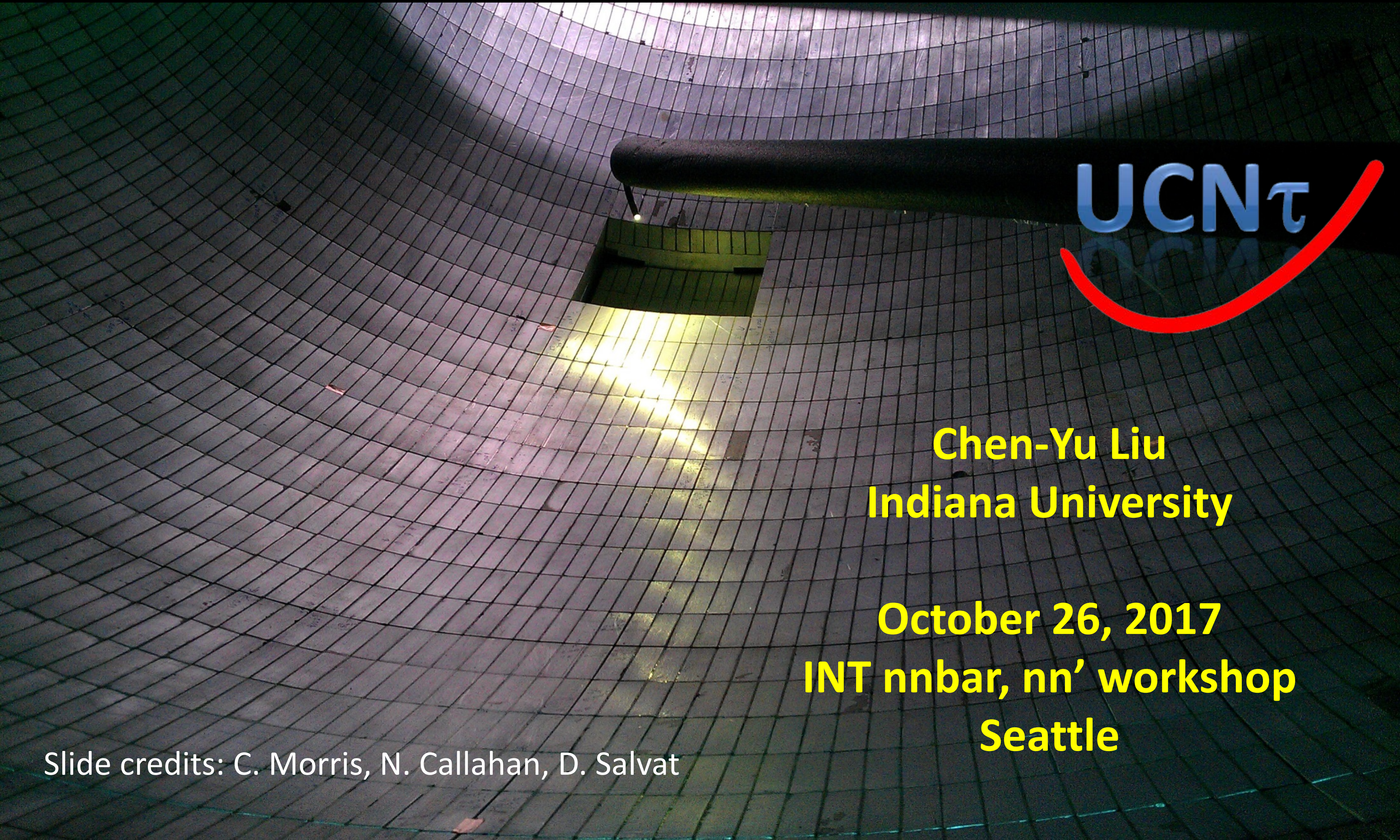
Precision Neutron Lifetime Measurement using UCN in a Magneto-Gravitational Trap



UCNτ

Chen-Yu Liu
Indiana University

October 26, 2017
INT nnbar, nn’ workshop
Seattle

Slide credits: C. Morris, N. Callahan, D. Salvat

UCNtau Collaboration

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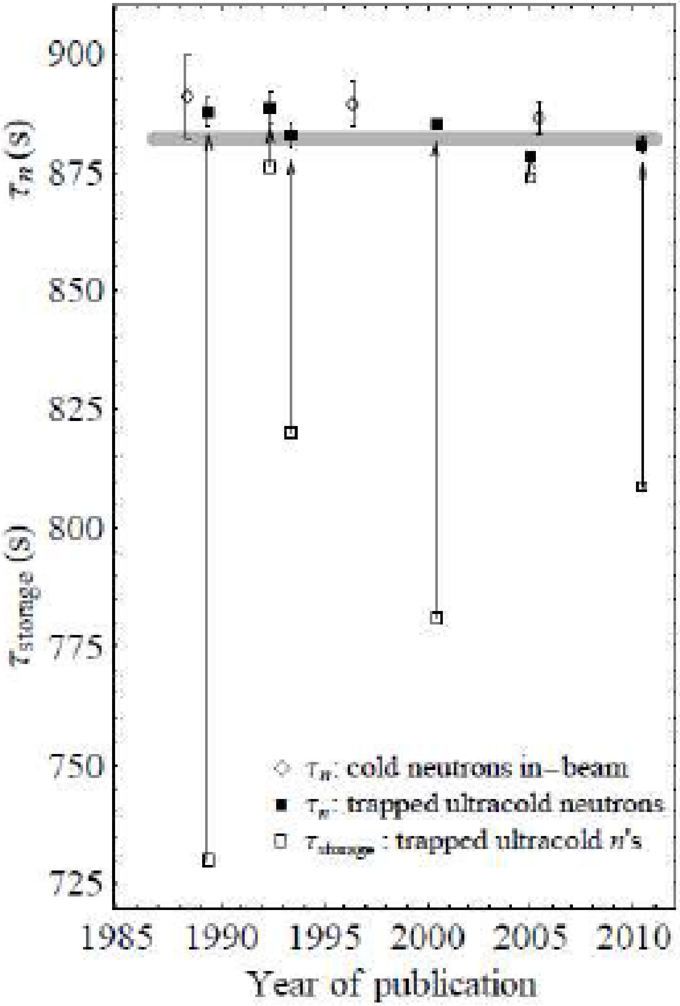
Student
Postdoc
Spokesperson
Spokesperson emeritus

R. W. Pattie, et al, "Measurement of the neutron lifetime using an asymmetric magneto-gravatational trap and in situ detection", submitted to Science; **https://arxiv.org/abs/1707.01817**

Measuring the lifetime with UCN is challenging!

- Beam measurements require absolute determination of the neutron beam fluence, decay volume, and absolute proton detector efficiency.
  - Have involved multiple systematic corrections of order 5 sec
- Bottle measurements must correct for UCN losses other than the neutron beta decay.
  - These corrections are often of the same order as the quoted uncertainty
- Our goal is to design a bottle that has negligible intrinsic losses using the magnetic interaction

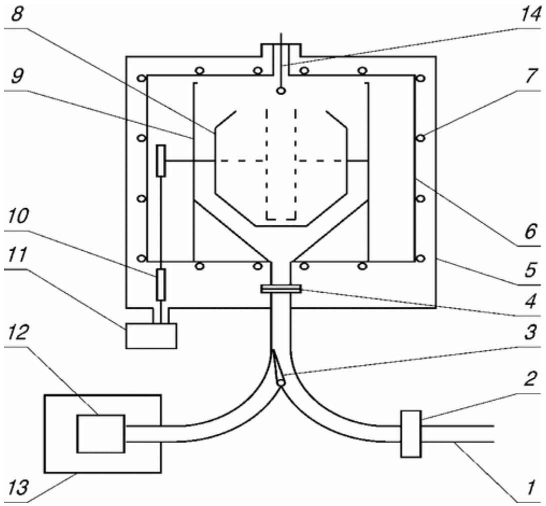


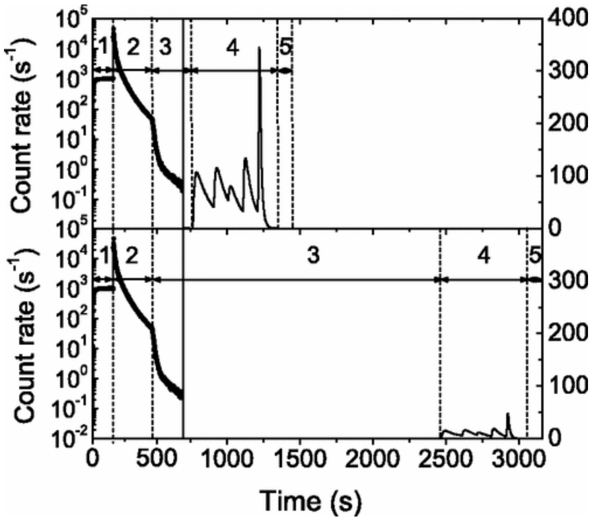
Dubbers & Schmidt, *Rev. Mod. Phy.* **83** (1111) 2011

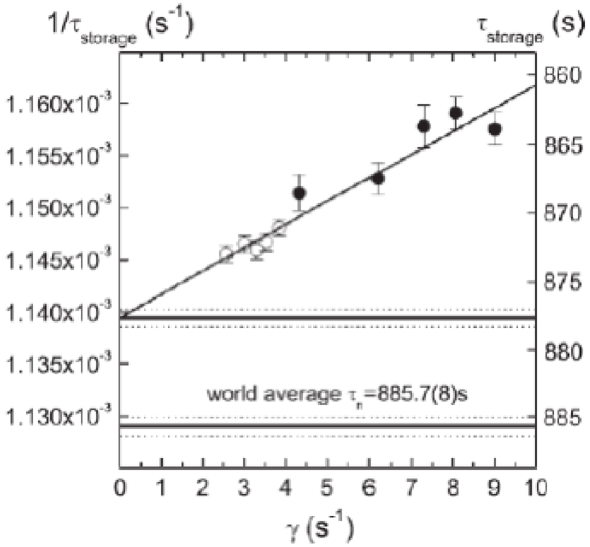
PHYSICAL REVIEW C **78**, 035505 (2008)

Neutron lifetime measurements using gravitationally trapped ultracold neutrons

A. P. Serebrov,[1,*] V. E. Varlamov,[1] A. G. Kharitonov,[1] A. K. Fomin,[1] Yu. N. Pokotilovski,[2] P. Geltenbort,[3]
I. A. Krasnoschekova,[1] M. S. Lasakov,[1] R. R. Taldaev,[1] A. V. Vassiljev,[1] and O. M. Zherebtsov[1]

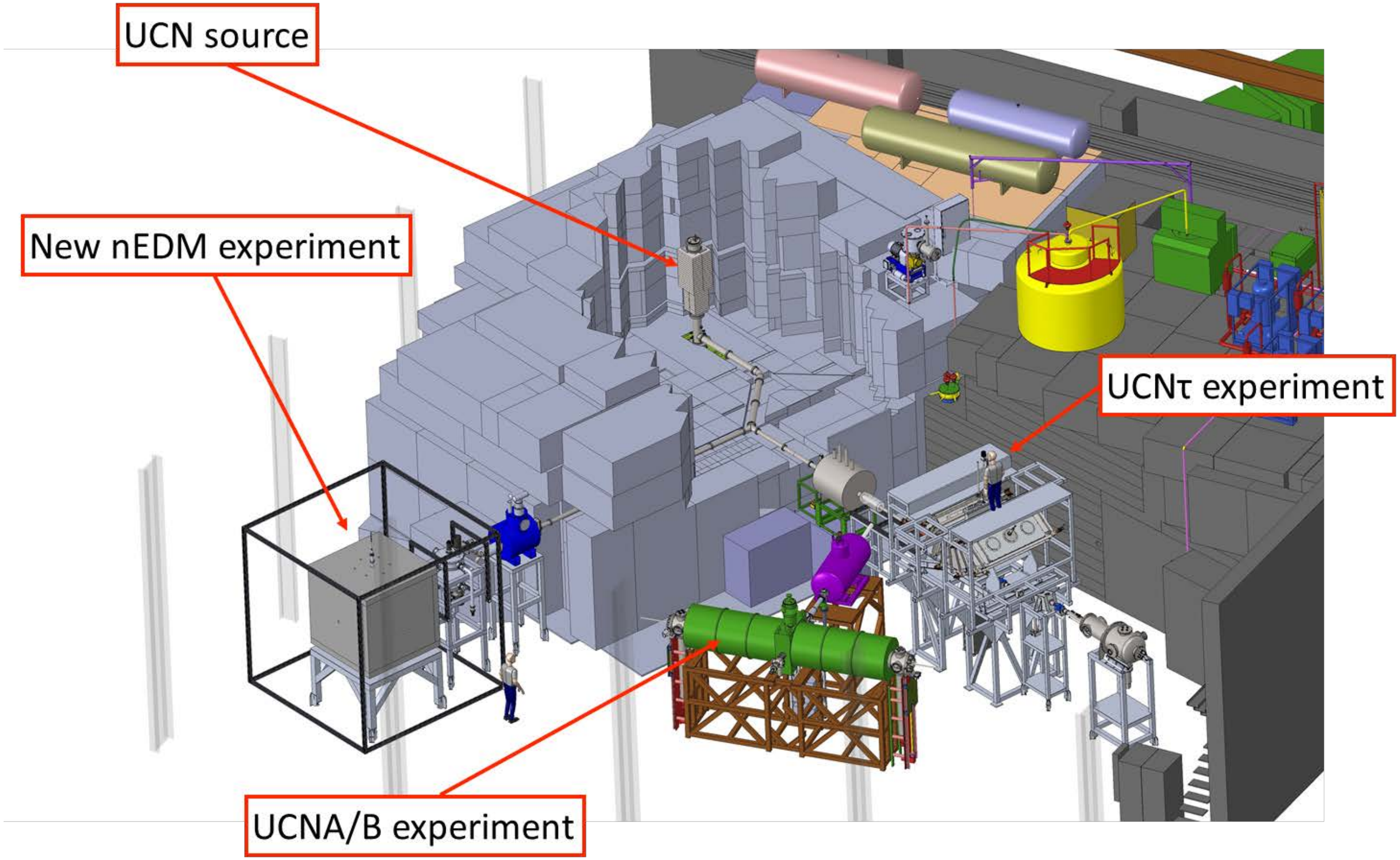






$$\tau_{st}^{-1}(E) = \tau_n^{-1} + \eta(T) \cdot \gamma(E)$$

UCN “*Pokotilovsky*”source operating at the Los Alamos Neutron Science Center (LANSCE)



UCN source

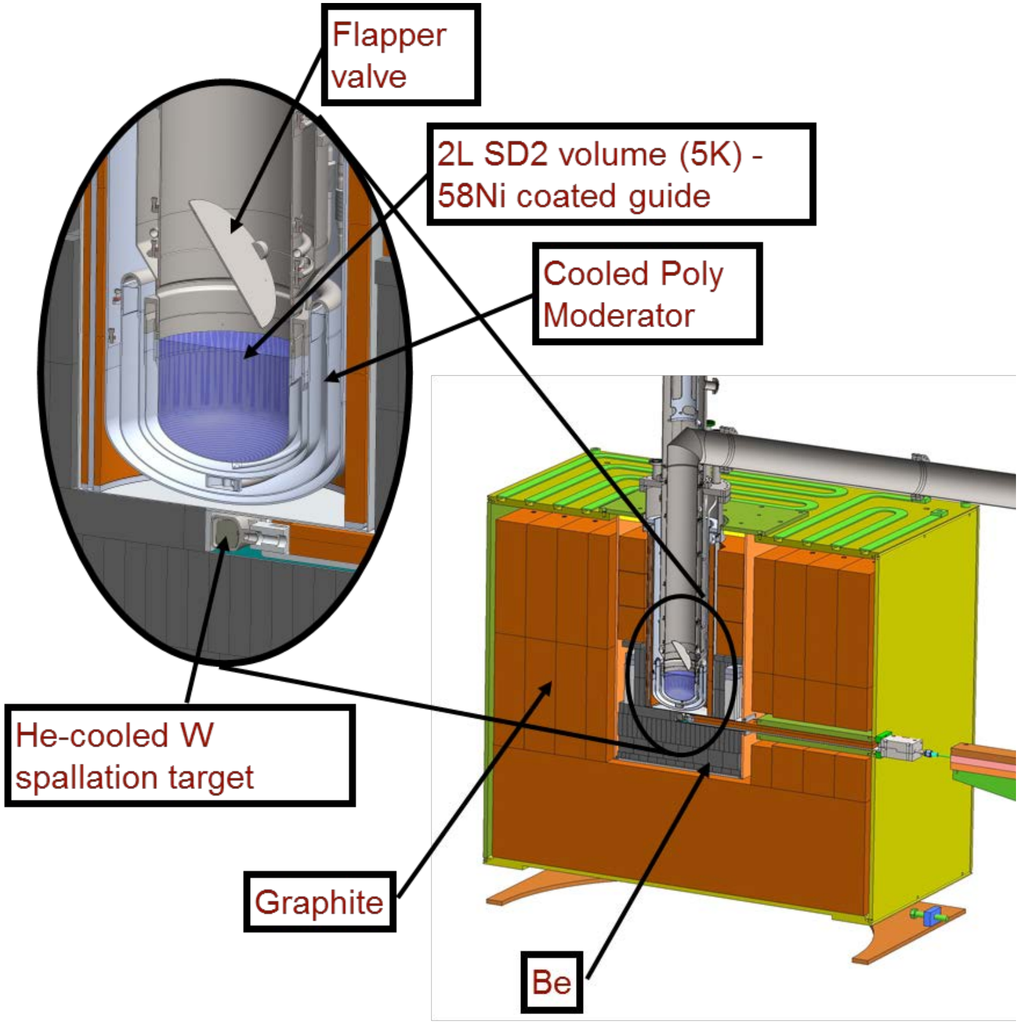
New nEDM experiment

UCNτ experiment

UCNA/B experiment

A. Saunders, et al. RSI 84, 013304 (2013)

UCN *"Pokotilovsky"* source operating at the Los Alamos Neutron Science Center (LANSCE)



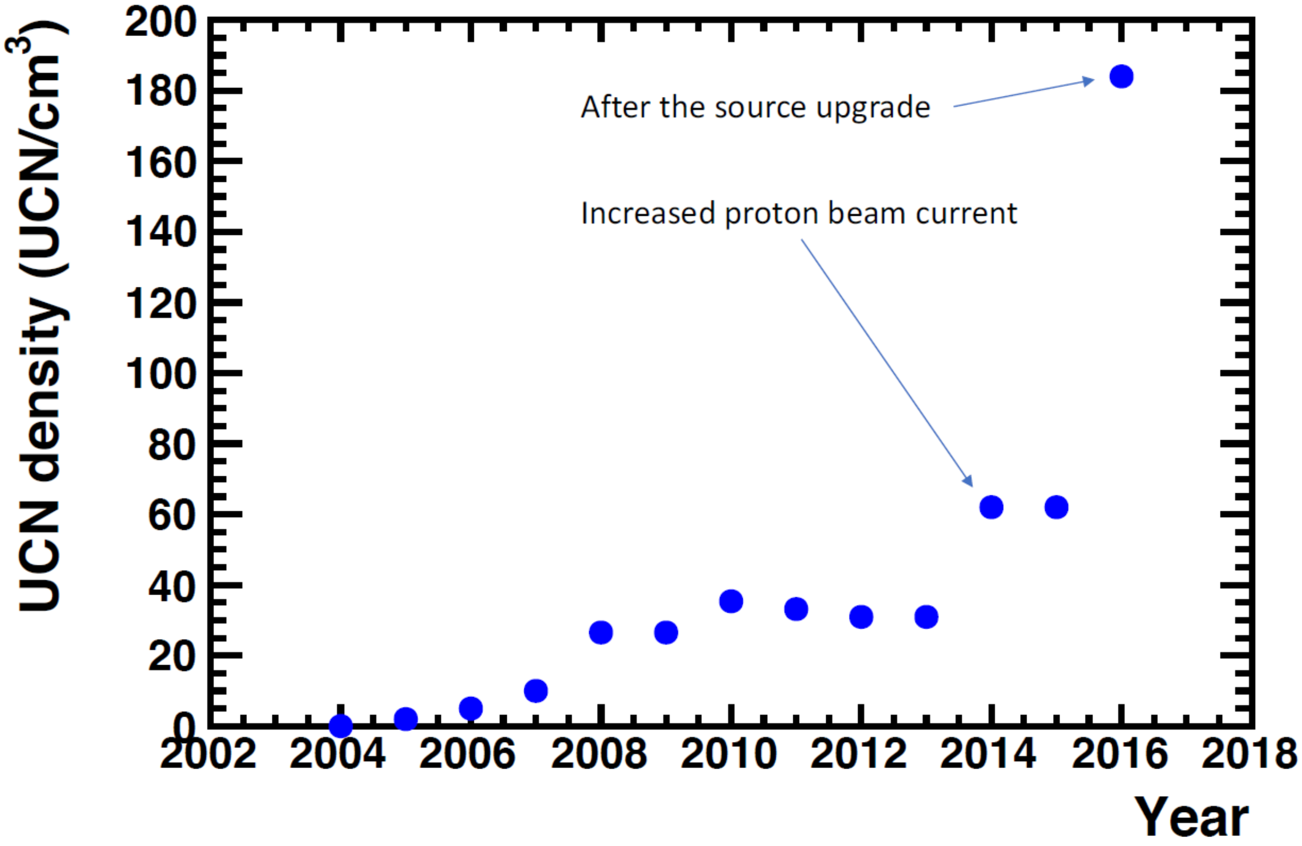
A. Saunders, et al. RSI 84, 013304 (2013)

Source upgrade:

- Better moderator cooling
- NiP guides
- Optimized geometry

UCN density measured by Vanadium activation: **184 UCN/cc**.

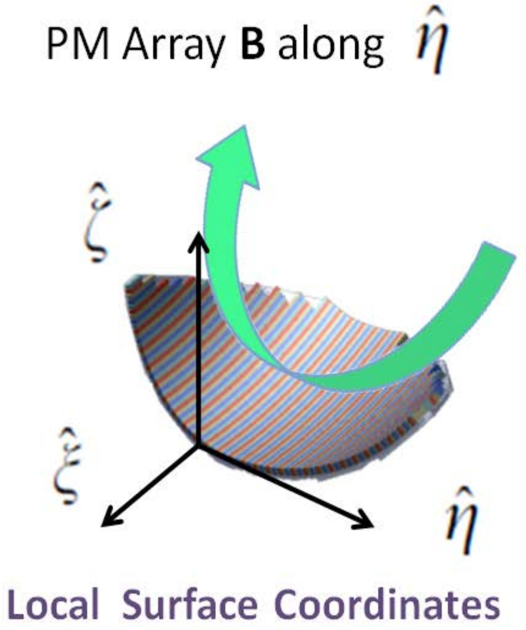
LANL UCN source yield

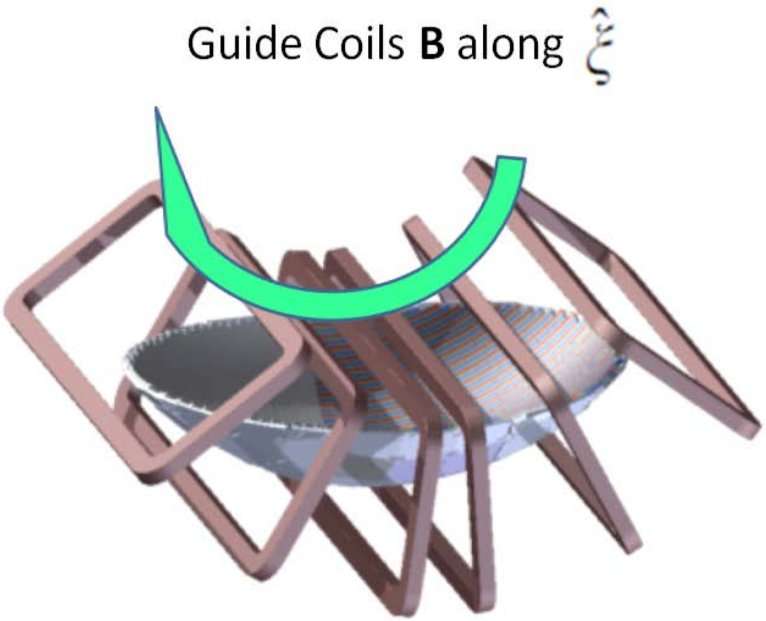


UCNτ: Magneto-Gravitational Trap

- **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)

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.

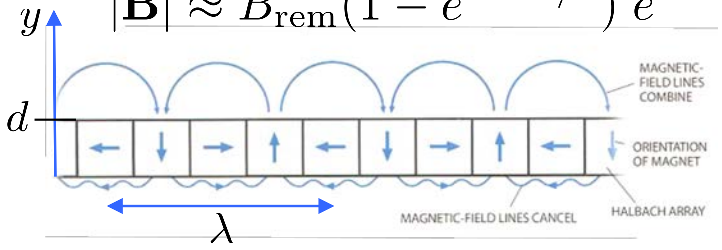
   → Negligible bias on neutron detection efficiency even if the neutron distribution could evolve between the short and long storage times.

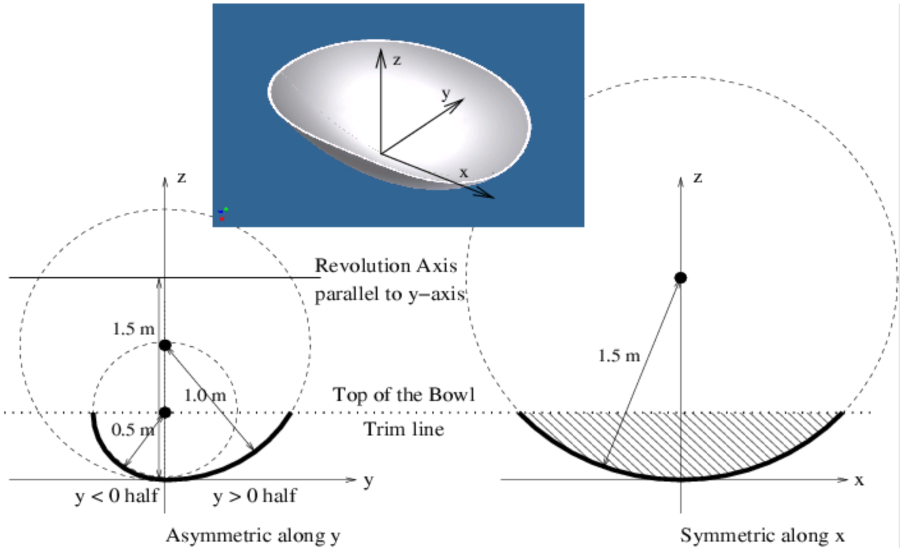
4. A large neutron statistics for sub-1 sec precision (1 s statistical uncertainty every few days)

   → enable data-driven study of systematic effects: needs a large volume, high UCN density, and high neutron detection efficiency.

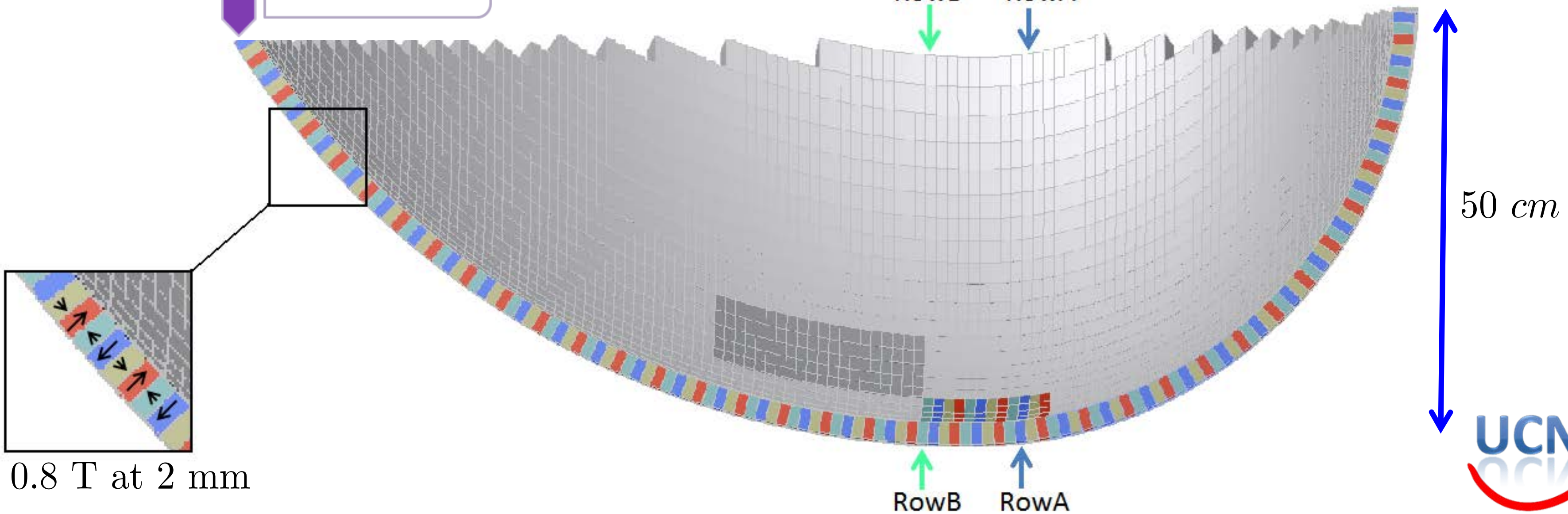
Details of the Halbach Array

$$|\mathbf{B}| \approx B_{\text{rem}}(1 - e^{-2\pi d/\lambda})\, e^{-2\pi y/\lambda}$$





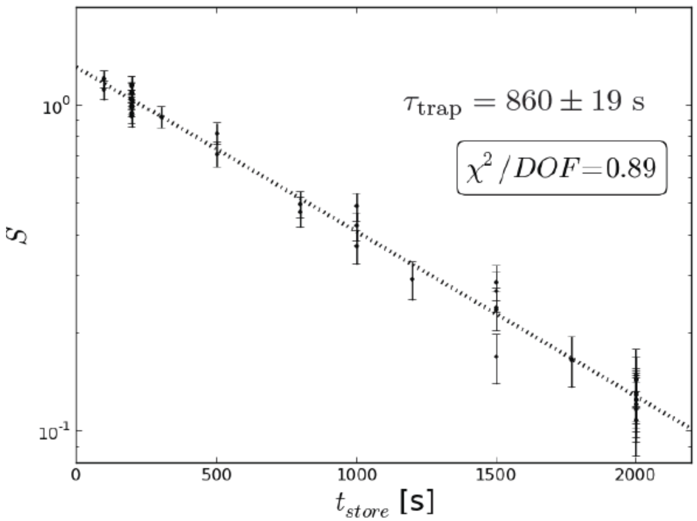
- Rows: 141
- PMs: 5310

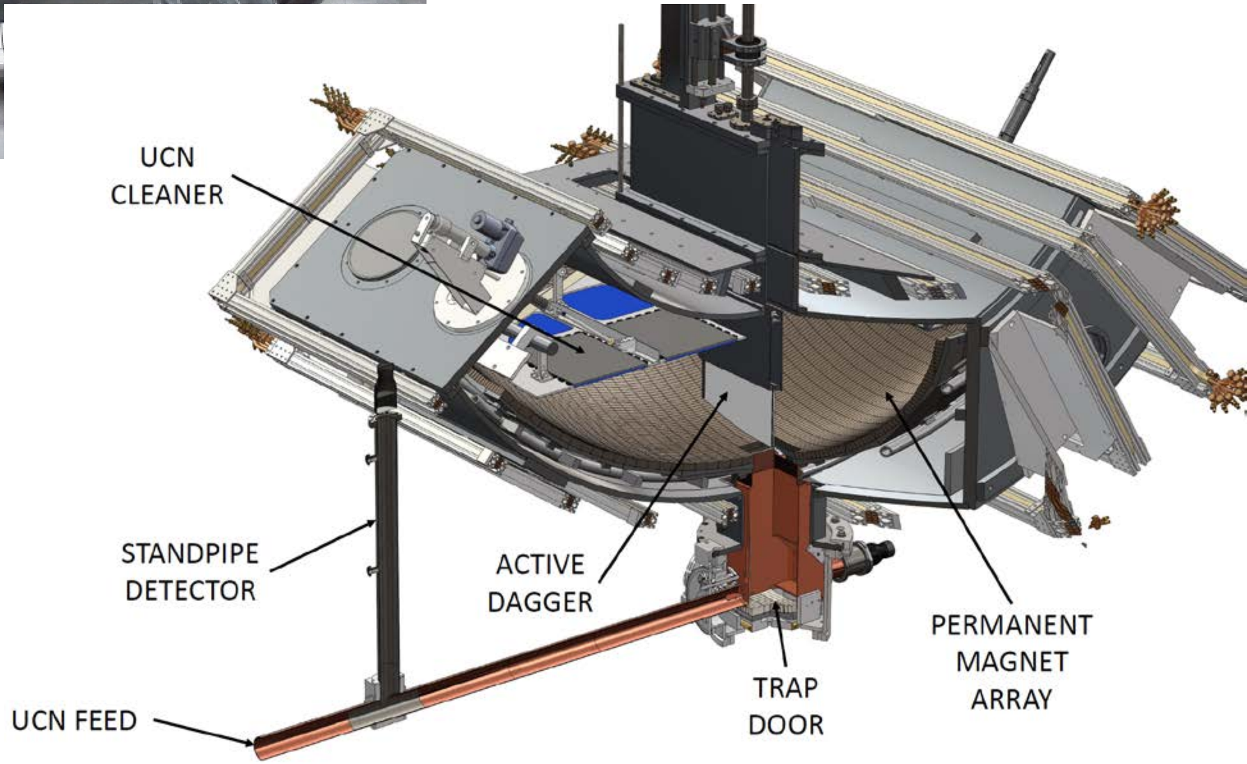


~ 0.8 T at 2 mm

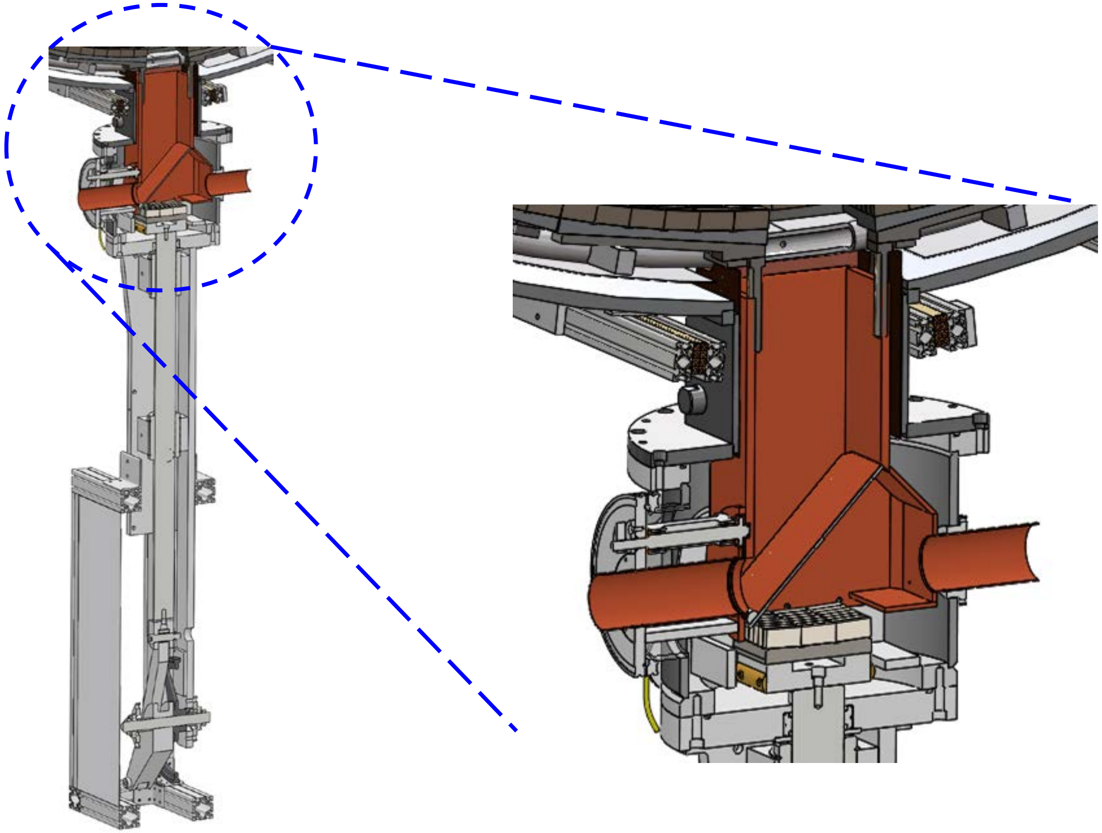
UCNτ Magneto-gravitational trap

D. Salvat, PRC 89, 052501 (2014)

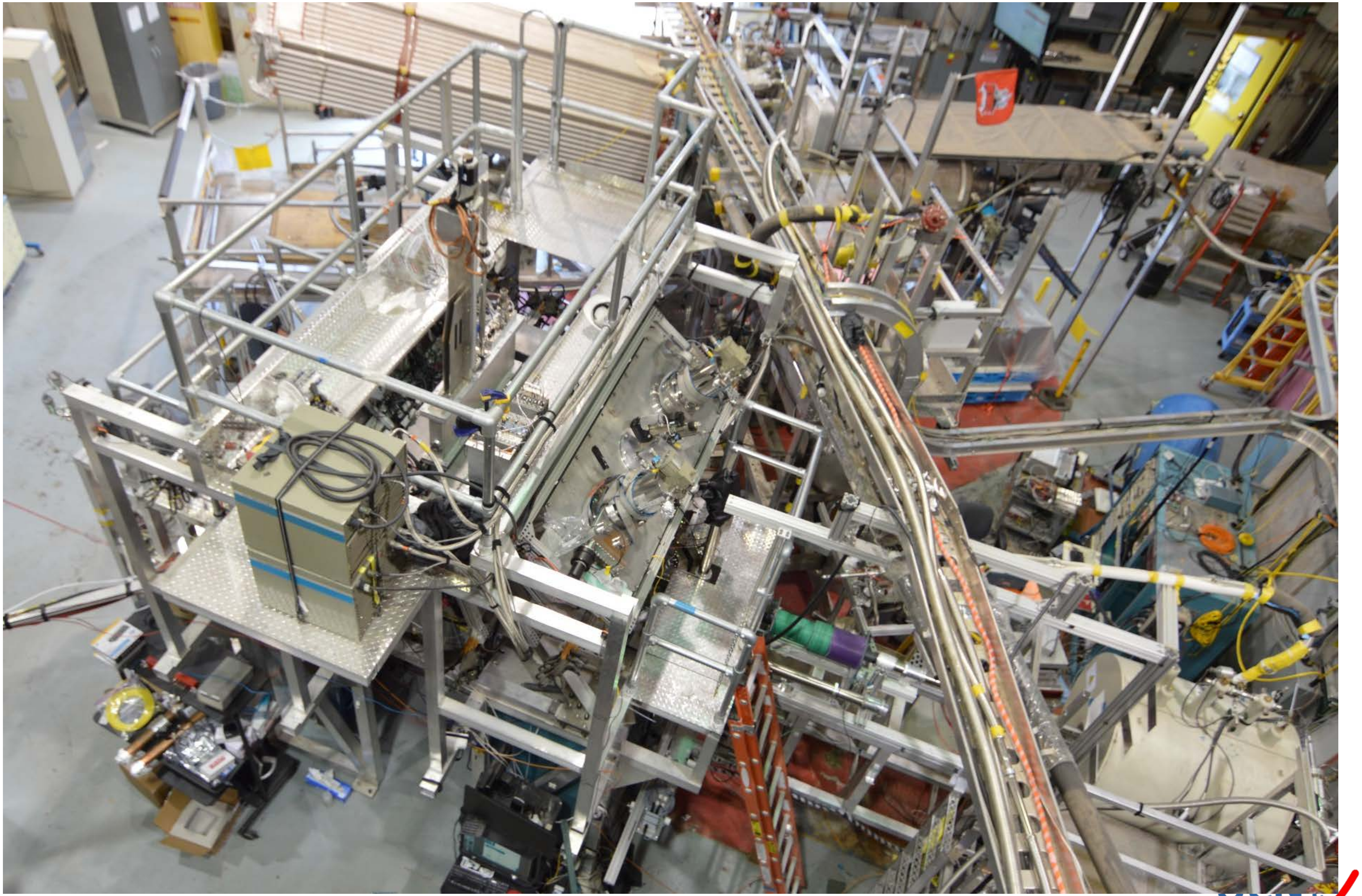




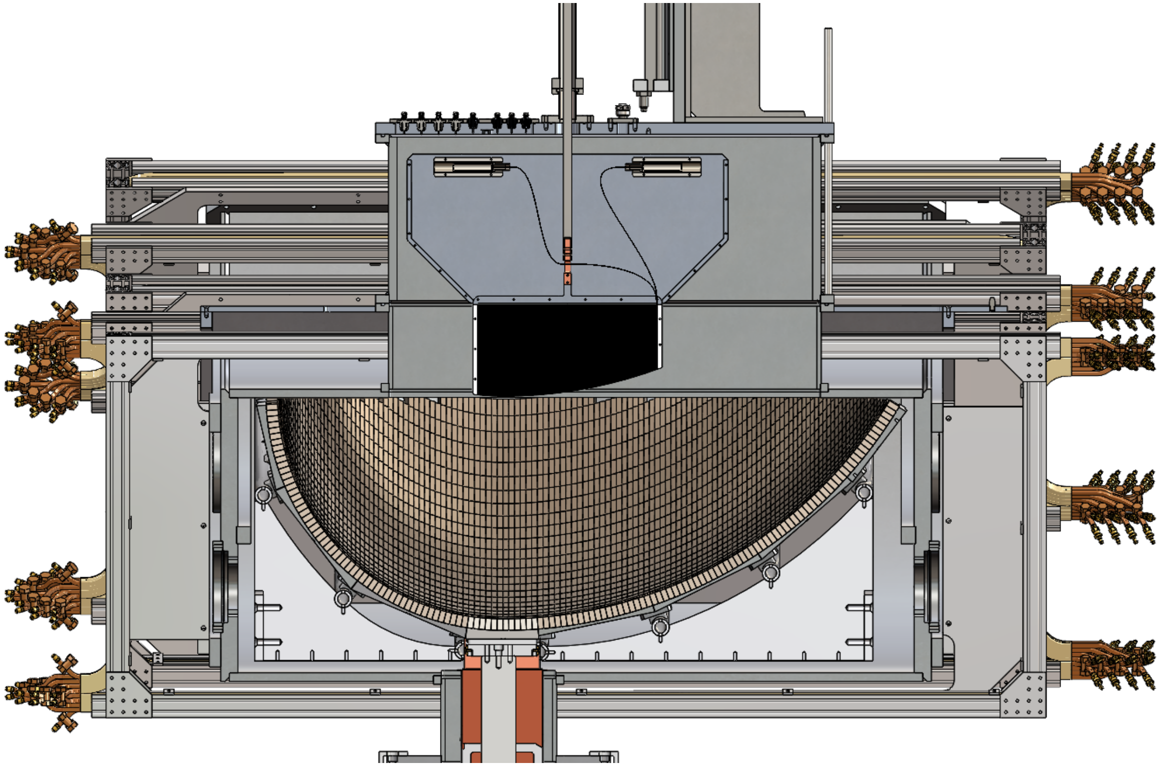
Loading UCN into the trap



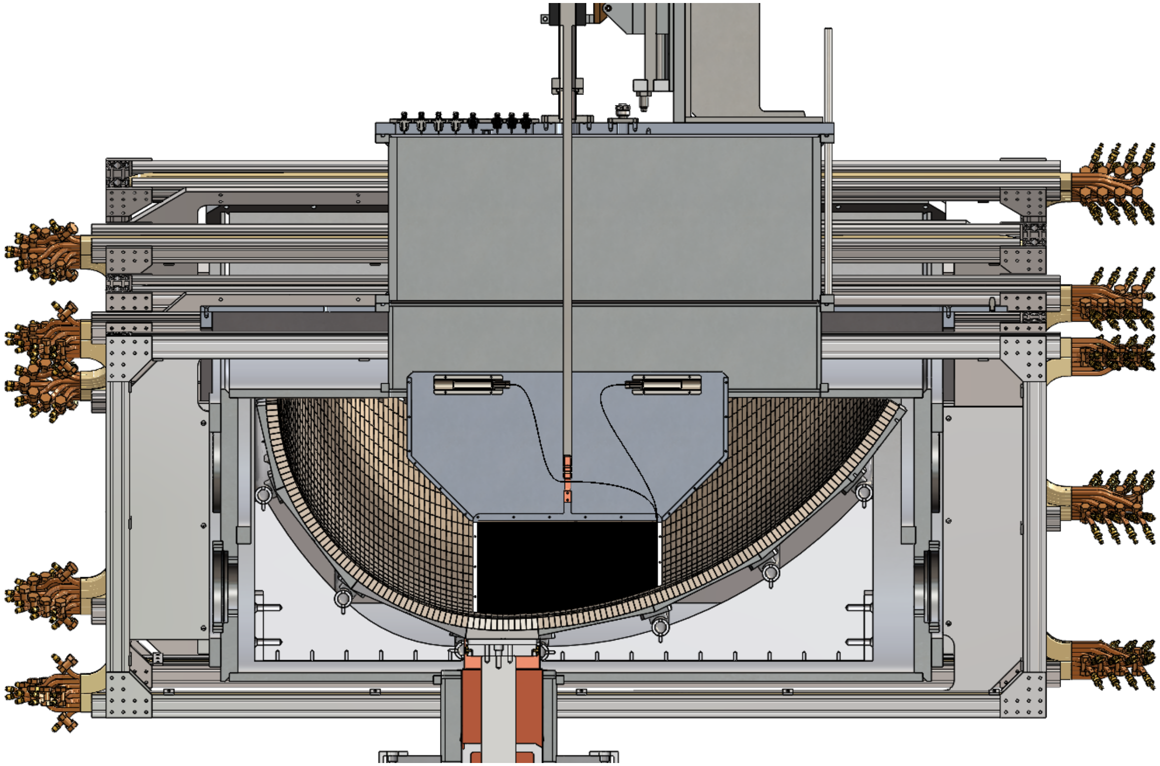
UCNτ Magneto-gravitational trap at Los Alamos Natl. Lab



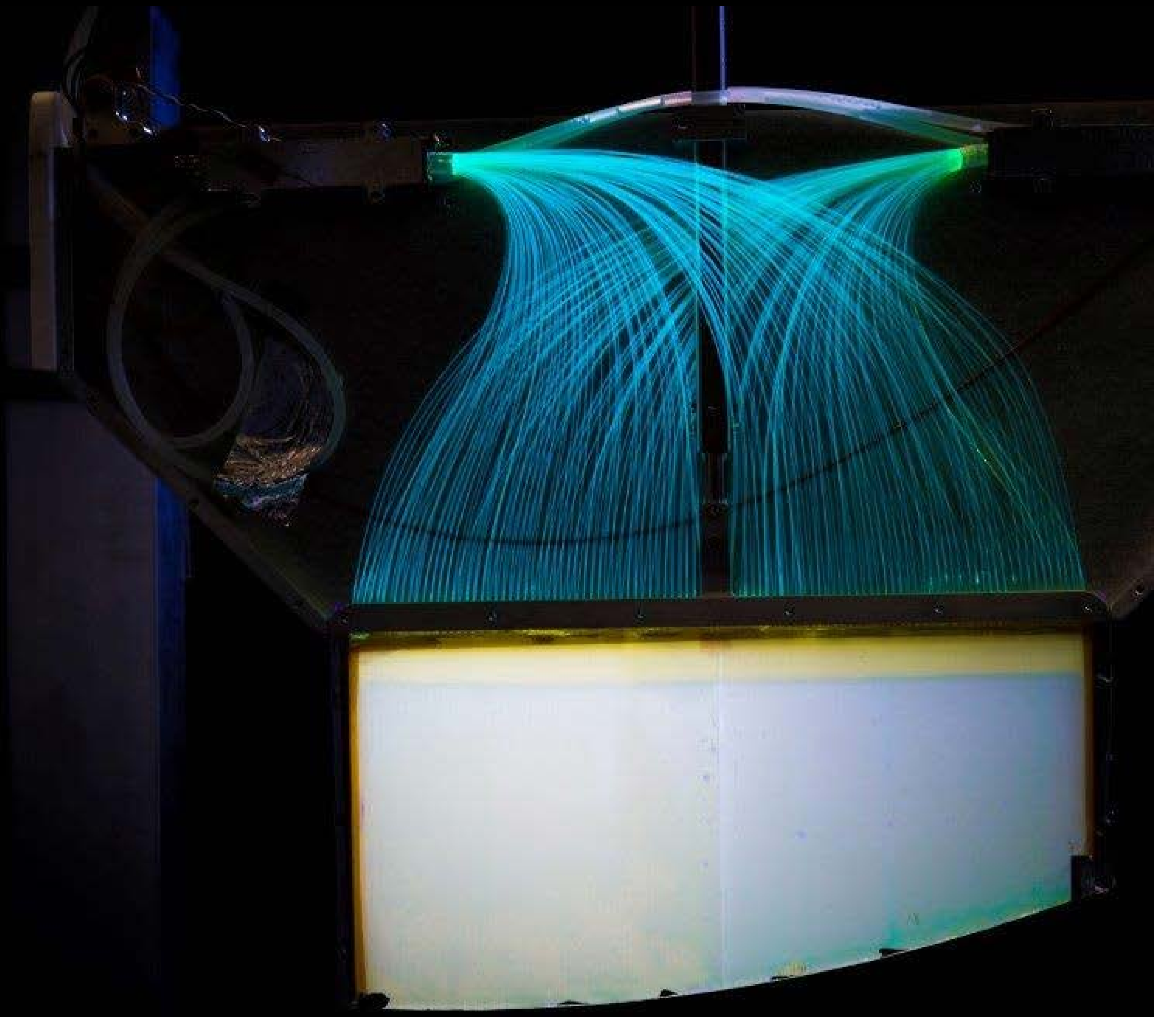
A new way to count the trapped neutrons:

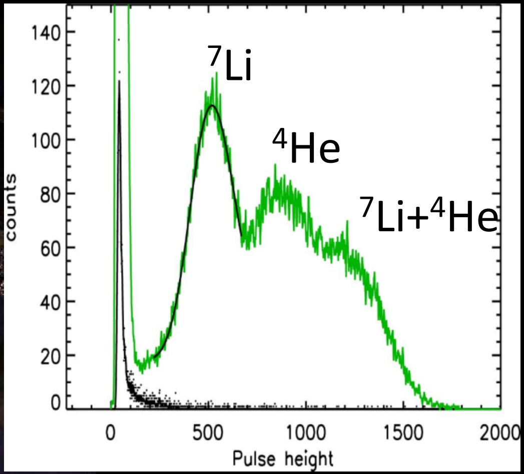


In-situ UCN detection: detection time ~ 8 s



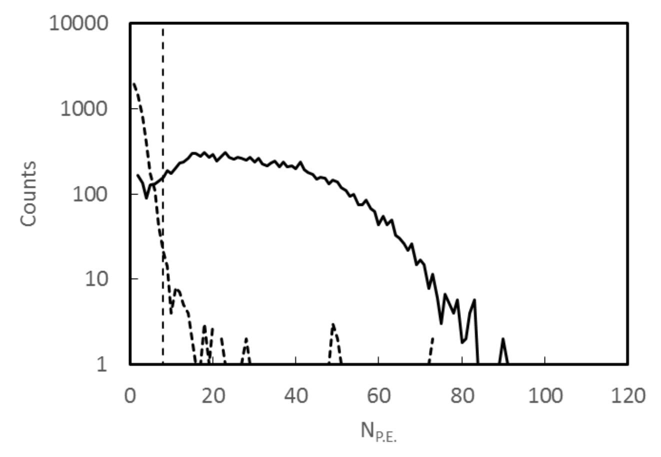
Z. Wang *et al.*, NIMA **798**, 30 (2015).



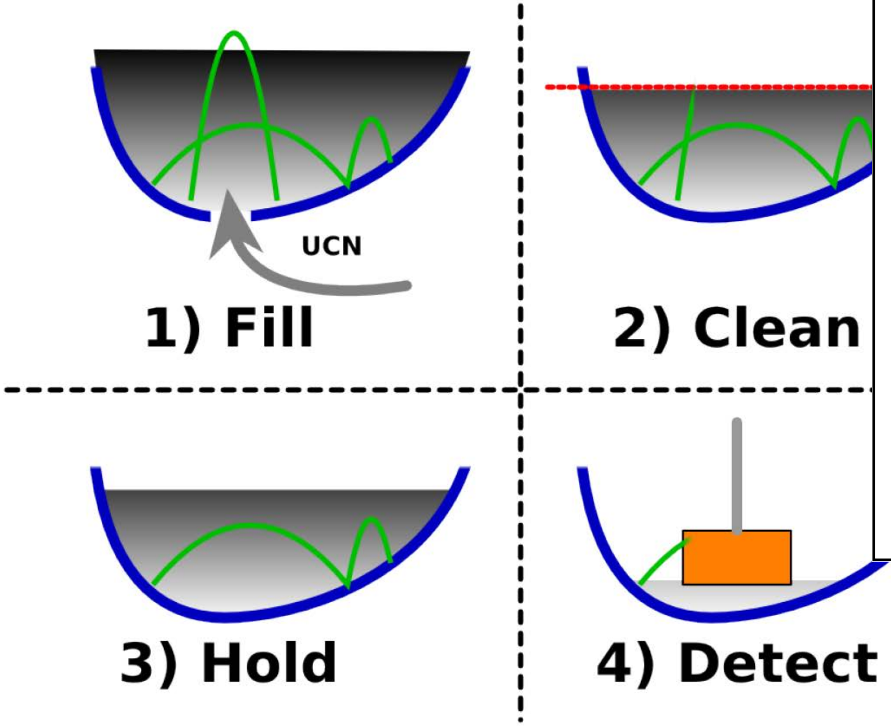


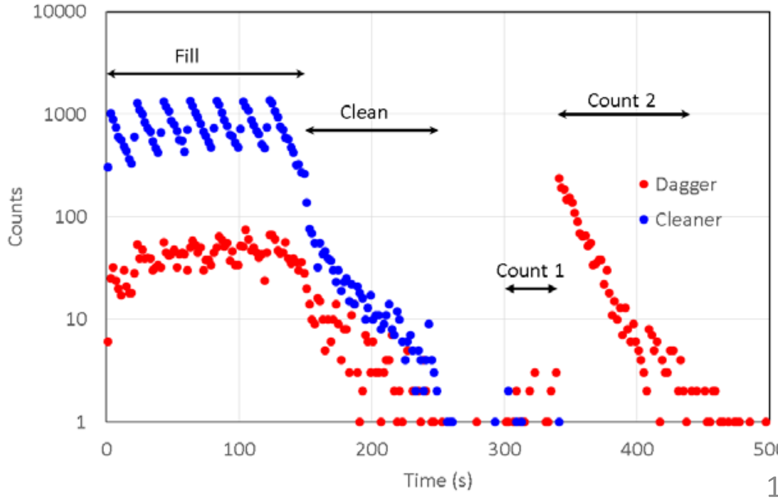
$$n + {}^{10}B \rightarrow {}^{7}Li + \alpha$$

Light Output

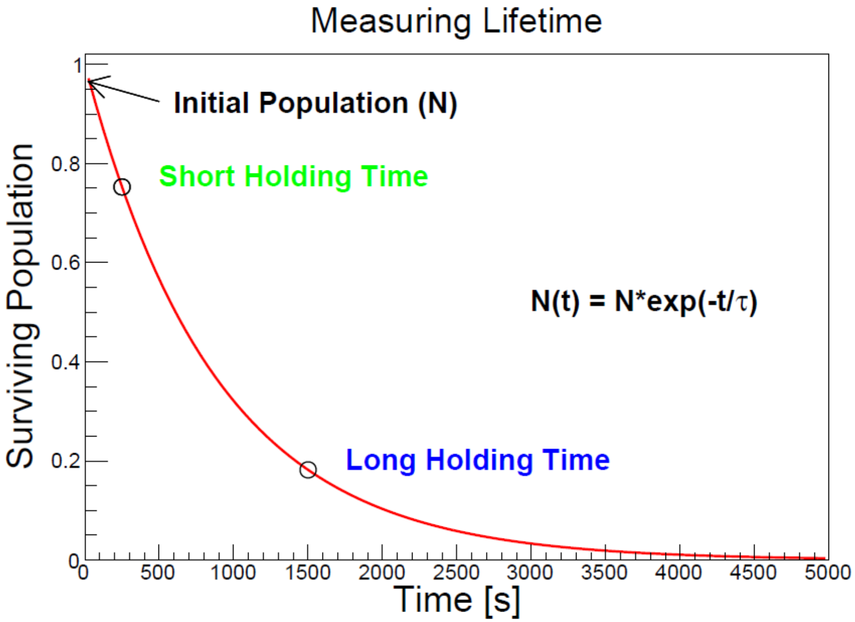


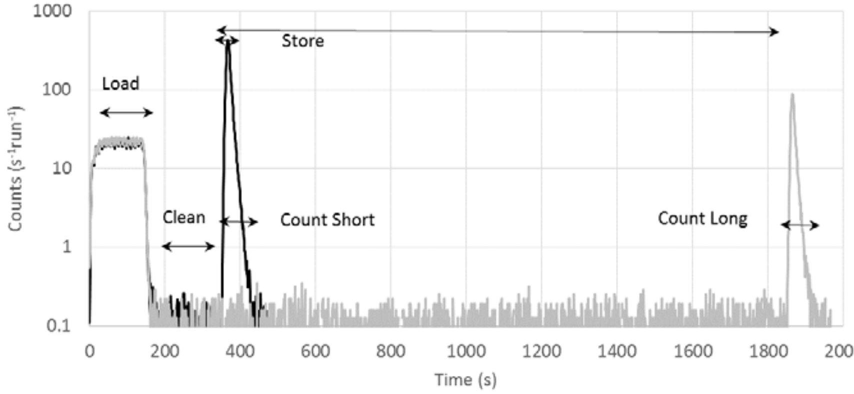
A typical lifetime run:





Pairs of short-long storage times





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

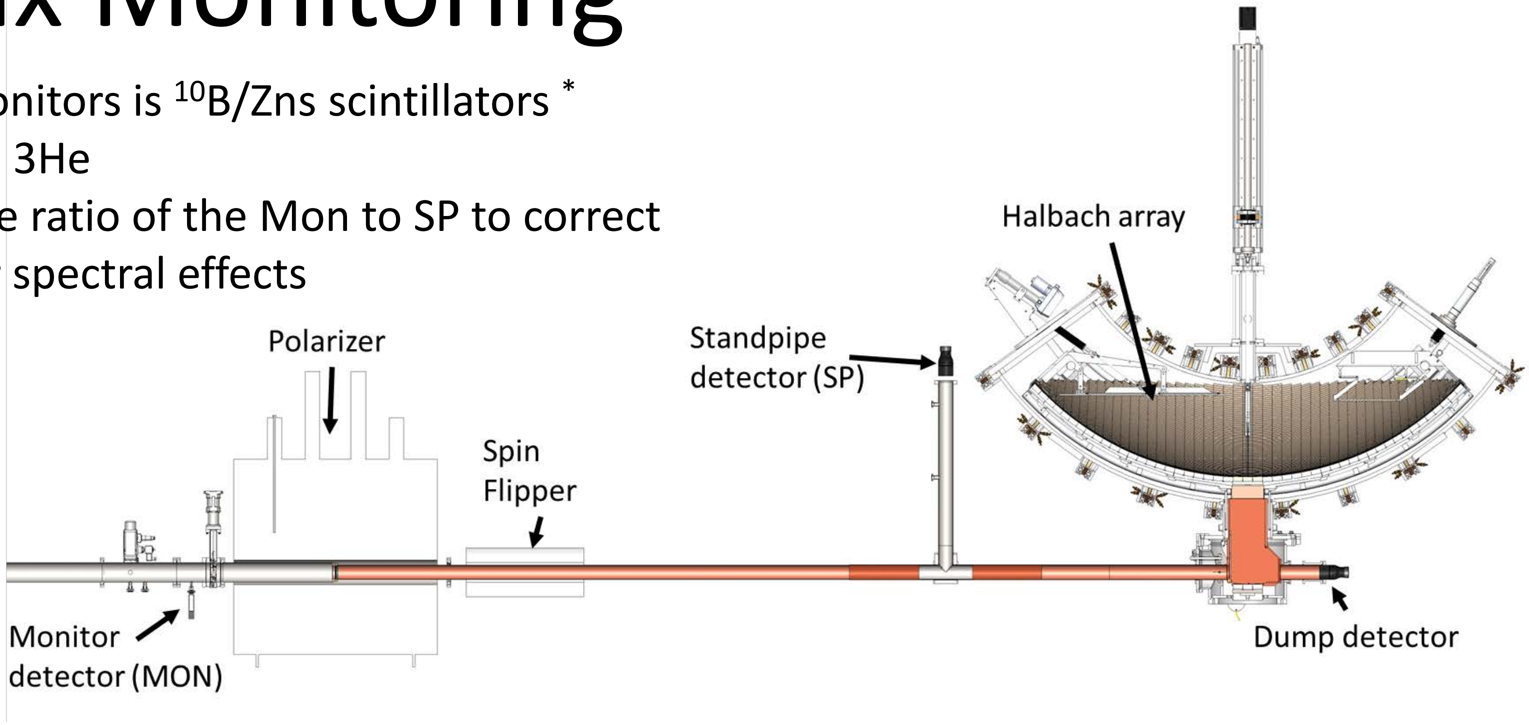
N: UCN counts
M: Monitor counts

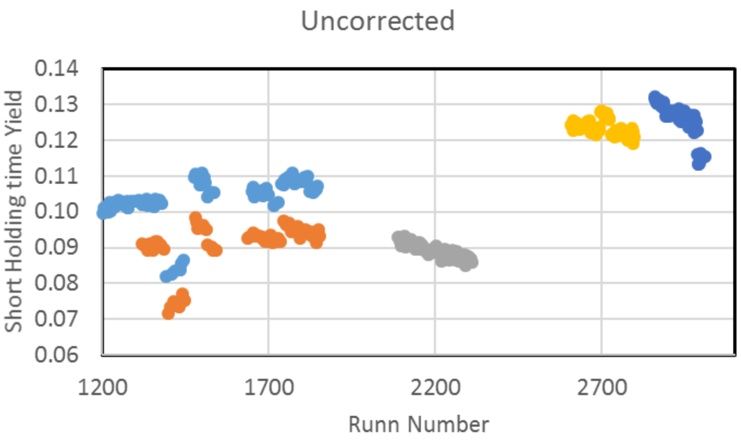
$$\frac{1}{\tau_{\text{trap}}} = \frac{1}{\tau_{\text{n}}} + \frac{1}{\tau_{\text{escape}}} + \frac{1}{\tau_{\text{heating}}} + \frac{1}{\tau_{\text{depol}}} + \dots$$

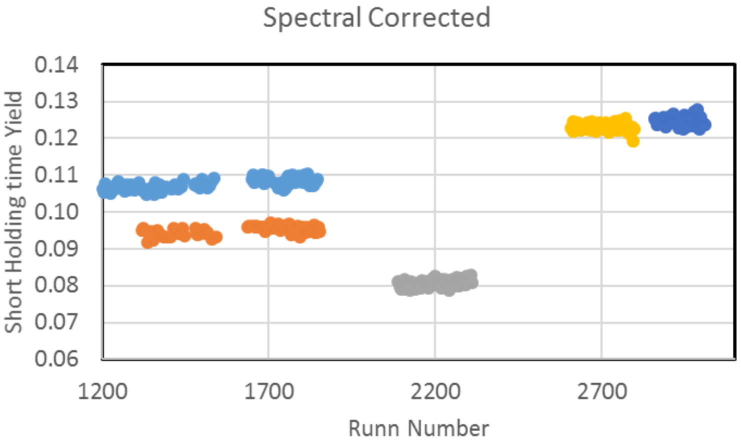
Flux Monitoring

All monitors is ^{10}B/Zns scintillators *

- No 3He
- Use ratio of the Mon to SP to correct for spectral effects

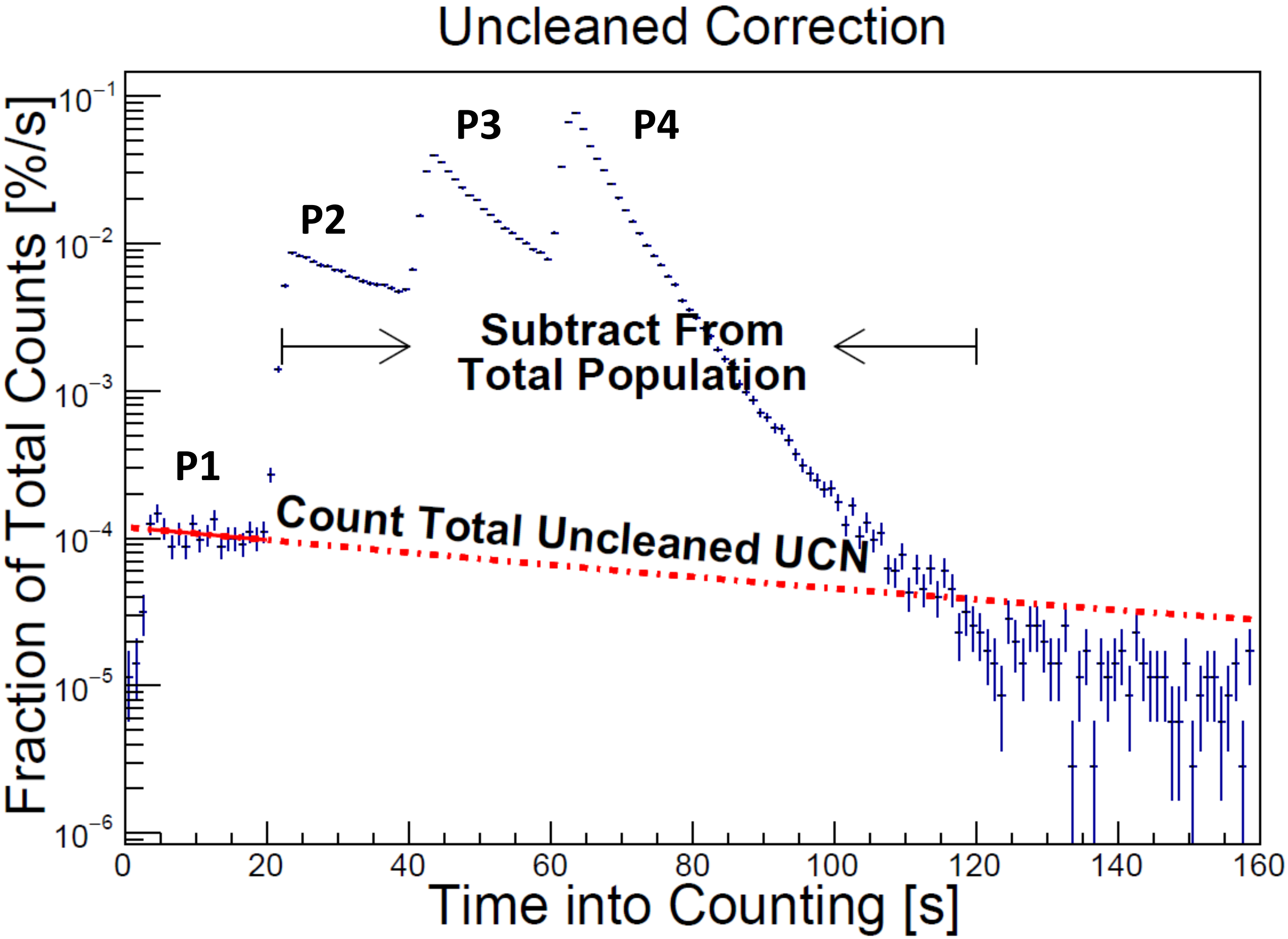


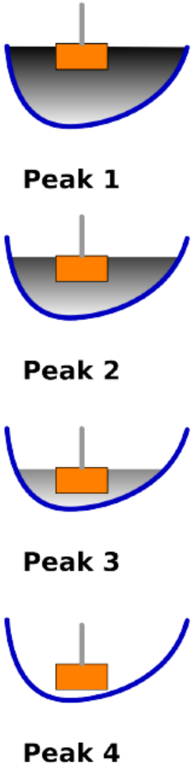




Multi-step UCN detection

Data from **2015-2016** BEFORE larger cleaner

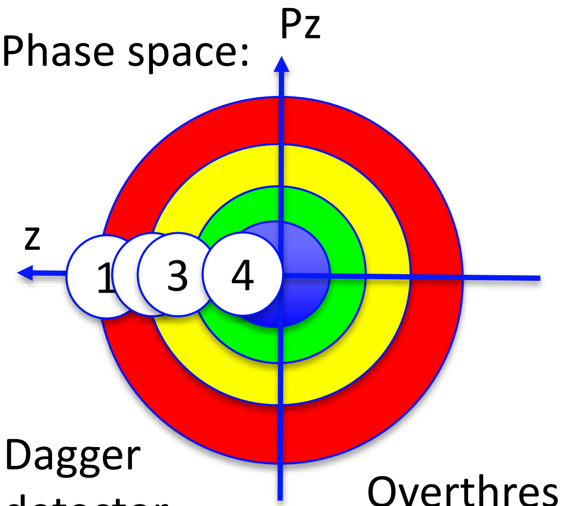




P1 counts HE-UCN reaching > 25 cm.
It has a large draining time ~ 100 s.

Spectral Cleaning vs Phase-space Evolution

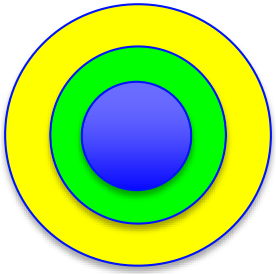
Phase space:



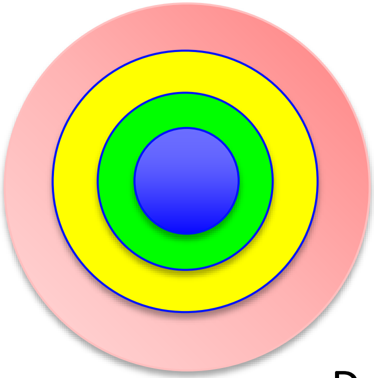
Dagger detector

Overthreshold, HE-UCNs

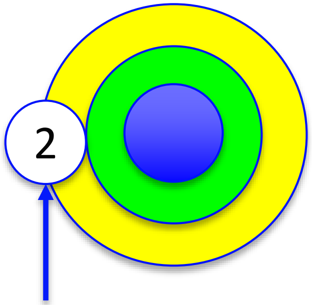
Ideal cleaning:



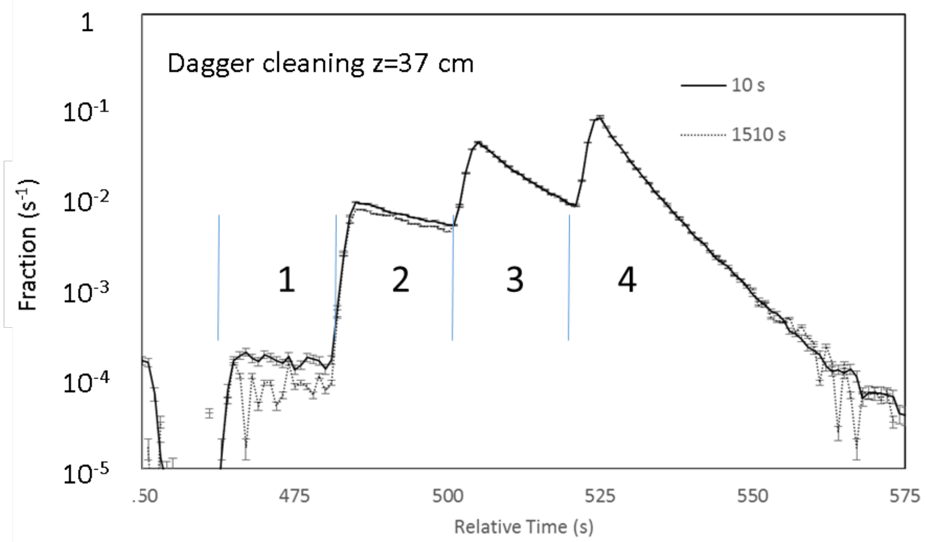
Incomplete cleaning:

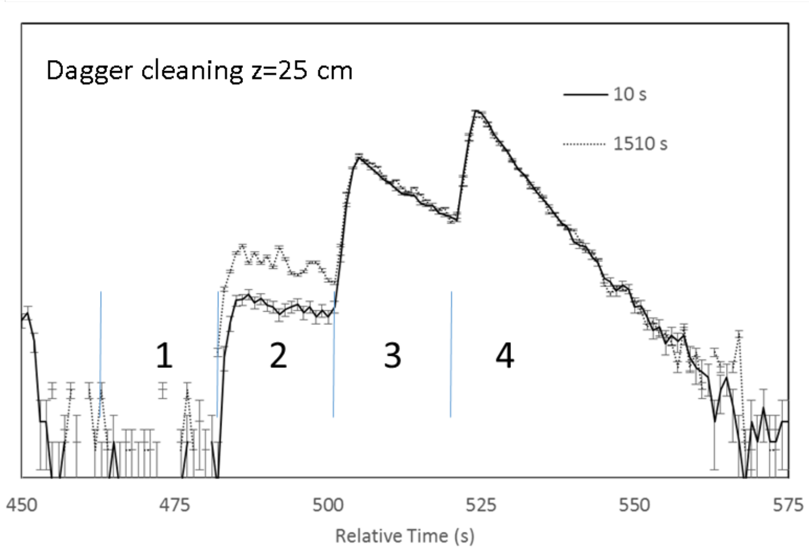


One solution is dagger "deep"-cleaning:



Dagger detector used as a cleaner.





Note that the draining time is height dependent.

Analysis of *non-blinded* tune-up data

P1 subtraction

A - One step counting
B - Two step counting
C - Two step counting with dagger cleaning

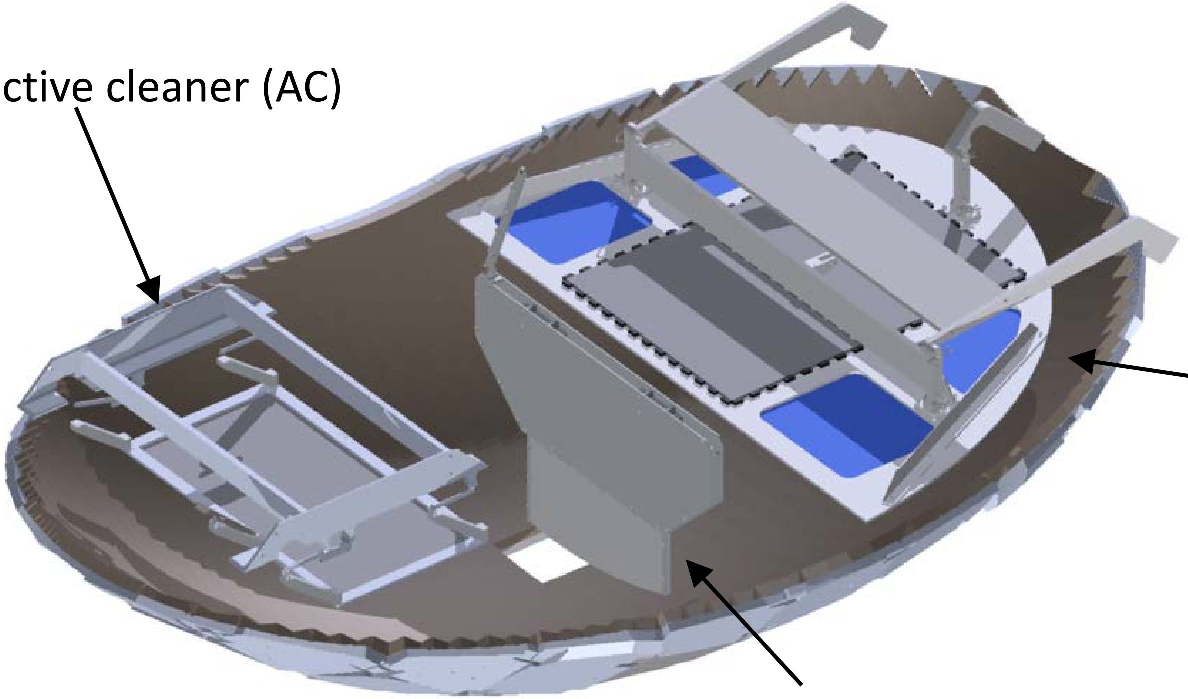
Set	Raw		Cleaning		Vacuum		Corrected	
	$\tau_{measued}$	$\Delta\tau_{measued}$	$\tau_{correction}$	$\Delta\tau_{correction}$	$\tau_{correction}$	$\Delta\tau_{correction}$	τ_n	$\Delta\tau_n$
	s	s	s	s	s	s	s	s
A	858.4	3.5	18.2	1.8	0.4	0.1	877.0	4.0
B	862.8	5.7	17.4	1.5	1.6	0.5	881.8	6.0
C	876.5	4.0	1.9	0.9	0.9	0.3	879.3	4.1
						Average	878.8	2.6
						X^2/dof	0.24	

effect	upper bound (s)	direction	Current Eval.	Method of Characterization
depolarization	0.01	+	calculated	theory
microphonic heating	0.1	+	simulated	accelerometer studies
dead time/pileup	0.5	±	simulated	coincidence studies
time dependent background	0.1	±	measured	measurements
gain drifts	0.2	±	measured	measurements
Phase space evolution	0.2	±	measured	measurements
total	0.6		(uncorrelated sum)	

Morris, et al., RSI **88**, 053508 (2017)

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)

A number of *blinded* data sets were taken in 2015/2016 to study UCN cleaning

Data Set		Conditions	Run Pairs	Statistical Uncertainty (sec)
1	**Feb**	200, 1 step, giant, **AC up**	16	2.7
2	**Feb**	200, 4 step, giant, **AC IN**	26	2.5
3	**Tday**	300, 4step, DC370, **AC**	83	1.9
4	**Feb**	400 s, 4 step, giant, **ACup**	14	4.1
5	**Jan Set 3**	100s, 1 step, AC DC (200,1430)	24	3.1
6	**Jan Set 3**	100s, 1 step, AC, DC (10,1430)	38	2.1
7	**Feb**	100s, 4 step, Giant , AC (20,1440)	29	2.3
8	**Feb**	100s, 4 step, Giant, AC DC (20,1440)	13	4.1
9	**Dec Big set**	100s, 1 step, DC (10, 1430),**AC**	35	2.2
10	**Jan set 1**	100s, 1 step, AC, DC (10,1430)	74	1.5

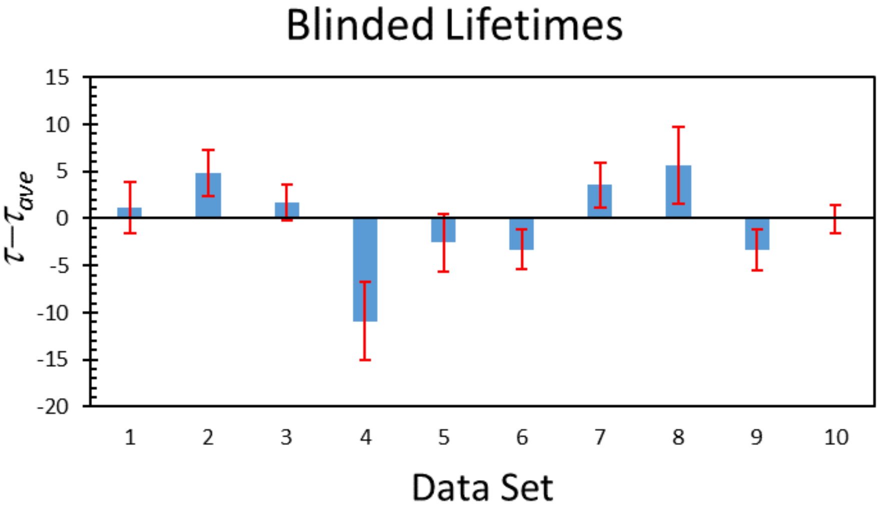
1. AC: small area, fitted with UCN detectors at 37 cm (P1).
2. DC: deep cleaning by lowering dagger at 25 cm (P2).
3. GC: large area, no detectors at 37 cm (P1).

Overall statistical uncertainty: 0.7 s

Blinded lifetimes for different conditions vary somewhat more than statistics (analysis of green shaded run-sets)

$$x^2/\mathrm{DOF} = 2.4$$

We believe this is due to normalization/timing problems. Uncertainties for this data have been scaled by $\sqrt{x^2/_{df}}$



Two *in-situ* HE-UCN monitoring detectors

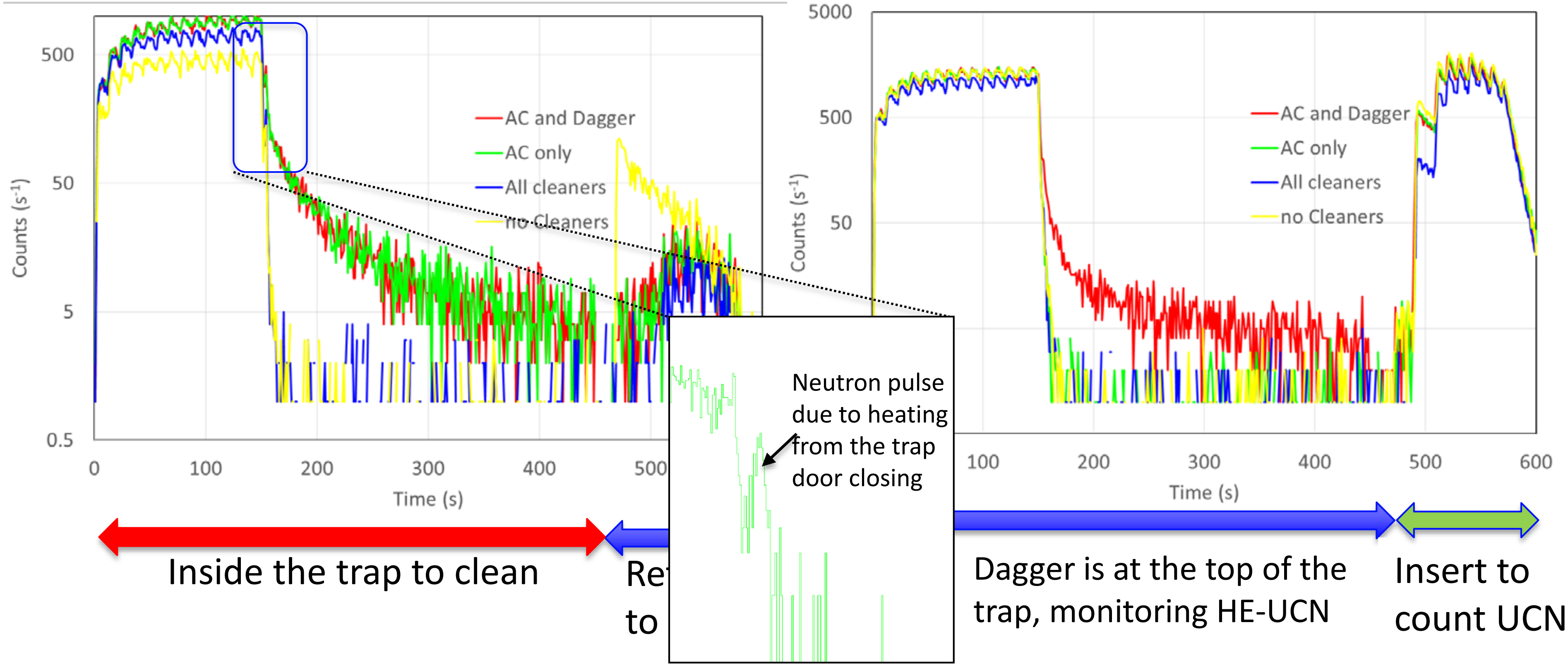
Both measures UCN above 32 cm

The **giant cleaner (at 32 cm)** *eliminates* the need for a cleaning correction

	AC	Dagger (P1)
AC + Dagger	66	107
AC only	54	68
All cleaners	1	-1
No cleaners	1278	91

Active cleaner (AC) signal

Dagger detector (DC) signal



Neutron pulse due to heating from the trap door closing

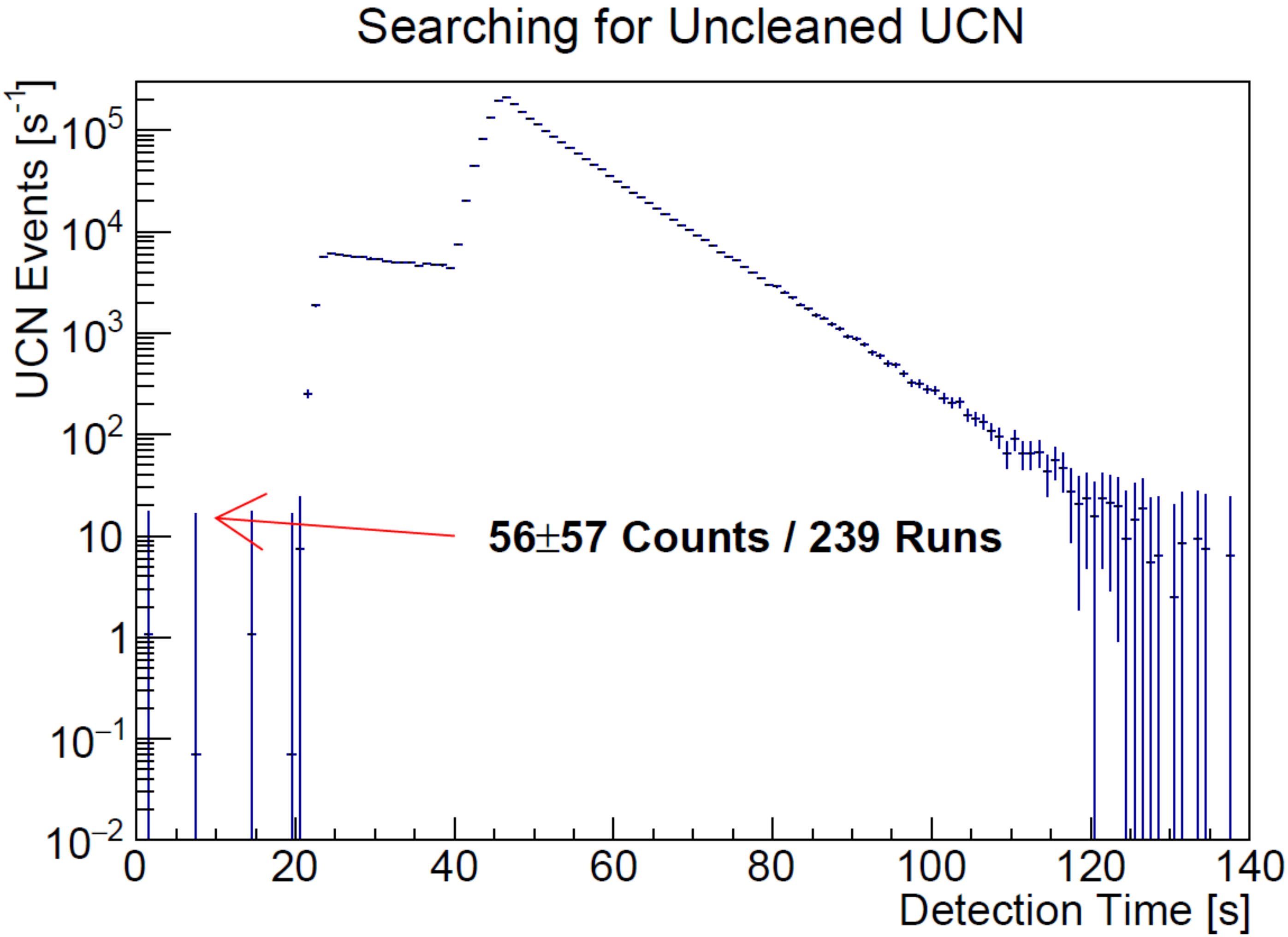
Inside the trap to clean

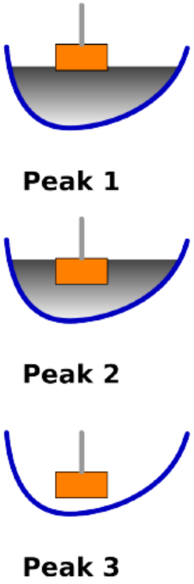
Re to

Dagger is at the top of the trap, monitoring HE-UCN

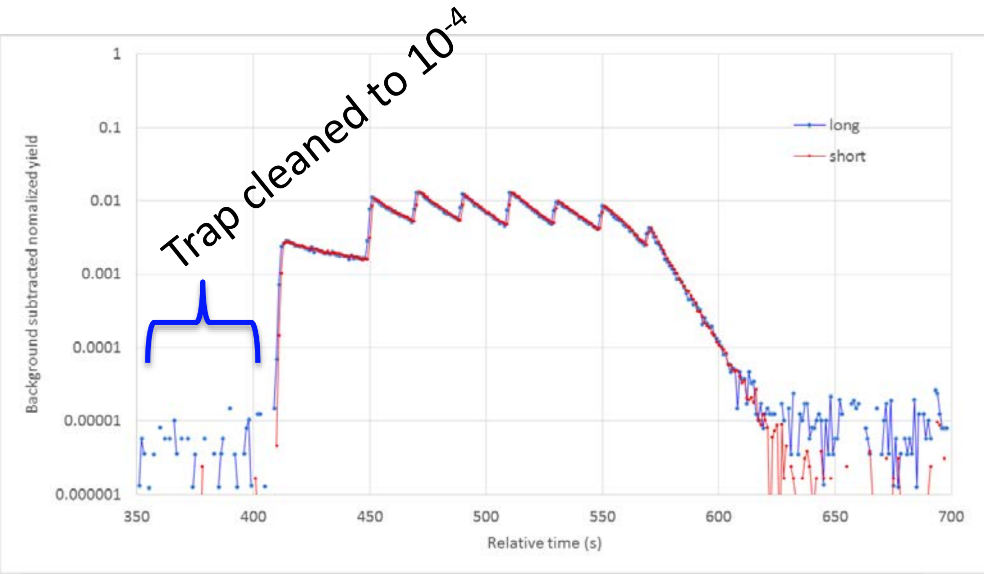
Insert to count UCN

Data from **2016-2017**



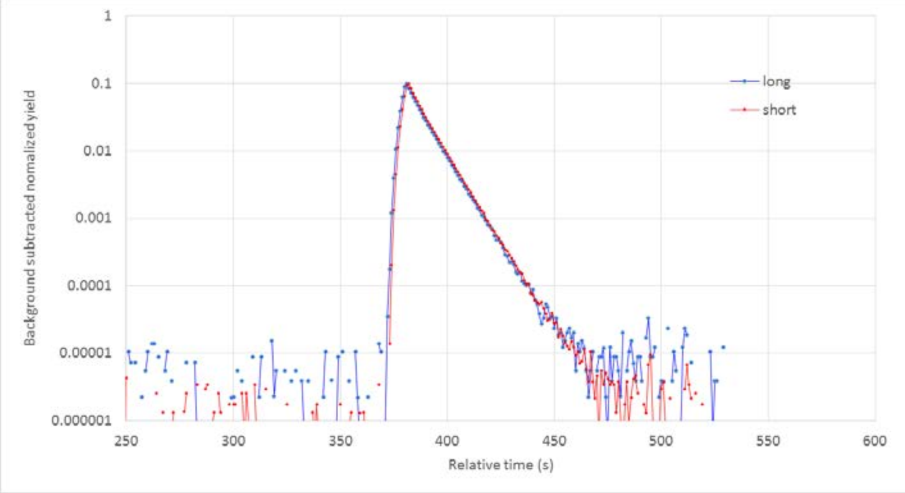


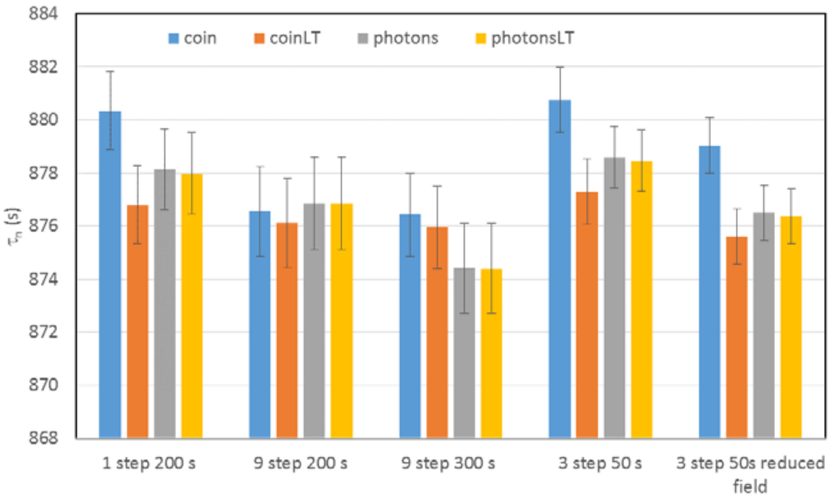
FY2017 results with giant cleaner and new source.



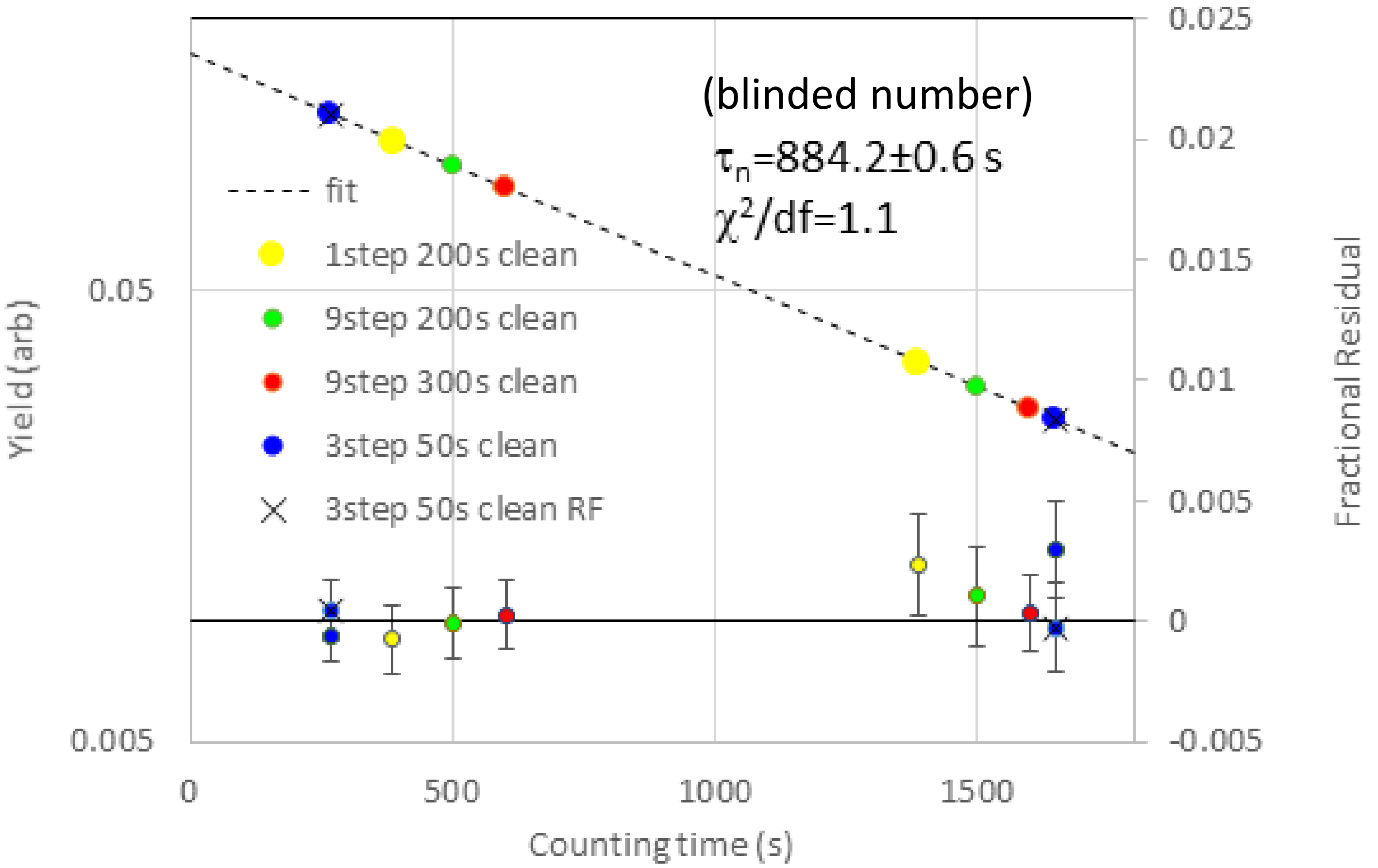
Trap cleaned to 10^{-4}

- No cleaning correction needed
- The UCN rate is too high!
  - Deadtime correction 1%
- New “current mode” counting method
- Used a different blinding factor from 2015/2016 data





Global fit into a single exponential function



(blinded number)

τ_n=884.2±0.6 s

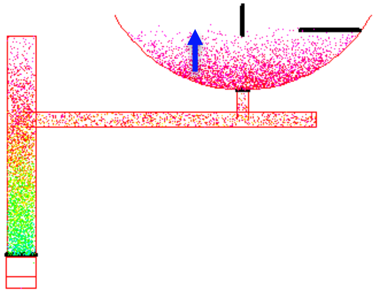
χ^2/df=1.1

Systematic uncertainties for the “current mode” counting

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)**

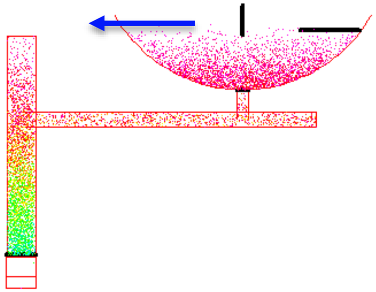
Heating

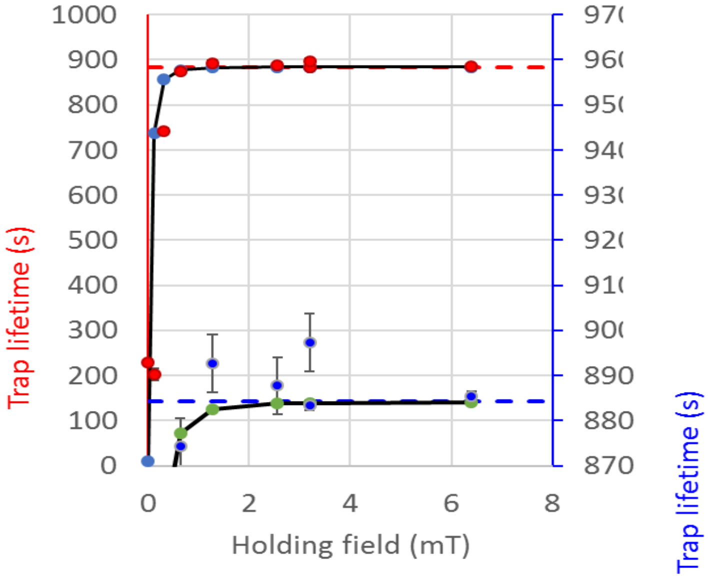
Limit established by long holding time excess



Insufficient Cleaning

Limit established by short holding time excess





Using analysis by Steyerl et al. 2016

Background variations (important for current-mode analysis)

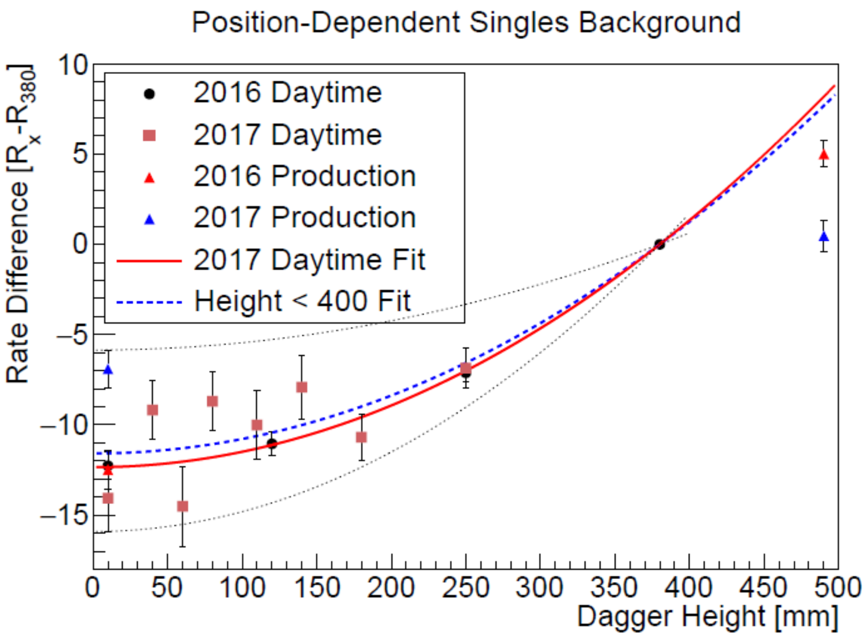


Figure 3: Position Dependence of singles background. Data comes from 4 sets - either dedicated background runs or production runs in either 2016 or 2017. One fit is from the cleanest dataset (2016 dedicated background), and the other is from all data points except ones with height > 380 mm. The thin, black dashed lines represent the extreme of the fit.

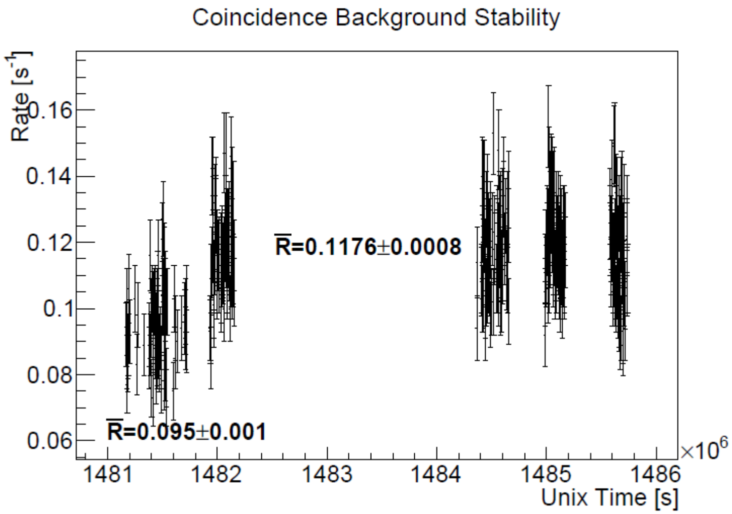
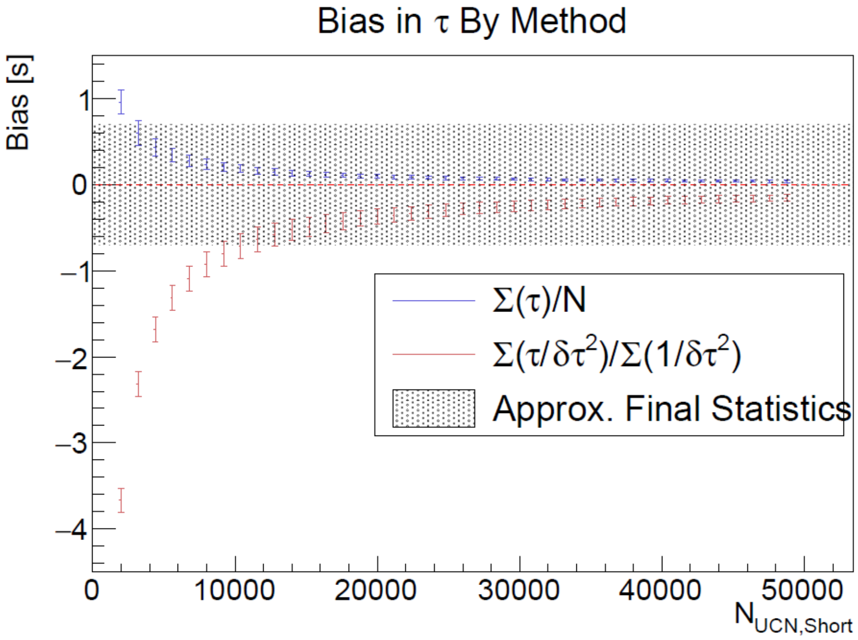


Figure 4: Coincidence Background Rate as a function of time.

Bias from statistical models



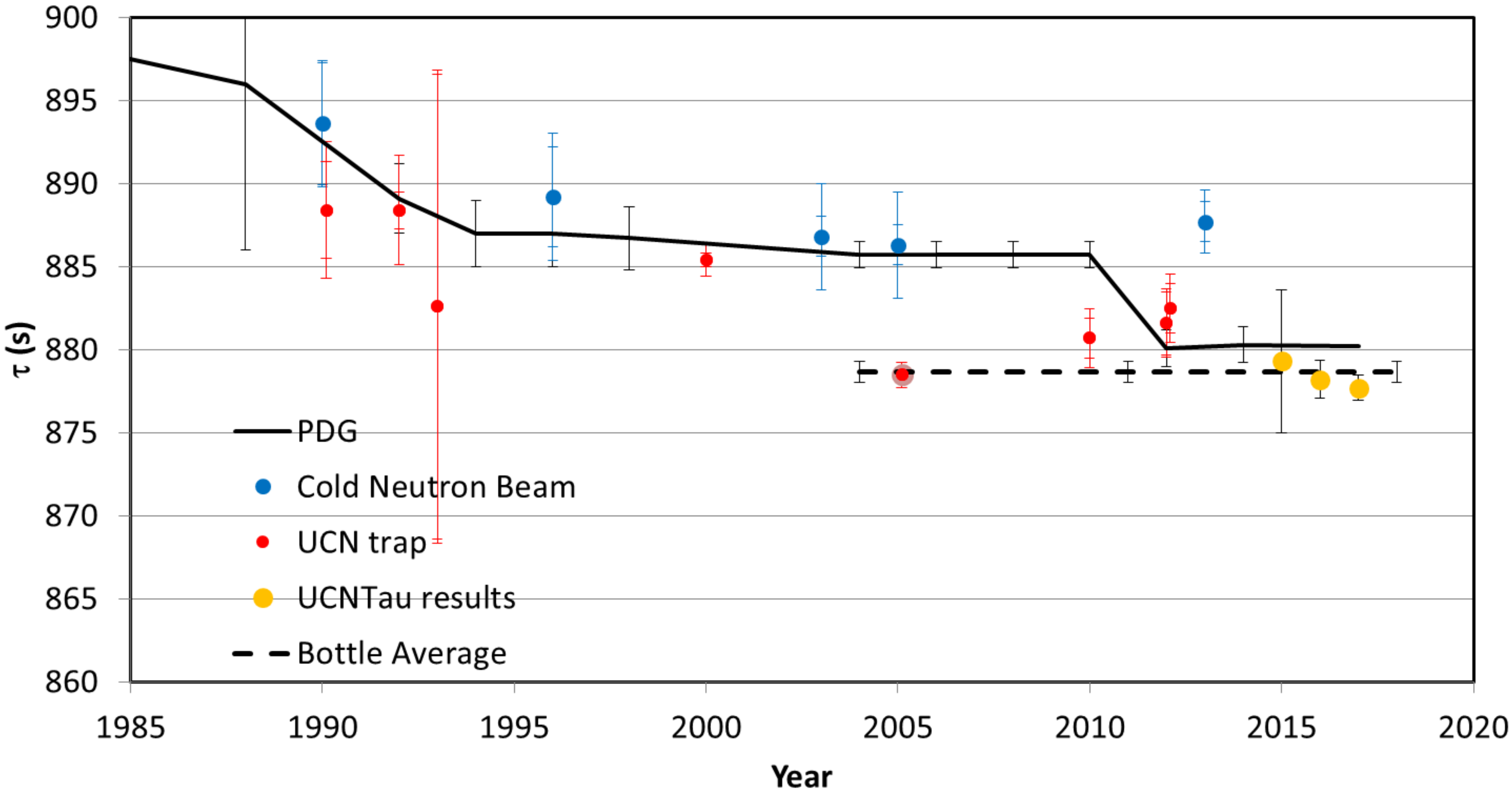
The standard "weighted average" assumes a Gaussian distributed event population and can result in a significant statistical bias.

Number of trapped neutrons are Poisson distributed.

Neutron decays follow binomial distribution, which gives a uncertainty much smaller than sqrt(N).

*The most probable is smaller than the mean for Poisson and binomial distributions.

New results


900
895
890
885
880
875
870
865
860
τ (s)
1985
1990
1995
2000
2005
2010
2015
2020
Year
PDG
Cold Neutron Beam
UCN trap
UCNTau results
Bottle Average

We have developed a new method for measuring the neutron lifetime

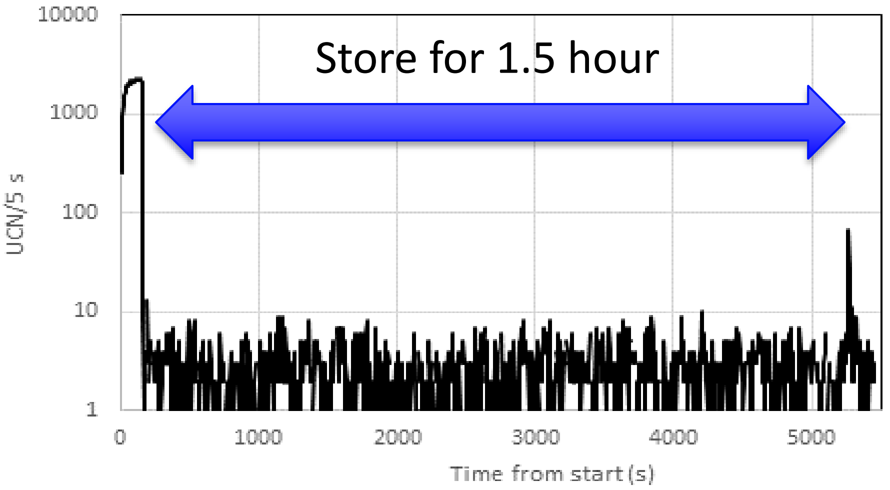
- We have demonstrated an *in situ* active neutron detector that allows for many systematic tests---enables the measurement to correct for insufficient cleaning and phase-space evolution.

- 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.

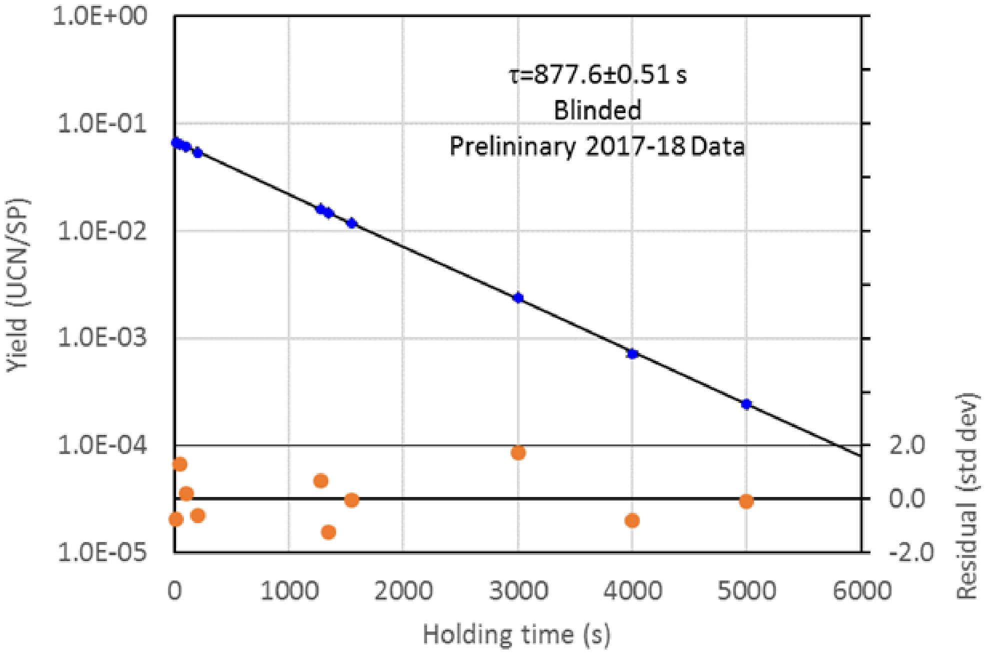
- All systematic uncertainties have been quantified by measurements, with size of corrections smaller than the statistical uncertainties.

- During 2017/2018 running, with x5 lower background and optimized data-taking, we hope to achieve a statistical uncertainty of ± 0.35 s (stat) ± 0.15 s (sys) with 20 weekends of data.

Moving forward



With ~7 weeks of running (since mid-August 2017):



- Discussion

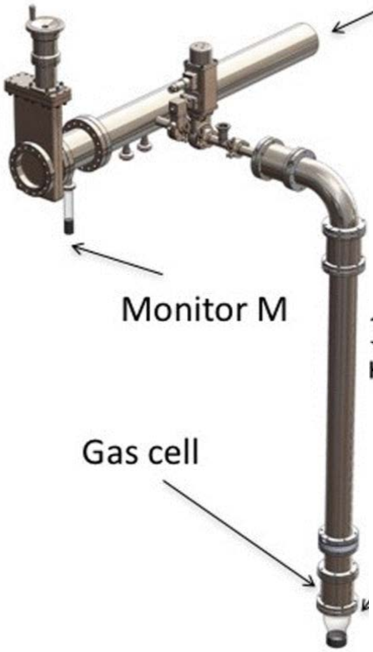
The 10 s n lifetime discrepancy

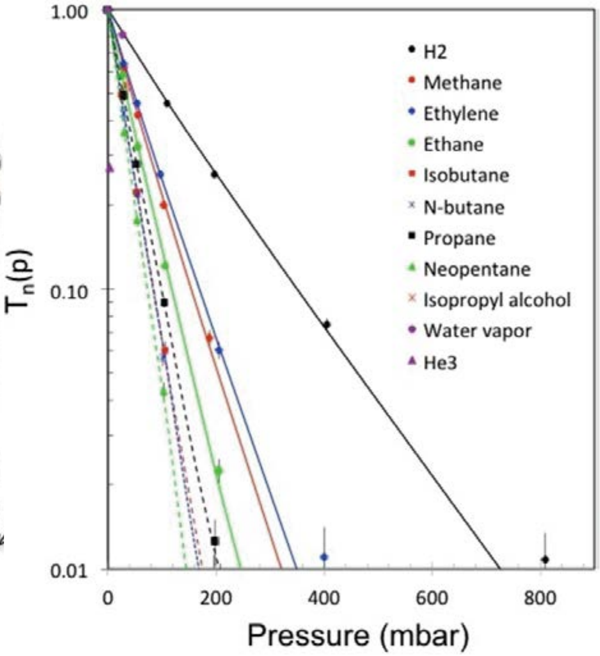
$$\frac{1}{\tau_n} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{BSM}}$$

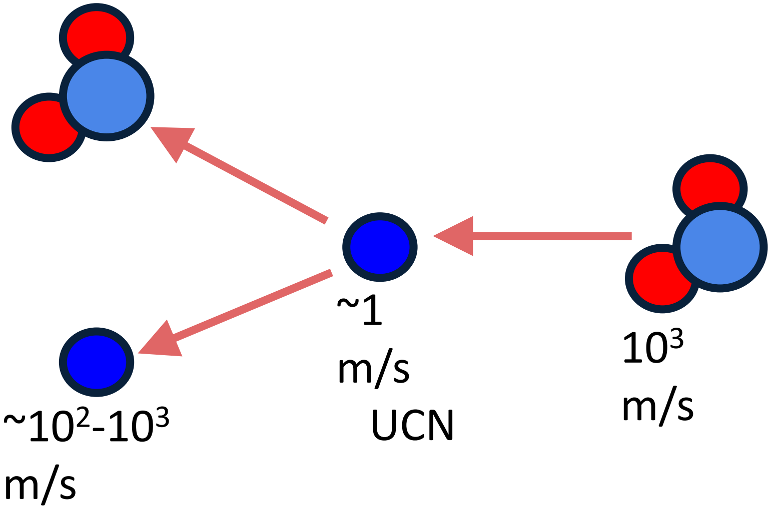
The 10 s discrepancy between beam (which measures τ_β) and bottled neutron (which measures τ_n) lifetimes needs a mechanism that gives τ_{BSM} = 80,000 s.

- **nnbar oscillation**
  - Experimental handle: suppressed by an external B field.
  - Current limit of (quasi-free) nnbar oscillation rate is already too small to explain the 10 s discrepancy.
  - Oscillation could be assisted with RF spin flip; B=0.5G, fRF= 15kHz.
  - We will push the lifetime uncertainty to 0.1 s in both material (B=0) & magnetic (B≠0) bottles. But the technique only help to constrain the $\tau_{BSM} = \tau_{nnbar}$ to 1e+7 s.
- **nn' oscillation**
  - Experimental handle: enhanced by matching the B & B' fields.
  - The bottle experiments are done in 0.5 G (material bottles) and 60 G- 800 G (UCNtau, Ezhov). They yield the same lifetime: 878 ± 1 s, and both indicates a neutron disappearance rate > beta-decay rate.
  - In the nn' oscillation scenario, this indicates a very broad resonance.
  - The preferred model of a long nnbar oscillation time (3e+8 s) and a short nn' oscillation time (~100 s) could source this large neutron disappearance rate.
- **UCN upscattered by dark matters**
  - The energy threshold for UCN nuclear recoil is ~ neV! (other DM detector thresholds ~ 2keV)
  - similar to UCN upscattering by residual gases.

Loss due to residual gas



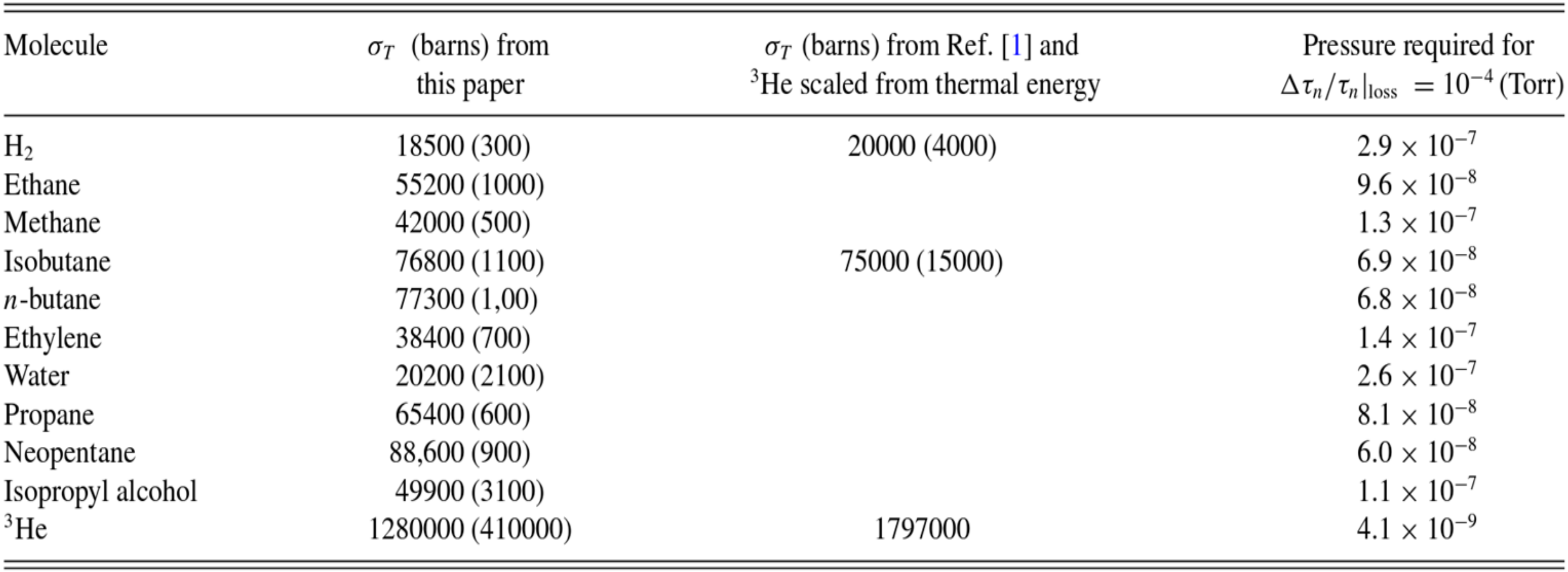




Loss due to residual gas

Total cross sections for ultracold neutrons scattered from gases

S. J. Seestrom *et al.*
Phys. Rev. C **95**, 015501 – Published 30 January 2017



Molecule	σ_T (barns) from this paper	σ_T (barns) from Ref. [1] and ^{3}He scaled from thermal energy	Pressure required for $\Delta\tau_n/\tau_n\|_{\text{loss}} = 10^{-4}$ (Torr)
H_2	18500 (300)	20000 (4000)	2.9×10^{-7}
Ethane	55200 (1000)		9.6×10^{-8}
Methane	42000 (500)		1.3×10^{-7}
Isobutane	76800 (1100)	75000 (15000)	6.9×10^{-8}
n-butane	77300 (1,00)		6.8×10^{-8}
Ethylene	38400 (700)		1.4×10^{-7}
Water	20200 (2100)		2.6×10^{-7}
Propane	65400 (600)		8.1×10^{-8}
Neopentane	88,600 (900)		6.0×10^{-8}
Isopropyl alcohol	49900 (3100)		1.1×10^{-7}
^{3}He	1280000 (410000)	1797000	4.1×10^{-9}

UCN upscattering by dark matters

- UCN is a sensitive dark matter probe: **$\sigma^{UCN}_{up}=\frac{v_f}{v_i}\sigma_{elastic}$=50,000 $\sigma_{elastic}$**
  - The energy threshold for UCN nuclear recoil is ~ neV!
- Consider the scenario of UCN upscattered by MM dark matters:
  - Similar to residual gas upscattering, τ_{up} =800,000 s for 10^{-6} torr of H_2 atoms (which leads to a 1 s lifetime correction).
  - With DM velocity of 250 km/s, the σ_{up} of UCN upscattering by the DM is

$$\frac{1}{\tau_{up}\,(DM)} = n'\sigma'_{up} = n'\varepsilon\frac{v'_f}{v_f}\sigma_{up}=n'\varepsilon\,\frac{250\;km/s}{2.2\;km/s}\,\sigma_{up} \approx 100\varepsilon\frac{n'}{n}\,\frac{1}{\tau_{up}(H_2)}$$

suggest that

$100\varepsilon\frac{n'}{n} \approx \frac{\tau_{up}(H2)}{\tau_{up}(DM)}$=10 → $\varepsilon n'$ ≈0.1 n = 0.1 x 10^{-9} atm

$\Omega_{DM} = 5\,\Omega_b$, assuming DM is MM and local density of ~ 1atm, then ε=1e-10!

ε = Coupling between OM & MM

Is this a viable solution?

It is certainly more compelling than nn’ oscillation, because it does not require transition in resonance (by tuning the B field or matching the mass spectrum).

Responses

- What are the experimental observables?
  - the daily modulation of the neutron lifetime.
- Another possibility is that neutrons decay into a mirror neutrons (which are lighter)