An Improved Ultracold Neutron Bottle for Measuring the Neutron Lifetime

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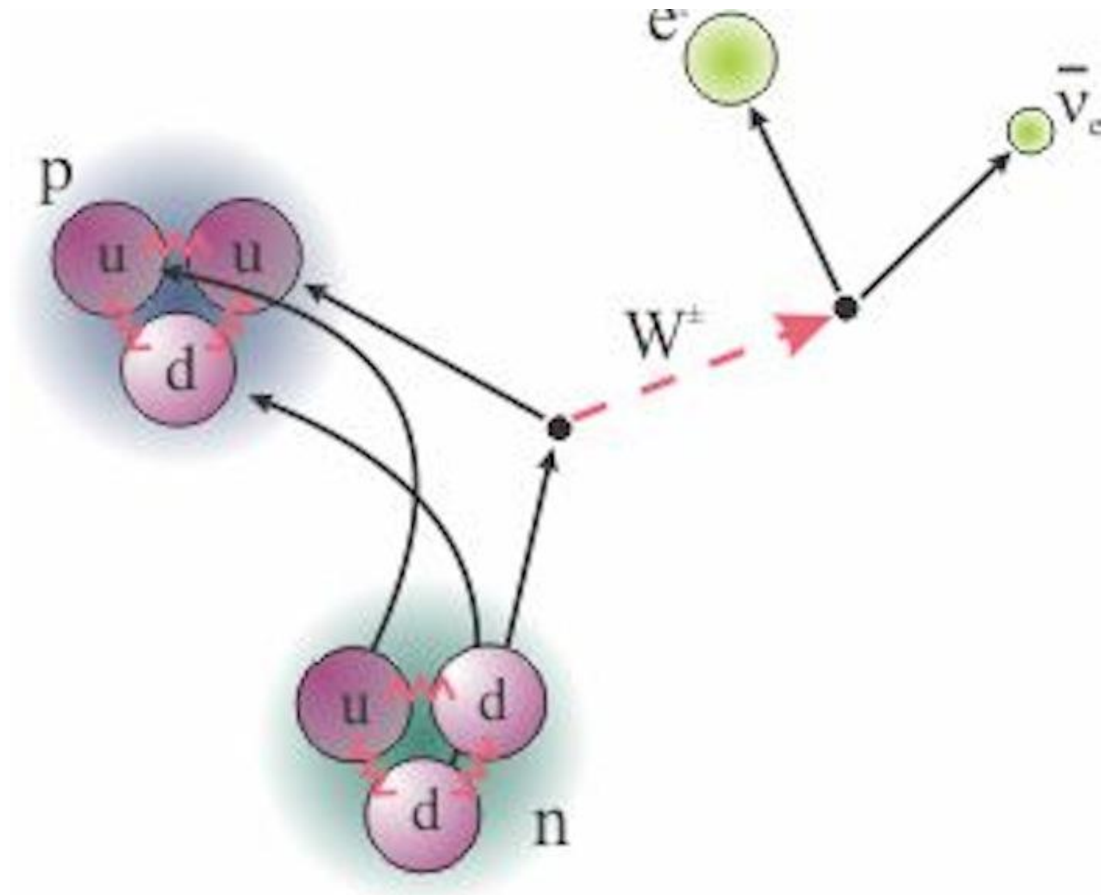
10 November 2016

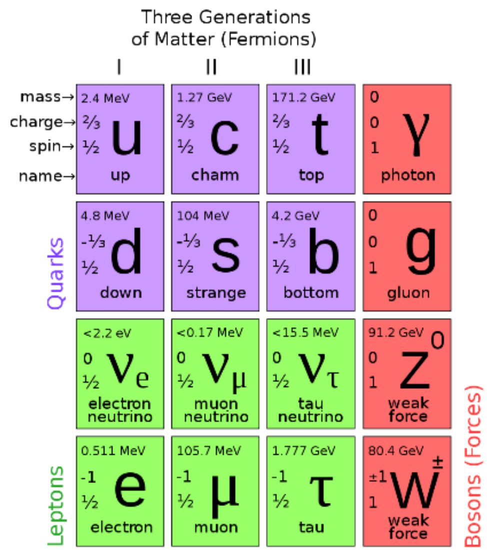
Neutron Beta Decay

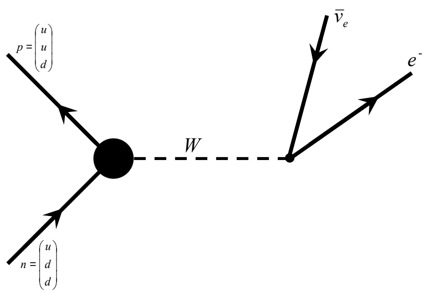
$n \rightarrow e^{-} + p + \bar{\nu}_e$

$\tau_n \approx 881$ s



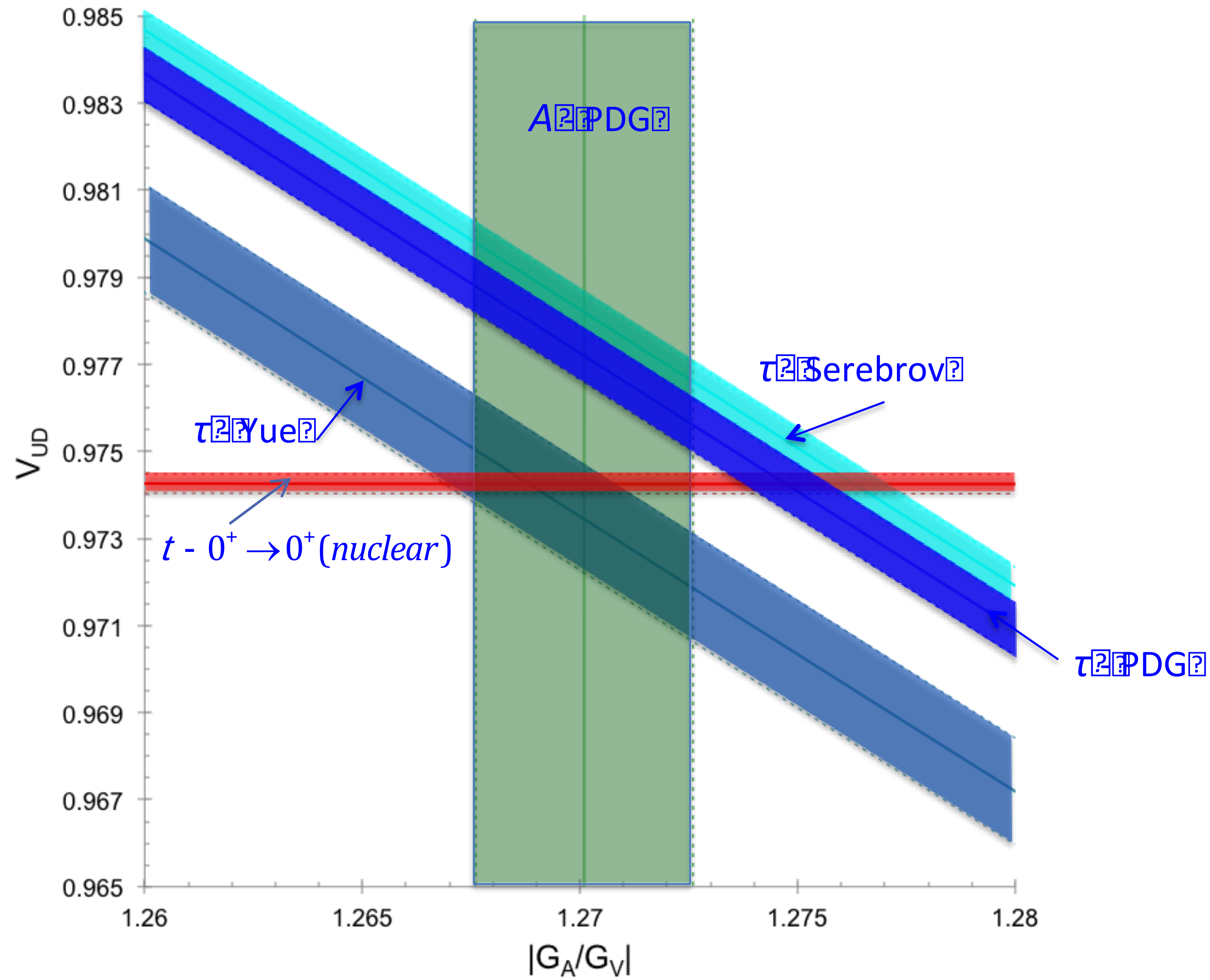
The Neutron and the Standard Model





$$|V_{ud}|^2 = \frac{4908.7s}{\tau_n(1+3\lambda^2)}$$

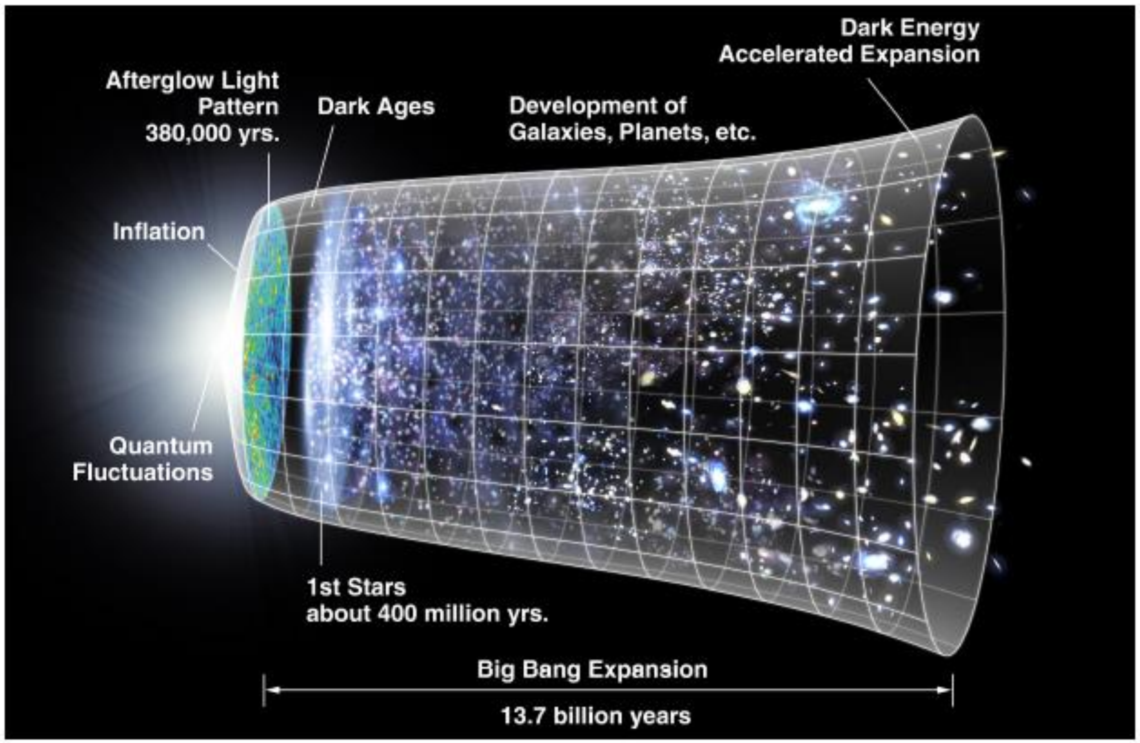
$$\lambda = {}^{G_A}/_{G_V}$$



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

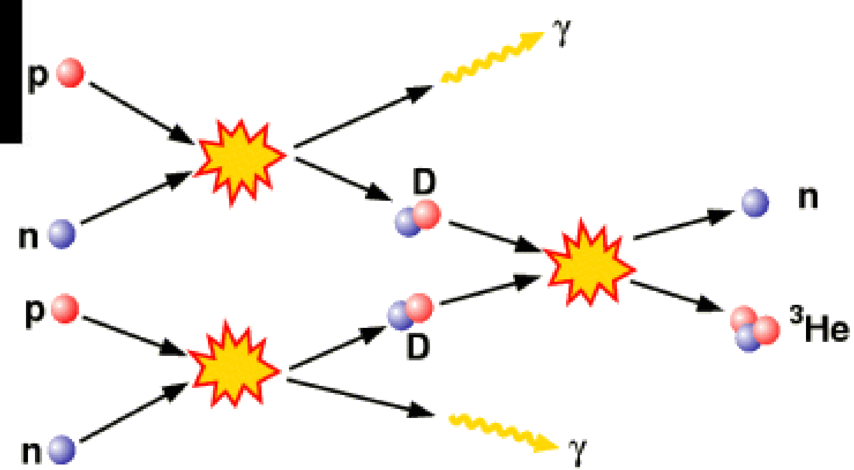
$$\left|V_{ud}\right|^2 + \left|V_{us}\right|^2 + \left|V_{ub}\right|^2 = 1$$

Big Bang Nucleosynthesis



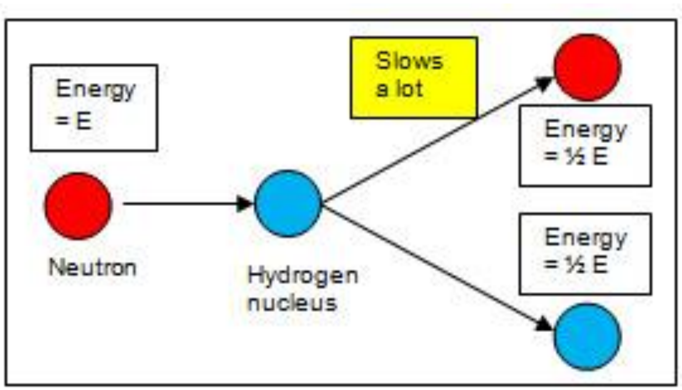
Universal He fraction depends on τ_n

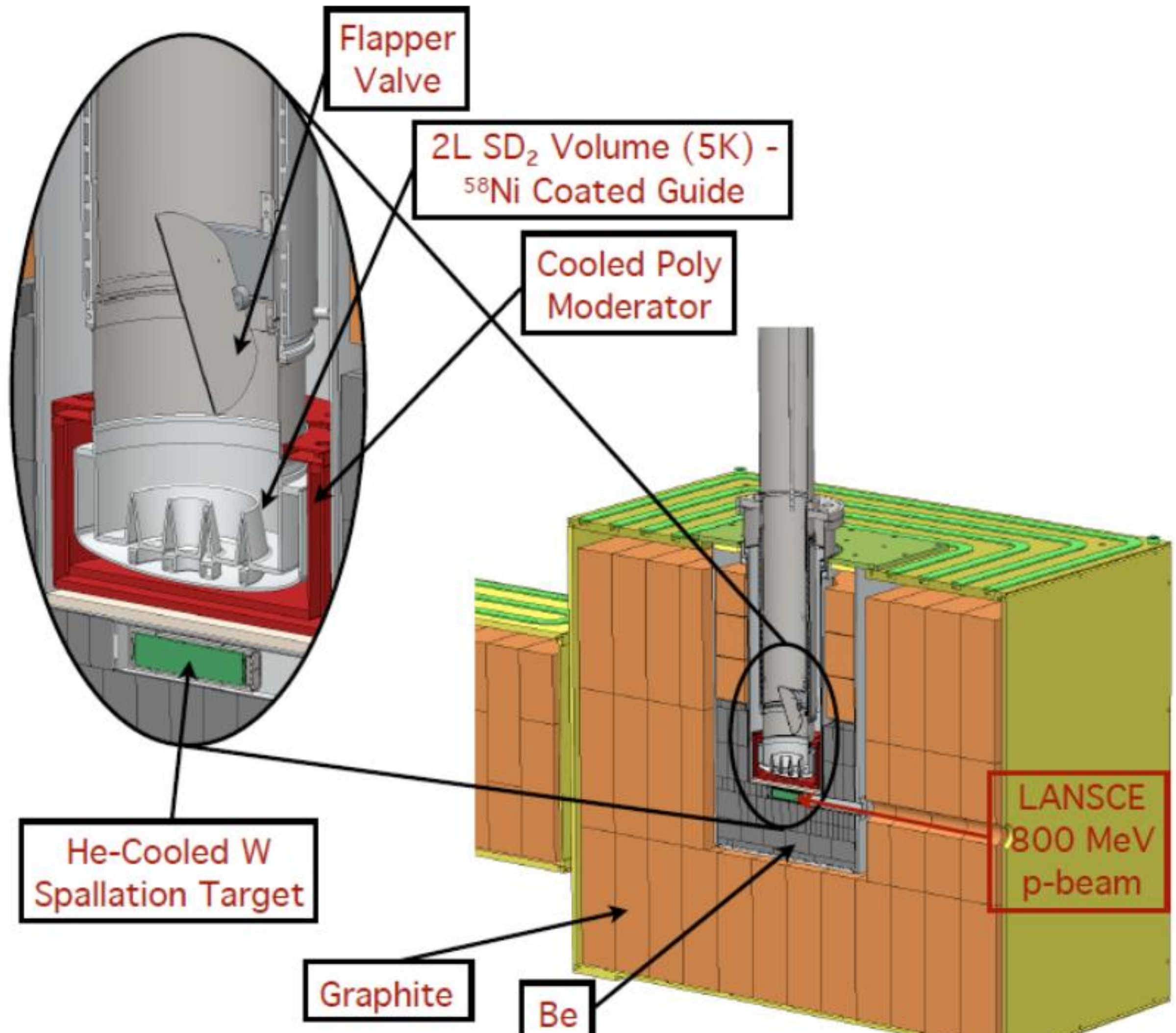
$$Y_p \sim \frac{2e^{-t_d/\tau_n}}{1 + e^{\Delta m / k T_f}}$$



Ultracold Neutrons

- LHe, SD_2 moderate spallation neutron energies
- $E_{UCN} \leq$ ~300neV

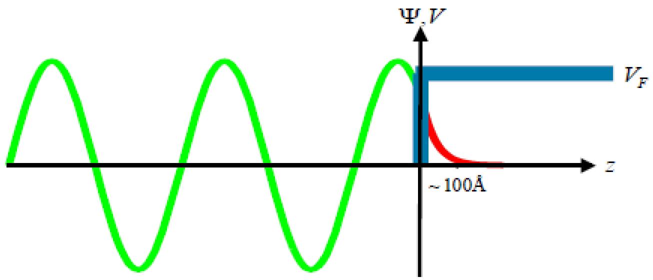




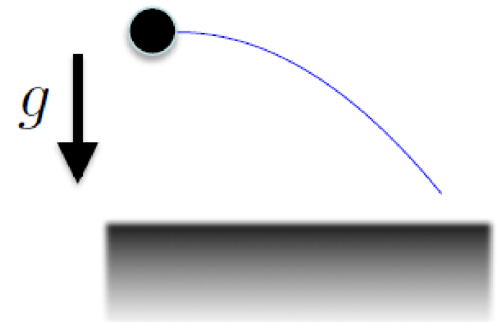
A. Saunders *et al.*, Rev. Sci. Inst. 84, 013304 (2013)

UCN Interactions

Nuclear Interaction

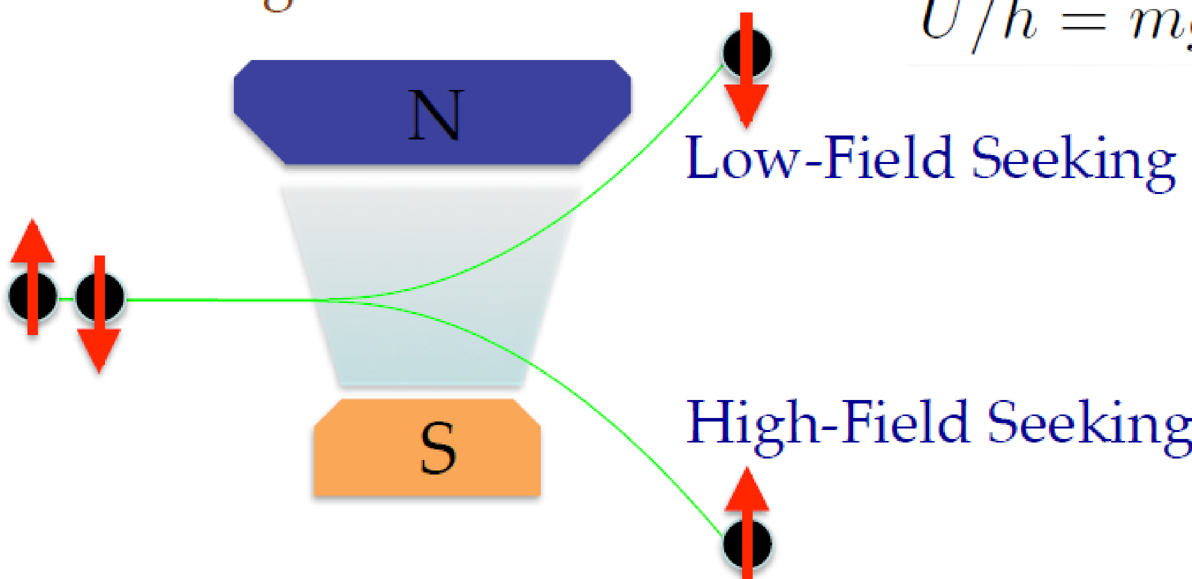


Gravitational Interaction



$$U/h = mg \sim 100\ \mathrm{neV/m}$$

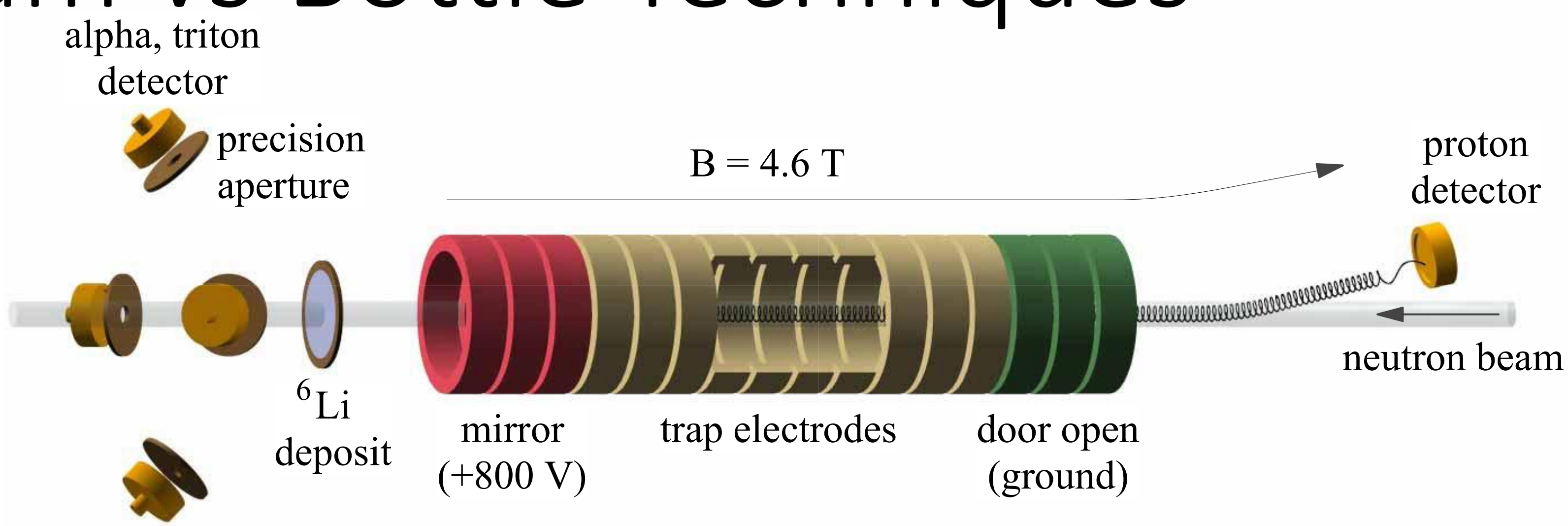
Magnetic Interaction



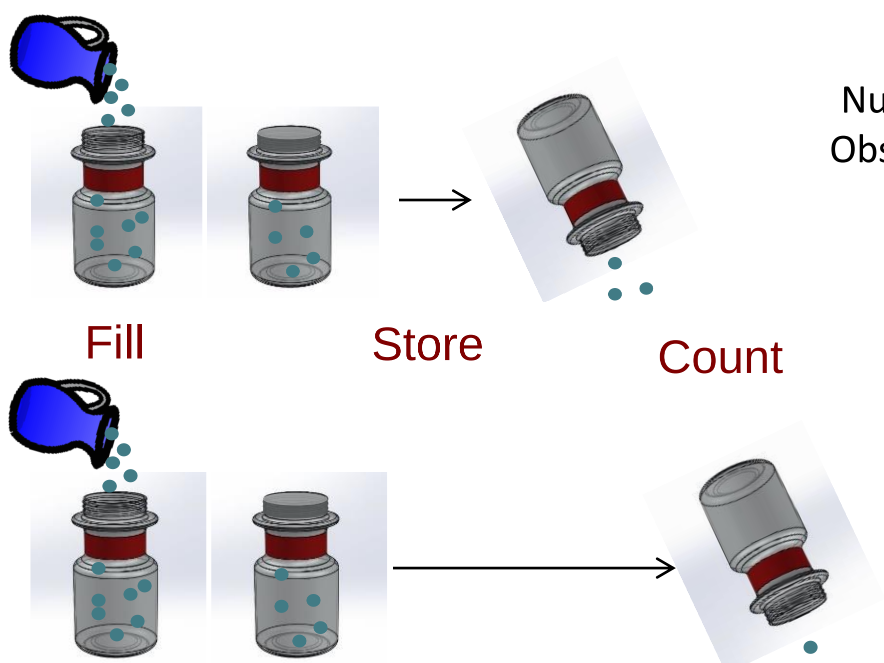
$$U = -\left[\,-|\gamma_{\mathrm{n}}|\vec{S}\,\right] \cdot \vec{B} \sim \pm 60\ \mathrm{neV/T}$$

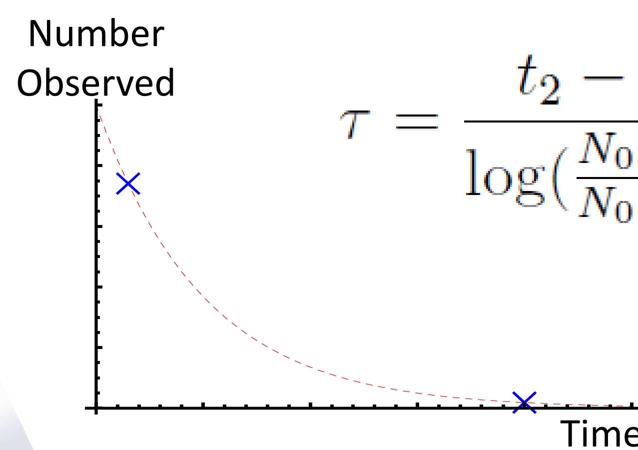
Beam vs Bottle Techniques

Cold Neutron Beam

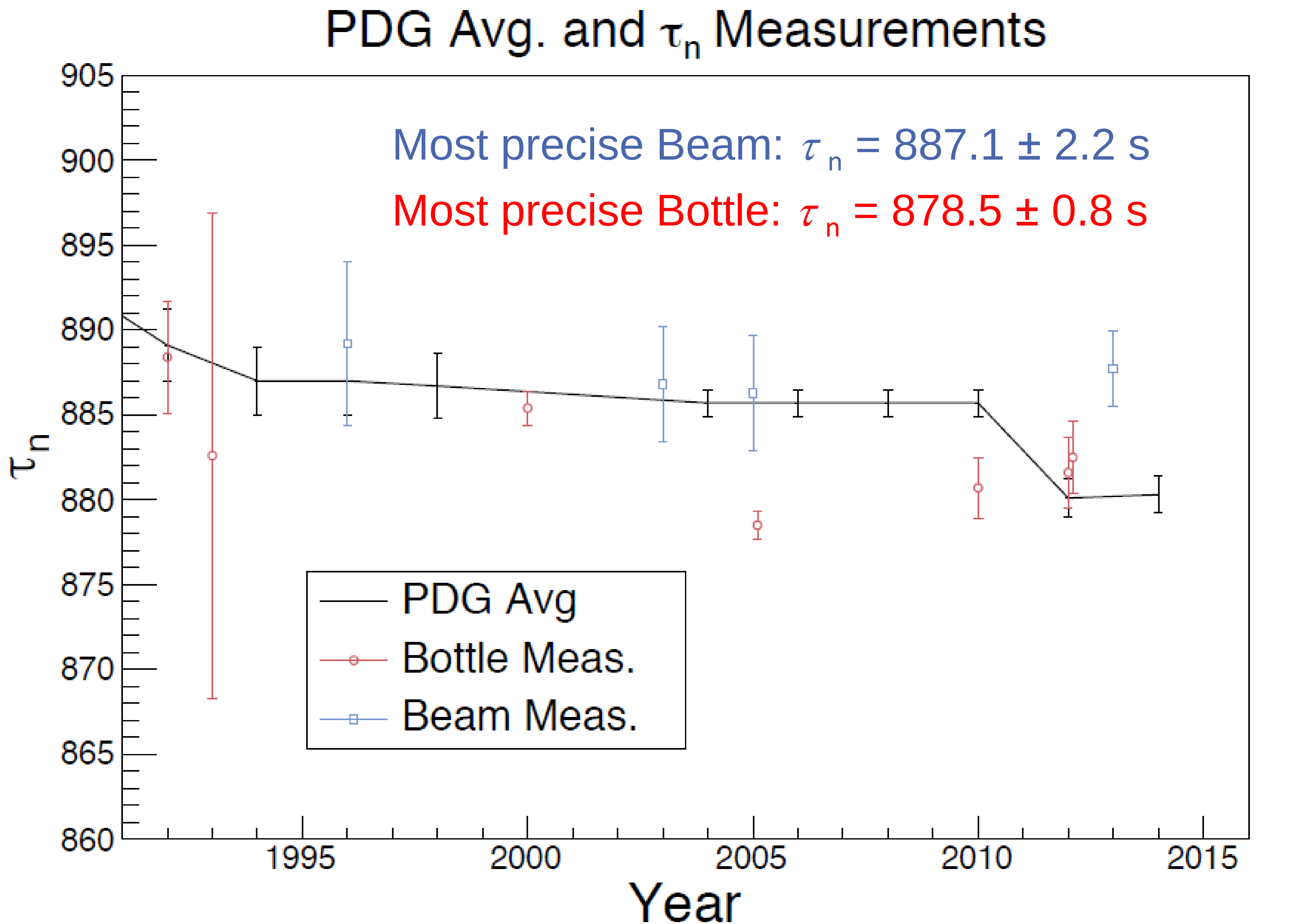


Ultracold Neutron (UCN) Bottle

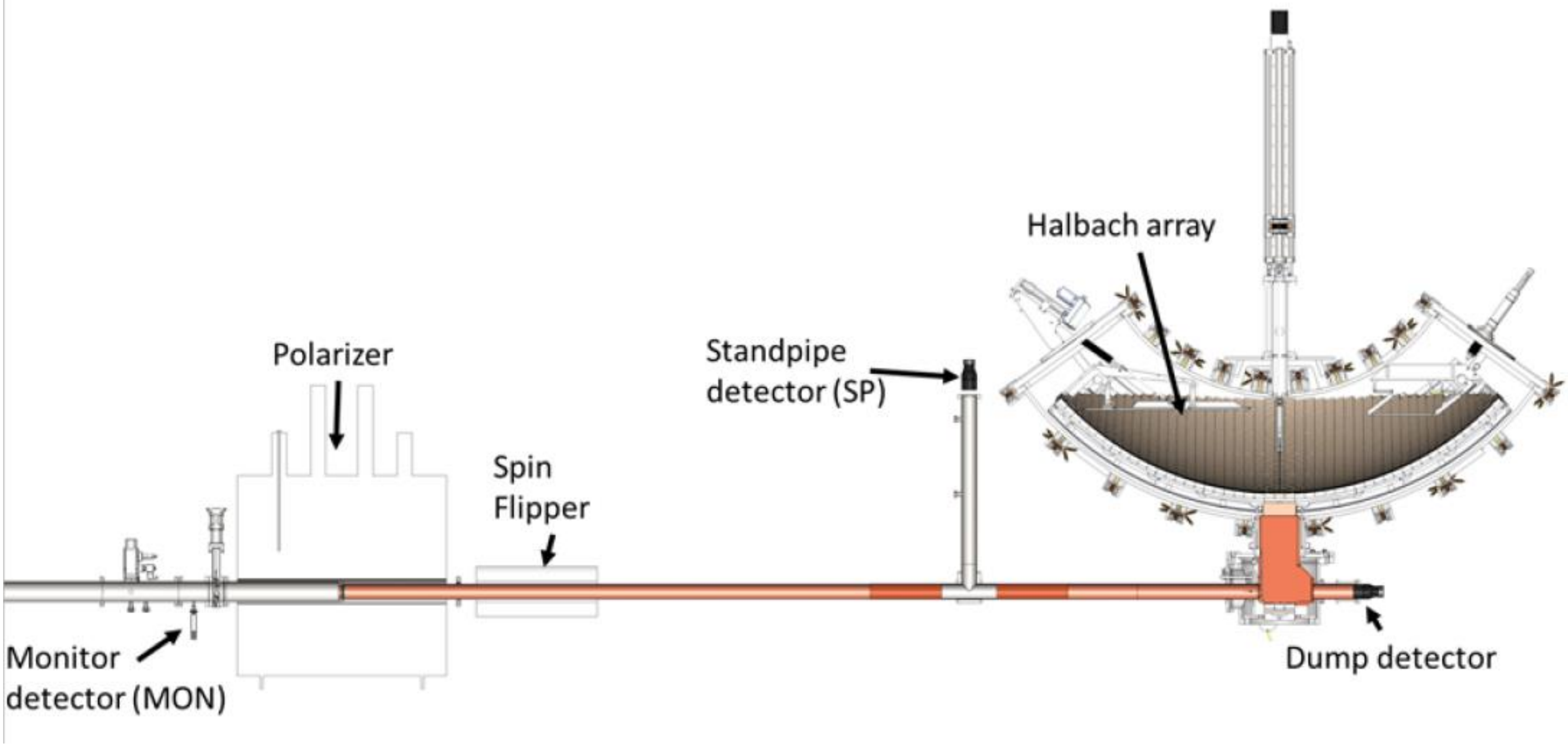




$$\tau = \frac{t_2 - t_1}{\log(\frac{N_0(t_1)}{N_0(t_2)})}$$

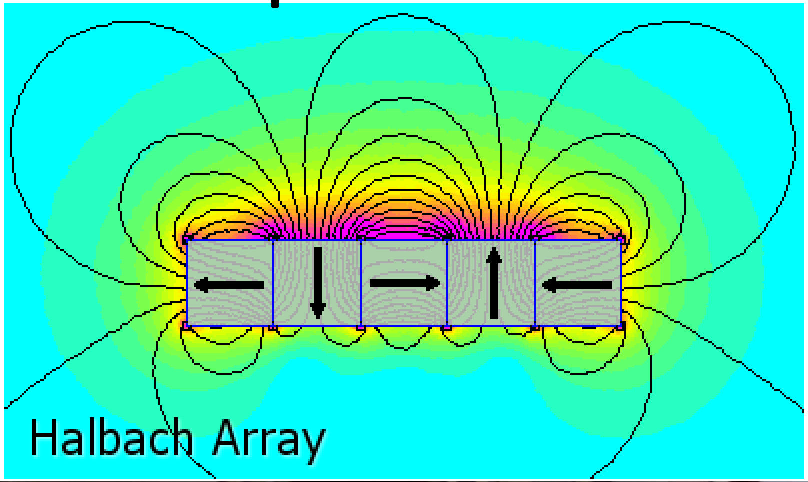

PDG Avg. and τ_n Measurements
Most precise Beam: τ_n = 887.1 ± 2.2 s
Most precise Bottle: τ_n = 878.5 ± 0.8 s
PDG Avg
Bottle Meas.
Beam Meas.
τ_n
905
900
895
890
885
880
875
870
865
860
1995
2000
2005
2010
2015
Year

The UCNtau Experiment



Magneto-gravitational trap

- 670L Halbach array bounds UCN from below
- Gravity bounds UCN (E<50neV) from above
- Open top allows in-situ detection
- Large volume, minimal surface interaction
- Asymmetry → phase space mixing
- Holding field prevents depolarization



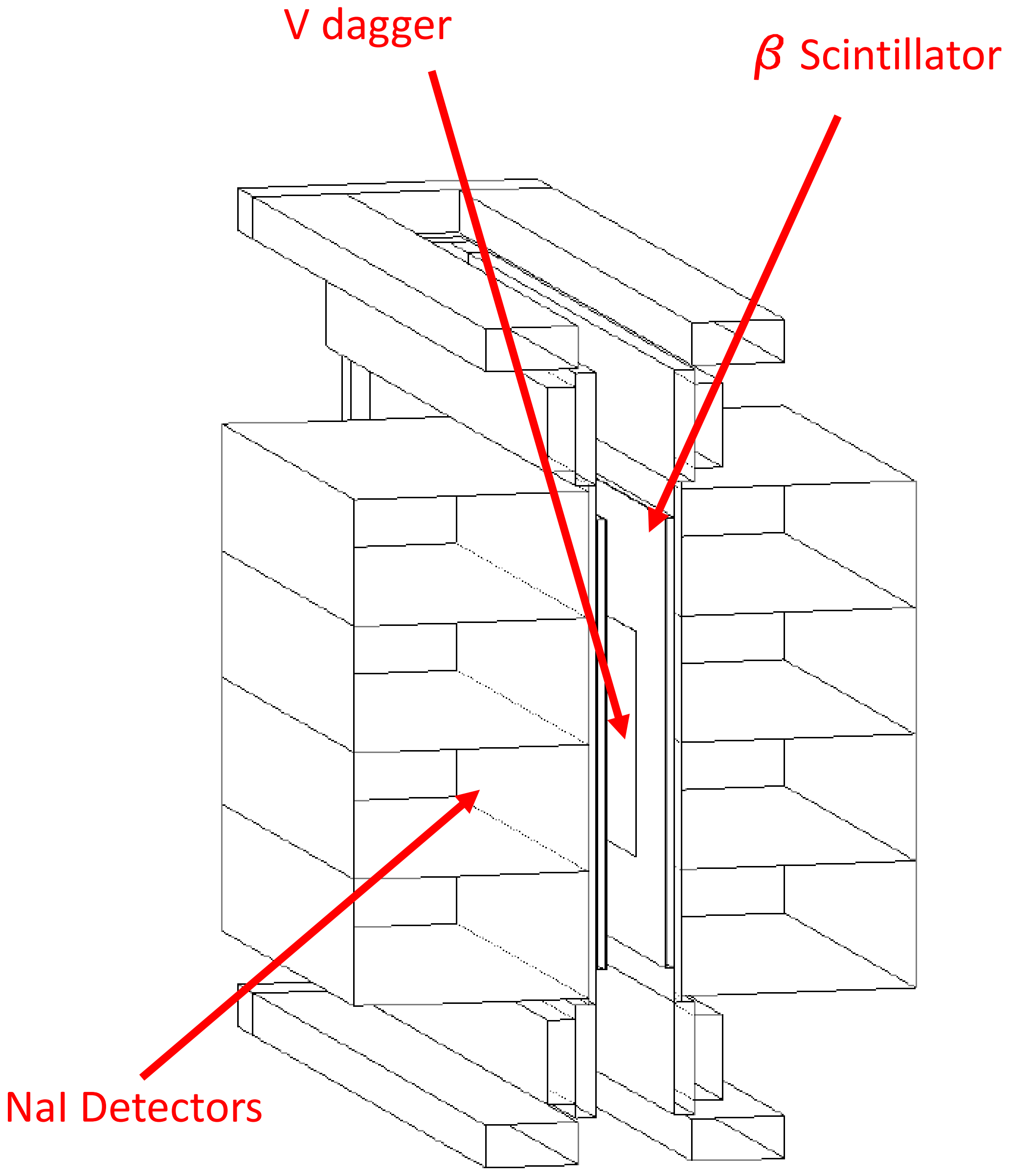
Vanadium detector

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

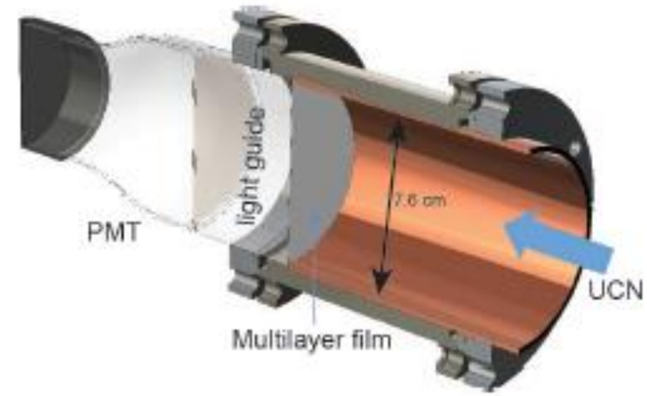
$^{52}V \rightarrow {}^{52}Cr^{*} + e^{-} + \bar{\nu}_e$

$^{52}Cr^{*} \rightarrow {}^{52}Cr + \gamma(1434keV)$

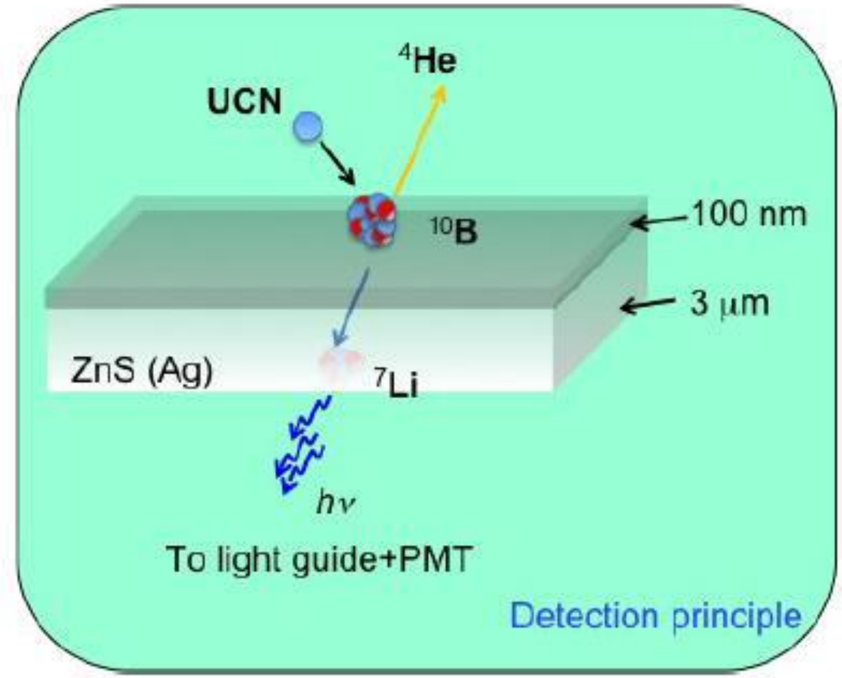
- Coincident γ and β captured by detector stack
- $\tau_V = 324s$



ZnS Detectors



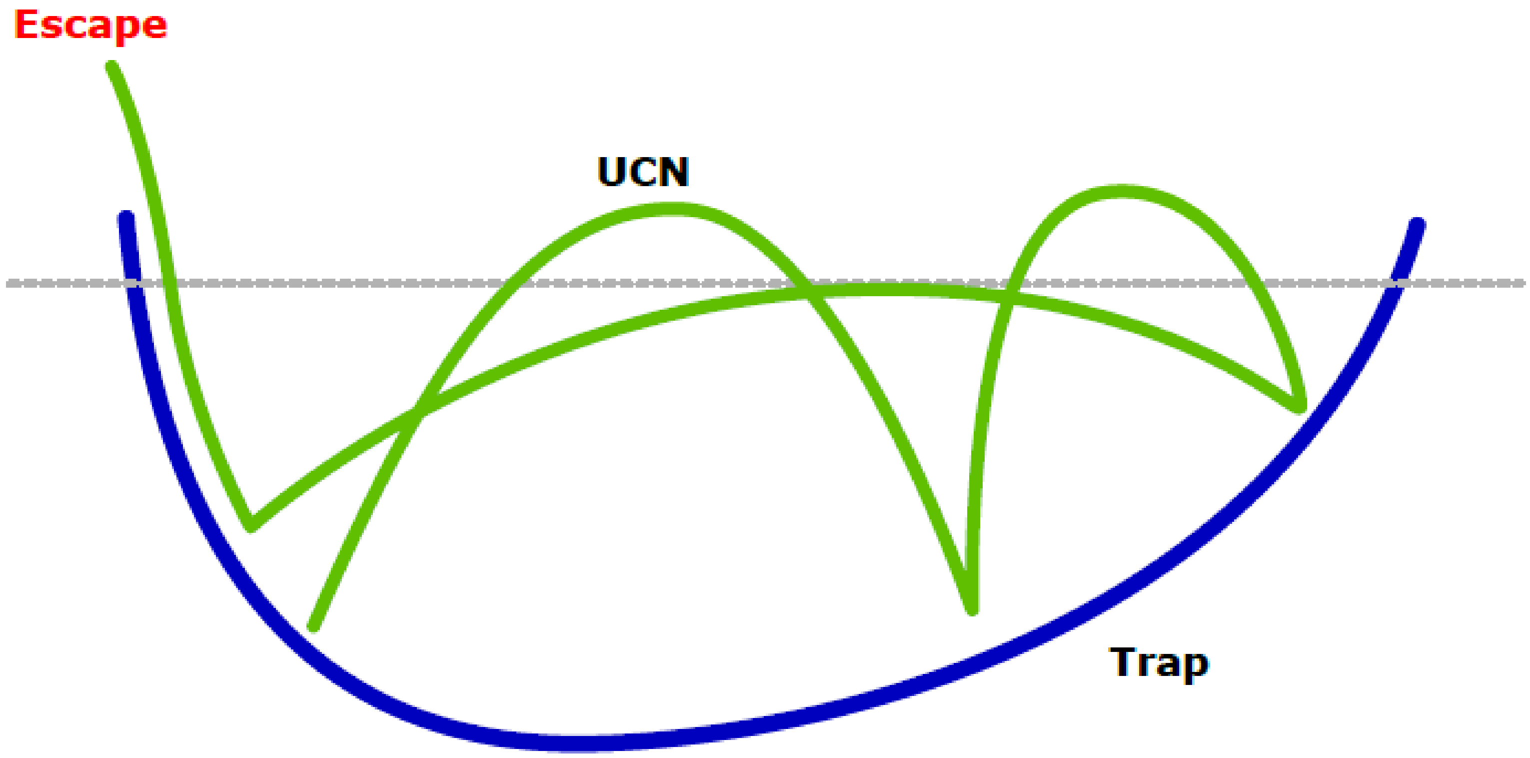
- Developed new detectors to replace ^{10}B monitors
- $n + {}^{10}B \rightarrow {}^{7}Li + \alpha$
- High eff, low bg
- No leak systematics



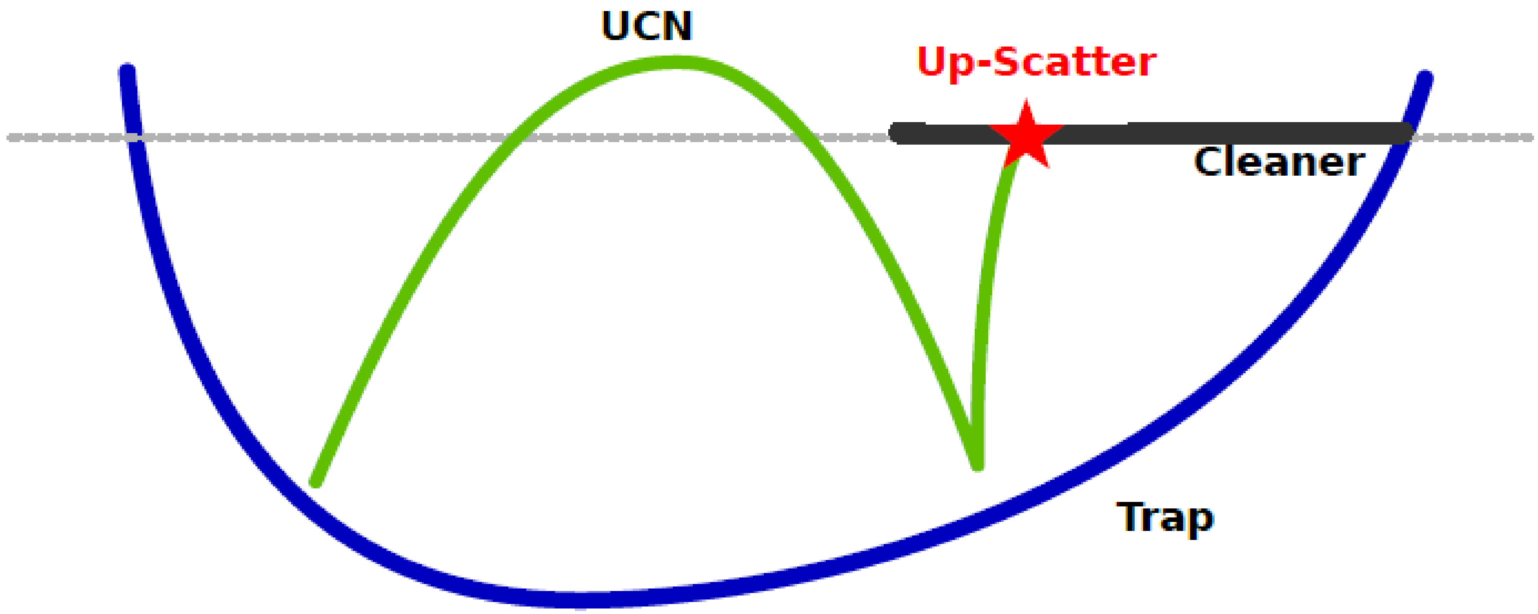
Ion (probability, w^i)	Energy (E_0^i, MeV)	Range in ^{10}B (R^i, μm)	Range in ZnS (R^i, μm)
α (47%)	1.47	3.5	4.2
α (3%)	1.78	4.4	5.1
^{7}Li (47%)	0.84	1.8	2.3
^{7}Li (3%)	1.02	2.1	2.5

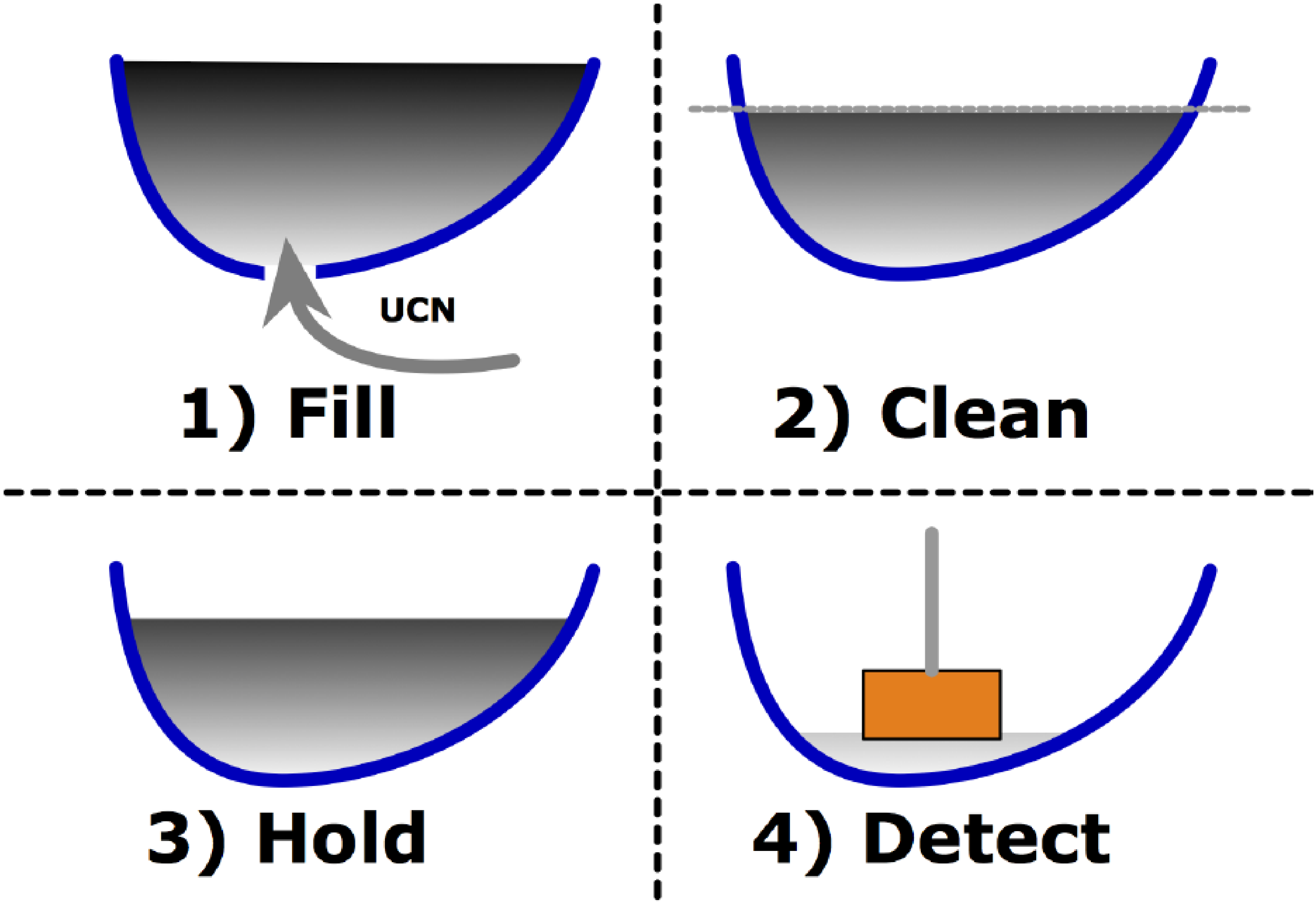
Z. Wang *et al.*, Nucl. Inst. Meth. A. 798 (2015) 30-35

Marginally Trapped UCN

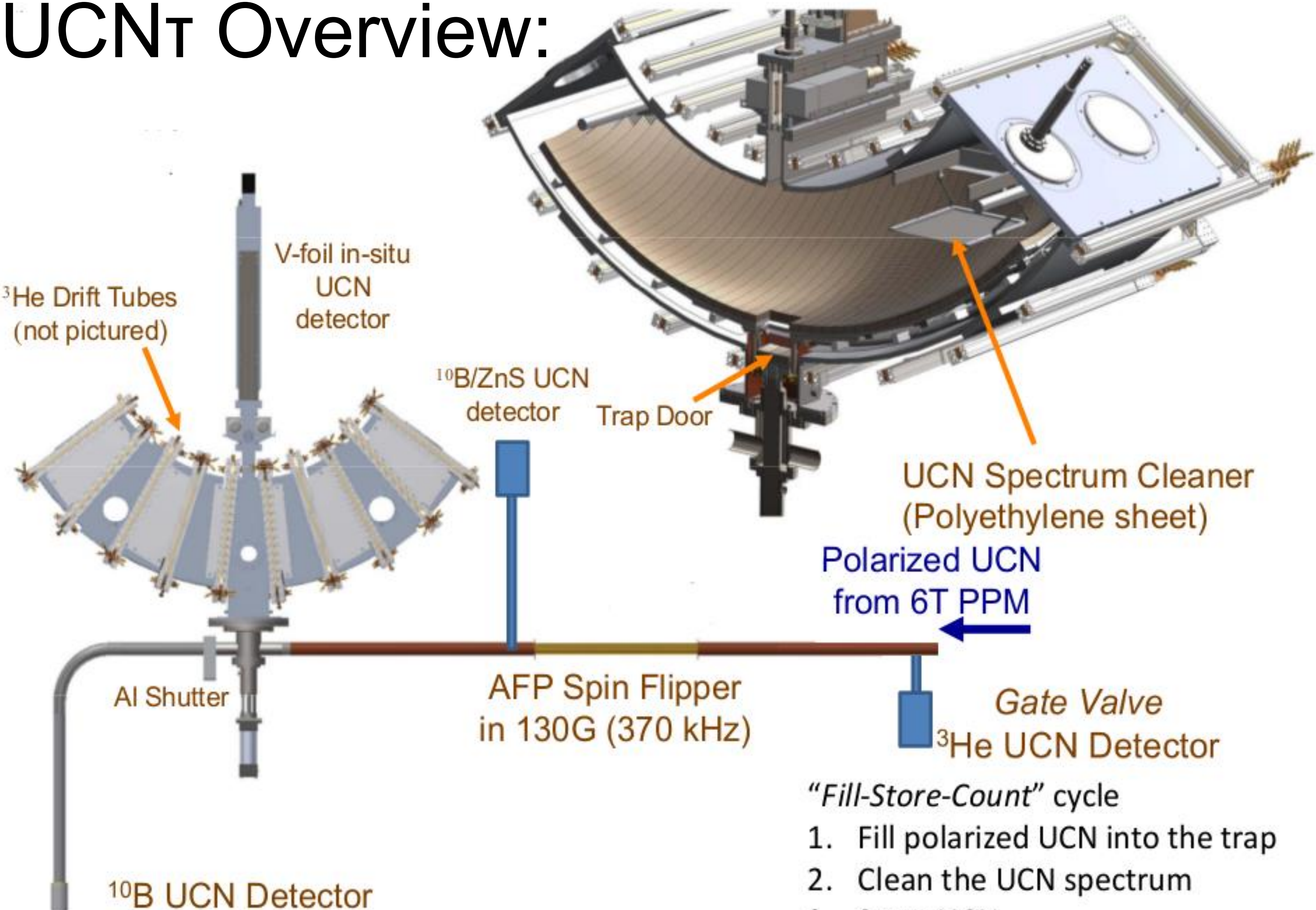


Marginally Trapped UCN



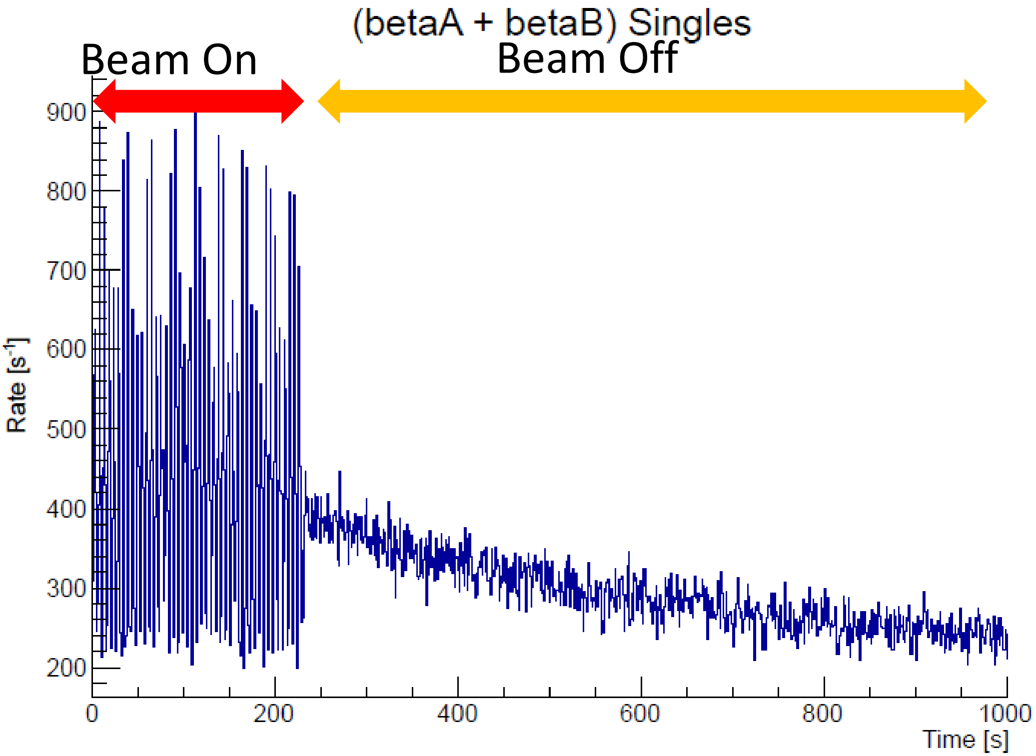

UCN
1) Fill
2) Clean
3) Hold
4) Detect

UCNτ Overview:

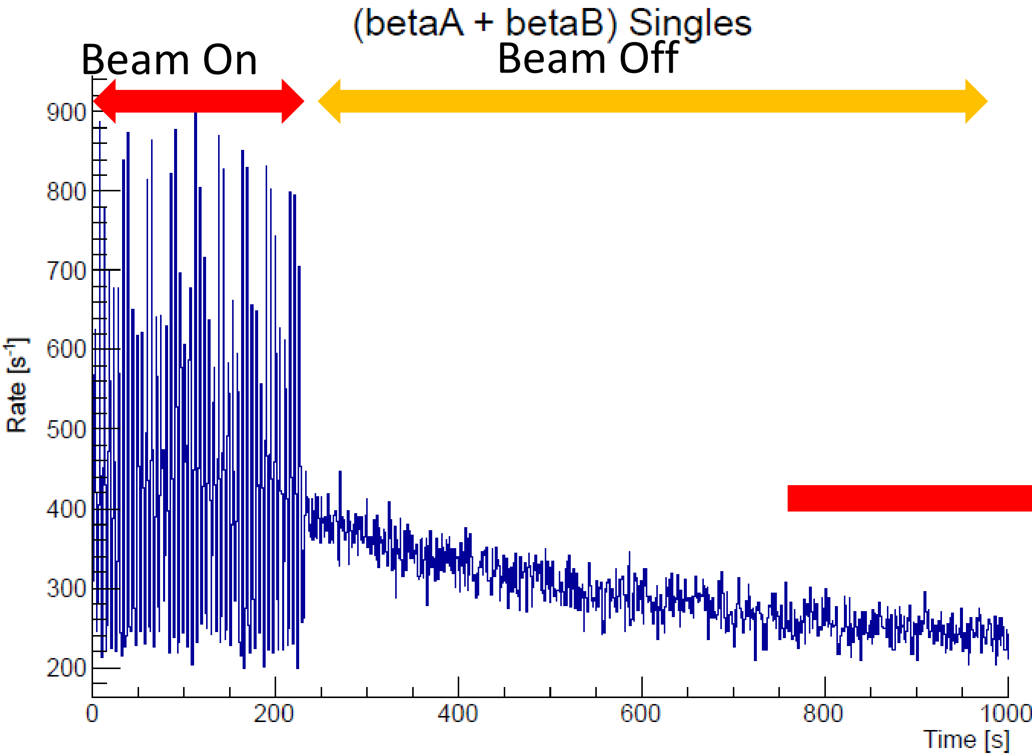


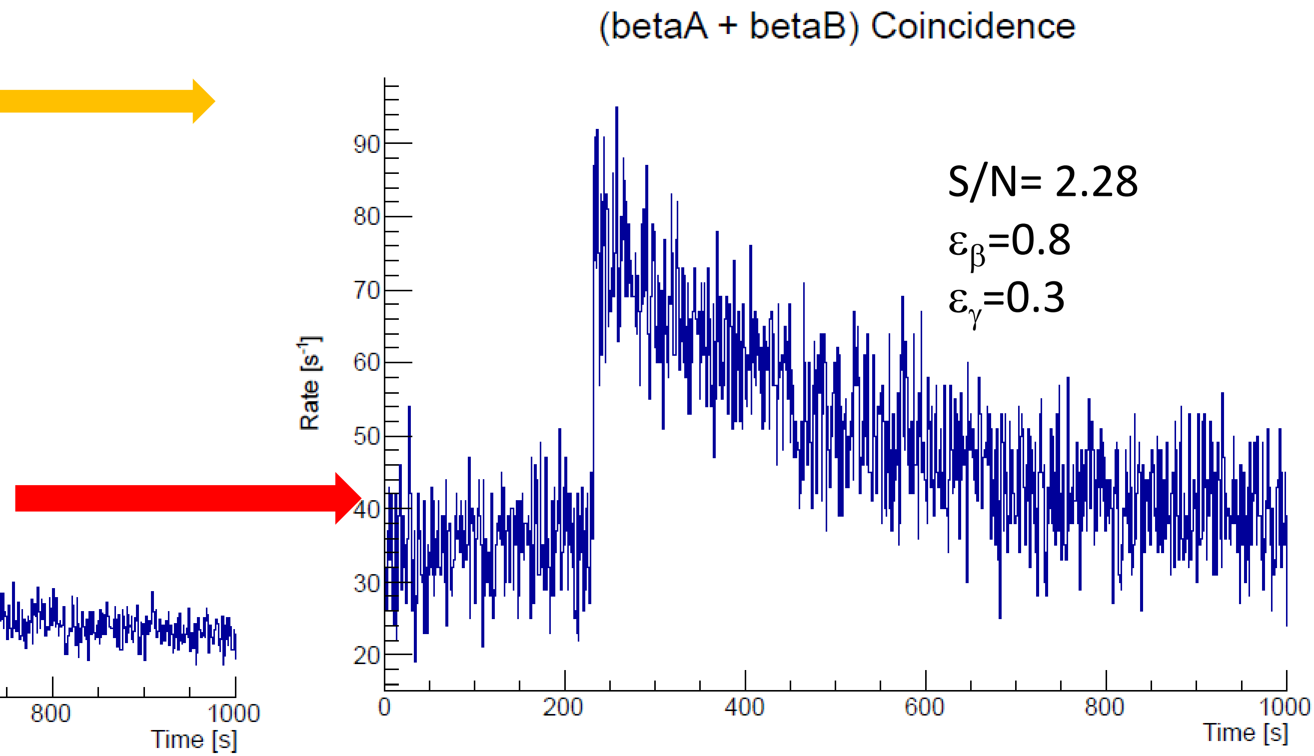
"*Fill-Store-Count*" cycle

1. Fill polarized UCN into the trap
2. Clean the UCN spectrum
3. Store UCN
4. Count UCN (In situ V detector)



Cut Criteria:



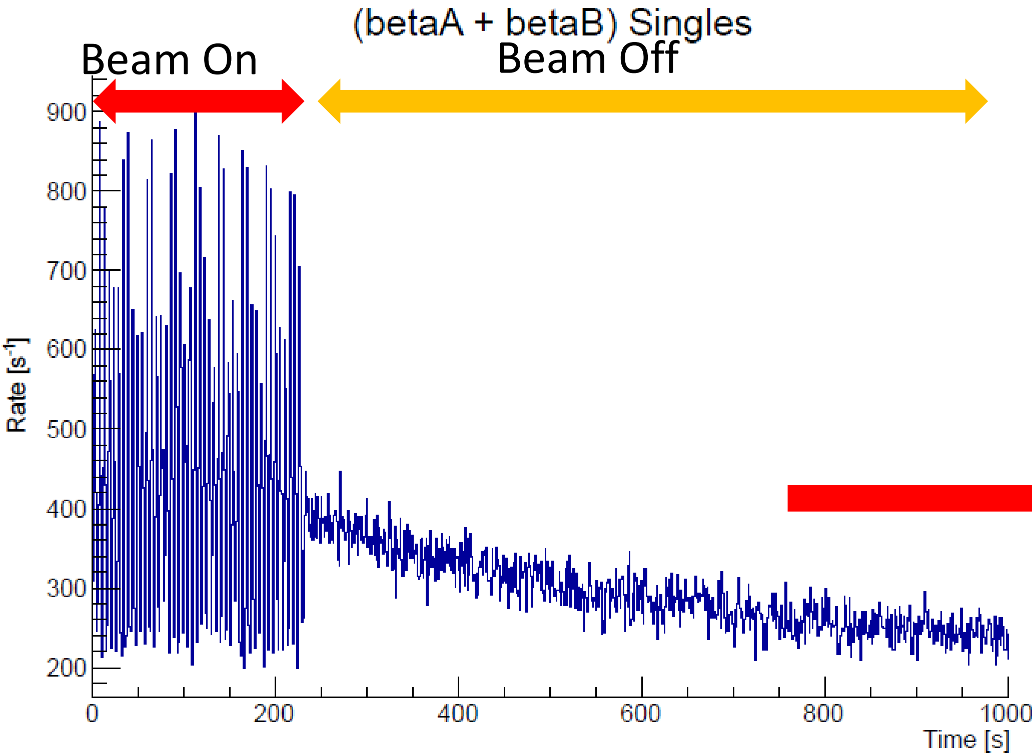


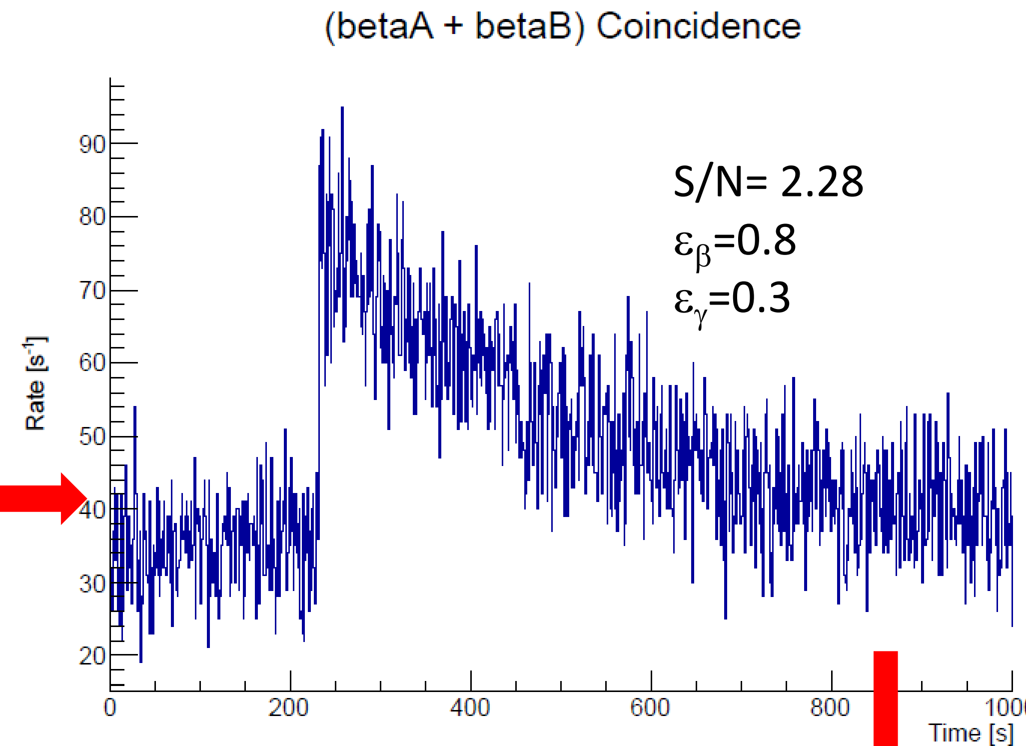
Cut Criteria:

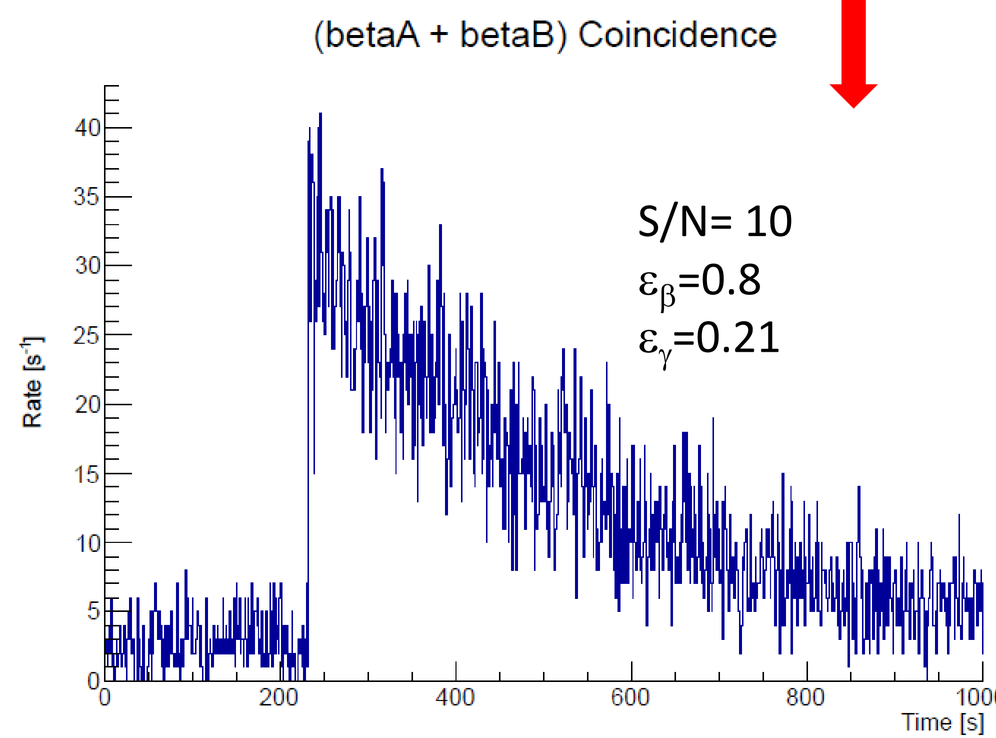
1)beta event is not coincident with a beta event in the other detector

2)beta event pulse-height cut

3)beta event is coincident with an NaI event







Cut Criteria:

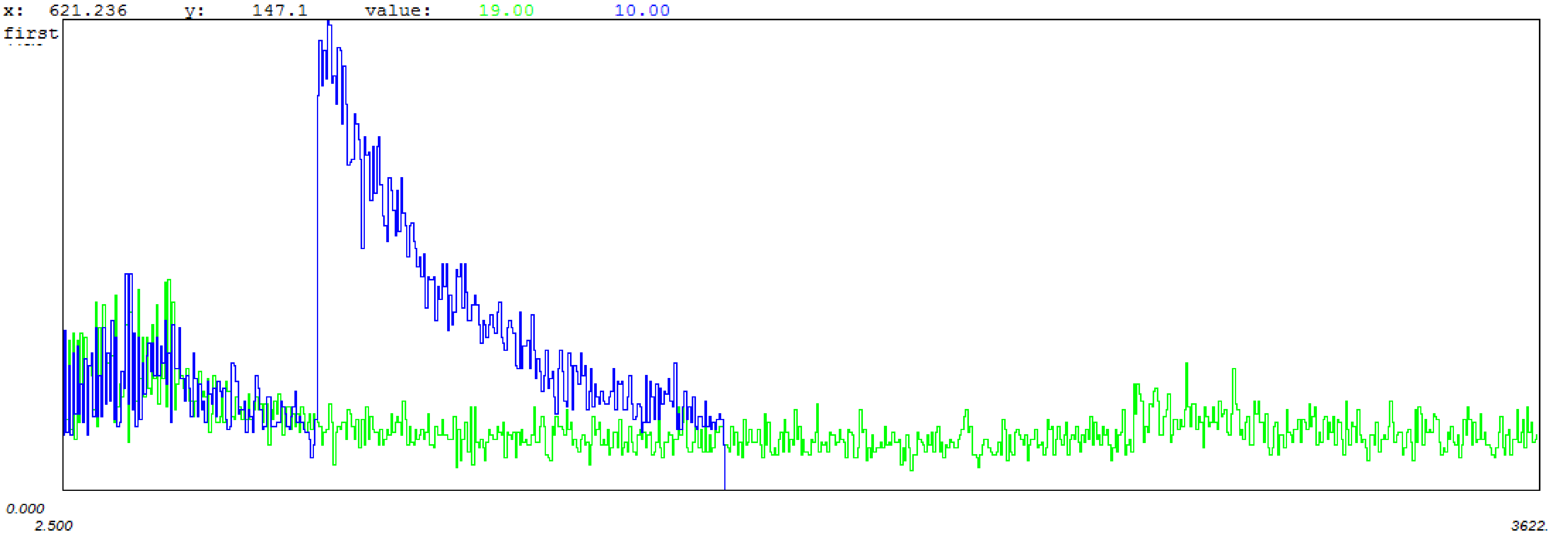
1)beta event is not coincident with a beta event in the other detector

2)beta event pulse-height cut

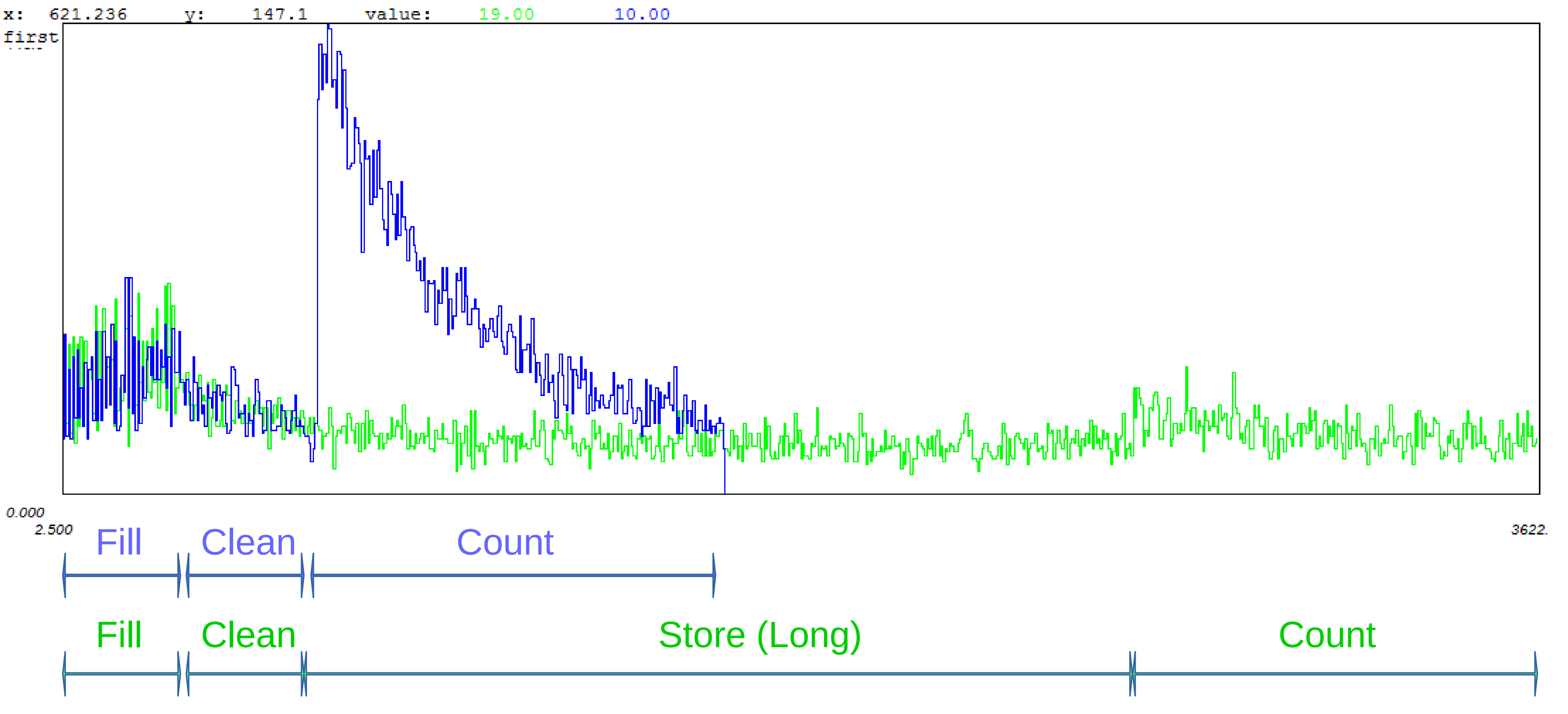
3)beta event is coincident with an NaI event

4)NaI event pulse-height cut

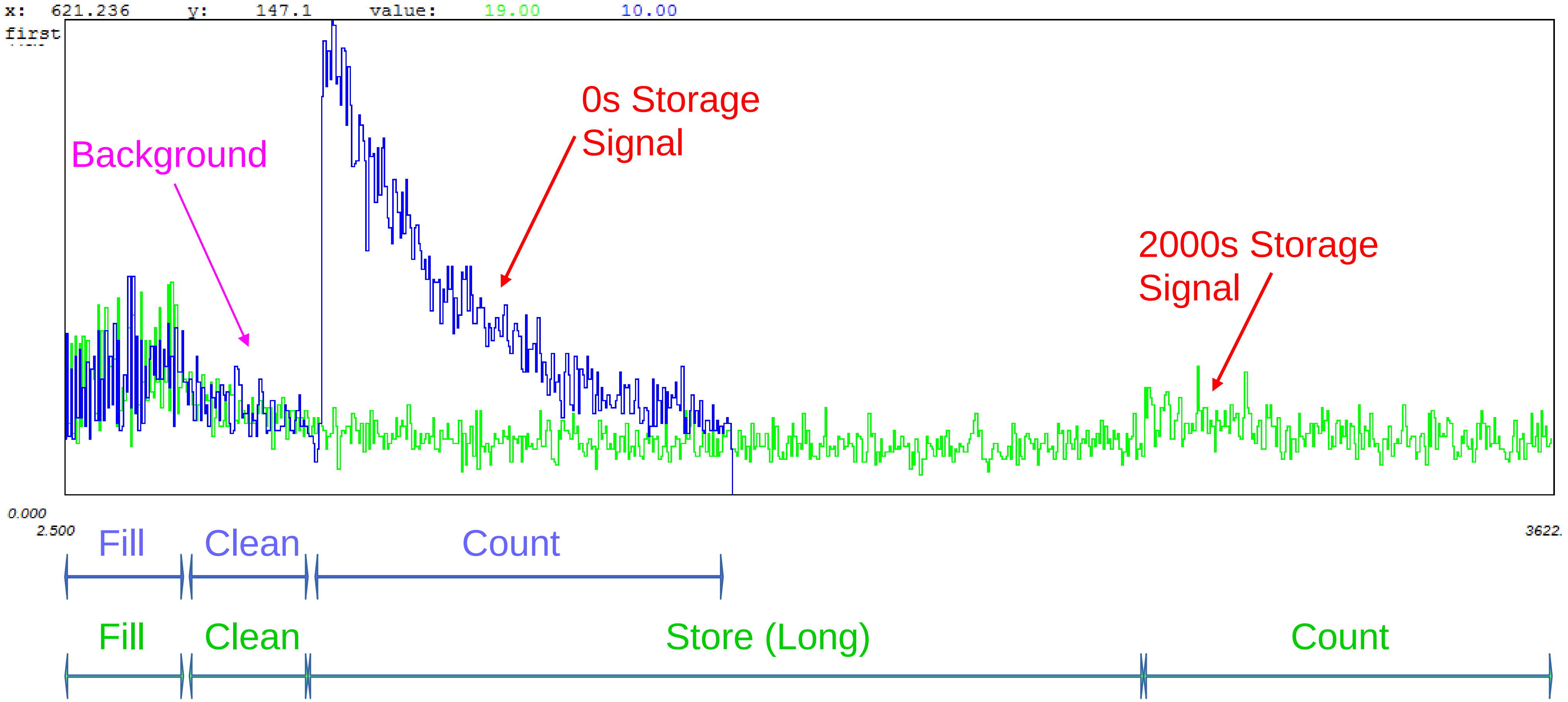
2014-2015 Lifetime Data



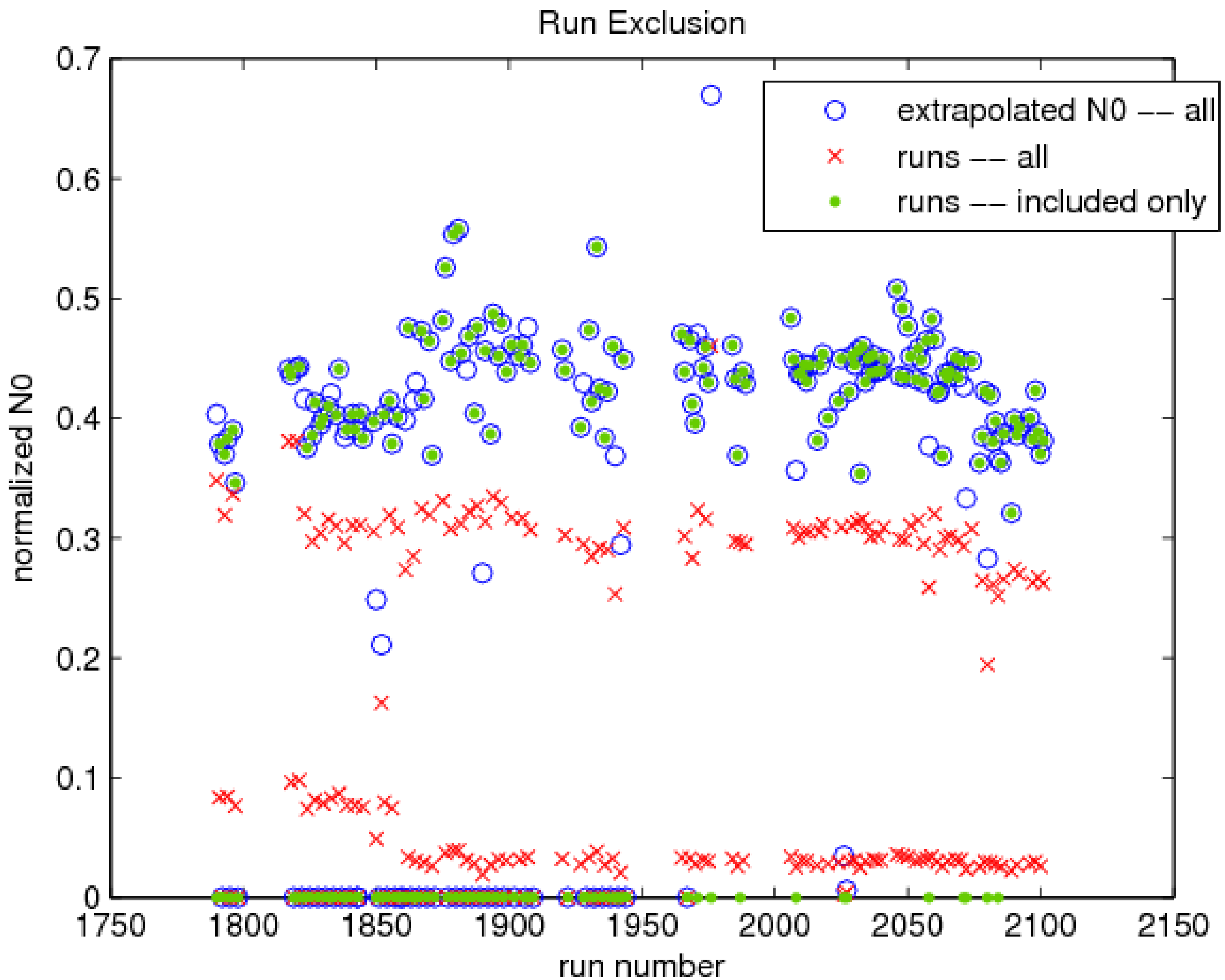
2014-2015 Lifetime Data



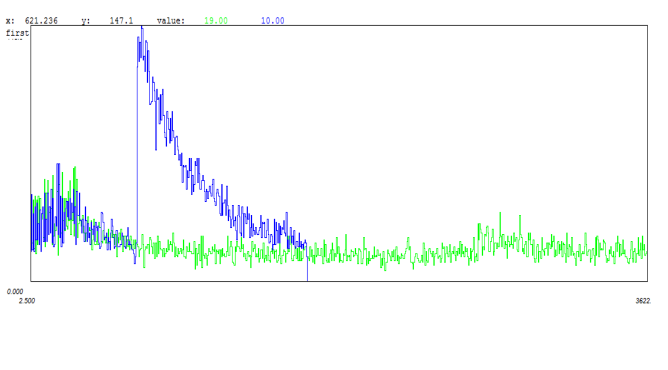
2014-2015 Lifetime Data



Run Exclusions



- Total # of runs: 210
- Adjacent NaI channel mixed (16 runs)
- Beam drops (10 runs)
- Beam reduction (5 runs)
- Low normalized N0 (5 runs)

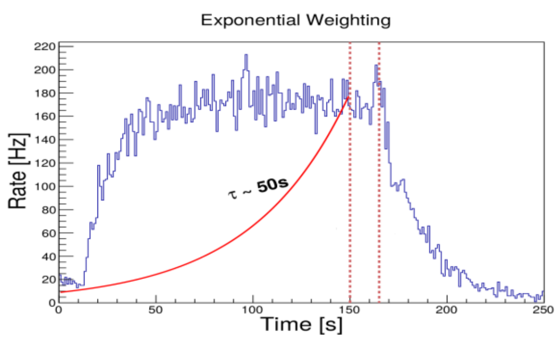


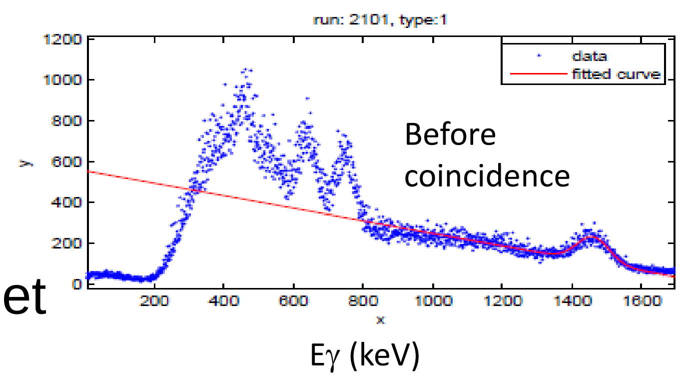
Coincidence Options

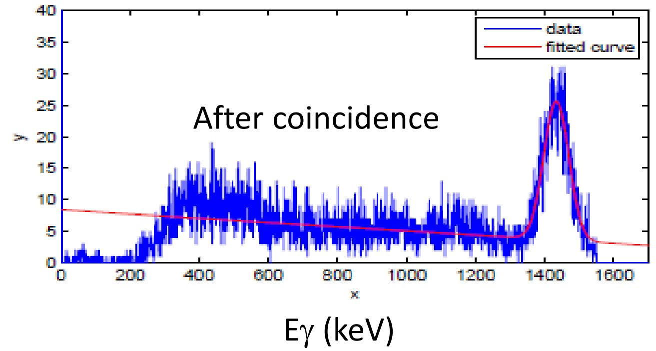
- Coincidence Time Window
  - No coincidence (Singles)
  - 1000ns
  - 200ns
- NaI photopeak cut (1434 keV)
  - (10,1550)
  - (600, 1550)
  - (1000,1550)
  - (1300,1550)
- Background Subtraction
  - Direct Subtraction (Triplet runs)
  - Independent Fitting
  - Trace Sums
  - Sandwich (individual short runs by adjacent long runs)

Normalization Options

- Gate valve detector vs. standpipe detector
- Integrated counts vs. exponential weighting







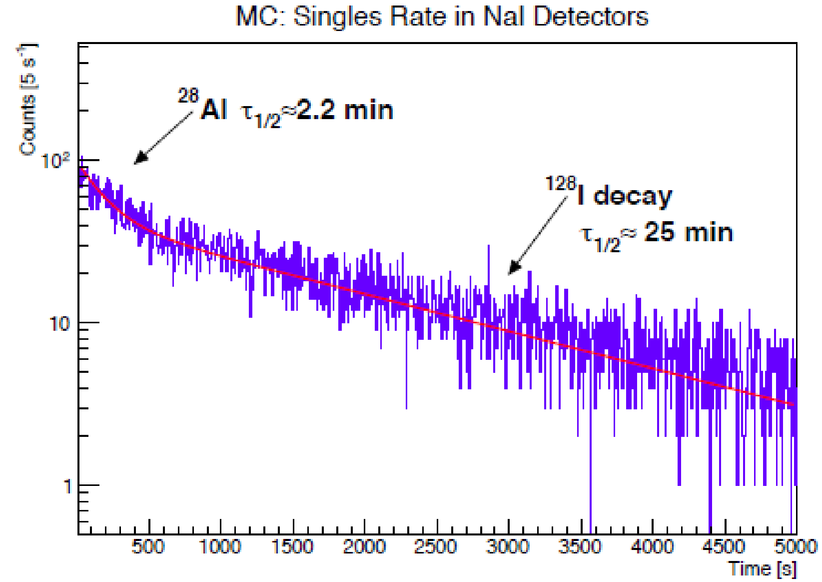
Systematic Effects

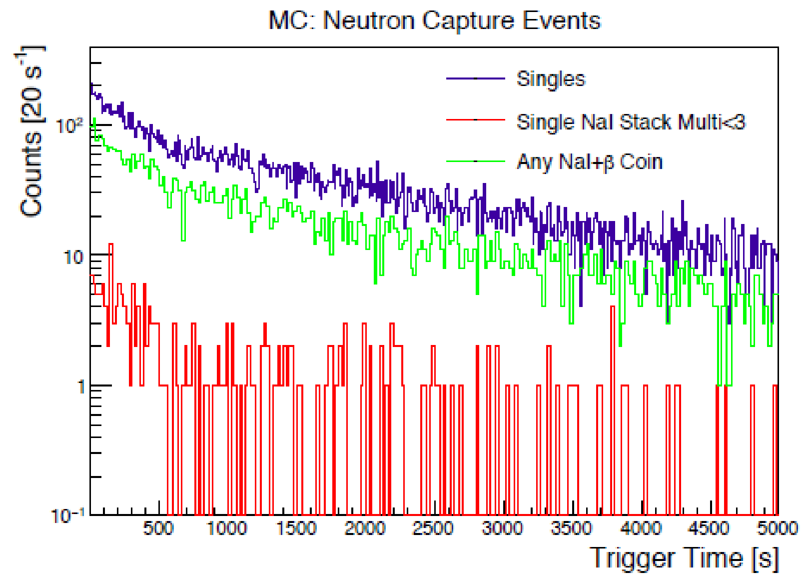
$$(\tau_{storage})^{-1} = (\tau_n)^{-1} + (\tau_{loss})^{-1}$$

Effect	Upper Bound	Direction	Current Eval.	Method of Characterization
residual gas	$< 1 \times 10^{-4}$	$+$	meas	RGA/cross-section measurements
depolarization	$< 1 \times 10^{-4}$	$+$	calc	field map, *in situ* detection
material loss	$< 4 \times 10^{-4}$	$+$	calc	measure Cu tape loss-per-bounce
cleaning	$\boxed{< 6 \times 10^{-4}}$	$+$	sim	vary cleaning time/depth, active cleaner
cleaner reliability	$\boxed{< 5 \times 10^{-4}}$	$\pm$	sim	verify position reproducibility
microphonic heating	$< 1 \times 10^{-4}$	$+$	sim	accelerometer measurements
dead time/pileup	$< 1 \times 10^{-4}$	$\pm$	calc	pileup ID/artificial dead time
gain drifts	$< 2 \times 10^{-4}$	$\pm$	meas	spectral monitoring/gain monitoring
time-dep. background	$\boxed{< 5 \times 10^{-4}}$	$\pm$	meas	background data analysis
phase space evolution	$\boxed{< 5 \times 10^{-4}}$	$\pm$	sim	vanadium time studies, active detector
UCN monitoring	$< 3 \times 10^{-4}$	$\pm$	meas	measure monitor response/source stability
total	$< 1.2 \times 10^{-3}$	$\pm$		(uncorrelated sum)

Sources of Background

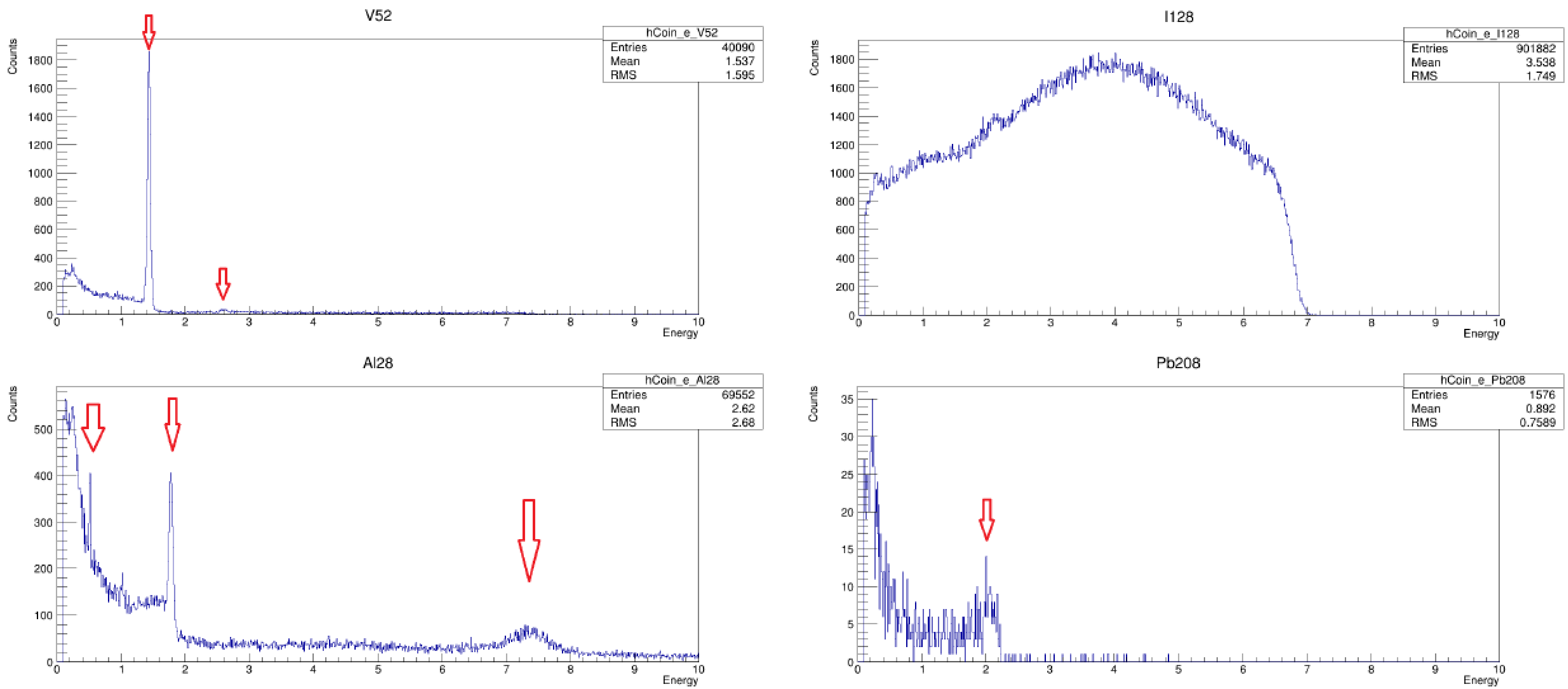
- Cosmic events
  - Most eliminated through E cuts
  - Remainder provides constant background, easily fit
- Beam induced background (mostly n activation)
  - Prompt gammas and fast neutrons
  - Decays from absorption on ^{28}Al, ^{128}I, etc.
- High energy UCN absorption on vanadium dagger
  - Non-constant background fit to ^{52}V exponential decay





Plots by R. Pattie

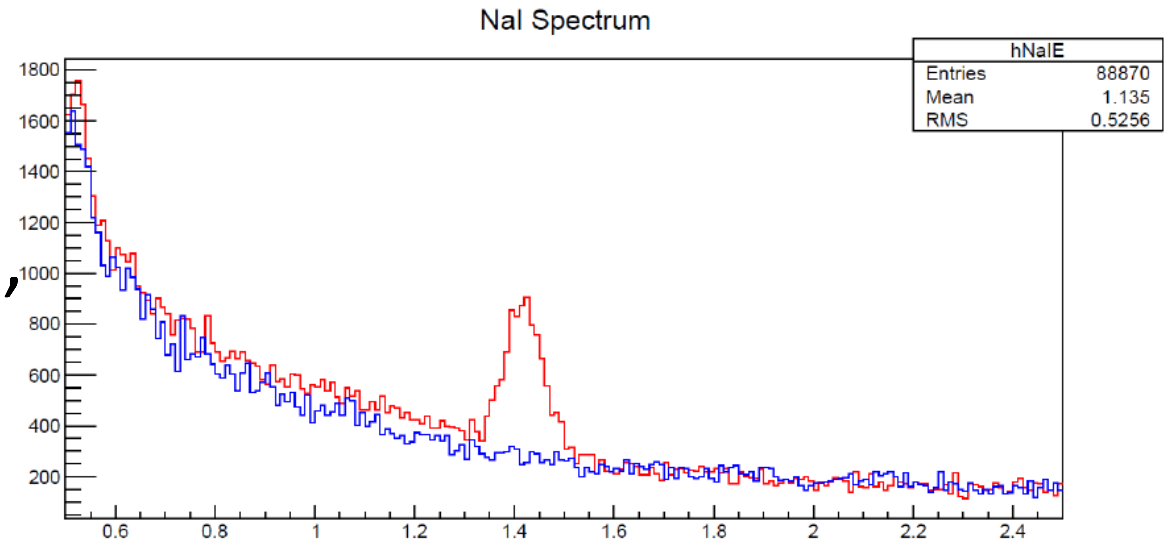
Simulated Background – Geant4

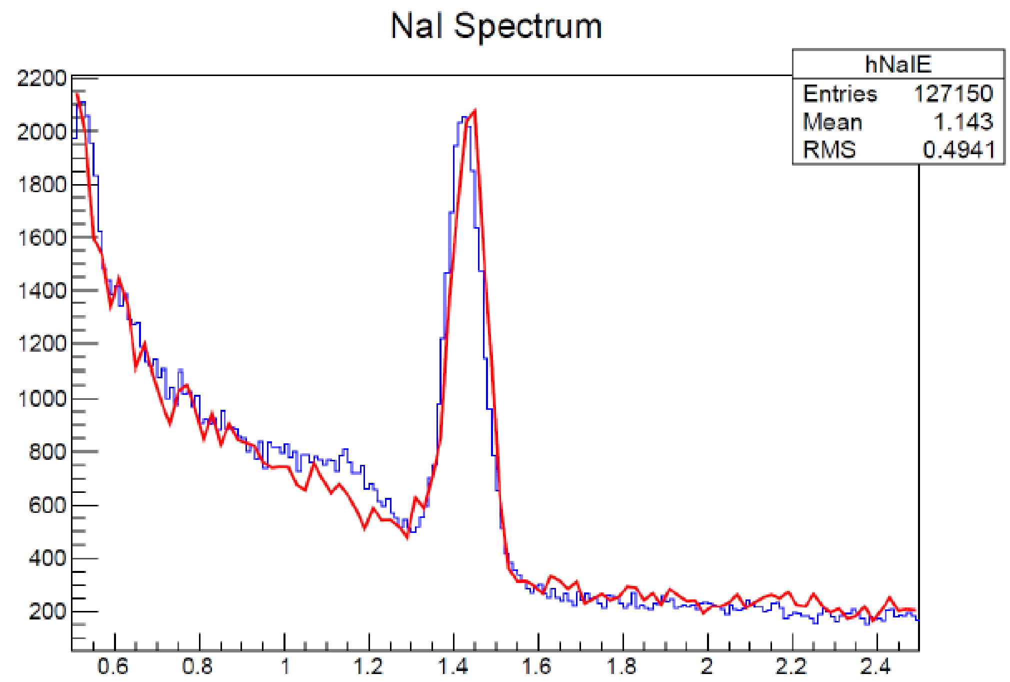


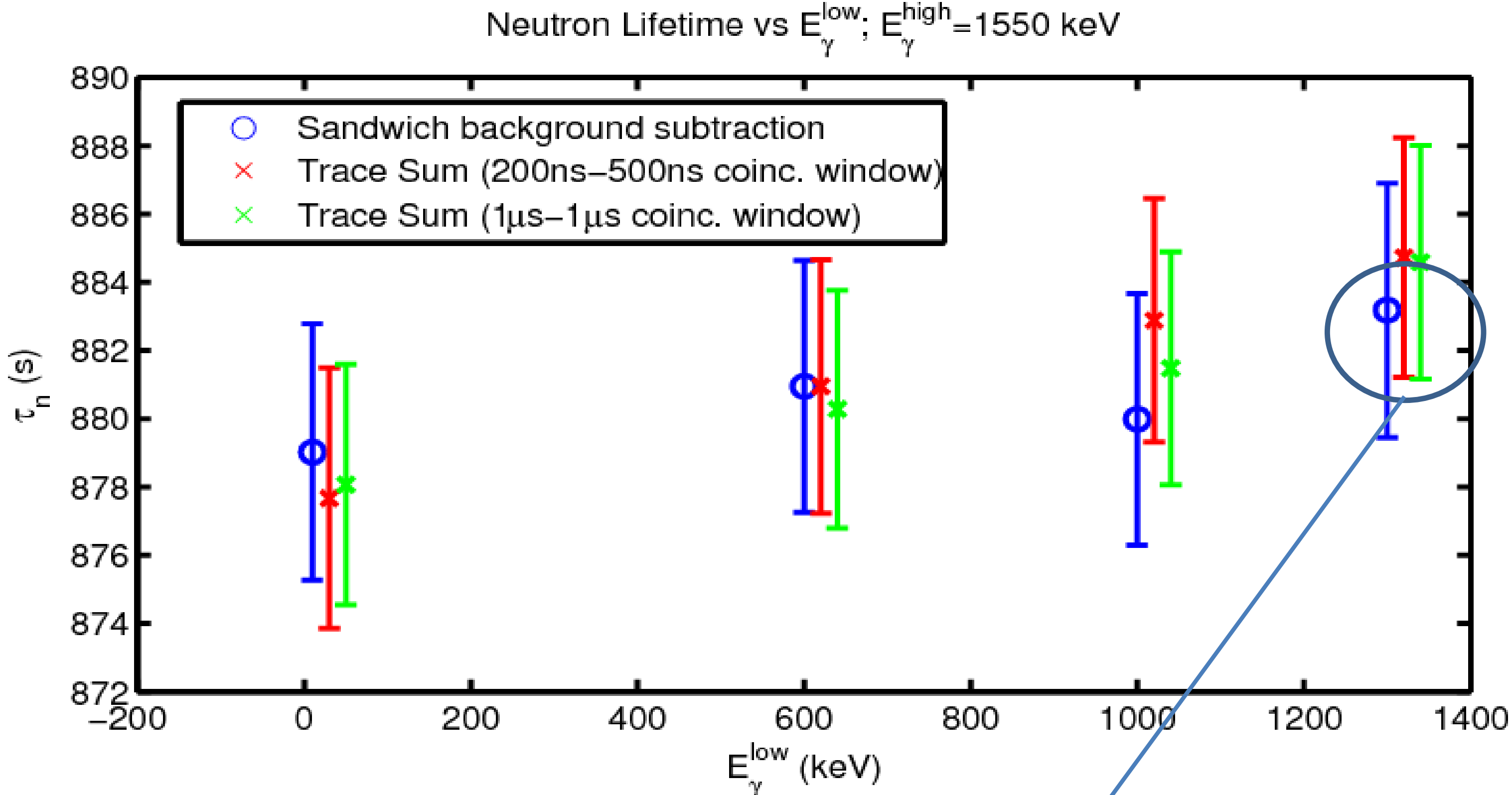
Images Courtesy of R.W. Pattie

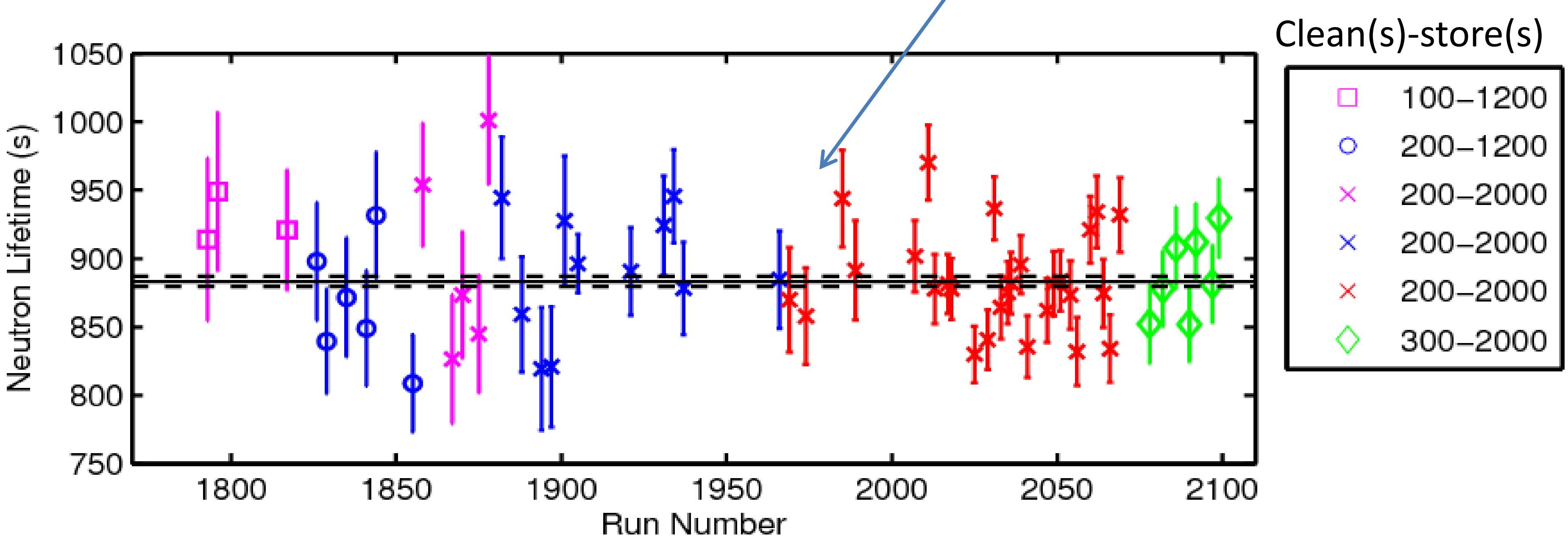
Extracting background from signal

- Fit to linear combination of V, Al, I, Pb, and measured BG
- Only V and measured BG components nonzero

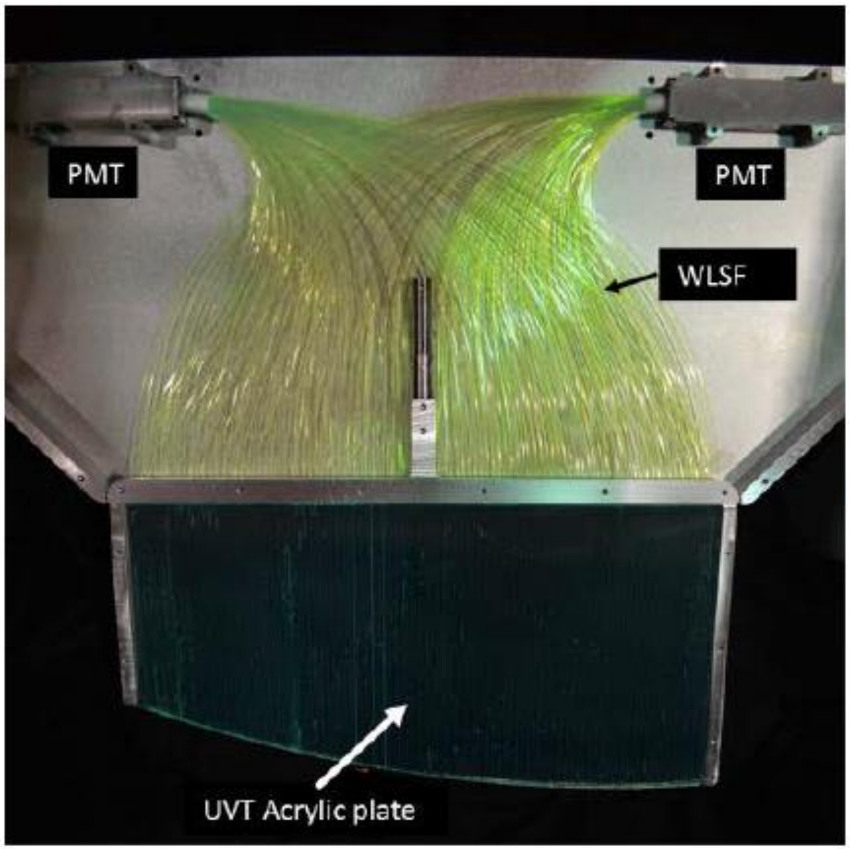


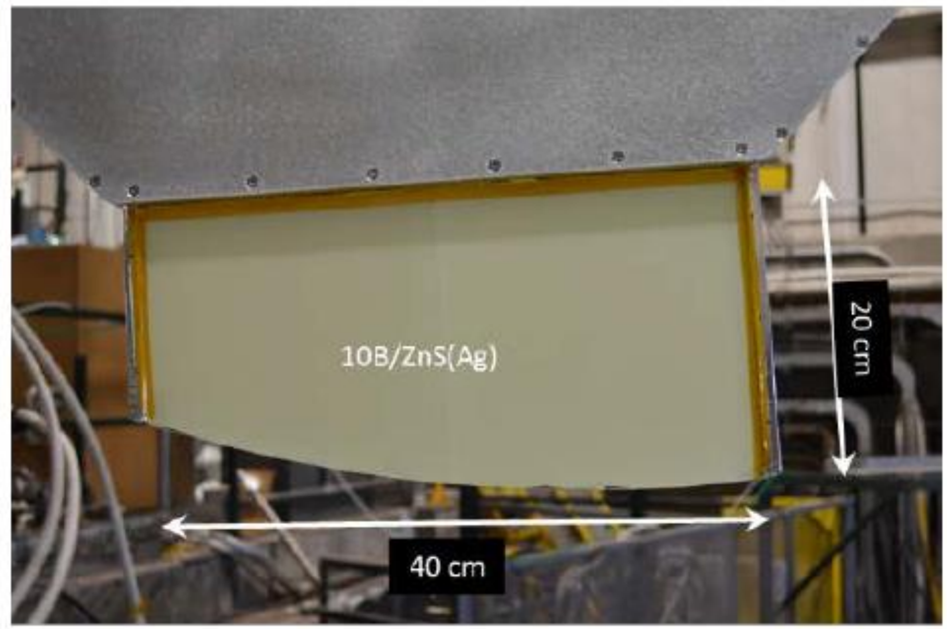



Neutron Lifetime vs E_γ^{low}; E_γ^{high}=1550 keV
Sandwich background subtraction
Trace Sum (200ns–500ns coinc. window)
Trace Sum (1µs–1µs coinc. window)
τ_n (s)
E_γ^{low} (keV)
890
888
886
884
882
880
878
876
874
872
–200
0
200
400
600
800
1000
1200
1400


Clean(s)-store(s)
100–1200
200–1200
200–2000
200–2000
200–2000
300–2000
Neutron Lifetime (s)
Run Number
1050
1000
950
900
850
800
750
1800
1850
1900
1950
2000
2050
2100

New Dagger Detector



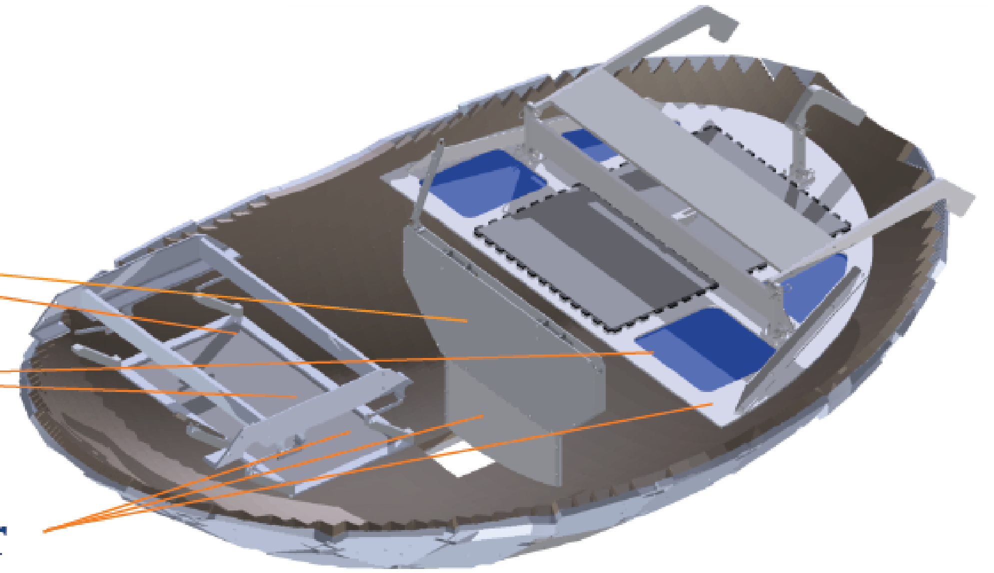


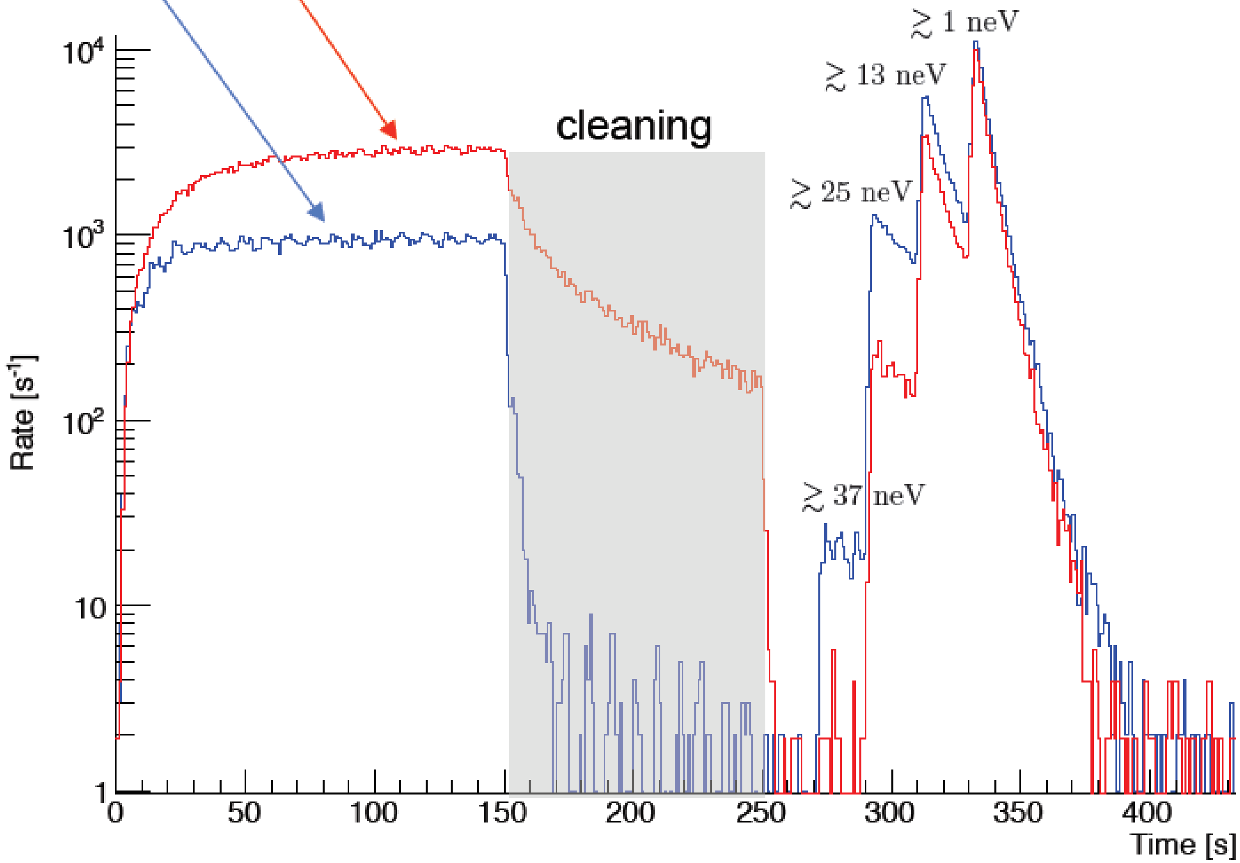
Cleaning with:

Active Cleaner + Dagger

Active Cleaner + Giant Cleaner

Active Cleaner + Giant Cleaner + Dagger





A short/short comparison showing the effect of cleaning at a particular holding time. The effect on the trap lifetime is demonstrated by a similar short/long comparison. There are two generic possibilities:

(1) The lifetime for an energy group is short… evidence for quasi-bound UCN.

(2) Between short and long holding times UCN move between energy groups… evidence for phase space evolution.

Unblinded Preliminary Results

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	

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

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)	

Conclusion

- Neutron lifetime key to insights into BBN, V-A weak interaction
- UCNτ provides new approach to bottling lifetime measurement
- Analysis allows for reduction of systematic effects:
  - Backgrounds are time independent, fully subtractable
  - Quasi-bound UCN can be completely cleaned
- Blinded result: $\tau_n = 878 \pm 2.6 \pm 0.6$ s
- Unblinding should give statistical error < 1s

UCNτ Collaboration

DePauw: A. Komives

Hamilton: G. Jones

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Extras

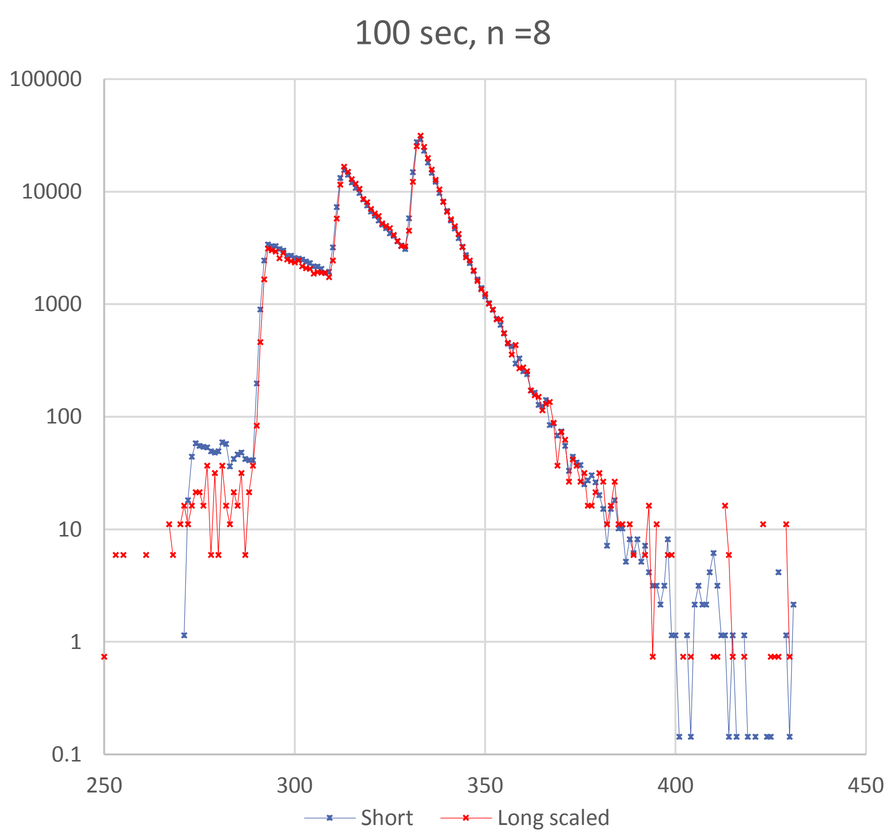
Numerical results from fits:

Spectrum	Vanadium	Iodine	Aluminum	Uncategorized P
Long Run, Al fixed	46.75 ± 0.45	$1.1 \times 10^{-18} \pm 0.0175$	0	53.25 ± 0.34
Short Run	66.42 ± 0.23	$5.4 \times 10^{-12} \pm 0.000199$	0	$33.576 \pm .065$
Short BG (against long)	24.47 ± 0.73	$8.8 \times 10^{-9} \pm 0.0966$	0.95 ± 1.23	74.58 ± 1.4
BG - Short minus Long	100 ± 17.2	$1.2 \times 10^{-11} \pm 0.173$	$3.7 \times 10^{-12} \pm 0.277$	0

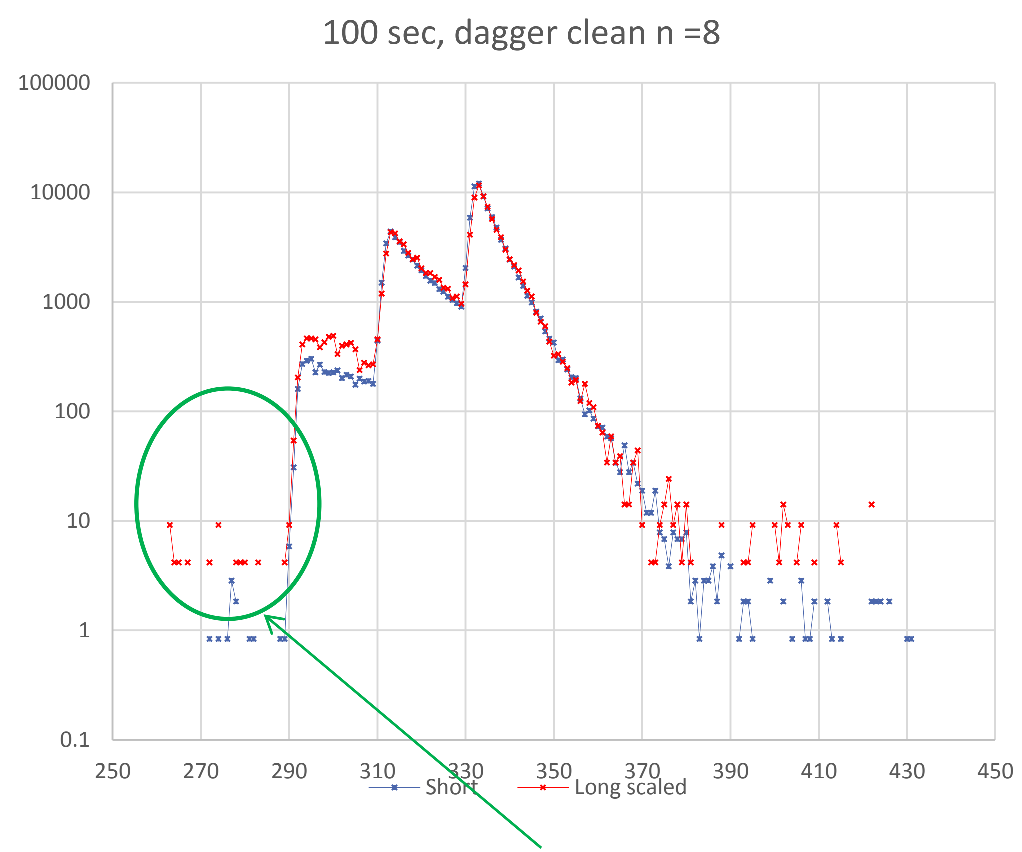
Phase Space evolution is evident in data that used dagger cleaning

Blue data points are short holding time, Red are long holding time (*shifted and scaled*)

No Dagger Cleaning



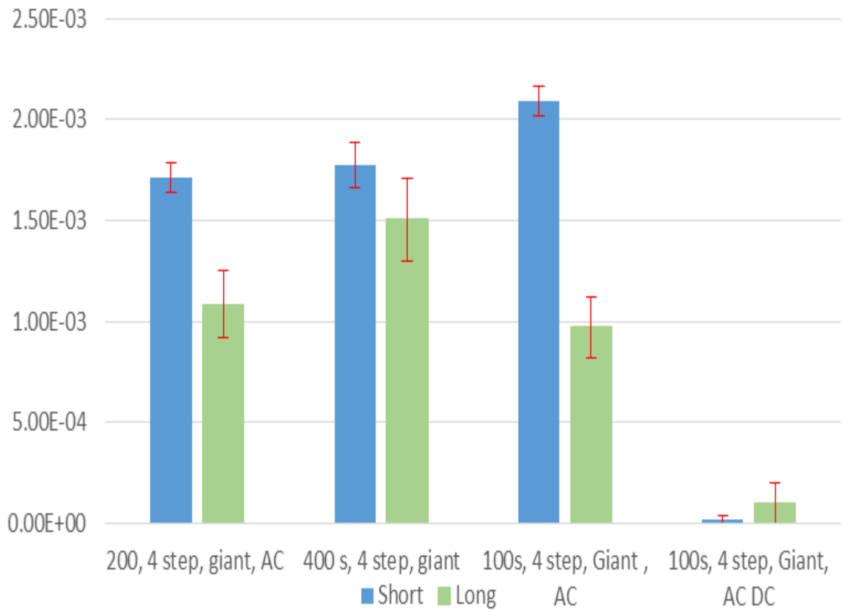
Dagger Cleaning



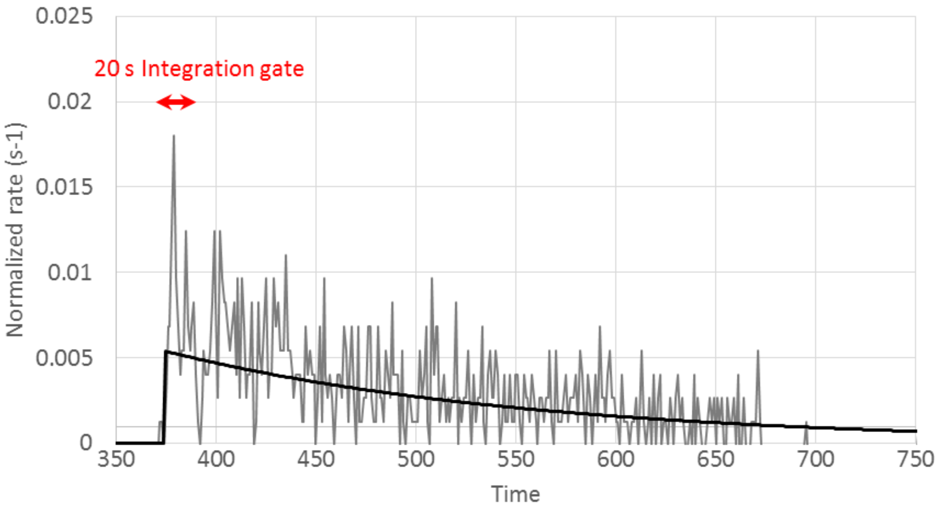
Data using dagger cleaning showed no counts in peak 1! Cleaning complete

We are able to correct for quasi-trapped neutrons

Fraction of Counts in Peak 1



Unloading curve for dagger in P1 position



- Fraction of counts in Peak 1 may be different for short and long runs – lifetime for Peak 1 can be shorter than for the total unloading if cleaning is inadequate
- When deep dagger cleaning is used there are no counts in Peak 1 - phase space evolution can be seen in the shape of the unloading curves and variation of lifetime extracted from peaks 2,3, and 4
- Unloading curve was used to estimate how many counts from Peak 1 remain in Peak 2,3,4 region – *This is used to make a correction for cleaning efficiency*
- *For data without dagger cleaning corrections are 3-9 sec, 10-40% uncertainty*
- No correction for cleaning is needed in deep dagger cleaning!

A number of blinded data were obtained Thanksgiving through February to study cleaning effectiveness

Data Set		Conditions	Run Pairs	Statistical Uncertainty (sec)
1	**Feb**	200, 1 step, giant, **AC up**	17	
2	**Jan Set 3**	200, 1 step, AC, DC	9	
3	**Feb**	200, 4 step, giant, AC	26	2.5
4	**Tday**	300, 4step, DC370, **AC**	83	1.9
5	**Feb**	400 s, 4 step, giant, **?AC?**	14	4.1
6	**Jan Set 3**	100s, 1 step, AC DC (200,1430)	24	3.1
7	**Jan Set 3**	100s, 1 step, AC, DC (10,1430)	38	2.1
8	**Feb**	100s, 4 step, Giant , AC (20,1440)	29	2.3
9	**Feb**	100s, 4 step, Giant, AC DC (20,1440)	13	4.1
10	**Dec**	100s, 1 step, DC (10, 1430),**AC**	35	2.2
11	**Jan set 1**	100s, 1 step, AC, DC (10,1430)	74	1.5

$\underbrace{\text{Data sets 3–11}}_{\text{Overall Statistical Uncertainty 0.8 sec}}$

Overall Statistical Uncertainty
0.8 sec

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

$$x^2/\mathrm{DOF} = 2.6$$