Precision Measurements of Neutron Beta Decay

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CEA Paris-Saclay Seminar

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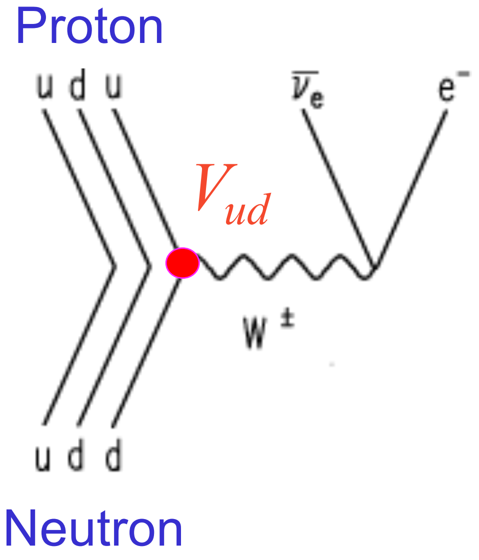

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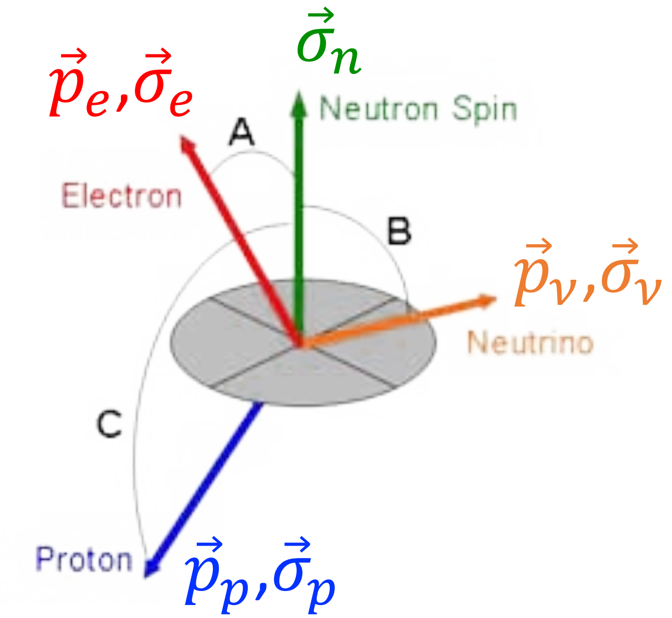
Neutron β decay observables

$n \rightarrow p + e + \bar{\nu}_e$, β endpoint energy 782 keV



Many observables (20+, Dubbers&Schmidt, Rev. Mod. Phys. **83** (2011), p. 1111-):

- Mean lifetime τ_n
- $A\ \vec{\sigma}_n \cdot \vec{p}_e$
- $B\ \vec{\sigma}_n \cdot \vec{p}_\nu$
- $\mathrm{C}\ \vec{\sigma}_n \cdot \vec{p}_p$
- $D\ \vec{\sigma}_n \cdot (\vec{p}_e \times \vec{p}_\nu)$
- $a\ \vec{p}_e \cdot \vec{p}_\nu$
- Twofold correlations involving electron spin
- Threefold correlations (*D*, *L*, *R*, *V*)
- …

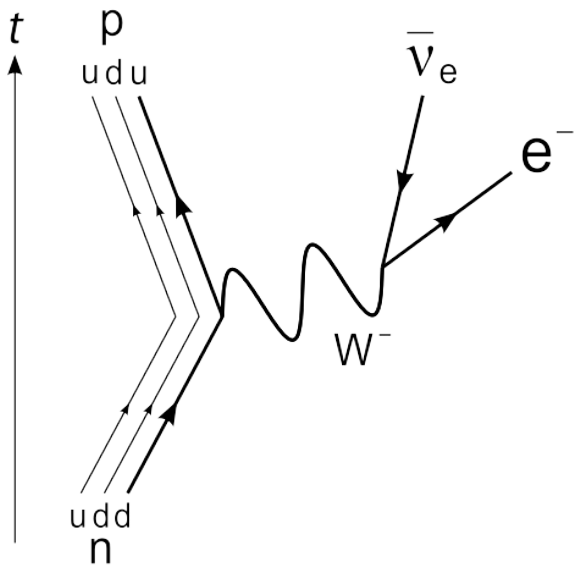
Differential decay rate:

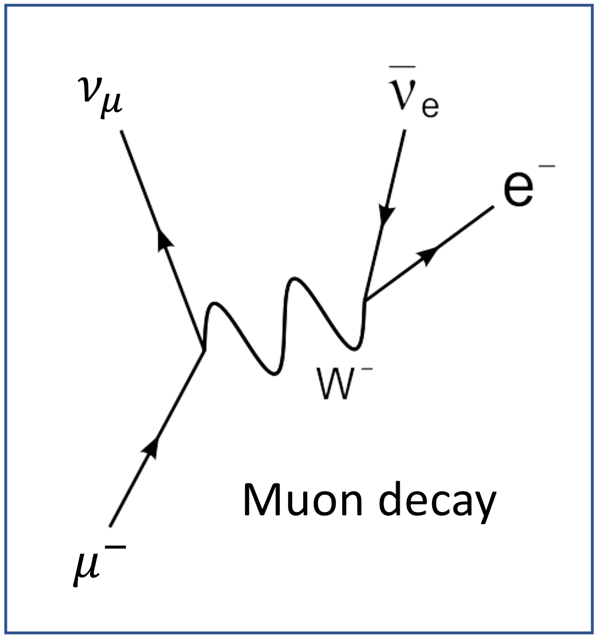
$$\frac{dW}{dE_e\,d\Omega_e\,d\Omega_\nu} = G(E_e)\left(1 + a\,\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\,\frac{m_e}{E_e} + \langle\vec{\sigma}_n\rangle \cdot \left(A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + D\,\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right)$$

…also $\vec{\sigma}_e$ combinations

Neutron β decay at the quark level

$n \rightarrow p + e + \bar{\nu}_e,$ β endpoint energy 782 keV





Muon decay

$q^2 \ll m_W$: 4-fermion interaction

$$\text{Quark level: } \mathcal{M}_q = \frac{G_F}{\sqrt{2}} V_{ud}\left[u \overbrace{\gamma_\mu(1-\gamma_5)}^{V-A\text{ interaction}} d\right]\left[e\gamma^\mu(1-\gamma_5)\nu_e\right]$$

CKM Matrix

Quark level: $\mathcal{M}_q = \frac{G_F}{\sqrt{2}} V_{ud} [u\gamma_\mu(1-\gamma_5)d][e\gamma^\mu(1-\gamma_5)\nu_e]$

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

Weak states | CKM mixing matrix | Mass eigenstates

Unitarity: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

Nucleon level: form factors

$$\mathcal{M}_q = \frac{G_F}{\sqrt{2}} V_{ud}\left[p\left(\gamma_\mu\left(\overset{=1\text{ by CVC}}{\overset{\downarrow}{g_V}} + \overset{\approx -1}{\overset{\downarrow}{g_A}}\gamma_5\right) + \frac{\kappa_p - \kappa_n}{2M}\sigma_{\mu\nu}q^\nu\right)n\right]\left[e\gamma^\mu(1-\gamma_5)\nu_e\right]$$

Weak magnetism:
determined from
electromagnetic
properties (anomalous
magnetic moments)

Other terms are forbidden in the SM or can be neglected at low energies.

→ Essentially a single parameter, g_A or $\lambda \equiv \frac{g_A}{g_V}$, accounts for nucleon structure.

Neutron decay master formula

$$|V_{ud}|^2 = \frac{5099.3(4)\mathrm{s}}{\tau_n(1+3g_A^2)(1+RC)}$$

V_{ud}: quark mixing parameter in CKM matrix

τ_n: neutron lifetime

g_A: axial charge of the neutron

RC: radiative corrections

Beta decay radiative corrections

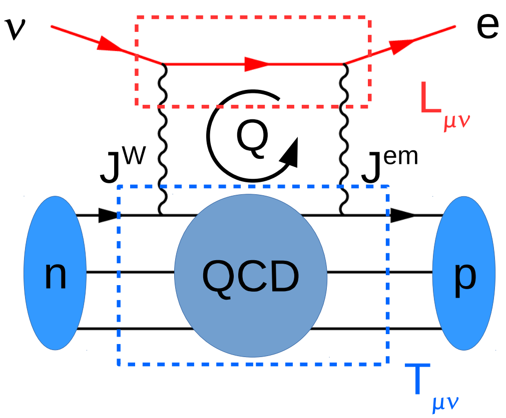
Neutron decay:

$$|V_{ud}|^2 = \frac{5099.3(4)\mathrm{s}}{\tau_n(1+3g_A^2)(1+RC)}$$

Superallowed nuclear decay:

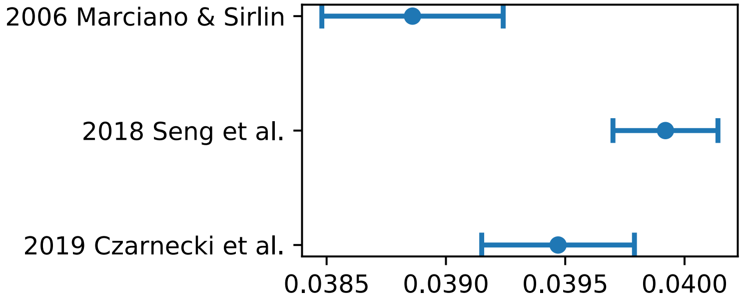
$$|V_{ud}|^2 = \frac{2984.432(3)\ \mathrm{s}}{\mathcal{F}t(1+\Delta_R^V)}$$

- The box diagram Δ_{np} contributes only ~3% but dominates the uncertainty.
- The integral $\int d^4Q$ requires control over low (non-perturbative) and high (perturbative) momenta



- Marciano and Sirlin, PRL **96**, 032002 (2006)
  - RC = 0.03886(38), Δ_R^V= 0.02361(38)
- Seng et al., PRL **121**, 241804 (2018)
  - RC = 0.03992(22), Δ_R^V= 0.02467(22)
- Czarnecki, Marciano, Sirlin, PRD **100**, 073008 (2019)
  - Update/extension of 2006 Marciano and Sirlin
  - RC = 0.03947(32), Δ_R^V= 0.02426(32)
- Work in progress: LQCD

RC for *n* decay



V_{ud} from experiments can test self-consistency of the Standard Model

CKM mixing matrix

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

Weak
states

Mass
eigenstates

$$\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$$

	$\lvert V_{ud}\rvert$	$\lvert V_{us}\rvert$	$\lvert V_{ub}\rvert$	Δ_{CKM}
PDG 2020	0.97370(14) [from **nuclear decay** measurements]	0.2243(8)	$3.82(24)\times 10^{-3}$	$\mathbf{-15.8(4.5)\times 10^{-4}}$

- (Using Seng et al. rad. Corrections) V_{ud} from *nuclear* decay shows 3.5-σ tension with the Standard Model!

- Neutron decay measurement is *clean* and the systematics are *independent*.

$$|V_{ud}|^2 = \frac{5099.3(4)\mathrm{s}}{\tau_n(1+3g_A^2)(1+RC)}$$

β decay beyond the standard model

- SM assumptions (pure V-A between quarks and leptons) can be relaxed
- Recent global fit for BSM parameters in beta decay: Falkowski, González-Alonso, Naviliat-Cuncic, JHEP04 (2021) 126
- Fit includes data from neutron and nuclear decay (lifetimes, correlations)
- Sensitive to BSM particle masses in the range 1 GeV—100 TeV

$$\begin{aligned}\mathcal{L} \supset -\frac{V_{ud}}{v^2}\Big[&(1+\epsilon_L)\ \bar{e}\gamma_\mu\nu_L\cdot\bar{u}\gamma^\mu(1-\gamma_5)d \ + \ \tilde{\epsilon}_L\,\bar{e}\gamma_\mu\nu_R\cdot\bar{u}\gamma^\mu(1-\gamma_5)d \\ &+\epsilon_R\,\bar{e}\gamma_\mu\nu_L\cdot\bar{u}\gamma^\mu(1+\gamma_5)d \ + \ \tilde{\epsilon}_R\,\bar{e}\gamma_\mu\nu_R\cdot\bar{u}\gamma^\mu(1+\gamma_5)d \\ &+\frac{1}{4}\epsilon_T\ \bar{e}\sigma_{\mu\nu}\nu_L\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \ + \ \frac{1}{4}\tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}\nu_R\cdot\bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \\ &+\epsilon_S\,\bar{e}\nu_L\cdot\bar{u}d \ + \ \tilde{\epsilon}_S\,\bar{e}(1+\gamma_5)\nu_R\cdot\bar{u}d \\ &-\epsilon_P\,\bar{e}\nu_L\cdot\bar{u}\gamma_5 d \ - \ \tilde{\epsilon}_P\,\bar{e}\nu_R\cdot\bar{u}\gamma_5 d\Big] + \text{h.c.}\end{aligned}$$

Quark level

Nucleon level

$$\begin{aligned}\mathcal{L}_{\text{Lee-Yang}} = &-\bar{p}\gamma^\mu n\left(C_V^+\bar{e}\gamma_\mu\nu_L + C_V^-\bar{e}\gamma_\mu\nu_R\right) - \bar{p}\gamma^\mu\gamma_5 n\left(C_A^+\bar{e}\gamma_\mu\nu_L - C_A^-\bar{e}\gamma_\mu\nu_R\right) \\ &-\bar{p}n\left(C_S^+\bar{e}\nu_L + C_S^-\bar{e}\nu_R\right) - \frac{1}{2}\bar{p}\sigma^{\mu\nu}n\left(C_T^+\bar{e}\sigma_{\mu\nu}\nu_L + C_T^-\bar{e}\sigma_{\mu\nu}\nu_R\right) \\ &+\bar{p}\gamma_5 n\left(C_P^+\bar{e}\nu_L - C_P^-\bar{e}\nu_R\right) + \text{h.c.}\end{aligned}$$

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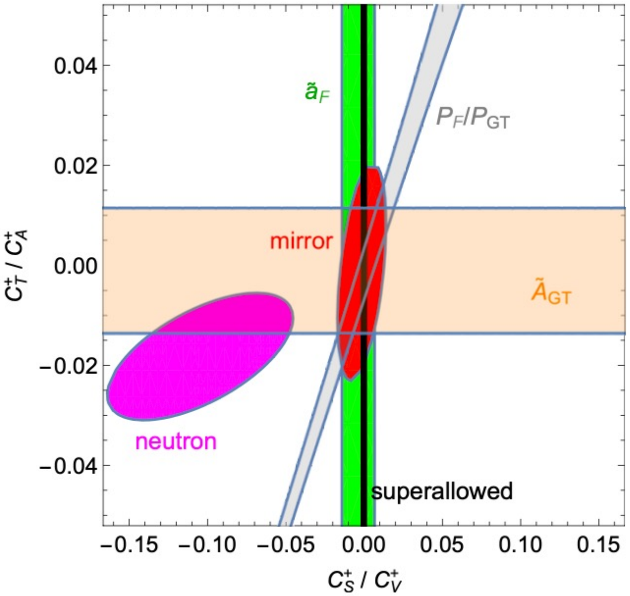
- Fit includes data from neutron and nuclear decay (lifetimes, correlations)
- Sensitive to BSM particle masses in the range 1 GeV—100 TeV
- Result of subsets of fits for scalar and tensor terms, assuming no right-handed neutrinos



$$
\begin{aligned}
\mathcal{L} \supset -\frac{V_{ud}}{v^2}\Big[& (1+\epsilon_L)\ \bar{e}\gamma_\mu\nu_L\cdot\bar{u}\gamma^\mu(1-\gamma_5)d \ + \ \cancel{\tilde{\epsilon}_L\,\bar{e}\gamma_\mu\nu_R\cdot\bar{u}\gamma^\mu(1-\gamma_5)d} \\
& +\epsilon_R\,\bar{e}\gamma_\mu\nu_L\cdot\bar{u}\gamma^\mu(1+\gamma_5)d \ + \ \cancel{\tilde{\epsilon}_R\,\bar{e}\gamma_\mu\nu_R\cdot\bar{u}\gamma^\mu(1+\gamma_5)d} \\
& +\frac{1}{4}\epsilon_T\ \bar{e}\sigma_{\mu\nu}\nu_L\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \ + \ \cancel{\frac{1}{4}\tilde{\epsilon}_T\ \bar{e}\sigma_{\mu\nu}\nu_R\cdot\bar{u}\sigma^{\mu\nu}(1+\gamma_5)d} \\
& +\epsilon_S\,\bar{e}\nu_L\cdot\bar{u}d \ + \ \cancel{\tilde{\epsilon}_S\,\bar{e}(1+\gamma_5)\nu_R\cdot\bar{u}d} \\
& -\epsilon_P\,\bar{e}\nu_L\cdot\bar{u}\gamma_5 d \ - \ \cancel{\tilde{\epsilon}_P\,\bar{e}\nu_R\cdot\bar{u}\gamma_5 d}\Big] + \text{h.c.}
\end{aligned}
$$

Quark level

↕

Nucleon level

$$
\begin{aligned}
\mathcal{L}_{\text{Lee-Yang}} = & -\bar{p}\gamma^\mu n\left(C_V^+\bar{e}\gamma_\mu\nu_L + \cancel{C_V^-\bar{e}\gamma_\mu\nu_R}\right) - \bar{p}\gamma^\mu\gamma_5 n\left(C_A^+\bar{e}\gamma_\mu\nu_L - \cancel{C_A^-\bar{e}\gamma_\mu\nu_R}\right) \\
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& +\bar{p}\gamma_5 n\left(C_P^+\bar{e}\nu_L - \cancel{C_P^-\bar{e}\nu_R}\right) + \text{h.c.}
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- Fit includes data from neutron and nuclear decay (lifetimes, correlations)
- Sensitive to BSM particle masses in the range 1 GeV—100 TeV
- Global fit for ε_S, ε_T compared to LHC fits, assuming no right-handed neutrinos

$$\begin{aligned}\mathcal{L} \supset -\frac{V_{ud}}{v^2}\Big[&(1+\epsilon_L)\;\bar e\gamma_\mu\nu_L\cdot\bar u\gamma^\mu(1-\gamma_5)d \;+\; \cancel{\tilde\epsilon_L\,\bar e\gamma_\mu\nu_R\cdot\bar u\gamma^\mu(1-\gamma_5)d}\\ &+\epsilon_R\,\bar e\gamma_\mu\nu_L\cdot\bar u\gamma^\mu(1+\gamma_5)d \;+\; \cancel{\tilde\epsilon_R\,\bar e\gamma_\mu\nu_R\cdot\bar u\gamma^\mu(1+\gamma_5)d}\\ &+\frac{1}{4}\epsilon_T\;\bar e\sigma_{\mu\nu}\nu_L\cdot\bar u\sigma^{\mu\nu}(1-\gamma_5)d \;+\; \cancel{\frac{1}{4}\tilde\epsilon_T\;\bar e\sigma_{\mu\nu}\nu_R\cdot\bar u\sigma^{\mu\nu}(1+\gamma_5)d}\\ &+\epsilon_S\,\bar e\nu_L\cdot\bar u d \;+\; \cancel{\tilde\epsilon_S\,\bar e(1+\gamma_5)\nu_R\cdot\bar u d}\\ &-\epsilon_P\,\bar e\nu_L\cdot\bar u\gamma_5 d \;-\; \cancel{\tilde\epsilon_P\,\bar e\nu_R\cdot\bar u\gamma_5 d}\Big] + \text{h.c.}\end{aligned}$$

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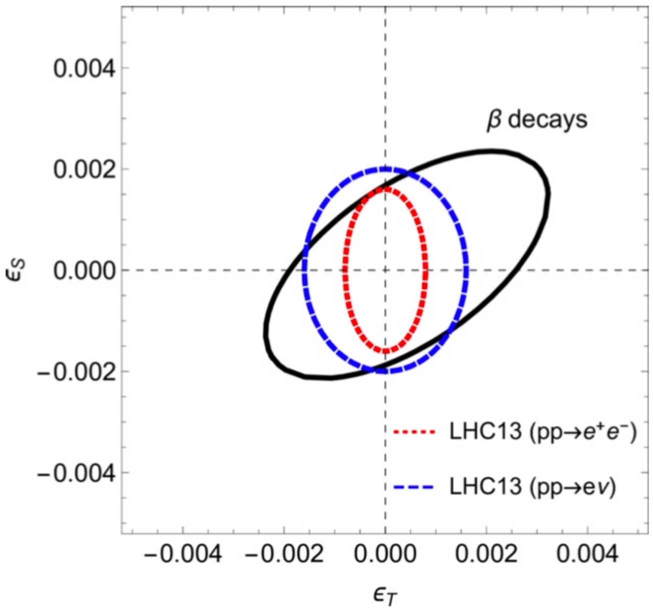
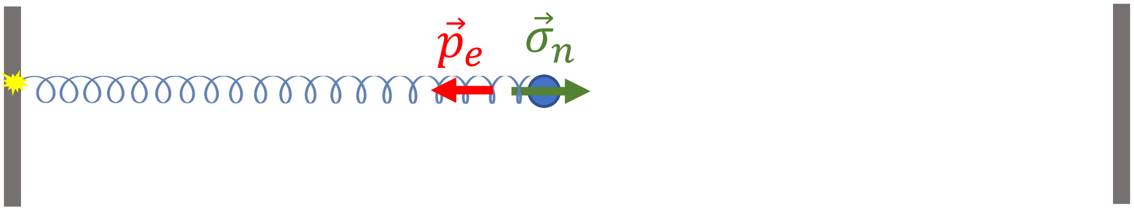


Neutron beta decay experiments to determine V_{ud}

$$|V_{ud}|^2 = \frac{5099.3(4)\mathrm{s}}{\tau_n(1+3g_A^2)(1+RC)}$$

$$\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$$

- Correlation measurements to determine g_A
  - *A*, *a*, *B*



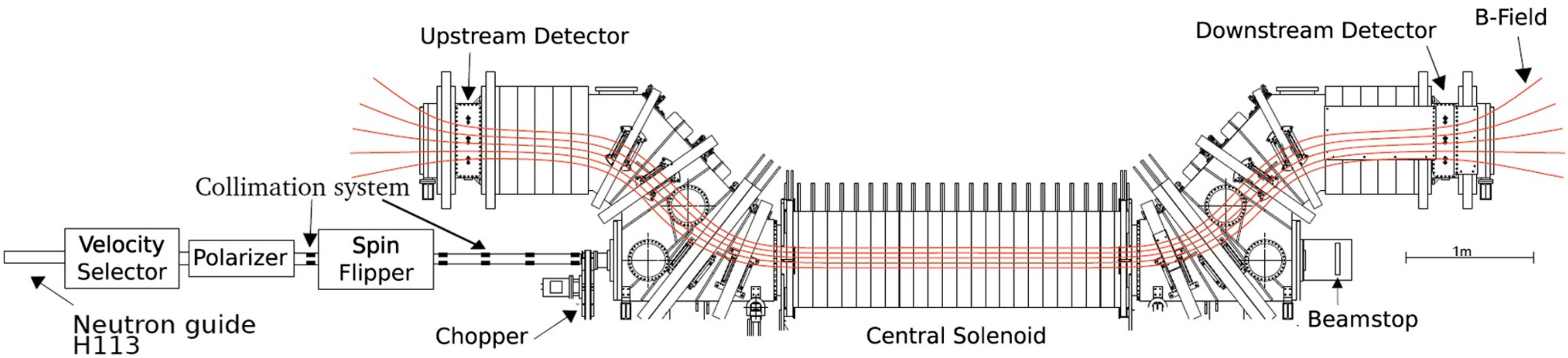
- Neutron lifetime
  - Beam
  - Bottle

Neutron decay beta-asymmetry (*A*) experiments: PERKEO III

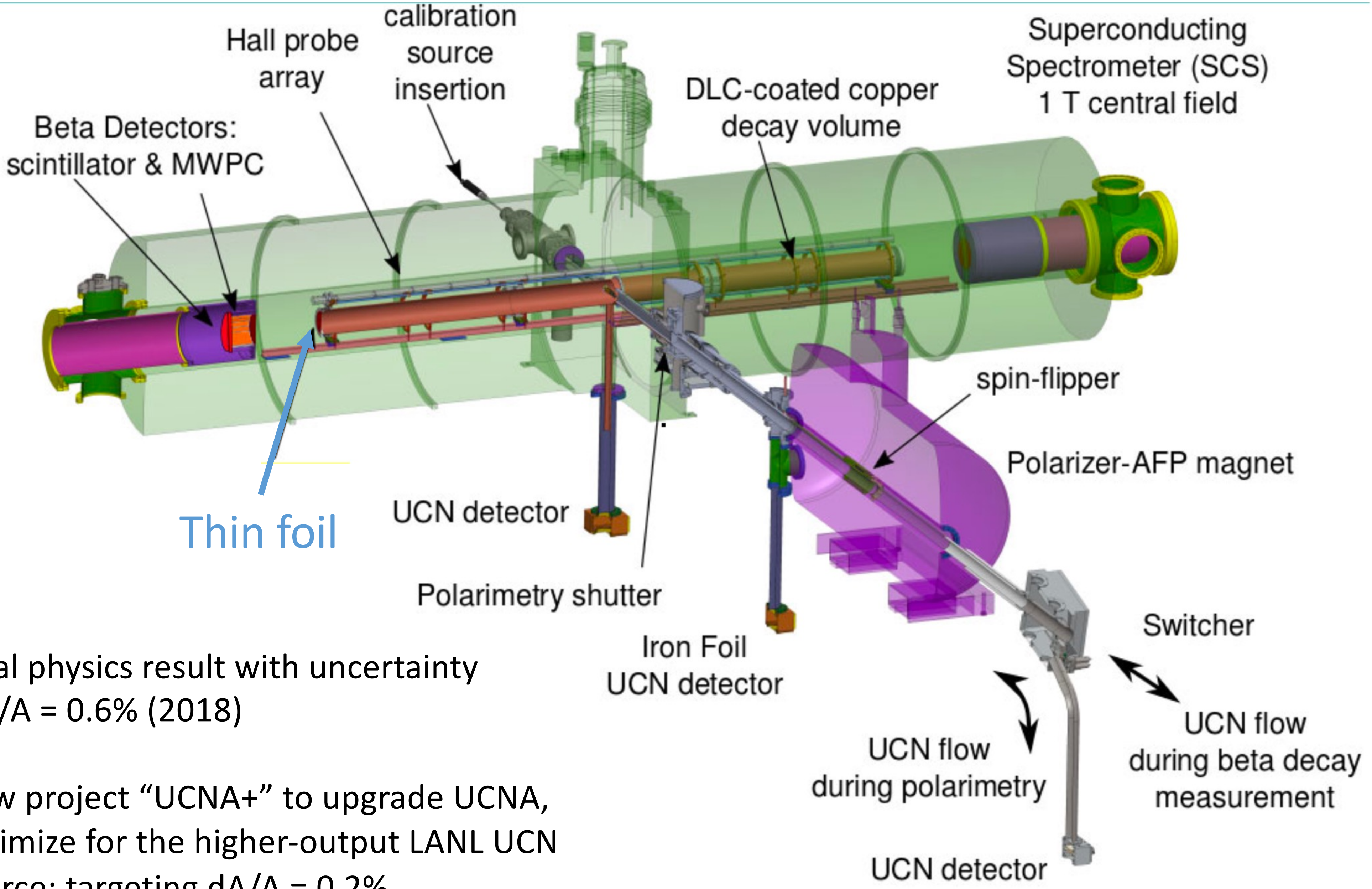
PRL **122**, 242501 (2019)

Final physics result with uncertainty (2019):

$\frac{\delta A}{A} = 0.17\%$ (2019) → $\frac{\delta g_A}{g_A} \sim 4\times 10^{-4}$



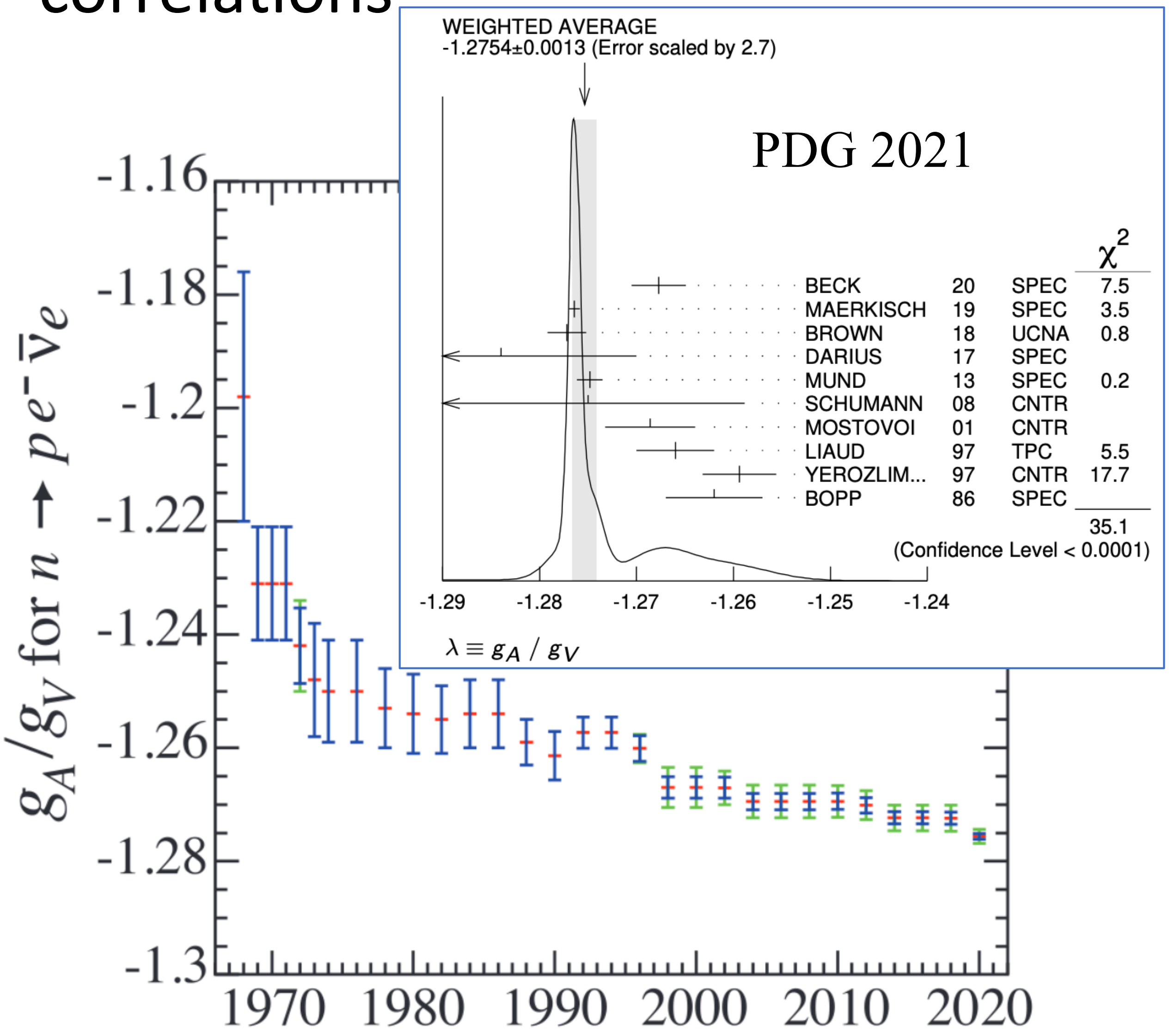
UCN Beta Asymmetry Experiment at Los Alamos



Final physics result with uncertainty
dA/A = 0.6% (2018)

New project “UCNA+” to upgrade UCNA, optimize for the higher-output LANL UCN source: targeting dA/A = 0.2%

Weak axial charge of the nucleon (g_A) from neutron decay correlations



WEIGHTED AVERAGE
-1.2754±0.0013 (Error scaled by 2.7)

			χ^2
BECK	20	SPEC	7.5
MAERKISCH	19	SPEC	3.5
BROWN	18	UCNA	0.8
DARIUS	17	SPEC	
MUND	13	SPEC	0.2
SCHUMANN	08	CNTR	
MOSTOVOI	01	CNTR	
LIAUD	97	TPC	5.5
YEROZLIM...	97	CNTR	17.7
BOPP	86	SPEC	
			35.1

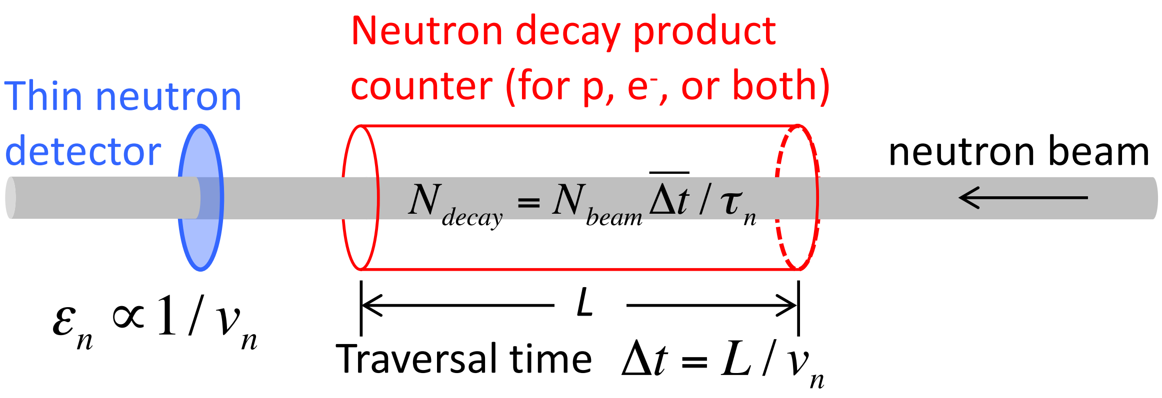
(Confidence Level < 0.0001)

- More recent experiments based on *A* correlation measurement are coming into agreement.
- Upcoming Nab and UCNA+ experiments are targeting similar precision as PERKEO III.
- Future PERC facility will target the next level of precision.

Two* techniques are used to measure τ_n

*Plus VCN storage ring by Paul et al.; also, other novel ideas…

Cold Neutron **Beam**



Thin neutron detector

Neutron decay product counter (for p, e^-, or both)

neutron beam

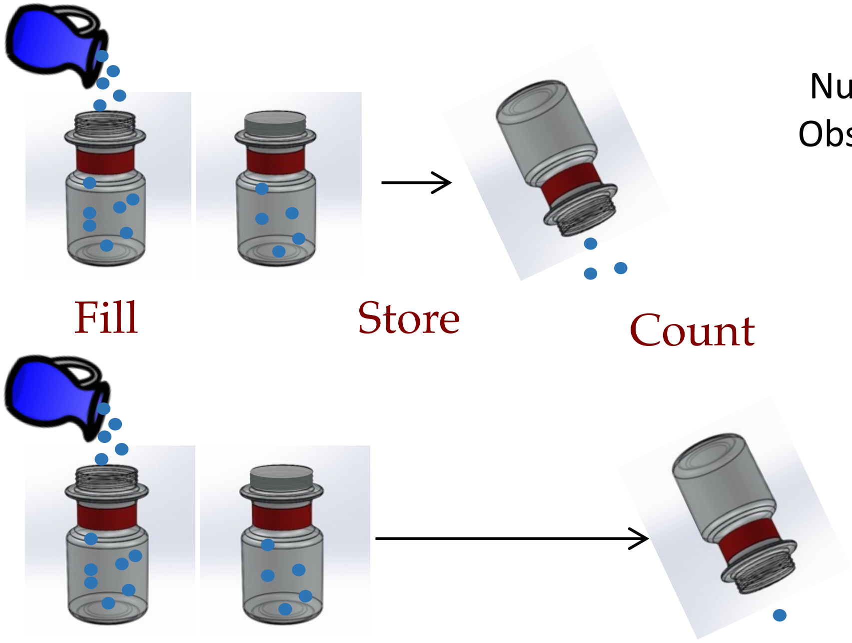
$$N_{decay} = N_{beam}\overline{\Delta t}/\tau_n$$

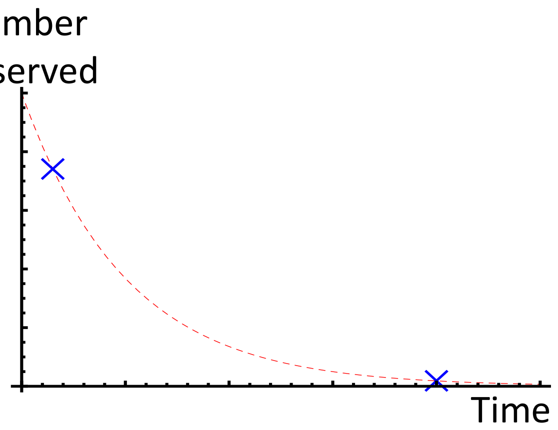
$$\varepsilon_n \propto 1/v_n$$

L

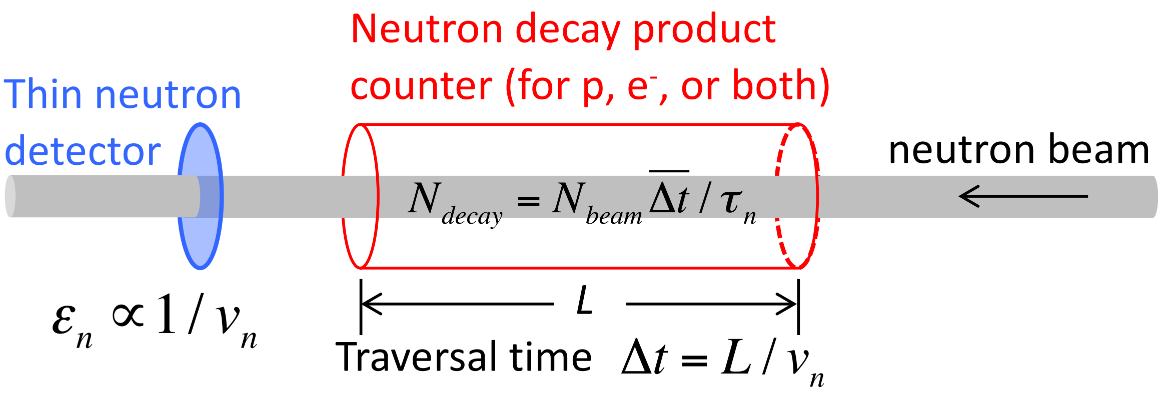
Traversal time $\Delta t = L/v_n$

Ultracold Neutron (UCN) **Bottle**





Could also detect decay products…



Thin neutron detector

$\varepsilon_n \propto 1/v_n$

Neutron decay product counter (for p, e$^-$, or both)

$N_{decay} = N_{beam}\overline{\Delta t}/\tau_n$

L

Traversal time $\Delta t = L/v_n$

neutron beam

Beam τ_n Experiments

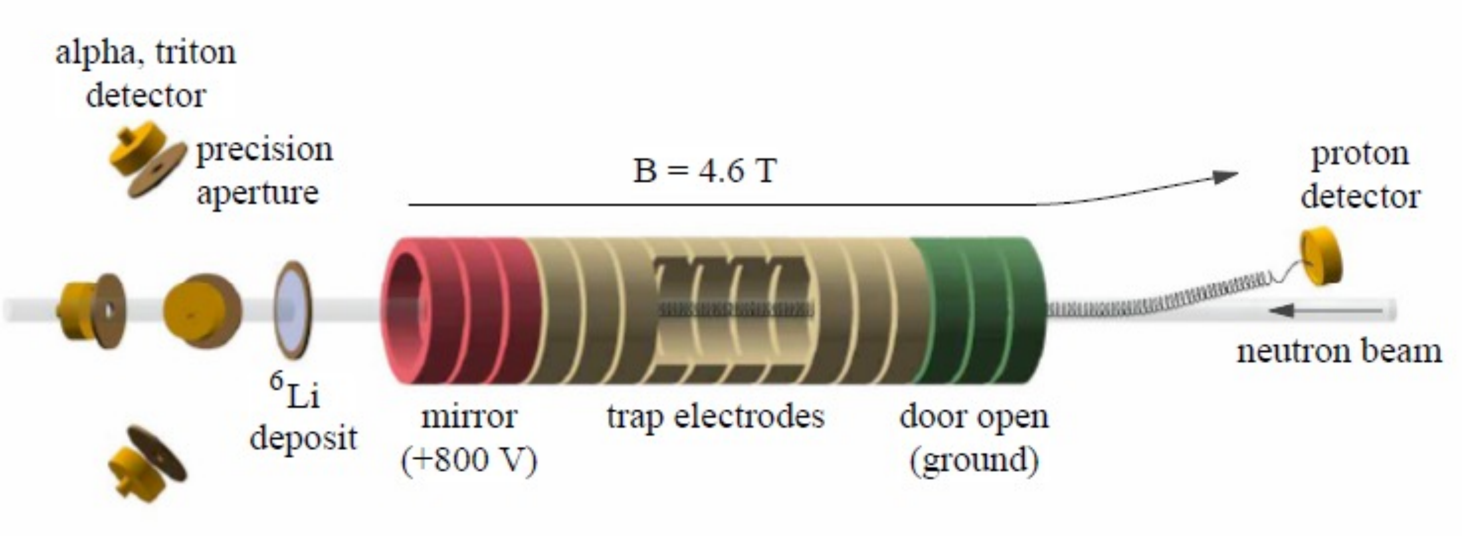
Measure decay products from well-characterized neutron beam

Key features:

- 1/*v* cancels out between neutron detector and time spent in fiducial volume: allows use of broadband beam.
- Need to know absolute detector efficiencies:
  - For neutron detector with known v_n
  - For decay product (*e* or *p*, or both)

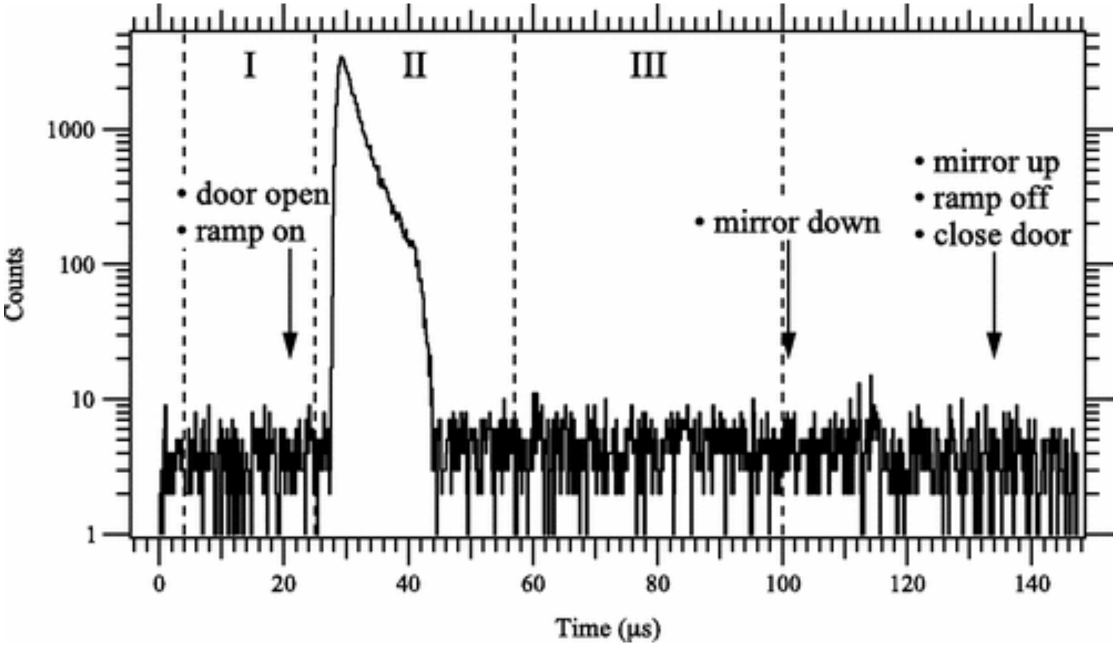
NIST Beam Experiment “BL-1”

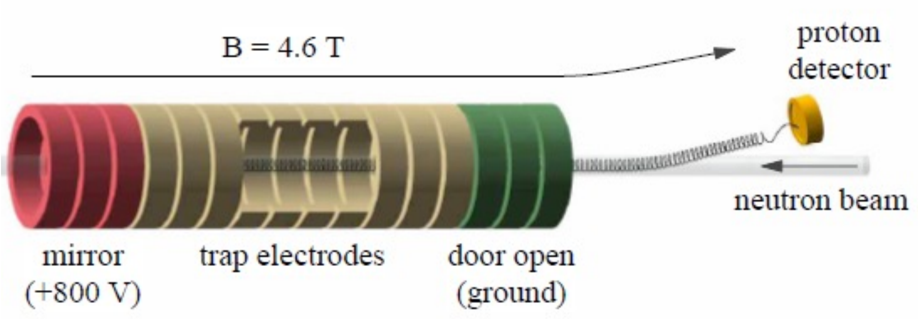
Original result (2005): τ_n = (886.3 ± 1.2[stat] ± 3.2[syst]) s
Updated (2013): τ_n = (887.7 ± 1.2[stat] ± 1.9[syst]) s



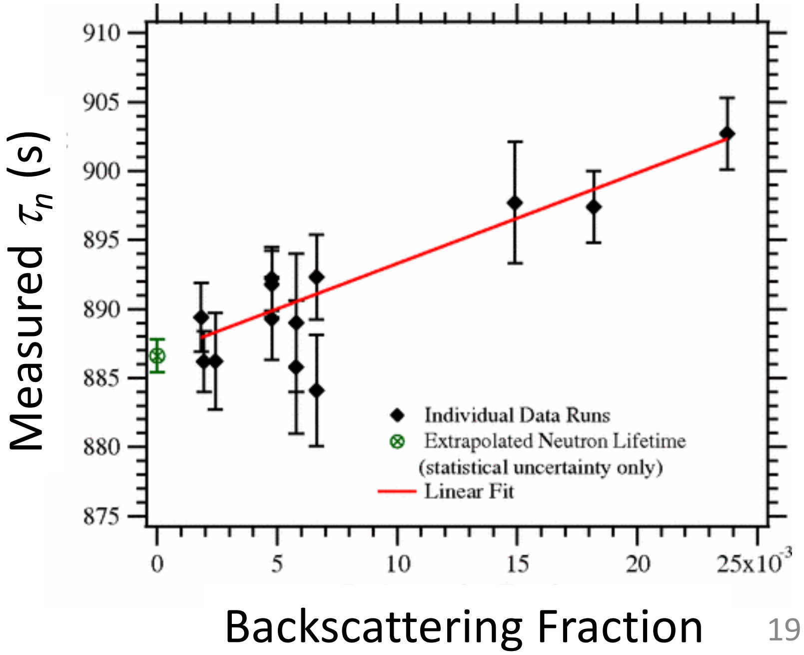
- Counts protons from beta-decays in flight
- Absolute neutron flux must be measured very accurately
- Absolute proton detection efficiency must be known very accurately
- The n counter absolute efficiency calibration was later improved, reducing systematic uncertainty in the original (2005) result.

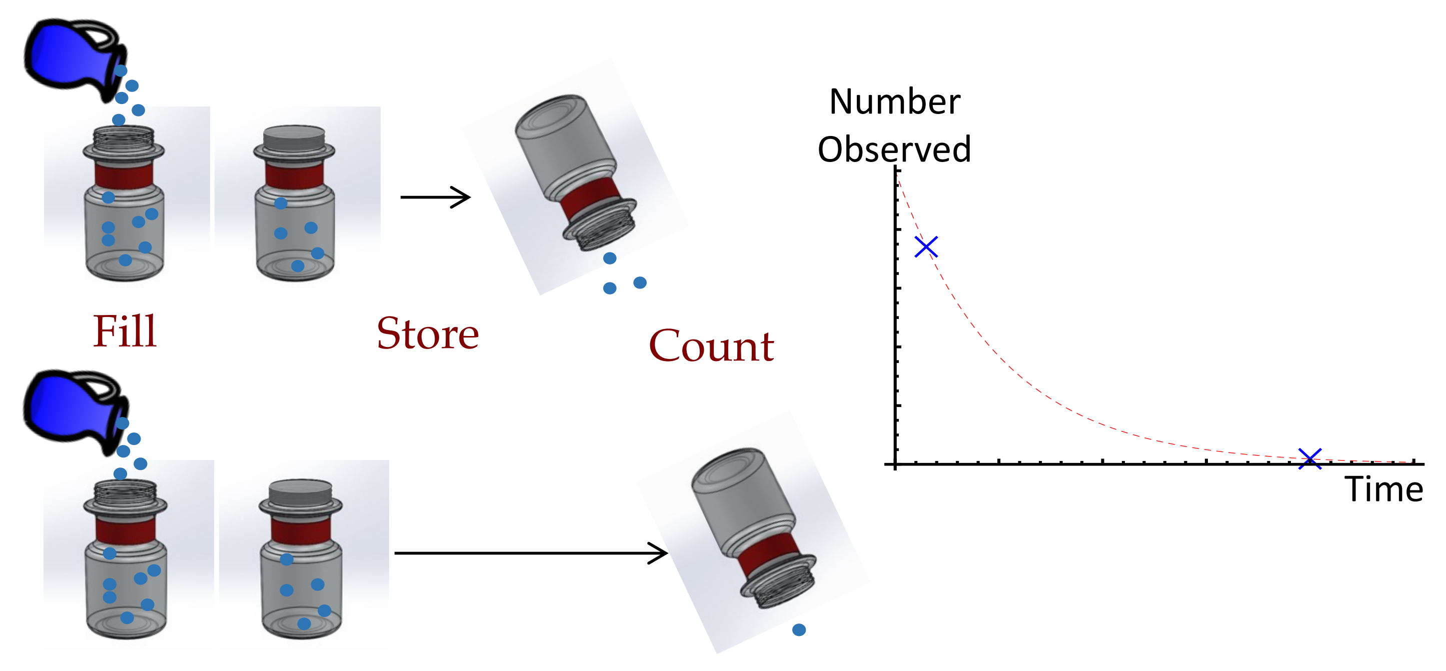
Proton detection





- Protons are accelerated into a ≈99%-efficient detector.
- Corrections must be applied for:
  - Dead layer
  - Backscattering
- Corrections were determined by combination of the following:
  - Dead layer measurement using radioactive sources
  - Taking data with thin coatings added to enhance backscattering
  - Monte Carlo calculations
  - Extrapolation to zero loss





Bottle τ_n Experiments

Measure total disappearance rate of neutrons

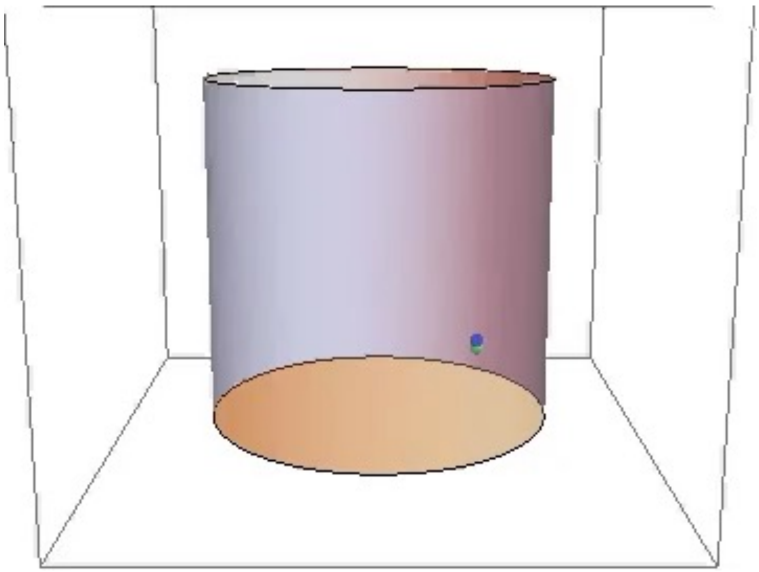
Key features:

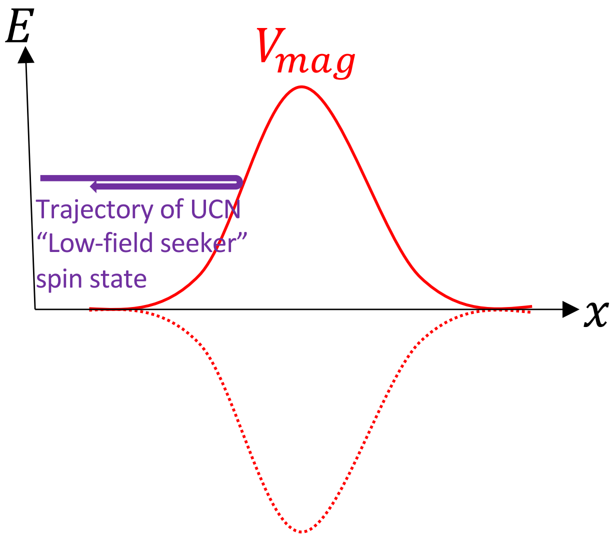
- Ultracold neutron storage
- Can either detect surviving neutrons after different holding periods, or detect the change in rate of decay products as neutrons decay away.

Ultracold neutrons (UCN) are convenient for measurements of neutron properties.

Ultracold neutrons

- Neutrons with kinetic energy < ≈ 350 neV (velocity up to ≈ 5 m/s)
- *Total external reflection* from common materials (e.g., stainless steel $V_F \approx 180$ neV, ^{58}Ni $V_F \approx 350$ neV) – can be stored in a material bottle.
- Gravitational confinement to a few meters height ($V_{grav} = mg \approx 100$ neV/m)
  - Can change KE by guiding to different height
- Magnetic potential similar to KE with a few Tesla field ($V_{mag} = \vec{\mu}_n \cdot \vec{B} \approx 60$ neV/T)
  - Total reflection from laboratory-scale fields
  - 100% spin selection filter
- One inconvenience: hard to get a high density of neutrons into an actual experiment.





All material bottles "leak" UCN to some extent.

Neutrons remaining after time Δt: $N(\Delta t) = N_0 e^{-\Delta t/\tau_s}$

$$\tau_s^{-1} = \tau_\beta^{-1} + \tau_w^{-1} + \tau_O^{-1}$$

Beta decay

Total loss rate due to interactions with the walls

All other mechanisms, e.g. gas upscattering

$$\tau_w^{-1} = \tau_u^{-1} + \tau_c^{-1} + \tau_{qb}^{-1} + \tau_g^{-1}$$

Upscattering

Capture

Escape of quasibound UCN

Gaps, etc.

Wall interaction loss contribution for process i:

$\tau_i^{-1} = \gamma(v)\mu_i(v)$, where γ = wall collision rate.

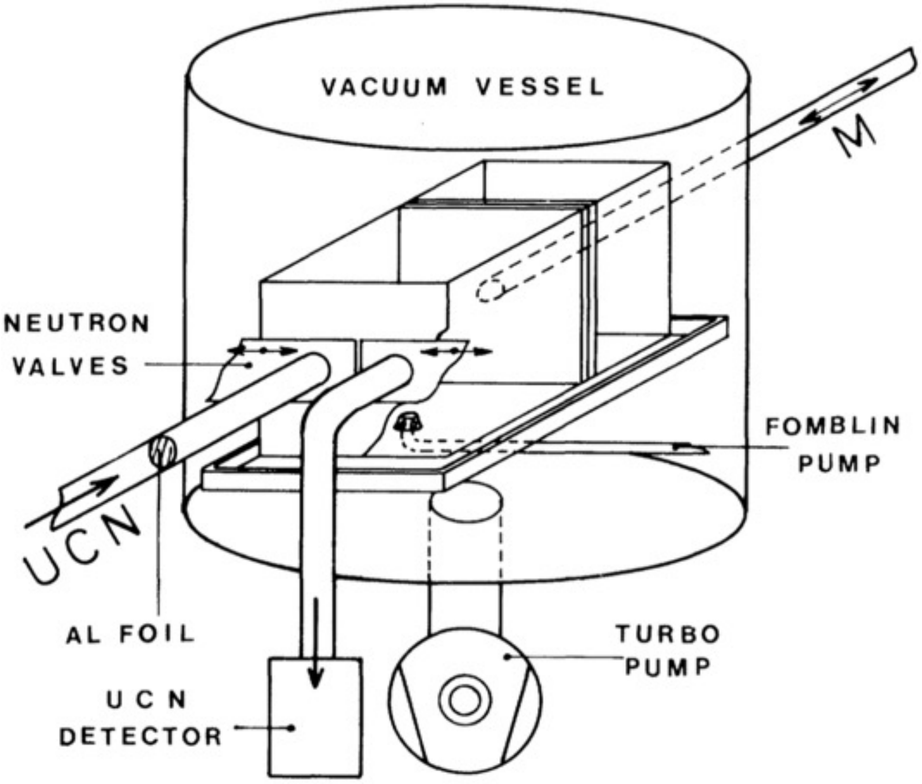
Vary $\gamma(v)$ to enable extrapolation to $\tau_w^{-1} = 0$

$$\tau_s^{-1}(v) = \tau_\beta^{-1} + \tau_w^{-1}(v) = \tau_\beta^{-1} + \mu(v)v/\lambda$$

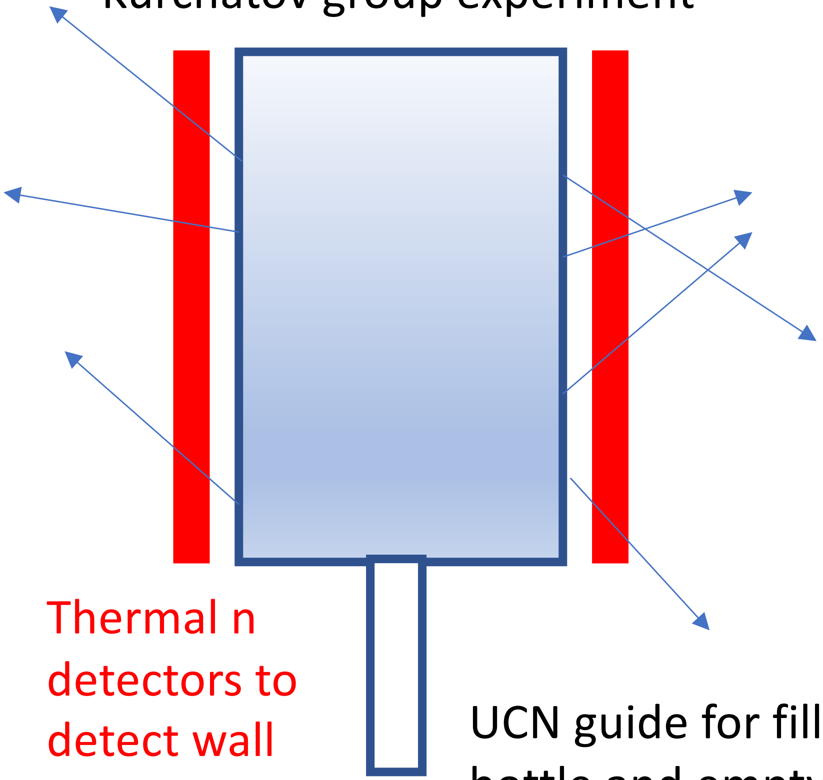
Mean free path between wall collisions

- Energy spectrum evolves over storage time
- Different approaches have been used to vary wall collision rate, typically by changing bottle surface-to-volume ratio

“MAMBO 1”



Kurchatov group experiment

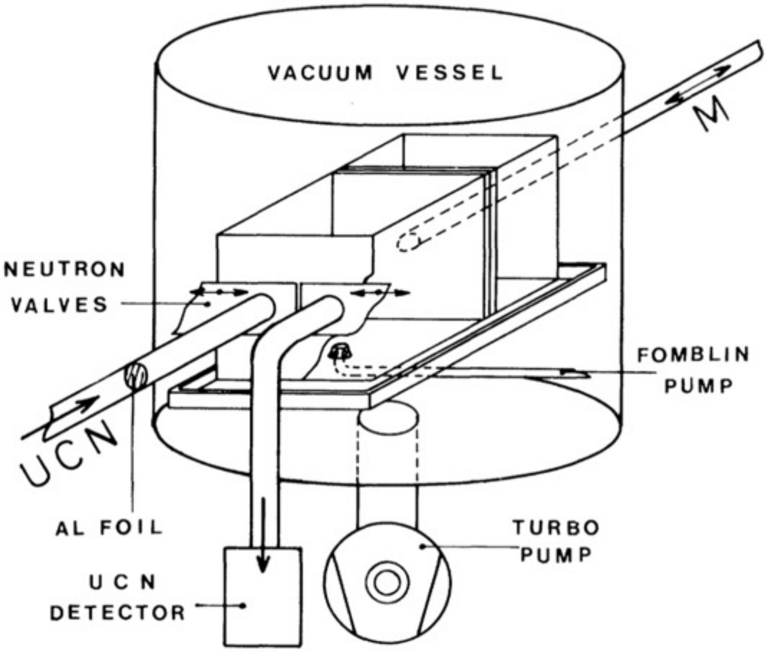


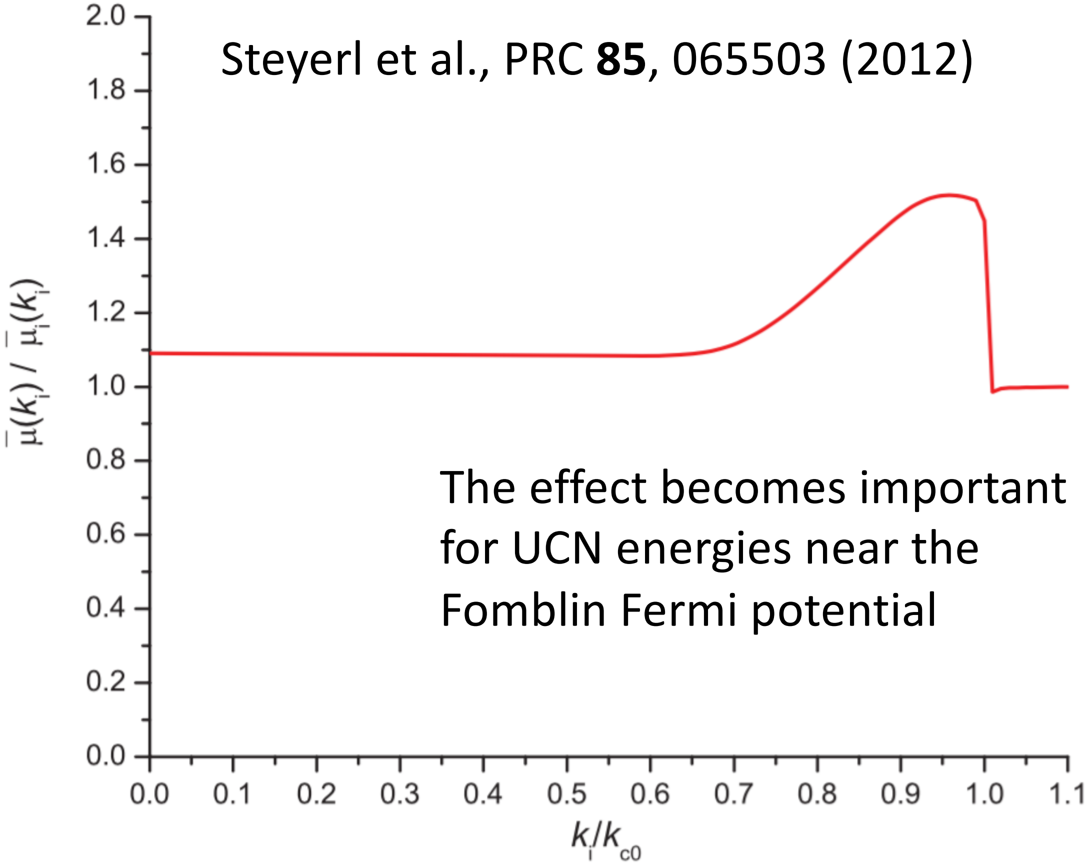
Thermal n detectors to detect wall upscattering

UCN guide for filling bottle and emptying into UCN detector

Mambo I

- Fomblin-coated bottle of variable size
- Corrections applied to original result for energy spectral evolution did not include surface waves in liquid-Fomblin coating
- Steyerl et al. calculated this effect for Mambo 1 (extended previous calculations by others):





Steyerl et al., PRC **85**, 065503 (2012)

The effect becomes important for UCN energies near the Fomblin Fermi potential

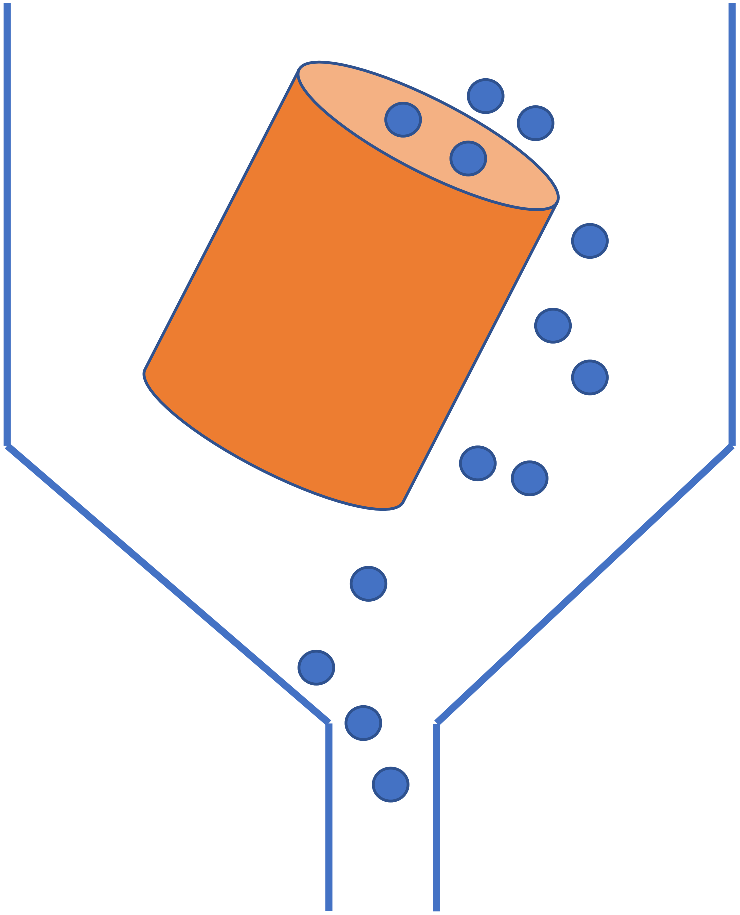
887.6 ± 3 s (1989)

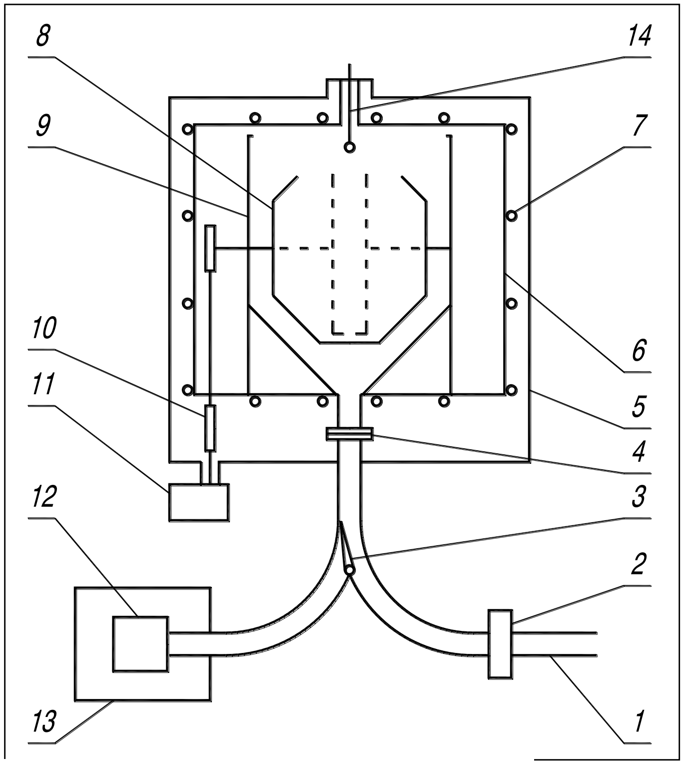
↓

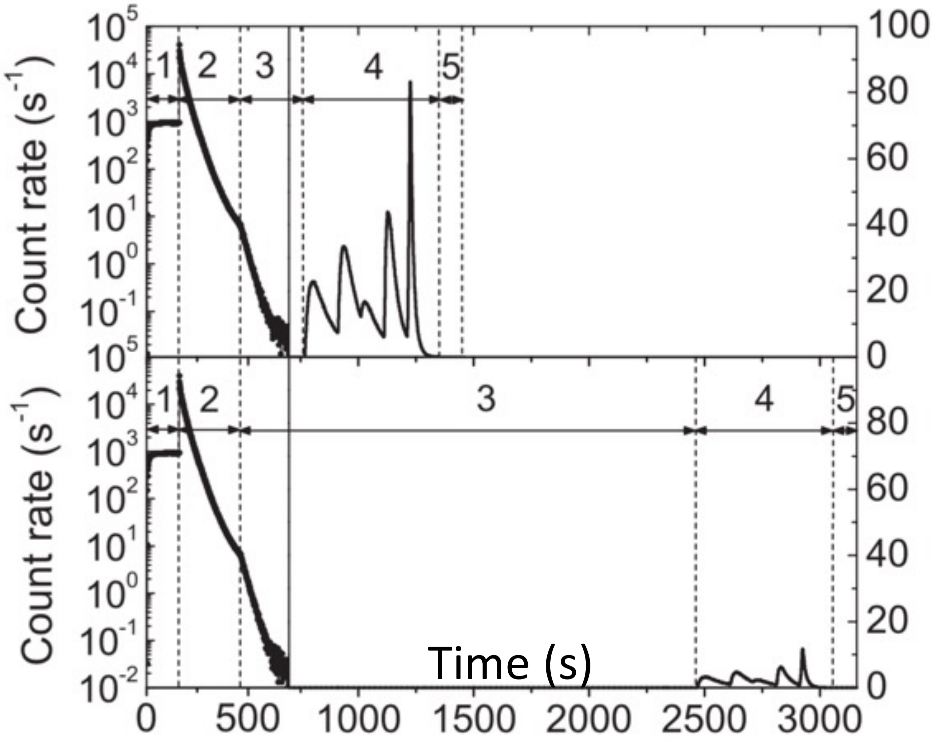
882.5 ± 2.1 s (2012)

Gravitrap I

Serebrov *et al.*, Phys. Lett. **B605**, 72 (2005).
Serebrov *et al.*, PHYSICAL REVIEW C **78**, 035505 (2008)







Gravitrap I

Serebrov *et al.*, Phys. Lett. **B605**, 72 (2005).
Serebrov *et al*., PHYSICAL REVIEW C **78**, 035505 (2008)

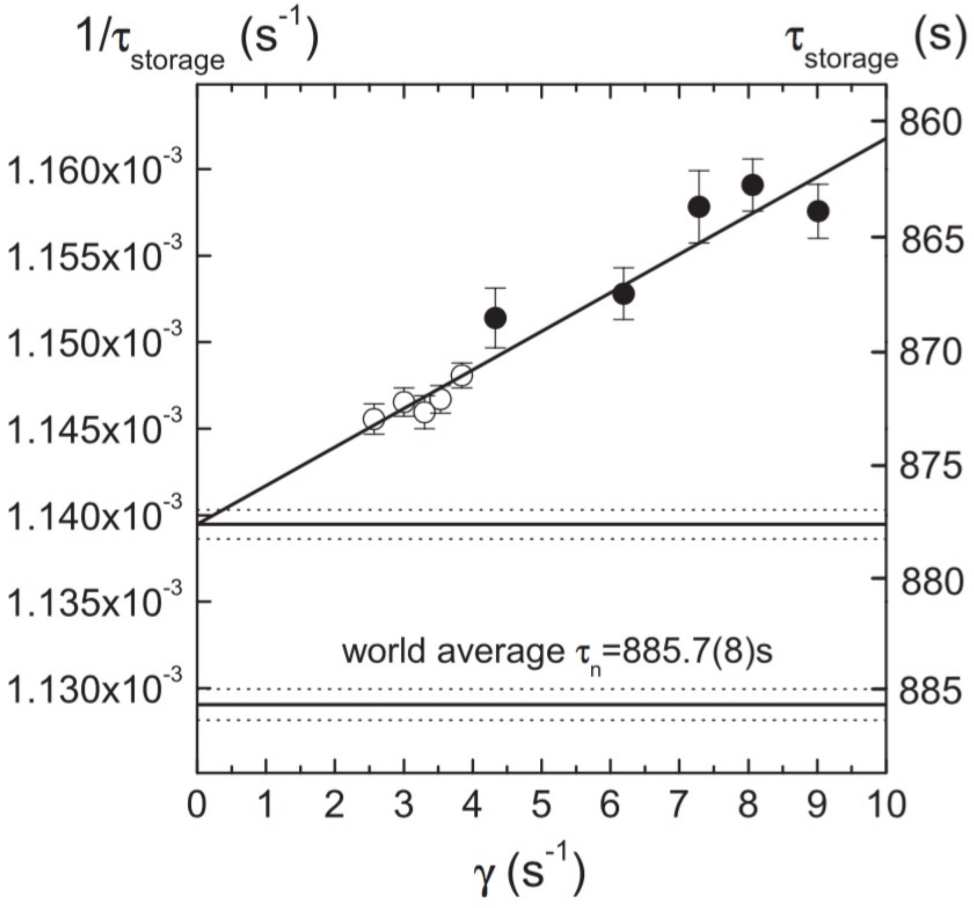
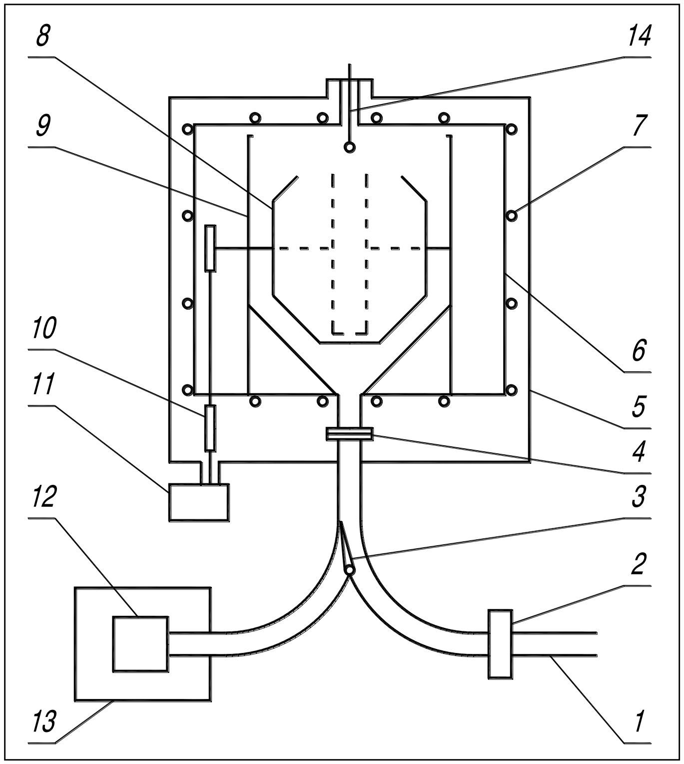


FIG. 12. Result of extrapolation to the neutron lifetime when combined energy and size extrapolations are used. The open circles represent the results of measurements for a quasispherical trap, and the full circles the results of measurements for a cylindrical trap.



Gravitrap II

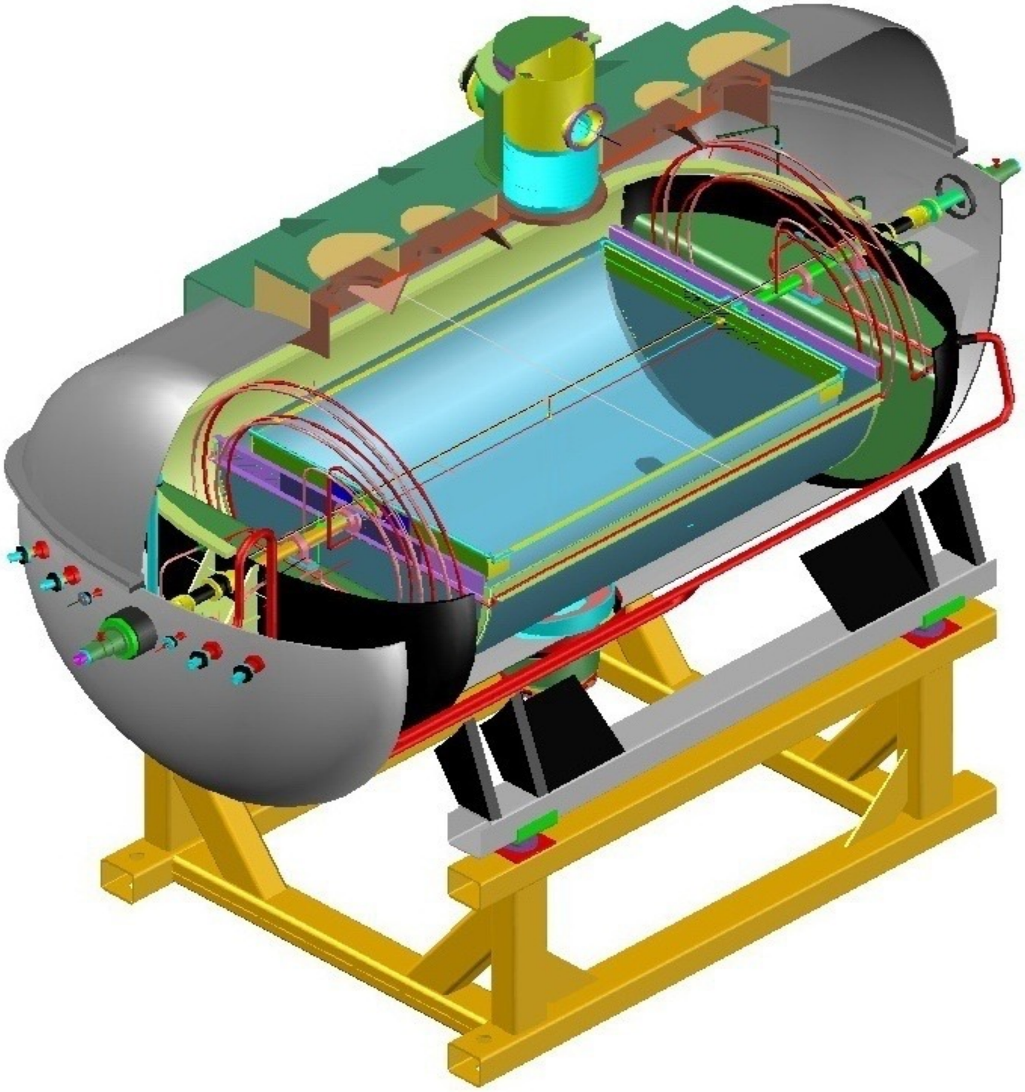
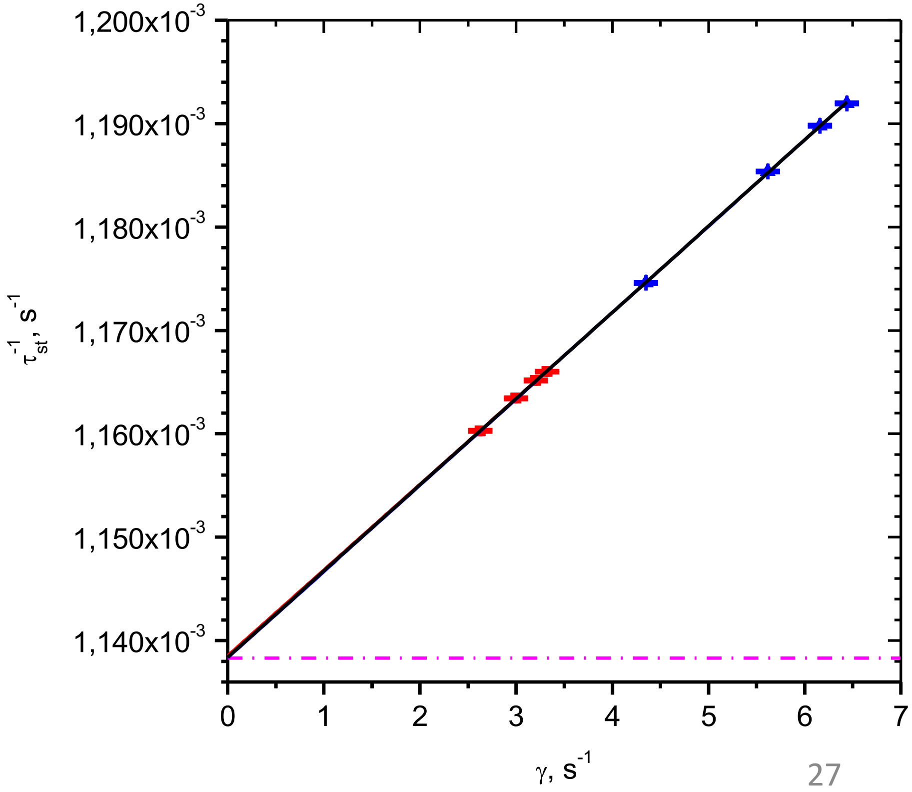
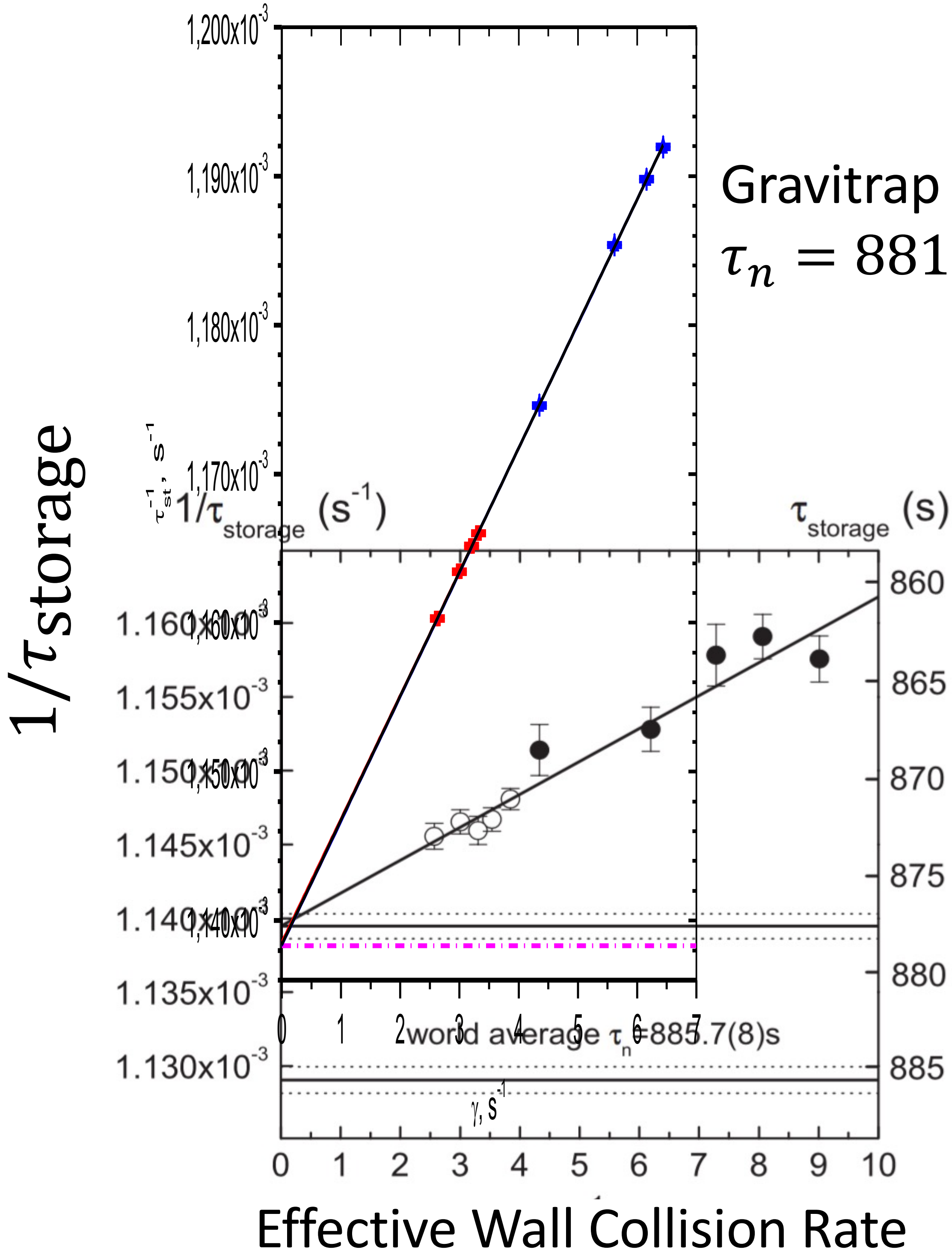


Fig.1. Gravitational spectrometer with service platforms



Content from A. Serebrov, PPNS2018



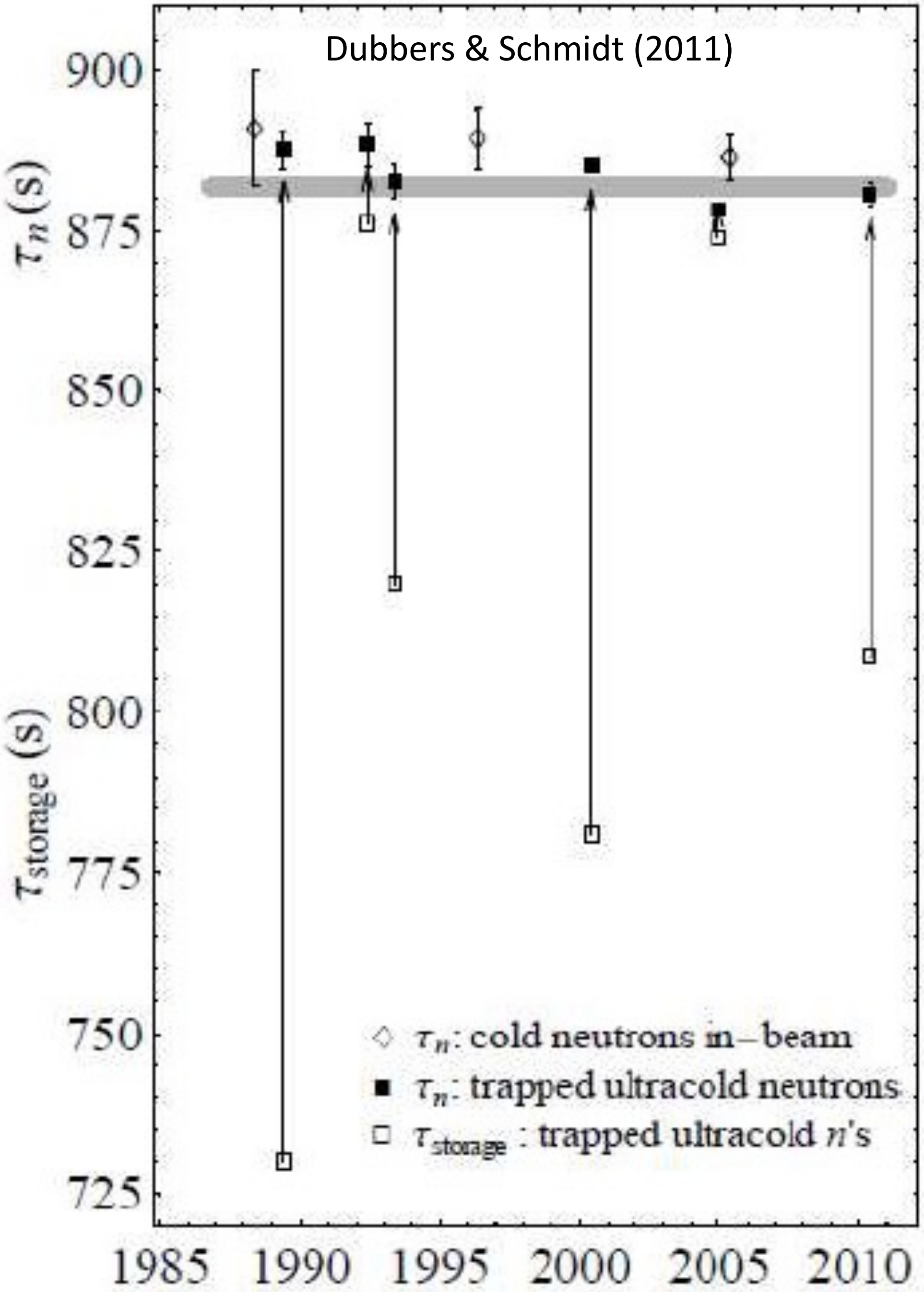
Gravitrap II

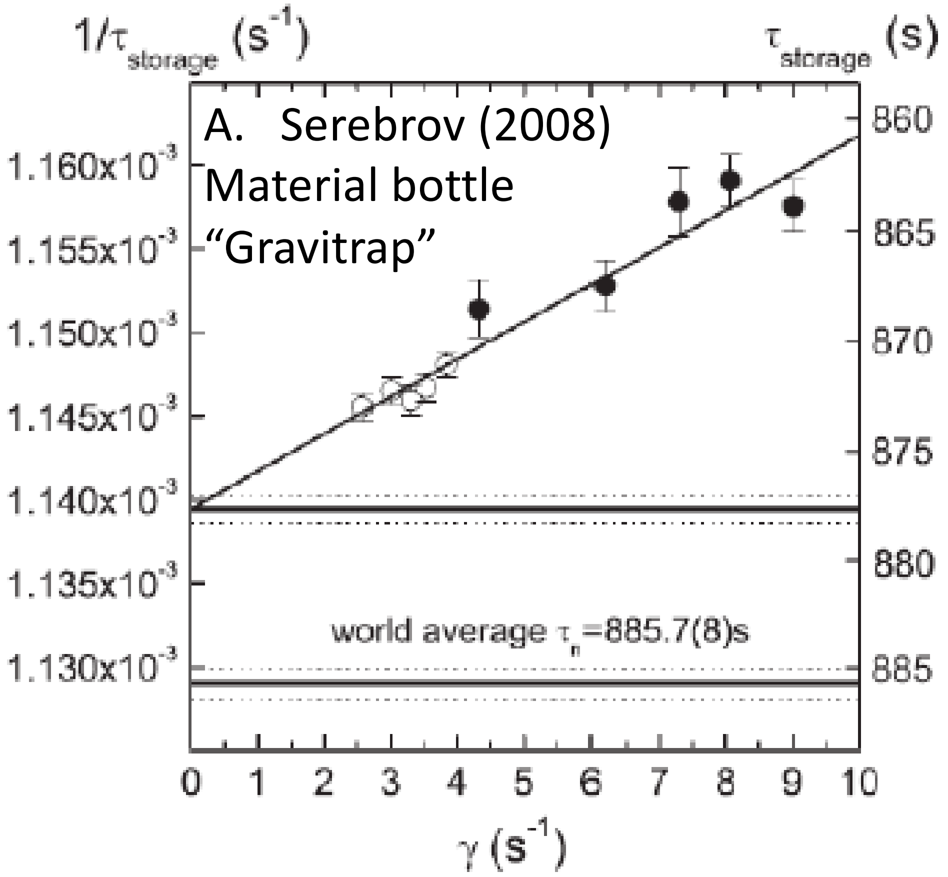
$\tau_n = 881.5 \pm 0.7 \pm 0.6$ s

Gravitrap I

$\tau_n = 878.5 \pm 0.7 \pm 0.3$ s

Size of Systematic Corrections for Losses

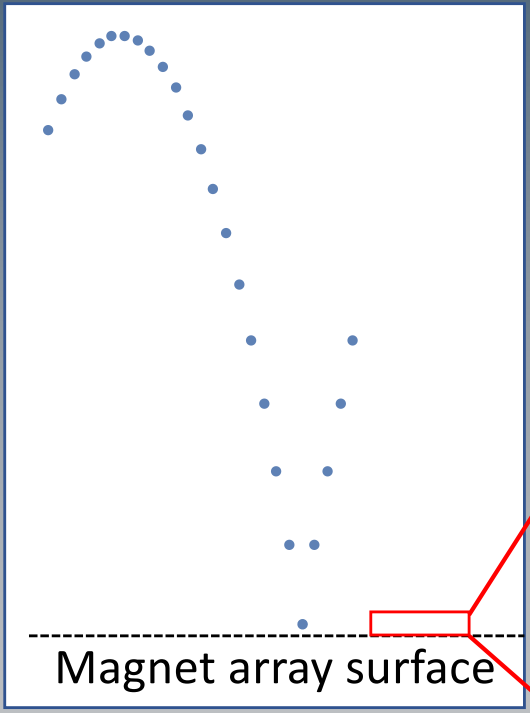


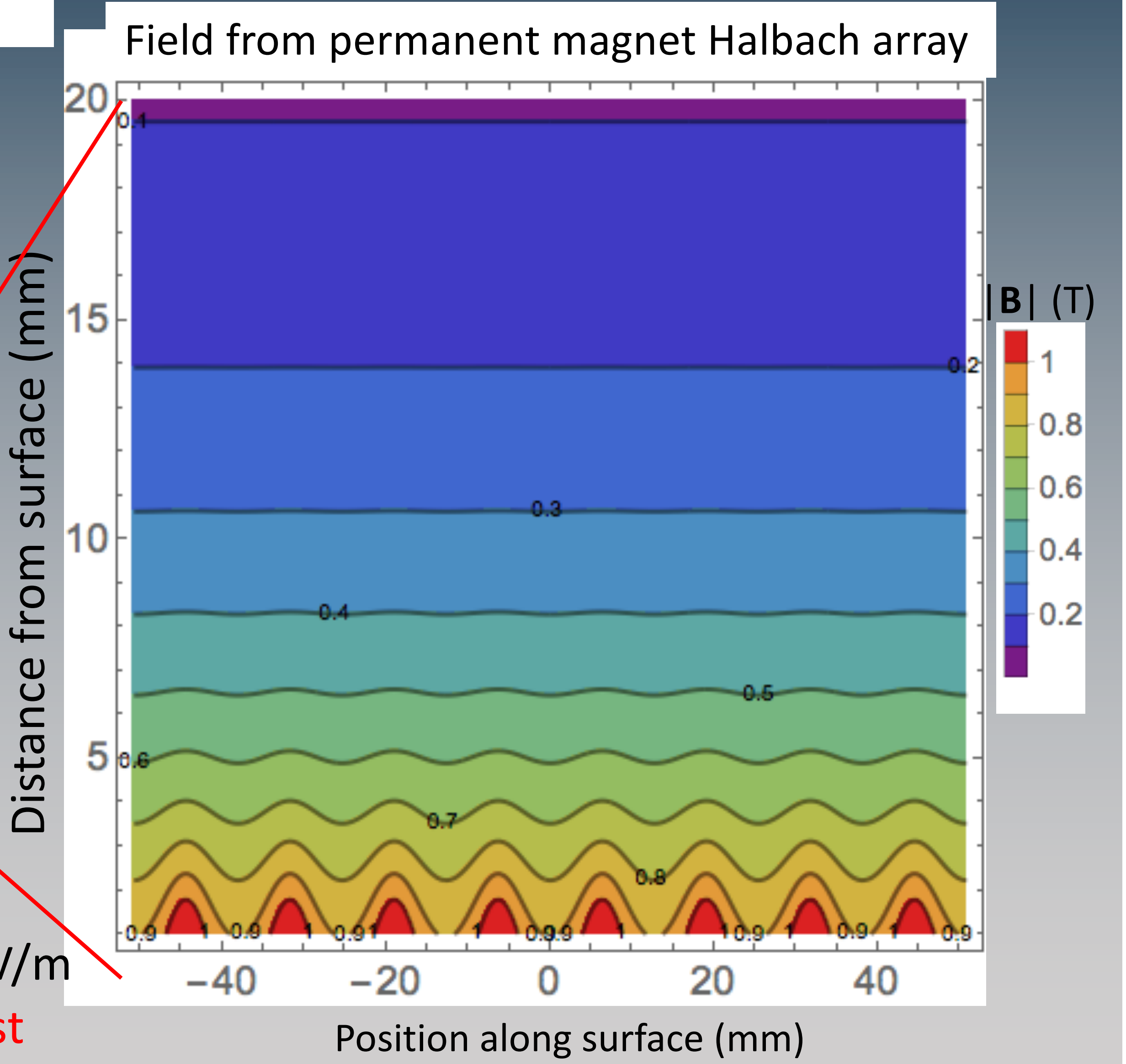


Large systematic corrections must be very well understood!

Magnetic bottles are designed to eliminate wall losses

Gravity confines from above, magnetic fields from below and laterally.




Field from permanent magnet Halbach array

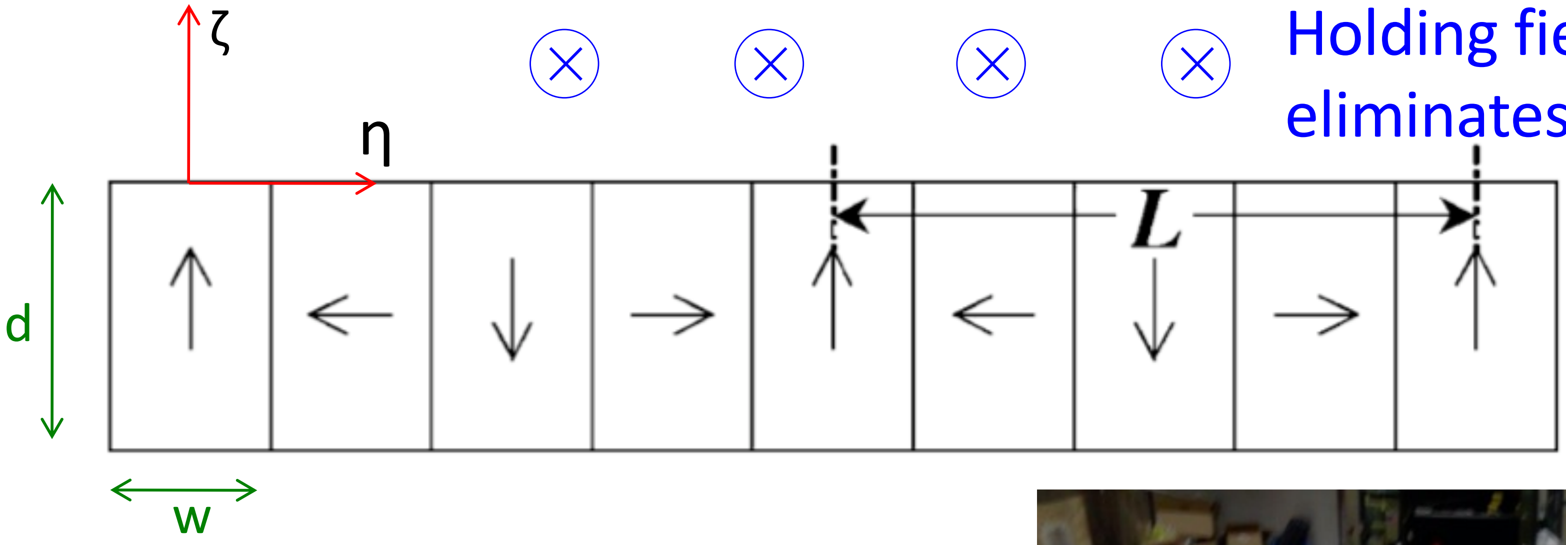
UCN τ Example:

- $\boldsymbol{\mu \cdot B}$ for neutron ≈60 neV/Tesla
- Gravitational potential ≈100 neV/m
- 50 cm drop (from rest) → closest approach to surface about 2 mm

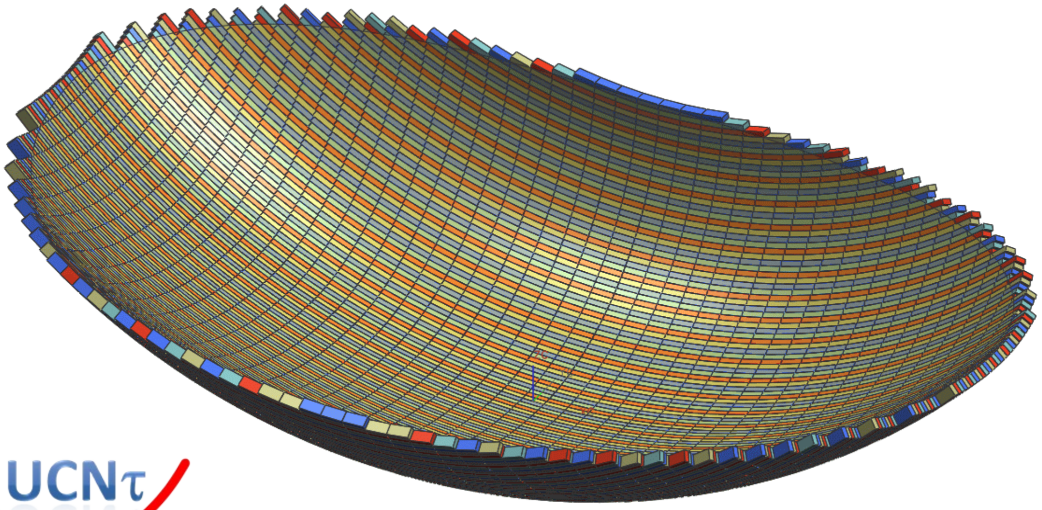
Halbach Array + Holding Field

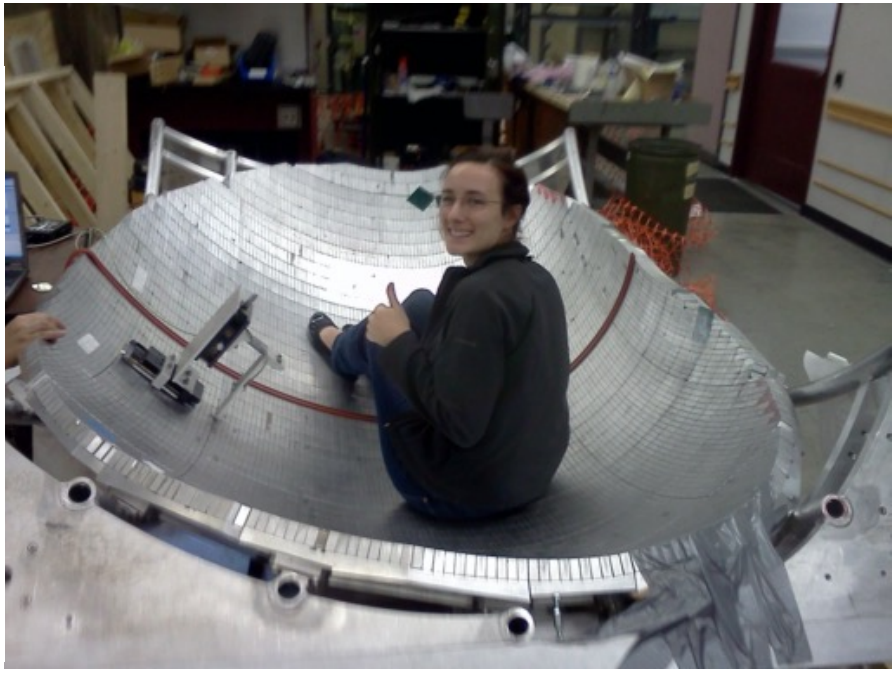
$$|\mathbf{B}| = B_{\mathrm{rem}}(1 - \mathrm{e}^{-kd})\mathrm{e}^{-k\zeta}$$

(if continuous rotation of M)

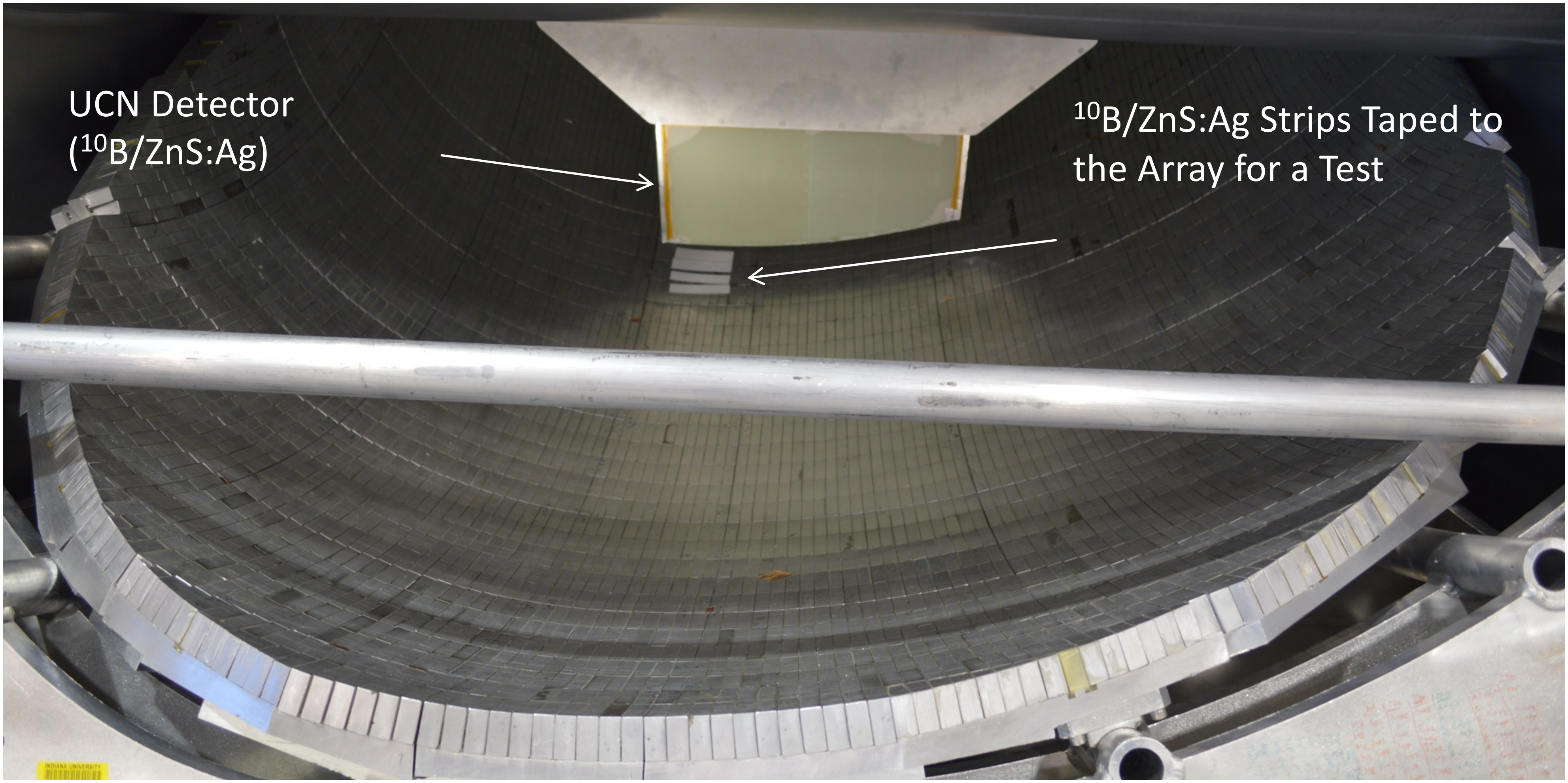


Holding field eliminates field zeros





View of the Halbach Array and Lowered UCN Detector



UCN Detector (^{10}B/ZnS:Ag)

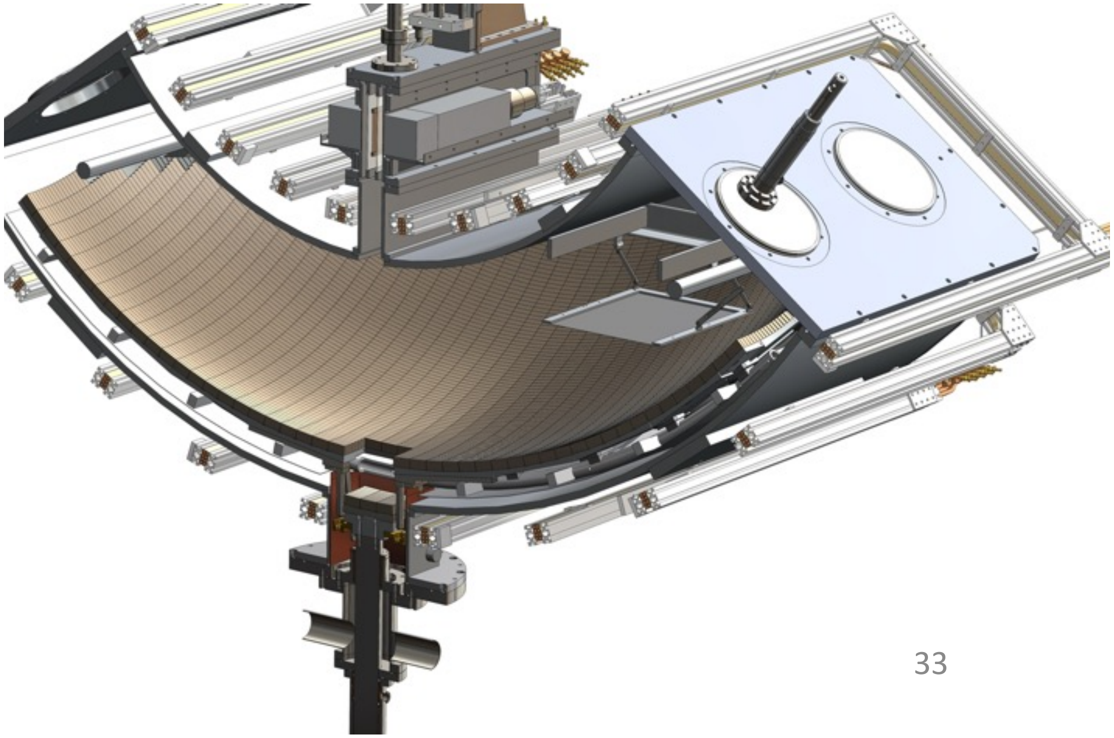
^{10}B/ZnS:Ag Strips Taped to the Array for a Test

UCNτ Overview

- UCN trap with very low intrinsic losses
  - Magneto-gravitational trap
  - Superposed holding field to eliminate B-field zeros (no depolarization losses)
  - Fast removal of quasi-bound UCNs possible through trap asymmetry and field ripple

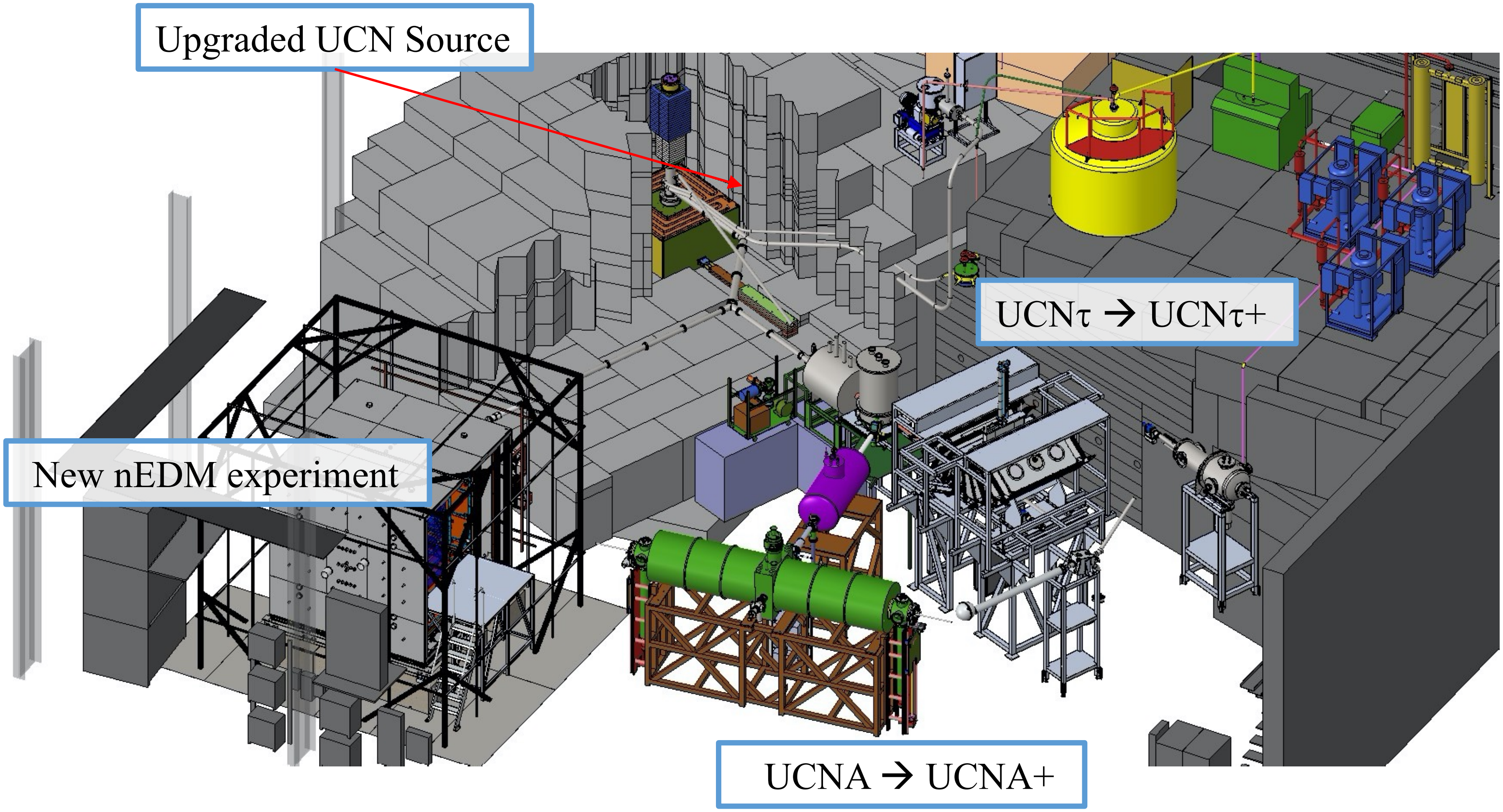
- High statistics are achievable
  - Large volume
  - *In situ* UCN detector
    - High overall efficiency
    - Also: Less sensitive to phase-space evolution than draining

Based on original concept: P.L. Walstrom, J.D. Bowman, S.I. Penttila, C. Morris, A. Saunders, NIMA 599 (2009) 82-92

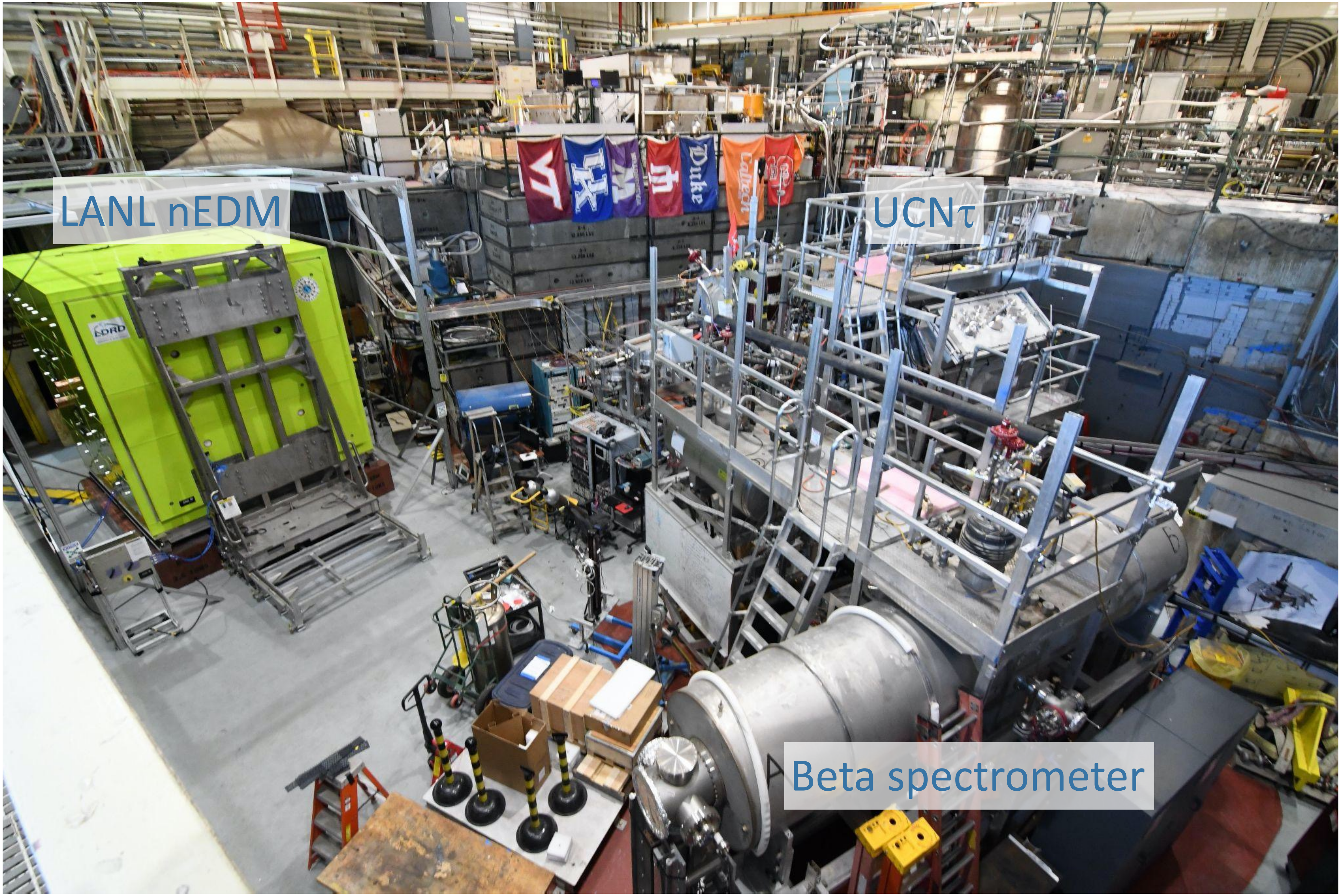


LANL’s UCN Source Feeds Multiple Experiments

2016 UCN Source Upgrade: 5x improved output

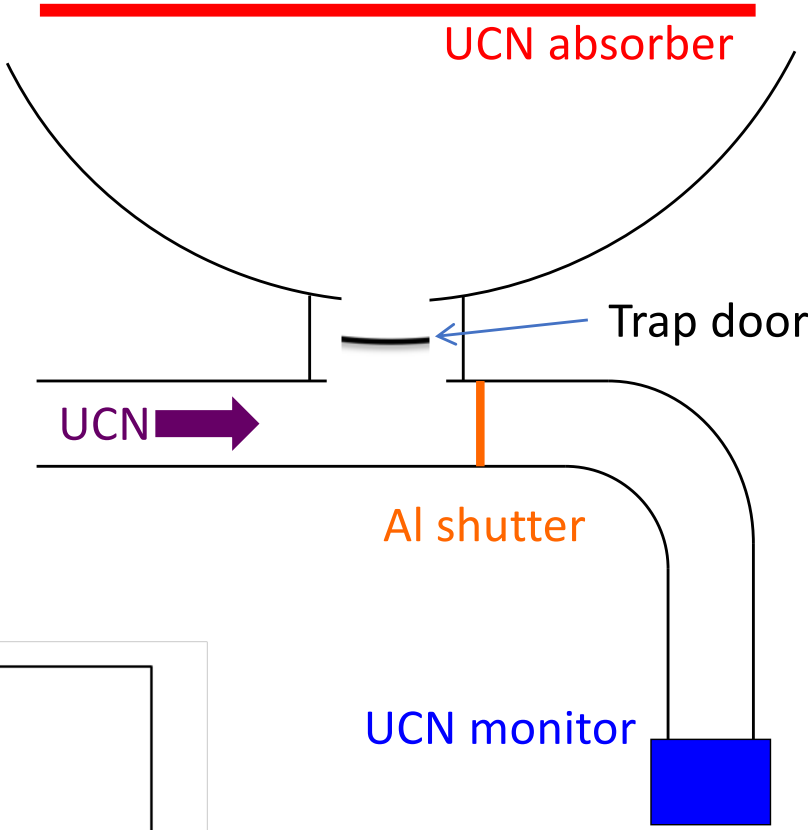


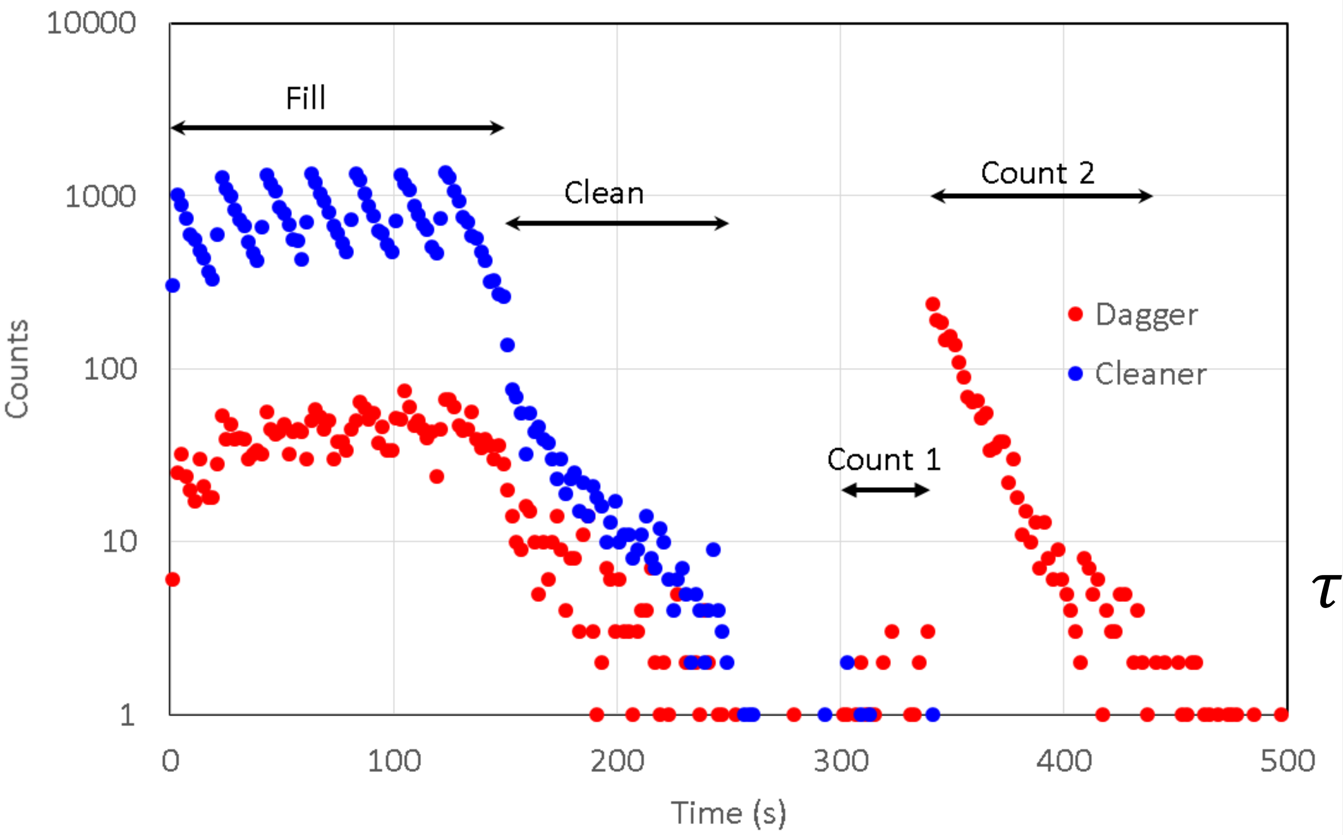
LANL UCN Experimental Hall



Measurement Cycle

1. Load the trap
2. Close the trap door
3. Remove quasi-bound UCNs (lower absorber, wait, raise absorber)
4. Hold UCNs in the trap for time *t*
5. Count the surviving UCN population *N*





Using two different cycles with holding times t_1 and t_2,

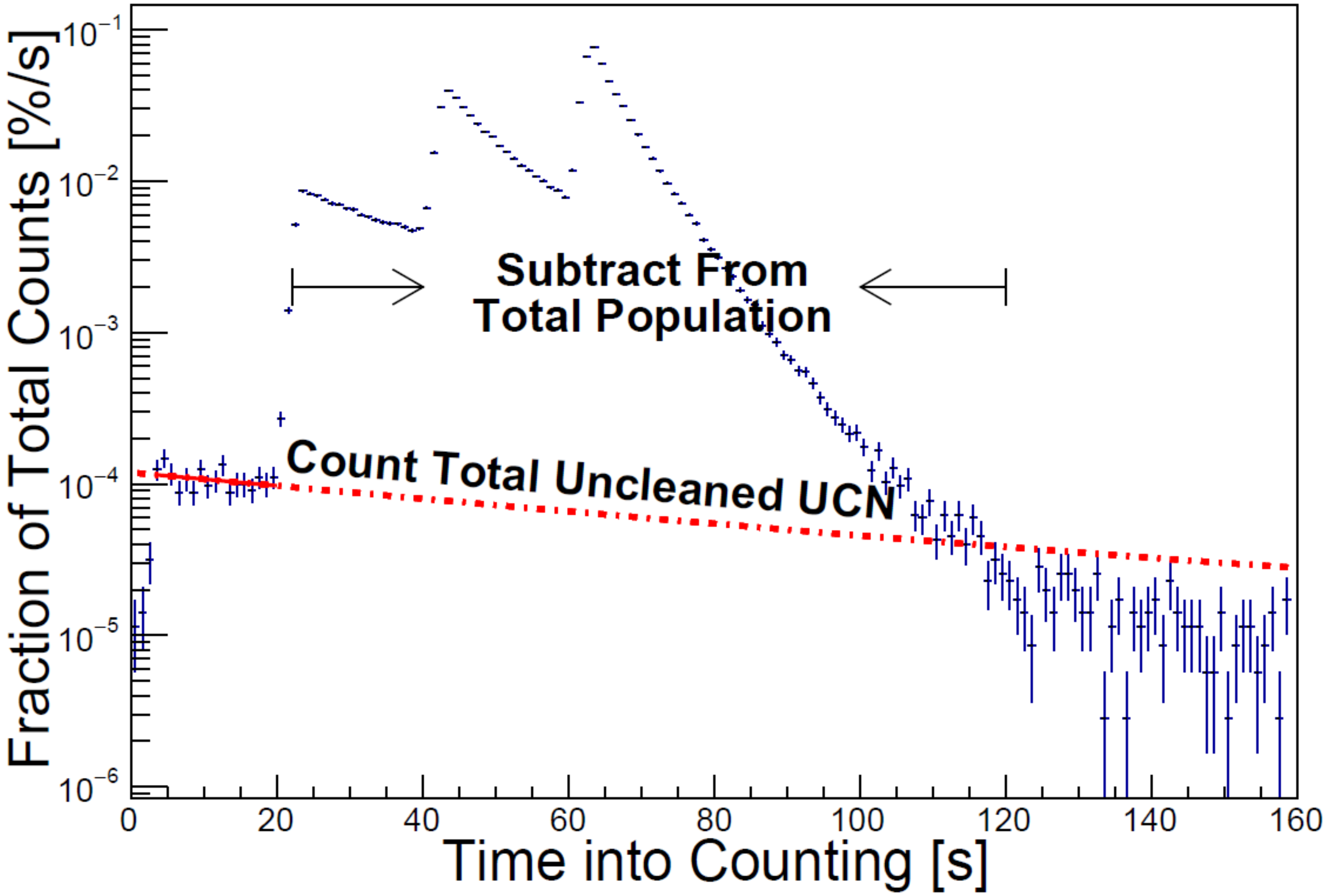
$$\tau_n = -(t_2 - t_1)/\log(\frac{N_2}{N_1})$$

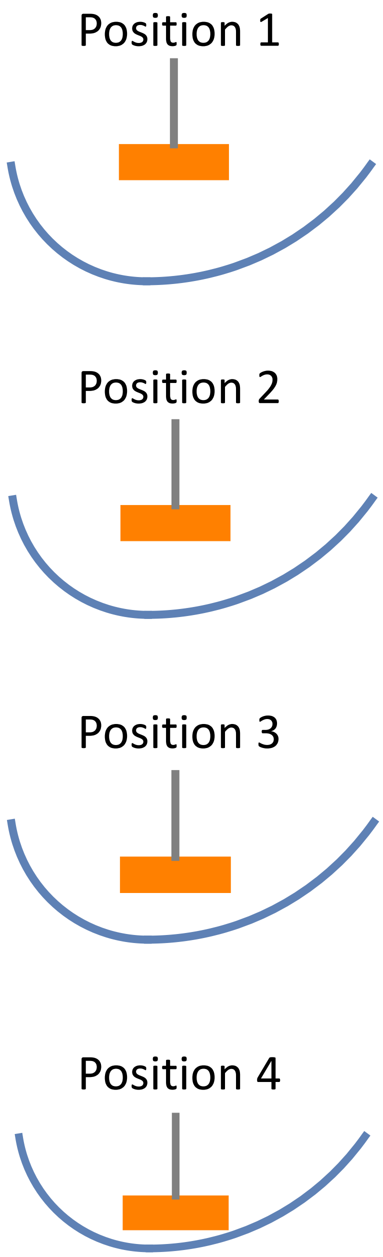
UCNτ

Multi-step UCN detection

Example with an insufficiently-cleaned UCN population

(Before we installed the “Giant Cleaner”)



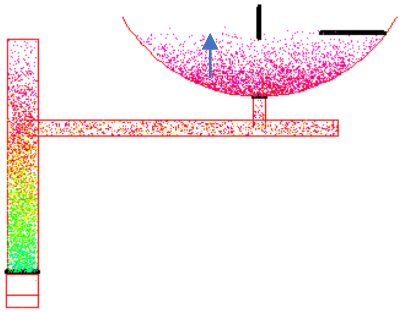


Systematic uncertainties in UCNτ 2018

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 variations	<0.01	±	Measured background as function of detector position
Total	**0.28**		**(uncorrelated sum)**

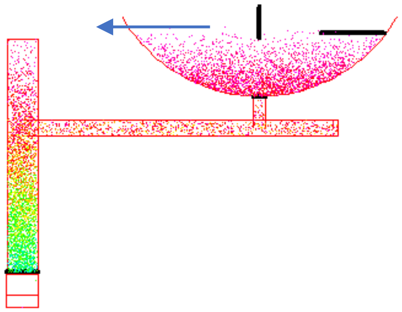
Heating

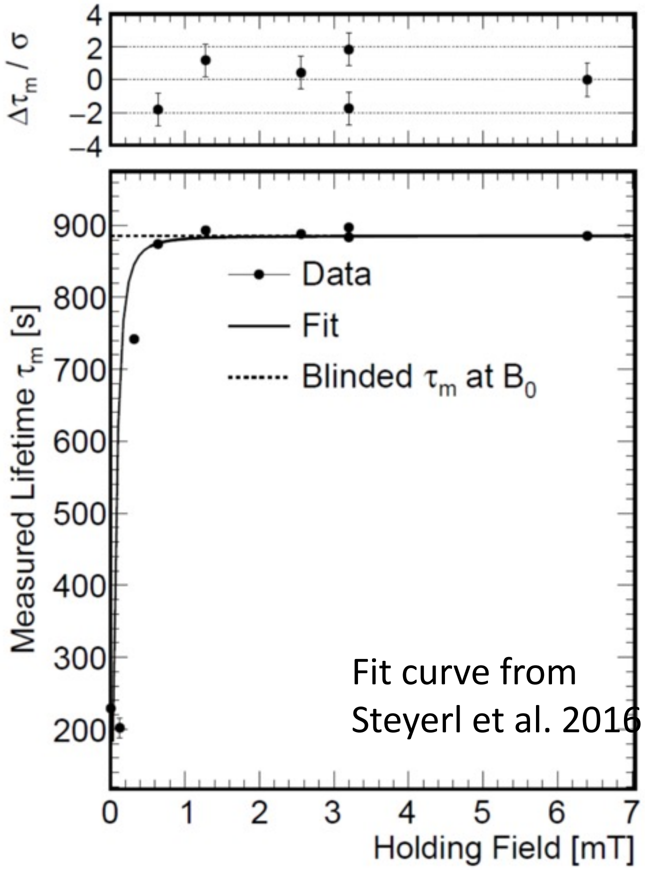
Limit established by long holding time excess



Insufficient Cleaning

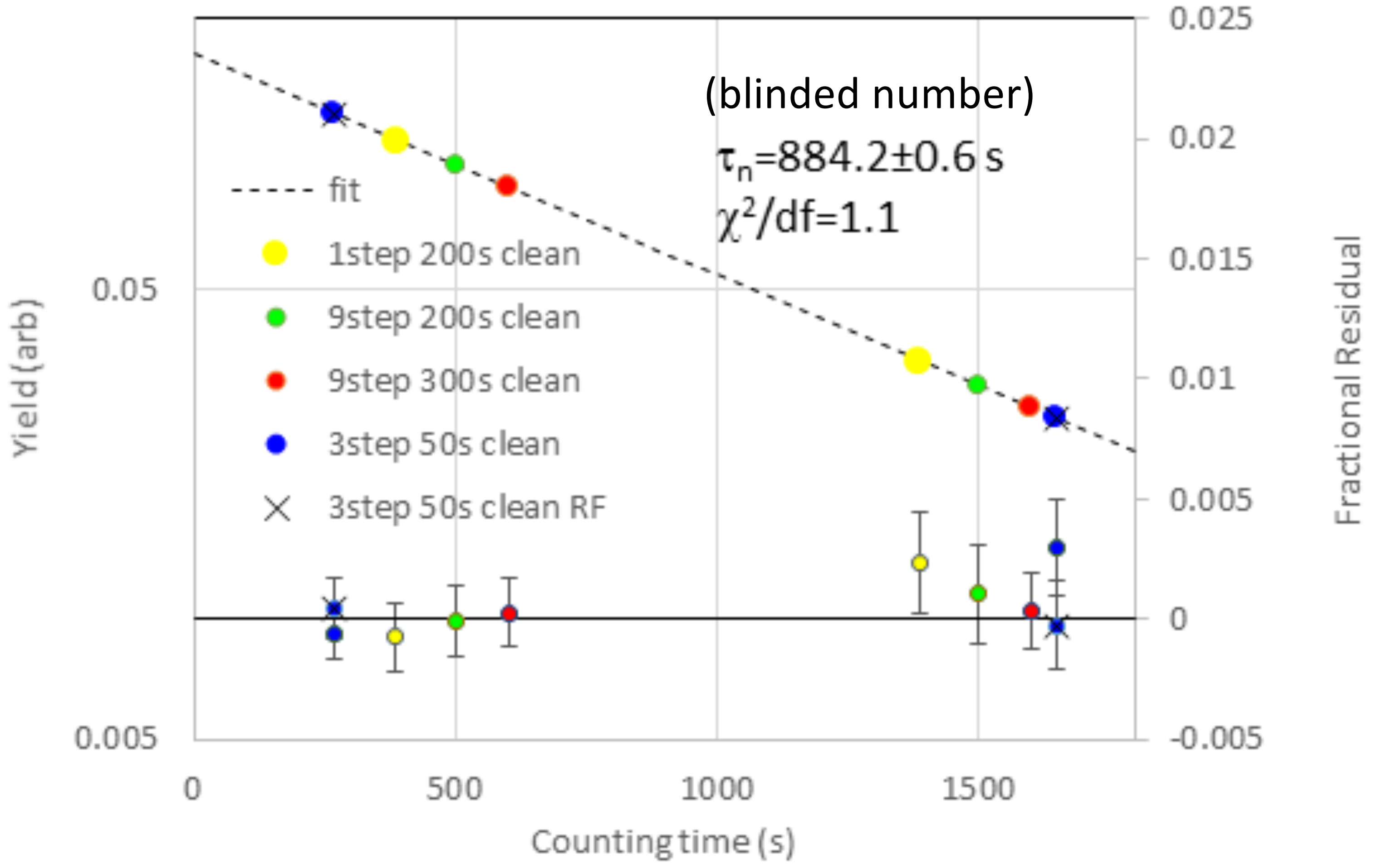
Limit established by short holding time excess





Fit curve from Steyerl et al. 2016

UCNτ first physics result was released in 2017



(blinded number)

τ_n=884.2±0.6 s

χ^2/df=1.1

After unblinding: 877.7 ± 0.7 (stat) +0.4/–0.2 (sys) s

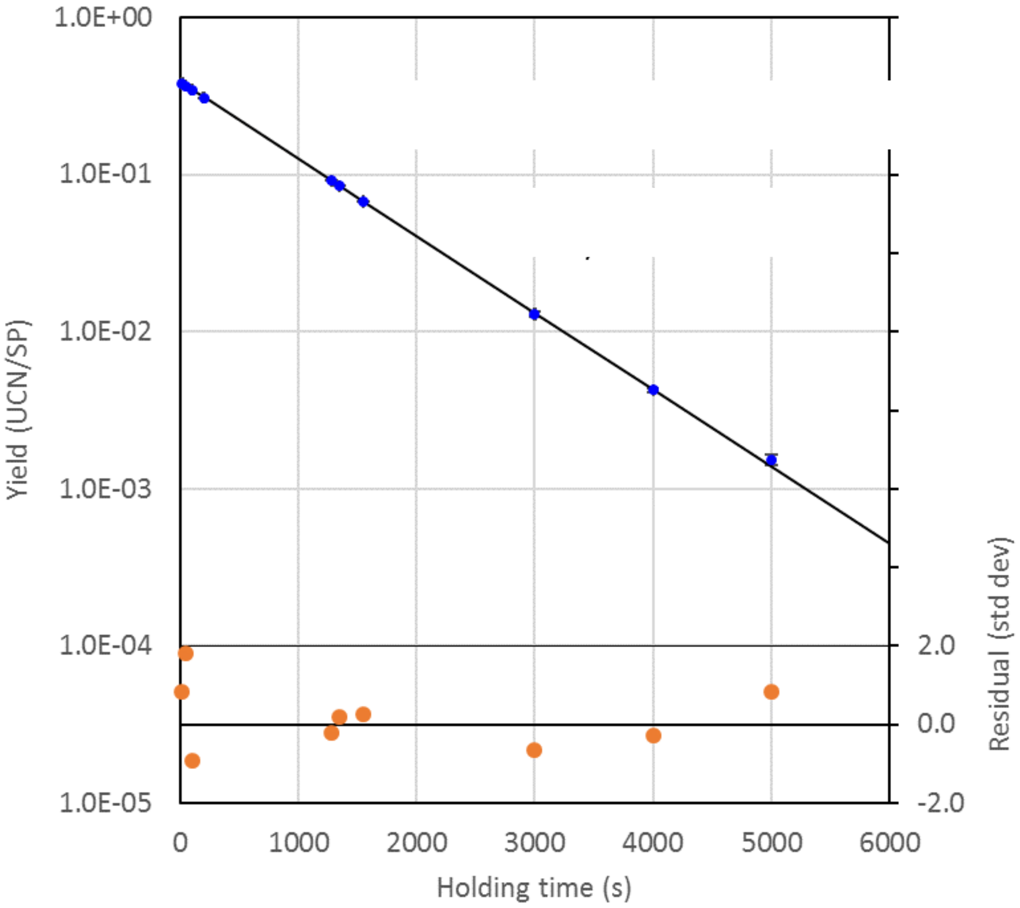
Science 06 May 2018, DOI: 10.1126/science.aan8895

New result from UCNτ

$\tau_n = 877.75 \pm 0.28_{\text{stat}} \; {+0.22}/{-0.16}_{\text{syst}}$ s

Phys. Rev. Lett. **127**, 162501 (Oct. 13, 2021)

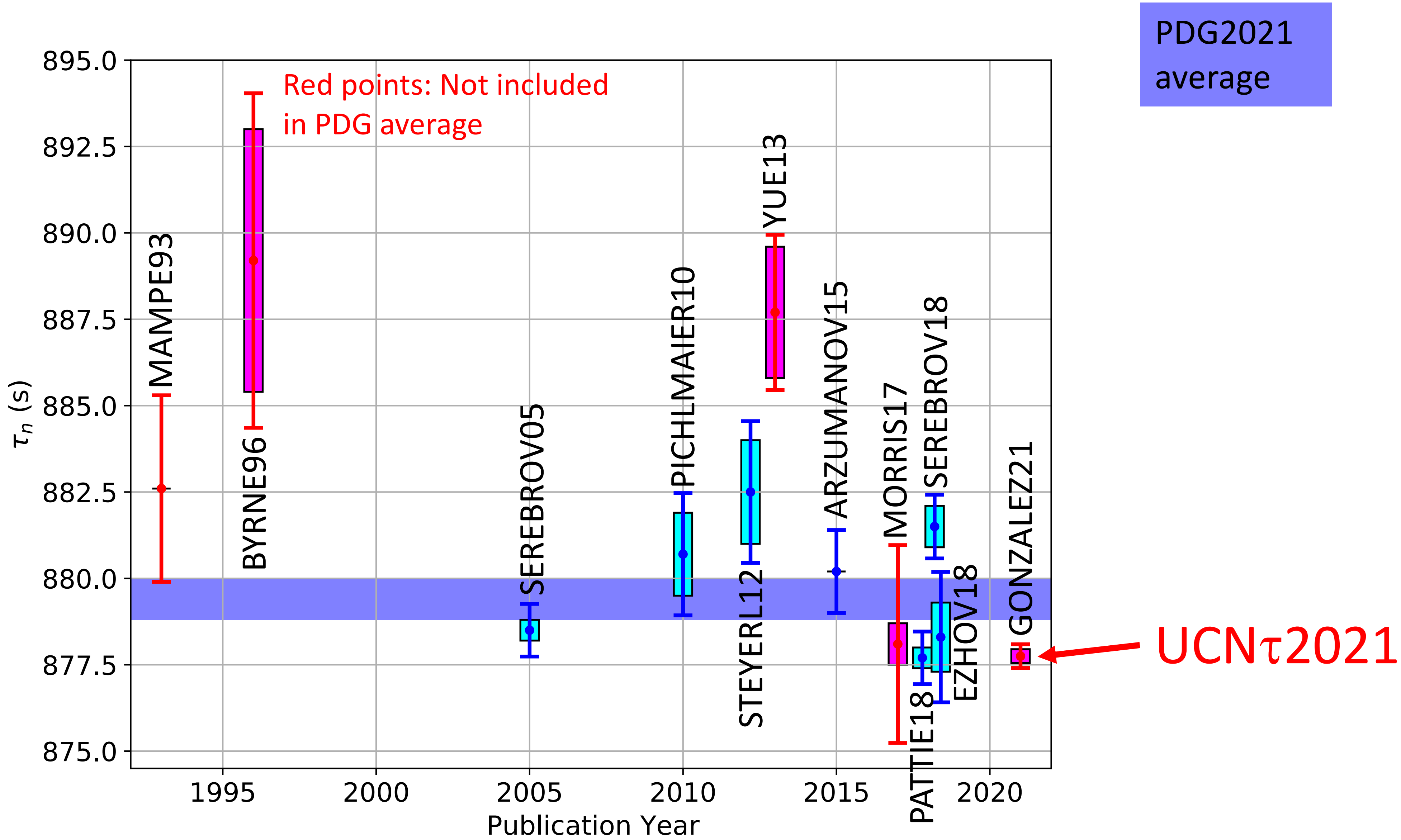
2017-2018 Run Campaigns:



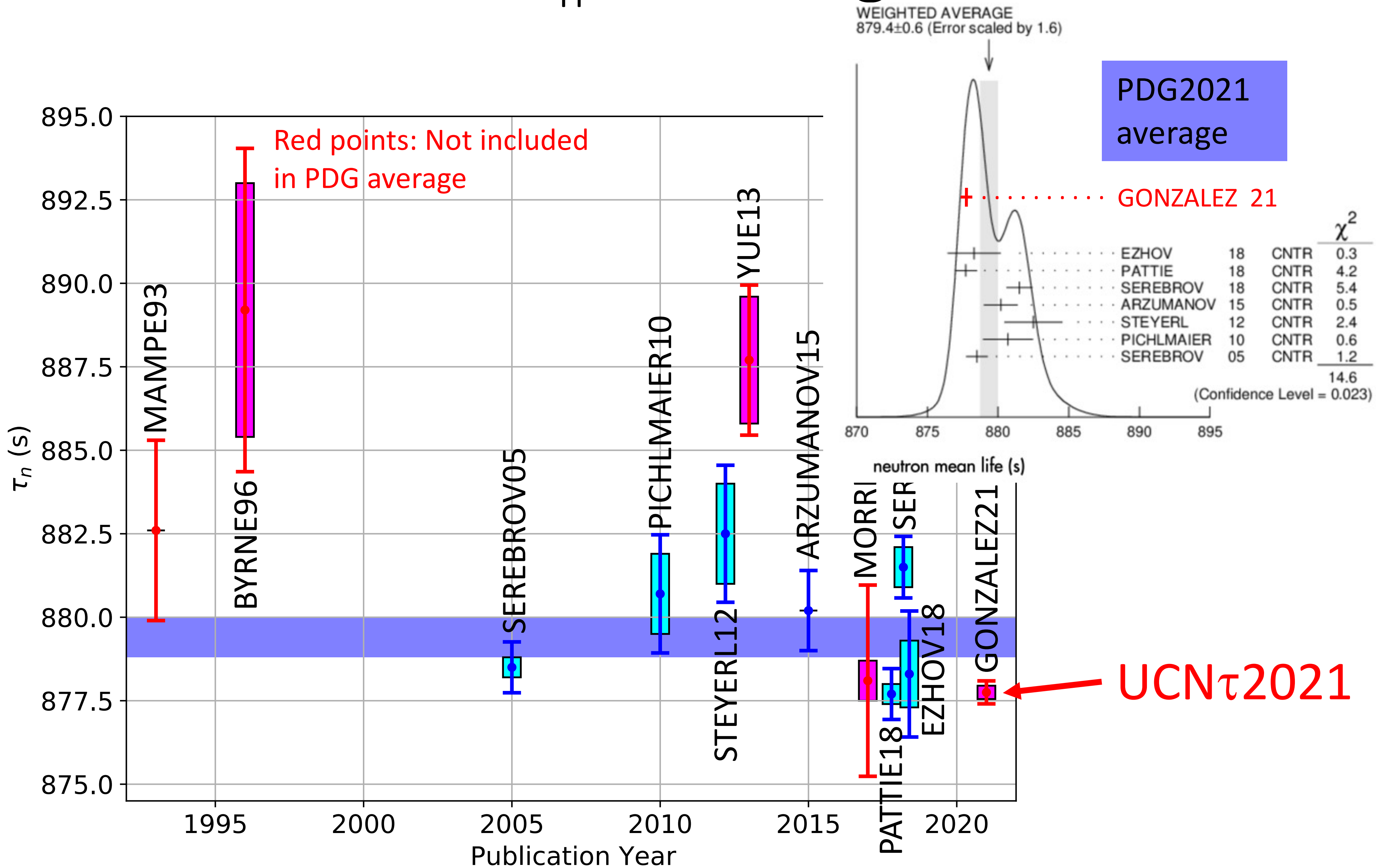
Final systematics table (2017-2018)

Effect	Correction	Uncertainty
UCN event definition	–	±0.13
Normalization weighting	–	±0.06
Depolarization	–	+0.07
Uncleaned UCN	–	+0.11
Heated UCN	–	+0.08
Al block	+0.06	±0.05
Residual gas scattering	+0.11	±0.06
Uncorrelated sum	$0.17^{+0.22}_{-0.16}$ s	

World data on τ_n including UCNτ2021



World data on τ_n including UCNτ2021

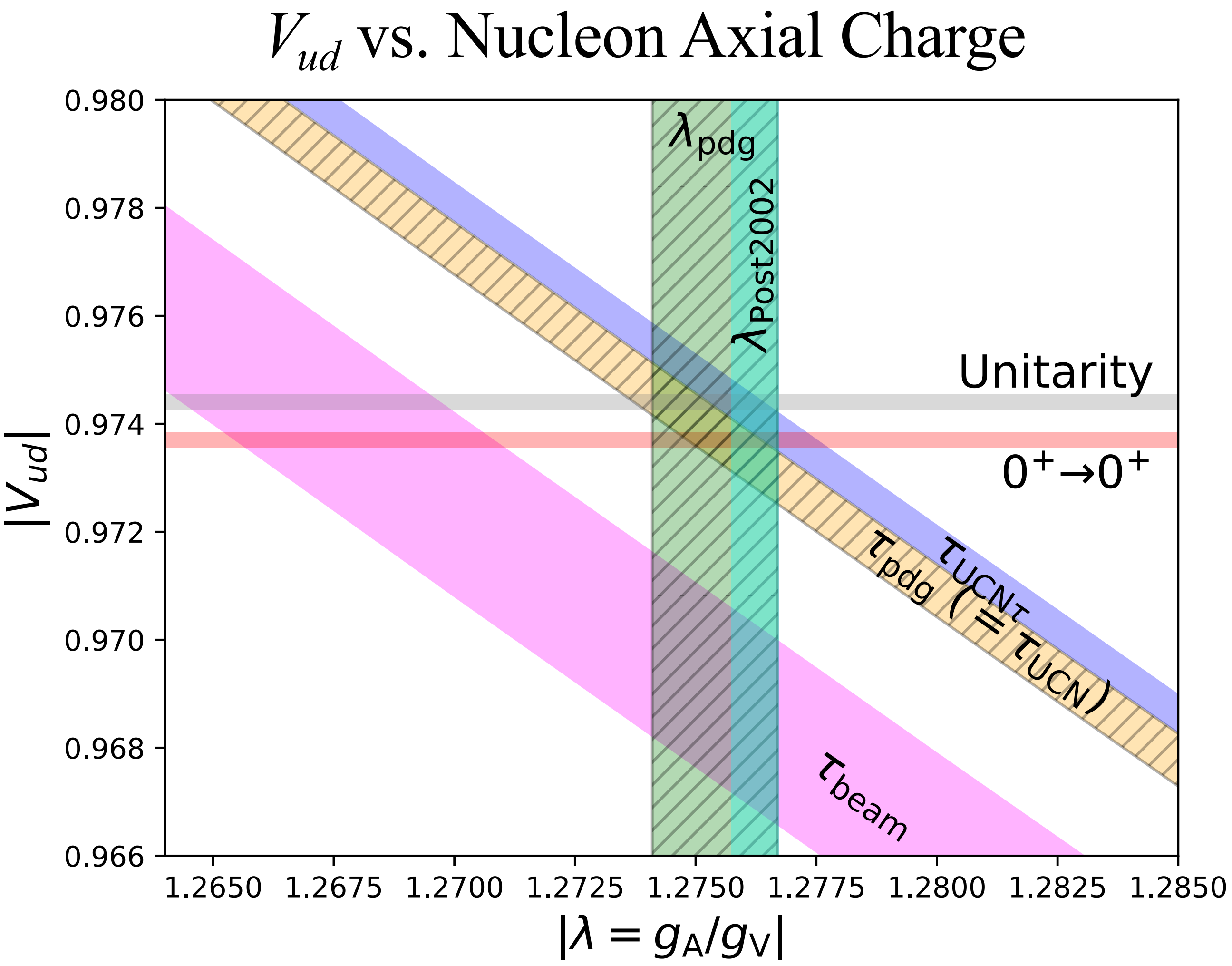


Red points: Not included in PDG average

PDG2021 average

UCNτ2021

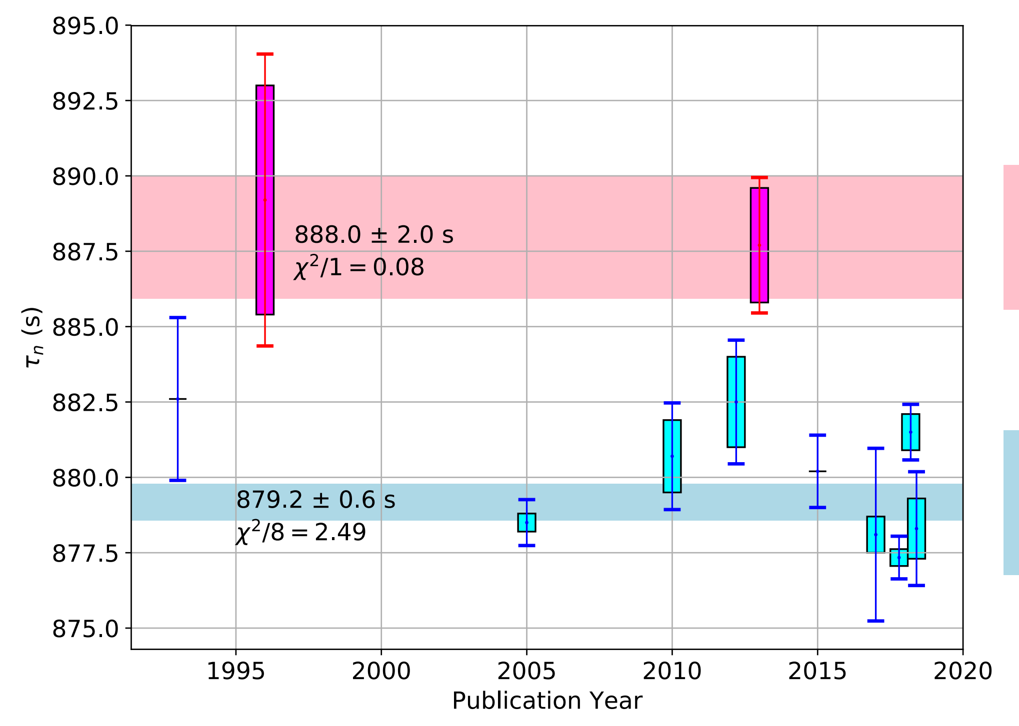
Can we test the standard model with neutron decay (yet)?



Neutron decay master formula:

$$|V_{ud}|^2 = \frac{5099.3(4)\mathrm{s}}{\tau_n(1+3g_A^2)(1+RC)}$$

Using RC from Seng et al., PRL **121**, 241804 (2018).



Beam average

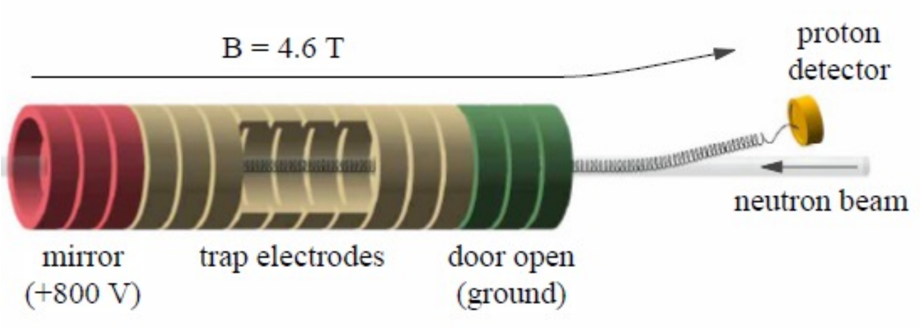
Bottle average

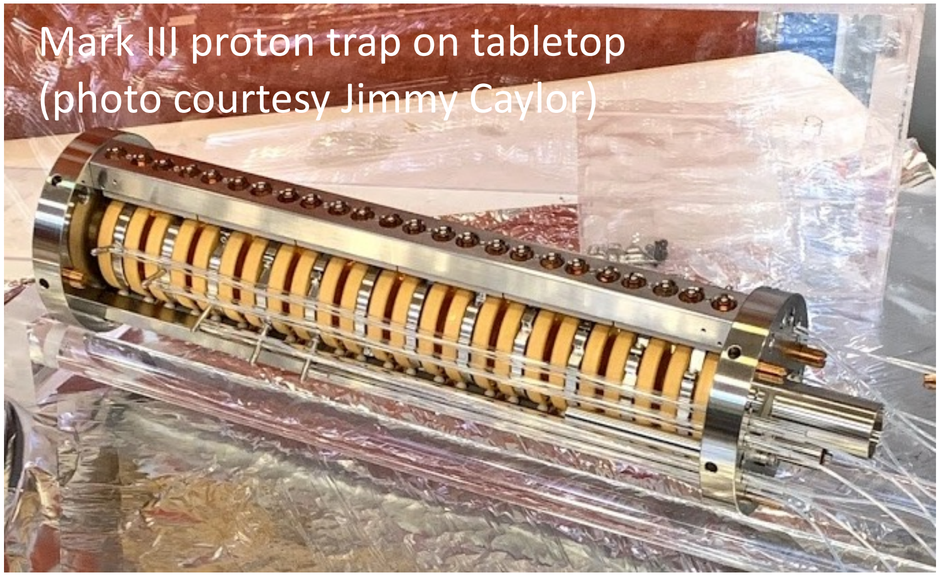
What about beam vs. bottle?

There were many publications in 2018 following a suggestion of a dark matter explanation for the beam vs. bottle discrepancy.

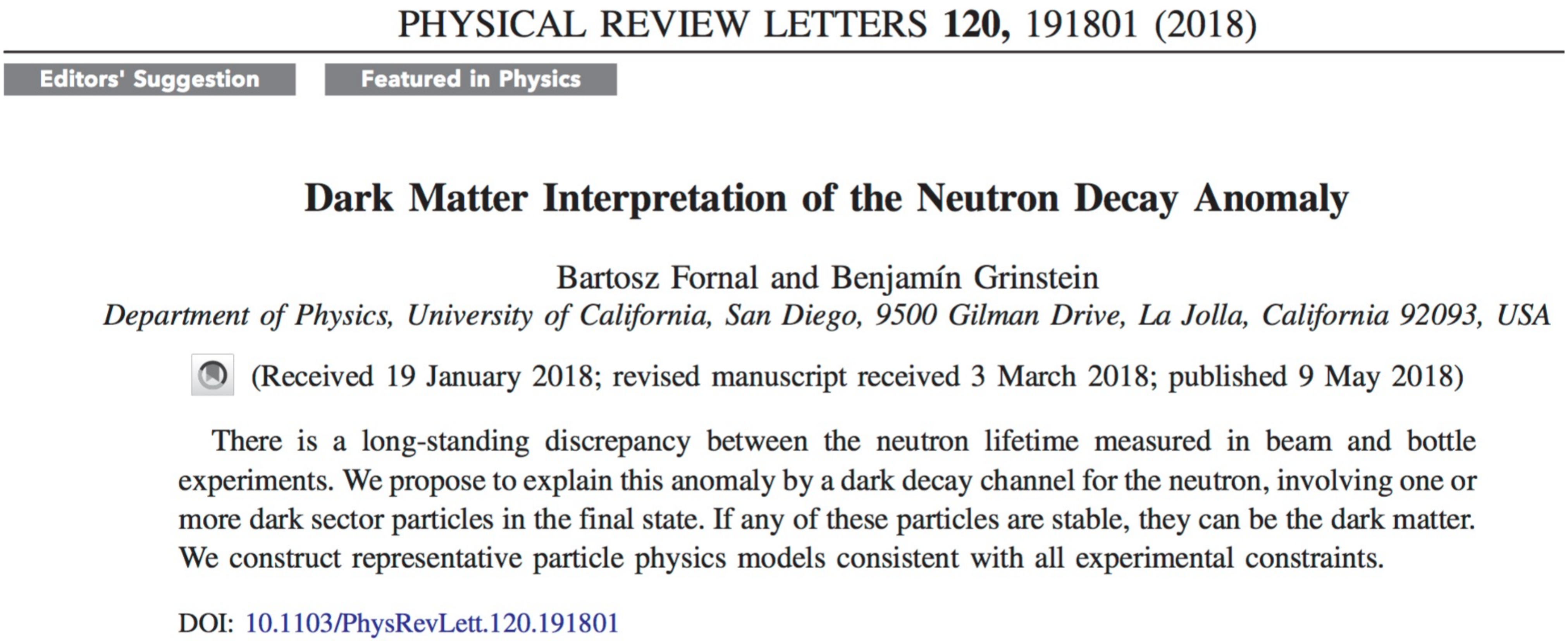
Is there an unknown systematic effect in the beam experiment?

- Charge exchange on residual gas?
  - Apparently longer lifetime is consistent with ~1% lost protons.
  - Byrne and Worcester, 2019 J. Phys. G: Nucl. Part. Phys. **46** 085001
    - Can test by increasing the proton trapping time…this is in fact what was done in subsequent beam experiment (BL2), but no results have been released.
  - Serebrov et al., Phys. Rev. D **103**, 074010 (2021)
    - Extensive MC studies exploring effects of residual gas on the beam experiment.
    - Showed that it is possible to create ~1% systematic effect depending on details of the vacuum and cryogenic conditions.
  - BL2 results will be informative
    - Original trap w/longer trapping time (done; no results released yet)
    - New, open trap w/better pumping




Mark III proton trap on tabletop (photo courtesy Jimmy Caylor)

Could the neutron β-decay branching ratio be <100%?


PHYSICAL REVIEW LETTERS **120,** 191801 (2018)

Editors' Suggestion Featured in Physics

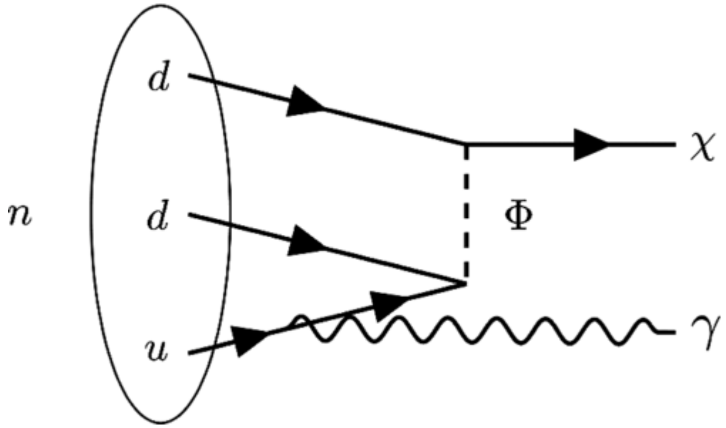
Dark Matter Interpretation of the Neutron Decay Anomaly

Bartosz Fornal and Benjamín Grinstein
Department of Physics, University of California, San Diego, 9500 Gilman Drive, La Jolla, California 92093, USA

(Received 19 January 2018; revised manuscript received 3 March 2018; published 9 May 2018)

There is a long-standing discrepancy between the neutron lifetime measured in beam and bottle experiments. We propose to explain this anomaly by a dark decay channel for the neutron, involving one or more dark sector particles in the final state. If any of these particles are stable, they can be the dark matter. We construct representative particle physics models consistent with all experimental constraints.

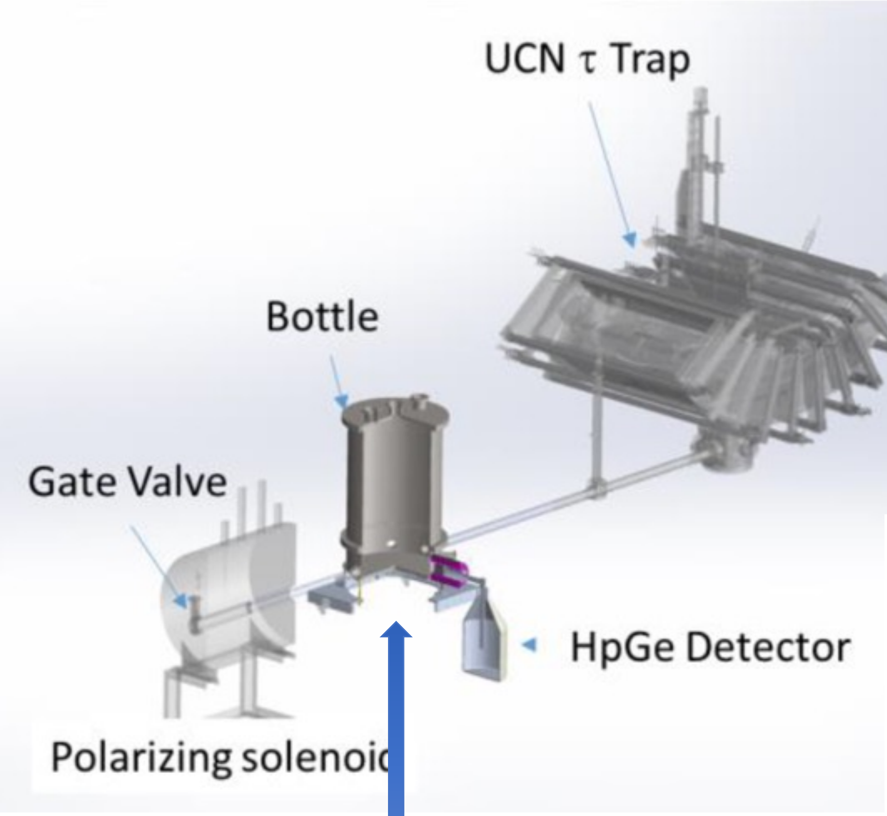
DOI: 10.1103/PhysRevLett.120.191801



Simplest signature: photon with
0.782 MeV < E_γ < 1.664 MeV

Also: e+/e- pair with total
E < 1.665 MeV

Search for the γ and e^+/e^- signatures at Los Alamos

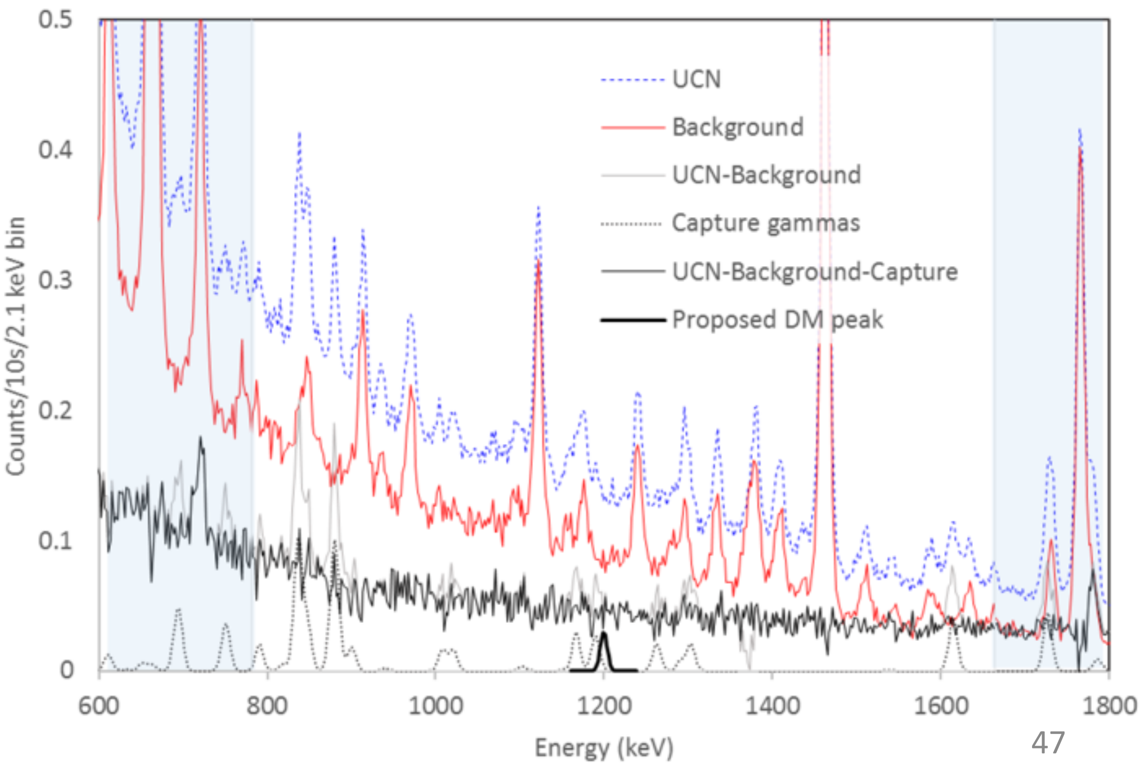


A buffer volume installed (2018) to smooth out the pulse response for more stable normalization.

Sun, X et al., "Search for dark matter decay of the free neutron from the UCNA experiment: $n \rightarrow \chi + e^+e^-$," PHYSICAL REVIEW C **97**, 052501(R) (2018) .

Tang, ZT et al., "Search for the Neutron Decay $n \rightarrow X + \gamma$ where X is a dark matter particle," PRL **121**, 022505 (2018).

→ Sets limit on this BR of ~10^{-3}



The simplest decay to (feebly-interacting) DM appears ruled out by observed heavier neutron star masses.

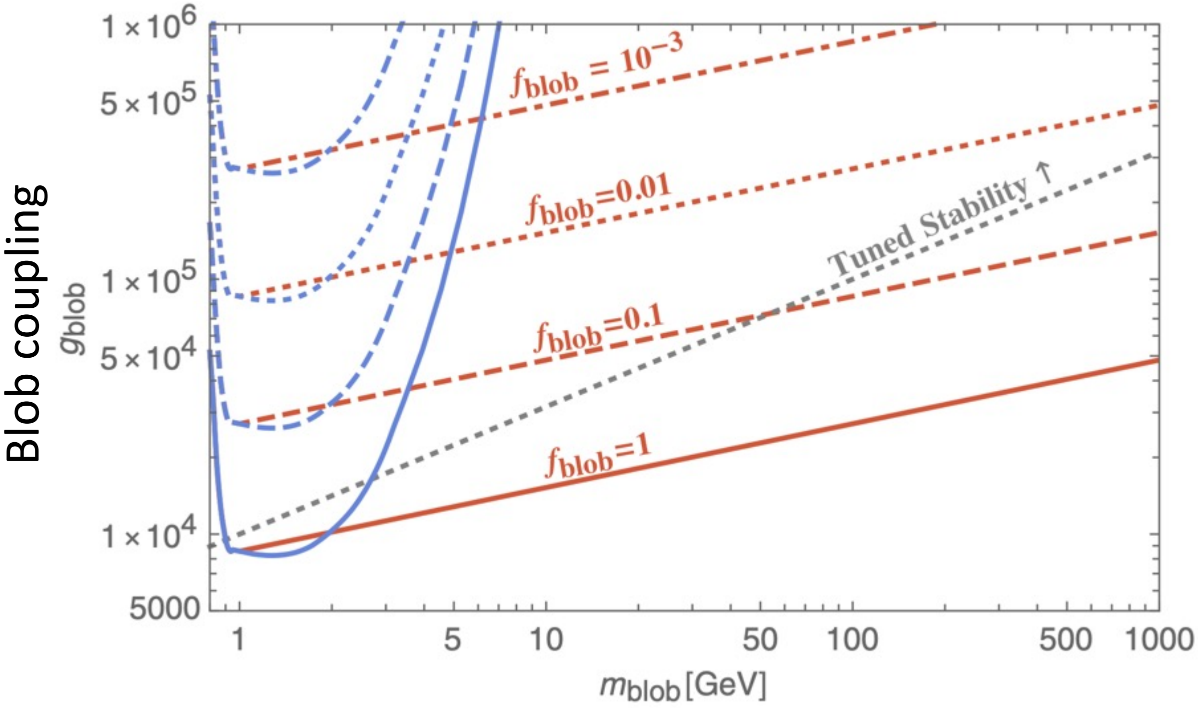
- McKeen, Nelson, Reddy, Zhou, “Neutron stars exclude light dark baryons,” Phys. Rev. Lett. **121**, 061802 (2018).
- Baym, Beck, Geltenbort, Shelton, “Testing dark decays of baryons in neutron stars,” Phys. Rev. Lett. **121**, 061801 (2018).

- However, there may still be scenarios consistent with neutron star observations:
  - Grinstein, Kouvaris, Nielsen, “Neutron star stability in light of the neutron decay anomaly,” Phys. Rev. Lett. 123, 091601 (2019): Appropriate DM-baryon interactions can accommodate neutron star masses above $2m_{\odot}$.

Soft scattering of UCN by dark matter "blobs"?

Rajendran and Ramani, "Composite solution to the neutron lifetime anomaly," Phys. Rev. D **103**, 035014 (2021)

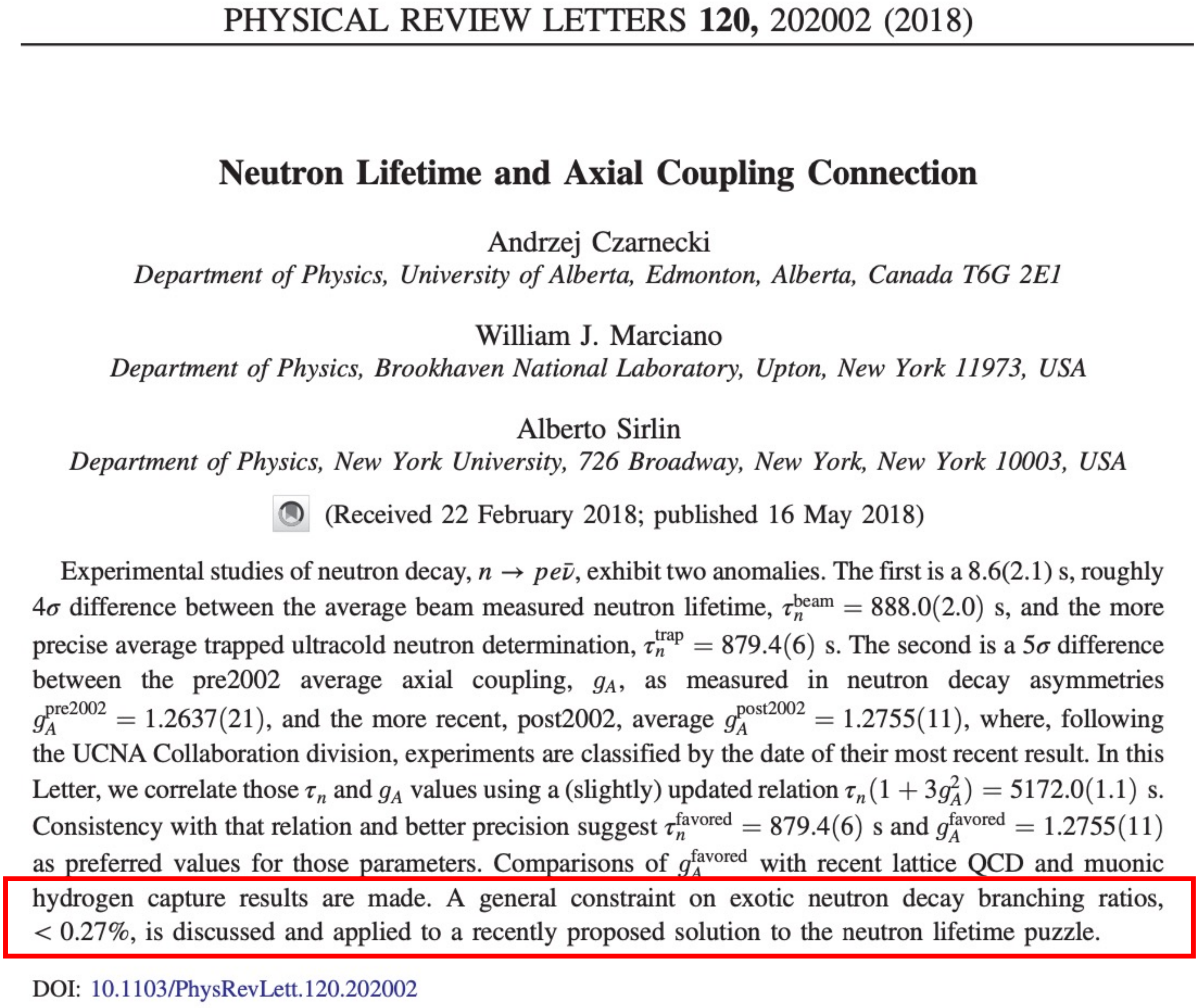
In this scenario, the bottle lifetime measurement results are anomalously low, beam lifetime is unaffected by this process.



- $f_{\rm blob}$: Fraction of dark matter in blobs
- Considering +50 neV kick to a neutron removes it from trap
- Blue/orange: different DM interaction scenarios

Might motivate space-based neutron lifetime measurements, which are total-disappearance-rate measurements not sensitive to this mechanism.

The bottle lifetime result is consistent with beta asymmetry measurements and V_{ud}.



PHYSICAL REVIEW LETTERS **120,** 202002 (2018)

Neutron Lifetime and Axial Coupling Connection

Andrzej Czarnecki
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William J. Marciano
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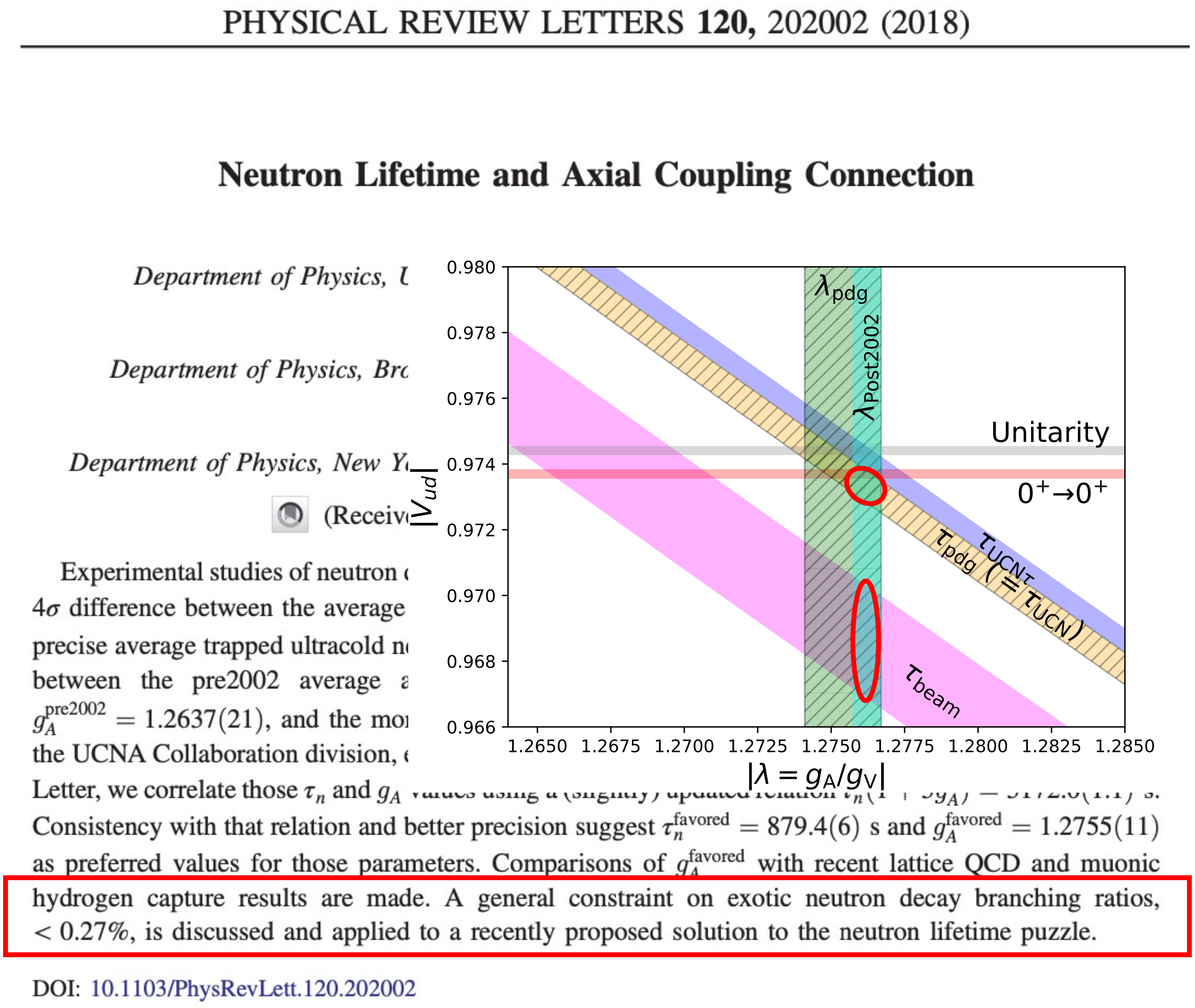
(Received 22 February 2018; published 16 May 2018)

Experimental studies of neutron decay, $n \to pe\bar{\nu}$, exhibit two anomalies. The first is a 8.6(2.1) s, roughly 4σ difference between the average beam measured neutron lifetime, $\tau_n^{\text{beam}} = 888.0(2.0)$ s, and the more precise average trapped ultracold neutron determination, $\tau_n^{\text{trap}} = 879.4(6)$ s. The second is a 5σ difference between the pre2002 average axial coupling, g_A, as measured in neutron decay asymmetries $g_A^{\text{pre2002}} = 1.2637(21)$, and the more recent, post2002, average $g_A^{\text{post2002}} = 1.2755(11)$, where, following the UCNA Collaboration division, experiments are classified by the date of their most recent result. In this Letter, we correlate those τ_n and g_A values using a (slightly) updated relation $\tau_n(1 + 3g_A^2) = 5172.0(1.1)$ s. Consistency with that relation and better precision suggest $\tau_n^{\text{favored}} = 879.4(6)$ s and $g_A^{\text{favored}} = 1.2755(11)$ as preferred values for those parameters. Comparisons of g_A^{favored} with recent lattice QCD and muonic hydrogen capture results are made. A general constraint on exotic neutron decay branching ratios, $< 0.27\%$, is discussed and applied to a recently proposed solution to the neutron lifetime puzzle.

DOI: 10.1103/PhysRevLett.120.202002

The bottle lifetime result is consistent with beta asymmetry measurements and V_{ud}.



PHYSICAL REVIEW LETTERS **120,** 202002 (2018)

Neutron Lifetime and Axial Coupling Connection

Department of Physics, U

Department of Physics, Bro

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Experimental studies of neutron
4σ difference between the average
precise average trapped ultracold n
between the pre2002 average a
$g_A^{\rm pre2002} = 1.2637(21)$, and the mo
the UCNA Collaboration division,
Letter, we correlate those τ_n and g_A values using a (slightly) updated relation $\tau_n(1 + 3g_A^2) = 5172.0(1.1)$ s. Consistency with that relation and better precision suggest $\tau_n^{\rm favored} = 879.4(6)$ s and $g_A^{\rm favored} = 1.2755(11)$ as preferred values for those parameters. Comparisons of $g_A^{\rm favored}$ with recent lattice QCD and muonic hydrogen capture results are made. A general constraint on exotic neutron decay branching ratios, $< 0.27\%$, is discussed and applied to a recently proposed solution to the neutron lifetime puzzle.

DOI: 10.1103/PhysRevLett.120.202002

The bottle lifetime result is consistent with beta asymmetry measurements and V_{ud}…but bottle result is still allowed in a BSM global fit to beta decay measurements.

Falkowski, González-Alonso, Naviliat-Cuncic,
JHEP04 (2021) 126

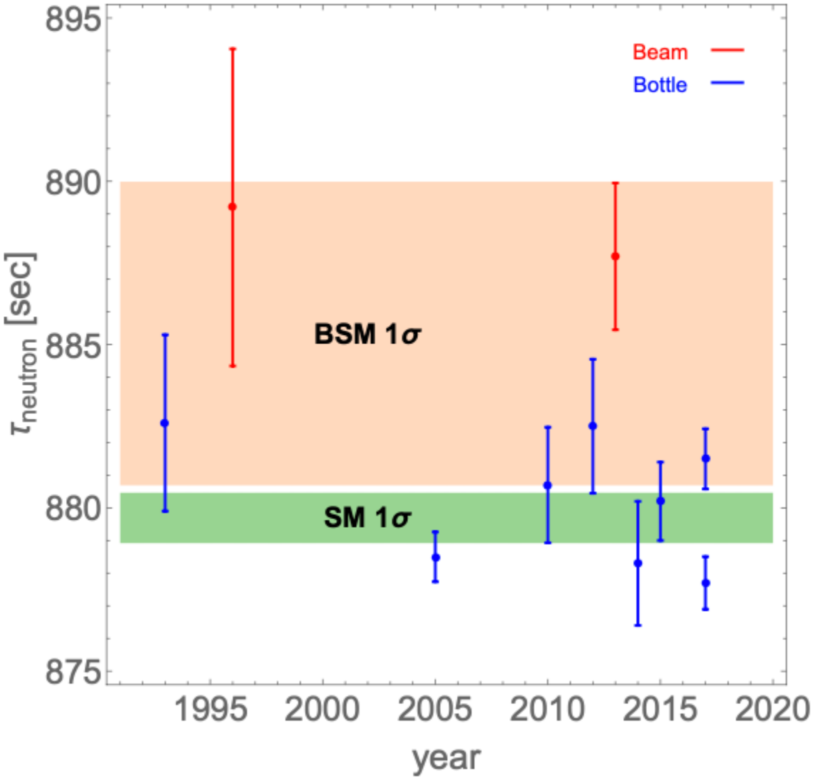

Figure 6. Neutron lifetime prediction in a global fit that includes all other measurements listed in appendix B. Bottle measurements are favored in the SM fit (green band) but not in the BSM scenario with only left-handed neutrinos (salmon band) (cf. section 4.2).

Ultimately, it's an experimental question

New idea: Ultra-Cold Neutron Experiment for Proton Branching Ratio in Neutron Beta Decay (UCNProBe)

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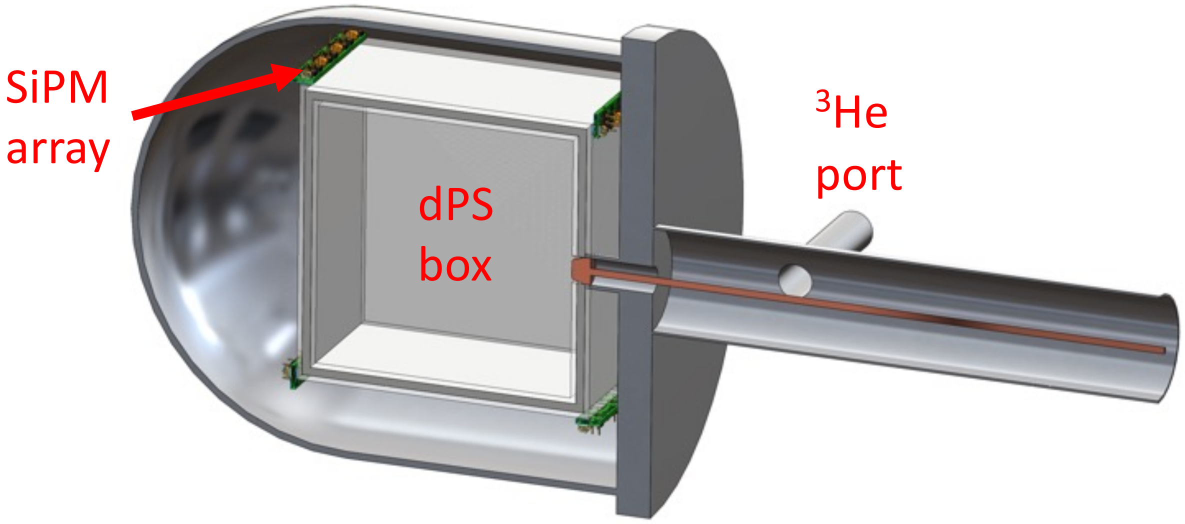
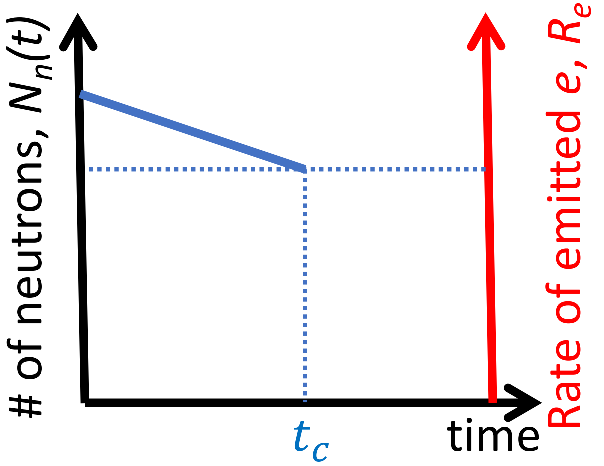


Quickly count neutrons at time t_c

$$R_e(t_c) = \tau_n^{-1} N_n(t_c)$$

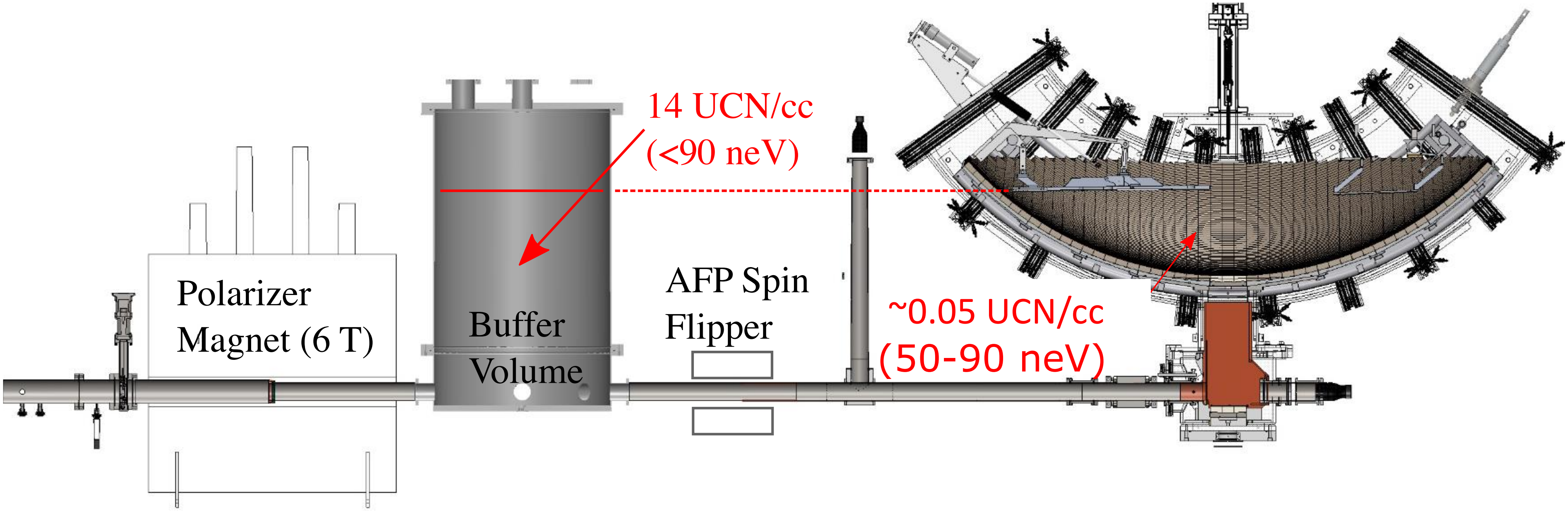


- Requires *absolute measurements* similar to the beam experiment:
  - Number of neutrons in the trap
  - Number of decay products
  - Needs precision <<1% for each quantity
- Now in R&D stage to determine feasibility

In the meantime, we are planning to upgrade the UCNτ experiment for ~3x improved precision (~0.1 s uncertainty)

Limitation of the present apparatus: low loading efficiency.

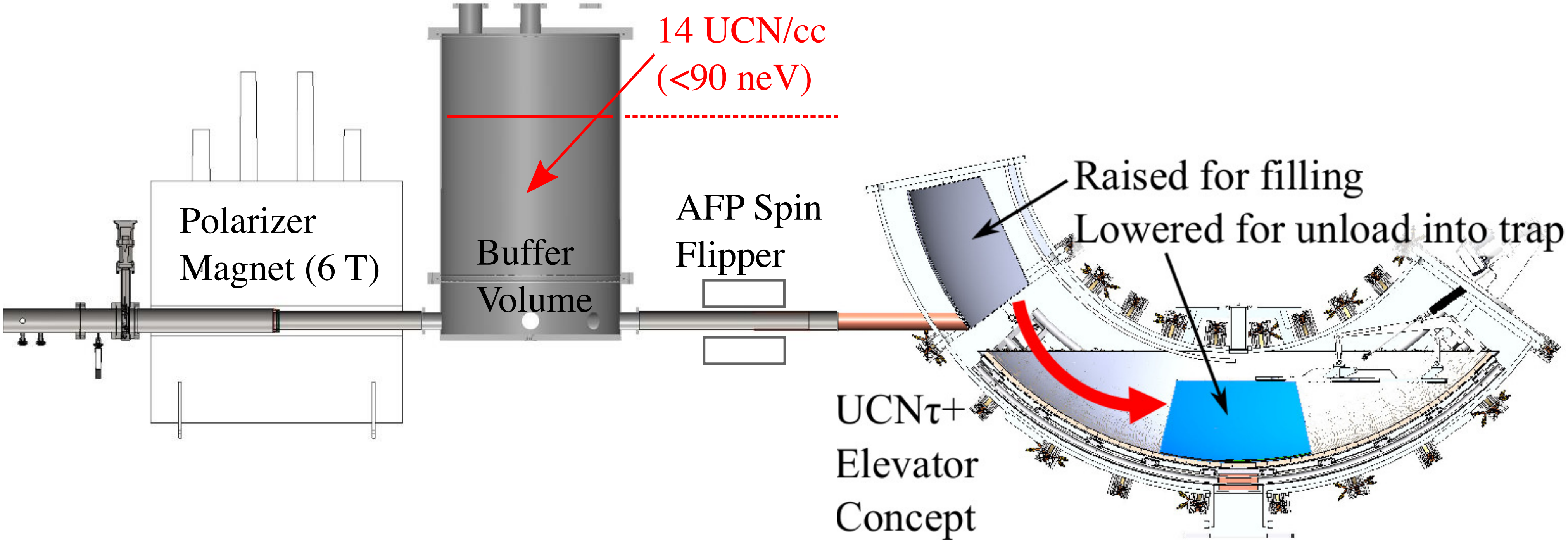
<1% loading efficiency



Gaps and magnetic field zeros in trapdoor region limit loading

UCNτ → UCNτ+ : Elevator Concept for **10**× loading increase

We expect at least 10× more UCN in the trap with this loading method.



Summary

- Neutron beta decay experiments are approaching a level of precision similar to *nuclear* decay for tests of the standard model of particle physics.
- With upcoming experiments, we can check the tension with first-row CKM unitarity when using V_{ud} from superallowed beta decay.
- There is reasonable agreement among UCN bottle lifetime experiments, each using quite different techniques (material bottles with different extrapolation strategies, magnetic bottles).
- Beam lifetime experimental result still a puzzle; we await BL-2 results, or UCNProBe.