Fundamental Neutron Physics IV

The Neutron Lifetime and Beta Decay

Geoffrey Greene
University of Tennessee / Oak Ridge National Laboratory

A free neutron decays

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

WHY?

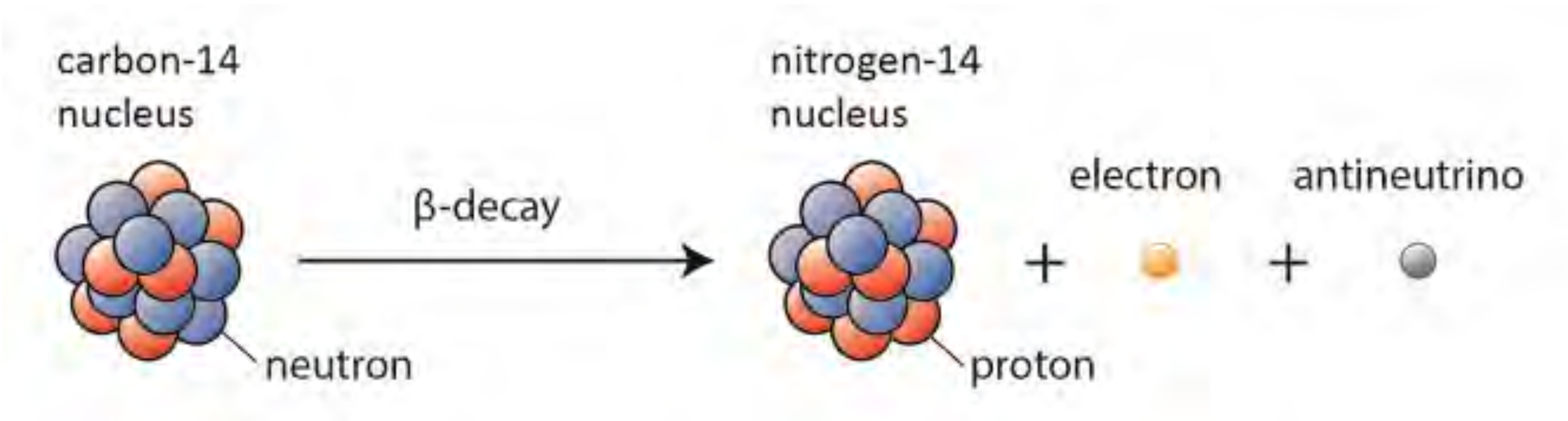
Because It Can!

No conservation laws are violated and,

$$m_n > m_p + m_e$$

Why don't neutrons decay inside nuclei?

Sometimes they do…it's called Nuclear Beta Decay:

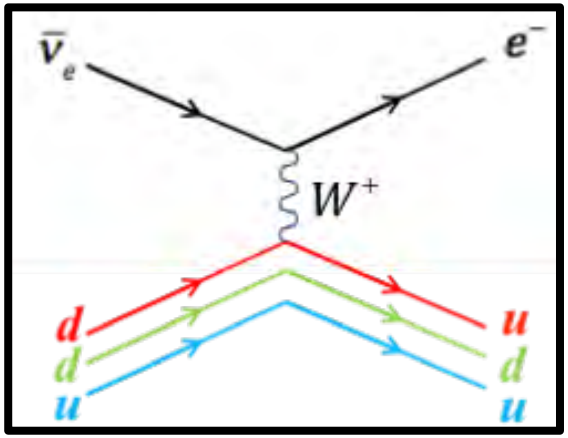


It happens when it is energetically allowed.

Variations in "mother-daughter" binding energies determine stability against beta decay.

Why is the Neutron Lifetime Interesting?

Neutron Decay is the Simplest "Semi-Leptonic" Weak Interaction*

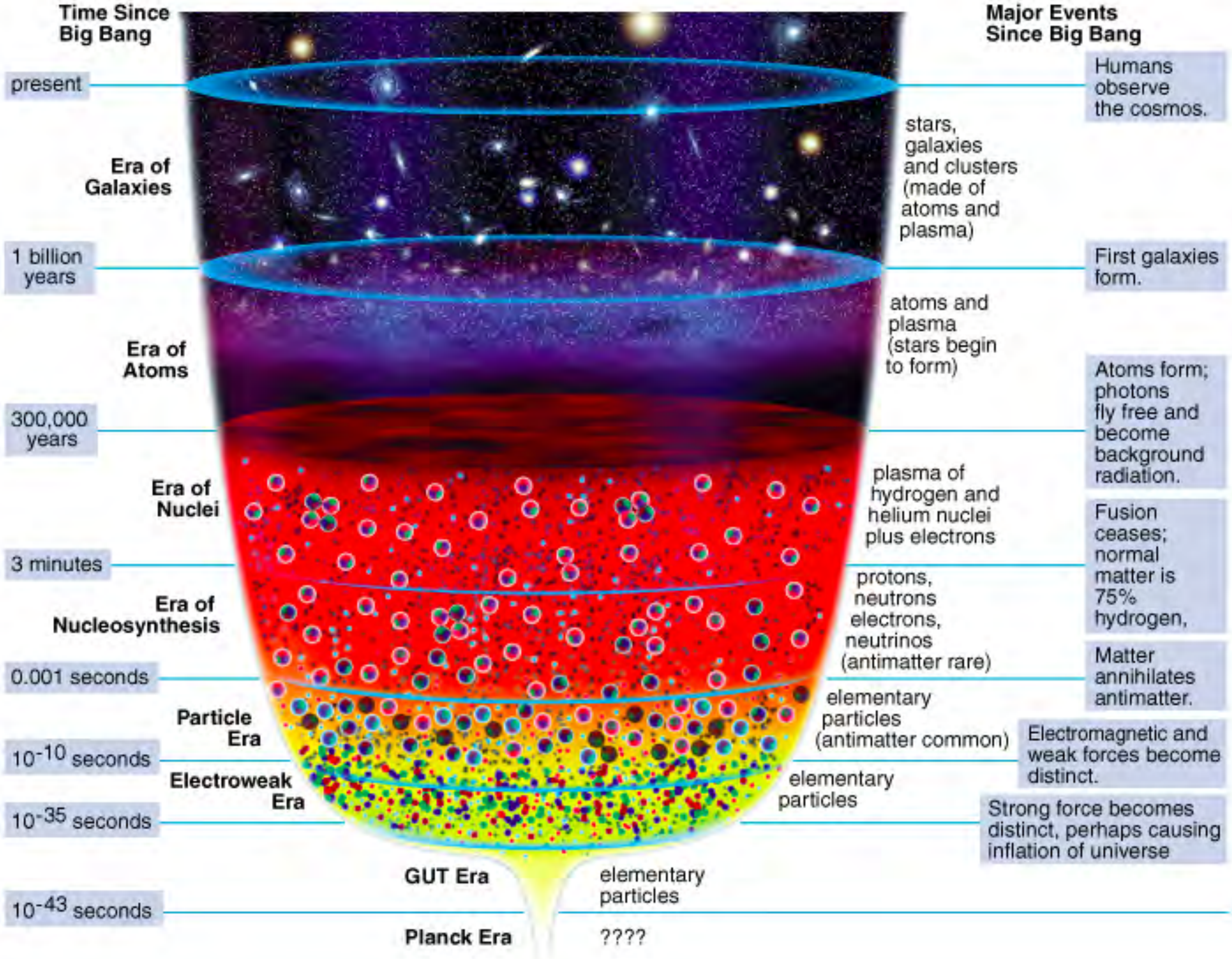


Some Processes with the same Feynman Diagram

Primordial element formation	$n + e^+ \longleftrightarrow p + \overline{\nu}_e$
	$p + e^- \longleftrightarrow n + \nu_e$
	$n \longrightarrow p + e^- + \overline{\nu}_e$
Solar cycle	$p + p \longrightarrow {}^2H + e^+ + \nu_e$
	$p + p + e^- \longrightarrow {}^2H + \nu_e$ etc.
Neutron star formation	$p + e^- \longrightarrow n + \nu_e$
Pion decay	$\pi^- \longrightarrow \pi^0 + e^- + \overline{\nu}_e{}'$
Neutrino detectors	$\nu_e{}' + p \longrightarrow e^+ + n$
Neutrino forward scattering	$\nu_e + n \longrightarrow e^- + p$ etc.

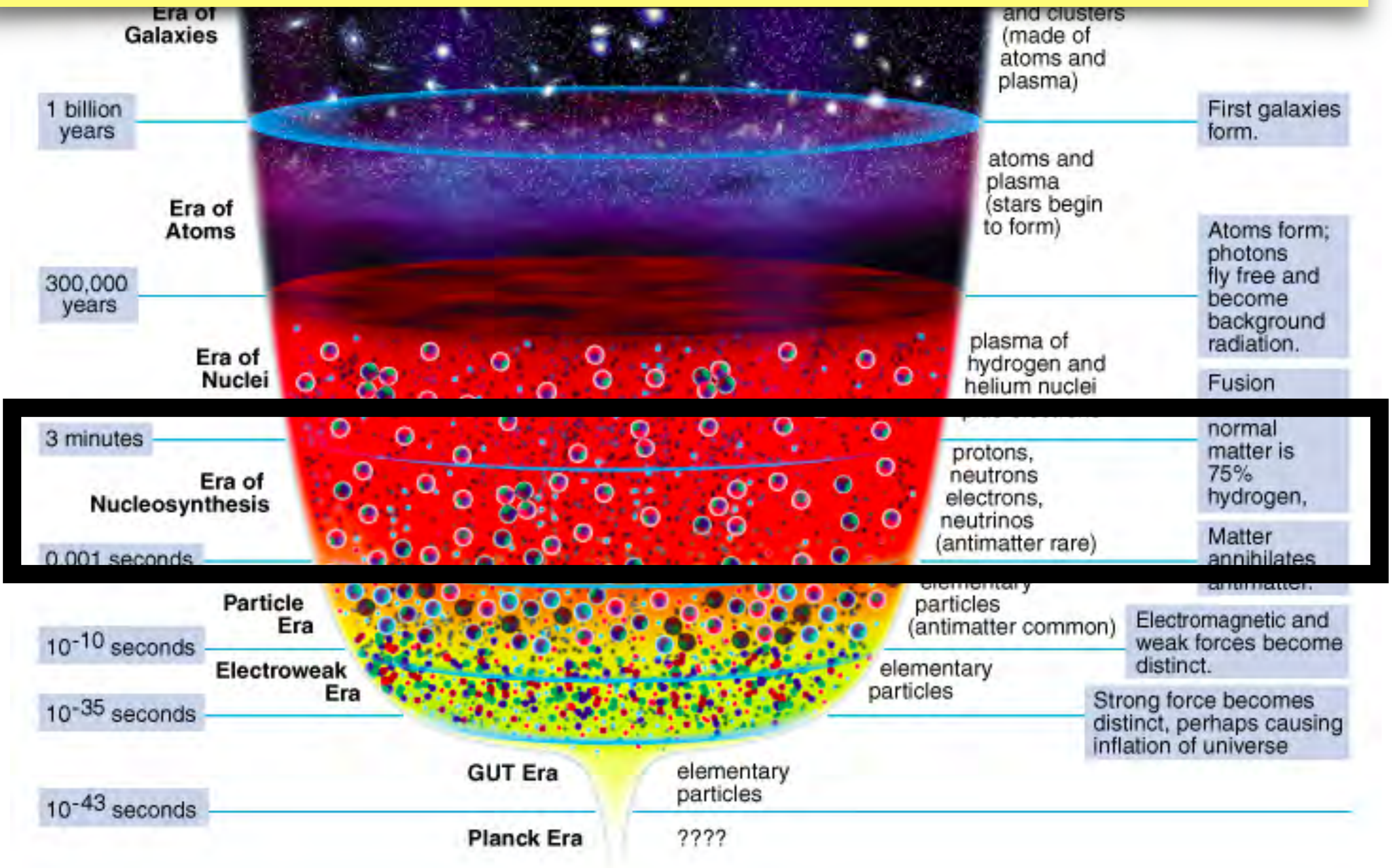
After D. Dubbers

The Neutron Lifetime and the Big-Bang


Time Since Big Bang
Major Events Since Big Bang
present
Humans observe the cosmos.
Era of Galaxies
stars, galaxies and clusters (made of atoms and plasma)
1 billion years
First galaxies form.
Era of Atoms
atoms and plasma (stars begin to form)
300,000 years
Atoms form; photons fly free and become background radiation.
Era of Nuclei
plasma of hydrogen and helium nuclei plus electrons
3 minutes
Fusion ceases; normal matter is 75% hydrogen,
Era of Nucleosynthesis
protons, neutrons electrons, neutrinos (antimatter rare)
0.001 seconds
Matter annihilates antimatter.
Particle Era
elementary particles (antimatter common)
10-10 seconds
Electromagnetic and weak forces become distinct.
Electroweak Era
elementary particles
10-35 seconds
Strong force becomes distinct, perhaps causing inflation of universe
GUT Era
elementary particles
10-43 seconds
Planck Era
????

The Era of Nuclear Physics

0.01 sec - 3 min

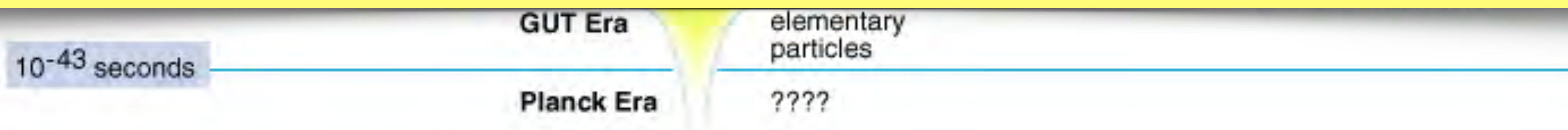


The Era of Nuclear Physics

0.01 sec - 3 min

Physics is Well Understood

- Only $n, p, e^+, e^-, \nu, \bar{\nu}, \gamma$ remain
- Density is "low"…only two body interactions
- Particle energies are MeV's
- Cross sections are well known



Neutron-Proton Equilibrium

time	temperature	
0.01s	***~10MeV***	***Era of Nuclear Physics Begins***

Neutrons and Protons are in thermal equilibrium through the processes:

$$\nu_e + n \rightleftarrows p^+ + e^-$$

$$e^+ + n \rightleftarrows p^+ + \nu_e$$

$$\boxed{\frac{N_n}{N_p} = e^{-(m_n - m_p)/kT}}$$

Neutrinos Decouple

time	temperature	
0.1s	**~1MeV**	**Neutrinos Decouple**

At this energy neutrino cross sections become so small that thermal equilibrium is no longer maintained.

$$\frac{N_n}{N_p} = \frac{1}{3}$$

If nothing else happened ALL the neutrons would decay via

$$n \to p + e^- + \overline{\nu}$$

The universe would end up with only protons (Hydrogen)

Nuclei Stable Against Photo-disassociation

time	temperature	
3min	***~100keV***	***Nucleosythesis begins***

Deuteron is now stable against photo disassociation e.g.

$$\gamma + d \rightarrow n + p$$

At this point there are 87% protons and 13% neutrons
Nuclei are quickly formed…

$$n + p \rightarrow \gamma + d$$

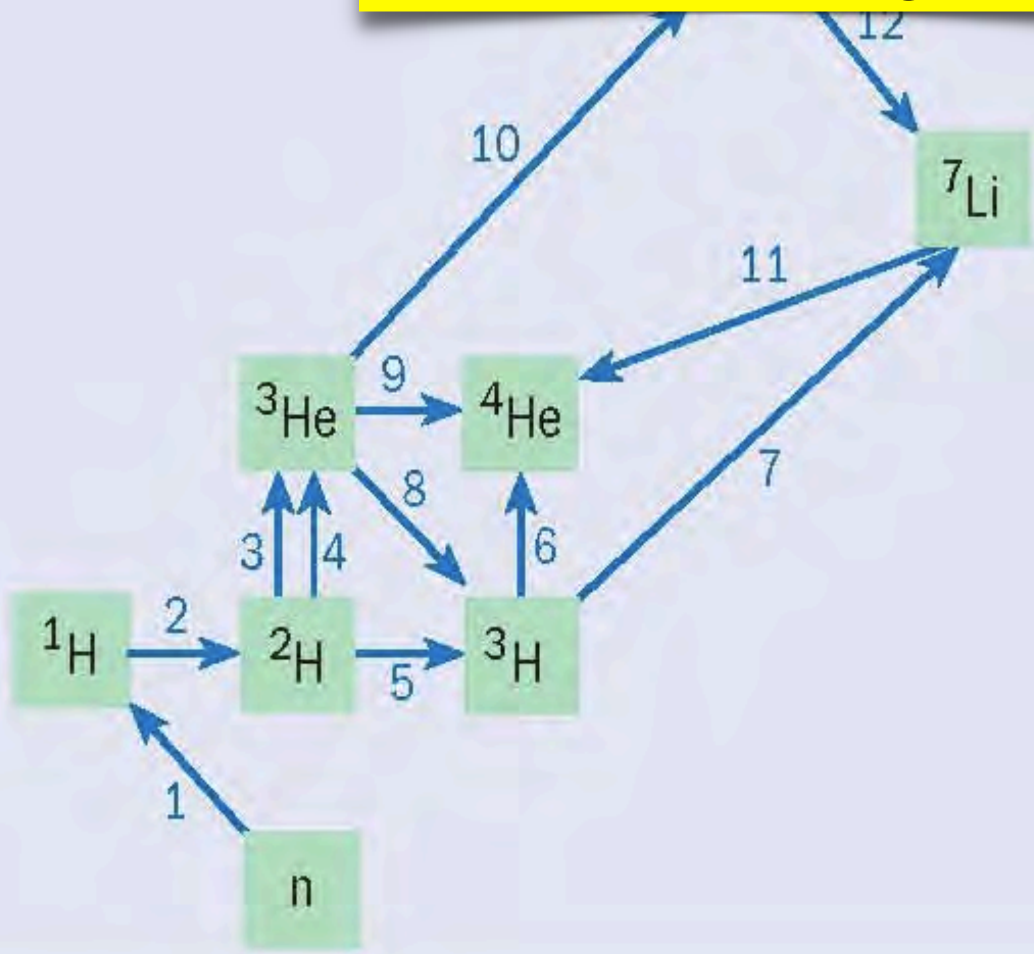
$$d + n \rightarrow {}^{3}He...$$

3½ min ***Nucleosynthesis Ends***

All neutrons have been "used up" making ^{4}He.

Important Reactions in Big Bang Nucleosynthesis

Neutron decay is the “rate determining” step



1. $n \rightarrow {}^1H + e^- + \bar{\nu}$
2. ${}^1H + n \rightarrow {}^2H + \gamma$
3. ${}^2H + {}^1H \rightarrow {}^3He + \gamma$
4. ${}^2H + {}^2H \rightarrow {}^3He + n$
5. ${}^2H + {}^2H \rightarrow {}^3H + {}^1H$
6. ${}^2H + {}^3H \rightarrow {}^4He + n$
7. ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$
8. ${}^3He + n \rightarrow {}^3H + {}^1H$
9. ${}^3He + {}^2H \rightarrow {}^4He + {}^1H$
10. ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11. ${}^7Li + {}^1H \rightarrow {}^4He + {}^4He$
12. ${}^7Be + n \rightarrow {}^7Li + {}^1H$

Image courtesy Ken Nollet

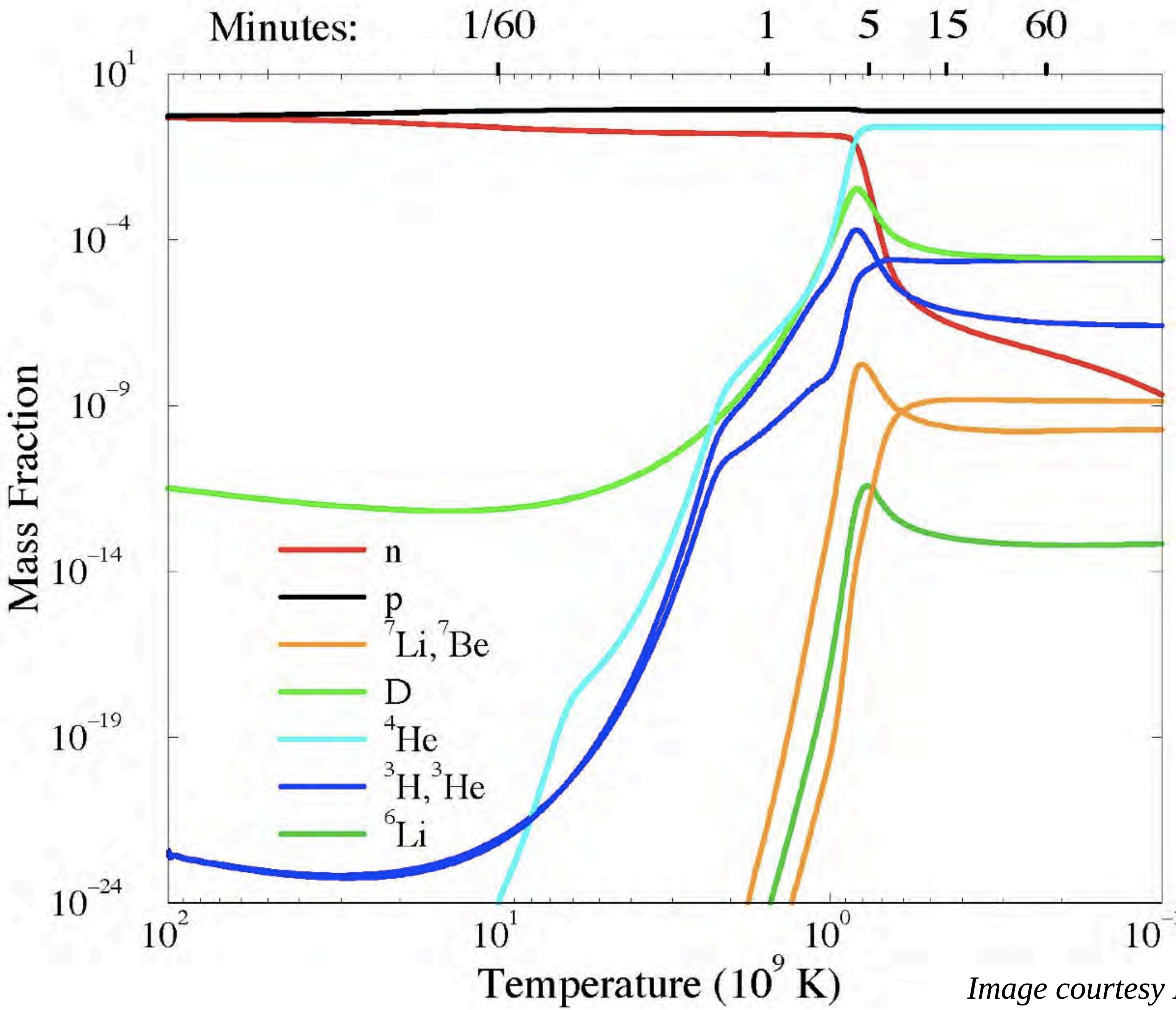


Image courtesy Ken Nollet

"After 3 minutes, the Helium to Hydrogen ratio was set…

Nothing of interest has happened since."

Steven Weinberg

The Cosmic He/H Ratio Depends upon three quantities:

1) The Cooling rate of the Universe

Given by the heat capacity of the Universe
Determined mainly by the number of "light particles" (m ≤ 1 MeV)
Includes photons, electrons (positrons), neutrinos (x3)

2) The Rate at which Neutrons are decaying

The neutron lifetime

3) The rate at which nuclear interactions occur

Determined by the the logarithm of the density of nucleons (baryons)*

**Because of expansion, the "absolute" baryon density is decreasing with time so the density is scaled as the ratio of matter to photons.*

The Parameters of Big Bang Nucleosynthesis

$$Y_p = 0.264 + 0.023\log\eta_{10} + 0.018(\tau_n - 10.28)$$

Cosmic Helium Abundance

Cosmic Baryon Density

Neutron Lifetime in Minutes

We can "invert" this line of reasoning. If we measure the Helium Abundance and the Neutron Lifetime, we can determine the density of "ordinary" matter in the universe.

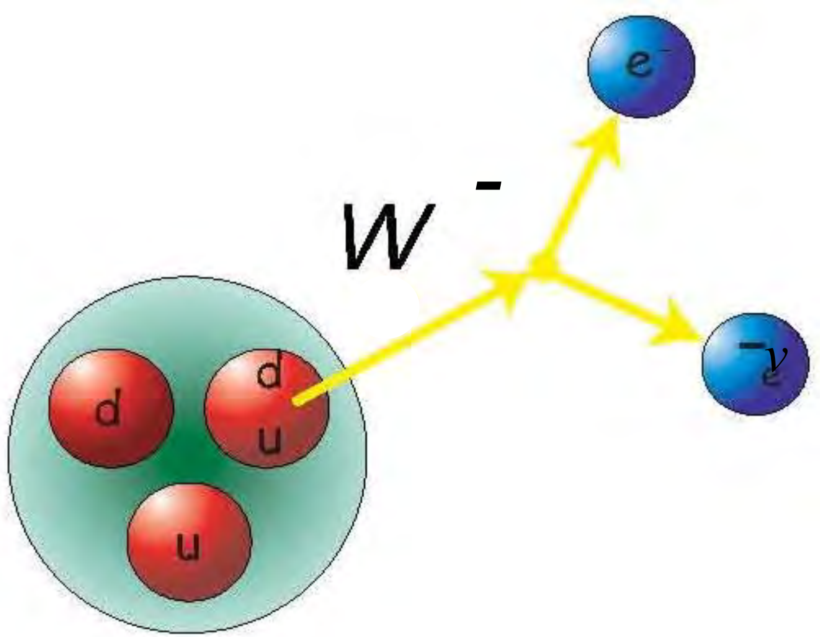
$$\log \eta_{10} = \left[0.264 - Y_P + 0.018(\tau_n - 10.28) \right] / 0.023$$

Cosmic Baryon Density

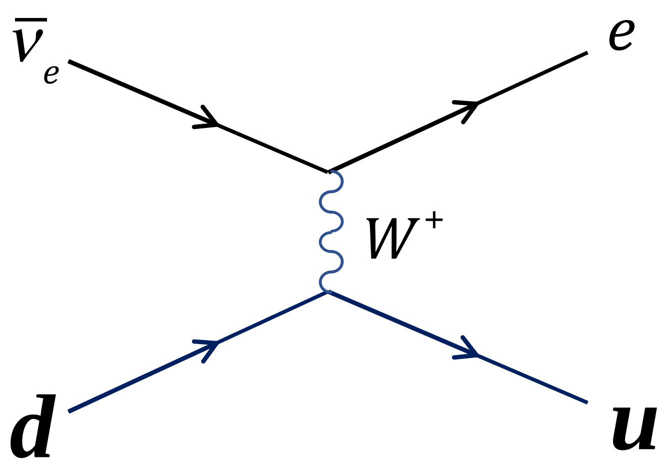
Cosmic Helium Abundance

Neutron Lifetime in Minutes

Introduction to the Theory of Neutron Beta Decay



"Ideal" View of Semi-Leptonic Weak Interaction

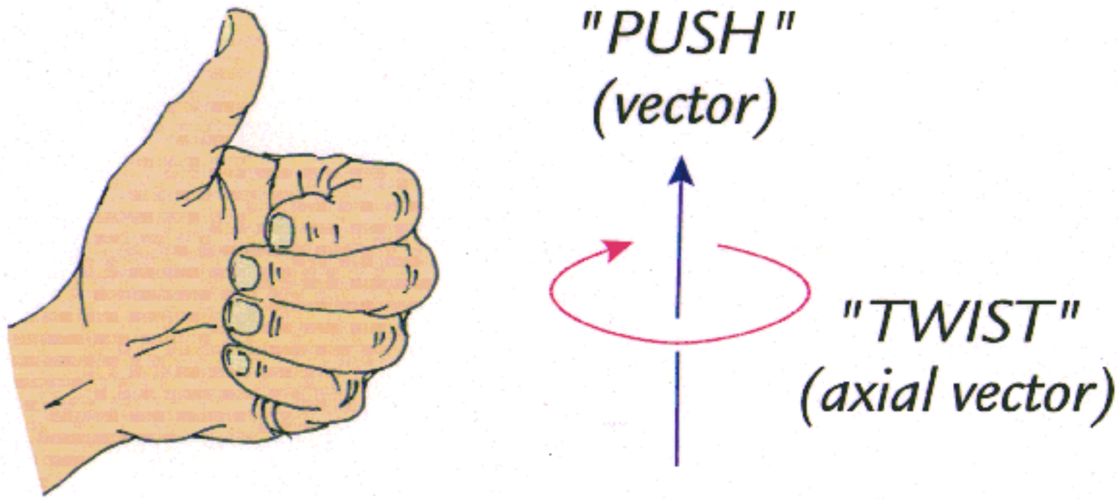


Construct a Current-Current Interaction that couples a down quark to an up quark, and an electron to antineutrino

$$\langle \bar{\nu}_e | \mathbf{H}_{Weak} | e^- \rangle \langle d | \mathbf{H}_{Weak} | u \rangle$$

How to include Parity Violation?

“Handedness”

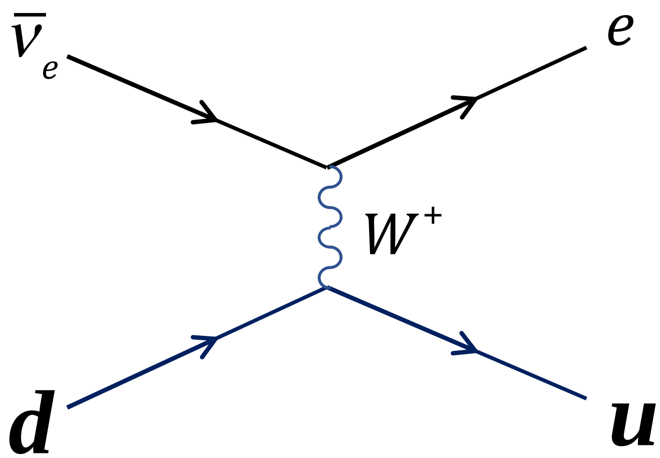


A “Handed” Interaction Results From:

A VECTOR	–	*“V”*	*“Push”*
and			
An Axial Vector	–	*“A”*	*“Twist”*

The relative signs of the vector and axial-vector determines the “handedness

The "Ideal" Standard Model Quark-Lepton Interaction



"vector" operator → **"axial-vector" operator**

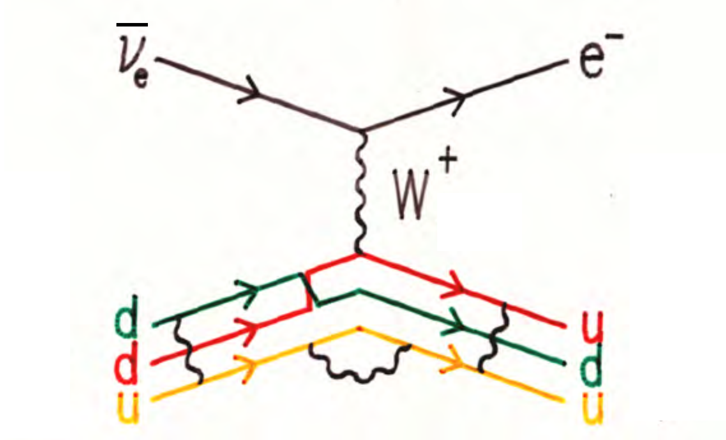
$$H_{Weak} = G_{Weak} \langle \nu_e | \gamma^\mu - \gamma^\mu \gamma^5 | e^- \rangle \langle d | \gamma^\mu - \gamma^\mu \gamma^5 | u \rangle$$

"V-A"

Vector "minus" Axial Vector Means a "Left-Handed" Interaction

Neutron Decay is a Bit More Complicated

Strongly interacting quarks within the neutron modify the relative size of the vector and axial vector couplings



The strong interaction conserves parity.

It does not change the relative phase (handedness).

In the low energy limit, the Hamiltonian is still quite simple:

$$H_{Weak} = G_{Weak} \langle \nu_e | \gamma^\mu - \gamma^\mu \gamma^5 | e^- \rangle \langle d | g_V \gamma^\mu - g_A \gamma^\mu \gamma^5 | u \rangle$$

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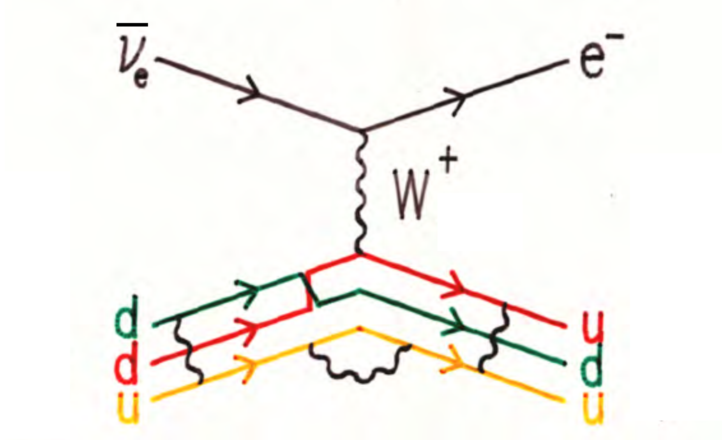

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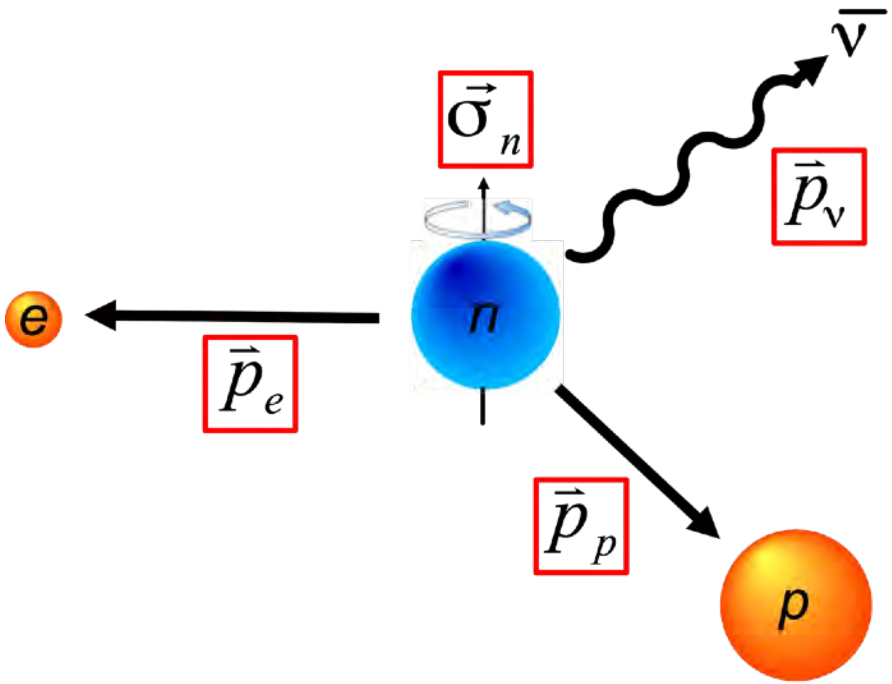
If Neutron Decay is Purely Left-Handed (V-A), only two parameters completely describe it

Phenomenology of Neutron Beta Decay

Momentum and Angular Momentum Must Be Conserved



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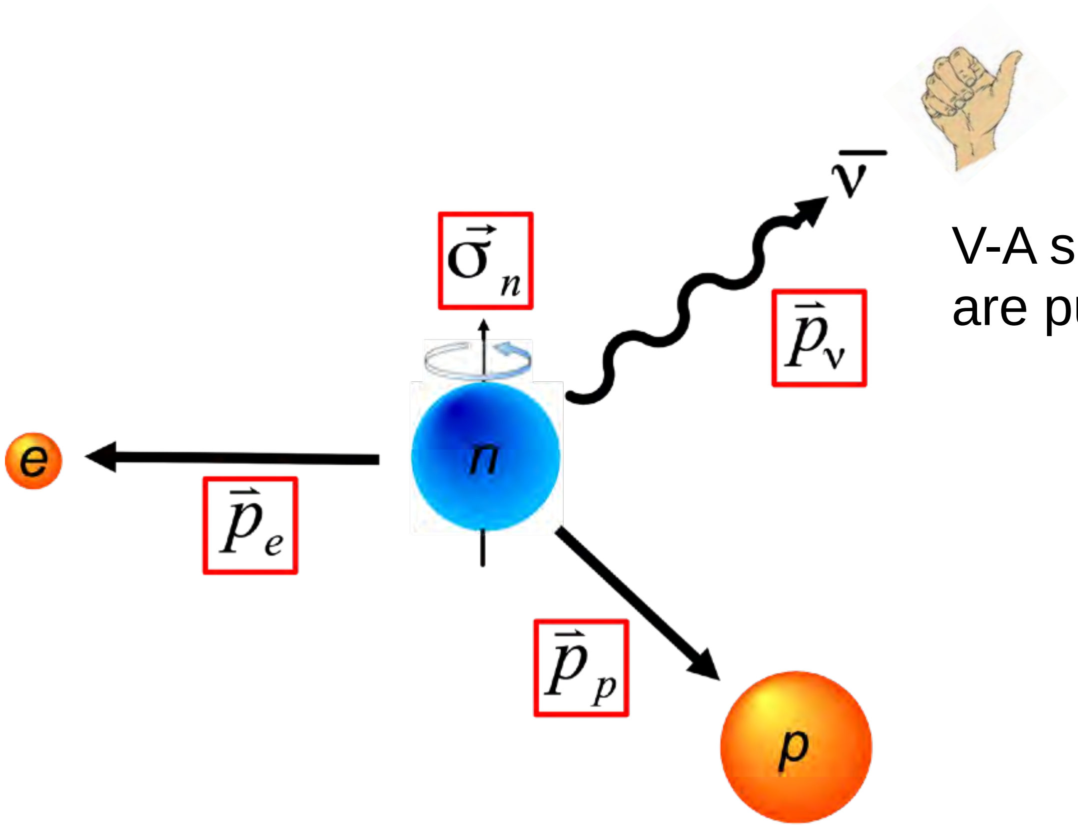


V-A says that anti-neutrinos are purely "right-handed" with:

$$\vec{\sigma} \cdot \vec{p} = 1$$

Conservation of linear and angular momentum implies that there are strong correlations between the initial neutron spin and decay particle momenta.

Correlations in Neutron Decay

$$dW \propto \frac{1}{\tau_n} F(E_e) \left[1 + a \frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\upsilon}{E_e \cdot E_\upsilon} + b \frac{m_e}{E_e} + A \frac{\sigma_n \cdot \boldsymbol{p}_e}{E_e} + B \frac{\sigma_n \cdot \boldsymbol{p}_\upsilon}{E_\upsilon} + \ldots \right]$$

(Jackson, Treiman, Wyld, 1957)

Correlations in Neutron Decay

Pure V-A, low energy limit

$$dW \propto \frac{1}{\tau_n} F(E_e) \left[1 + a \frac{\boldsymbol{p}_e \cdot \boldsymbol{p}_\upsilon}{E_e \cdot E_\upsilon} + b \frac{m_e}{E_e} + A \frac{\sigma_n \cdot \boldsymbol{p}_e}{E_e} + B \frac{\sigma_n \cdot \boldsymbol{p}_\upsilon}{E_\upsilon} + \dots \right]$$

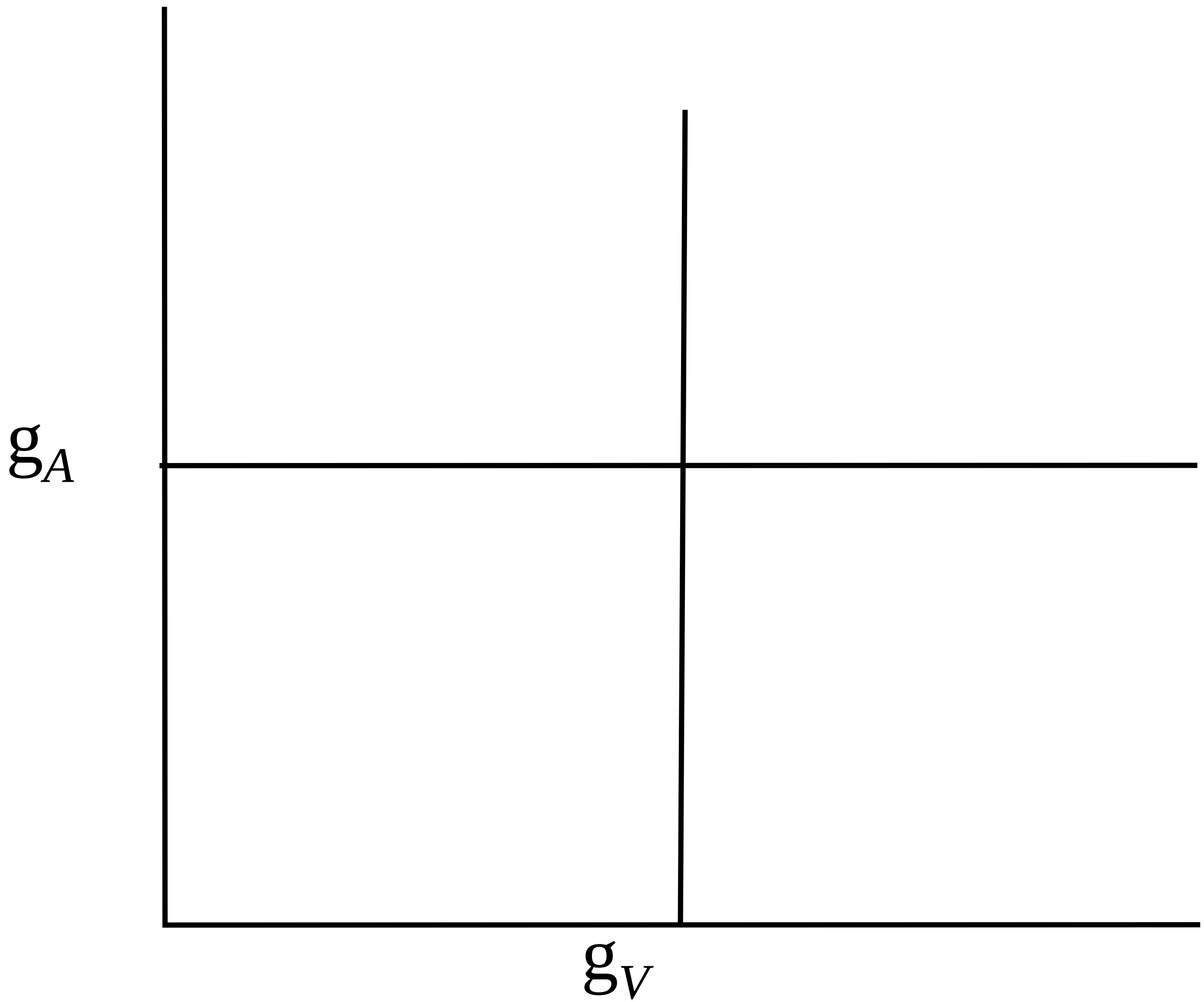
$$\frac{1}{\left(G_V^2 + 3G_A^2\right)} \qquad \frac{1 - \left(\frac{G_A}{G_V}\right)^2}{1 - 3\left(\frac{G_A}{G_V}\right)^2} \qquad b = 0 \qquad -2\frac{\left(\frac{G_A}{G_V}\right)^2 + \left(\frac{G_A}{G_V}\right)}{1 - 3\left(\frac{G_A}{G_V}\right)^2} \qquad -2\frac{\left(\frac{G_A}{G_V}\right)^2 - \left(\frac{G_A}{G_V}\right)}{1 - 3\left(\frac{G_A}{G_V}\right)^2}$$

Neutron beta decay measurements give:

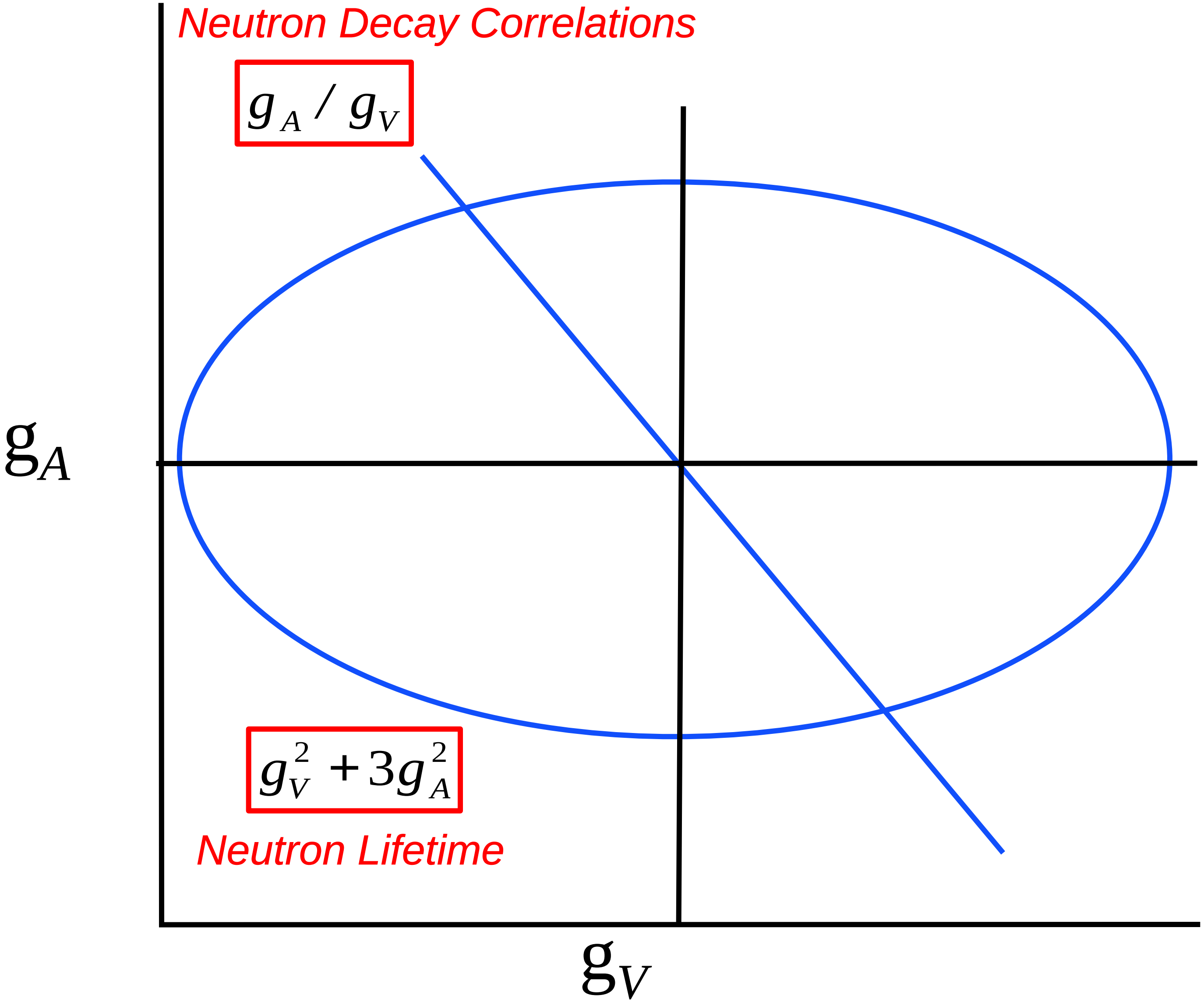
$$G_A^2 + 3G_V^2$$

$$G_A / G_V$$

(Jackson, Treiman, Wyld, 1957)



g_A
g_V


Neutron Decay Correlations
g_A / g_V
g_A
$g_V^2 + 3g_A^2$
Neutron Lifetime
g_V

The “Conserved Vector Current” - CVC

- *Electric Charge is a conserved quantity*

- *“Electroweak” theory provides a common framework for Electromagnetism and the Weak Interaction*

- *Electric Charge Conservation implies conservation of "something else” in the Weak sector.*

- *That “something else” is the Weak “Vector Current”*

Conservation of the Vector Current implies that the vector coupling constant g_V is same for all nuclear interactions!

n.b. g_A is not similarly constrained but, there are certain nuclear decays ($0^+ \rightarrow 0^+$) where g_A must be identically zero

Sharing the Weak Charge Between Quarks

The eigenstates of the weak interaction are not the quark states

Weak Interaction Basis States

Cabbibo-Kobayshi-Maskawa Matrix

Quark States

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

The C-K-M matrix must be unitary or there will be hell to pay!

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

Kaon Physics give V_{us} $(V_{ub} << 1)$

Sharing the Weak Charge Between Quarks

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Weak Interaction Basis States

Cabbibo-Kobayshi-Maskawa Matrix

Quark States

$$g_V = V_{ud} G_{Fermi}$$

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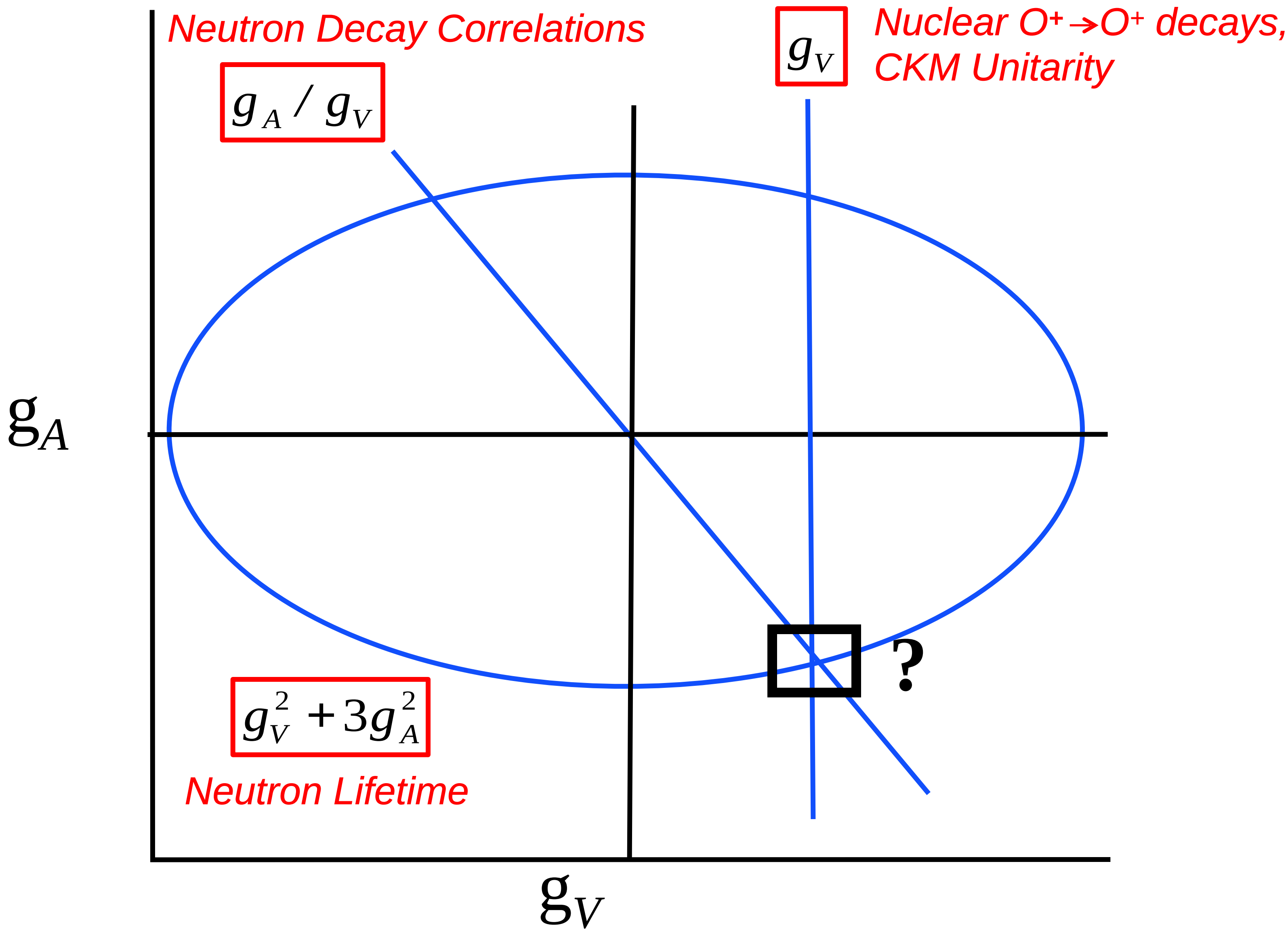
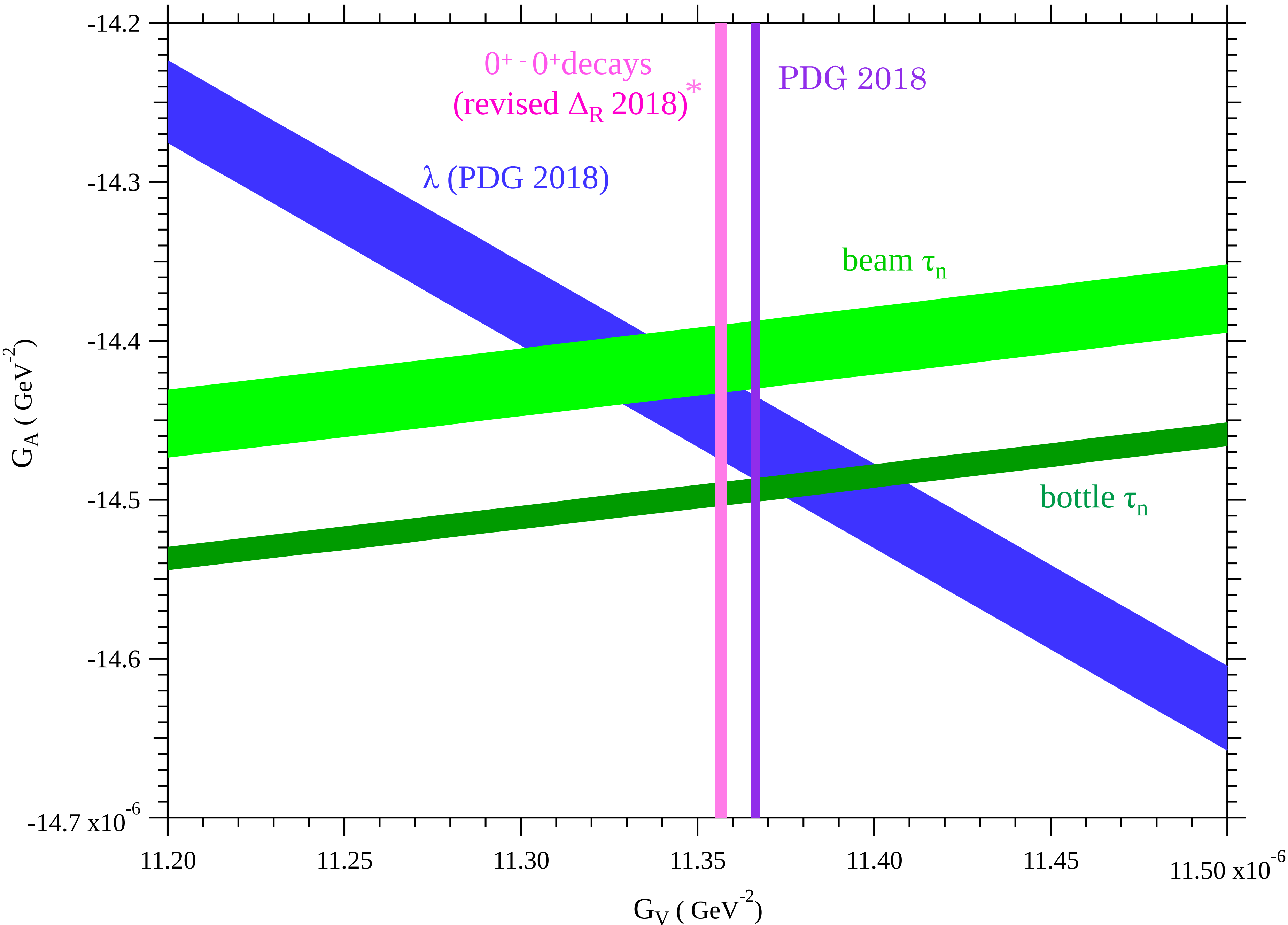


Neutron Decay Correlations
g_A / g_V
g_V
Nuclear $0^+ \rightarrow 0^+$ decays,
CKM Unitarity
g_A
$g_V^2 + 3g_A^2$
Neutron Lifetime
?
g_V



*Seng, et al, https://arxiv.org/abs/1807.10197

Image courtesy Fred Weidtfeldt

Measuring the Neutron Lifetime

Two Approaches to Measuring a Lifetime

1. Observation time is longer than (or comparable to) the lifetime.

STEP 1: Determine $N(0)$ number unstable nuclei in a sample at $t=0$, and
STEP 2: Determine $N(t)$ number unstable nuclei in a sample at $t=t$.

$$N(t) = N(0)e^{-t/\tau}$$

2. Observation time is much shorter than the lifetime.

STEP 1: Determine N, the number of unstable nuclei in a sample, and
STEP 2: Determine the rate of decays $\dot{N}$.

$$\frac{dN}{dt} = -\frac{N}{\tau}$$

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Bottle Method

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Beam Method

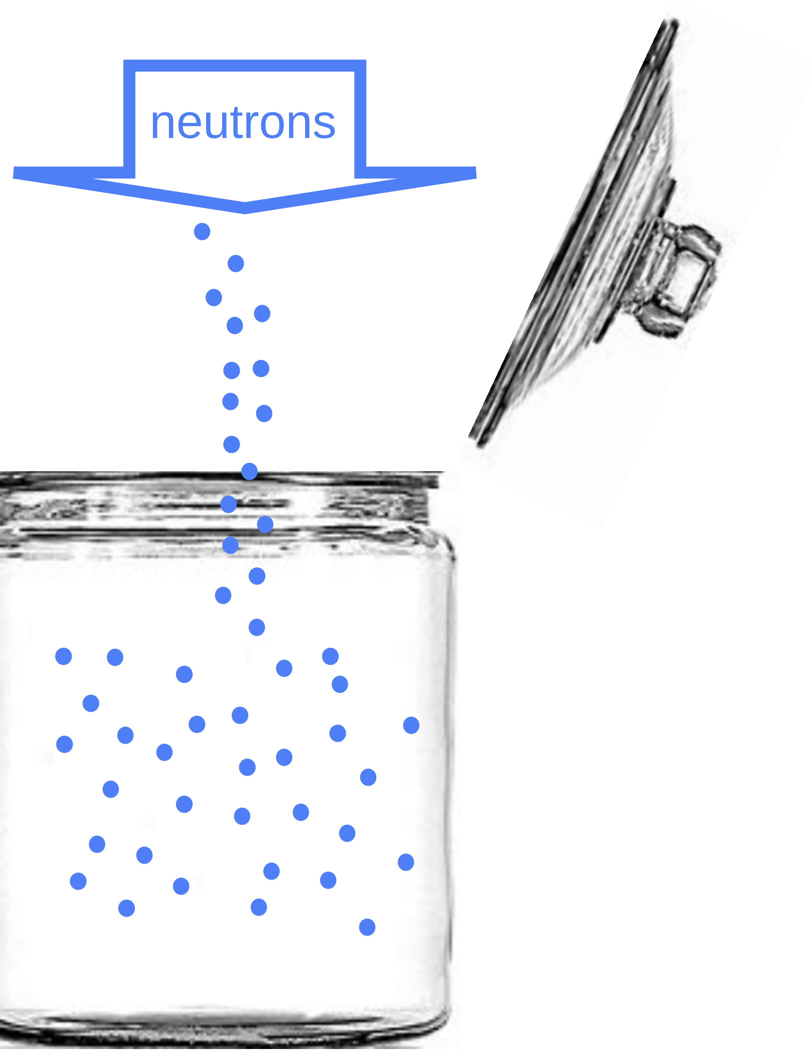
The Bottle Method

The "Bottle" Method

Step 1. Get one "Neutron Bottle"

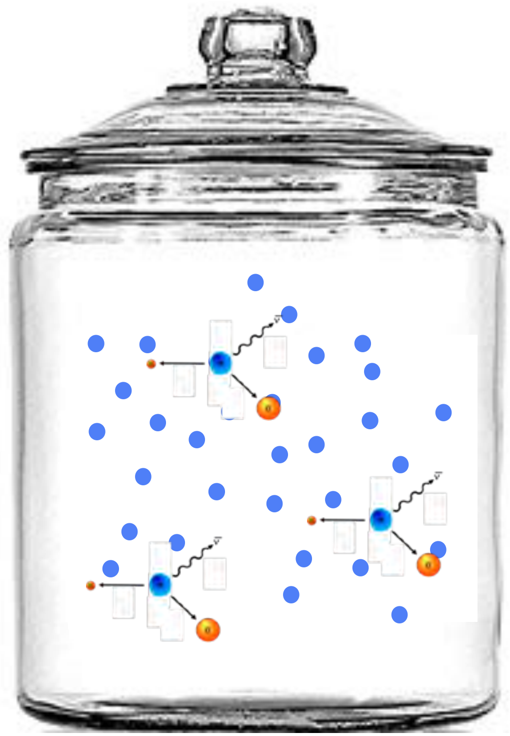
The "Bottle" Method

Step 2. Fill with neutrons



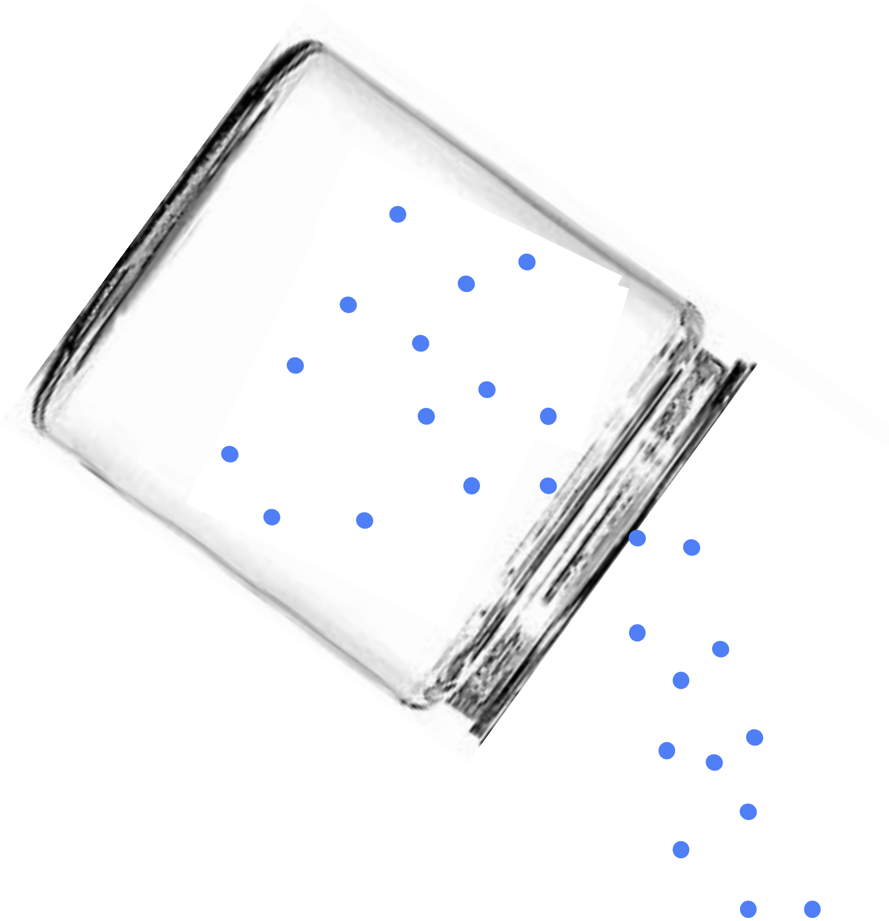
The "Bottle" Method

Step 3. Let neutrons decay for time "t"



The "Bottle" Method

Step 4. Count remaining neutrons



The “Bottle” Method

Step 1. Get one “Neutron Bottle”

“Ultracold” Neutrons

Neutrons with extremely low energy:

$E_k \leq 100$ neV $\quad\quad v \leq 5$m/s

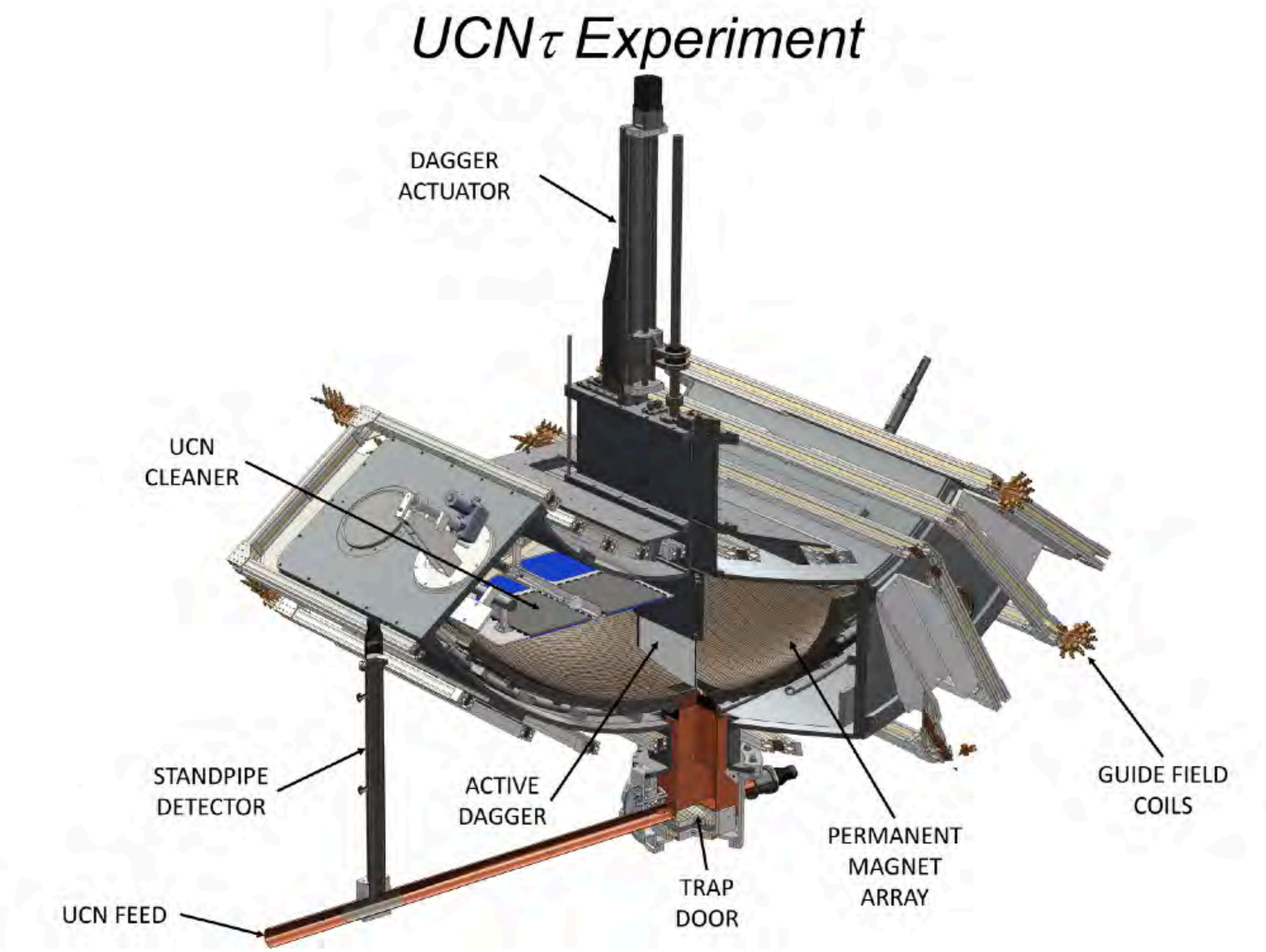
can be confined in material, gravitational, or magnetic “bottles”

with confinement lifetimes much greater than the beta decay lifetime.

Such neutrons are called “ultracold” with a “temperature” of a few mK

This is far below the energies normally
available from a high flux neutron source

The LANL UCN τ Magnetic Bottle Experiment



877.7 ± 0.7 (stat) +0.3/–0.1 (sys) seconds

Pattie, et al, Science,10.1126/aan8895 (2018)

A Challenge with Bottles

Loss rate in a Bottle can also come from other Mechanisms.

Neutrons can be lost to absorption on walls, up-scattering on walls, escape through gaps in the wall,…

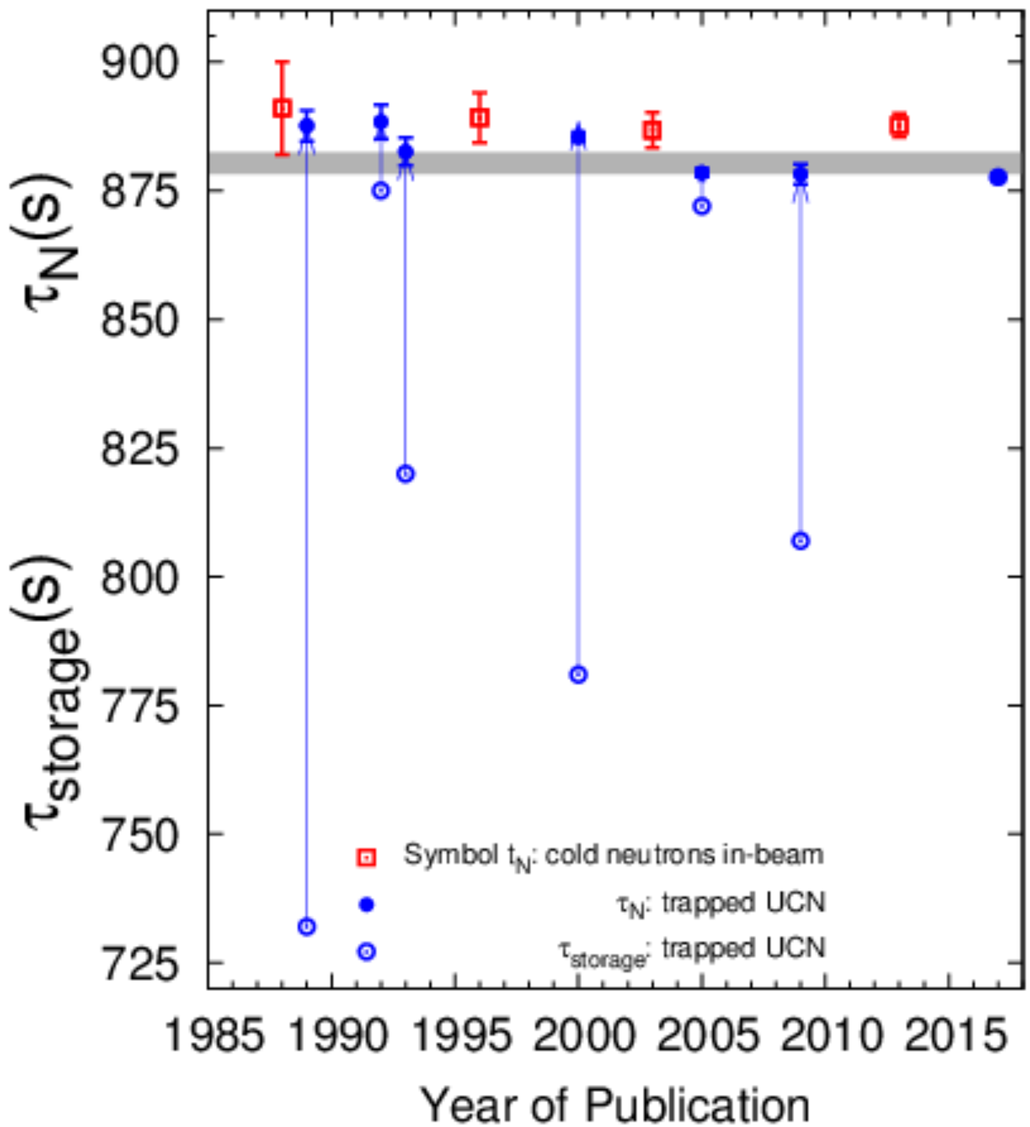
$$\frac{1}{\tau_{\text{exp}}} = \frac{1}{\tau_n} + \frac{1}{\tau_{absorb}} + \frac{1}{\tau_{escape}} + \frac{1}{\tau_{up-scatter}} + \ldots^{*}$$

What we want (τ_n)

What we measure (τ_{exp})

**True if all loss rates are constant… which is not necessarily true.*

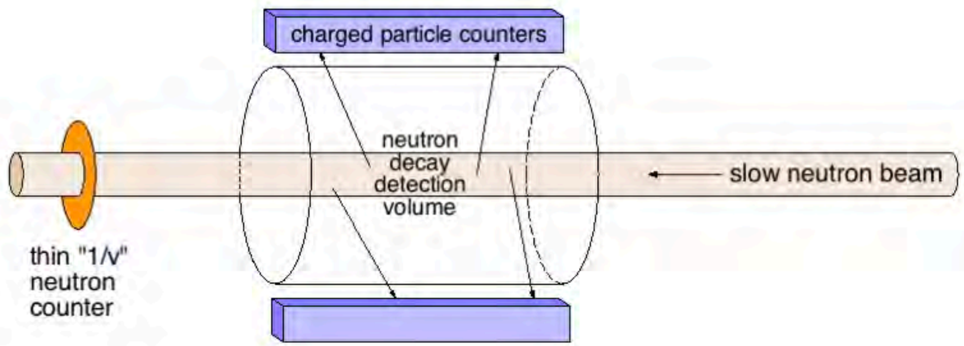
Adjustment for Bottle Losses



Courtesy N.Fomin

Measuring the Neutron Lifetime
with a Neutron Beam

In-Beam Neutron Lifetime Determination



Neutron Decay Rate $\Gamma = \frac{N}{\tau}$ $N=$ *average number of neutrons in detector*

Must make several ***ABSOLUTE*** *measurements:*

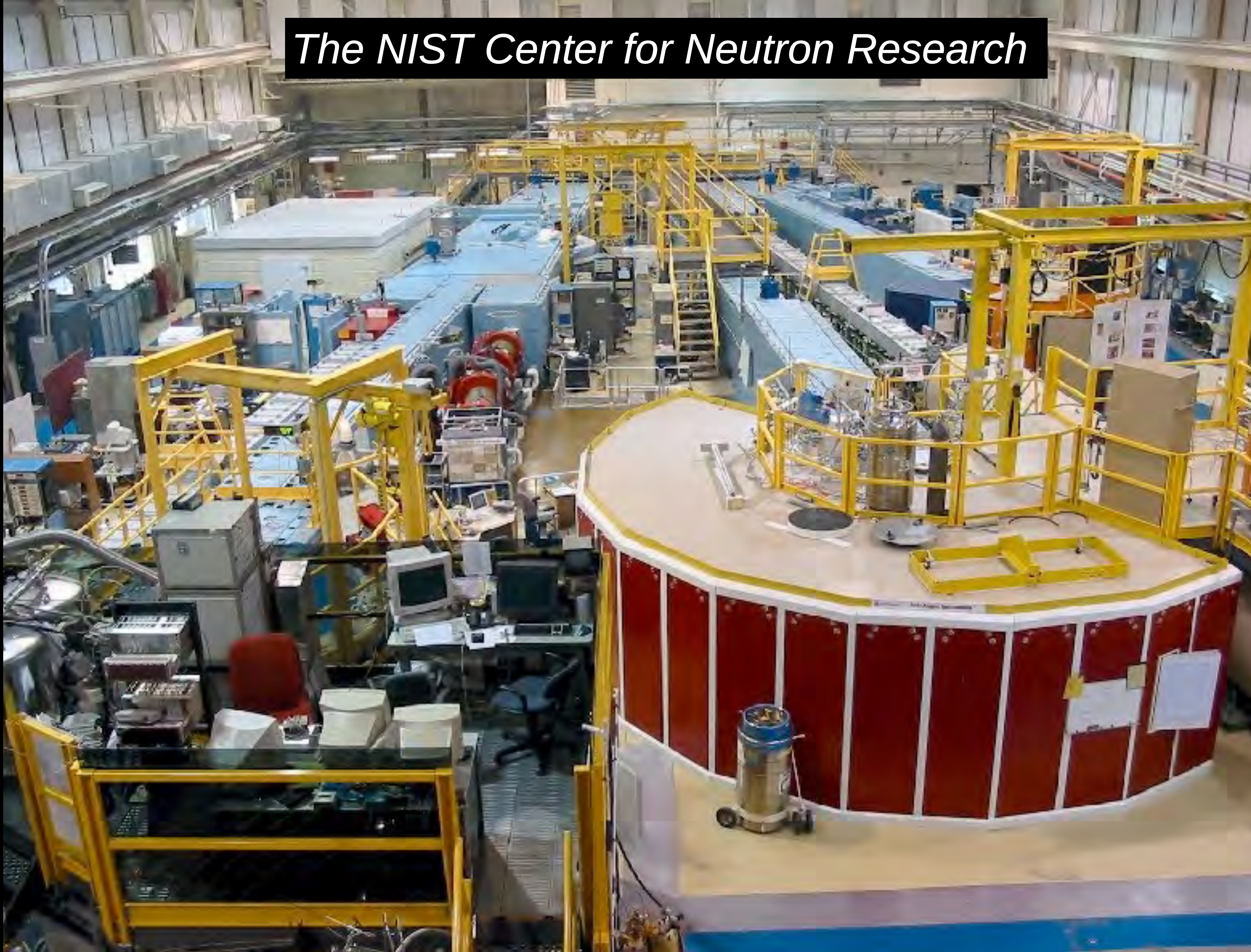
1. ***Decay Rate***
2. ***Detection Fiducial Volume***
3. ***Detector Efficiency***
4. ***Neutron Density in Beam (flux weighted by 1/v)***

The Beam Method at NIST

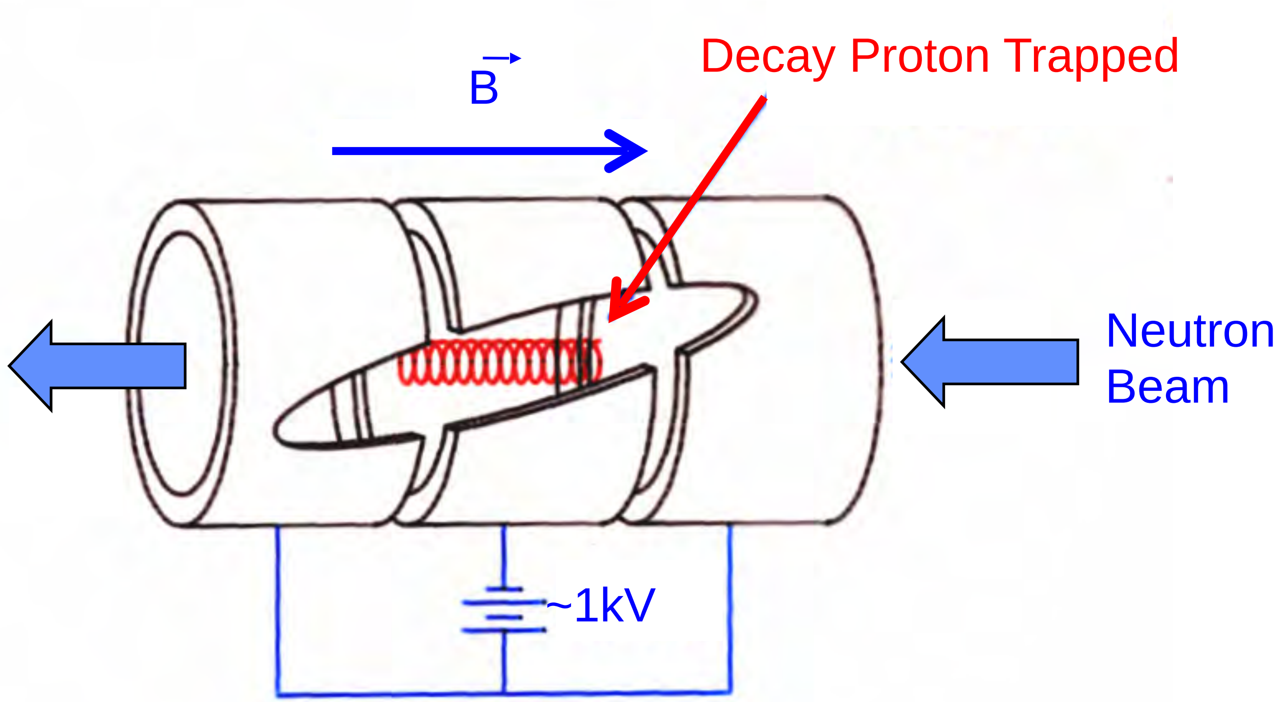
The NIST Center for Neutron Research

Gaithersburg, Md.

The NIST Center for Neutron Research



Decay Protons are Trapped in the
NIST "Beam" Neutron Lifetime Experiment



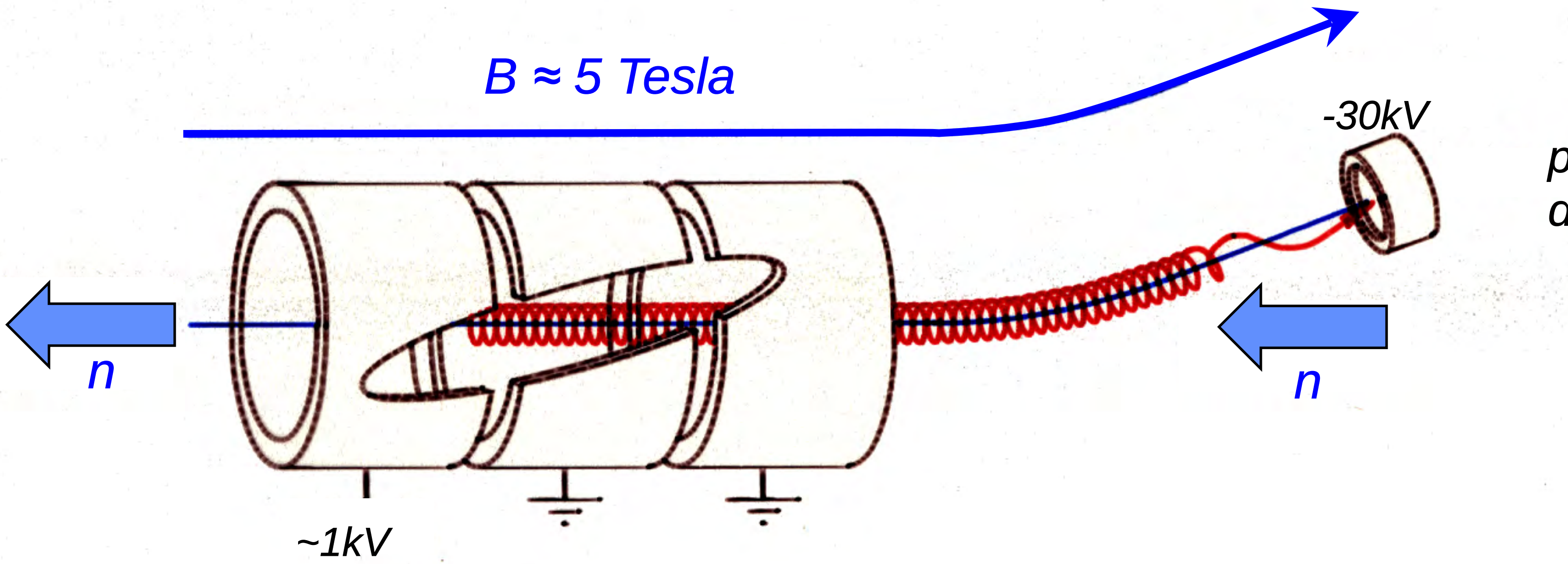
Uncharged neutrons pass through a charged particle "Penning" Trap.

Decay protons have low energy (E_p<750eV) and are trapped in a combination of electric and magnetic fields.

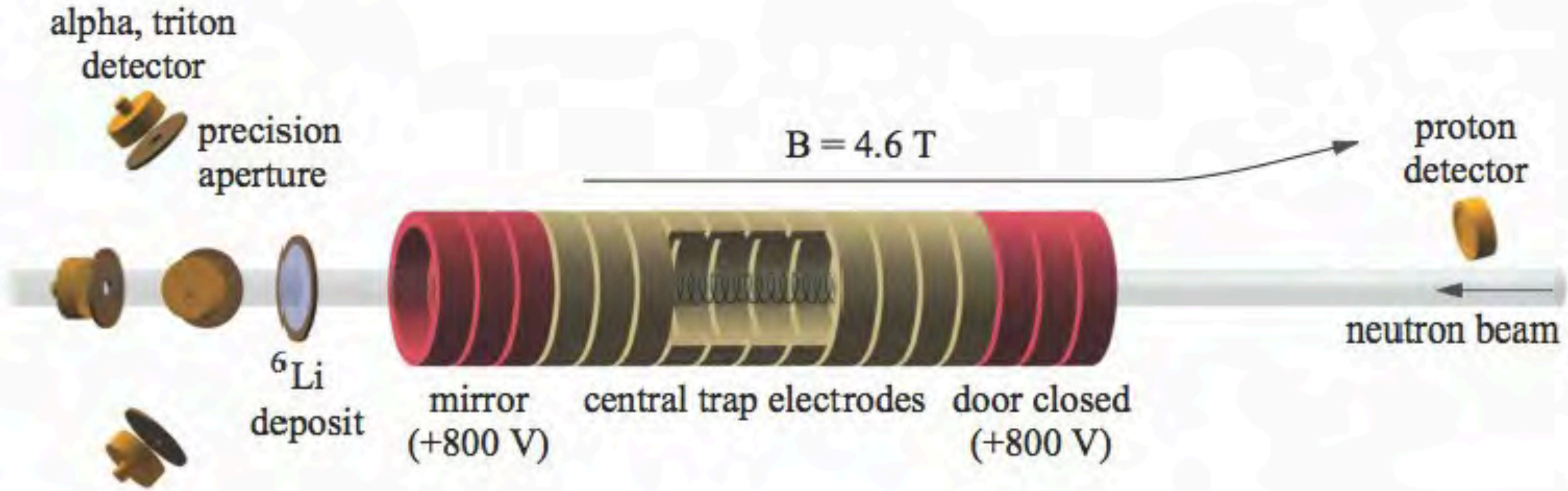
Neutrons spend a short time in trap so probability of decay is ~10^{-7}.

Problem: The decay protons have low energy and are stuck in the trap

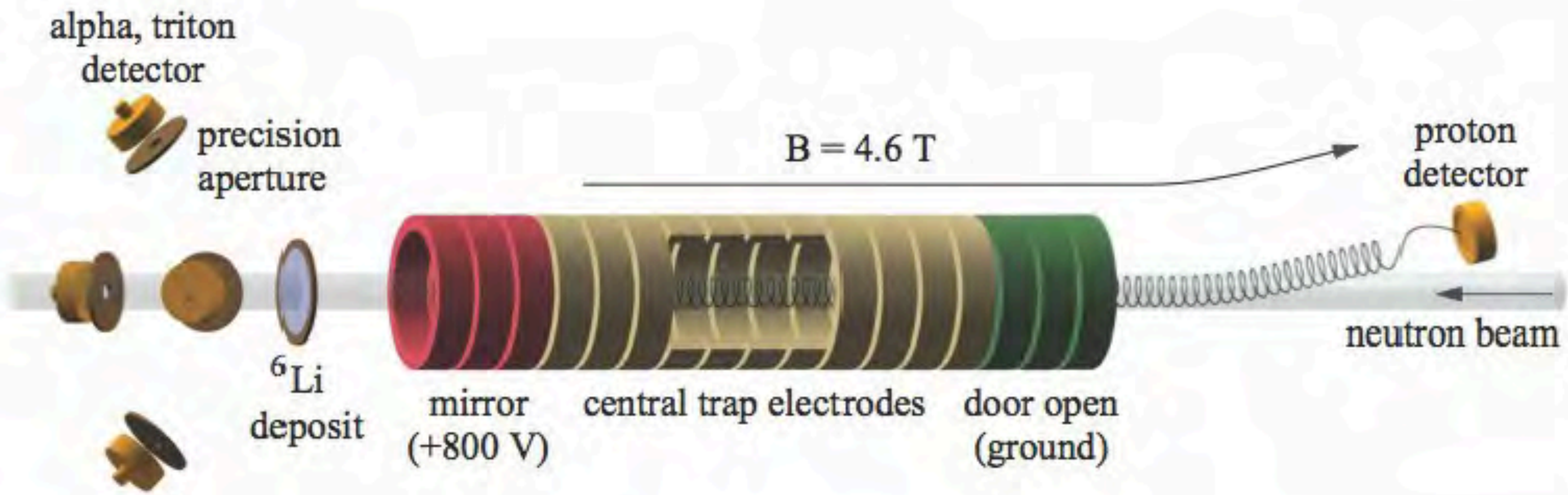
Solution: The trap is "opened" and the emerging protons are accelerated and detected in off axis detector



Trap Cycle ~10ms

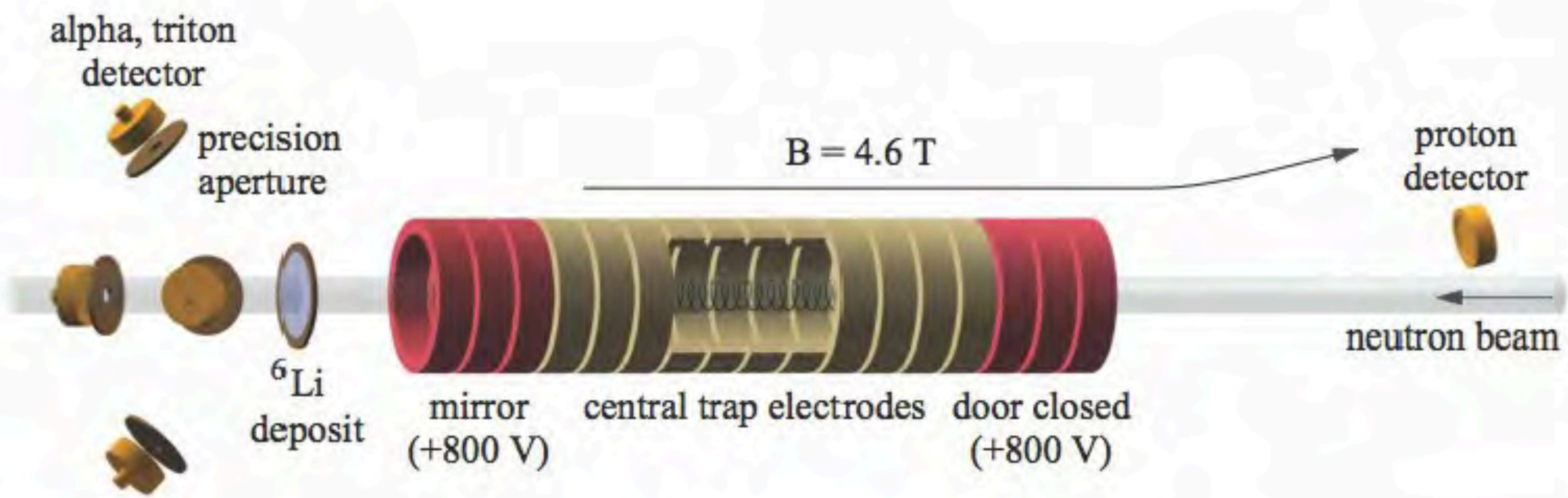


Count Cycle ~100us



Only count during count cycle
S/N increase by x100 or more

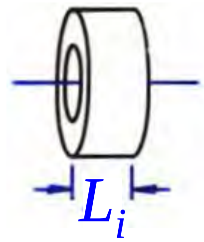
What is the detection volume?



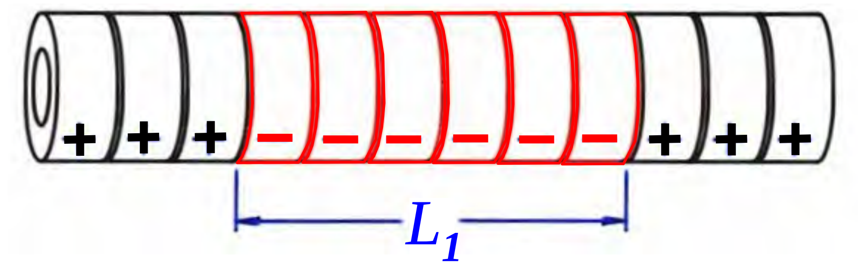
Determination of detection volume (i.e. length) requires knowledge of trap "end-effects"

Method of "Virtual" Trap

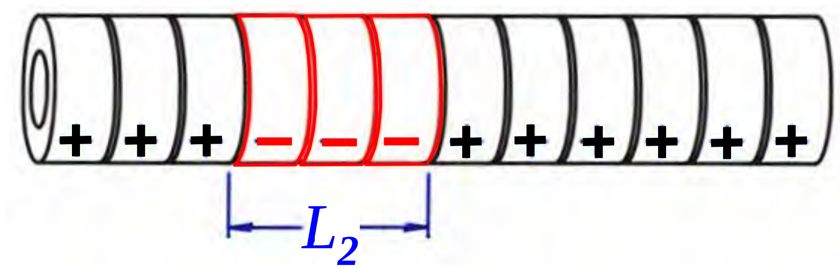
Step 1. Construct trap elements with well known length:



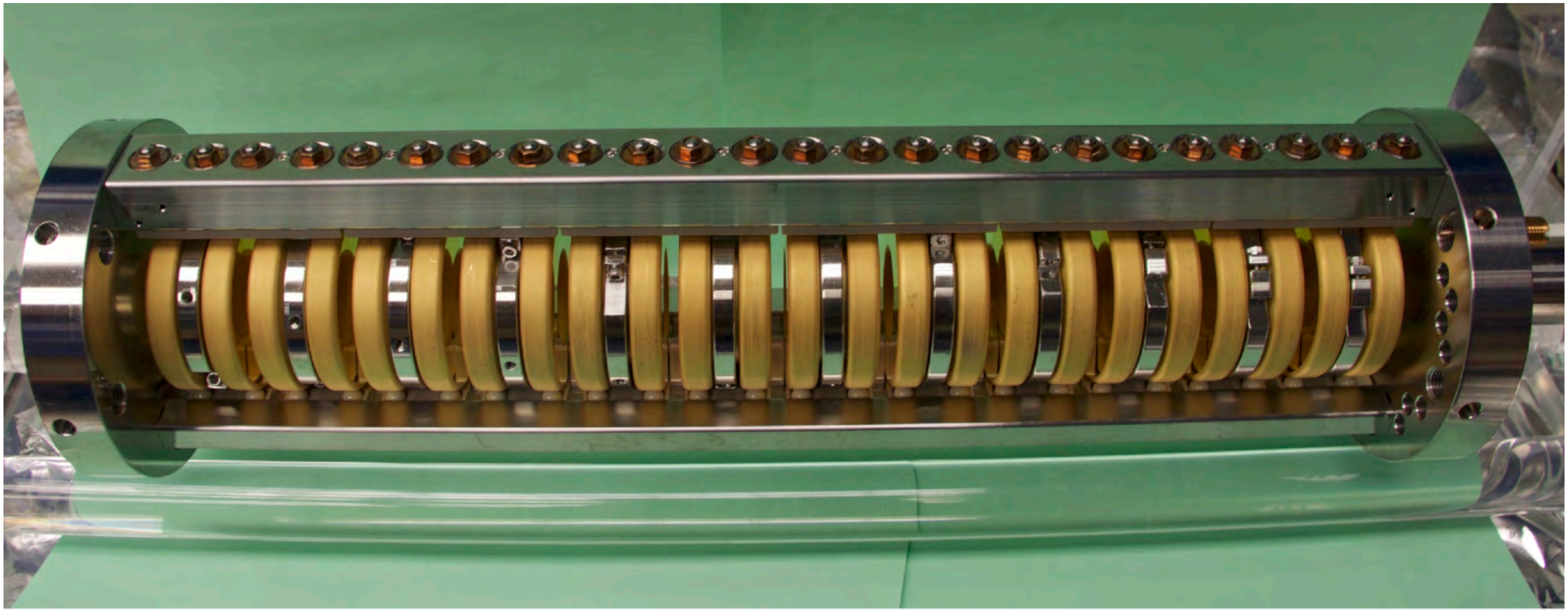
Step 2. Perform decay measurement with a trap length with unknown end effects:

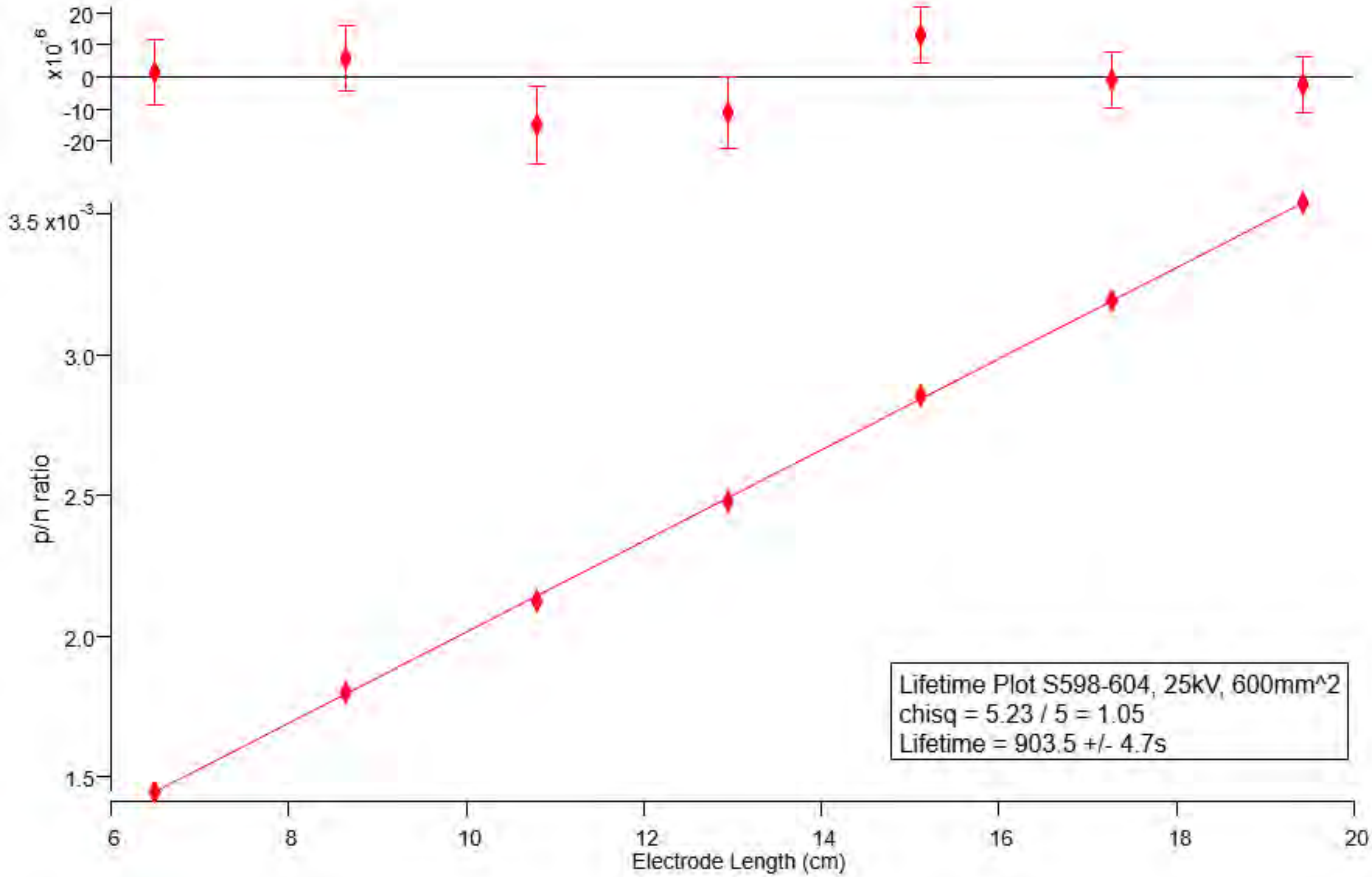


Step 3. Repeat with different length - Length Change is immune to end effects



The NIST Mk III Penning Trap



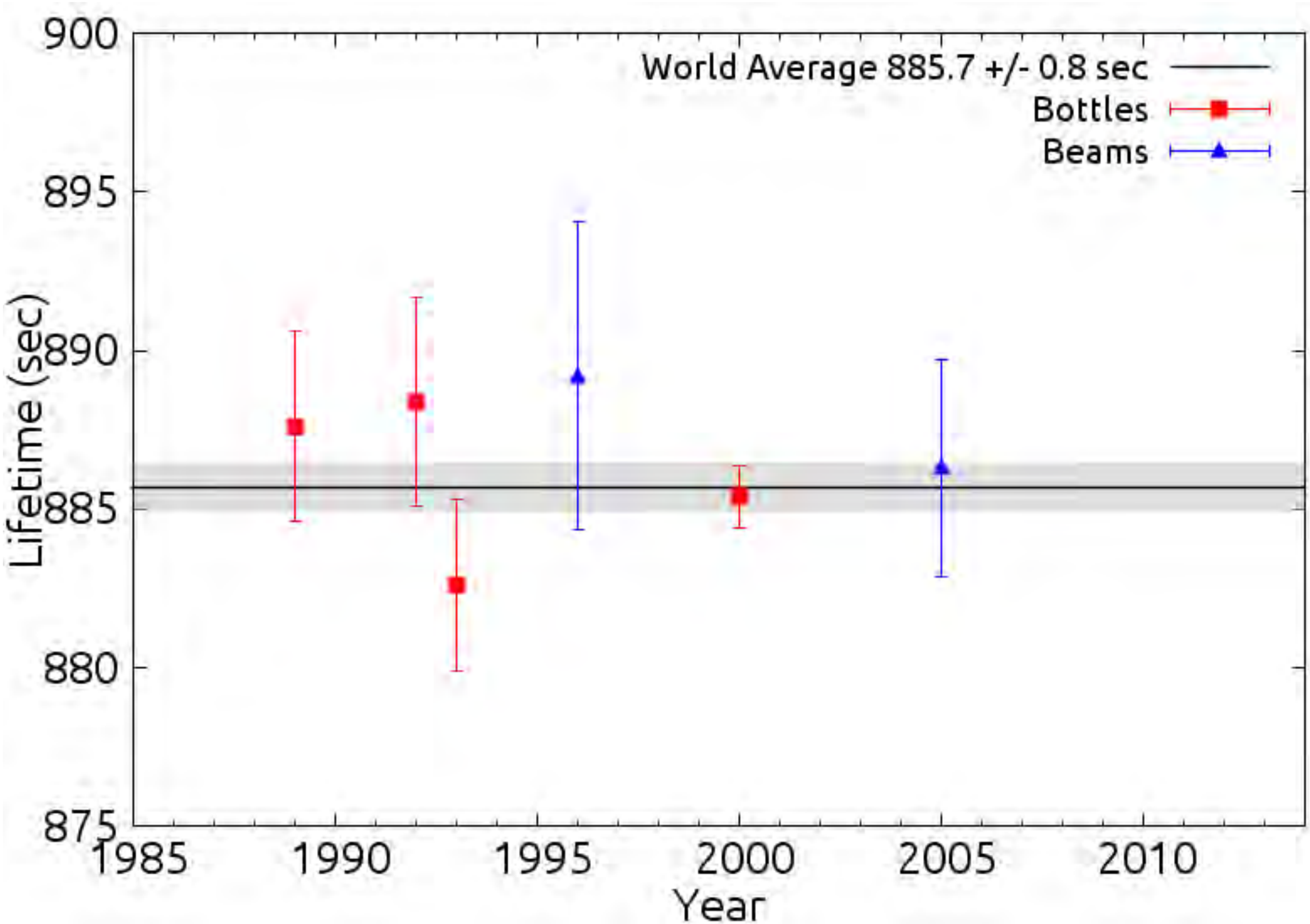


x10^-6
20
10
0
-10
-20
3.5 x10^-3
3.0
2.5
2.0
1.5
p/n ratio
6
8
10
12
14
16
18
20
Electrode Length (cm)
Lifetime Plot S598-604, 25kV, 600mm^2
chisq = 5.23 / 5 = 1.05
Lifetime = 903.5 +/- 4.7s

The Neutron Lifetime "Problem"

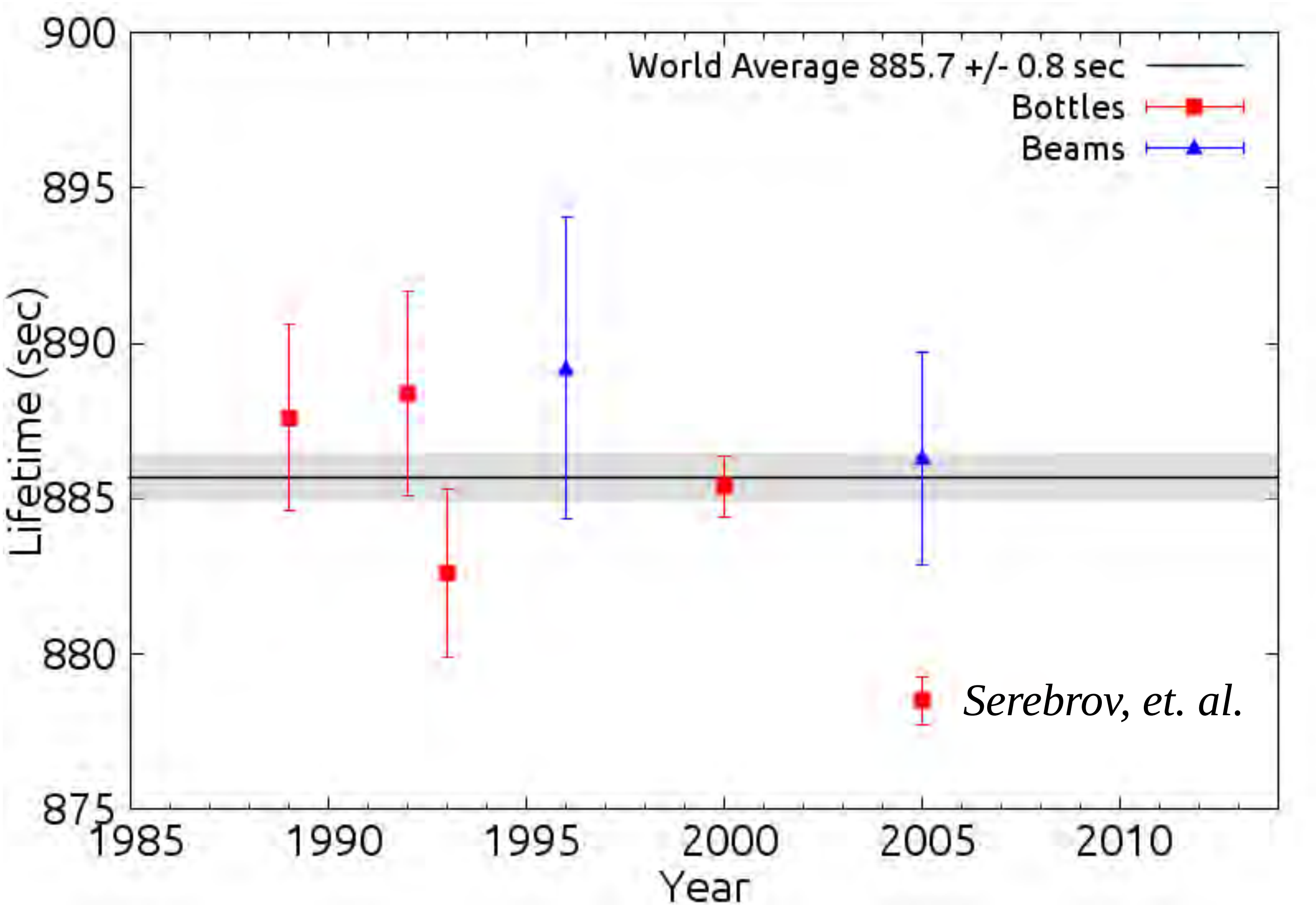
- A short history -

Neutron Lifetime Measurements in 2005



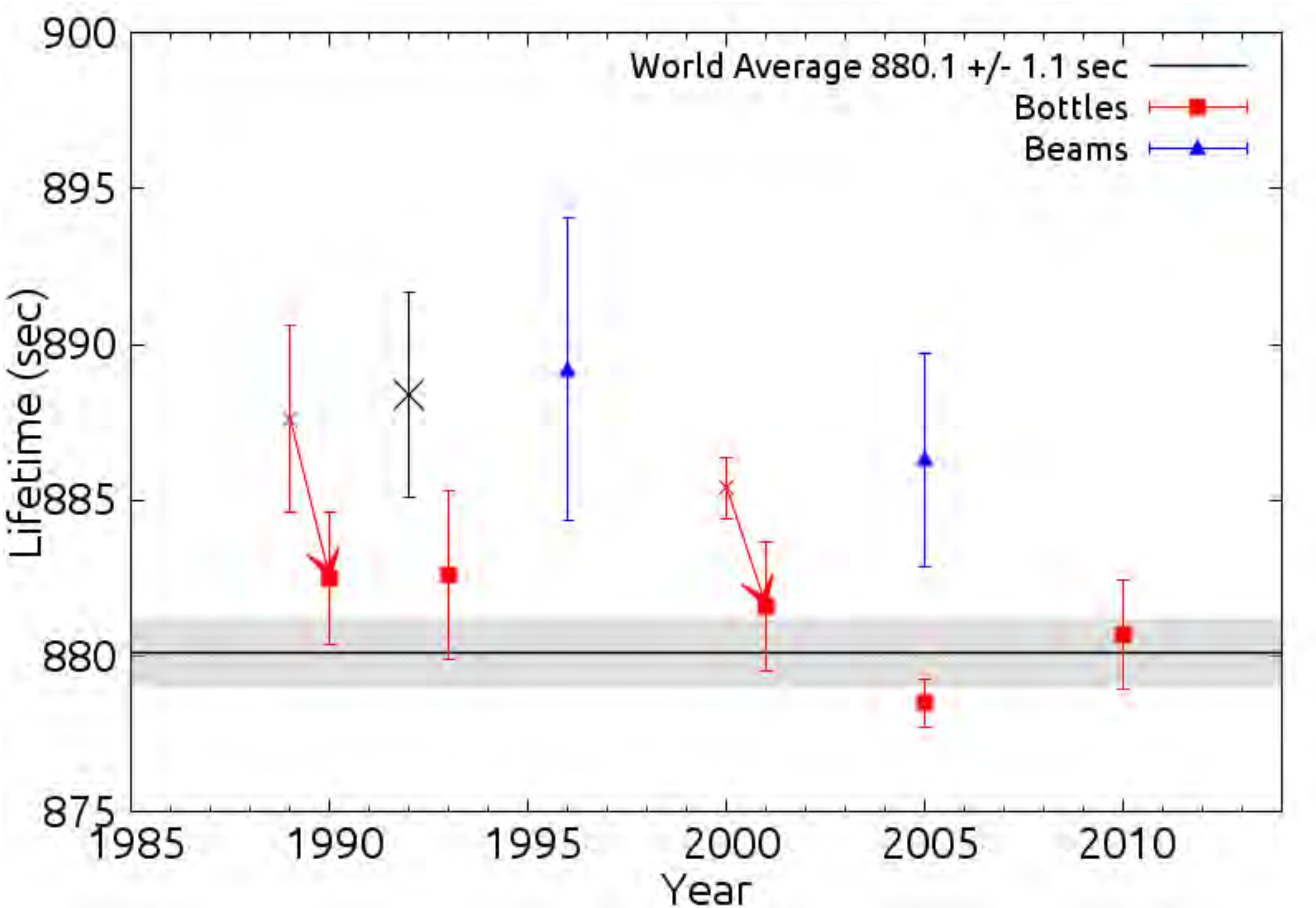
plot courtesy K. Grammer

A New Bottle Result



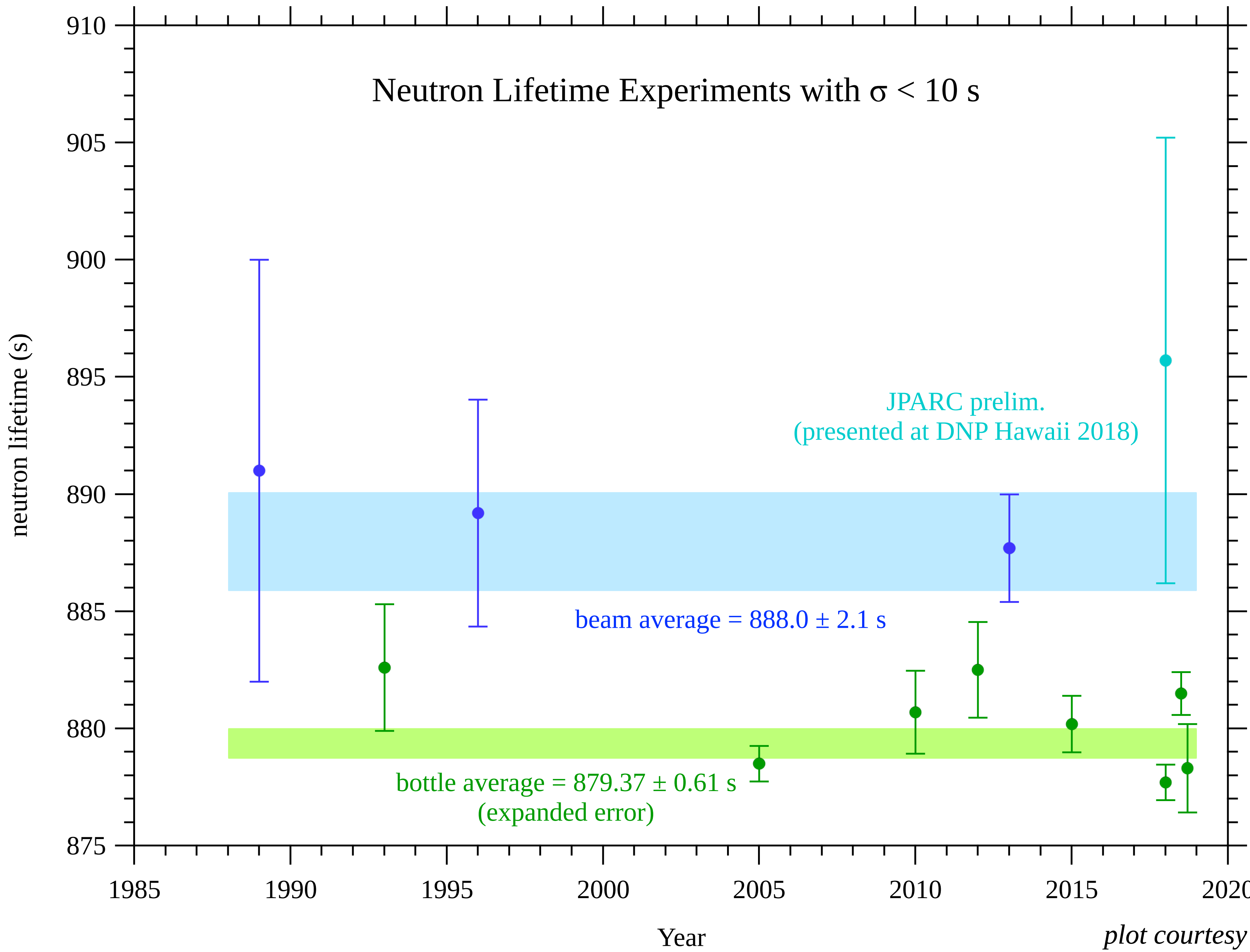
plot courtesy K. Grammer

And Then…



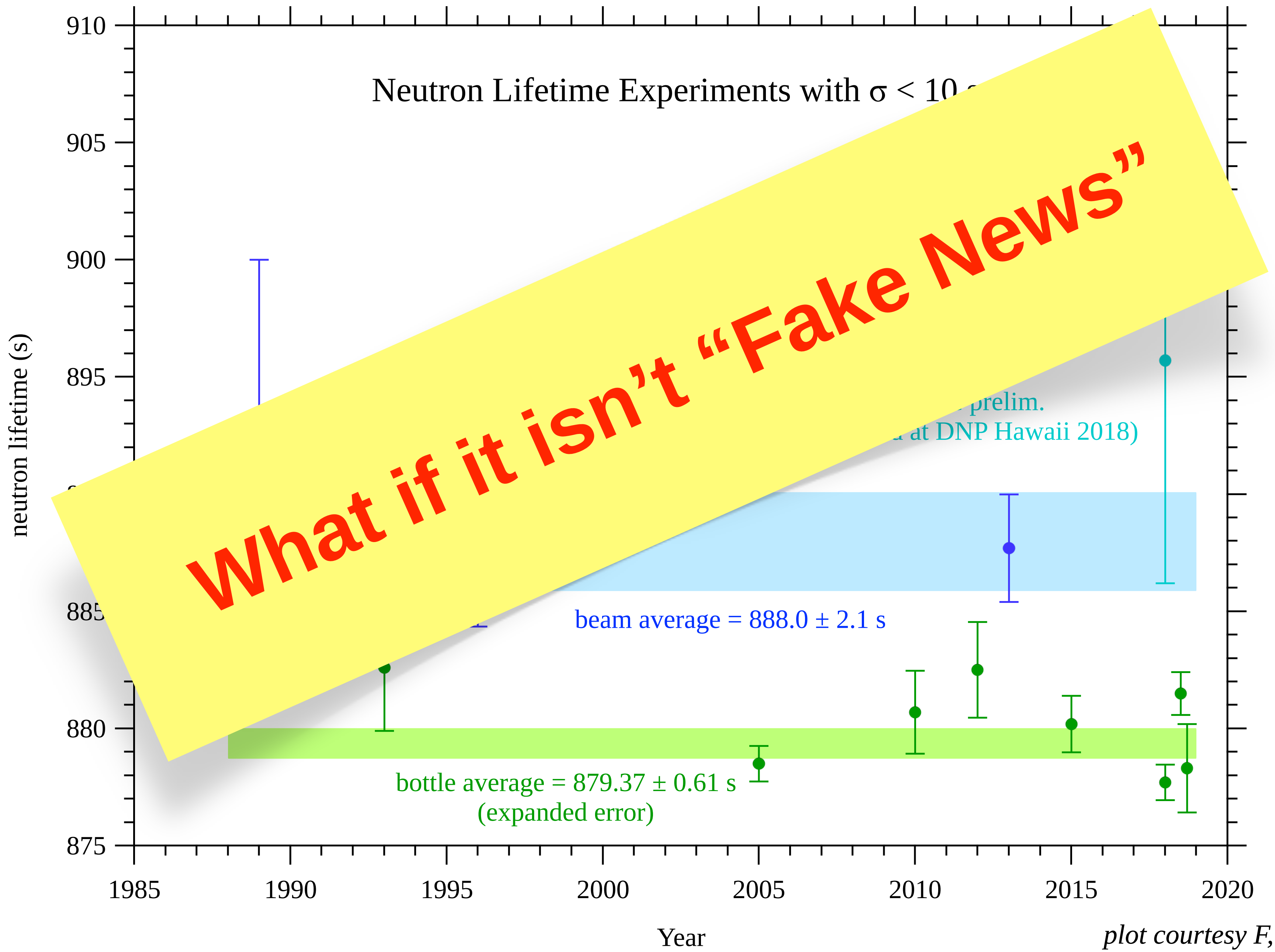
plot courtesy K. Grammer

The Situation Today - 2019



plot courtesy F, Weidtfeldt

The Situation Today - 2019



plot courtesy F, Weidtfeldt

NEW PHYSICS?

Suppose a neutron also decayed via a different channel,

$$\mathrm{n} \rightarrow ? + \mathrm{ZERO\ protons}$$

Measurements would give:

$$\tau_{BOTTLE} < \tau_{BEAM}$$

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)

neutron ➡ dark particle + photon

neutron ➡ dark particle + e^+e^-

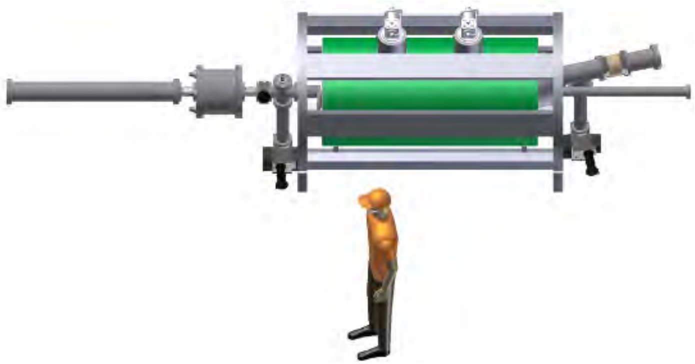
neutron ➡ two dark particles

neutron ➡ …

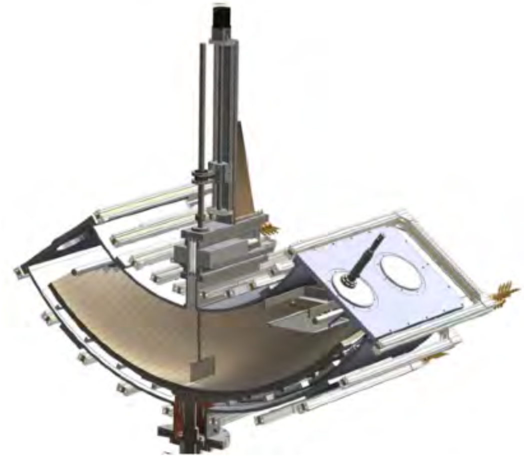
Some Recent Related Work

Pfutzner & Riisager, PRC 97, 042501(R) (2018)
McKeen, et. al, PRL 121, 061802 (2018),
Baym, et. al., PRL 121, 061801 (2018),
Motta, Guichon & Thomas, J. Phys. G 45, 05LT01 (2018)
Bringmann, Cline & Cornell, arXiv:1810.08215
Karananas & Kassiteridis, JCAP 09, 036 (2018)
Grinstein, Kouvaris & Nielsen, arXiv:1811.06546
Barducci, Fabbrichesi & Gabrielli, PRD 98, 035049
Berezhiani, arXiv:1807.07906
Berezhiani, LHEP 118, 1 (2019)
Foral & Grinstein, arXiv:1812.11089 (2018)
Tang et al., PRL 121, 022505 (2018)
Sun et al., PRC 97, 052501 (2018)
…

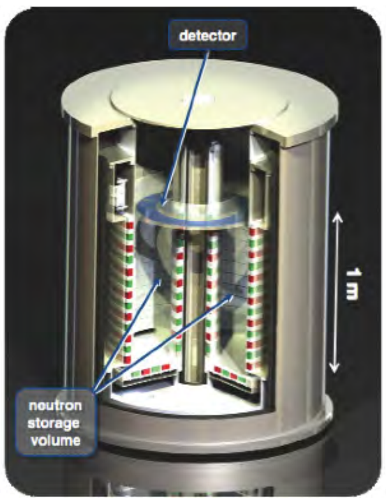
Several New Lifetime Experiments Worldwide



Beam Lifetime 3, NIST
Beam

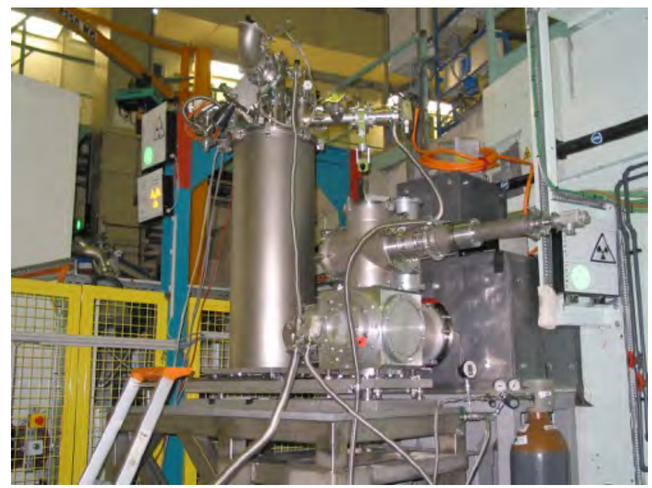


UCN τ , Los Alamos
Magnetic Bottle



PENELOPE, Munich
Magnetic Bottle

“Big” Gravitational Trap, St. Petersburg
Material Bottle



HOPE, Grenoble
Magnetic Bottle

Reviews of Modern Physics, *83*, 1173 (2011)

The neutron lifetime

Fred E. Wietfeldt*

Department of Physics, Tulane University, New Orleans, Louisiana 70118, USA

Geoffrey L. Greene†

Department of Physics, University of Tennessee, Knoxville, Tennessee 37996
and Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

The decay of the free neutron into a proton, electron, and antineutrino is the prototype semileptonic weak decay and is the simplest example of nuclear beta decay. It played a key role in the early Universe as it determined the ratio of neutrons to protons during the era of primordial light element nucleosynthesis. Neutron decay is physically related to important processes in solar physics and neutrino detection. The mean neutron lifetime has been the subject of more than 20 major experiments done, using a variety of methods, between 1950 and the present. The most precise recent measurements have stated accuracies approaching 0.1%, but are not in good agreement as they differ by as much as 5σ using quoted uncertainties. The history of neutron lifetime measurements is reviewed and the different methods used are described, giving important examples of each. The discrepancies and some systematic issues in the experiments that may be responsible are discussed, and it is shown by means of global averages that the neutron lifetime is likely to lie in the range of 880–884 s. Plans and prospects for future experiments are considered that will address these systematic issues and improve our knowledge of the neutron lifetime.

DOI: 10.1103/RevModPhys.83.1173 PACS numbers: 14.20.Dh, 23.40.−s

Measuring Decay Correlations in Neuton Decay

Correlations in Neutron Decay

Pure V-A, low energy limit

$$dW \propto \frac{1}{\tau_n} F(E_e)\left[1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\upsilon}{E_e \cdot E_\upsilon} + b\frac{m_e}{E_e} + A\frac{\sigma_n \cdot \mathbf{p}_e}{E_e} + B\frac{\sigma_n \cdot \mathbf{p}_\upsilon}{E_\upsilon} + \ldots\right]$$

$$\frac{1}{\tau_n} \propto \frac{1}{\left(G_V^2 + 3G_A^2\right)}$$

$$a = \frac{1-\left(\frac{G_A}{G_V}\right)^2}{1-3\left(\frac{G_A}{G_V}\right)^2}$$

$$b = 0$$

$$A = -2\frac{\left(\frac{G_A}{G_V}\right)^2 + \left(\frac{G_A}{G_V}\right)}{1-3\left(\frac{G_A}{G_V}\right)^2}$$

$$B = -2\frac{\left(\frac{G_A}{G_V}\right)^2 - \left(\frac{G_A}{G_V}\right)}{1-3\left(\frac{G_A}{G_V}\right)^2}$$

Neutron beta decay measurements give:

$$G_A^2 + 3G_V^2$$

$$G_A / G_V$$

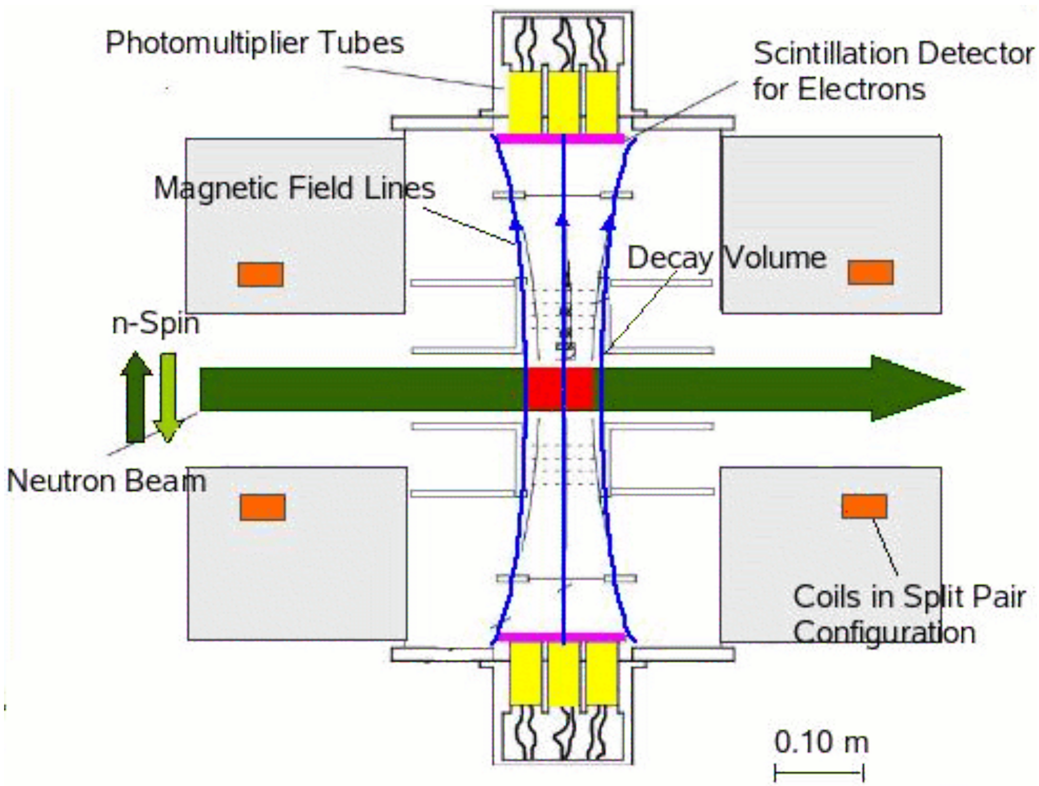
(Jackson, Treiman, Wyld, 1957)

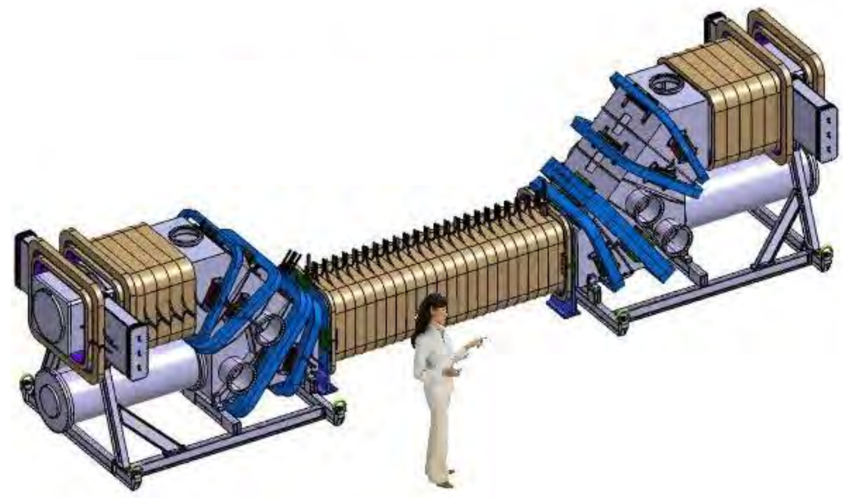
Some selected recent and ongoing neutron decay experiments

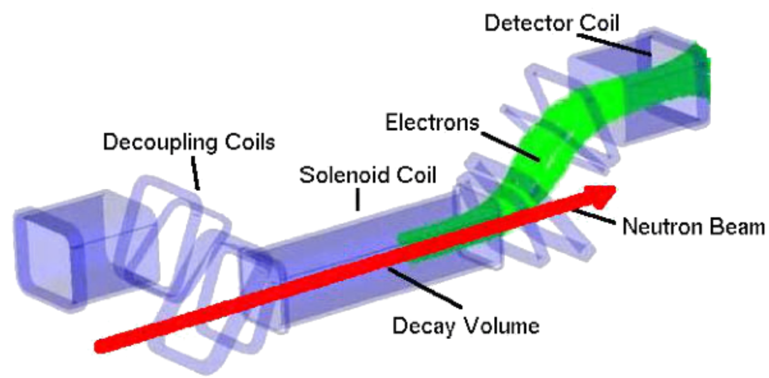
PERKEO at ILL, Grenoble

Polarized neutrons used to determine "A"

$$A\vec{\sigma}_n \cdot \vec{p}_e$$



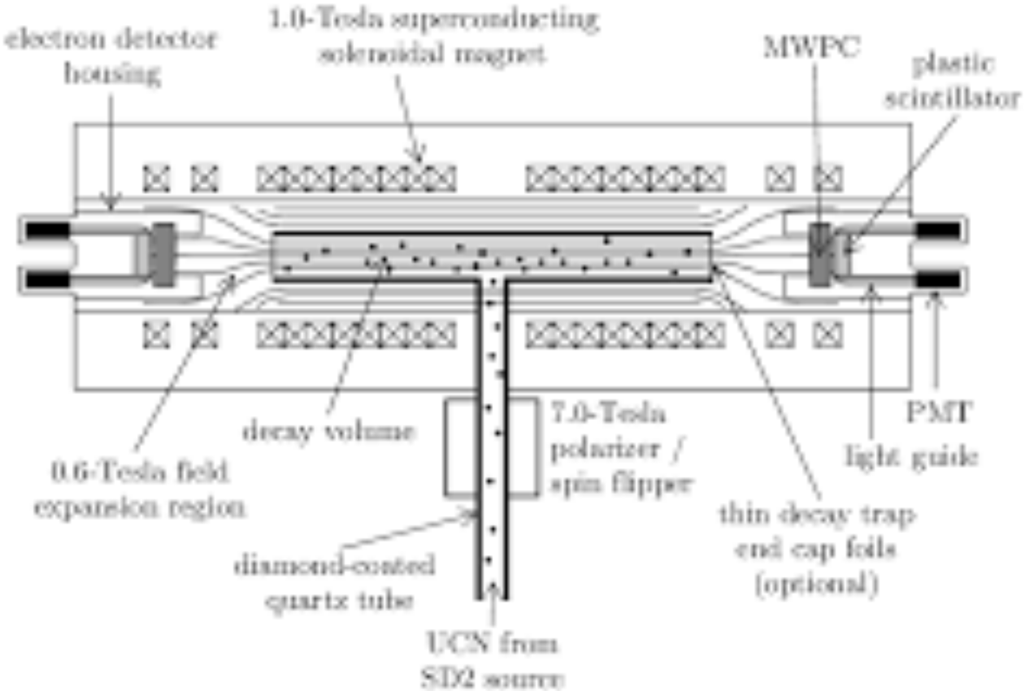


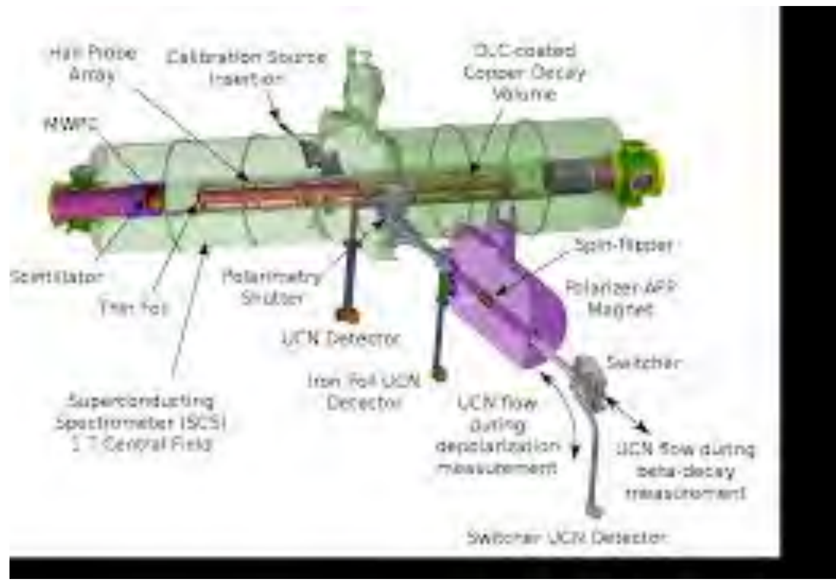


UCNA at Los Alamos

Polarized neutrons used to determine "A"

$$A\vec{\sigma}_n \cdot \vec{p}_e$$



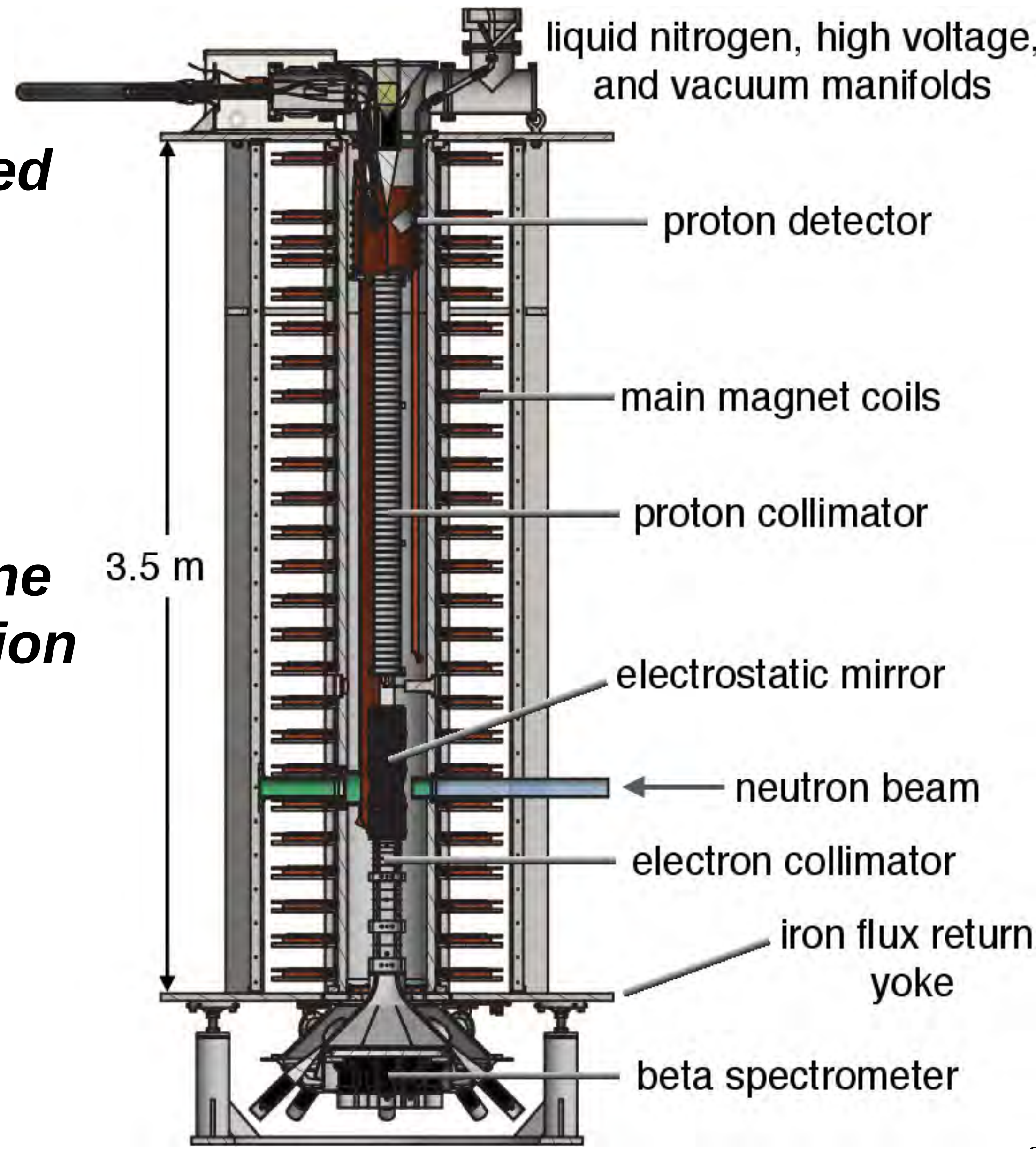


aCORN at NIST

Unpolarized neutrons used to determine "a"

$$a\vec{p}_{\overline{\nu}} \cdot \vec{p}_e$$

Cannot determine $\vec{p}_{\overline{\nu}}$ so one deduces this from information about $\vec{p}_e$ and $\vec{p}_p$

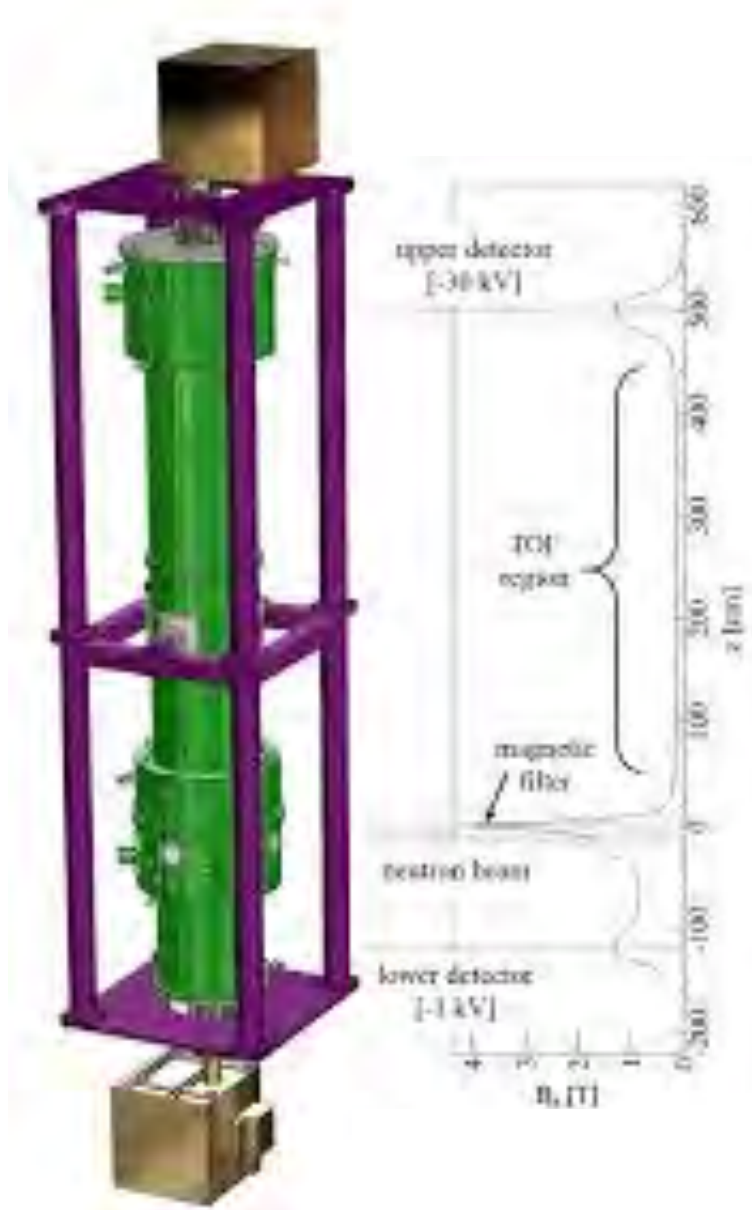


Nab at the Spallation Neutron Source

Unpolarized neutrons used to determine "a"

$$a\vec{p}_{\bar{\upsilon}} \cdot \vec{p}_e$$

Cannot determine $\vec{p}_{\bar{\upsilon}}$ so one deduces this from information about $\vec{p}_e$ and $\vec{p}_p$



End of Presentation

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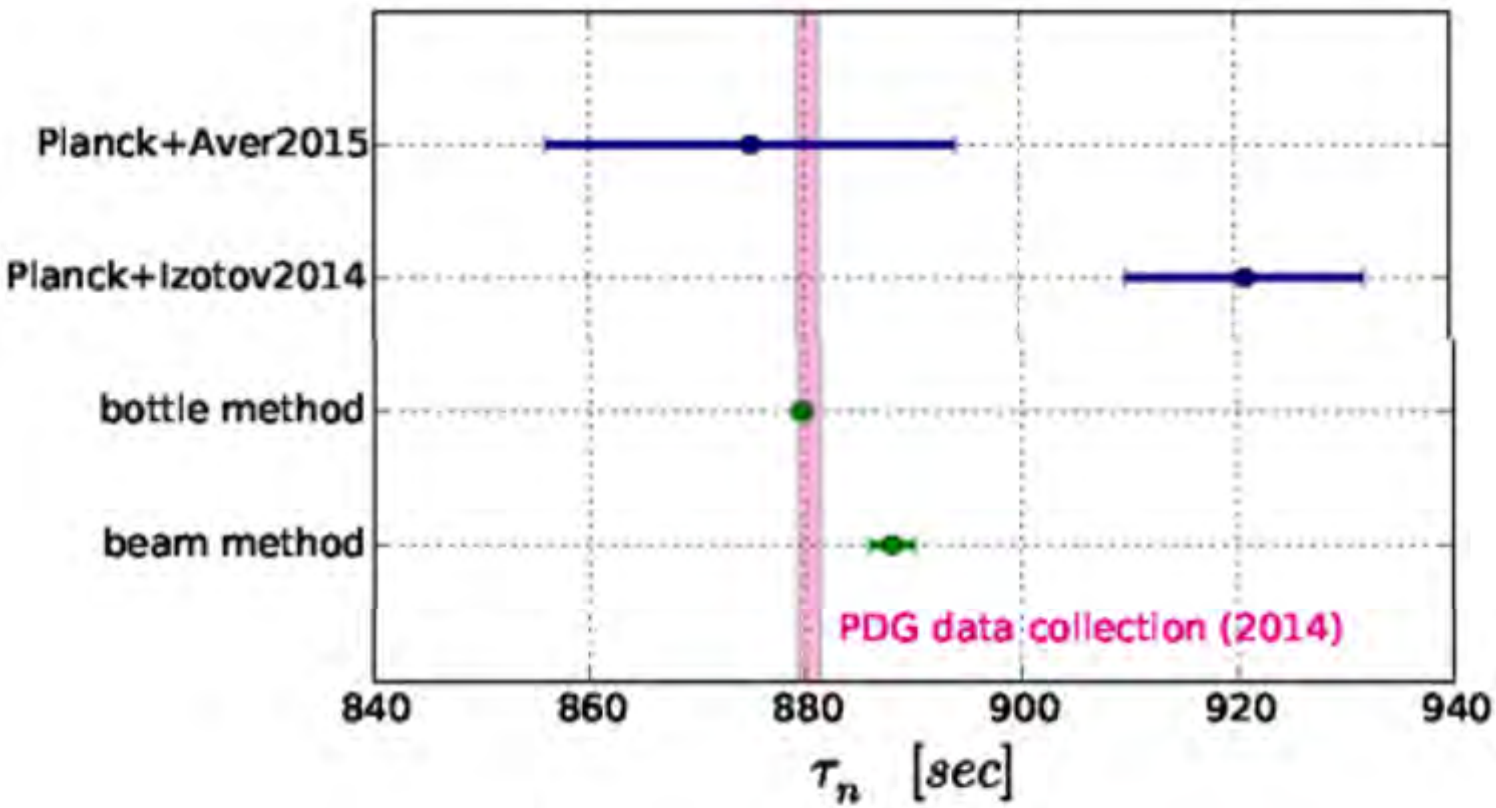
Cosmological constraints on the neutron lifetime

Laura Salvati, Luca Pagano, Rosa Consiglio, Alessandro Melchiorri

(Submitted on 26 Jul 2015 (v1), last revised 29 Mar 2016 (this version, v3))



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arXiv.org > hep-ph > arXiv:1802.01804

High Energy Physics – Phenomenology

The Neutron Lifetime and Axial Coupling Connection

Andrzej Czarnecki, William J. Marciano, Alberto Sirlin

(Submitted on 6 Feb 2018)

$$\tau_n^{favored} = 879.4 \pm 0.6 s$$

$$\tau_n^{bottle} = 879.3 \pm 0.75 s$$

$$\tau_n^{beam} = 888.0 \pm 2.1 s$$