Prospects for Precision Measurements of Neutron Decays

Chen-Yu Liu

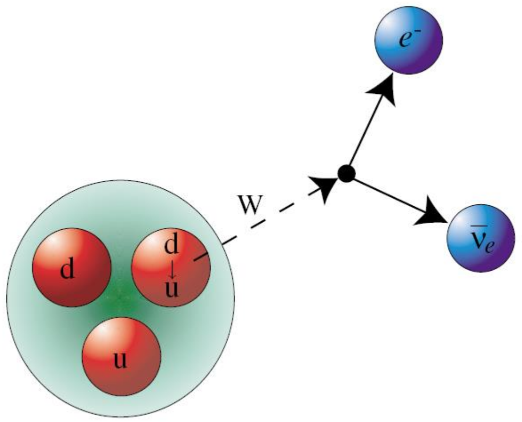
University of Illinois at Urbana-Champaign

10/24/2022

Electro2022, Electroweak Precision Physics from Beta Decays to the Z Pole

Mainz

Theory of Nuclear Beta-decay



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

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

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

Table 1.2. Elementary fermion transition operators

$\hat{O}_i$	Transformation property of $\overline{\Psi}\hat{O}_i\Psi$	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

- S, V → $\phi_p^\dagger \phi_n$ Fermi (spin-preserving)
- T, A → $\phi_p^\dagger \sigma \phi_n$ Gamow-Teller (spin-changing, ΔI = ±1,0)
- P → 0

Spectral measurements (pre-1950)

$$
\begin{aligned}
H_{\text{int}} = & (\bar\psi_p\psi_n)(C_S\bar\psi_e\psi_\nu + C_S'\bar\psi_e\gamma_5\psi_\nu) \\
& + (\bar\psi_p\gamma_\mu\psi_n)(C_V\bar\psi_e\gamma_\mu\psi_\nu + C_V'\bar\psi_e\gamma_\mu\gamma_5\psi_\nu) \\
& + \tfrac{1}{2}(\bar\psi_p\sigma_{\lambda\mu}\psi_n)(C_T\bar\psi_e\sigma_{\lambda\mu}\psi_\nu + C_T'\bar\psi_e\sigma_{\lambda\mu}\gamma_5\psi_\nu) \\
& - (\bar\psi_p\gamma_\mu\gamma_5\psi_n)(C_A\bar\psi_e\gamma_\mu\gamma_5\psi_\nu + C_A'\bar\psi_e\gamma_\mu\psi_\nu) \\
& + (\bar\psi_p\gamma_5\psi_n)(C_P\bar\psi_e\gamma_5\psi_\nu + C_P'\bar\psi_e\psi_\nu) \\
& + \text{Hermitian conjugate},
\end{aligned}
$$

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

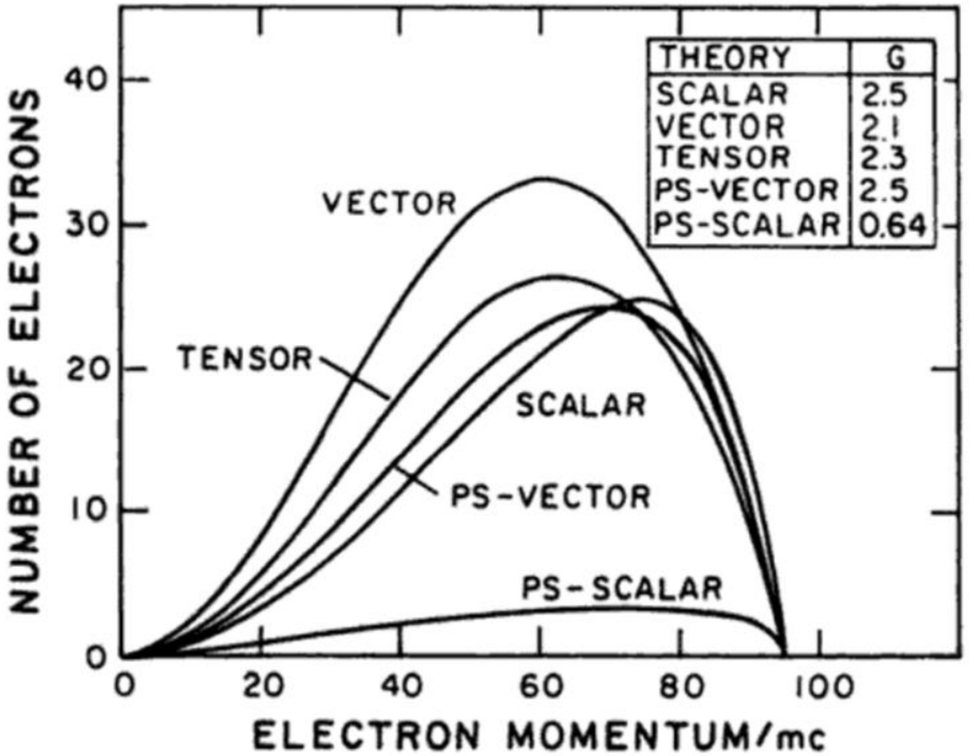
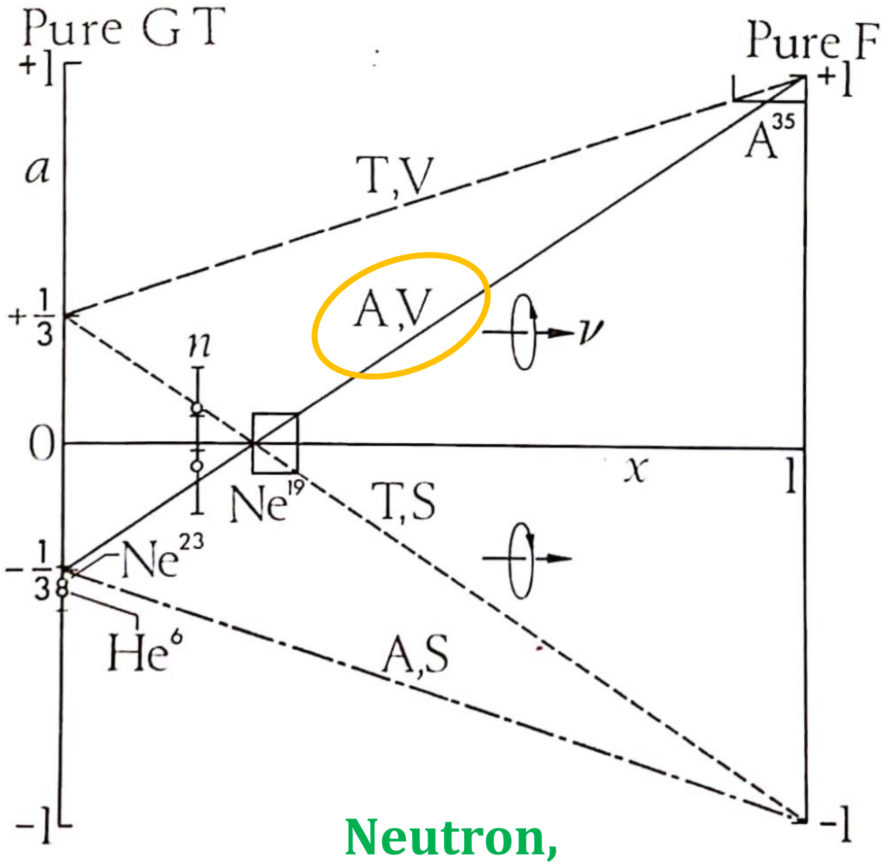


Figure 2.4. "Influence of form of coupling on shape of spectrum for fixed values of the mass of the μ-and μ_0 meson. Contrast this result with the case of ordinary beta-decay, where the atomic nucleus has negligible velocity and the decay curves have the same shape in all five cases" (Tiomno and Wheeler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

Experimental evidence supports the "V—A" structure (nuclear data)

beta-neutrino correlation, "a"



Superallowed $0^+ \rightarrow 0^+$

^{10}C, ^{14}O, etc.

^{6}He, ^{8}Li, …

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

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

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. Telegdi, *University of Chicago, Chicago, Illinois*

(Received April 17, 1958)

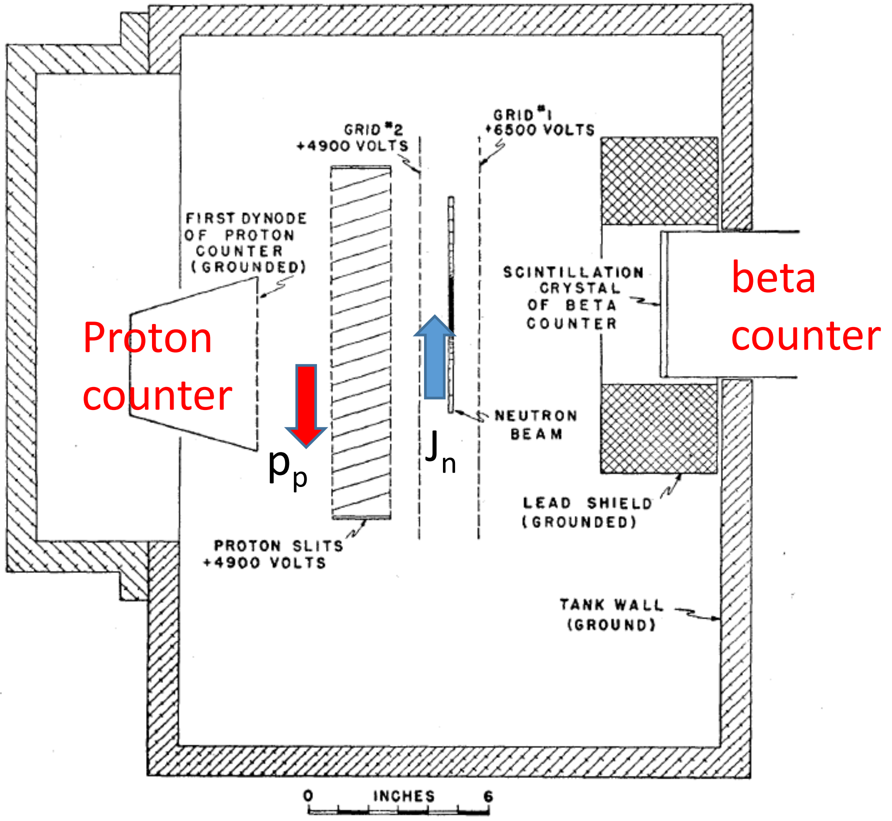


Fig. 1. Vertical cross section (normal to the neutron beam) through the detector system of the experiment measuring the correlation of the neutrino momentum and the neutron spin.

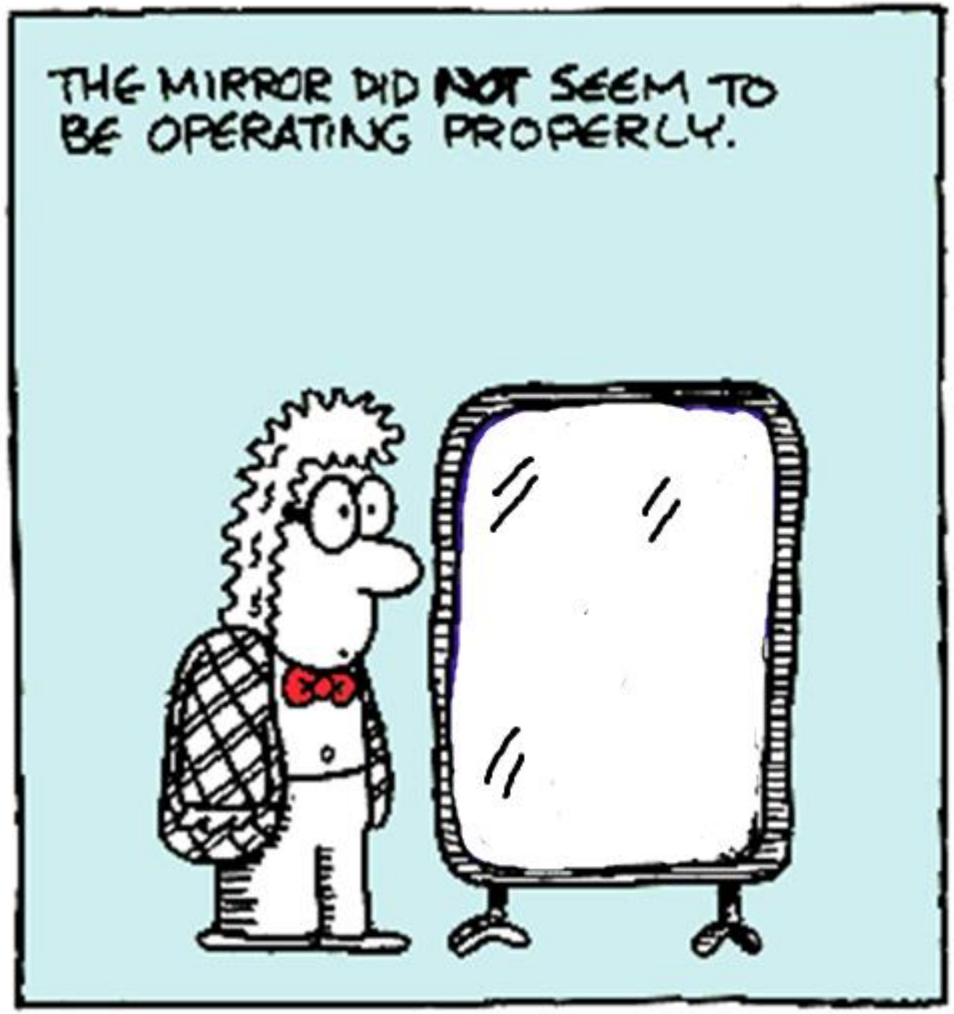
a (beta-neutrino correlation)
B (neutrino asymmetry)

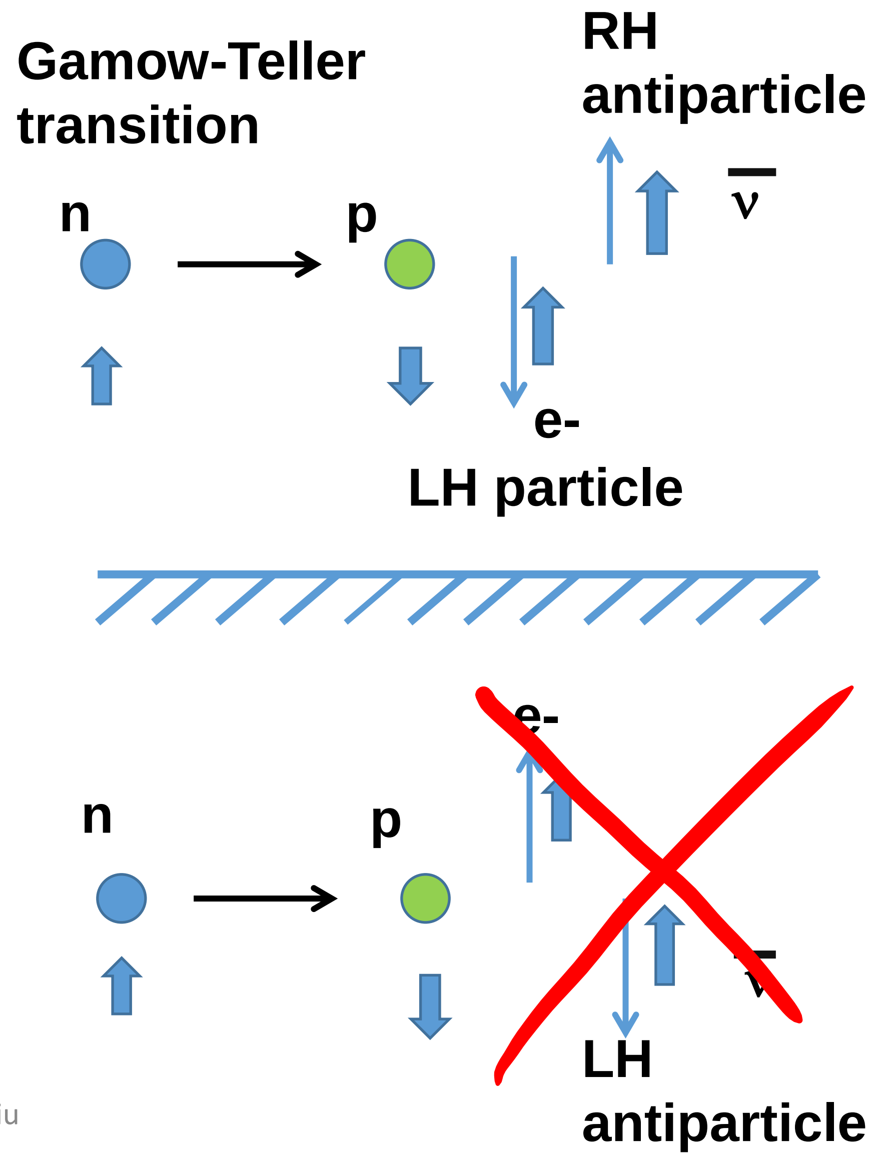
Table II. Predicted values for $\mathfrak{A}$ and $\mathfrak{B}$.

	$S+T$[a]		$S-T$		$V+A$		$V-A$[a]		
	$\bar{\nu}_L$[b]	$\bar{\nu}_R$	$\bar{\nu}_L$	$\bar{\nu}_R$	$\bar{\nu}_L$	$\bar{\nu}_R$	$\bar{\nu}_L$	$\bar{\nu}_R$	Exp.
$\mathfrak{A}$	−1	+1	−0.07[c]	0.07	+1	−1	0.07	−0.07	−0.09
$\mathfrak{B}$	−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 $C_i/C_i'=-1\,(+1)$.
[c] The uncertainty of ±0.05 in x introduces an uncertainty of ±0.02 in this number, 0.07, wherever it appears.

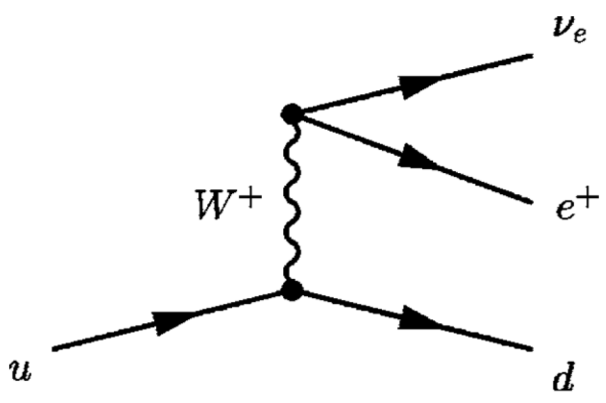
"V–A" → The Spatial Inversion Symmetry (or Parity) is Broken!





Girl before a mirror,
Pablo Picasso (1932)

Neutron beta-decay (minimal V—A)

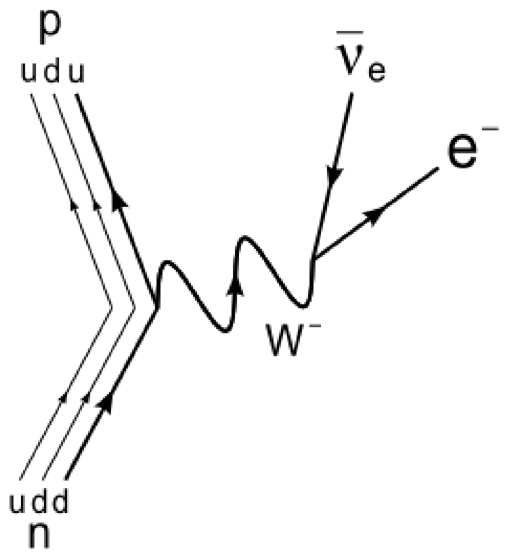


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabbibo-Kobayasi-Maskawa (CKM) matrix

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

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



= 1 (CVC)

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

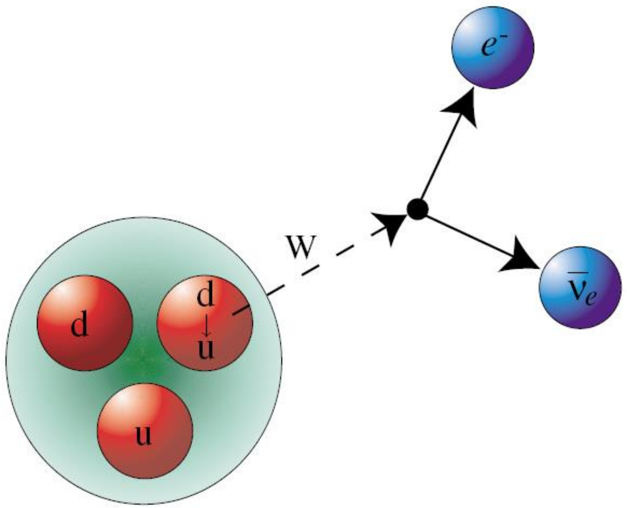
$$g_A (\bar{p}\gamma_\mu \gamma_5 n) = \langle p | \bar{u}\gamma_\mu \gamma_5 d | n \rangle$$

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

Gerstein S. S. and Zeldovich Ya. B.: Zh. Eksp. Teor. Fiz. *29* (1955) 698.
Feynman R. P. and Gell-Mann M.: Phys. Rev. *109* (1958) 193.

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

$$p + p \longrightarrow \underset{}{\overset{(np)}{D}} + e^{+} + \nu$$

$$p + p + e^{-} \longrightarrow \underset{(np)}{D} + \nu$$

BBN and neutron stars

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

$$p + e^{-} \longleftrightarrow n + \nu$$

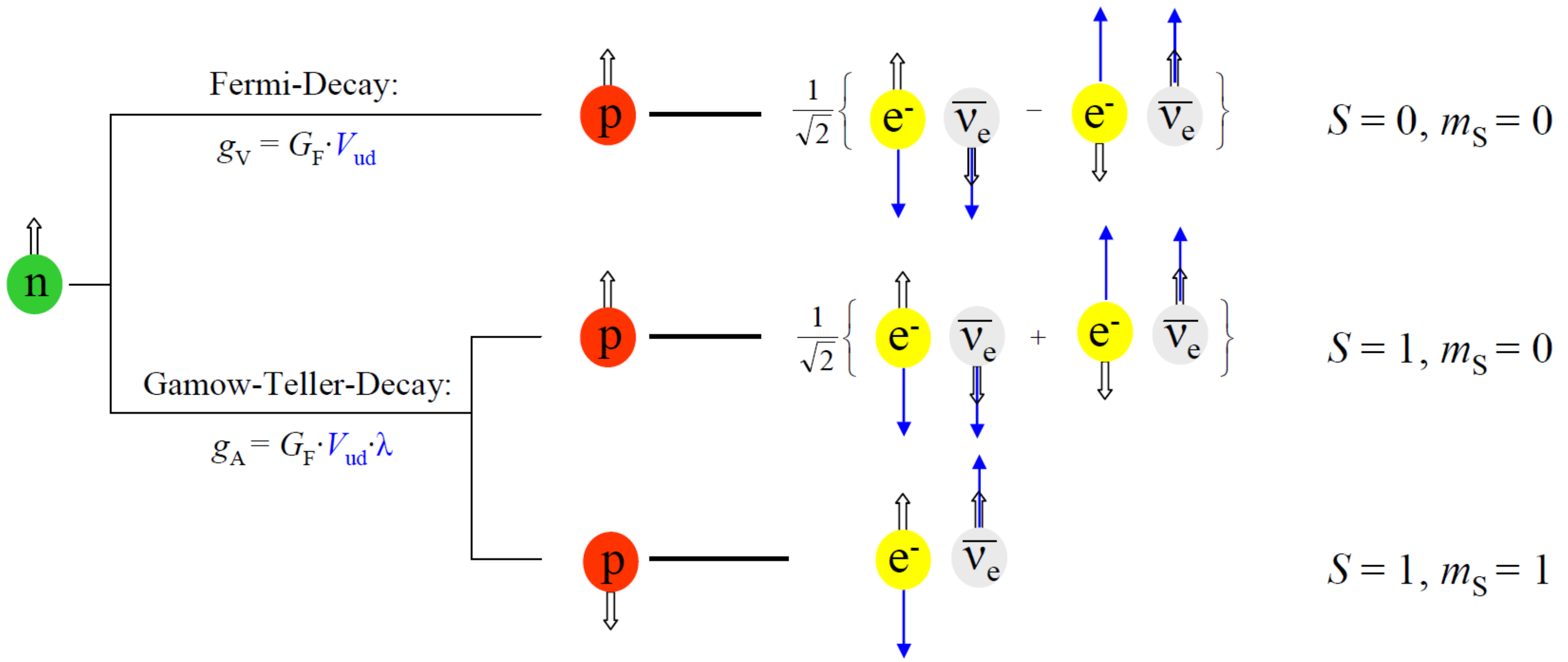
$$n + e^{+} \longleftrightarrow p + \bar{\nu}$$

(anti)neutrino detection

$$\nu + n \longrightarrow e^{-} + p$$

$$\bar{\nu} + p \longrightarrow e^{+} + n$$

Neutron beta-decay

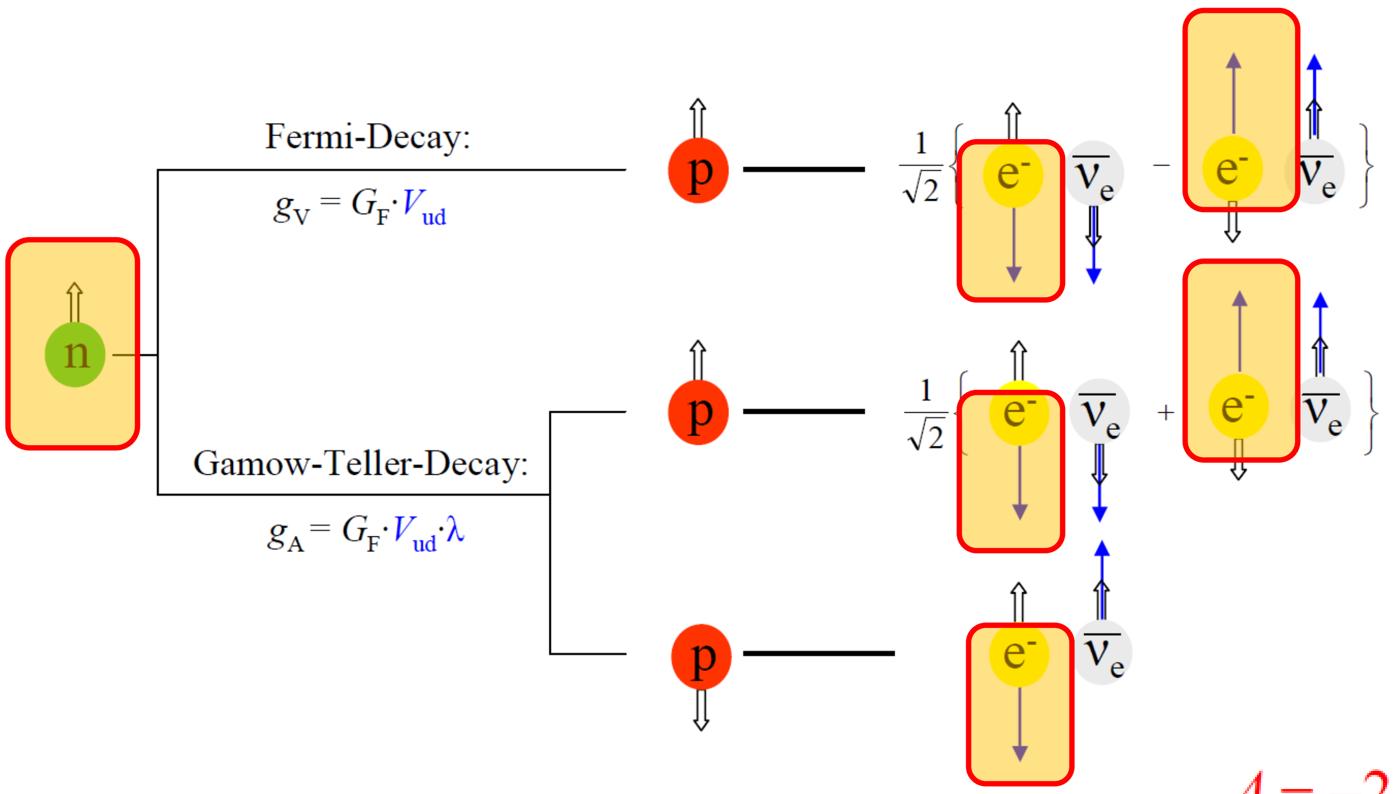


Two unknown parameters, g_A and g_V, need to be determined in 2 experiments

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

Slide credit: Stefan Baeβler

Neutron beta-decay & angular correlations



Beta asymmetry

A = 0

A = 0

A =-1

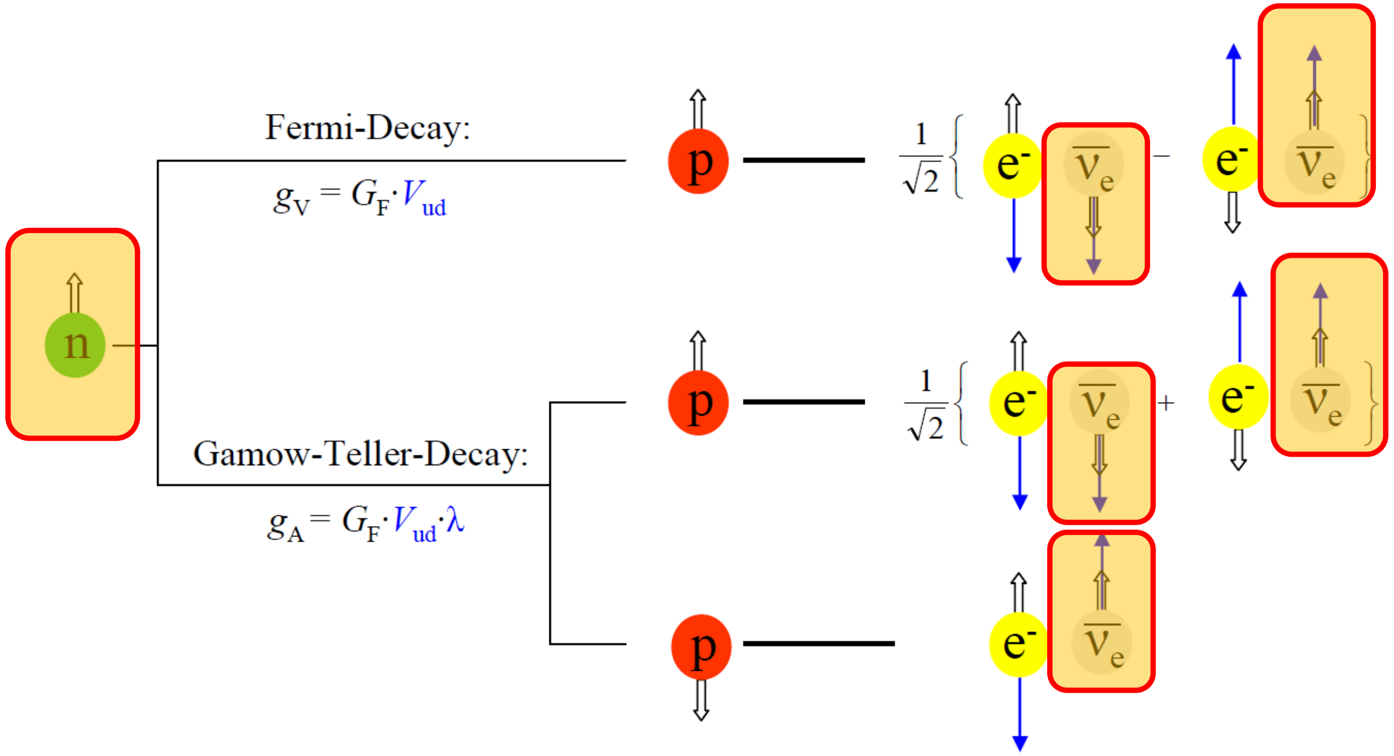
$$A = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \approx -0.1$$

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

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

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

Neutron beta-decay & angular correlations



Beta asymmetry	Neutrino asymmetry
A = 0	B = 0
A = 0	B = 0
A =-1	B = 1

$$A = -2\frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \approx -0.1$$

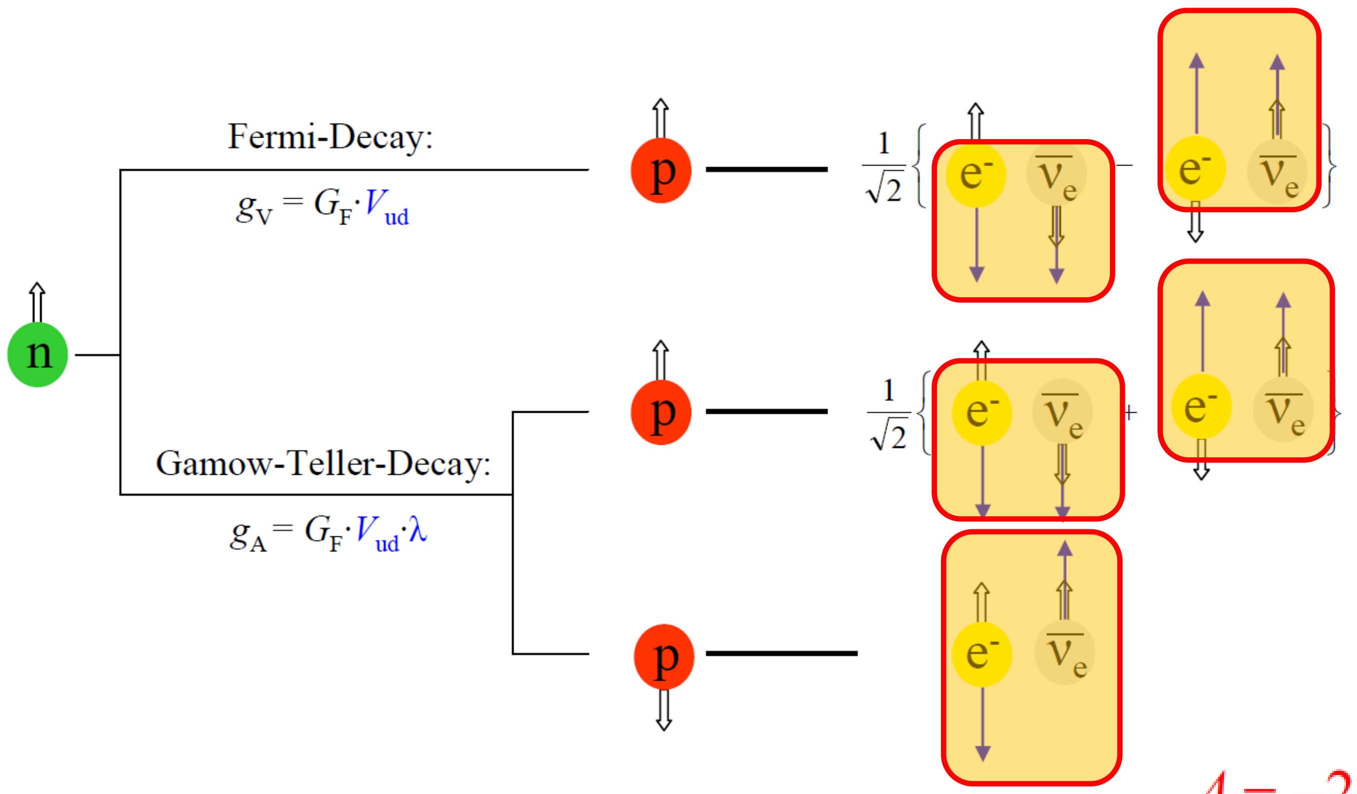
Two unknown parameters, g_A and g_V, need to be determined in 2 experiments

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



Beta asymmetry	Neutrino asymmetry	beta-neutrino correlation
A = 0	B = 0	a = 1
A = 0	B = 0	a = 1
A =-1	B = 1	a = -1

$$A = -2\frac{\lambda^2 + \lambda}{1+3\lambda^2} \approx -0.1 \qquad a = \frac{1-\lambda^2}{1+3\lambda^2} \sim -0.1$$

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

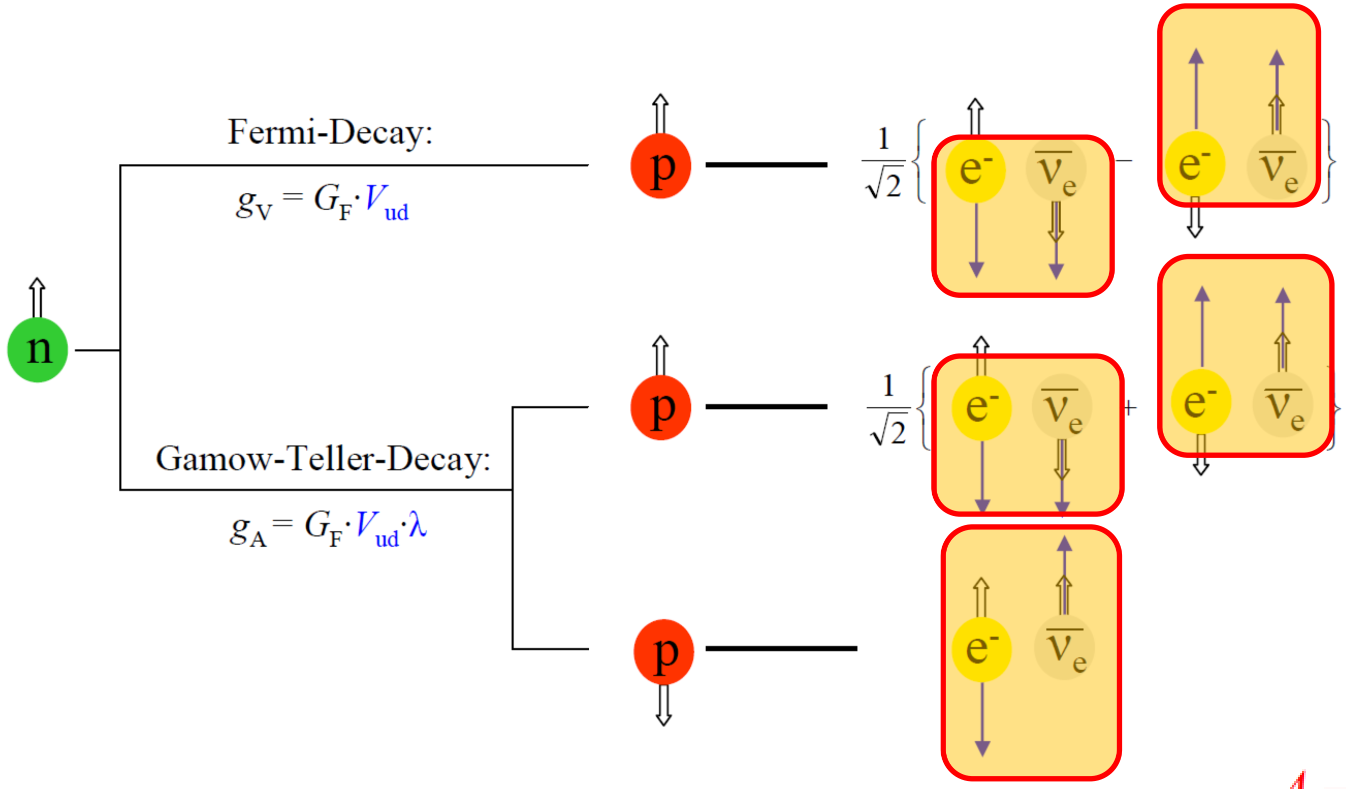
$$B = 2\frac{\lambda^2 - \lambda}{1+3\lambda^2} \approx 0.98$$

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

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

Slide credit: Stefan Baeβler

Neutron beta-decay & angular correlations



Beta asymmetry	Neutrino asymmetry	beta-neutrino correlation
Perkeo III **UCNA+,** **PERC**		**Nab**

$$A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2} \approx -0.1$$

$$a = \frac{1-\lambda^2}{1+3\lambda^2} \sim -0.1$$

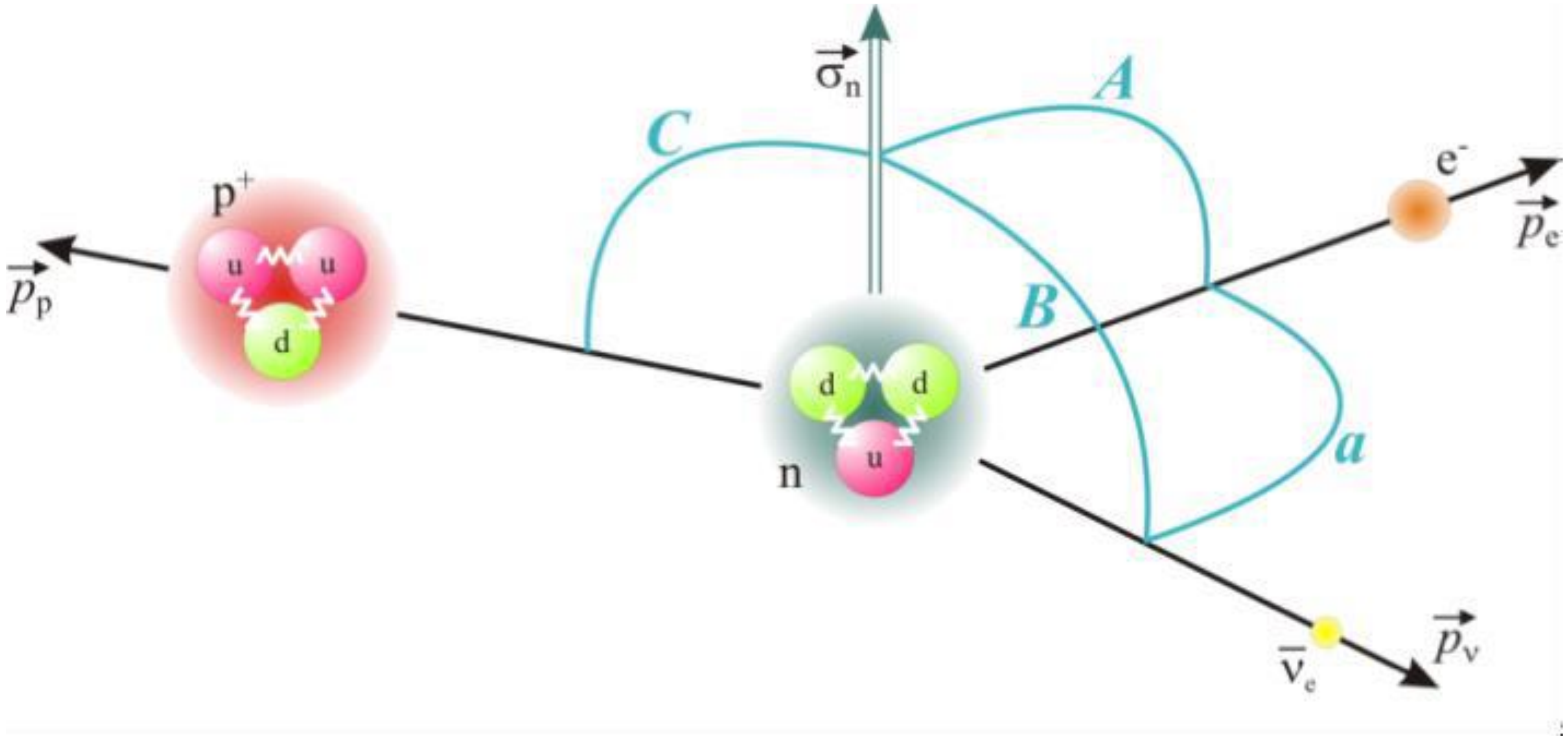
$$B = 2\frac{\lambda^2-\lambda}{1+3\lambda^2} \approx 0.98$$

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

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

UCNtau, BL2, BL3, J-PARC lifetime, …

Beta-decay Alphabets

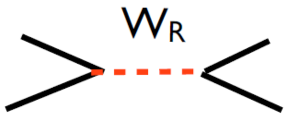


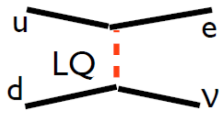
Beta decays and new physics models

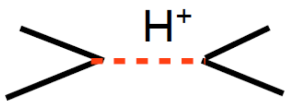
- Model → <u>set overall size and pattern</u> of effective couplings
- Beta decays can play very useful diagnosing role
- Qualitative picture:

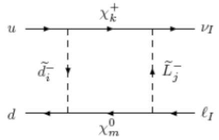
Can be made quantitative

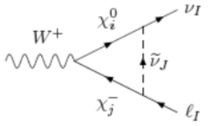
	ε_L	ε_R	ε_P	ε_S	ε_T
LRSM	x	✓	x	x	x
LQ	✓	x	✓	✓	✓
2HDM	x	x	✓	✓	x
MSSM	✓	✓	✓	✓	✓
YOUR FAVORITE MODEL		...		...	





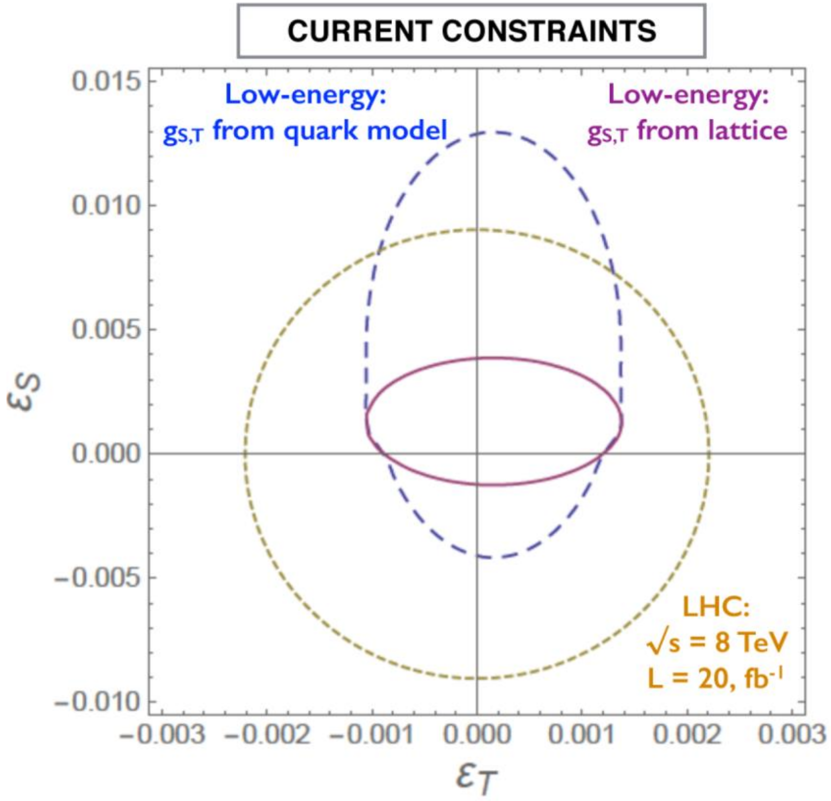


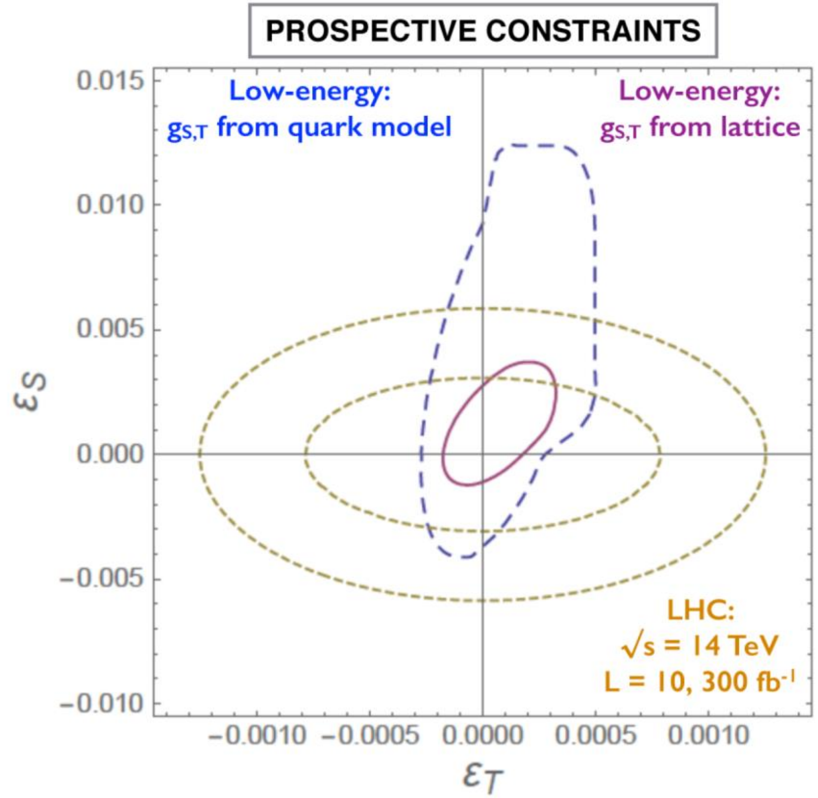




Slide credit: V. Cirigliano

Scalar and Tensor Couplings – beyond the Standard Model

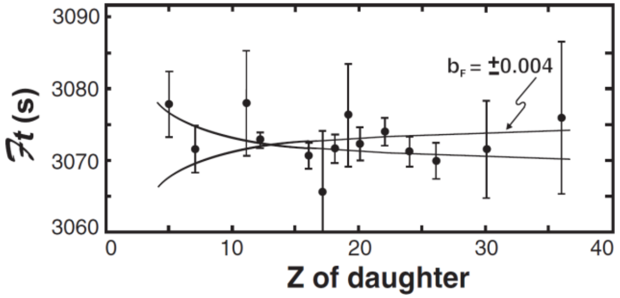




Scalar Currents: b_F

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

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



LHC: $pp \to e\nu + X$

ε_S: $0^+ \to 0^+$ Fierz b_F

ε_T: $\pi \to e\,\nu\,\gamma$

$\Lambda_S > 7\,\text{TeV}$

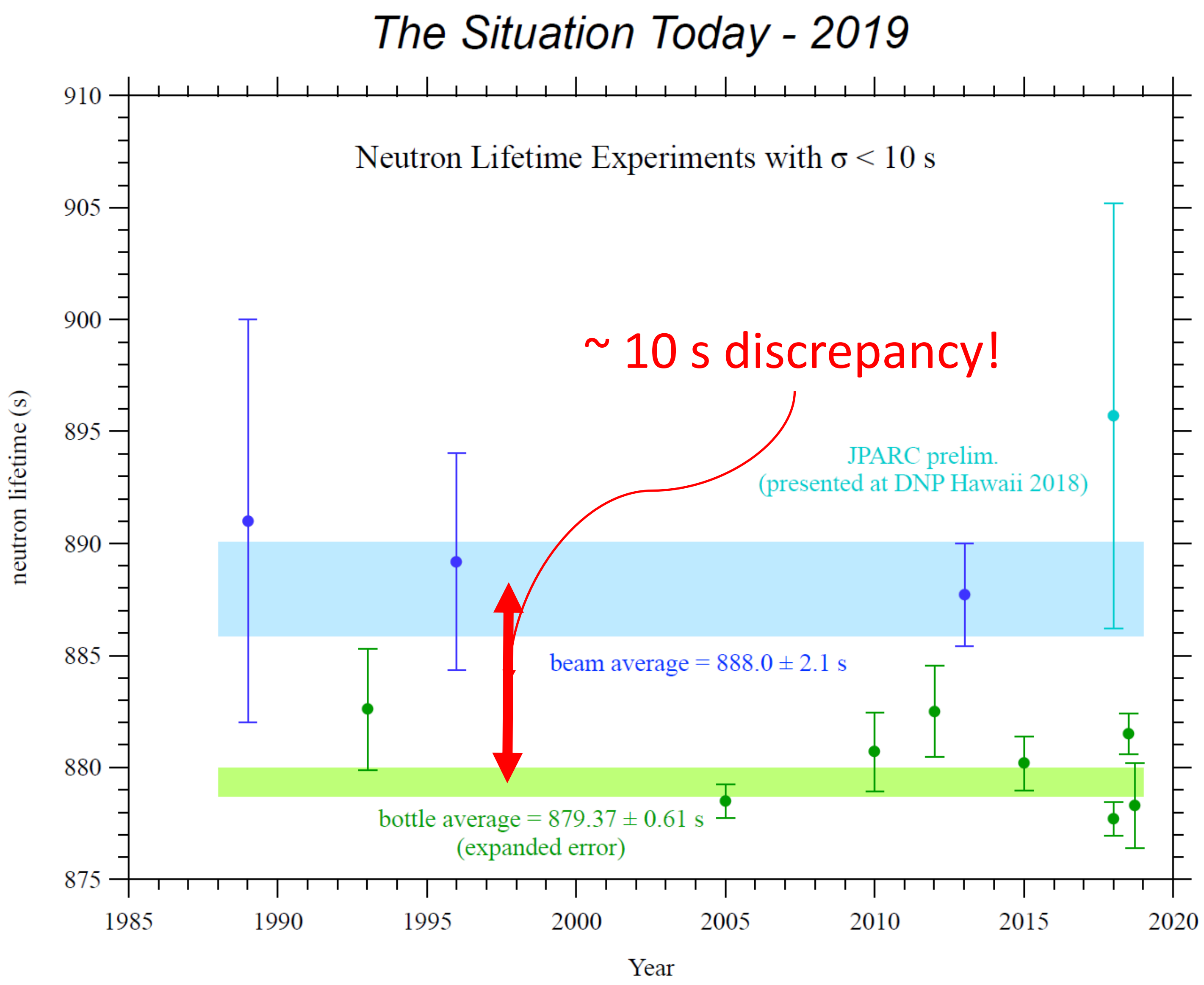
$\Lambda_T > 13\,\text{TeV}$

Future $\varepsilon_S, \varepsilon_T$: Neutron b, b_ν

Future ε_T: ^{6}He b

T. Bhattacharya, V. Cirigliano, S.D. Cohen, R. Gupta, H.-W. Lin, and B. Yoon (PNDME Collaboration), PRD 94, 054508 (2016)

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



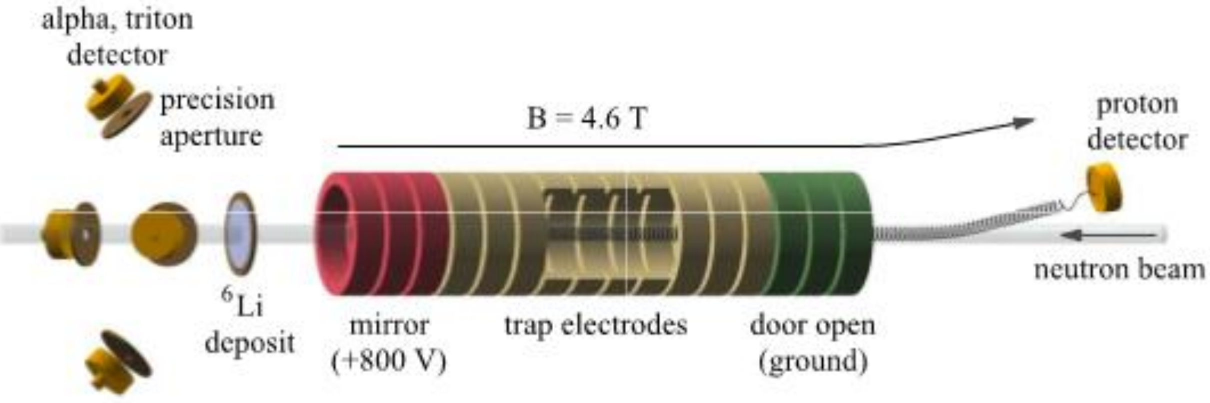
Neutrons in a bottle seem to disappear faster ???

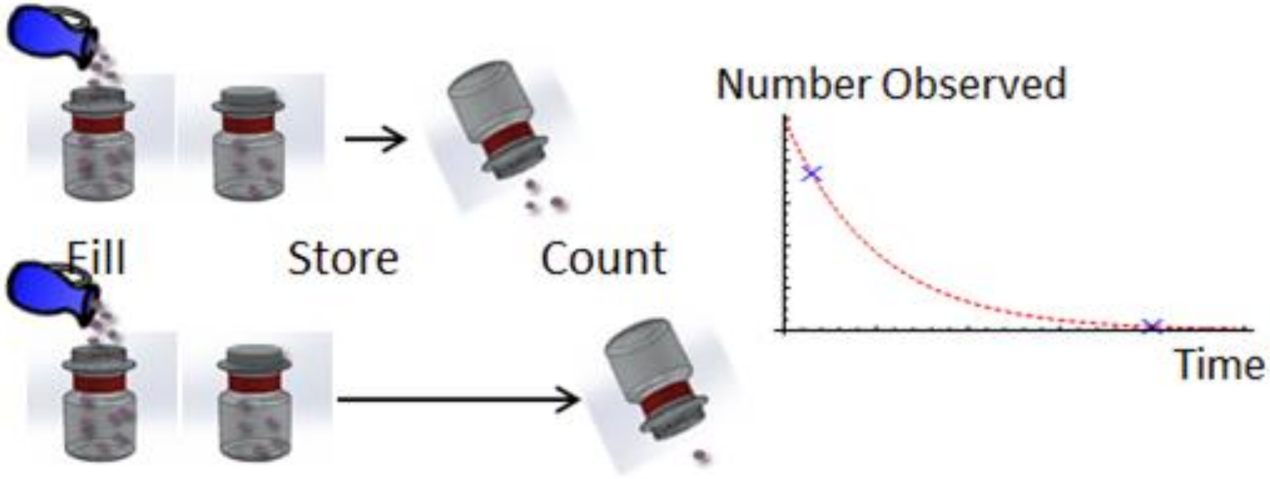
“beam” VS “bottle”

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

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

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





BL3 talk, Fred Wietfeldt

count the dead
(appearance)

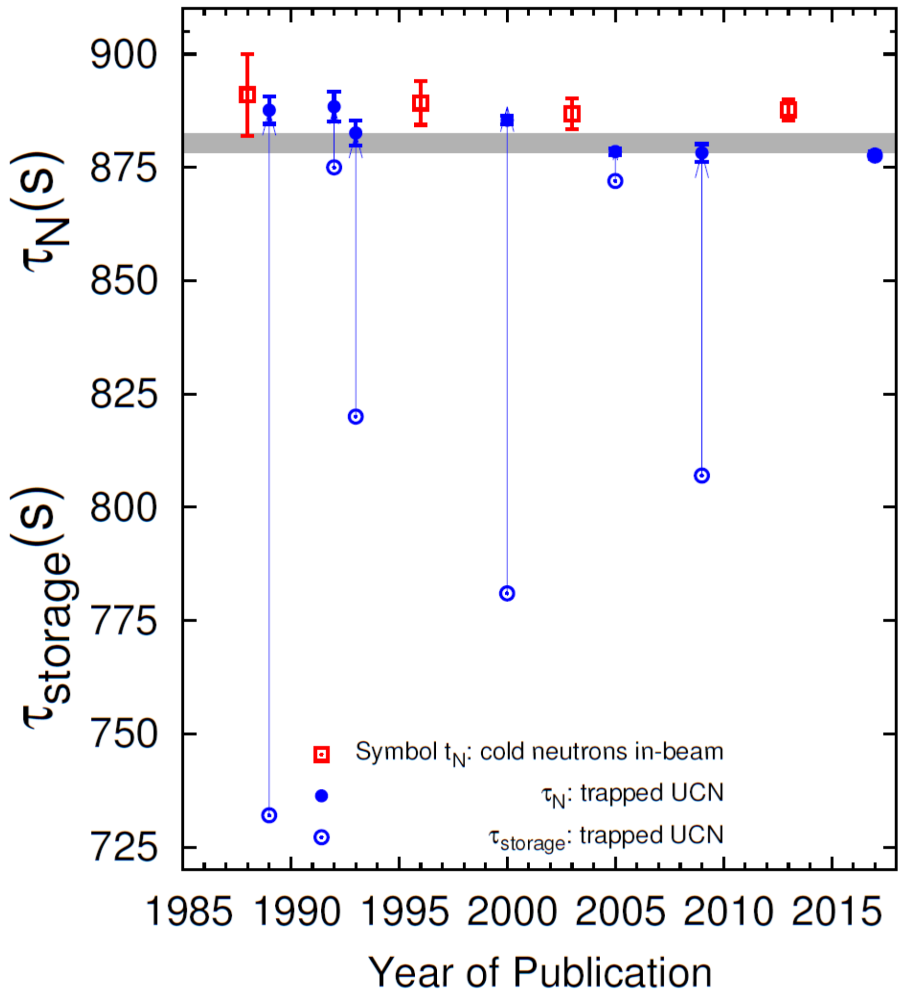
≠
?????

count the living
(disappearance)

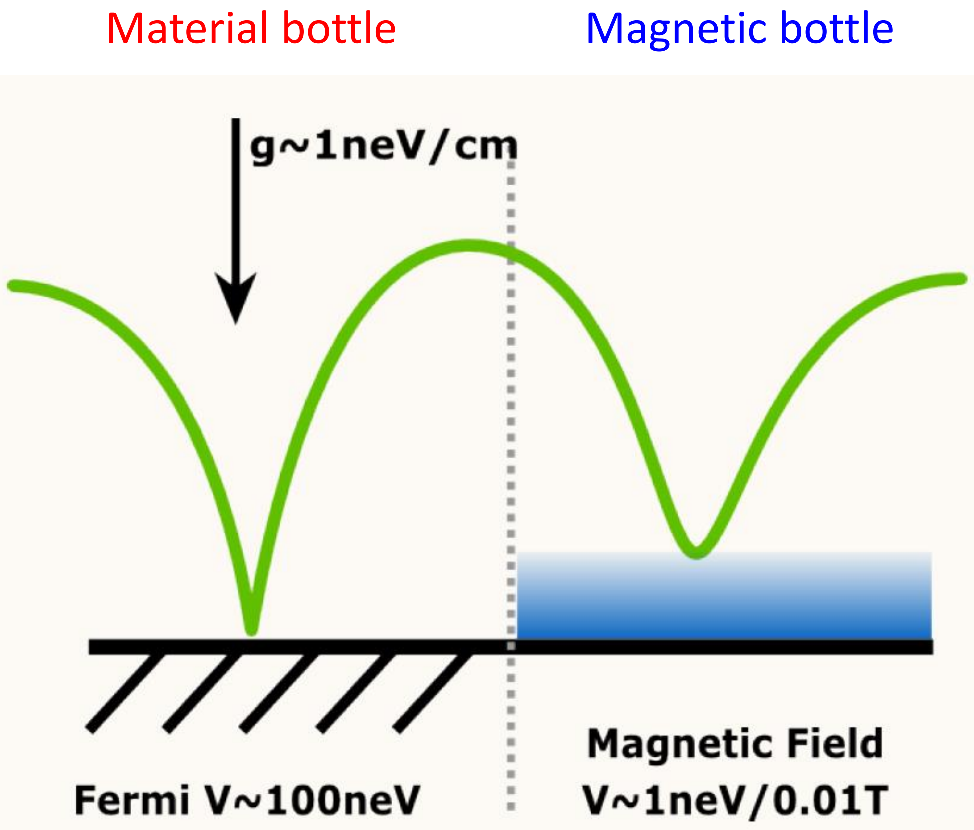
Many experiments need to correct for the systematic effects and extrapolate from the measured lifetime to report the Neutron Lifetime

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

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

The UCNτ Magneto-Gravitational Trap using a "Halbach" array

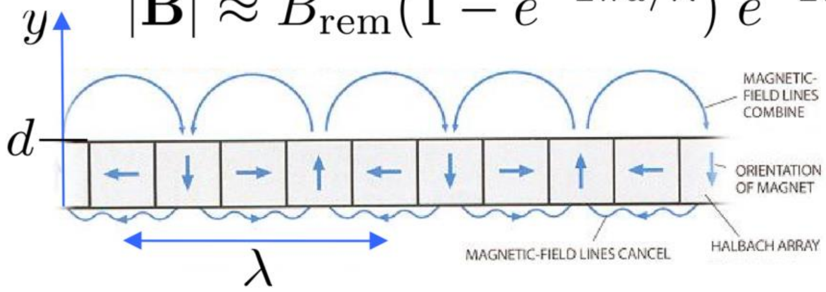
DESIGN OF PERMANENT MULTIPOLE MAGNETS WITH ORIENTED RARE EARTH COBALT MATERIAL*

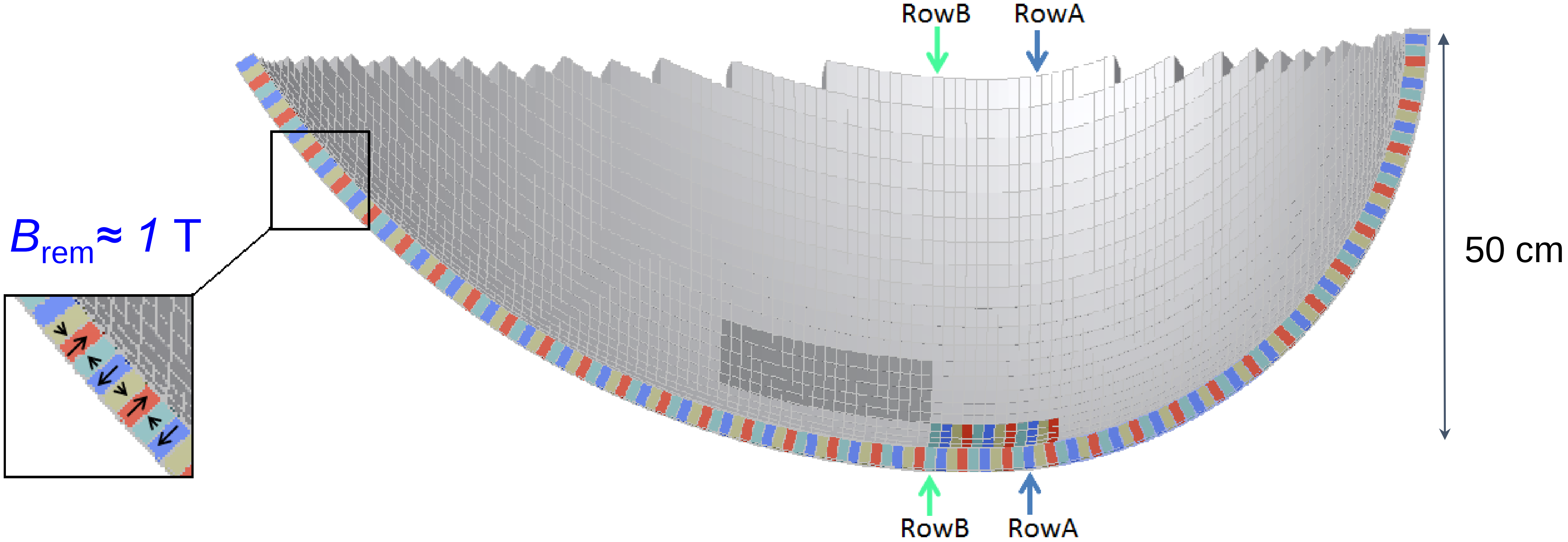
K. HALBACH

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

Received 20 August 1979

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





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

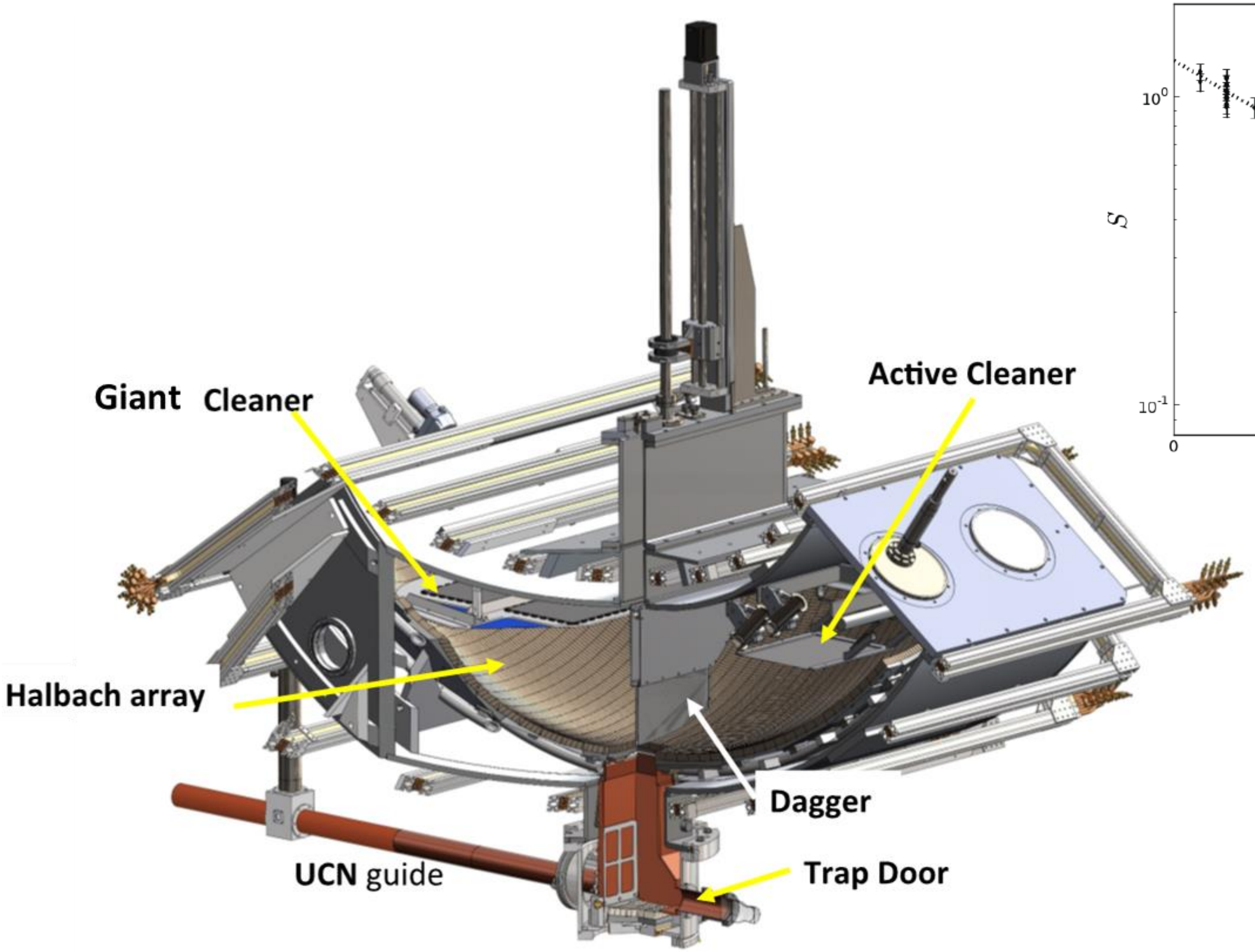
← Tweet

Chris Hadfield
@Cmdr_Hadfield

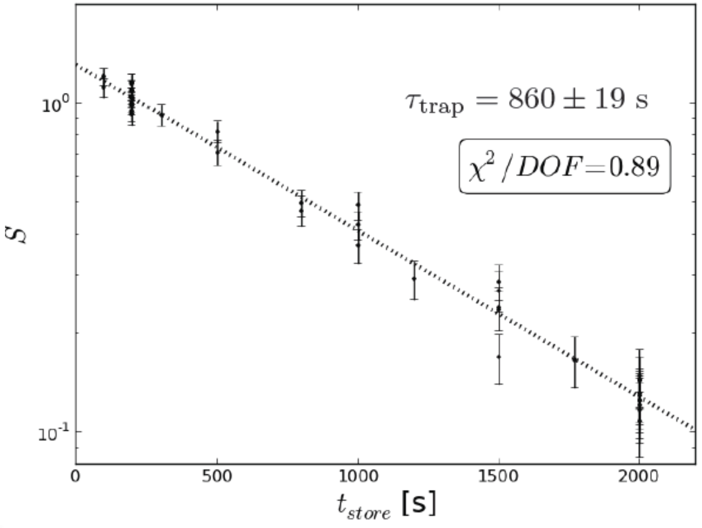
That's Bailey in a neutron bottle. She helped discover that neutrons in the wild last 14.629 minutes (in an atom they can last billions of years).
@LosAlamosNatLab
The details: bit.ly/3mBp5Tm

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

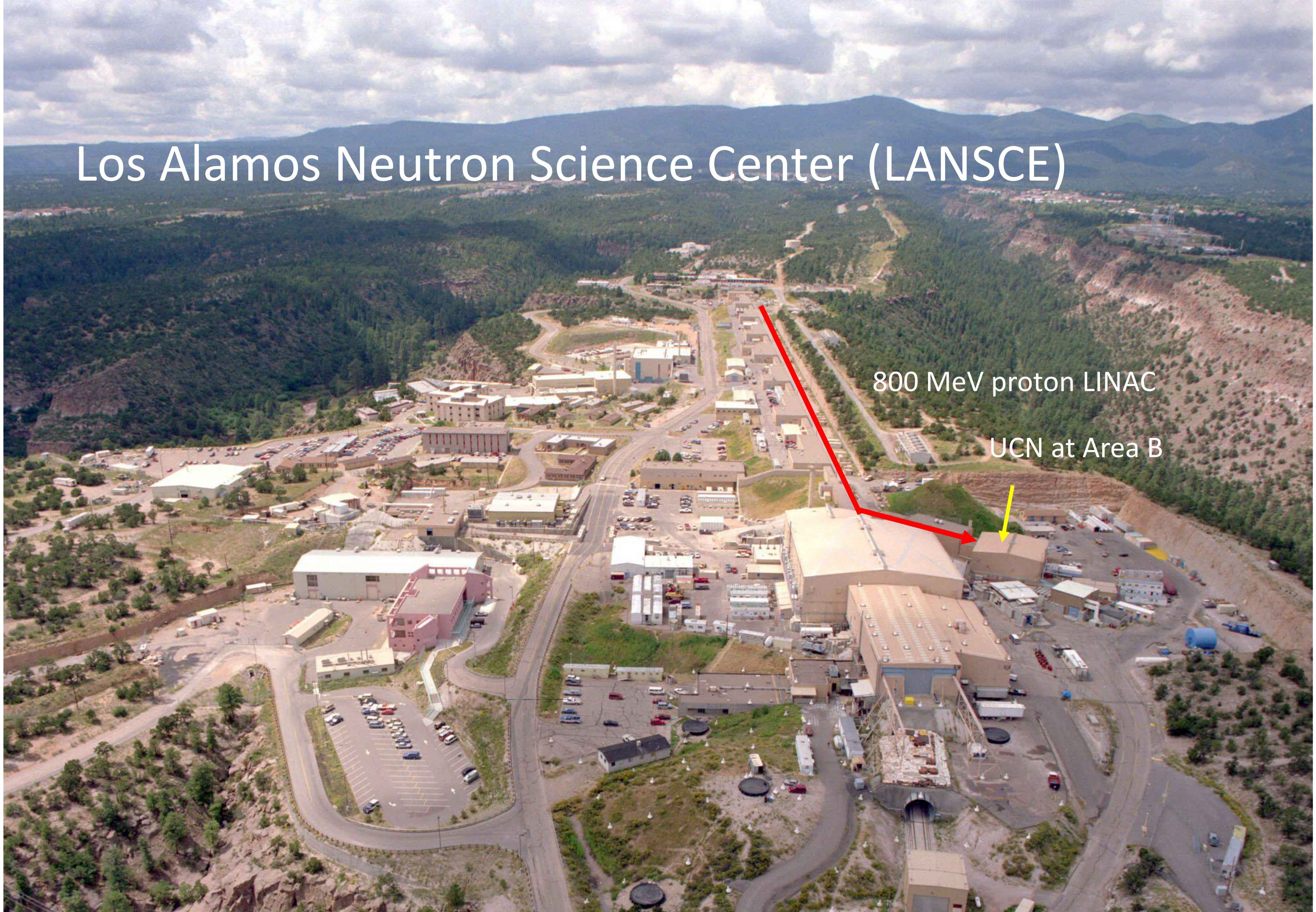
The UCNτ Apparatus



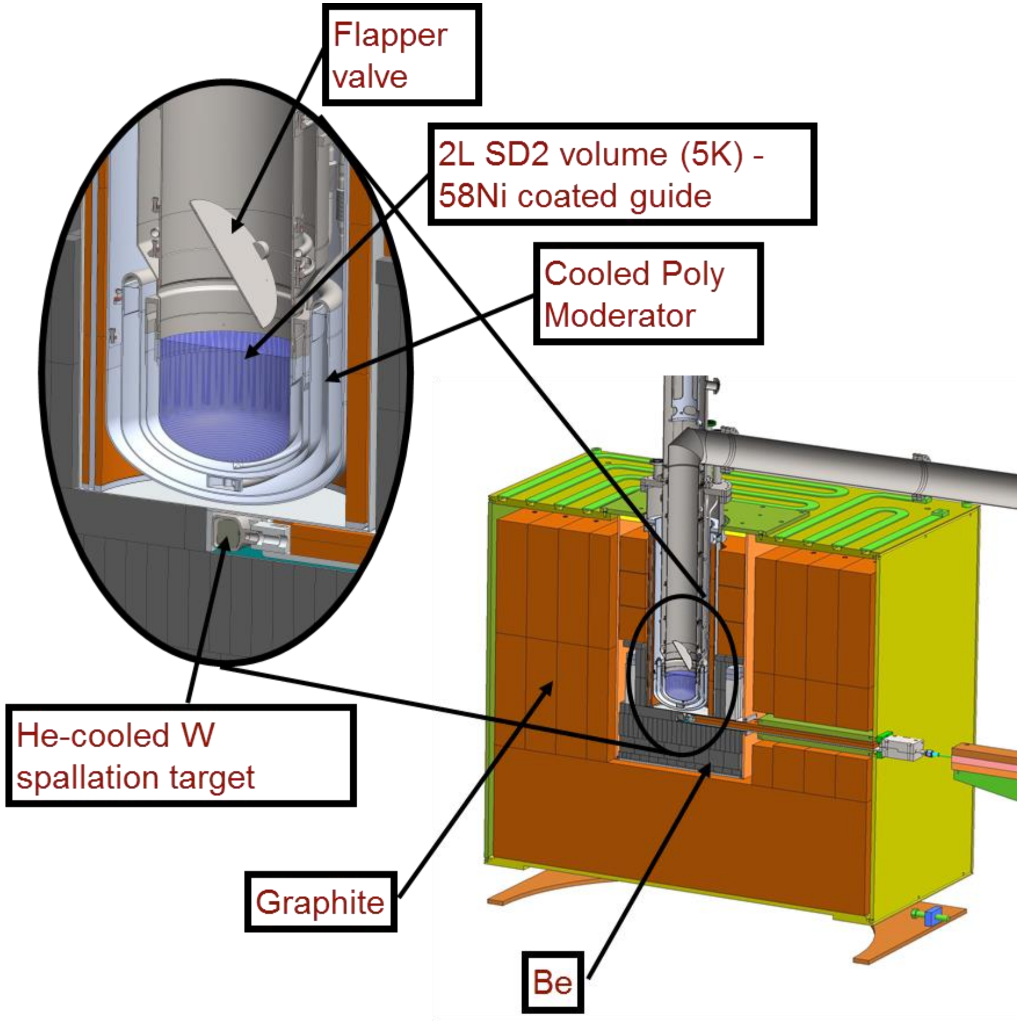
First Physics Data: 2013



D. Salvat, PRC 89, 052501 (2014)

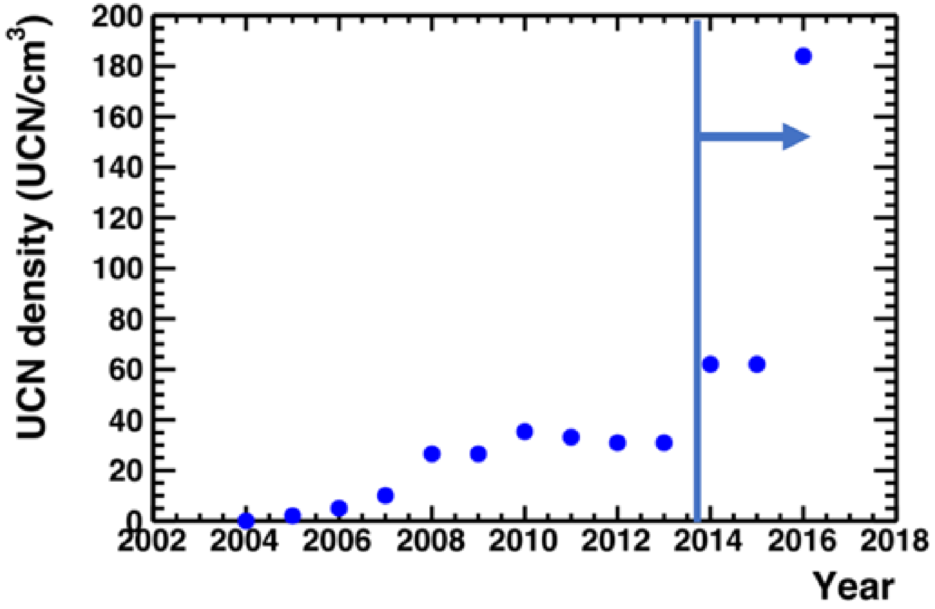

Los Alamos Neutron Science Center (LANSCE)
800 MeV proton LINAC
UCN at Area B

UCN "*Pokotilovsky*" source operating at the Los Alamos Neutron Science Center (LANSCE)



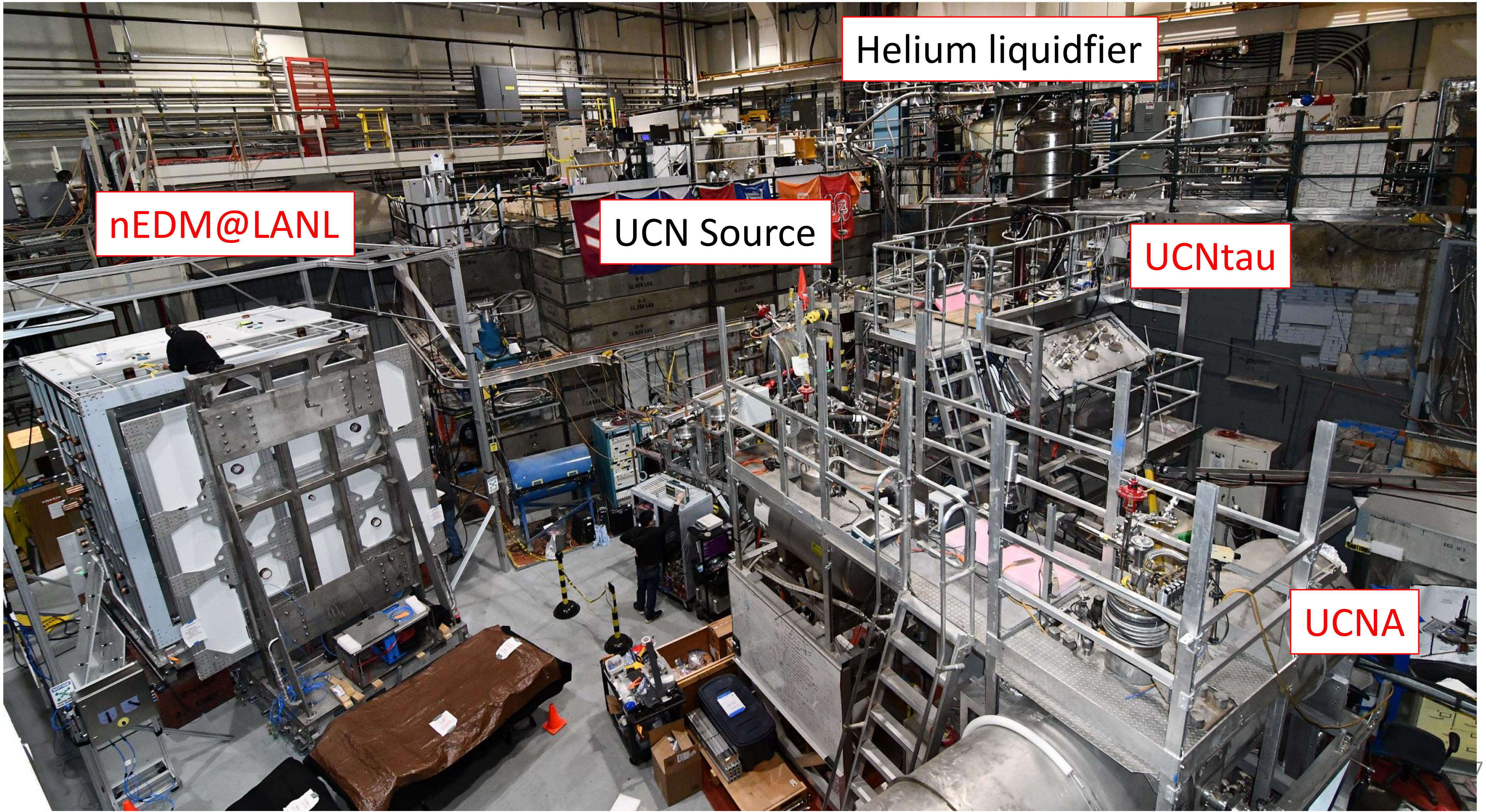
Source upgrade (2016):
- Better moderator cooling
- NiP guides
- Optimized geometry

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

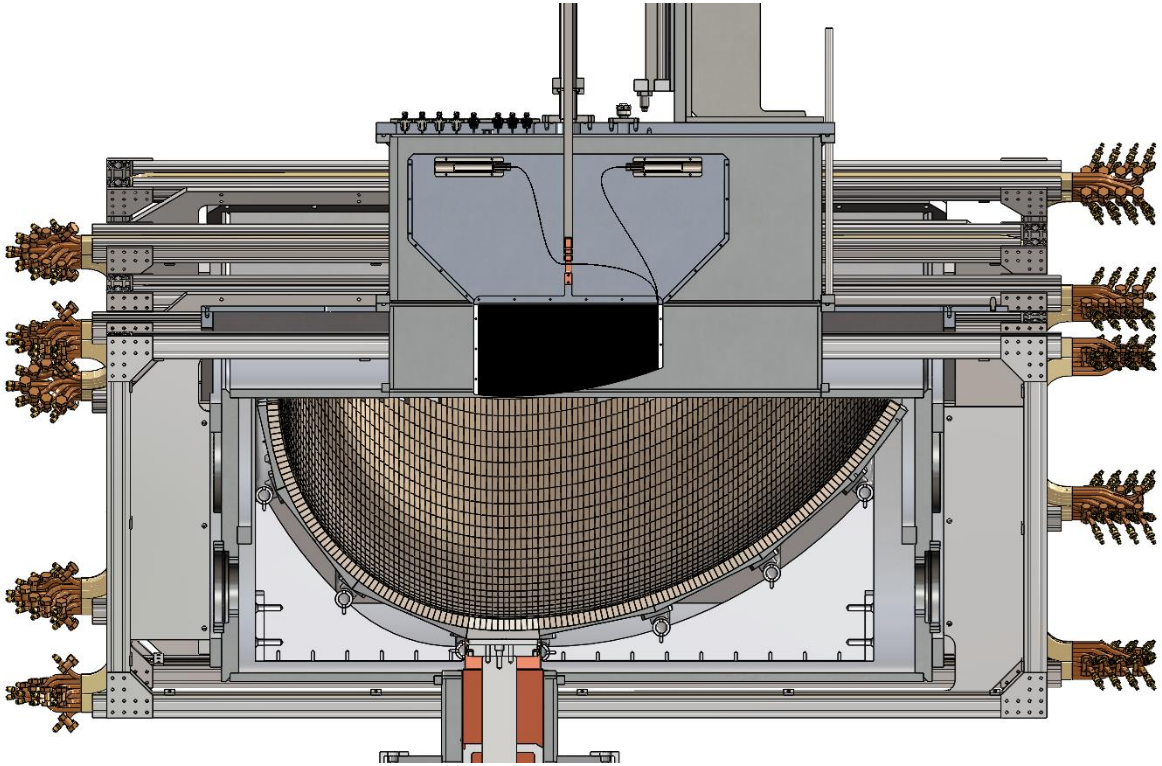


A. Saunders, et al. RSI 84, 013304 (2013); T. M. Ito *et al.* Phys. Rev. C **97**, 012501(R) (2018)

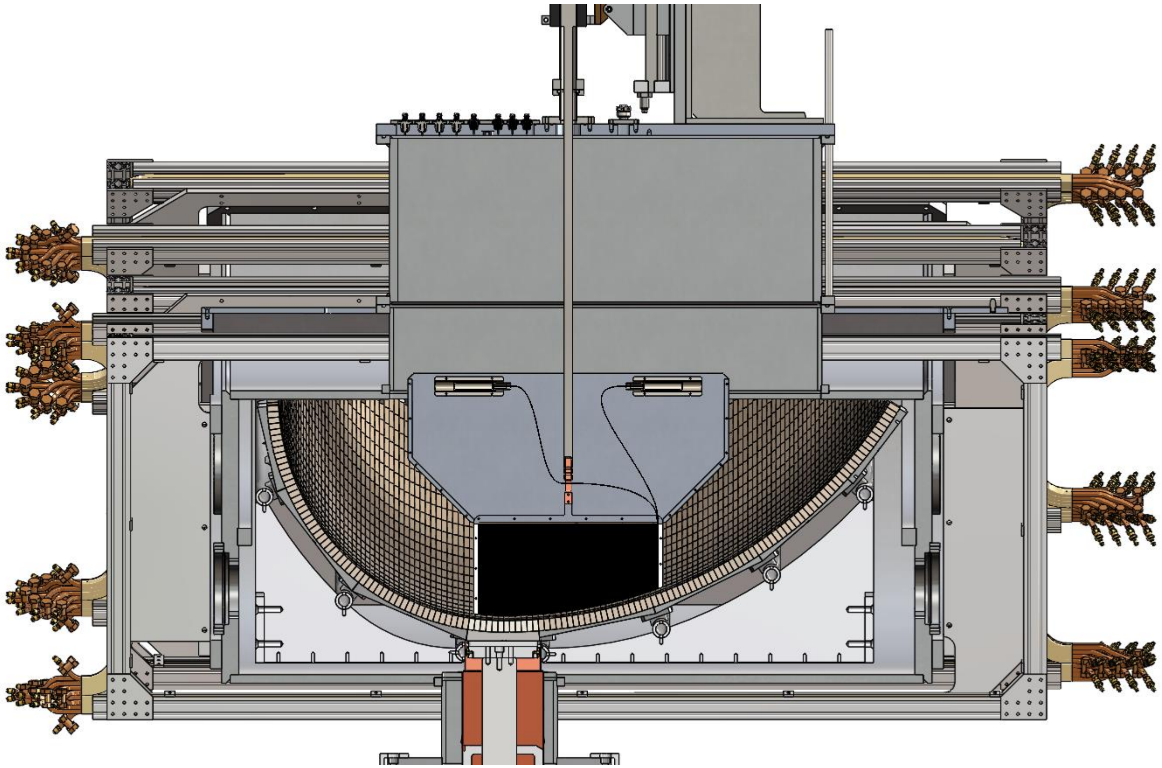
LANSCE UCN Experimental Area (2021)



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

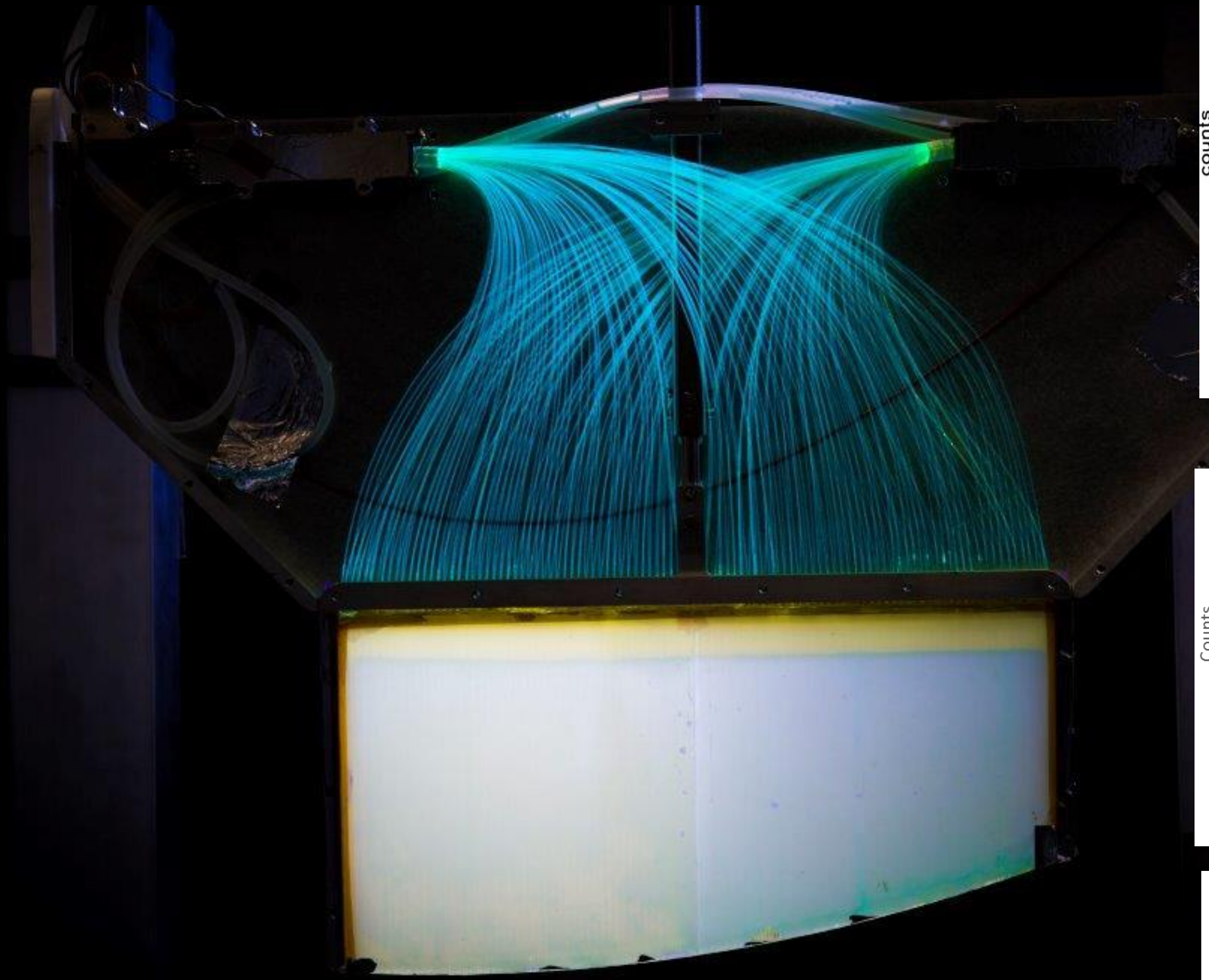


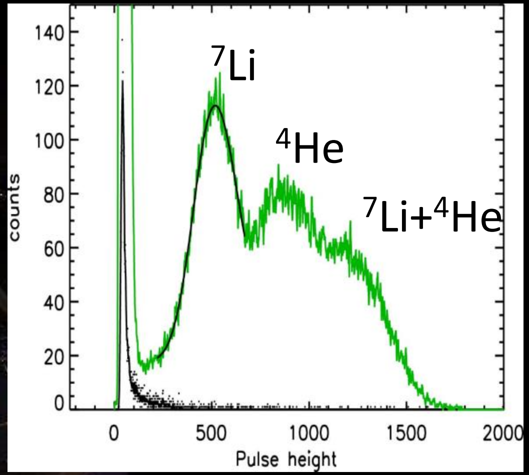
In-situ UCN detection using a "dagger" detector:
detection time ~ 8 s



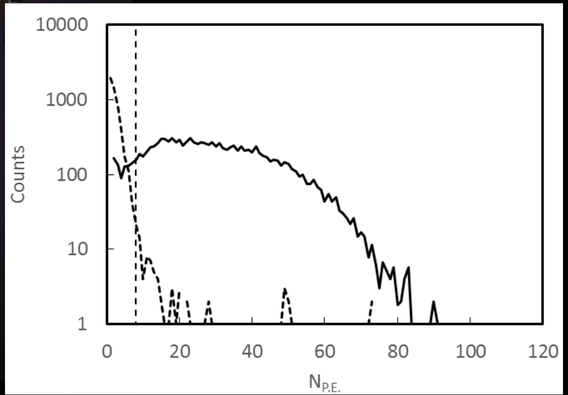
Z. Wang *et al.*, NIMA **798**, 30 (2015).

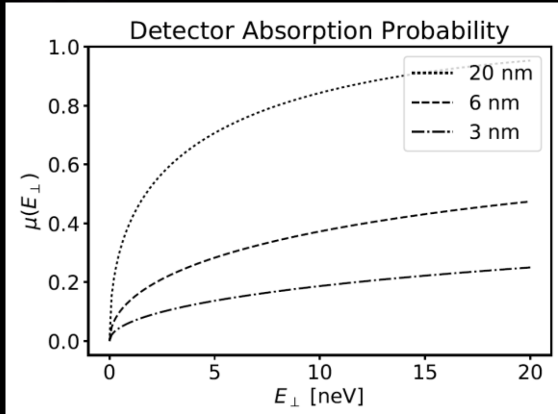
$n + {}^{10}B \rightarrow {}^{7}Li + \alpha$



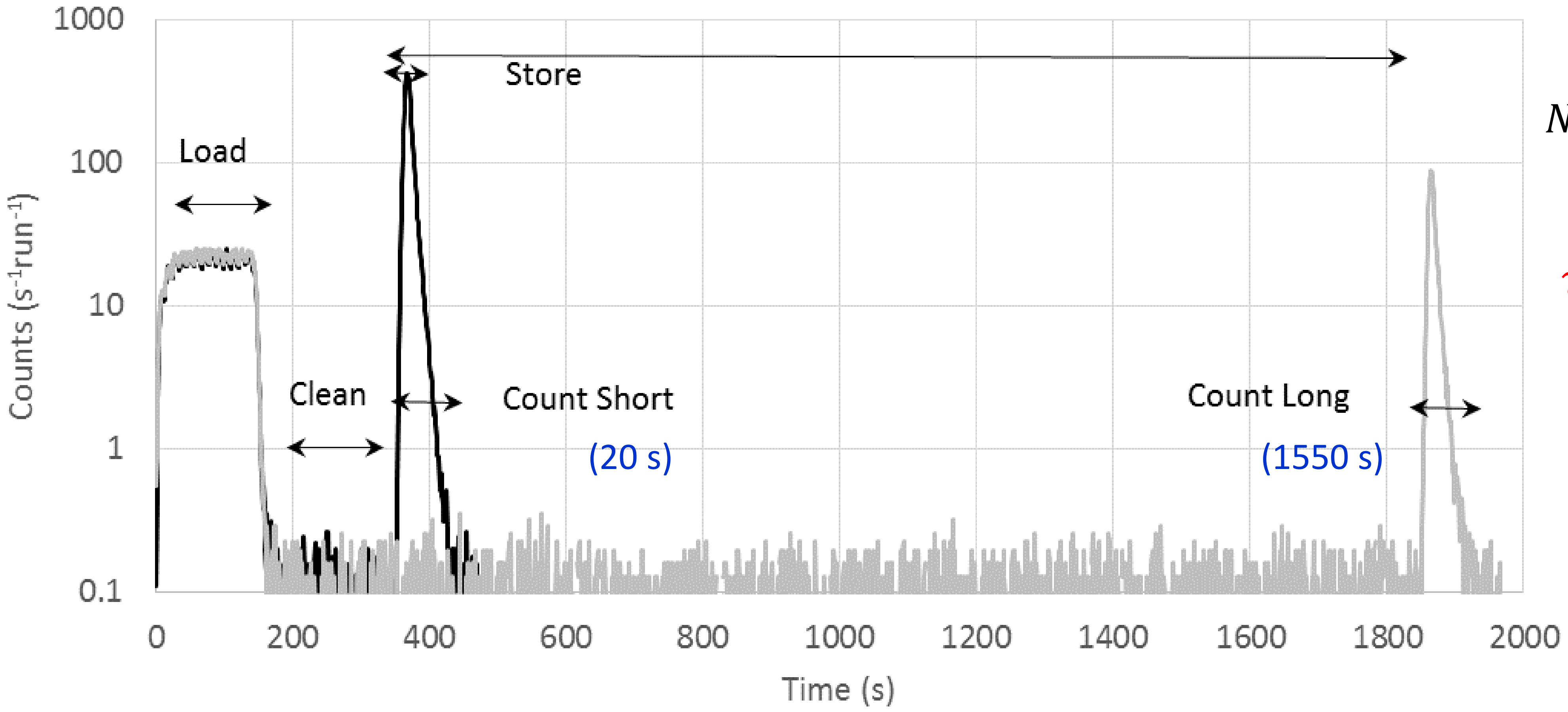


Light Output



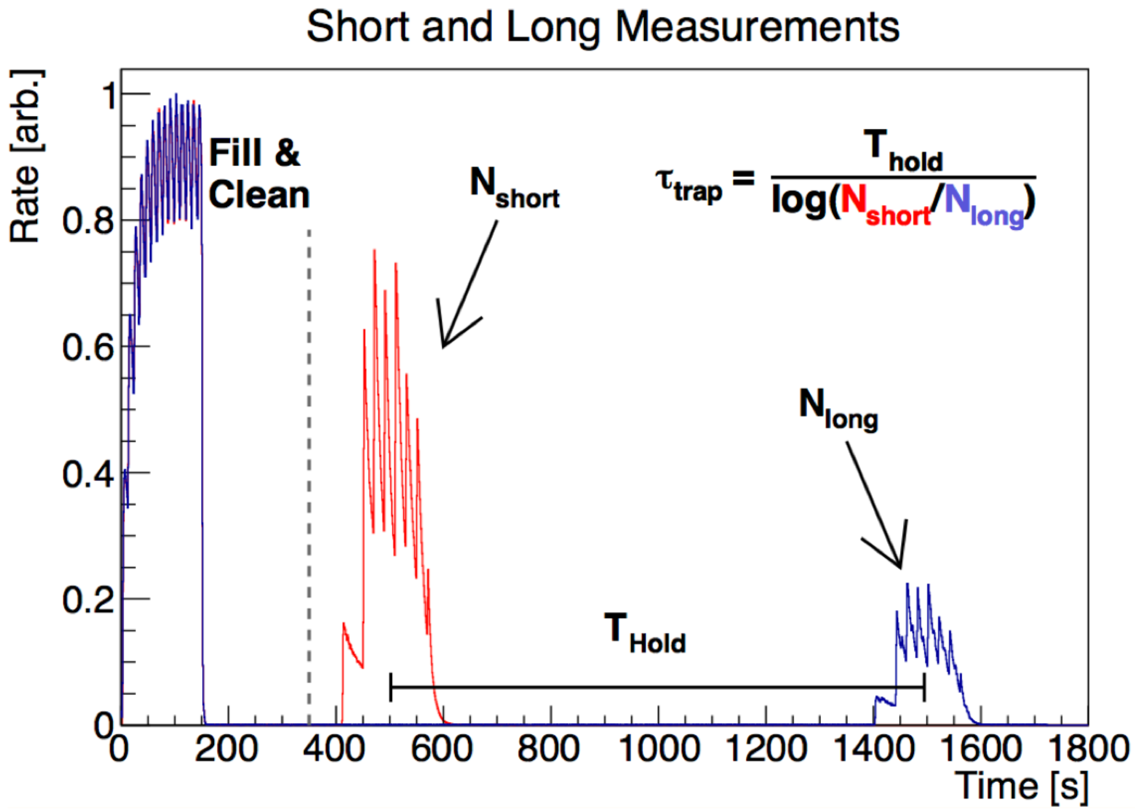


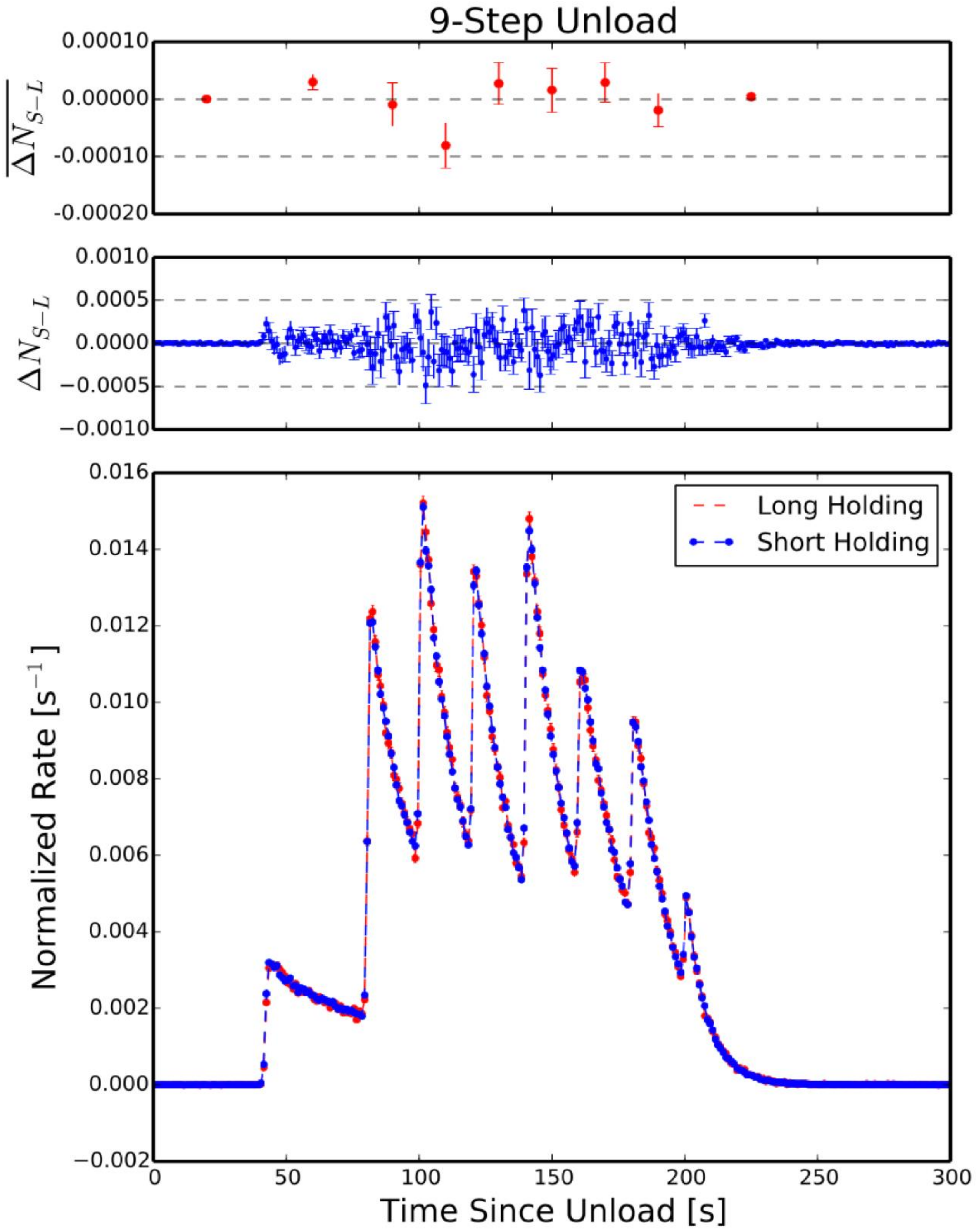
Paired runs:
a short-storage followed by a long-storage:



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

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





Use difference between mean arrival times

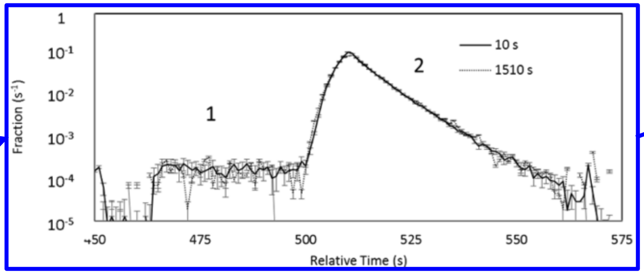
$$\bar{T} = \frac{\sum N_i t_i}{\sum N_i}$$

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

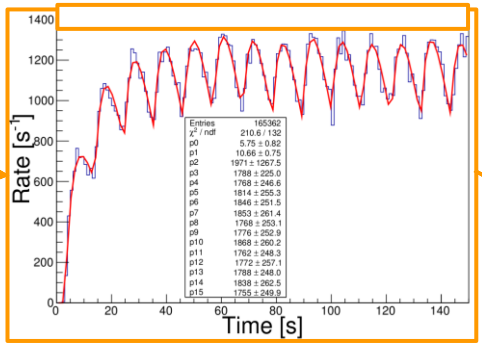


Dagger unload counts

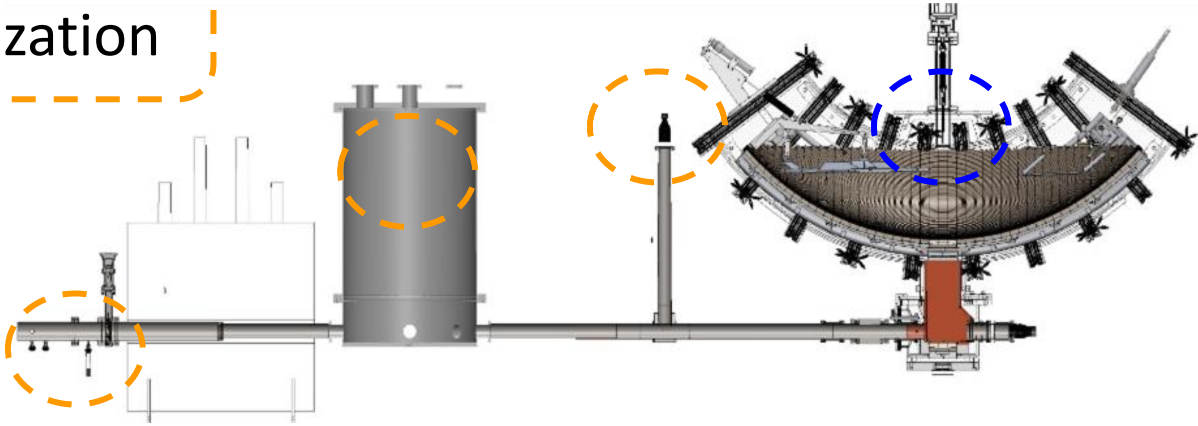
Background measurements

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

"Monitor" detector counts

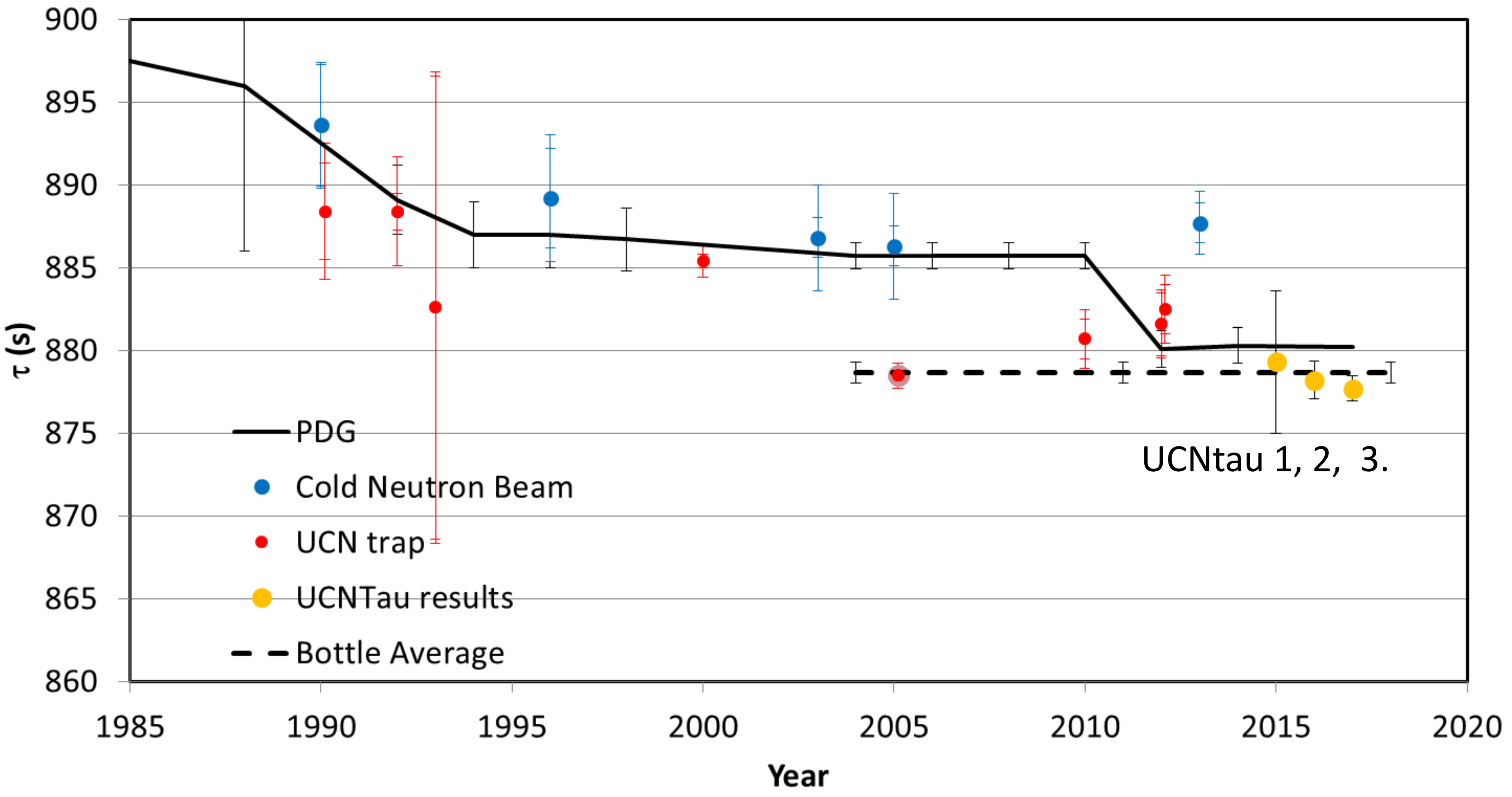


"**M**onitor" normalization



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.

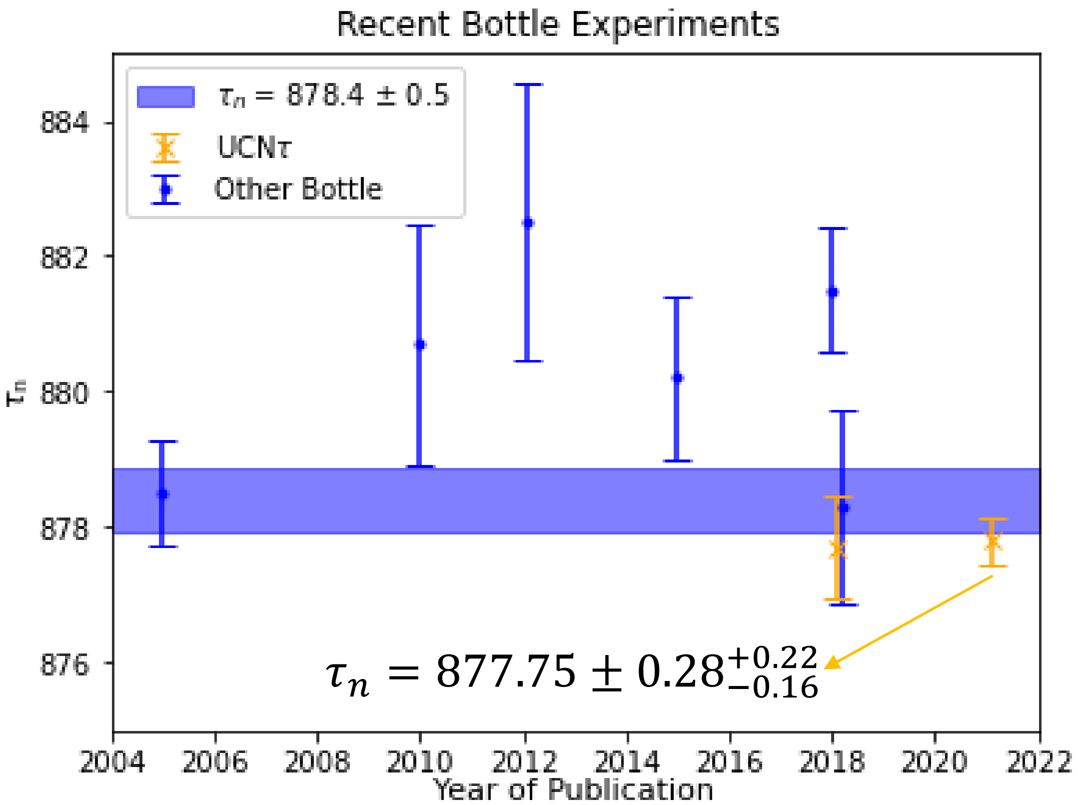
New Result (2021): $\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}$ s

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)

UCNτ

Latest: 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)].

UCNτ

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*
$\mathbf{878.4 \pm 0.5}$	**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 n rate
$887.7 \pm 1.2 \pm 1.9$	[5] YUE	2013	CNTR	In-beam n, trapped p
$881.6 \pm 0.8 \pm 1.9$	[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

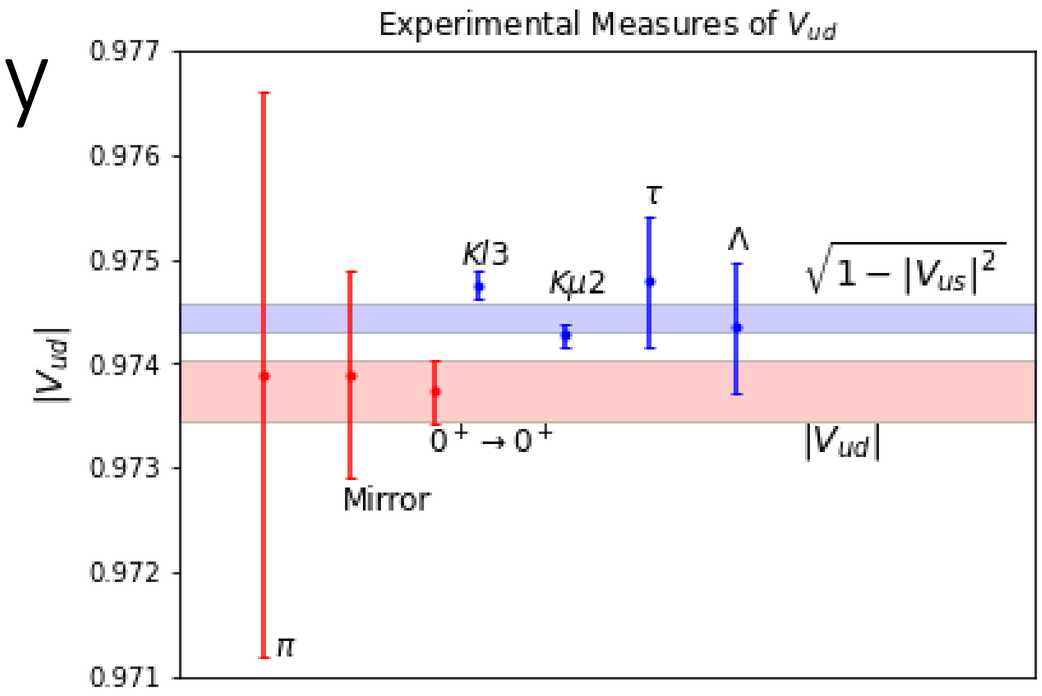
Measurements of V_{ud}:

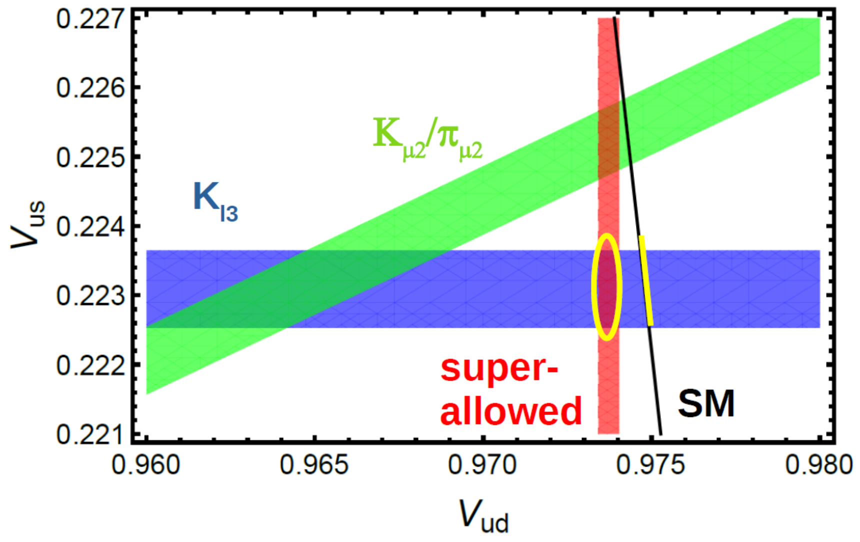
- Most precise "Superallowed" $0^+ \to 0^+$ decays
- Mirror nuclei and Pions less precise
- Large theoretical uncertainties from radiative corrections and nuclear structure

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

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

SOURCES OF UNCERTAINTY:

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

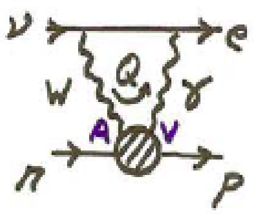
Theory uncertainties in the single-nucleon radiative corrections (RC)

$\lvert V_{ud}\rvert^2_{0^+} + \lvert V_{us}\rvert^2_{K_{\ell 3}} - 1$	-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

CYS, Galviz, Marciano and Meißner, 2107.14708

Chien-Yeah Seng's talk DNP 2021

Extracting V_{ud} with neutron decays



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

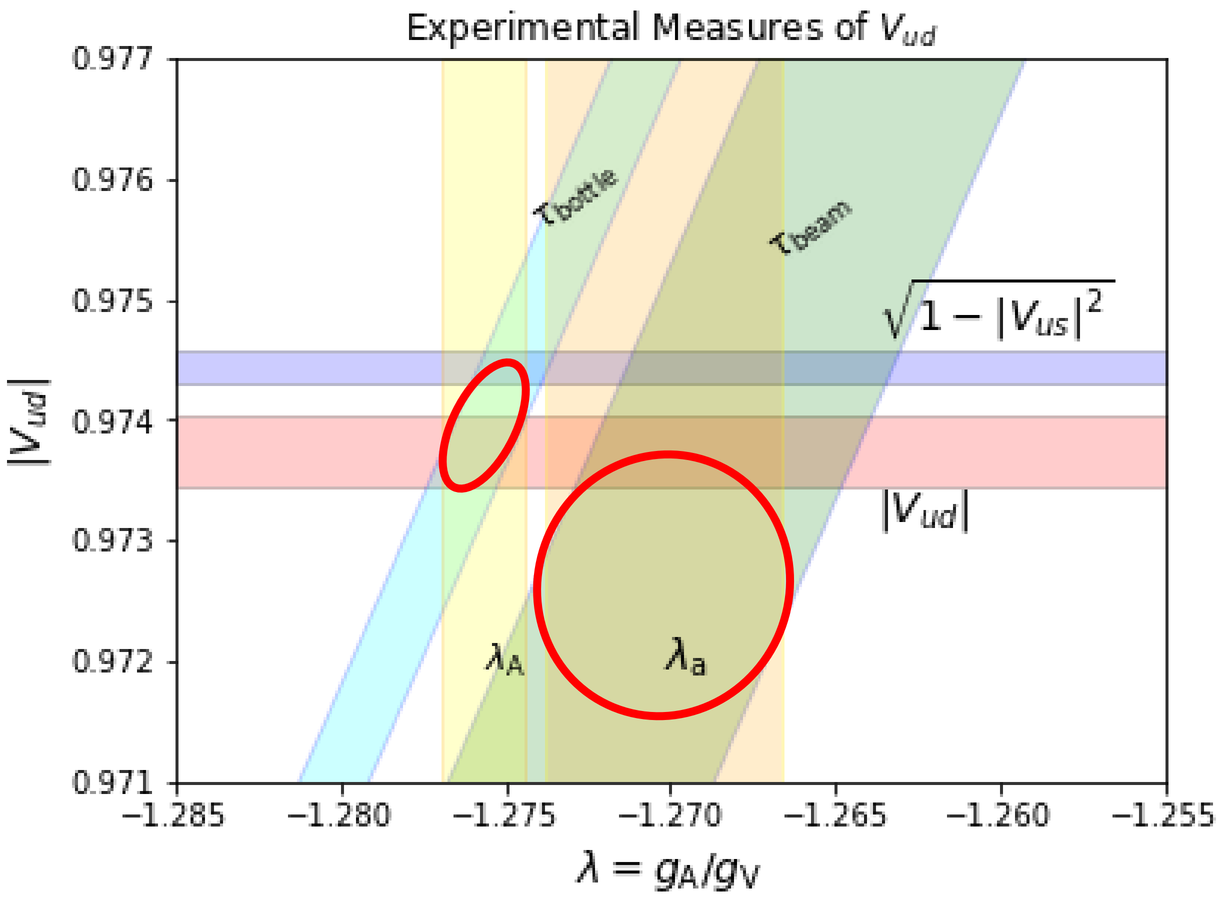
$1/\tau_n = f G_F^2 |V_{ud}|^2 m_e^5 (1+3g_A^2)(1+RC)/2\pi^3$

From μ-decay: 0.6 ppm (MuLan 2011)

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

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.

Status of $\lambda = g_A/g_V$ from Decay Correlations

New beta asymmetry A results **consistent** – but disagree with older measurements and new *a*Spect electron-neutrino correlation a result.

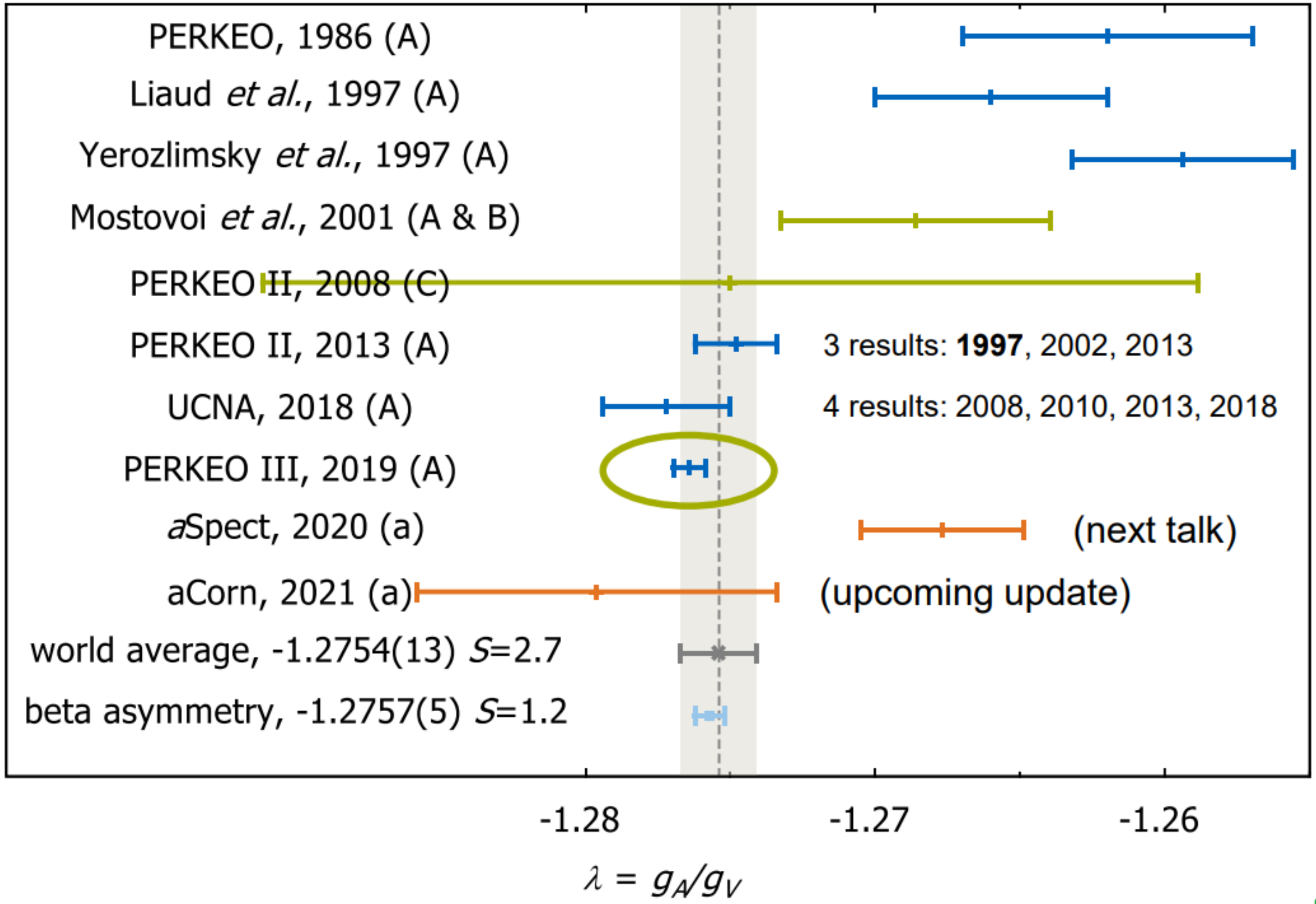
$$A_{avg} = -0.11958(21), \qquad S = 1.2$$

Newer measurements of A have order of magnitude **smaller corrections**.

UCNA, PERKEO III, aCorn, *a*Spect: **blinded analysis** to avoid potential bias.

(Newer results of UCNA & PERKEO II include older results)

Aim of PERC is five-fold improvement.



Experimental observables are *not* the correlation parameters: radiative corrections change

See L. Hayen's talk, and Glück arXiv:2205.05042

Summary and Outlook

PERKEO III Leading beta asymmetry and Fierz term results. Analysis of proton asymmetry and beta spectrum campaigns ongoing, Establishes *pulsed cold beam* technique.

PERC Aims at improved measurements of A, (B), C, a, b. Commissioning!

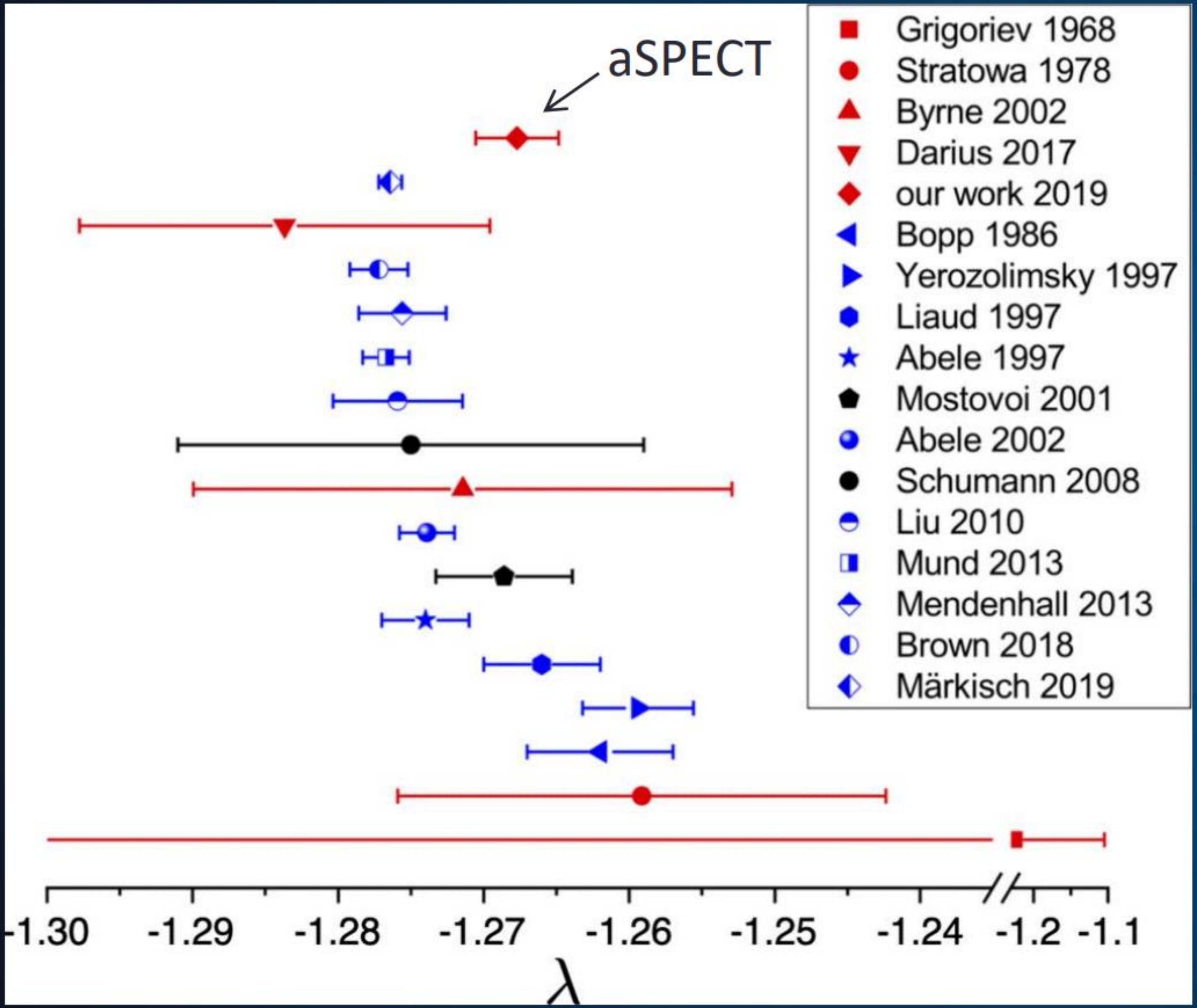
ANNI at ESS Proposed beam line at the ESS. Statistics gain factor for a PERC-like system: ×15 !

T. Soldner, *et al.*, EPJ Web Conf. 219, 10003 (2019)

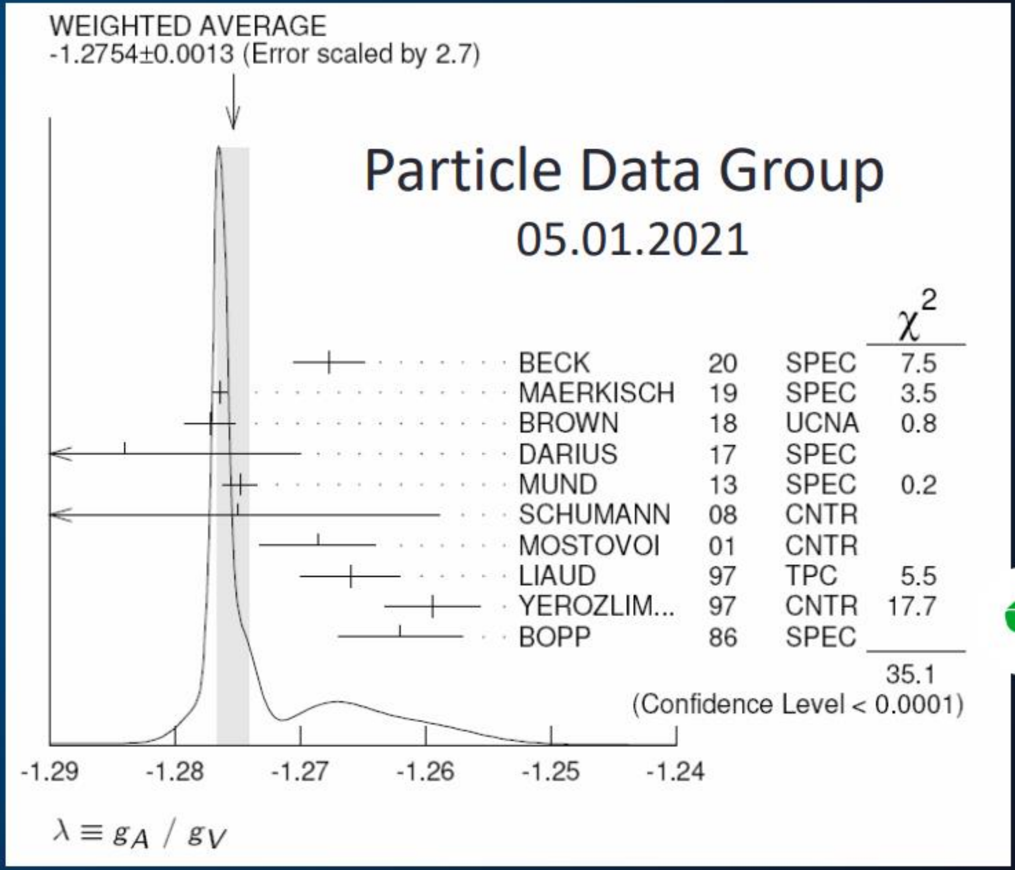
DFG Schwerpunktprogramm
SPP1491
SLOW NEUTRONS
DFG SPP 1491
Particle Physics with Cold and Ultra-Cold Neutrons

Global fit result λ

Ulrich Schmidt, PSI2022



aSPECT result:
$$\lambda = -1.2677 \pm 0.0028$$
Phys.Rev. C 101, 055506 (2020)

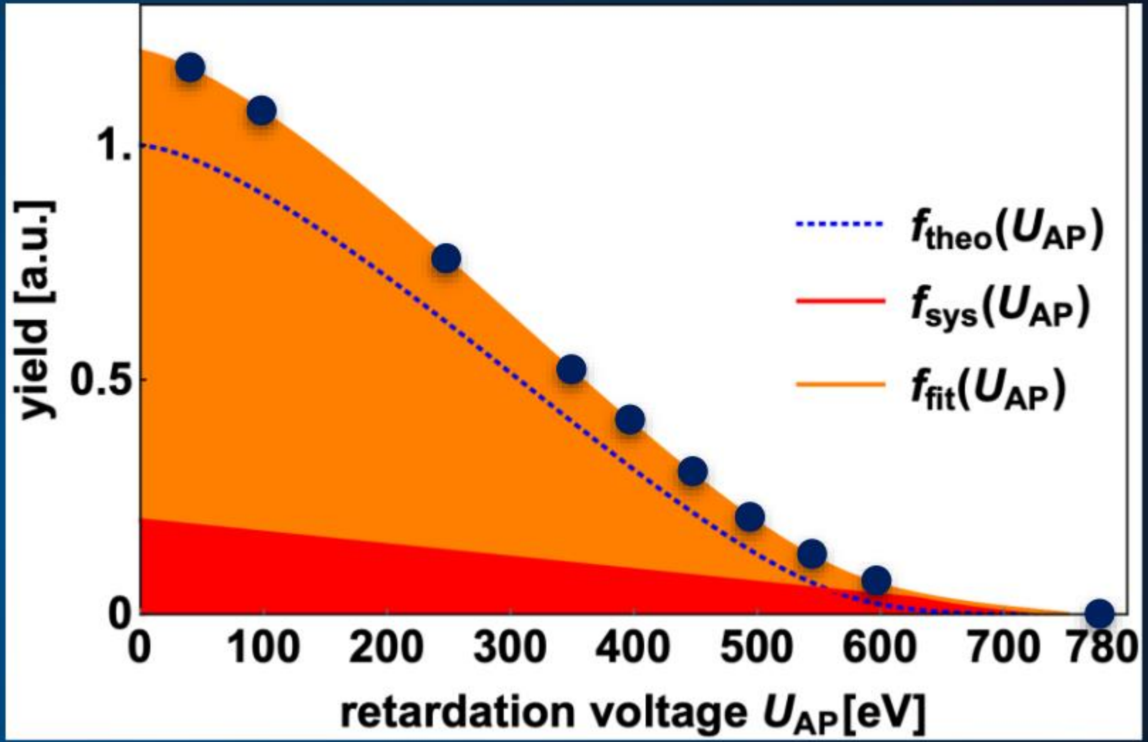


Analysis

Ulrich Schmidt, PSI2022

Systematic effects

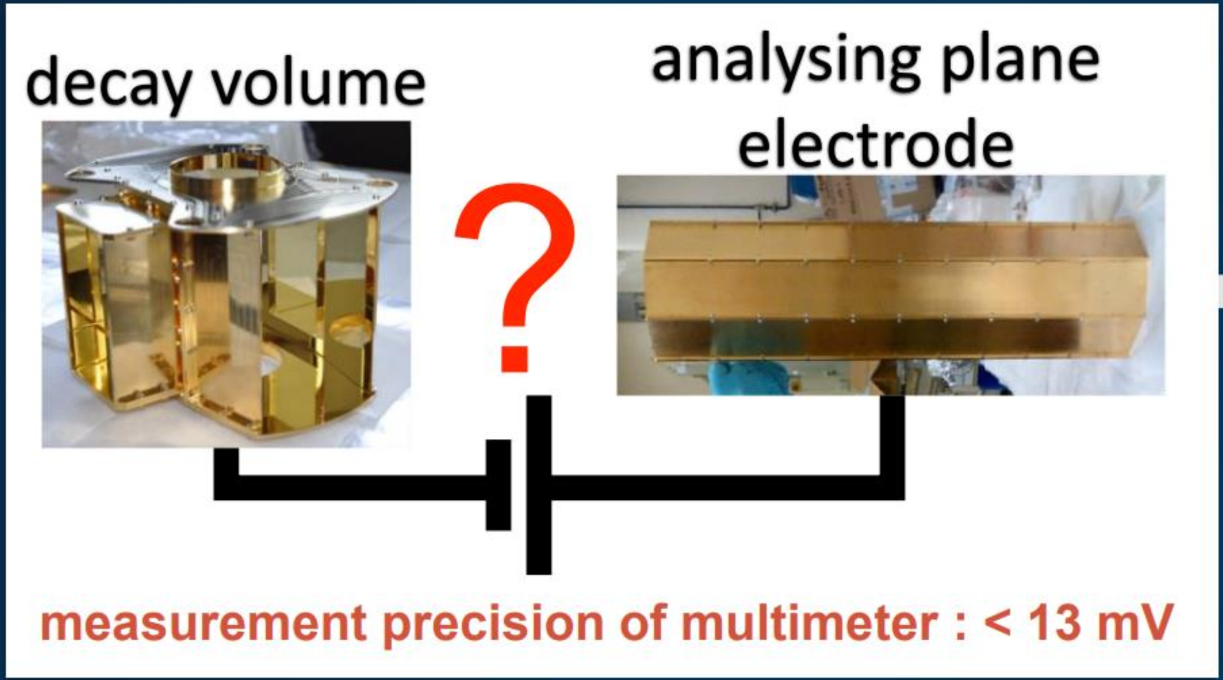
A. Temporal stability and normalization
B. Magnetic field ratio <rB>
C. Retardation voltage <UAP>
D. Background
E. Edge effect
F. Backscattering and below-threshold losses
G. Dead time and pile-up
H. Proton traps in the DV region

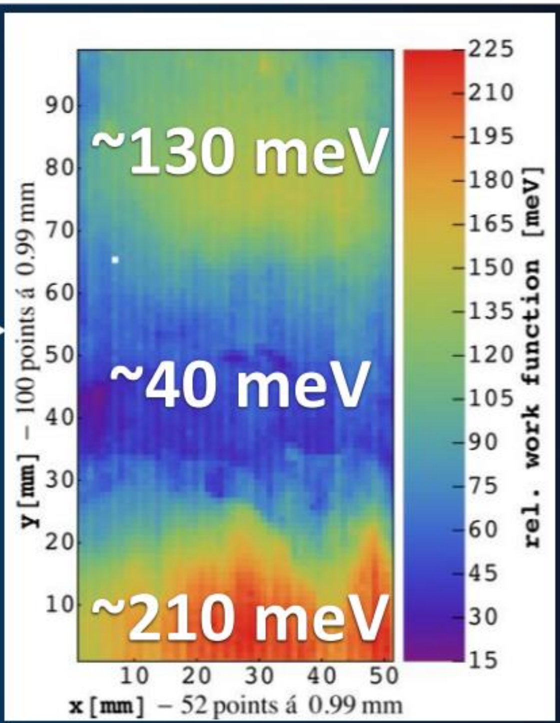


$$f_{fit}(U_{AP}) = f_{theo}(U_{AP}, a) + \sum_i f_{sys_i}(U_{AP})$$

Retardation voltage - WF measurements

$$\Delta U_{AP} = 10\ \text{mV}$$
$$\cong$$
$$\Delta a/a \approx\ 0.1\ \%$$





Production run
***a*SPECT**
2013
~120 K
$\leq 10^{-9}$ mbar

⟷

WF measurements with Kelvin probe under ambient and HV conditions
until 2017

- ✓ **Aging effects < 20 meV**
- ✓ **Temperature effects < 10 meV**
- ✓ **Air-vacuum difference < 11 meV**

Reanalysis

Went something wrong?

→ normalization of the errors of the independent variables (x-errors)

after proper normalisation:

$\chi\hat{}2/\nu \;= 1.440 \;\rightarrow\; \chi\hat{}2/\nu \;= 1.2$

value of a shift by $1/2\sigma_a$

error σ_a stayes the same

Revised Systematic effects

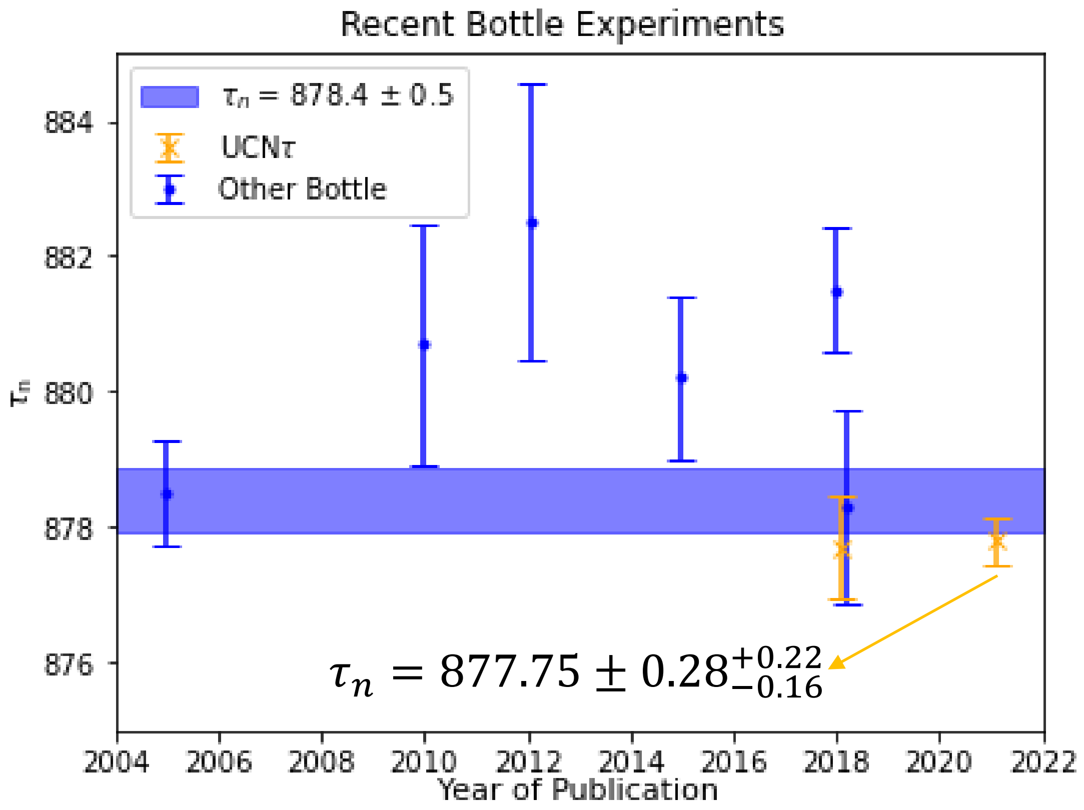
F. Backscattering and below-threshold losses: effects from channeling?

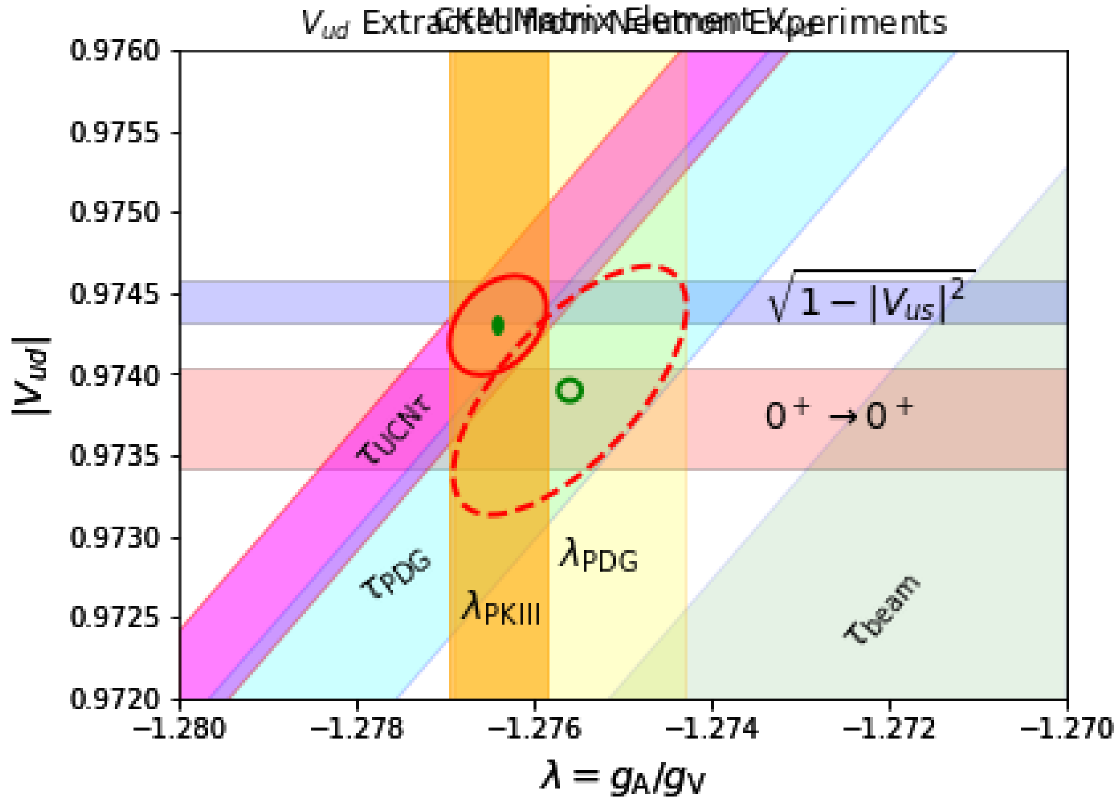
Coulomb and radiative Correction:

Ferenc Glück is a collaboration member so we aware of the 4 body kinematic in case of Bremsstrahlung:

Radiative corrections to neutron and nuclear β-decays: a serious kinematics problem in the literature
arXiv:2205.05042v1 [hep-ph] 10 May 2022

With new UCNτ 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

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)

Moving forward:

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

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

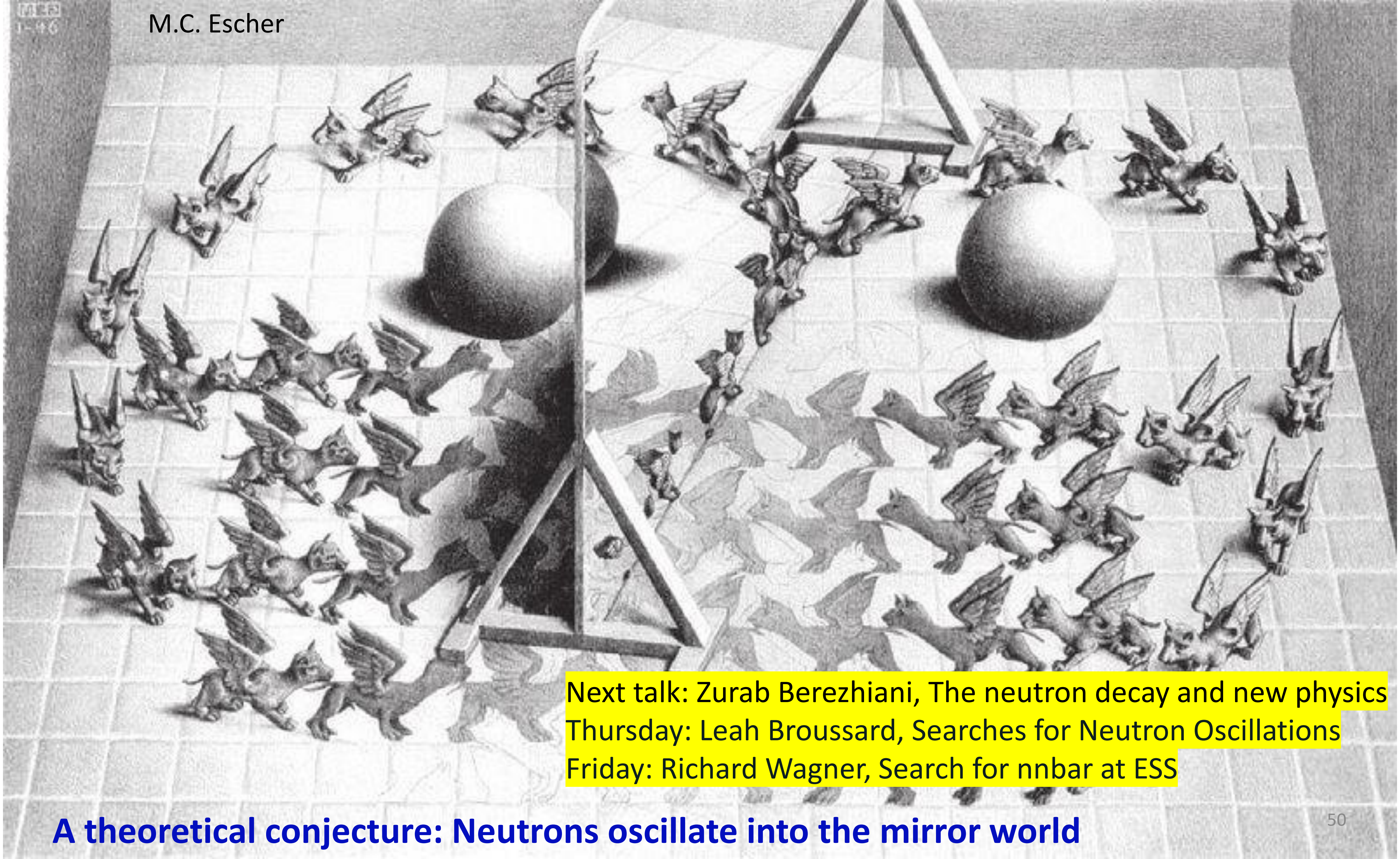
Discrepancy with CKM unitarity is an opportunity for new physics.

Other neutron beta-decay talks:
Wednesday: Kazimierz Bodek, BRAND Experiment,
Thursday: Bastian Markisch, Neutron beta decay with cold neutron beams
Thursday, Ulrich Schmidt, Reanalysis of aSPECT result

After ~ 10 years of work,
we concluded that the neutron lifetime in a bottle is shorter than the pre-2010 PDG value.

The discrepancy of neutron lifetime persists.

M.C. Escher

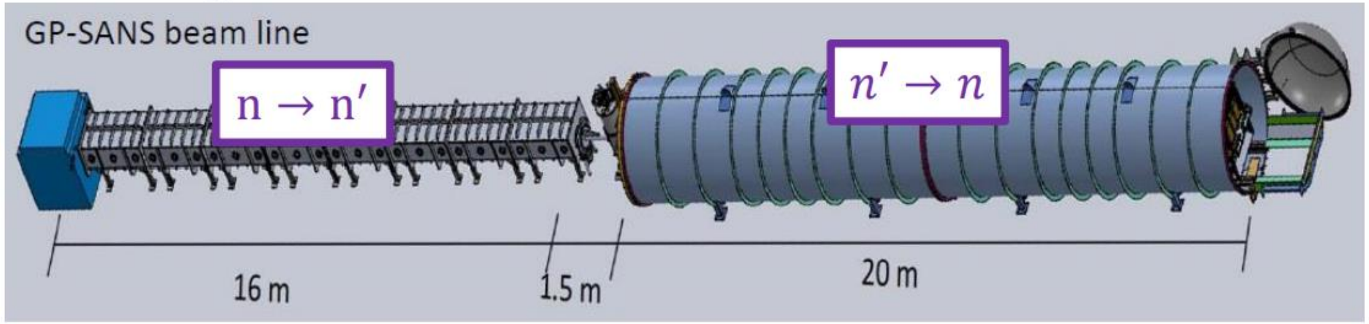


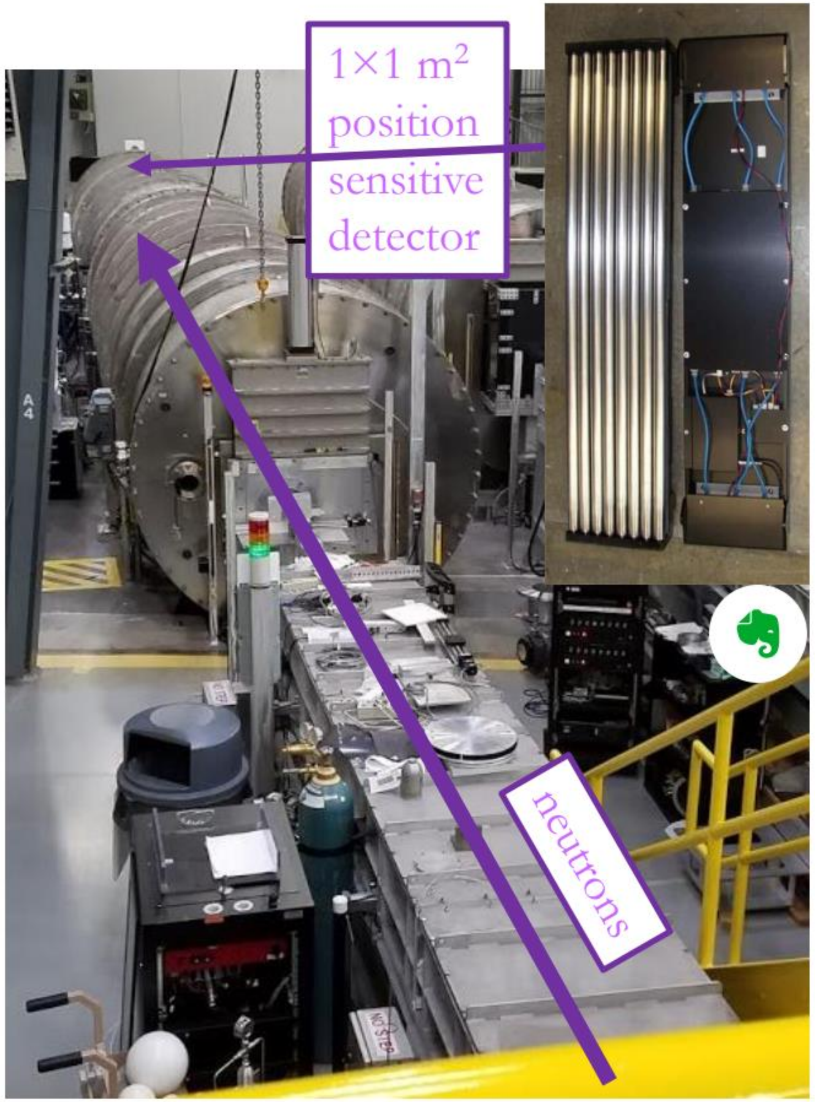
Next talk: Zurab Berezhiani, The neutron decay and new physics
Thursday: Leah Broussard, Searches for Neutron Oscillations
Friday: Richard Wagner, Search for nnbar at ESS

A theoretical conjecture: Neutrons oscillate into the mirror world

Next: searches for $n \rightarrow n'$@ HFIR

- High Flux Isotope Reactor - 85 MW: highest reactor-based source of neutrons for research in US
- New program of searches using General-Purpose Small Angle Neutron Scattering instrument
- ~10,000× more neutron intensity than SNS Mag Ref
- Lower backgrounds: ^{3}He neutron detector in Cd shielded tank
- 15 m and 20 m long beamguides for "disappearance" and "regeneration"



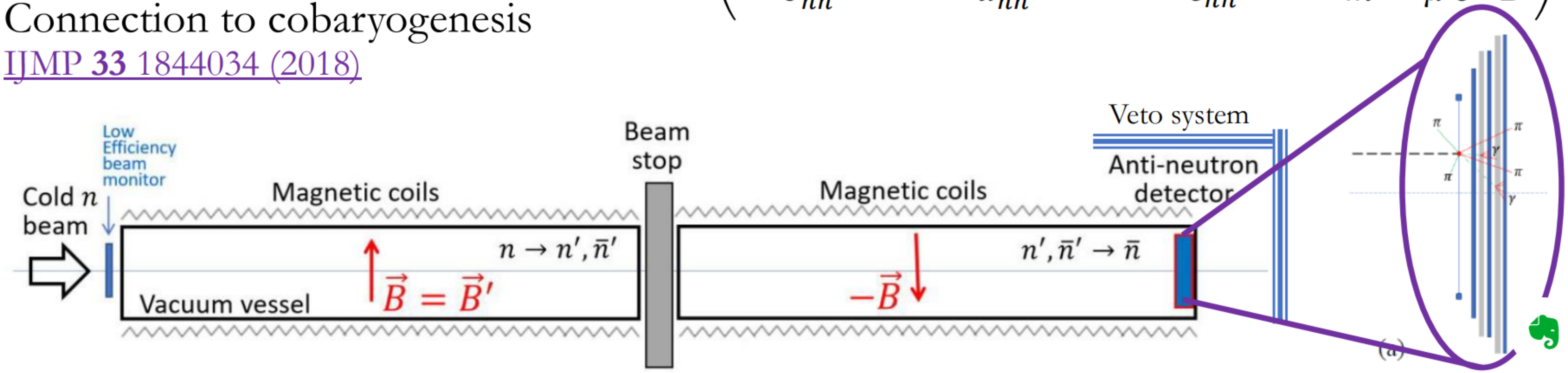


Mirror neutrons and antineutrons

$$|\phi_n\rangle = \begin{vmatrix} n \\ n' \\ \bar{n}' \\ \bar{n} \end{vmatrix}\Bigg\rangle$$

- Straightforward extension of formalism to consider $n \rightarrow \bar{n}, n', \bar{n}'$
- Shortcut for neutron-antineutron oscillations
  EPJC 81 (2021) 33
- New Avenue for search for baryon number violation
- Connection to cobaryogenesis
  IJMP **33** 1844034 (2018)

$$\mathcal{H}_{int} = \begin{pmatrix} m + \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \varepsilon_{n\bar{n}} & \alpha_{nn'} & \delta_{n\bar{n}'} \\ \varepsilon_{n\bar{n}} & m - \mu\boldsymbol{\sigma}\cdot\boldsymbol{B} & \delta_{n\bar{n}'} & \alpha_{nn'} \\ \alpha_{nn'} & \delta_{n\bar{n}'} & m' + \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' & \varepsilon_{n\bar{n}} \\ \delta_{n\bar{n}'} & \alpha_{nn'} & \varepsilon_{n\bar{n}} & m' - \mu'\boldsymbol{\sigma}\cdot\boldsymbol{B}' \end{pmatrix}$$



- Bonus: R&D for a high sensitivity $n \rightarrow \bar{n}$ search NNBAR [R. Wagner Friday]

The UCNτ Collaboration

Argonne National Laboratory
N. B. Callahan

California Institute of Technology
M. Blatnik, B. Filippone, E. M. Fries, K. P. Hickerson, S. Slutsky, V. Su, X. Sun, C. Swank, W. Wei

DePauw University
A. Komives

East Tennessee State University
R. W. Pattie, Jr.

Indiana University/CEEM
M. Dawid, W. Fox, C.-Y. Liu, D. J. Salvat, J. Vanderwerp, G. Visser

Institute Laue-Langevin
P. Geltenbort

Joint Institute for Nuclear Research
E. I. Sharapov

Los Alamos National Laboratory
S. M. Clayton (co-spokesperson), S. A. Currie, M. A. Hoffbauer, T. M. Ito, M. Makela, C. L. Morris, C. O'Shaughnessy, Z. Tang, W. Uhrich, P. L. Walstrom, Z. Wang

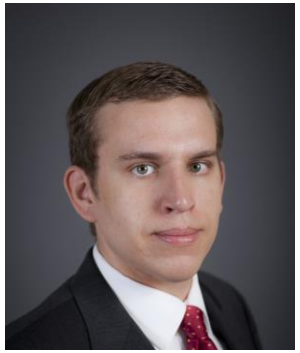
North Carolina State University
T. Bailey, J. H. Choi, C. Cude-Woods, E.B. Dees, L. Hayen, R. Musedinovic, A. R. Young, B. A. Zeck

Oak Ridge National Laboratory
L. J. Broussard, F. Gonzalez, J. Ramsey, A. Saunders

Tennessee Technological University
R. Colon, D. Dinger, J. Ginder, A. T. Holley (co-spokesperson), M. Kemp, C. Swindell

3 independent analyses

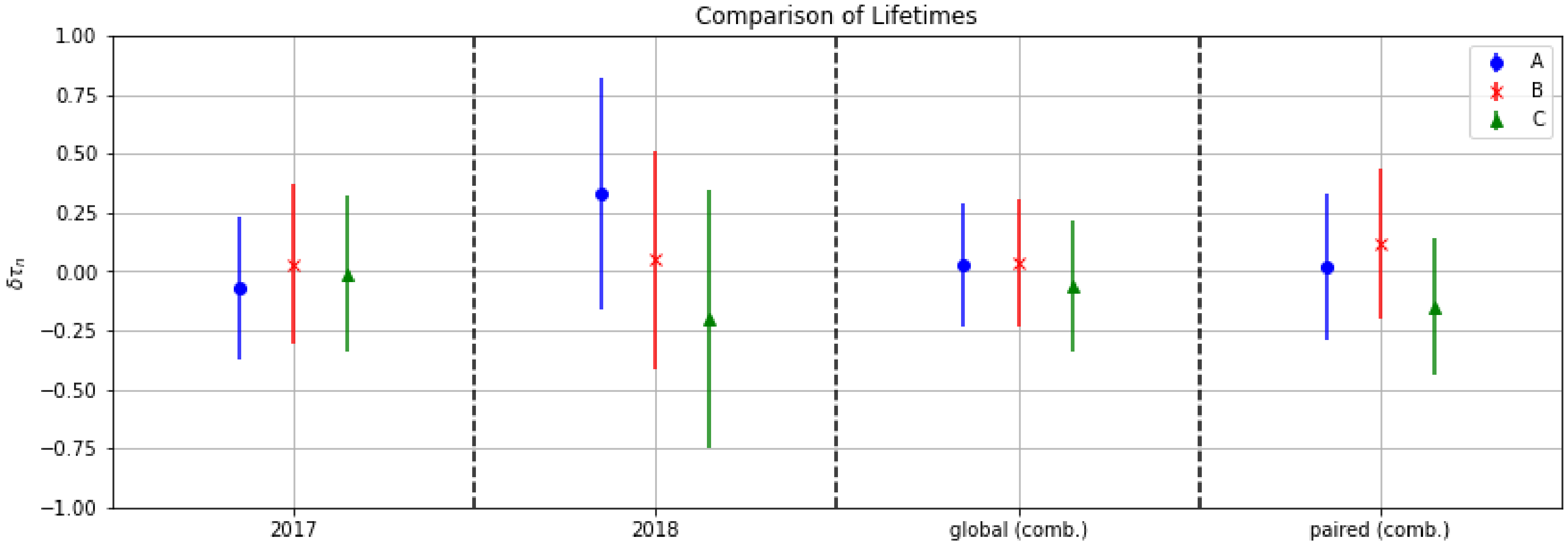
Frank Gonzalez (Indiana)



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



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