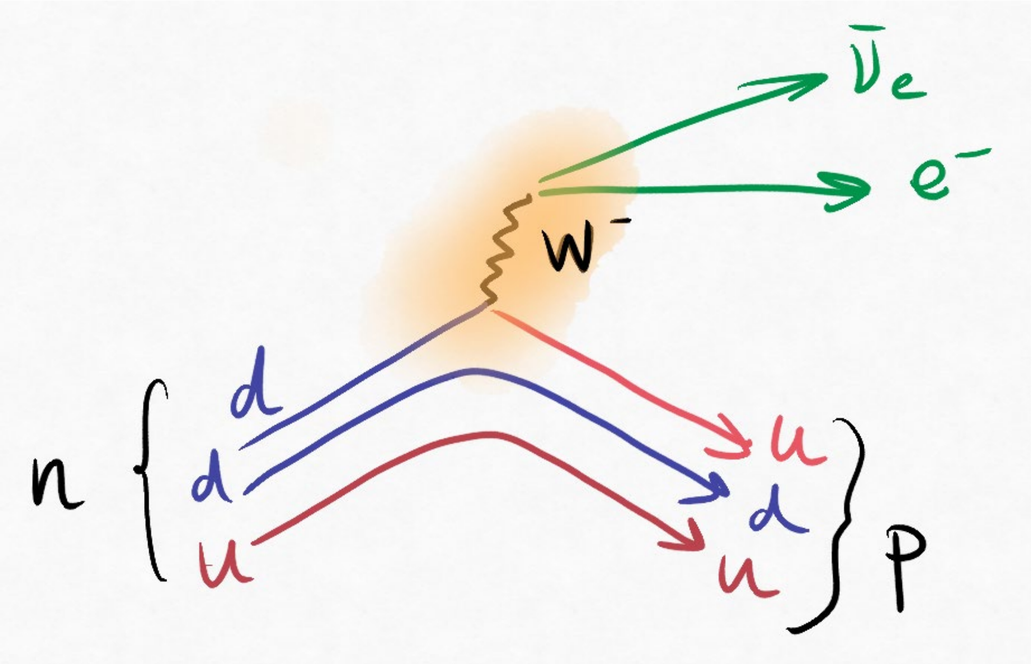
The Neutron Lifetime Puzzle



Chen-Yu Liu

University of Illinois Urbana-Champaign

1/12/2026

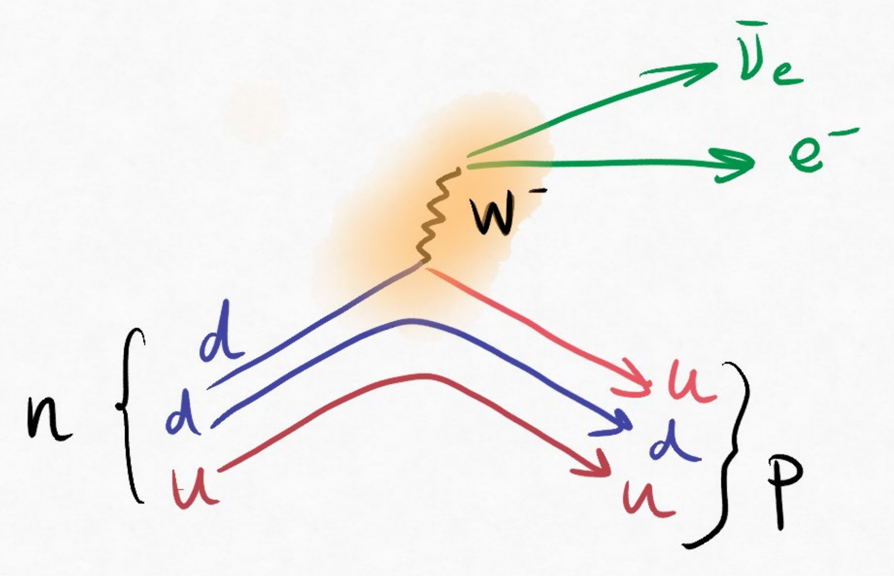
UW Institute for Nuclear Theory:
Testing the Standard Model in Charged-Weak Decays (26-95W)

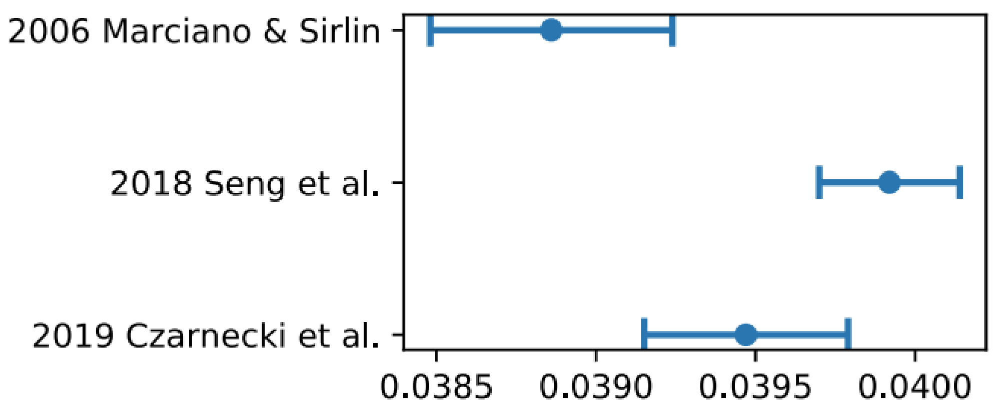
Weak interaction: V-A theory →Left-Handed Neutrinos Only

Left-Handed Neutrino
& RH antineutrino (assumes CP symmetry)

Right-Handed Neutrino
& LH antineutrino

Standard Model tests with neutron beta-decays





Radiative correction

0.5ppm (MuLAN)

$= 1$ (CVC) ~ -1

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

$$\rightarrow |V_{ud}|^2 = \frac{5099.3}{\tau_n (1 + 3\lambda^2)(1 + \Delta_R)}$$

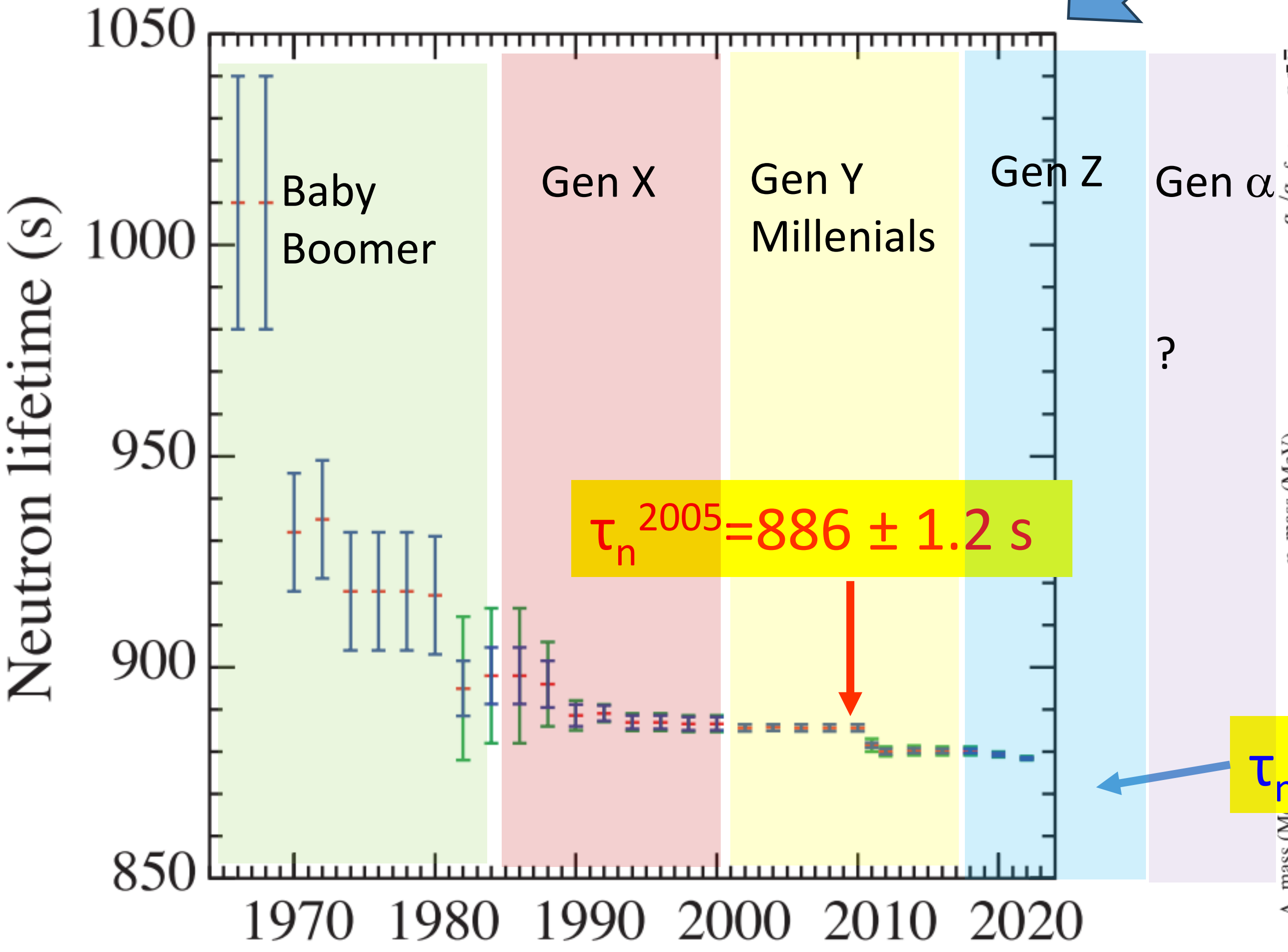
$$\lambda = \frac{g_A}{g_V}$$

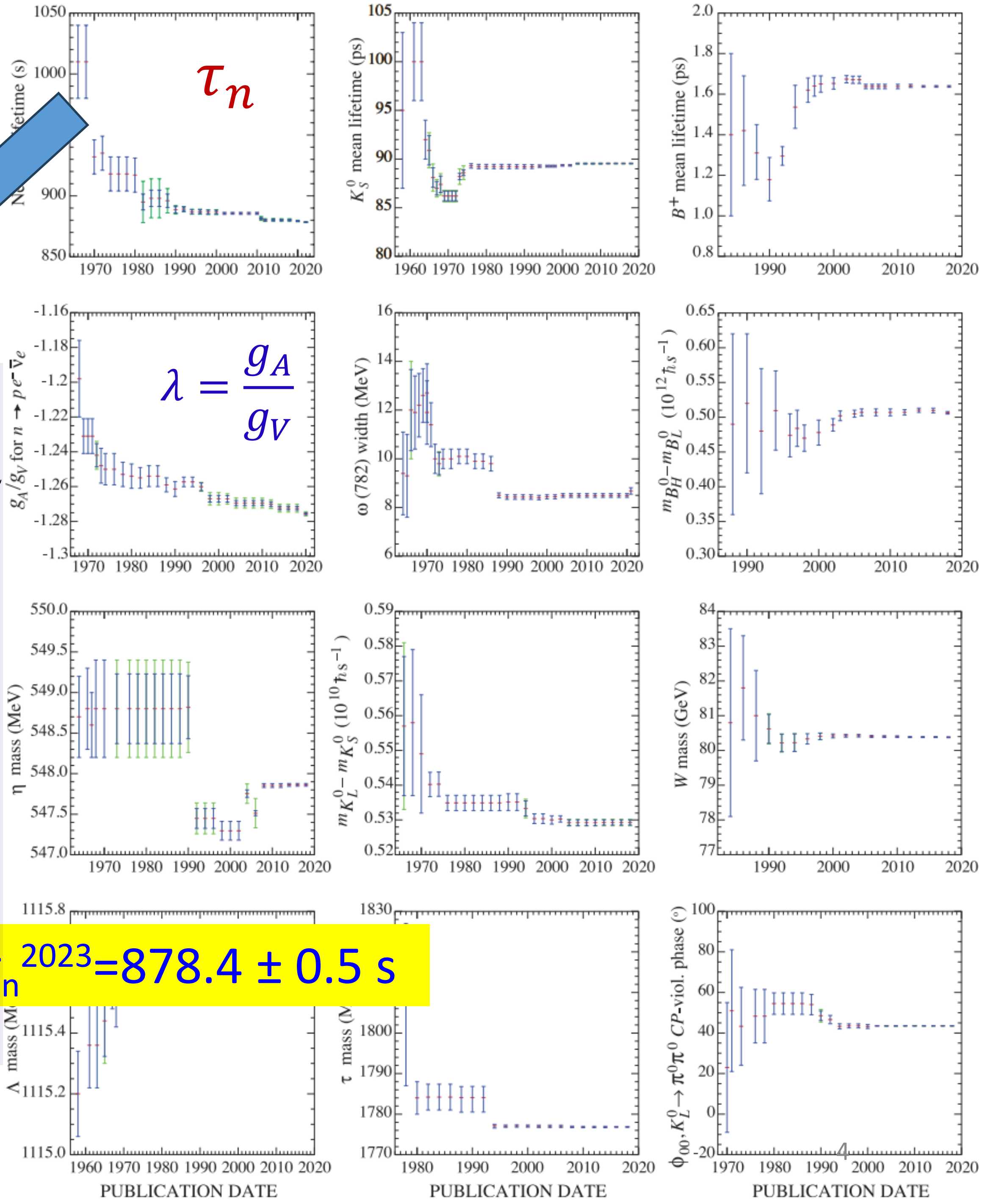
See talks by A. Young, D. Pocanic,
W. Schreyer (Tuesday), S. Baessler (Friday)

Precision CKM unitarity test to the 1e-4 level of precision requires:

- $\Delta\tau_n < 0.3\ s$
- $\Delta\lambda < 0.03\%$

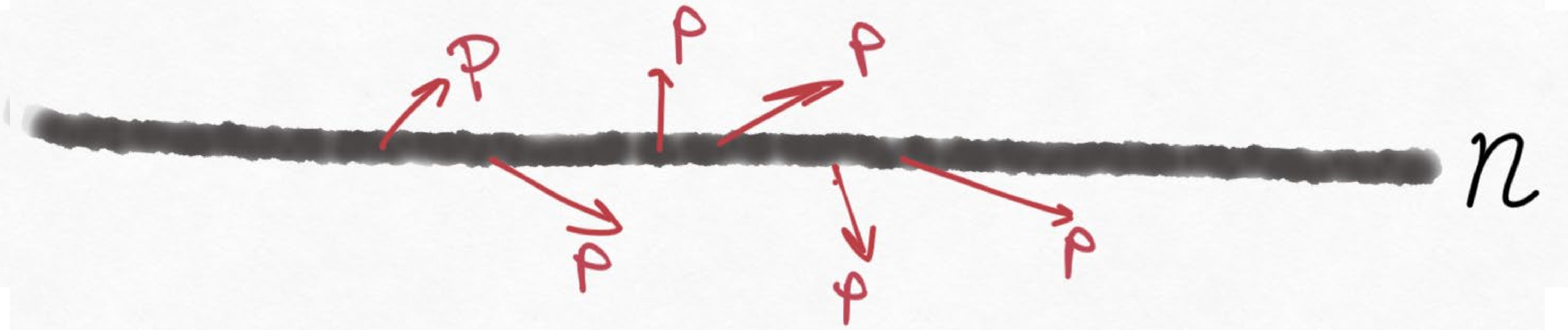
PDG History of physics measurements:





The Beam Method:

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



Rate of Decay: $\frac{dN_p}{dt} = N_n \frac{1}{\tau}$

$$= (\rho_n V)\frac{1}{\tau} = \underbrace{\phi A}_{\frac{dN_n}{dt}} \frac{L}{v}\frac{1}{\tau}, \qquad \rho_n v = \phi$$

Neutron Lifetime: $\tau = \frac{\dot{N}_n}{\dot{N}_p}\frac{L}{v}$

Absolute measurements!

Needs to know the detection efficiencies of both the neutron counting and proton counting.

A Beam Experiment in the early days

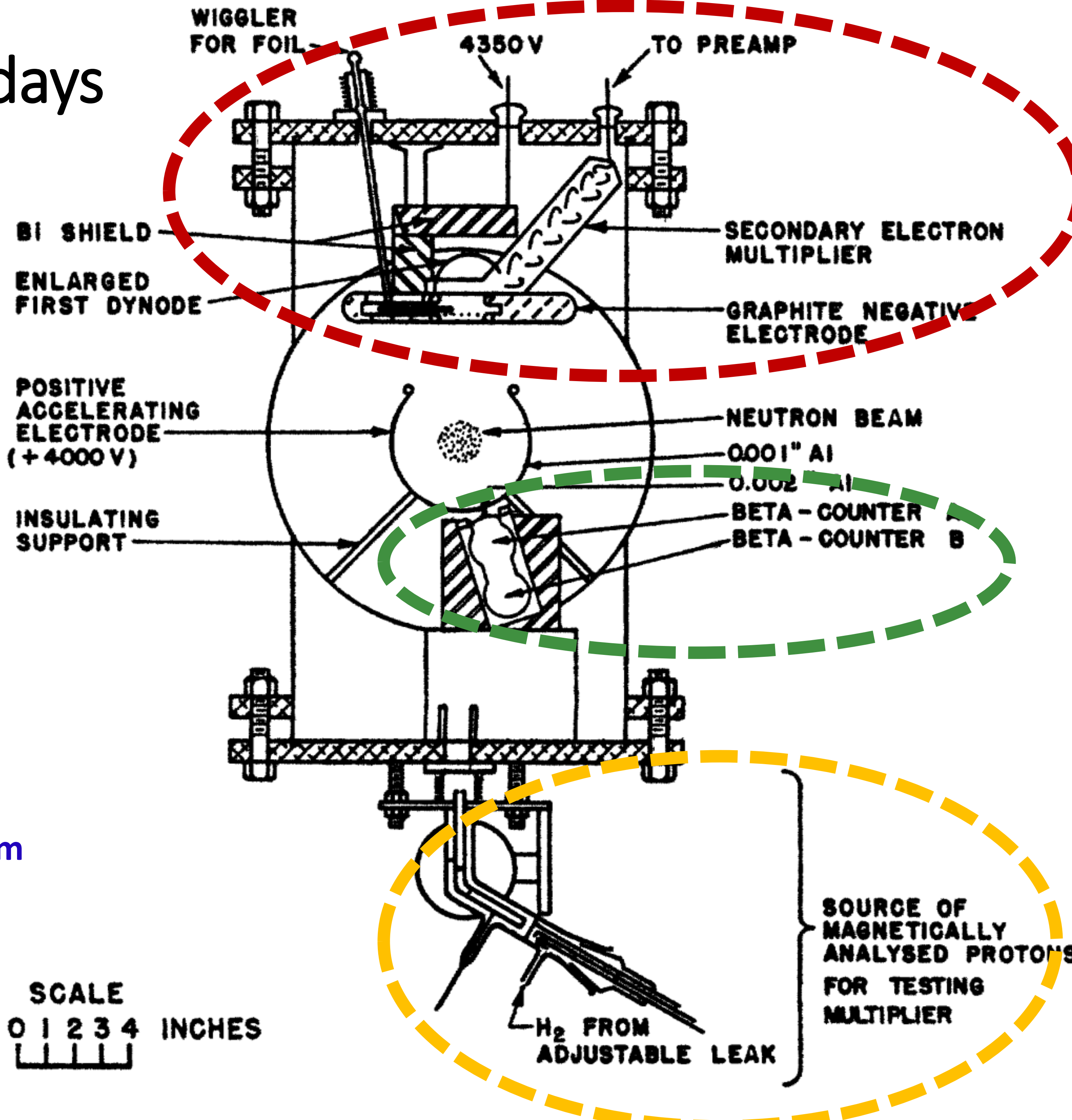
Oak ridge graphite reactor operated ~ 1 year after the first reaction in the CP-1 Stagg field in U. Chicago.

Snell, Pleasonton, McCord, ORNL, Phys. Rev. 78 (1950)

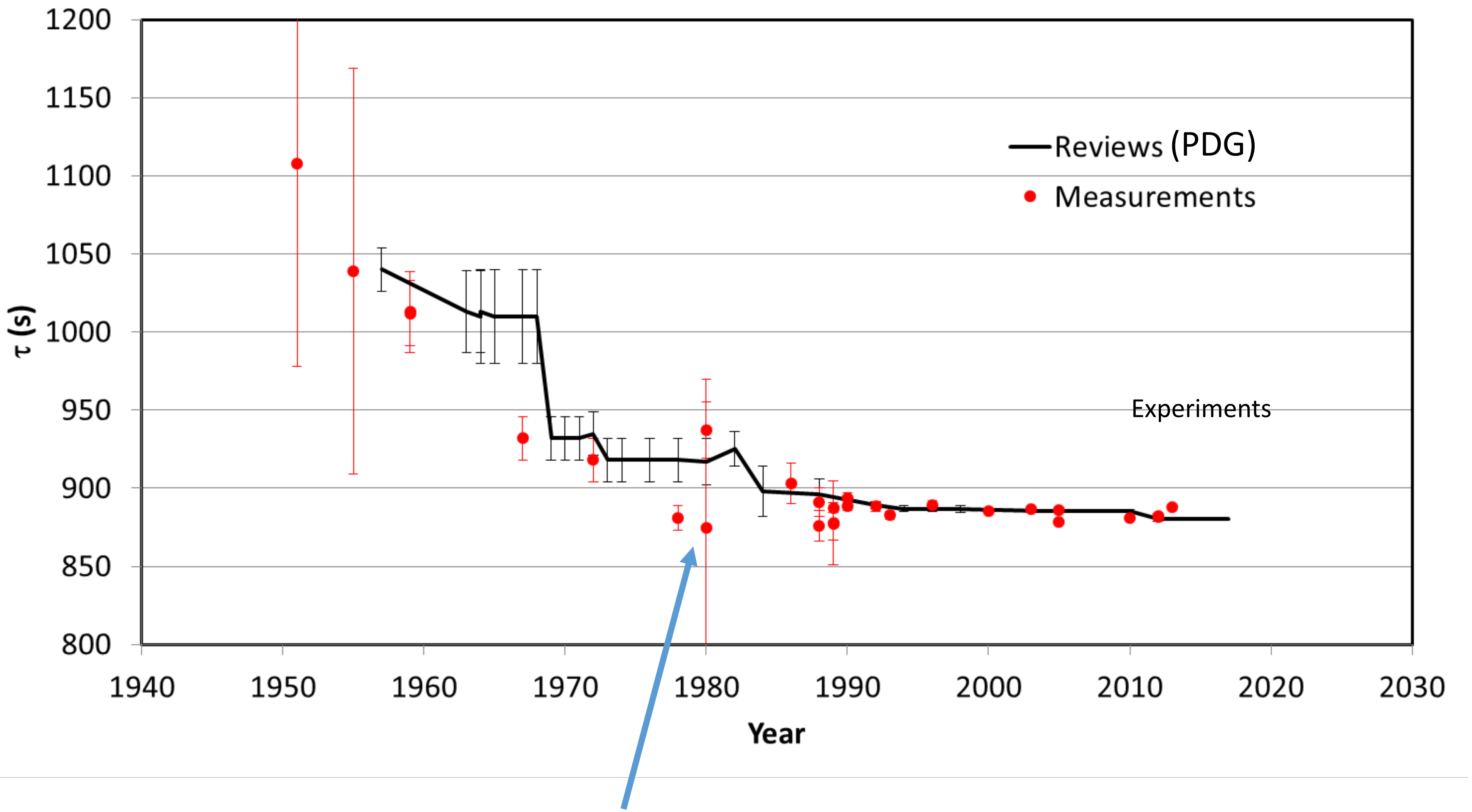
Challenges:

1. **Beta energy is continuous**
2. **High backgrund in reactors**
3. **Protons are low energy < 780 eV**

Count rate of each beta detector: **75,000 cpm**
Coincident between beta detectors: **1,500 cpm**
Coincident between electron and proton counters: **1 cpm**



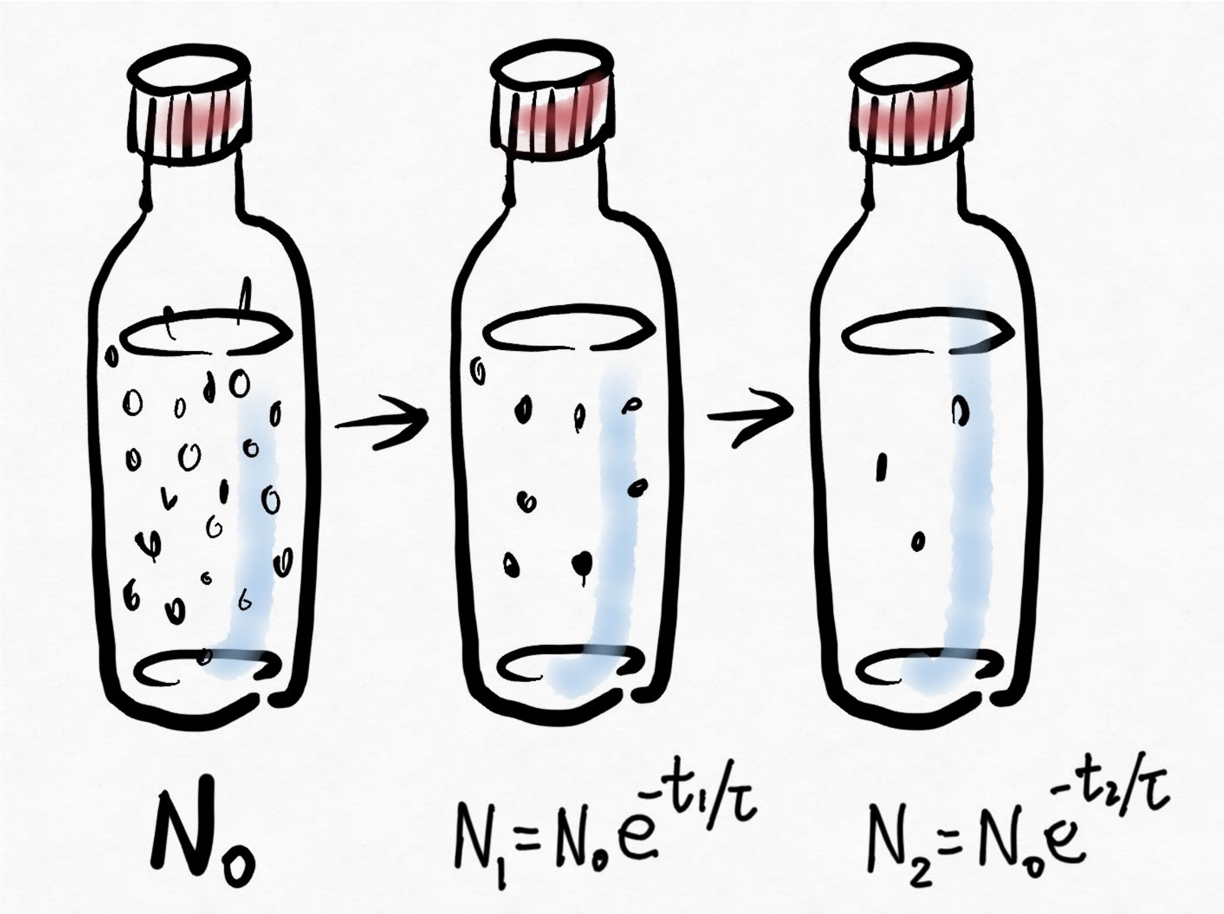
History of τ_n measurements:

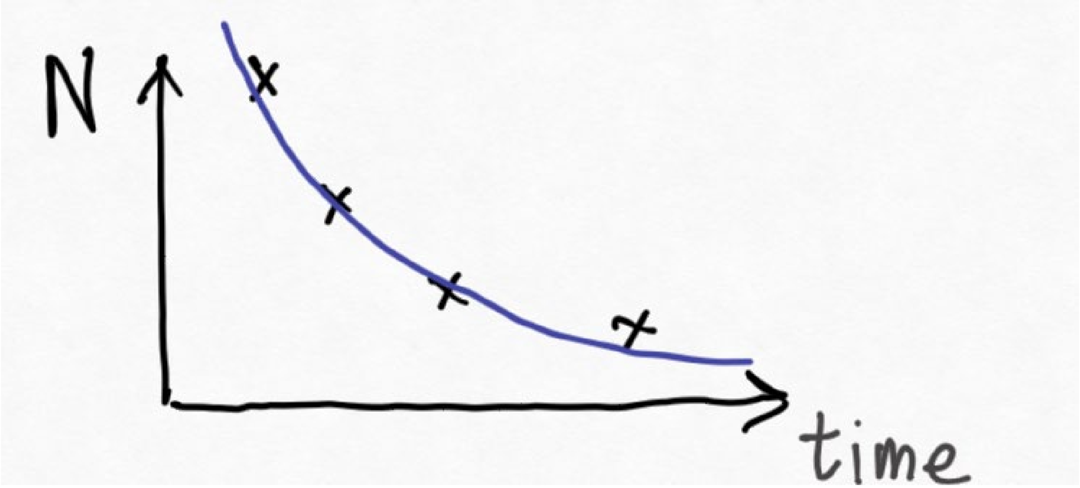


1st UCN bottle lifetime experiment

Kosvintsev, Kushnir, Morozov, Terekhov, *JETP Lett.* 31 (1980) 236, *Pisma Zh.Eksp.Teor.Fiz.* 31 (1980) 257-261

The Bottle Method:



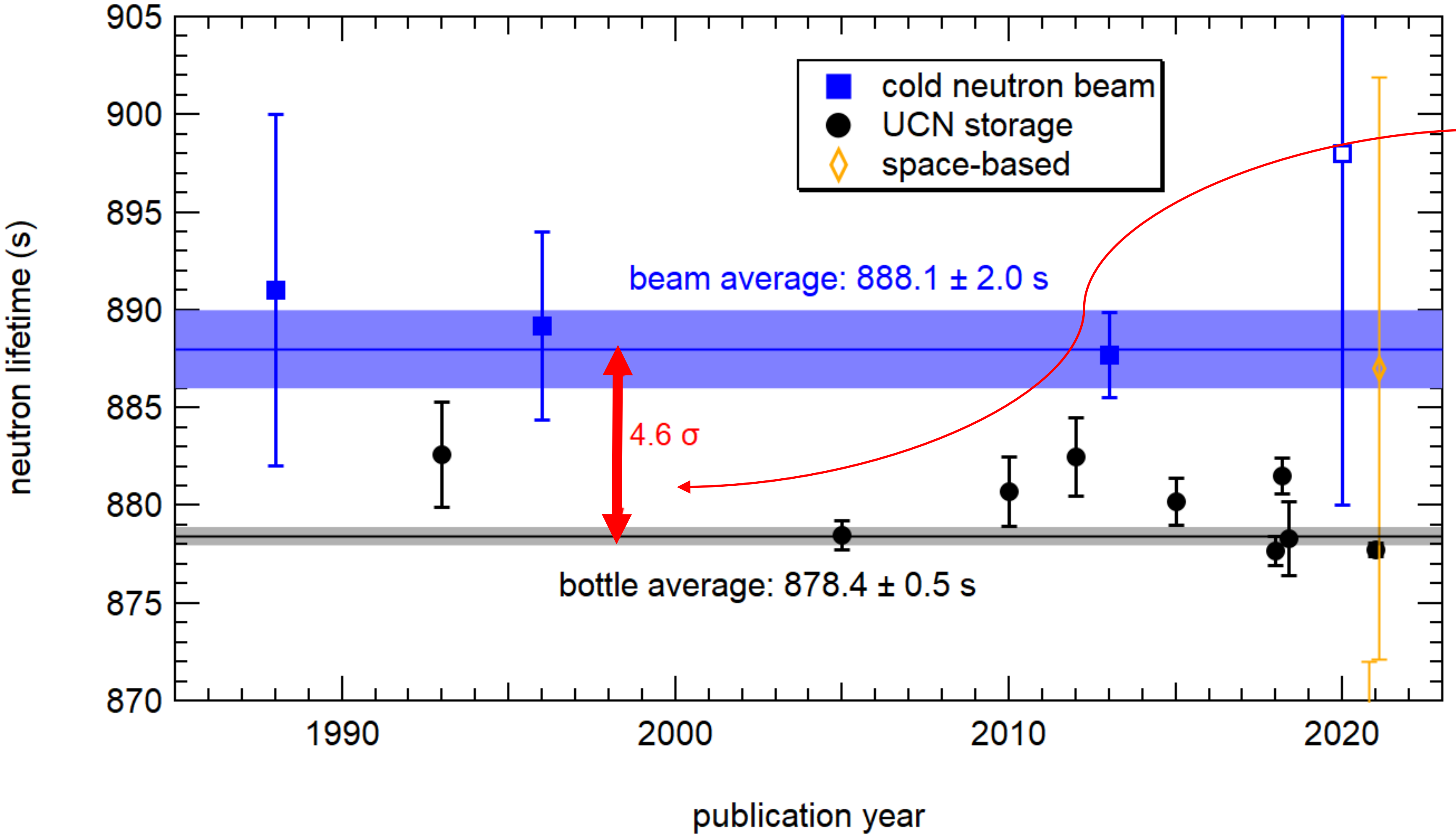


$$\frac{N_1}{N_2} = e^{(t_2 - t_1)/\tau}$$

$$\tau = \frac{t_2 - t_1}{\ln(N_1/N_2)}$$

Relative measurements using only one detector → Easy! …..?

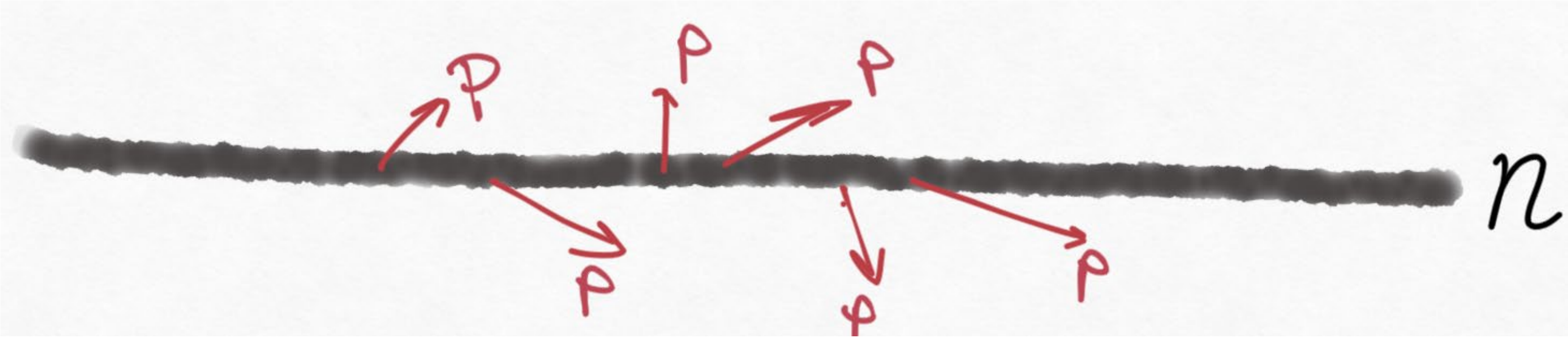
Neutron Lifetime Puzzle: discrepancy between the two methods to measure the neutron lifetime

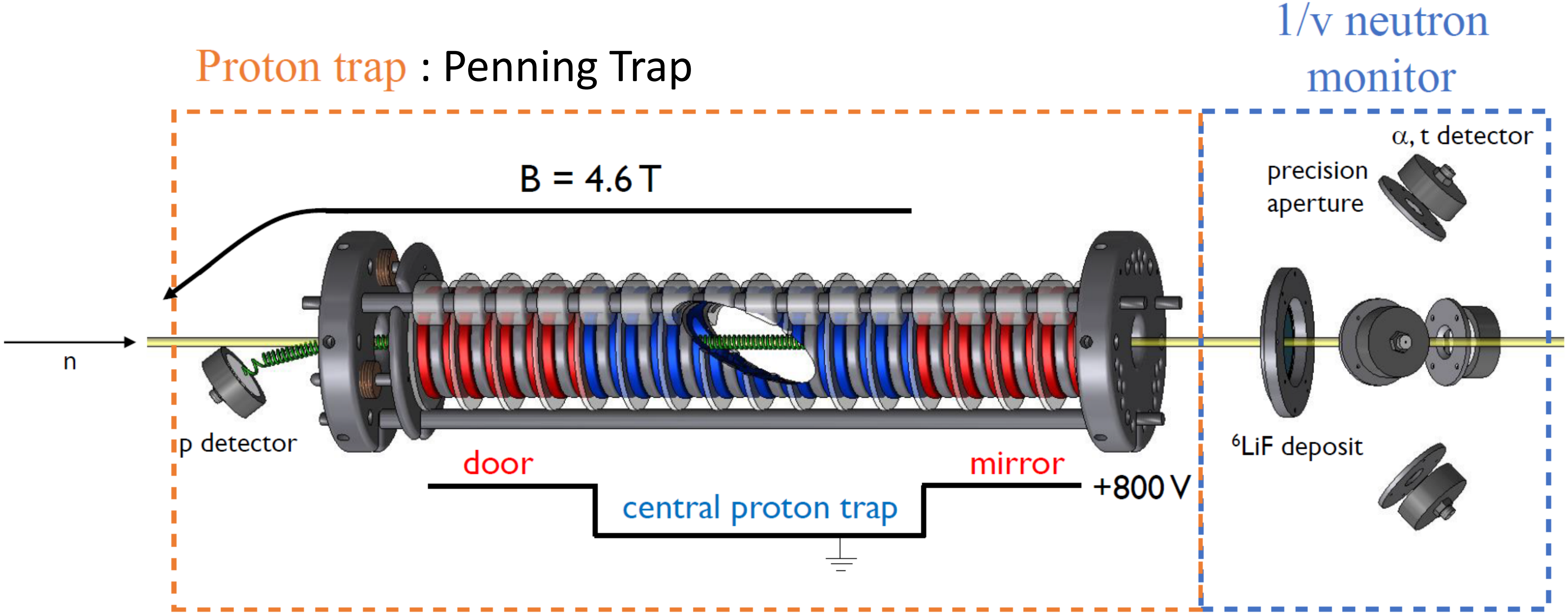


~ 10 s discrepancy!

Neutrons in flight decay *slower* than in bottles ???

Sussex-ILL-NIST Beam Method

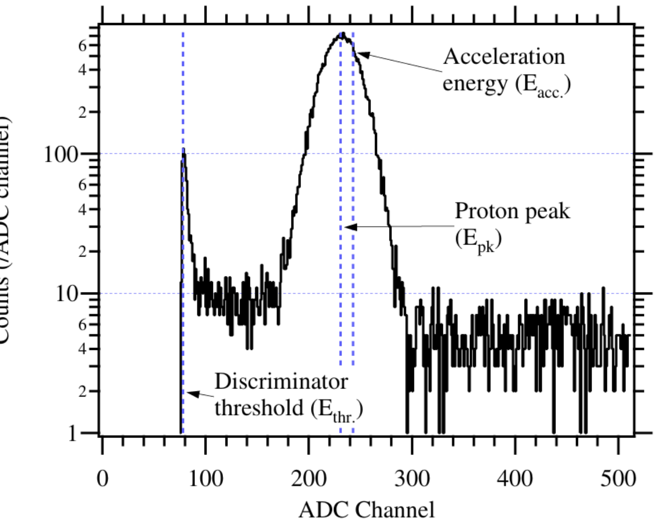


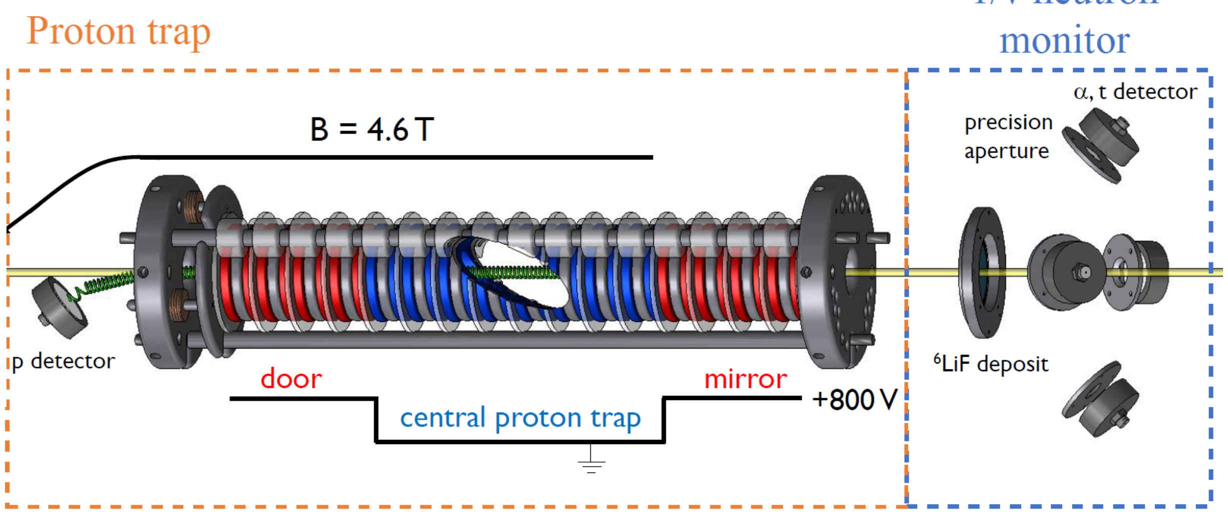


Sussex-ILL-NIST Beam Method

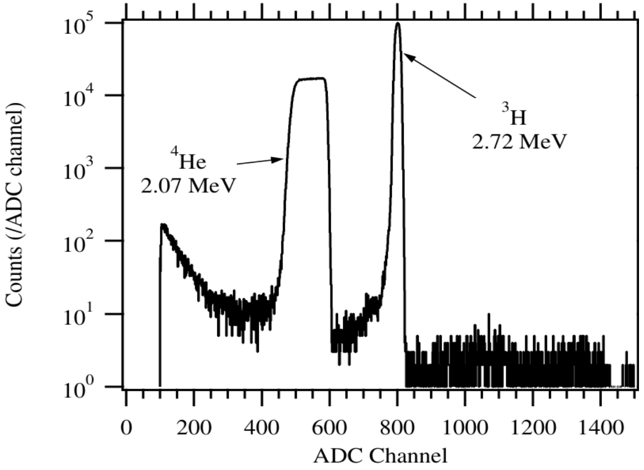
- 1/v dependence cancels!

$$\tau_n = \frac{\dot{N}_{\alpha+t}}{\dot{N}_p}\frac{\varepsilon_p}{\varepsilon_0 v_0}(nl + L_{end})$$





$n + {}^7Li \rightarrow {}^4He + {}^3H$



- Proton counting:

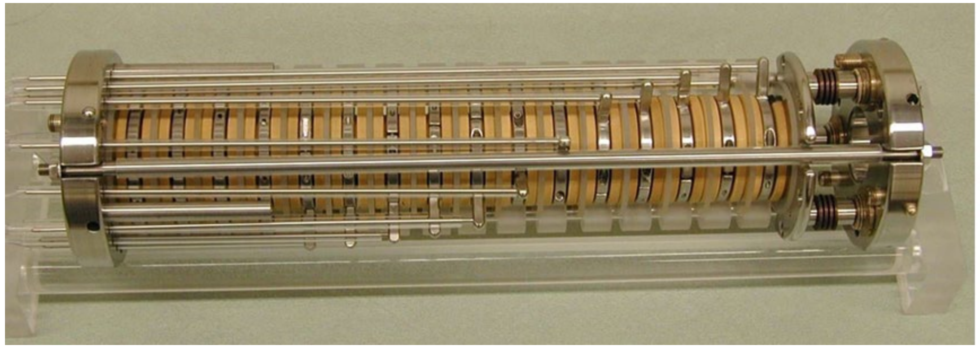
$$\dot{N}_p = \tau^{-1}\epsilon_p L \int_A da\, I(v)\frac{1}{v}$$

Strategies: make each unit modular, which can be calibrated independently

- Neutron counting:

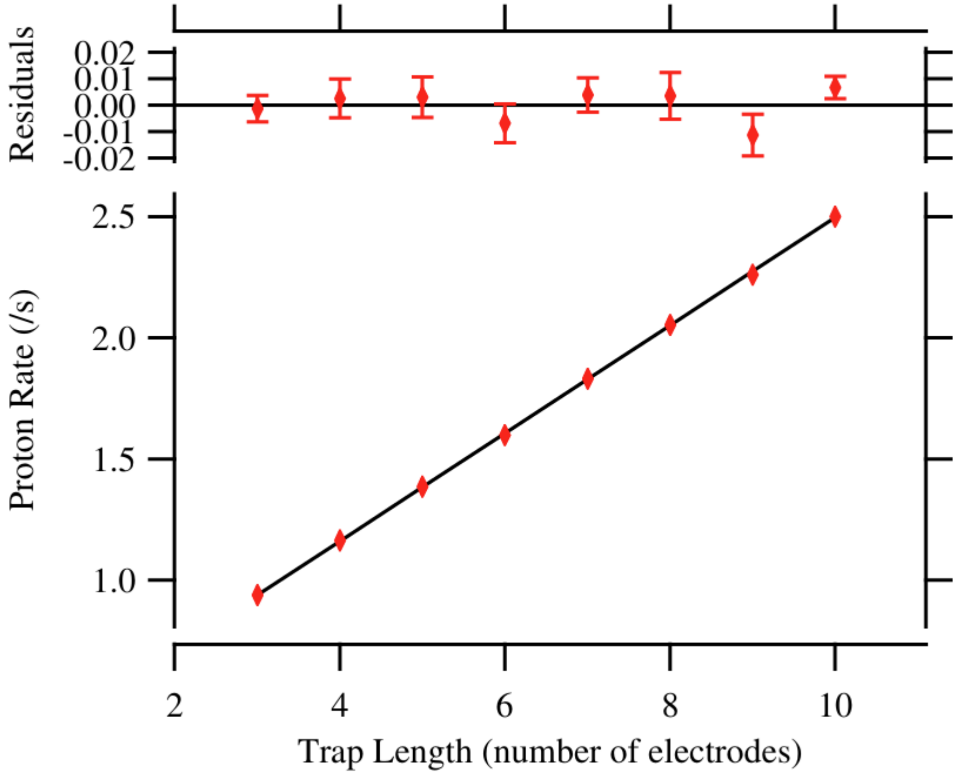
$$N_n = L\int_A da I(v)\frac{1}{v}$$

Sussex-ILL-NIST Beam Method



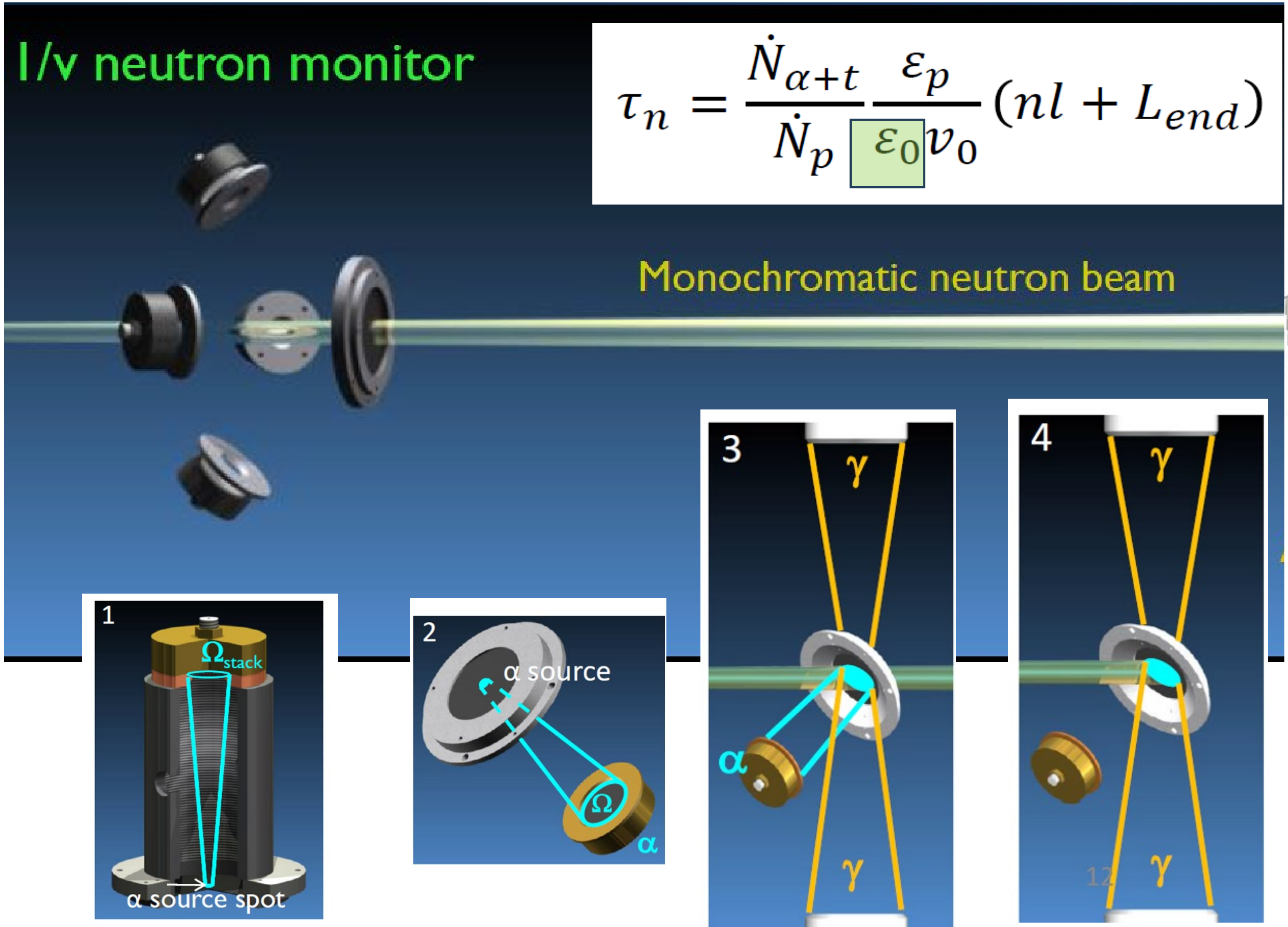
$$\tau_n = \frac{\dot{N}_{\alpha+t}}{\dot{N}_p} \frac{\varepsilon_p}{\varepsilon_0 v_0} (nl + L_{end})$$

The Penning potential is not square well!



- increase the trap length
  → proton rate increases
- The slope is proportional to τ_n

Measure the neutron counting efficiency ε_0 using the Alpha-Gamma device



$$\tau_n = \frac{\dot{N}_{\alpha+t}}{\dot{N}_p}\frac{\varepsilon_p}{\varepsilon_0 v_0}(nl + L_{end})$$

Using a procedure involving multi-target calibration

$n + {}^{10}B \rightarrow {}^{7}Li^* + \alpha(1.472\text{MeV}) + \gamma(478\ \text{keV})$, BR=93.7%

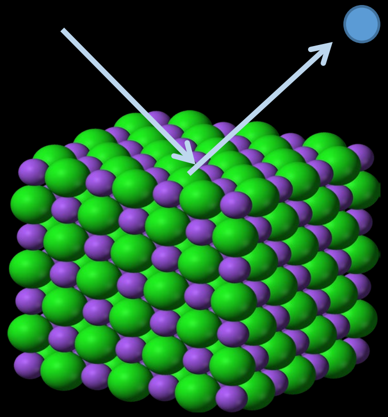
Beam Lifetime Results

- $\boldsymbol{\tau_n = 886.3 \ \pm 1.2_{stat} \pm 3.4_{sys}}$ s (Nico et al 2005)
  - Limited by the knowledge of the neutron absorption cross-section on ^{6}Li.

- $\boldsymbol{\tau_n = 887.7 \ \pm 1.2_{stat} \pm 1.9_{sys}}$ s (Yue et al 2013)
  - After the work to calibrate the neutron monitor using the AG device

UCN experiences the four fundamental forces of comparable energy scales of ~100 neV

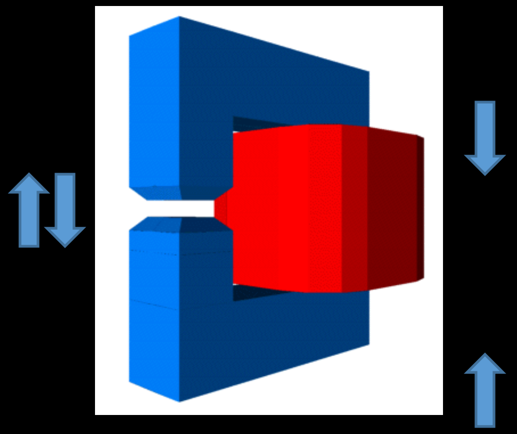
- Nuclear force (max: 350neV)



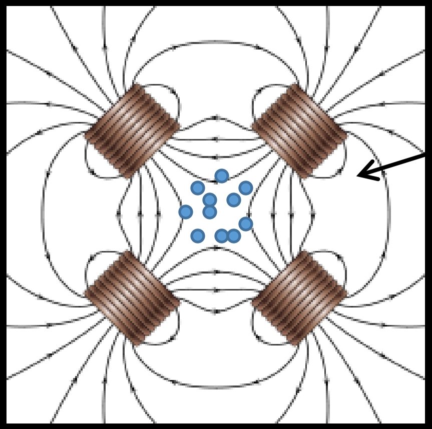
- Gravitational force (100neV/m)

- Magnetic force (60neV/T)

High field seeking state



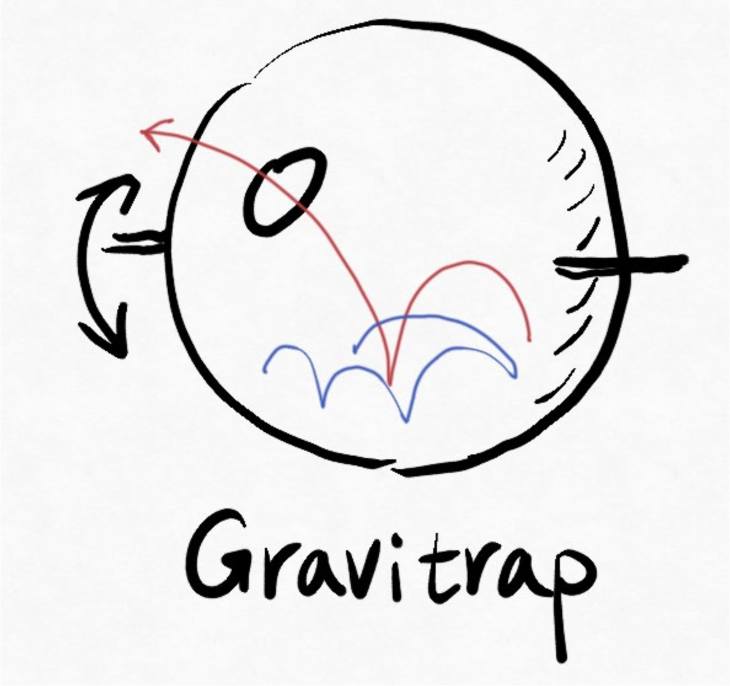
Low field seeking state

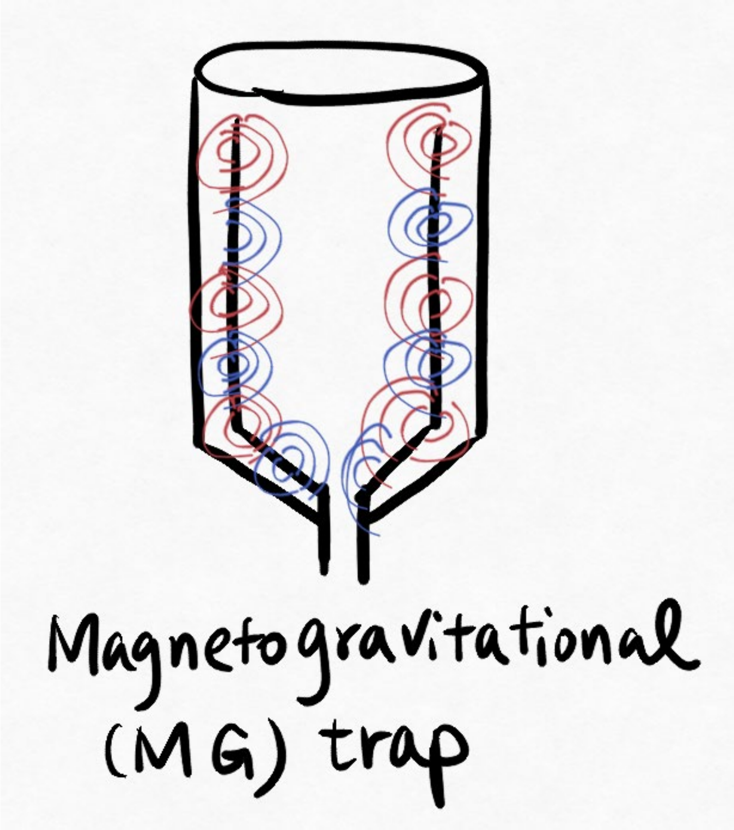


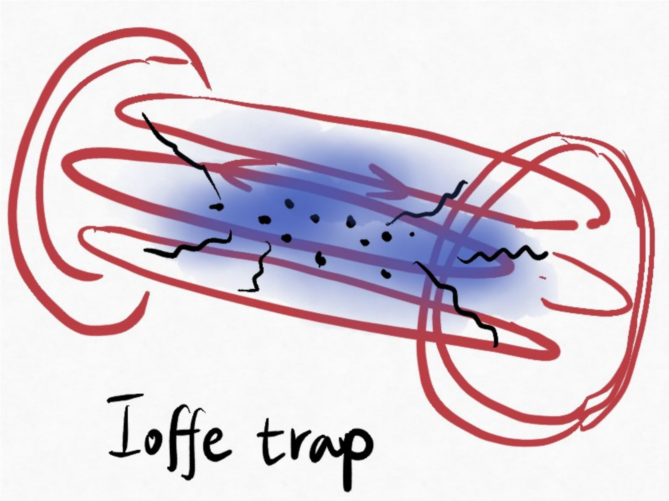
Low field seekers

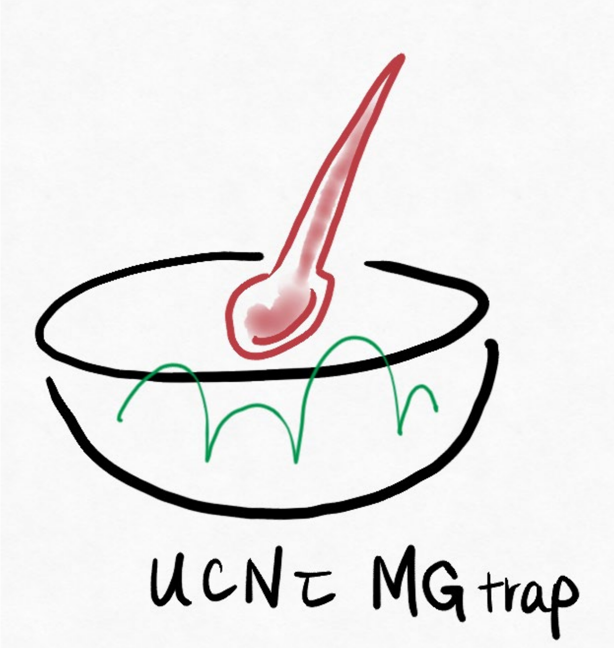
magnetic quadruple trap

Various styles of neutron bottles









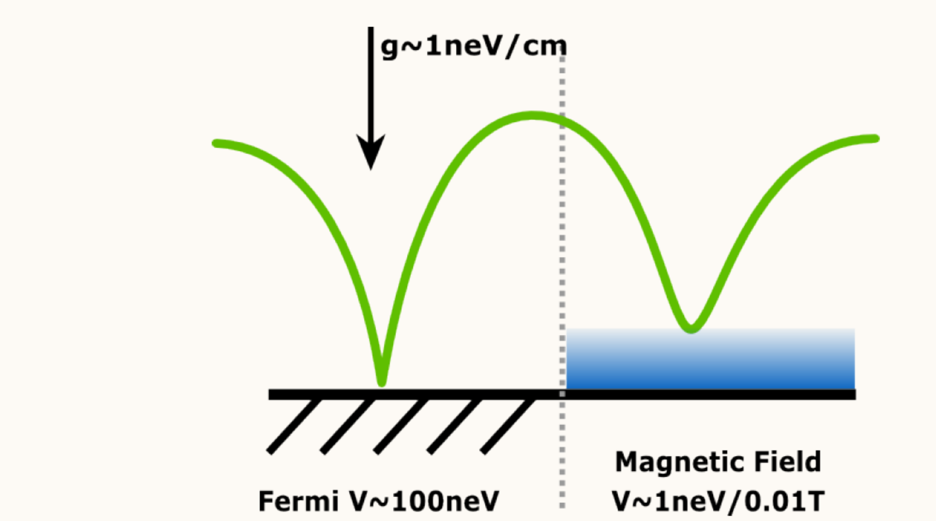
Material bottle

Magnetic bottles

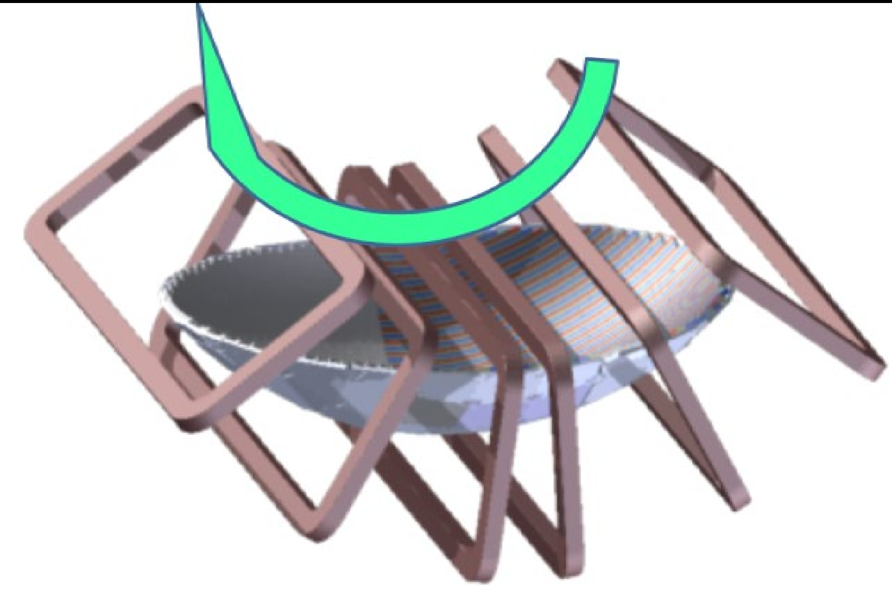
Neutrons can be held inside a magneto-gravitational trap; this eliminates neutron losses on the walls

- **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).
- Asymmetric trap geometry to induce chaotic orbit mixing (suggested by Dave Bowman)

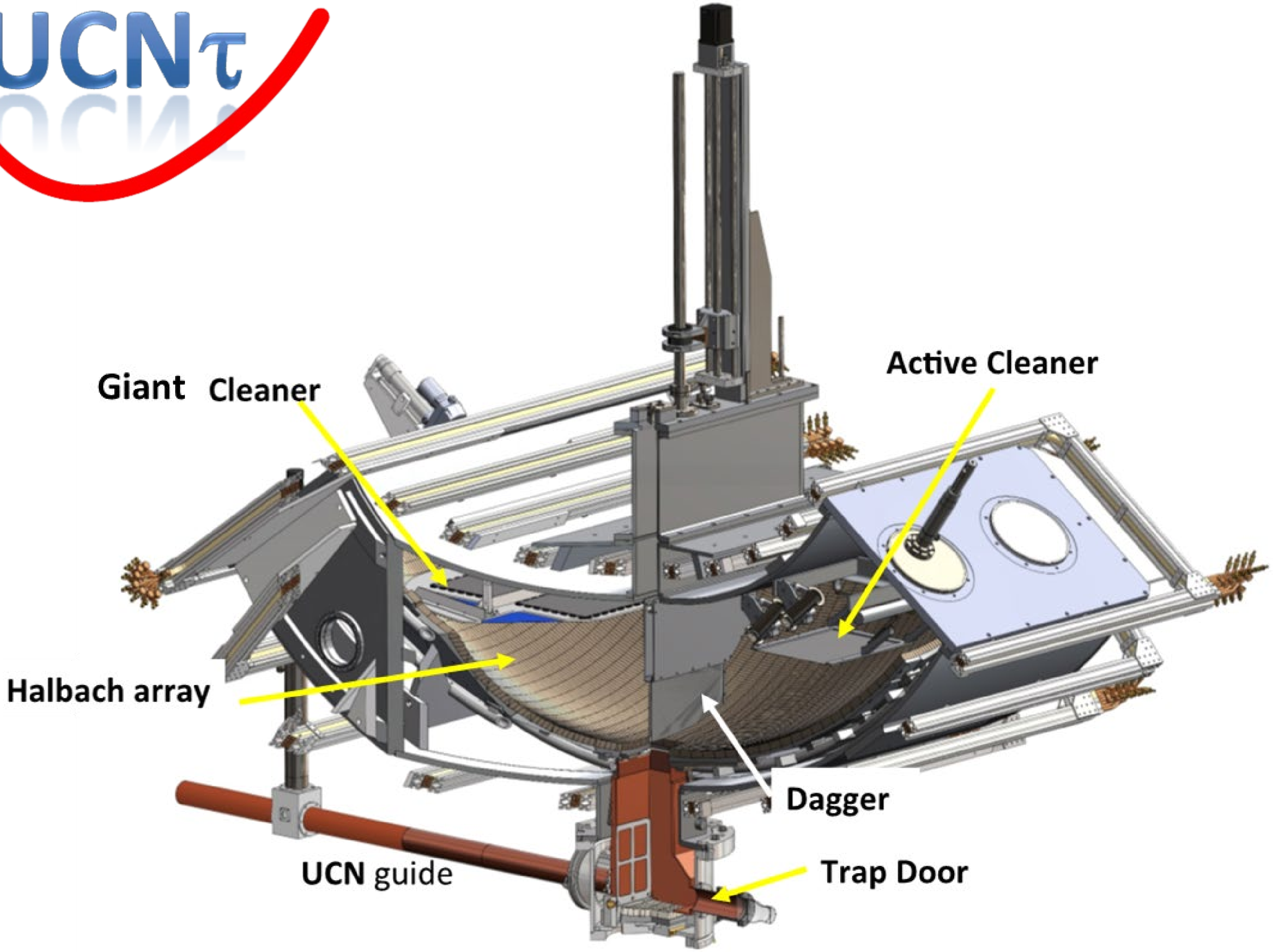
Walstrom et al, NIMA, 599, 82 (2009)



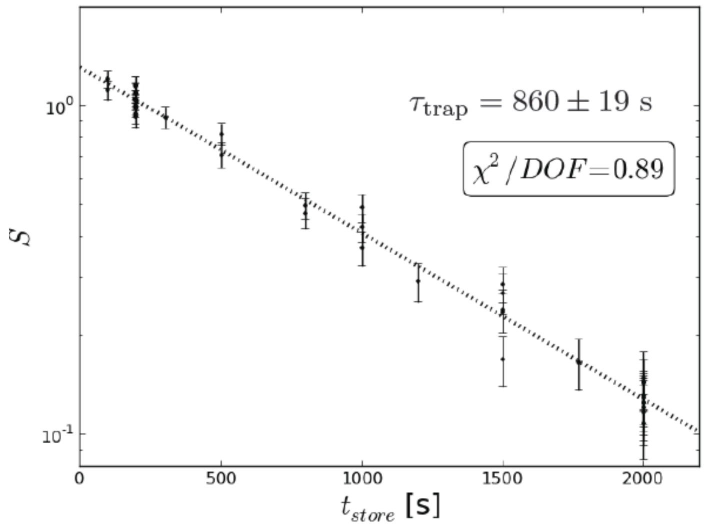
- Material - $V_f \sim \mathcal{O}$(100s neV)
- Magnetic Field - $V_B \sim$ 1neV/1000 Gauss
- Gravity - $V_g \sim$ 1 neV/cm



The UCNτ Apparatus (2013)



First Physics Data: 2013

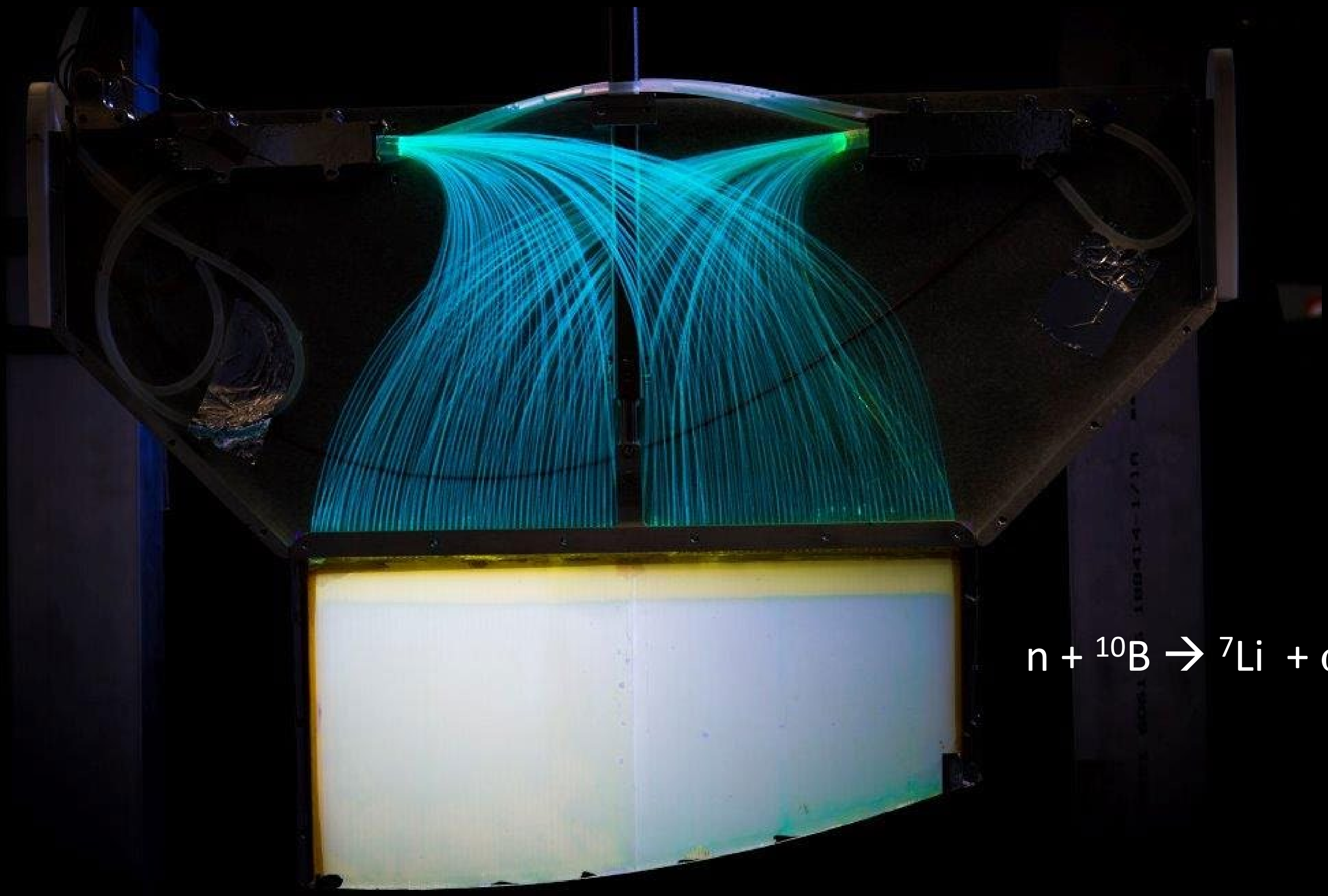


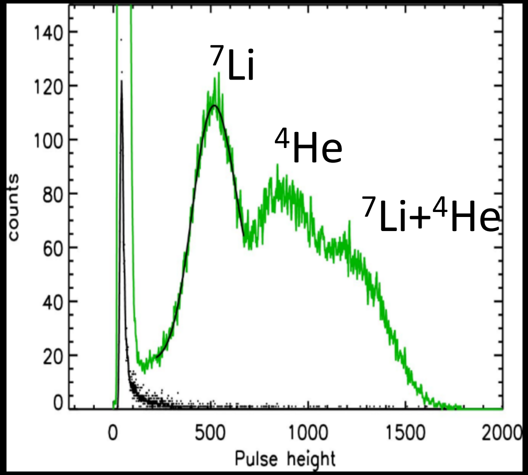
D. Salvat, PRC 89, 052501 (2014)

Neutrons counted with an external neutron counter.

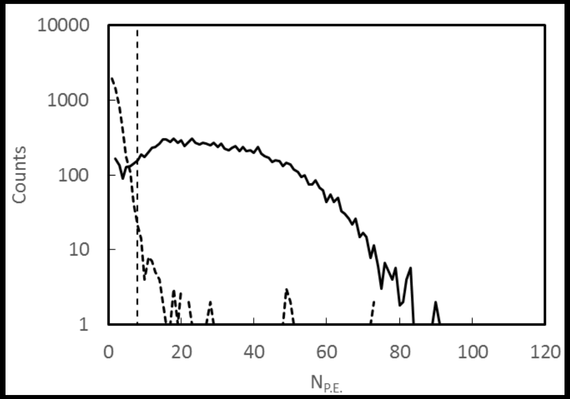
The UCNτ *in-situ* detector

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

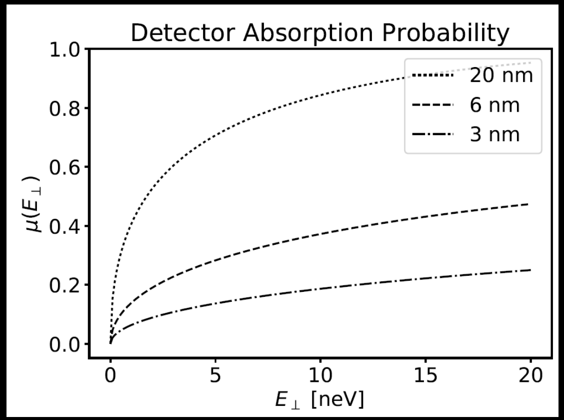




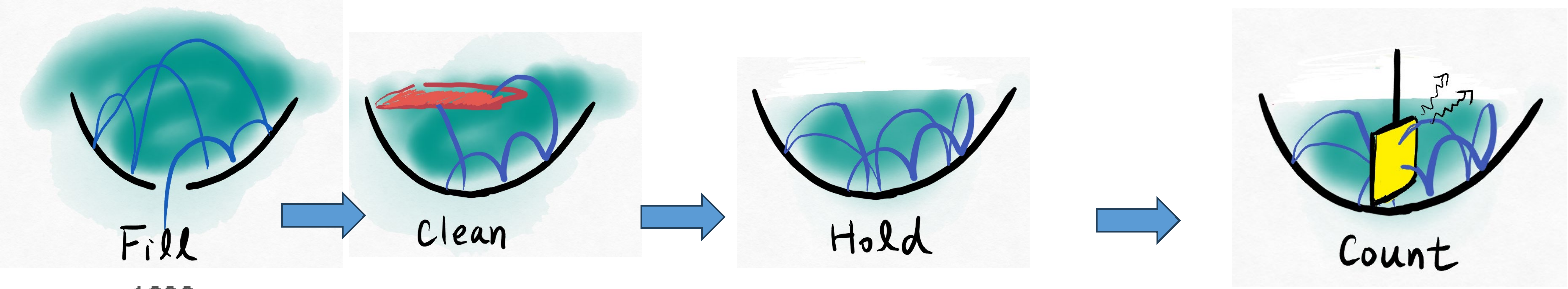
Light Output

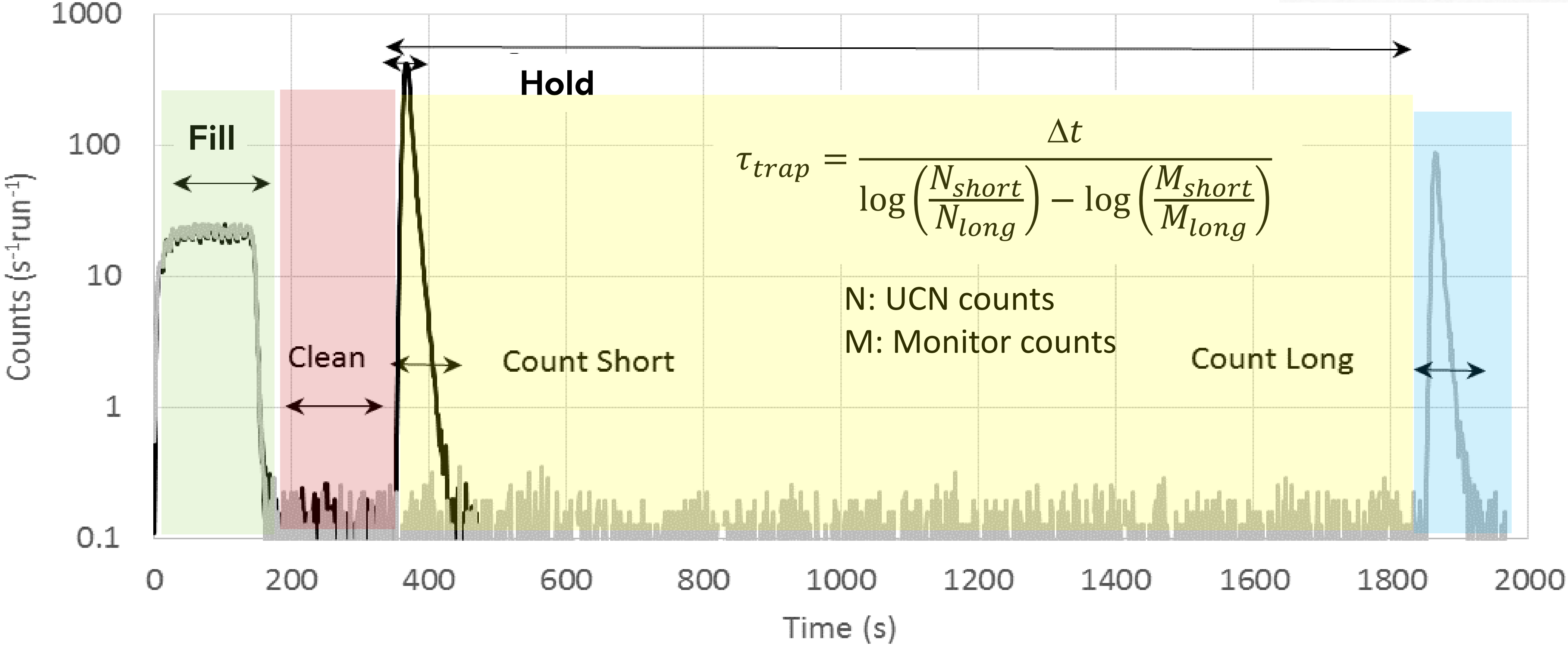


$n + {}^{10}B \rightarrow {}^{7}Li + \alpha$



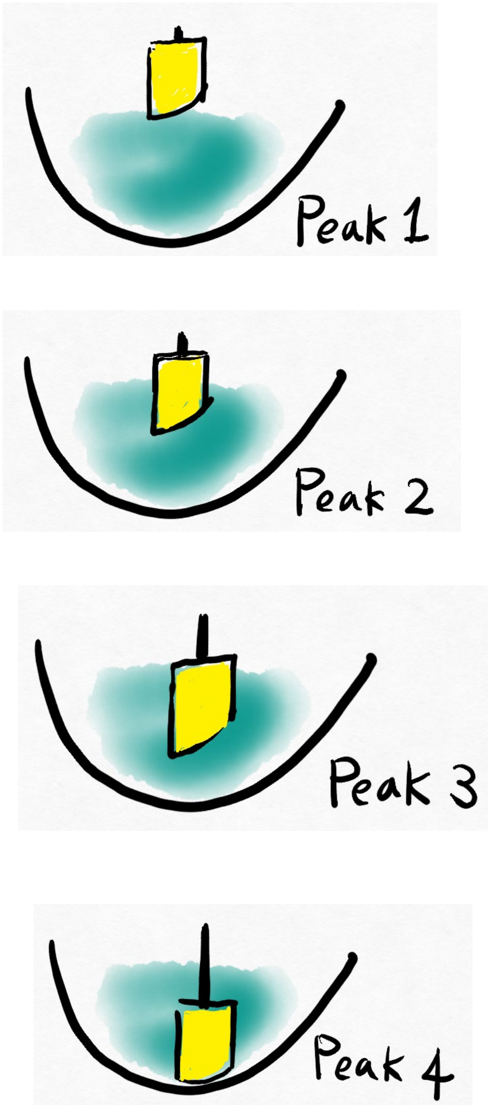
A typical lifetime run in UCNtau:

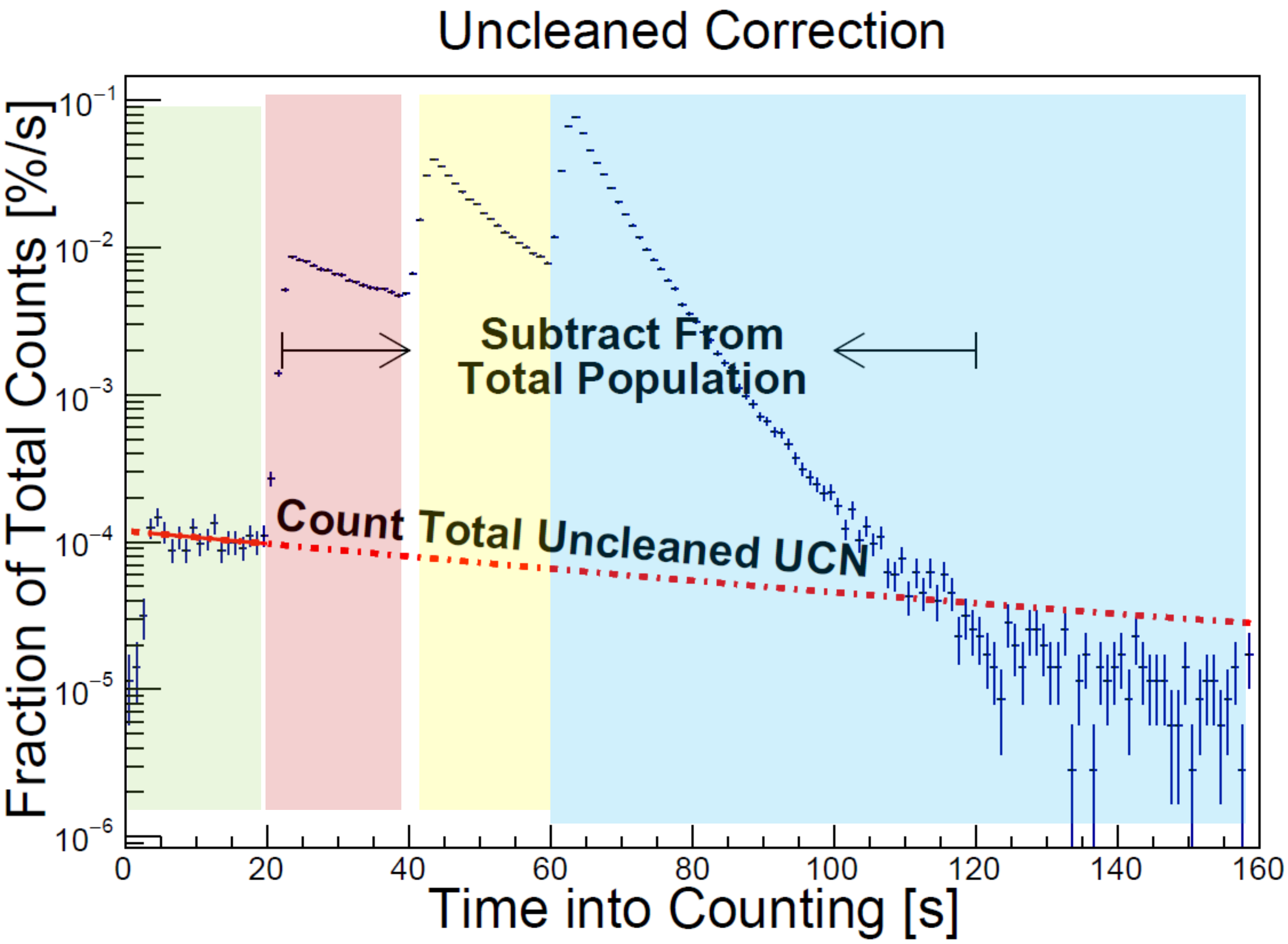




$$\tau_{trap} = \frac{\Delta t}{\log\left(\frac{N_{short}}{N_{long}}\right) - \log\left(\frac{M_{short}}{M_{long}}\right)}$$

Multi-step neutron counting → measure over-threshold neutrons





P1 counts overthreshold neutrons reaching > 25 cm. It has a large draining time ~ 100 s.

UCNτ: Final result

V_{ud} extraction using neutron measurements

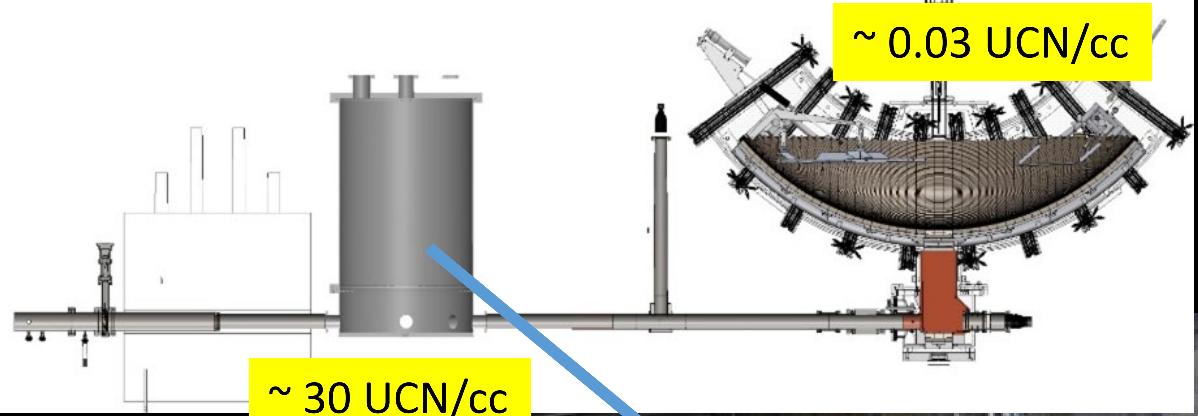
Final combined UCNτ result sets new record for τ_n precision: **877.82 ± 0.22(stat)+0.20-0.17(sys) s**

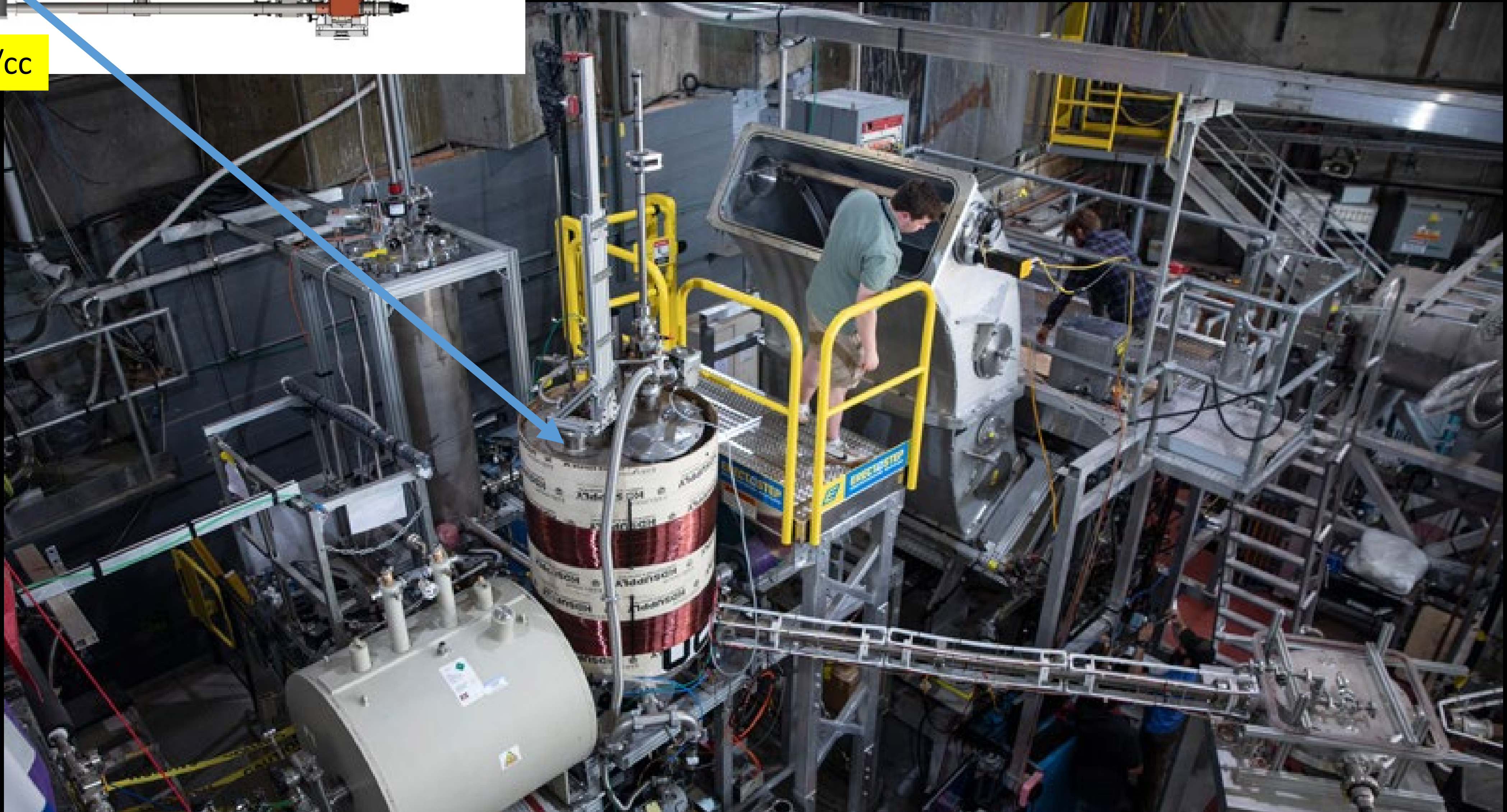
See talks by A. Young, D. Pocanic, W. Schreyer (Tuesday), S. Baessler (Friday)

UCNτ+: Towards 0.1 s precision

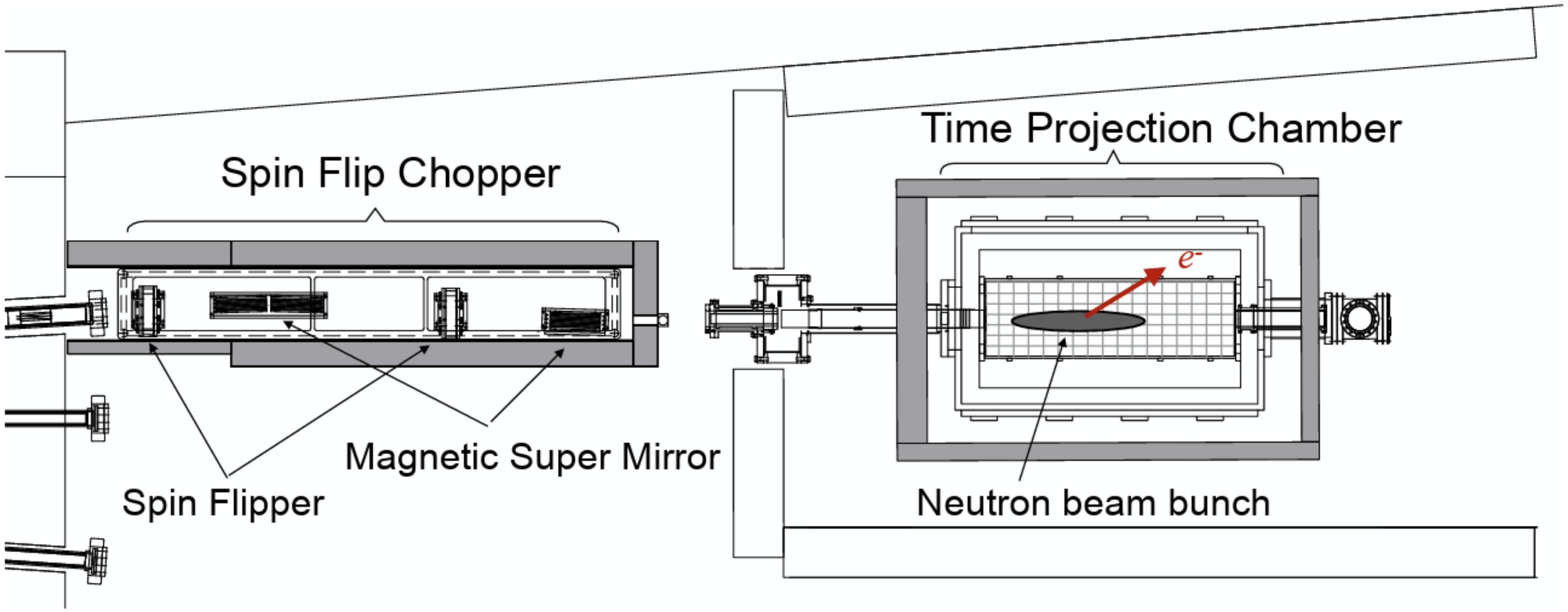
by increasing neutron loading with an elevator

See Steven Clayton's talk next





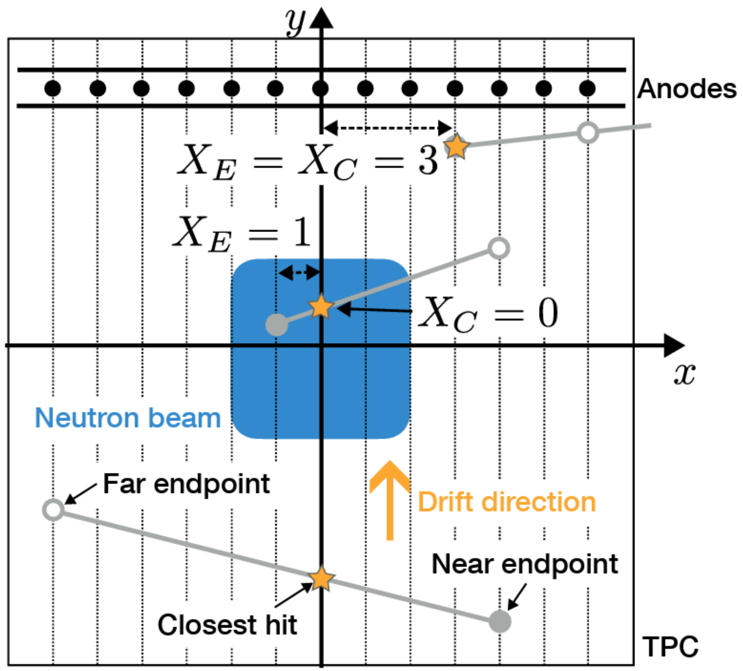
J-PARC Neutron Lifetime Experiment



arXiv:2412.19519

- A Time Projection Chamber (TPC) for both *neutron* and *beta* counting.
- Spin polarizer (super mirror) + Spin flippers to produce *neutron bunches*
  →a single neutron bunch is fully contained inside the TPC

J-PARC Neutron Lifetime Experiment



X_E: distance from the "near endpoint" of a track to center

X_C: distance from closest hit to center

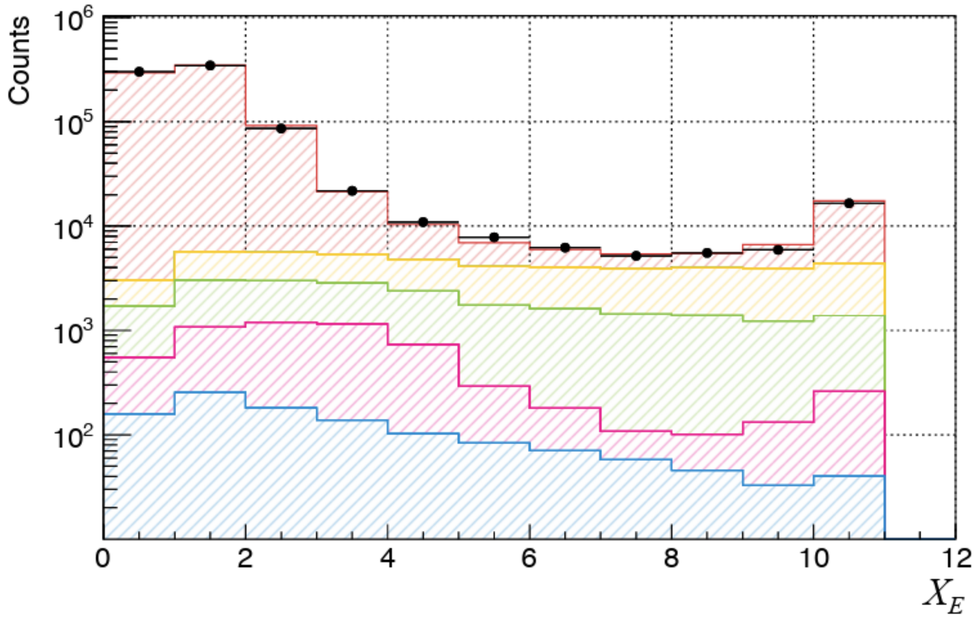


FIG. 3. X_E distribution for 50 kPa/new SFC. Black points represent measured data, and colored regions represent the stacked MC distributions. From top to bottom: red (β), yellow (gas-scattered 5000 keV γ rays), green (gas-scattered 200 keV γ rays), magenta (γ rays scattered by the ^{6}LiF tile shutter), and blue (β events from gas-scattered neutrons).

Effect	Uncertainty
Statistic	1.7
Cut position	0.9
Gas-induced background	+1.1/-2.0
Pile up	+1.5/-0.6
Contamination from ^{12}C(n,γ)^{13}C	+1.7/-0.0
γ-ray scattering at LiF shutter	1.3
Unbunched neutron from SFC	+1.1/-1.0
Inject ^{3}He	1.2
^{3}He in G1He	+1.5/-1.4
^{3}He(n,p)^{3}H cross section	1.2
Total systematic	+4.0/-3.6

arXiv:2412.19519

J-PARC Neutron Lifetime Experiment

$$\tau_{\rm n} = 877.2 \pm 1.7_{\rm (stat.)}\ {}^{+4.0}_{-3.6}{\rm (sys.)}\ \text{s}$$

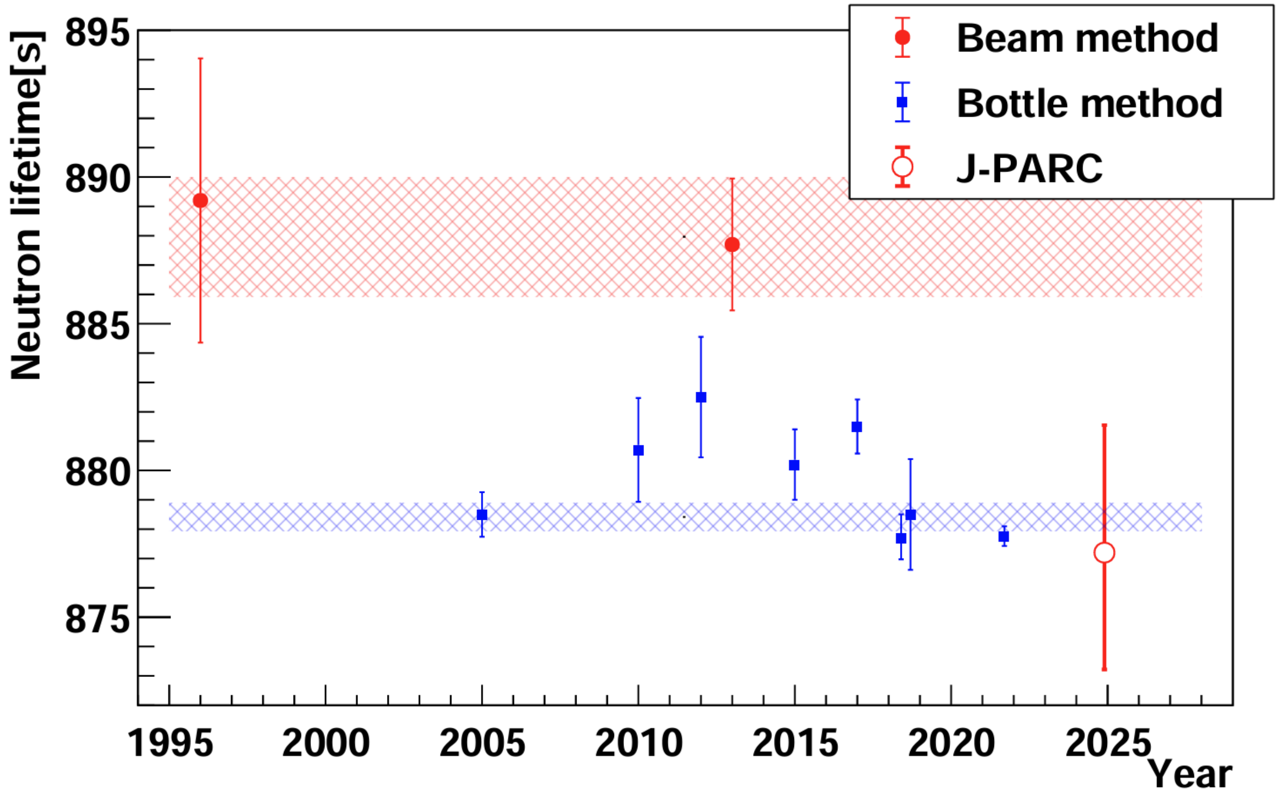
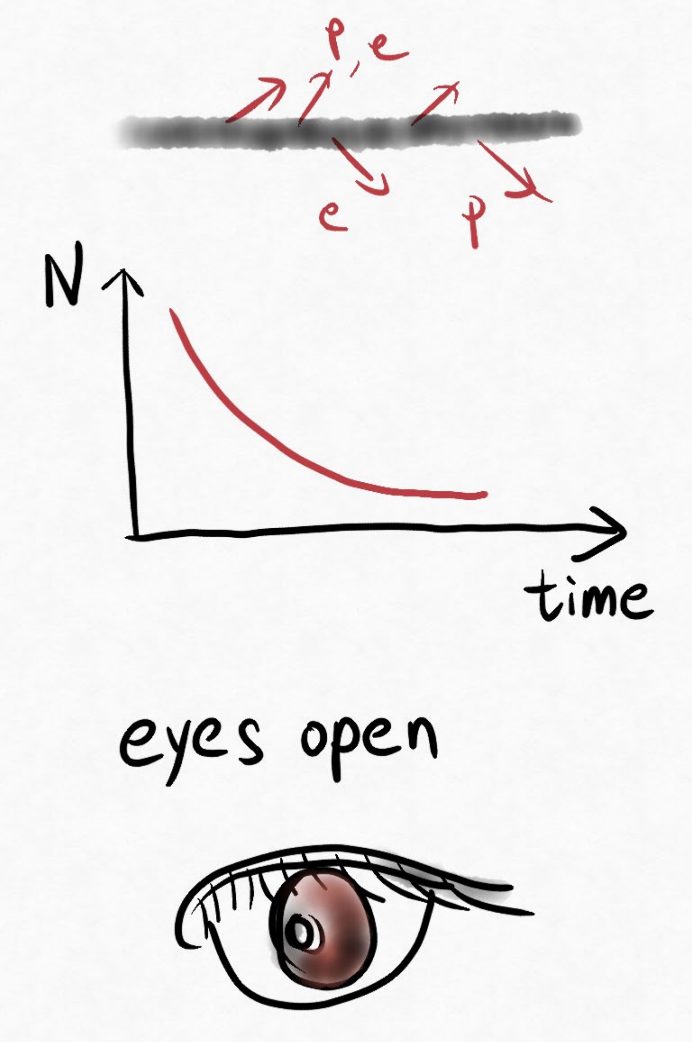


TABLE II. Neutron lifetime values for each gas pressure (100 kPa, 50 kPa) and SFC configuration (new, old), with averages. Units in seconds.

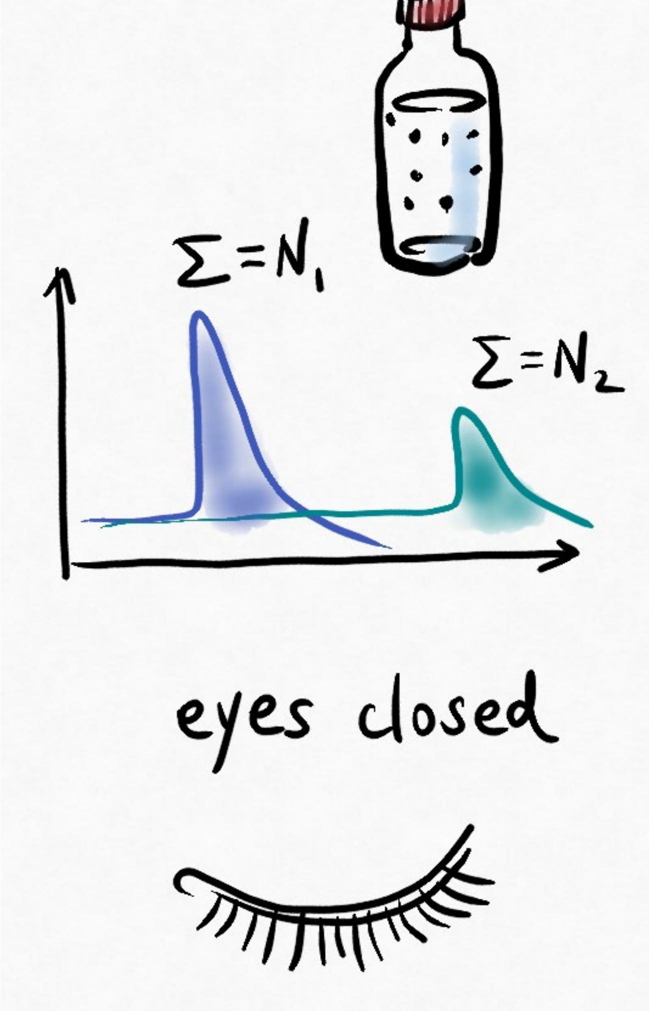
Conditions	Value	Stat.	Cut position	Other sys.
100 kPa/old SFC	870.9	3.5	+1.8/-2.8	+5.5/-4.9
100 kPa/new SFC	868.3	4.0	+1.5/-2.9	+3.8/-3.2
50 kPa/old SFC	868.2	7.7	+2.7/-0.9	+4.8/-3.9
50 kPa/new SFC	884.8	2.4	+0.8/-1.3	+3.2/-3.0
Combined	877.2	1.7		+4.0/-3.6

Measuring lifetime with eyes open or closed?

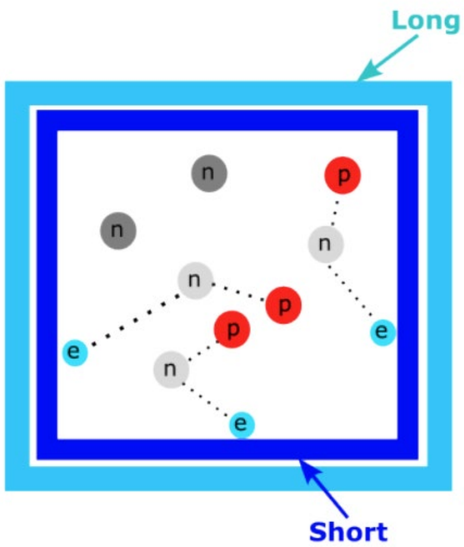
e-: JPARC, NIST UCN
p: PENeLOPE

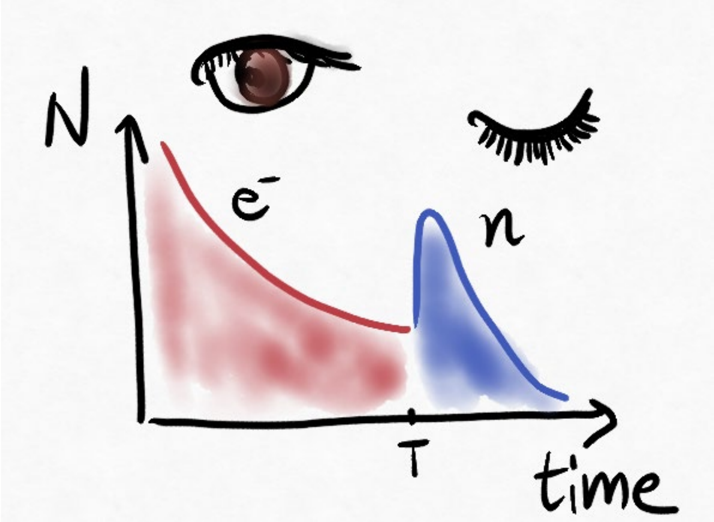


n: Gravitrap, UCNtau, UCNtau+, tauSPECT;
p: BL-1,2,3



Branching Ratio (BR):
UCNProBe (e-, n)





$$N_e = \int_0^T N_0 e^{-t/\tau'}$$

$$N_0 = N_n(T) e^{T/\tau'}$$

$$BR = \frac{N_e(T \to \infty)}{N_0} \overset{?}{=} 1$$

Systematic Effects

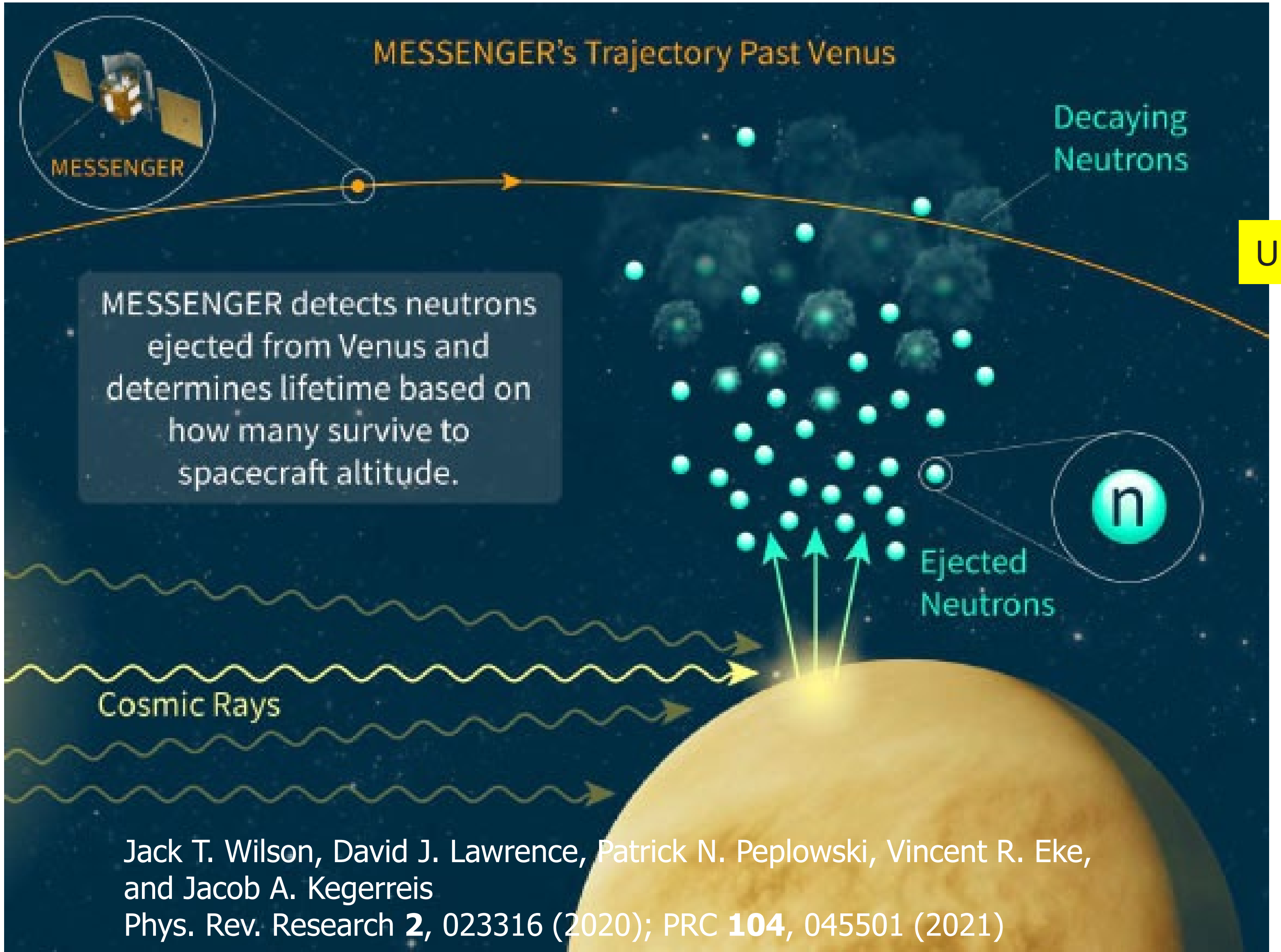
Bottle

- UCN loss
  - Over-threshold (or marginally trapped) neutrons
  - Heating (during storage)
- Spin flip loss (magnetic traps only)
- Detector effects
  - Pile up; threshold variation
  - Background
  - Particle identification
- Phase-space evolution

Beam

- Neutron counting
  - Capture cross-section on Li-6 or He-3
  - Neutron scatterings (off target and gas in gas counters)
  - Beam profile & instability
  - Deposit (in)stability
- Proton counting
  - Backscattering from detector deadlayer
  - Background from ionized residual H_2 gas
- Proton storage
  - Loss in the Penning trap

Using data acquired in 2007 and 2008 during flybys of Venus and Mercury by NASA's MESSENGER spacecraft, researchers measure the neutron lifetime…

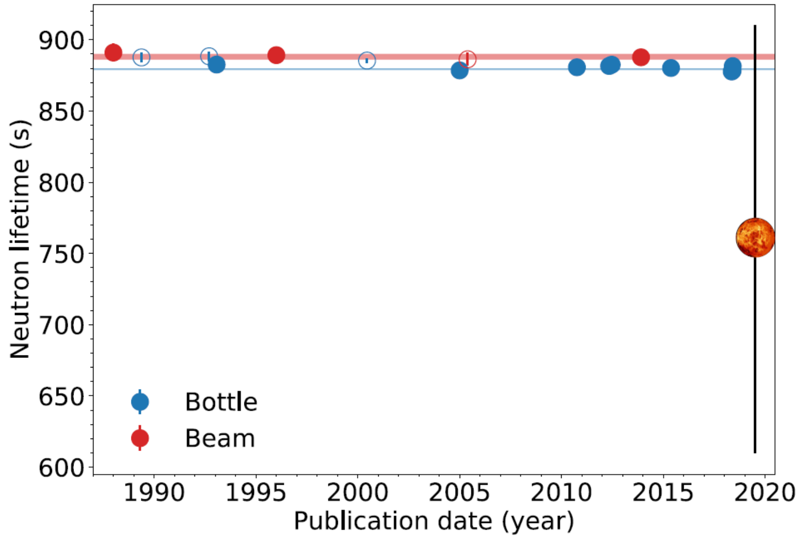


Jack T. Wilson, David J. Lawrence, Patrick N. Peplowski, Vincent R. Eke, and Jacob A. Kegerreis
Phys. Rev. Research **2**, 023316 (2020); PRC **104**, 045501 (2021)

- *Cosmic-ray-generated thermal neutrons* are strongly gravitationally influenced by the host planetary body.
- *Gravitationally bound neutrons:* characteristic time-of-flight ~ 900 s
- Surface-to-sensor neutron transport based on Newtonian mechanics

Updated analysis (2021): $\tau_n = 887 \pm 14(\text{stat})^{+7}_{-3}(\text{syst})$

MESSENGER's flyby of Venus provided a low-statistics and low-systematic measurement of τ_n of 760±50 s.

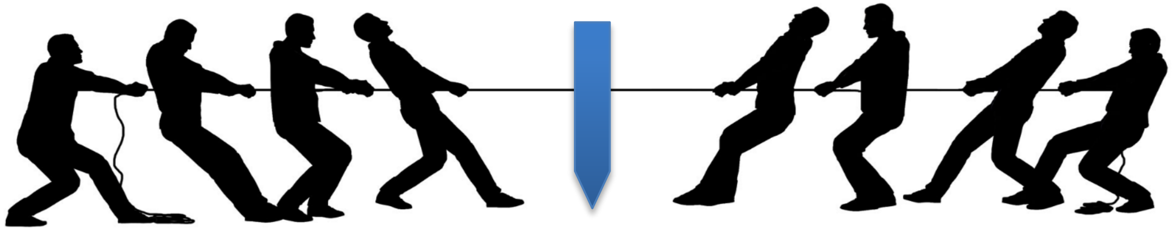


A new lunar mission will get more precise results to measure neutron lifetime in space!

Summary: Measure τ_n is challenging!

- The neutron lifetime is long: 880 s →14.6 mins
- Beam method:
  - Signal rate is small
  - High background in reactors →(e-, p) coincidence →p in a trap (NIST BL experiment)
  - Absolute detection efficiencies !! → requires offline calibrations
- Bottle method:
  - Needs long observation times 🕔≈2.2×τ
  - Ultracold neutrons in a “lossless” bottle →magnetic traps with good spectral cleaning

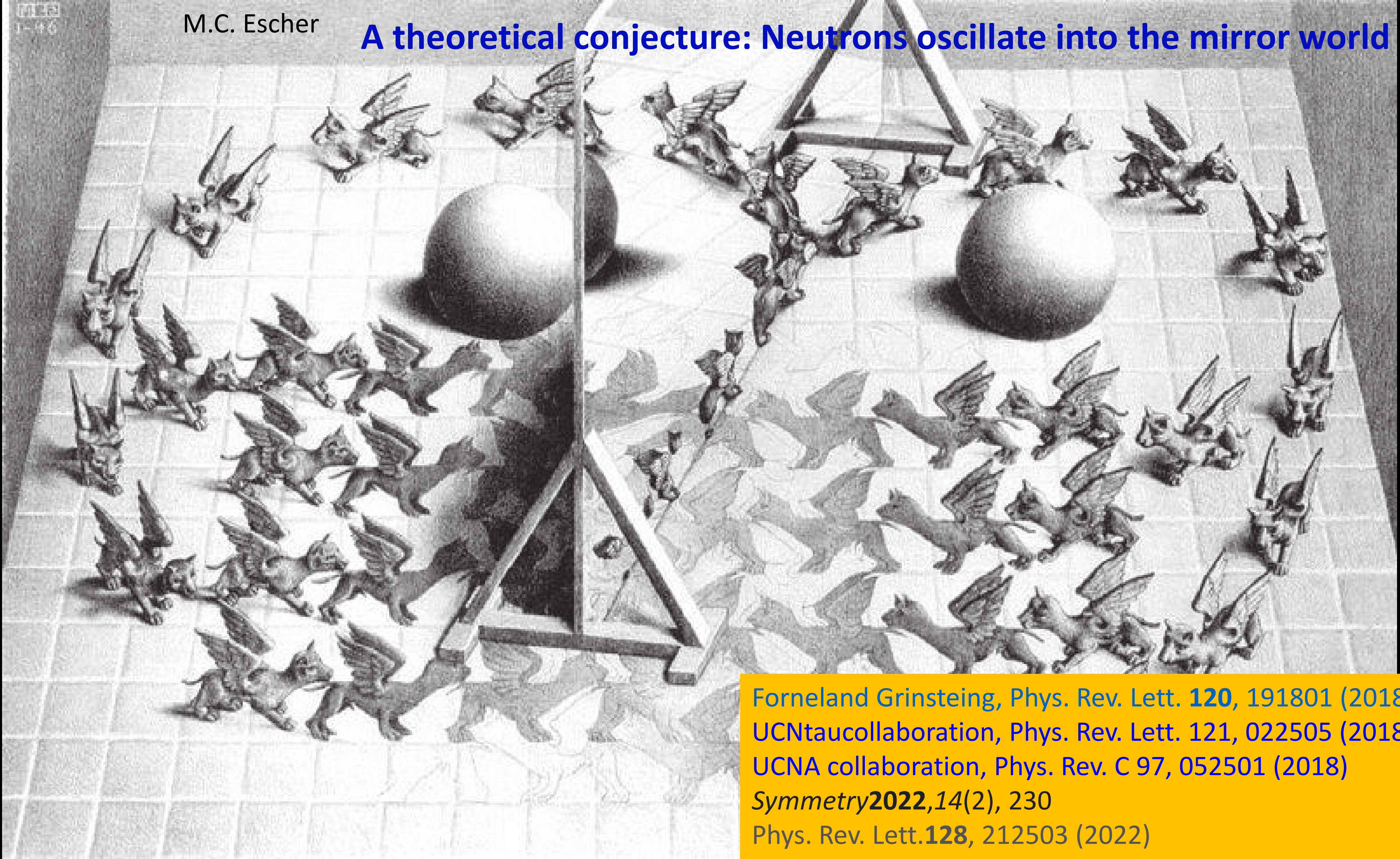
Beam vs Bottle



PDG value

BUT we keep trying to do a better job:
A handful of dedicated efforts (both using beam and bottle methods) are working towards resolving the neutron lifetime puzzle.

A theoretical conjecture: Neutrons oscillate into the mirror world



M.C. Escher

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