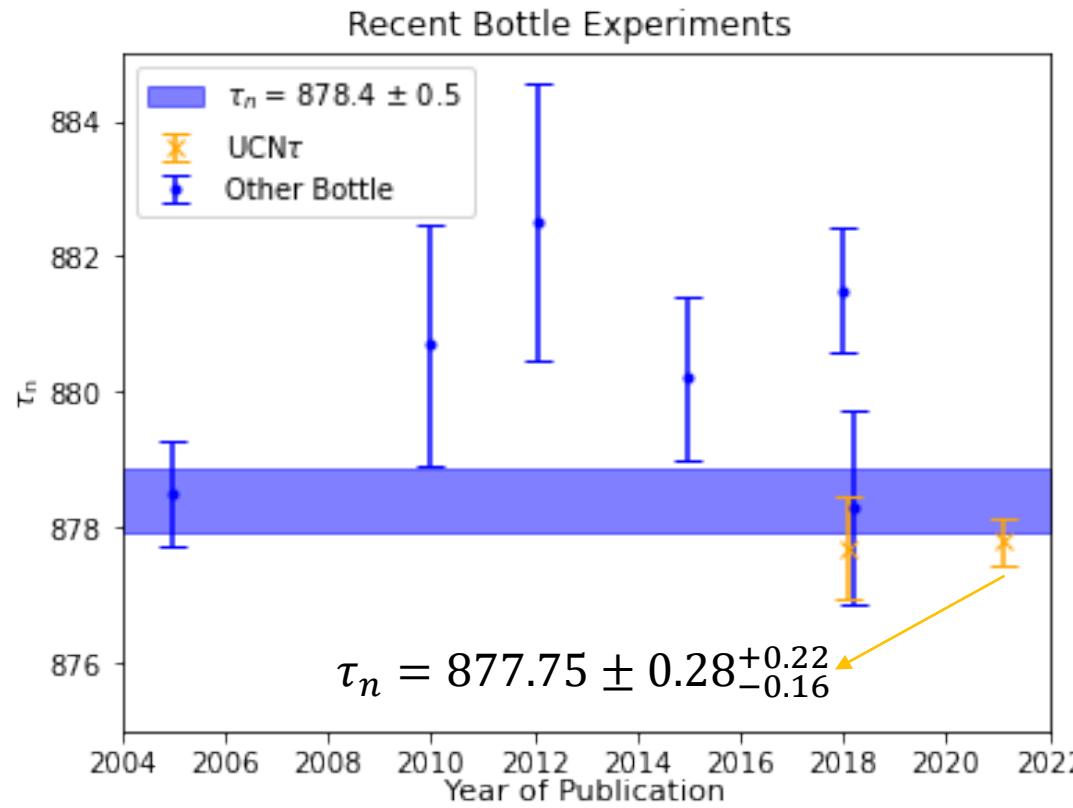
UCNtau results (2018)

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.

Neutron Lifetime Measurements (2021)



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)].

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

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	$0.16^{+0.4}_{-0.2}$	$0.17^{+0.22}_{-0.16}$	
TOTAL	$877.7 \pm 0.7^{+0.4}_{-0.2}$	$877.75 \pm 0.28^{+0.22}_{-0.16}$	

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
878.4 ± 0.5	OUR AVERAGE Error includes scale factor of 1.8. See the ideogram below.		
$877.75 \pm 0.28^{+0.22}_{-0.16}$	GONZALEZ	2021	CNTR UCN asym. magnetic trap
$878.3 \pm 1.6 \pm 1.0$	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. • •

$887 \pm 14^{+7}_{-3}$	⁴ WILSON	2021	CNTR space-based <i>n</i> rate
$887.7 \pm 1.2 \pm 1.9$	⁵ YUE	2013	CNTR In-beam <i>n</i> , trapped <i>p</i>
$881.6 \pm 0.8 \pm 1.9$	⁶ 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

Precision Test on the CKM Unitarity

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

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

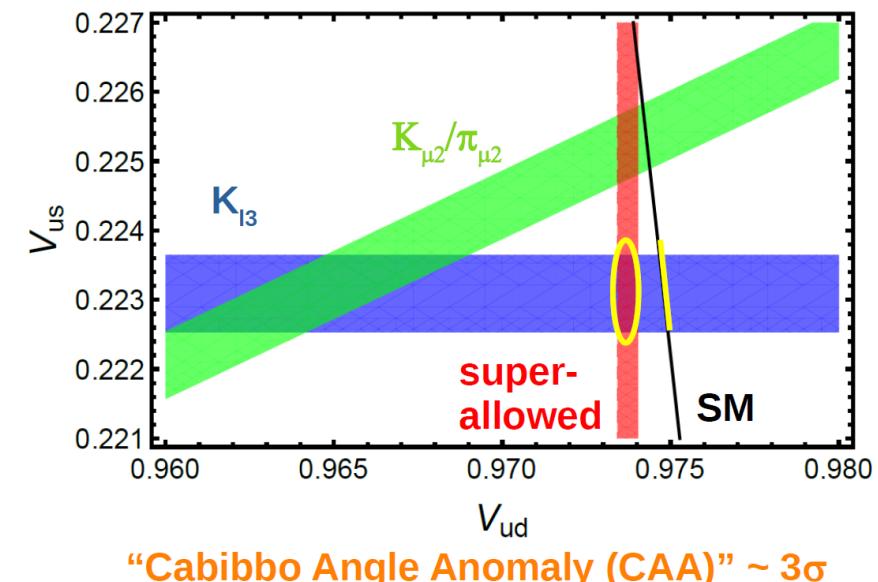
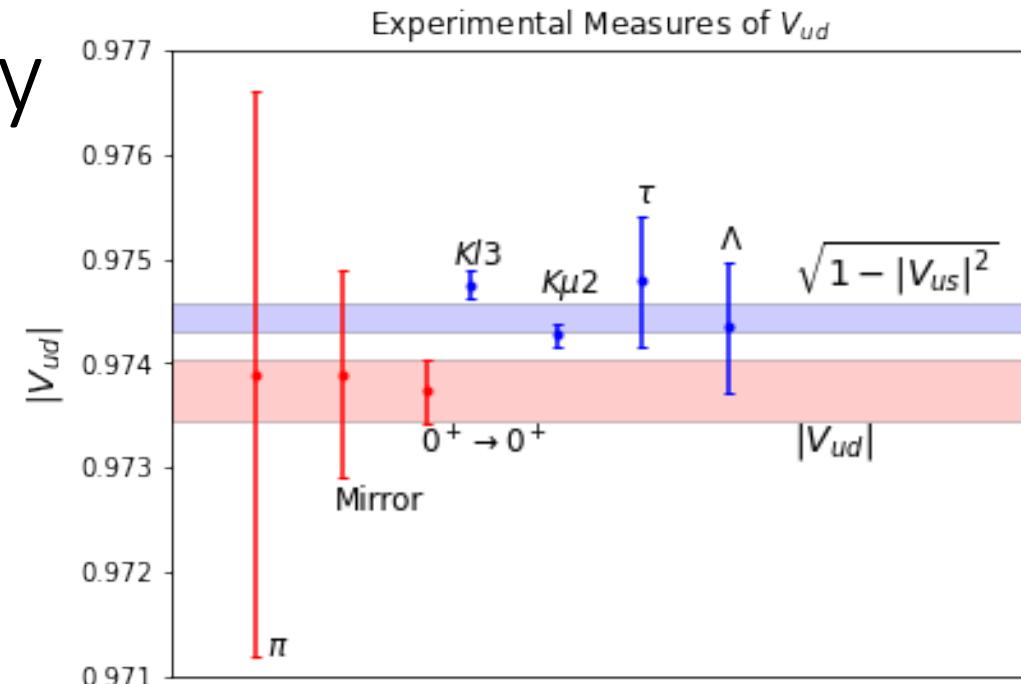
Measurements of V_{ud} :

- 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 ($V_{us} = \lambda = \sin \Theta_c$) between different decay channels
- Also limits from τ and Λ hyperons

Most precise measurements disagree (up to 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

$$|V_{ud}|_{0+}^2 + |V_{us}|_{K_{l3}}^2 + \cancel{|V_{ub}|^2} - 1 = -0.0021(7)$$

SOURCES OF UNCERTAINTY:

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

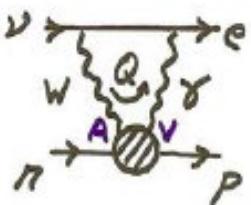


Theory uncertainties in the single-nucleon radiative corrections (RC)

$ V_{ud} _{0+}^2 + V_{us} _{K_{l3}}^2 - 1$	-2.1×10^{-3}
$\delta V_{ud} _{0+}^2$, exp	2.1×10^{-4}
$\delta V_{ud} _{0+}^2$, RC	1.8×10^{-4}
$\delta V_{ud} _{0+}^2$, NS	5.3×10^{-4}
$\delta V_{us} _{K_{l3}}^2$, exp+th	1.8×10^{-4}
$\delta V_{us} _{K_{l3}}^2$, lat	1.7×10^{-4}
Total uncertainty	6.5×10^{-4}
Significance level	3.2σ

Extracting V_{ud} with neutron decays

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



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

From μ -decay: 0.6 ppm (MuLan 2011)

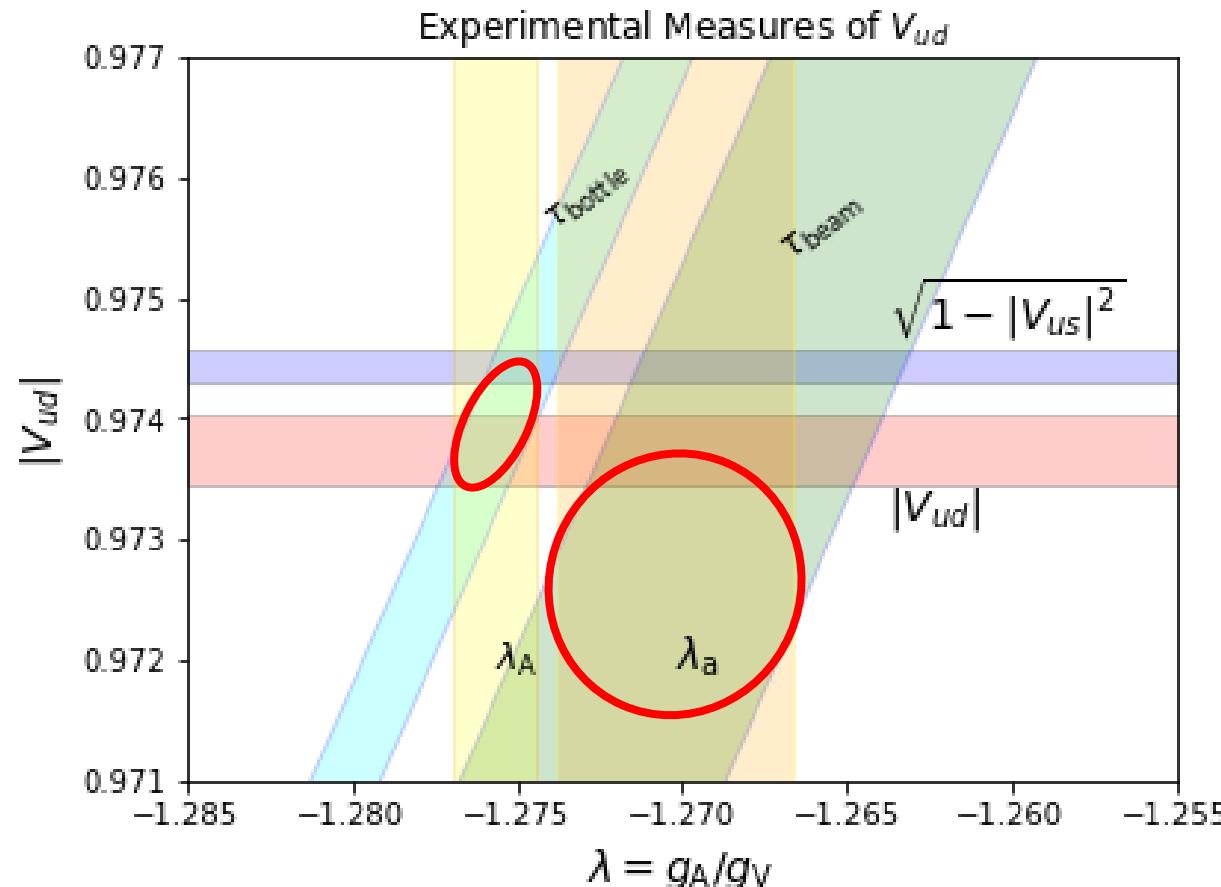
$$|V_{ud}|^2 = \frac{4905.7 \pm 1.7 \text{ s}}{\tau_n(g_V + 3g_A^2)}$$

Marciano & Sirlin, PRL 96, 032002 (2006)

Seng et al, PRL 121 (2018); Seng et al, PRD 100 (2019);

Czarnecki, Marciano & Sirlin, PRD 100 (2019)

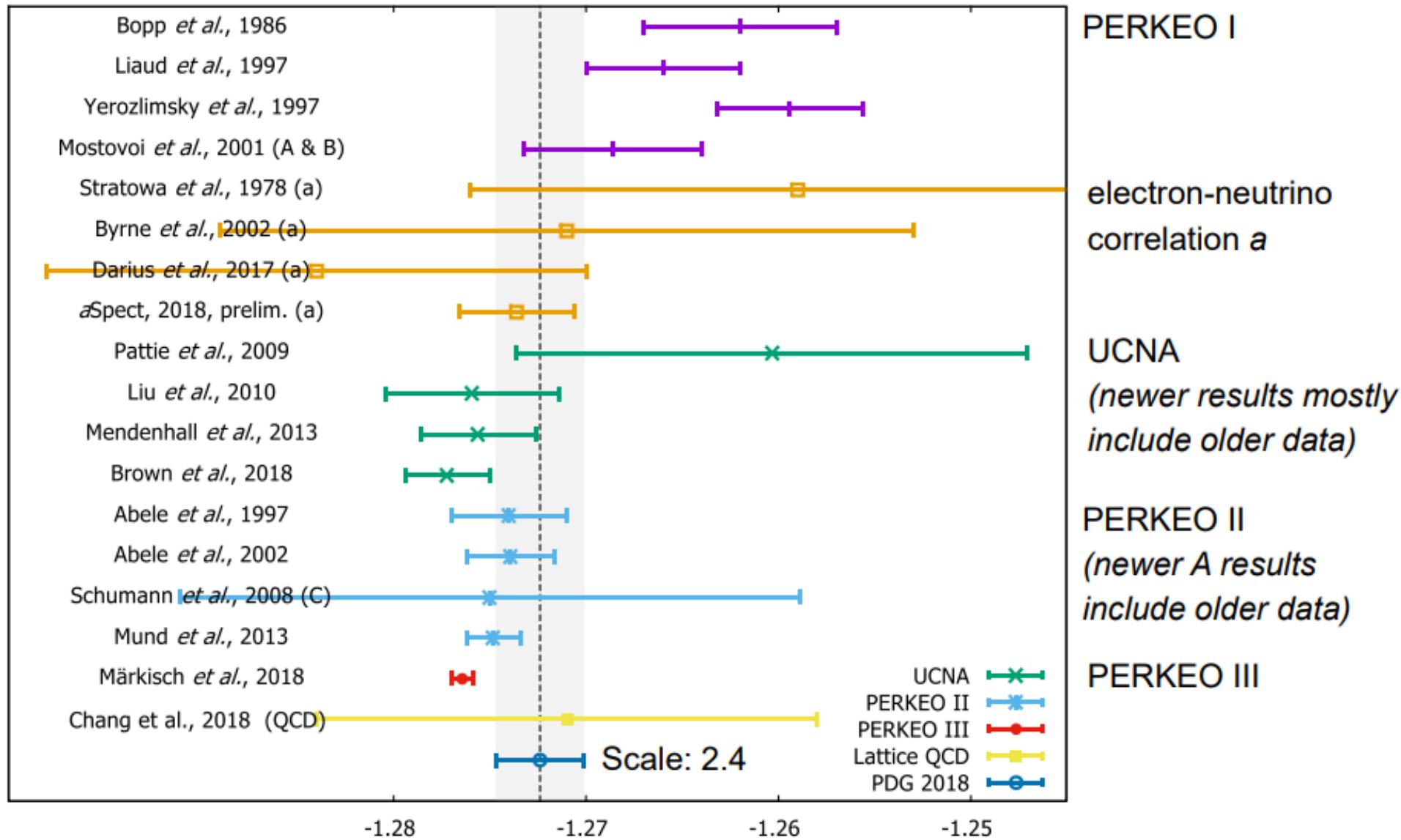
To match the theoretical uncertainty: 3.5×10^{-4} , it requires experimental uncertainties of: $\Delta A/A = 4\Delta\lambda/\lambda < 2 \times 10^{-3}$ and $\Delta\tau/\tau = 3.5 \times 10^{-4}$.



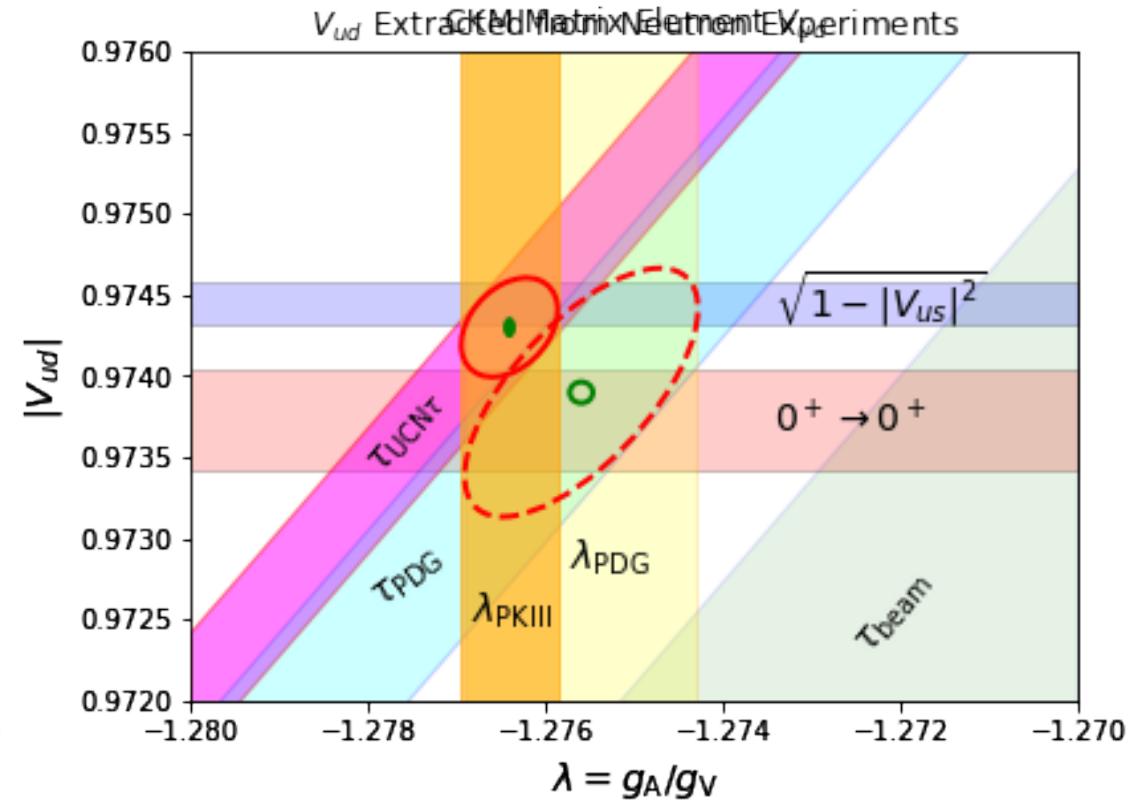
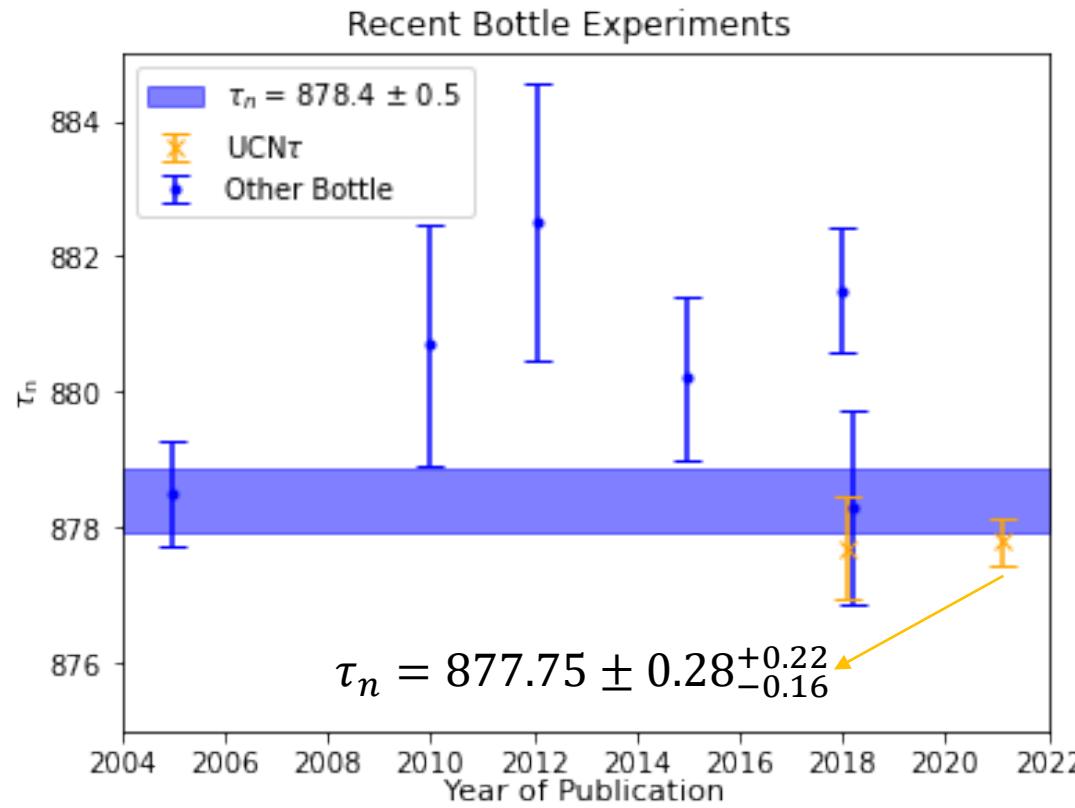
To be consistent with CKM unitarity, it requires a smaller $|g_A|$, or a shorter τ_n .

Axial Coupling: Status

Results from beta asymmetry A, unless where noted otherwise



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



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

Neutron beta-decay shaped the electroweak theory in early days; contemporary neutron experiments continue to push the physics frontier via precision tests of 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 ($\delta\tau_n < 0.1$ s), combined with the beta-decay asymmetry ($\delta A/A < 0.1\%$), test the unitarity of the CKM matrix (to 10^{-4} level of precision) and probe physics beyond the Standard Model. With $\text{UCN}\tau$, 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 either a smaller $|g_A|$ or a shorter τ_n .

Discrepancy with CKM unitarity is an opportunity for new physics.

Moving forward:

- $\text{UCN}\tau +$ (immediate future): elevator loading, reaching $\delta\tau_n = 0.1$ s
- $\text{UCN}\tau 2$ (future): superconducting coils (conceptual design), reaching $\delta\tau_n = 0.01$ s

Postdoc opportunities

We have openings for postdocs and graduate students at University of Illinois Urbana-Champaign. Join us to take the leading role in the following experiments:

- UCNtau
- BL3
- Project-8 (tritium beta-decay to measure the neutrino mass)
- nEDM measurements at LANL & SNS

Please contact me (chenyliu@illinois.edu), if you are interested.

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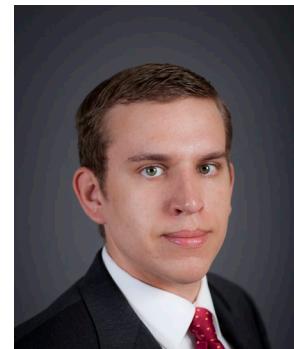


3 independent analyses

- 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



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