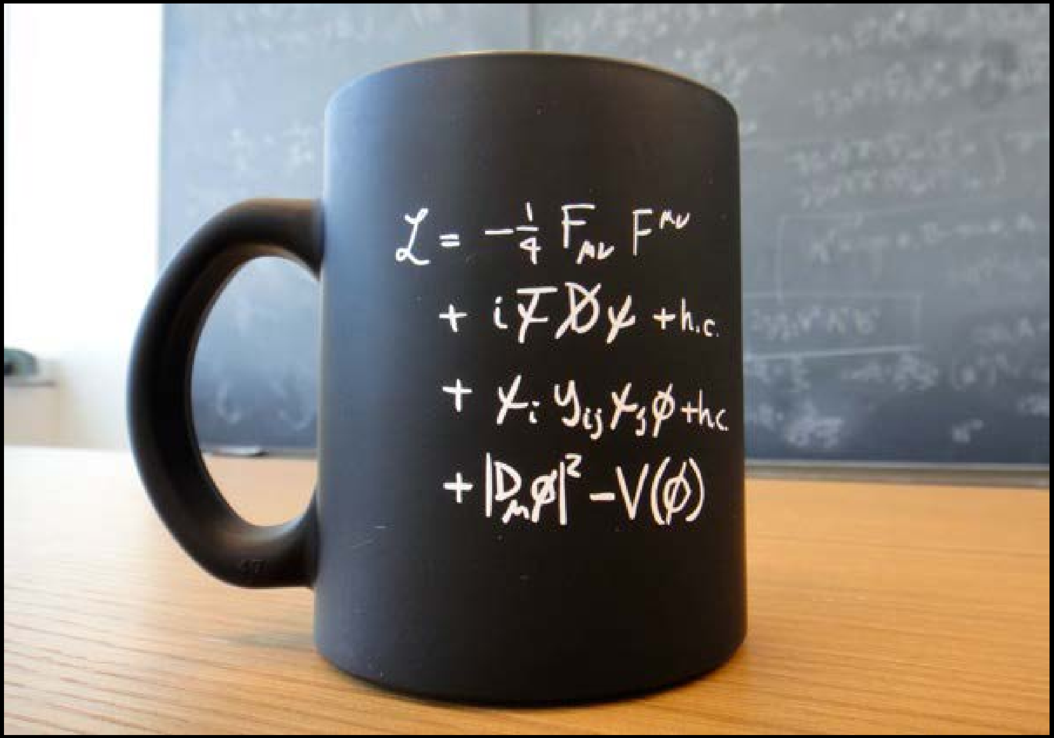
Overview of Neutron Lifetime (and Correlation) Experiments

Chen-Yu Liu
Indiana University
Symmetry Tests in Nuclei and Atoms
September 23, 2016

Slide courtesy: A. Young, A. Saunders, S. Baesler, S. Seestrom, B. Plaster, S. Dewey, K. Dubbers


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

Neutron Beta-decay

- Types of Lorentz-invariant couplings
  - P is small for non-relativistic particles
  - S, V: Fermi transition (ΔJ=0)
  - A, T: Gamow-Teller transition (ΔJ=$\pm$1,0)
  - No evidence of S and T.

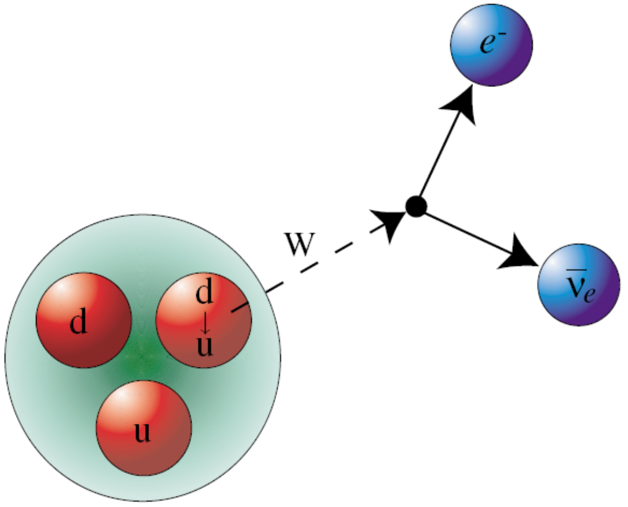
Parity violation:
V-A weak interaction

Vector (Fermi)

$$H_\beta = H_{V,A}$$

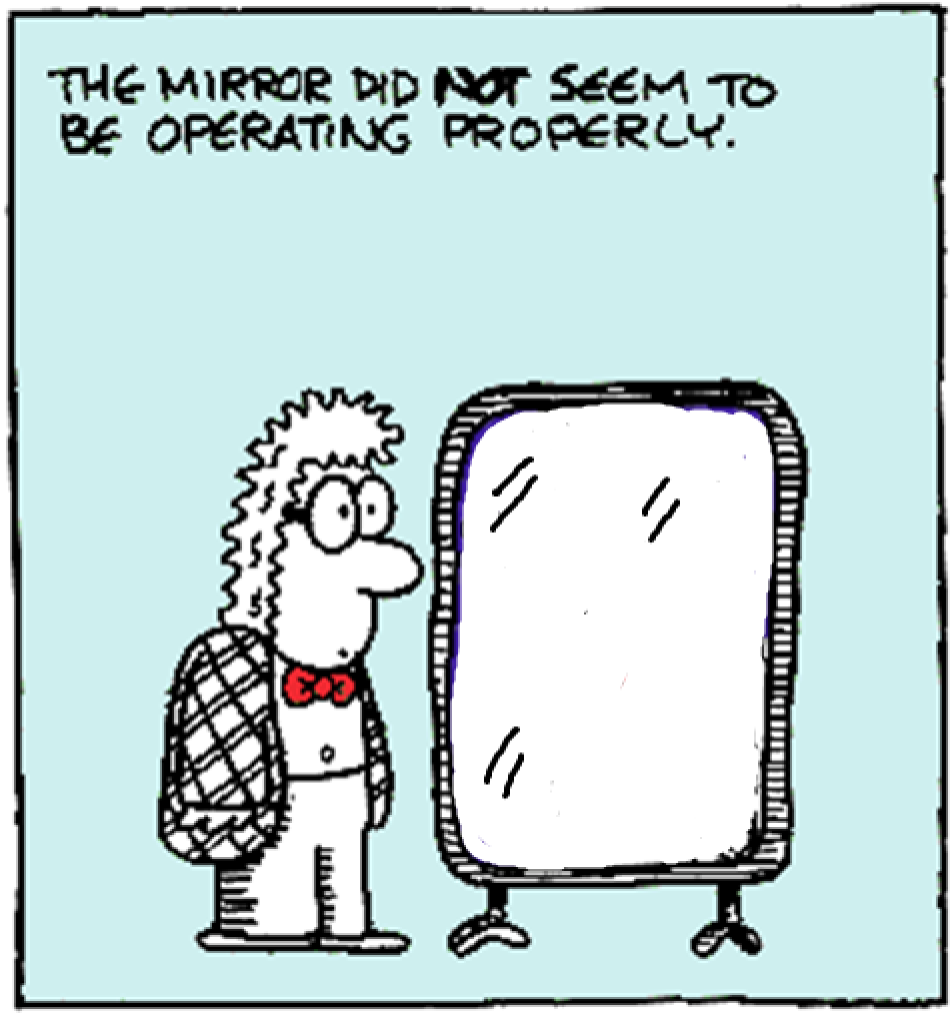
$$= \bar{e}\gamma_\lambda(1-\gamma^5)\nu_e \bar{p}(g_V + g_A\gamma^5)\gamma^\lambda n$$

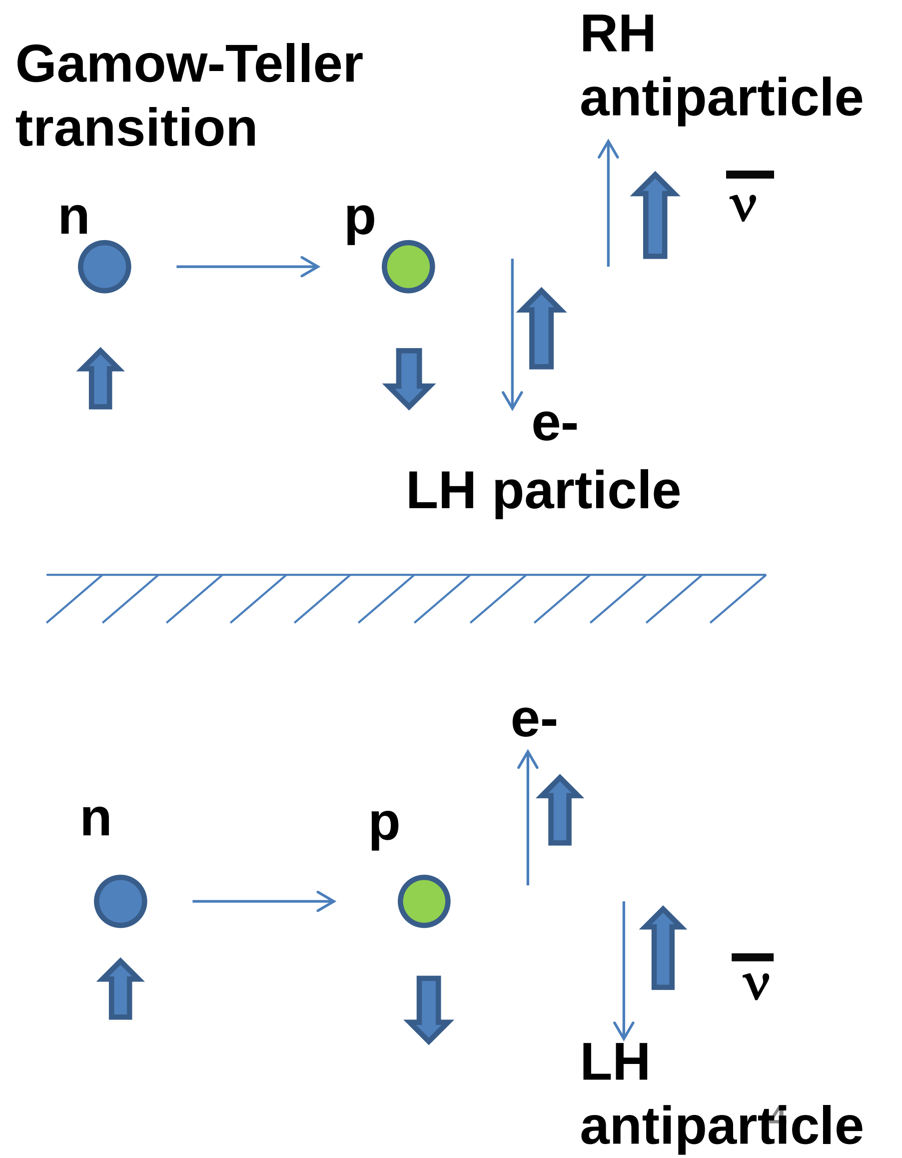
Axial Vector (Gamow-Teller)

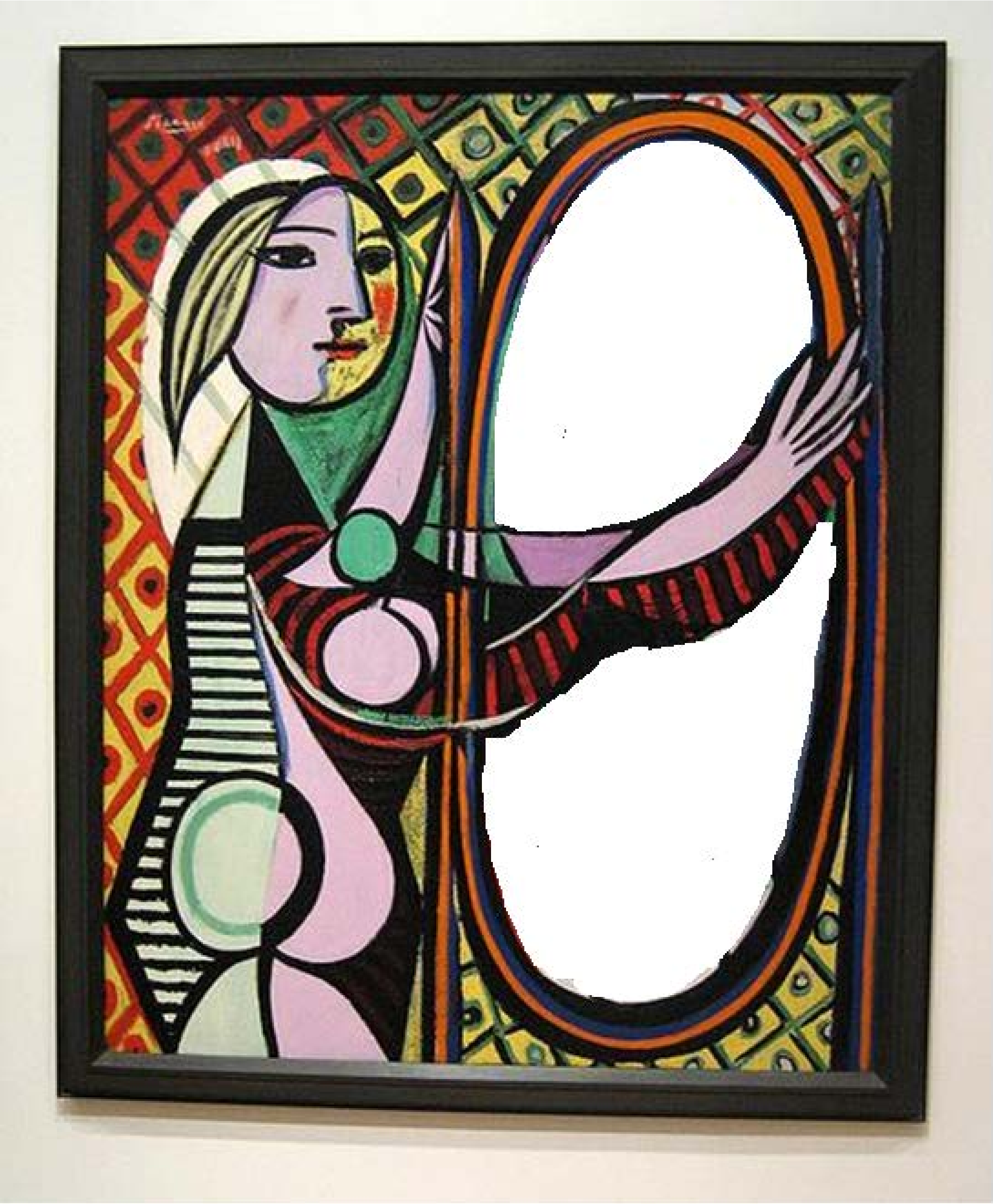


$$n \rightarrow p^+ + e^- + \bar{\nu}_e + 782\ \text{keV}$$

Mirror Symmetry is Broken!







Girl before a mirror, Picasso
1932

P451, Modern Physics Lab Course, Indiana University -- Bloomington

Lawrence M. Langer

(1914--2000)

THE EXPERIMENTAL CLARIFICATION OF THE THEORY OF β-DECAY[1]

1953

By E. J. Konopinski and L. M. Langer
Physics Department, Indiana University, Bloomington, Indiana

INTRODUCTION

Fermi advanced his successful theory of β-decay in 1934. It has since then undergone development in which two general directions may be discerned. One has been a broadening of the scope of the theory, the other a narrowing of its initial ambiguities.

The Fermi type of interaction was invented expressly for nucleonic β-processes but now promises to apply to all known processes involving the direct interaction of four fermions (spin 1/2 particles). The known fermions are: the electron ($e^{\pm}$), the neutrino (ν), and antineutrino ($\bar{\nu}$), the nucleon (N or P) and the μ-meson or muon ($\mu^{\pm}$). The direct interactions among these for which evidence exists are listed in Table I. This review is primarily concerned with the β-processes only. The relation of the others to β-decay is briefly summarized in the section on the *Universal Fermi interaction*.

TABLE I

The Fermi-Type Processes

β-emission	$N \to P + e^- + \bar{\nu}$
	$P \to N + e^+ + \nu$
Orbital capture:	$P + e^+ \to N + \nu$
μ-decay:	$\mu^+ \to e^+ + 2\nu$
μ-capture:	$P + \mu^- \to N + \nu$

The other direction of development has been toward a progressive experimental clarification. Fermi provided criteria for a β-coupling which are not quite sufficient to give it a unique form. An arbitrary linear combination of five interaction forms (symbolized by S, V, T, A, and P) is consistent with the a priori provisions of the Fermi theory. The experimental effort has been to reduce this arbitrariness. As we shall interpret the evidence here, the correct law must be what is known as an STP combination. This remains for the present a phenomenological result. No principle has been suggested so far (cf. THE A PRIORI THEORETICAL BASIS) which escapes contradiction by the experiments as interpreted here.

TABLE II*

Selection Rules

Order	Nuclear Matrix Element $\int\Omega$	Occurring for Interaction Type	Selection Rules on Nuclear Spin, I
Allowed (no parity change)	$\int 1$ (or $\int\beta$)	S, V	$\Delta I = 0$
	$\int \boldsymbol{\sigma}$ (or $\int \beta\boldsymbol{\sigma}$)	T, A	$\Delta I = 0, \pm 1$ (not $0 \to 0$)
Once Forbidden (parity change)	$\int \gamma_5$ (or $\int \beta\gamma_5$)	P, A	$\Delta I = 0$
	$\int \boldsymbol{r}$	S, V	$\Delta I = 0, \pm 1$ (not $0 \to 0$)
	$\int \boldsymbol{\alpha}$	V, T	
	$\int \boldsymbol{\sigma} \times \boldsymbol{r}$	T, A	
	$\int \boldsymbol{\sigma} \cdot \boldsymbol{r}$	T, A	$\Delta I = 0$
	$S_{ij} = \int \sigma_i x_j + \sigma_j x_i - \frac{2}{3}\boldsymbol{\sigma}\cdot\boldsymbol{r}\,\delta_{ij}$	T, A	$\Delta I = 0, \pm 1, \pm 2$ (not $0 \to 0$, $\frac{1}{2} \to \frac{1}{2}$, $0 \leftrightarrow 1$)
Twice Forbidden (no parity change)	$\int \gamma_5 \boldsymbol{r}$	P, A	$\Delta I = 0, \pm 1$ (not $0 \to 0$)
	$R_{ij} = \int x_i x_j - \frac{1}{3} r^2 \delta_{ij}$	S, V	$\Delta I = 0, \pm 1, \pm 2$ (not $0 \to 0$, $\frac{1}{2} \to \frac{1}{2}$, $0 \leftrightarrow 1$)
	$A_{ij} = \int \alpha_i x_j + \alpha_j x_i - \frac{2}{3}\boldsymbol{\alpha}\cdot\boldsymbol{r}\,\delta_{ij}$	V, T	
	$T_{ij} = \int [\boldsymbol{\sigma}\times\boldsymbol{r}]_i x_j + [\boldsymbol{\sigma}\times\boldsymbol{r}]_j x_i$	T, A	
	$\int \boldsymbol{\alpha} \cdot \boldsymbol{r}$	V, T	$\Delta I = 0$
	$\int \boldsymbol{\alpha} \times \boldsymbol{r}$	V, T	$\Delta I = 0, \pm 1$ (not $0 \to 0$)
	$S_{ijk} = \int \sigma_i x_j x_k - \cdots$	T, A	$\Delta I = 0, \pm 1, \pm 2, \pm 3$ (not $0 \to 0$, $\frac{1}{2} \to \frac{1}{2}$, $\frac{1}{2} \leftrightarrow \frac{3}{2}$, $1 \to 1$, $0 \leftrightarrow 1$, $0 \leftrightarrow 2$)

* Actually, the operator enters all the matrix elements arising from the S, T, and P interactions. It is ignored to permit contraction of the Table. It has no effect on selection rules, but may affect sizes which are treated as unknown here anyway.

The chief information gained from spectra other than RaE and the "unique" spectra, is that the Fierz-type of interference is absent. Its absence in allowed spectra forbids combining S and V or T and A. That, alone, narrows the alternatives to STP, SAP, VTP, and VAP. Next, the like absence of Fierz-type interference in once- and twice-forbidden spectra eliminates SA, AP, and VT combinations. Hence, from such arguments alone, one is left with only STP, or VP, or VA. Then VP must be discarded because it does not yield Gamow-Teller selection rules. However, STP is favored over VA only by the evidence of RaE. ^{210}Bi

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)

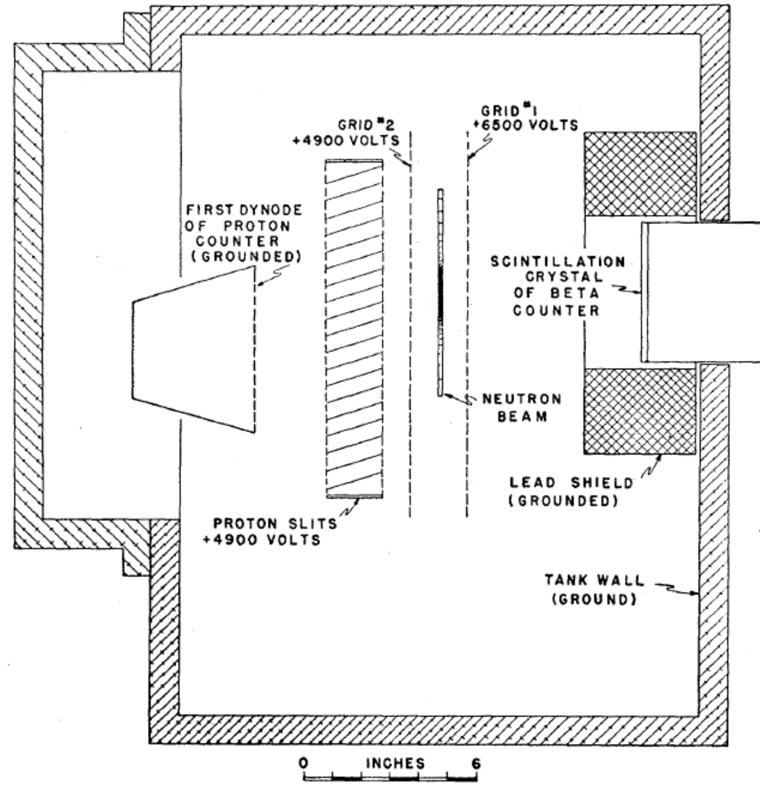


FIG. 1. Vertical cross section (normal to the neutron beam) through the detector system of the experiment measuring the correlation of the neutrino momentum and the neutron spin.

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

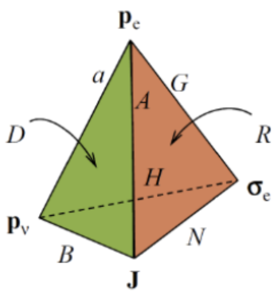
	$S+T$[a]		$S-T$		$V+A$		$V-A$[a]		
	$\bar{\nu}_L$[b]	$\bar{\nu}_R$	$\bar{\nu}_L$	$\bar{\nu}_R$	$\bar{\nu}_L$	$\bar{\nu}_R$	$\bar{\nu}_L$	$\bar{\nu}_R$	Exp.
$\mathfrak{A}$	−1	+1	−0.07[c]	0.07	+1	−1	0.07	−0.07	−0.09
$\mathfrak{B}$	−0.07	0.07	−1	+1	−0.07	0.07	−1	+1	+0.88

[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.

Beta Decay Parameters

Jackson, Treiman and Wyld (Phys. Rev. **106** and Nucl. Phys. **4**, 1957)

$$\frac{d^5W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \overbrace{\frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_\circ - E_e)^2 \xi}^{\text{basic decay rate}} \left(1 + \overbrace{a_{\beta\nu} \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}}}^{\beta-\nu \text{ correlation}} + \overbrace{b \frac{\Gamma m_e}{E_e}}^{\text{Fierz term}} + \frac{\langle \vec{I} \rangle}{I} \cdot \left[\underbrace{A_\beta \frac{\vec{p}_e}{E_e}}_{\beta \text{ asym}} + \underbrace{B_\nu \frac{\vec{p}_\nu}{E_\nu}}_{\nu \text{ asym}} + \underbrace{D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}}_{T-\text{violating}} \right] \right) + \ldots$$



US program has on-going or planned efforts to measure:

(1) **Decay rates and β-spectra** ($G_F V_{ud}, \xi, b$)

(2) **Unpolarized angular correlations** ($a_{\beta\nu}, b$)

(3) **Polarized angular correlations** (A_β, B_ν, b, b_ν)

(4) New program to measure **circular polarization asymmetry**

Asymmetry in angular correlations

In SM, V-A interaction

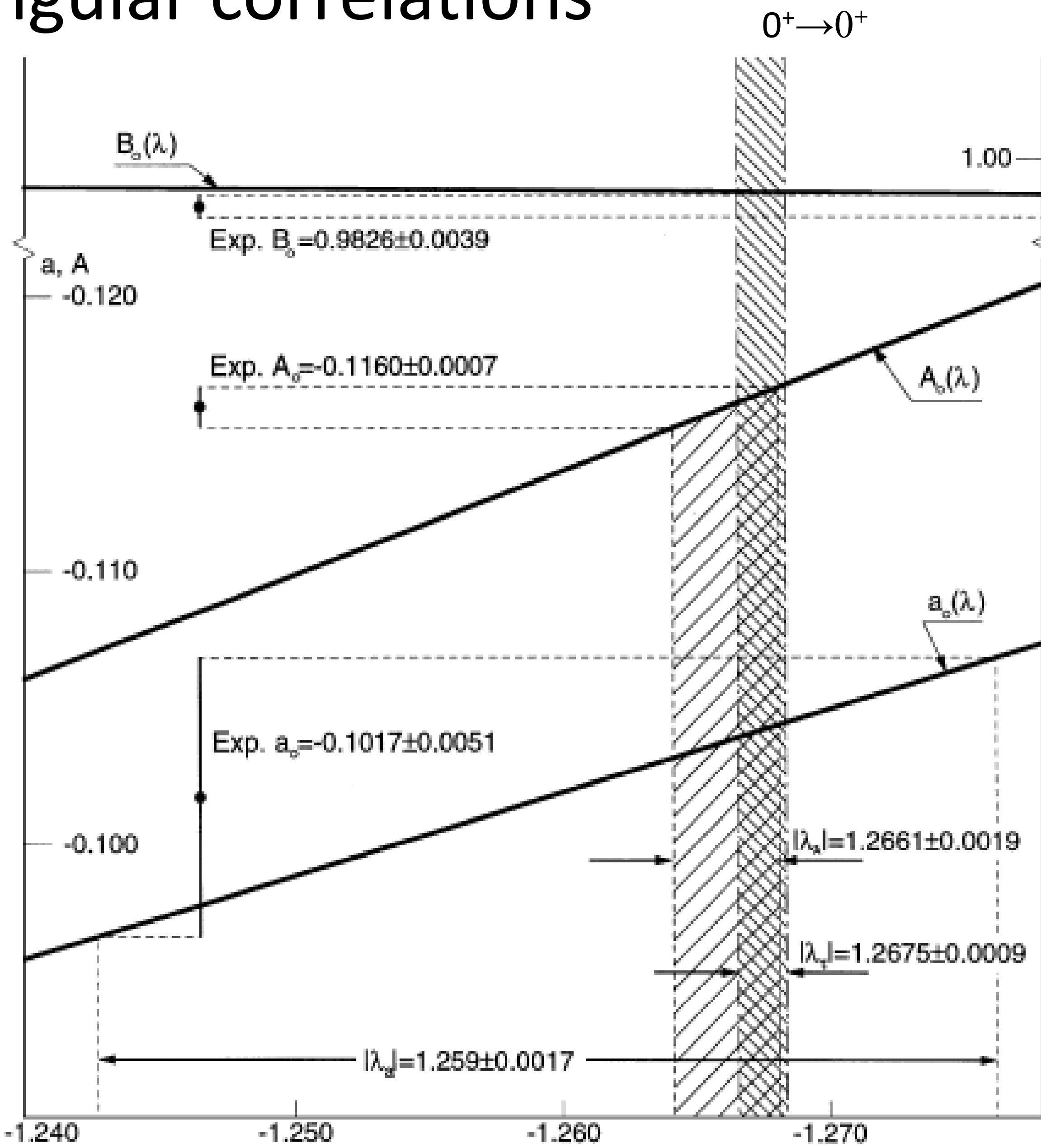
$$a = \frac{1-\lambda^2}{1+3\lambda^2}, \quad b = 0$$

$$A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2}, \quad B = 2\frac{\lambda^2-\lambda}{1+3\lambda^2}$$

$$D = 2\frac{\mathrm{Im}(\lambda)}{1+3\lambda^2}$$

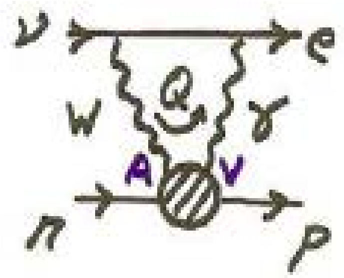
λ: an important parameter to
Input into the solar neutrino
estimates

Yerozolimsky, NIMA 2000



V_{ud} for CKM Unitarity Test

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)

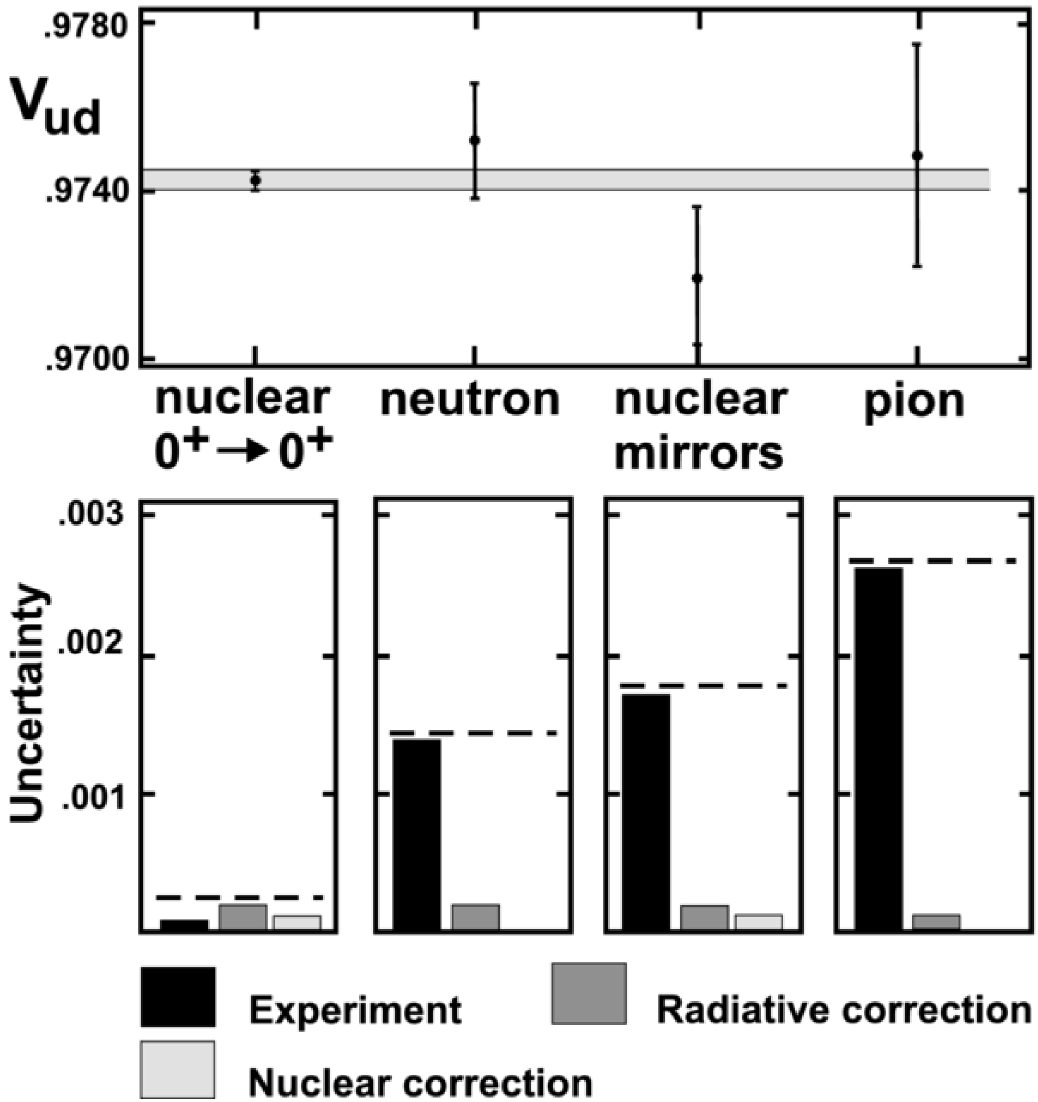
$$RC = \frac{\alpha}{4\pi}\int_0^\infty dQ \frac{m_W^2}{Q^2 + m_W^2} F(Q^2)$$

Marciano & Sirlin, PRL 96, 032002 (2006)

$$|V_{ud}|^2 = \frac{4908.7 \pm 1.9 s}{\tau_n (g_V + 3g_A^2)}$$

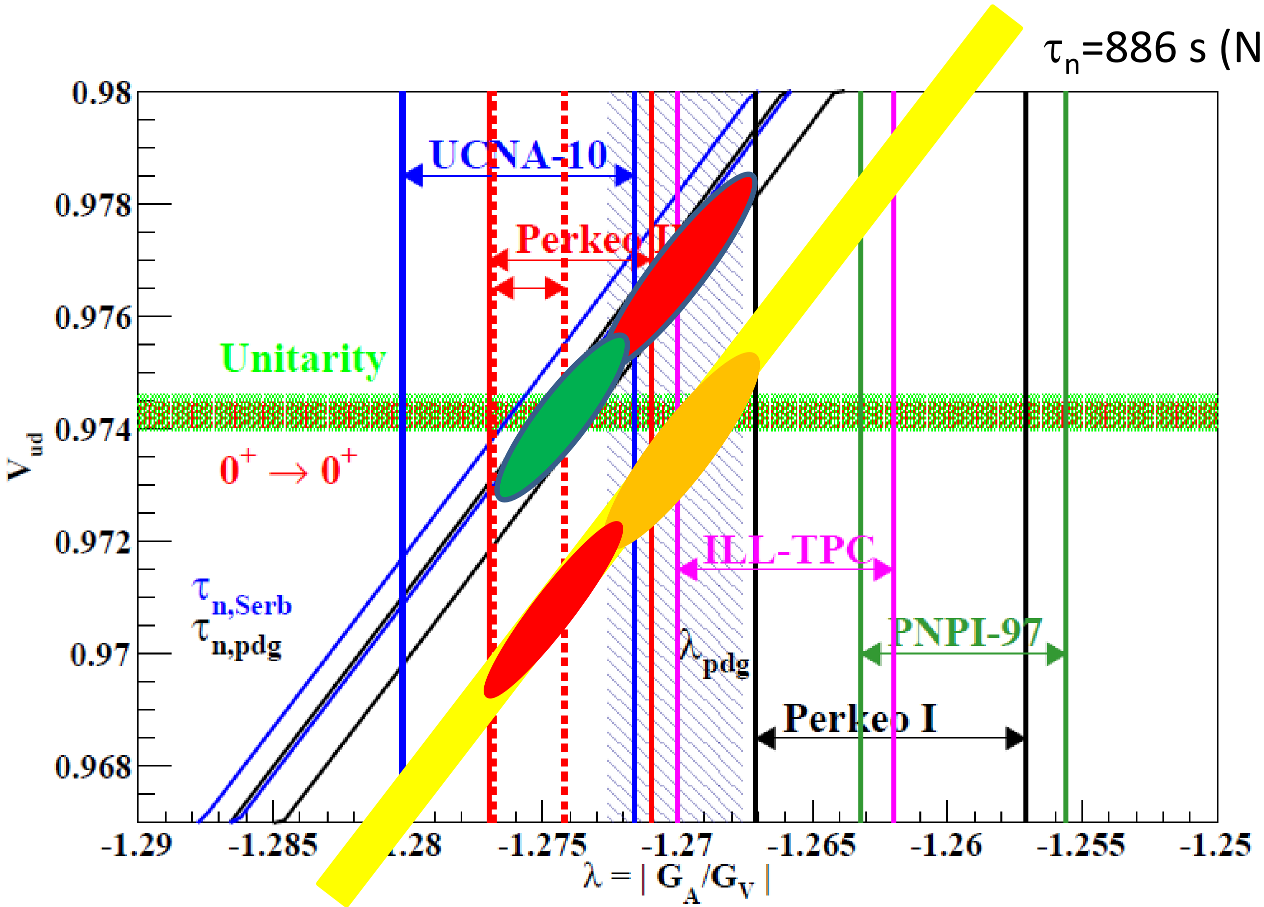
To be comparable to the theoretical uncertainty: 4×10^{-4}, requires experimental uncertainty: $\Delta A/A = 4\Delta\lambda/\lambda < 2 \times 10^{-3}$ and $\Delta\tau/\tau = 4 \times 10^{-4}$.

V_{ud}



Hardy & Towner, Ann. Phys. 525, 443 (2013)

V_{ud} : τ_n & G_A/G_V



R. Pattie Thesis (2012)

$0^+ \rightarrow 0^+$ nuclear decays:

Vud $=0.97425(8)_{exp}(10)_{nucl}(18)_{RC}$

Neutron:

$\tau_n = 880.0(0.9)$ s

$g_A = 1.2701(25)$

→ Vud $= 0.9774(5)_{\tau n}(16)_{gA}(2)_{RC}$

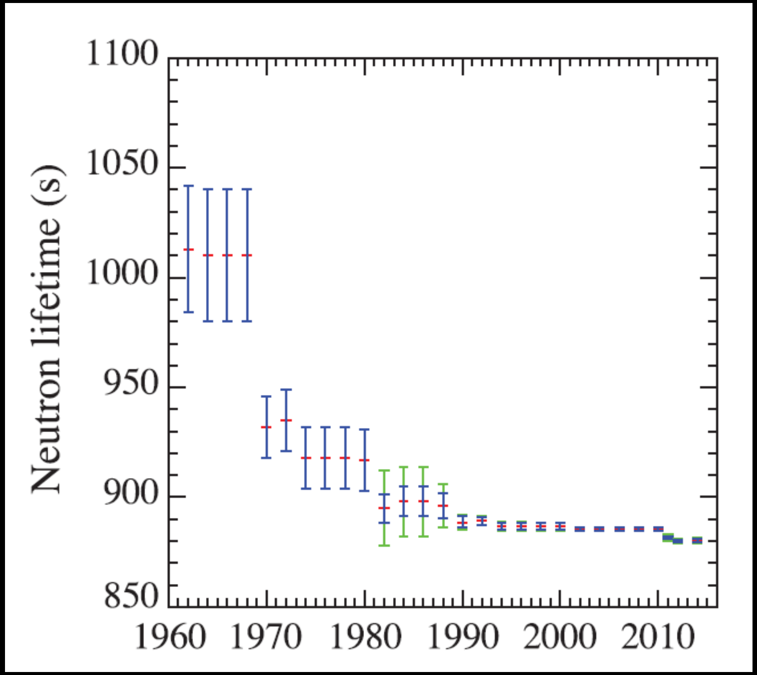
This is 2 σ discrepancy between the neutron and super-allowed decays.

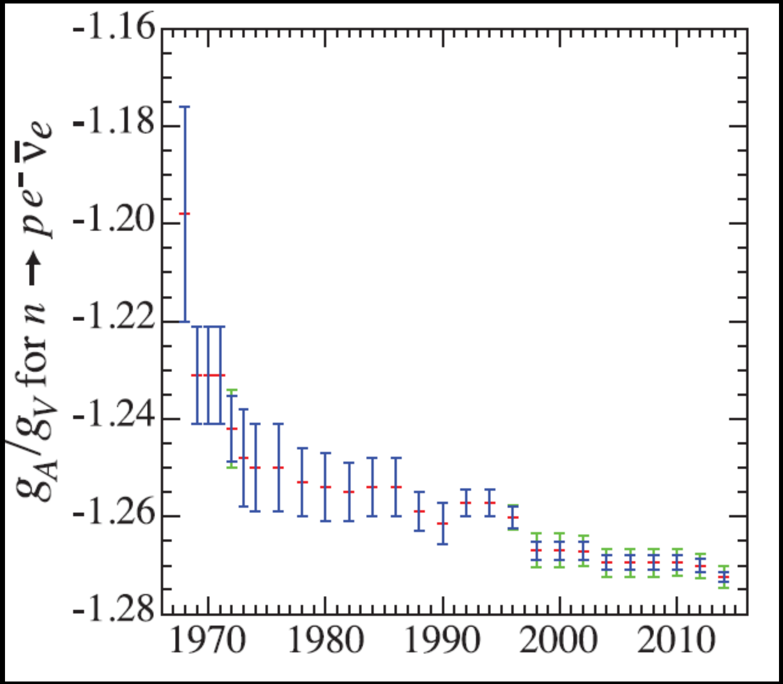
To bring these two into agreement, we need

- Shift $g_A = 1.275$
- Or a longer τ_n=886 s

Present

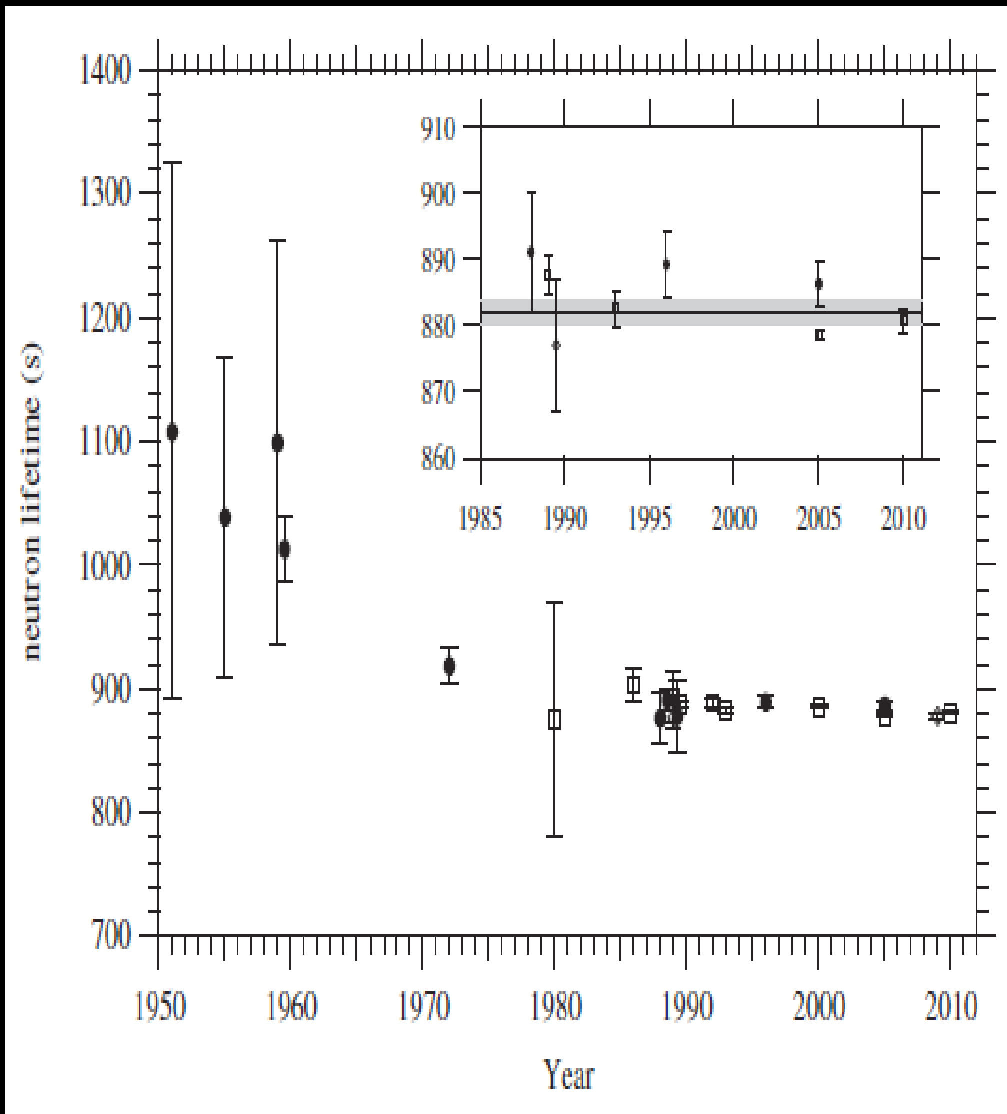
- Neutron lifetime measurements disagree.
- Neutron asymmetry measurements disagree.





The History of Neutron Lifetime Measurement

Experiments

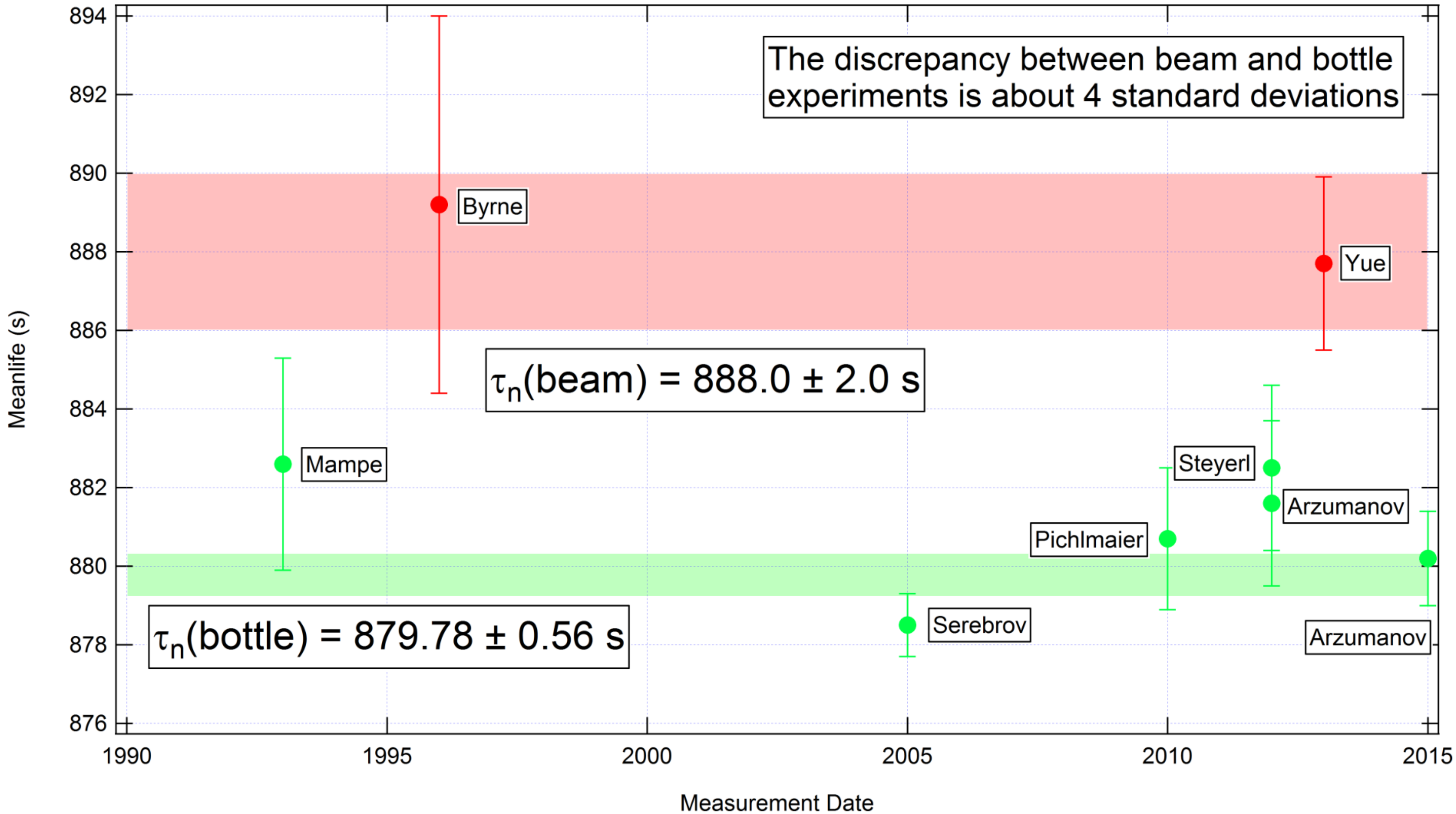


Solid circle: beam
Open square: bottle

PDG average

PDG 2004-2010: 885.7 ± 0.8 s
PDG 2011: 881.0 ± 1.5 s
PDG 2013: 880.0 ± 0.9 s
PDG 2014: 880.3 ± 1.1 s

Discrepancy: Beam vs Bottle



courtesy: Scott Dewey

Future

- Resolve the Neutron lifetime discrepancy.
- Resolve the Neutron A measurement.
- Improve both to 1e-4 level of precision.
- BSM searches
  - By testing the V-A structure.

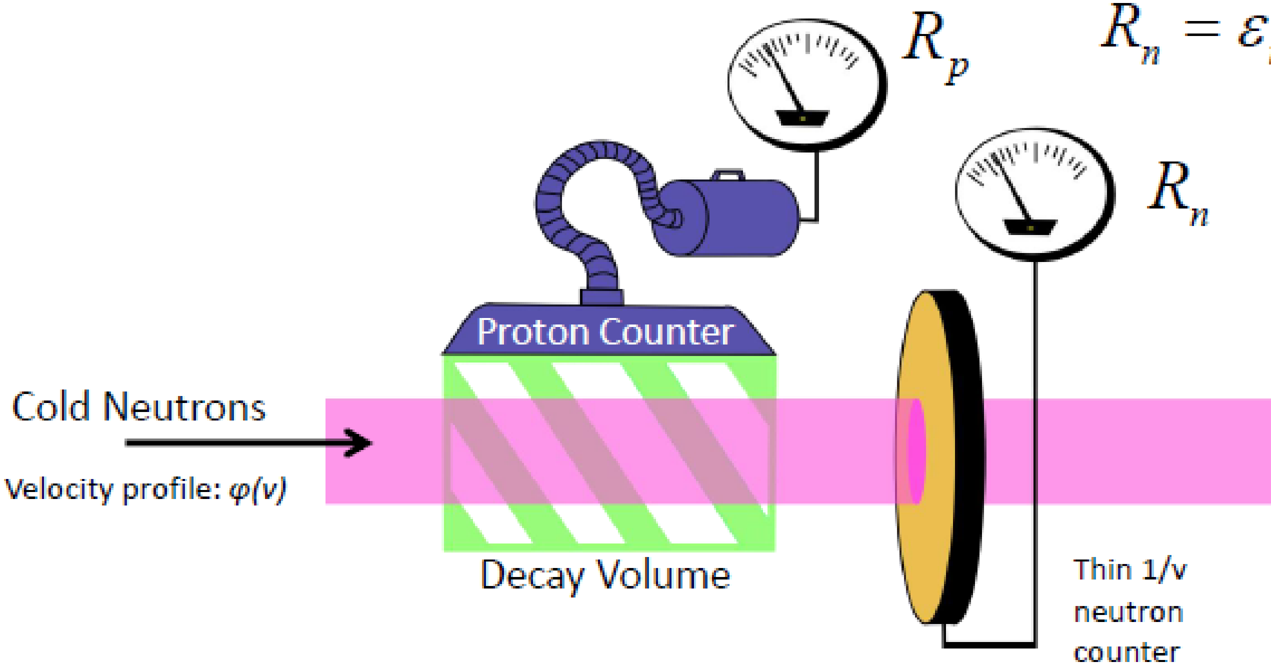
Neutron Lifetime

The Two Pillars: Beam vs Bottle Techniques

The Beam Method

$$R_p = \varepsilon_p \frac{A_{beam} L_{\det}}{\tau_n} \int \frac{\varphi(v)}{v} dv$$

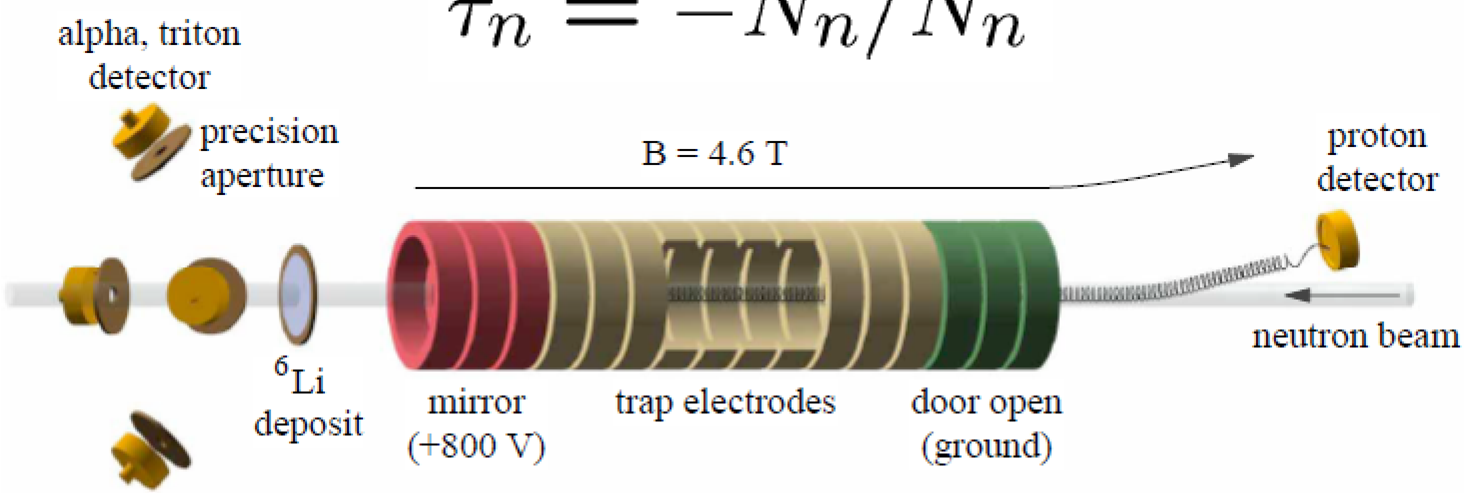
$$R_n = \varepsilon_{th} A_{beam} v_{th} \int \frac{\varphi(v)}{v} dv$$



$$\tau_n = \frac{R_n \varepsilon_p L_{\det}}{R_p \varepsilon_{th} v_{th}}$$

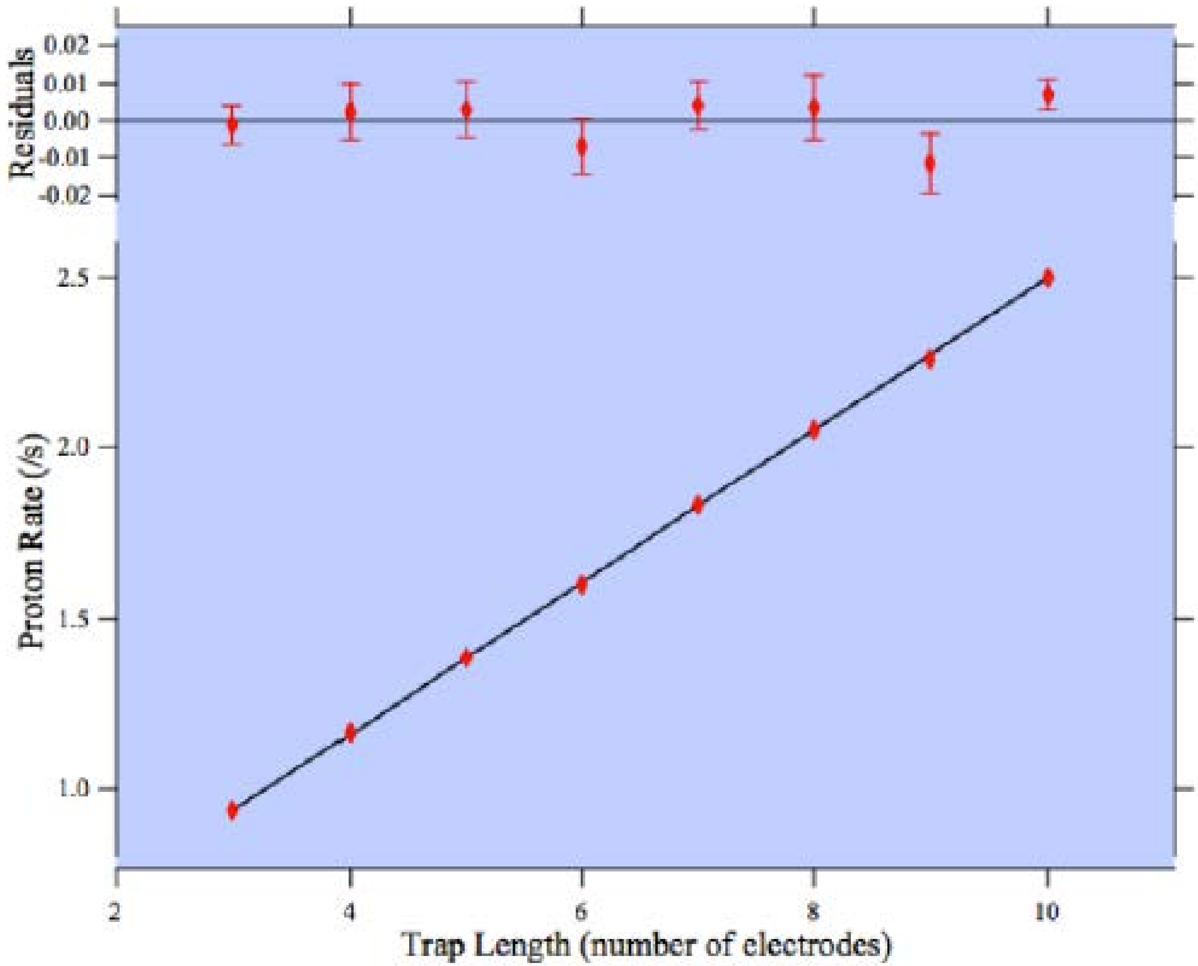
The NIST Beam Lifetime Experiment (BL1, BL2)

$$\tau_n = -\bar{N}_n / \dot{N}_n$$



- A quasi-penning trap electrostatically traps decay protons, which are guided to detector via a B field, when the door electrodes are lowered to the ground potential.
- Neutron monitor measures incident neutron rate by counting n+^{6}Li→ α+t.

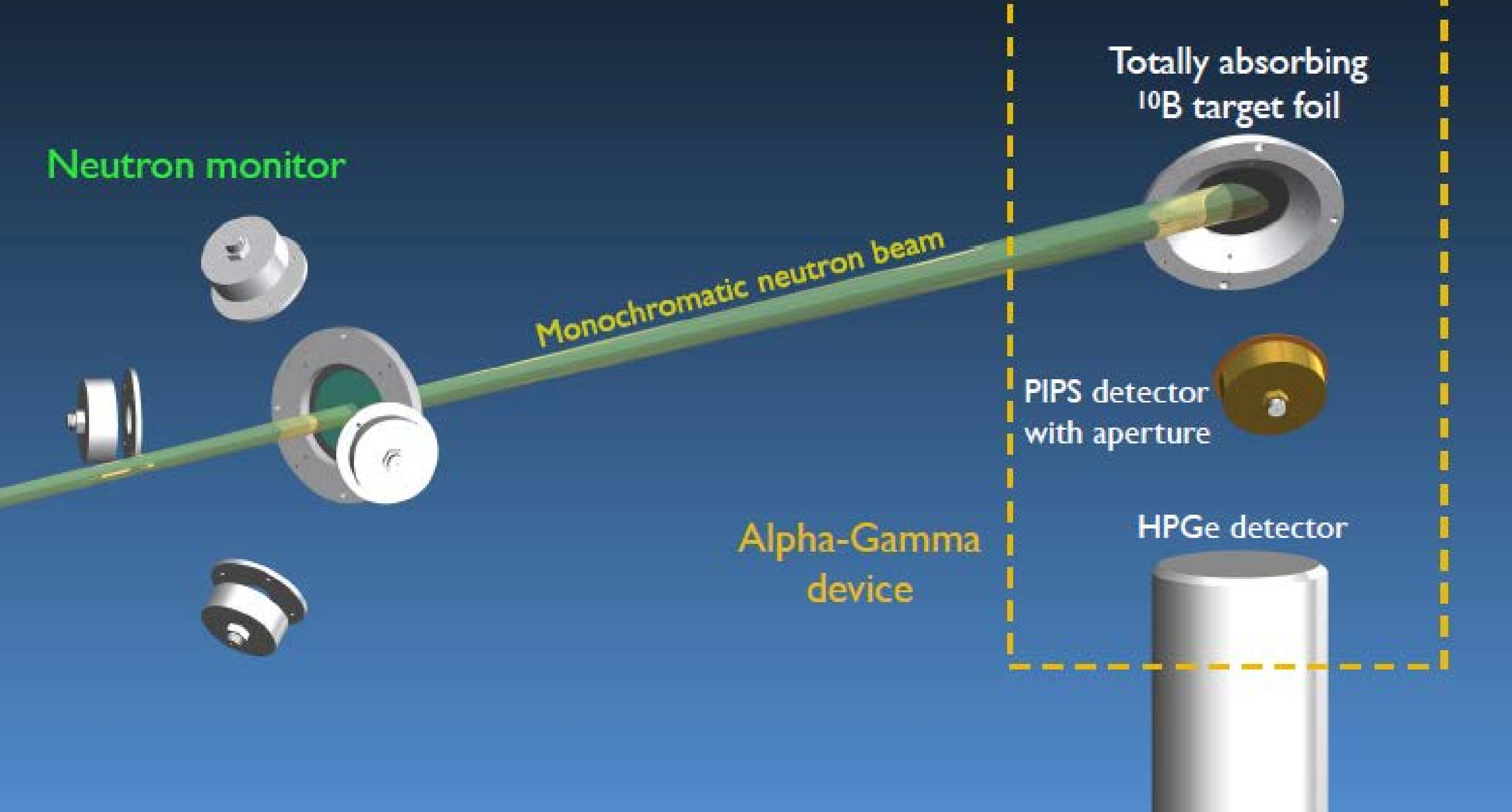
$$\dot{N}_p = \dot{N}_{\alpha+t} \left(\frac{L}{\tau_n} \right) \frac{\epsilon_p}{\epsilon_0 v_0}$$



The Alpha-Gamma device

Andrew Yue, UT Ph.D. thesis (2013), Advisor: Geoff Greene

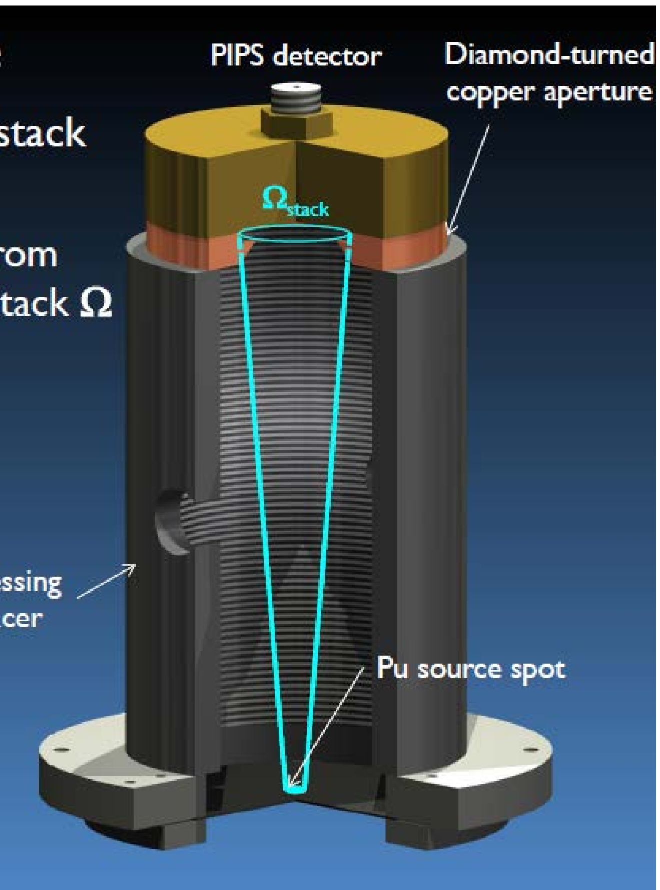
R_n determined by absolute γ counting from $^{10}B(n,\gamma)^7Li$ reaction

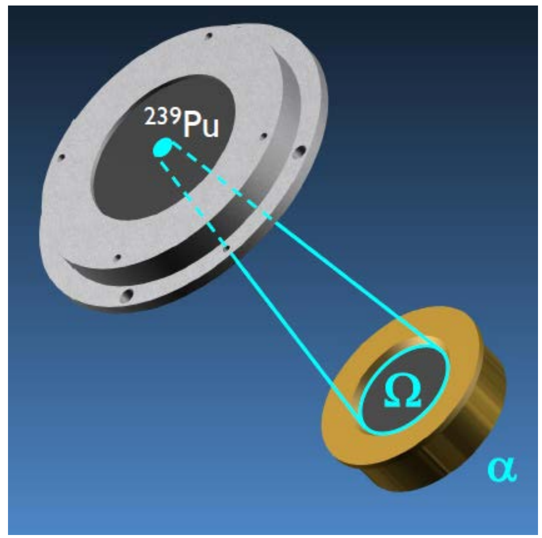


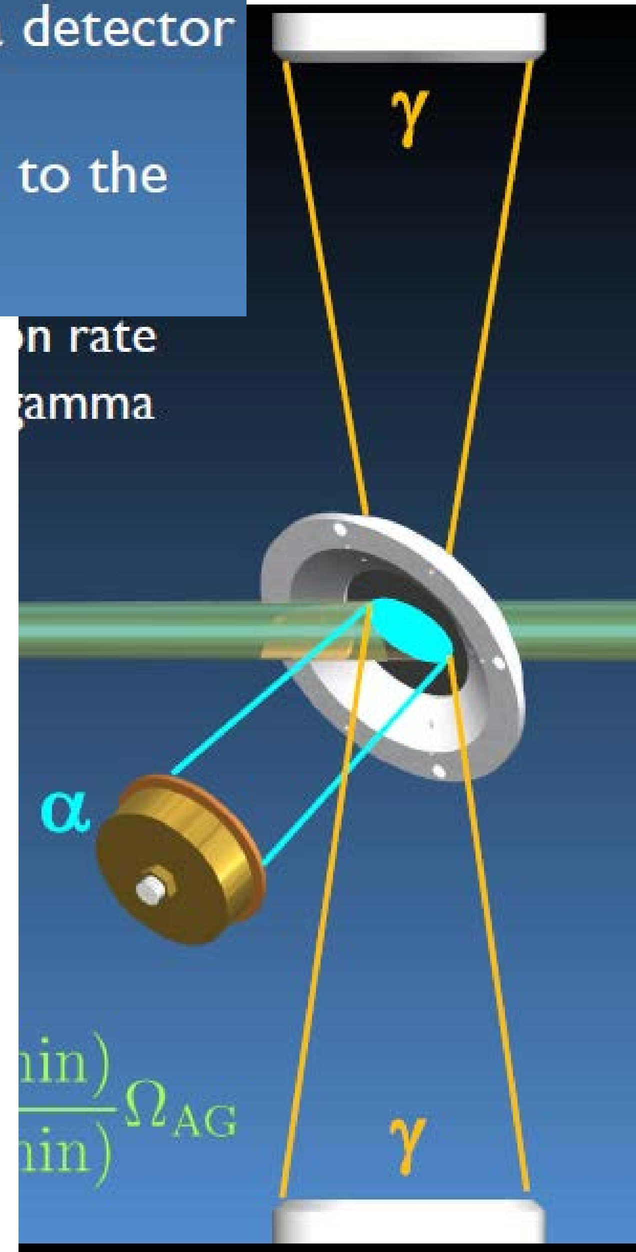
1 Measure the absolute activity of an alpha source

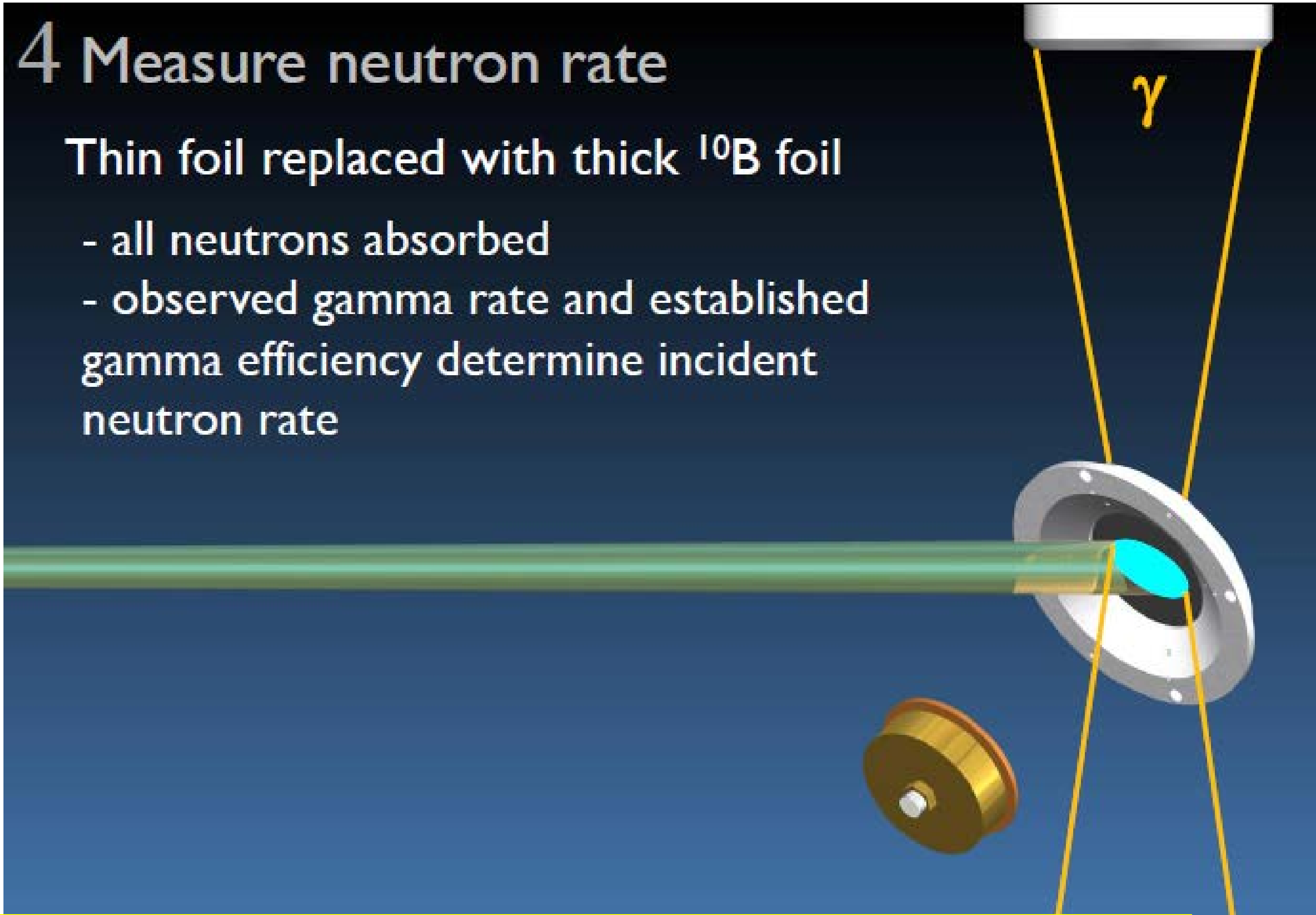
2 Use this source to determine solid angle of alpha detector

3 Use an (n,$\alpha\gamma$) reaction to transfer the calibration to the gamma detectors





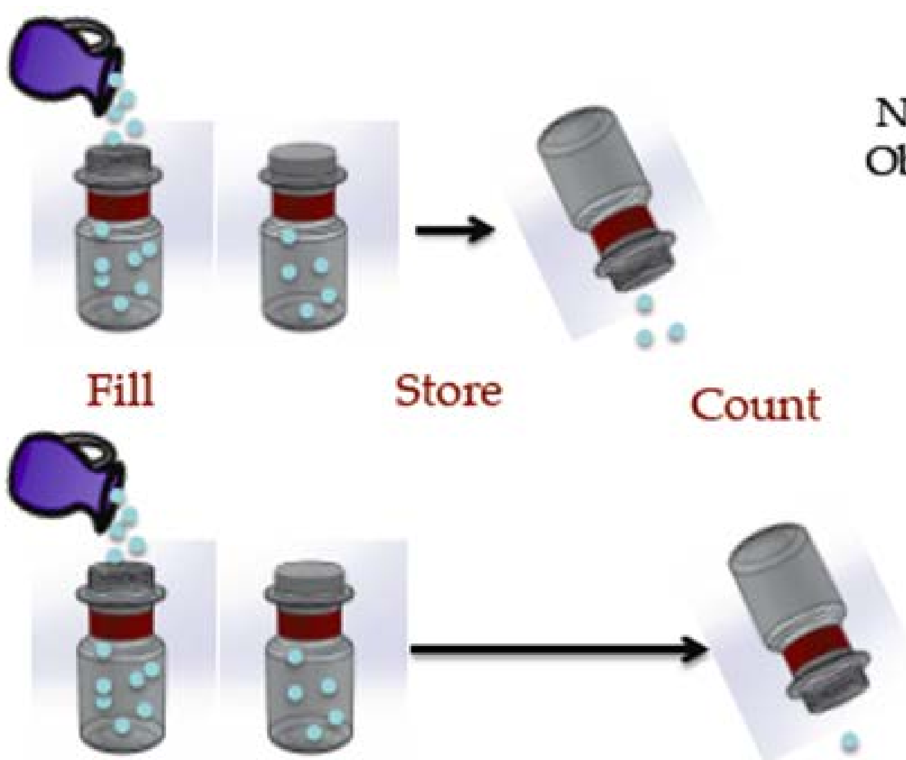


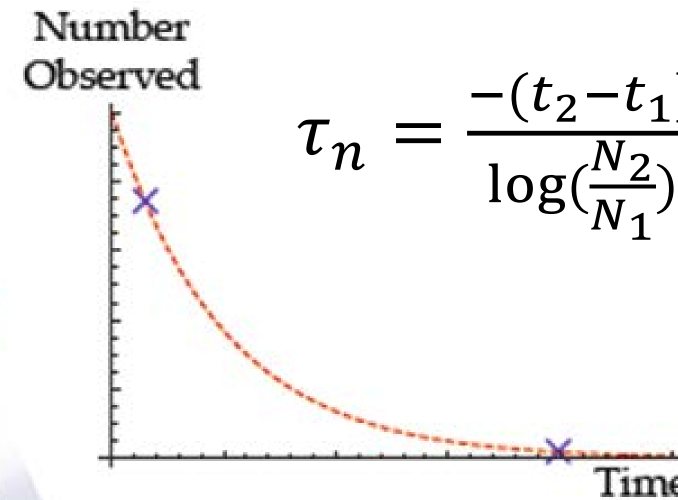


886.3 ± 1.2 [stat] ± 3.4 [sys] seconds   Nico et al 2005

887.7 ± 1.2 [stat] ± 1.9 [sys] seconds   Yue et al 2013

The Bottle Method: *fill-store-count*



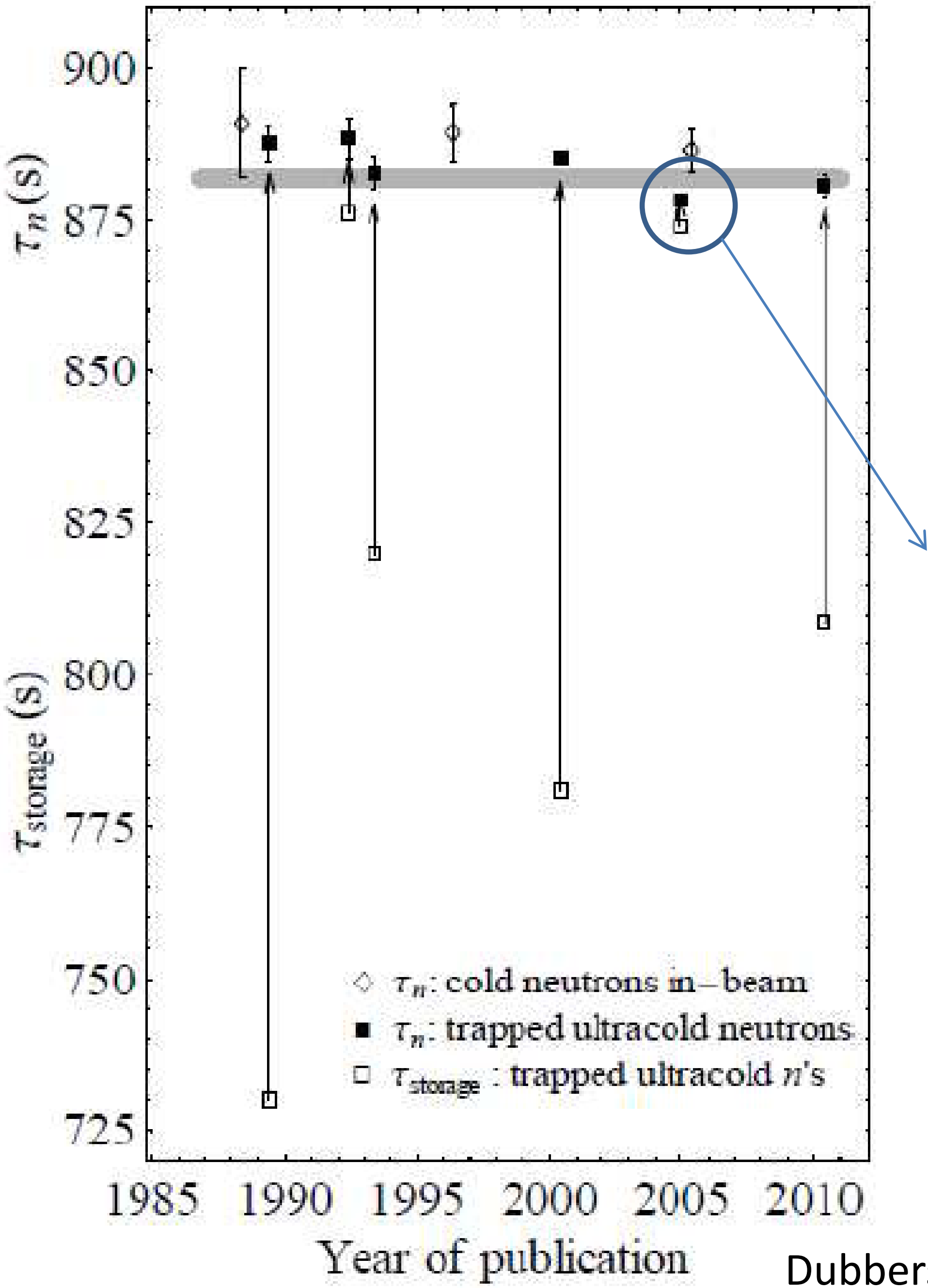


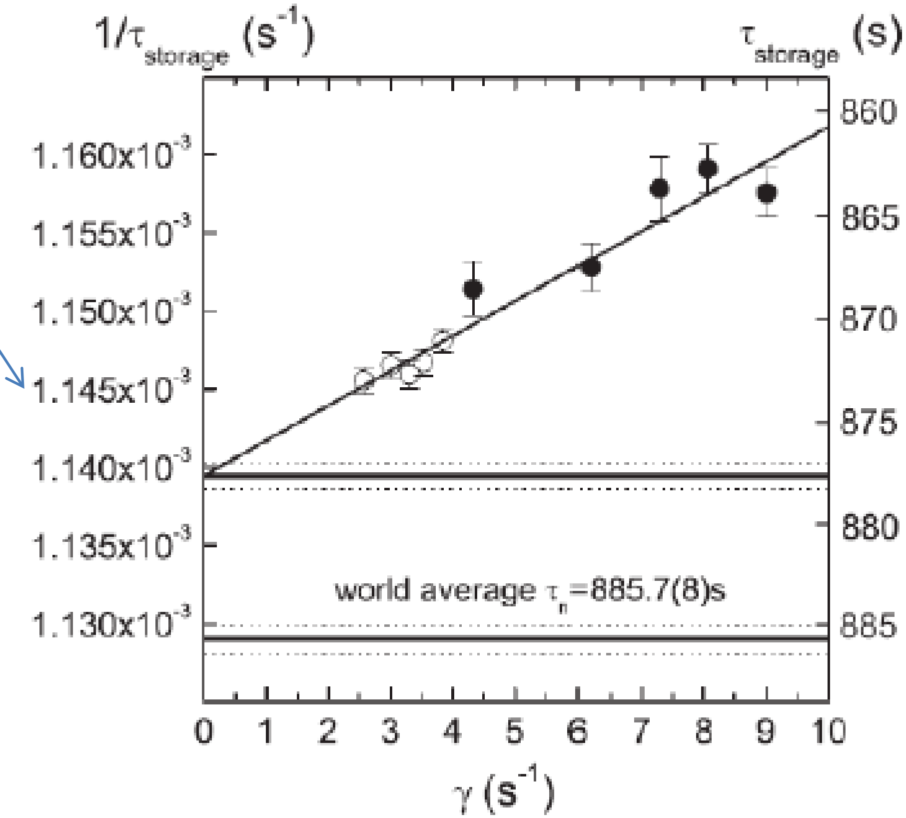
$$\tau_n = \frac{-(t_2 - t_1)}{\log(\frac{N_2}{N_1})}$$

Measures the Storage Time

$$\frac{1}{\tau_{mea}} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{ab}} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{sf}} + \frac{1}{\tau_{heat}} + \frac{1}{\tau_{qb}} + \ \ldots$$

Material Bottle Experiments





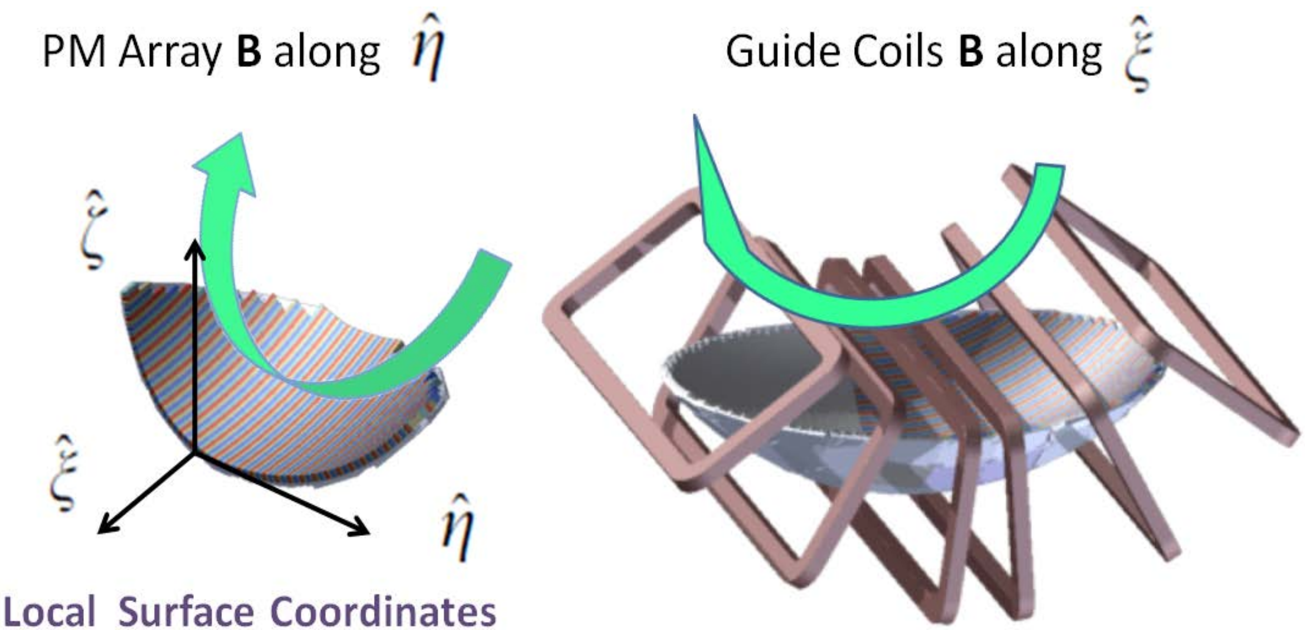
A. Serebrov et al., Phys. Rev. C 78, 035505 (2008)

Dubbers & Schmidt , Rev. Mod. Phys., 83, 1111 (2011)

UCNτ: Magneto-Gravitational Trap

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

- **Minimize UCN spin-depolarization loss**: EM Coils arranged on the toroidal axis generates holding **B** field throughout the trap (perpendicular to the Halbach array field).

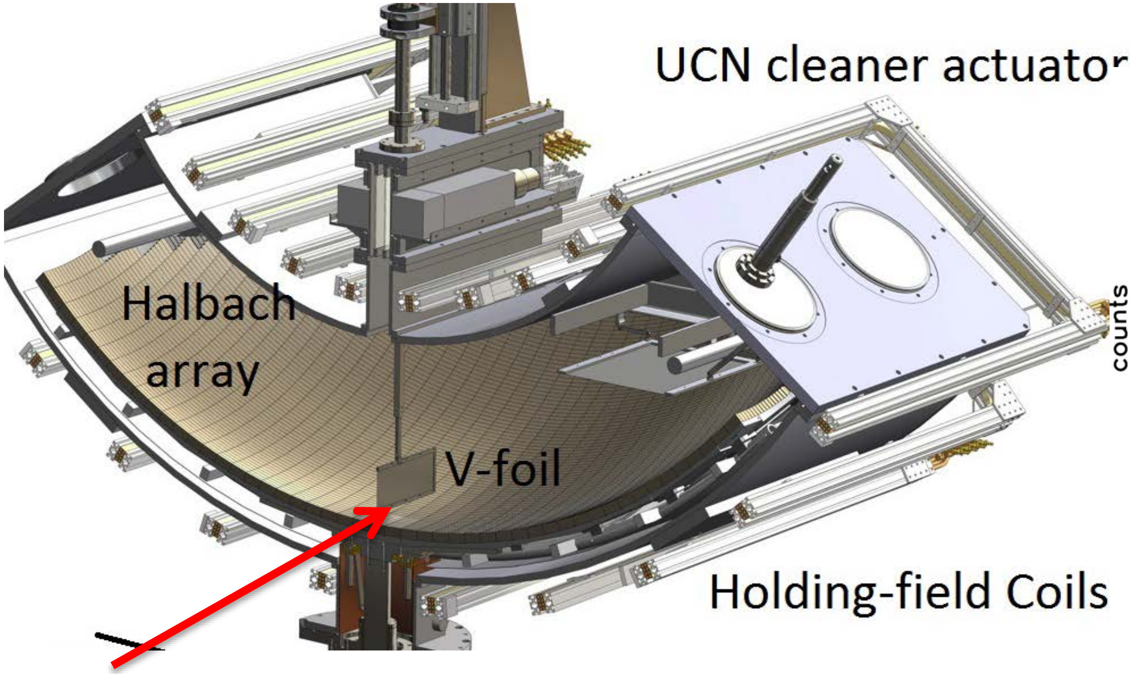


Walstrom et al, NIMA, 599, 82 (2009)

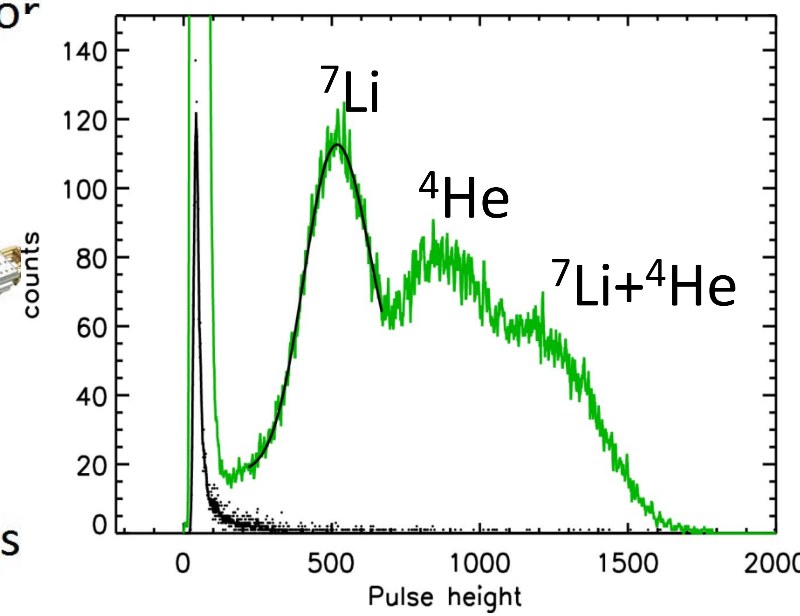
Halbach Array Completion: Dec 2012

First UCN storage, D. Salvat, Phys. Rev. C 89, 052501 (2014)

2015 upgrade: "Active" *in-situ* UCN Detectors



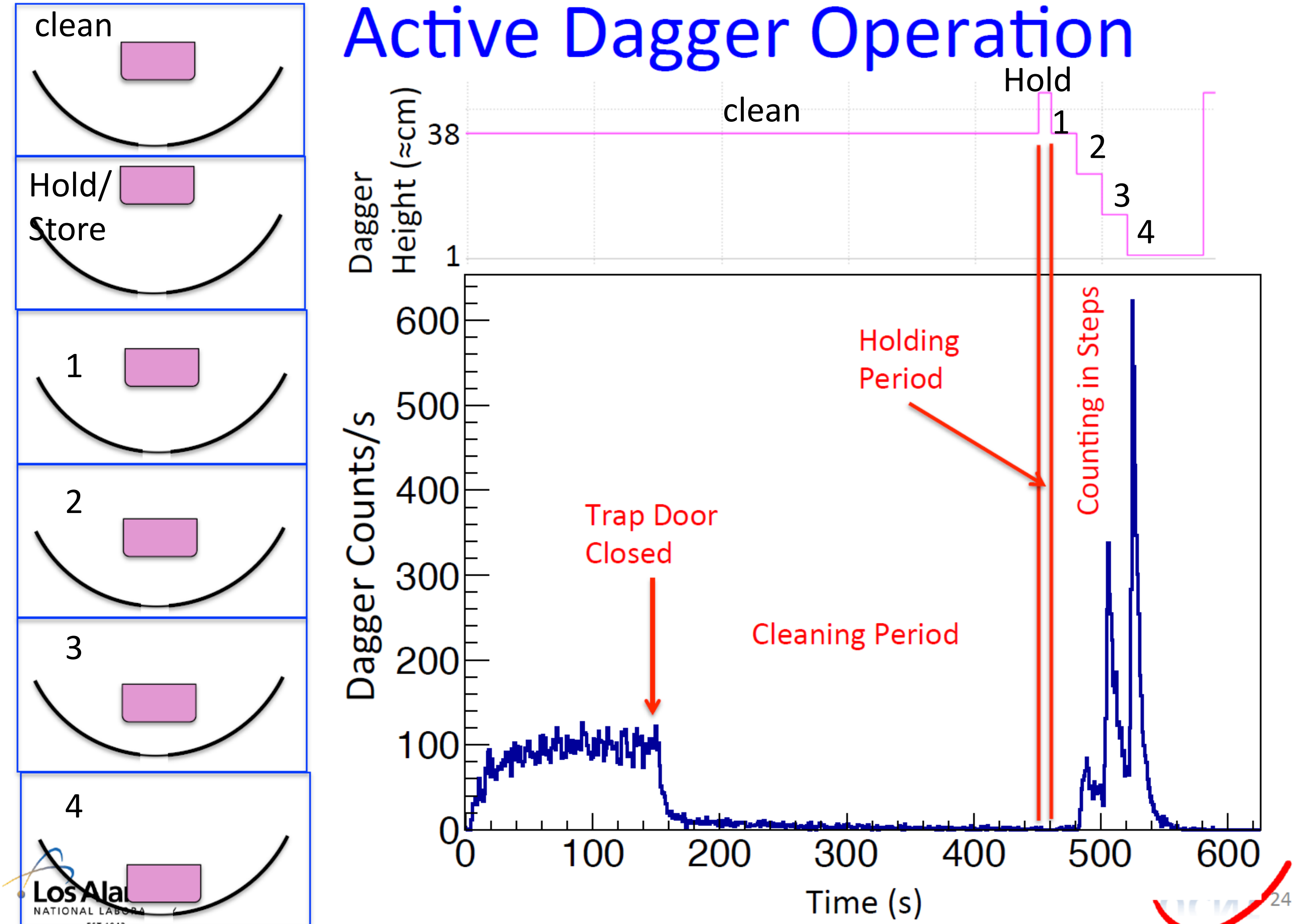
$n + {}^{10}B \rightarrow {}^{7}Li + \alpha$



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

V-foil replaced with a $^{10}B/ZnS$ detector

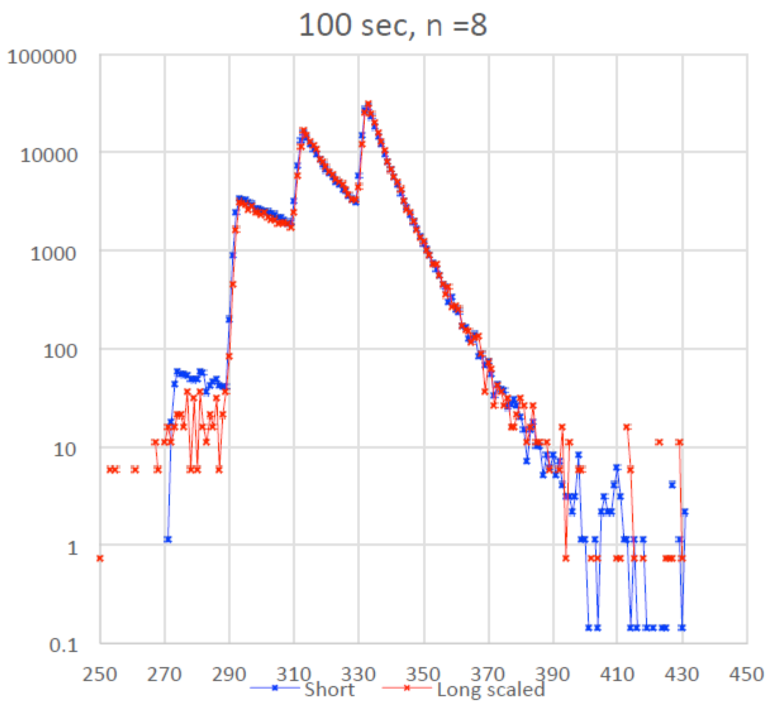
Active Dagger Operation



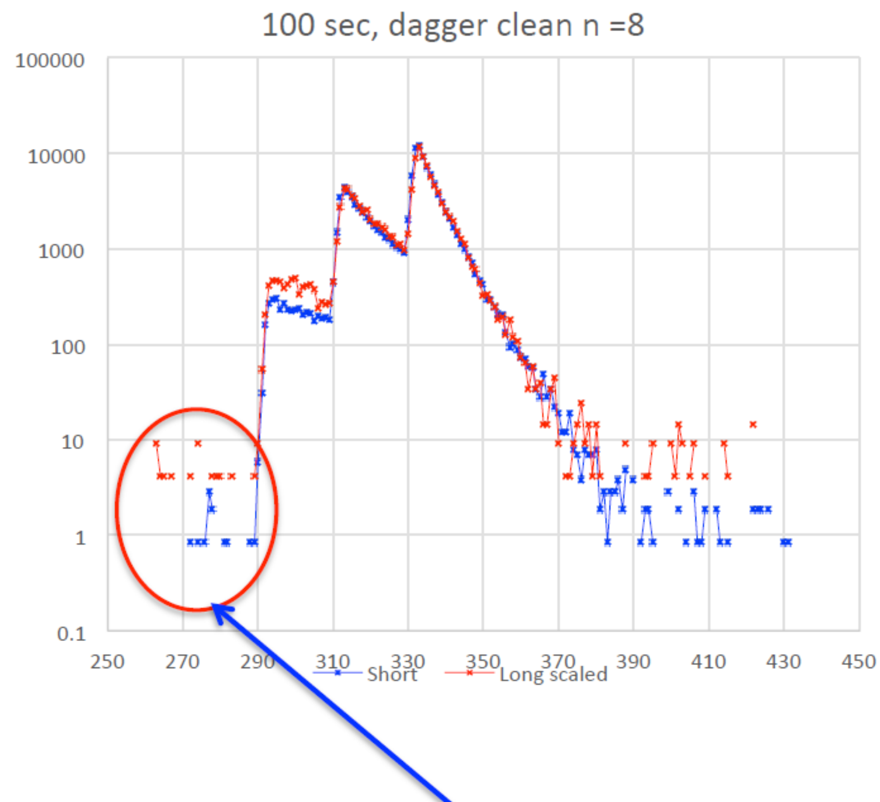
Phase Space Evolution is evident in data that used dagger cleaning

Blue points are short holding time, Red are long holding time (*shifted and scaled*)

No Dagger Cleaning

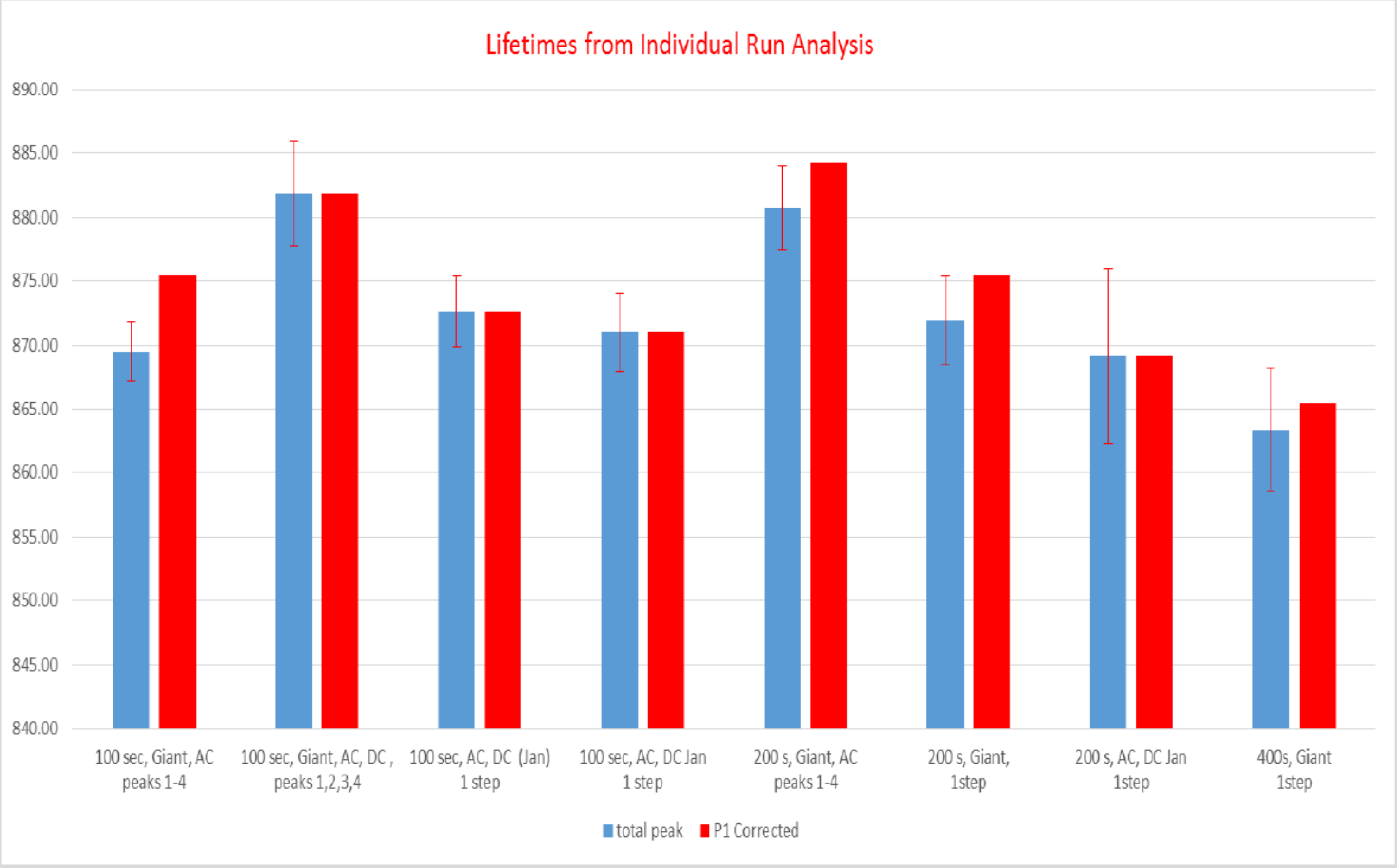


Dagger Cleaning



Data using dagger cleaning showed no counts in peak 1!

Variation in BLINDED lifetimes is roughly consistent with uncertainty



$$\chi^2 / DOF = 2.5$$

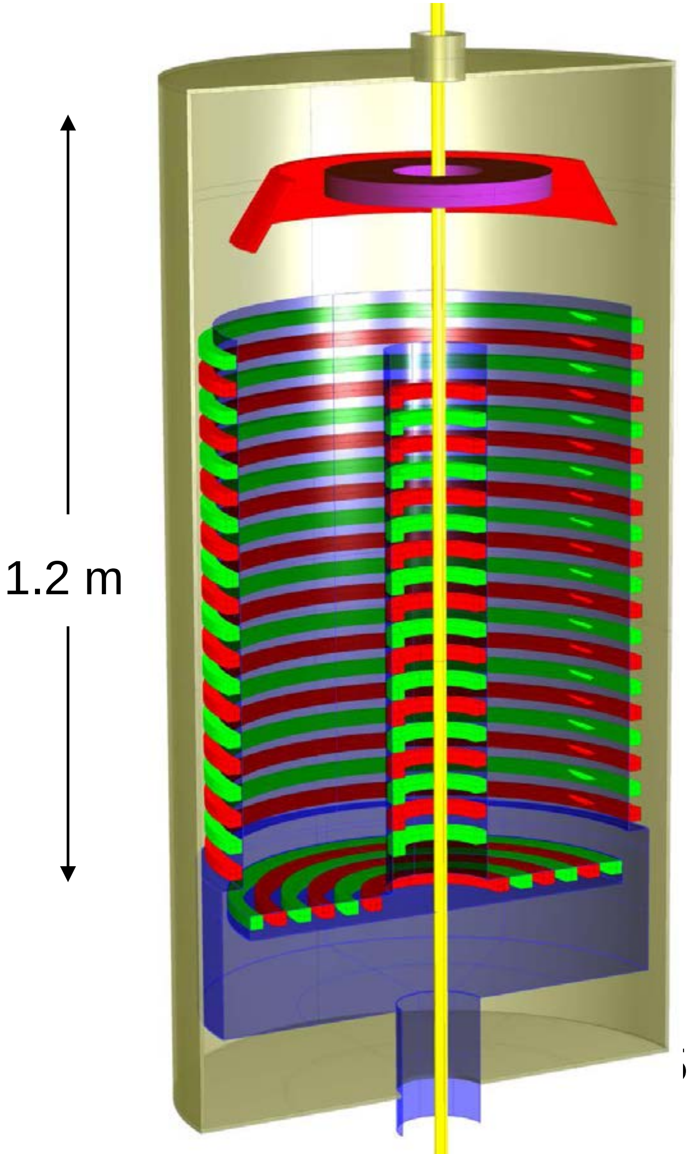
Estimate of Systematic Effects

D. Salvat Thesis (2015)

Effect	Upper Bound	Direction	Current Eval.	Method of Characterization
residual gas	$< 1 \times 10^{-4}$	$+$	meas	RGA/cross-section measurements
depolarization	$< 1 \times 10^{-4}$	$+$	calc	field map, *in situ* detection
material loss	$< 4 \times 10^{-4}$	$+$	calc	measure Cu tape loss-per-bounce
cleaning	$< 6 \times 10^{-4}$	$+$	sim	vary cleaning time/depth, active cleaner
cleaner reliability	$< 5 \times 10^{-4}$	$\pm$	sim	verify position reproducibility
microphonic heating	$< 1 \times 10^{-4}$	$+$	sim	accelerometer measurements
dead time/pileup	$< 1 \times 10^{-4}$	$\pm$	calc	pileup ID/artificial dead time
gain drifts	$< 2 \times 10^{-4}$	$\pm$	meas	spectral monitoring/gain monitoring
time-dep. background	$< 5 \times 10^{-4}$	$\pm$	meas	background data analysis
phase space evolution	$< 5 \times 10^{-4}$	$\pm$	sim	vanadium time studies, active detector
UCN monitoring	$< 3 \times 10^{-4}$	$\pm$	meas	measure monitor response/source stability
total	$< 1.2 \times 10^{-3}$	$\pm$		(uncorrelated sum)

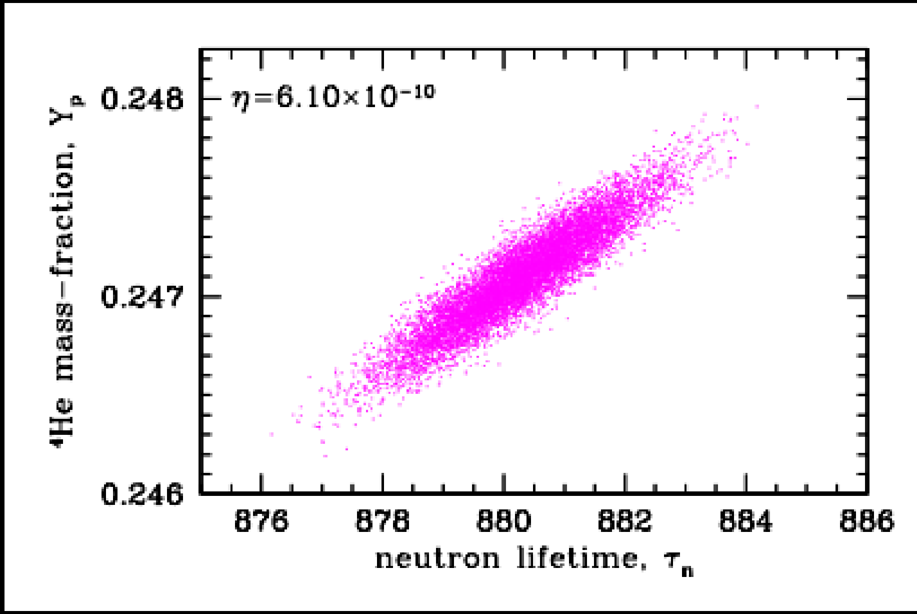
Penelope experiment under development

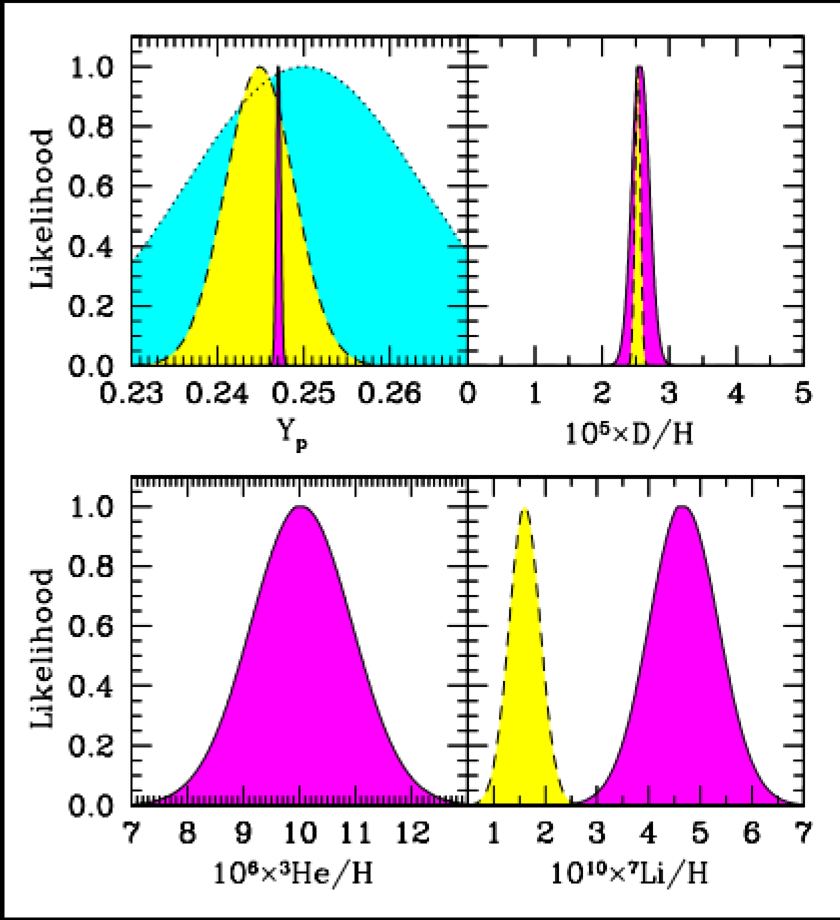
- Superconducting multipole
  - Field zero in center eliminated by inner conductors
- Filled with UCN from FRM-2 through gap in bottom
- Decay products detected at top, guided by field lines
- Spectrum cleaned using absorber lowered from top
- Magnet now under construction



Neutron Lifetime & ^{4}He abundance (Y_p)

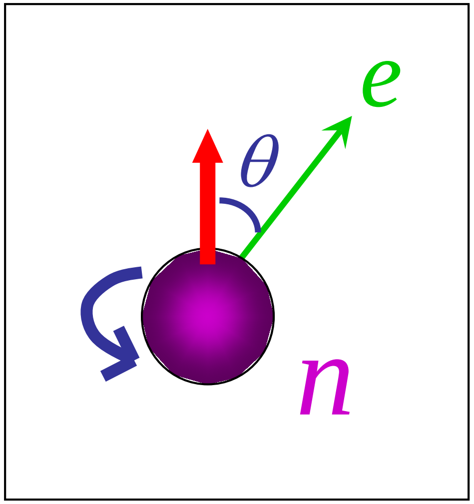
BBN
CMB
Astrophysical Observations



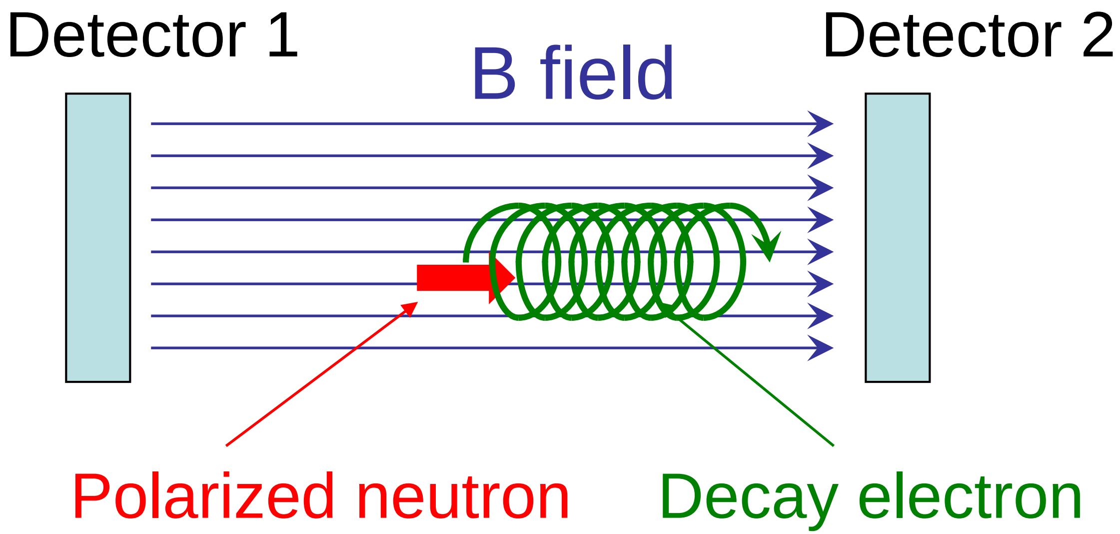


-R. H. Cyburt, B.D. Fields, K.A. Olive, T-H Yeh, Rev. Mod. Phys. 88, 015004 (2016); arXiv:1505.01076
- L. Salvati et al. JCAP 1603 (2016) no.03, 055; arXiv:1507.07243

Principle of the *A*-coefficient Measurement (and *B* and *C* as well)



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



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

(End point energy = 782 keV)

Spectrometer Perkeo II

up:

$$A_{exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}}$$

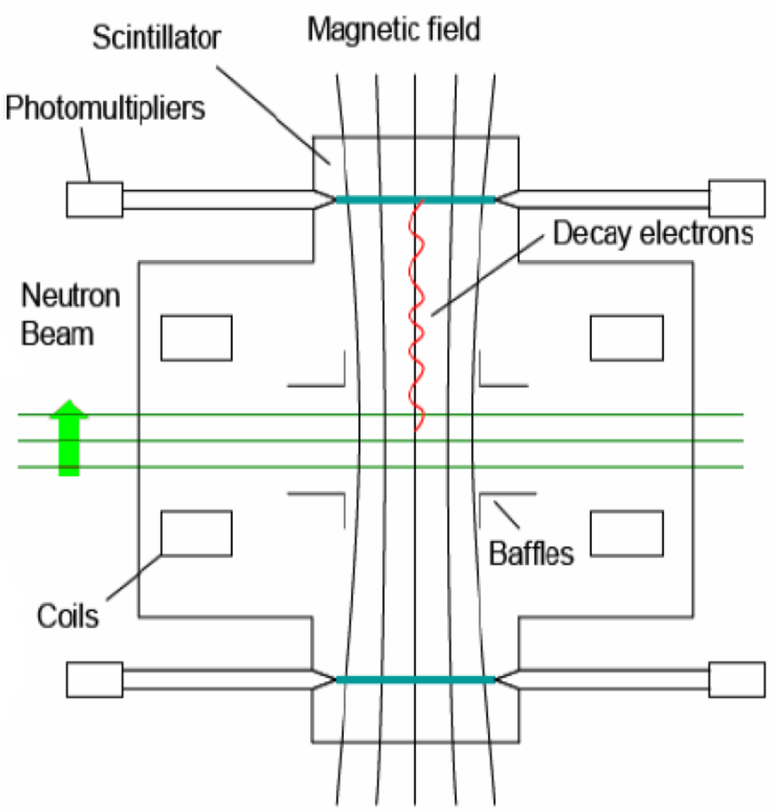
down:

$$A_{exp} = \frac{N^{\Uparrow} - N^{\Downarrow}}{N^{\Uparrow} + N^{\Downarrow}}$$

precise electron spectroscopy

Principle:

- 2x2π- Detection
- two hemispheres
- backscattering suppression
- low background
- strong beam PF1:
  - count rate→systematic



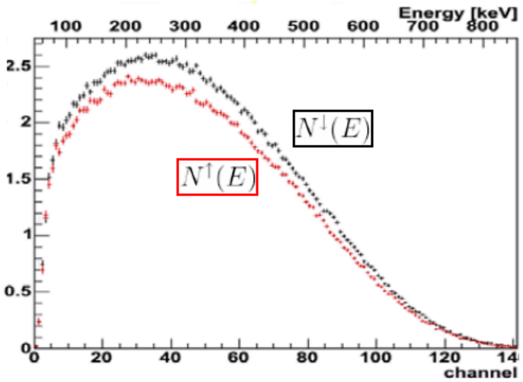
$$A_{exp} = A\frac{v}{c}Pf \quad A = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$$

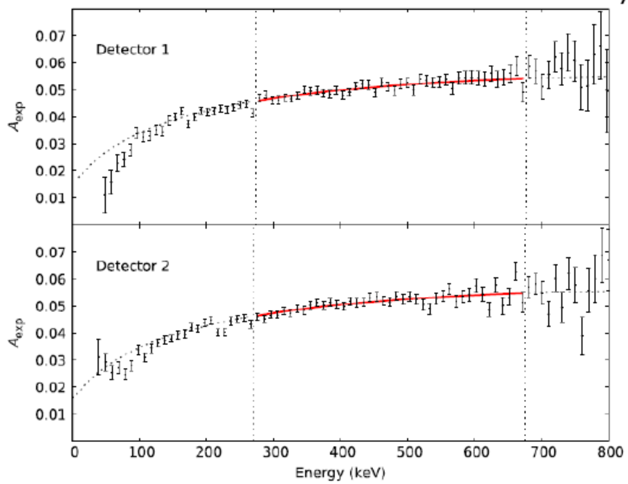
$\lambda = g_A/g_V$

Method see also: H. Abele et al., 17 keV Neutrino PLB 316 26 1993

Recent Results: PERKEO Collaboration

Electron Asymmetry A:





A =-0.1197(6)

PERKEO II combined:

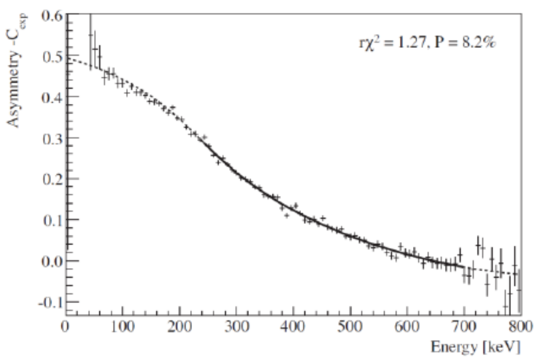
$A_{PII} = -0.1193(5)$

$\lambda_{PII} = -1.2748(13)$

error: 1×10^{-3}

PRL 110, 172502 (2013)

Neutrino Asymmetry B



$B = 0.9802(50)$

Schumann et a.

PRL **99**, 191803 (2007)

Proton Asymmetry C:

first precision measurement $C = x_C(A + B)$

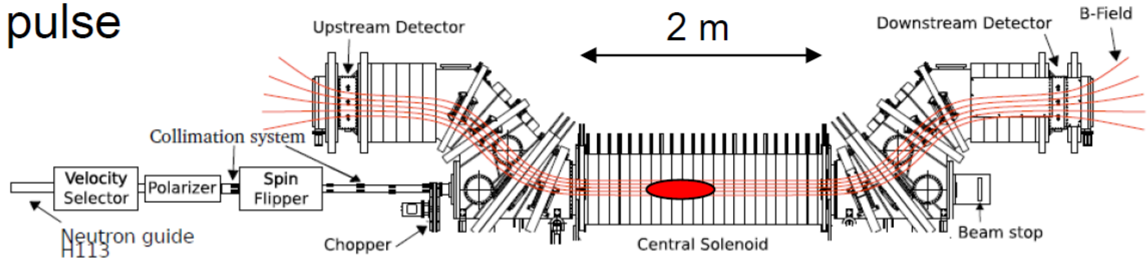
$C = -0.2377(36)$

Schumann et al.,

PRL **100**, 151801 (2008)

β-asymmetry A with pulsed cold n-beam

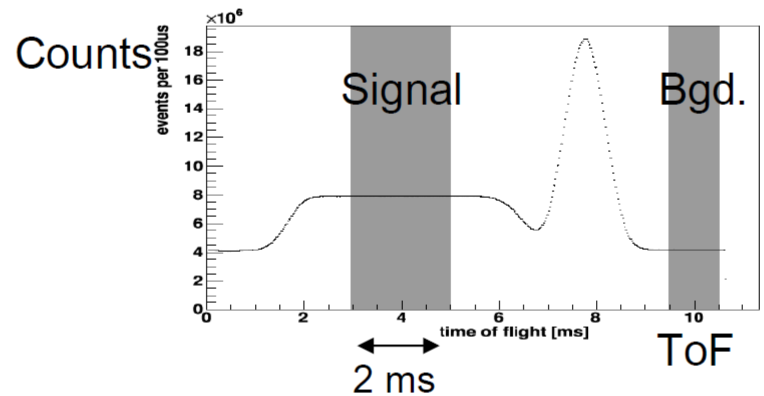
PERKEO III@ILL: neutron storage „in-flight",
2×10^6 polarized neutrons in one pulse
3×10^4 neutrons/cm^3
renewed 80 times per second



Decay rates:
5×10^4 s^{-1} continuous unpolarized
2000 s^{-1} pulsed polarized, peak
140 s^{-1} time average

6×10^8 events
Märkisch et al. NIM A 611, 215 (2009)

Results not yet unblinded



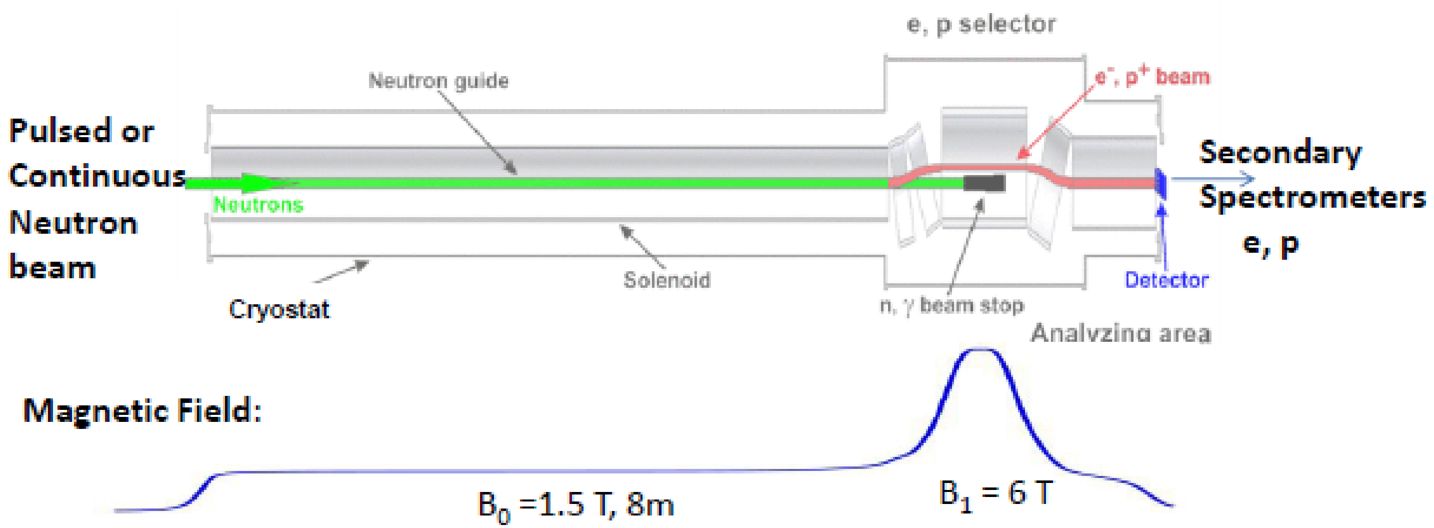
PERC@FRM II
Neutron storage In-flight within guide:
decay rate 10^6 s^{-1} per meter guide, over 8 m

Improvements vs. PERKEO II:

e^- on detector without edge effect
Bgd., signal, both with shutter closed
e^- mirror effect negligible

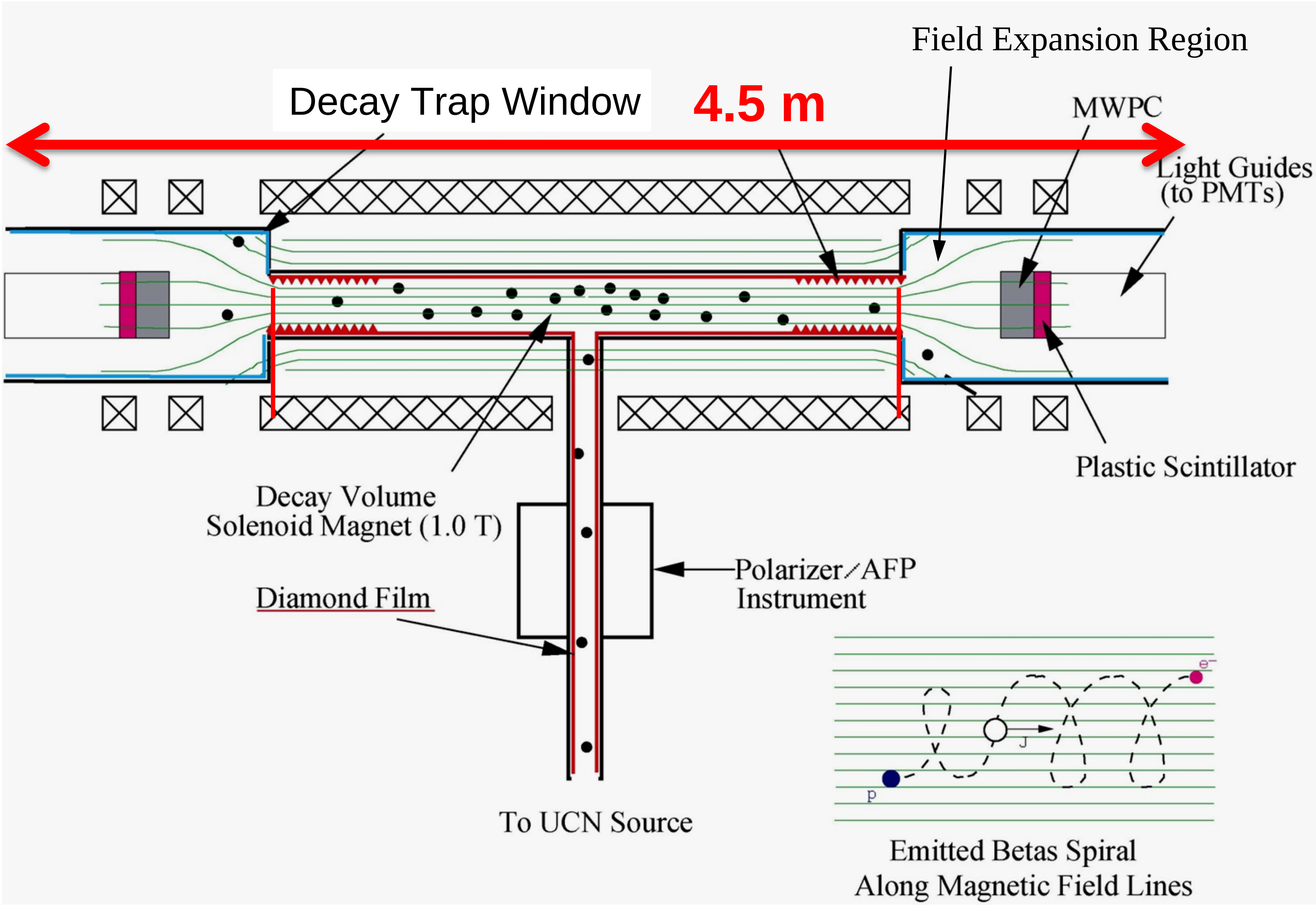
PERC is the next generation

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

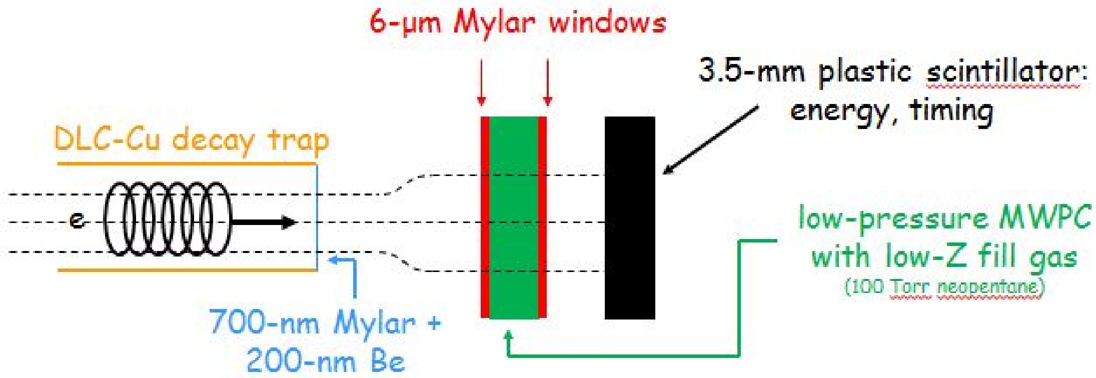


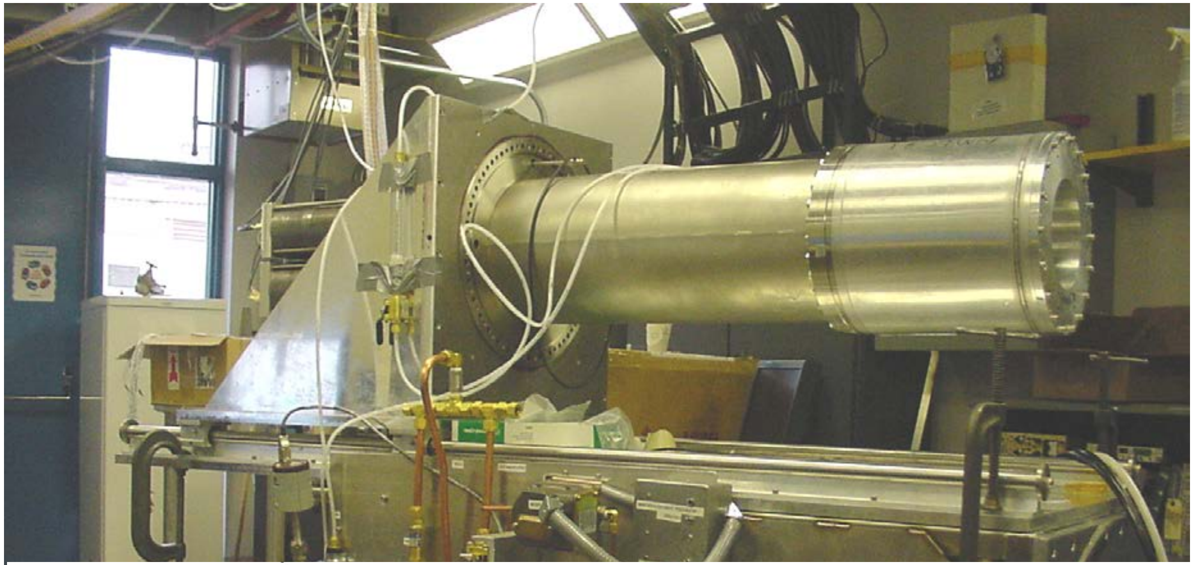
D. Dubbers *et al*., NIM A **596**, 238 (2008)

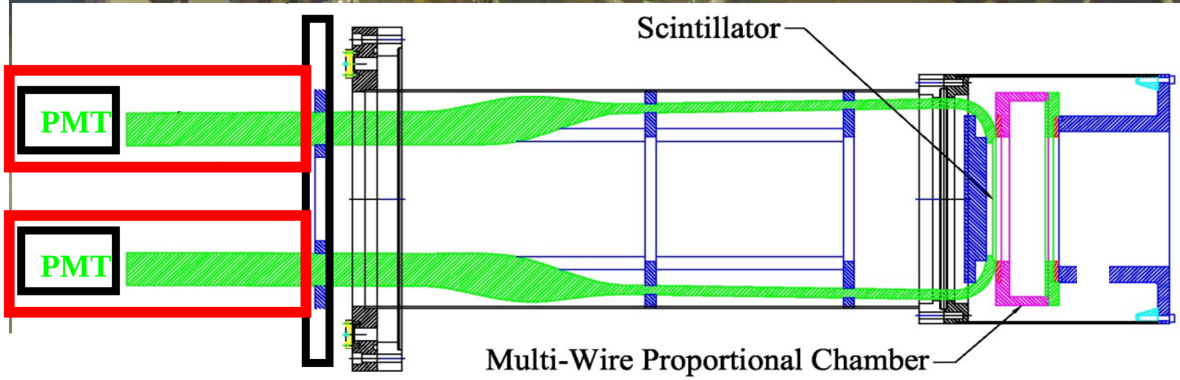
UCNA Experiment



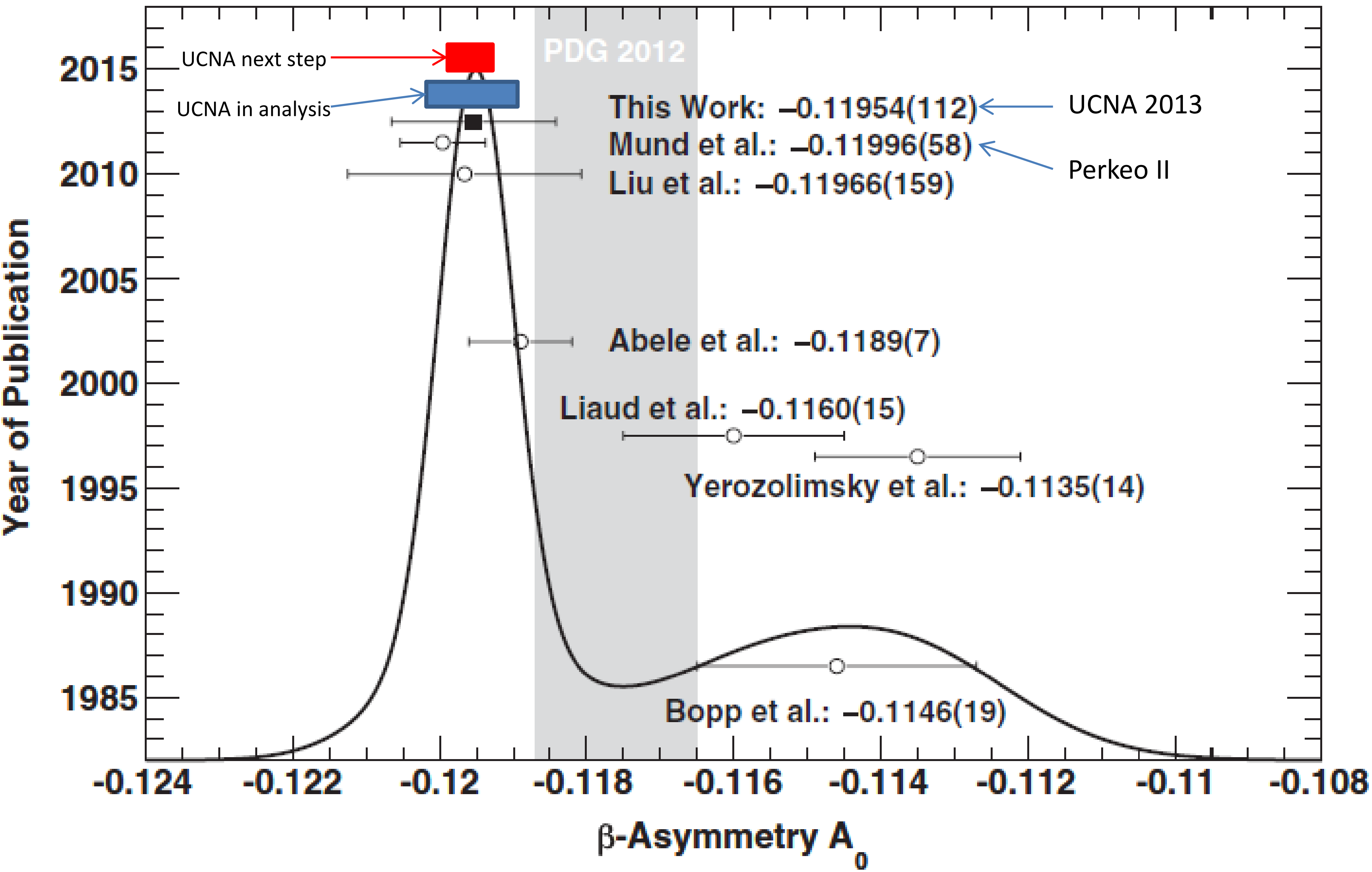
Assembled Detector Package







Much of remaining uncertainty caused by discrepancy: precise UCNA result will overcome this



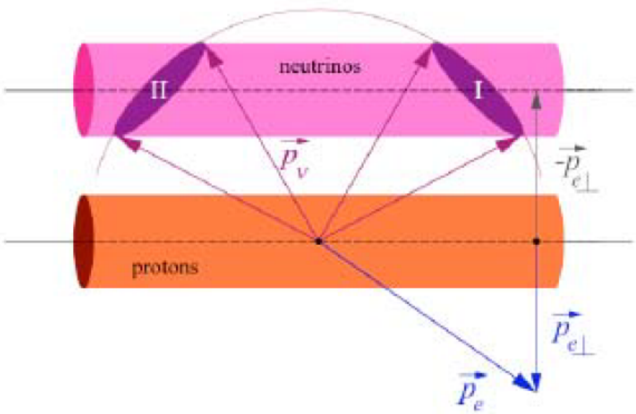
Mendenhall, 2013

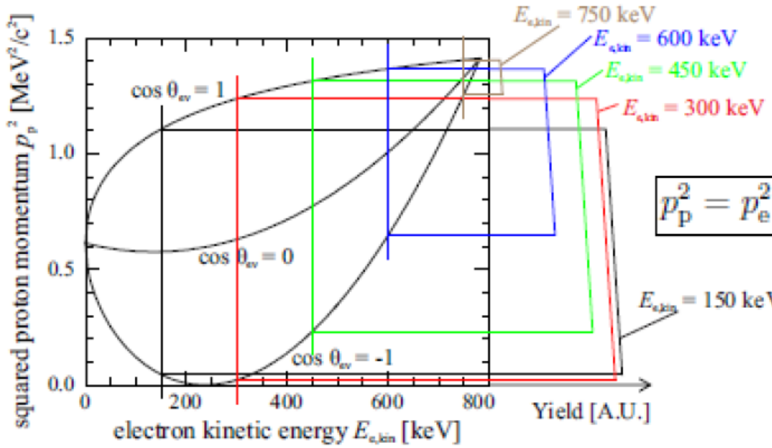
UCNA Error Budget Over Time

Corr. +/- Uncertainty (%)	Mendenhall (2013)	2011-13 data: In analysis	Next Step	Source of improvement
Statistics	+/- 0.46	+/- 0.40	+/- 0.28	Decay rate!
Depolarization	+0.67 +/- 0.56	+0.67 +/- 0.1	+0.1 +/- 0.05	Shutter+ ex situ
Backscatter	+1.36 +/- 0.34	+0.5 +/- 0.15	+0.5 +/- 0.15	Thin windows
Angle effect	-1.21 +/- 0.30	-0.8 +/- 0.2	-0.8 +/- 0.1	Windows+APD
Energy Reconstruction	+/- 0.31	+/- 0.43	+/- 0.08	Xenon + LED
Total Sys.	+/- 0.82	+/- 0.5	+/- 0.22	
Total	+/- 0.94	+/- 0.66	+/- 0.35	

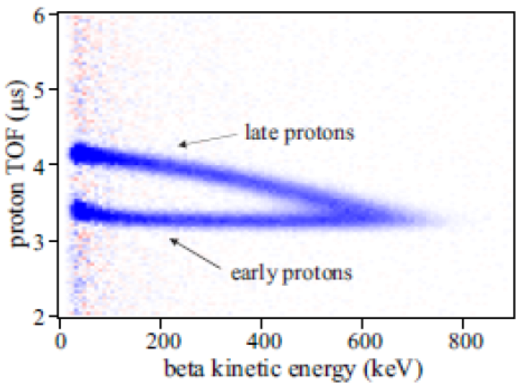
Statistics: 0.28% requires 150x10^6 raw decays
@100 Hz, 50% duty factor, requires 13 weekends, or ~one full run cycle
(But could be split over multiple cycles)

"*a*" Correlation: $\vec{p}_e \cdot \vec{p}_\nu$ $\cos\theta_{e\nu}$

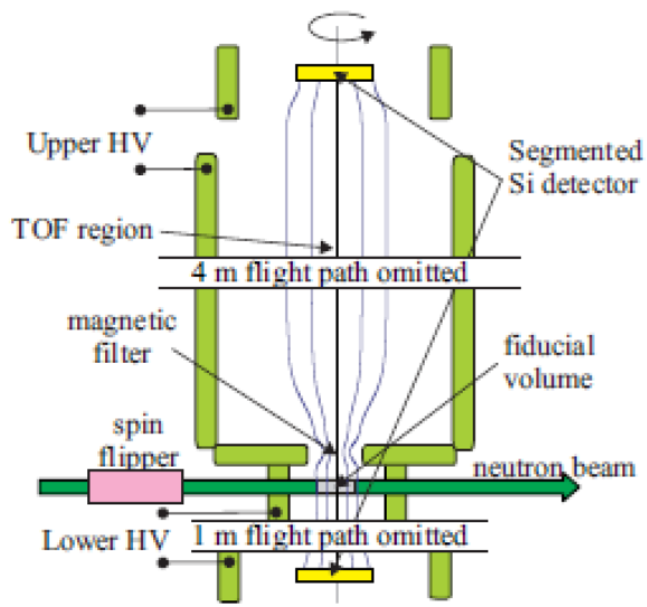




$$p_p^2 = p_e^2 + p_\nu^2 + 2 p_e p_\nu \cos\theta_{e\nu}$$



aCORN at NIST:
2013: ~3% (stat), ~2-3% (syst)
Current Run: ~1%



Nab at SNS:
Construction
$a \sim 0.2\%$

Global Fit – Theory Uncertainties

$$\langle p(p')|\bar{u}\gamma^\mu d|n(p)\rangle \equiv \bar{u}_p(p')\left[f_1(q^2)\gamma^\mu - i\frac{f_2(q^2)}{M}\sigma^{\mu\nu}q_\nu + \frac{f_3(q^2)}{M}q^\mu\right]u_n(p),$$

$$\langle p(p')|\bar{u}\gamma^\mu\gamma_5 d|n(p)\rangle \equiv \bar{u}_p(p')\left[g_1(q^2)\gamma^\mu\gamma_5 - i\frac{g_2(q^2)}{M}\sigma^{\mu\nu}\gamma_5 q_\nu + \dots\right]u_n(p),$$

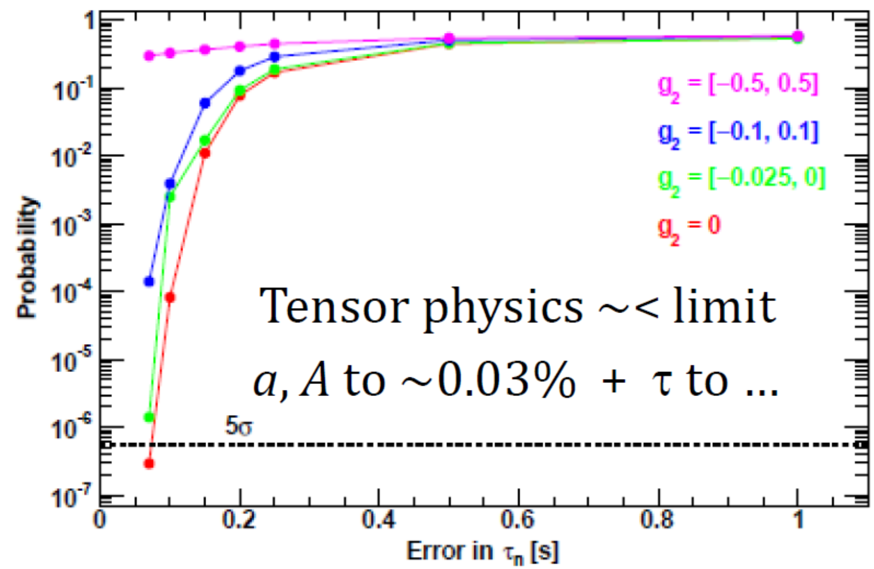
$$a_{\rm exp} = \frac{1}{2}\beta\frac{a_1}{1 + b_{\rm BSM}\frac{m_e}{E_e} + \frac{1}{3}a_2\beta^2}, \qquad A_{\rm exp} = \frac{1}{2}\beta\frac{A}{1 + b_{\rm BSM}\frac{m_e}{E_e}}.$$

"Rfit" Scheme:

$$\chi^2 = \sum_{i=1}^{N_{\rm exp}}\left(\frac{x_{{\rm exp},i} - x_{\rm theo,i}}{\sigma_{{\rm exp},i}}\right)^2 - 2\ln\mathcal{L}_{\rm calc}(\{y_{\rm calc}\}),$$

where

$$-2\ln\mathcal{L}_{\rm calc}(\{y_{\rm calc}\}) \equiv \begin{cases} 0, & \forall\, y_{{\rm calc},i} \in [y_{{\rm calc},i} \pm \delta y_{{\rm calc},i}] \\ \infty, & \text{otherwise} \end{cases}$$



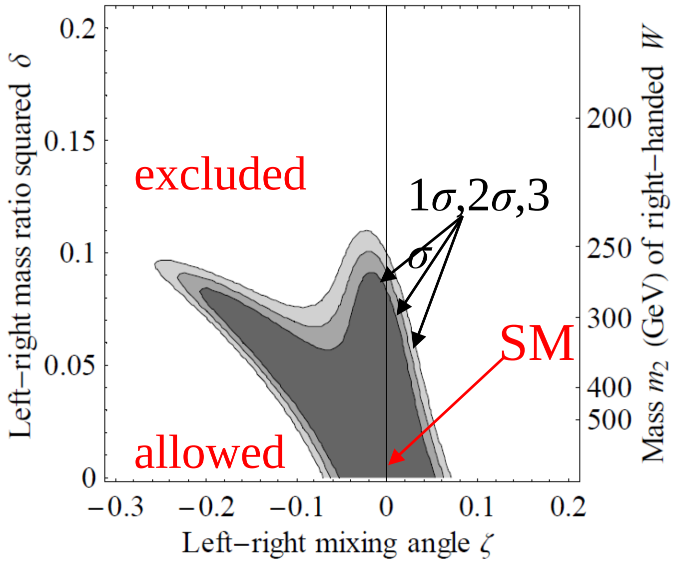
Reach for new physics

- A single parameter yields λ, multiple measurements yield V_{ud} and beyond
- CKM unitarity

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

  - Do neutrons and superallowed beta decays agree?

- Search for right-handed currents (250 GeV limit from n decay)
- Scalar and tensor couplings from B and b
  - Cirigliano 2012



Holeczek *et al.*, **Acta Phys.Polon. B42 (2011) 2493-2499**
arxiv 1303.5295 (2013)