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JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

Neutron lifetime experiments (beyond UCNτ)

MITP workshop “From beta decay to the Z pole”

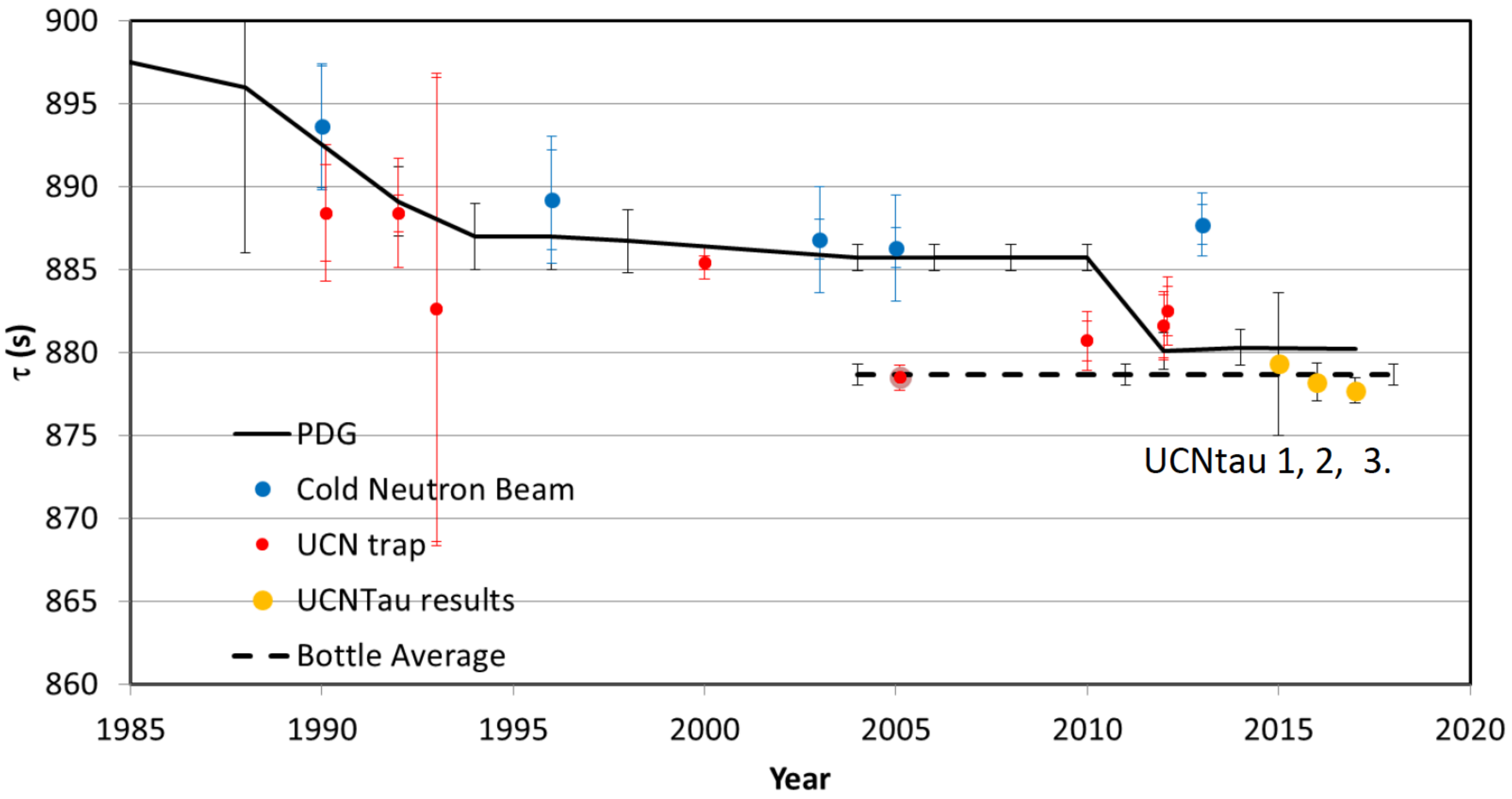
Prof. Dr. M. Fertl
October 28^{th}, 2022

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

From Chen-Yu's talk on Monday

UCNtau results (2018)

1. 2015 commission data (RSI)
2. 2015-2016 data
3. 2016-2017 data (Science, 2018)



With UCNtau, we have made a measurement of τ_n for the first time with **no extrapolation**: 877.7 ± 0.7 (stat) +0.3/-0.1 (sys) s.

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From Chen-Yu's talk on Monday

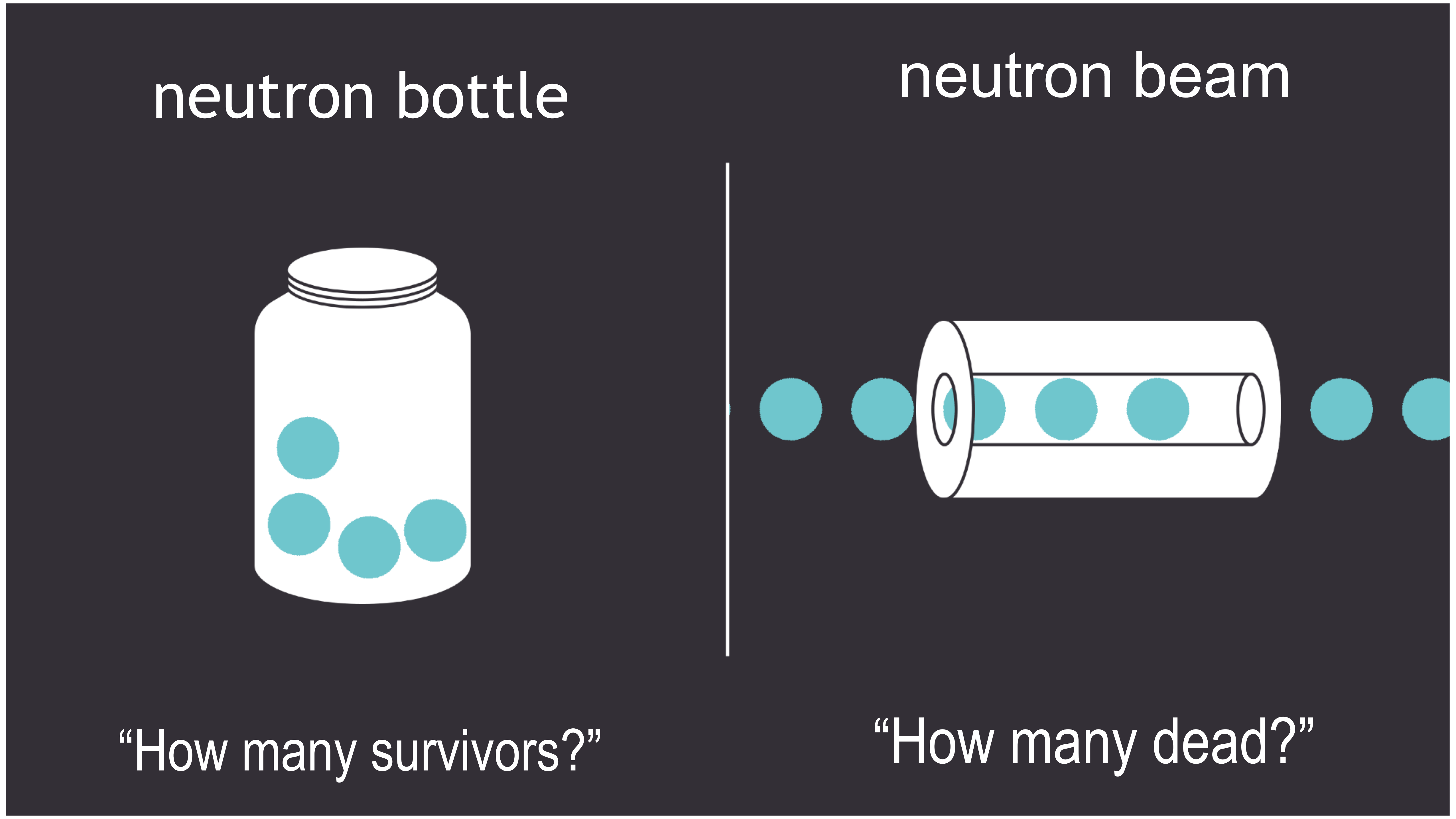
New Result (2021): $\tau_n = 877.75 \pm 0.28^{+0.22}_{-0.16}$ s

Effect	Previous Reported Value (s)	New Reported Value (s)	Notes
τ_{meas}	877.5 ± 0.7	877.58 ± 0.28	Uncorrected Value!
UCN Event Definition	0 ± 0.04	0 ± 0.13	Single photon analysis vs. Coincidence analysis
Normalization Weighting	--	0 ± 0.06	Previously unable to estimate
Depolarization	$0 + 0.07$	$0 + 0.07$	
Uncleaned UCN	$0 + 0.07$	$0 + 0.11$	
Heated UCN	$0 + 0.24$	$0 + 0.08$	
Phase Space Evolution	0 ± 0.10	--	Now included in stat. uncertainty
Al Block	--	0.06 ± 0.05	Accidentally dropped into trap…
Residual Gas Scattering	0.16 ± 0.03	0.11 ± 0.06	
Sys. Total	$\mathbf{0.16^{+0.4}_{-0.2}}$	$\mathbf{0.17^{+0.22}_{-0.16}}$	
TOTAL	$\mathbf{877.7 \pm 0.7^{+0.4}_{-0.2}}$	$\mathbf{877.75 \pm 0.28^{+0.22}_{-0.16}}$	

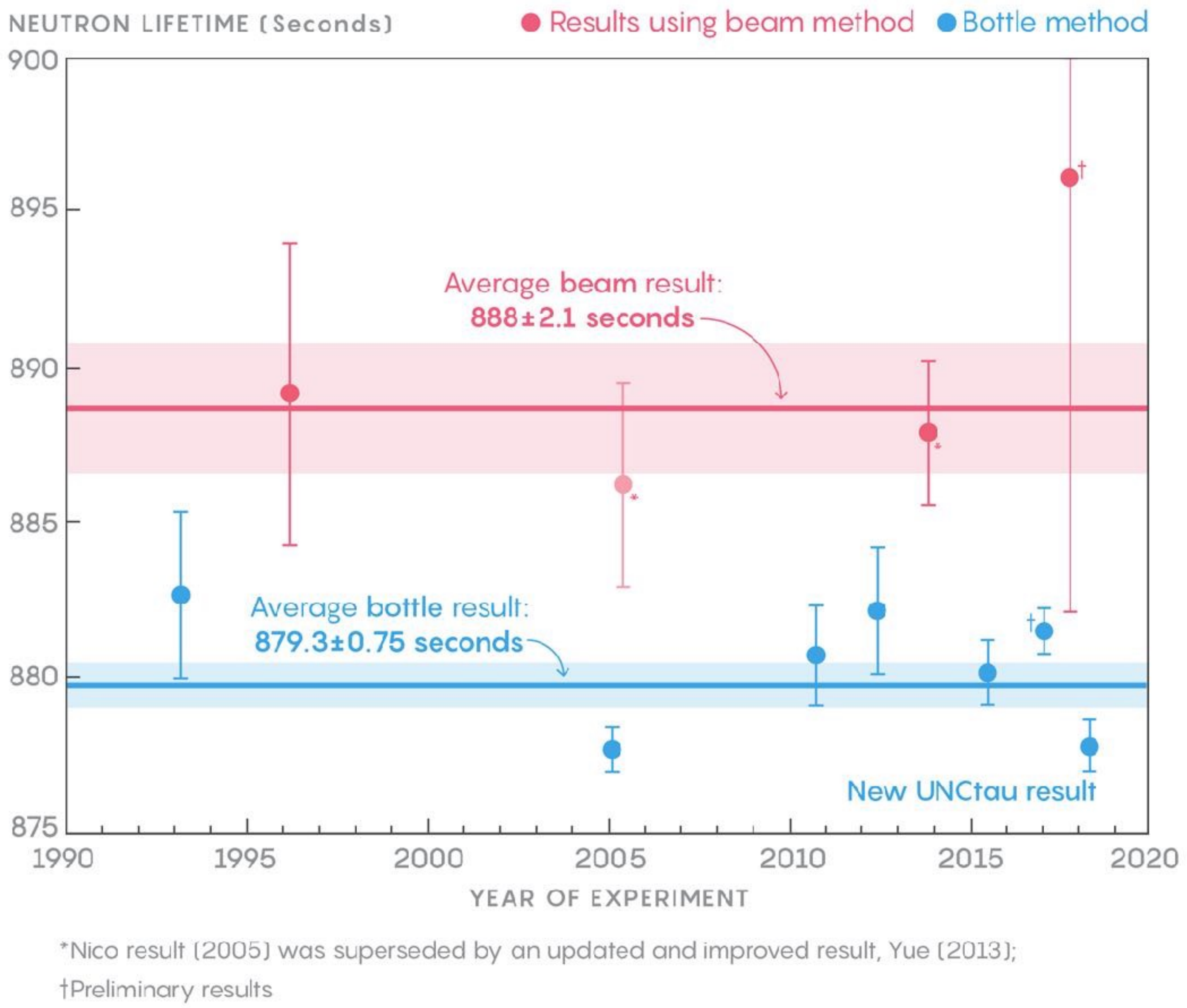
F. M. Gonzalez et al. Phys. Rev. Lett. 127 162501 (October 13, 2021)

The neutron lifetime puzzle

Question: How long does a free neutron live?



adapted form https://www.quantamagazine.org/neutron-lifetime-puzzle-deepens-but-no-dark-matter-seen-20180213/



Discrepancy of ~ 4σ:

Beam: (888 ± 2.1) s

Bottle: (879.3 ± 0.75) s

Systematic effects of beam or bottle experiments?

New Physics is rather unlikely!

Many “dark decay channels” have been proposed but are very unlikely, see e.g. Dubbers et al., PLB, 791, 2019

Alternative approaches

Counting the dead
⇒ neutron beam lifetime experiment

Full magnetic neutron confinement
⇒ τSPECT experiment at JGU

Counting the parents and the daughter
⇒ ^{3}He TPC-based experiment

Flying to the Moon!
⇒ Astrophysical measurement proposal

Provide a summary of the latest complementary and alternative ideas as presented at the PSI 2022 workshop last week.

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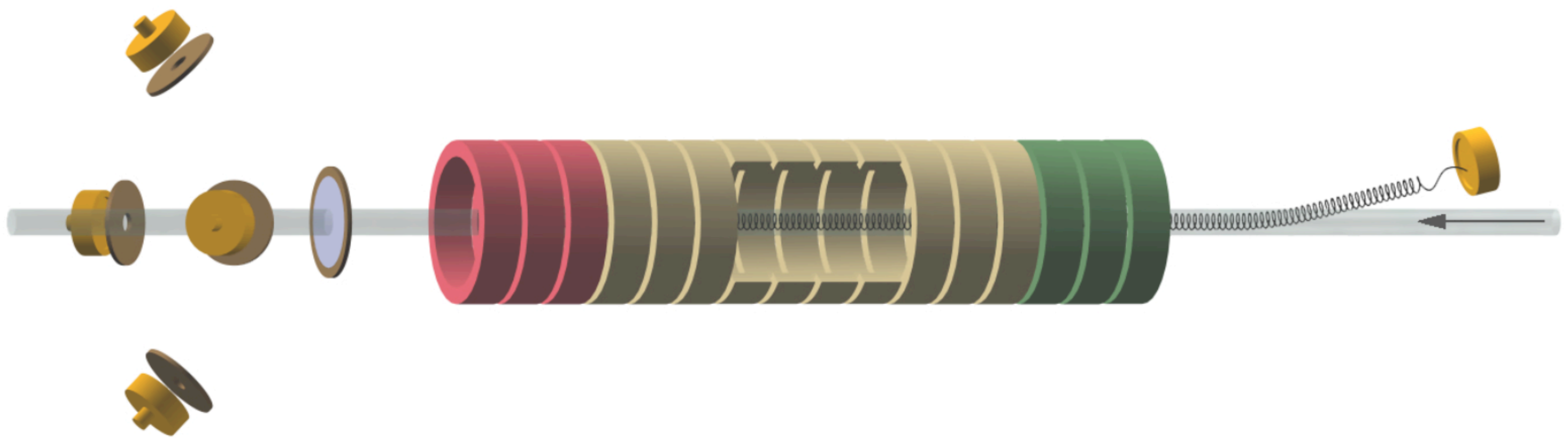
Counting the dead: the cold neutron beam decay experiments

Recent Developments in Beam Neutron Lifetime Experiments



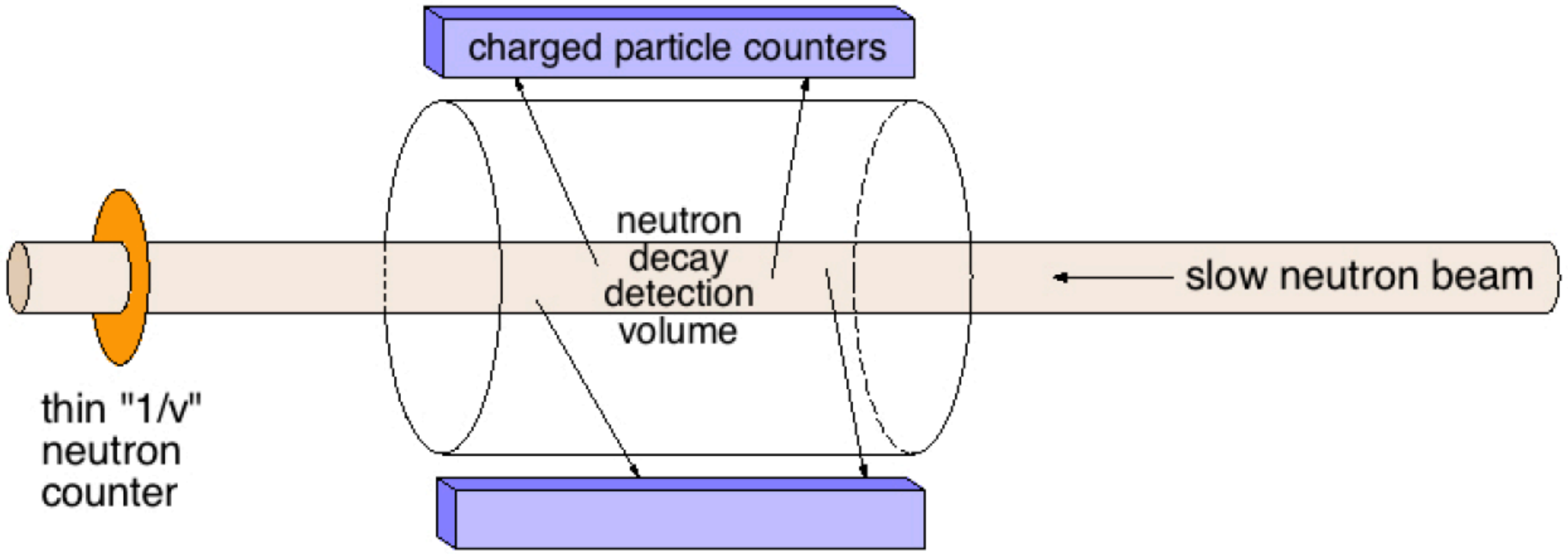
F. E. Wietfeldt
Tulane University

Slide shown by Fred Wietfeldt as PSI 2022

PSI 2022
Physics of Fundamental Symmetries and Interactions

Beam Method

Slide shown by Fred Wietfeldt
as PSI 2022



neutron decay rate: $\Gamma = -\frac{dN}{dt} = \frac{N}{\tau}$

neutrons in detection volume: $N = \rho_n V_{\mathrm{det}} = \left(\frac{\phi}{v}\right) A_{\mathrm{beam}} L_{\mathrm{det}}$

with "white" neutron beam: $N = \rho_n V_{\mathrm{det}} = A_{\mathrm{beam}} L_{\mathrm{det}} \int \frac{\phi(v)}{v} dv$

$\varepsilon_p =$ efficiency for counting a neutron decay charged particle

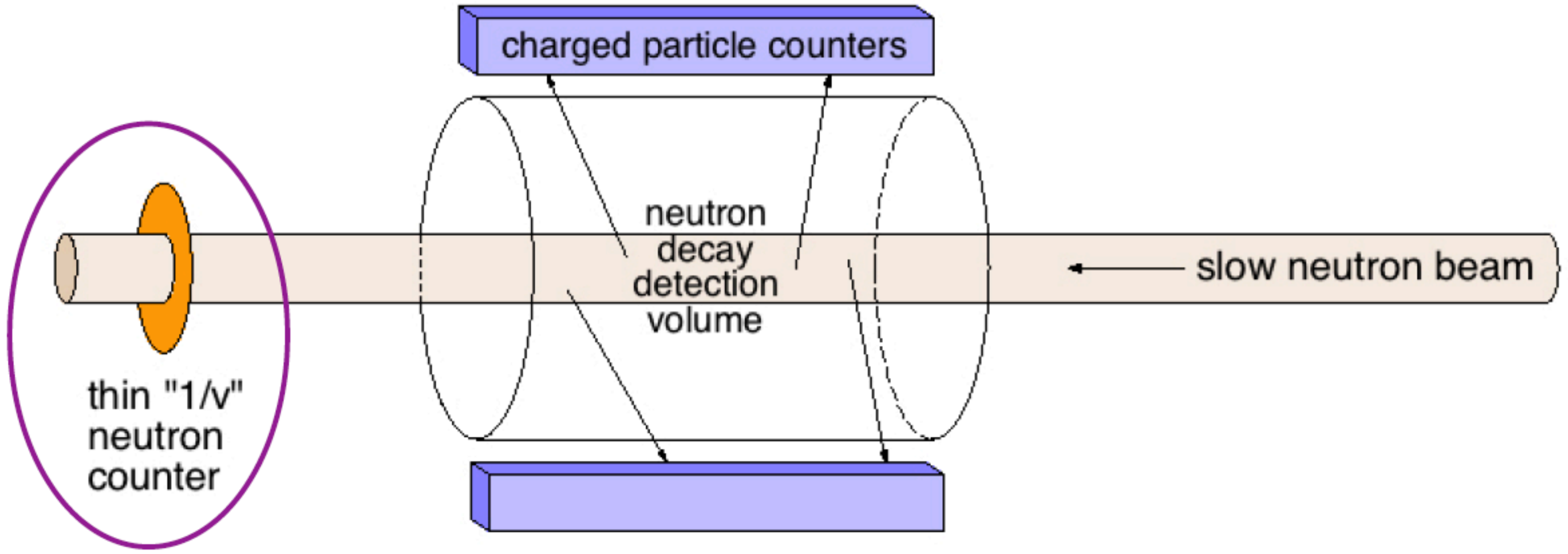
$$R_p = \varepsilon_p \Gamma = \varepsilon_p \frac{N}{\tau} = \varepsilon_p \frac{A_{\mathrm{beam}} L_{\mathrm{det}}}{\tau} \int \frac{\phi(v)}{v} dv$$

The biggest challenge

Determination of proton detection efficiency to better than 10^{-4}!

Neutron Counting

Slide shown by Fred Wietfeldt as PSI 2022



$\varepsilon_0 =$ efficiency for counting a neutron at reference thermal velocity v_{th} (2200 m/s)

$\varepsilon(v) =$ efficiency for counting a neutron of velocity v

"1/v law" for neutron absorption in a thin target: $\varepsilon(v) = \varepsilon_0 \frac{v_{th}}{v}$

neutron count rate: $R_n = \int A_{beam}\varepsilon(v)\phi(v)dv = \varepsilon_0 A_{beam} v_{th} \int \frac{\phi(v)}{v} dv$

The biggest challenge

Determination of neutron detection efficiency to better than 10^{-4}!

Slide shown by Fred Wietfeldt
as PSI 2022

Beam Method

$$R_p = \varepsilon_p \frac{A_{\text{beam}} L_{\text{det}}}{\tau} \int \frac{\phi(v)}{v} dv \qquad R_n = \varepsilon_0 A_{\text{beam}} v_{\text{th}} \int \frac{\phi(v)}{v} dv$$

$$\tau = \frac{R_n\, \varepsilon_p\, L_{\text{det}}}{R_p\, \varepsilon_0\, v_{\text{th}}}$$

$R_n =$ neutron counter rate

$R_p =$ neutron decay product count rate

$\varepsilon_0 =$ neutron counter thermal equivalent efficiency

$\varepsilon_p =$ neutron decay product counting efficiency

$v_{\text{th}} = 2200$ m/s

$L_{\text{det}} =$ effective length of detection region

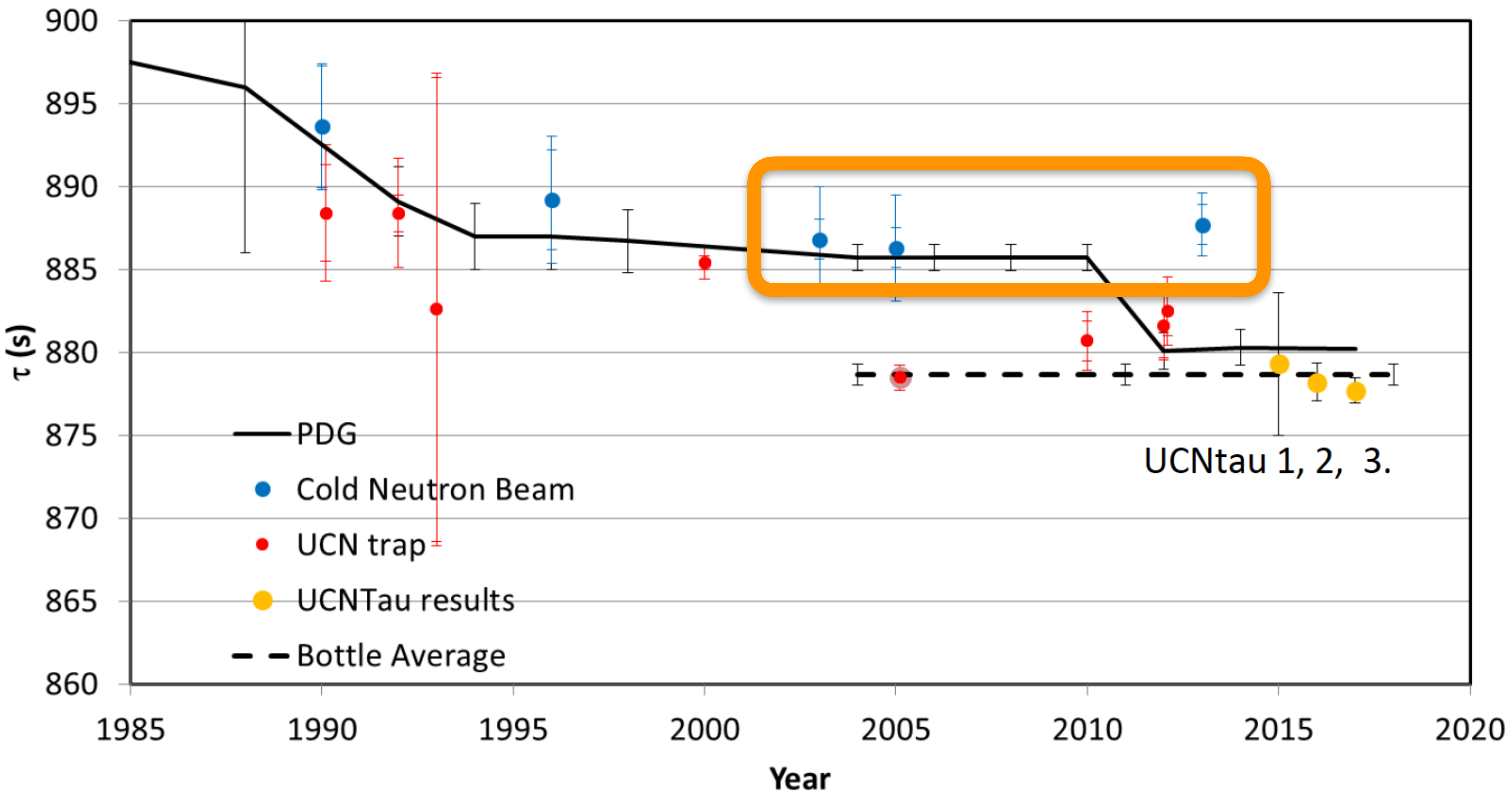
The method suppresses the effects related to the velocity-weighted-flux integral!

But the detection efficiencies for protons and neutrons need to be known to better than 10^{-4}

BL1 experiment

UCNtau results (2018)

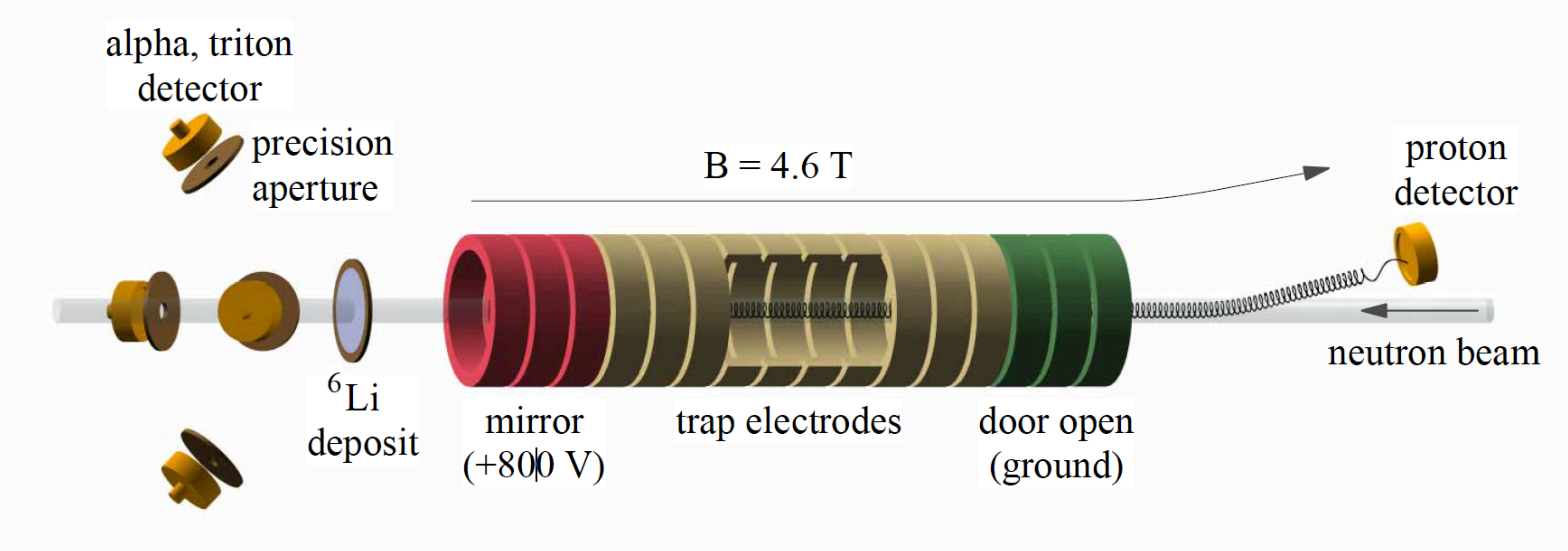
1. 2015 commission data (RSI)
2. 2015-2016 data
3. 2016-2017 data (Science, 2018)



With UCNtau, we have made a measurement of τ_n for the first time with **no extrapolation**: 877.7 ± 0.7 (stat) +0.3/-0.1 (sys) s.

26

The BL1 setup



Slide shown by Fred Wietfeldt
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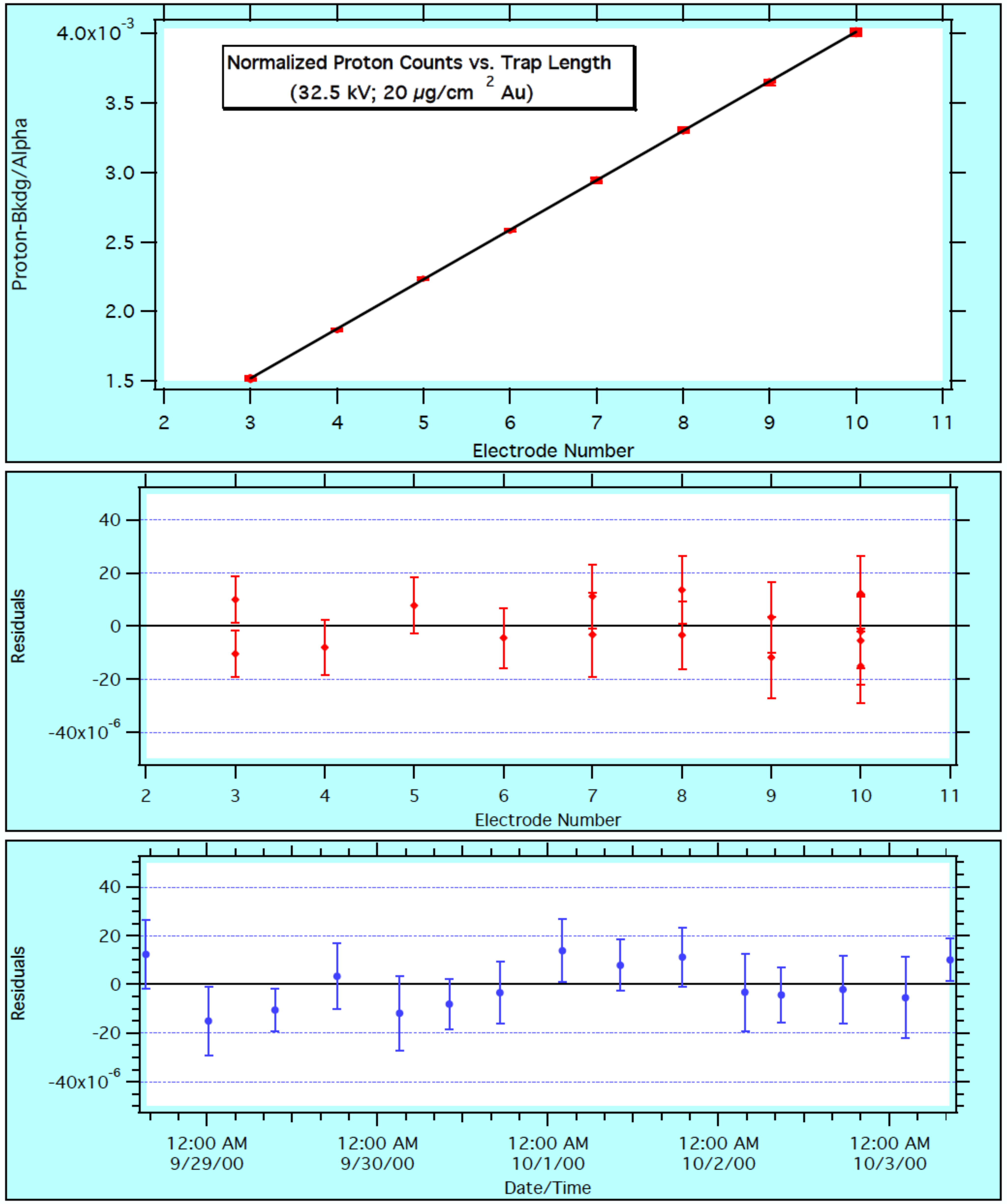


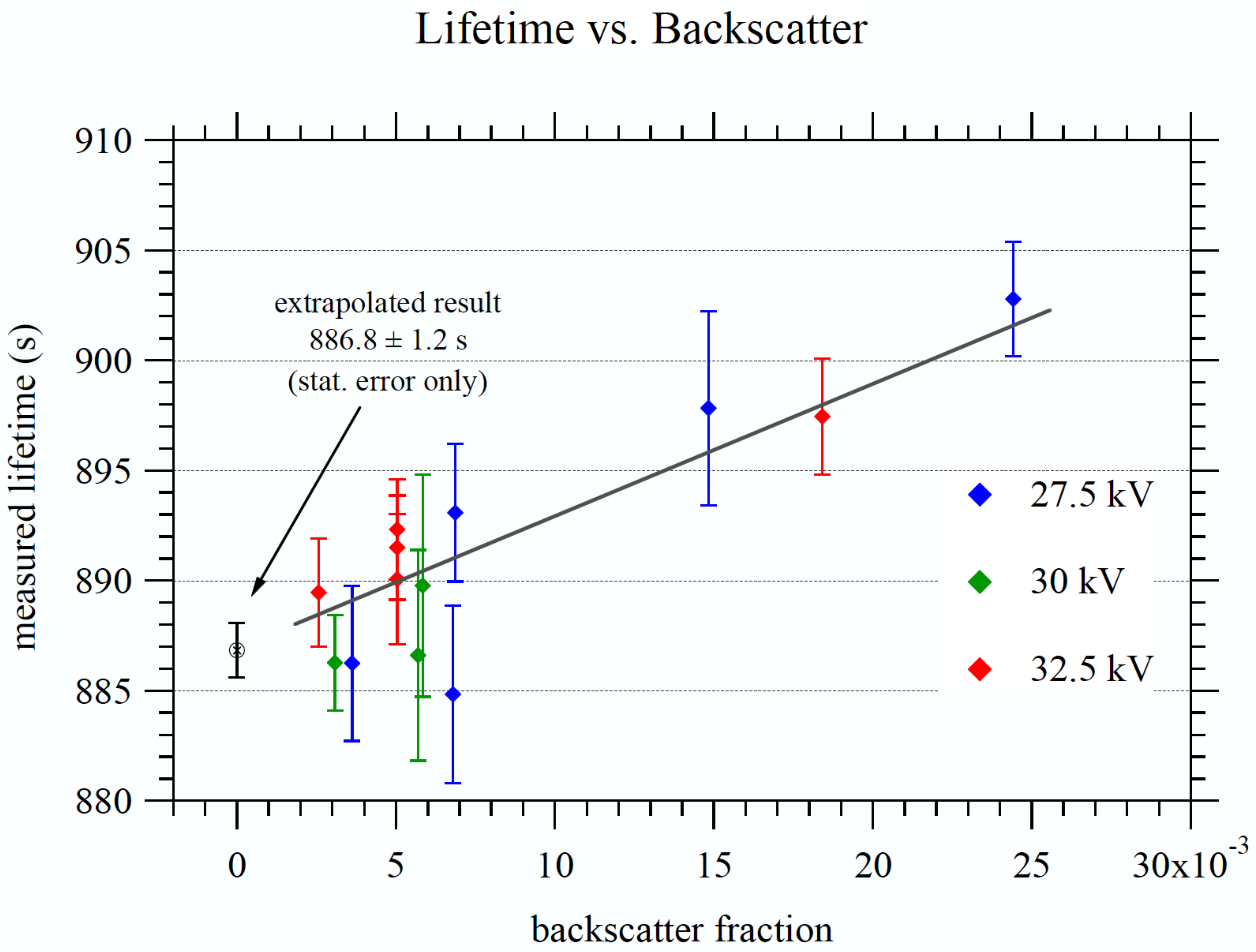
Fit $\frac{R_p}{R_n}$ *vs. n*

to a straight line

$$\text{slope} = \tau^{-1}\left(\frac{\varepsilon_p}{\varepsilon_0 v_{th}}\right)$$

Systematically extend the length of the trap to compensate for the edge effect of the trap

Backscattering of protons from the detector



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The protons need to be post accelerated!

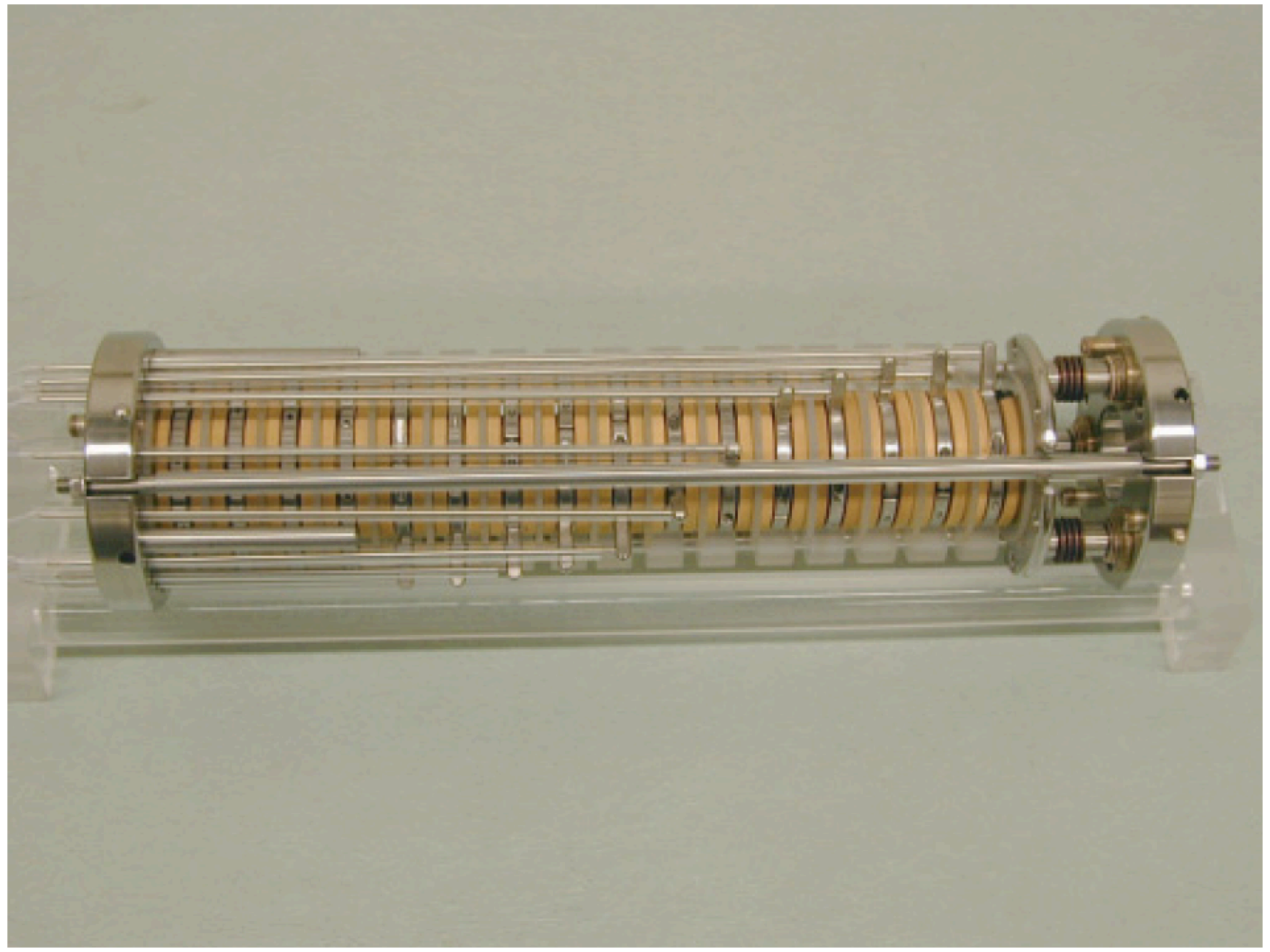
Systematic study as a function of post-acceleration voltage

PHYSICAL REVIEW C **71**, 055502 (2005)

Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam

J. S. Nico, M. S. Dewey, and D. M. Gilliam
National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

F. E. Wietfeldt
Tulane University, New Orleans, Louisiana 70118, USA

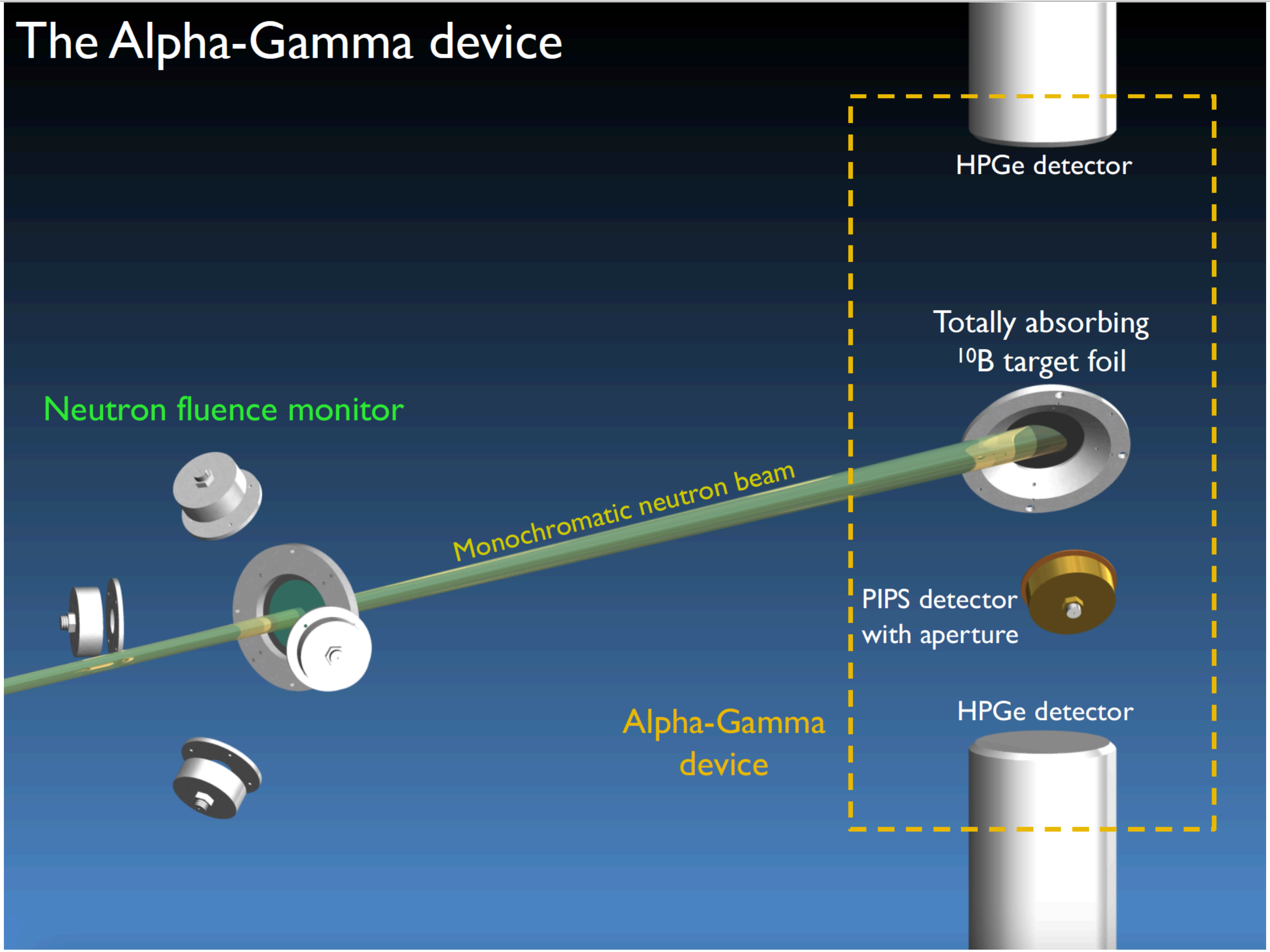


$$\tau_n = \left(886.3 \pm 3.4\right)\,\mathrm{s}$$

TABLE V. Summary of the systematic corrections and uncertainties for the measured neutron lifetime. Several of these terms also appear in Table VII where it is seen that their magnitude depends weakly on the running configuration. In those cases, the values given in this table are the configuration average. The origin of each quantity is discussed in the section noted in the table.

Source of correction	Correction (s)	Uncertainty (s)	Section
^{6}LiF deposit areal density		2.2	IV A
^{6}Li cross section		1.2	II D
Neutron detector solid angle		1.0	II D 1
Absorption of neutrons by ^{6}Li	+5.2	0.8	IV A 2
Neutron beam profile and detector solid angle	+1.3	0.1	IV A 2
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1	IV A 2
Neutron beam halo	−1.0	1.0	IV B 2
Absorption of neutrons by Si substrate	+1.2	0.1	IV A 2
Scattering of neutrons by Si substrate	−0.2	0.5	IV A 3
Trap nonlinearity	−5.3	0.8	IV C
Proton backscatter calculation		0.4	IV D 3
Neutron counting dead time	+0.1	0.1	II D
Proton counting statistics		1.2	IV D 2
Neutron counting statistics		0.1	II D
Total	−0.4	3.4	

Major improvements by better absolute calibration for neutron flux



PRL 111, 222501 (2013) PHYSICAL REVIEW LETTERS week ending 27 NOVEMBER 2013

Improved Determination of the Neutron Lifetime

A. T. Yue,[1,2,3,*] M. S. Dewey,[2] D. M. Gilliam,[2] G. L. Greene,[3,4] A. B. Laptev,[5,6] J. S. Nico,[2] W. M. Snow,[7] and F. E. Wietfeldt[5]

TABLE II. The new uncertainty budget for the neutron lifetime. Corrections shown are relative to the 2005 beam lifetime result.

Source of uncertainty	Correction (s)	Uncertainty (s)
Improved neutron fluence determination	+1.4	0.5
Change in ^{6}Li deposit mass	+0.0	0.9
Systematics unassociated with neutron fluence		1.7
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	+1.4	2.3

$$\tau_n = (887.7 \pm 2.3)\,\mathrm{s}$$

Improved measurement using the original BL1 setup

Slide shown by Fred Wietfeldt as PSI 2022

BL2

A repeat of the NIST beam lifetime experiment using the original apparatus with some improvements:

- improved, lower noise proton preamplifier
- digitized detector output for improved analysis techniques, e.g. trapezoid filter
- 3x higher neutron flux at NCNR NG-C end position
- more flexible vacuum configuration to improve trap stability and study residual gas effects
- larger (up to 600 mm^2) silicon proton detectors

Goals:

1. test and study systematic effects in the NIST neutron lifetime apparatus
2. improved neutron lifetime measurement (< 2 s)

BL2

NCNR operational issues:

- shutdown **March 2020 - August 2020** due to COVID
- shutdown **February 2021 - present** due to fuel element failure at reactor startup

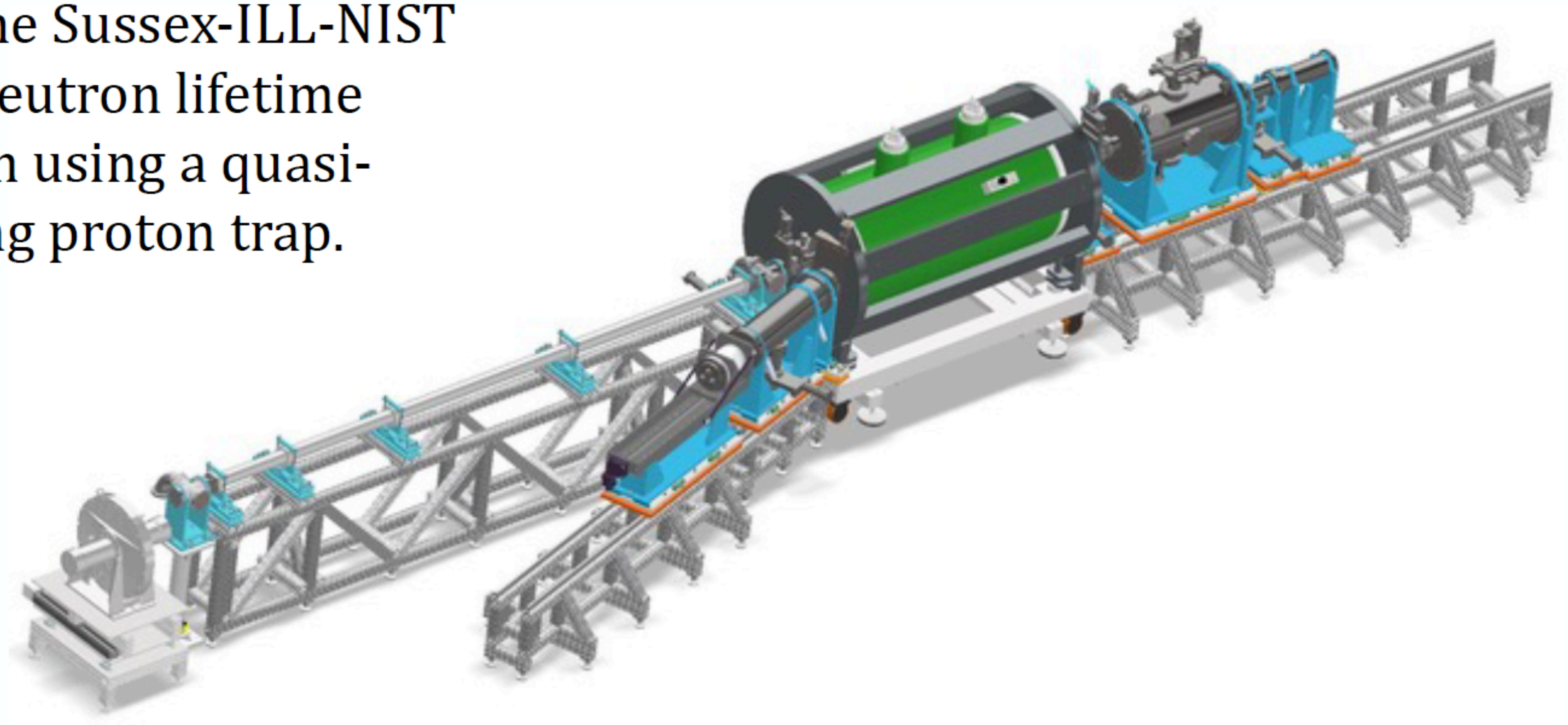
NCNR restart planned for early 2023

BL3: bigger and better, and fully funded by NSF

BL3: A Next Generation Beam Neutron Lifetime Experiment

Slide shown by Fred Wietfeldt as PSI 2022

Based on the Sussex-ILL-NIST beam neutron lifetime program using a quasi-Penning proton trap.



BL3 Key Features

- Higher flux (NIST NG-C) and larger diameter neutron beam (7 mm ⟶ 40 mm)
- Longer proton trapping region (35 cm ⟶ 50 cm)
- Larger and more uniform magnetic field (<0.2% in trapping region)
- Large (10 cm active diameter) segmented silicon proton detector
- Close to 100% efficiency for detecting backscattered protons (no large extrapolation to zero backscatter needed)
- A new, larger ^{10}B Alpha-Gamma spectrometer to calibrate the neutron counter to relative precision < 3×10^{-4}
- *In situ* neutron time-of-flight system to measure the neutron wavelength spectrum to 0.03 Å precision

Scientific Goals:

1. Further explore, cross check, and reduce all systematic uncertainties to $<10^{-4}$ relative.
2. Reduce the neutron lifetime uncertainty from the beam method to <0.3 s.

Start of data taking planned for 2026

Fully magnetically confined UCN: τSPECT

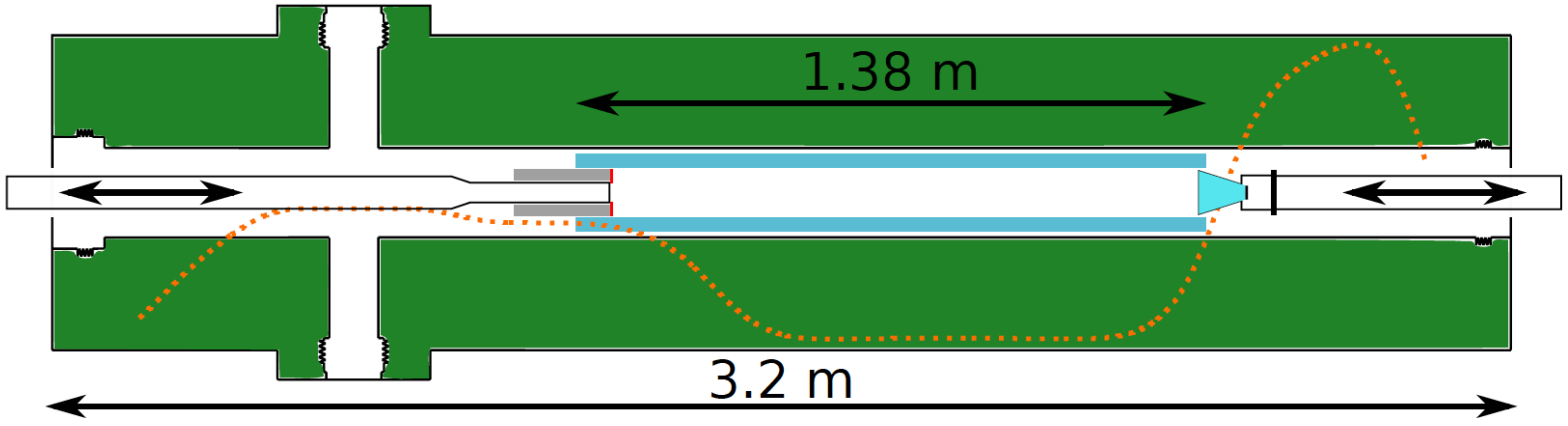
τSPECT

Concept:

- 3-D magnetic storage
  - Two solenoids + Octupole
- Spinflip-loading
  - Holding field polarizes neutrons
  - Fast adiabatic spinflip as loading mechanism
- In-situ UCN detection
  - Minimizes extraction losses
  - High detector requirements wrt temp. & B-field

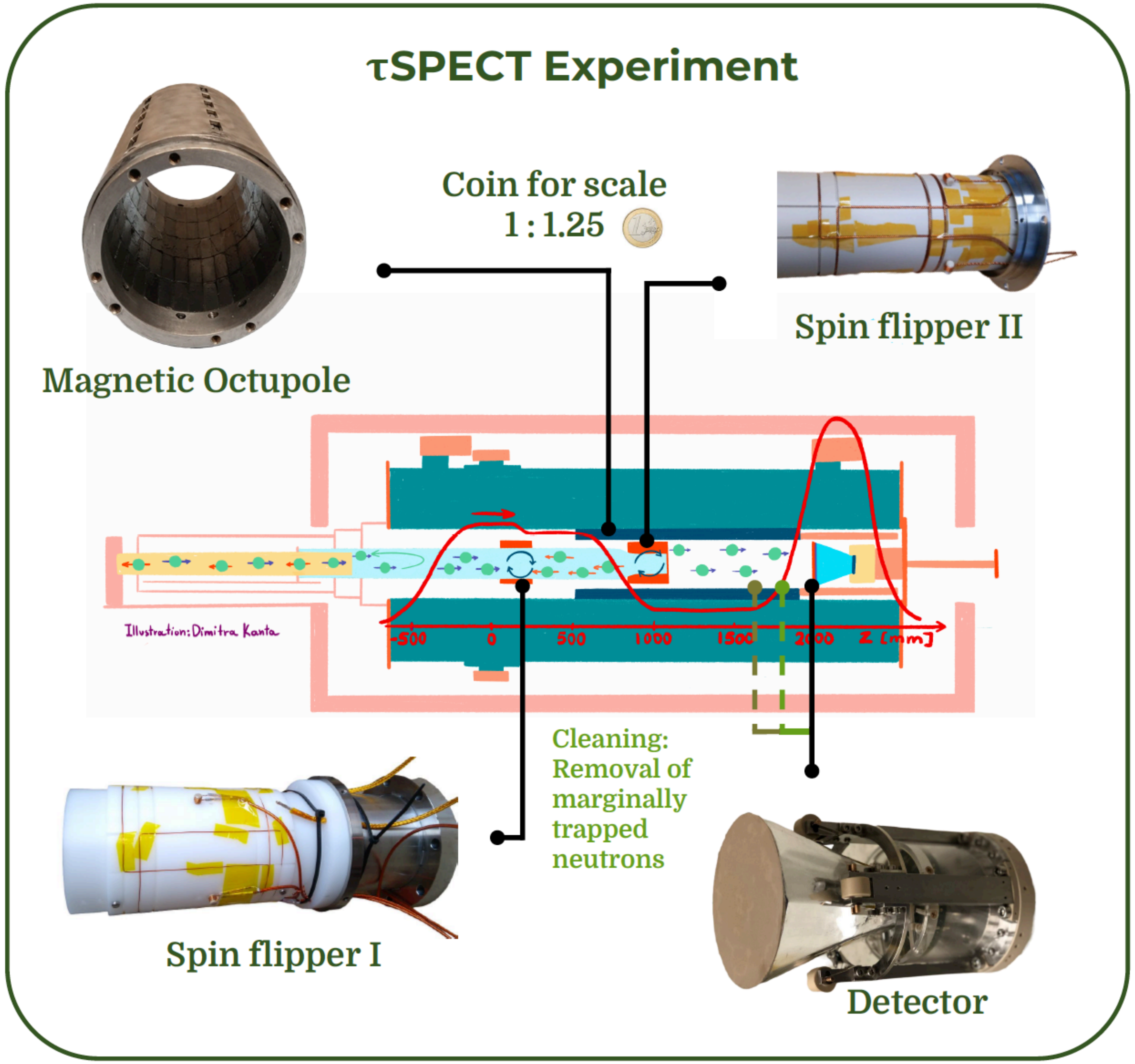
Fully magnetically confined UCN: τSPECT

Measurement Procedure

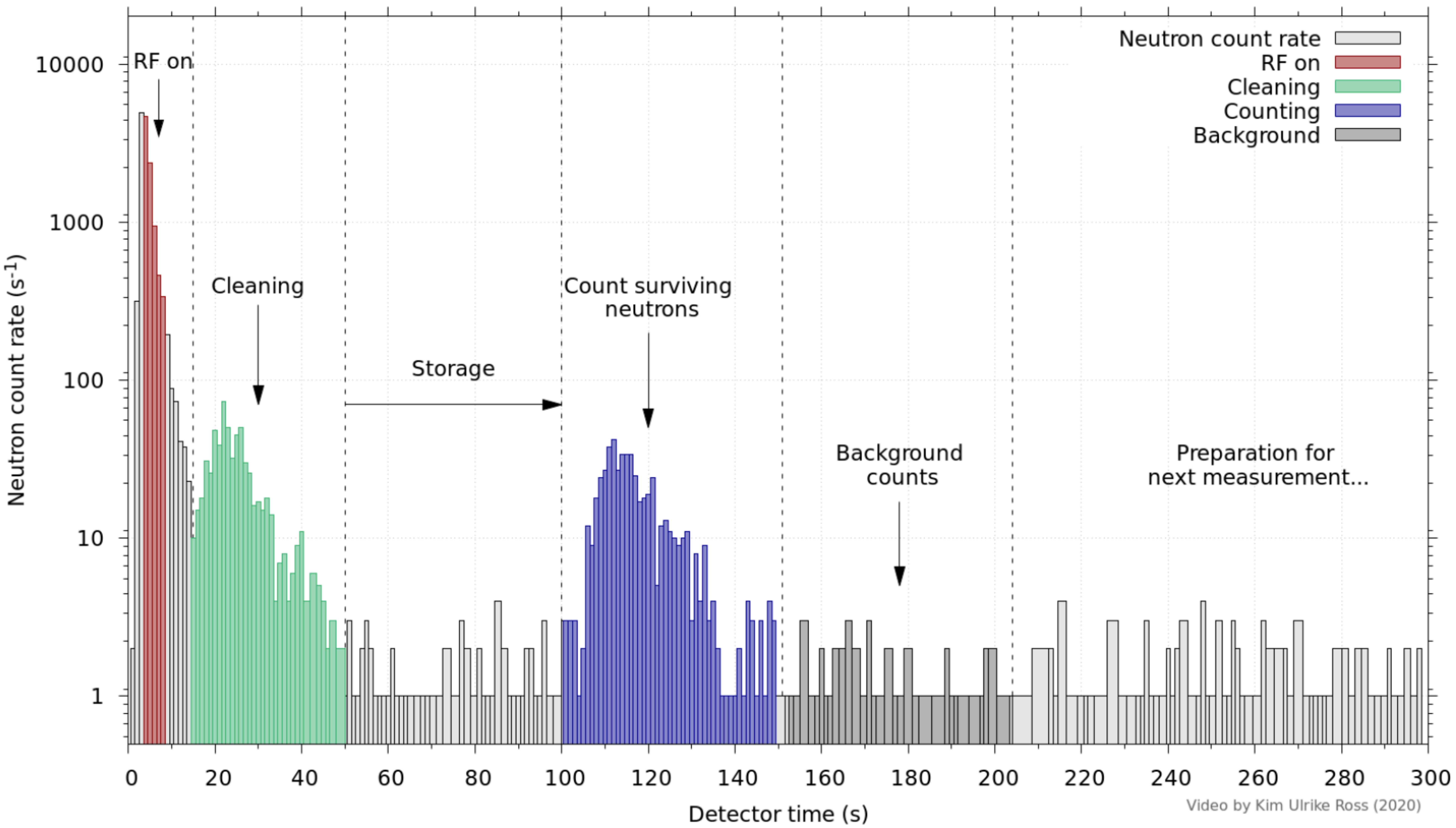


1. UCN production (30 ms reactor pulse)
2. Fill UCN into τSPECT Magnet from the left
   - Polarization due to high Magnetic Field, SF on
   - Simultaneously: Intensity Monitoring (non-trappable UCN)
3. Remove SF from storage region
4. Detector to cleaning position and back
5. Wait ... then count UCN

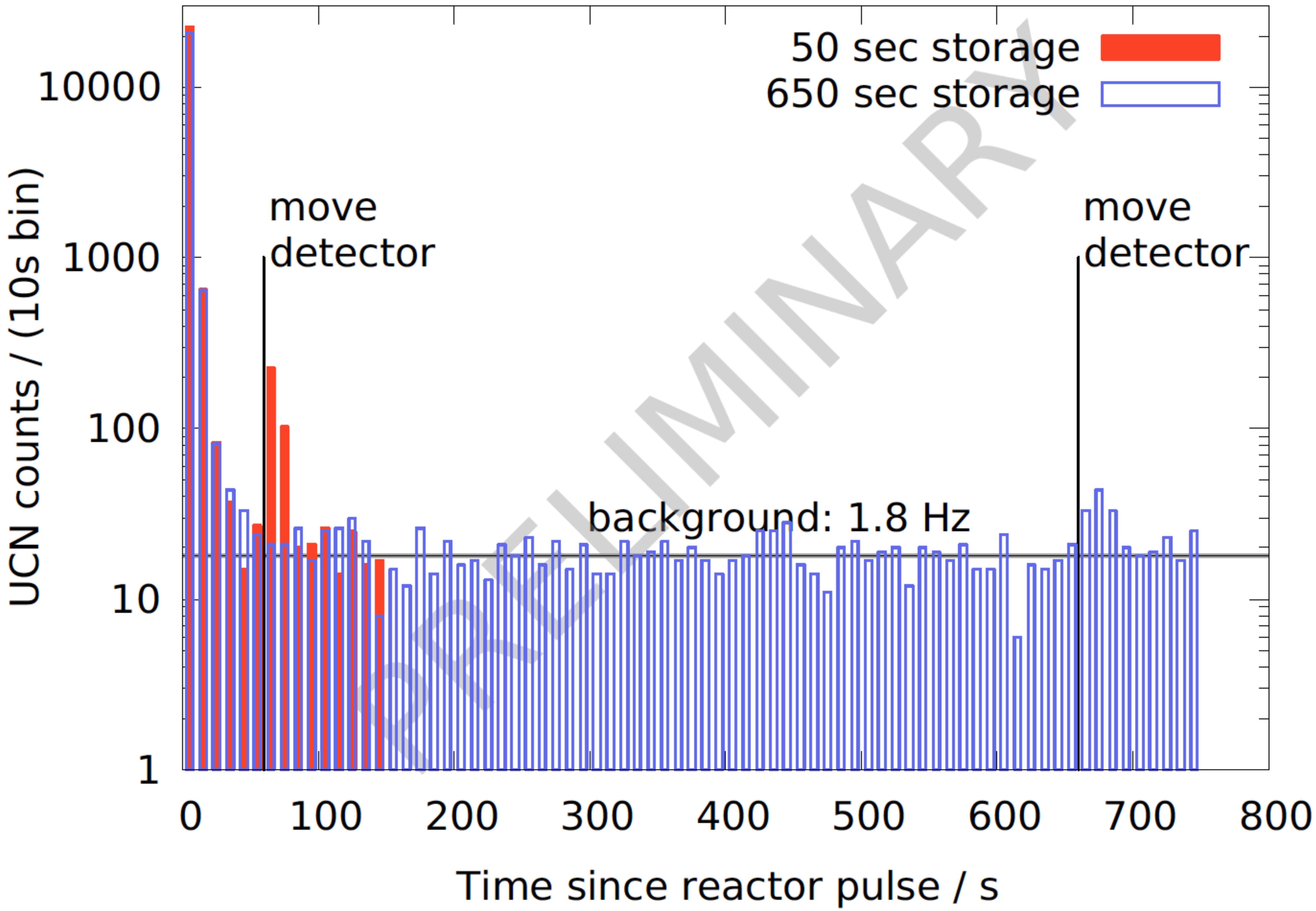
The inner working parts



The τSPECT measurement cycle in data

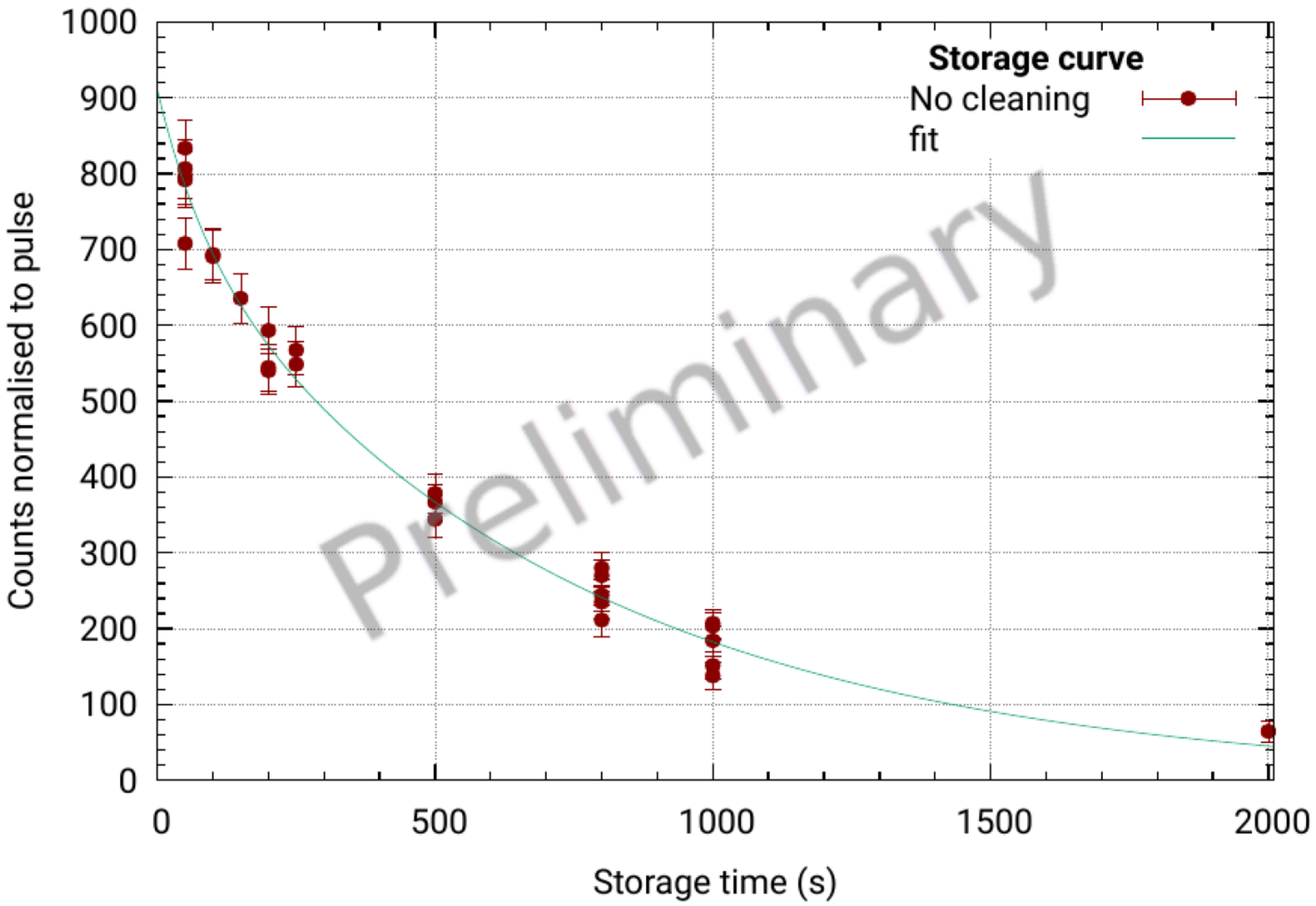


Commissioning of τSPECT with neutrons since 2019



September 2019!

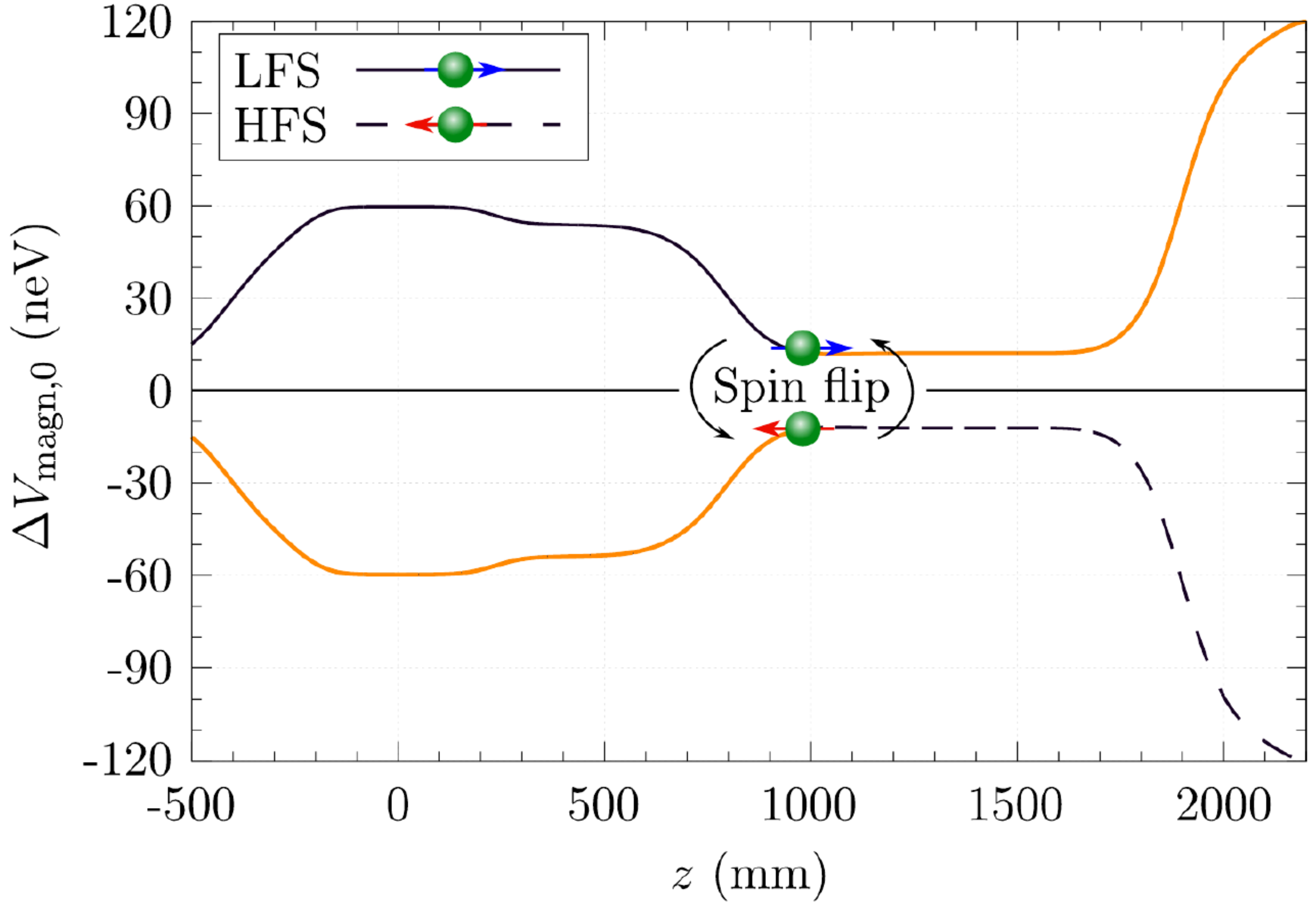
Optimizing the spin flipper settings allowed to increase # of UCN

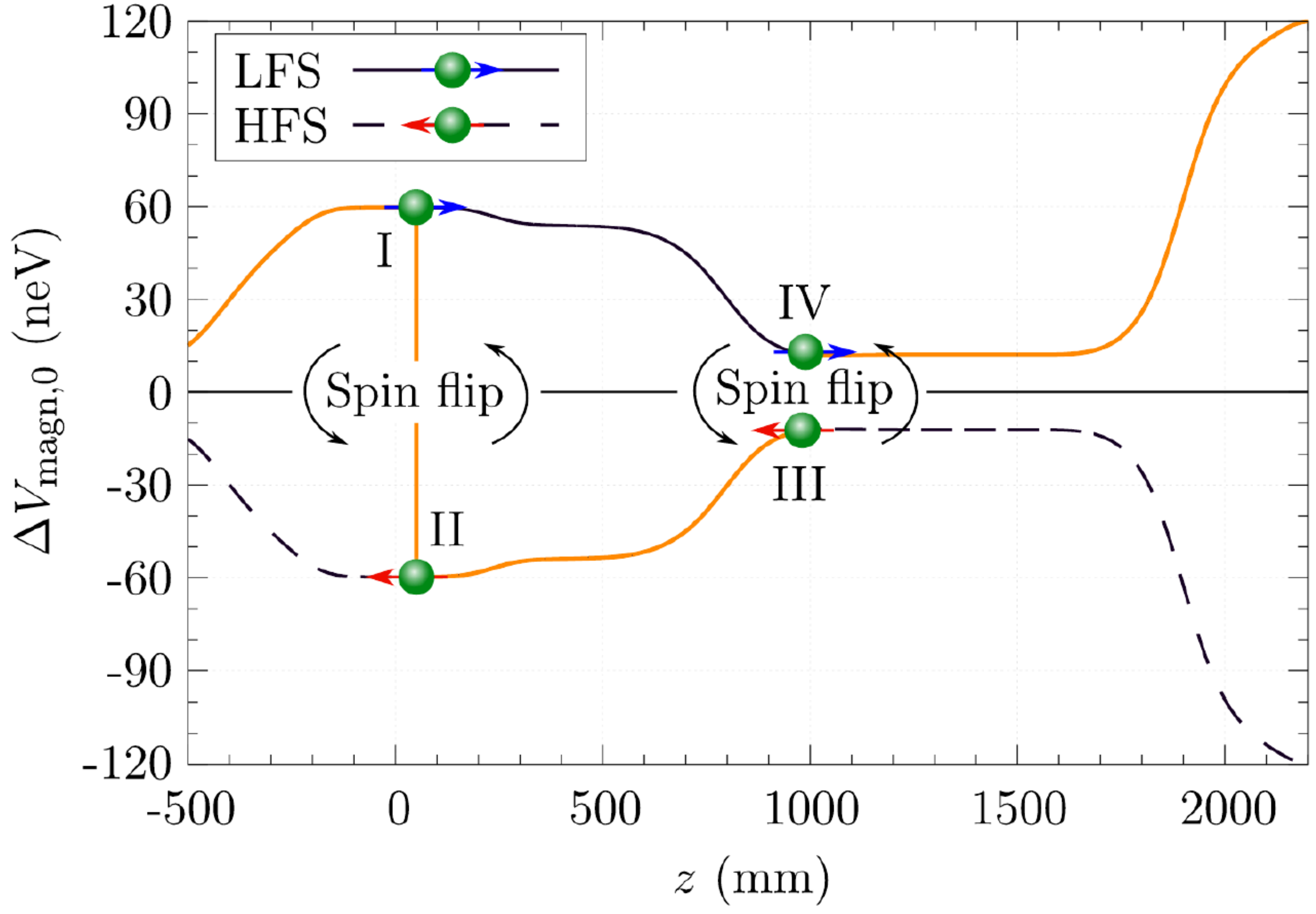


February 2020!

Just before the pandemic

Single vs. double spin flip loading





Double spin flip scheme increases the trap acceptance i.e. the storable energy range

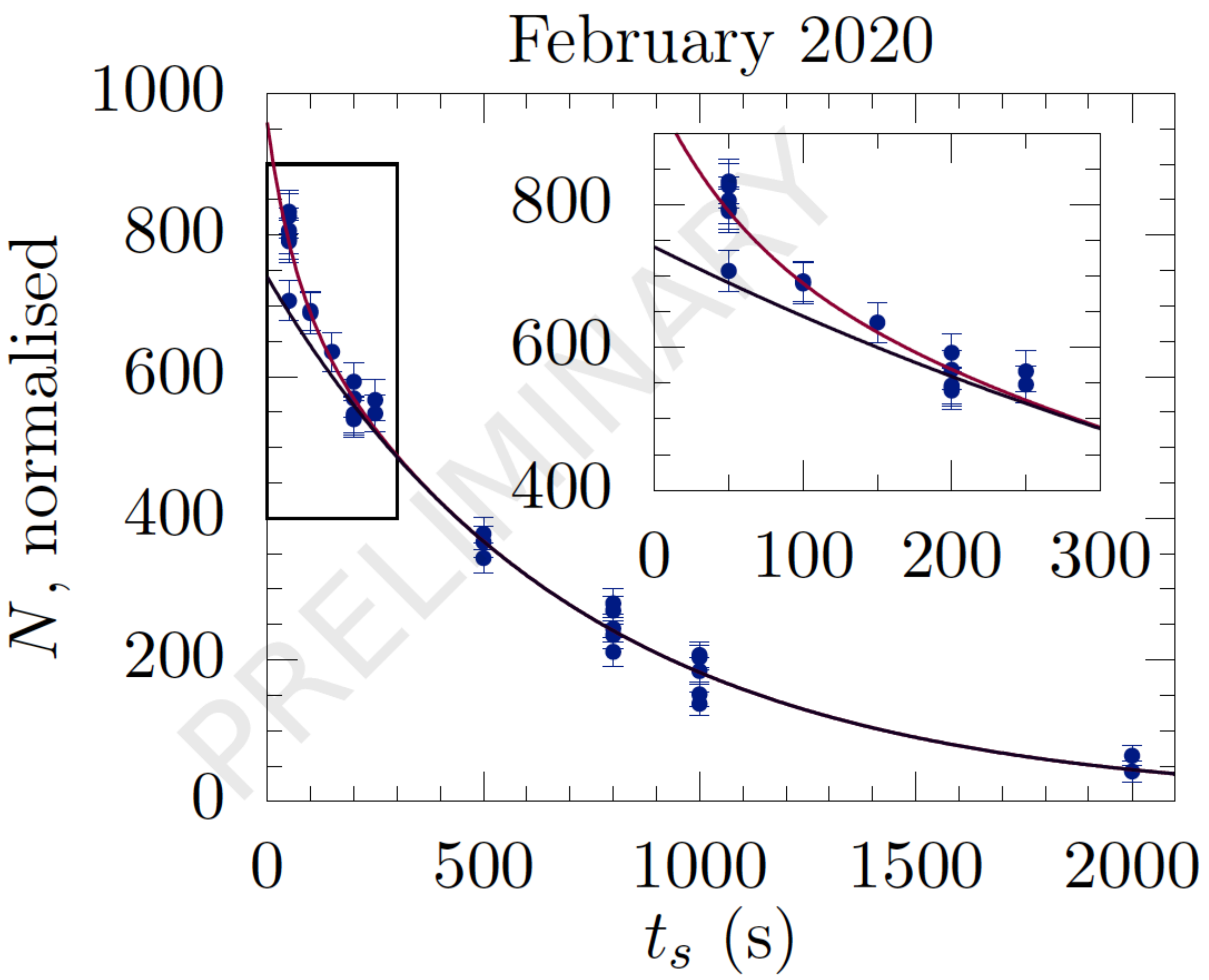
Systematics with τSPECT

Systematics

- Gaps: $\rightarrow 0$ ✓
- Wall losses: $\rightarrow 0$ ✓
- Depolarisation: $<< 0.1\,\mathrm{s}$✓
- Rest gas interactions: $\lesssim 0.1\,\mathrm{s}$ ✓
- Microphonic heating: Has not been observed, measure. ✓
- Marginally trapped neutrons: Spectrum cleaning necessary! ✓

D. Ries (PSI UCN/LTP Seminar) tauSPECT October 26, 2022 28 / 44

Spectral cleaning studies in τSPECT

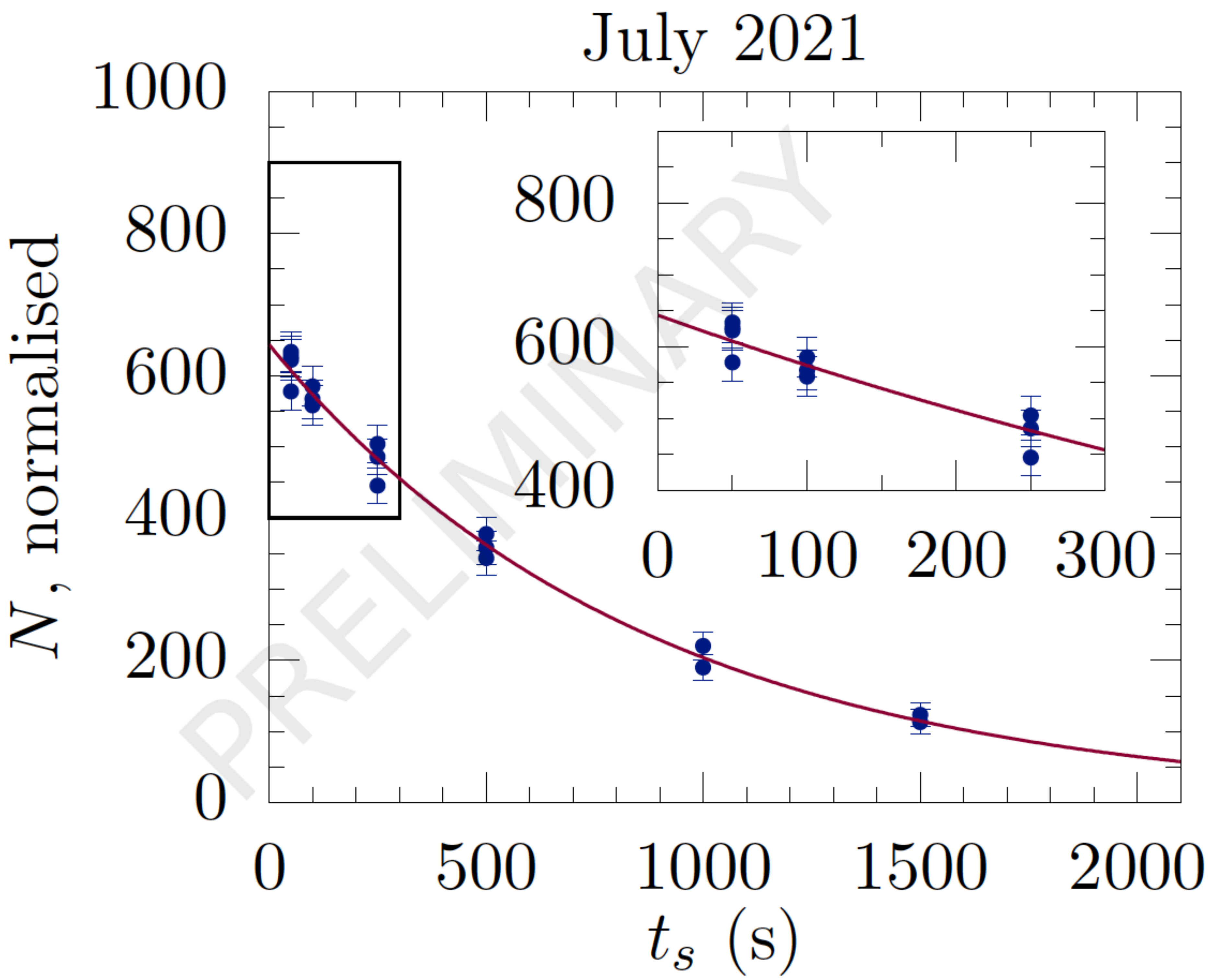


Decay times:
Fast:
$\tau = 64.5\,\mathrm{s}$
Slow:
$\tau = 740(47)\,\mathrm{s}$

$\chi^2 = 1.6$

Storage without spectral cleaning

Storage with spectral cleaning



Decay times:

$\tau = 869(29)\,\mathrm{s}$

$\chi^2 = 0.6$

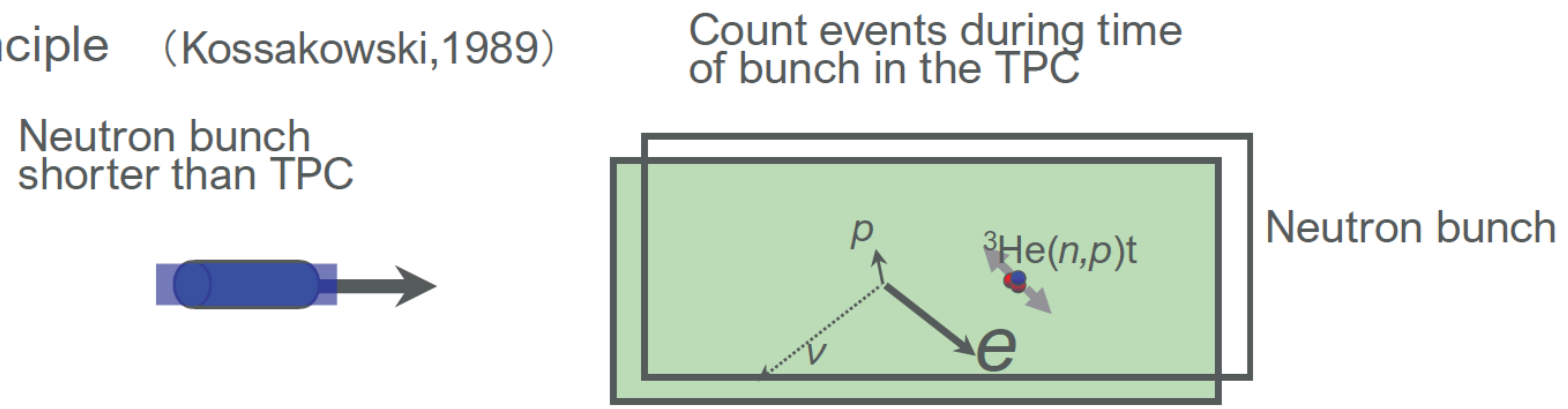
Improved systematic studies need higher statistics!

^{3}He TPC neutron lifetime approach

Principle of J-PARC experiment

Cold neutrons are injected into a TPC.
The neutron β-decay and the ^{3}He(n,p)^{3}H reaction are measured simultaneously.

Principle (Kossakowski,1989)



$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\left(\frac{S_n/\epsilon_n}{S_\beta/\epsilon_\beta}\right)$$

β-decay $S_\beta = \epsilon_e N \frac{L}{\tau_n v}$

^{3}He(n,p)^{3}H $S_n = \epsilon_n N \rho \sigma L$

- τ_n : lifetime of neutron
- v : velocity of neutron
- ϵ_e : detection efficiency of electron
- ϵ_n : detection efficiency of ^{3}He reaction
- ρ : density of ^{3}He
- σ : cross section of ^{3}He reaction

$$\sigma v = \sigma_0 v_0$$ σ_0=cross section@v_0, v_0=2200[m/s]

This method is free from the uncertainties due to external flux monitor, wall loss, depolarization, etc.

Courtesy K Mishima

The published result by using data using 2014-2016 was

$$\tau_n = 898 \pm 10(stat.)^{+15}_{-18}\,(sys.) = 898^{+18}_{-20}\ \mathrm{s}$$

Origin	First result (<2017) [s]	Present estimates [s]
Statistics	± 10	$\pm \mathbf{4}$
Background by scattered neutrons	$+2\,/\,-14$	
Efficiency for β-ray	$+6\,/\,-7$	$\pm \mathbf{1}$
Pileup	$+11\,/\,-4$	$+\mathbf{4}\,/\,-\mathbf{0.5}$
^{3}He number density	± 4	$\pm \mathbf{1.4}$
^{3}He(n,p)^{3}H cross section	± 1.2	$\pm \mathbf{1.2}$
Total	$+18\,/\,-20$	

K. Hirota et al., Prog. Theor. Exp. Phys. **2020**, 123C02

Courtesy K Mishima

Flying to and around the moon: the astrophysical approach

Measurement of the Free Neutron Lifetime using the Neutron Spectrometer on NASA's Lunar Prospector Mission

Jack T. Wilson,* David J. Lawrence, and Patrick N. Peplowski
The Johns Hopkins Applied Physics Laboratory,
11101 Johns Hopkins Road,
Laurel, Md. 20723, USA.

Vincent R. Eke and Jacob A. Kegerreis
Institute for Computational Cosmology,
Durham University, South Road,
Durham DH1 3LE, UK.
(Dated: August 5, 2021)

We use data from the Lunar Prospector Neutron Spectrometer to make the second space-based measurement of the free neutron lifetime finding $\tau_n = 887 \pm 14_{\rm stat}\,{}^{+7}_{-3\,{\rm syst}}$ s, which is within 1σ of the accepted value. This measurement expands the range of planetary bodies where the neutron lifetime

tron Spectrometer to make
$\tau_n = 887 \pm 14_{\rm stat}\,{}^{+7}_{-3\,{\rm syst}}$ s,
ange of planetary bodies w

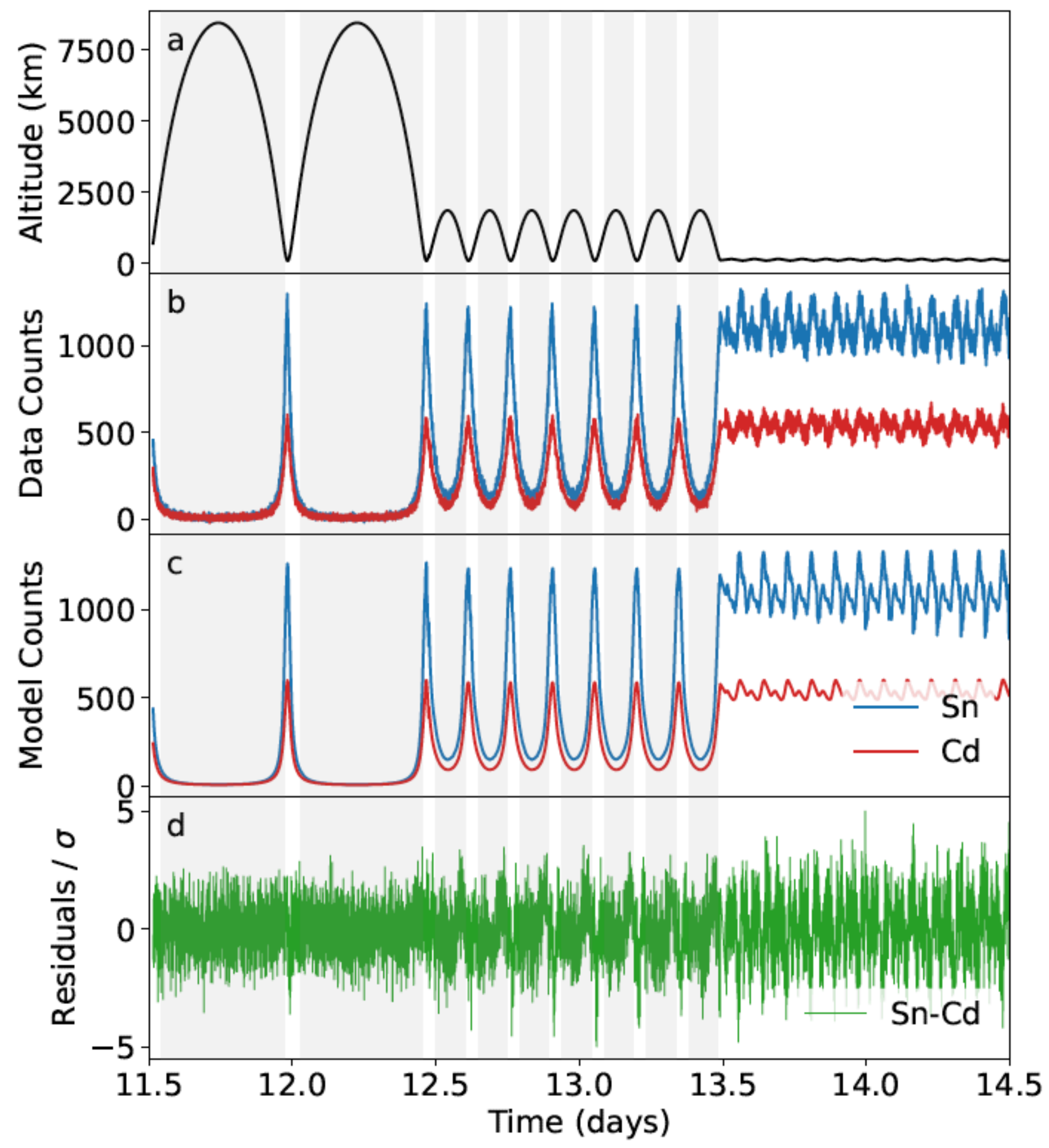


FIG. 1. (a) LP altitude during the initial elliptical orbits. (b) The measured count rates in the Cd- and Sn-covered NS detectors. (c) The modeled count rates in the Cd- and Sn-covered detectors as described in section III. (d) The residuals of the thermal neutron counts (i.e., the difference between the Sn- and Cd- covered detectors) normalized by the uncertainty due to counting statistics. The grey regions show the data used to produce the final result based on the cuts described in section IV. Time on the x-axis is measured from January 1st, 1998.

Exciting idea, but along way to go and significant
model dependence of neutron flux generated on Moon's surface!