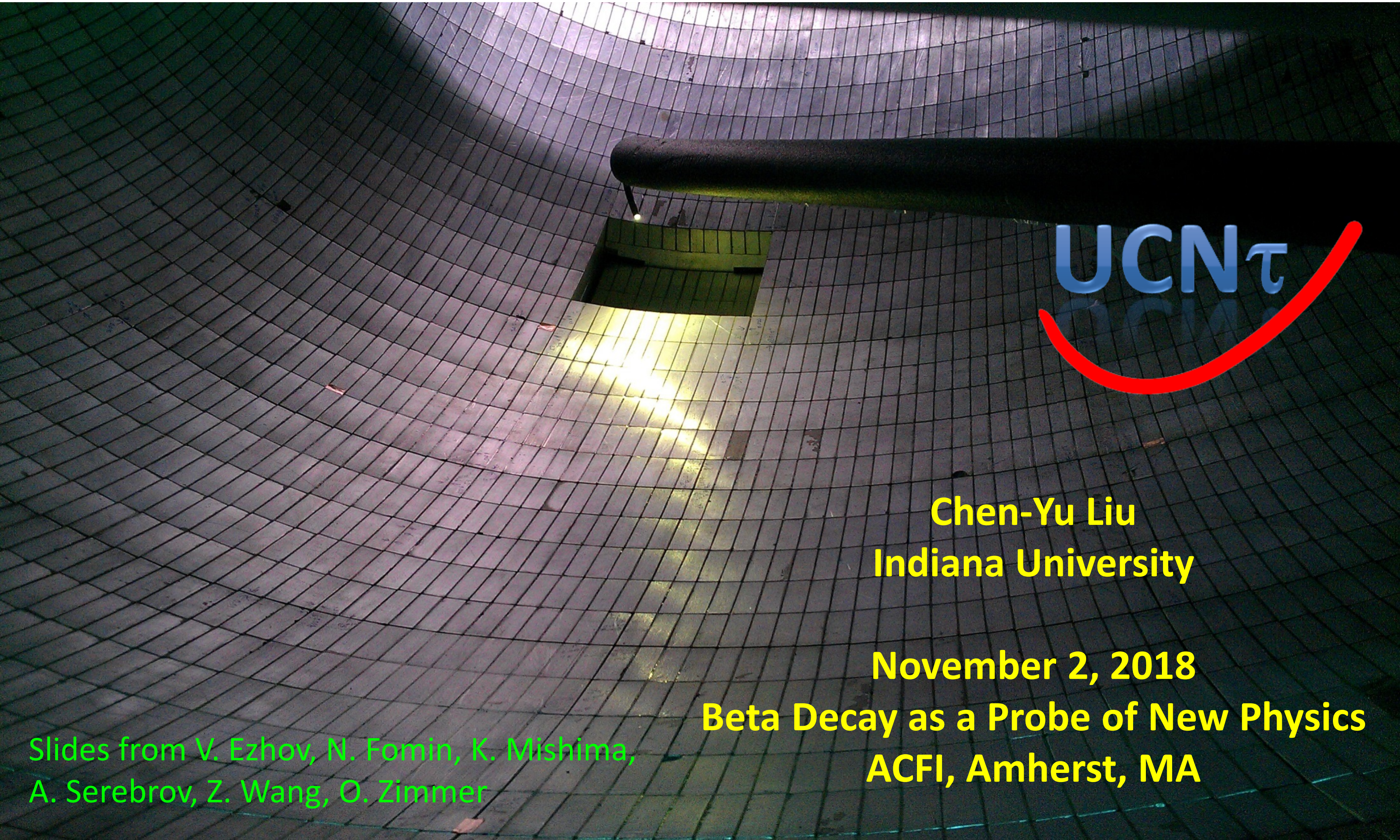
Neutron Lifetime Experiments

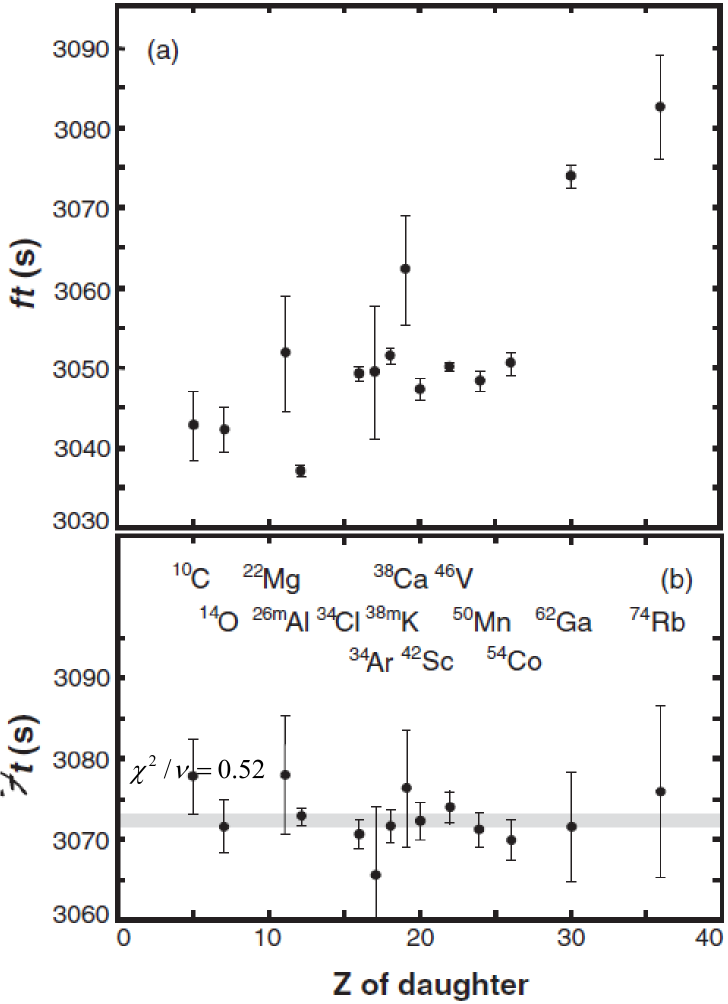


Chen-Yu Liu
Indiana University

November 2, 2018
Beta Decay as a Probe of New Physics
ACFI, Amherst, MA

Slides from V. Ezhov, N. Fomin, K. Mishima,
A. Serebrov, Z. Wang, O. Zimmer

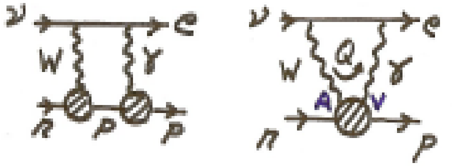
V_{ud} from Superallowed $0^+ \rightarrow 0^+$ Decays



$$\mathcal{F}t \equiv ft(1+\underset{\sim 1.5\%}{\delta'_R})(1+\underbrace{\delta_{\mathrm{NS}}-\delta_C}_{0.5\%-1.2\%}) = \frac{K}{2G_{\mathrm{V}}^2\left(1+\underset{2.361(38)\%}{\Delta_{\mathrm{R}}^{\mathrm{V}}}\right)}$$

$\downarrow$

$$G_V = G_F \cdot V_{ud}$$



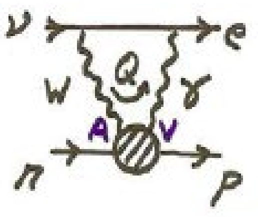
J.C. Hardy and I.S. Towner, PRC 91, 025501 (2015)

V_{ud} from neutron decays

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

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

From μ-decay: 0.6 ppm (MuLan 2011)



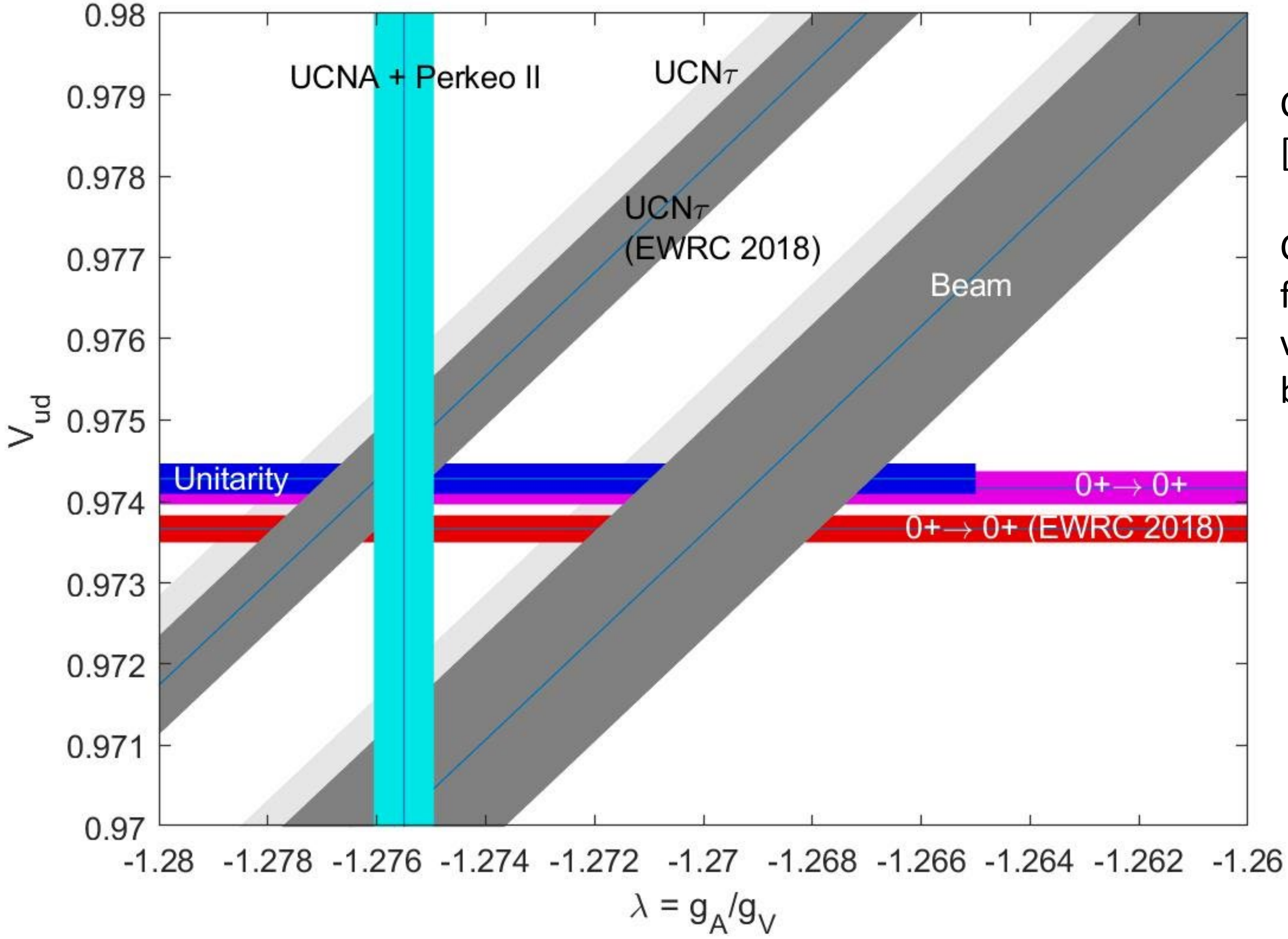
$$RC = \frac{\alpha}{4\pi}\int_0^\infty dQ \frac{m_W{}^2}{Q^2 + m_W{}^2} F(Q^2)$$

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

To math the theoretical uncertainty: 4 ×$10^{-4,}$ it requires experimental uncertainties of: ΔA/A = 4Δλ/λ < 2 ×10^{-3} and Δτ/τ = 4 ×10^{-4}.

Marciano & Sirlin, PRL 96, 032002 (2006)

The confusing situation of V_{ud}



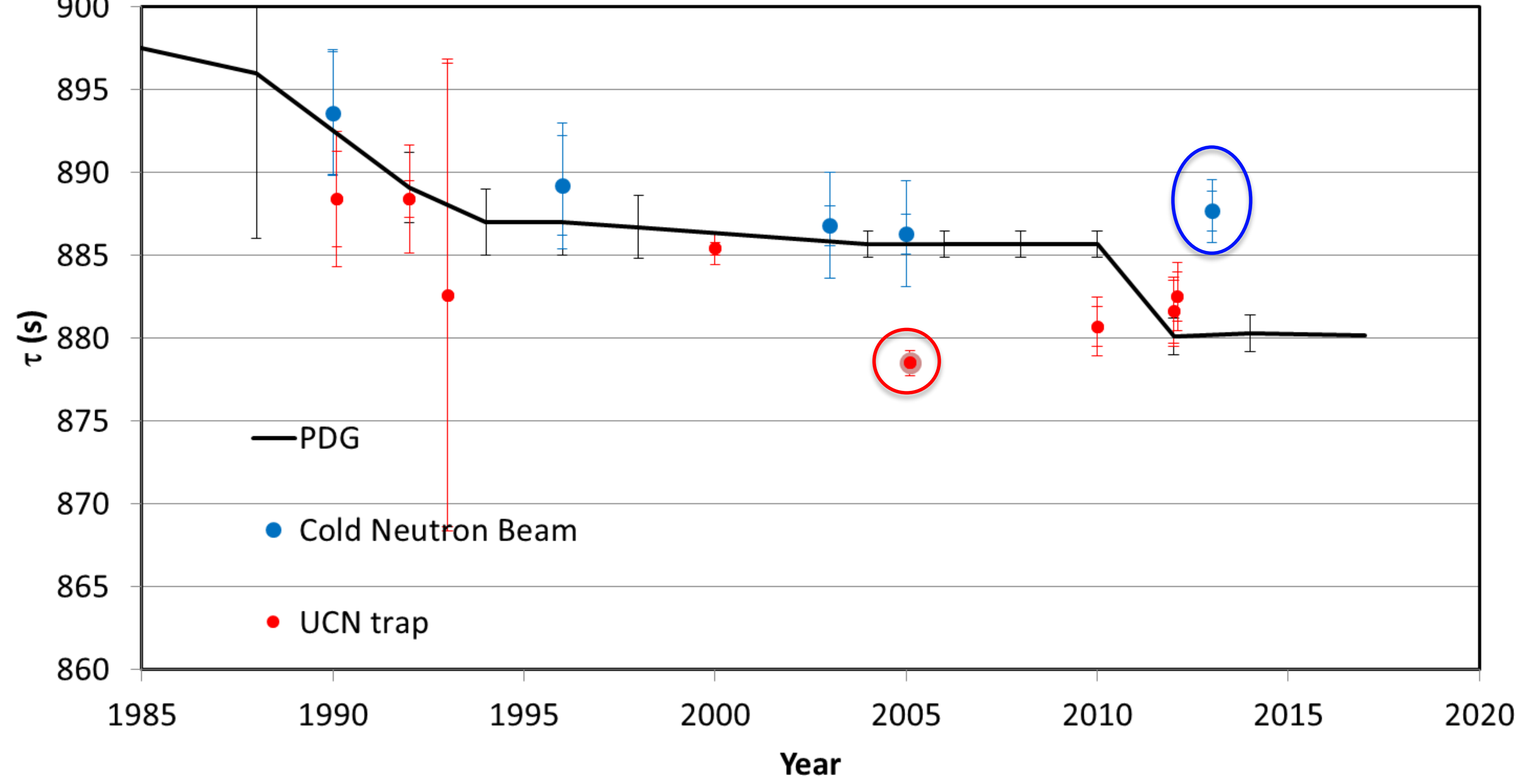
Czarnecki, arXiv:1802.01804 [hep-ph] (2018)

Cross-comparisons of Vud favors the neutron lifetime value measured by the bottle experiments.

An updated EWRC gives an 3.6 σ discrepancy between the Vud derived from the unitarity condition and the direct measurements from superallowed nuclear decays.
Seng, Gorchtein, Patel, Ramsey-Musolf, arXiv:1807.10197 [hep-ph]

History of τ_n measurements: a new discrepancy!

“The Neutron Enigma,” Greene & Geltenbort, Sci Am. 2016 Apr;314(4):36-41



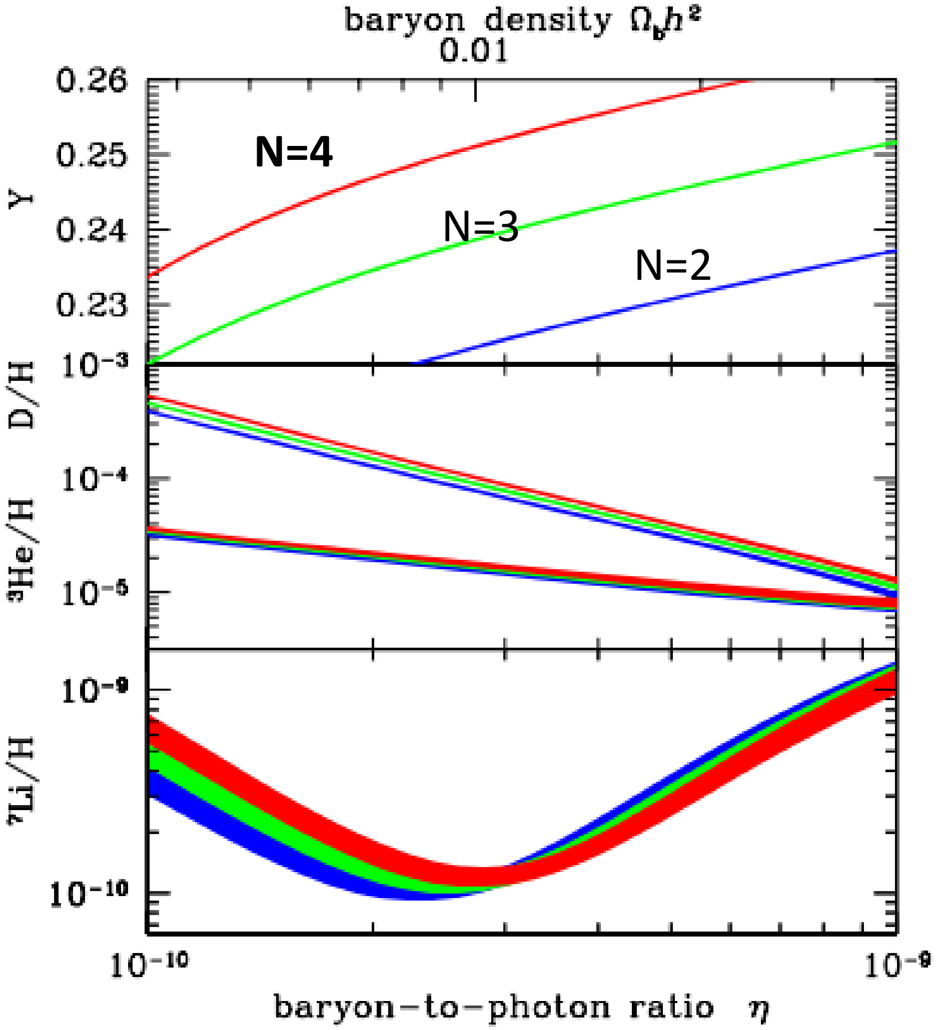
Most precise Beam: τ_n = 887.1 ± 2.2 s

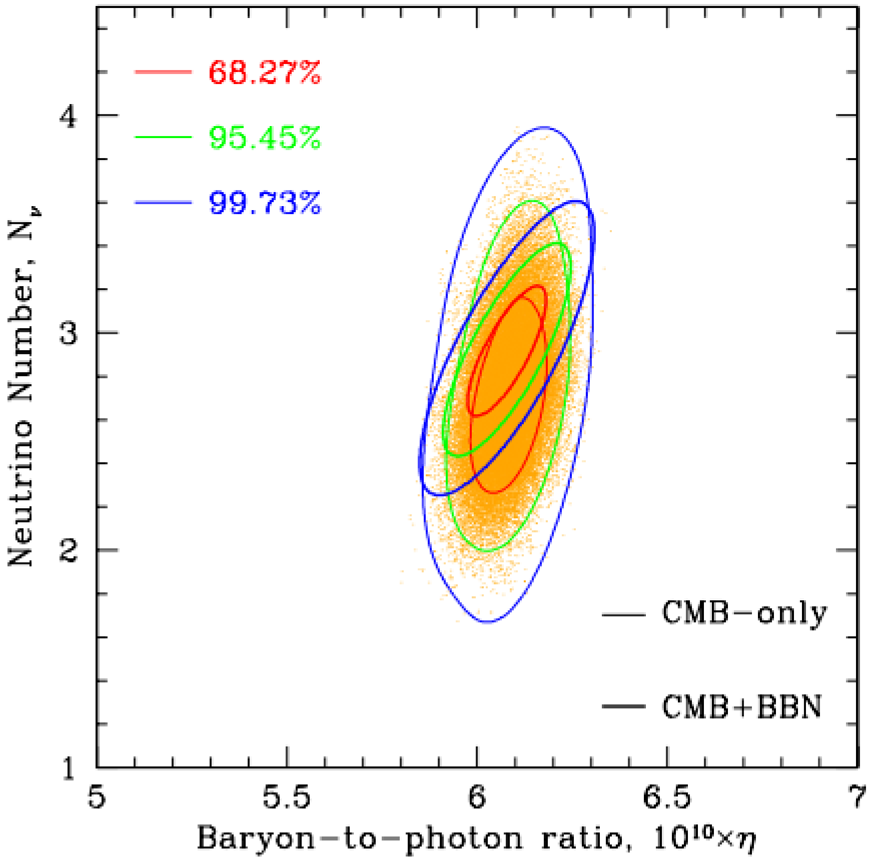
Yue et al., Phys. Rev. Lett. 111, 222501 (2013)

Most precise Bottle: τ_n = 878.5 ± 0.8 s

A.P. Serebrov, *UFN*, **175**:9 (2005), 905–924; *Phys. Usp.*, **48**:9 (2005), 867–885

Big Bang Nucleosynthesis (BBN): Neutron lifetime & the primordial ^{4}He abundance (Y_p)



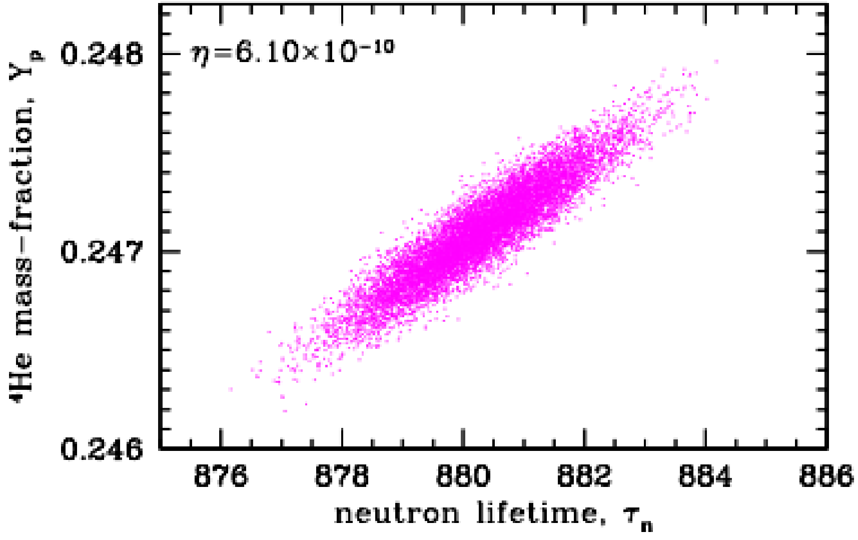


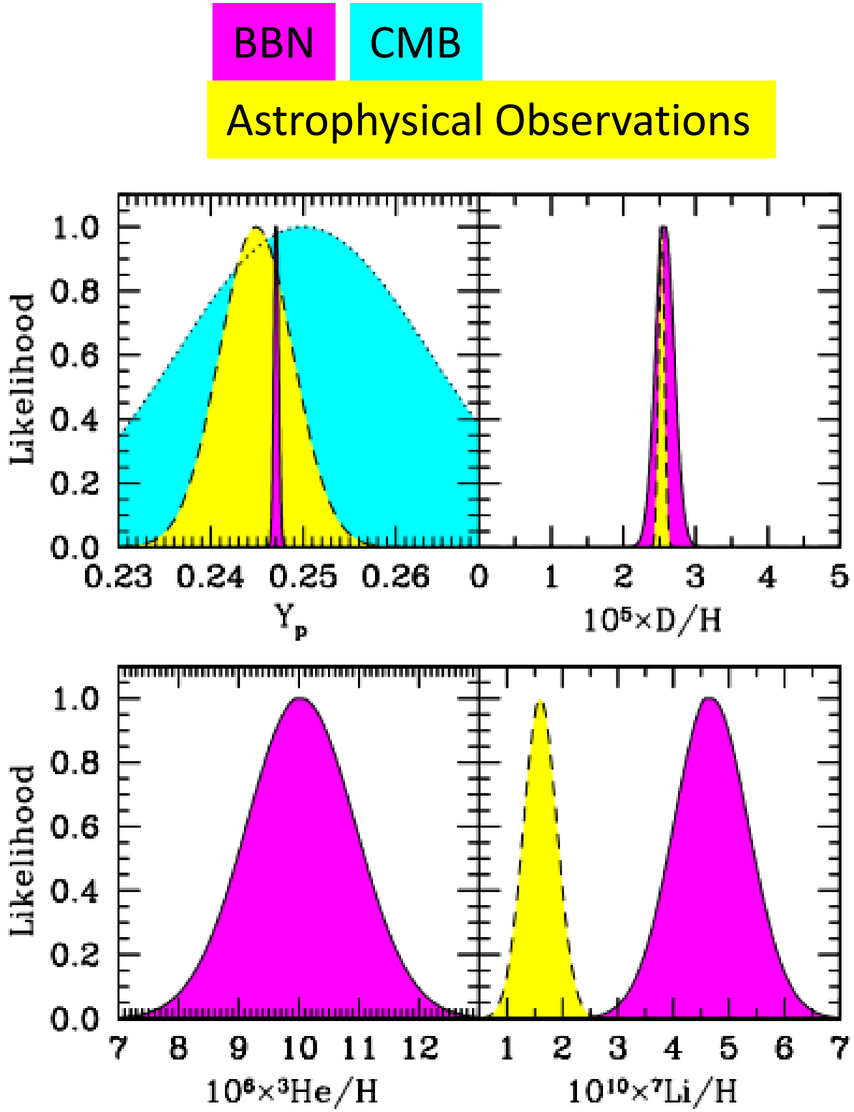
R. H. Cyburt, B.D. Fields, K.A. Olive, T-H Yeh,
Rev. Mod. Phys. 88, 015004 (2016)

Big Bang Nucleosynthesis (BBN): Neutron lifetime & the primordial ^{4}He abundance (Y_p)

$$Y_p \sim \frac{2e^{-t_d/\tau_n}}{1+e^{\Delta m/kT_f}}$$

Sensitive to τ_n



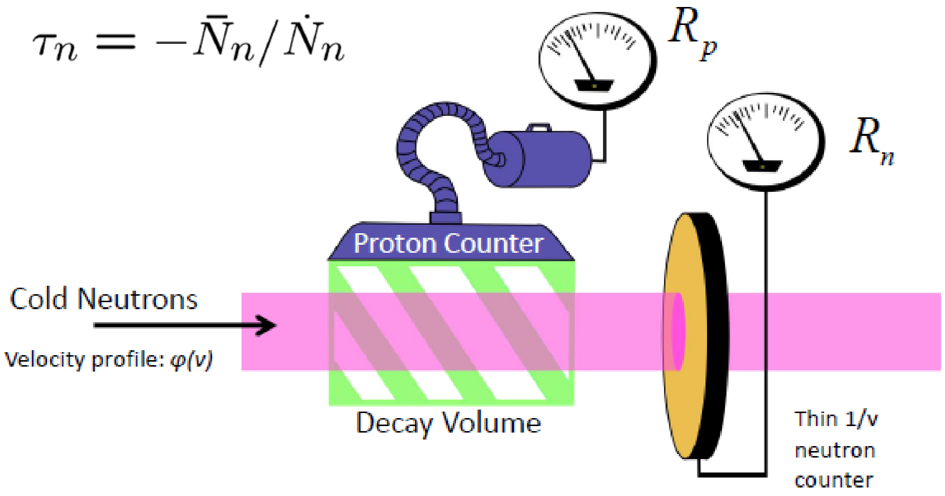


-R. H. Cyburt, B.D. Fields, K.A. Olive, T-H Yeh, Rev. Mod. Phys. 88, 015004 (2016)

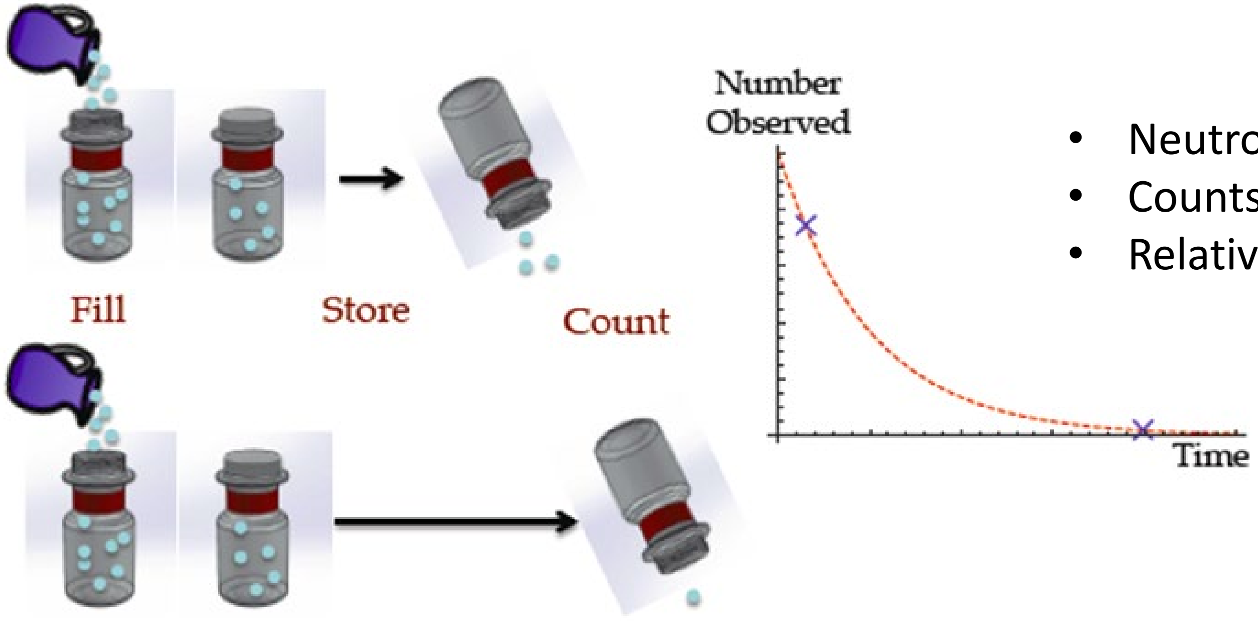
-L. Salvati *et al.* JCAP 1603 (2016) no.03, 055

Beam vs Bottle: Appearance vs Disappearance

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



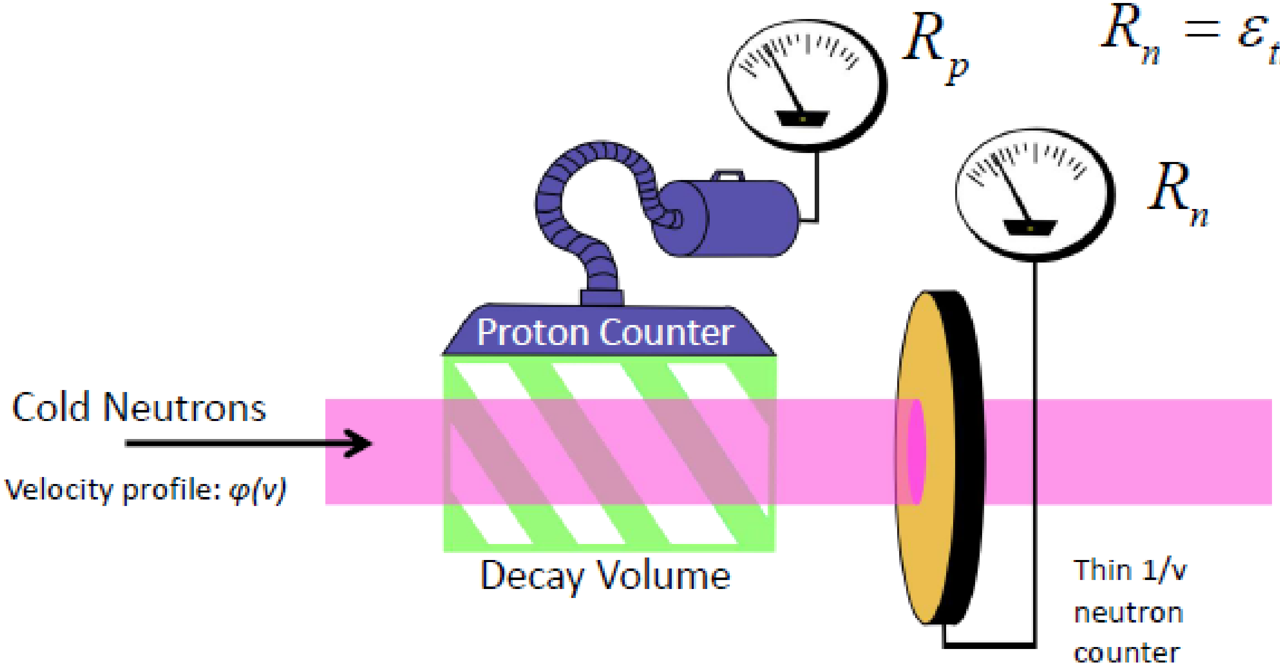
- Neutrons decay in flight
- Counts decay charge particles (e or p)
- Absolute efficiency required.



- Neutrons decay in bottle
- Counts surviving neutrons
- Relative measurement

1. The Beam Method

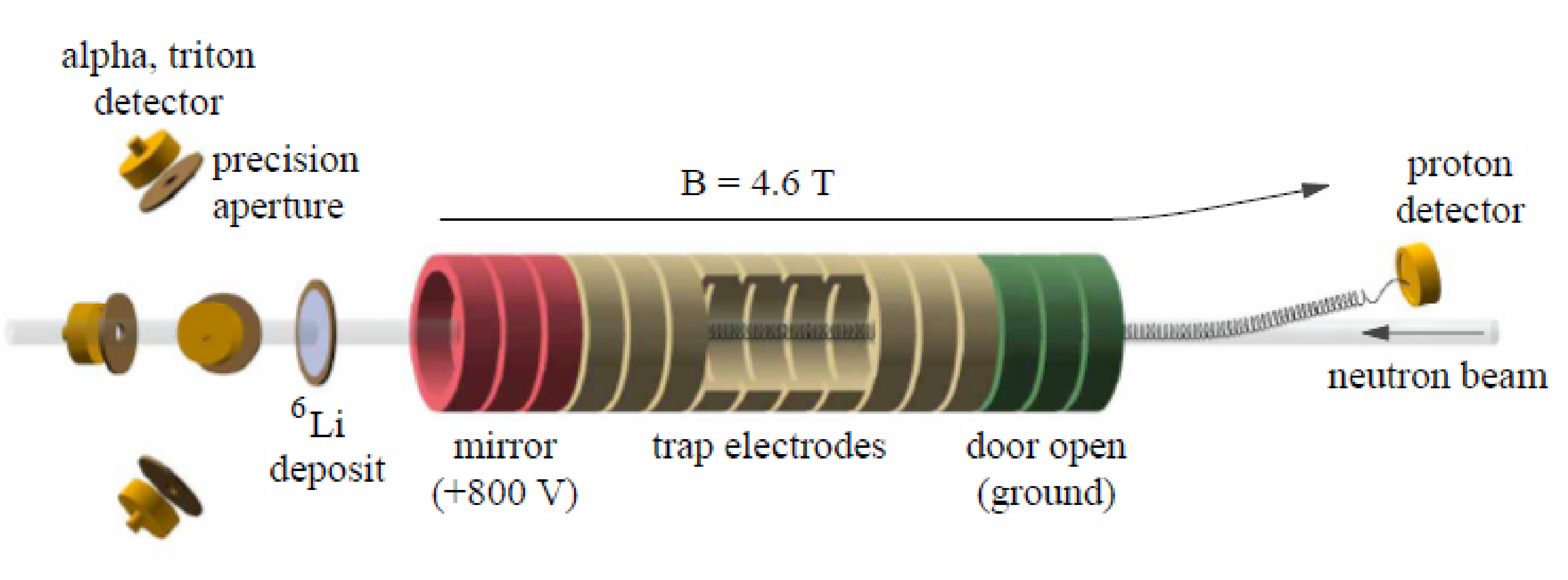
$$R_p = \varepsilon_p \frac{A_{beam} L_{\det}}{\tau_n} \int \frac{\varphi(v)}{v} dv$$



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

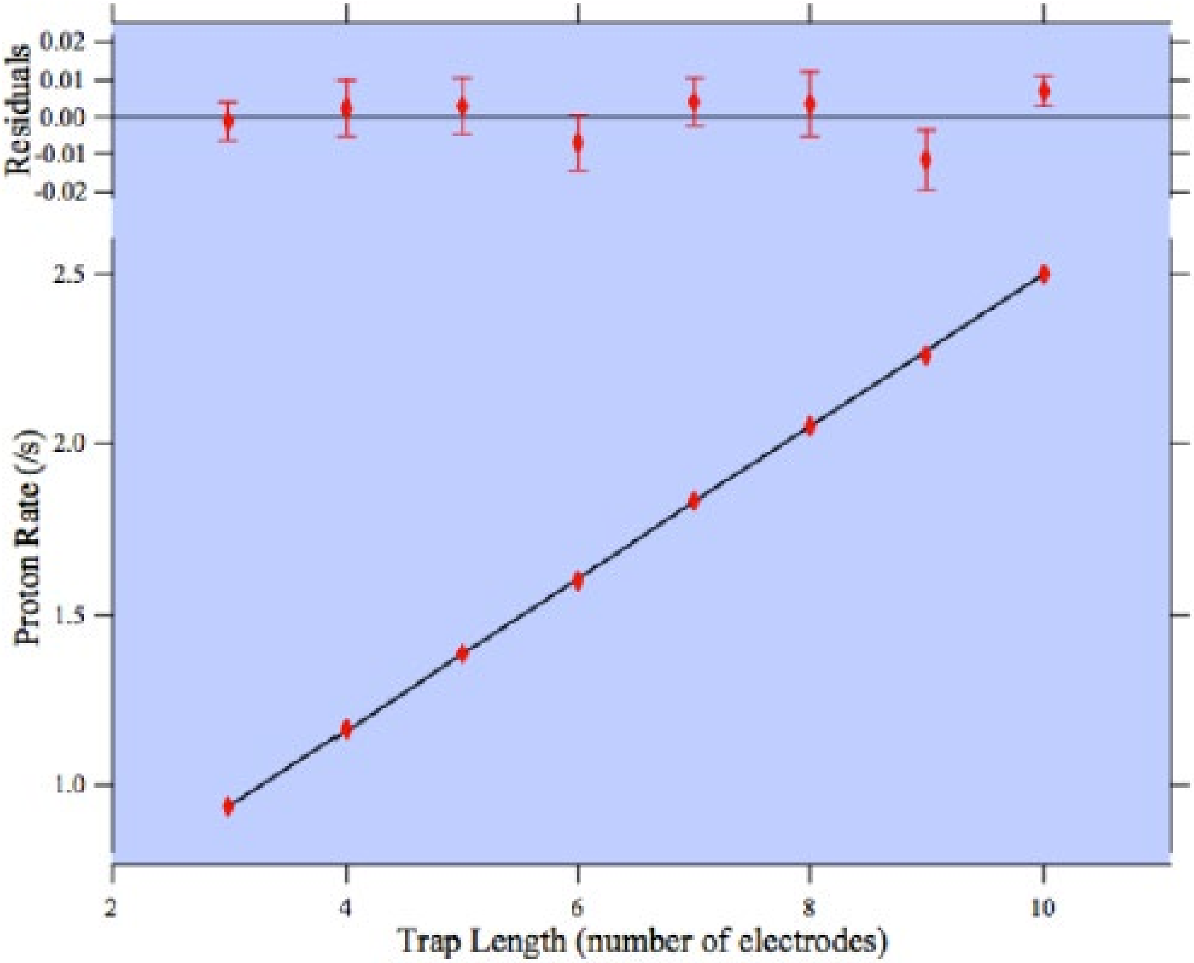
$$\tau_n = \frac{R_n \varepsilon_p L_{\det}}{R_p \varepsilon_{th} v_{th}}$$

The best beam experiment is at NIST



- Cold neutron beam, collimated to 2 mm (BL2) → 30mm (BL3).
- A quasi-penning trap electrostatically traps beta-decay protons. When the door electrodes are set to ground, the protons are guided by a B field to an external detector (surface barrier Si detector).
- Neutron monitor measures the incident neutron flux by counting n+^{6}Li→ α+t.

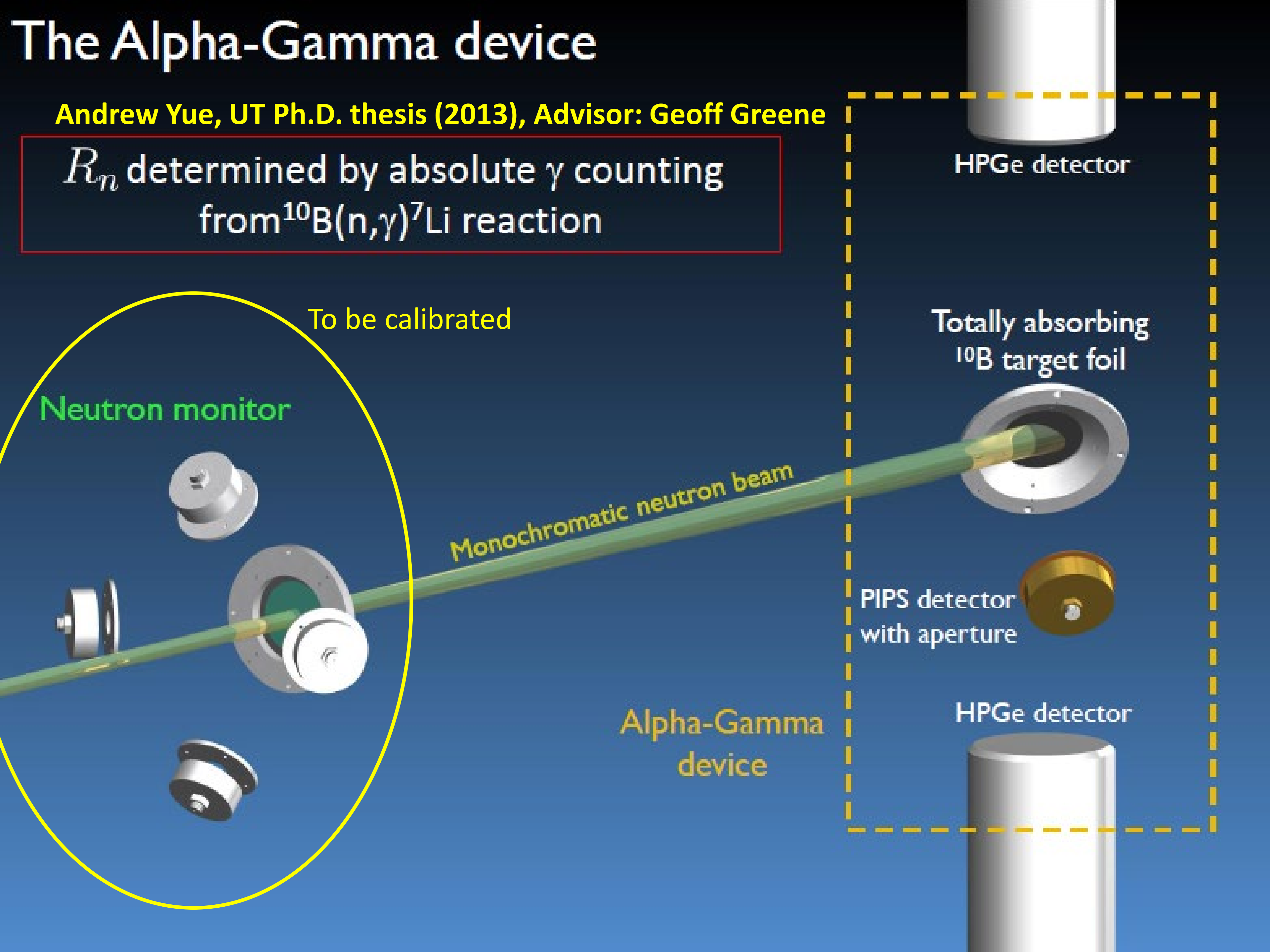
$$\dot{N}_p = \dot{N}_{\alpha+t}\left(\frac{L}{\tau_n}\right)\frac{\epsilon_p}{\epsilon_0 v_0}$$



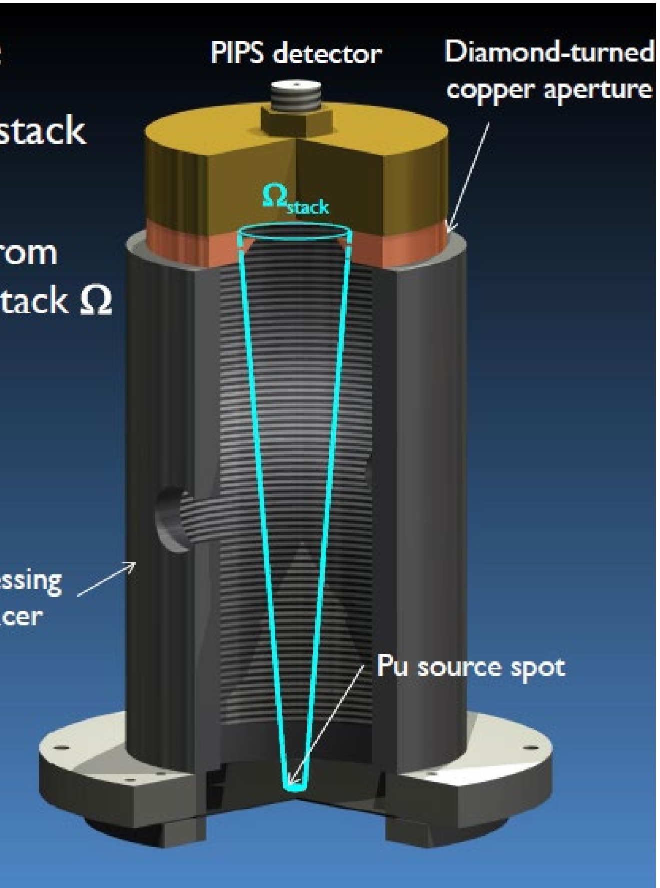
The Alpha-Gamma device

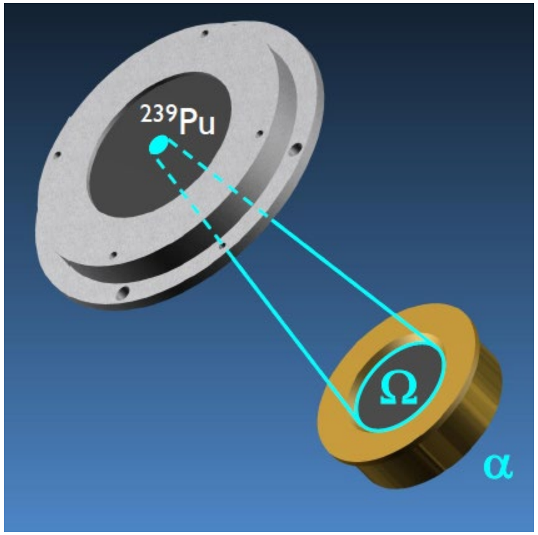
Andrew Yue, UT Ph.D. thesis (2013), Advisor: Geoff Greene

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

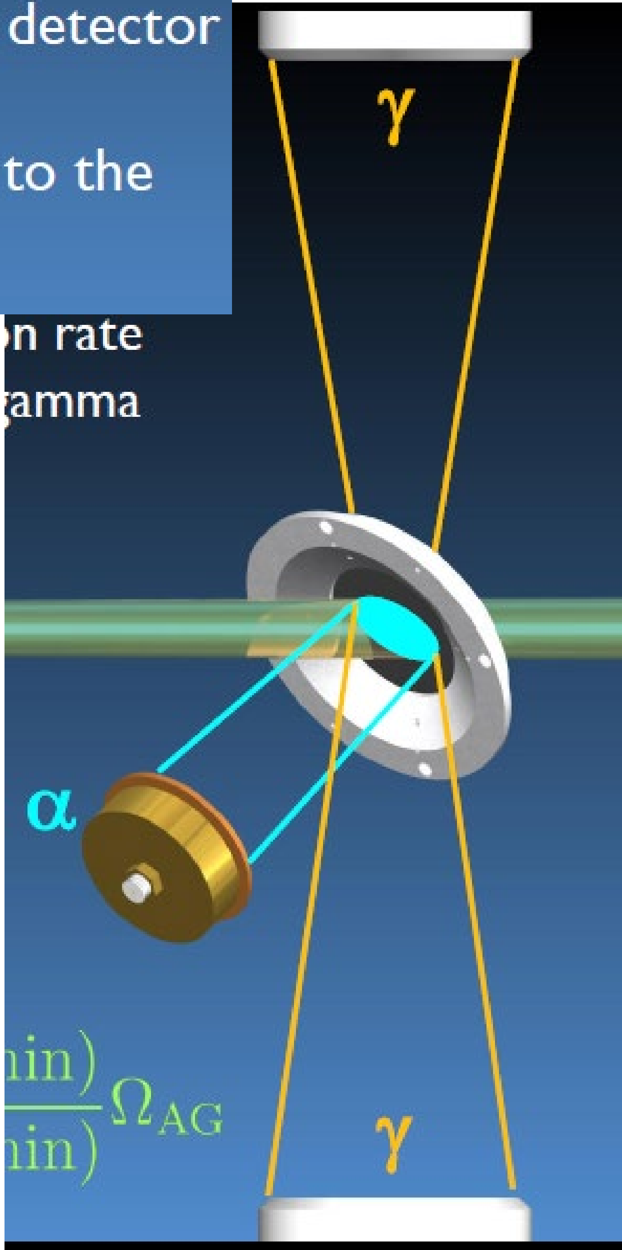


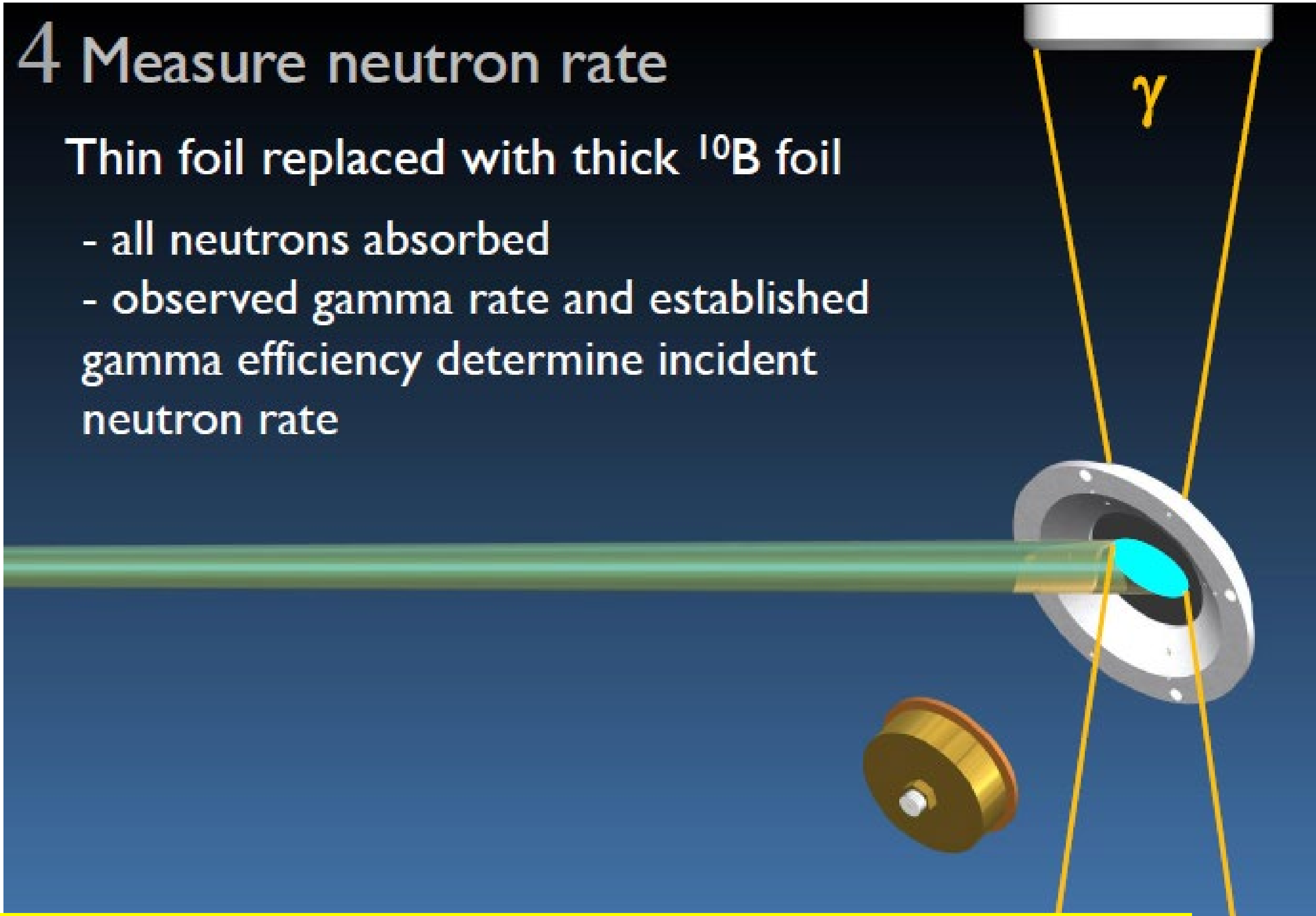
1. Measure the absolute activity of an alpha source
2. Use this source to determine solid angle of alpha detector
3. Use an (n,$\alpha\gamma$) reaction to transfer the calibration to the gamma detectors





n rate
amma





4 Measure neutron rate

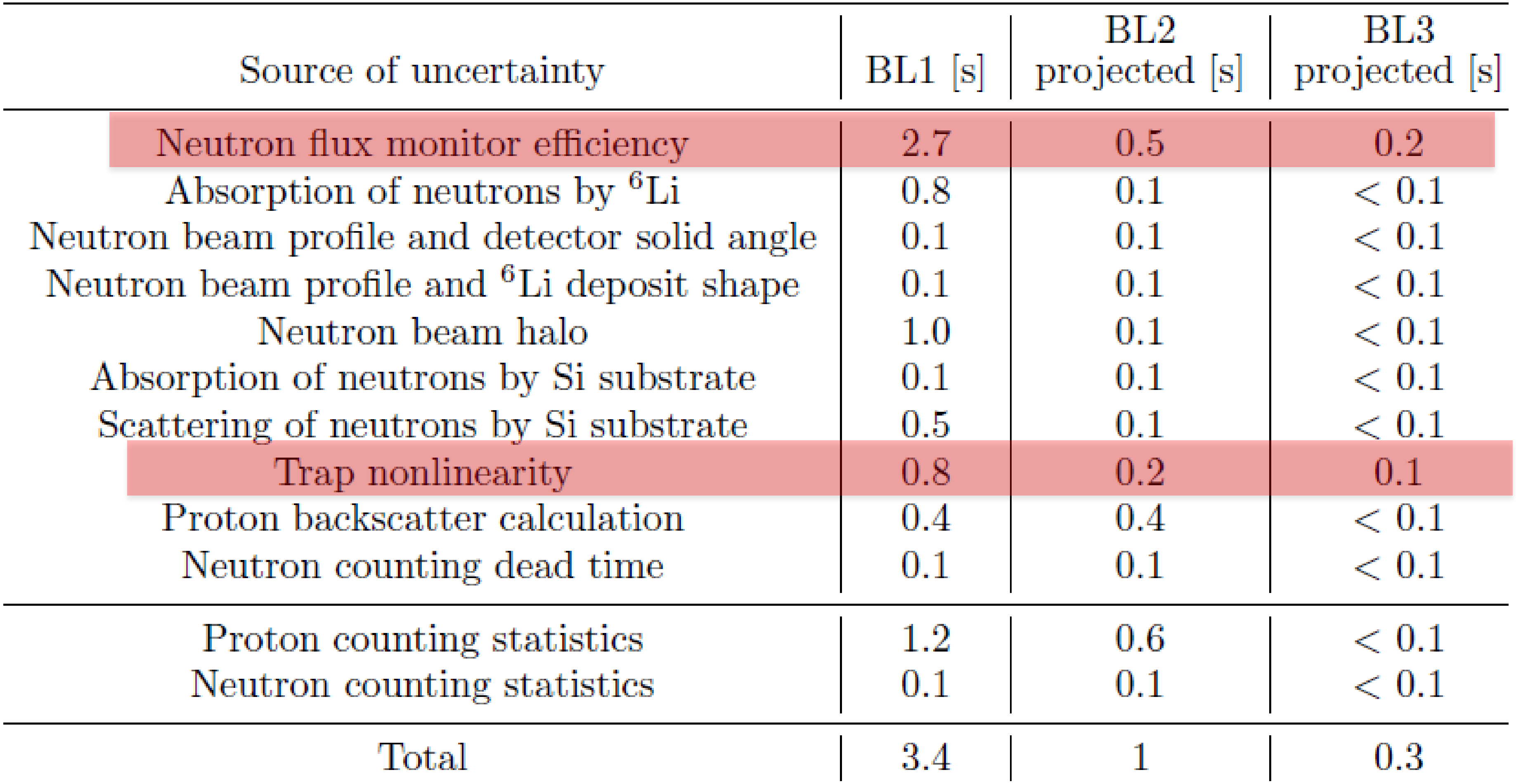
Thin foil replaced with thick ^{10}B foil

- 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

Systematic Effects for the NIST Beam Lifetime (BL) Experiments



Source of uncertainty	BL1 [s]	BL2 projected [s]	BL3 projected [s]
Neutron flux monitor efficiency	2.7	0.5	0.2
Absorption of neutrons by ^{6}Li	0.8	0.1	< 0.1
Neutron beam profile and detector solid angle	0.1	0.1	< 0.1
Neutron beam profile and ^{6}Li deposit shape	0.1	0.1	< 0.1
Neutron beam halo	1.0	0.1	< 0.1
Absorption of neutrons by Si substrate	0.1	0.1	< 0.1
Scattering of neutrons by Si substrate	0.5	0.1	< 0.1
Trap nonlinearity	0.8	0.2	0.1
Proton backscatter calculation	0.4	0.4	< 0.1
Neutron counting dead time	0.1	0.1	< 0.1
Proton counting statistics	1.2	0.6	< 0.1
Neutron counting statistics	0.1	0.1	< 0.1
Total	3.4	1	0.3

BL1: 886.3 ± 1.2 [stat] ± 3.4 [sys] seconds Nico et al 2005

BL1: 887.7 ± 1.2 [stat] ± 1.9 [sys] seconds Yue et al 2013 (improved n monitor)

BL2: on-going data-taking; expect to finish in 2019.

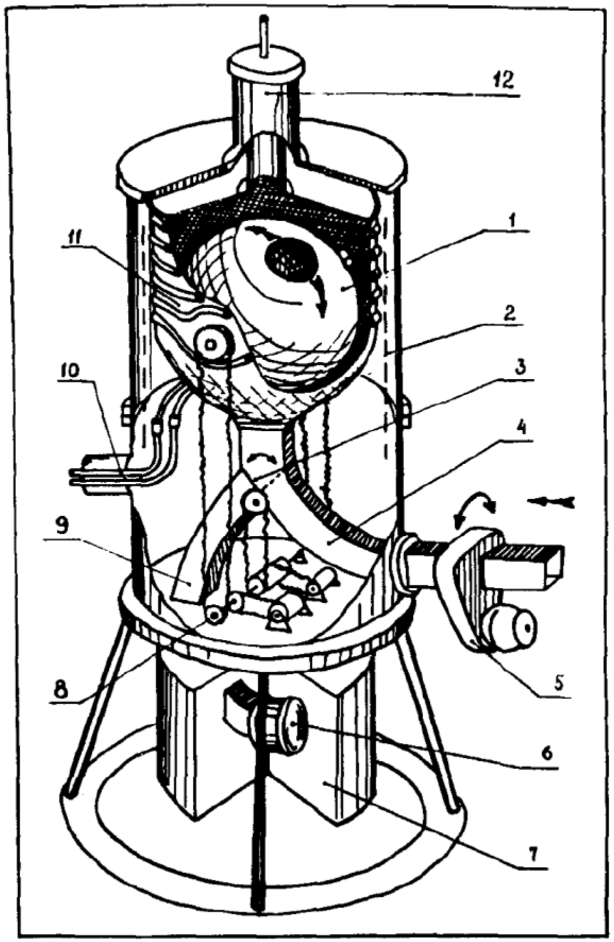
Information provided by N. Fomin

2. The Bottle Method

Experiment with Gravitational trap for UCN (PNPI,Gatchina)

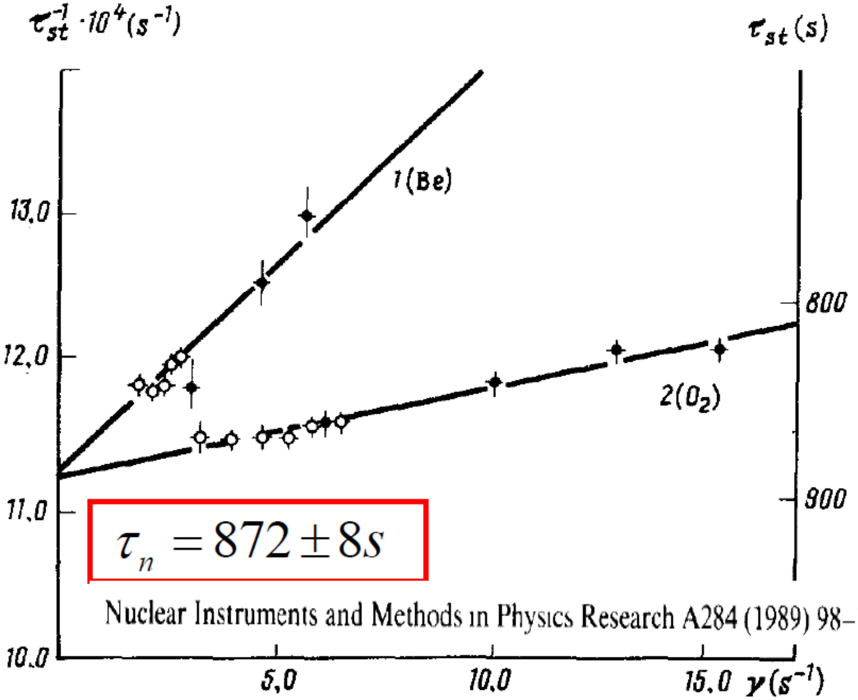
Pis'ma Zh. Eksp. Teor. Fiz. **52**, No. 7, 984–989 (10 October 1990)

V. P. Alfimenkov,[1] V. E. Varlamov, A. V. Vasil'ev, V. P. Gudkov,
V. I. Lushchikov,[1] V. V. Nesvizhevskiĭ, A. P. Serebrov, A. V. Strelkov,[1]
S. O. Sumbaev, R. R. Tal'daev, A. G. Kharitonov, and V. N. Shvetsov[1]



5 liters

$$\boxed{\tau_n = 888.4 \pm 2.9\ \text{s.}}$$



$$\boxed{\tau_n = 872 \pm 8 s}$$

Nuclear Instruments and Methods in Physics Research A284 (1989) 98–100

FIG. 1. 1—Trap for confining ultracold neutrons; 2—liquid-nitrogen screen; 3—distribution valve; 4,9—inlet and outlet guides for ultracold neutrons; 5—inlet valve; 6—detector; 7—detector shielding; 8—valve and trap drive mechanism; 10—cryogenic conductors; 11—volume held at cryogenic temperature; 12—lock for the coating-freezing system.

FIG. 2. Results of the measurements of τ_{st}^{-1} versus the calculation parameter γ. 1(Be)—Extrapolation to the neutron lifetime according to data from traps with a beryllium coating; 2(O_2)—extrapolation to the neutron lifetime according to data for traps with an oxygen coating and a beryllium sublayer. O—Results for a spherical trap; ●—results for a cylindrical trap.

The Gravitrap Experiment

PHYSICAL REVIEW C **78**, 035505 (2008)

A. P. SEREBROV *et al.*

7 liters

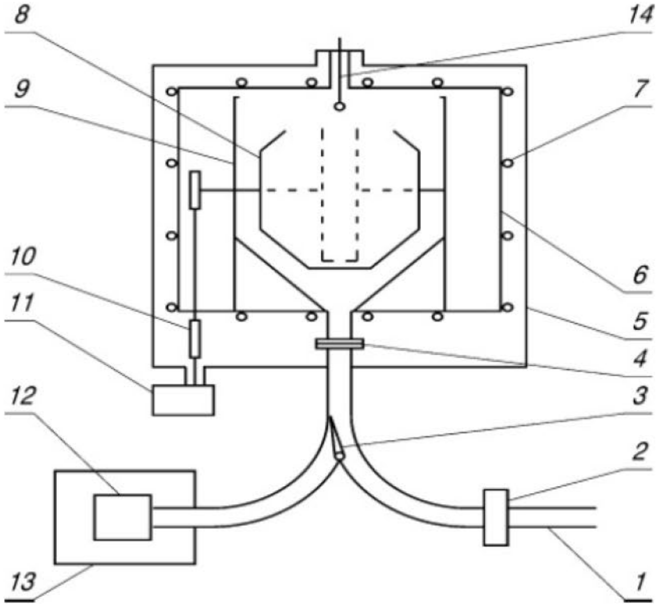


FIG. 1. Schematic of the gravitational UCN storage system: 1—input neutron guide for UCN, 2—inlet valve, 3—selector valve (shown in the position in which the trap is being filled with neutrons), 4—foil unit, 5—vacuum volume, 6—separate vacuum volume of the cryostat, 7—cooling system for the thermal shields, 8—UCN storage trap (with the dashed lines depicting a narrow cylindrical trap), 9—cryostat, 10—trap rotation drive, 11—step motor, 12—UCN detector, 13—detector shield, and 14—vaporizer.

Gravitrap experiment

A.Serebrov et al. , Phys Lett B 605, (2005) 72-78 :

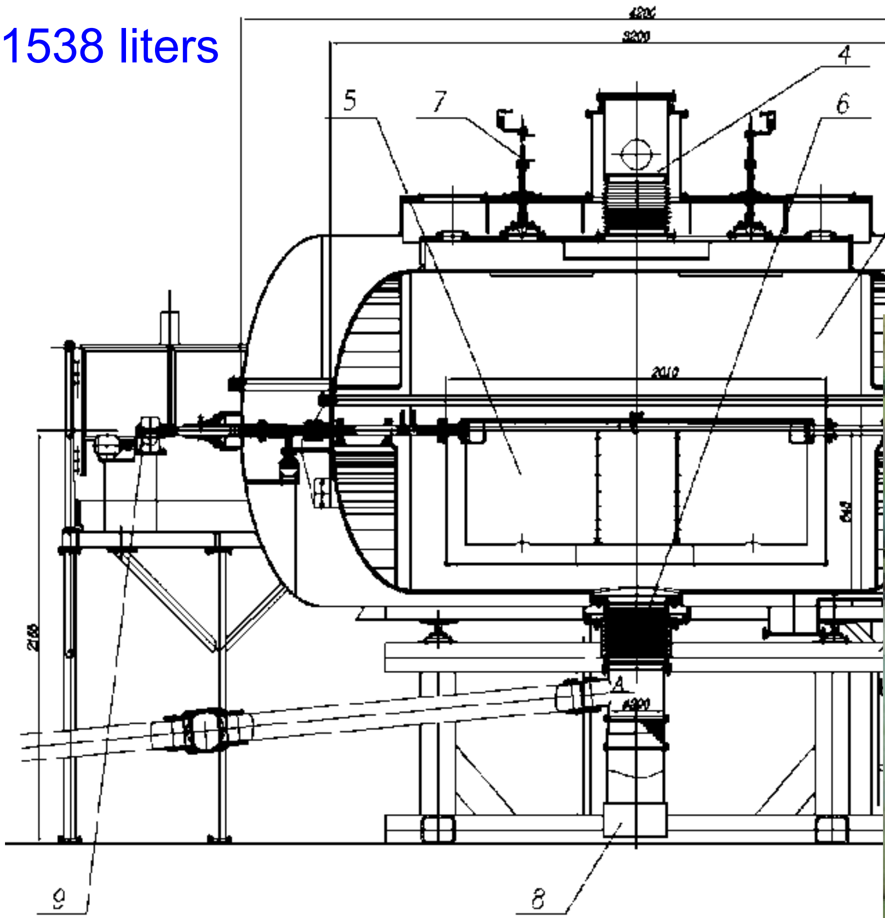
878.5 ± 0.8 s

2002-2004 (PNPI-JINR-ILL), ILL reactor, Grenoble

Measurements of neutron lifetime with Large Gravitational Trap

PNPI – ILL - RAL collaboration

1538 liters



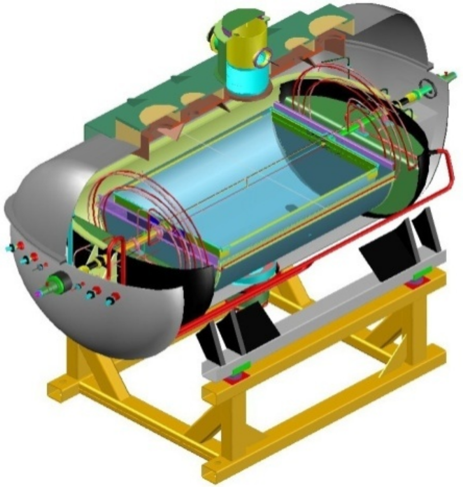
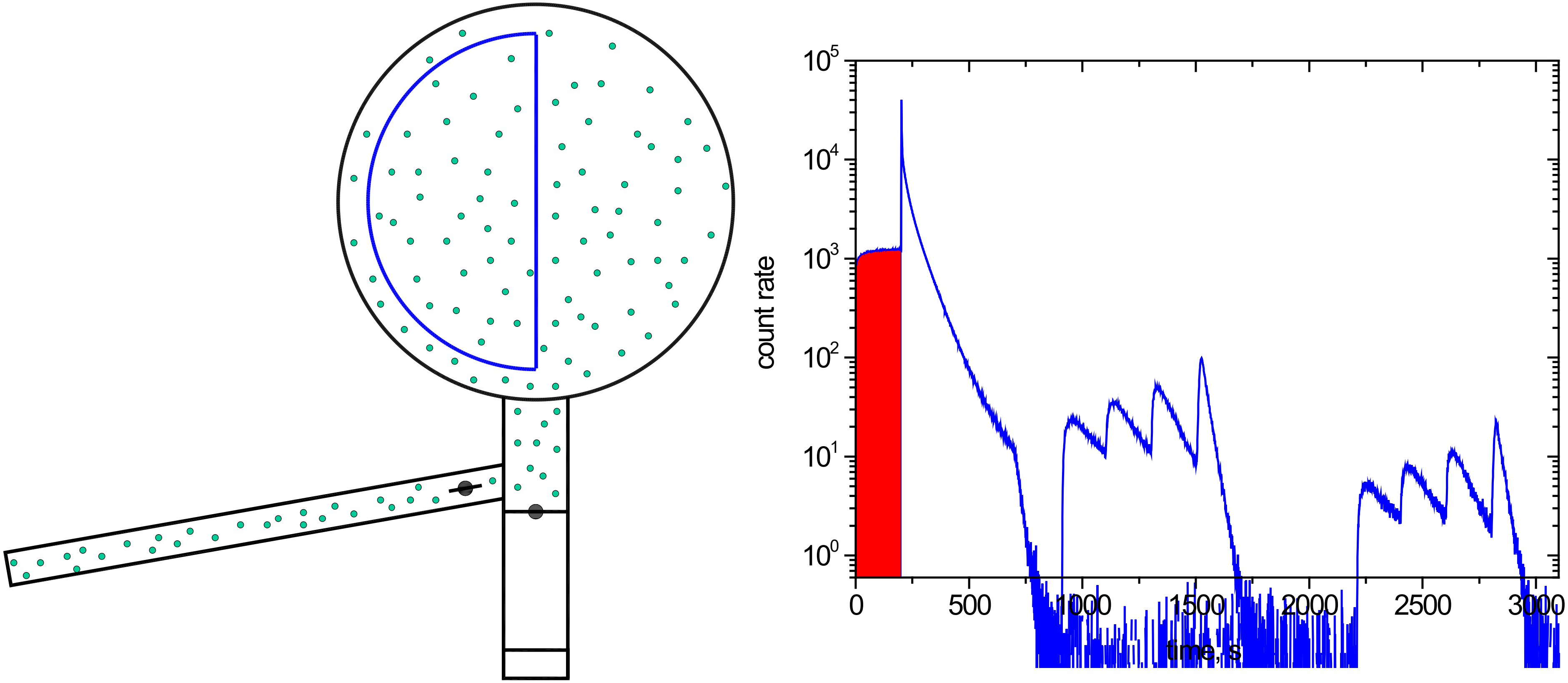
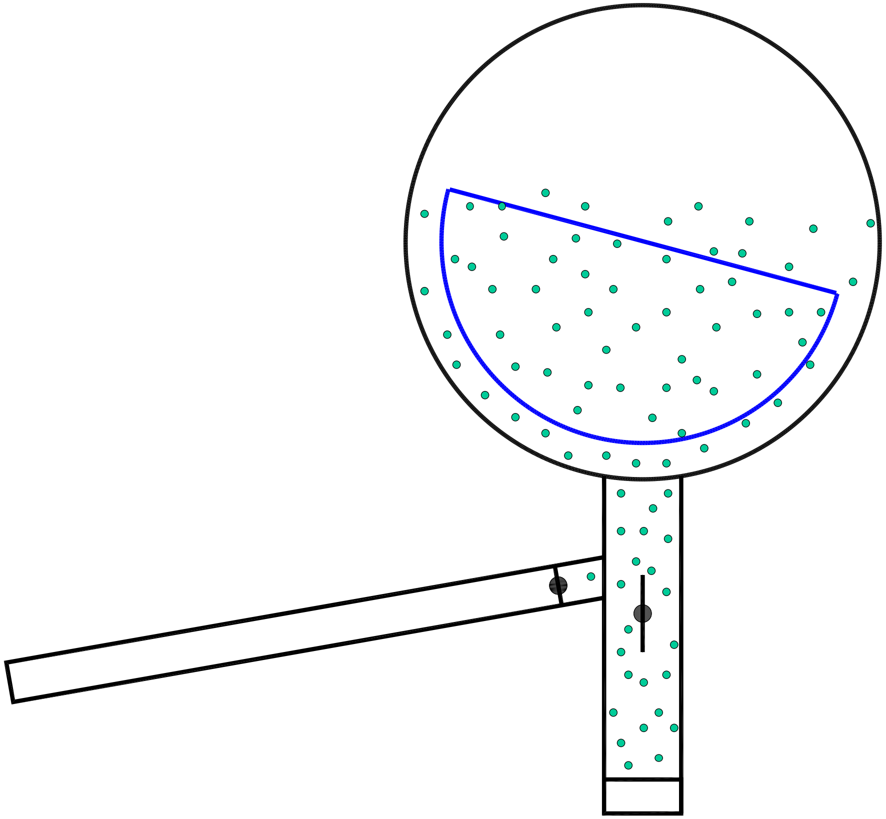
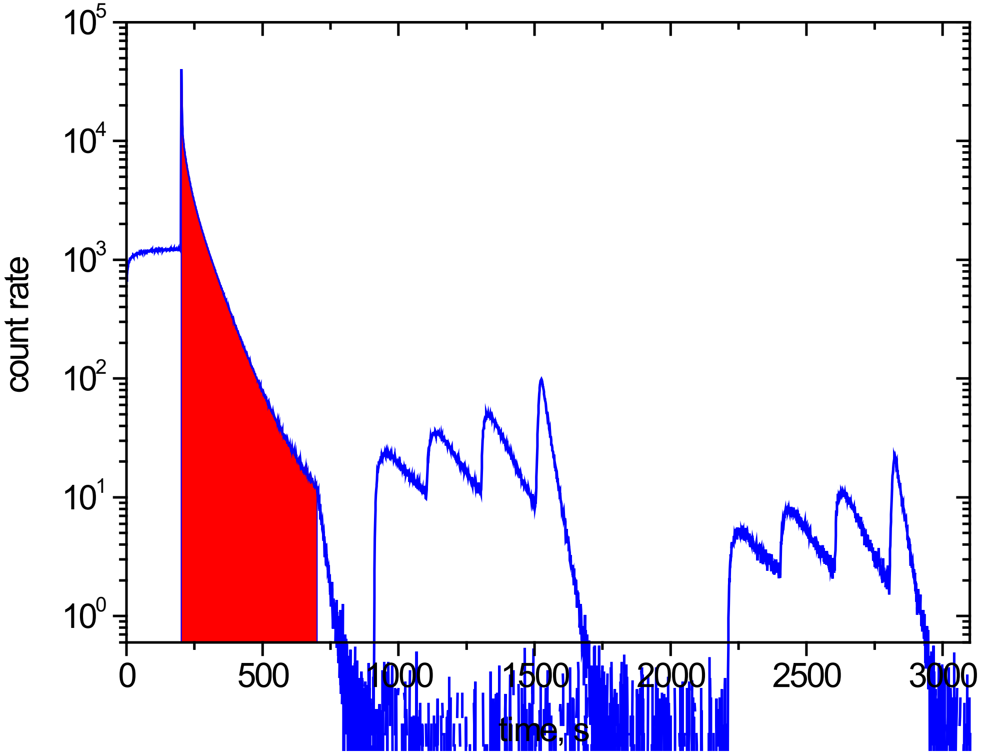


Fig.1. Gravitational spectrometer with service platforms

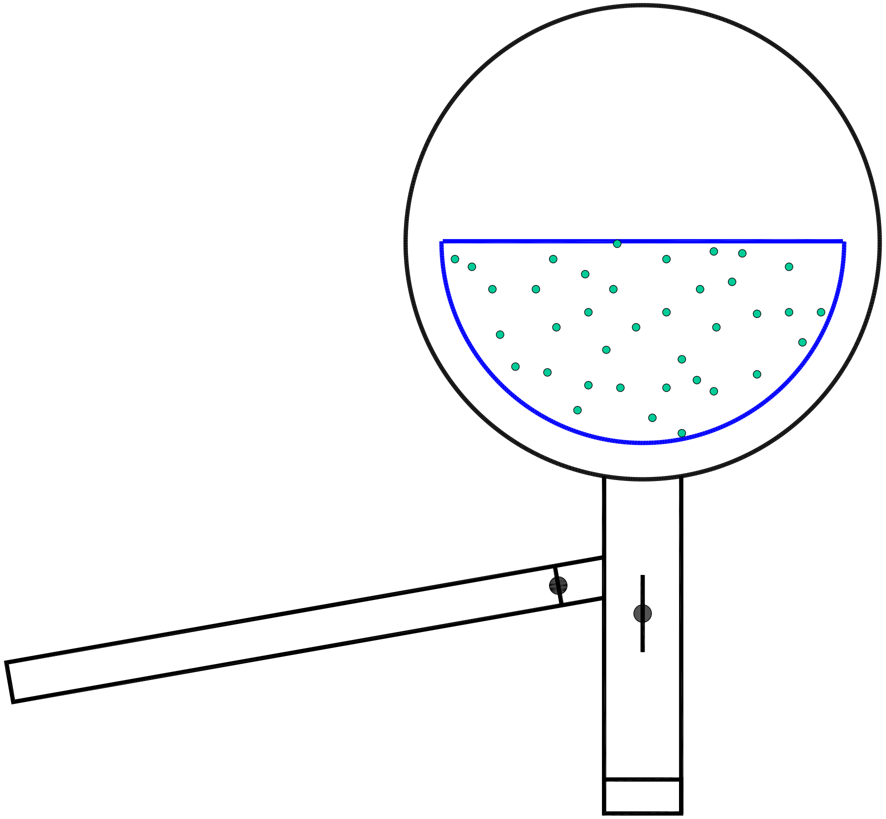


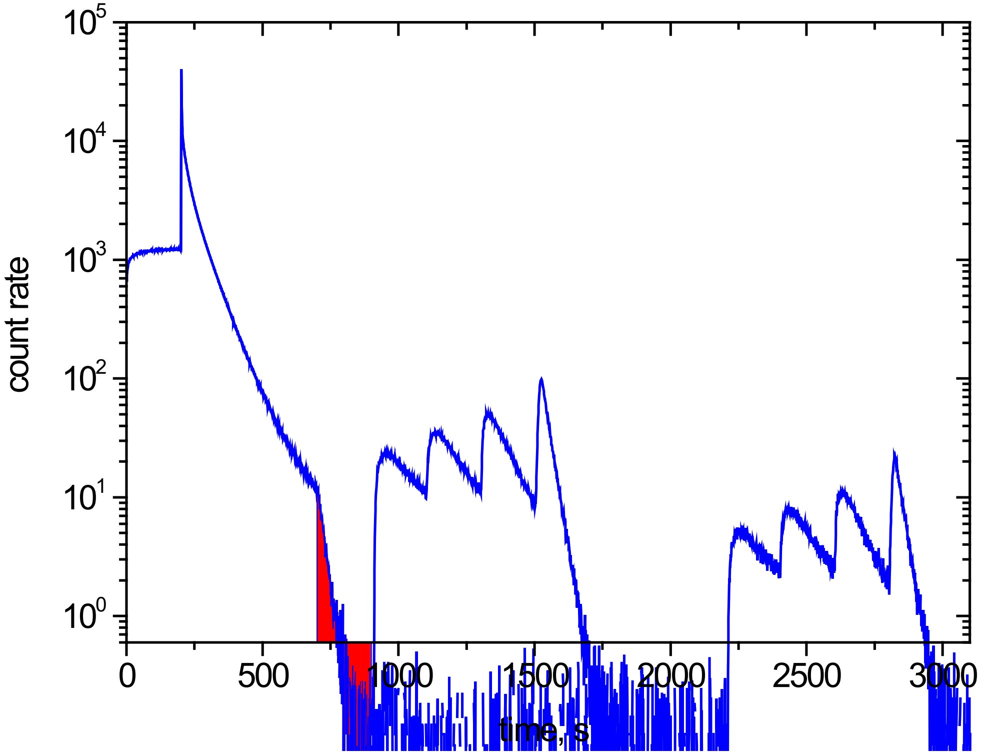
Filling of the trap with UCN: θ=90°.



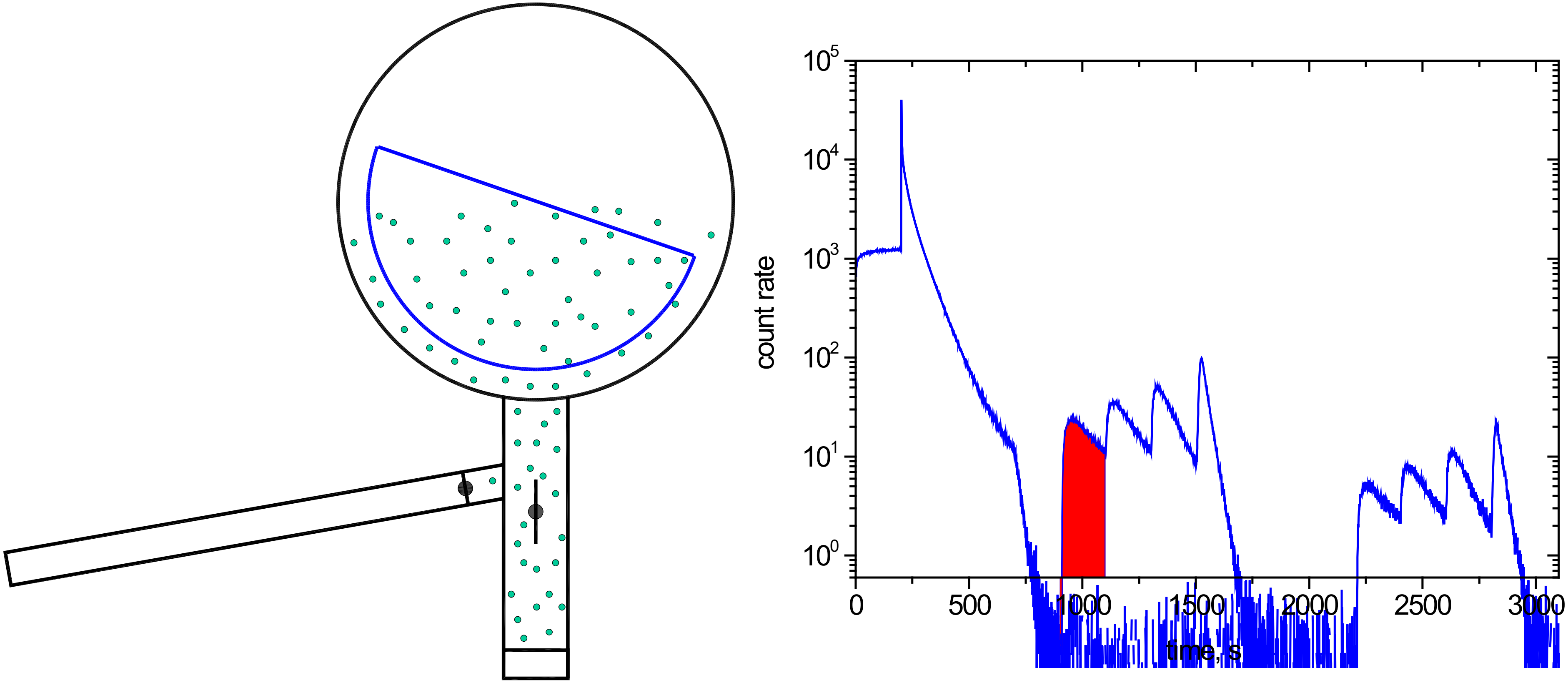


Monitoring: θ=15°.

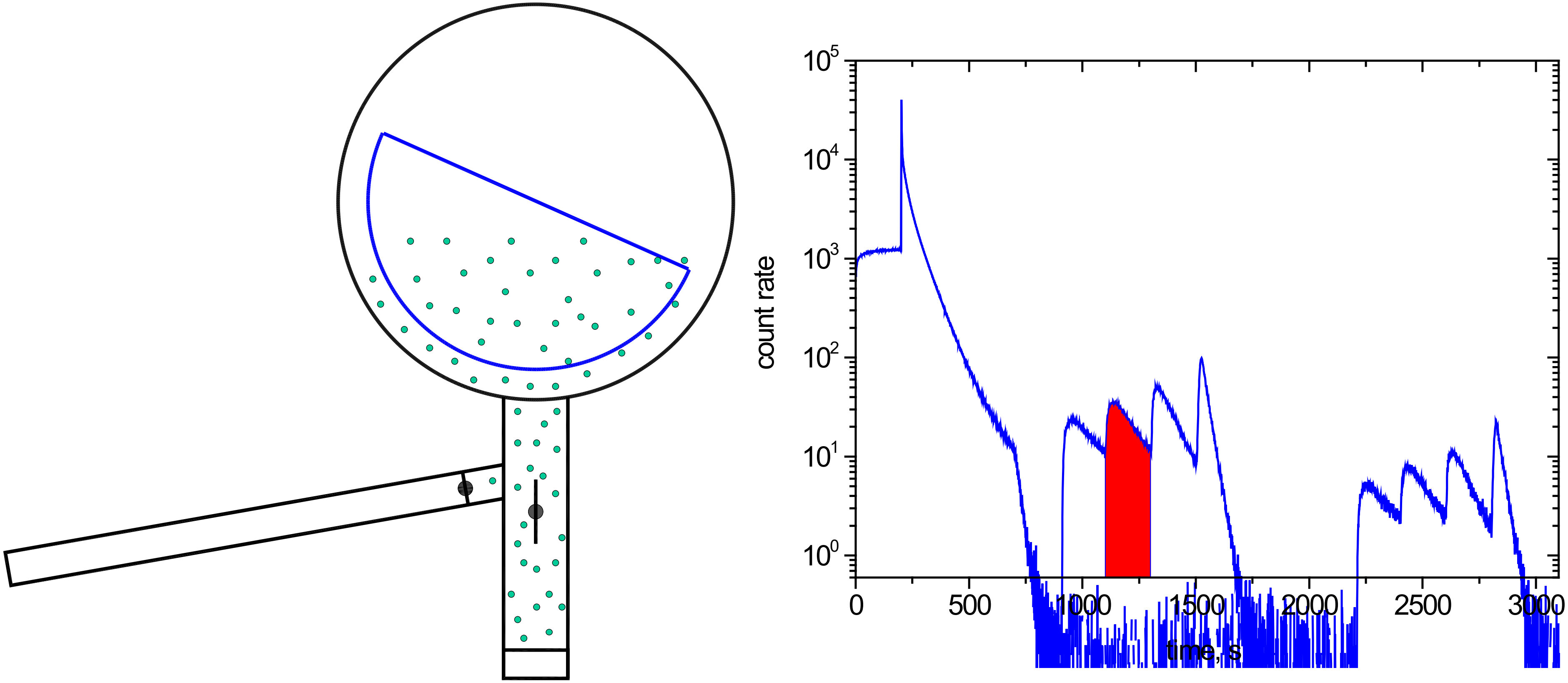



count rate
10^5
10^4
10^3
10^2
10^1
10^0
0
500
1000
1500
2000
2500
3000
time, s

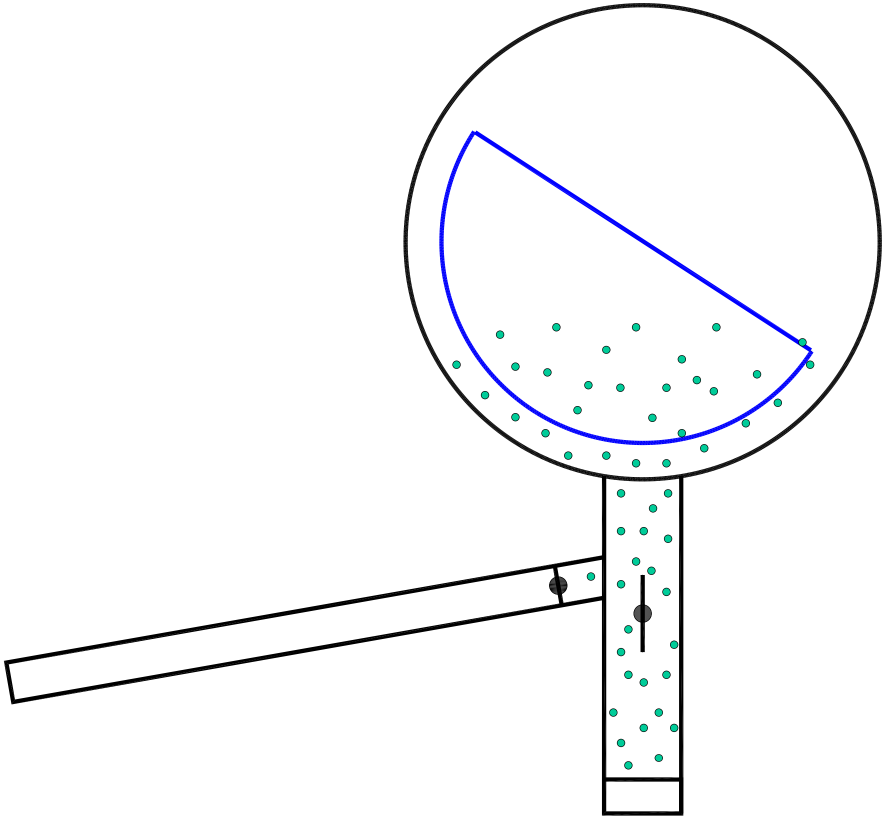
Holding: θ=0°.

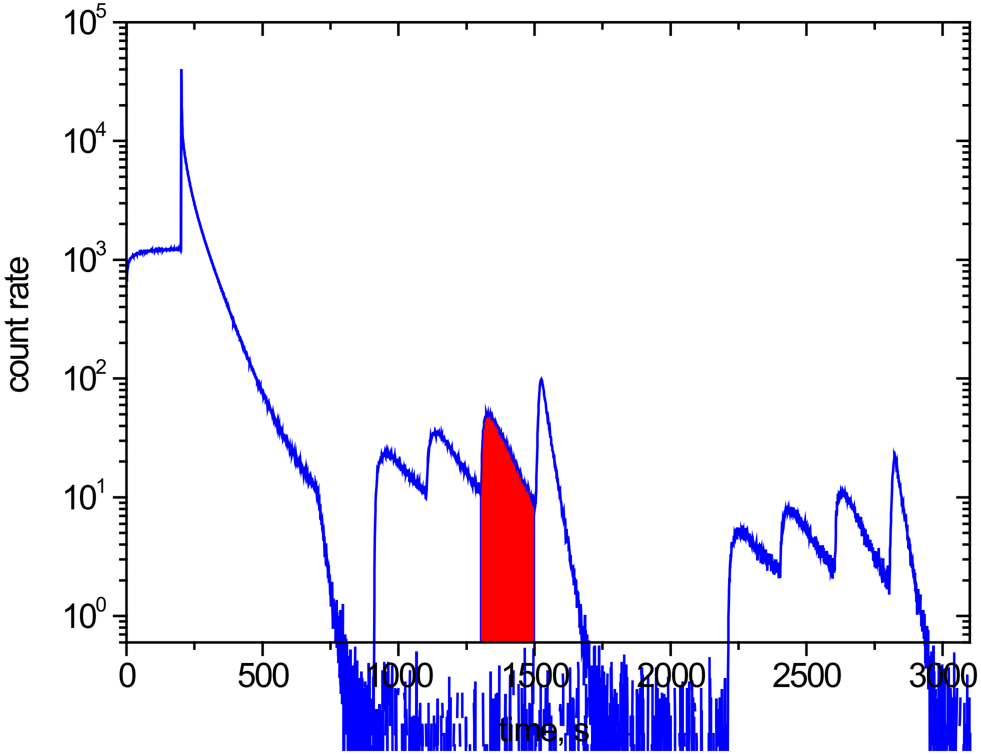


Registration of UCN 1: $\theta=19°$.

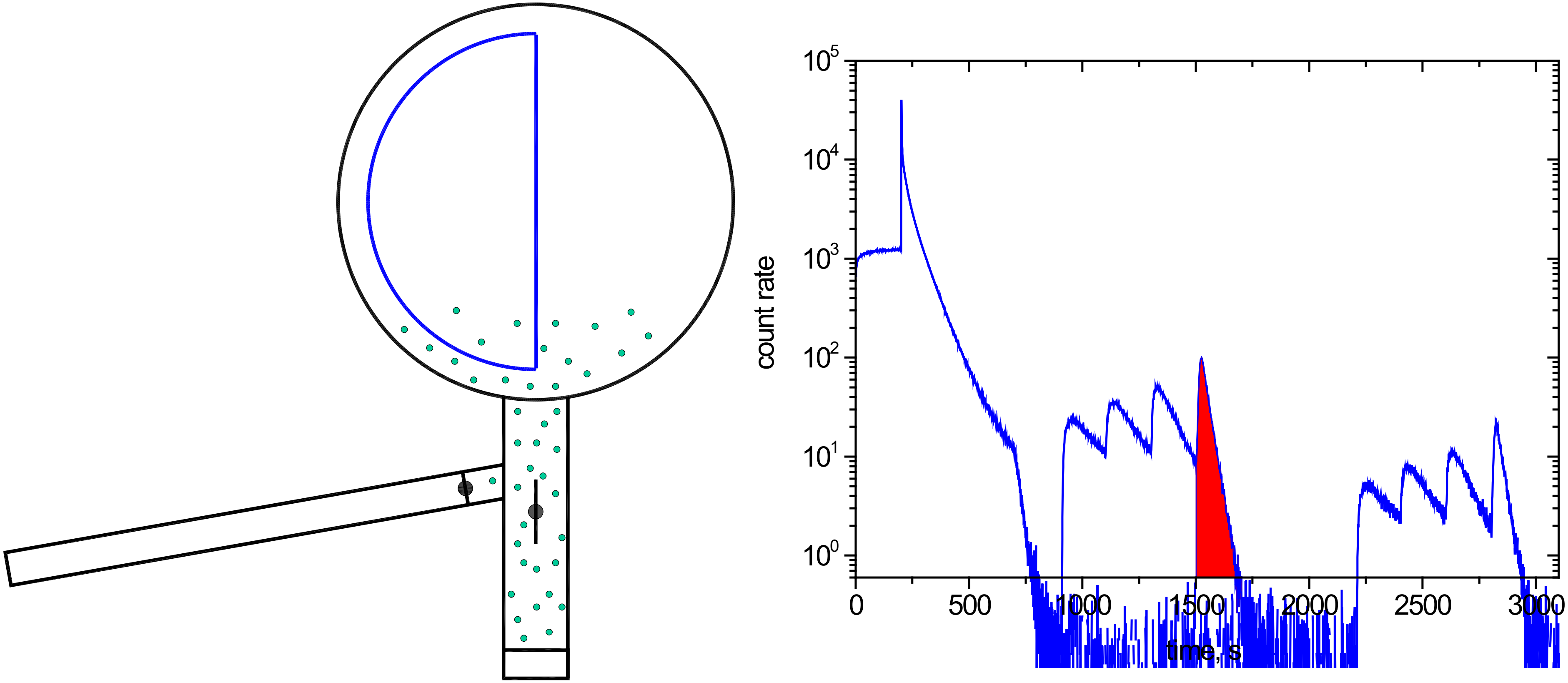


Registration of UCN 2: θ=24°.

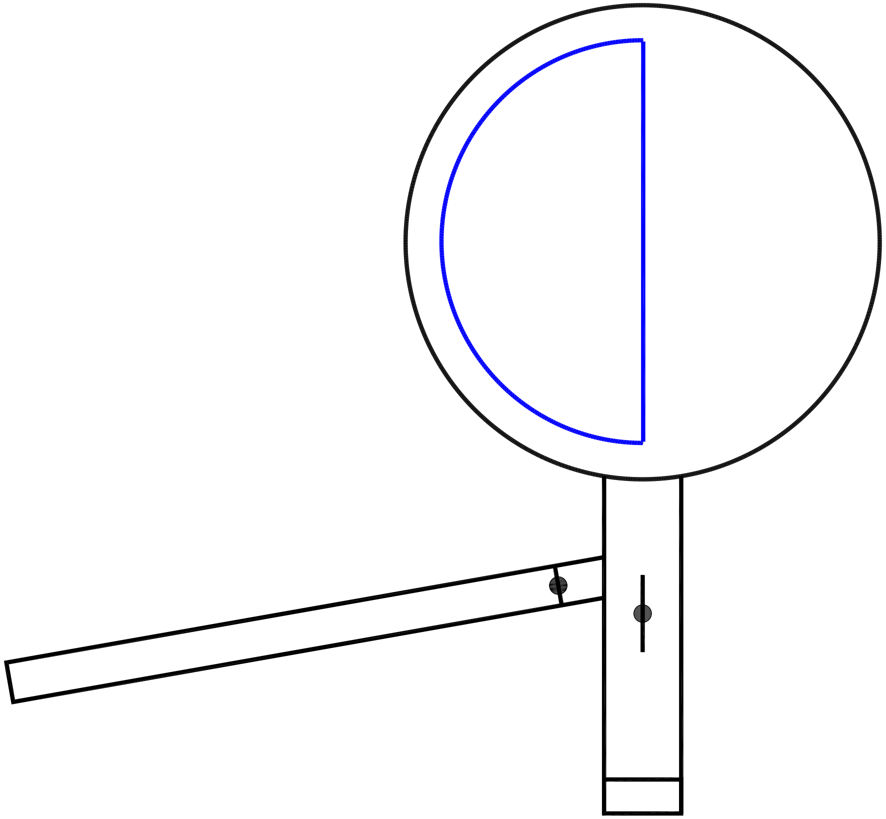


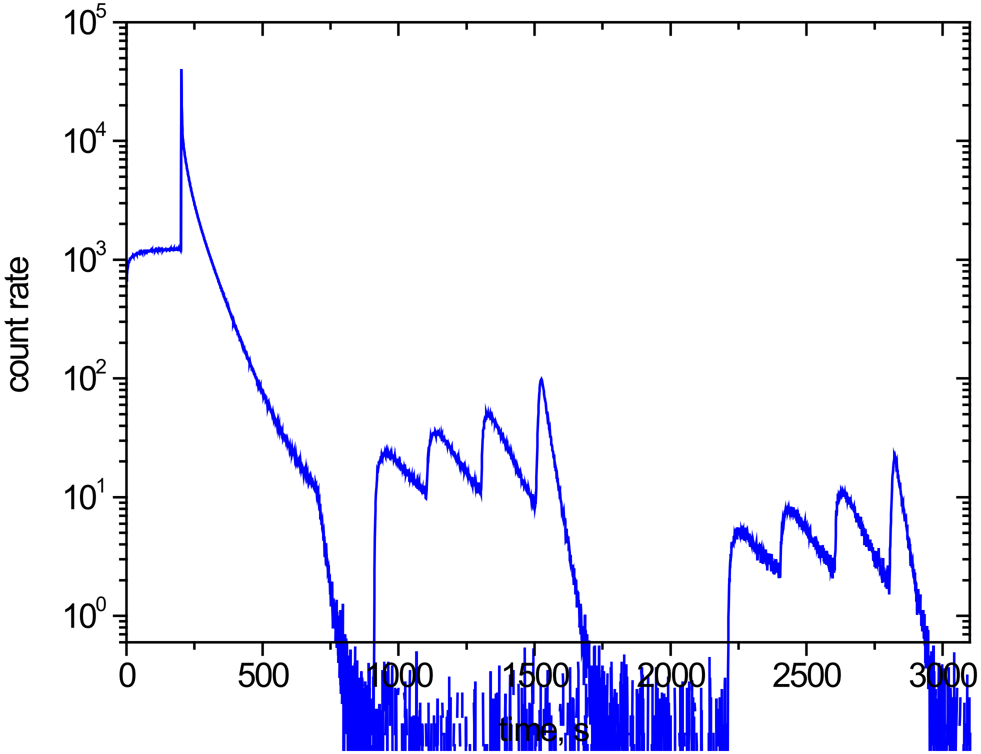


Registration of UCN 3: θ=33°.



Registration of UCN 4: θ=90°.

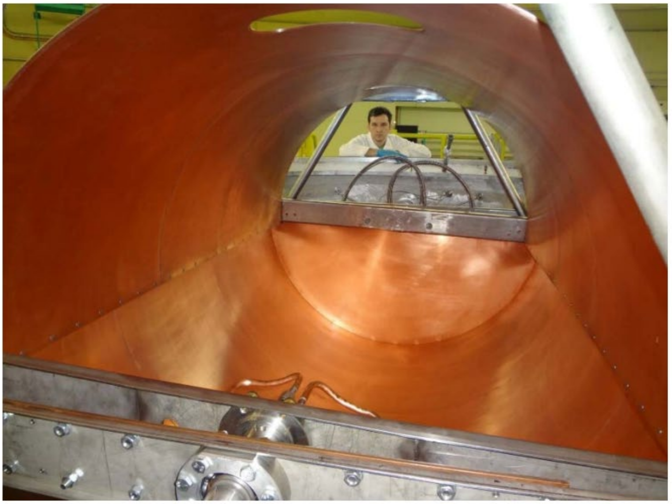


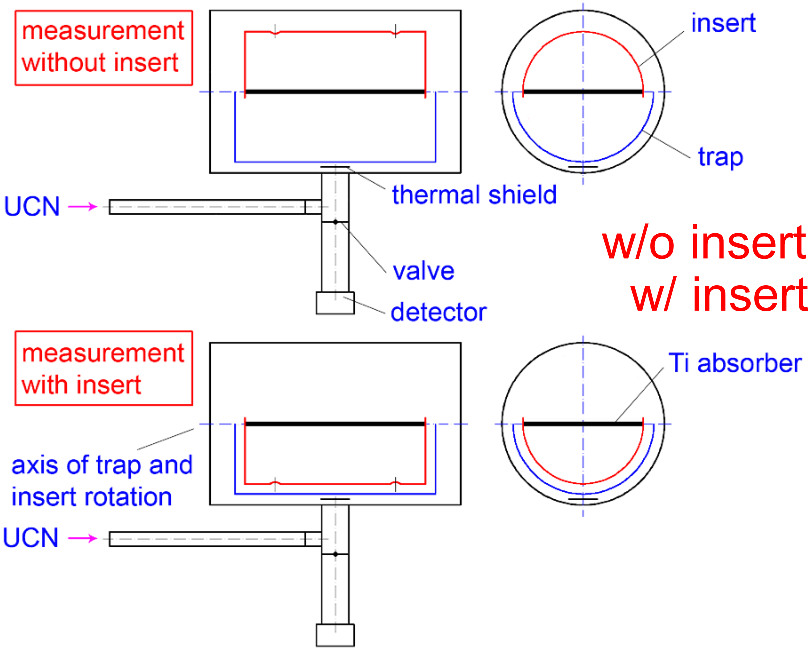


Background: θ=90°.

New GraviTrap (at ILL)

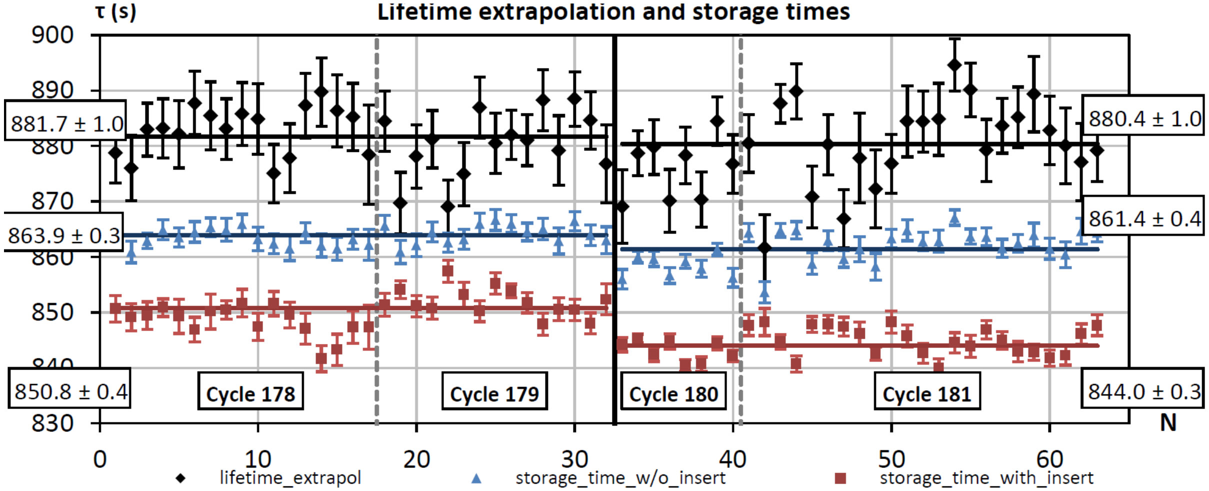
A. Serebrov et al.,(2017)
arXiv:1712.05663 [nucl-ex]





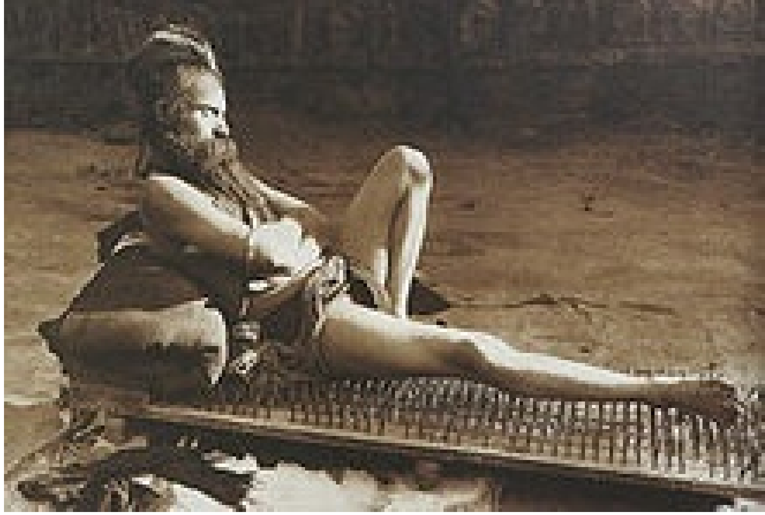
w/o insert:1540 l
w/ insert: 780 l

Gravitrap (2017): τ_n = (881.5 ± 0.7 ± 0.6) s



Material Potential

$$V_F = \frac{2\pi\hbar^2 N b_C}{m_n}$$ **Fermi potential**



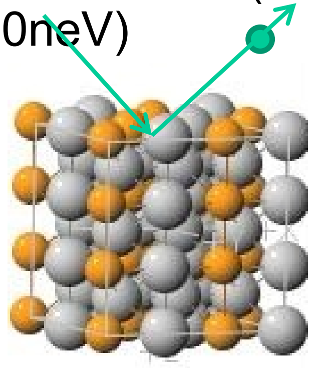
Material	V_F(neV)	v_c (m/s)	η ($\times 10^{-4}$)
D_2O	170	5.6	
Be (BeO)	250	6.9	2.0-8.5
C	180	5.8	
Mg	60	3.4	
Al	50	3.2	2.9-10
SiO_2 (quartz)	110	4.6	
Cu	170	5.6	2.1-16
Fe	220	6.5	1.7-28
Co	70	3.7	
Ni	230	6.8	5.1

Critical velocity

$$v_c = \sqrt{\frac{2V_F}{m_n}}$$

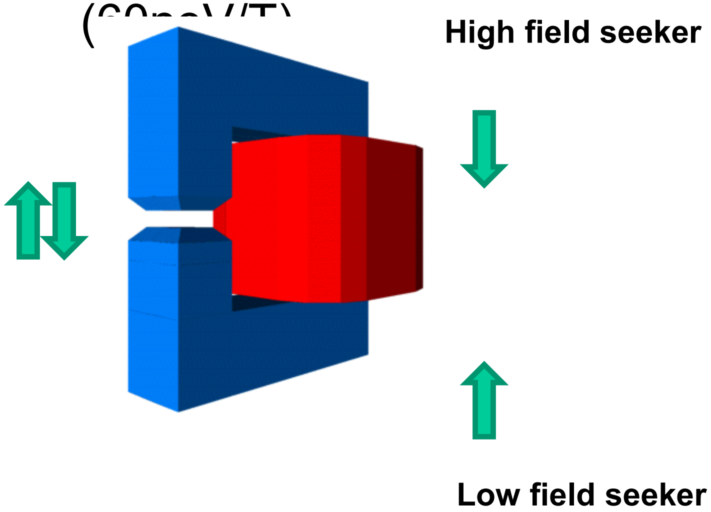
Different ways to manipulate UCN

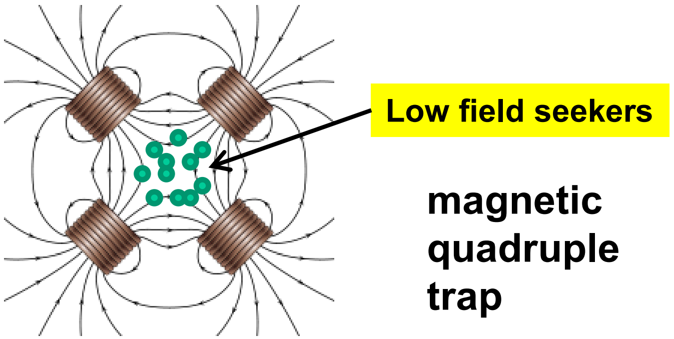
- Nuclear force (max: 350neV)



- Gravitational force (100neV/m)

- Magnetic force (60neV/T)



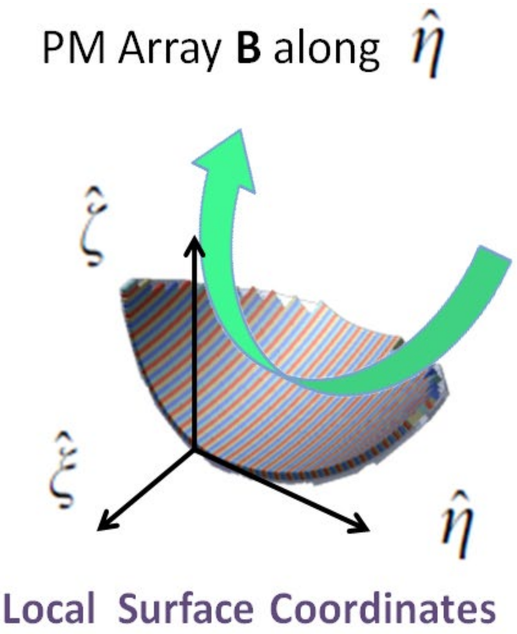


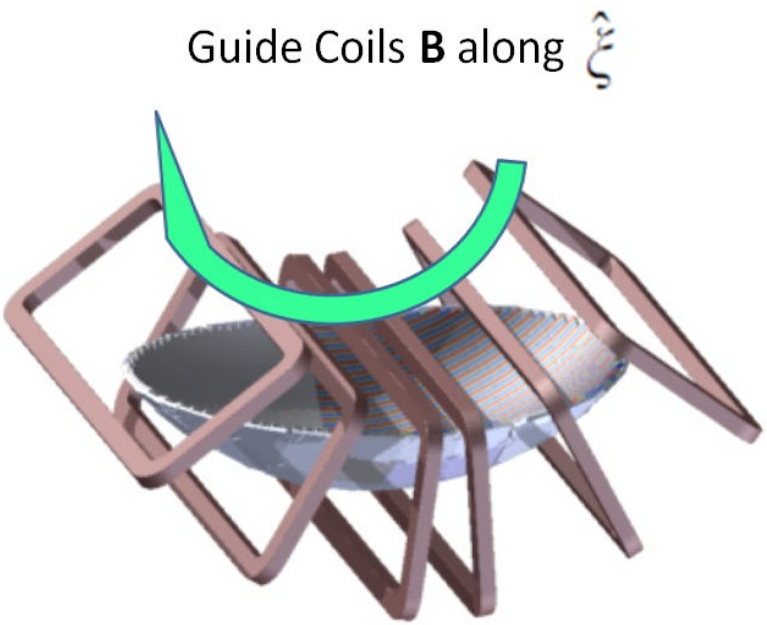
magnetic quadruple trap

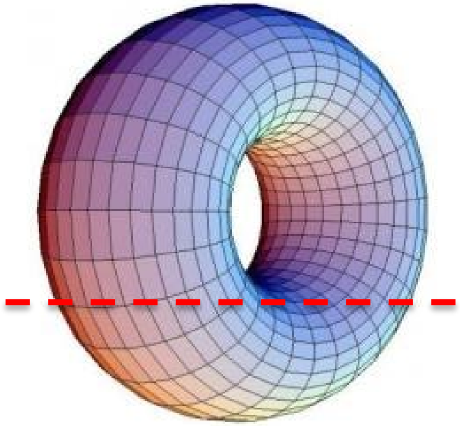
UCNτ: Magneto-Gravitational Trap

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

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

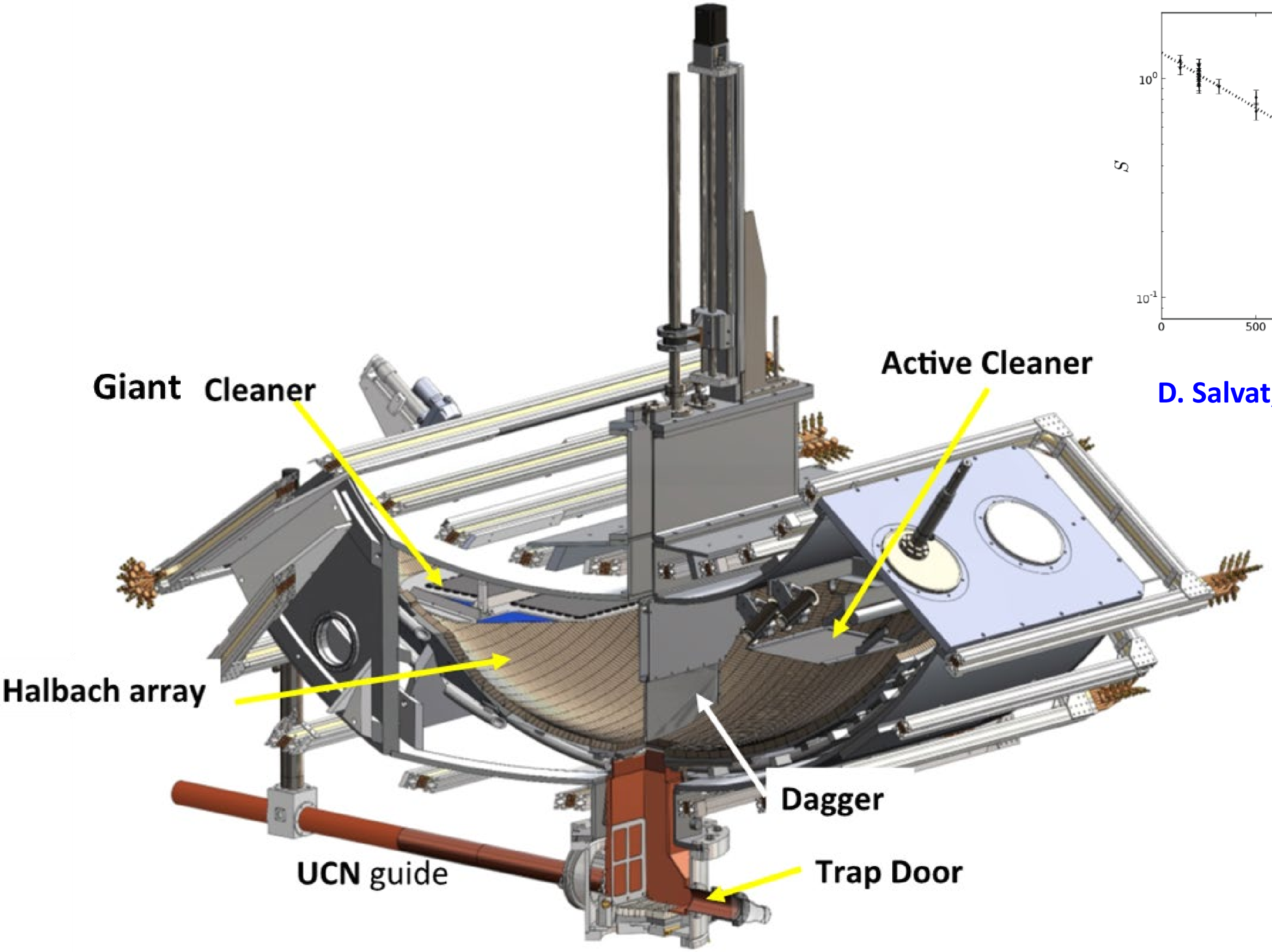




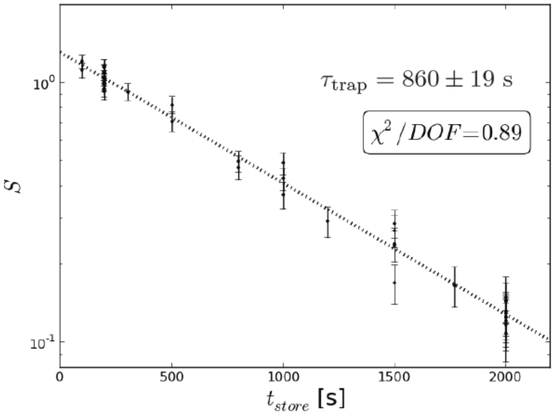


Walstrom et al, NIMA, 599, 82 (2009)

The UCNτ apparatus



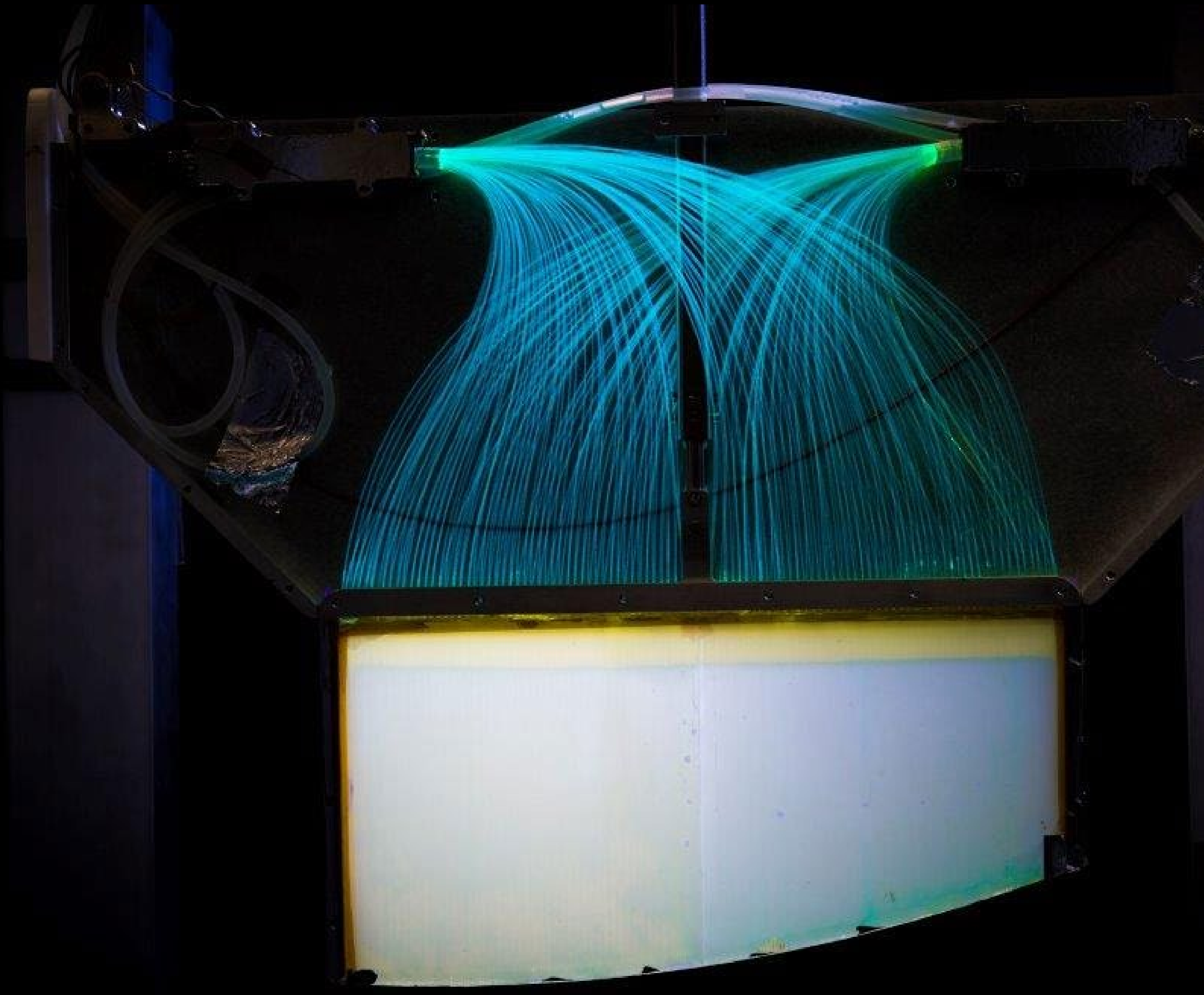
1st measurement

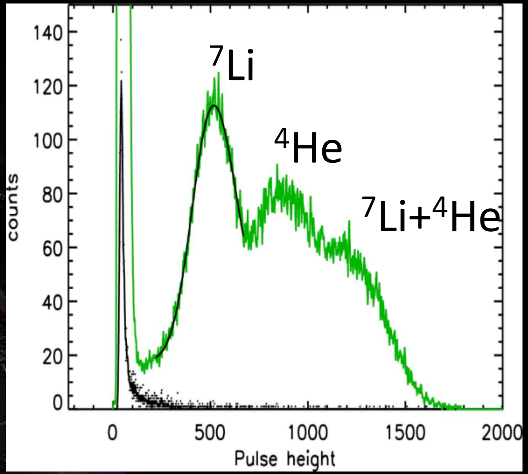


D. Salvat, PRC 89, 052501 (2014)

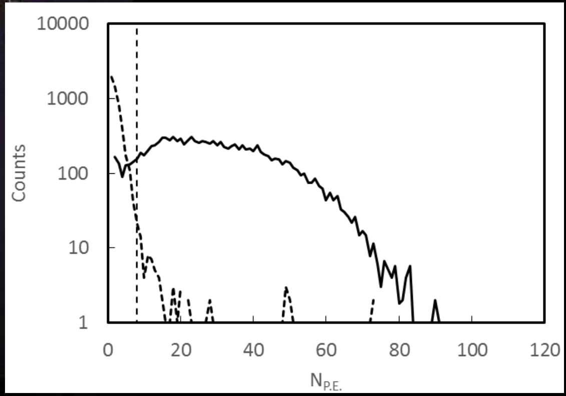
Z. Wang *et al.*, NIMA **798**, 30 (2015).

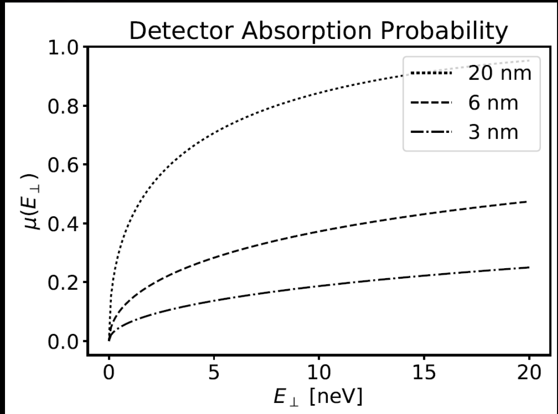
$n + {}^{10}B \rightarrow {}^{7}Li + \alpha$



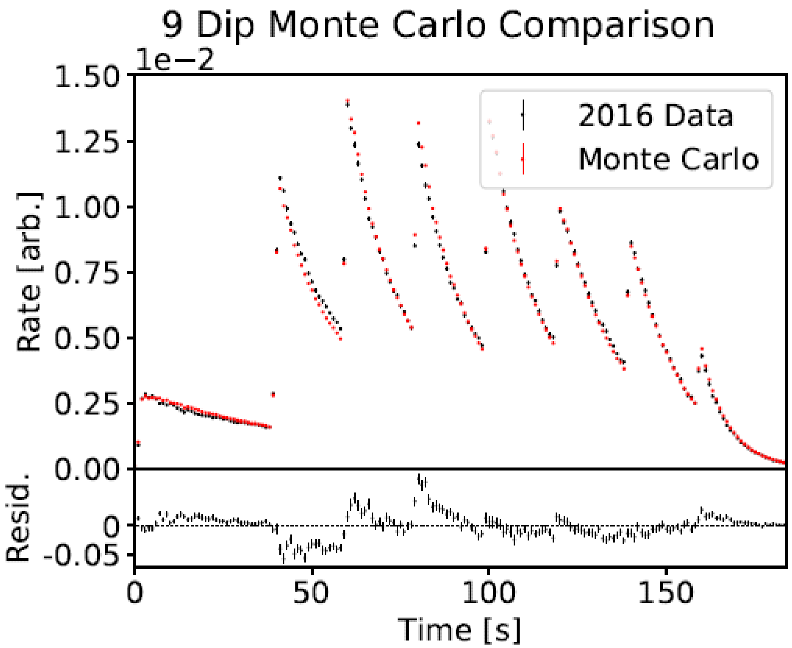


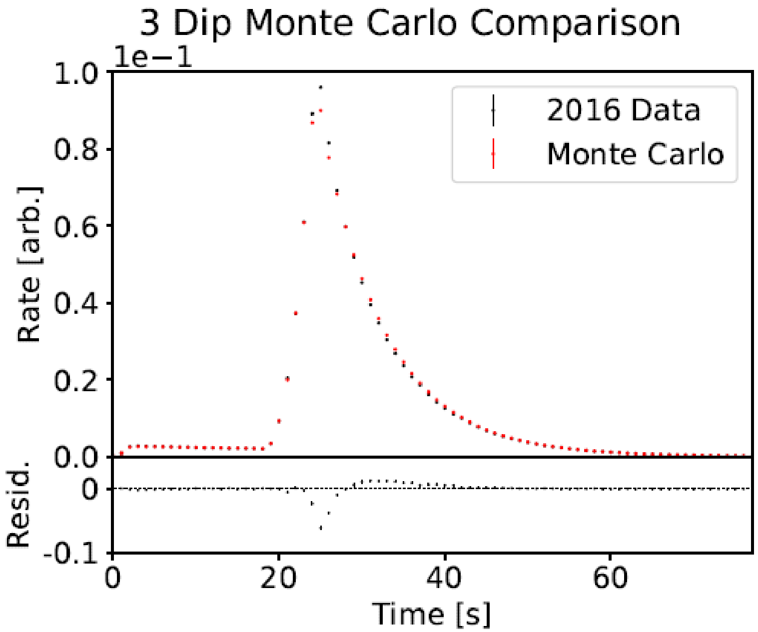
Light Output





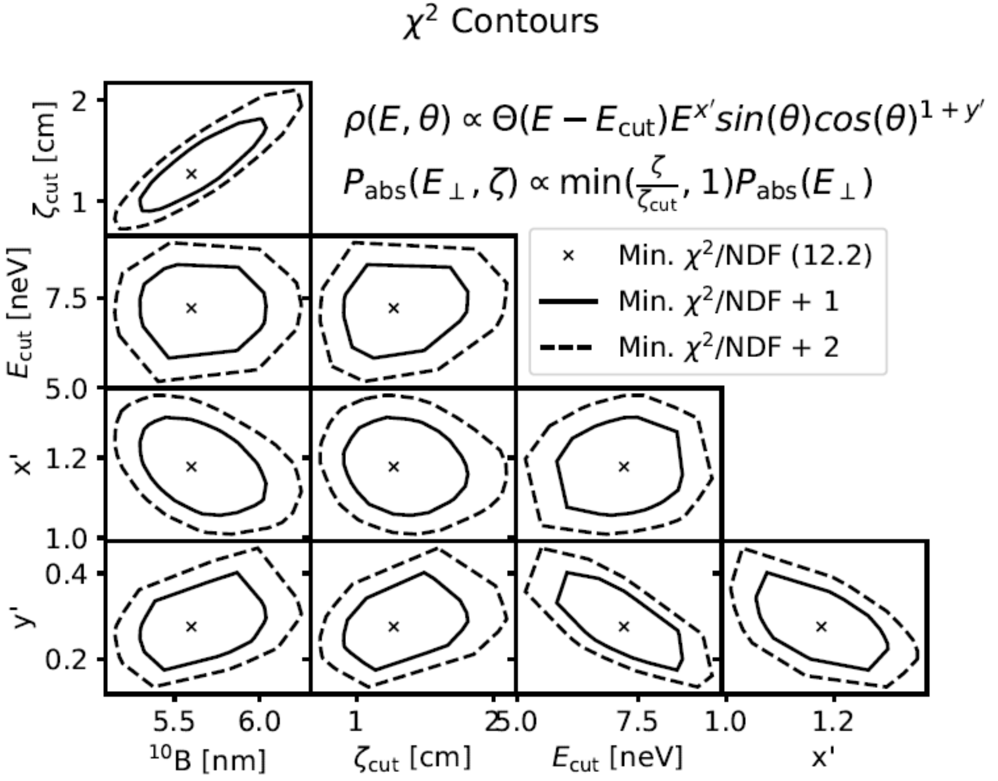
Multi-step detections & Monte-Carlo studies



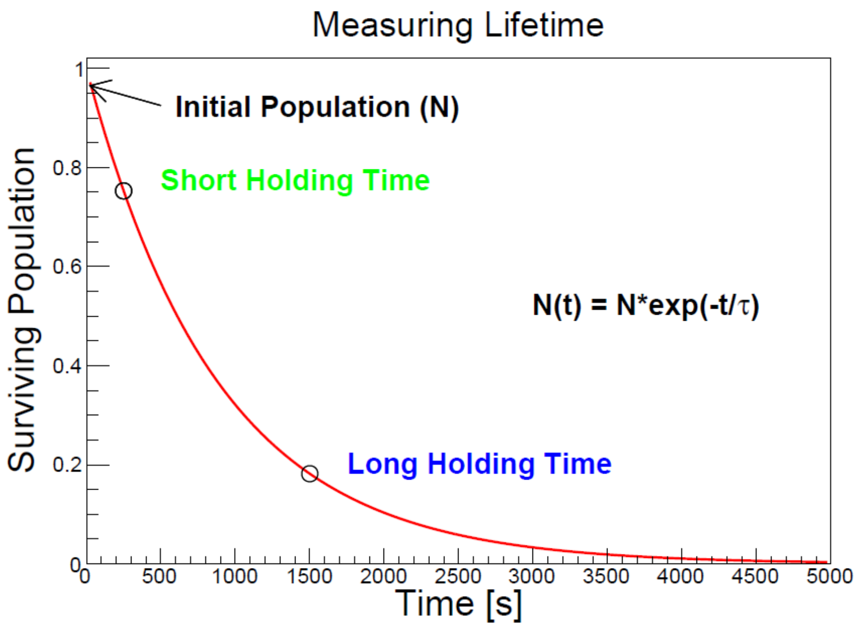


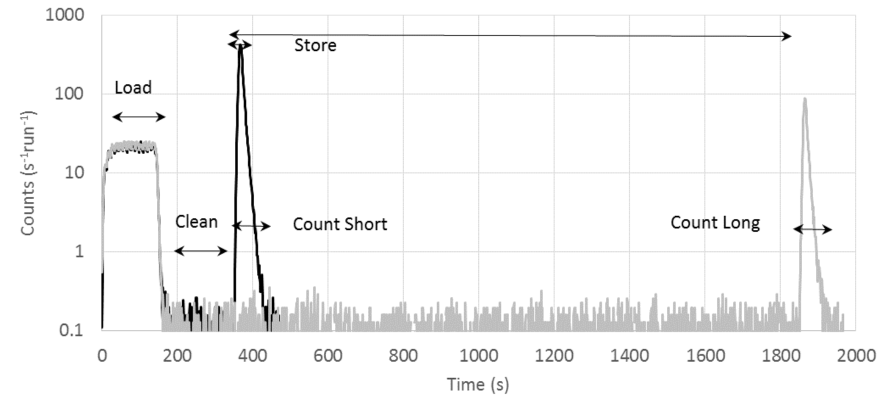
Tunable Parameters:

- Input UCN: energy spectrum (x’, Ecut), angular distribution (y’)
- Detector: Boron thickness, oxide layer, damage depth



Pairs of short-long storage times



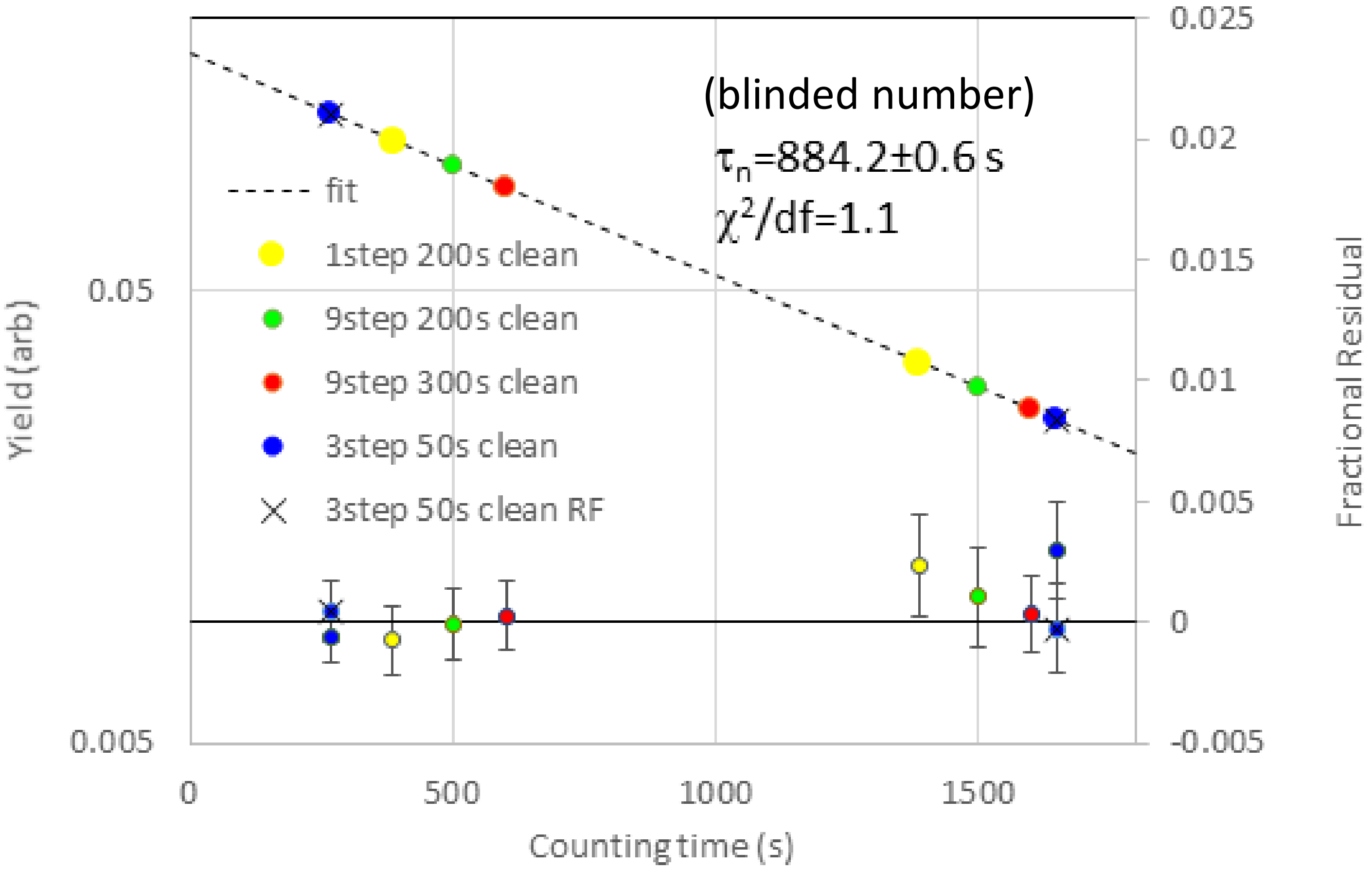


$$\tau_{trap} = \frac{\Delta t}{\log\left(\frac{N_{short}}{N_{long}}\right) - \log\left(\frac{M_{short}}{M_{long}}\right)}$$

N: UCN counts
M: Monitor counts

$$\frac{1}{\tau_{\text{trap}}} = \frac{1}{\tau_{\text{n}}} + \frac{1}{\tau_{\text{escape}}} + \frac{1}{\tau_{\text{heating}}} + \frac{1}{\tau_{\text{depol}}} + \ldots$$

Global fit into a single exponential function



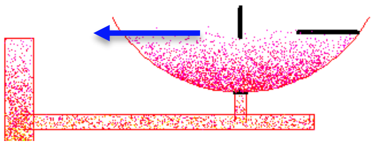
Systematic uncertainties for the “current mode” counting

R. W. Pattie Jr. *et al.*, Science 360, 627 (2018)

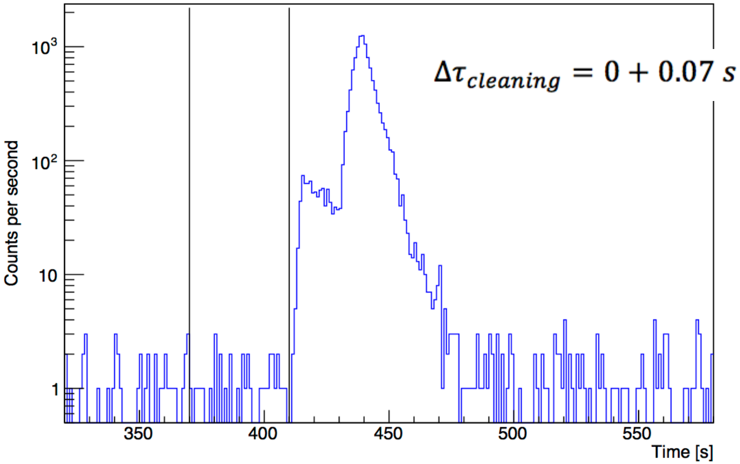
Effect	Upper bound (s)	Direction	Method of evaluation
Depolarization	0.07	+	Varied external holding field
Microphonic heating	0.24	+	Detector for heated neutrons
Insufficient cleaning	0.07	+	Detector for uncleaned neutrons
Dead time/pileup	0.04	±	Known hardware dead time
Phase space evolution	0.10	±	Measured neutron arrival time
Residual gas interactions	0.03	±	Measured gas cross sections and pressure
Background variations	<0.01	±	Measured background as function of detector position
Total	**0.28**		**(uncorrelated sum)**

Insufficient Cleaning

Limit established by short holding time excess

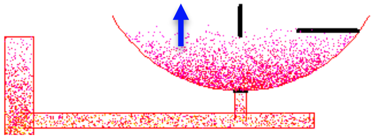


20s hold

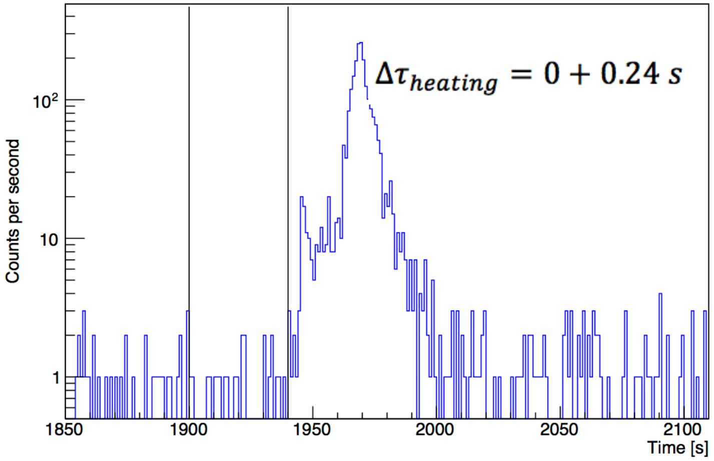


Heating

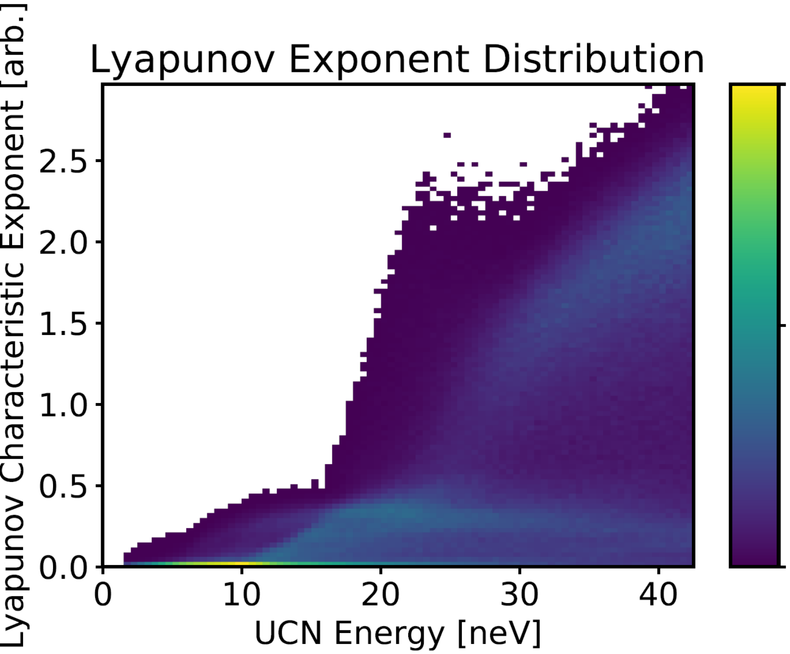
Limit established by long holding time excess

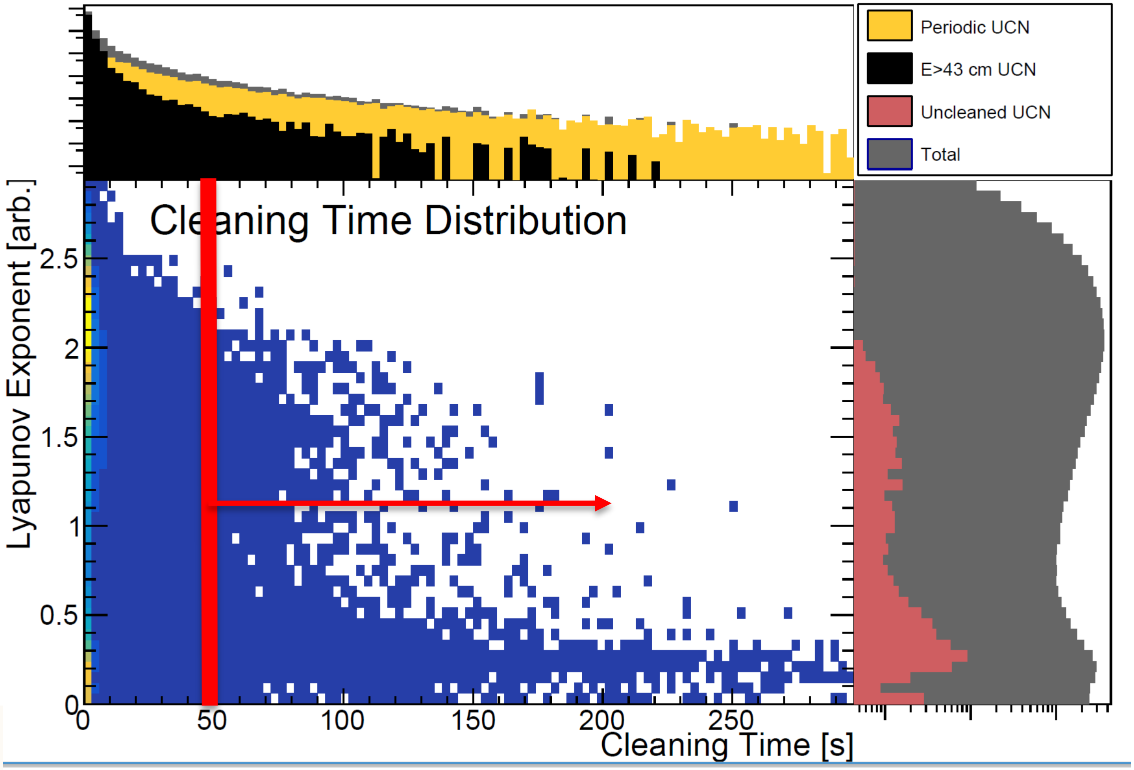


1550s hold



Chaotic Motion & Spectral Cleaning





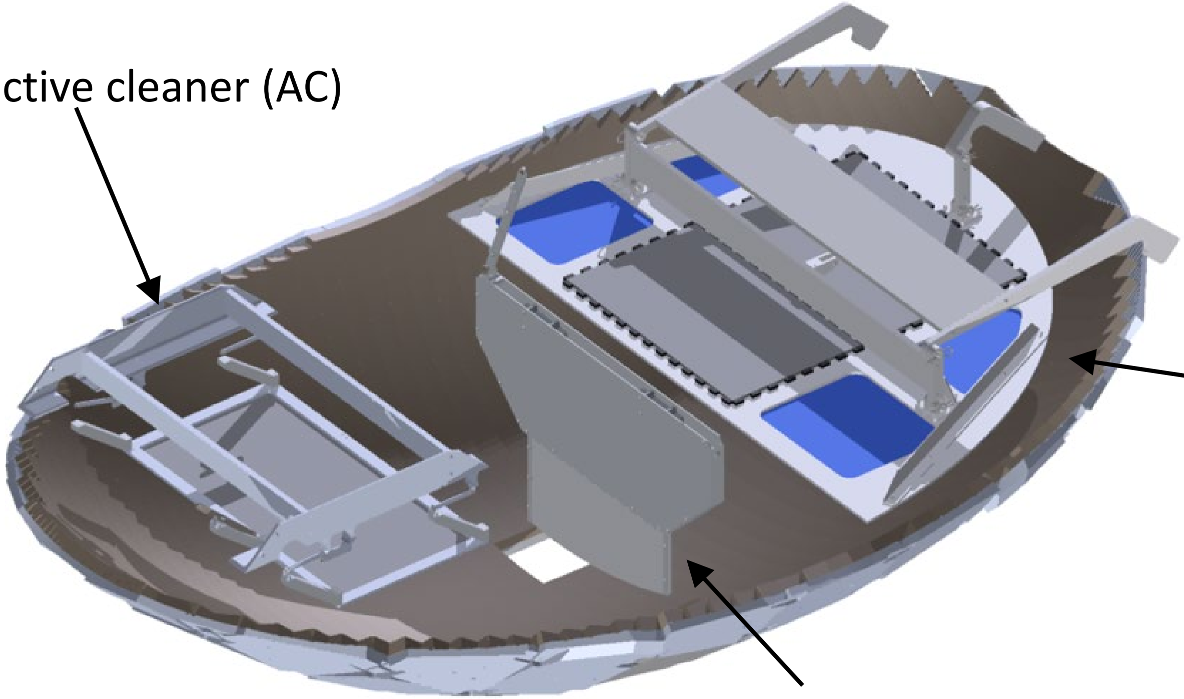
Use Monte Carlo with realistic vibrations to estimate lifetime shift

Set	$\delta\tau$ [s]	Statistical Uncertainty [s]
Cleaning		
100% Absorption	0.034	0.0006
50% Absorption	0.050	0.0007
200 s Cleaning	0.0017	0.0001
35 cm Cleaning	8×10^{-5}	3×10^{-5}
Heating		
Accelerometer	0.031	0.005
x40 ($\sim 40\mu$m)	0.151	0.009
x80	7.68	0.06

N. Callahan et al,.(2018) arXiv:1810.07691

We tried three options of UCN spectral cleaners:

1. AC: small area, fitted with UCN detectors at 37 cm (P1).
2. DC: deep cleaning by lowering dagger at 25 cm (P2).
3. GC: large area, no detectors at 37 cm (P1).



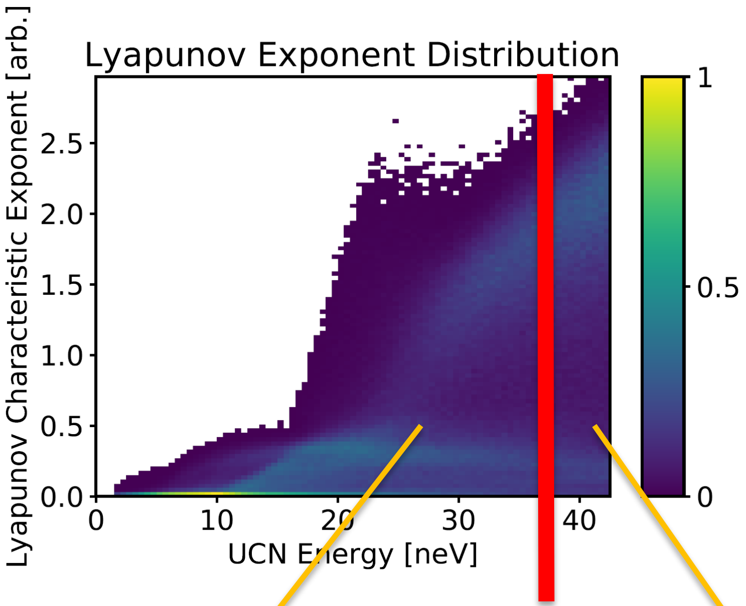
active cleaner (AC)

giant cleaner (GC), available in 2017

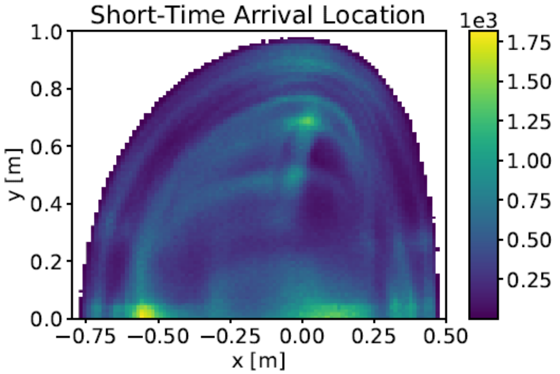
active “dagger” detector (AD)

UCN dynamics in the trap

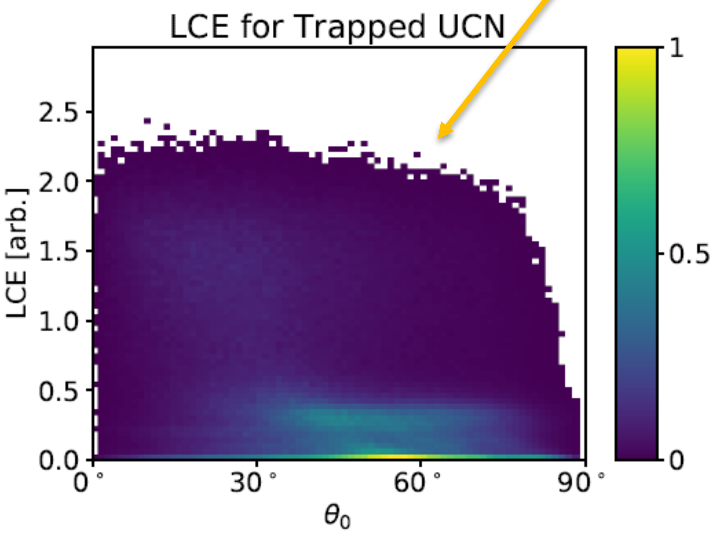
N. Callahan et al,.(2018) **arXiv:1810.07691**



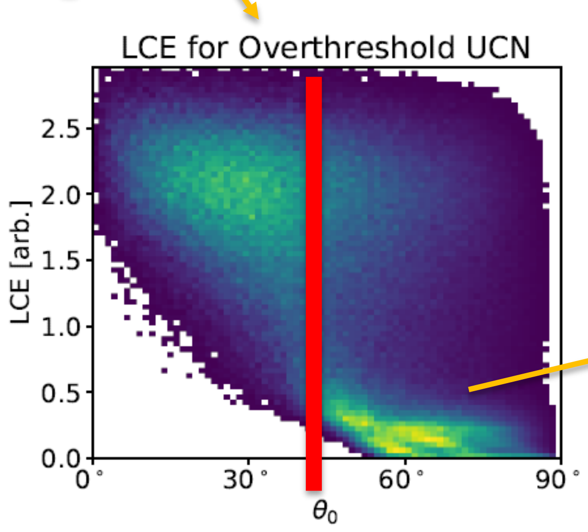
UCN hit on the cleaner



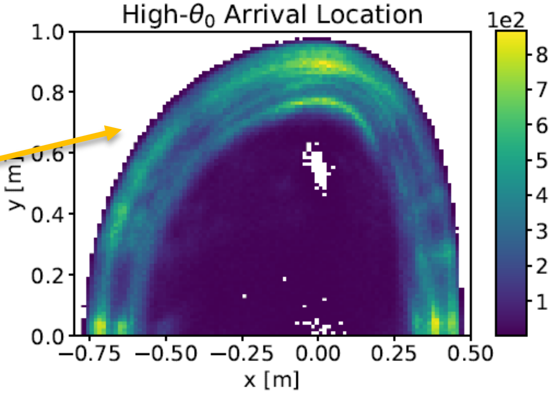
(a) $t < 50$ s



(b) Trappable neutrons ($E/m_ng < 38$ cm)



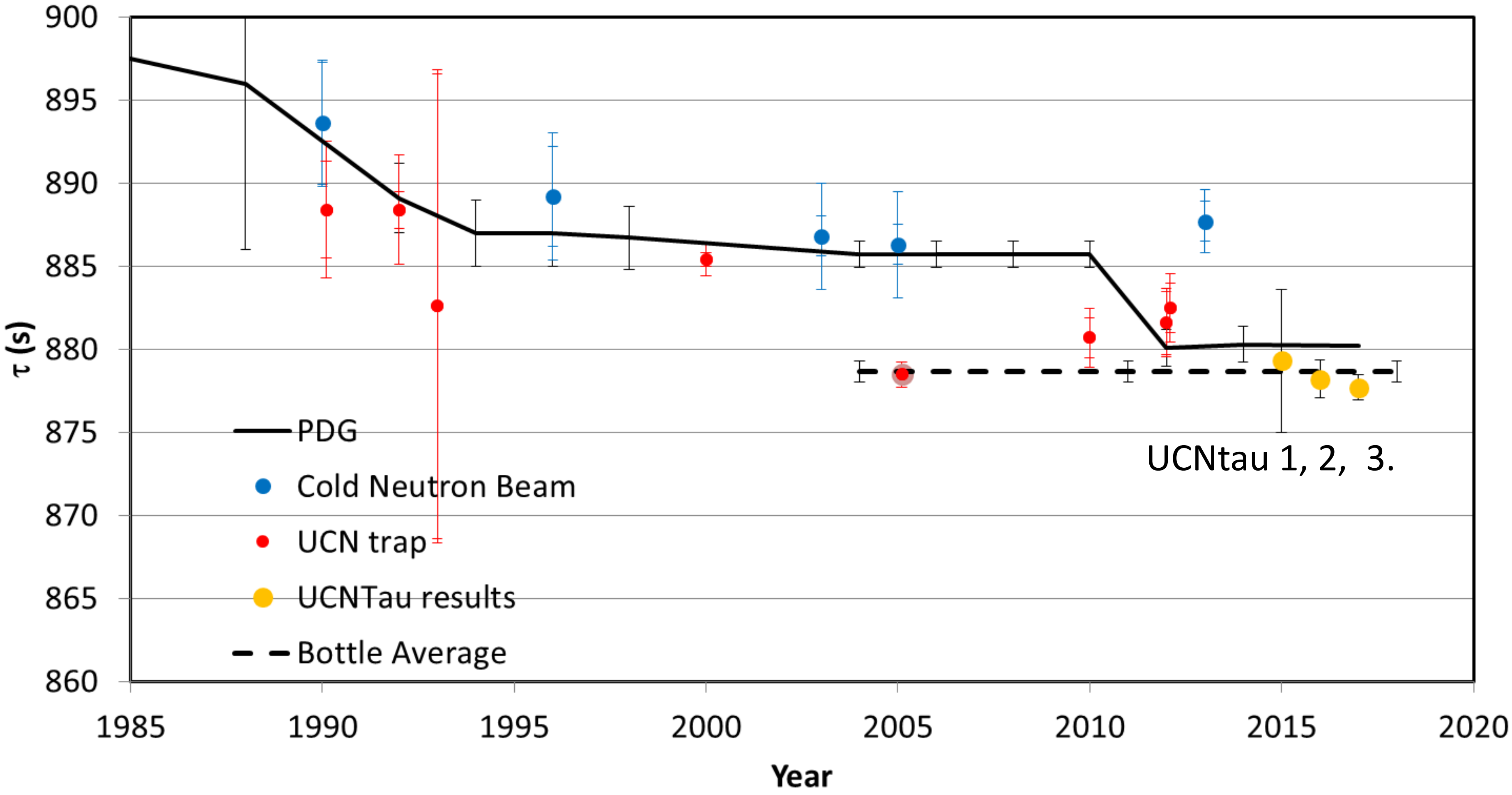
(a) Overthreshold neutrons ($E/m_ng > 38$



(c) $\theta_0 > 45°$

UCNtau results

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

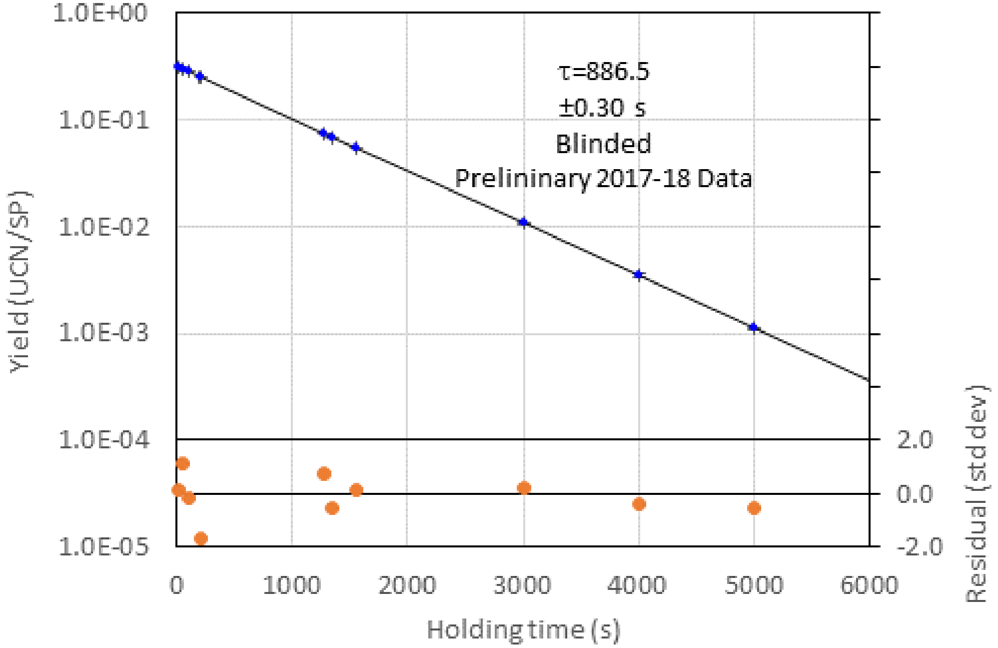


With UCNtau, we have made a measurement of τ_n for the first time with **no extrapolation**: 877.7 ± 0.7 (stat) +0.3/-0.1 (sys) s.

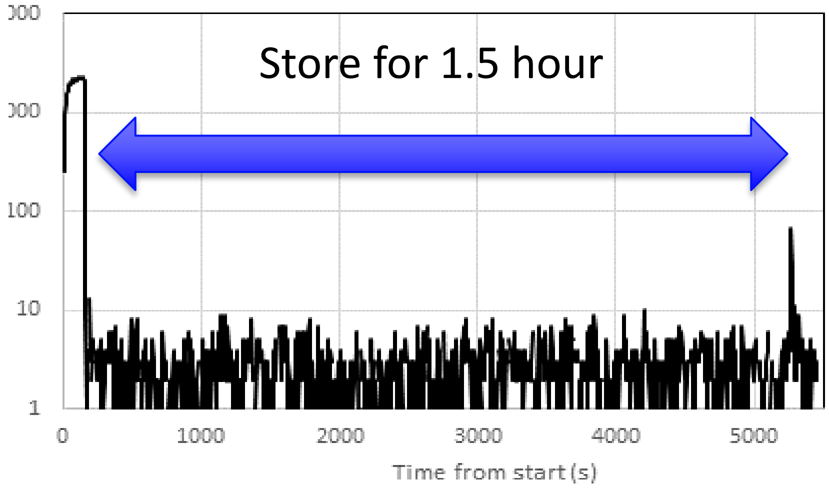
UCNtau: Moving forward

Effect	Upper bound (s)		Direction	Method of evaluation
Depolarization	0.07		+	Varied external holding field
Microphonic heating	~~0.24~~	0.05	+	Detector for heated neutrons
Insufficient cleaning	~~0.07~~	0.02	+	Detector for uncleaned neutrons
Dead time/pileup	0.04		±	Known hardware dead time
Phase space evolution	~~0.10~~	0.02	±	Measured neutron arrival time
Residual gas interactions	~~0.03~~	0.01	±	Measured gas cross sections and pressure
Background shifts	<0.01		±	Measured background as function of detector position
Total	~~0.28~~	0.10		(uncorrelated sum)

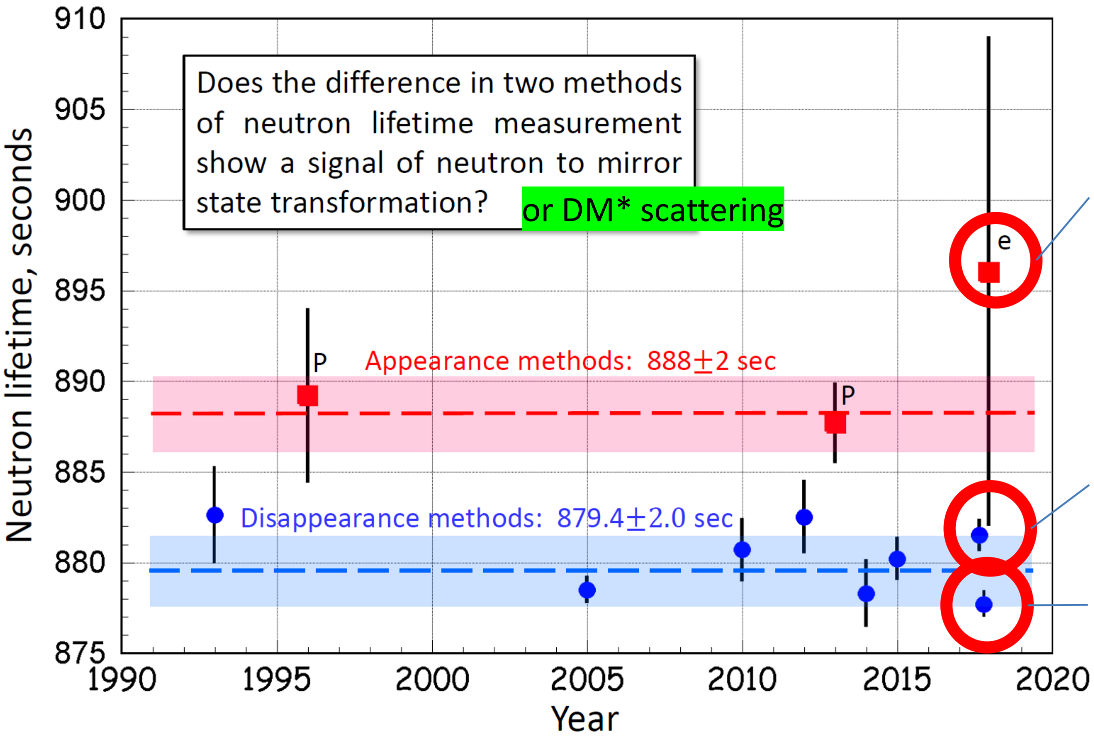
Last beam cycle (2017-2018):



Projected statistical uncertainty: 0.15 s
systematic uncertainty: 0.10 s
→ total uncertainty: 0.18 s



Are neutrons disappearing at a rate faster than the rate of beta-decay?



Does the difference in two methods of neutron lifetime measurement show a signal of neutron to mirror state transformation? or DM* scattering

JPARC TPC experiment
895.7 +17/-14 s
New preliminary result (DNP2018) with δt: +8.8/-9.7 s

Serebrov's large Gravitrap experiment
881.5 ± 0.7 (stat) ± 0.6 (syst) s
(Phys. Rev. C **97**, 055503, 2018)

UCNtau: 877.7 ± 0.7 (stat) +0.3/-0.1 (sys) s
(Science 360, 627 (2018))

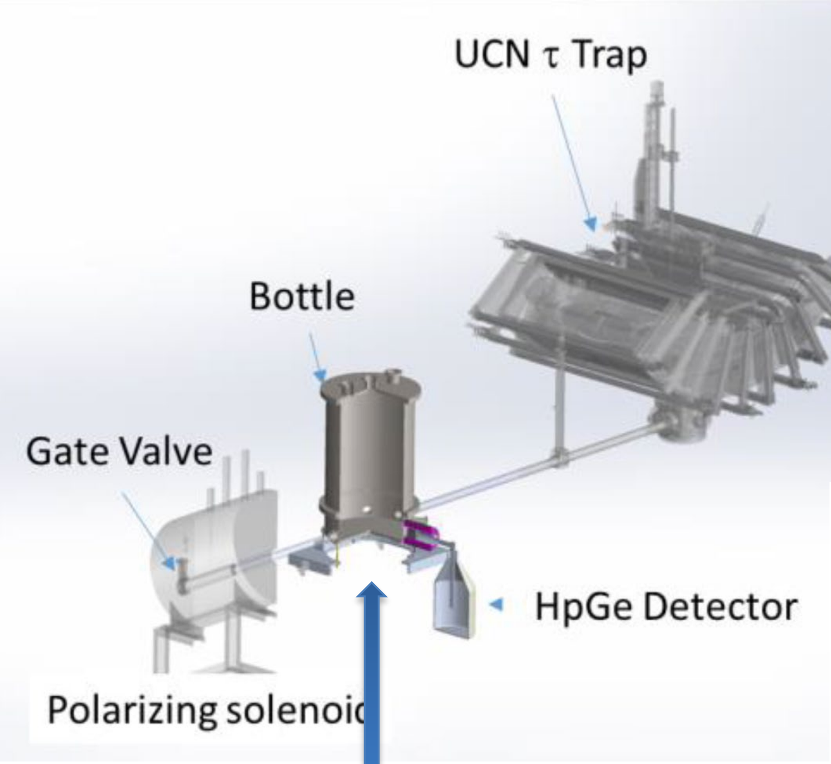
INT workshop on Neutron-Antineutron Oscillations: Appearance, Disappearance, and Baryogenesis (Oct 2017)

Ezhov : $\tau_n = (878.3 \pm 1.6_{\text{stat}} \pm 1.0_{\text{syst}})$
Jetp Lett. (2018) 107: 671

Mirror matters
T. D. Lee and C. N. Yang, Phys. Rev. 104, 254 (1956); I. Y. Kobzarev, L. B. Okun and I. Y. Pomeranchuk, Yad. Fiz. 3, 1154 (1966); R. Foot, H. Lew and R. R. Volkas, Phys. Lett. B 272 (1991) 67. For a historical overview, see L. B. Okun, Phys. Usp. 50, 380 (2007)

Decay into dark matter?

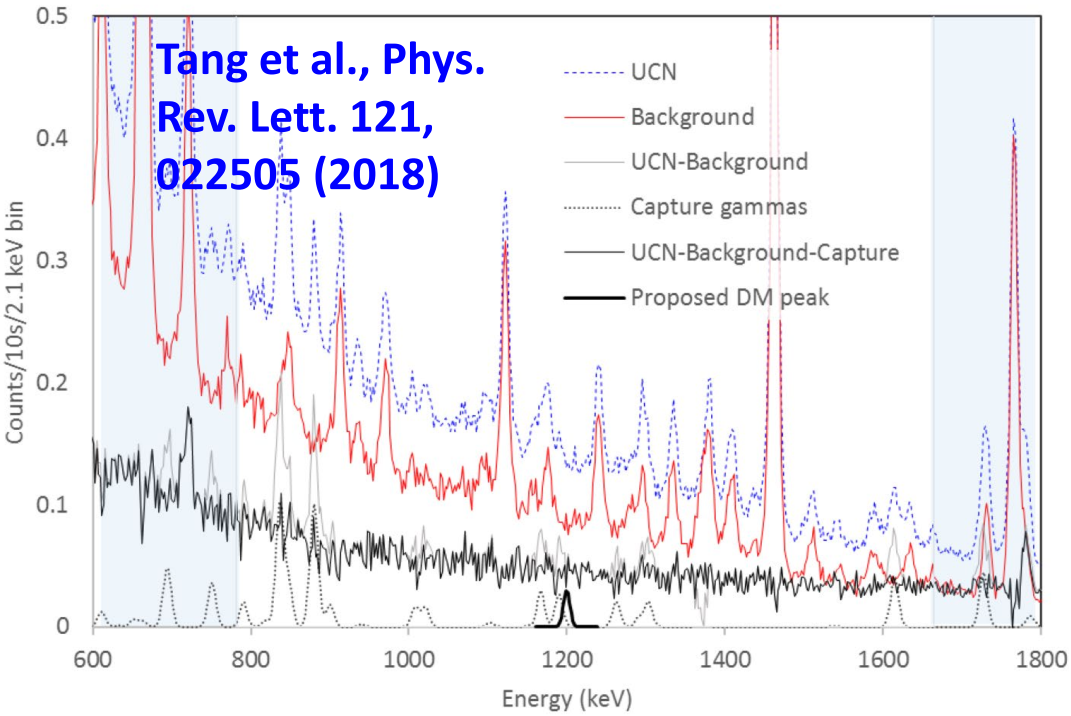
Fornal & Grinstein, Phys. Rev. Lett. 120, 191801 (2018)



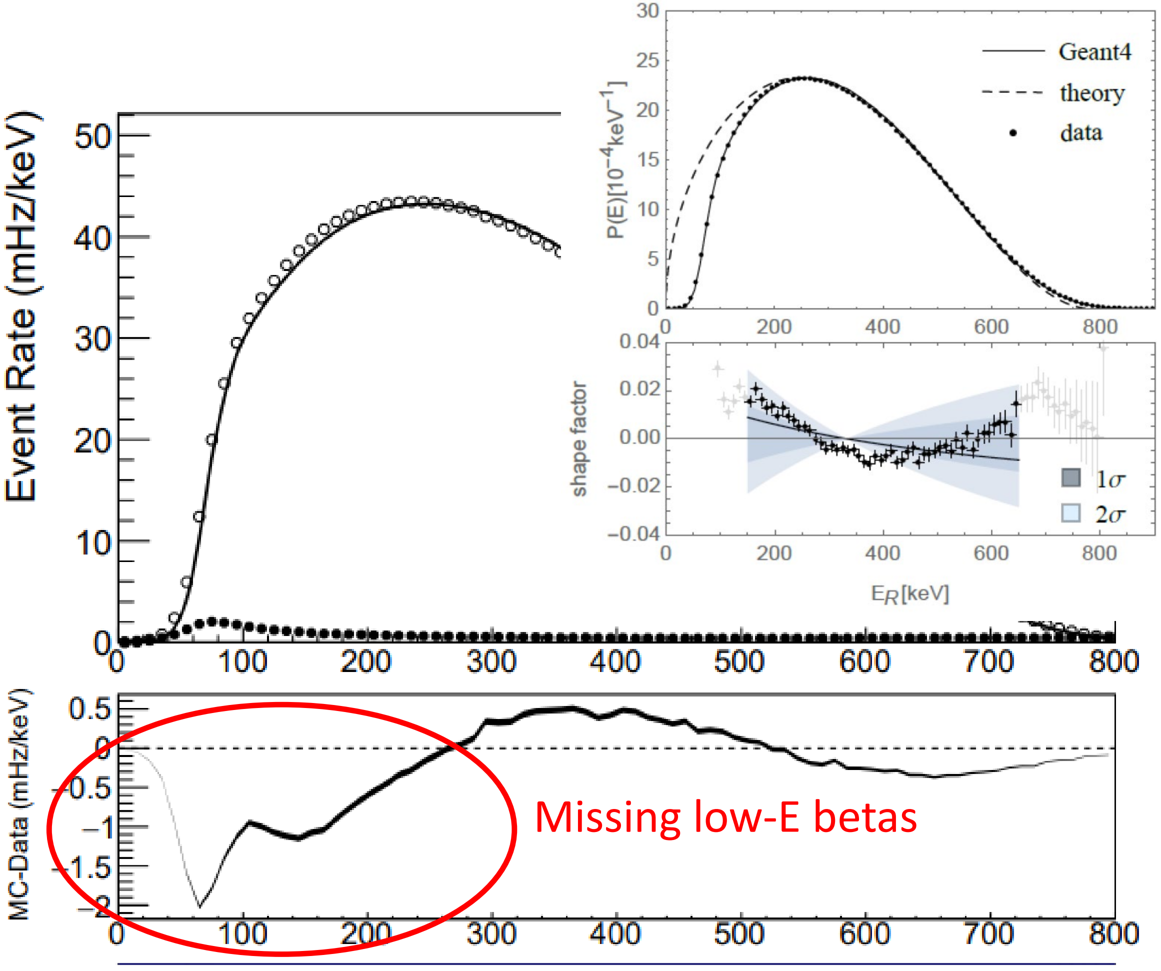
A buffer volume installed (2018) to smooth out the pulse response for more stable normalization.

$$\text{(A) } n \to \chi\gamma$$
$$\text{(B) } n \to \chi e^+e^-$$
$$\text{(C) } n \to \chi\phi.$$

Monochromatic photon in the range of 0.782 MeV - 1.664 MeV, branching fraction 1%.


Tang et al., Phys. Rev. Lett. 121, 022505 (2018)

A possible way to lose protons: Formation of bound-state hydrogen as a final state of beta-decay?



Missing low-E betas

Beta spectrum measured in the UCNA experiment.
Brown et al., Phys. Rev. C 97, 035505 (2018)

Yuri Pokotilovski

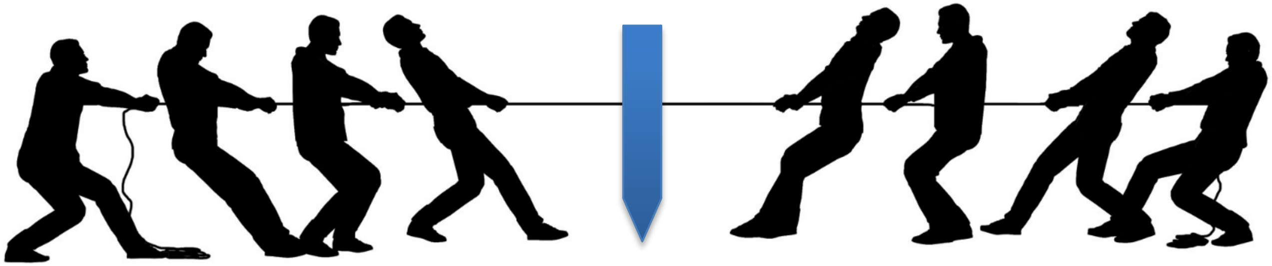
Beta loses energy with bremsstrahlung

If the proton captures the beta, then it will evade the charged particle detection.

Need to revisit the atomic calculations to estimate the probability of bound-state formation, under a high magnetic field (1 T, used in the NIST experiment)

``Bound-state β− decay of the neutron re-examined," A. N. Ivanov, M. Pitschmann, N. I. Troitskaya, and Ya. A. Berdnikov Phys. Rev. C **89**, 055502 (2014)

Beam vs Bottle



PDG value

Measurements better than 10^{-3} are challenging

In UCNtau, we store N_1=25,000 neutrons, and count N_2=6000 neutrons after storing them for t_2-t_1=1000 s.

100 neutrons unaccounted for (due to upscatter, spin flip, or heating) will *decrease* the measured neutron lifetime by 10 s.

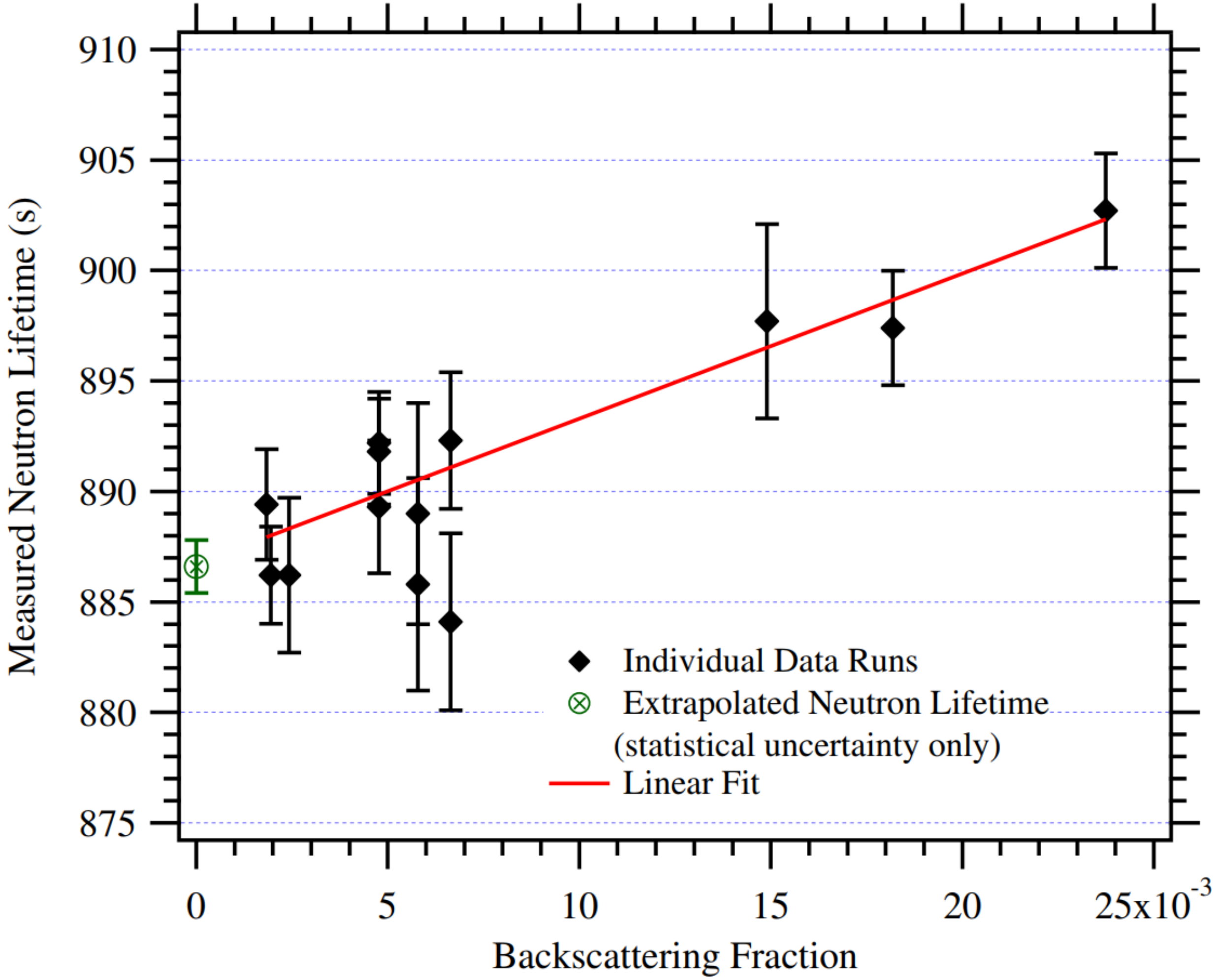
$$\frac{1}{\tau_{mea}} = \frac{1}{\tau_{\beta}} + \frac{1}{\tau_{ab}} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{sf}} + \frac{1}{\tau_{heat}} + \frac{1}{\tau_{qb}} + \ \ldots$$

-

To reach 1 s, we can miss no more than 10 neutrons (per run).
To reach 0.1 s, no more than 1 neutron.

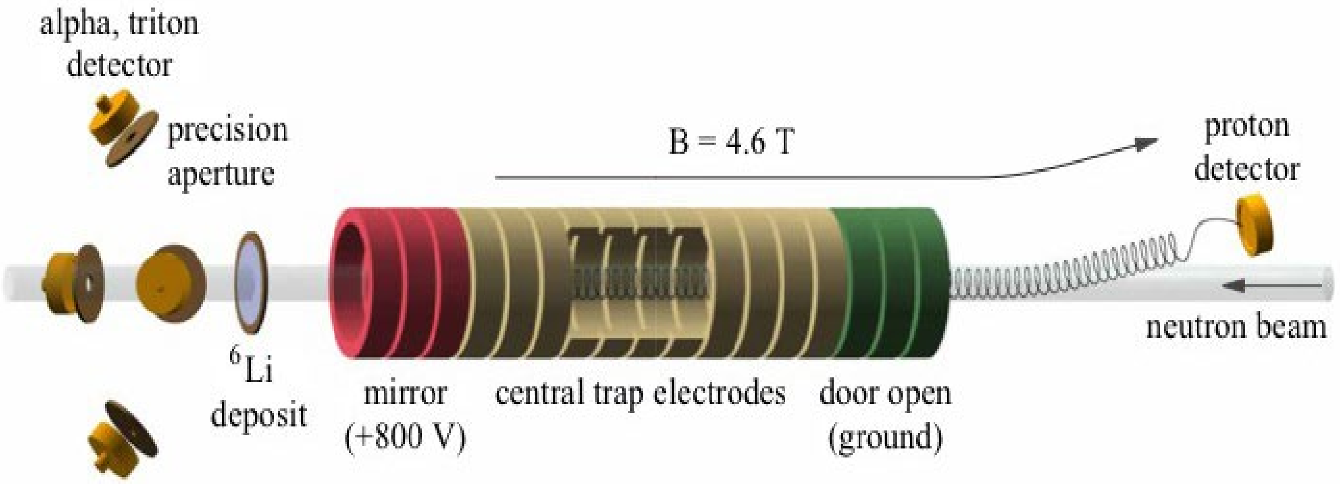
In the beam experiment, underestimate the proton efficiency (storage, transport, detection) by 1 % will *increase* the measured neutron lifetime by 8 s.

BL1: Proton Backscattering Studies



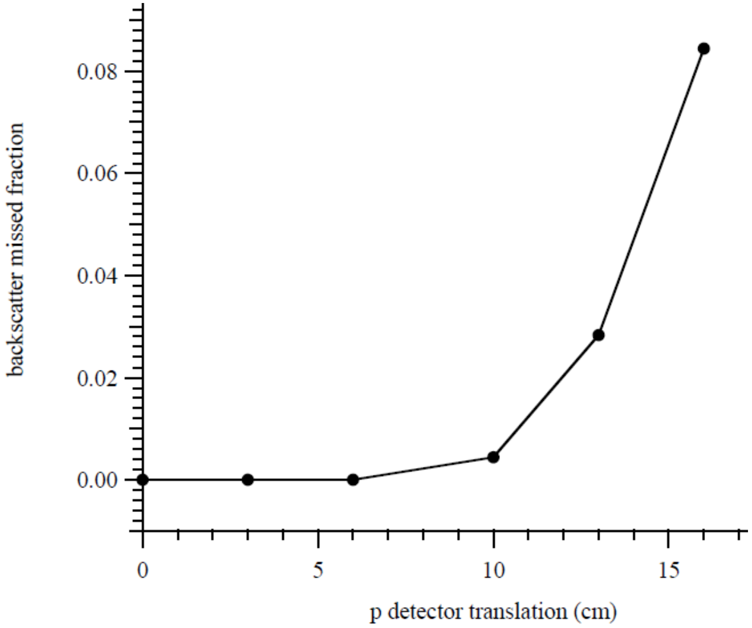
Nico et al., Phys.Rev.C71:055502,2005

Proton Backscattering

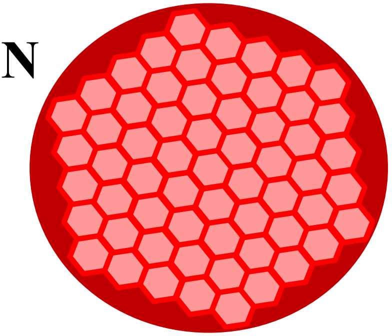


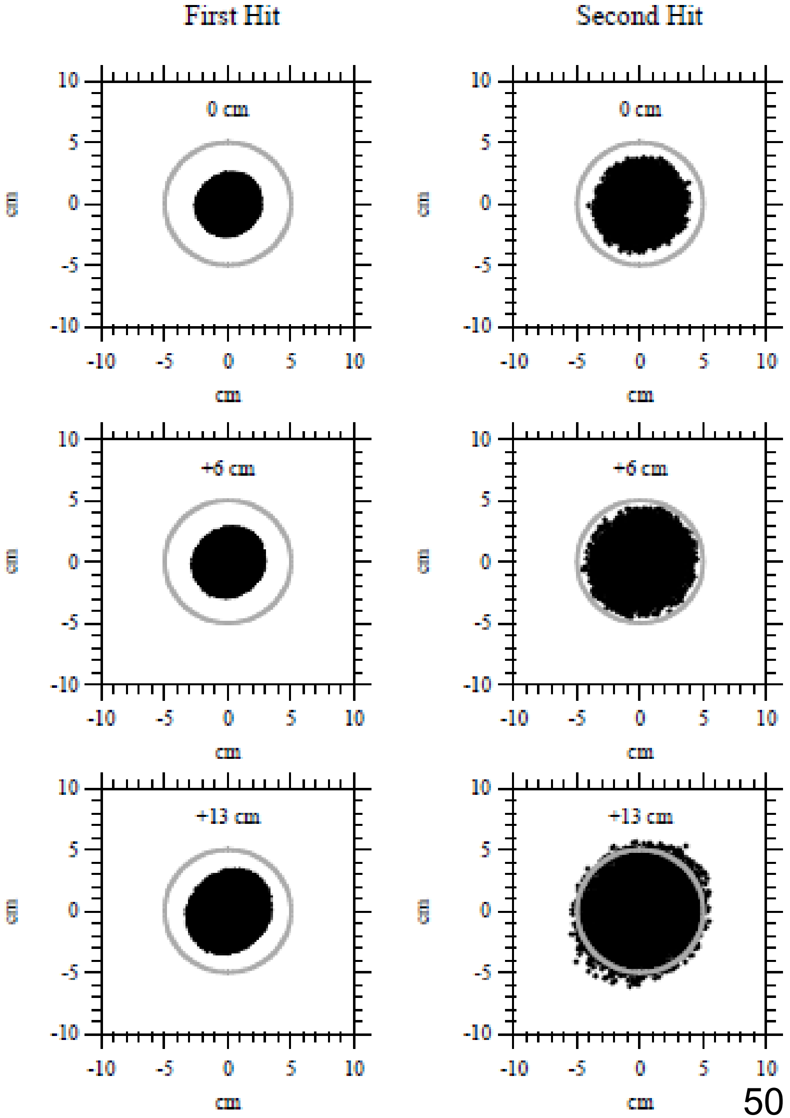
Source of uncertainty	BL1 [s]	BL2 projected [s]	BL3 projected [s]
Proton backscatter calculation	0.4	0.4	< 0.1

Proton Backscattering



Nab/UNCB/KATRIN style pixelated proton detector





Model by F. Wietfeldt

Ongoing efforts of n lifetime experiments

Experiment	**Methods**	**Status**	**Current sensitivity**		**Projected sensitivity (s)**
			Stat (s)	Sys (s)	
BL @ NIST	Beam	BL2: Data-taking	1.2	1.9	1
		BL3: R&D	-	-	0.3
JParc	Beam	Data-taking	4.4	+7.6/-8.6	1
Gravitrap	Bottle-material	Data-taking	0.7	0.6	
UCNtau	Bottle-magnetic (perm. Magnets)	Data-taking	0.7	+0.3/-0.1	0.2
		tau2: conceptual	-	-	< 0.1
Hope	Bottle-magnetic (Perm. Magnets)	UCN Source R&D Trap commissioned	39		0.7
Ezhov	Bottle-magnetic (perm. Magnets)	Data-taking finished; Large trap upgrade	1.6	1.0	0.2
Penelope	Bottle-magnetic (superconducting magnets)	R&D	-	-	0.1
UCNProBe	Beam w/ UCN	R&D	-	-	3

UCNProBe: measures the proton branching ratio

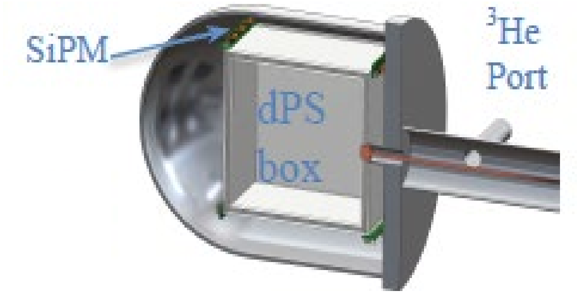
Zhaowen Tang et al

- Ultra-Cold Neutron Experiment for Proton Branching Ratio in Neutron Beta Decay (UCNProBe)
- Aims to understand the discrepancy between the beam and the bottle lifetime experiments; precision goal: sub %.
- Need to measure the neutron density and the number of decays absolutely
- Two methods for measuring the number of decays:
  - Protons
  - Electrons
- Required to know the efficiencies of the neutron detector and the decay product detector to ~0.1% level
- We are currently scoping out different experiment ideas

UCNProBe Experimental Concept

Measure τ_β using UCNs

- if $\tau_\beta = \tau_n$(from Bottle), then unaccounted systematic error in beam method
- $\tau_\beta > \tau_n$, then possible new physics



Requires absolute measurements of two quantities

- Number of neutrons in the trap
- Number of neutrons that decayed (measurement of charged particles)

Charged particle detection

- Electron (Using deuterated polystyrene (dPS) as a UCN trap and detector)
- dPS scintillator (Eljen 299-2D) potential measured at 168 neV

Neutron detection

- UCN capture on ^{3}He gas

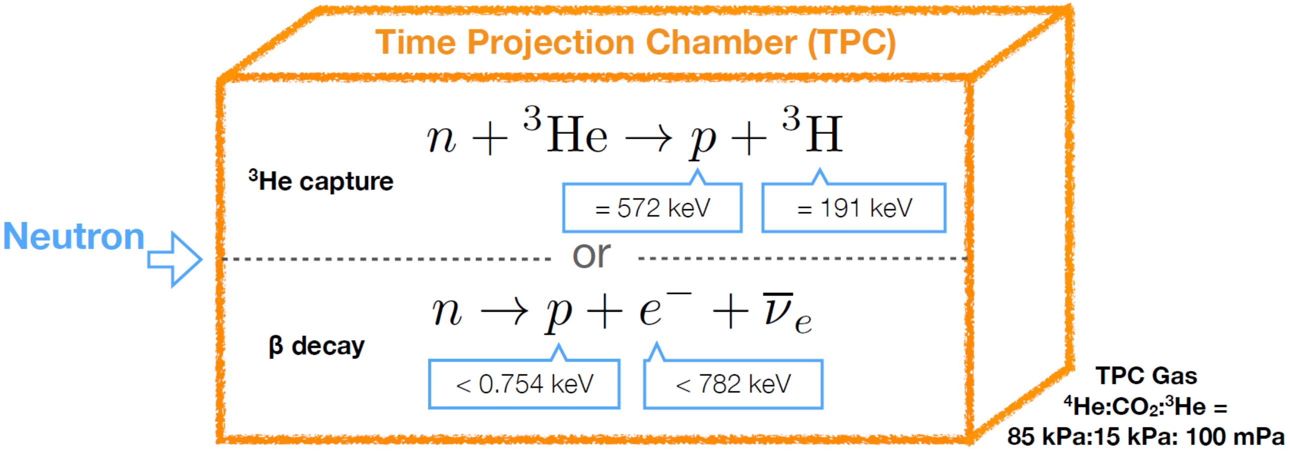
Jparc Beam Experiment

The method of neutron lifetime measurement

- **Electron-Counting method**
  Neutron lifetime is obtained from neutron β decay and flux (^{3}He capture).

$$\tau_n = \frac{1}{\rho \sigma v}\left(\frac{S_{\mathrm{He}}/\varepsilon_{\mathrm{He}}}{S_\beta/\varepsilon_\beta}\right)$$

τ_n	Neutron Lifetime		
ρ	^{3}He density (Blind)	S_β	Number of β decay signal
σ	^{3}He neutron capture cross section	S_{He}	Number of ^{3}He capture signal
v	Neutron velocity	ε	Cut efficiency



Time Projection Chamber (TPC)

Neutron

^{3}He capture

$$n + {}^3\mathrm{He} \rightarrow p + {}^3\mathrm{H}$$

= 572 keV

= 191 keV

or

β decay

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

< 0.754 keV

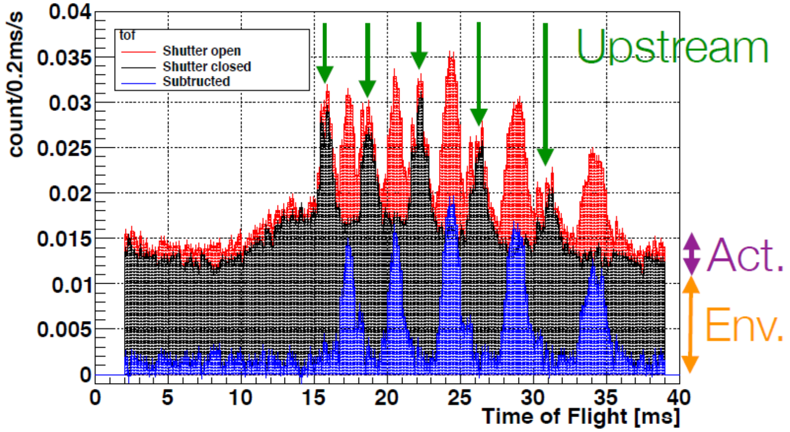
< 782 keV

TPC Gas
^{4}He:CO$_2$:^{3}He =
85 kPa:15 kPa: 100 mPa

First result : O(10) sec accuracy

⇒ Final goal : 1 sec accuracy

Background against beta decay

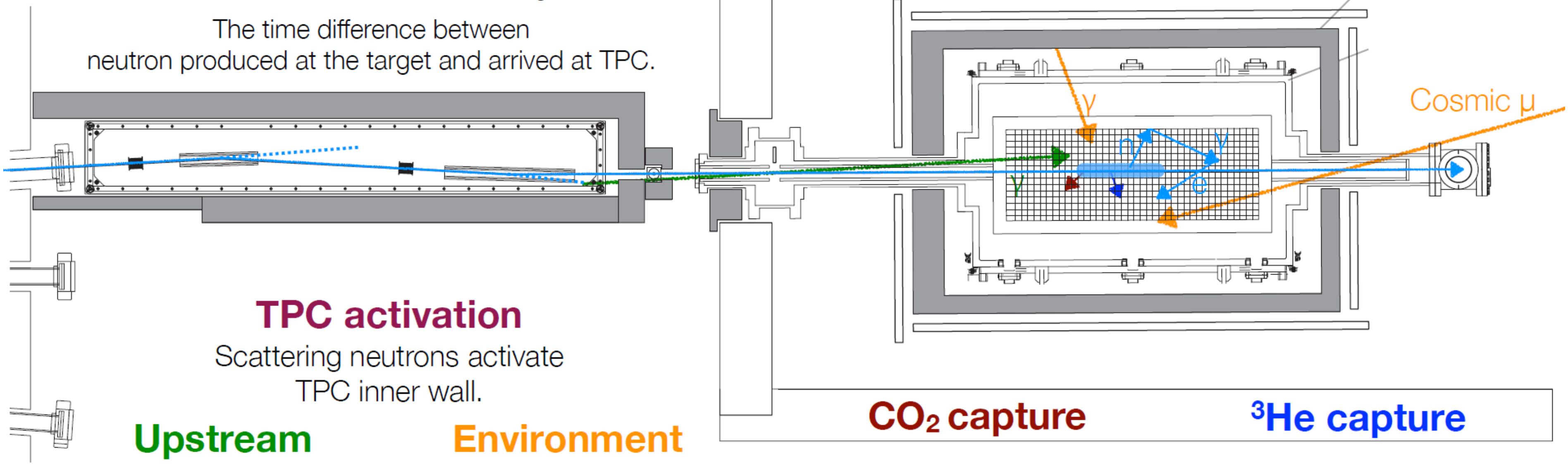


The time difference between
neutron produced at the target and arrived at TPC.

Cut & Simulation

Gas induced

Neutrons produce γ rays
in the TPC gas.



TPC activation

Scattering neutrons activate
TPC inner wall.

Upstream

γ rays from SFC
produce electrons in the TPC
via Compton scattering

Environment

Cosmic rays
Radioisotopes
in the shields

CO_2 capture

^{3}He capture

$$^{3}\mathrm{He} + n \rightarrow t + p + 764\ \mathrm{keV}$$

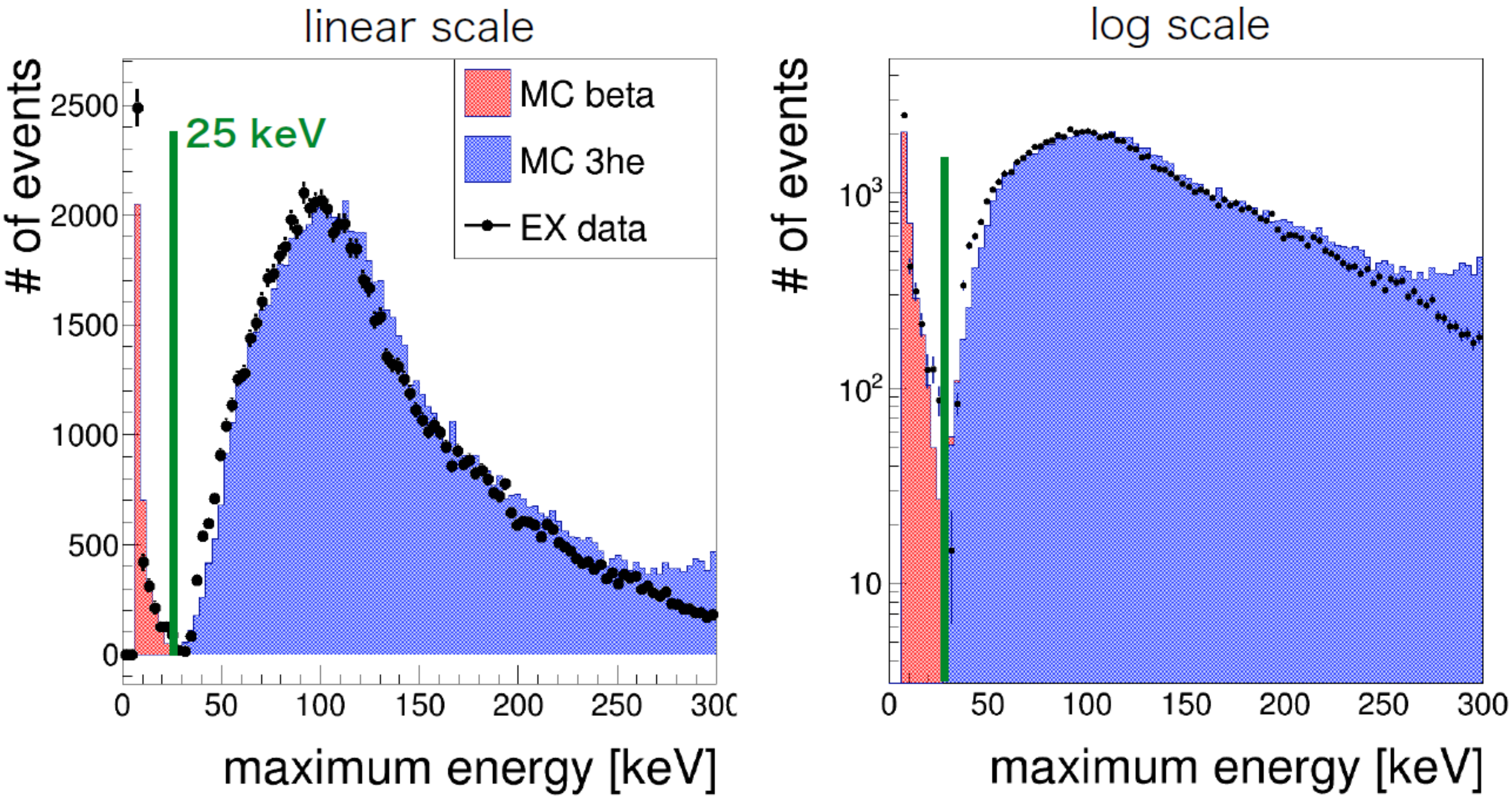
$$^{12}\mathrm{C} + \mathrm{n} \rightarrow ^{13}\mathrm{C}(1\,\mathrm{keV}) + \gamma$$

Time of Flight

Energy and Range cut

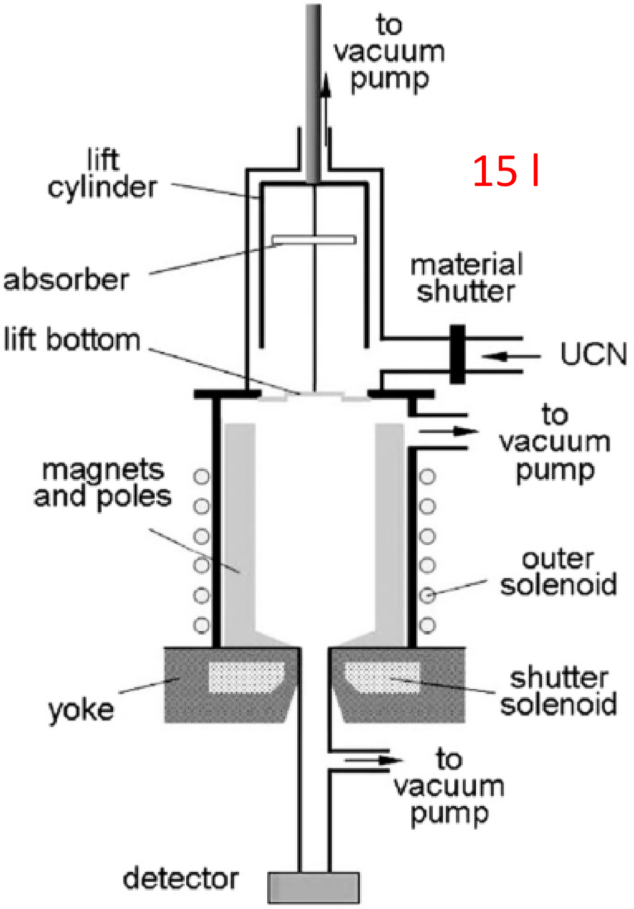
Separation of β decay and ^{3}He(n, p)^{3}H

two kinds of signal events (β **decay** and **^{3}H(n, p)^{3}H**) in the TPC can be separated by **maximum energy deposit among all wires**



Magnetic Bottles

(proton detection)



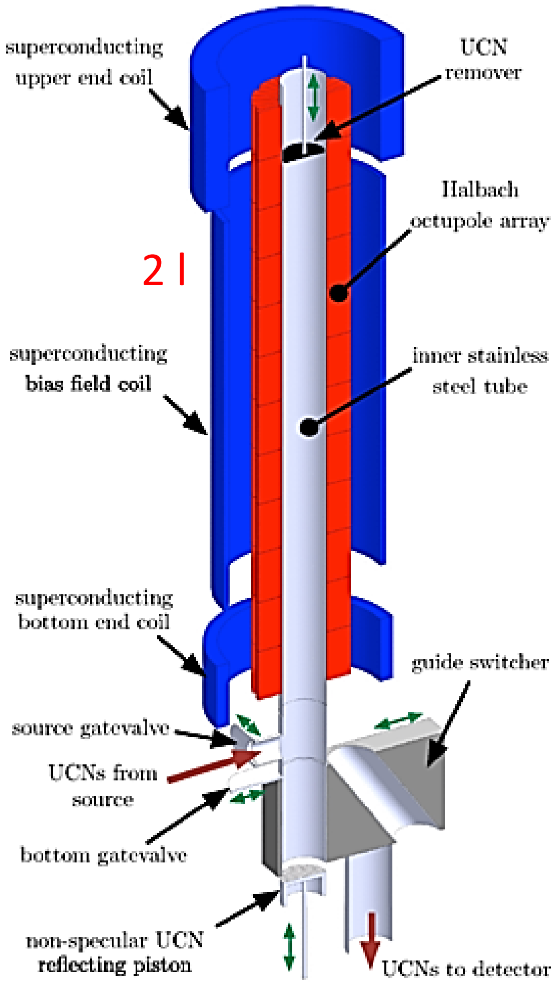
15 l

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

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

HOPE

2 l



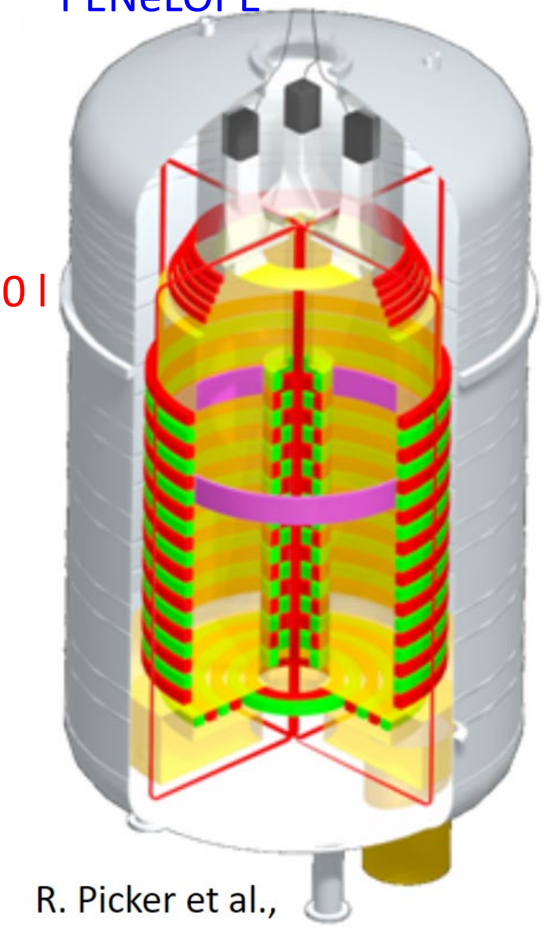
$\tau_n = (887 \pm 39)$s

Leung, et al, PRC **94**, 045502 (2016)

PENeLOPE

TU Munich

700 l



R. Picker et al.,

J. Res. NIST 110 (2005) 357

$\rho_{UCN} = 10^3 - 10^4$ cm^{-3} (FRM II)

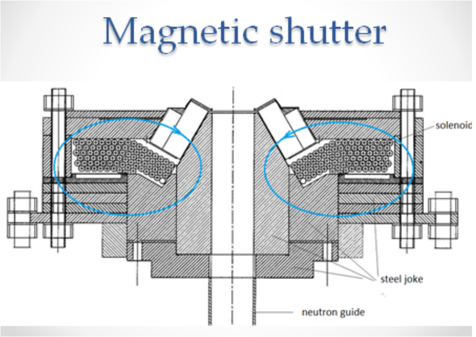
$N_{stored} = 10^7 - 10^8$

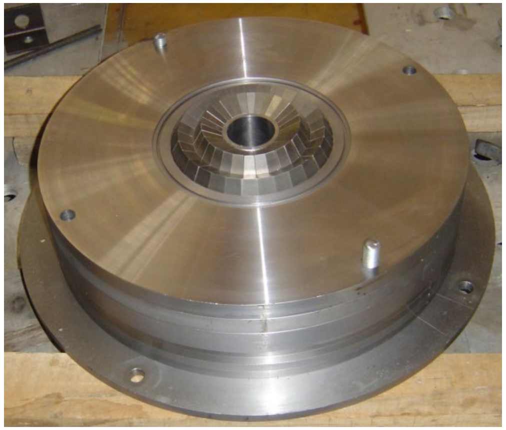
Statistical $\delta\tau_n$ ~ 0.1 s in 2-4 days

V.F. Ezhov et. al. *JETP Letters, 2018, Vol. 107, No. 11, pp. 671–675*

- $\tau_n = (878.3 \pm 1.6 \pm 1.0)$ s

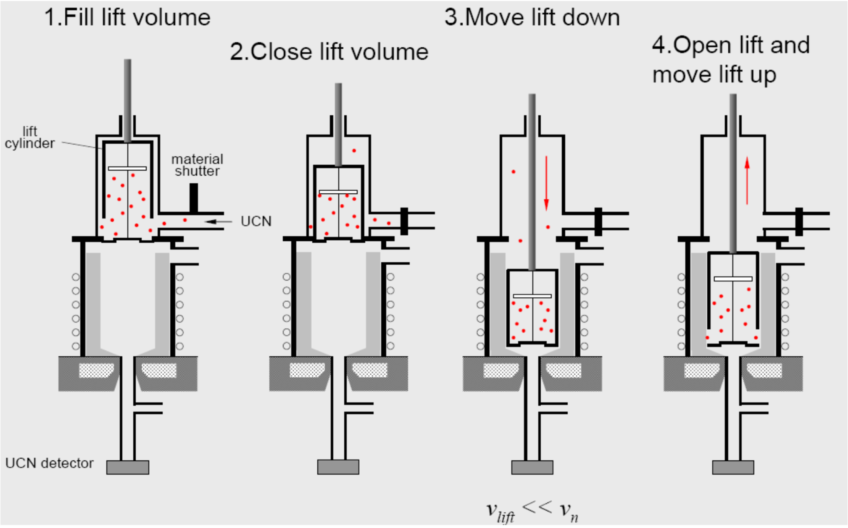
Magnetic shutter in lower part of trap permits to collect depolarized UCN during storage time





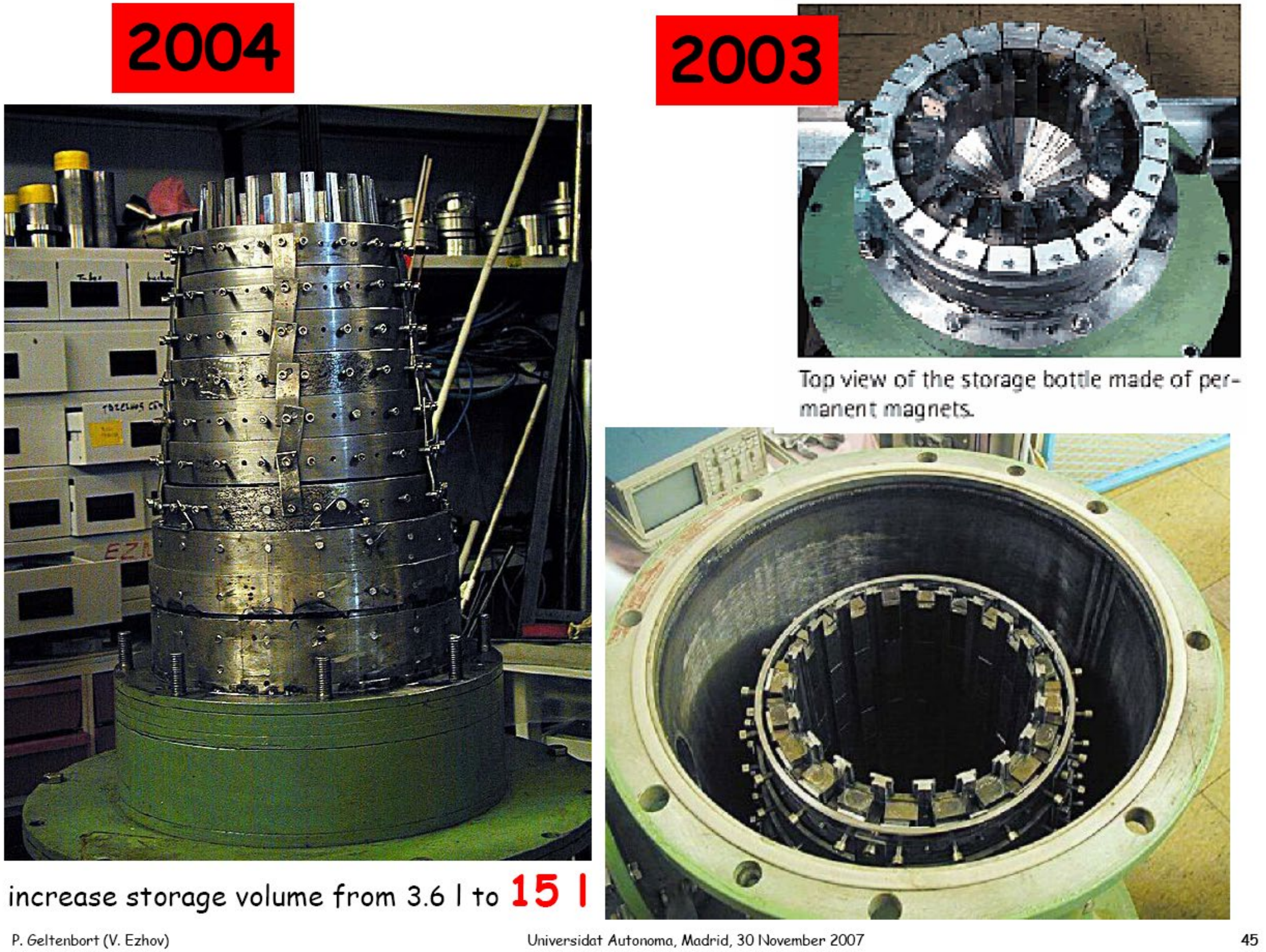
V.F. Ezhov, et al, Technical Physics Letters, Vol. 44, No. 7, pp. 602–604, 2018.

Trap is filled using elevator in upper part of trap. There are an absorber inside elevator for preliminary preparation of UCN spectrum. Final cleaning proceeds inside the trap throw magnetic shutter in lower part of trap



Trap is filled with unpolarized UCN. In this case half of neutrons are leaking during trap filling and they will be detected just during the filling. So before each run real quantity of UCN in trap is measured.

UCN Lifetime Experiment at the ILL



2004

2003

Top view of the storage bottle made of permanent magnets.

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

P. Geltenbort (V. Ezhov)

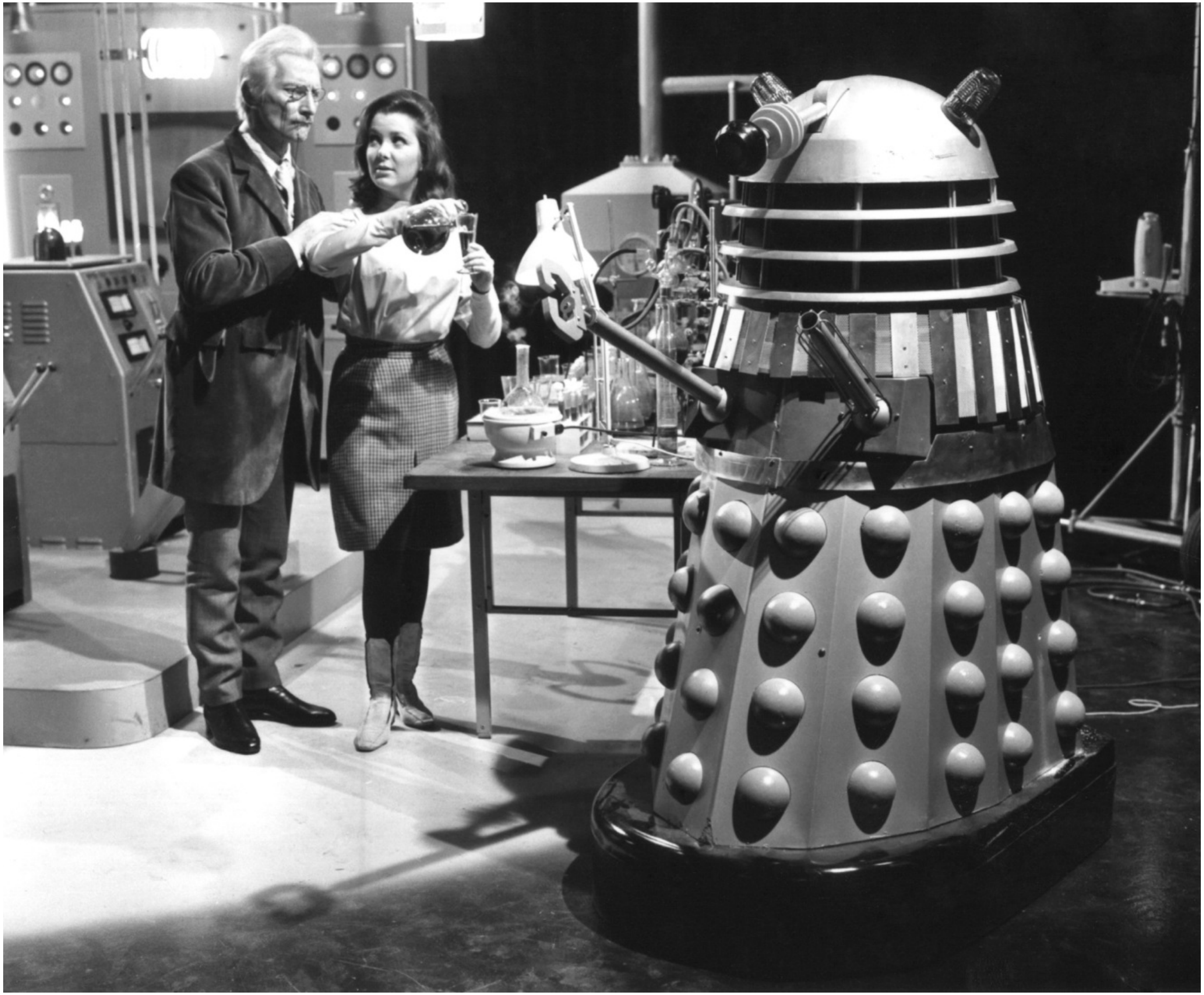
Universidat Autonoma, Madrid, 30 November 2007

45

- Neutrons from the ILL turbine.
- Trapped with permanent magnets and gravity.
- Surviving neutrons counted.

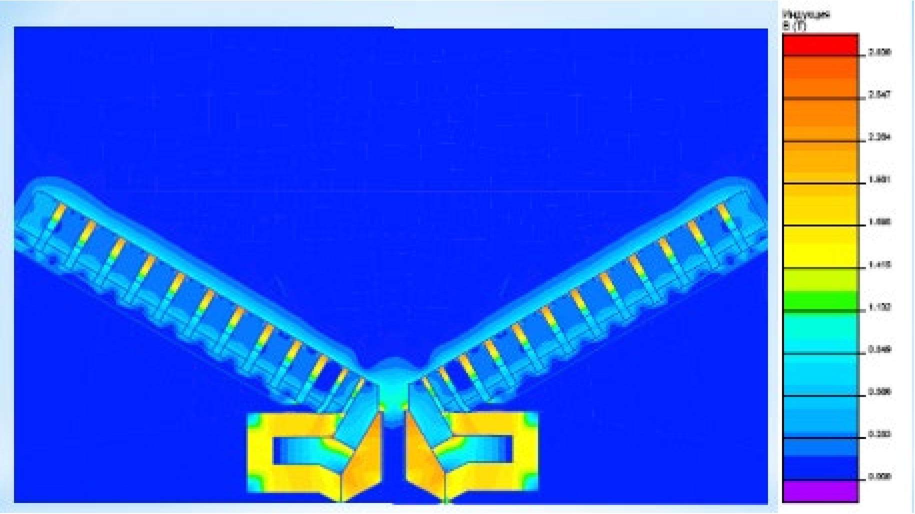
Analysis unpublished

V. Ezhov *et al.*, J. Res. NIST 110 (2005) 345



Dr. Who, an assistant, and a captured Dalek

New trap under construction



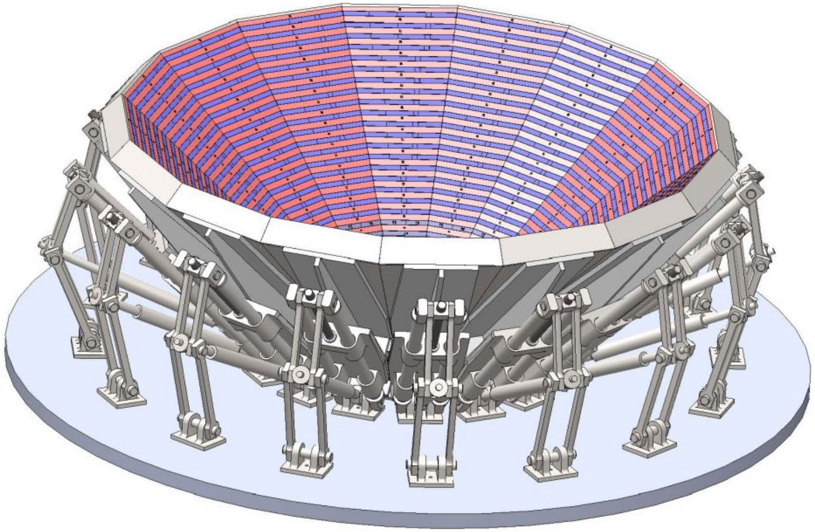
Calculated map of magnetic field for a new trap

B. A. Bazarov et al, Technical Physics Letters 42(7), 663-666, (2016)

Increasing of volume is about 15 times

Increasing of stored UCN energy in 2 times

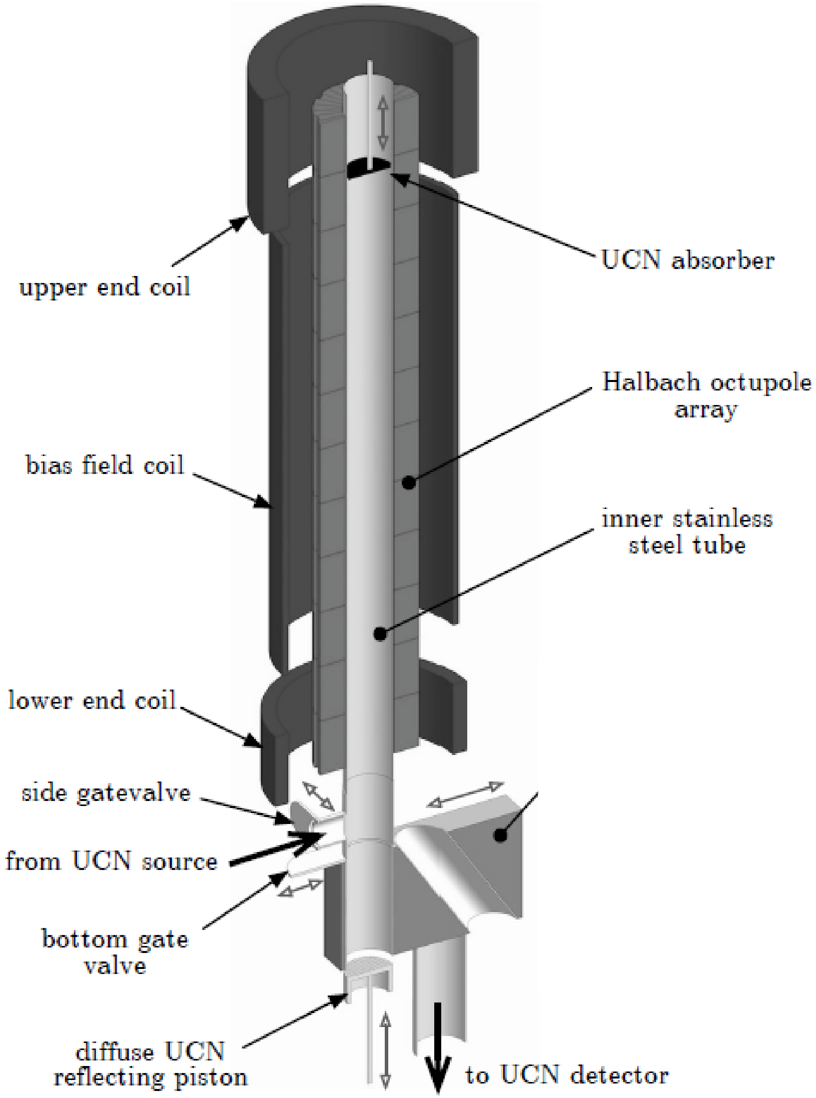
Waited accuracy about 0.2 s.



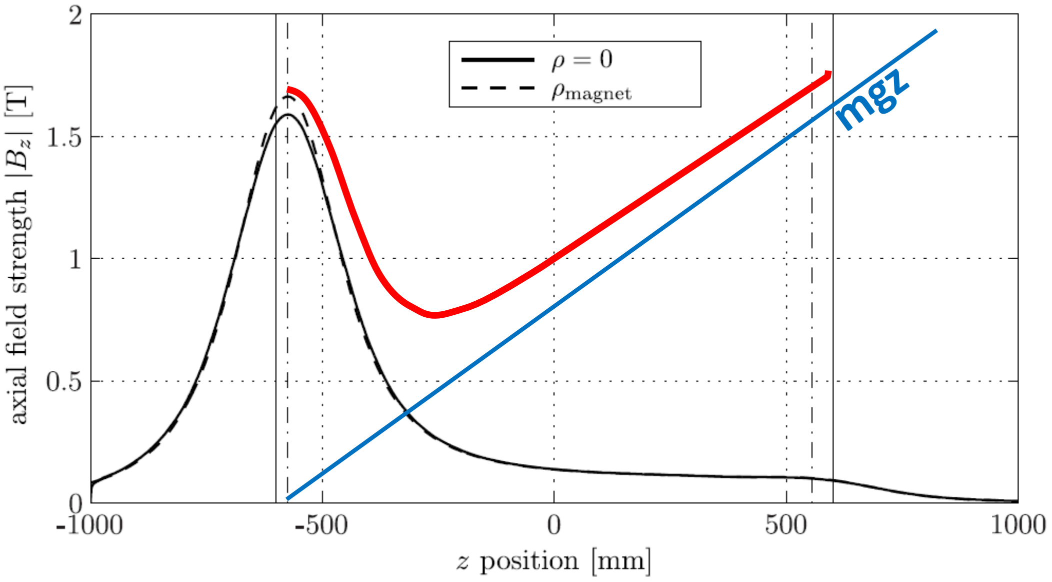
System for new trap filling in ILL

HOPE – Halbach OctuPole neutron lifetime Experiment

Ph.D. theses: **Felix Rosenau, Fabien Lafont, Loris Babin, Kent Leung**



- magneto-gravitational trap
- $V_{\text{eff}} \approx 2$ l
- trap depth 47 neV
- high-density UCN source
- counting the dead & survivors



Experiments?

Start with well established
“fill and empty” method

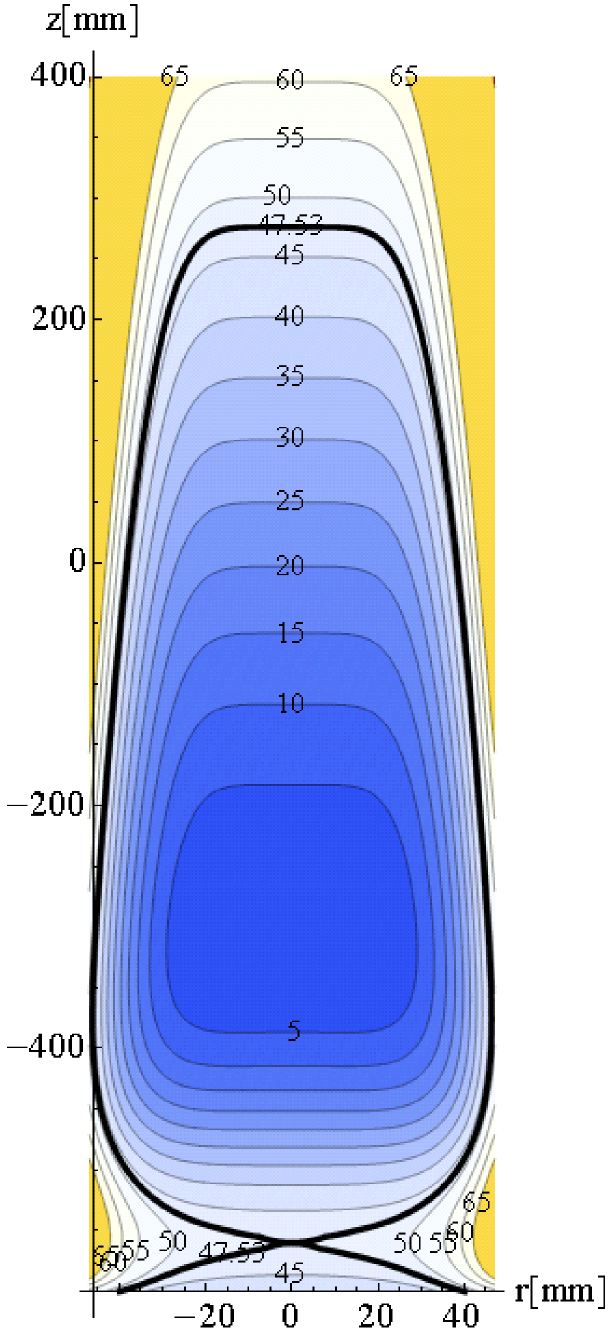
Full-bore access from top and bottom:

- insertion of diffusive paddle and absorber
- monitoring of depolarisation
- detection of marginally trapped neutrons

Couple experiment to superfluid-helium
UCN source **SUN-2** at ILL
(pessimistic estimate: 3000 UCN/fill)

$\delta\tau_n$ **~ 0.7 s in 50 days** (statistical)

Experiments @ PF2 performed in fall 2014
Experiments @ SUN-2 in preparation **L. Babin**

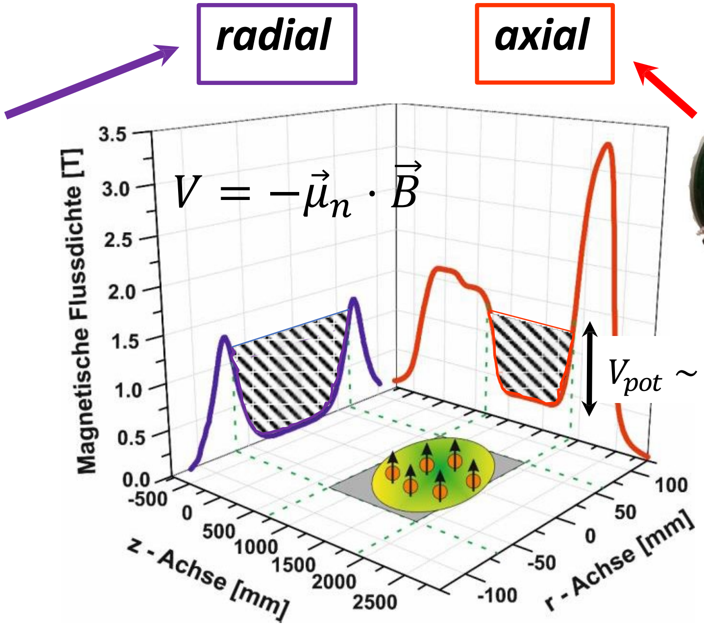


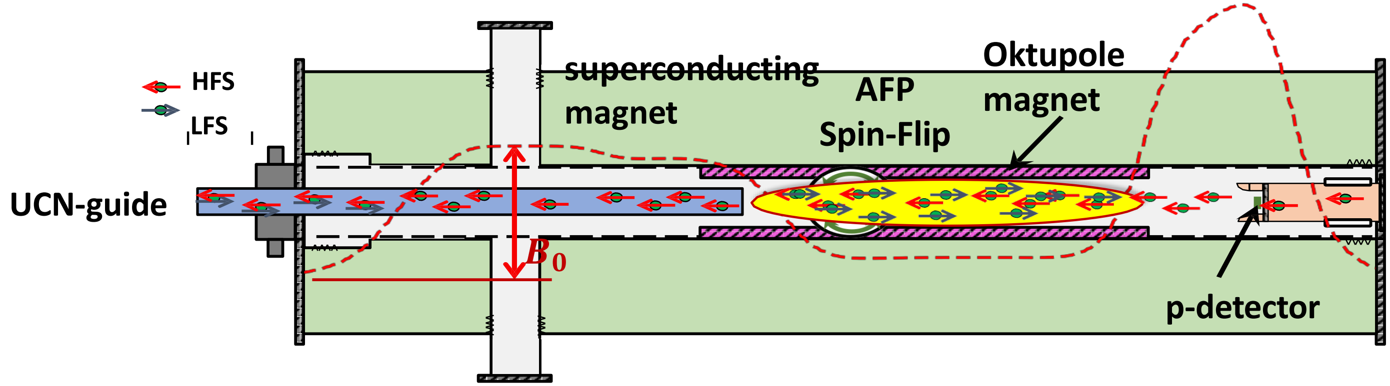
Neutron lifetime in magnetic trap - $\tau SPECT$

Octupole magnet
Halbach-configuration

permanent magnets Sm_2Co_{17}

aSPECT superconducting magnet (see later)

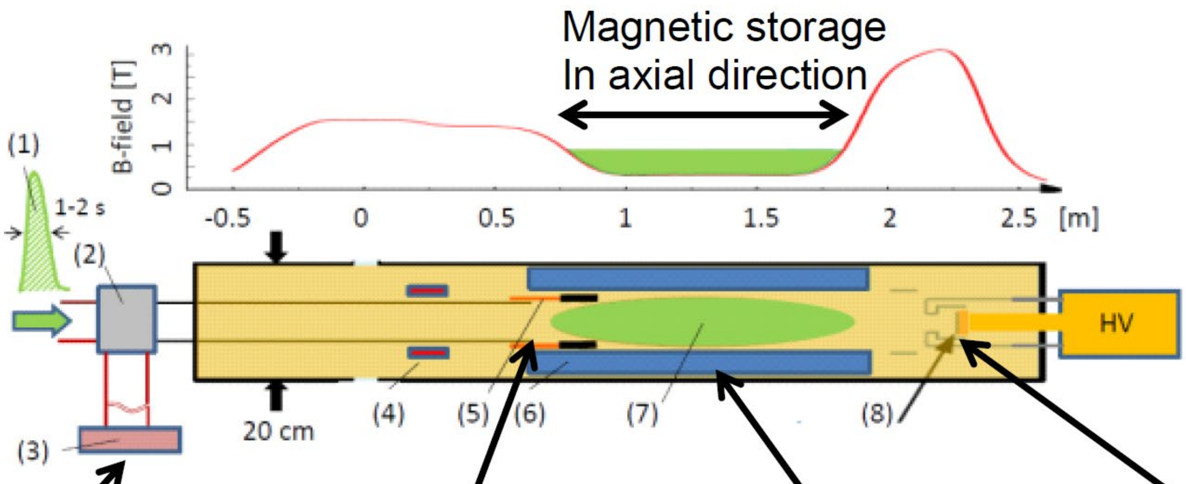


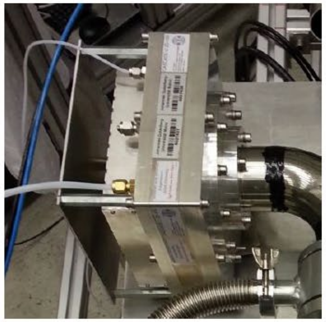


Goal:
$\Delta\tau_n \leq 2$ s (soon)
$\Delta\tau_n \leq 0.3$ s (2023?)

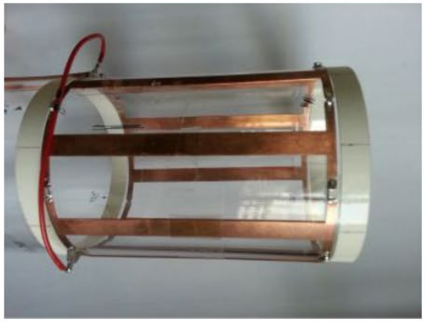
τSPECT principle

Talk by Marcus Beck

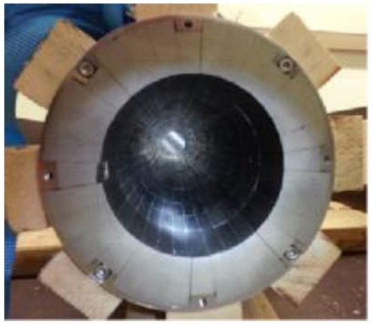




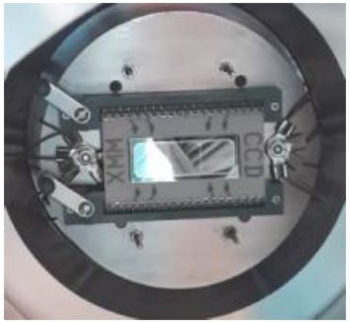
CASCADE detector for neutron detection



AFP spin flipper



Magnetic octupole for radial storage

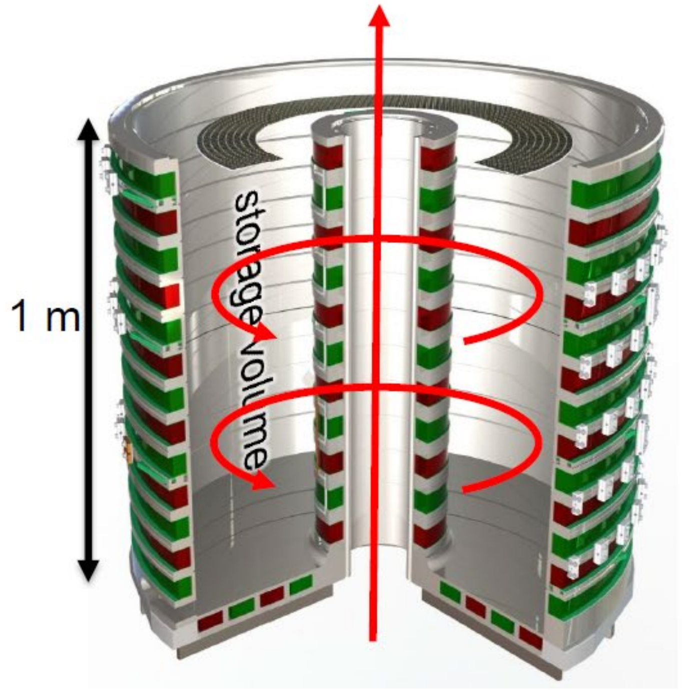


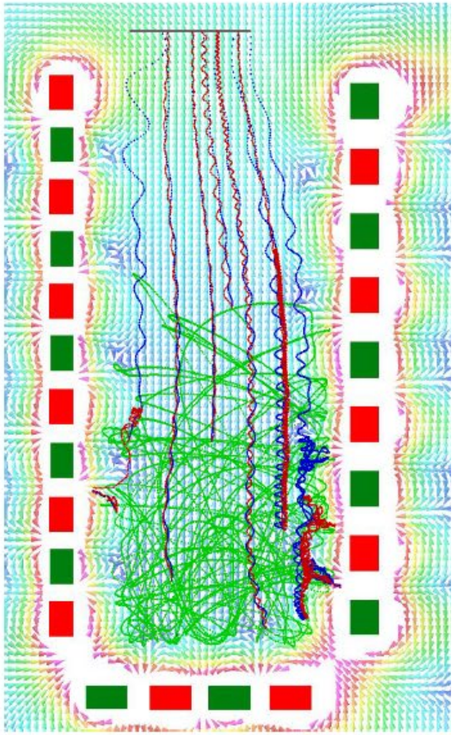
SDD for decay proton detection

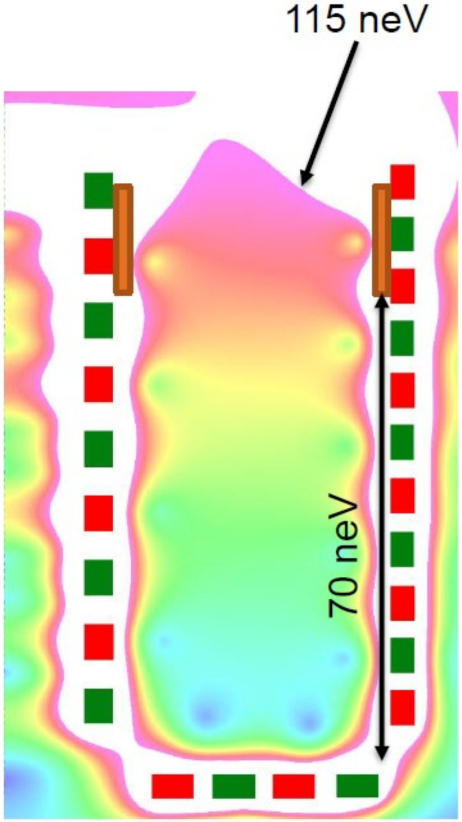
PENeLOPE

Precision Experiment on Neutron Lifetime Operating with Proton Extraction

- n lifetime measurement ± 0.1 s
- Magneto-gravitational trap for UCN
- On-line proton detection







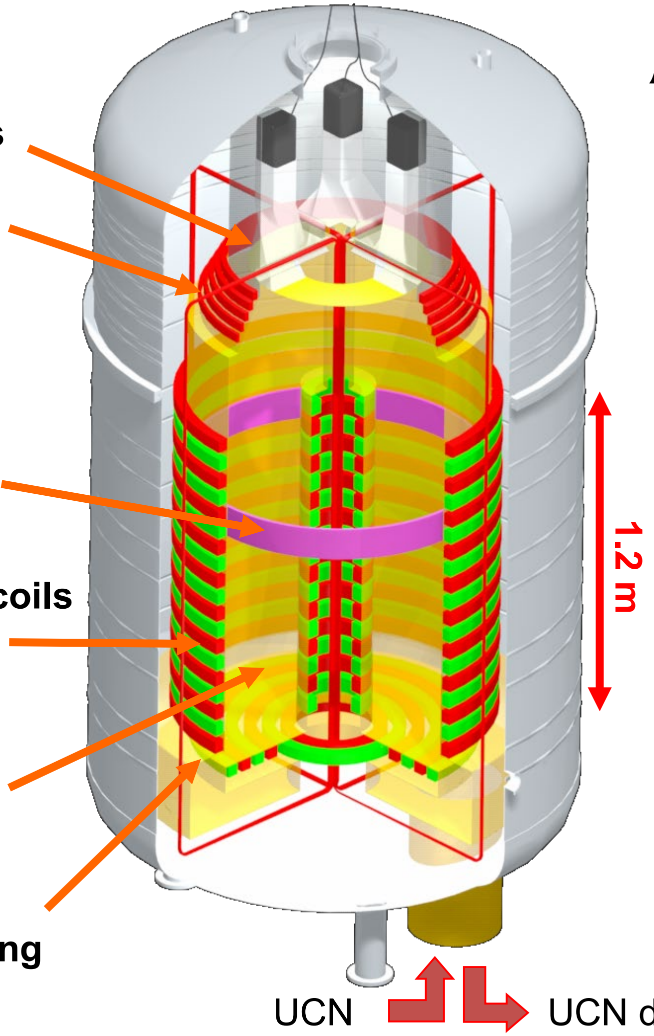
Proposed large volume magnetic storage experiment

$$N(t) = N(t_0)\exp\left(-\frac{t}{\tau_\mathrm{n}}\right)$$

PENeLOPE

Magnetic storage of UCN & proton extraction

S. Paul et al.



proton detectors

focusing coils

neutron absorber

superconducting coils
$B \approx 2$ T (at wall)

volume ~ 700 l

slit for filling

UCN

UCN detector

$\rho_\mathrm{UCN} = 10^3 – 10^4\ \mathrm{cm}^{-3}$ (PSI /FRM II):

$N_\mathrm{stored} = 10^7 – 10^8$

- **Statistical accuracy:**

  $\delta\tau_\mathrm{n}$ ~ 0.1 s in 2-4 days

- **Systematics:**
  - **Spin flips negligible (simulation)**
  - **use different values B_max to check expected E_UCN independence of τ**

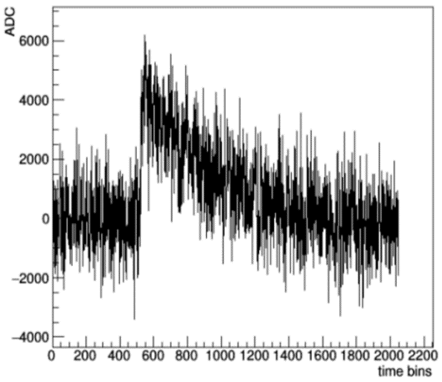
R. Picker et al., J. Res. NIST 110 (2005) 357

BL2 experiment is running now at NIST.

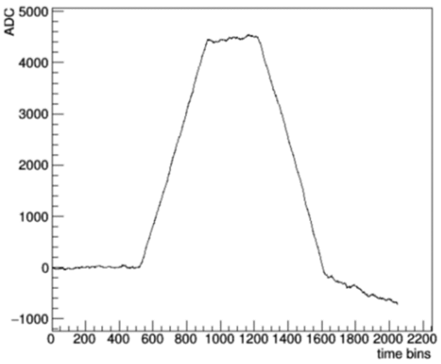
Trapezoid Filter Analysis

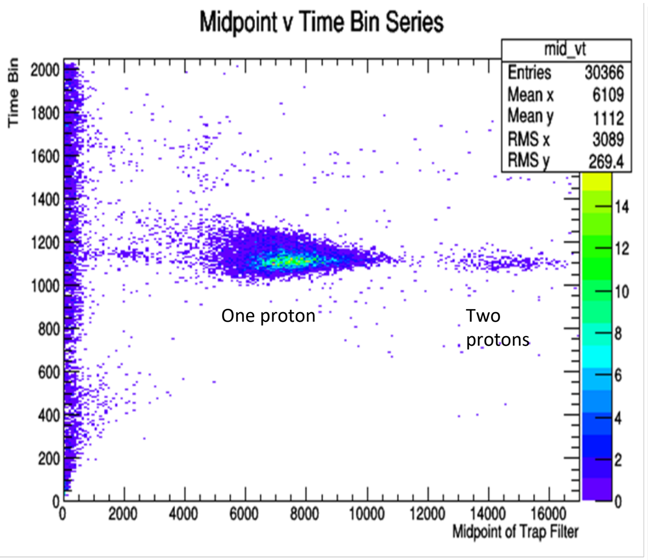
- Uses a convolution for pulse shape discrimination
- Retains information from the original pulse
- Able to identify multiple proton events

Preamp pulse



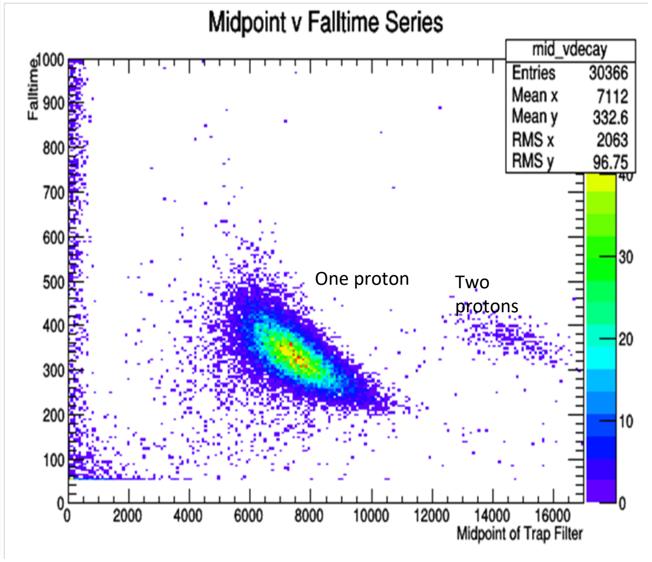
Trapezoid filter output





One proton

Two protons



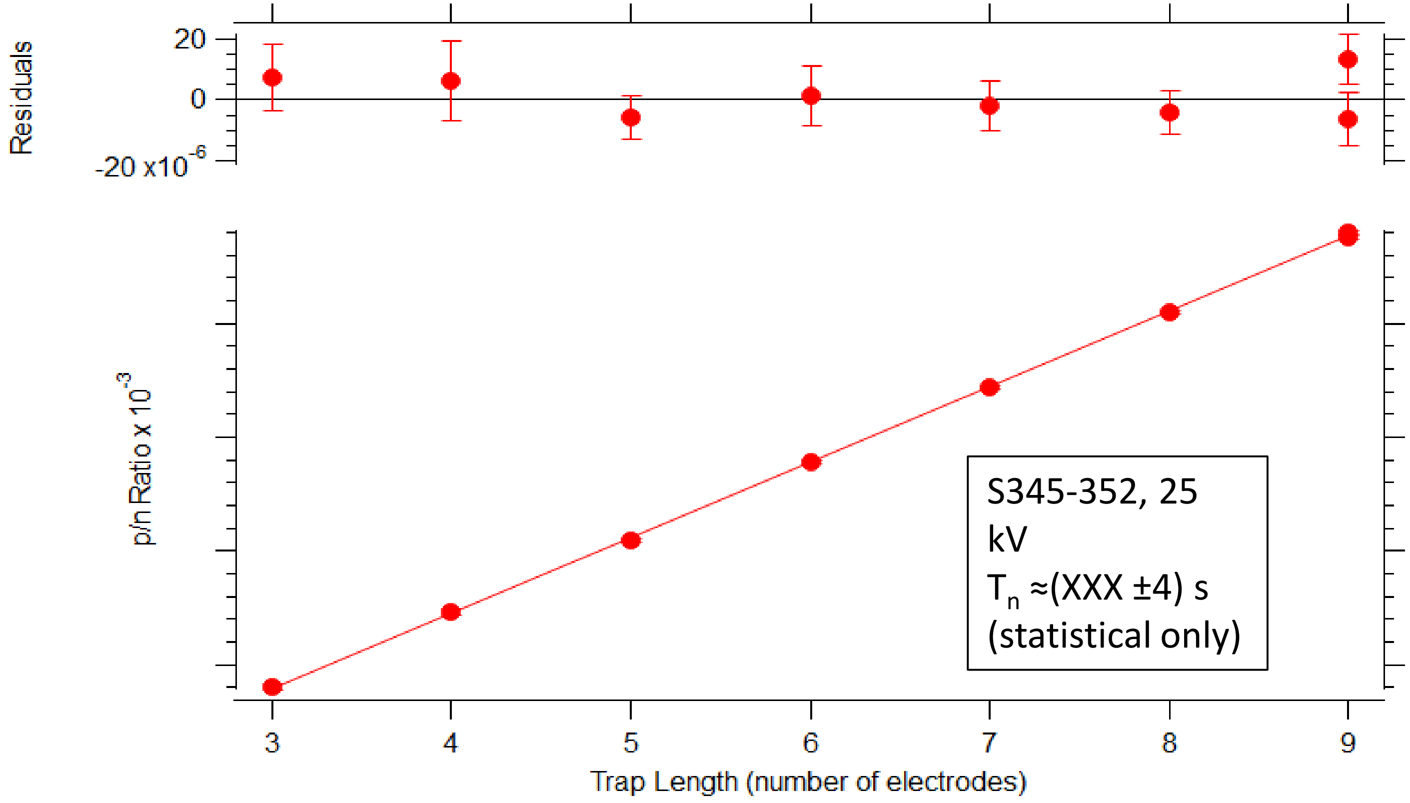
One proton

Two protons

From Jimmy Caylor

Lifetime fit example

$$\frac{\dot{N}_p}{\dot{N}_n} = \tau_n^{-1}\left(\frac{\epsilon_p}{\epsilon_o}\right)(nl + L_{end})$$



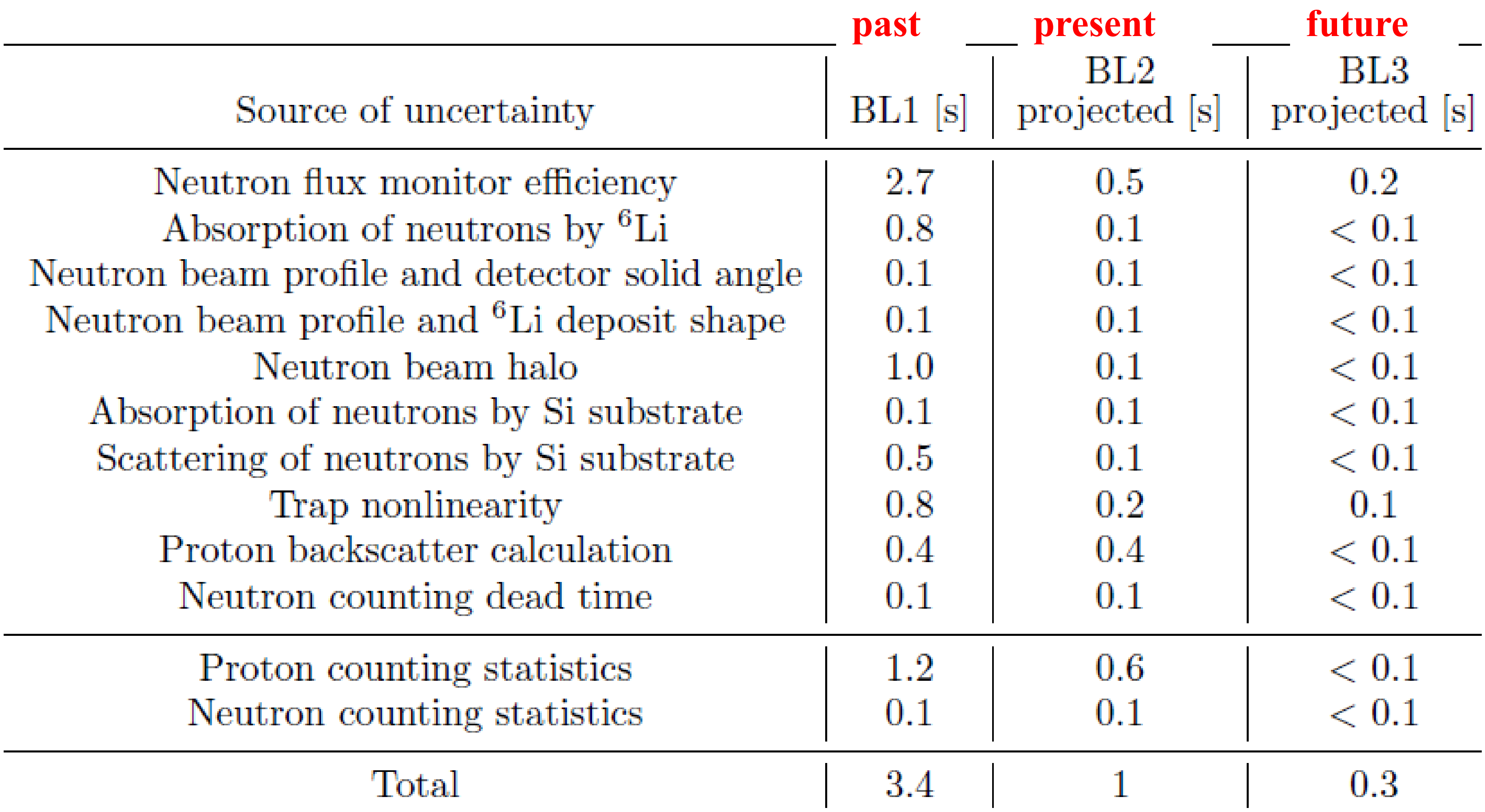
S345-352, 25 kV

T_n ≈(XXX ±4) s

(statistical only)

From Jimmy Caylor

Critical Improvements over previous measurements



	past	**present**	**future**
Source of uncertainty	BL1 [s]	BL2 projected [s]	BL3 projected [s]
Neutron flux monitor efficiency	2.7	0.5	0.2
Absorption of neutrons by ^{6}Li	0.8	0.1	< 0.1
Neutron beam profile and detector solid angle	0.1	0.1	< 0.1
Neutron beam profile and ^{6}Li deposit shape	0.1	0.1	< 0.1
Neutron beam halo	1.0	0.1	< 0.1
Absorption of neutrons by Si substrate	0.1	0.1	< 0.1
Scattering of neutrons by Si substrate	0.5	0.1	< 0.1
Trap nonlinearity	0.8	0.2	0.1
Proton backscatter calculation	0.4	0.4	< 0.1
Neutron counting dead time	0.1	0.1	< 0.1
Proton counting statistics	1.2	0.6	< 0.1
Neutron counting statistics	0.1	0.1	< 0.1
Total	3.4	1	0.3

BL3: Bigger!

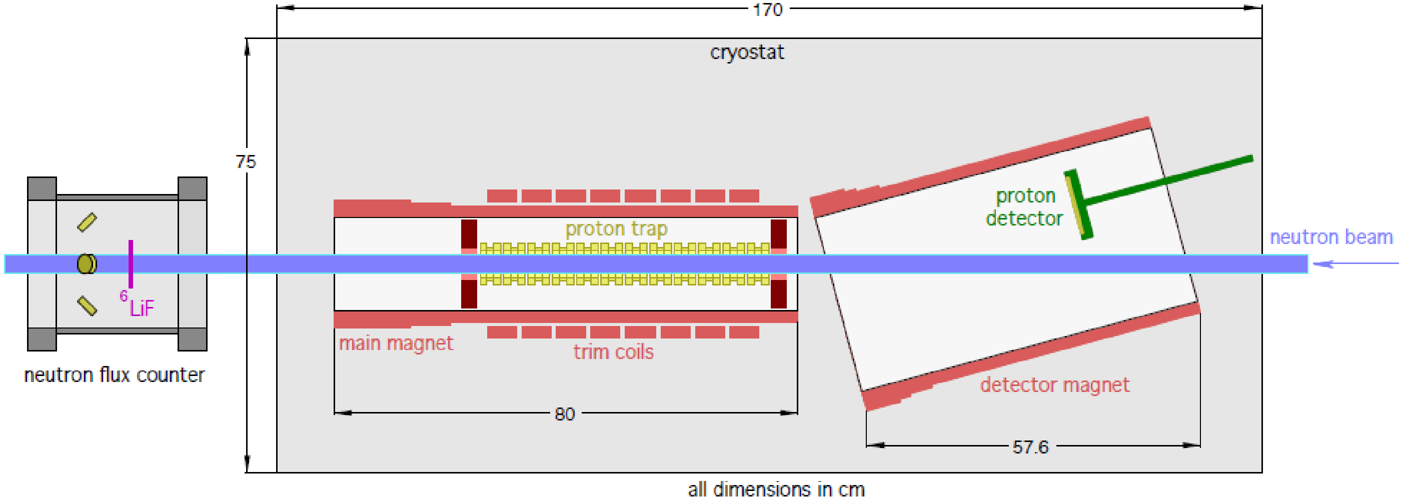
- Increased neutron beam diameter

  7 mm → 35 mm

- Uniformity requirements:

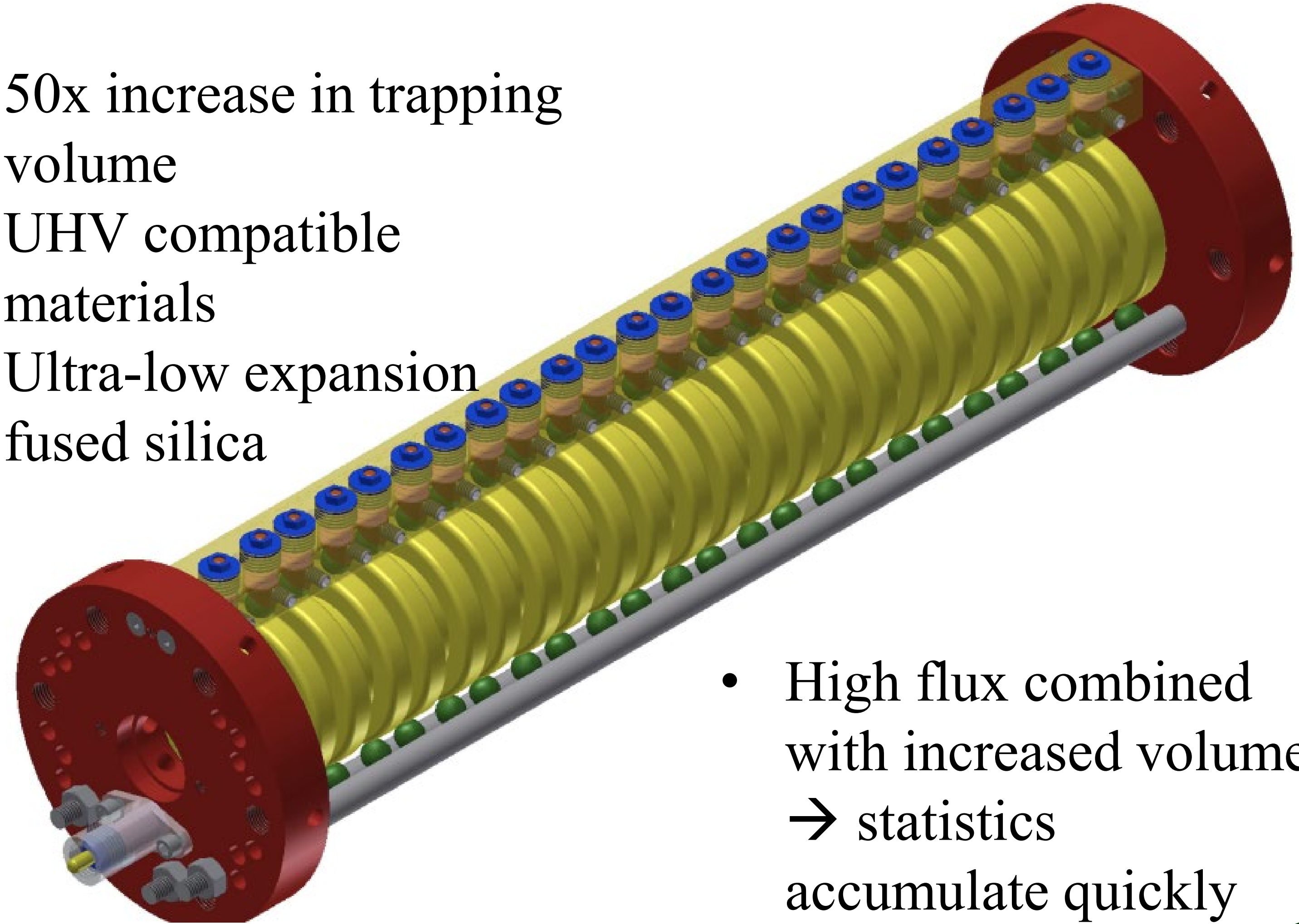
  $\Delta B/B < 10^{-3}$ (in proton trap)

- 50x increase in trapping volume



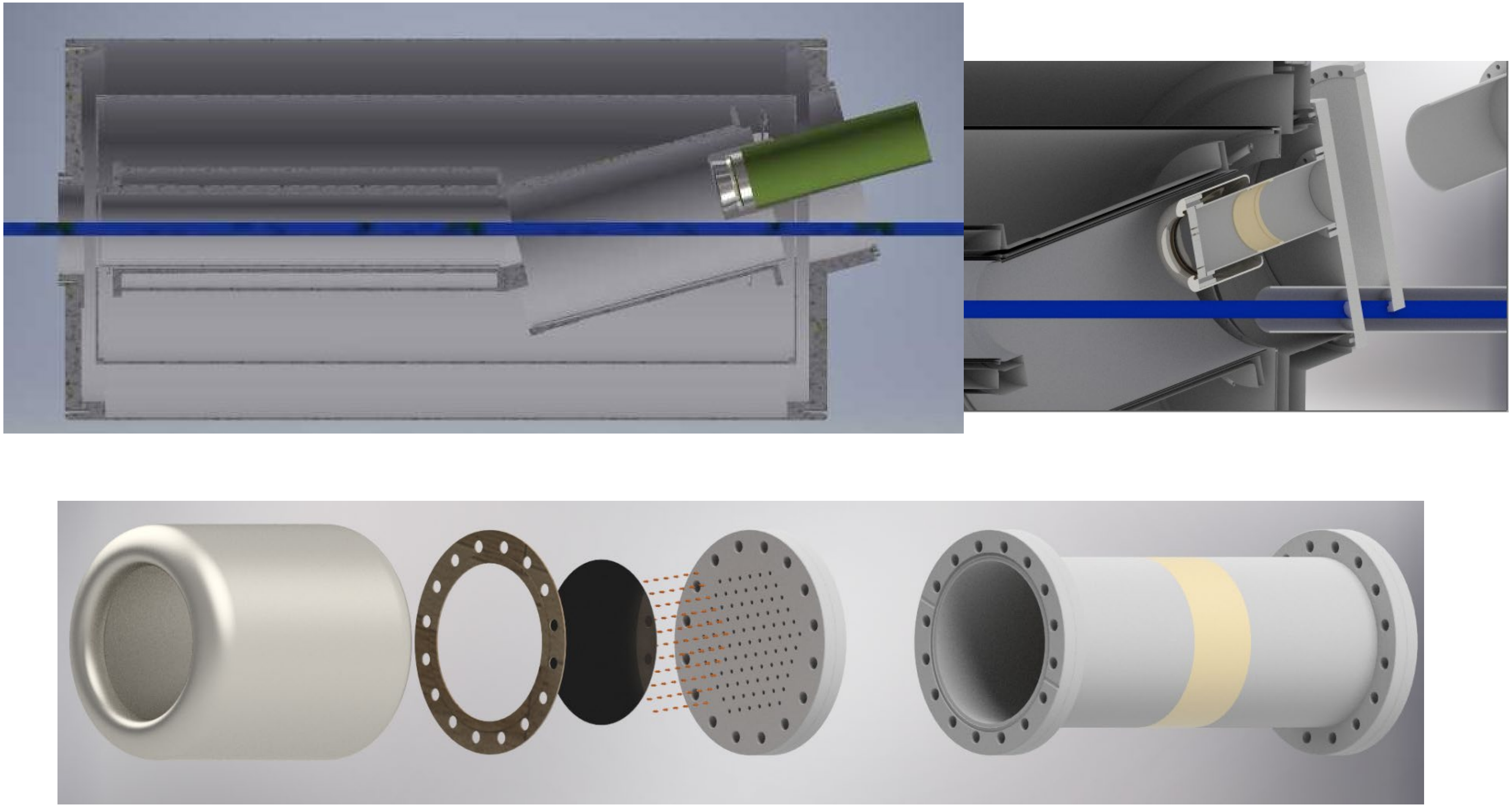
New Quasi-PenningTrap

- 50x increase in trapping volume
- UHV compatible materials
- Ultra-low expansion fused silica

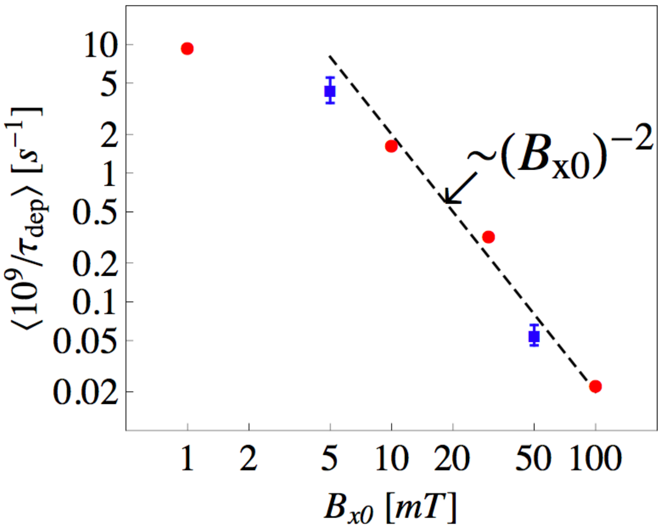


- High flux combined with increased volume → statistics accumulate quickly

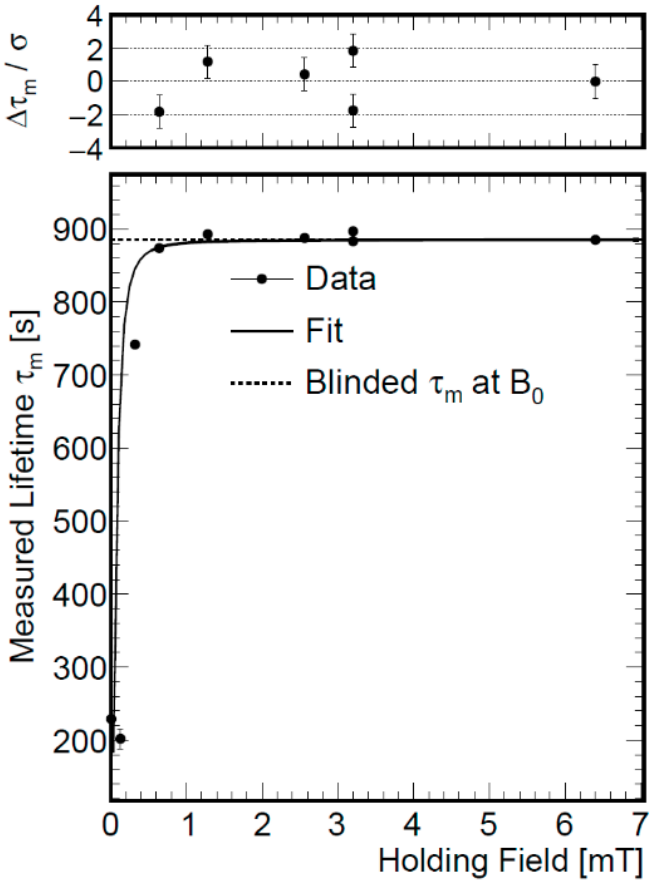
Exists in Inventor, not just our imaginations



Depolarization in UCNtau



A. Steyerl, *et. al.,* Phys. Rev. C Nucl. Phys. 95, 035502 (2017).
R. W



$$\frac{1}{\tau_{meas}} = \frac{1}{\tau_n} + \left(\frac{B_{\perp 0}}{B_{\perp}}\right)^2 \frac{1}{\tau_{depol}}$$

$$\tau_{depol} = 1.1\times 10^7\ s$$

$$\Delta\tau = 0 + 0.07\ s$$

R. W. Pattie Jr. *et al.,* Science 360, 627 (2018).