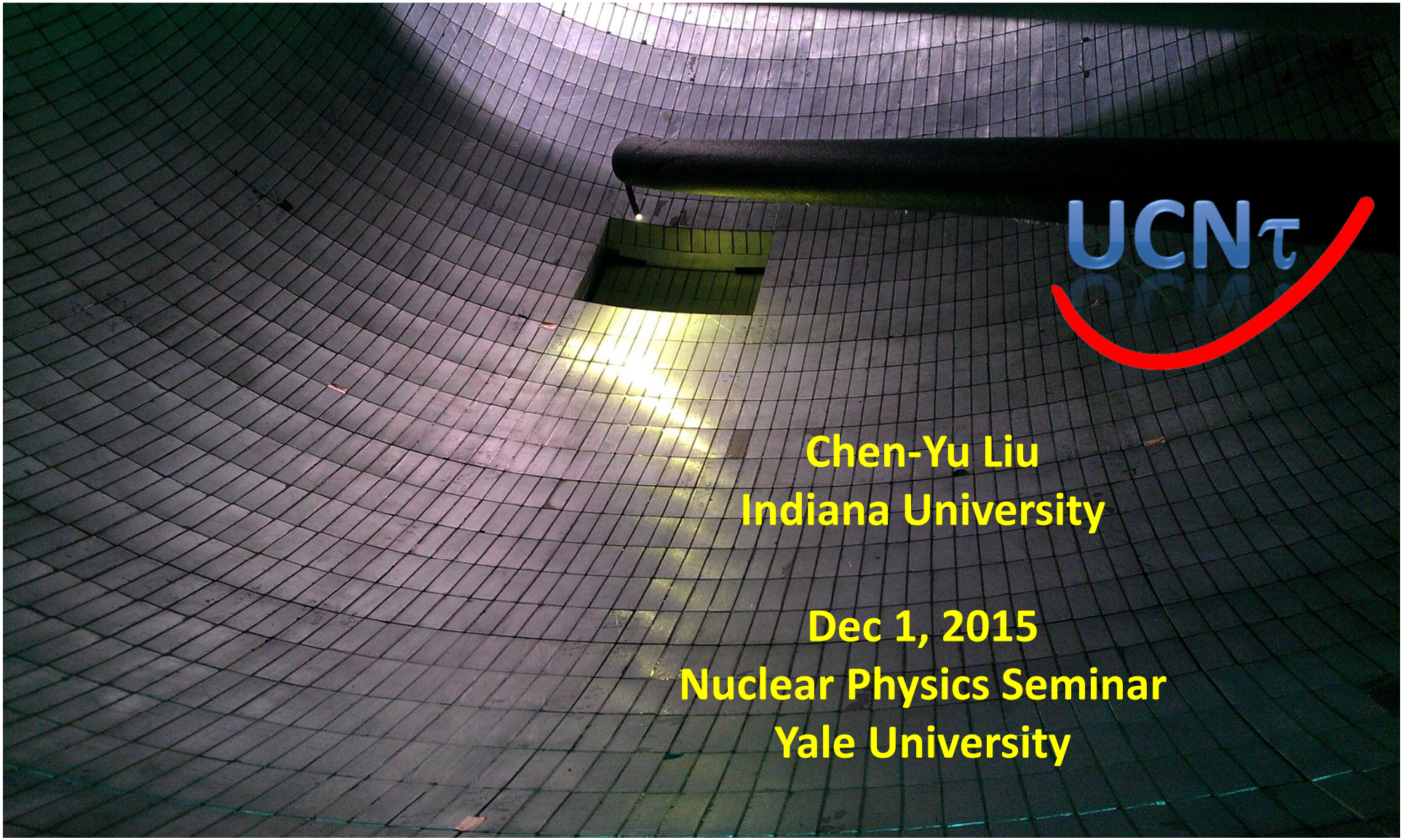
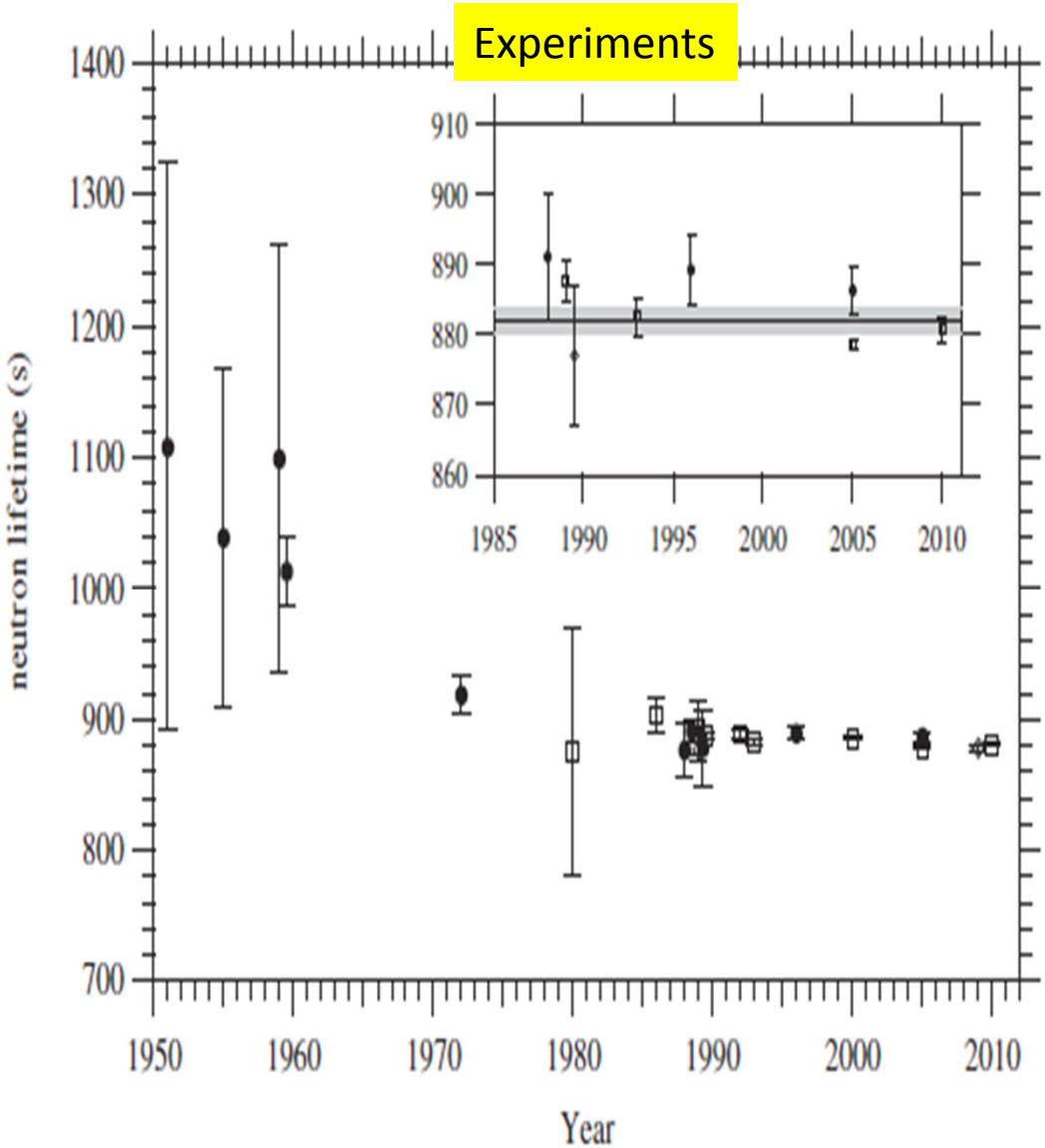
Neutron Lifetime Measurements: Much Ado About 1 second



Chen-Yu Liu
Indiana University

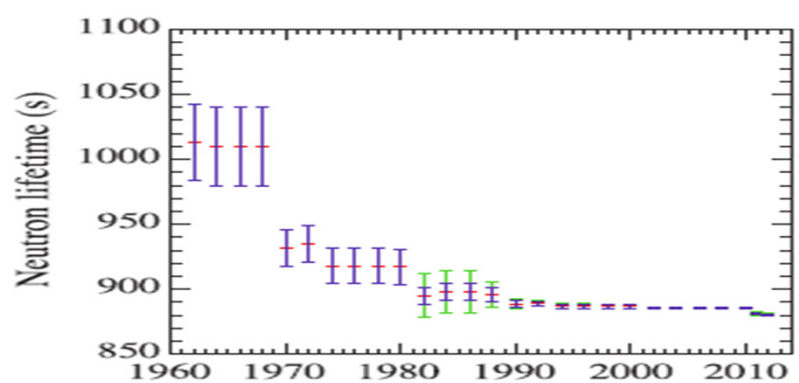
Dec 1, 2015
Nuclear Physics Seminar
Yale University

The History of Neutron Lifetime: PDG compilation



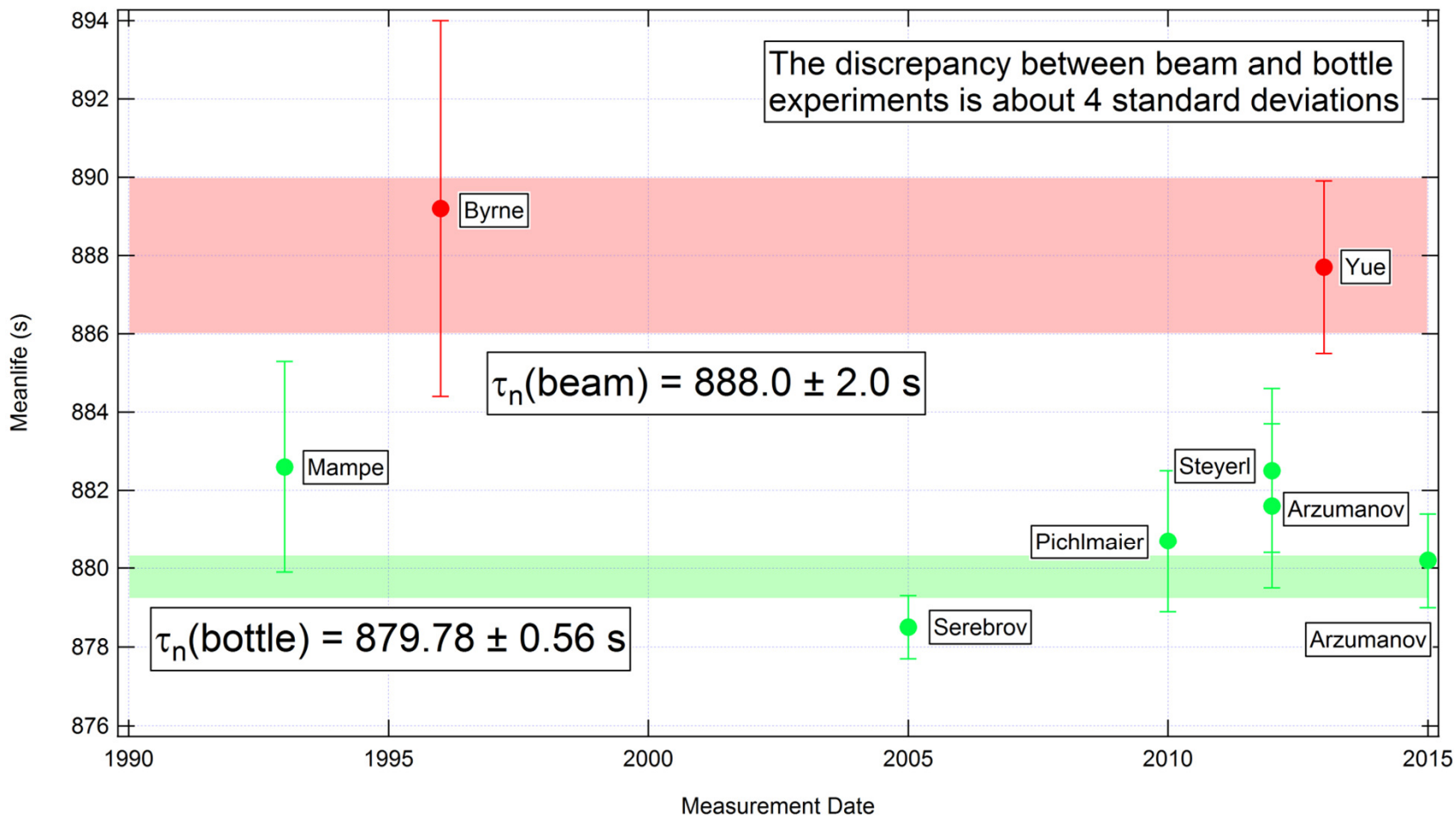
Solid circle: beam
Open square: bottle

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

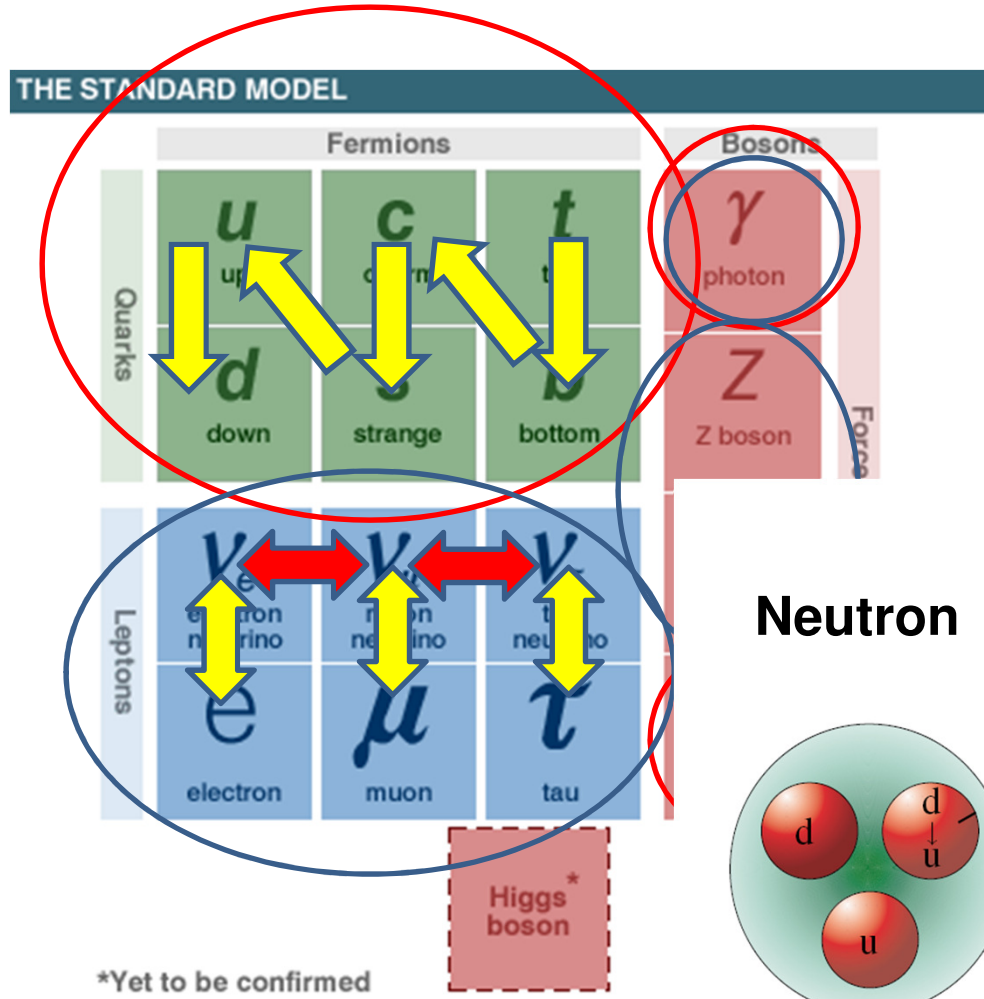
Outline

- How do we use neutrons to test the Standard Model of particle physics?
- How to measure the neutron lifetime?
  - The beam method: NIST BL experiments.
  - The bottle method (material, magnetic): the UCNtau experiment at LANL
- Broader Impact
  - Big-Bang Nucleosynthesis

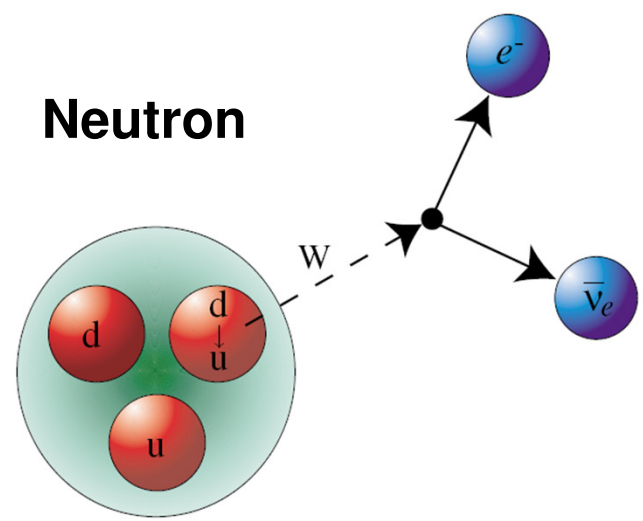
The Standard Model of Particle Physics

Hadrons

Leptons



Neutron

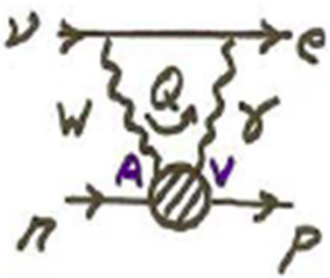


If the electrons were to feel the strong force, there would be no chemistry or crystallography or biology -- only nuclear physics. **S. Weinberg**

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

V_{ud} for CKM Unitarity Test

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



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

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

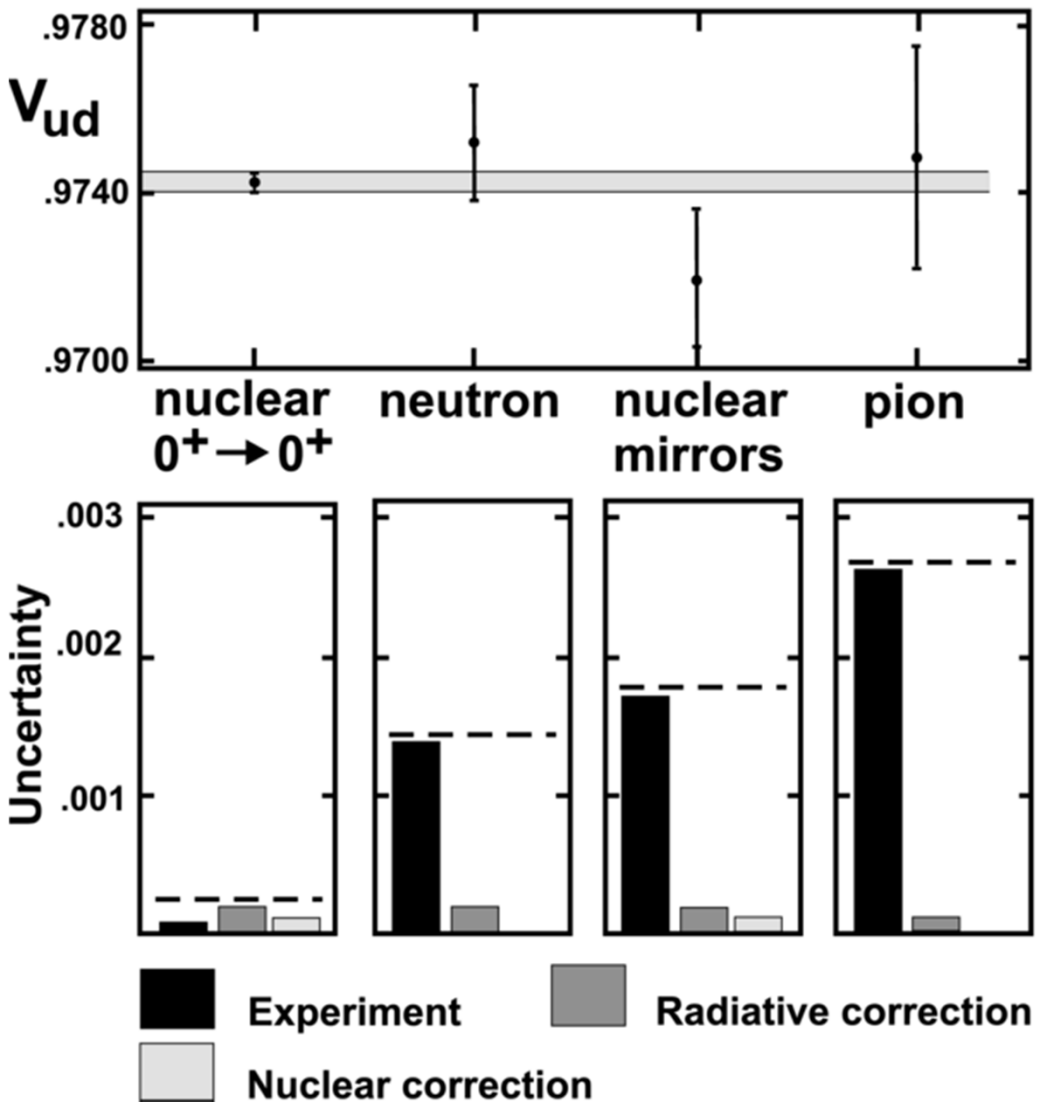
Marciano & Sirlin, PRL 96, 032002 (2006)

From μ-decay: 0.6 ppm (MuLan 2011)

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

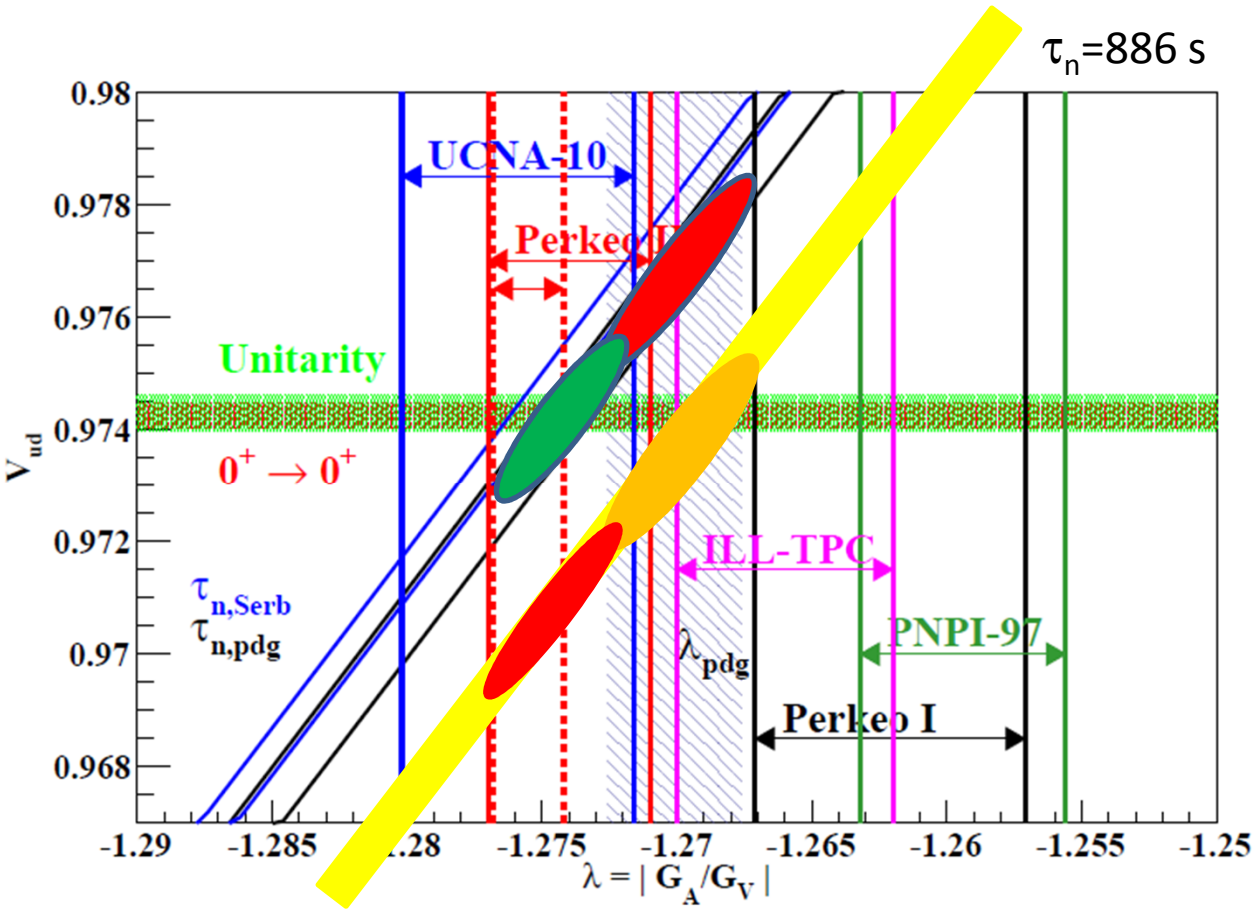
To be comparable to the theoretical uncertainty: 4×10^{-4}, requires experimental uncertainty: $\Delta A/A = 4\Delta\lambda/\lambda < 2 \times 10^{-3}$ and $\Delta\tau/\tau = 4 \times 10^{-4}$.

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
$g_A = 1.2701(25)$
$\rightarrow$ Vud $= 0.9774(5)_{\tau n}(16)_{gA}(2)_{RC}$

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

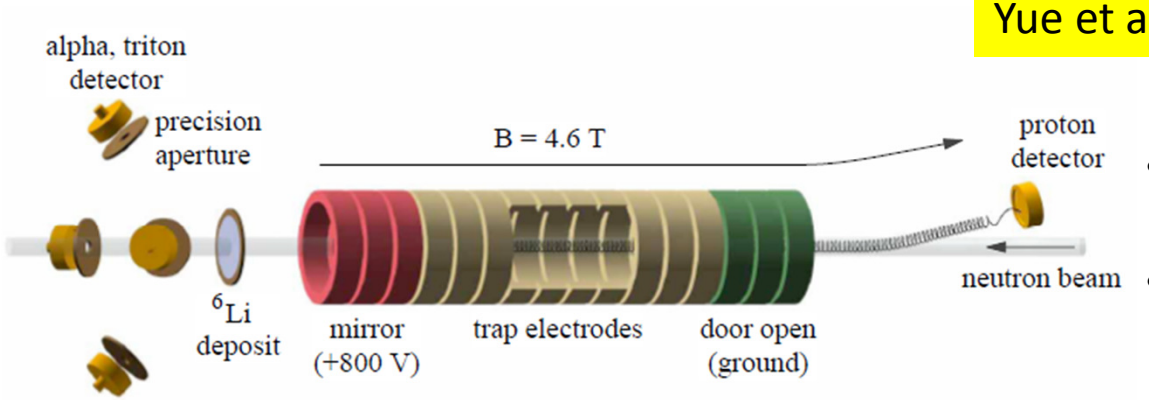
To bring these two into agreement, we need

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

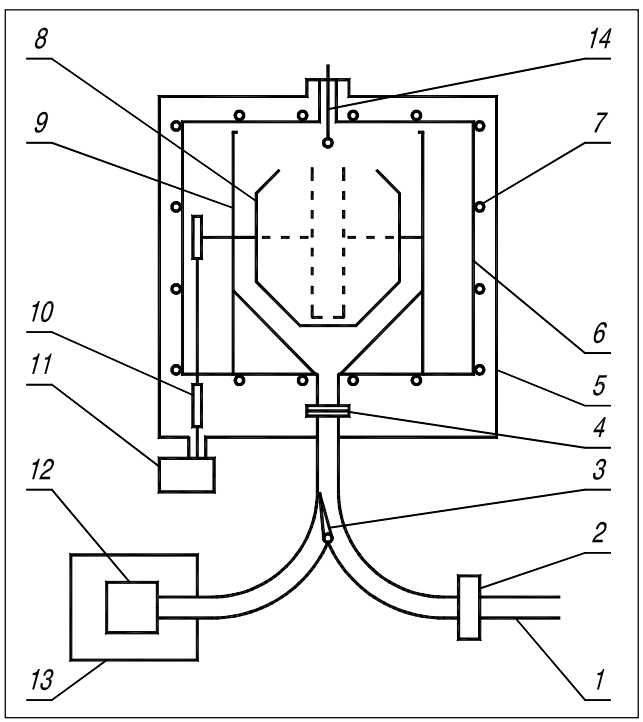
The Two Pillars: Beam and Bottle Experiments

NIST beam experiment: τ_n **= (887.7 ± 1.2 ± 1.9) s**

Yue et al., Phys. Rev. Lett. 111, 222501 (2013)



- Counts protons from beta-decays in flight
- Absolute neutron flux must be measured very accurately



Gravitrap: τ_n **= (878.5 ± 0.7 ± 0.3) s**

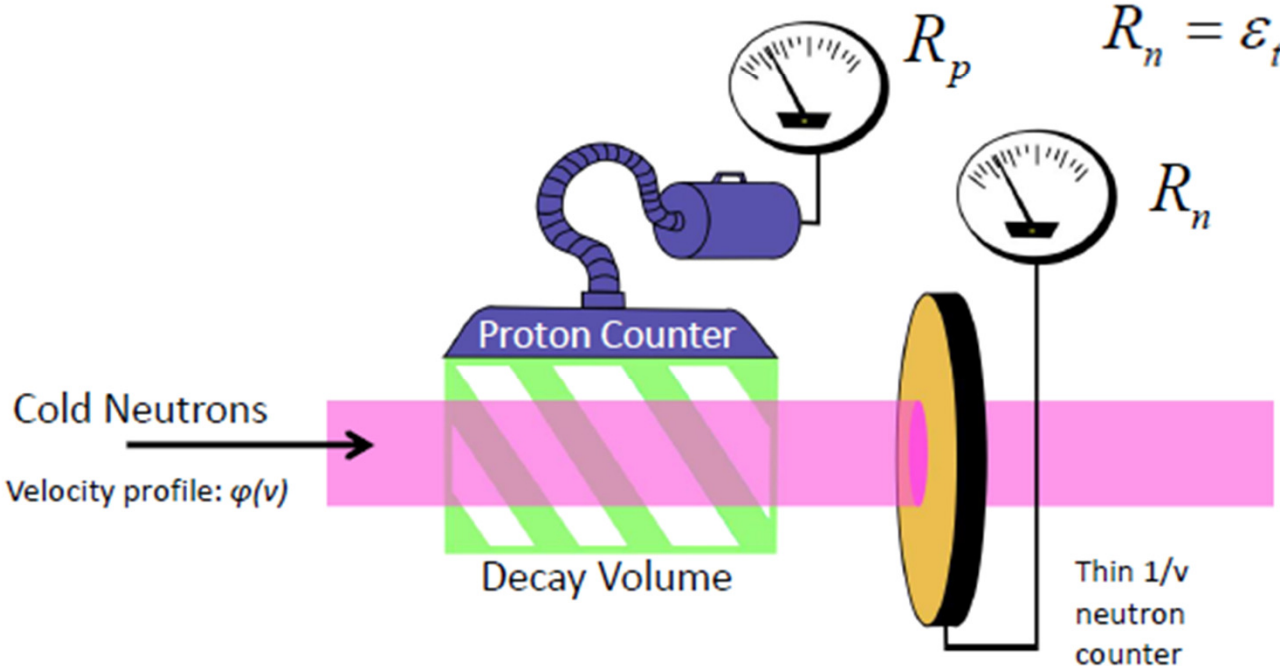
A. Serebrov et al., Phys. Rev. C 78, 035505 (2008)

- Material trap w/frozen Fomblin coating gives a long storage time.
- Some dependence on Monte Carlo to extrapolate to zero-wall-loss storage time.

The Beam Method

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

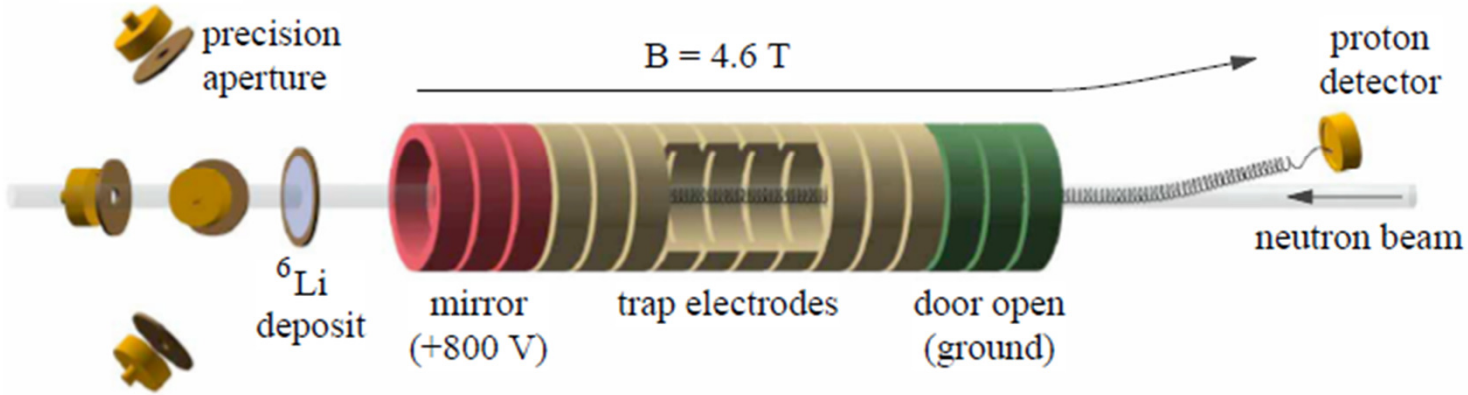
$$R_n = \varepsilon_{th} A_{beam} v_{th} \int \frac{\varphi(v)}{v} dv$$



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

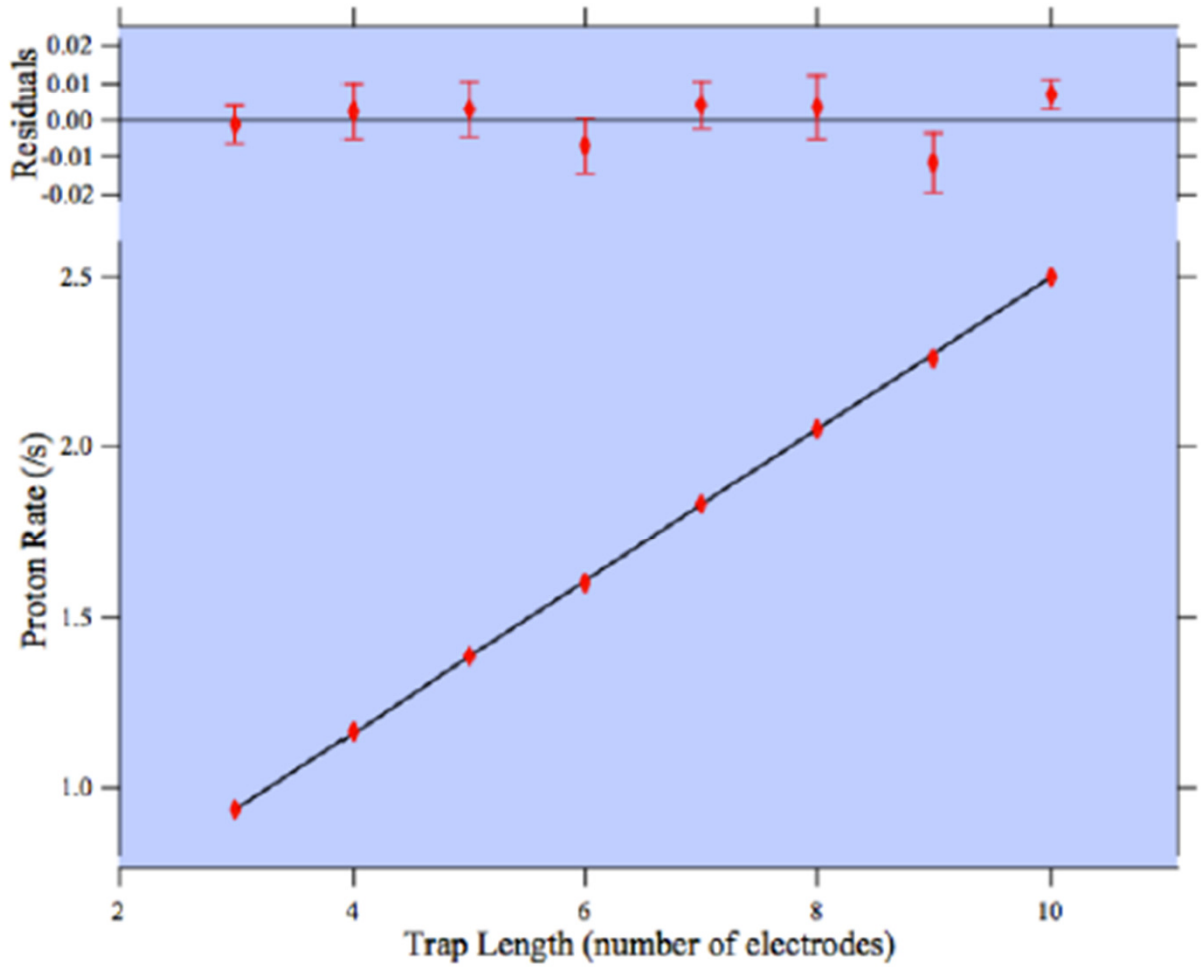
The NIST Beam Lifetime Experiment (BL1, BL2)

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



- 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.

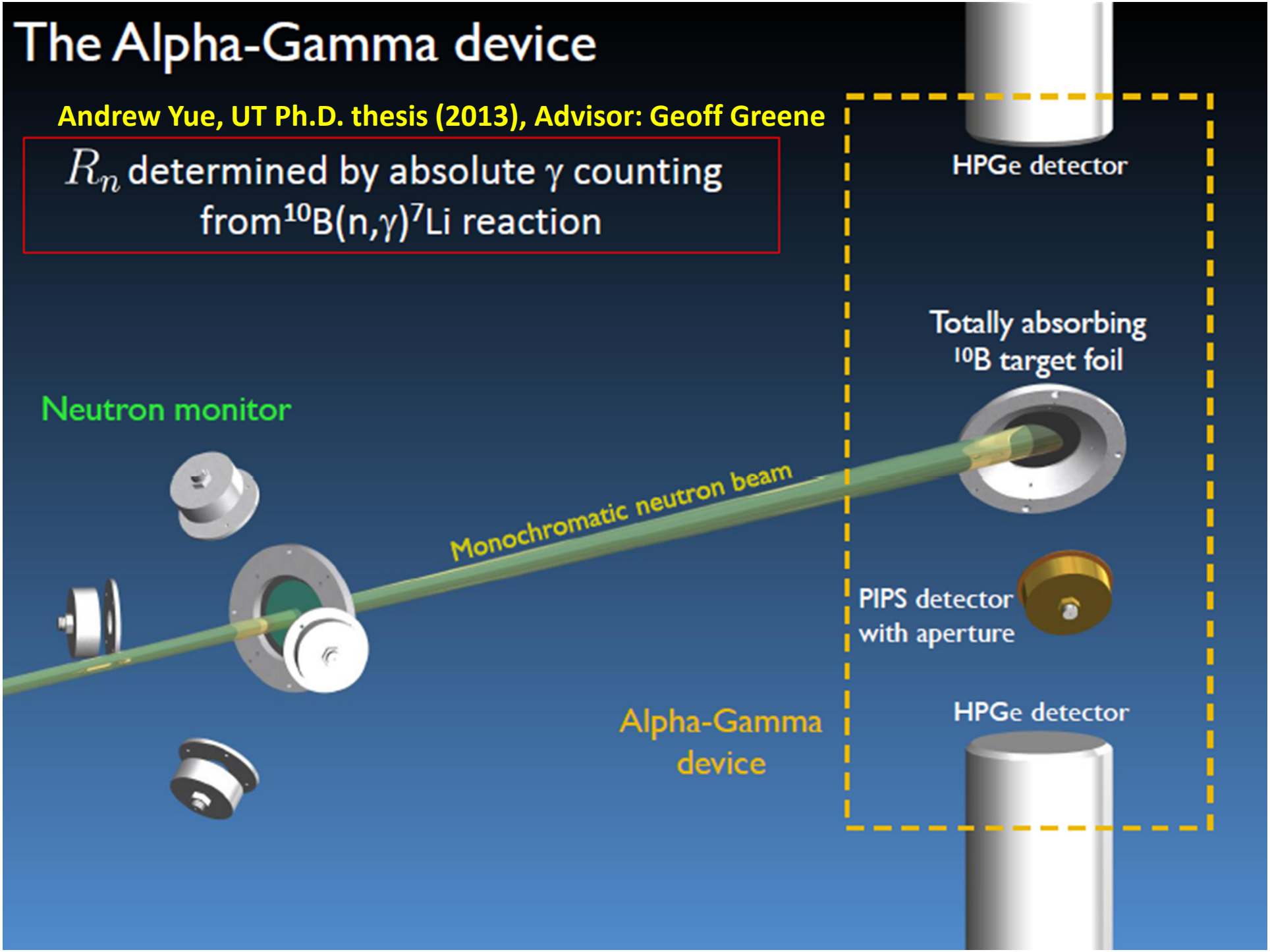
$$\dot{N}_p = \dot{N}_{\alpha+t} \left(\frac{L}{\tau_n} \right) \frac{\epsilon_p}{\epsilon_0 v_0}$$



The Alpha-Gamma device

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

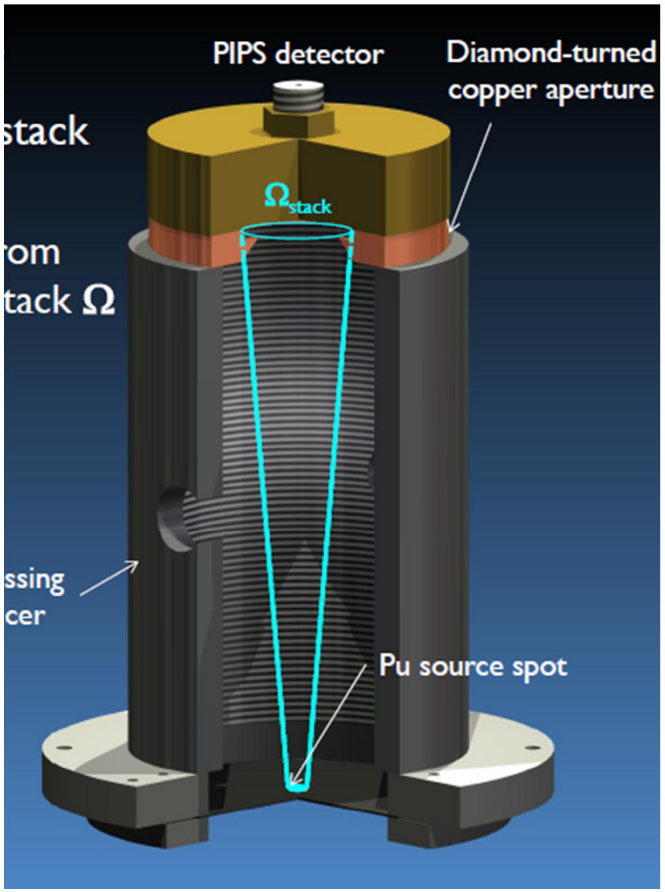
R_n determined by absolute γ counting from $^{10}B(n,\gamma)^{7}Li$ reaction

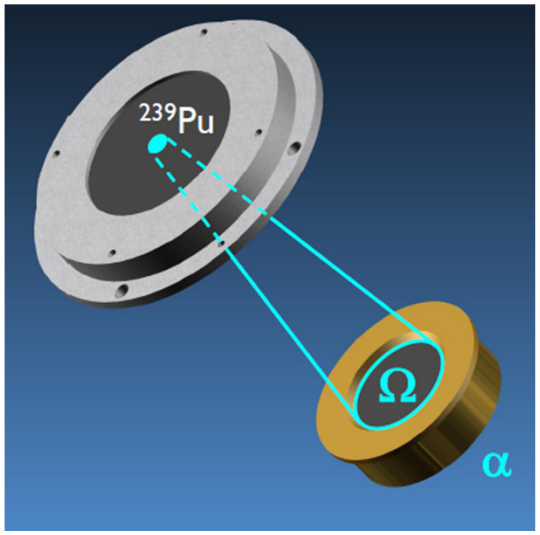


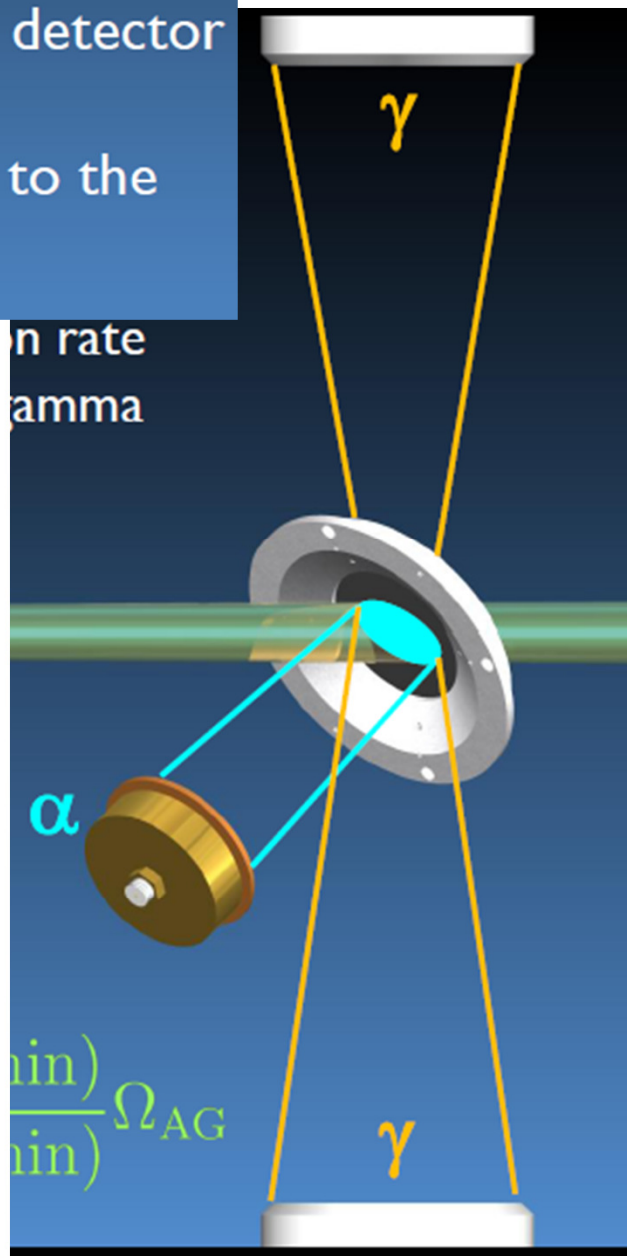
1 Measure the absolute activity of an alpha source

2 Use this source to determine solid angle of alpha detector

3 Use an (n,αγ) reaction to transfer the calibration to the gamma detectors



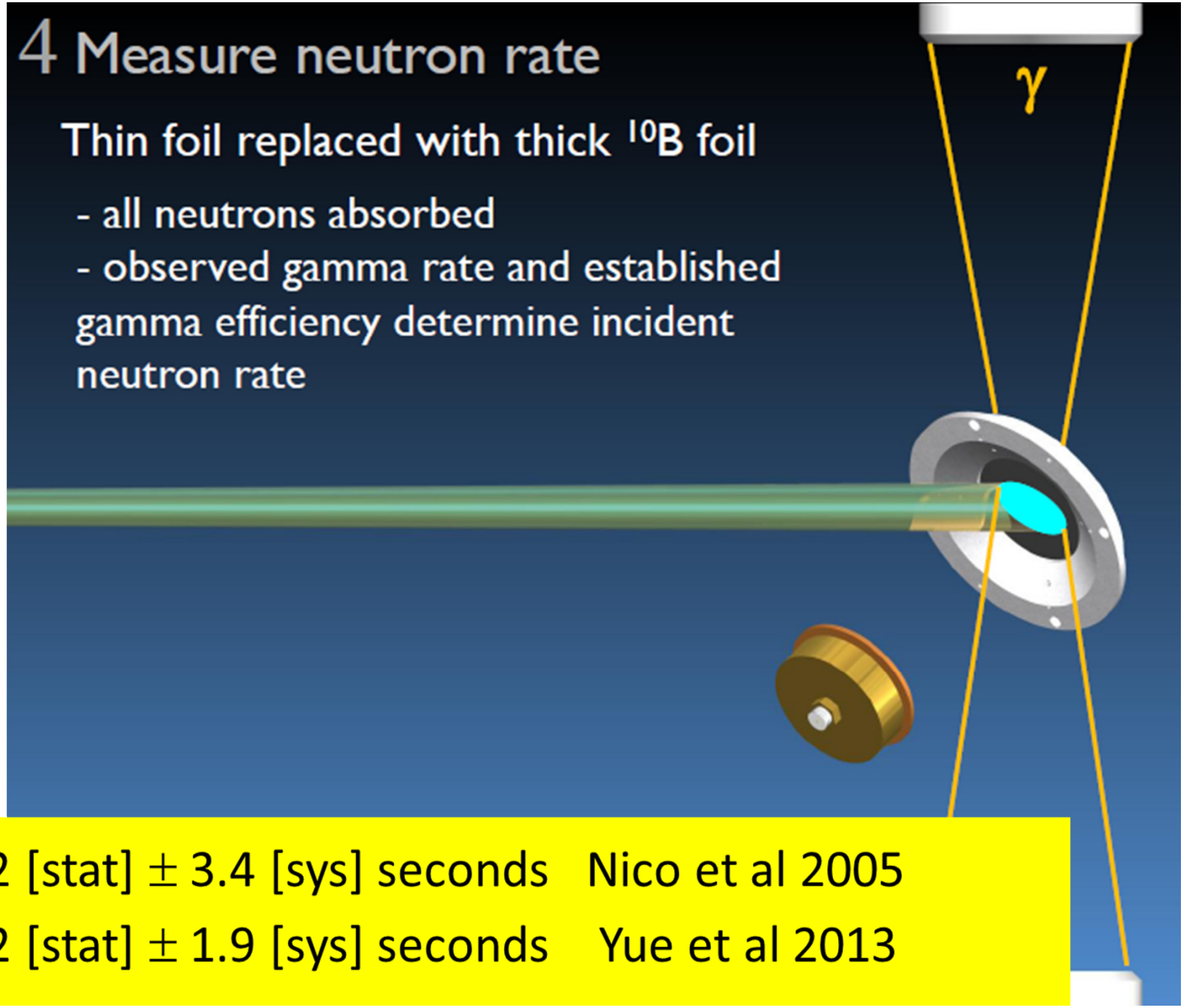




4 Measure neutron rate

Thin foil replaced with thick ^{10}B foil

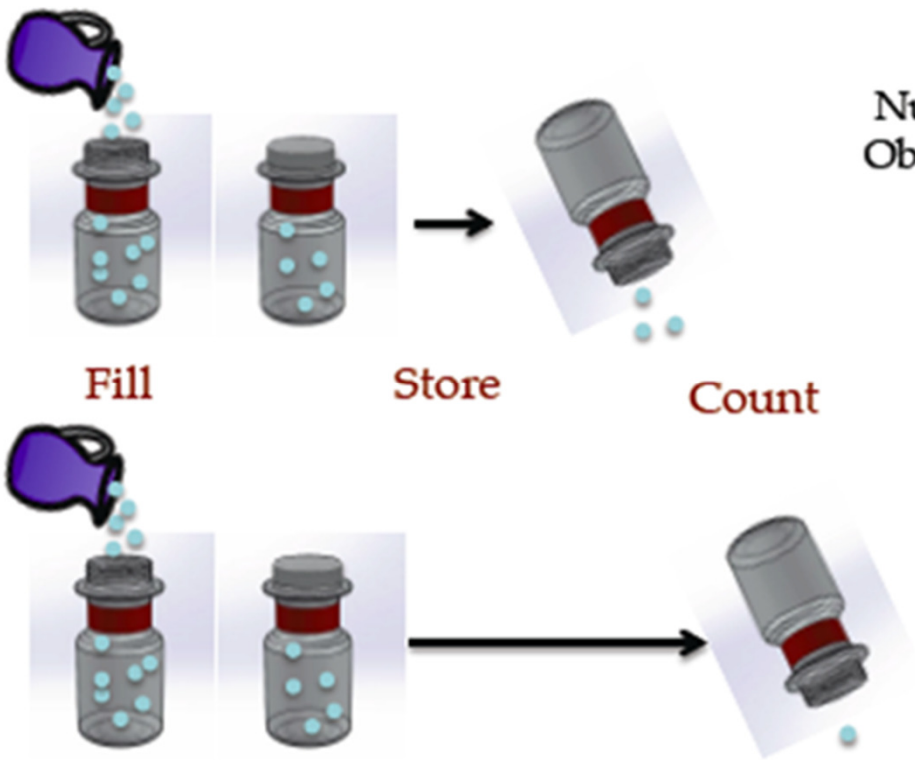
- all neutrons absorbed
- observed gamma rate and established gamma efficiency determine incident neutron rate

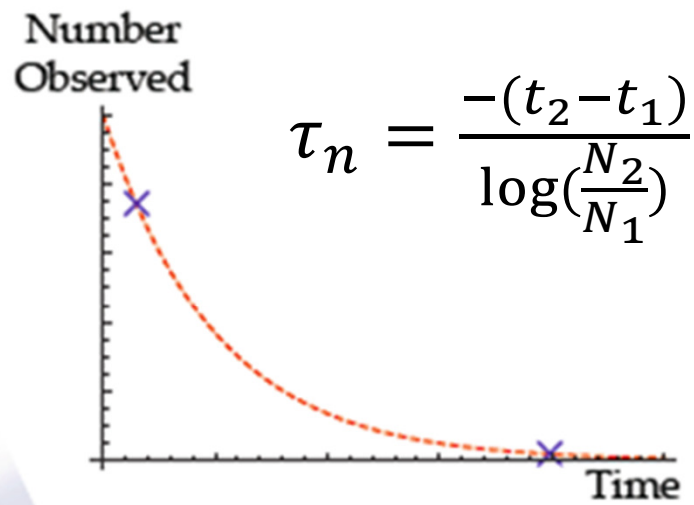


886.3 ± 1.2 [stat] ± 3.4 [sys] seconds Nico et al 2005

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

The Bottle Method: *fill-store-count*



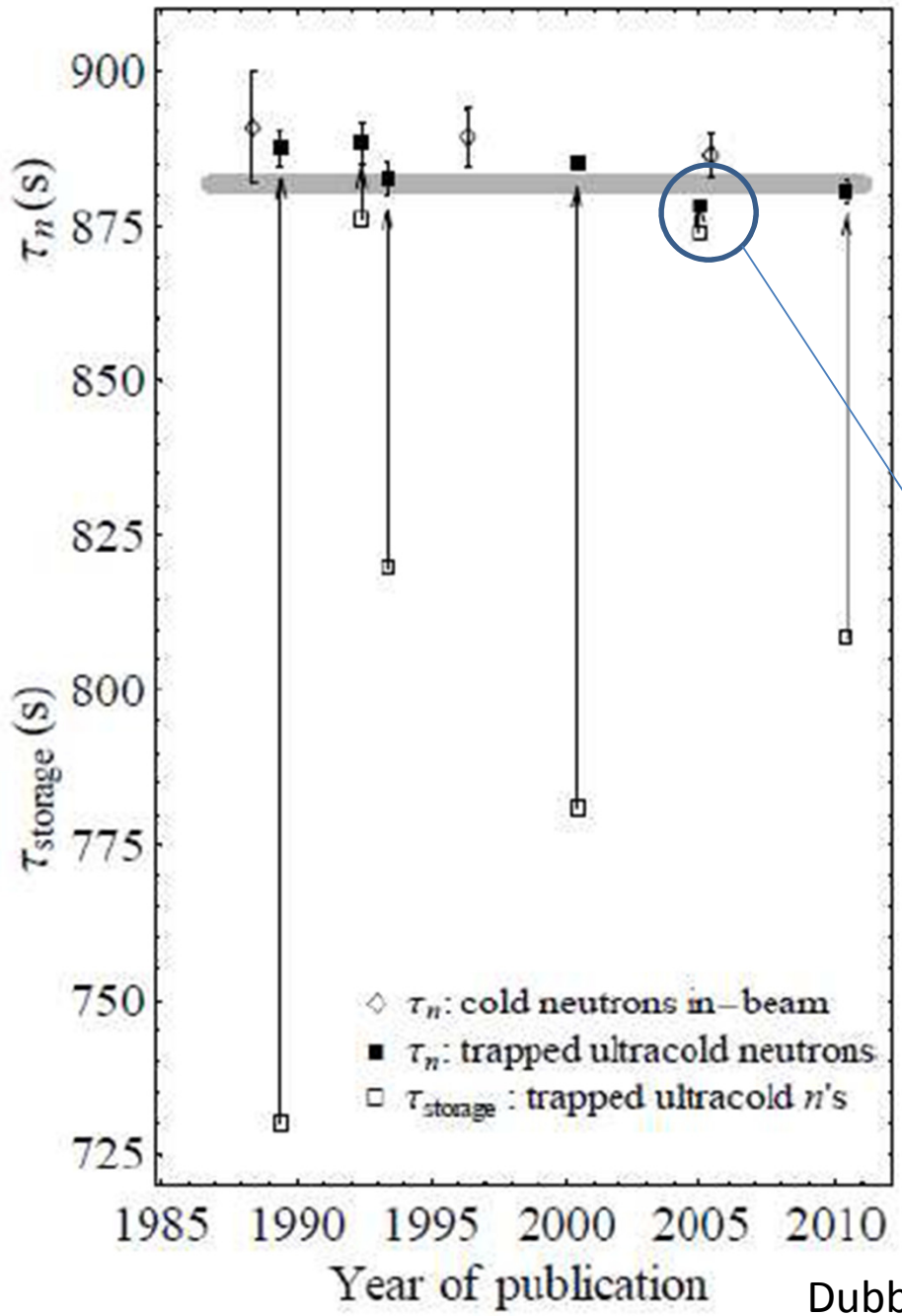


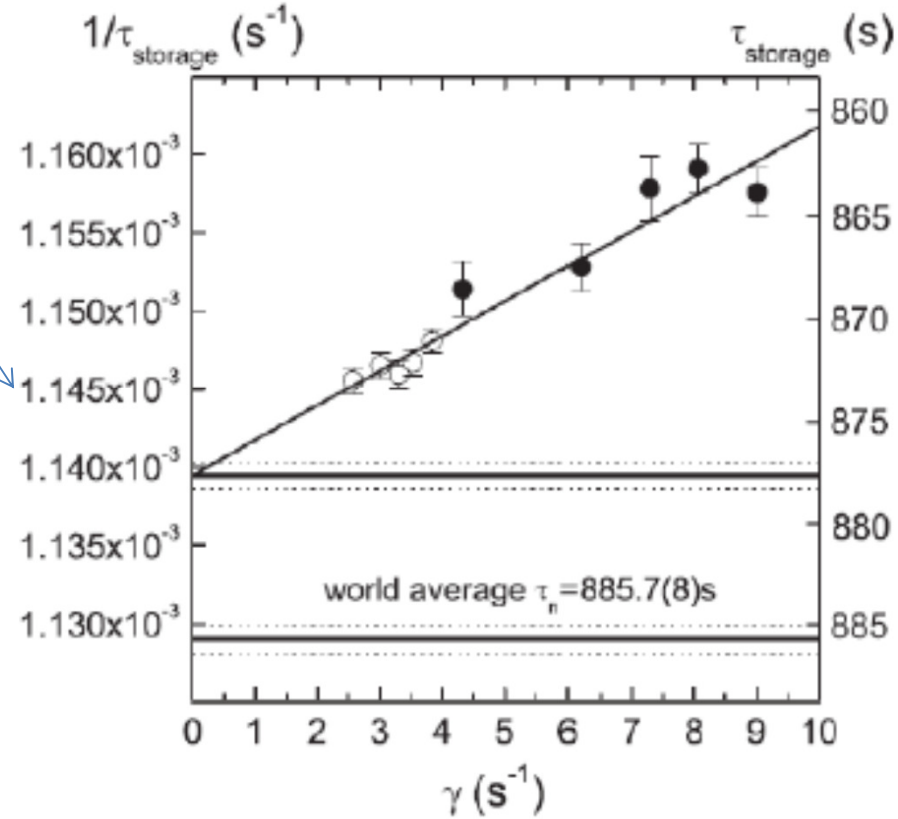
$$\tau_n = \frac{-(t_2 - t_1)}{\log(\frac{N_2}{N_1})}$$

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

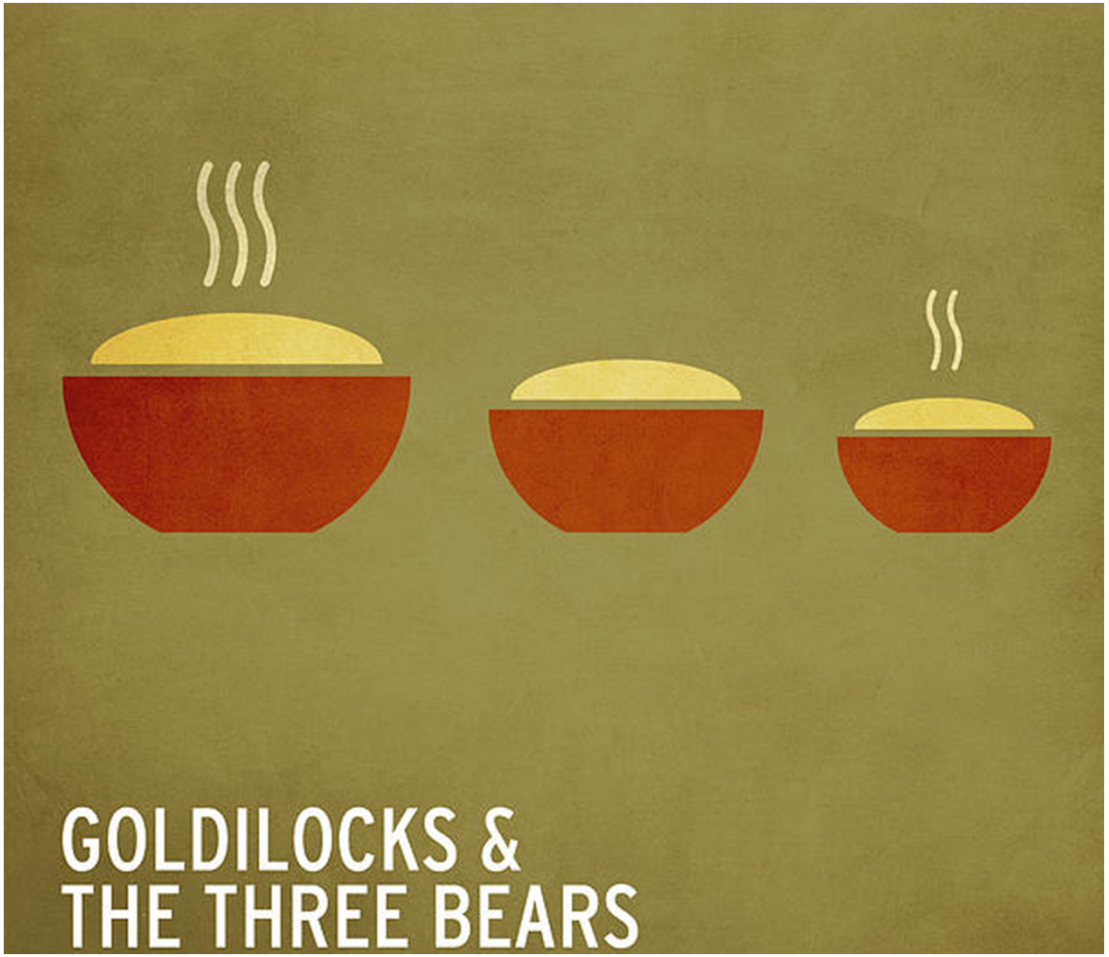




A. Serebrov et al., Phys. Rev. C 78, 035505 (2008)

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

Neutron Lifetime Measurement and the Three Bears

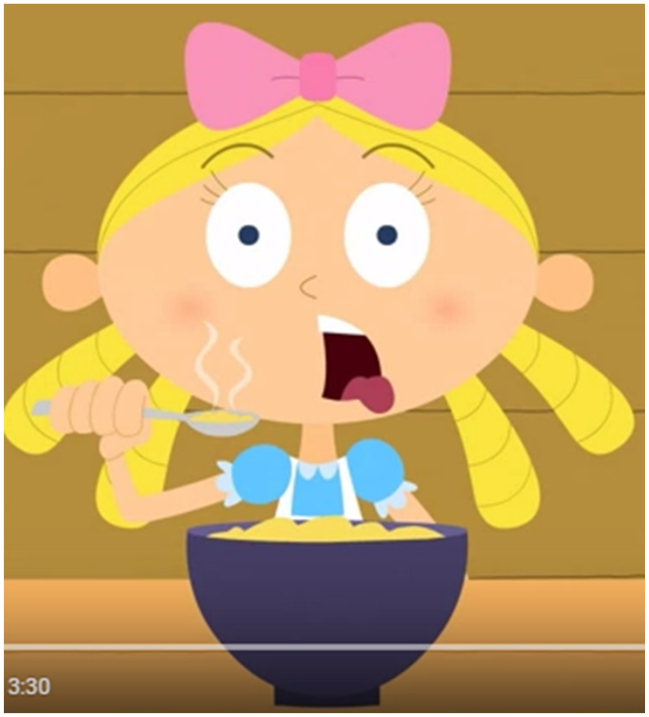


Experimentalists

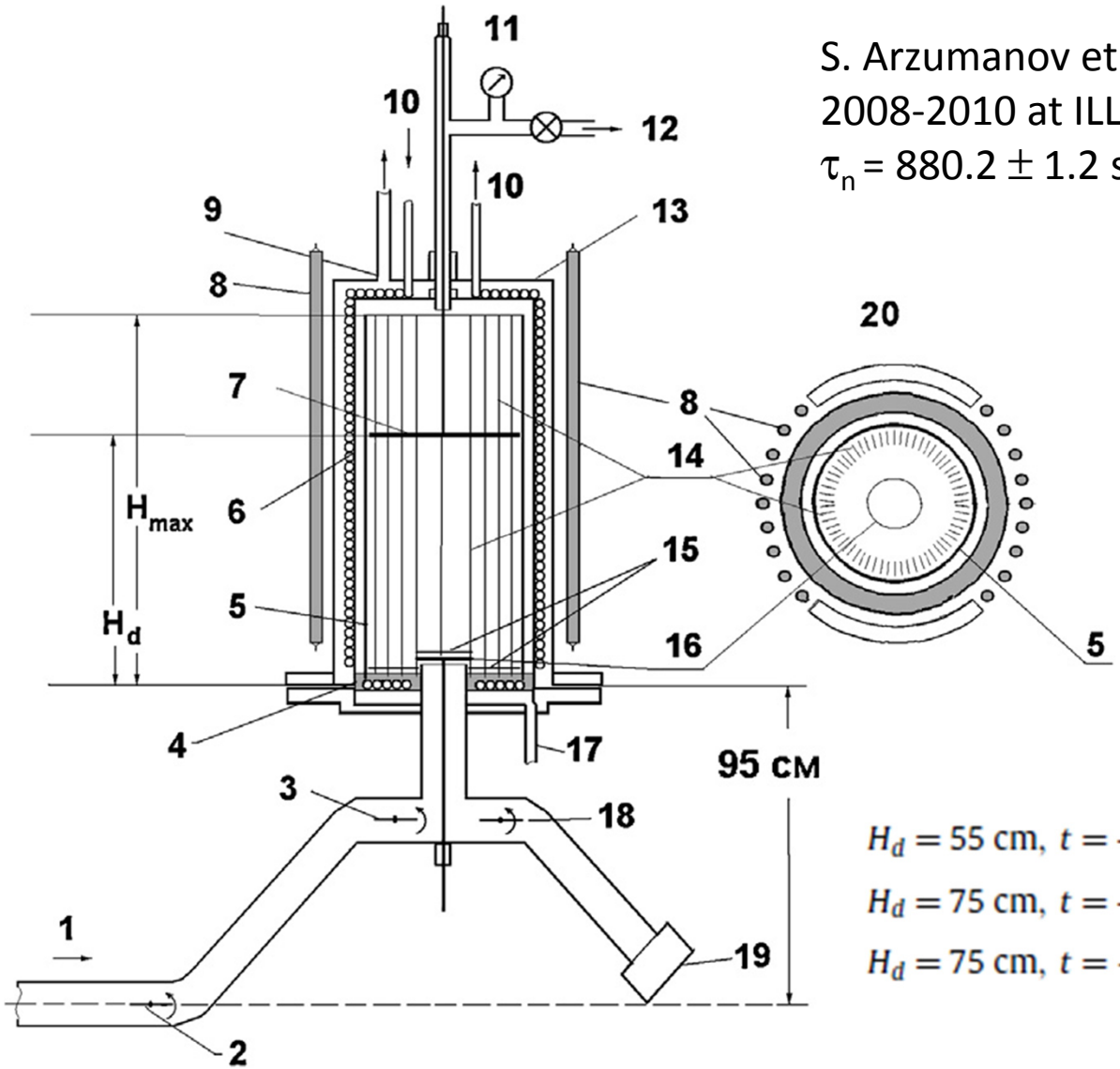
Baby Bear:
“Someone has been eating my porridge,…

and it is ALL GONE.”

The Culprit



The most recent result from a material bottle experiment



S. Arzumanov et al., Phys. Lett. B, 745, 79 (2015)
2008-2010 at ILL
$\tau_n = 880.2 \pm 1.2$ s

$H_d = 55$ cm, $t = +23\,^\circ$C; $\tau_\beta = 880.89 \pm 2.10_{st} \pm 1.49_{meth}$ s

$H_d = 75$ cm, $t = +23\,^\circ$C; $\tau_\beta = 880.57 \pm 0.95_{st} \pm 1.26_{meth}$ s

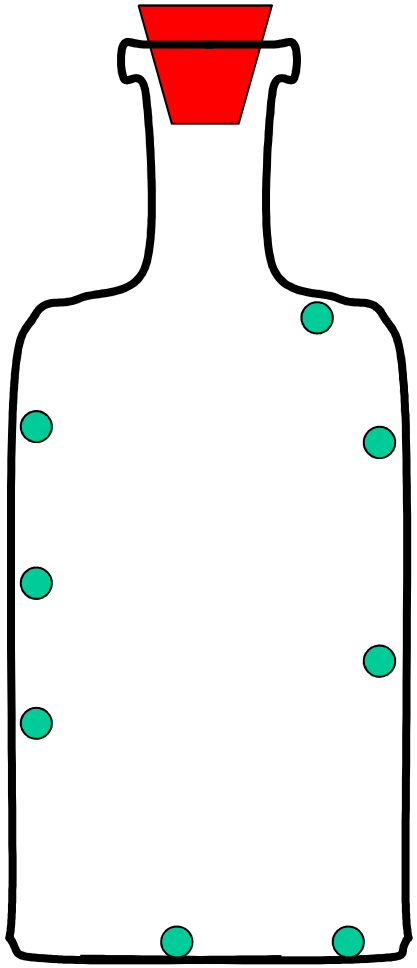
$H_d = 75$ cm, $t = -26\,^\circ$C; $\tau_\beta = 879.97 \pm 0.95_{st} \pm 0.57_{meth}$ s

Ultra-Cold Neutrons (UCN)

- What are UCN ?
  - Very slow neutrons

    ($v < 8$ m/s → $\lambda > 500$ Å)

    that cannot penetrate into certain material.

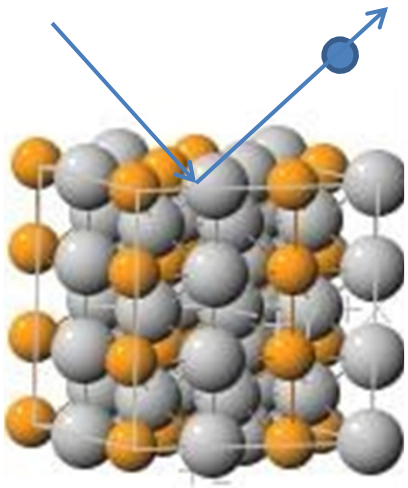


- **Long storage time**
- **Low radiation background**
- **100% polarization**

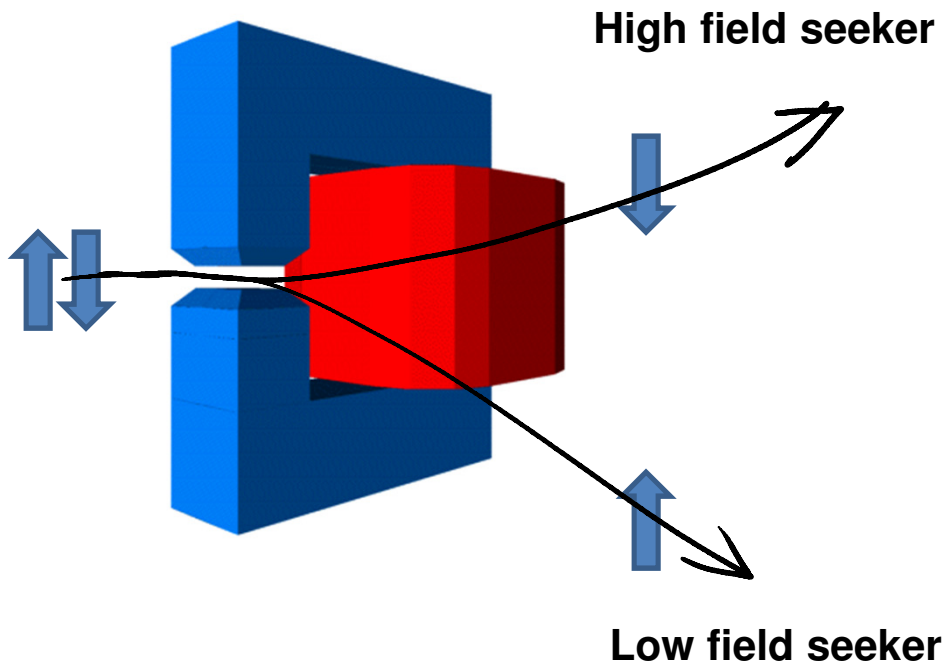
→ **Precision measurements**

Ultracold Neutrons

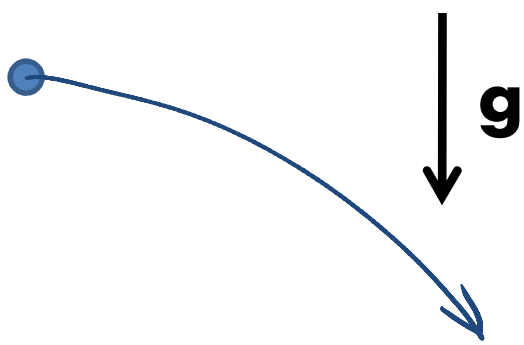
- Nuclear force (max: 350neV)

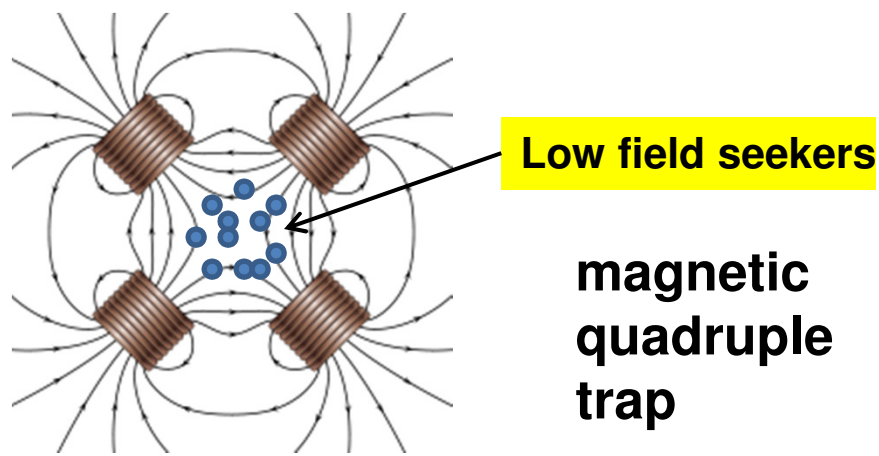


- Magnetic force (60neV/T)

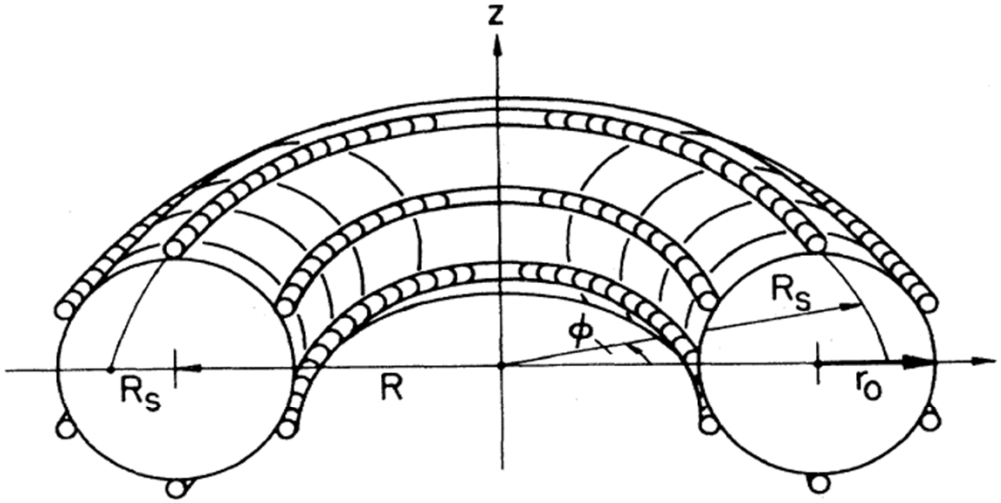


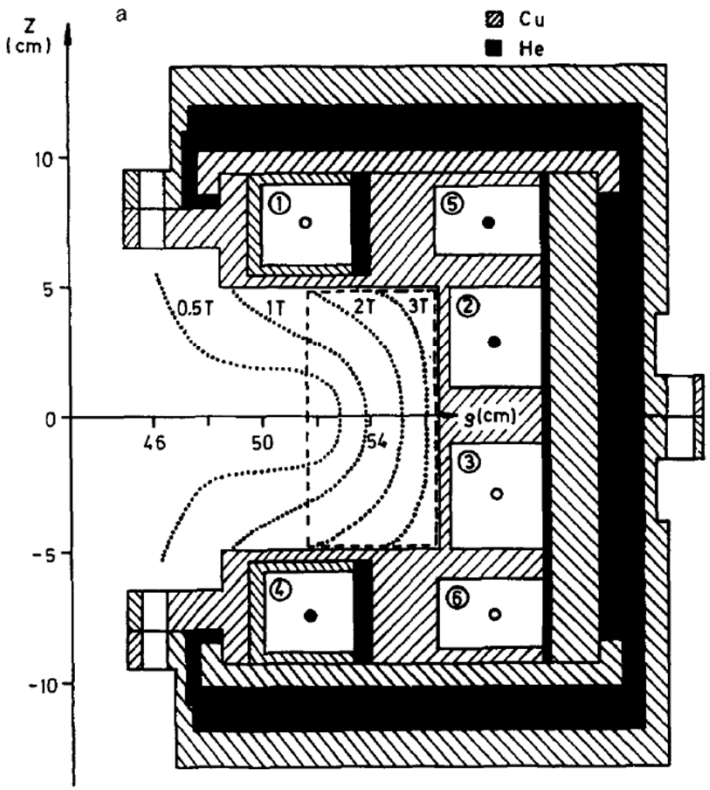
- Gravitational force (100neV/m)





NEtron STOrage Ring (NESTOR)





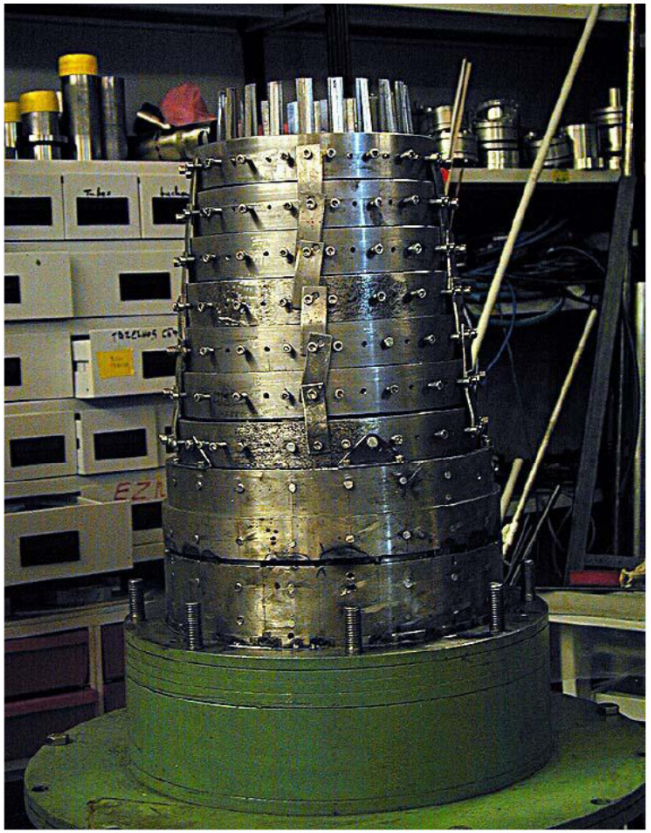
R ~ 0.5 m, Bmax = 3.5 T, current density: 250 A/mm

W. Paul et al (1970)

1989: τ_n = (877.0 ± 10) s

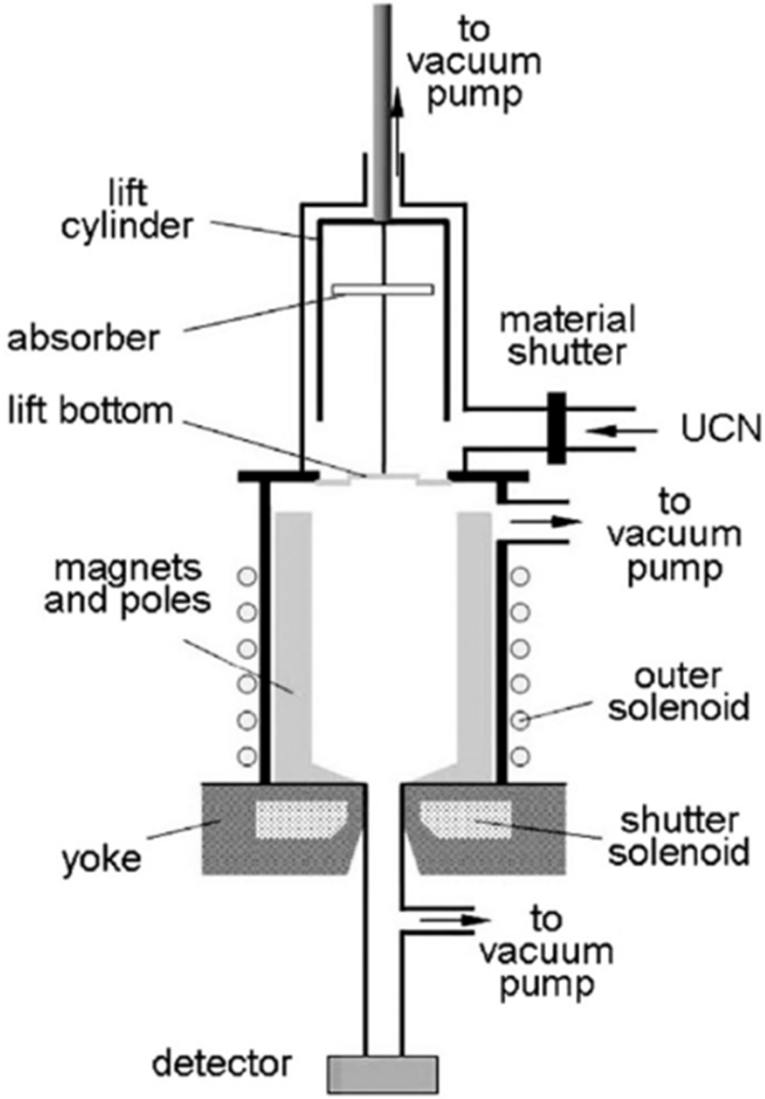
Problem: betatron motions mix with the cyclotron motion

UCN Lifetime Experiment at Institut Laue-Langevin



increase storage volume from 3.6 l to **15 l**

P. Geltenbort (V. Ezhov) Universida



Neutrons from the ILL turbine.

Trapped with permanent magnets and gravity.

Surviving neutrons counted.

V. Ezhov *et al.*, NIMA, 611, 167 (2009)

$\tau_n = 878.3 \pm 1.9$ s, arXiv:1412.7434 (2014)

Dr. Who & a captured Dalek

Main Features of the UCNτ Experiment

1. An intrinsically low loss rate and long trap lifetime
   → confinement w/ **magnetic fields & gravit**y; no material interaction.

2. Rapid evolution and mixing of the phase space
   → fast removal of quasi-bound neutrons; The neutron population quickly reach a stochastic distribution.

3. Phase-space insensitive detection scheme.
   → Negligible bias on neutron detection efficiency even if the neutron distribution could evolve between the short and long storage times.

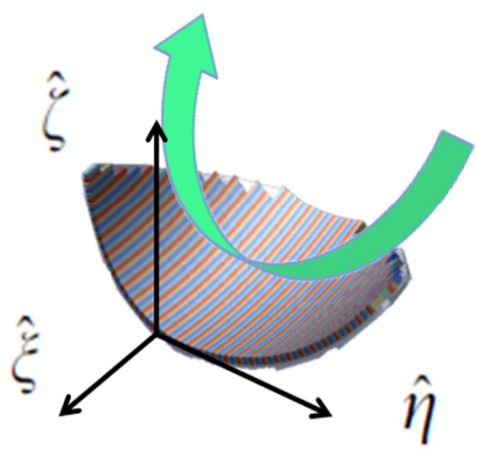
4. A large neutron statistics for sub-1 sec precision (1 s statistical uncertainty every few days)
   → enable data-driven study of systematic effects: needs a large volume, high UCN density, and high neutron detection efficiency.

UCNτ: Magneto-Gravitational Trap

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

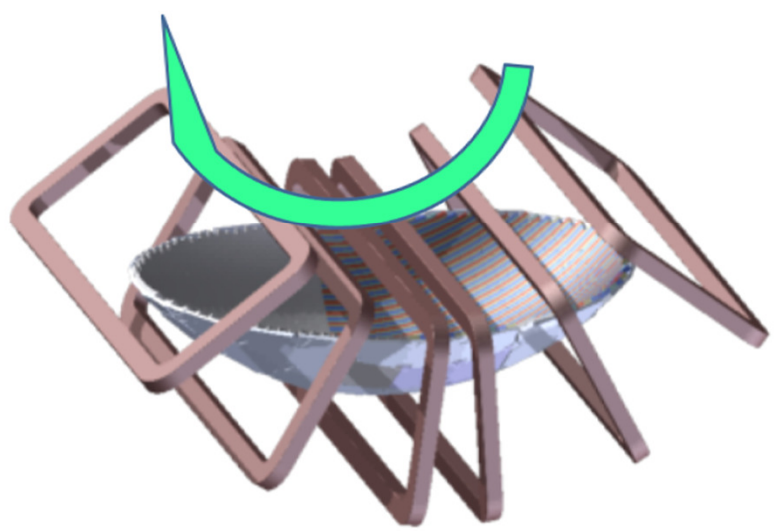
- **Minimize UCN spin-depolarization loss**: EM Coils arranged on the toroidal axis generates holding **B** field throughout the trap (perpendicular to the Halbach array field).

PM Array **B** along $\hat{\eta}$



Local Surface Coordinates

Guide Coils **B** along $\hat{\xi}$

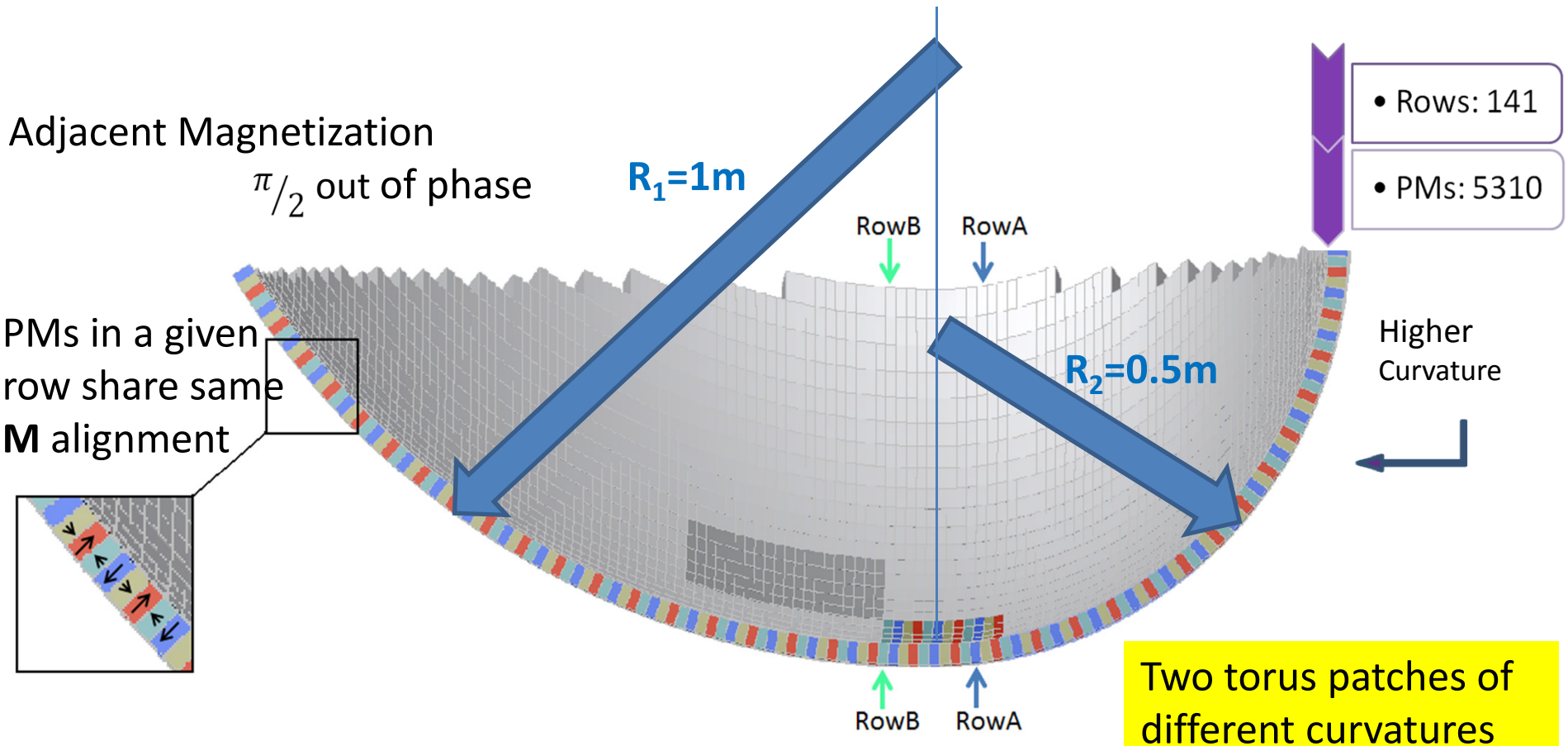


Walstrom et al, NIMA, 599, 82 (2009)

Asymmetric Trap induces ``Phase Space Mixing”

Low symmetry, together with **field ripples**, enhance states mixing between (quasi)-periodic orbits through chaotic motion.

→ **quick cleaning** (~ 10s of seconds) of the ‘quasi-bound’ UCN.



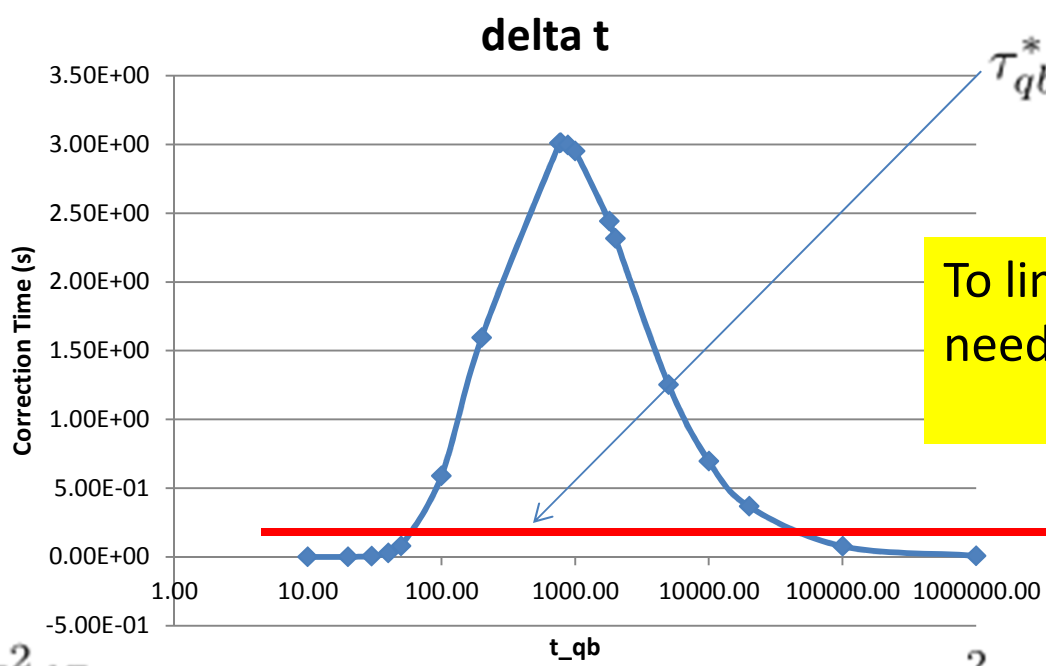
Two torus patches of different curvatures join along middle row

Quasi-bound Neutrons

If the QB neutrons are not sufficiently cleaned, they will leak out of the trap with its own characteristic time constant τ_{qb}. The resulting correction time is:

$$\Delta\tau = \frac{\tau_\beta^2}{(t_2 - t_1)}\epsilon\left[\exp(-t_1/\tau_{qb}) - \exp(-t_2/\tau_{qb})\right]$$

t_2 = 2000 s
t_1 = 200 s
ε = 0.01



$$\tau_{qb}^* = \frac{t_2 - t_1}{\ln(\frac{t_2}{t_1})}$$

To limit $\Delta t < 0.1$ s for all τ_{qb}, need $\varepsilon < 3e\text{-}4$

$\Delta t = 0.1$ s

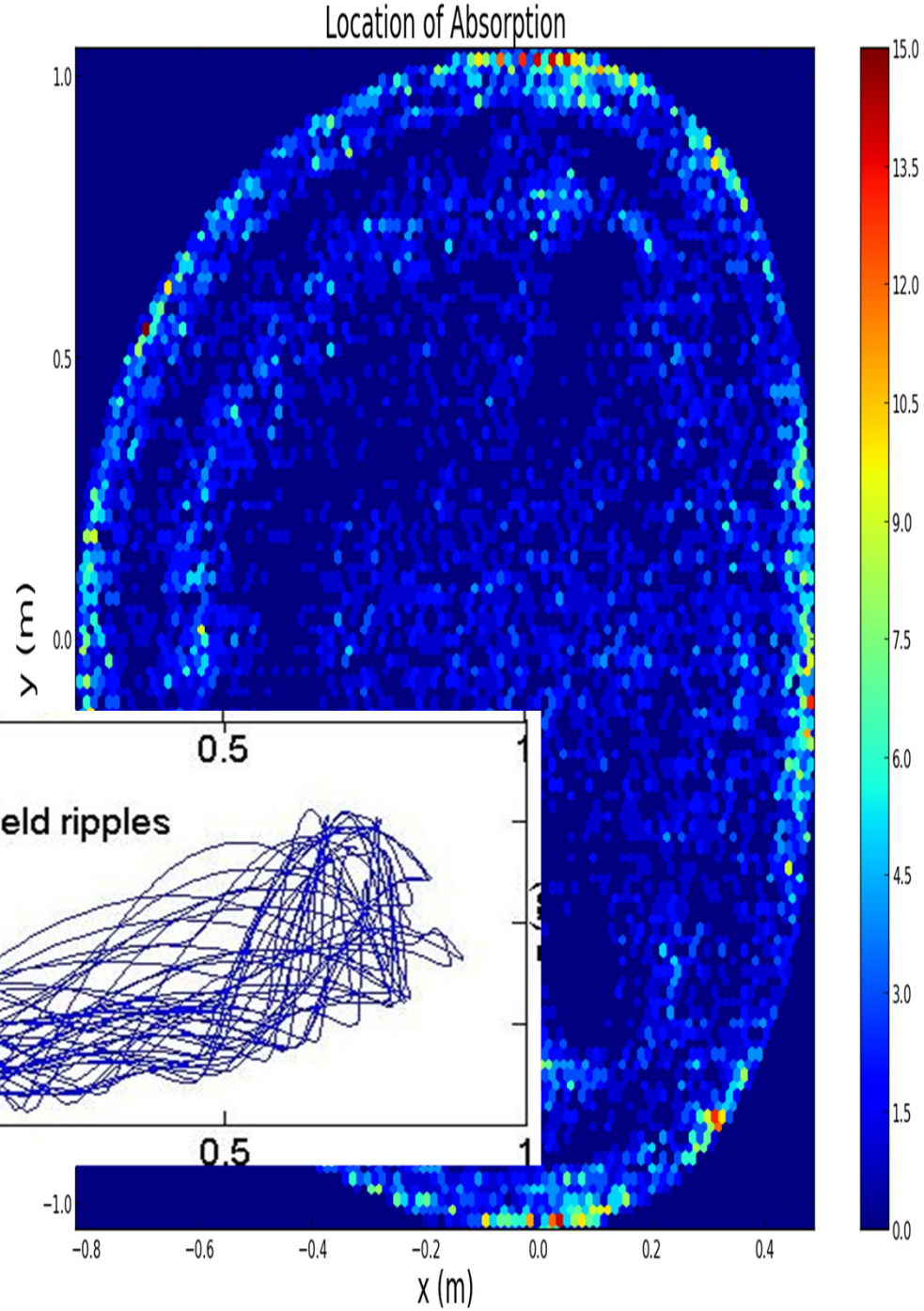
$$\Delta\tau \cong \frac{\tau_\beta^2 \epsilon \tau_{qb}}{t_1 t_2} \text{ for } \tau_{qb} \to 0$$

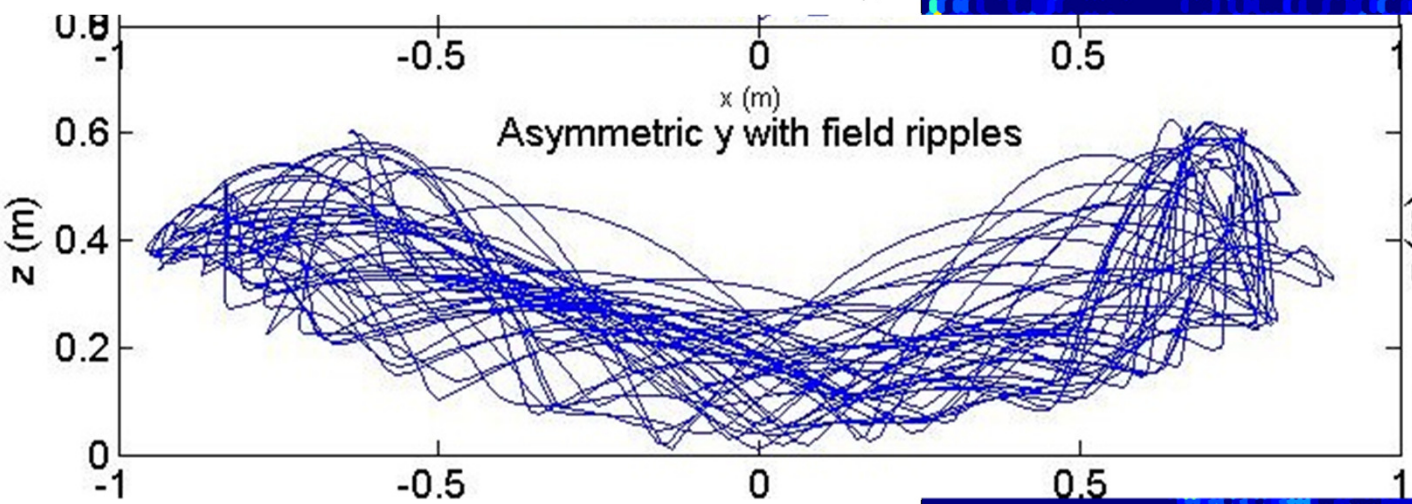
$$\Delta\tau \cong \frac{\tau_\beta^2 \epsilon}{\tau_{qb}} \text{ for } \tau_{qb} \to \infty$$

UCN Spectrum Cleaning

$E_{max} = E_0 + 6$ neV

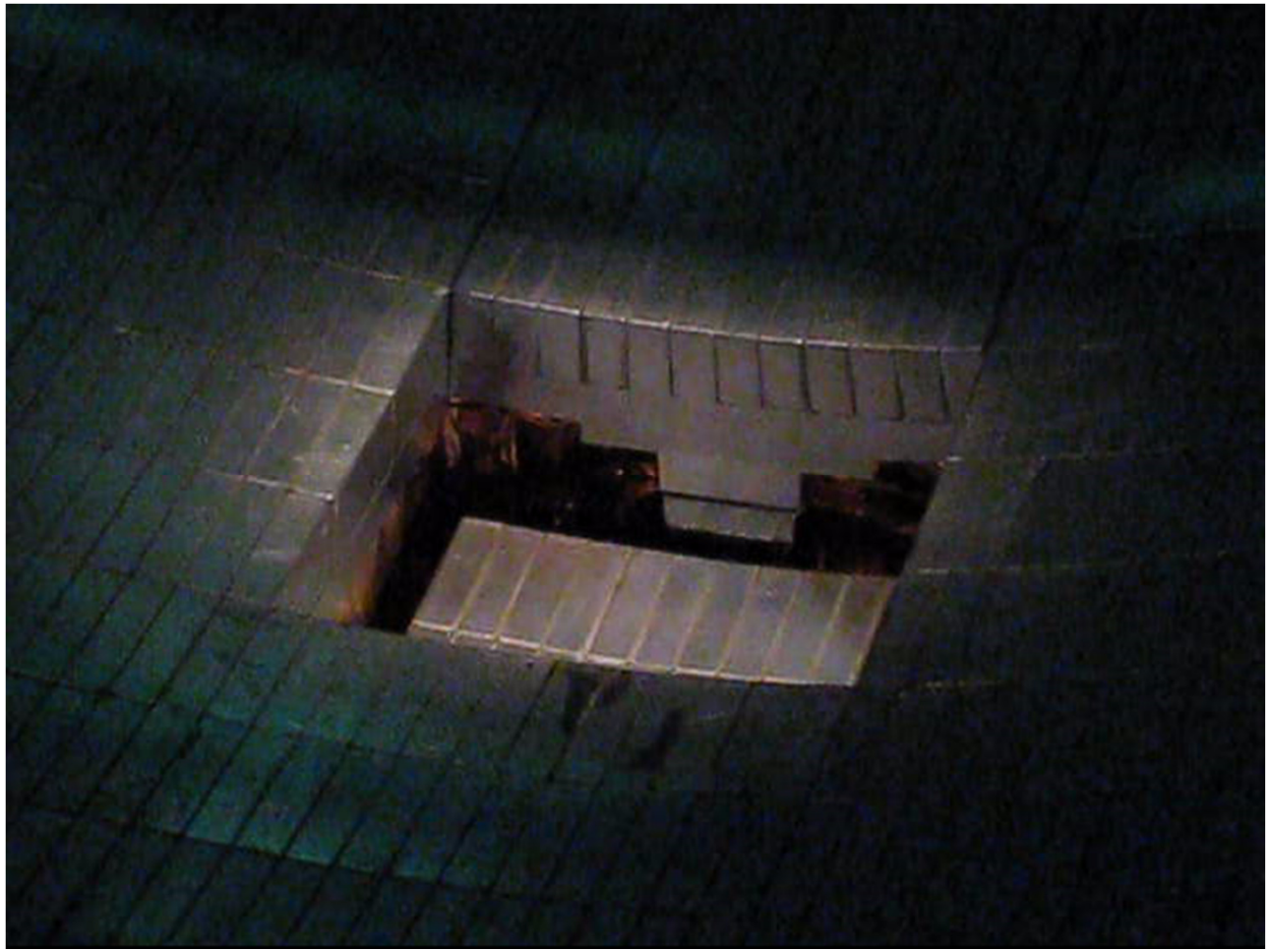
$E_0 = 50$ neV: trap threshold





Halbach Array Completion: Dec 2012

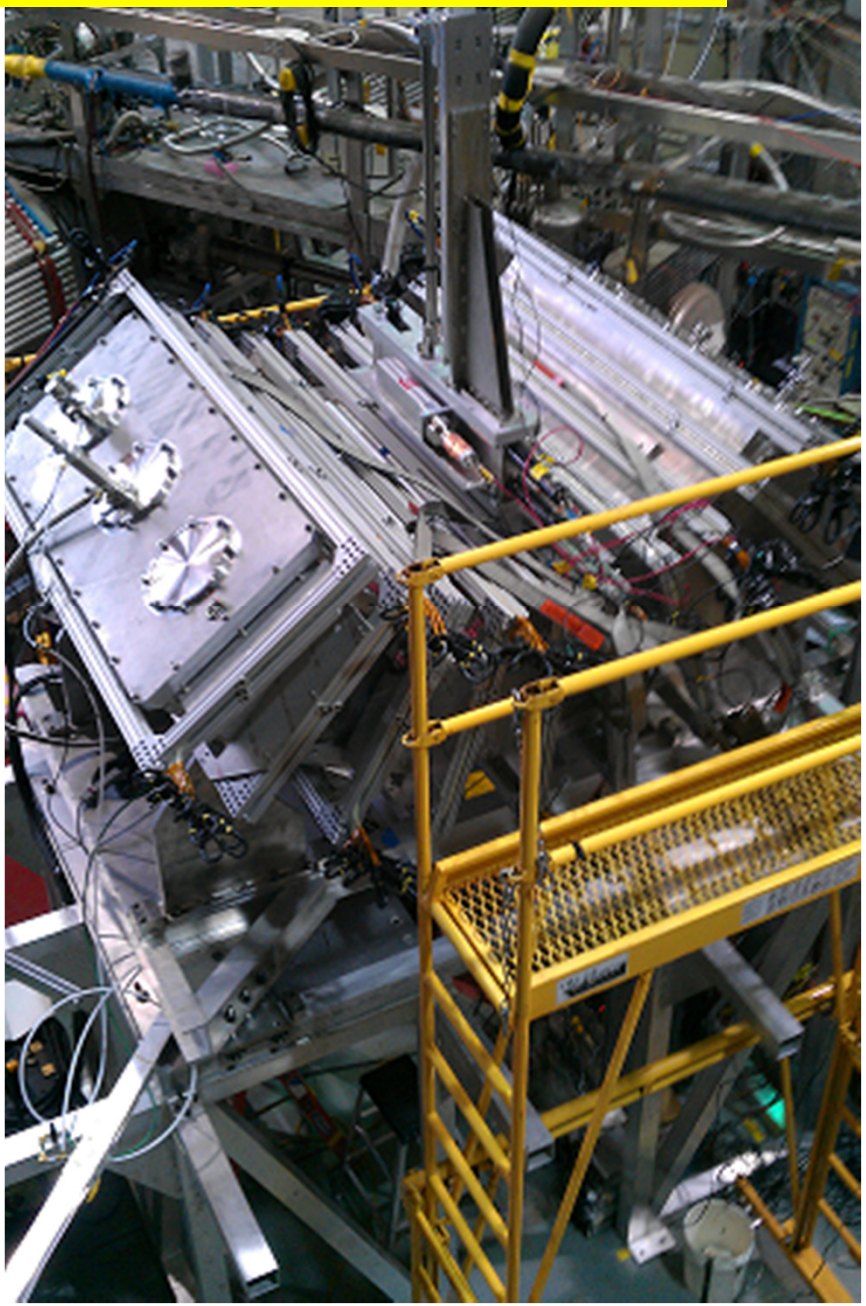
Trap Door Actuation



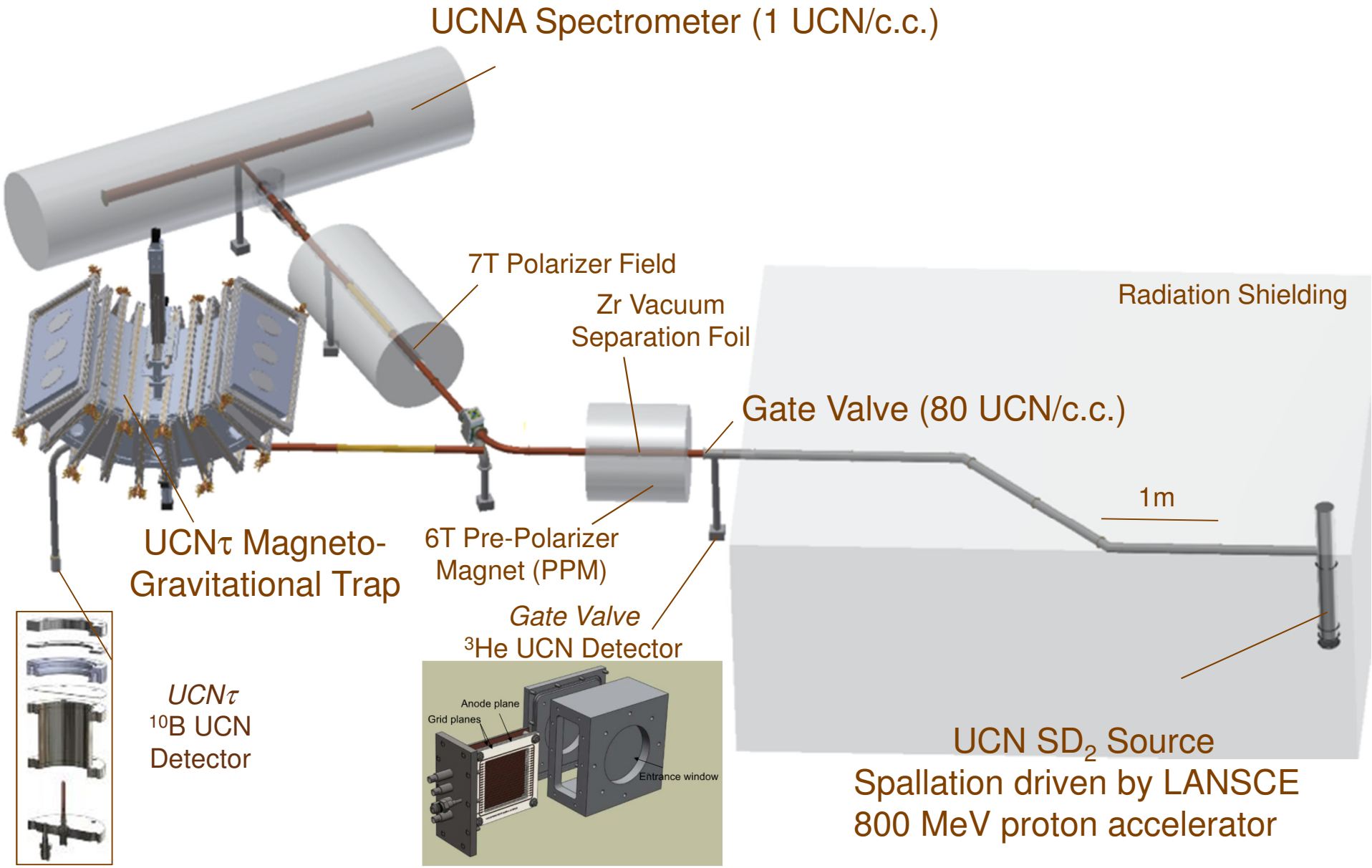
Gap size ~ 0.003”.

Continous B fields prevent the UCN from leaking through the gaps.

UCNtau apparatus installed at the LANSCE UCN facility: Feb. 2013



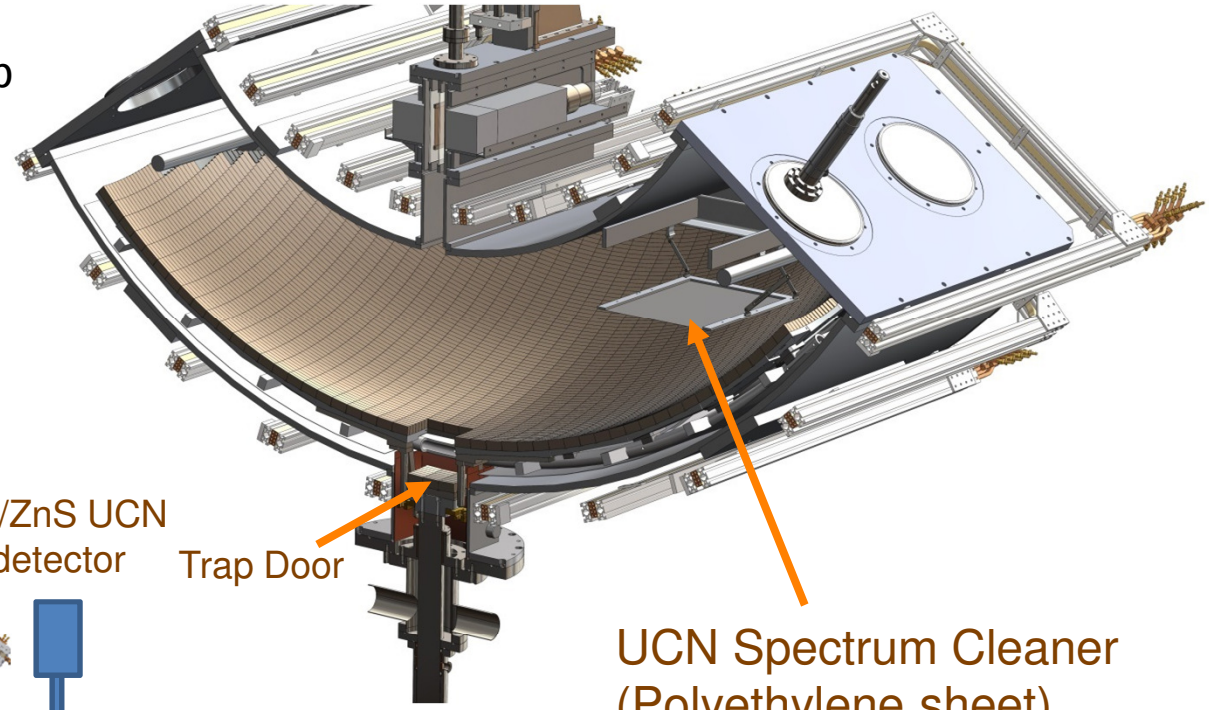
The UCNτ Experiment at LANSCE

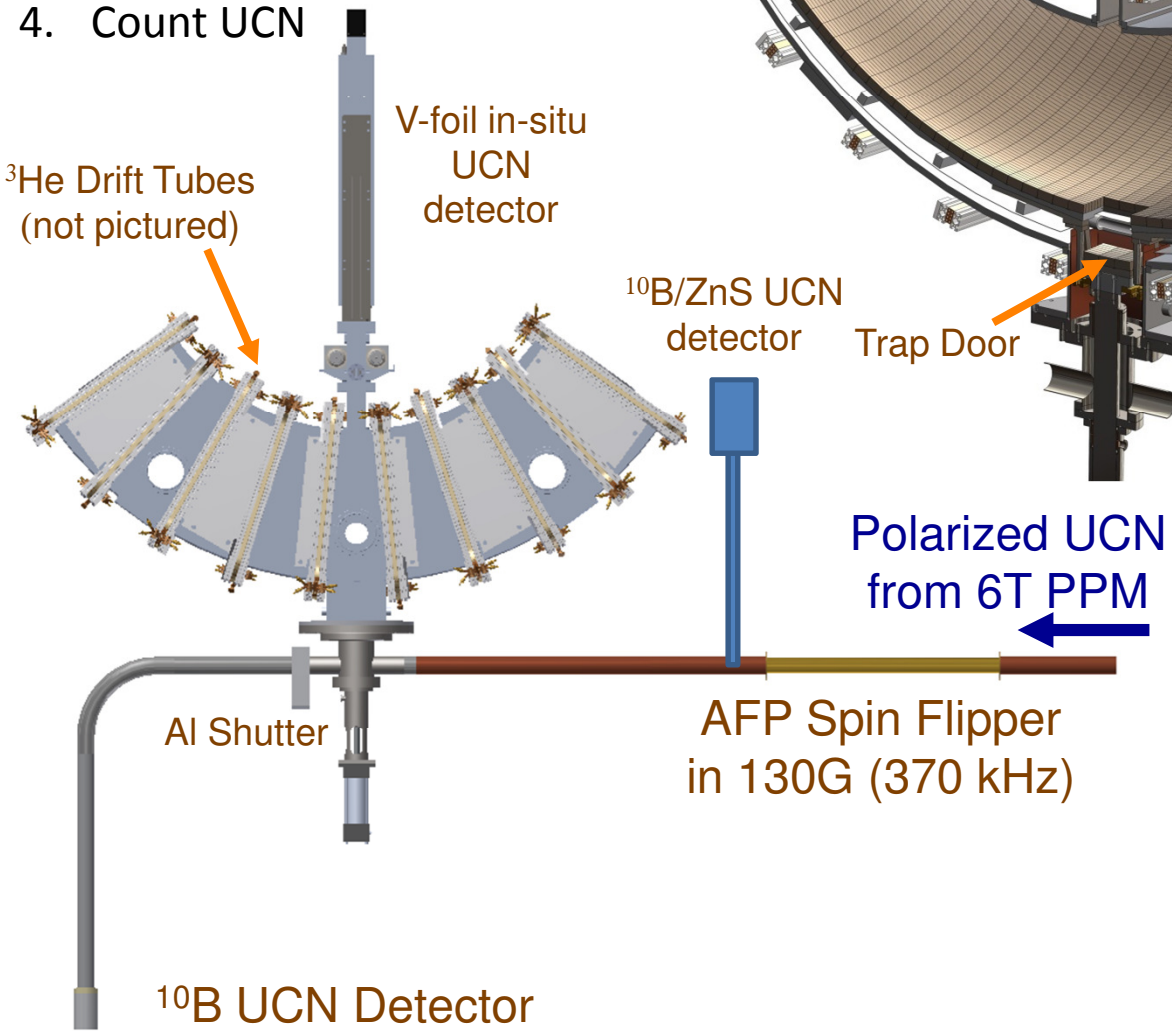


Operation of the UCNτ Experiment

"*Fill-Store-Count*" cycle

1. Fill polarized UCN into the trap
2. Clean the UCN spectrum
3. Store UCN
4. Count UCN





Detector R&D:

2013: External UCN detector

2014-2015: V-foil *in-situ* UCN detector

2015-2016: 10B/ZnS *in-situ* UCN detector

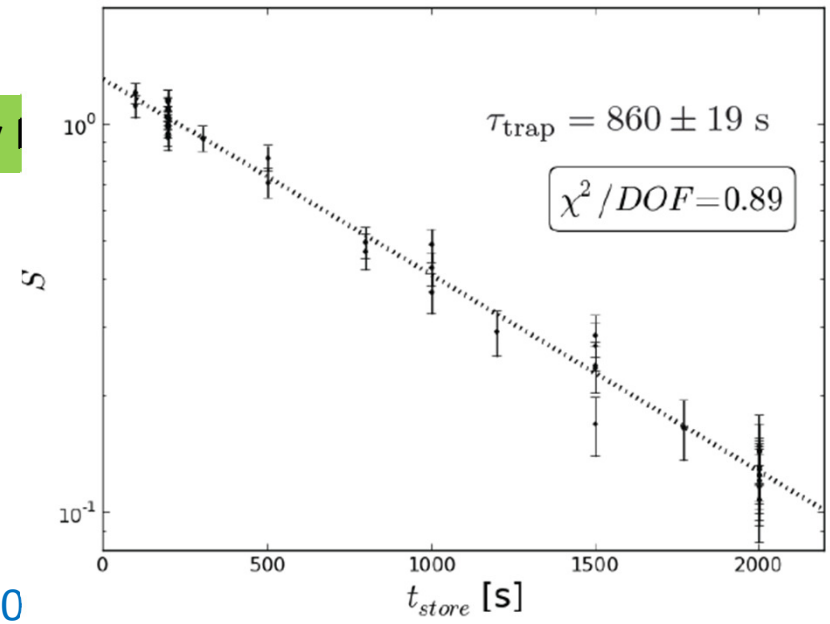
Fill-Store-Count: UCN dumped into an external detector

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

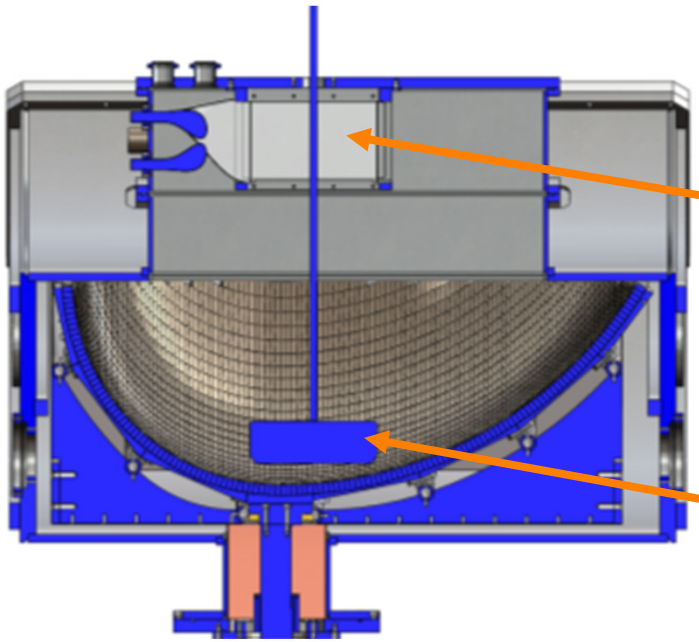
200 s storage run, followed
by a 2000 second storage run

Example Fill-and-Empty

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



Fill-Store-Count: neutron hit and activate a V foil



Plastic Scintillator for β's
NaI for γ's

coincidence: suppress background

① V foil lowered into trap from above (~1s)
② Remaining UCN are absorbed (~20s for current small foil)
③ V foil raised and activity is measured

Neutron scattering lengths and cross sections							
Isotope	conc	Coh b	Inc b	Coh xs	Inc xs	Scatt xs	Abs xs
V	---	-0.3824	---	0.0184	5.08	5.1	5.08
50V	0.25	7.6	---	7.3(1.1)	0.5	7.8(1.0)	60.(40.)
51V	99.75	-0.402	6.35	0.0203	5.07	5.09	4.9

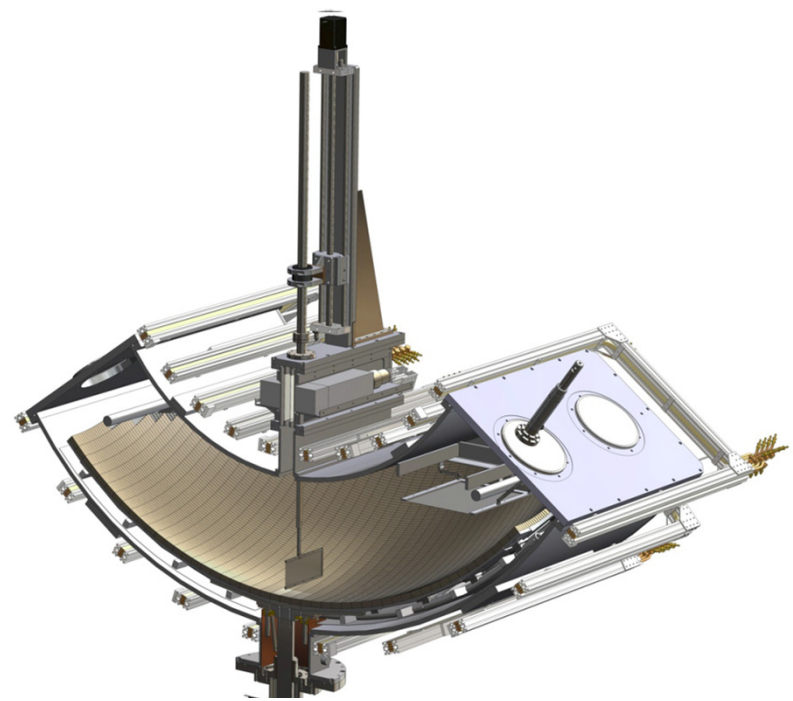
Negative Material Potential

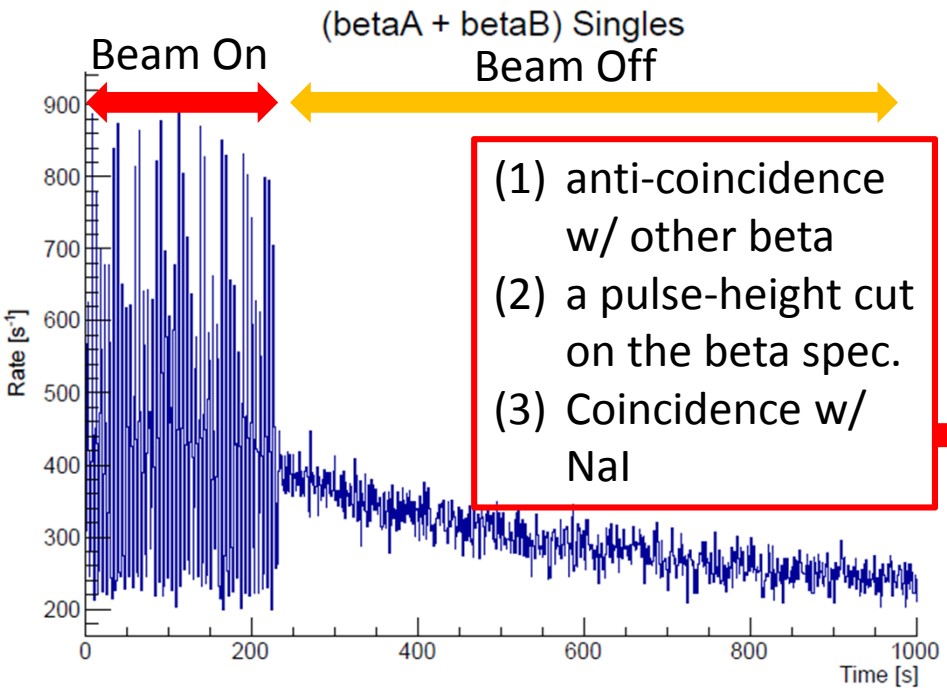
Good n Absorber

$$^{51}\mathrm{V} + \mathrm{n} \rightarrow {}^{52}\mathrm{V}$$

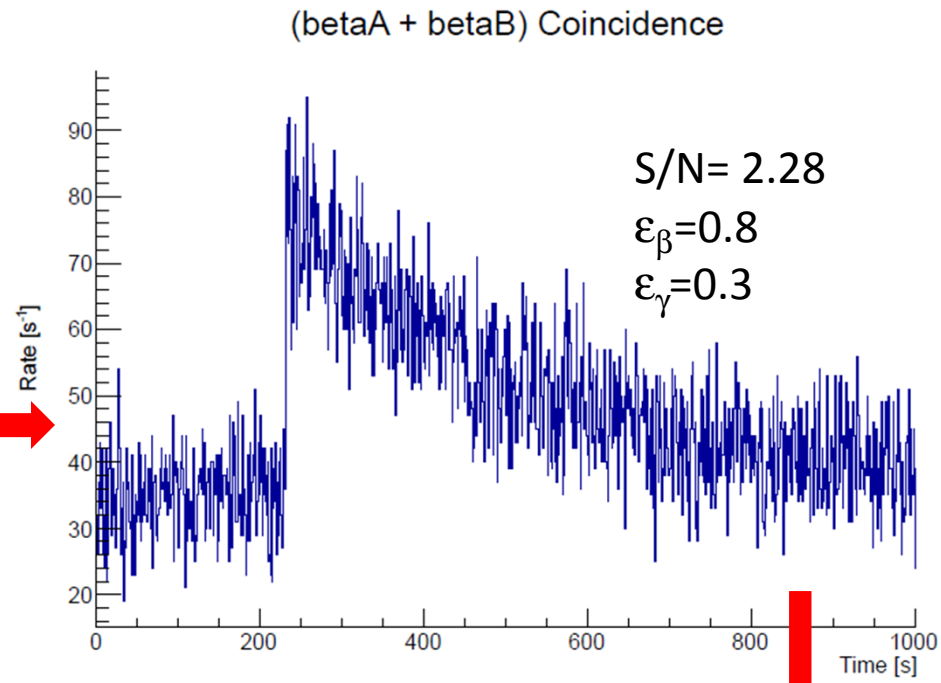
$$T_{1/2} = 3.7 \text{ min.}$$

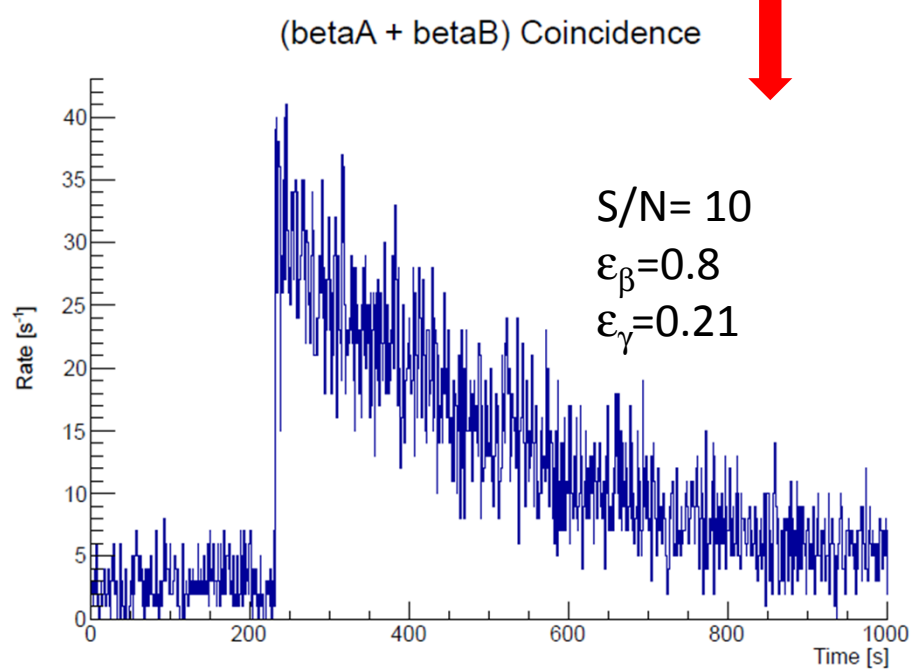
$$^{52}\mathrm{V} \rightarrow {}^{52}\mathrm{Cr} + \beta^{-}(0 \text{ -- } 2.54 \text{ MeV}) + \gamma\,(1.43 \text{ MeV})$$





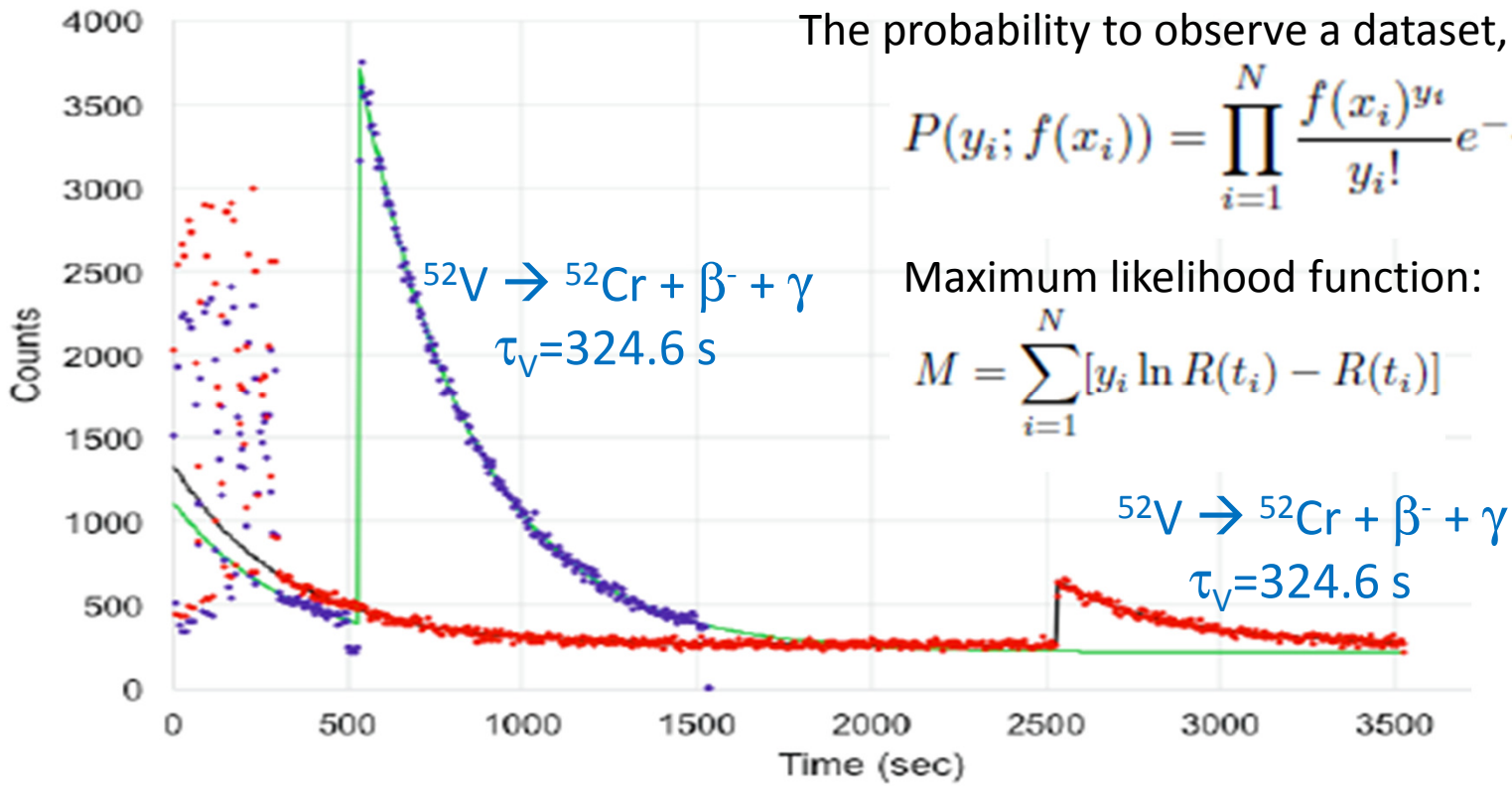
(1) anti-coincidence w/ other beta
(2) a pulse-height cut on the beta spec.
(3) Coincidence w/ NaI





Cut Criteria:
(1) beta event is not coincident with a beta event in the other detector
(2) beta event pulse-height (460~8000).
(3) beta event is coincident with an NaI event
(4) NaI event a pulse-height (2500~3500)

Data Analysis on 2014-2015 Dataset



The probability to observe a dataset, (x_i, y_i) , is

$$P(y_i; f(x_i)) = \prod_{i=1}^{N} \frac{f(x_i)^{y_i}}{y_i!} e^{-f(x_i)}$$

Maximum likelihood function:

$$M = \sum_{i=1}^{N} [y_i \ln R(t_i) - R(t_i)]$$

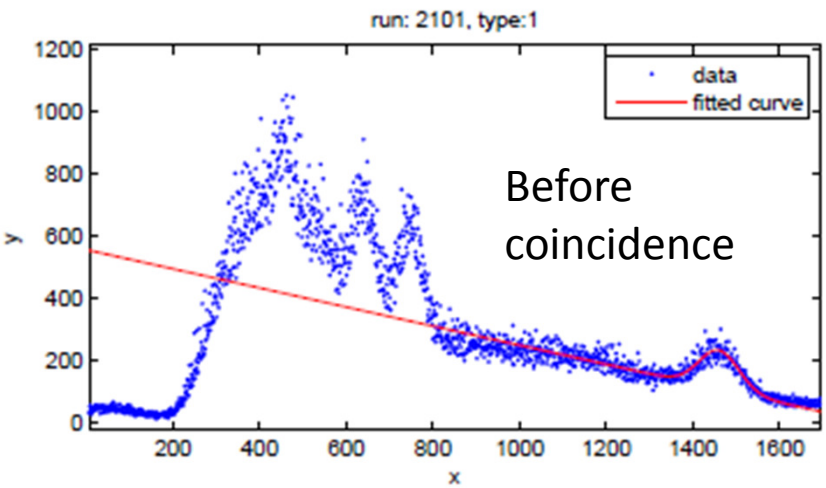
$$R(t) = \begin{cases} a\exp(-t/324.6) + c & \text{if } t < t_{count} \\ a\exp(-t/324.6) + c + (d/324.6)\exp(-(t - t_{count})/324.6) & \text{if } t > t_{count}, \end{cases}$$

N_1 or N_2

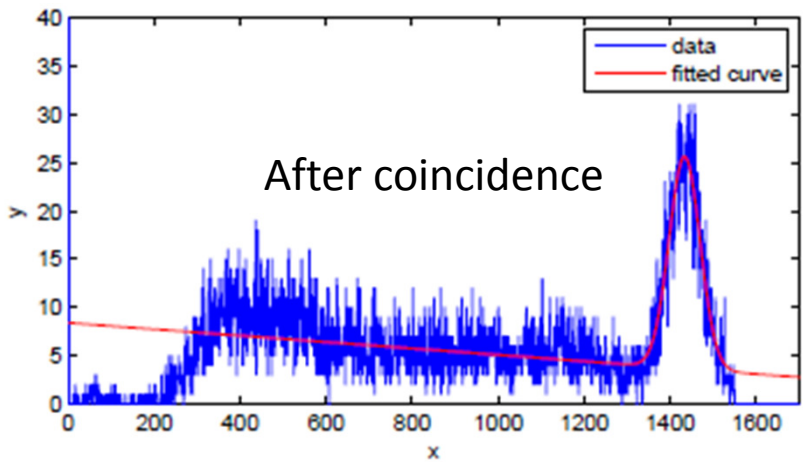
Background

UCN signal

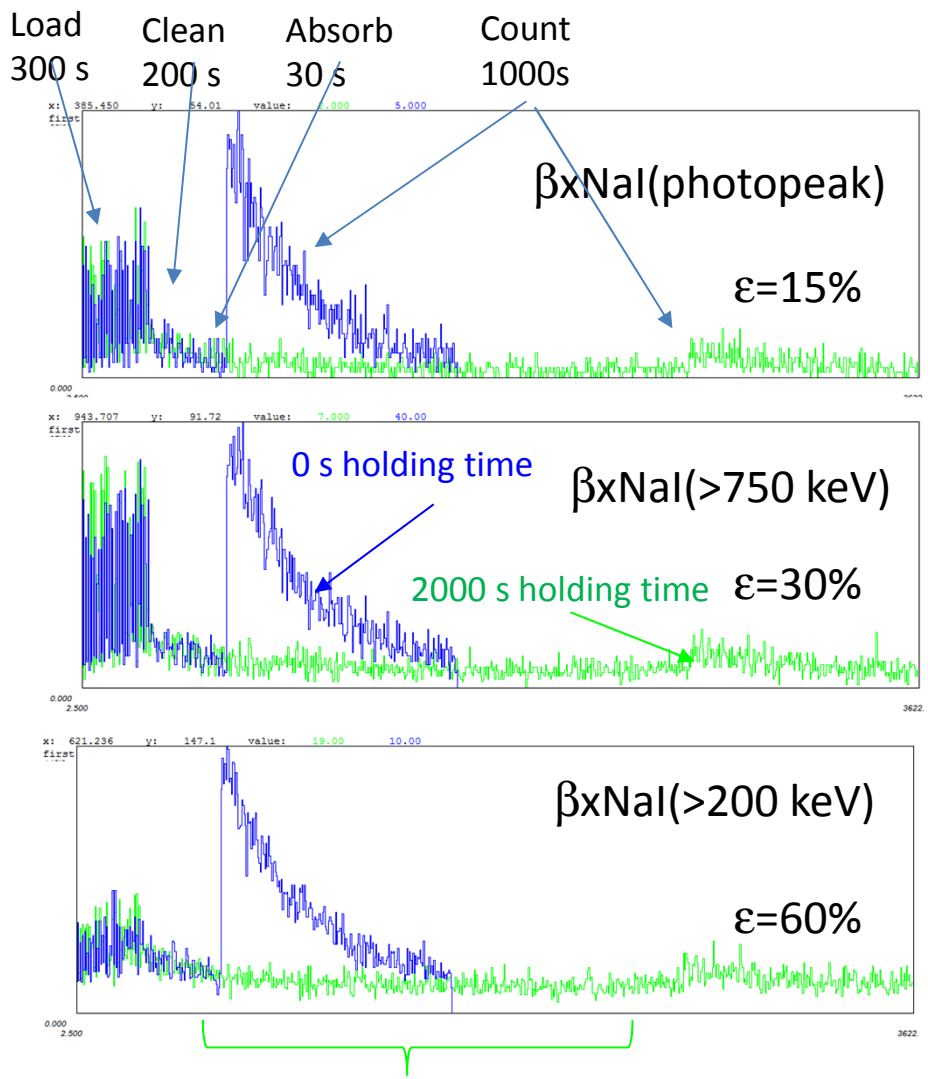
Energy cut on gamma events

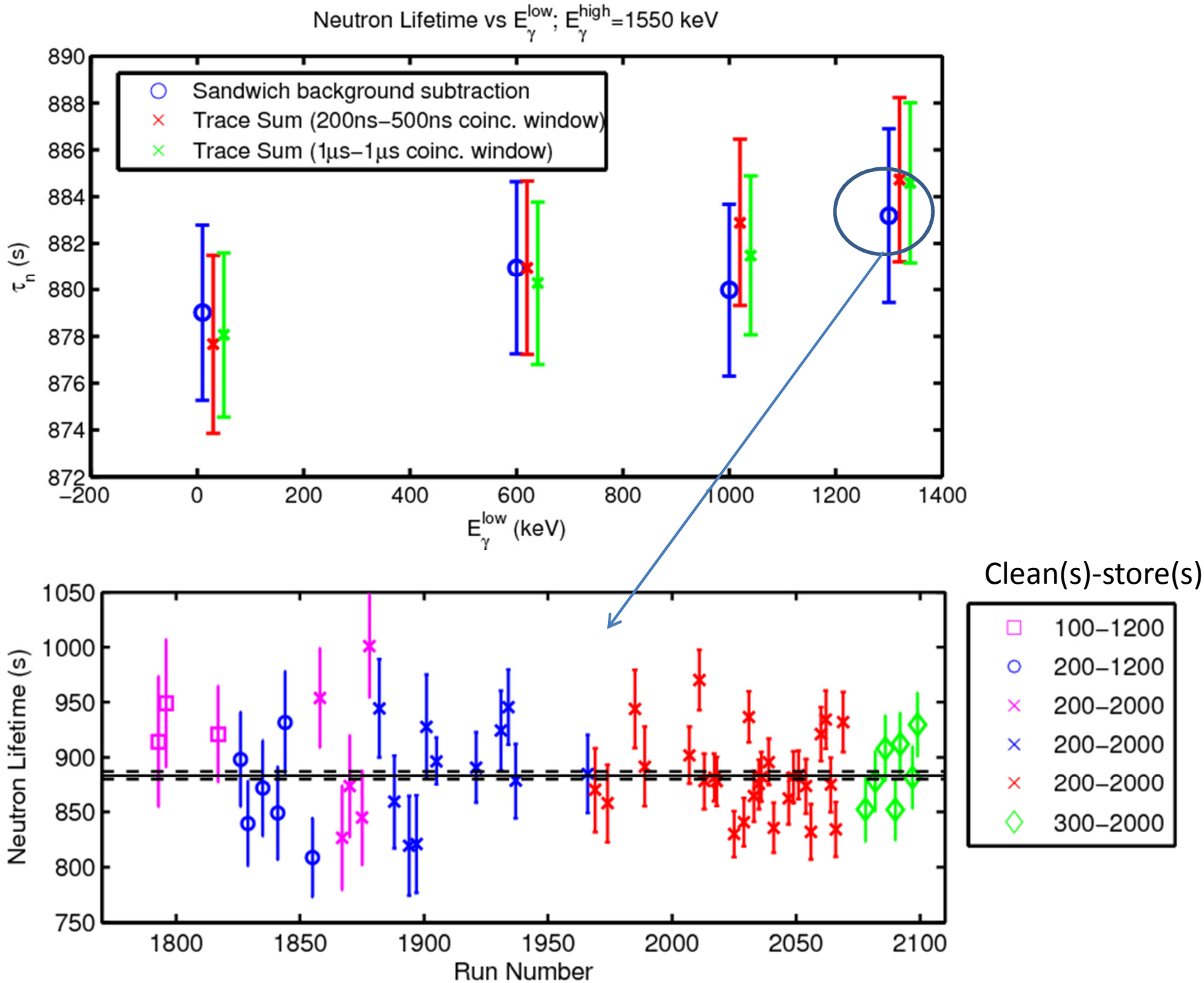


Eγ (keV)



Eγ (keV)



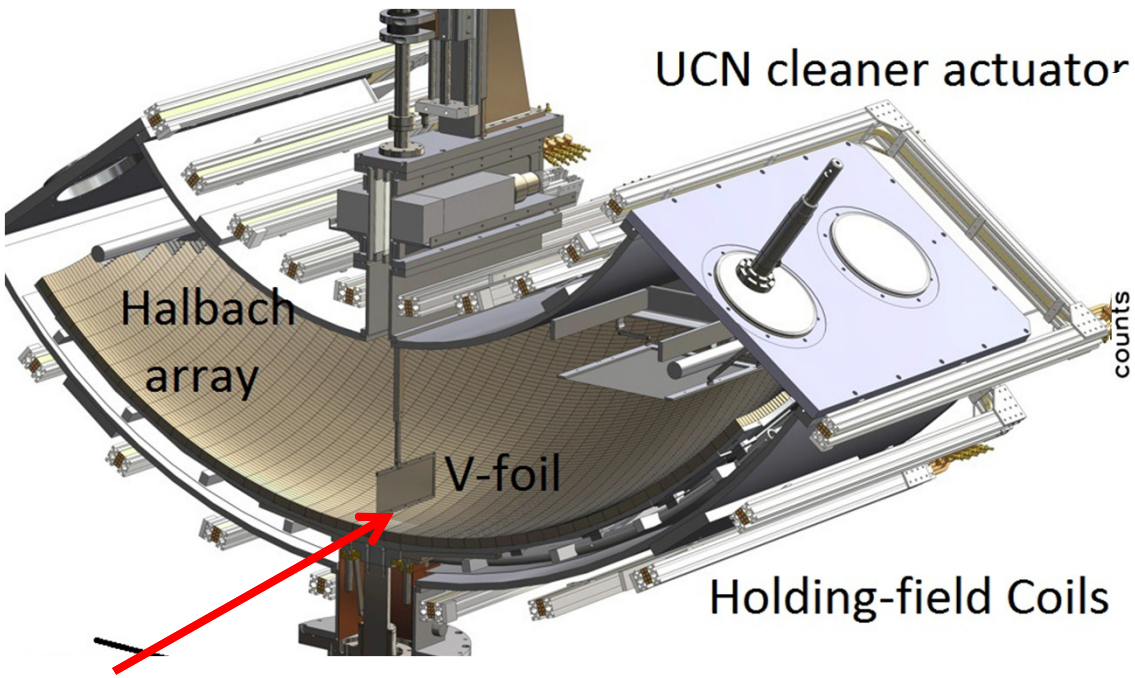

Neutron Lifetime vs E_γ^{low}; E_γ^{high}=1550 keV
Sandwich background subtraction
Trace Sum (200ns–500ns coinc. window)
Trace Sum (1μs–1μs coinc. window)
τ_n (s)
E_γ^{low} (keV)
Clean(s)-store(s)
100–1200
200–1200
200–2000
200–2000
200–2000
300–2000
Neutron Lifetime (s)
Run Number

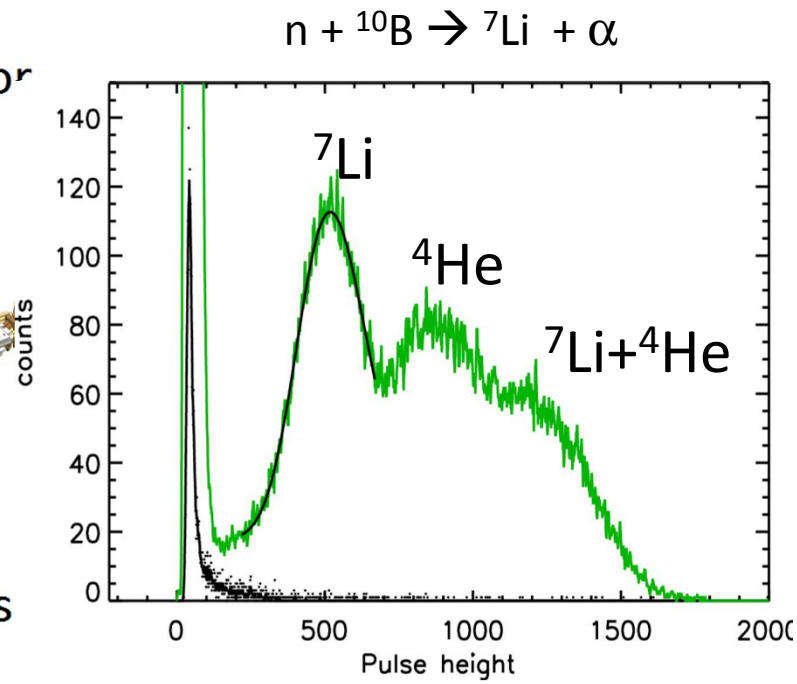
Estimate of Systematic Effects

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	$< 5 \times 10^{-4}$	±	sim	verify position reproducibility
microphonic heating	$< 1 \times 10^{-4}$	+	sim	accelerometer measurements
dead time/pileup	$< 1 \times 10^{-4}$	±	calc	pileup ID/artificial dead time
gain drifts	$< 2 \times 10^{-4}$	±	meas	spectral monitoring/gain monitoring
time-dep. background	$< 5 \times 10^{-4}$	±	meas	background data analysis
phase space evolution	$< 5 \times 10^{-4}$	±	sim	vanadium time studies, active detector
UCN monitoring	$< 3 \times 10^{-4}$	±	meas	measure monitor response/source stability
total	$< 1.2 \times 10^{-3}$	±		(uncorrelated sum)

2015 upgrade: Active *in-situ* UCN Detectors



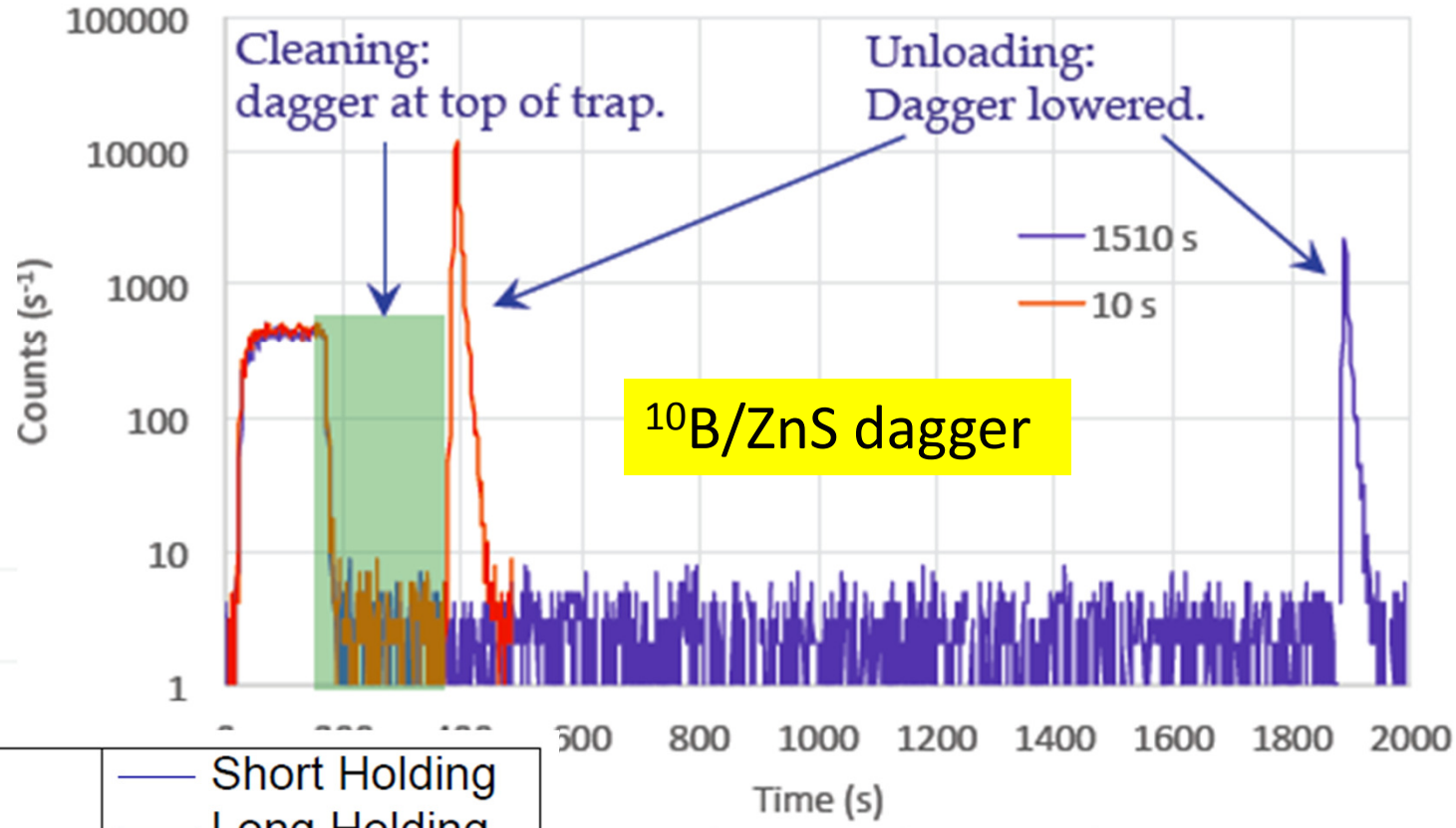


Z. Wang et al., NIMA 798, 30 (2015).

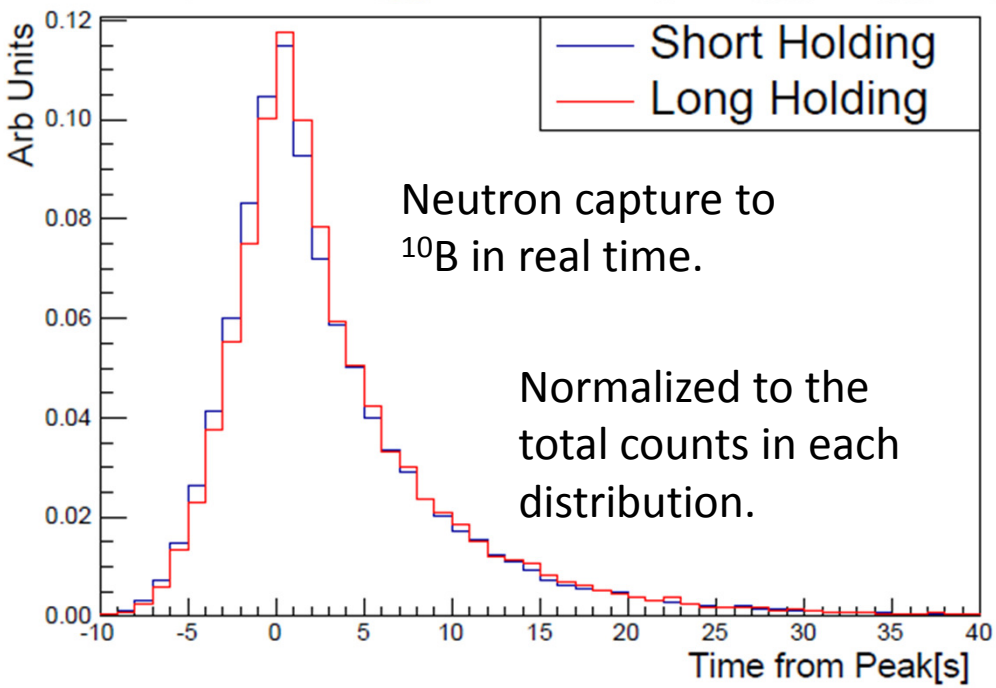
V-foil replaced with a ^{10}B/ZnS detector, which allows:

- Counting UCNs *as they are absorbed* (in real time) rather than the delayed decays of the absorption product.
- Measuring the timing spectrum of UCN absorption, to monitor the possible phase-space evolution of UCN in the trap.

The new detector works great!

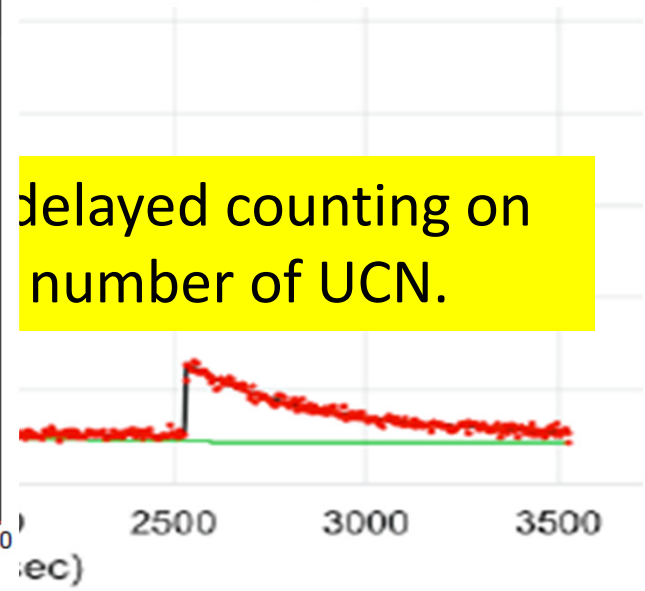


^{10}B/ZnS dagger



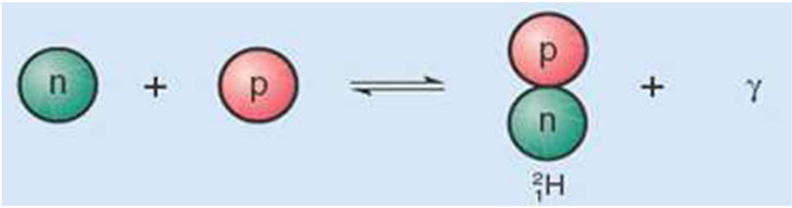
Neutron capture to ^{10}B in real time.

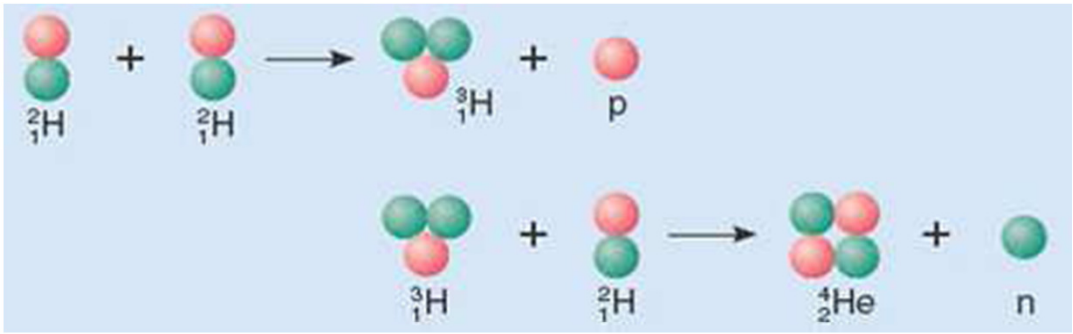
Normalized to the total counts in each distribution.



delayed counting on number of UCN.

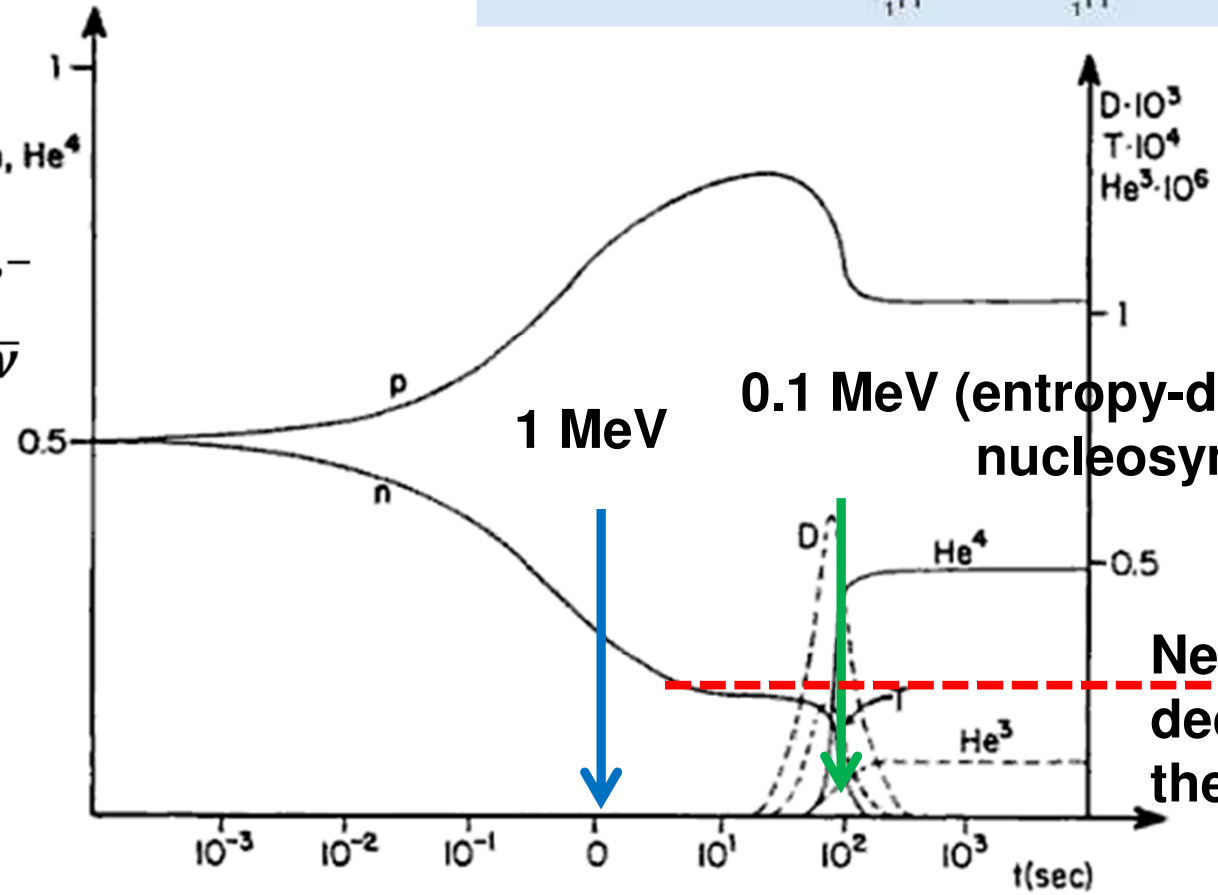
Big-Bang Nucleosynthesis





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

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



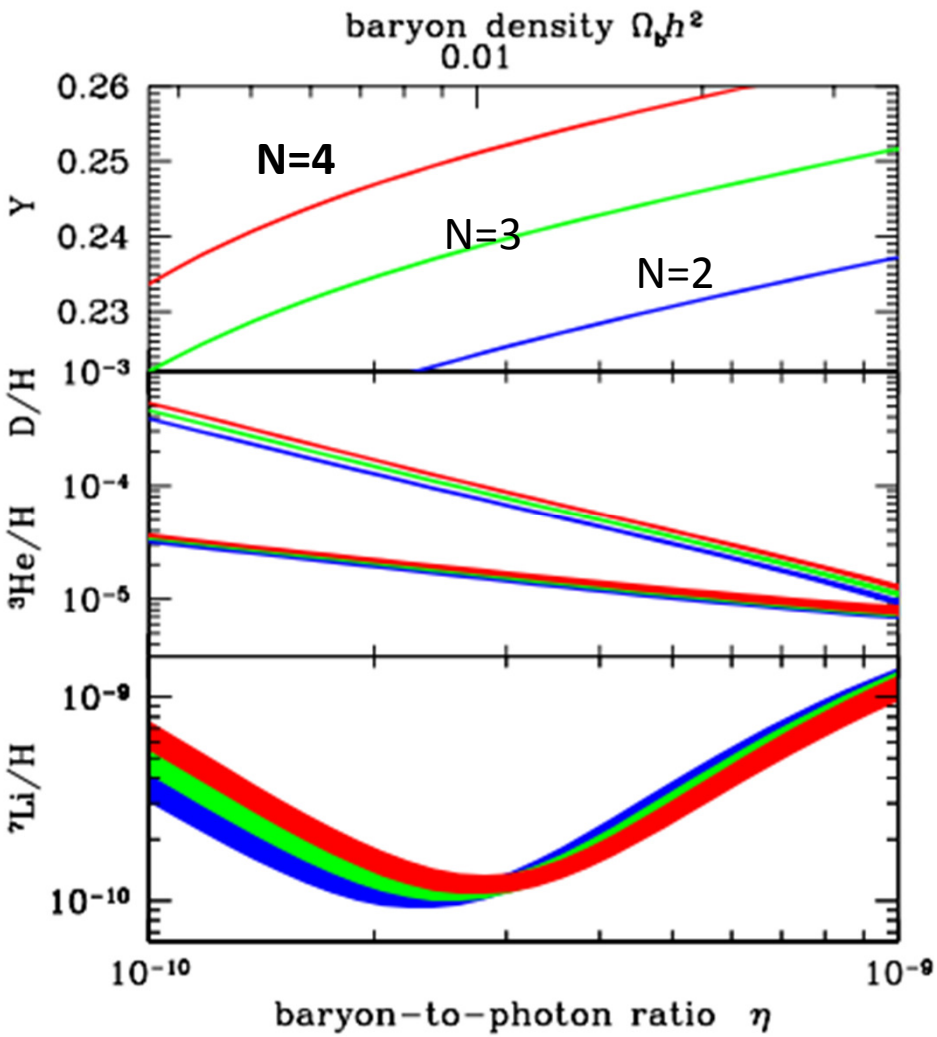
1 MeV

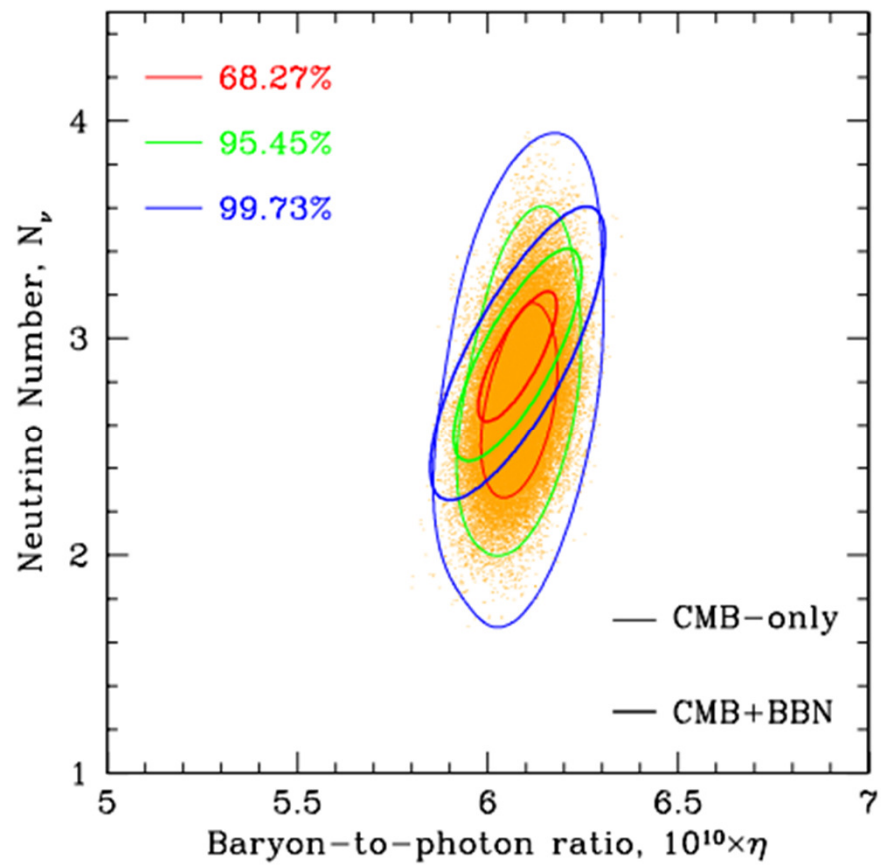
0.1 MeV (entropy-delayed nucleosynthesis)

Neutrinos decouple from thermal bath

Composition of matter in the early universe.

BBN: τ_n and Y_p (primordial ^{4}He abundance)



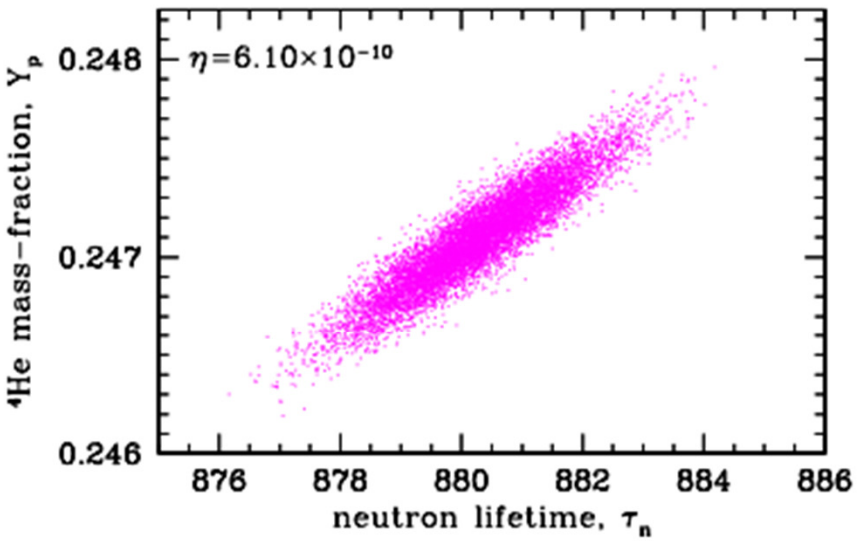


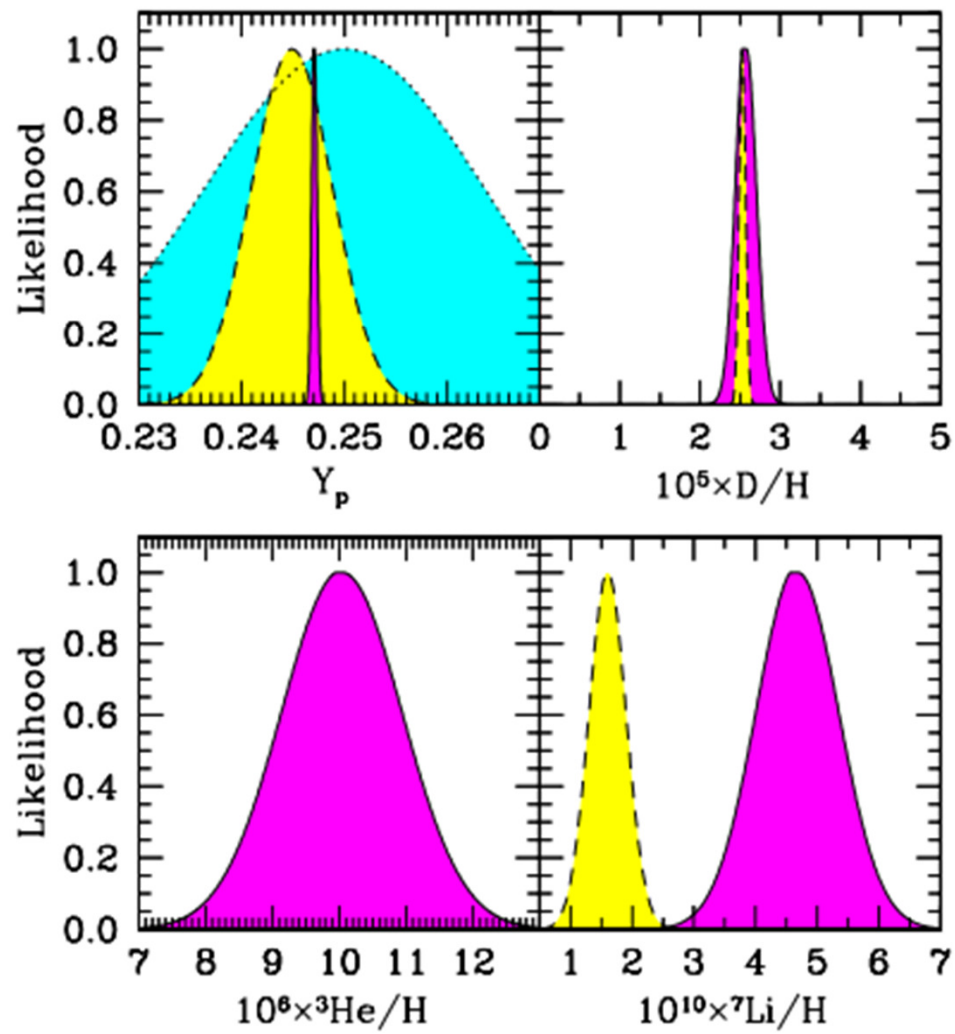
R. H. Cyburt, B.D. Fields, K.A. Olive, T-H Yeh, arXiv:1505.01076

BBN: τ_n & Y_p

BBN CMB

Astrophysical Observations





-R. H. Cyburt, B.D. Fields, K.A. Olive, T-H Yeh, arXiv:1505.01076

- L. Salvati *et al.* arXiv:1507.07243

Summary

- **The 2014-2015 data set, measured using the V-foil *in-situ* neutron detector, yields a *preliminary* neutron lifetime** between
  - 884.7 ± 3.5 s (narrow E cut) to
  - 878.6 ± 3.5 s (wide E cut).
  - UCN statistics: ~20,000 UCN per load (210 cycles of measurements)
  - Monte-Carlo studies on neutron activated background are underway.
- **The systematics appear to be under control to one second level.**
  - New ^{10}B/ZnS detector eliminates systematic dependence on NaI gamma ray detector energy cuts. New 2015 data hints at phase space insensitivity.
  - First pass of B field mapping finds no zero-field crossing. Improved mapping planned.
  - Testing the new detector this beam cycle for a 1 s measurement.