LA-UR-26-20092

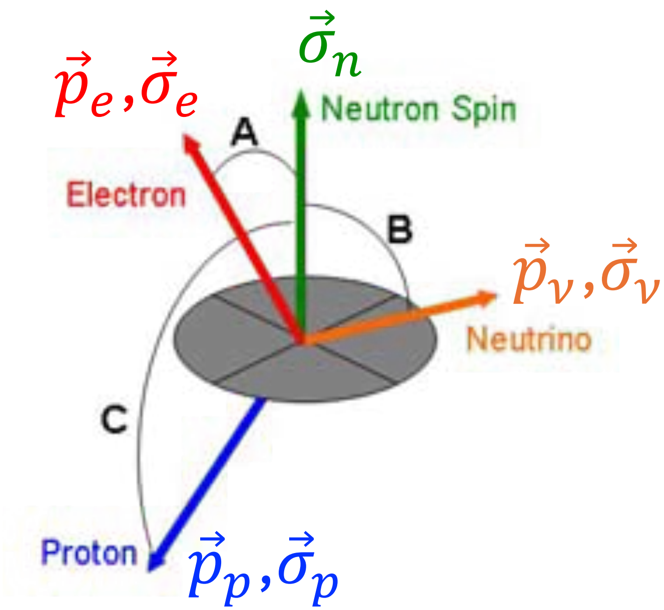
Neutron β-decay experiments at Los Alamos

Steven Clayton, LANL

INT Workshop: Testing the Standard Model in Charged-Weak Decays, January 12-16, 2026, Seattle, WA

Neutron β decay observables

$n \rightarrow p + e + \bar{\nu}_e$, β endpoint energy 782 keV



Many observables:

LANL Experiments

- Mean lifetime τ_n ← UCNτ/UCNτ+, UCNProBe
- $A\ \vec{\sigma}_n \cdot \vec{p}_e$ ← UCNA/UCNA+
- $B\ \vec{\sigma}_n \cdot \vec{p}_\nu$ ← (UCNB)
- $C\ \vec{\sigma}_n \cdot \vec{p}_p$
- $D\ \vec{\sigma}_n \cdot (\vec{p}_e \times \vec{p}_\nu)$
- $a\ \vec{p}_e \cdot \vec{p}_\nu$
- Twofold correlations involving electron spin
- Threefold correlations (*D*, *L*, *R*, *V*)
- ...

Differential decay rate:

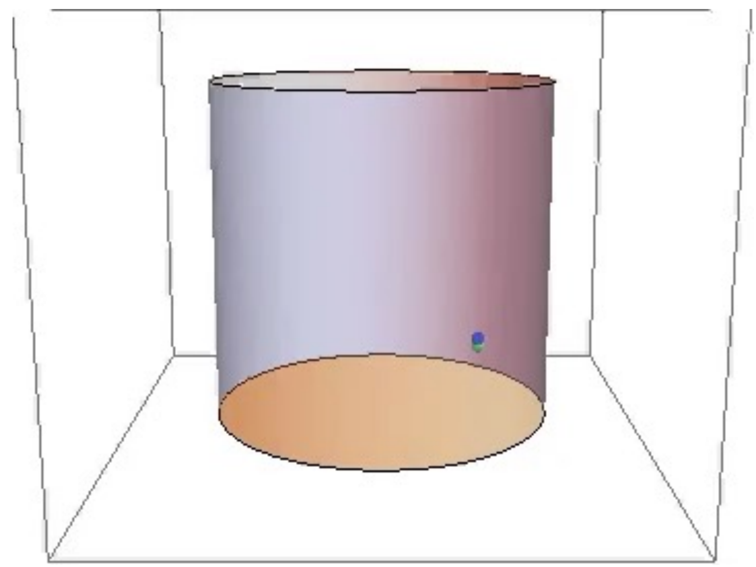
$$\frac{dW}{dE_e d\Omega_e d\Omega_\nu} = G(E_e)\left(1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \langle\vec{\sigma}_n\rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right)$$

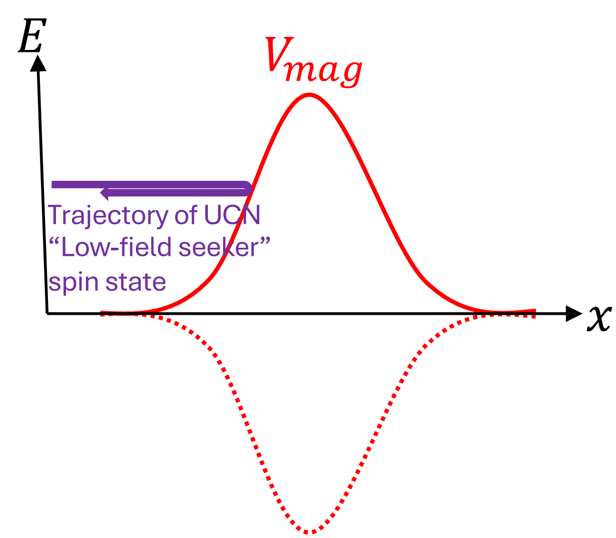
...also $\vec{\sigma}_e$ combinations

Experiments on neutron properties typically use cold or ultracold neutrons

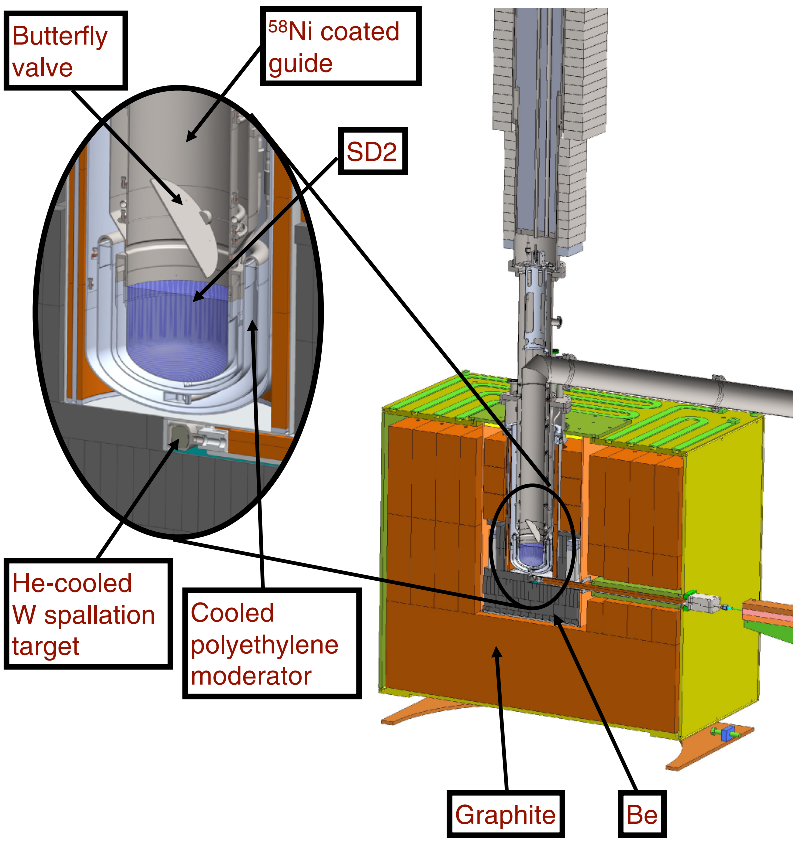
Ultracold neutrons

- Neutrons with kinetic energy < ≈ 350 neV (velocity up to ≈ 10 mph)
- *Total external reflection* from common materials (e.g., stainless steel V_F ≈180 neV, ^{58}Ni V_F ≈350 neV) – can be stored in a material bottle.
- Gravitational confinement to a few meters height ($V_{grav} = mg \approx$ 100 neV/m)
- Magnetic potential similar to KE with a few Tesla field ($V_{mag} = \vec{\mu}_n \cdot \vec{B} \approx$ 60 neV/T)
  - Total reflection from laboratory-scale fields
  - 100% spin selection filter





LANL UCN Source



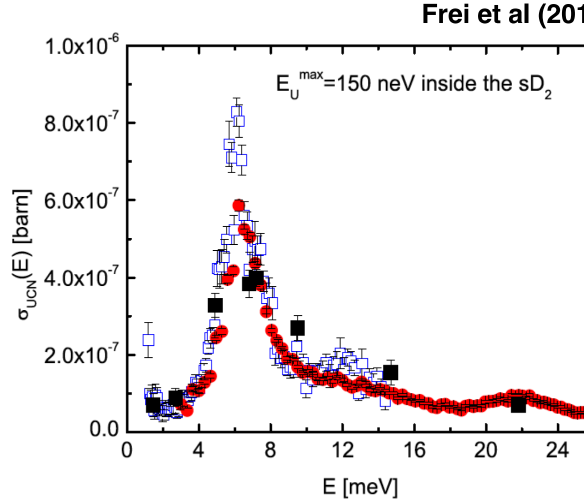
Spallation neutrons from W target
K.E. ~ 2 MeV

Thermal neutrons in Be and graphite moderator
K.E. ~ 25 meV

Cold neutrons in polyethylene cold moderator
K.E. ~ 6 meV

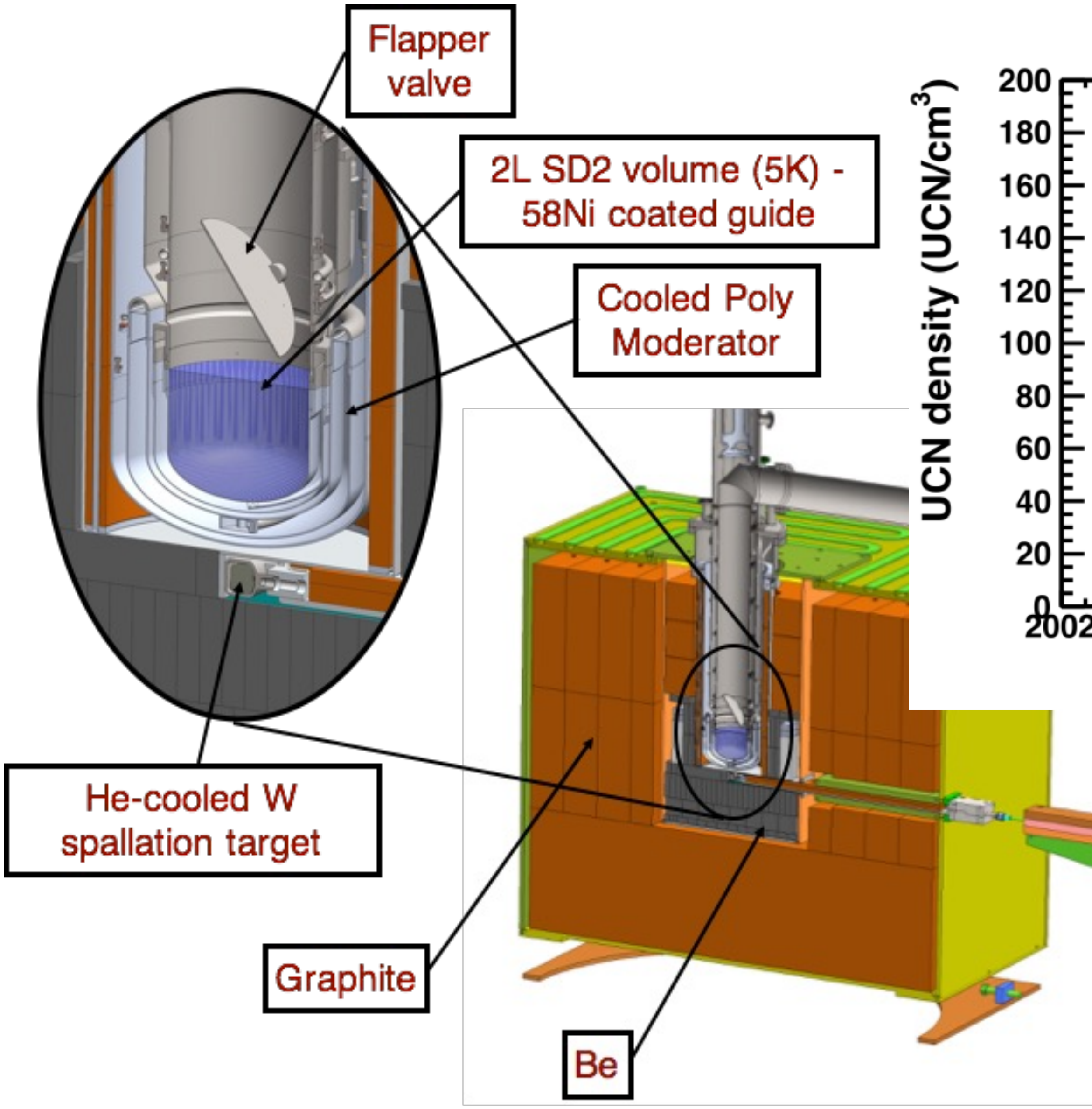
Ultracold neutrons in SD2 converter
K.E. ~ 100 neV

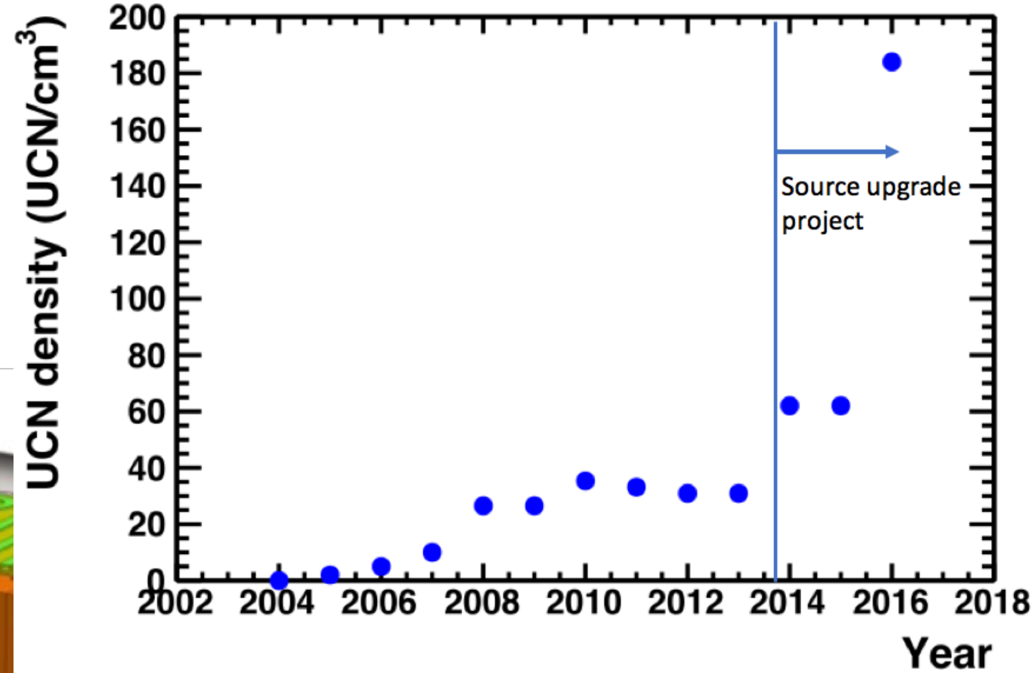
Frei et al (2010)



$P_{UCN} = \rho_{SD} \int \Phi_{CN}(E) \sigma_{UCN}(E) dE$

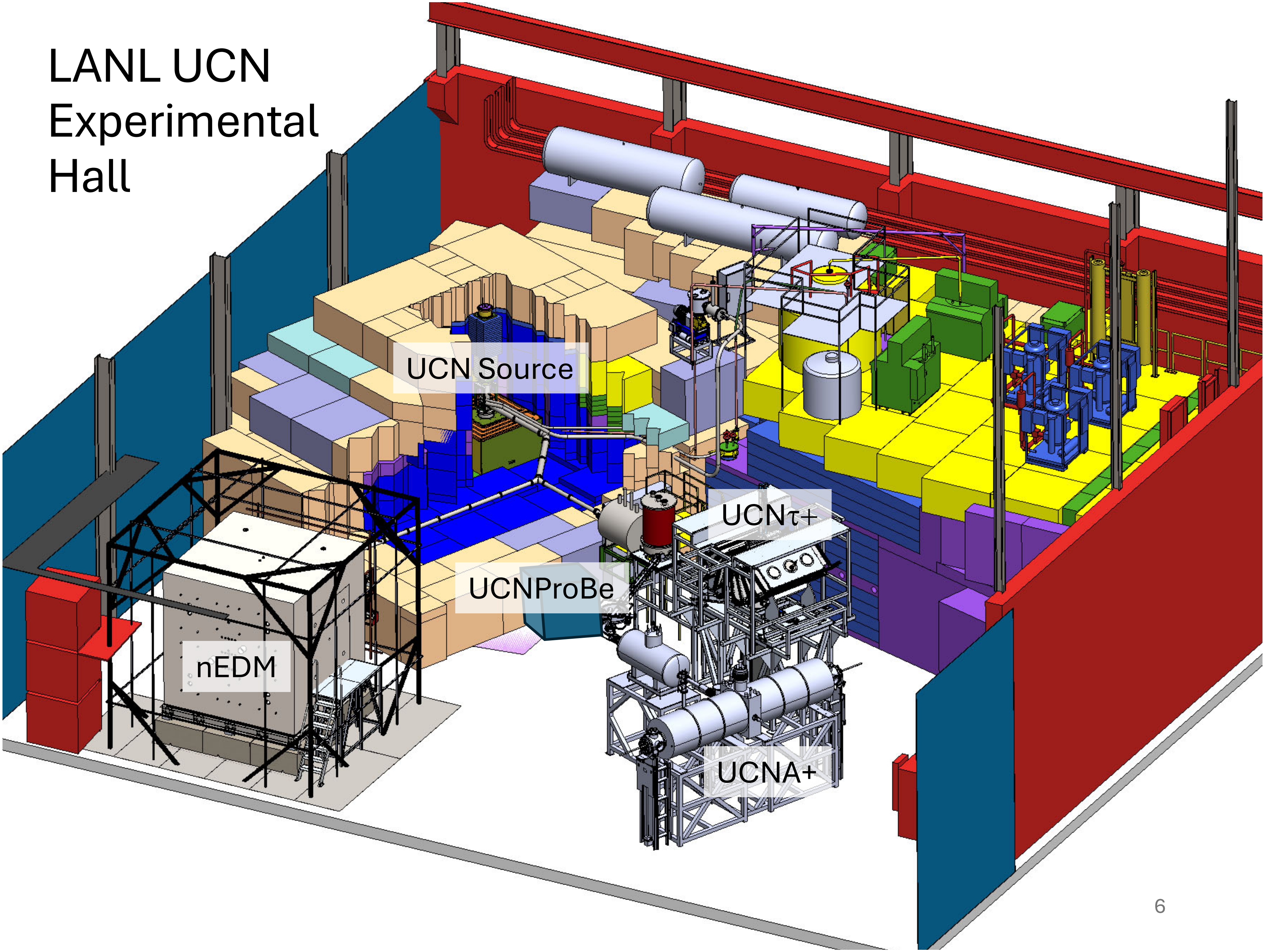
LANL UCN Source



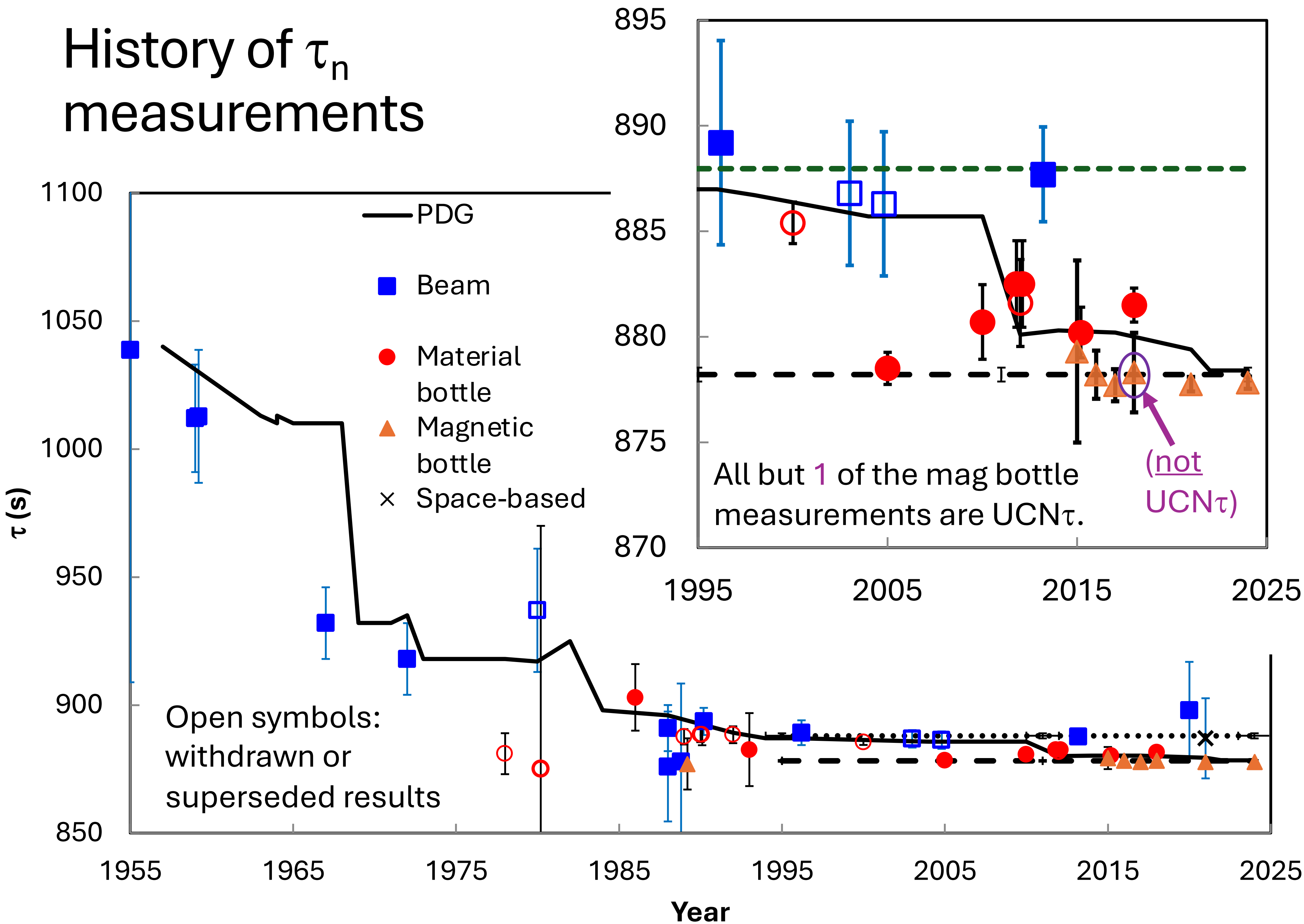


T. M. Ito et al., Phys. Rev. C **97**, 012501(R) – 29 January 2018

LANL UCN Experimental Hall



History of τ_n measurements



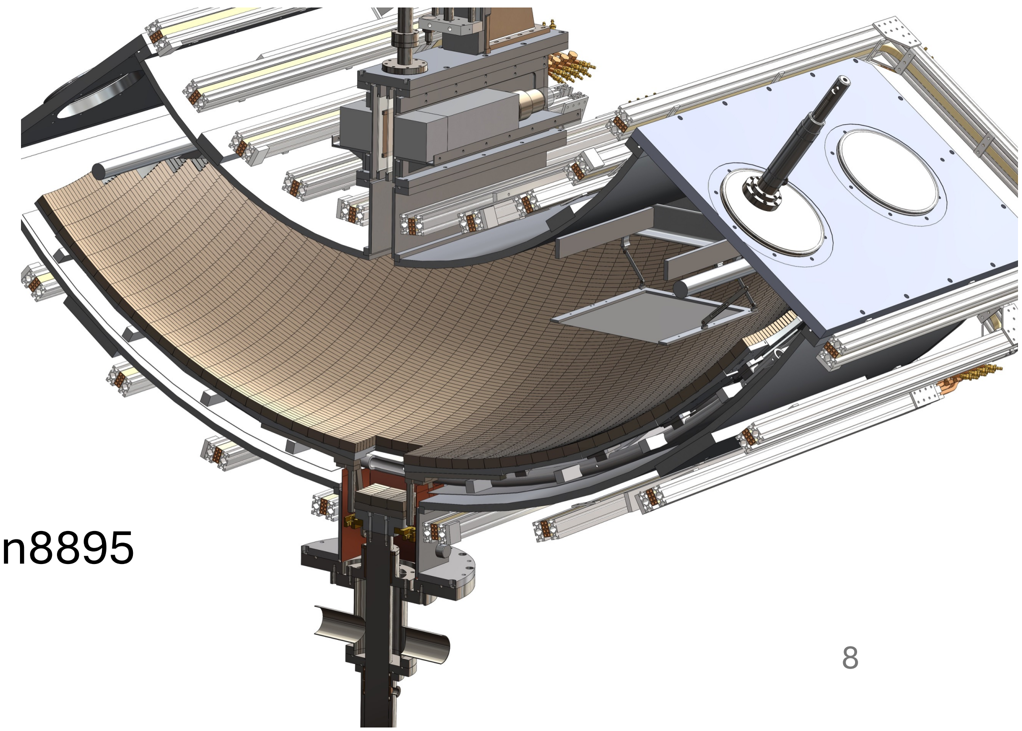
UCNτ experiment traps ultracold neutrons via magnetic and gravitational forces, avoiding big systematic corrections.

- UCN trap with very low intrinsic losses
  - Magneto-gravitational trap
  - Superposed holding field to eliminate B-field zeros (no depolarization losses)
  - Fast removal of quasi-bound UCNs possible through trap asymmetry and field ripple

- High statistics are achievable
  - Large volume
  - *In situ* UCN detector
    - High overall efficiency
    - Also: Less sensitive to phase-space evolution than draining

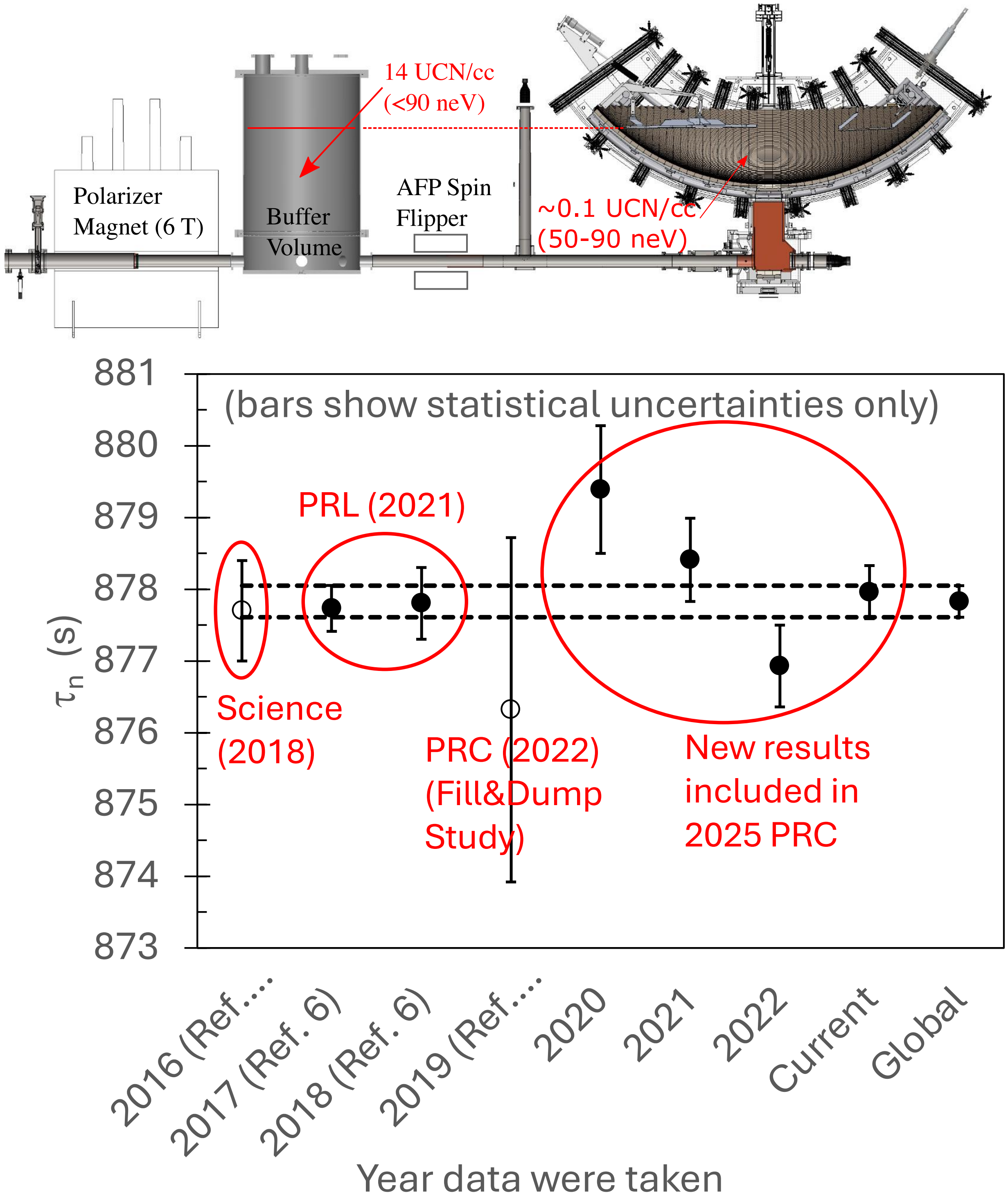
Based on original concept: P.L. Walstrom, J.D. Bowman, S.I. Penttila, C. Morris, A. Saunders, NIMA 599 (2009) 82-92

Physics results:
Phys. Rev. C **111**, 045501 (2025)
Phys. Rev. Lett. **127**, 162501 (2021)
Science 06 May 2018, 10.1126/science.aan8895



UCNτ

UCNτ Summary



- **2017**: Improved removal of quasi-trapped UCN (“Giant Cleaner”)
- **2018**: Improved normalization of initial UCN population by adding upstream buffer volume.
- **2019**: Special run of “Fill and Dump” mode, in which UCN are drained through the trapdoor into a detector
- **2020**: Improved normalization by adding detector to count UCN in upstream buffer volume at end of fill.
- **2021**: Improved $^{10}B/ZnS$ screens (better efficiency)
- **2022**: Segmented dagger detector (smaller rate-dependent effects).

UCNτ+

Upgrade UCNτ for higher rate:

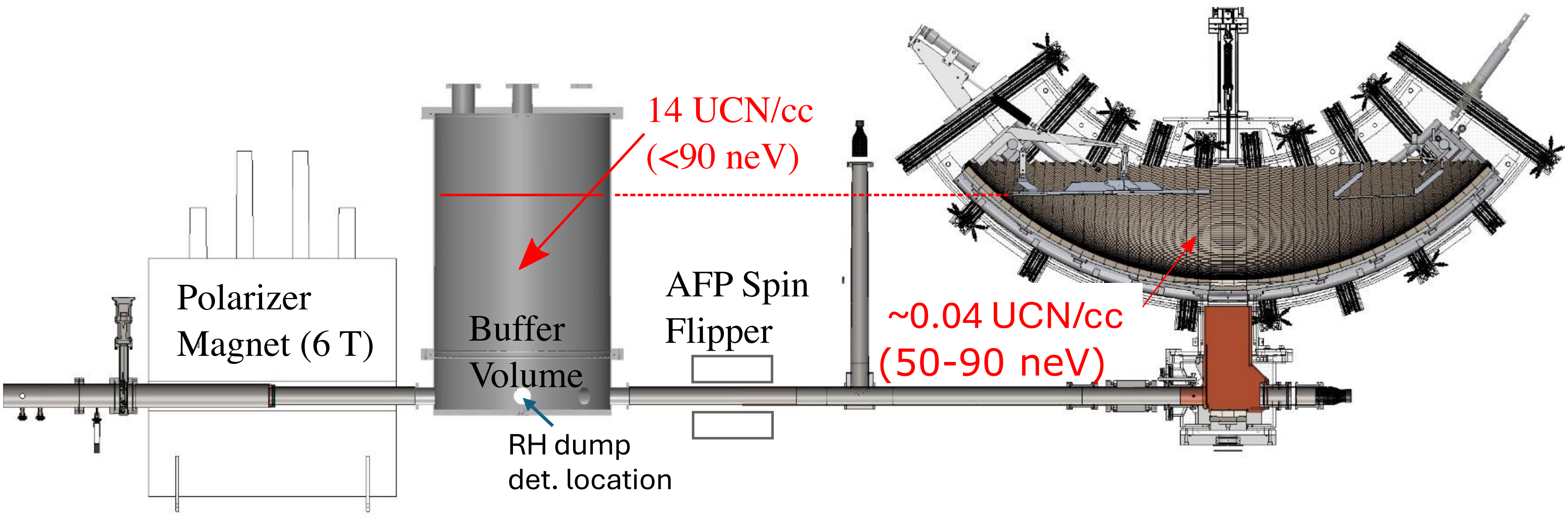
In progress →
- Increase number of trapped UCN

Done* →
- Improve main detector to reduce rate-dependent effects
- Goal: $\sigma(\tau_n) \sim 0.15$ s

*Further improvements planned...

UCNτ has low loading efficiency.

- Trap volume ~500 L
- < 20,000 UCN per fill
- Average trapped density < 0.04 UCN/cm^3,
- < 1% of the density in an upstream volume



We attribute the poor loading efficiency to gaps, magnetic field zeros, and/or non-adiabatic spin transport in trapdoor region.

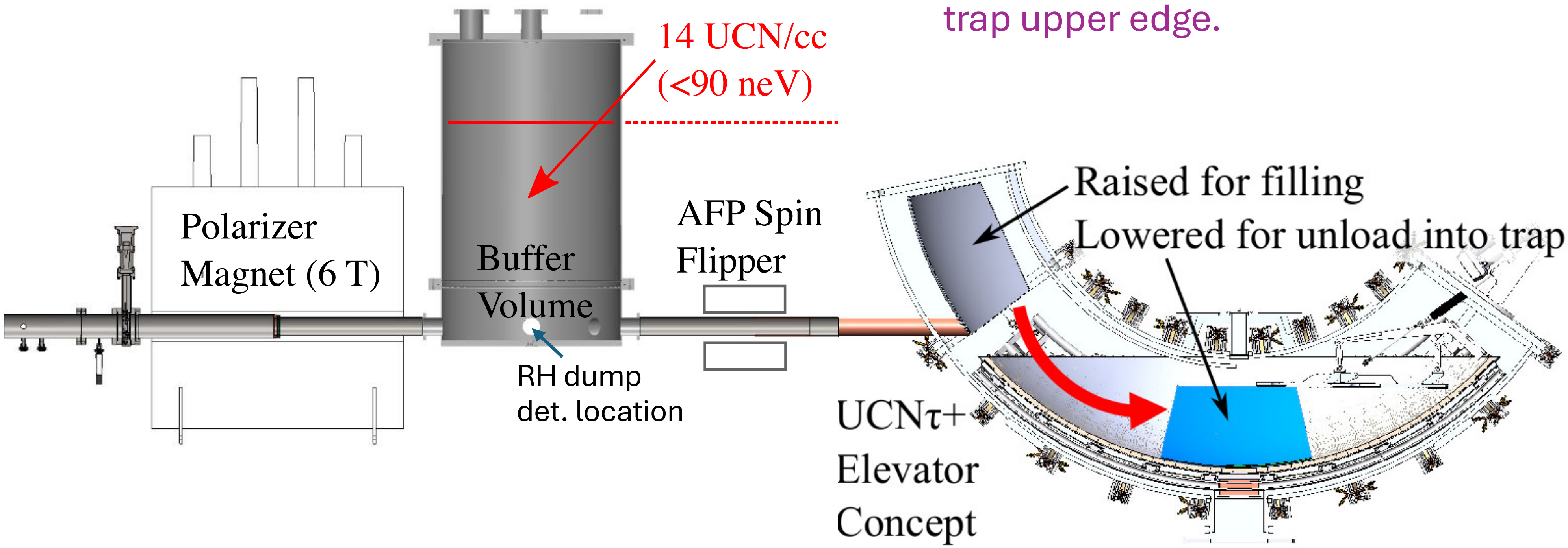
UCNτ+ Elevator Concept

1. Load a material bottle with similar volume to the trap.
2. Slowly ($v << v_{UCN}$) move the volume into the trap.
3. Somehow retract the material bottle and leave the UCN.

We expect ~10× more UCN in the trap with this loading method.

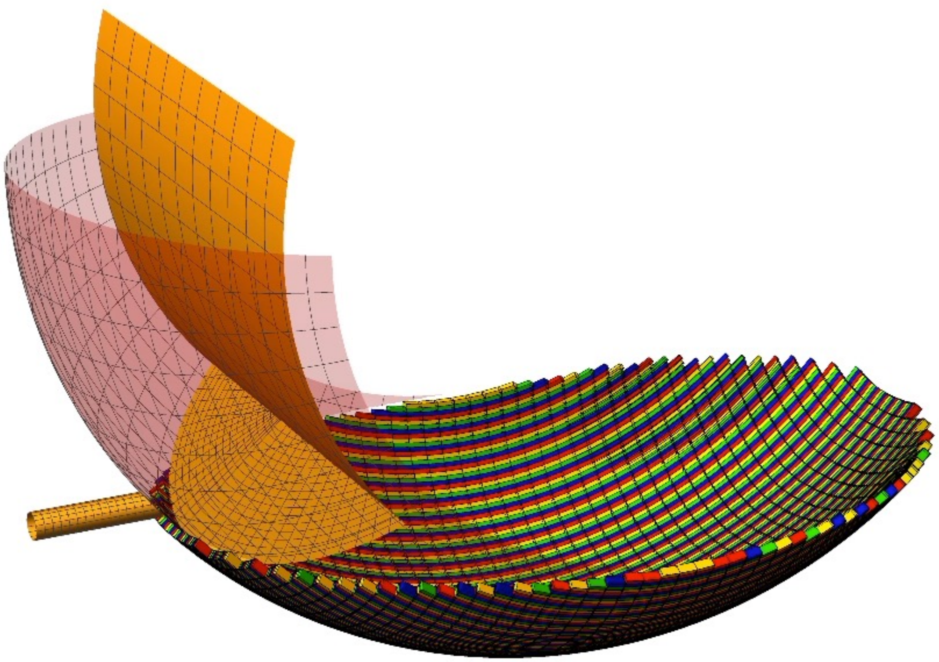
Immediate concerns:

- Need good storage time in loading volume;
- Need sufficiently smooth motion;
- Need to avoid depolarization at trap upper edge.

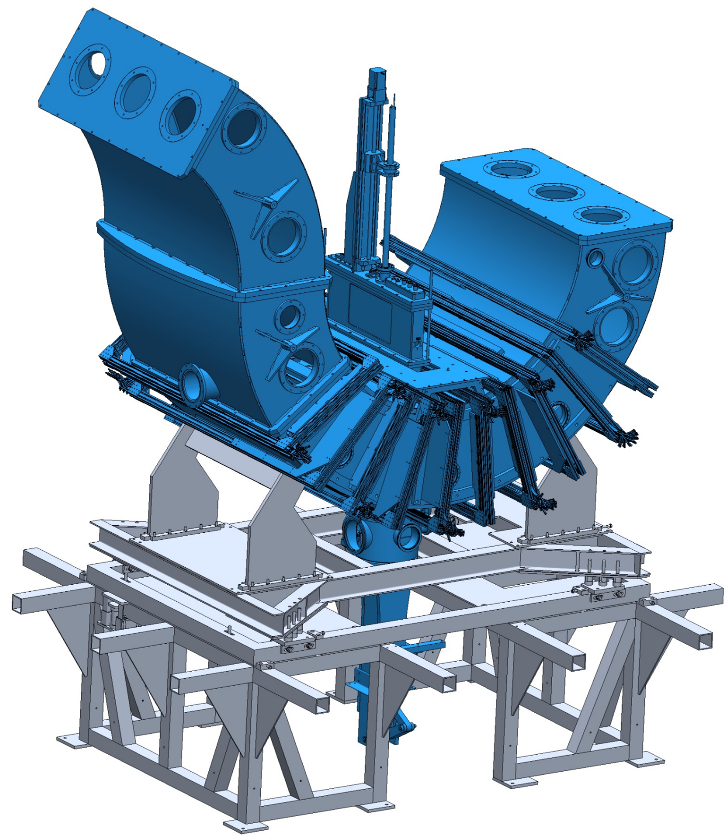


Elevator concept

- Here, the elevator sweeps all the way through the trap and stays on the other side until after surviving UCN are counted.
- The cleaner is attached to and follows the elevator until it is positioned at the top (left) of the trap.
- Raising the cleaner is done by slightly backing up the elevator+cleaner.

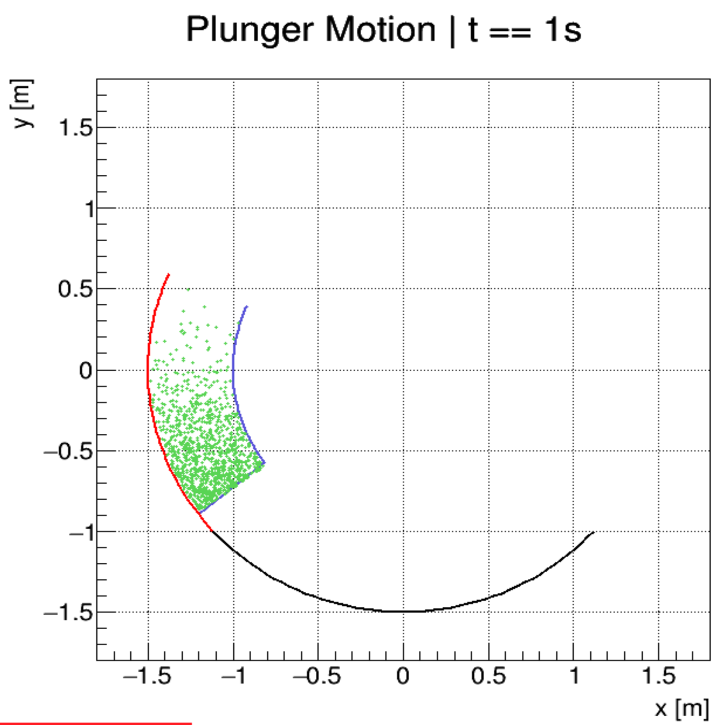


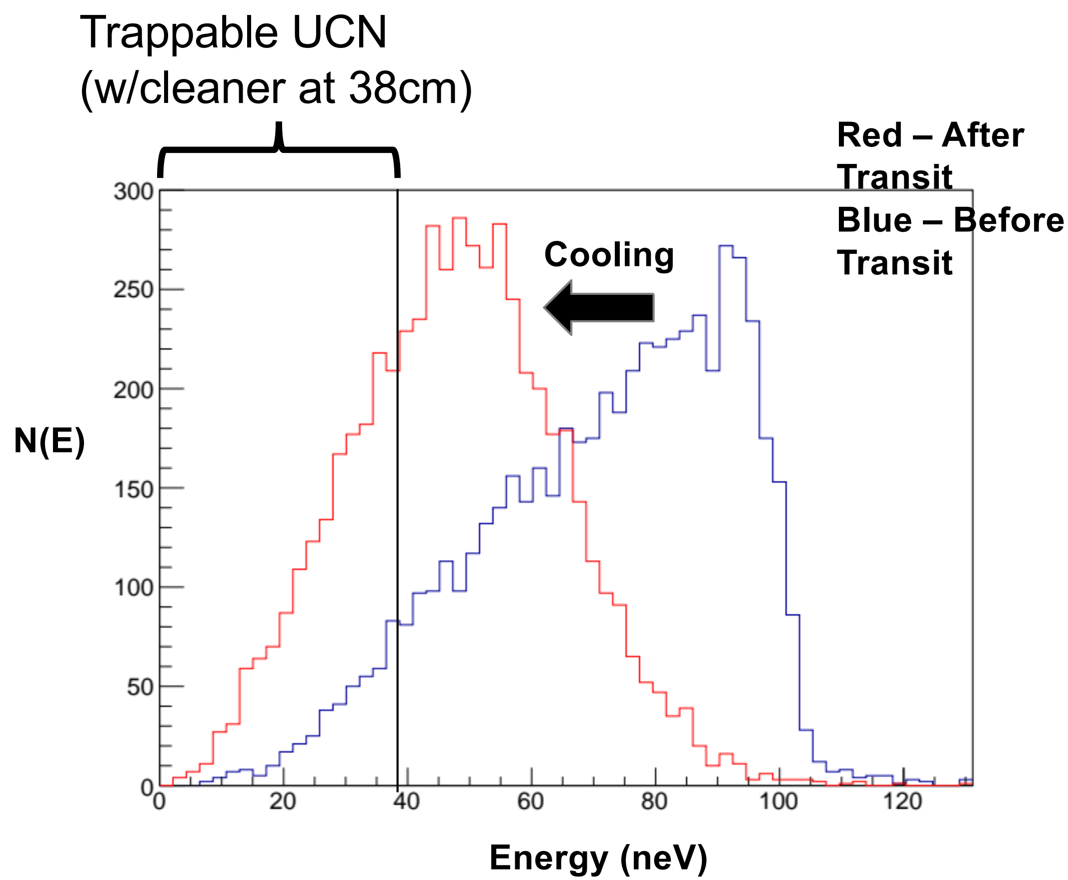
Vacuum vessel is extended to fit the elevator (and cleaner).



Simulation of elevator loading

- Interesting result: UCN spectral cooling is significant!
- It seems to be effectively a horizontal expansion of the ensemble.
- Subsequent simulations with more detail (e.g. reasonable losses) show potential gain of 50% compared to no cooling.

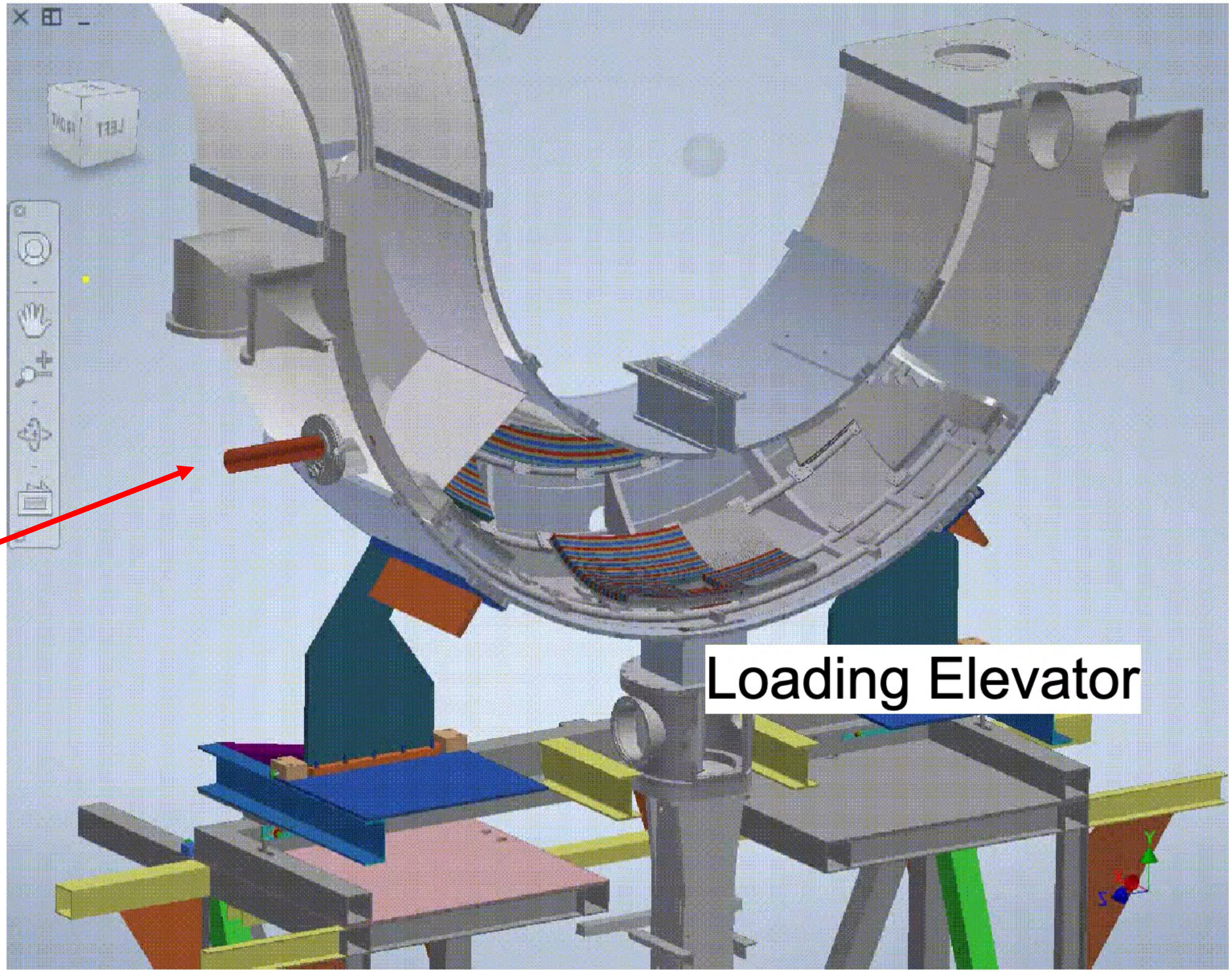




NC STATE UNIVERSITY

Filling, cleaning and measurement cycle

UCN feed guide

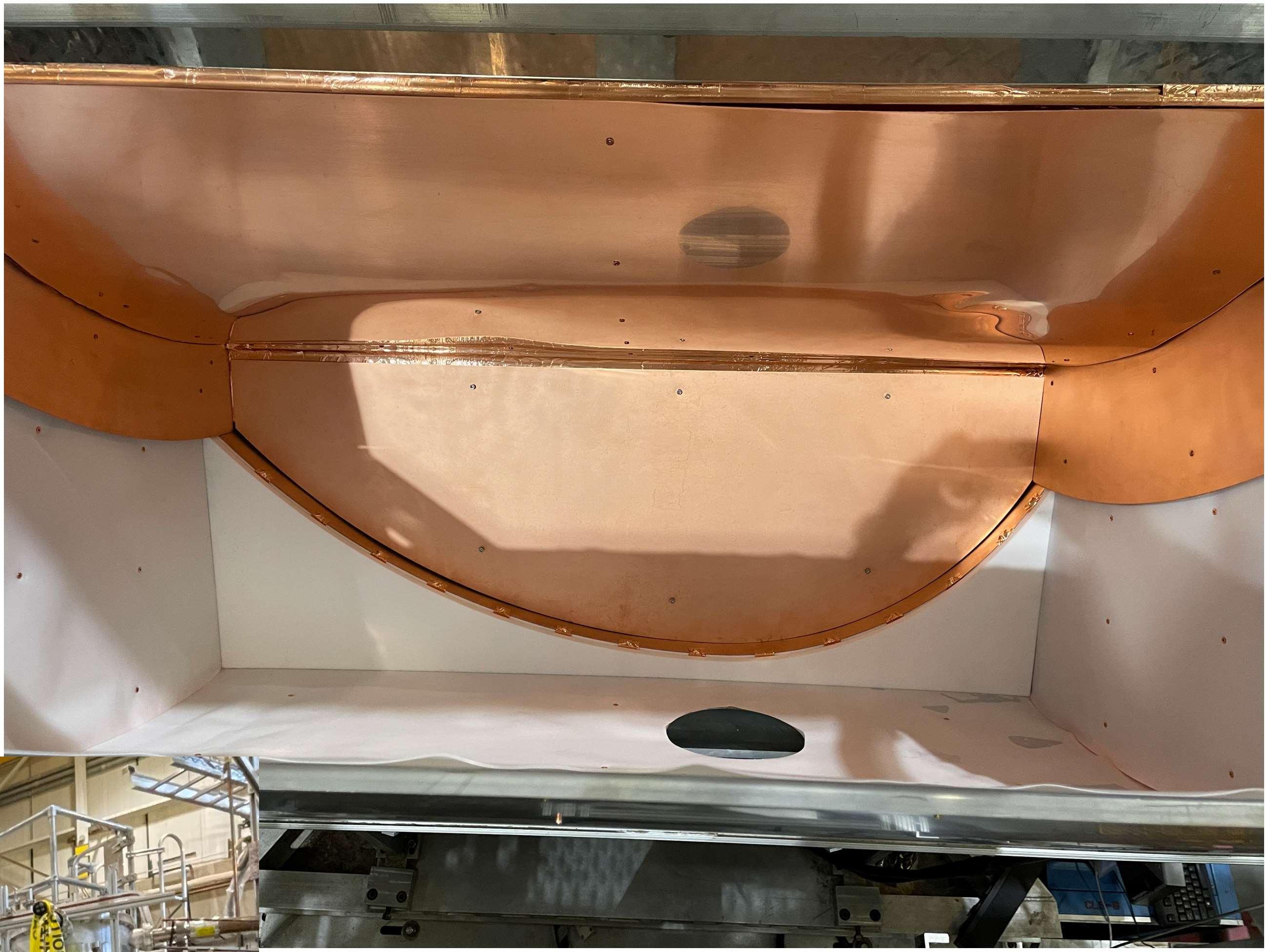


Prototype UCN elevator in test stand at University of Illinois

C-Y Liu group

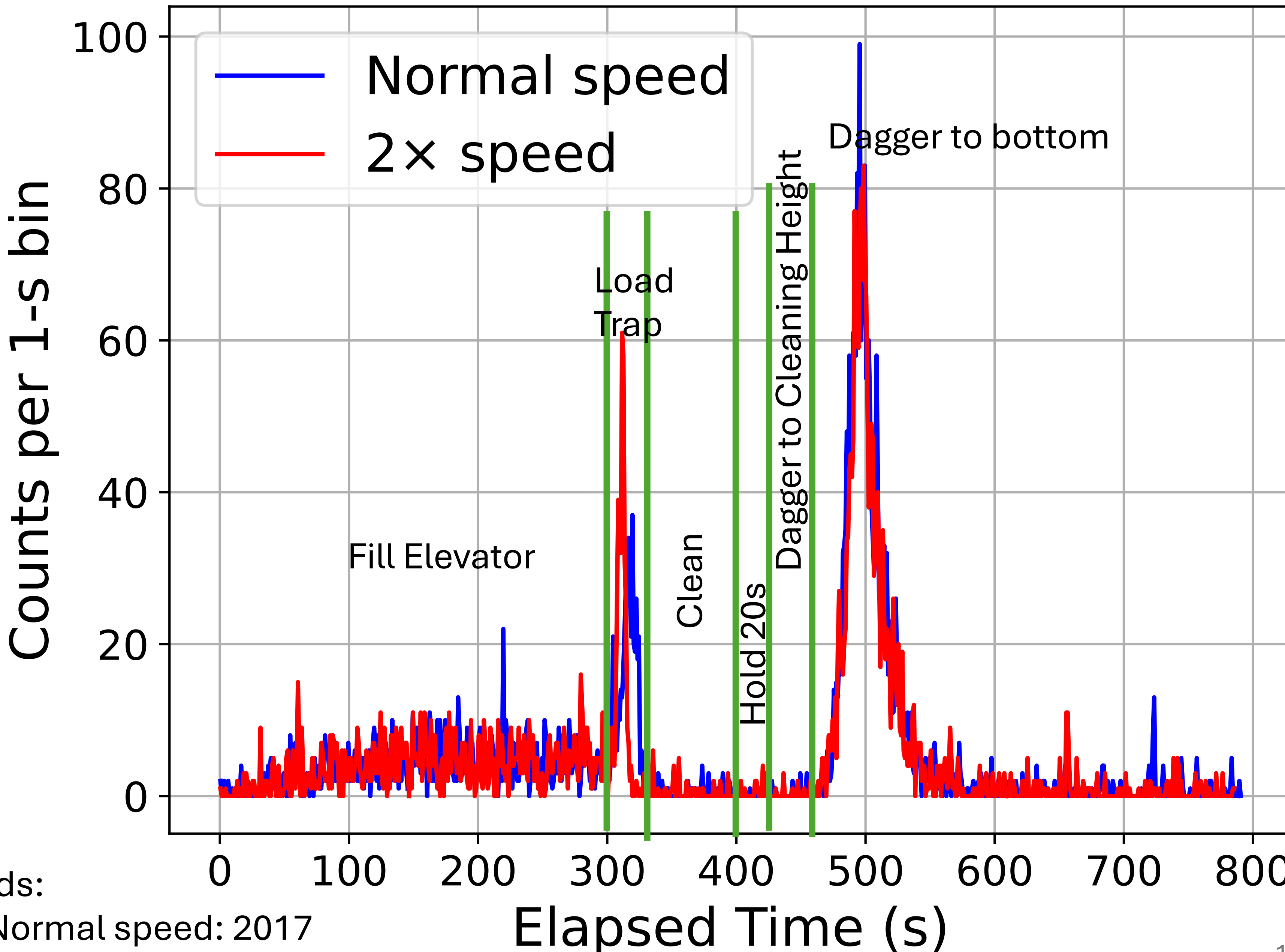
Elevator upgrade (Feb. 2025)

- Elevator was replaced with copper version for better workability.
- We never got to test first prototype with UCN, but this one looks better.



Crew from University of Illinois at Los Alamos for the elevator installation

Example study: loaded UCN vs. elevator speed



Yields:

- Normal speed: 2017
- 2x speed: 2170

Summary of CY2025 UCNτ+ prototype test

- We ran the complete experiment with a prototype elevator and demonstrated UCN cooling into the UCNτ trap.
- Yields normalized to UCN source output were comparable to previous trapdoor loading.

- Preliminary conclusions are that we should:
  1. Improve the bin storage time by reducing gaps (3-4x?)
  2. Improve upstream transport (3-4x?)
  3. Smooth out elevator motion
  4. Increase the mechanical precision of the elevator

UCNτ/UCNτ+ Collaboration

Los Alamos National Laboratory: M. Blatnik, S. M. Clayton (co-spokesperson), C. Cude-Woods, S. A. Currie, M. A. Hoffbauer, T. M. Ito, S. Lin, M. Makela, C. L. Morris, S. Seestrom, C. O'Shaughnessy, M. Singh, I. Smythe, Z. Tang, F. W. Uhrich, P. L. Walstrom, Z. Wang

North Carolina State University: J. H. Choi, B. Chrysler, R. Musedinovic, N. Washecheck, A. R. Young

Oak Ridge National Laboratory: L. J. Broussard, F. Gonzalez, J. Ramsey, A. Saunders

Tennessee Technological University: C. Alfaro, A. Grice, A. T. Holley (co-spokesperson)

University of Illinois Urbana-Champaign: A. Clarke, W. Fox, C.-Y. Huang, C.-Y. Liu, A. Paghadal, L. Reeves, E. Thorsland, A. Wehe, K. Young

Argonne National Laboratory: N. B. Callahan

California Institute of Technology: A. Croley, B. Filippone, K. P. Hickerson, R. Zhu

DePauw University: A. Komives

East Tennessee State University: R. W. Pattie, Jr.

Indiana University/CEEM: L. Blokland, D. J. Salvat, W. M. Snow

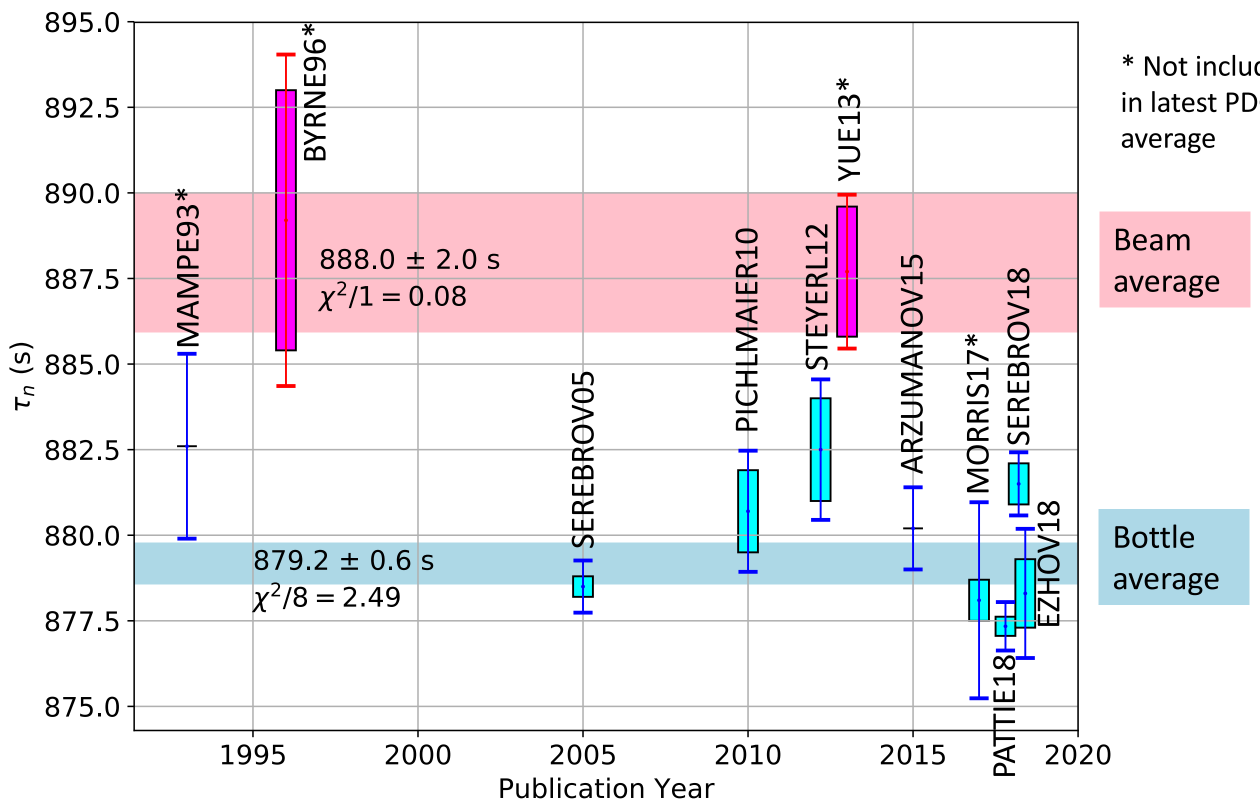
Institut Laue-Langevin: P. Geltenbort

Joint Institute for Nuclear Research: E. I. Sharapov

UCNProBe

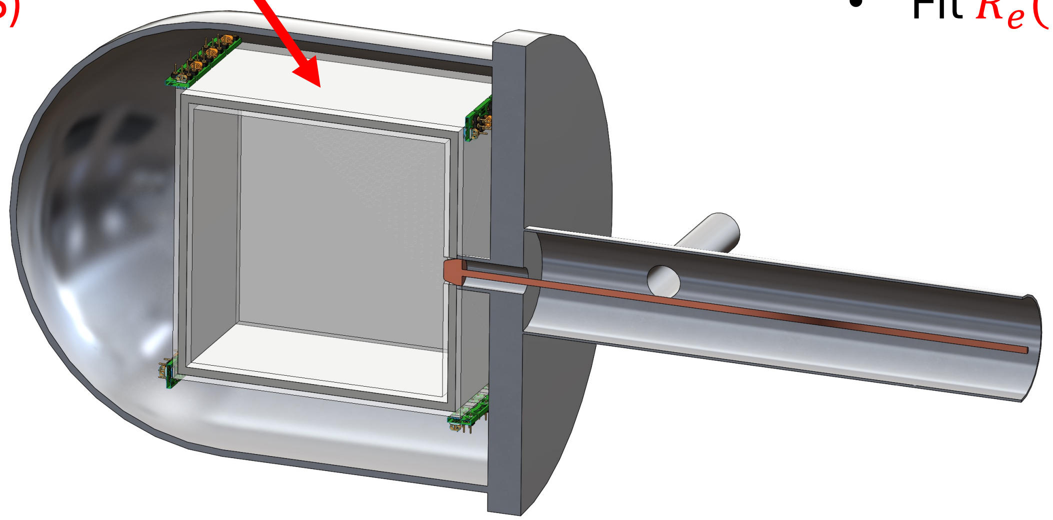
Do a "beam-style" neutron lifetime measurement with UCN to study the neutron lifetime puzzle:

- Absolute measurement of decay rate into electrons
- Absolute measurement of neutron population
- Goal: $\sigma(\tau_n) \sim$ 1-2 s



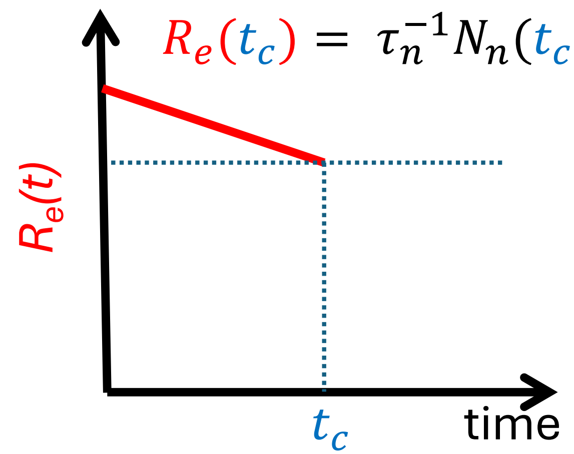
Ultra-Cold Neutron Experiment for Proton Branching Ratio in Neutron Beta Decay (UCNProBe)

UCN storage box comprised of scintillator plates (dPS)



Concept:

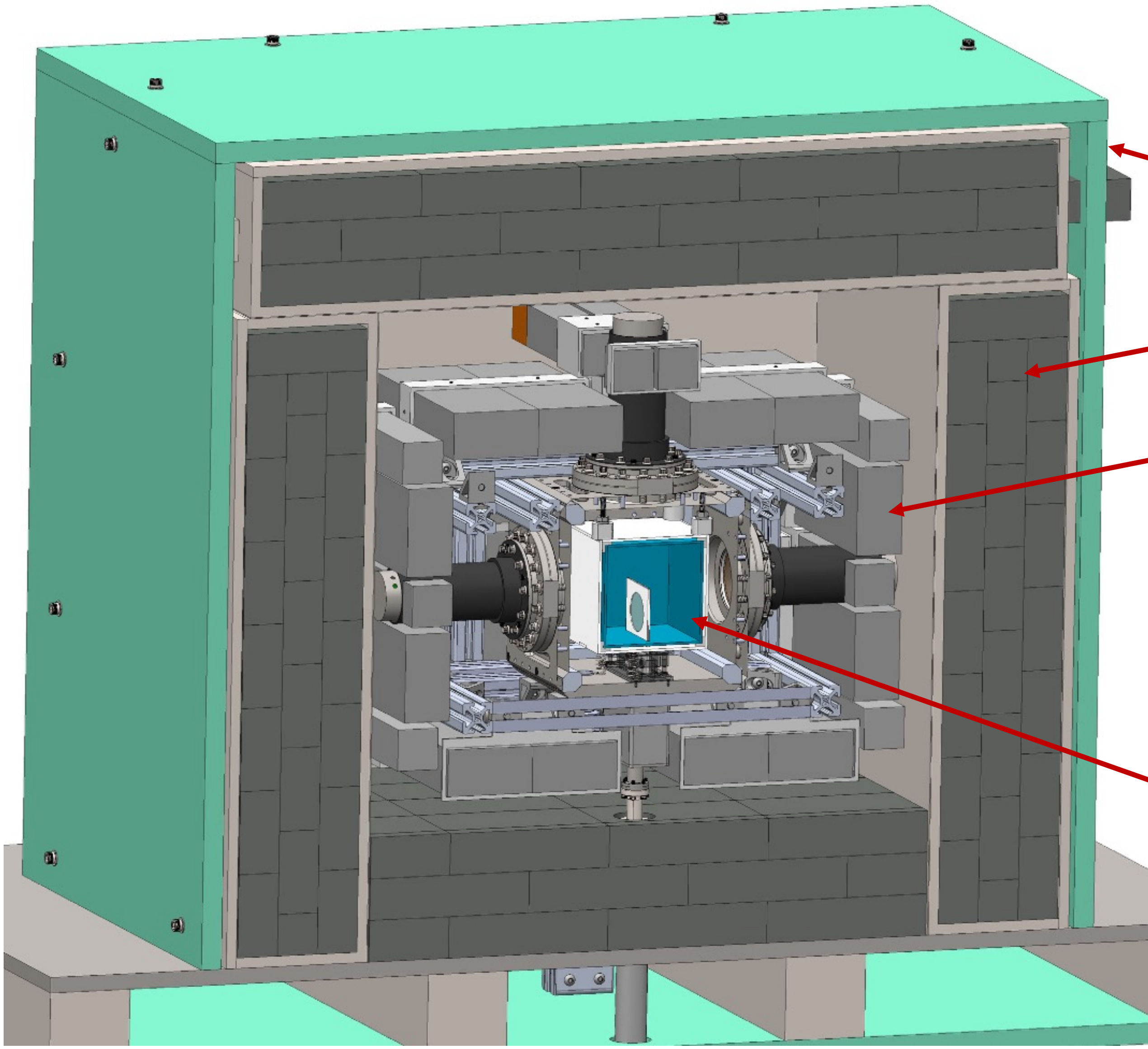
- Observe rate R_e of emitted electrons
- Quickly count neutrons N_n at time t_c
- Fit $R_e(t)$ curve to get $R_e(t_c)$



- Requires *absolute measurements* similar to the beam experiment:
  - Number of neutrons in the trap
  - Number of decay products
  - Needs precision ~0.1% for each quantity
- Z. Tang (LANL) DOE Early Career project

Martin Krivos

UCNProbe Design

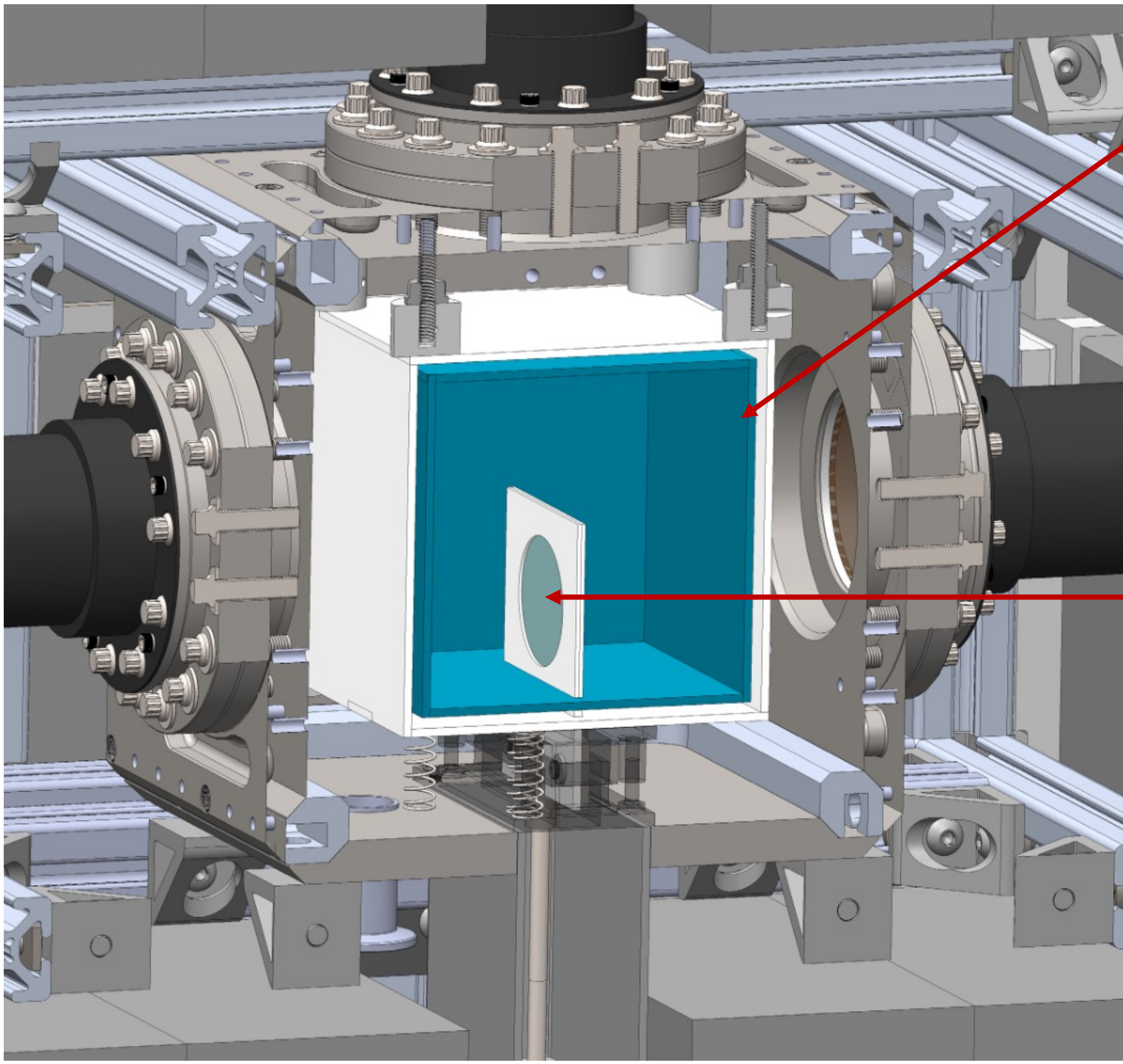


1. Borated Polyethylene – 1-2”
2. Lead shielding – 6”
3. Active veto (NaI) –
   - 16 crystals
   - 57% solid angle coverage

UCN Storage Box

Storing and counting UCN

Martin Krivos



$\underline{\dot{\beta}\ (t):}$

Eljen EJ-299

Deuterated

$V_F = 168$ neV

12 cm cube

$\underline{N(t):}$

YAP:Ce

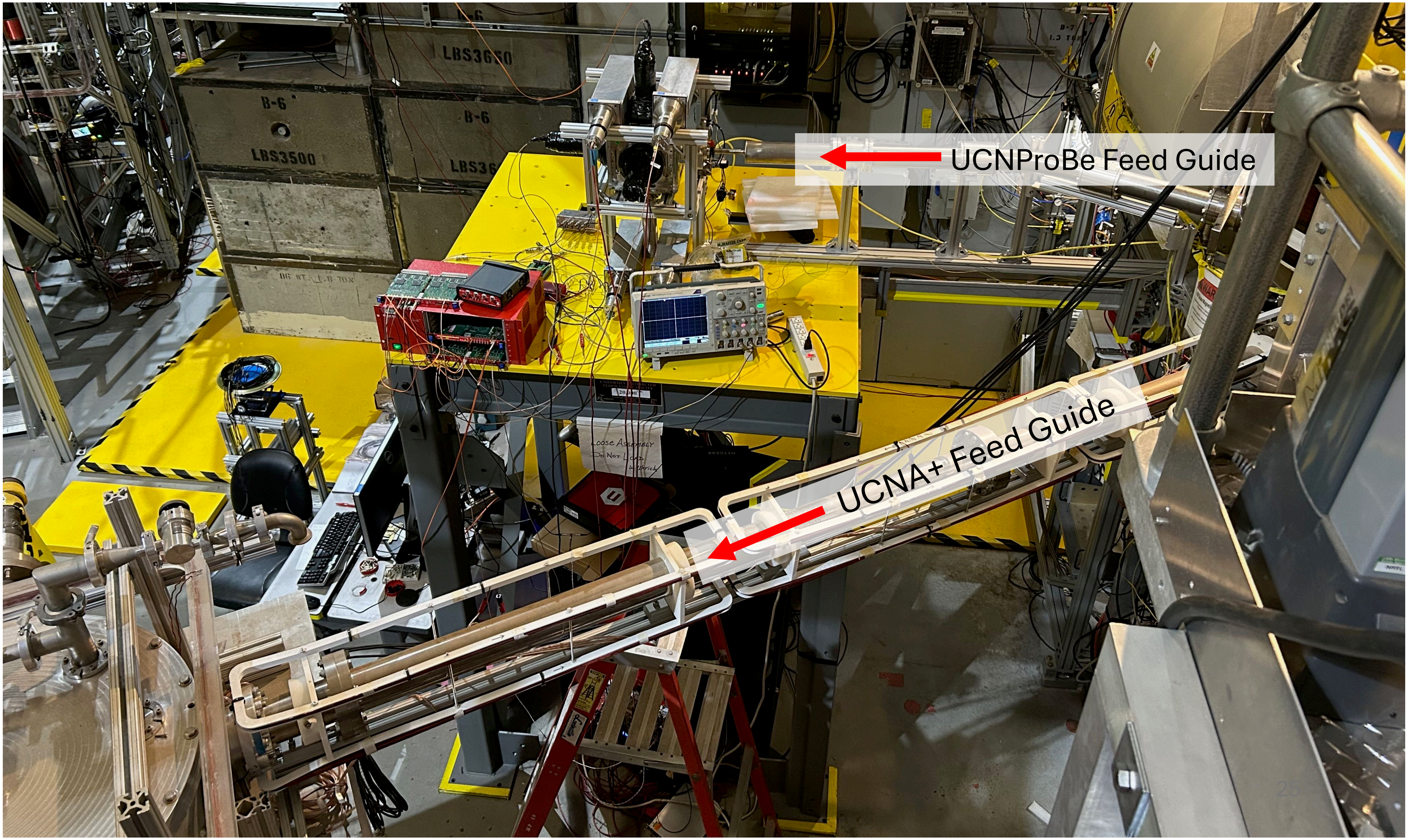
^{10}B-coated

Crystal

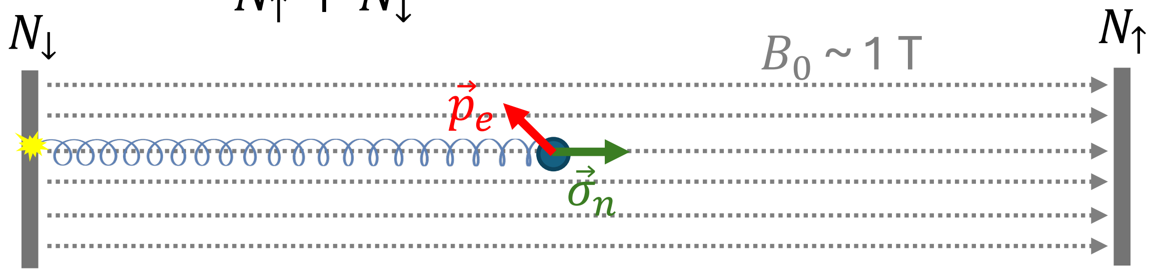
$V_F = 148$ neV

Test of UCNProBe neutron detector with UCN

- First test with UCN (Late CY2025; data analysis underway).
- All major components are expected this year (2026).



$$\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = A(E)\beta_e\langle P_n\rangle$$

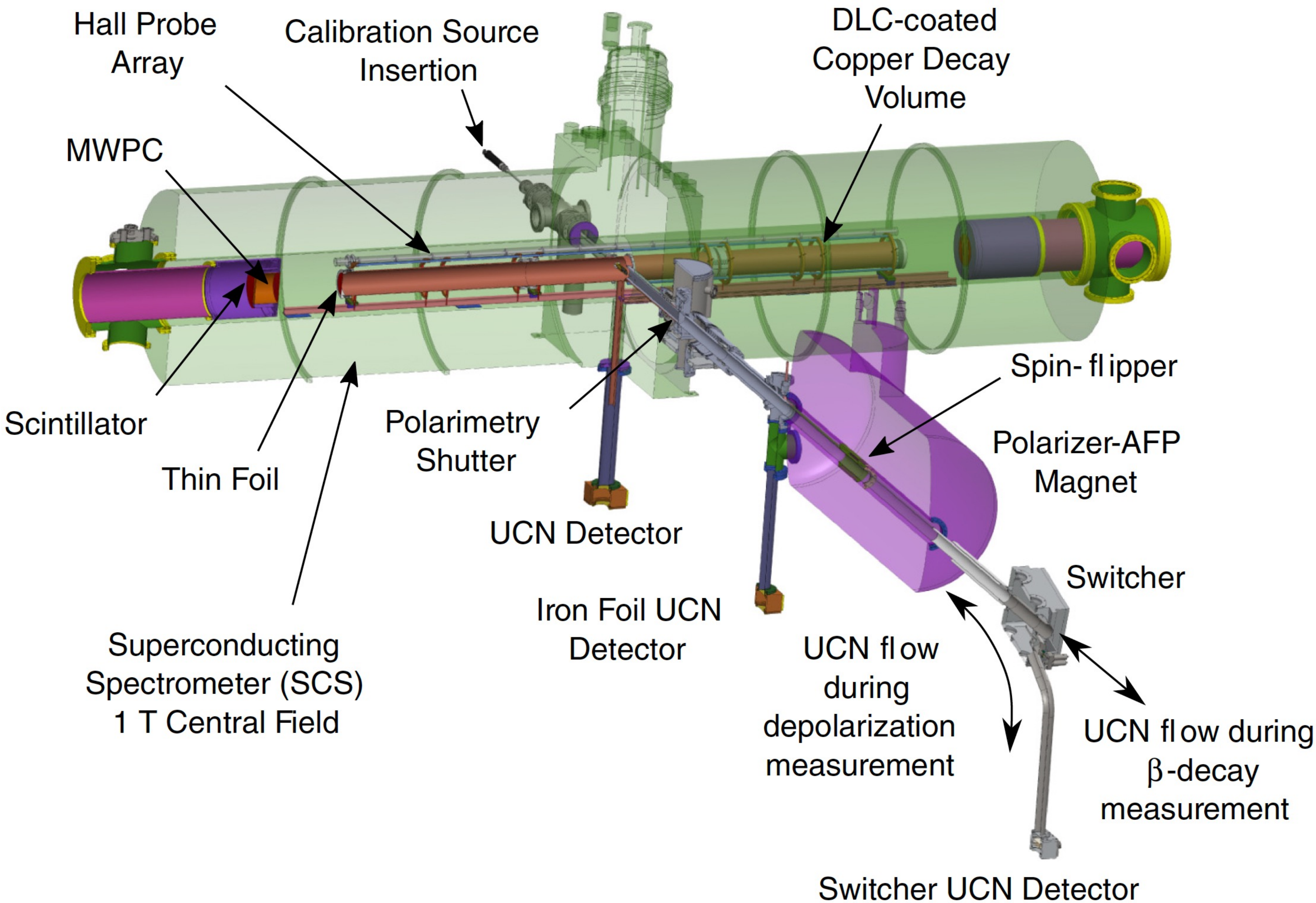


UCNA+

Upgrade UCNA to take advantage of increased output from 2016 upgrade of LANL UCN source:

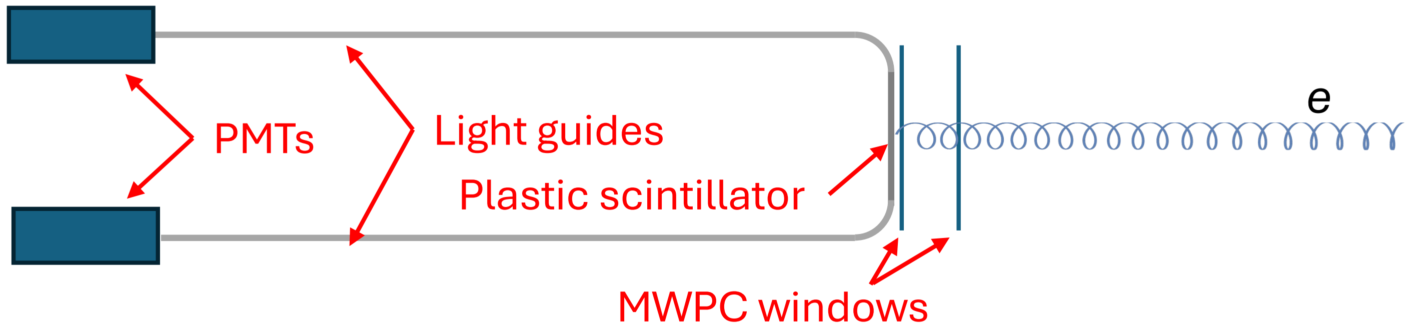
- Replace beta detector with modern version to have less undetected backscatter
- Improve calibration with built-in calibration source scanner
- Goal: $\sigma(A_0) \sim 0.2\%$

UCNA Diagram

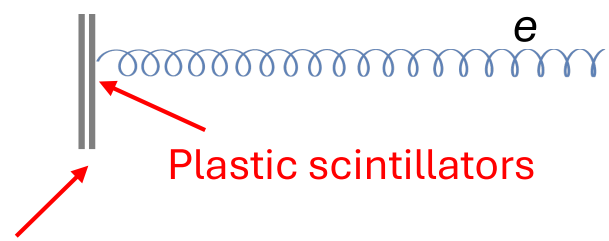


Replace MWPC+Scintillator+Light guides+PMTs with Scintillator+SiPMs

UCNA



UCNA+



Edge readout with SiPM arrays

- No light guide → better uniformity
- Array of SiPMs enables position reconstruction → no need for MWPC for fiducial cut
- Add second scintillator in sandwich configuration → muon veto and continuous background measurement

UCNA Systematic Uncertainties

	% Corr.		% Unc.
	2011–2012	2012–2013	
$\Delta_{\cos\theta}$	– 1.53	– 1.51	0.33
$\Delta_{\text{backscattering}}$	1.08	0.88	0.30
Energy recon.			0.20
Depolarization	0.45	0.34	0.17
Gain			0.16
Field nonunif.			0.12
Muon veto			0.03
UCN background	0.01	0.01	0.02
MWPC efficiency	0.13	0.11	0.01
Statistics			0.36
Theory Corrections [11,12,26–29]			
Recoil Order	– 1.68	– 1.67	0.03
Radiative	– 0.12	– 0.12	0.05

UCNA+ Strategy

Retain end foils for better statistics.
Upgrade detectors.
Improve calibration source scanner.

New switcher and detector for depolarization measurement.
Add absorber to empty guides faster during depolarization measurement.

Improve calibration source scanner.

Add external shim coils.
Improve B-field monitoring.

UCNA Systematic Uncertainties

	% Corr. 2011–2012	% Corr. 2012–2013	% Unc.
$\Delta_{\cos\theta}$	– 1.53	– 1.51	0.33
$\Delta_{\text{backscattering}}$	1.08	0.88	0.30
Energy recon.			0.20
Depolarization	0.45	0.34	0.17
Gain			0.16
Field nonunif.			0.12
Muon veto			0.03
UCN background	0.01	0.01	0.02
MWPC efficiency	0.13	0.11	0.01
Statistics			0.36
Theory Corrections [11,12,26–29]			
Recoil Order	– 1.68	– 1.67	0.03
Radiative	– 0.12	– 0.12	0.05

UCNA+ Strategy

Retain end foils for better statistics.
Upgrade detectors.
Improve calibration source scanner.

New switcher and detector for depolarization measurement.
Add absorber to empty guides faster during depolarization measurement.

Improve calibration source scanner.

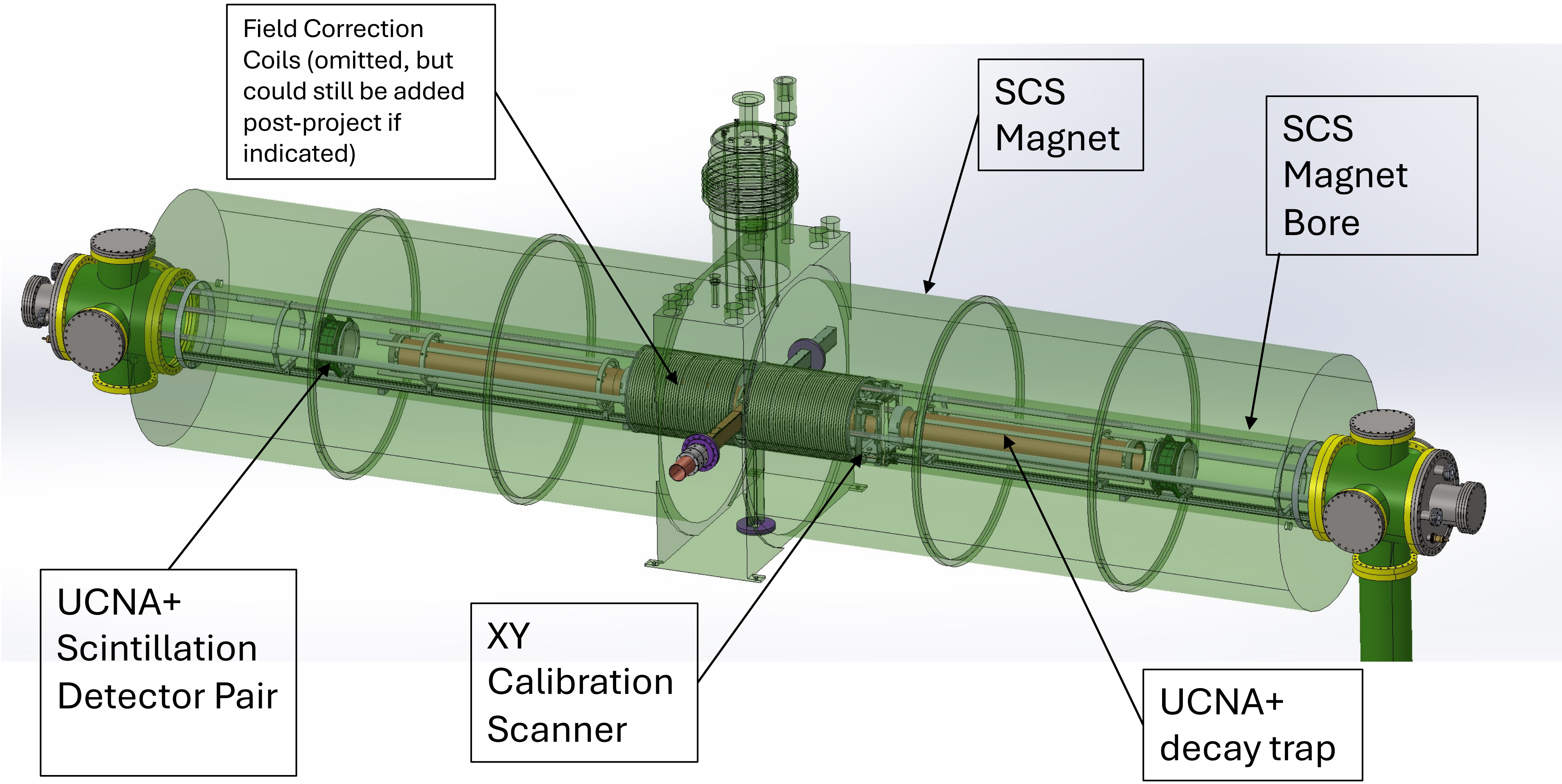
(Optional) external shim coils.
Improve B-field monitoring.

Less material (no MWPC), less dead layer (and measured), better linearity (SiPMs)

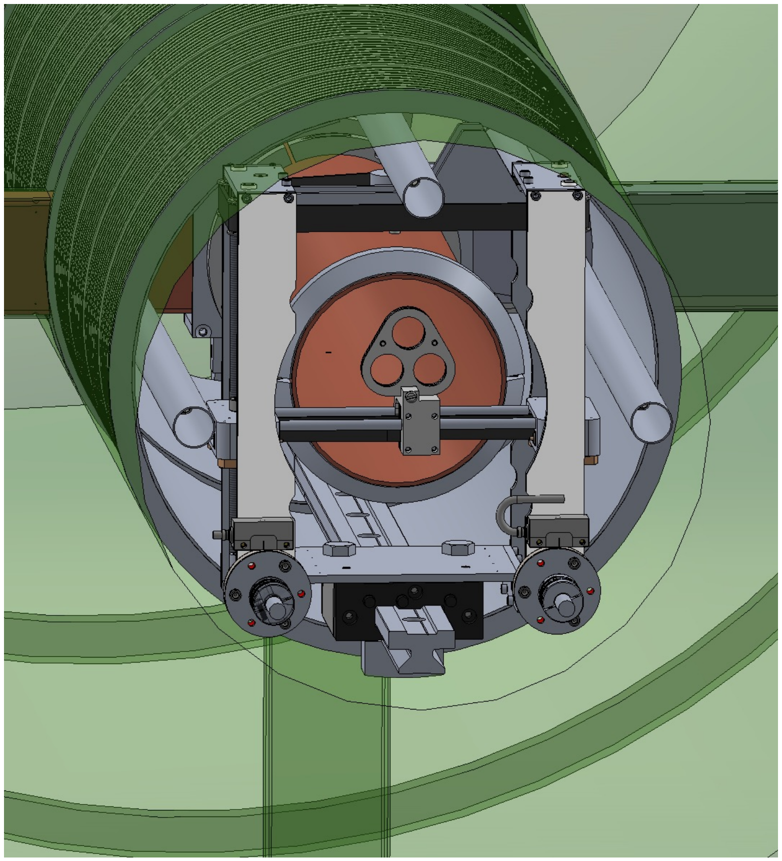
Built-in XY source scanner for frequent, automated scans.

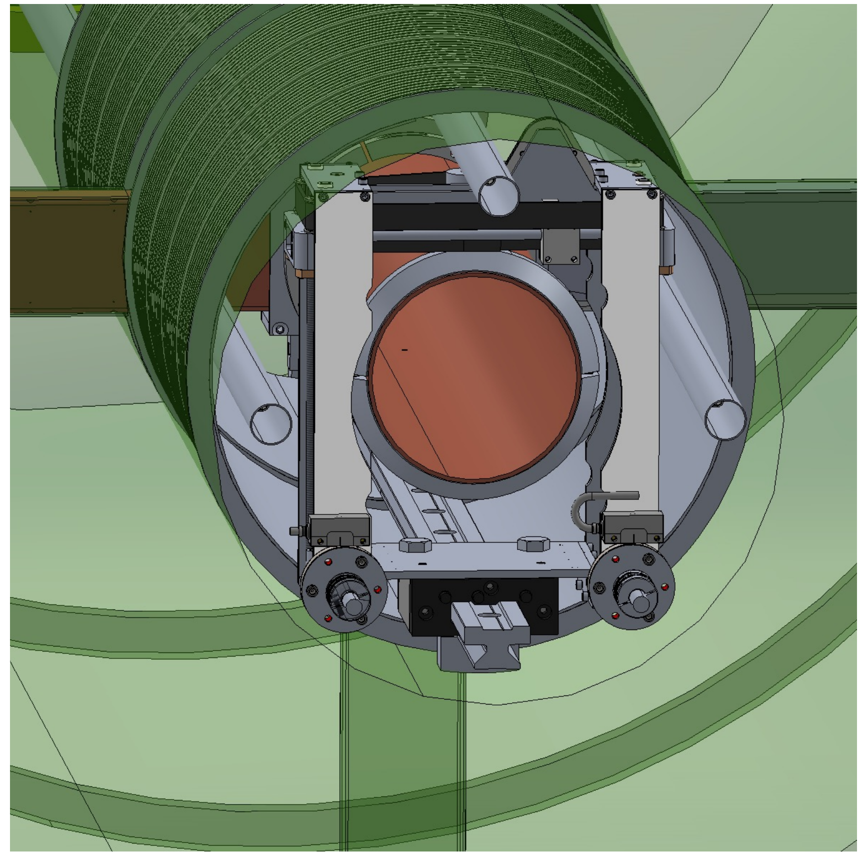
Characterize effect w/source measurements and improved MC.

UCNA+ engineering drawing incorporating all features



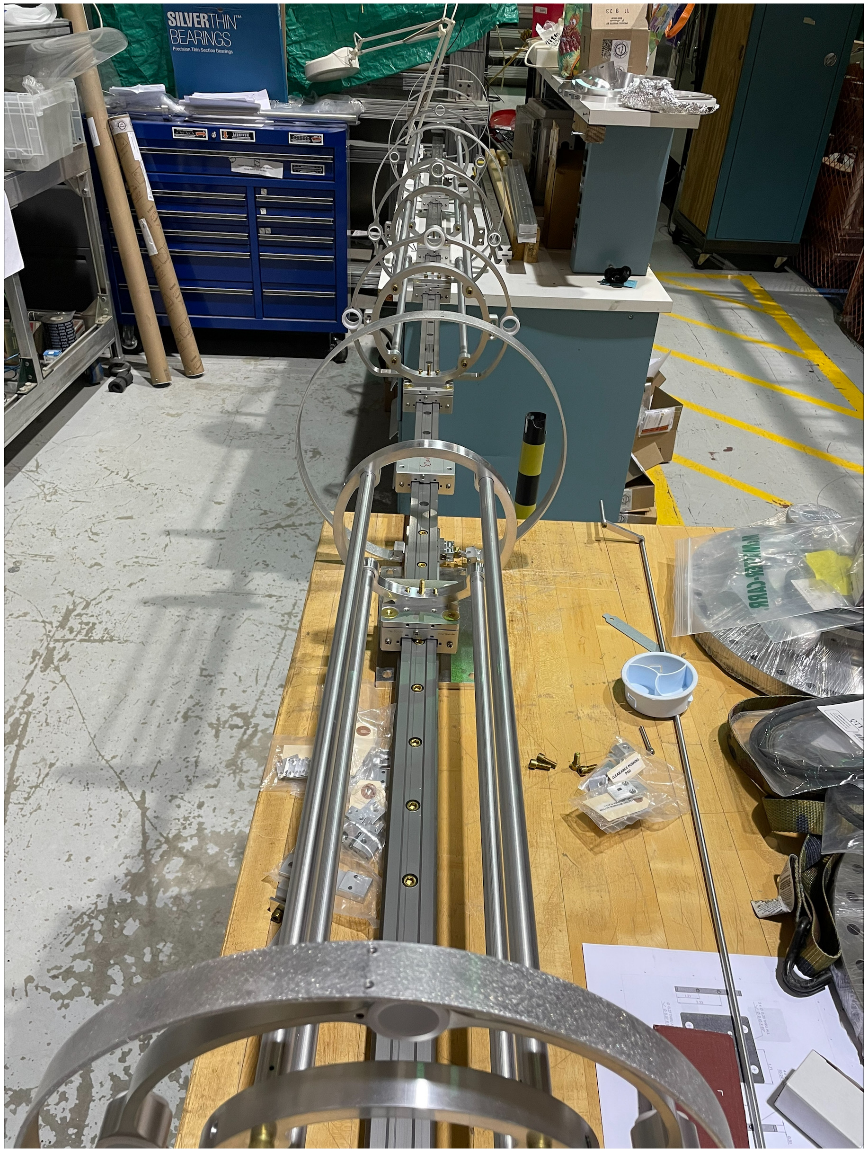
UCNA+ source calibration scanner

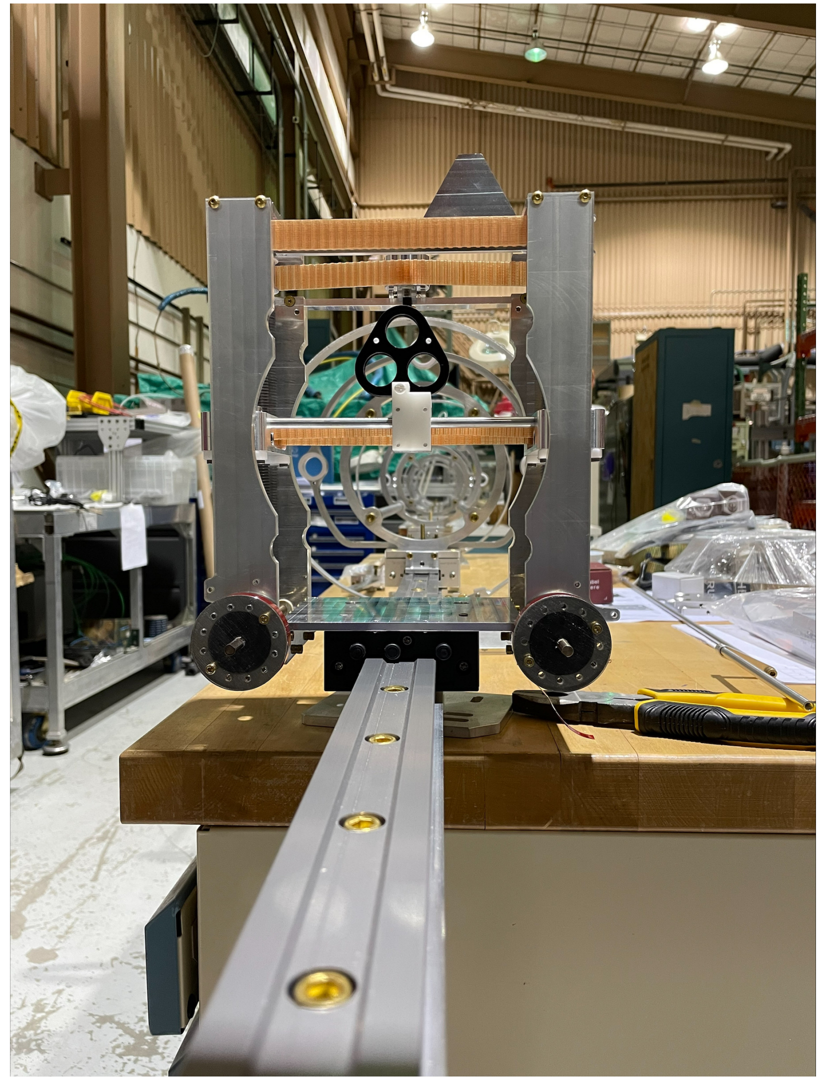




Prototype was fabricated and assembled.

UCNA+ insert and XY scanner assembled on the bench

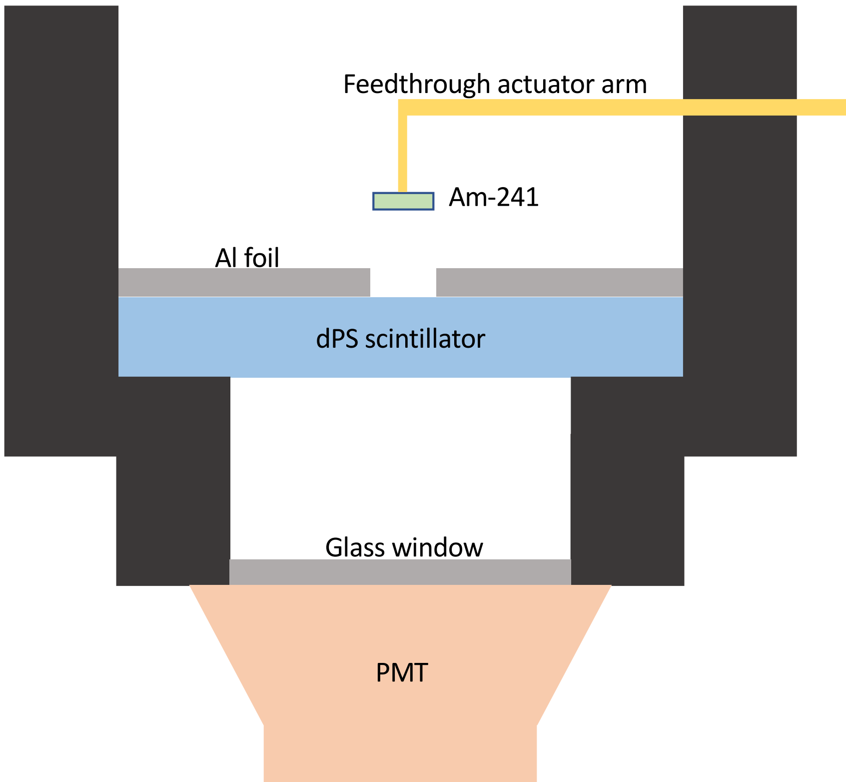


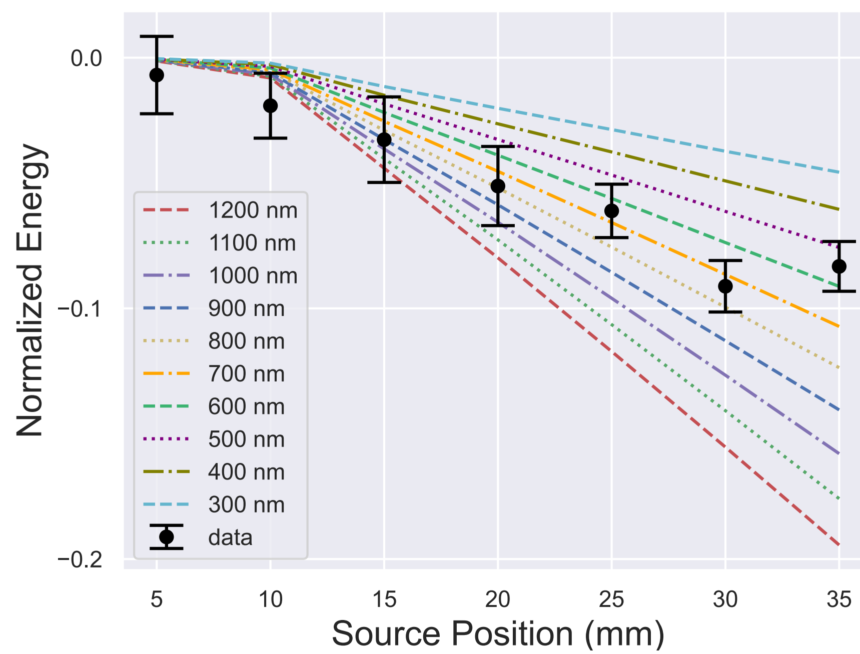


Decay trap assembly has since been installed into the SCS.

Measure scintillator dead layer

Use same method as was developed for UCNProBe to measure detector dead layer of dPS scintillator



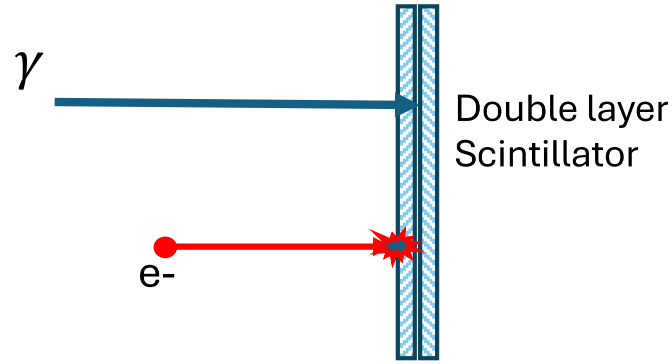


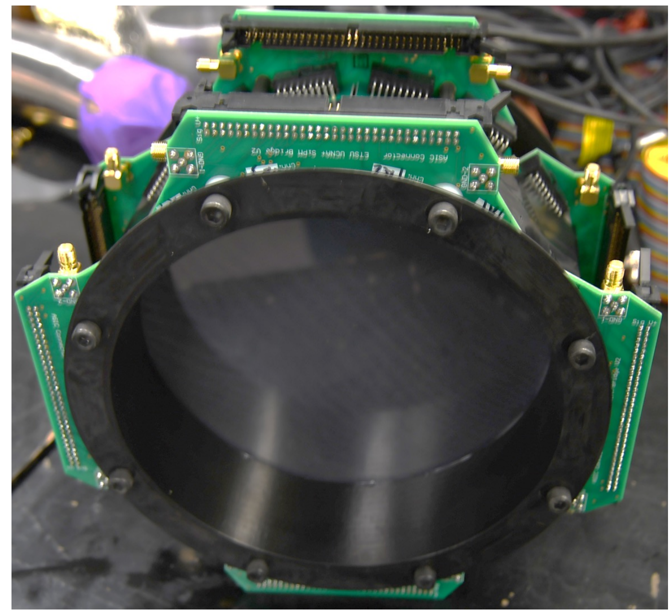
Experiment	Dead Layer Thickness (nm)
No Heat Treatment	630 ± 40
Argon Heat Treatment	760 ± 60
Nitrogen Heat Treatment	670 ± 50

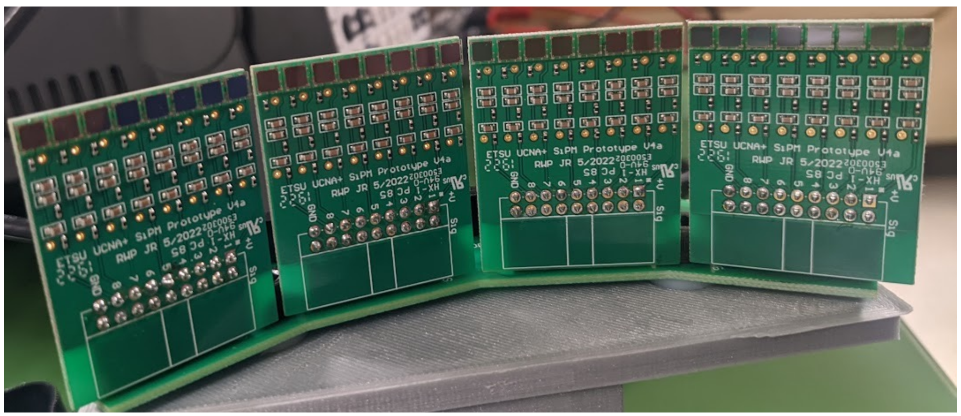
N. Floyd et al., Scintillation characteristics of the EJ-299-02H scintillator. *Rev. Sci. Instrum.* 1 April 2024; 95 (4): 045108. https://doi.org/10.1063/5.0179451

UCNA+ detector

- 256 edge coupled SiPM (Sensl C-Series)
  - 2xEljen EJ-200 scintillator
  - 2xCAEN DT5550w 128 SiPM readout/bias system (Citiroc)
- Position and Energy read out with same detector





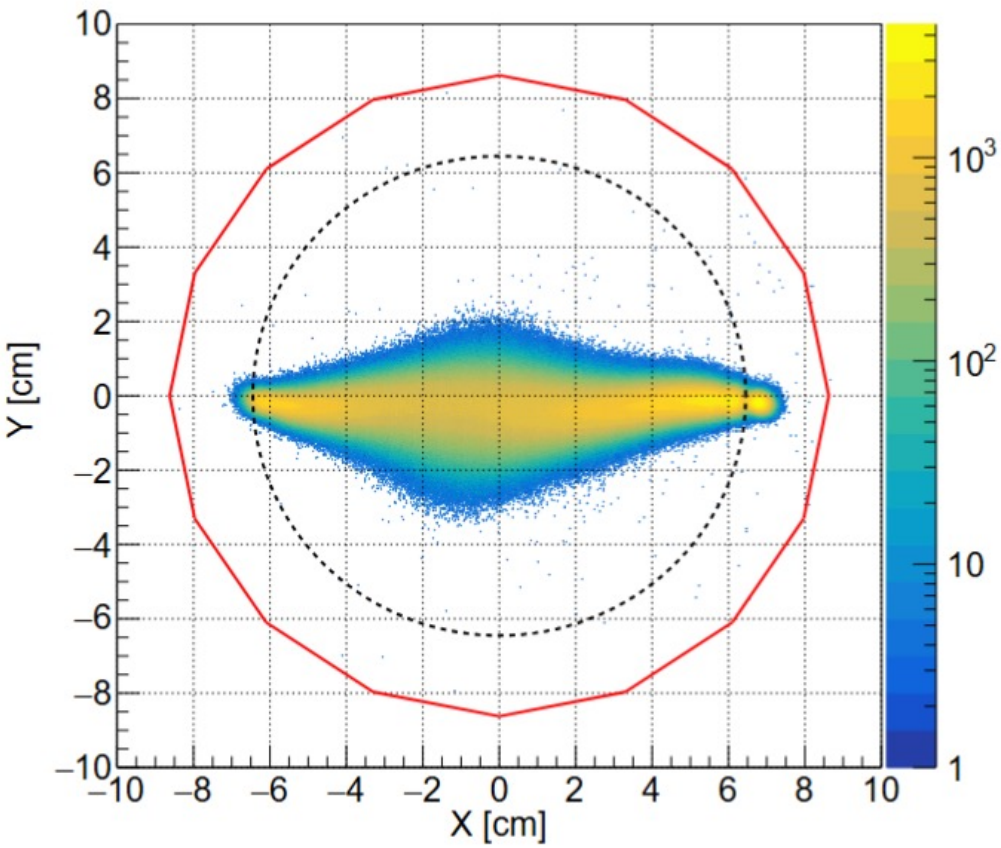


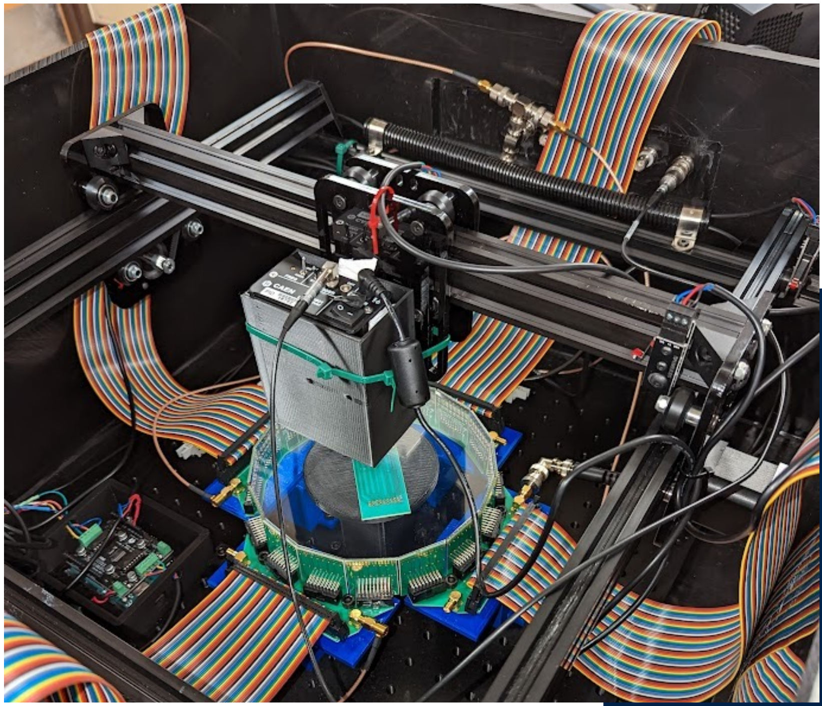
ETSU

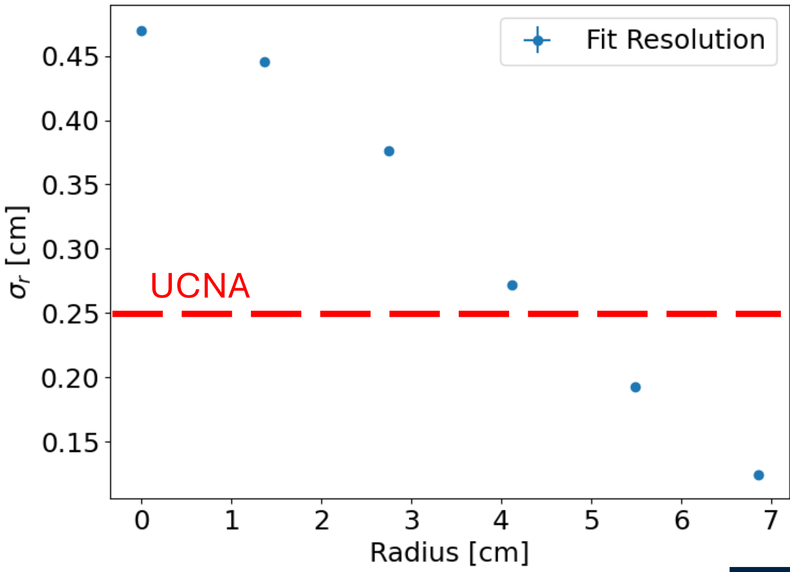
Detector built by Prof. R. Pattie,Jr and undergraduate students

- Detectors are fully assembled
- Tests with calibration sources in vacuum and with applied magnetic field are planned for early 2026.

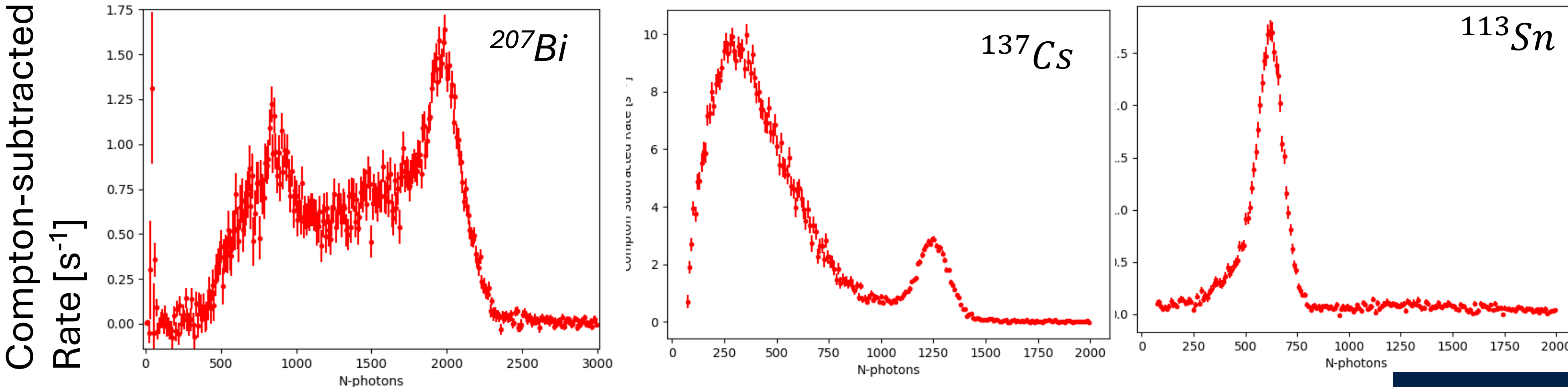
Reconstruction from LED

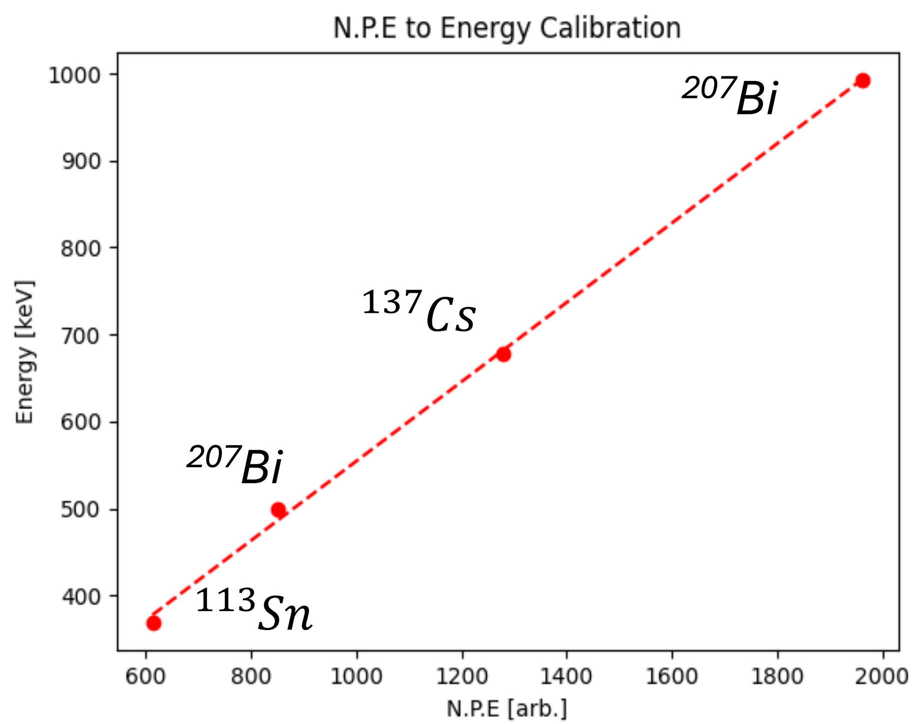






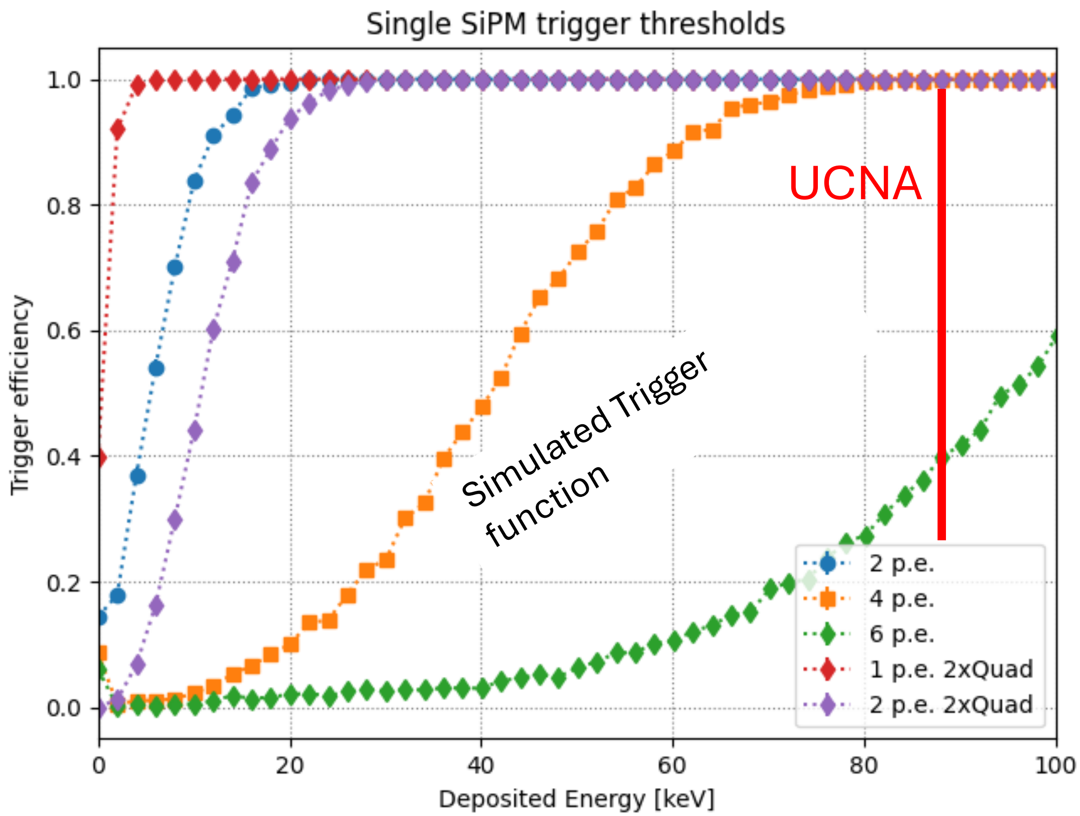
Energy calibration and linearity





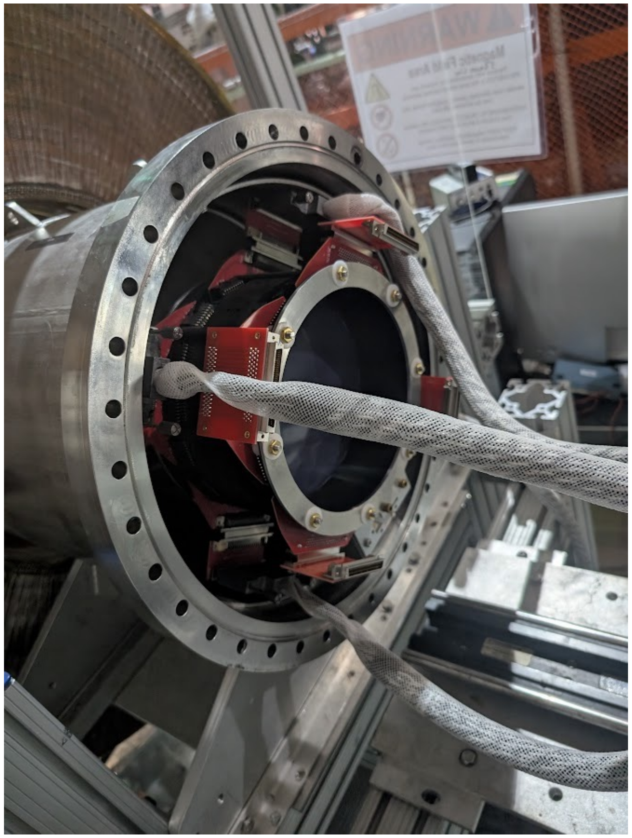
Trigger Efficiency simulations

- Simulated incident e- 1-150 keV
- Global trigger for all 128 SiPMs
- N p.e. 2xQuad requires a SiPM in two separate quadrants.
- Current estimate is a 4 p.e. threshold



ETSU

UCNA+ Detector Test Stand at LANL



ETSU

UCNA+ R&D Collaboration

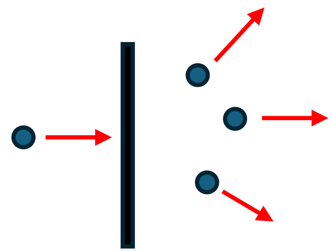
- East Tennessee State University:
  - **T. Cox, J. Fry, A. Greathouse, K. Hawkins**, **R.E. McDonald IV, N. Meredith,** R. W. Pattie JR
- Indiana University/CEEM:
  - **M. Dawid,** W. Fox, M. Luxnat, D.J. Salvat, J. Vanderwerp, G. Visser,
- Los Alamos National Lab:
  - M. C. Anderson, S. Clayton, **,** C. Cude-Woods, D. Fernandez, R. Gupta, T.M. Ito, S. Lin, M. Makela, C. Morris, C. O'Shaughnessy, E. Renner, Z. Tang, Z. Wang
- North Carolina State University:
  - **J.H. Choi, B. Chrysler, K. Murer, R. Musedinovic**, **N. Washecheck**, A.R. Young
- Oak Ridge National Laboratory:
  - F. Gonzalez, A. Saunders
- Tennessee Technical University:
  - A.T. Holley**, L. Chapman, C. Hasting, E. Upton, C. Shepherd**
- University of Kentucky:
  - **R. Gupta**, B. Plaster
- University of Illinois- Urbana Champaign
  - C.Y. Liu

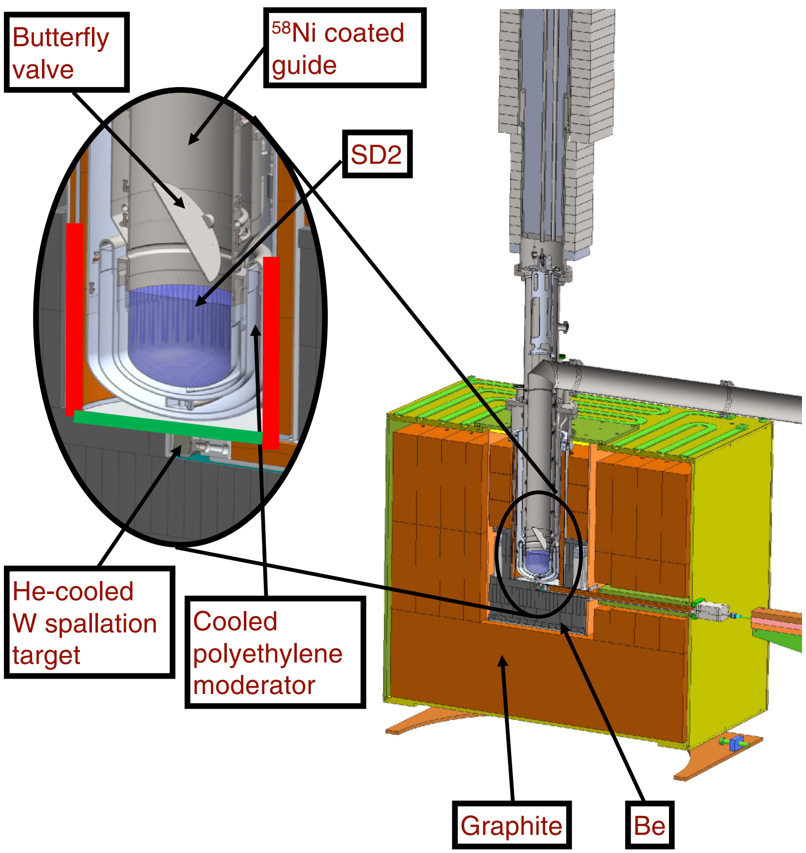
- Work supported by LANL LDRD program; the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under Awards No. DE-FG02-ER41042, No. DE-AC52-06NA25396, No. DE-AC05-00OR2272 and No. 89233218CNA000001 under proposal LANLEEDM; NSF Grants No. 1614545, No. 1914133, No. 1506459, No. 1553861, No. 1812340, No. 1714461, No. 1913789, No. 2209511, No 2515036.

- Student researchers in bold.

LEU fission plate for LANL UCN source

C. O'Shaughnessy





Spallation neutrons from W target
K.E. ~ 2 MeV

Thermal neutrons in Be and graphite moderator
K.E. ~ 25 meV

H2O Pre-moderator

LEU FISSION PLATE
K.E. > 1 MeV

Cold neutrons in polyethylene cold moderator
K.E. ~ 6 meV

Ultracold neutrons in SD2 converter
K.E. ~ 100 neV

Goals:

- Add LEU to space surrounding source to boost UCN density.
- Utilize fission process to multiply and reradiate thermal neutrons that are otherwise lost.
- Models show that a pre-moderator is necessary to prevent the LEU from being a sink rather than a source.

How to Make More UCN

M. Blatnik, DNP2025

Spallation
K.E. ~ 2 MeV

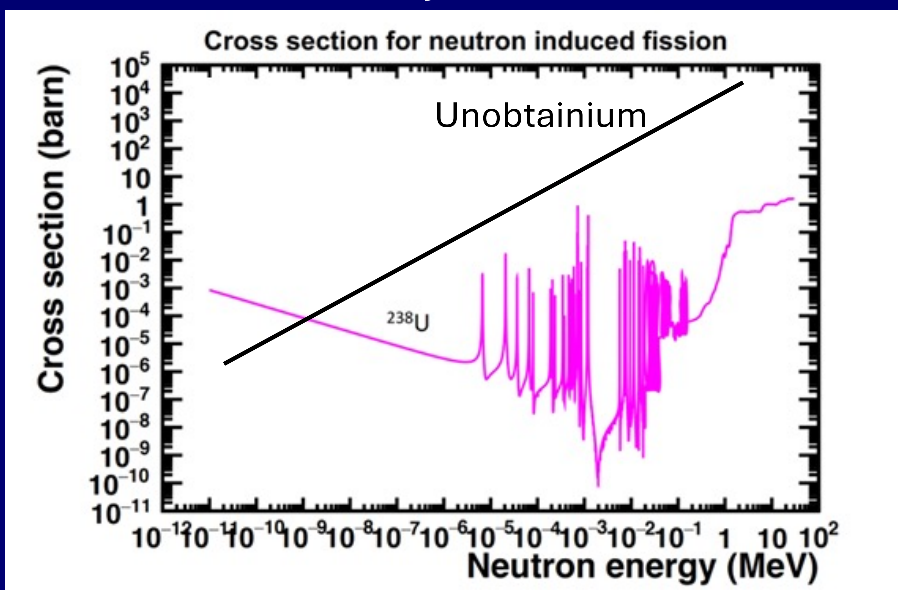
Thermalize in Be and graphite moderator
K.E. ~ 25 meV

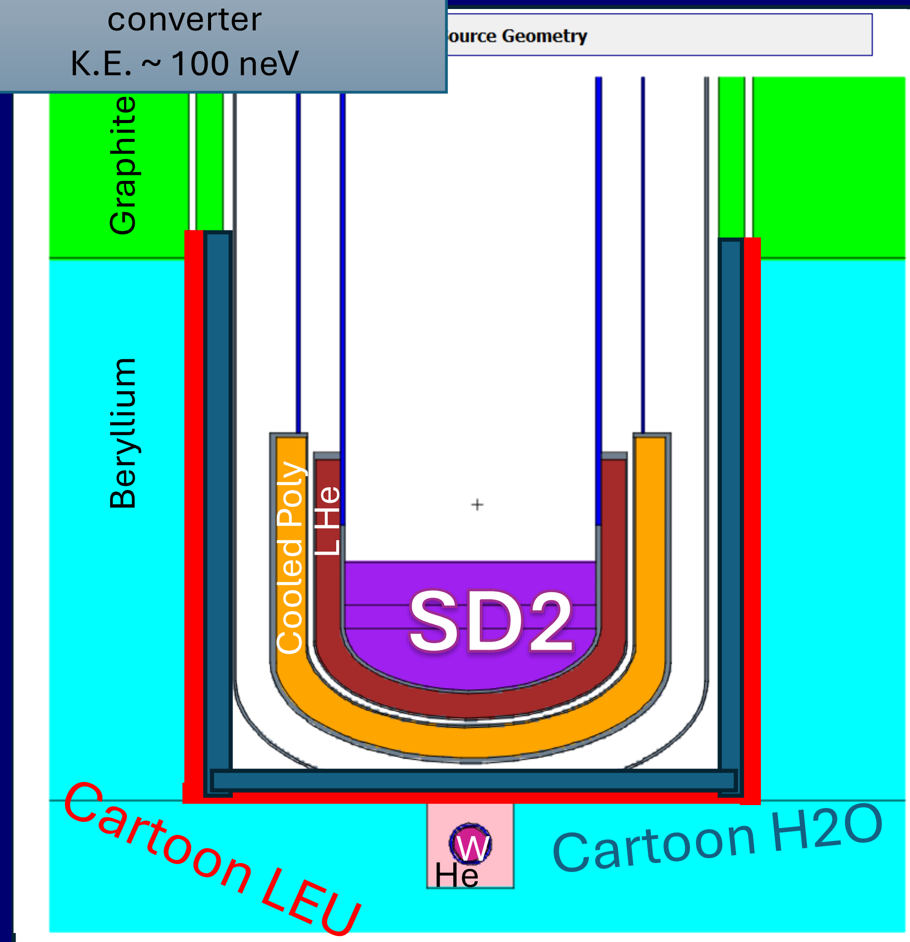
Cold neutrons in polyethylene cold moderator
K.E. ~ 6 meV

Ultracold neutrons in SD2 converter
K.E. ~ 100 neV

Fission Uranium for More Neutrons

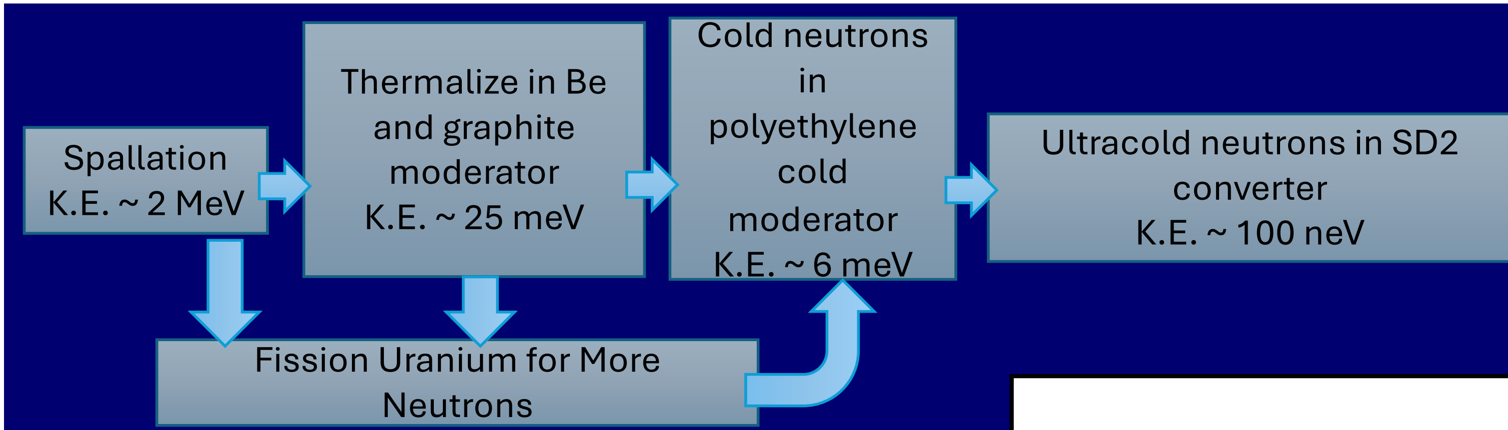
Don't Throw the Baby out with the Bathwater



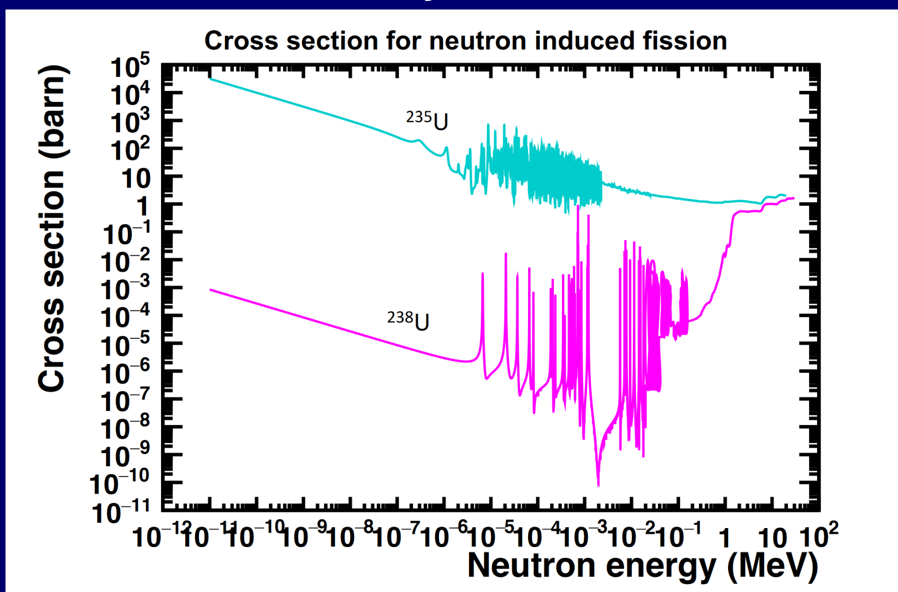


How to Make More UCN

M. Blatnik, DNP2025



Don't Throw the Baby out with the Bathwate

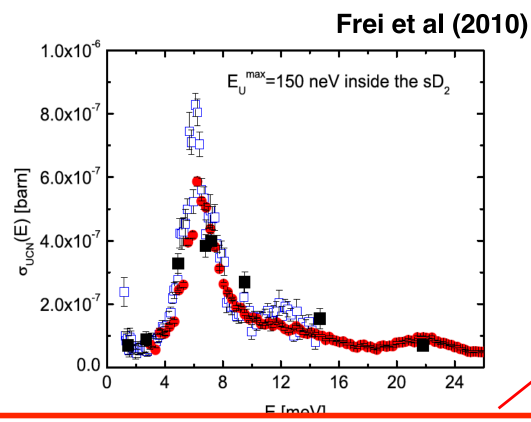


- Ideal process: fission fast neutrons and preserve thermal neutrons
- Mean free path for fission:
  - Fast neutrons
    - 40 cm in DU
    - 20 cm in U-235
  - Thermal neutrons
    - 0.02 cm in U-235
    - 0.1 cm in 20% LEU
- Can create fission neutrons from thermal neutrons, but not reasonably well from fast neutrons
- Need U-235 to increase fission rate in compact space and reduce material budget

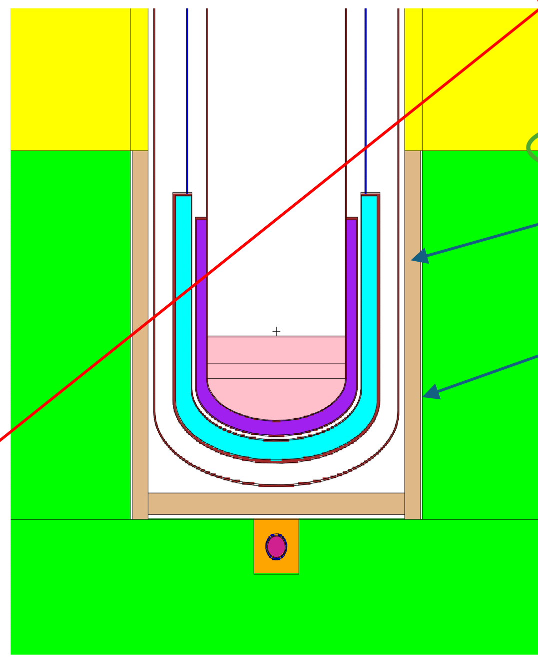
C. O'Shaughnessy

LEU Boosted Source / Thermal Moderators

Material	Thermal MFP (cm)	Thermal Abs (cm)	1 MeV MFP (cm)	1 MeV Abs (cm)	UCN prod (/319 UCN/cm^3/μC)	Ave Heat SD_2 (/6.5 W)	Prod Gain/ Heat Gain
CH_2	0.37	37	2.2	(>10 m)	3.0	2.8	1.1
H_20	0.46	45	1.8	(>10 m)	6.7	5.6	1.2
Be	0.26	167	0.51	556	3.5	4.5	0.7
C	2.1	3333	4.1	(>1 m)	1.4	1.4	1.0



$$P_{UCN} = \rho_{SD} \int \Phi_{CN}(E) \sigma_{UCN}(E) dE$$



Thermal Moderator – 1.79 cm wall

LEU Shell – 2.1 mm wall / 16.5cm radius

Current Source – Graphite Shell – 2 cm wall: 319 UCN/cm^3/μC and 6.5 W

Summary

- UCNτ+: Designed to increase statistics and reduce rate-dependent effects.
  - Recently demonstrated UCN cooling (elevator transport) with yield comparable to UCNτ, and there are prospects for big improvements.
  - Higher rate detector was built and tested in 2022 UCNτ production running; further improvements are planned.
- UCNProBe: New idea to measure neutron partial decay width w/electron in final state
  - Recently did first tests of neutron detector with UCN.
  - Apparatus is nearly ready for testing later this year.
- UCNA+: Designed to reduce systematics to take advantage of higher UCN source output after 2016 upgrade
  - Upgrade is nearly complete and will continue to be developed, including offline tests of beta detectors with calibration sources.
- Increasing the LANL source output 5-10x appears feasible, and an effort to design this in detail is underway.
  - Would extend the reach of UCNA+ (and nEDM)
  - Would enable new experiments with strict phase-space cuts.

CKM test using V_{ud} from neutron decay [Snapshot from a few years ago]

$$\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$$

$$\delta|V_{ud}|^2 \approx \left[\left(0.95\,\frac{\delta\tau_n}{\tau_n}\right)^2 + \left(0.39\,\frac{\delta A}{A}\right)^2 + \left(0.036\,\frac{\delta RC}{RC}\right)^2\right]^{1/2}$$

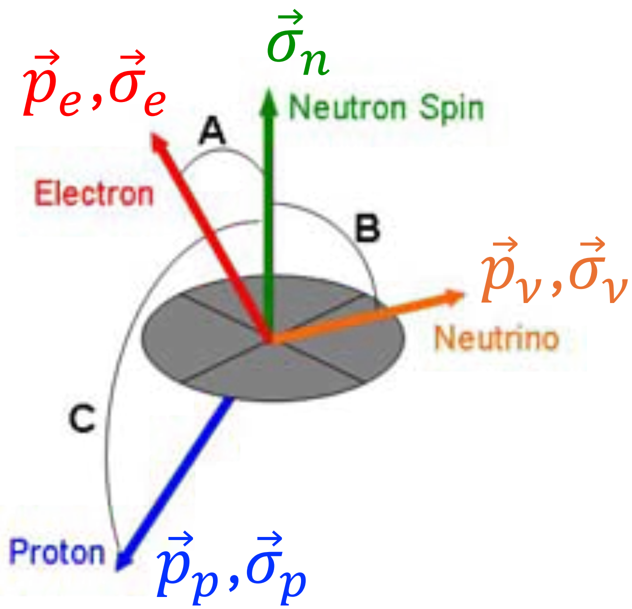
	$\delta\tau_n$	$\frac{\delta A}{A}$ **or** $\approx \frac{\delta a}{a}$	$\frac{\delta\Delta_{np}}{\Delta_{np}}$	$0.95\,\frac{\delta\tau_n}{\tau_n}$ $\times 10^4$	$0.39\,\frac{\delta A}{A}$ $\times 10^4$	$0.036\,\frac{\delta RC}{RC}$ $\times 10^4$	Total $\delta\lvert V_{ud}\rvert^2$ $\times 10^4$
Present values (PDG, post-2002 *A*)	0.6 s	0.18% (including PERKEO3)	20%	6.5	6.8	1.9	9.6
Expected results of existing efforts	0.3 s (UCNτ)	0.13% (PERKEO3, Nab)	20%	3.2	5.2	1.9	6.4
With UCNτ+ and UCNA+	0.1 s (UCNτ+)	0.11% (UCNA+, PERKEO3, Nab)	10%	1.1	4.3	1.0	4.6
With future, next-gen asymmetry expt.	0.1 s	0.03% (PERC, future UCN expt.?)	10%	1.1	1.2	1.0	1.9

Compare to nuclear decay $\delta|V_{ud}|^2 \approx 5\times10^{-4}$

Extra slides

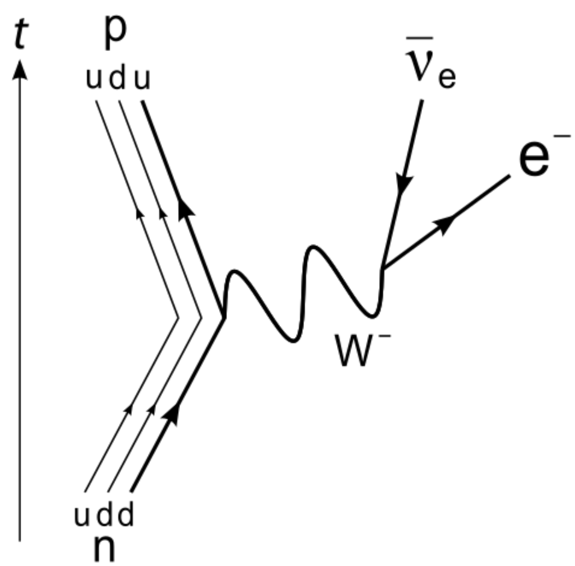
Correlation parameters sensitive to $\lambda \equiv \frac{g_A}{g_V}$

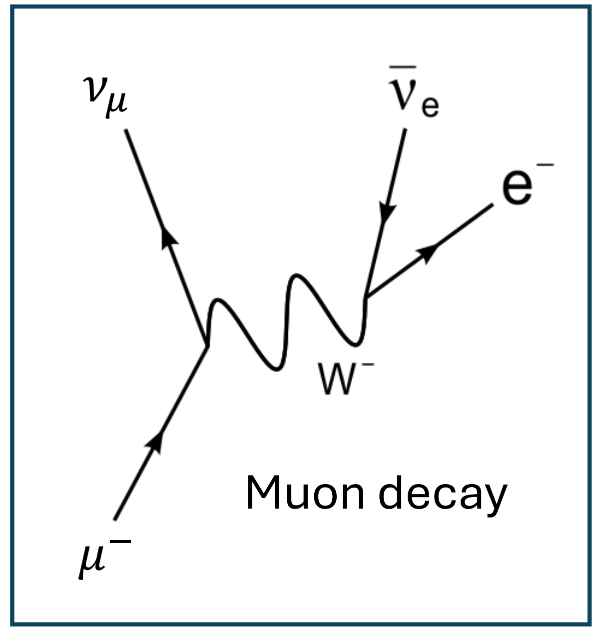
Correlation Parameter	Approx. value	
$a = \frac{1-\lambda^2}{1+3\lambda^2}$	-0.11	$a\, \vec{p}_e \cdot \vec{p}_\nu$
$A = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$	-0.12	$A\, \vec{\sigma}_n \cdot \vec{p}_e$
$B = 2\frac{\lambda(\lambda-1)}{1+3\lambda^2}$	0.99	$B\, \vec{\sigma}_n \cdot \vec{p}_\nu$
$C = x_C \frac{4\lambda}{1+3\lambda^2}$	-0.24	$\mathrm{C}\, \vec{\sigma}_n \cdot \vec{p}_p$
$D = -2\frac{\lvert\lambda\rvert \sin\varphi}{1+3\lambda^2}$	0 (Non-zero φ would mean T violation)	$D\, \vec{\sigma}_n \cdot (\vec{p}_e \times \vec{p}_\nu)$



Neutron β decay at the quark level

$n \rightarrow p + e + \bar{\nu}_e$, β endpoint energy 782 keV





$q^2 \ll m_W$: 4-fermion interaction

$V - A$ interaction

Quark level: $\mathcal{M}_q = \frac{G_F}{\sqrt{2}} V_{ud} [u\gamma_\mu(1-\gamma_5)d][e\gamma^\mu(1-\gamma_5)\nu_e]$

CKM Matrix

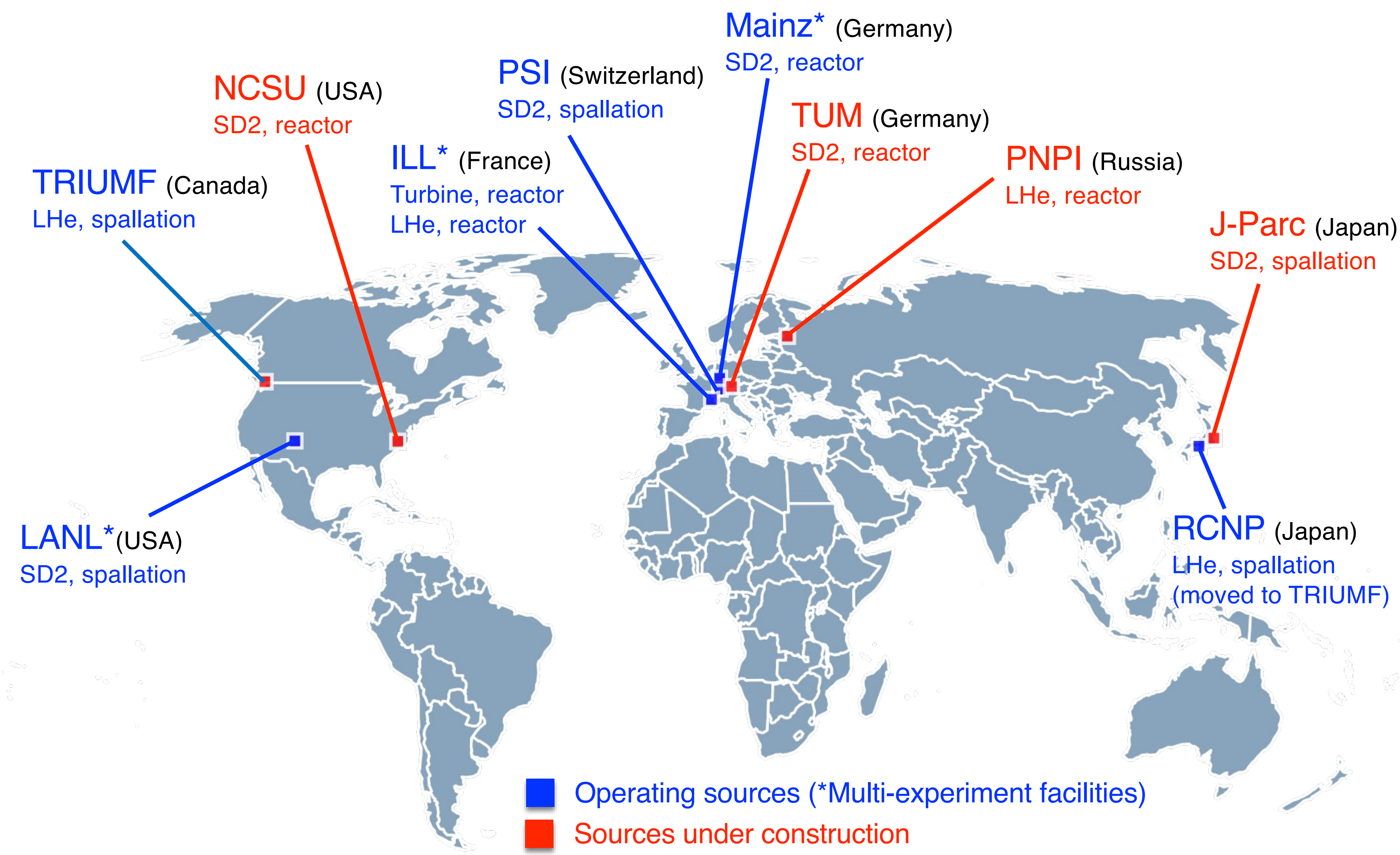
Quark level: $\mathcal{M}_q = \frac{G_F}{\sqrt{2}} V_{ud} [u\gamma_\mu(1-\gamma_5)d][e\gamma^\mu(1-\gamma_5)\nu_e]$

$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak states | CKM mixing matrix | Mass eigenstates

Unitarity: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$

UCN sources around the world



First version of elevator was installed in late 2024

Nucleon level: form factors

=1 by CVC ≈ -1

$$\mathcal{M}_q = \frac{G_F}{\sqrt{2}} V_{ud} \left[p(\gamma_\mu (g_V + g_A \gamma_5) + \frac{\kappa_p - \kappa_n}{2M} \sigma_{\mu\nu} q^\nu) n \right] [e \gamma^\mu (1 - \gamma_5) \nu_e]$$

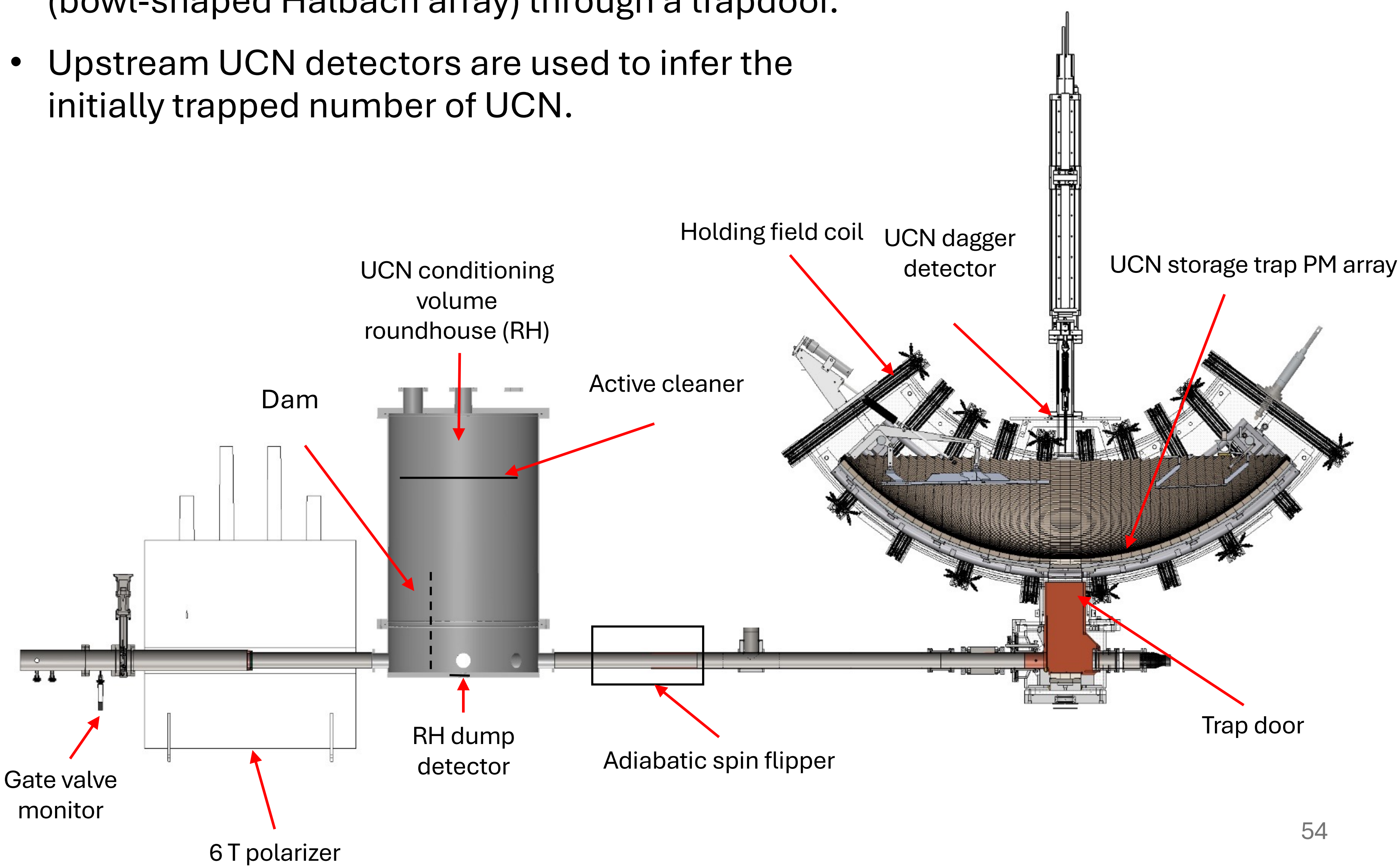
Weak magnetism: determined from electromagnetic properties (anomalous magnetic moments)

Other terms are forbidden in the SM or can be neglected at low energies.

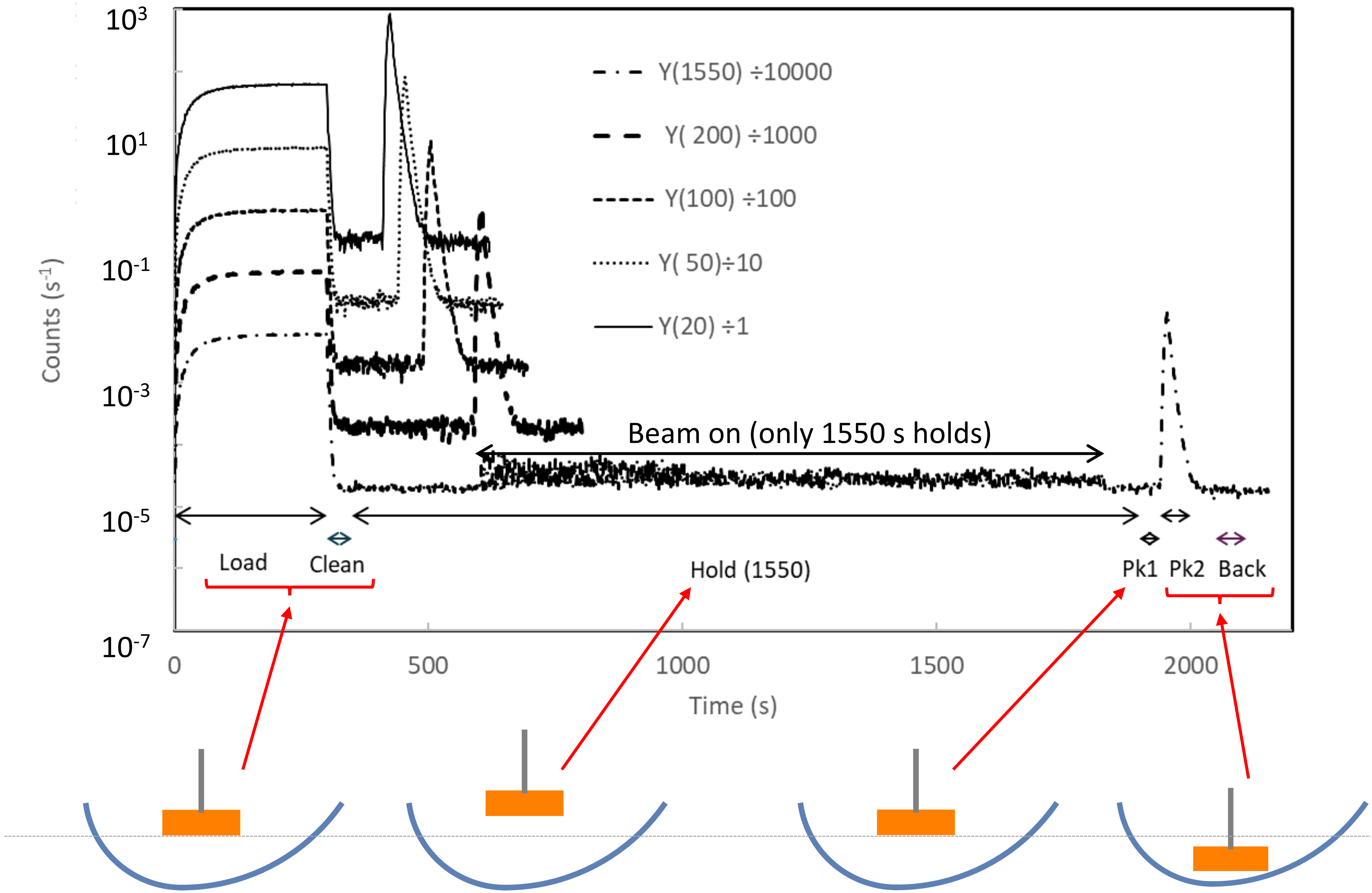
→ Essentially a single parameter, g_A or $\lambda \equiv \frac{g_A}{g_V}$, accounts for nucleon structure.

UCNτ experimental layout

- UCN are loaded into a magneto-gravitational trap (bowl-shaped Halbach array) through a trapdoor.
- Upstream UCN detectors are used to infer the initially trapped number of UCN.



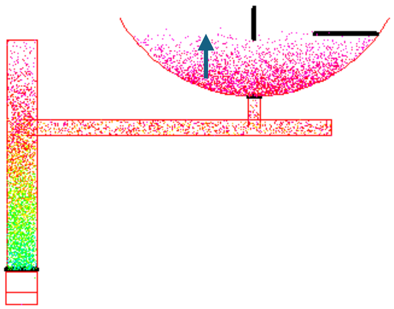
UCN detection



What can go wrong?

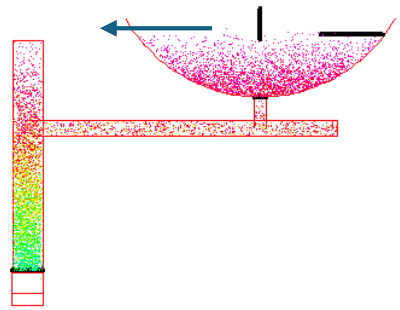
Heating

Limit established by long holding time excess

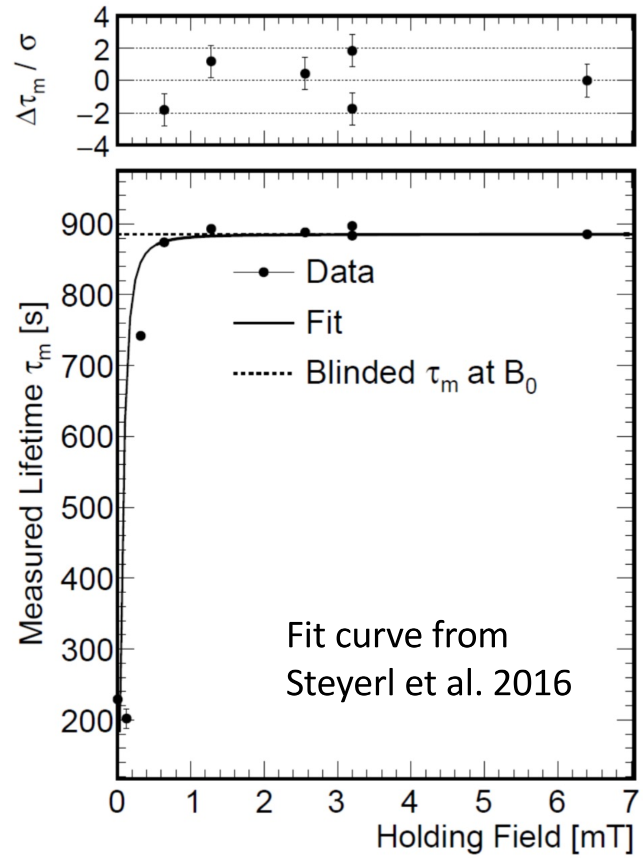


Insufficient Cleaning

Limit established by short holding time excess



Depolarization



Detector Rate-Dependent Effects

- Pileup: adjust photon threshold in analysis based on probability of extra photons.
- Dead time: track analysis clustering dead time and correct for.
- Depends on each analysis group's "Event Definition"

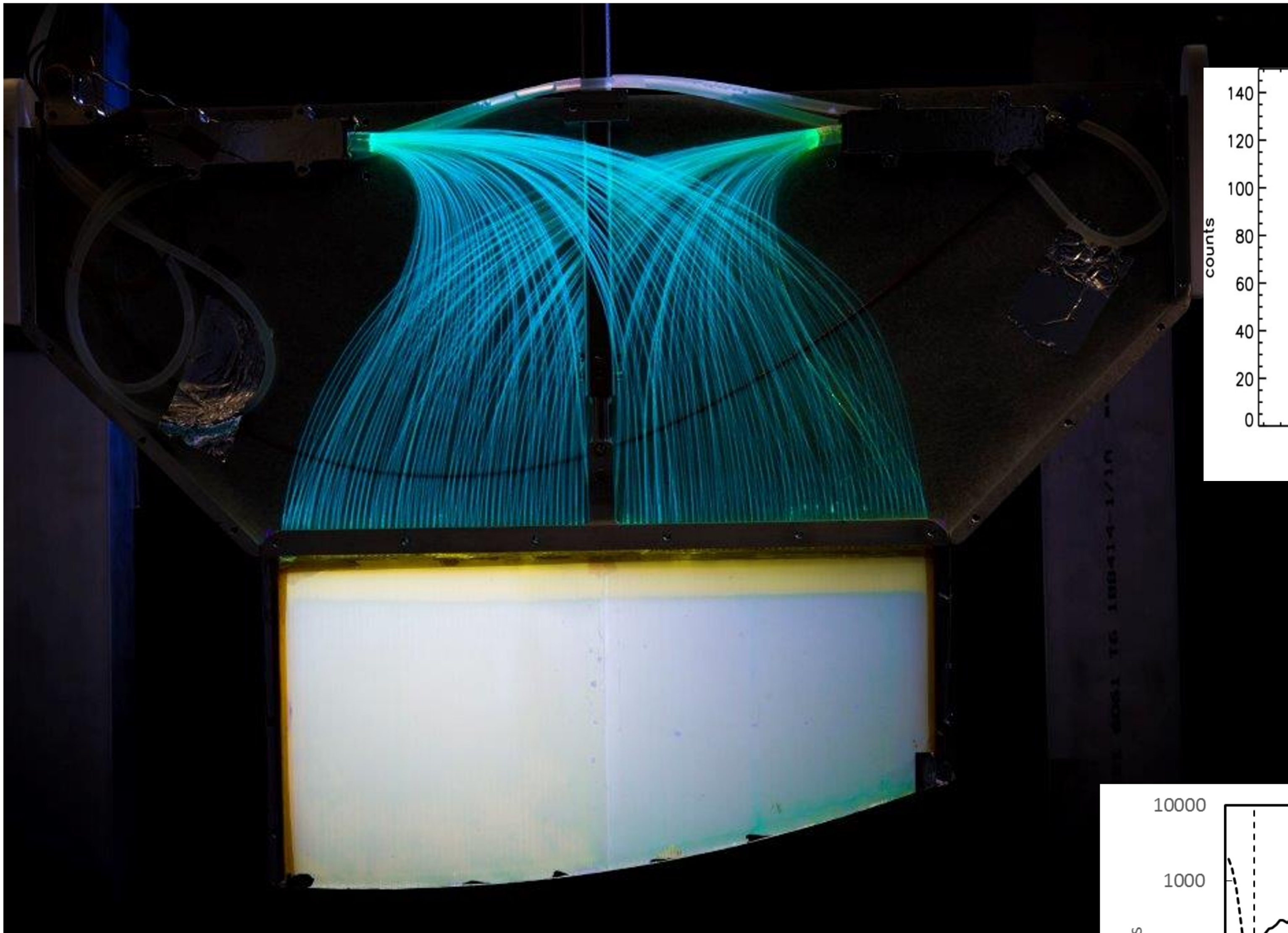
Phase-space Evolution

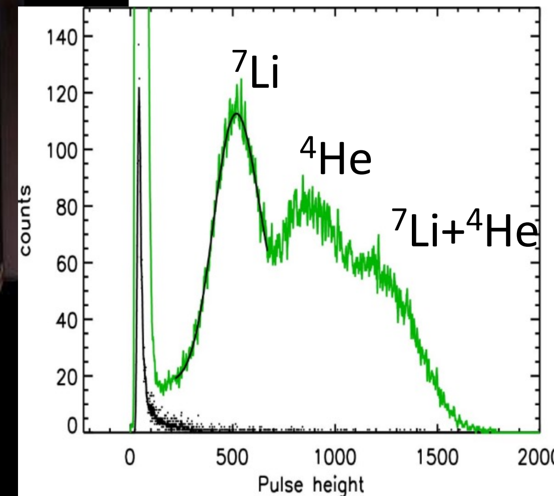
- Compare counting time spectra after short and long holds.
- Offline studies of detector uniformity.
- Also: simulation studies [Next talk]

UCNτ

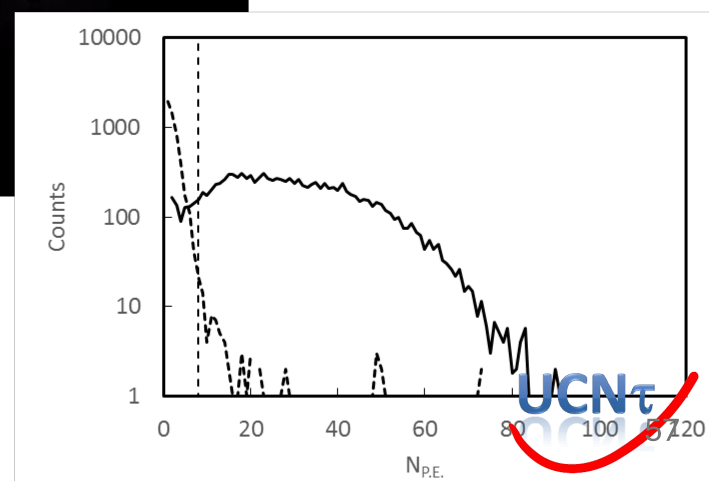
The *in-situ* Neutron Detector

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



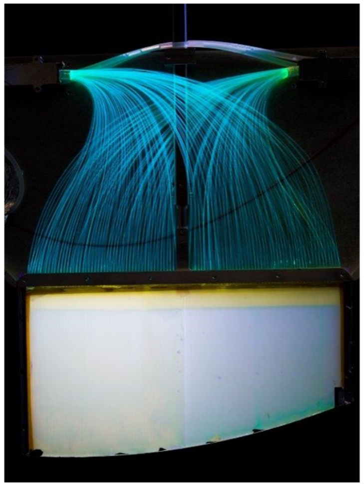


$$n + {}^{10}B \rightarrow {}^{7}Li + \alpha$$

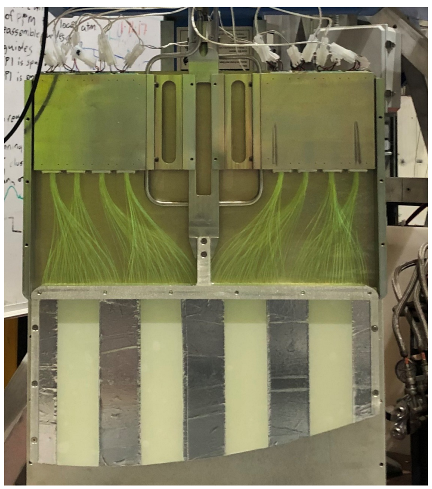


- Vacuum compatible: low outgassing
- Realtime neutron counting (scintillation light)
- (Relatively) fast neutron counting: detection time is 8-10 s
- High neutron efficiency: each trapped neutron can have multiple interactions until absorbed.

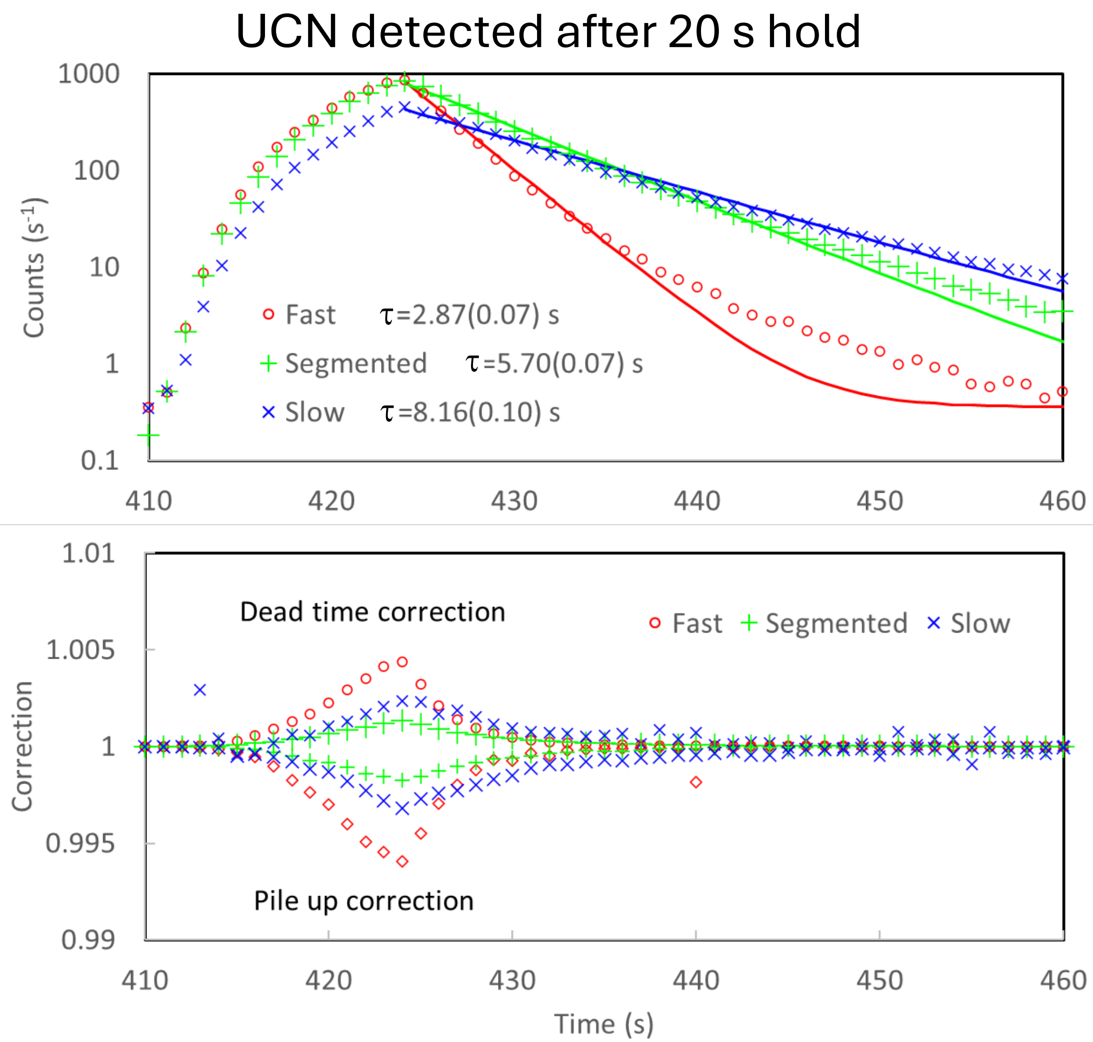
Segmented main UCN detector for higher rate capability



UCNtau
- Double sided
- $^{10}B/ZnS$
- Two PMTs (interleaved)

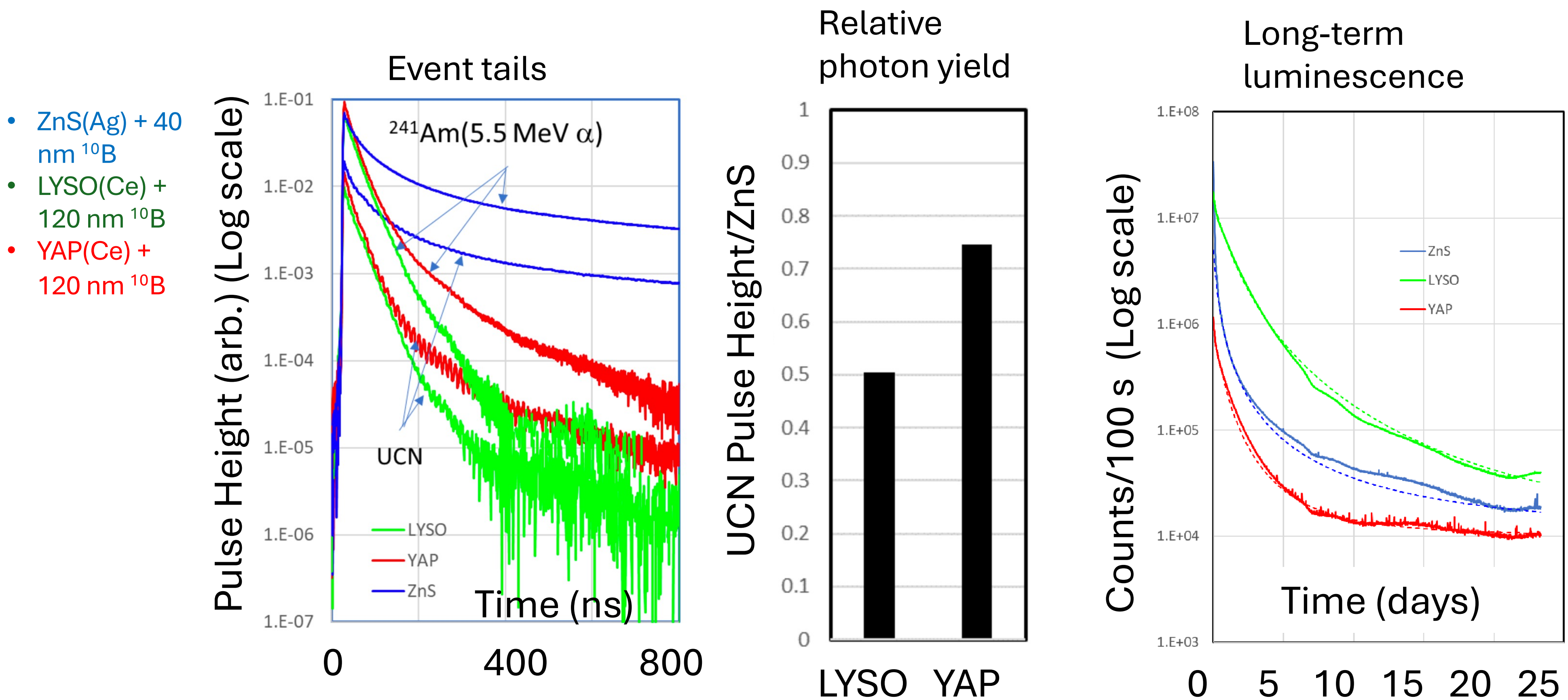


UCNtau+
- Double sided, half masked
- $^{10}B/ZnS$
- Eight PMTs (interleaved pairs)



- The UCNτ+ detector was commissioned in CY2022 and used to take the last year of UCNτ production data.
- Revealed lateral phase space evolution(!).

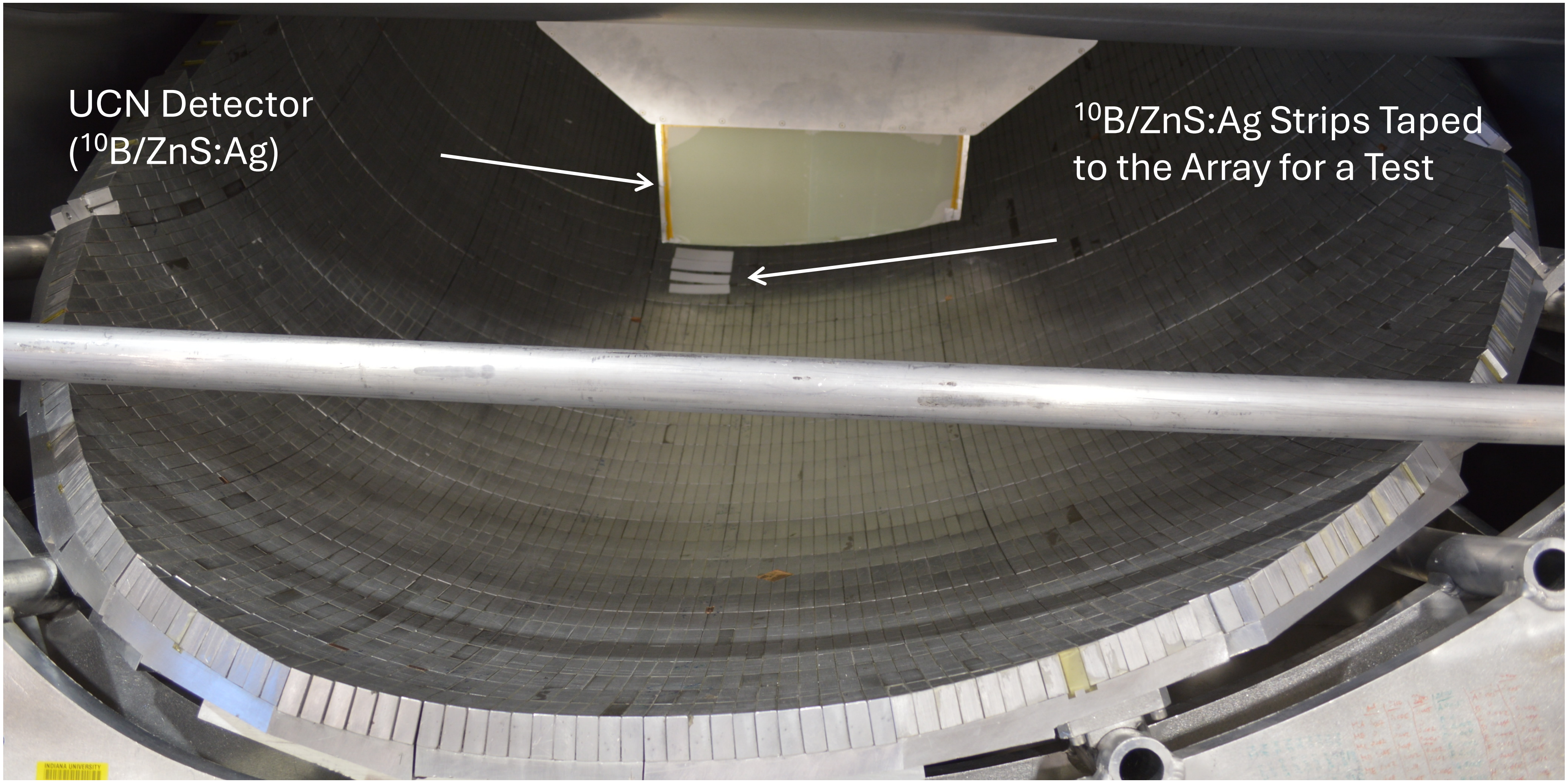
Largest systematic uncertainty is the UCN event definition related to rate-dependent effects. This can be fixed by using ^{10}B/YAP for the detector.



[See also Krivos et al., "Detection of ultracold neutrons with powdered scintillator screens", arXiv:2509:04332 [physics.ins-det]

- Tail on ZnS:Ag extends for μs's. LYSO:Ce and $YAlO_3$:Ce (YAP) have much lower tails.
- We looked at LYSO previously: too much phosphorescence!
- A YAP-based detector should greatly reduce rate-dependent effects that entered at the $\delta\tau_n$~0.1s level in previous (ZnS) versions.
- The ZnS multichannel detector is sufficient for UCNτ+ commissioning.
- The YAP detector looks promising!

View of the Halbach array and lowered UCN detector



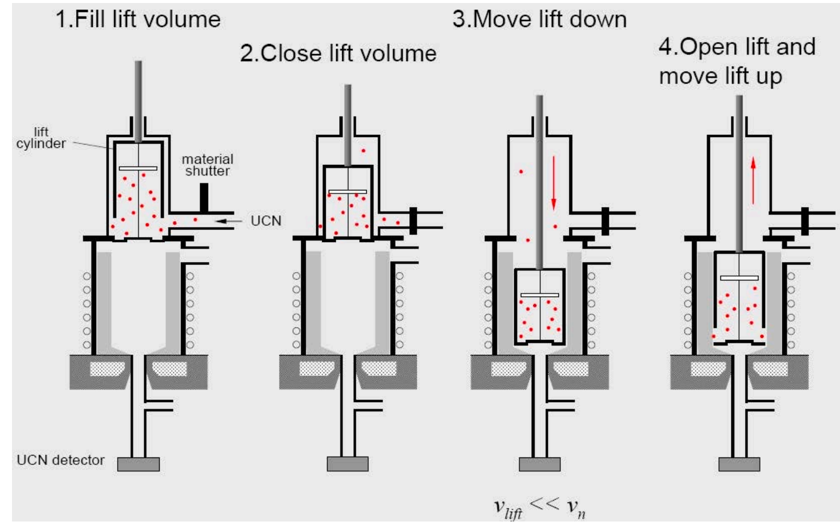
UCNτ apparatus modifications for UCN elevator:

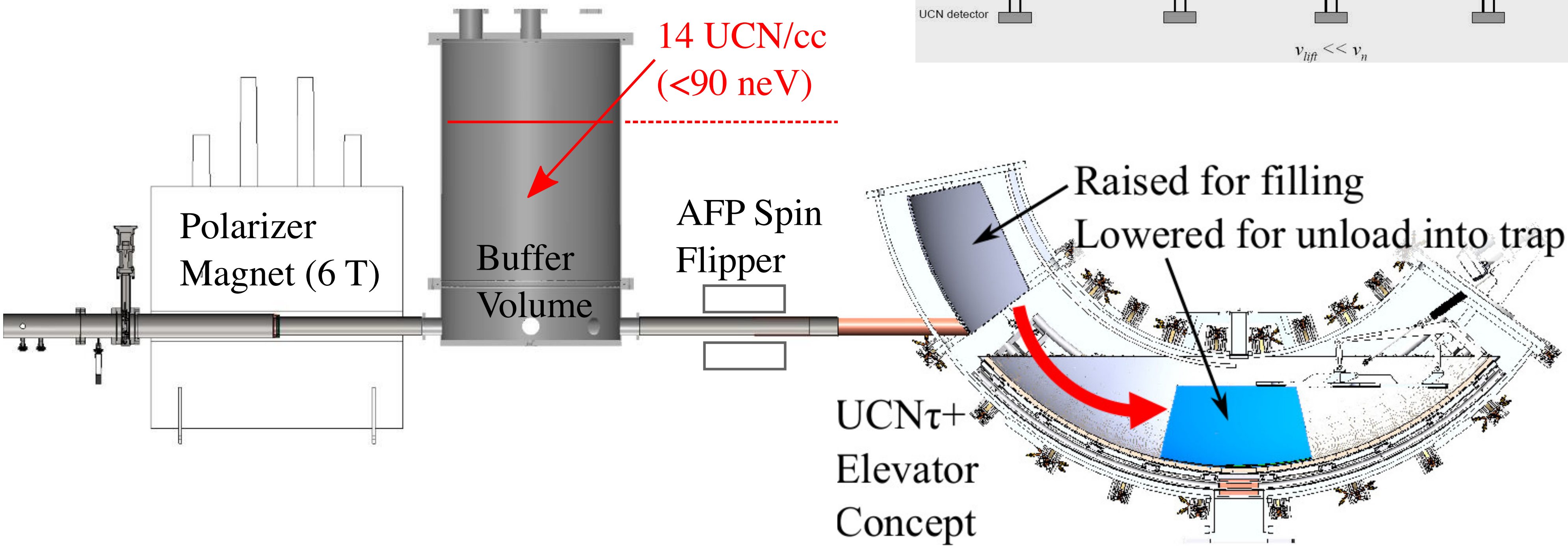
- Stand lowered 1.2 m
- Trapdoor fixed in closed position
- Vacuum extensions added to cover elevator path

Photo of trapdoor array in docked position

UCNτ+ Elevator Concept

Ezhov: achived polarized storage ~0.3 UCN/cc (polarized) up to 27 neV at the ILL (less intense UCN source)





UCNtau trap endplate brackets were modified for clearance, elevator was adjusted, and loading volume (“Neutron bin”) was installed.

View looking down into the loading bin

UCNA event types

B. Plaster, https://doi.org/10.1051/epjconf/201921904004

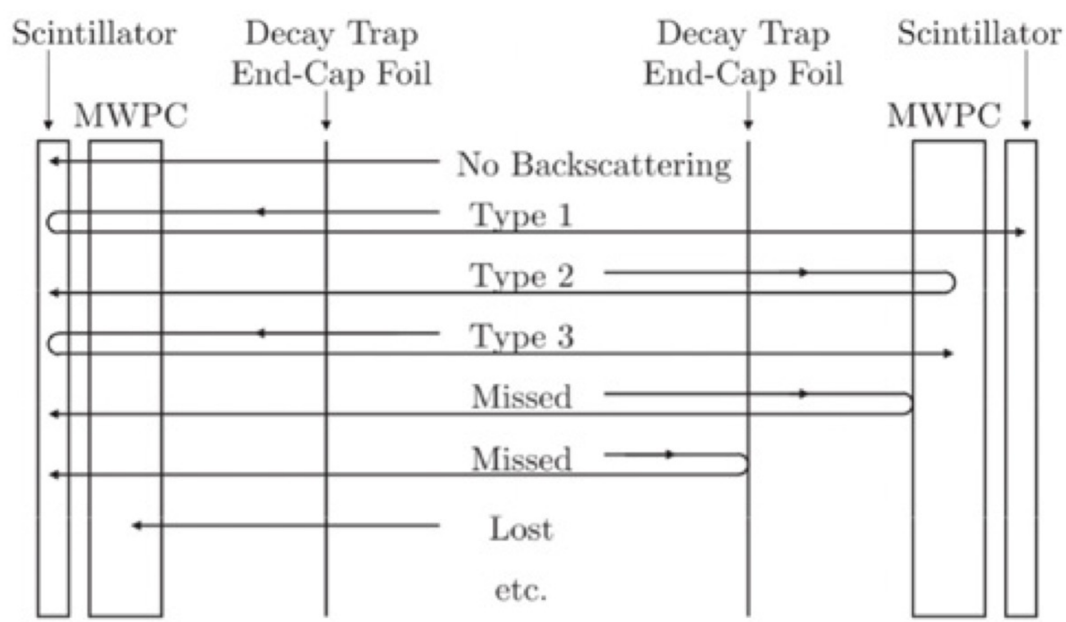
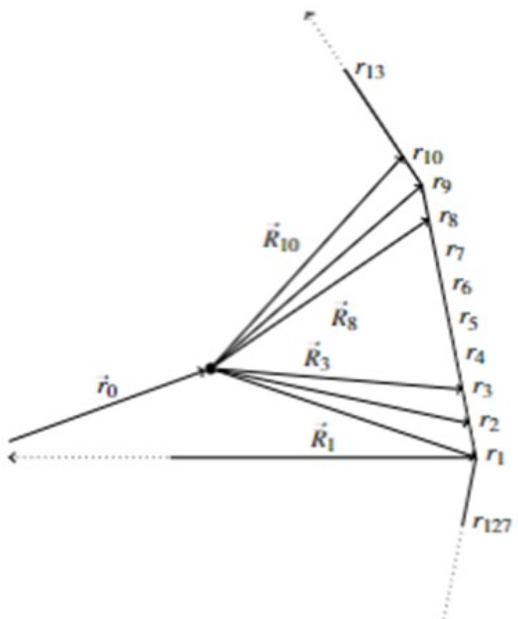
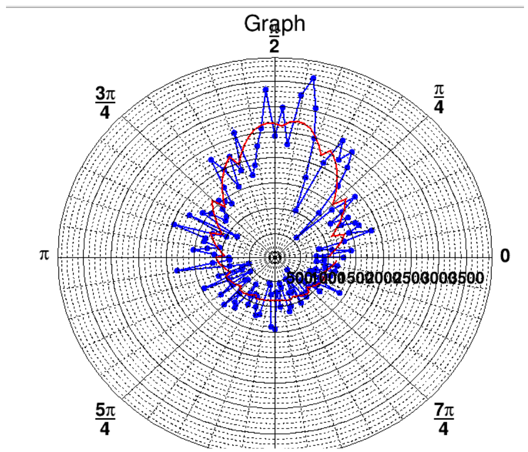


Figure 5. Classification of the different types of events in the experiment.

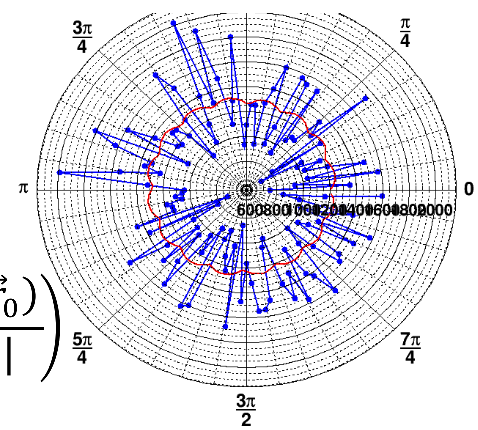
Position Reconstruction Validation From LED scan

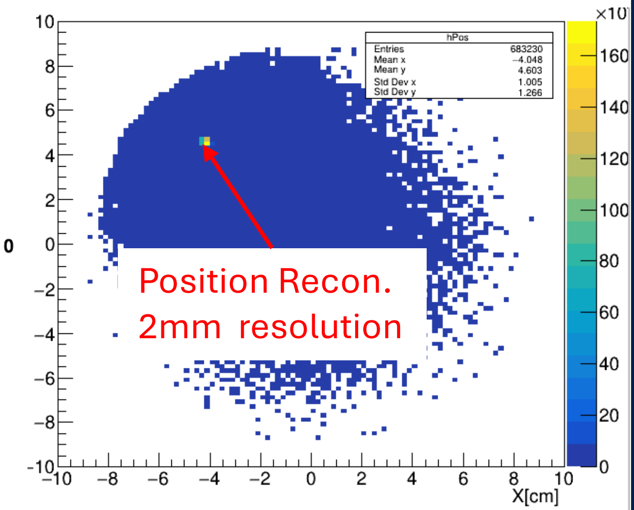


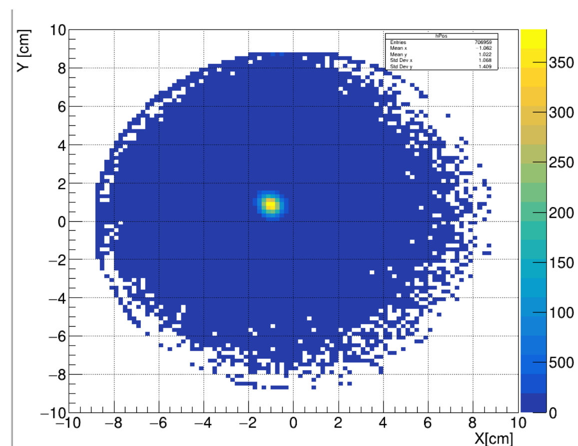
$$w_i(\vec{r}_0) = \cos^{-1}\left(\frac{(\vec{r}_i - \vec{r}_0)\cdot(\vec{r}_{i+1} - \vec{r}_0)}{|\vec{r}_i - \vec{r}_0||\vec{r}_{i+1} - \vec{r}_0|}\right)$$



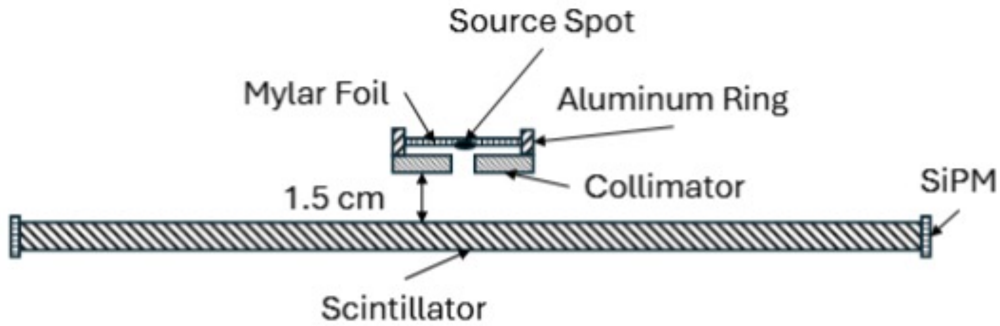
Single Event SiPM PHA Distribution

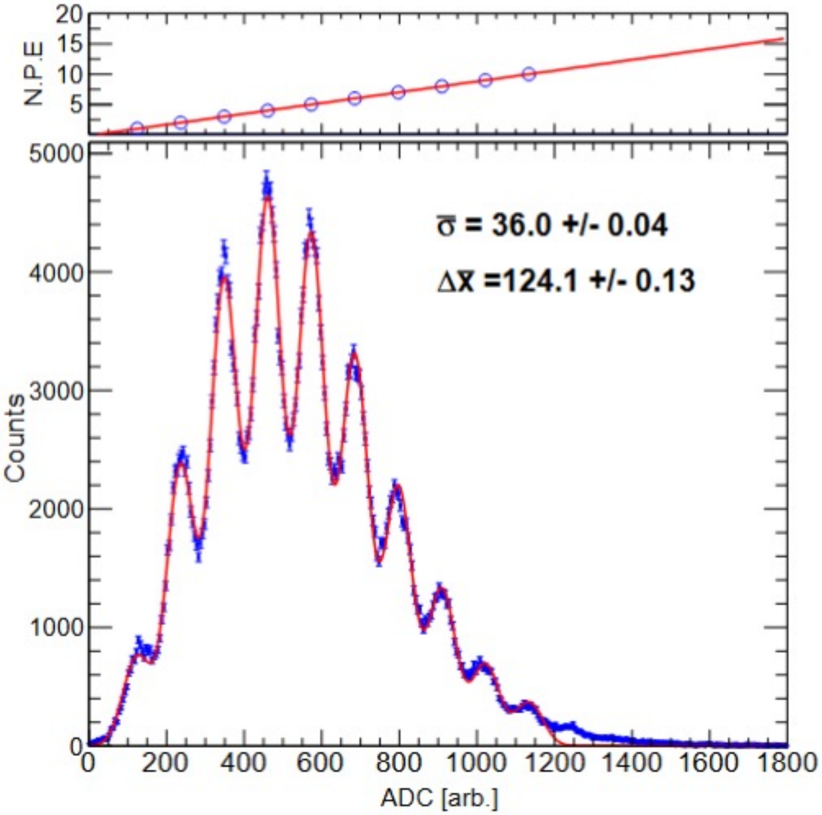


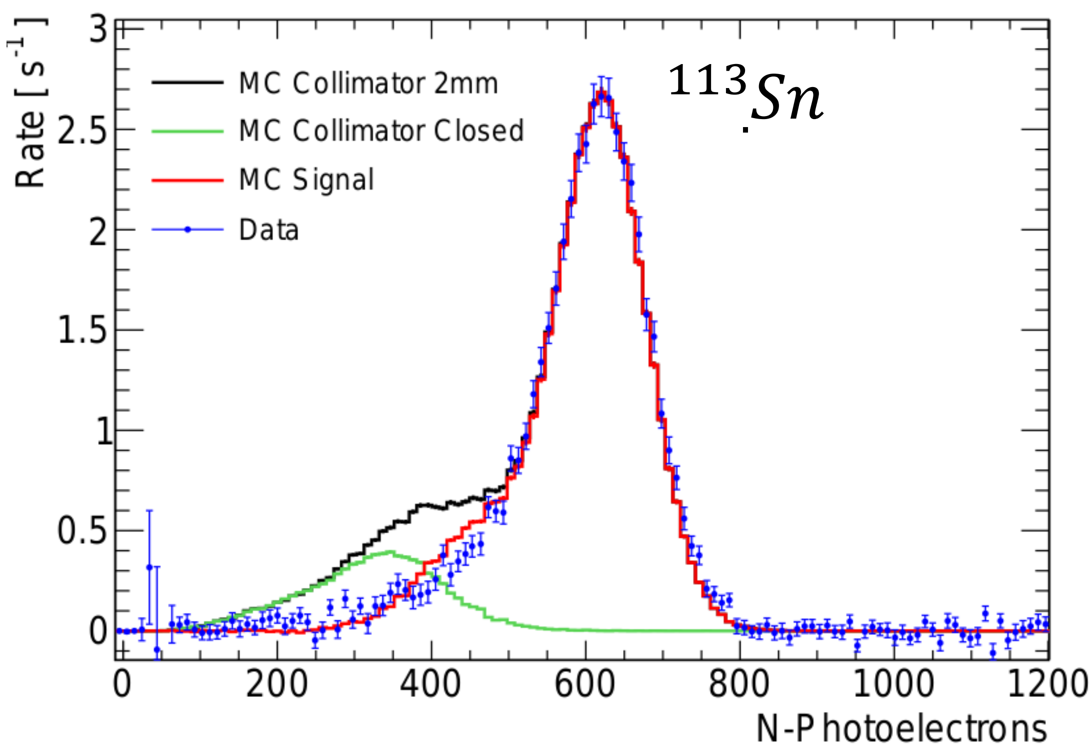




Detector Calibration







Requires 4 pe trigger threshold

ETSU

Cooling tests

- Cooling test confirm x10 reduction of 1-pe noise at -15 C.
- Further reduction possible by cooling to -40 C