Neutron Decay Probes of the Standard Model

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University of Tennessee Physics Colloquium

February 26, 2024

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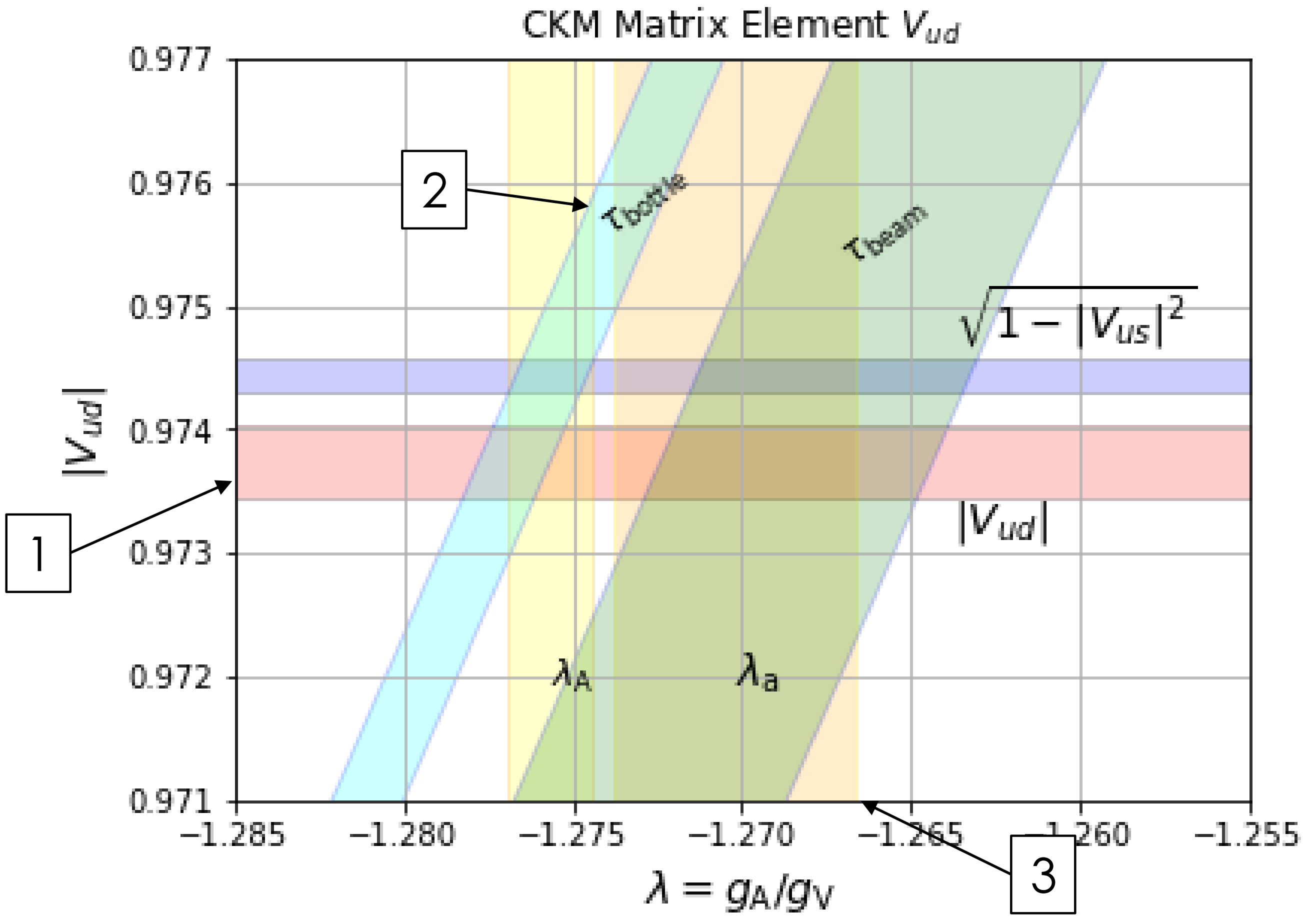
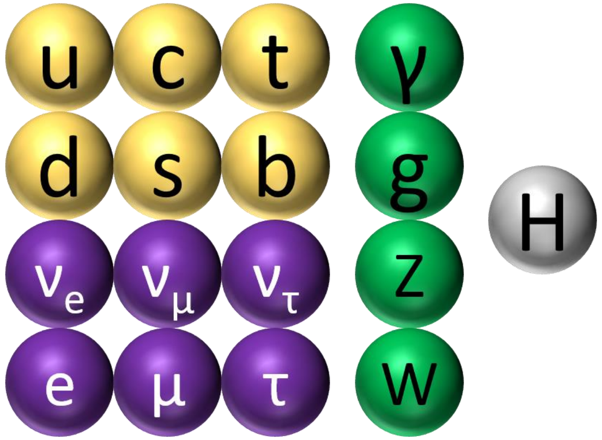


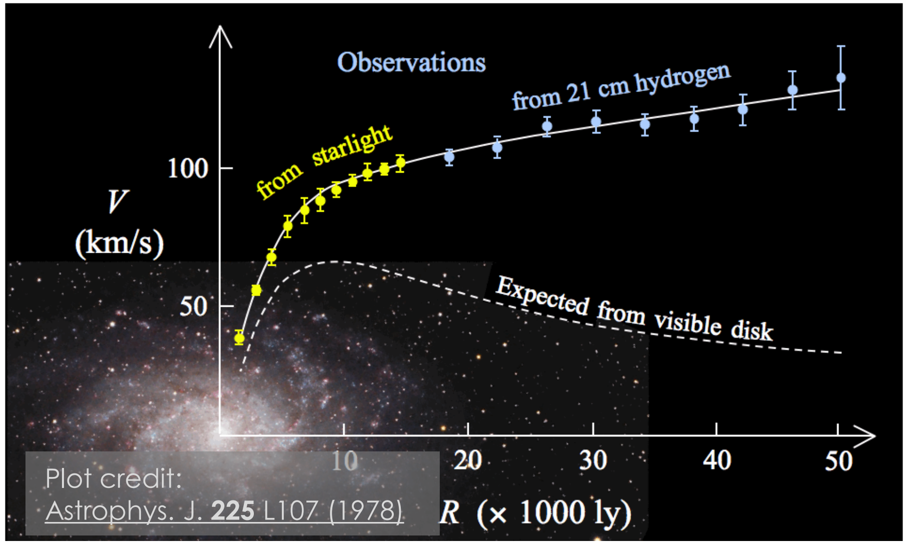
Particle Physics: The Standard Model

- Standard Model:
  - Universe made of quarks, leptons
  - Interaction carried by gauge bosons
  - Can form composite particles
  - Incredibly precise predictive power!
- Does not explain everything!
  - Gravity
  - Dark Matter
  - We're here!
    - More matter than antimatter
    - Needs CP, B-number violation
  - Fine-tuning problems?
    - Left-handed Weak Interaction

New Particles?

New Interactions?



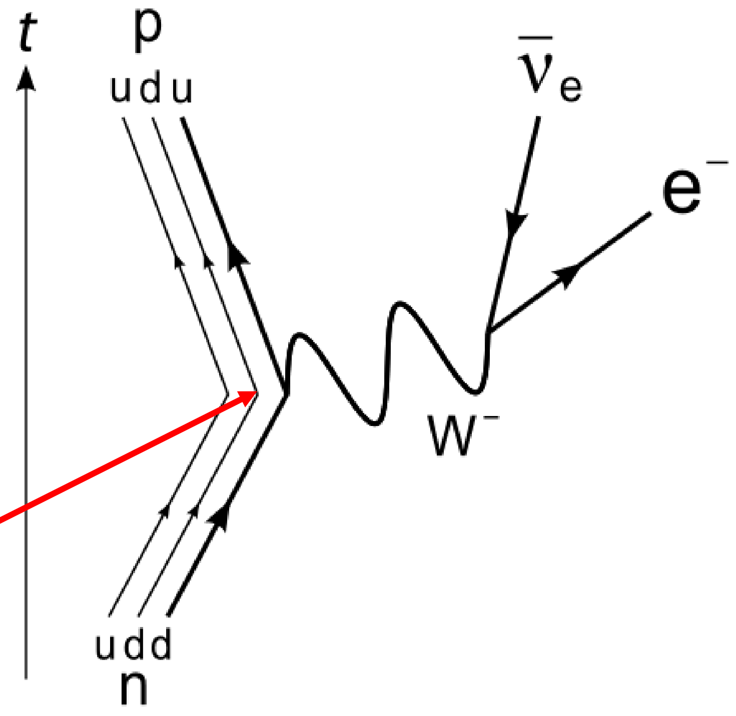


Plot credit: Astrophys. J. **225** L107 (1978)

The Weak Interaction and Neutron Decay

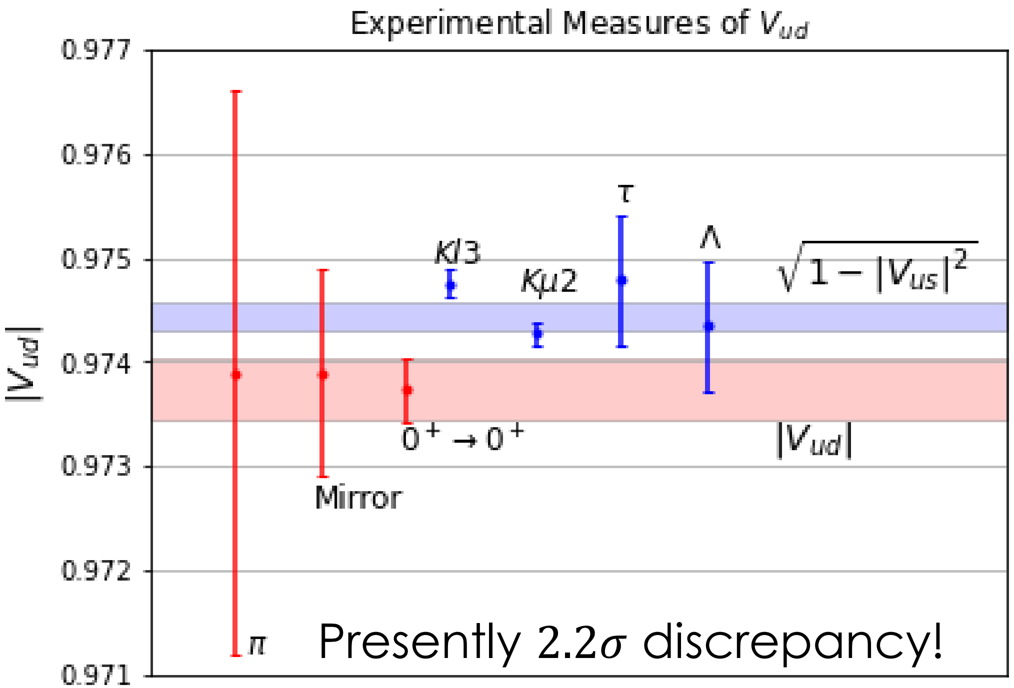
- Neutron β-decay:
  - $n \rightarrow p^+ + e^- + \overline{\nu_e}$
  - Transition between $d \rightarrow u$ quarks
- Precision measurements of neutron decay can probe:
  - Formation of Elements (Big Bang Nucleosynthesis)
  - Understanding the Weak Interaction (CKM quark-mixing Matrix):

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



Experimental Probes of CKM Unitarity (V_{ud} and V_{us})

- Unitarity implies:
  - $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{BSM}$
  - Same for all other rows/columns
    - $\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$
- Measurements of V_{ud}:
  - Most precise from “Superallowed” $0^+ \to 0^+$ decays
  - Uncertainties due to radiative and nuclear structure corrections ($0^+ \to 0^+$, Mirrors)
- Measurements of V_{us}:
  - Most precise from Kaon decays
  - Tension between different decay channels

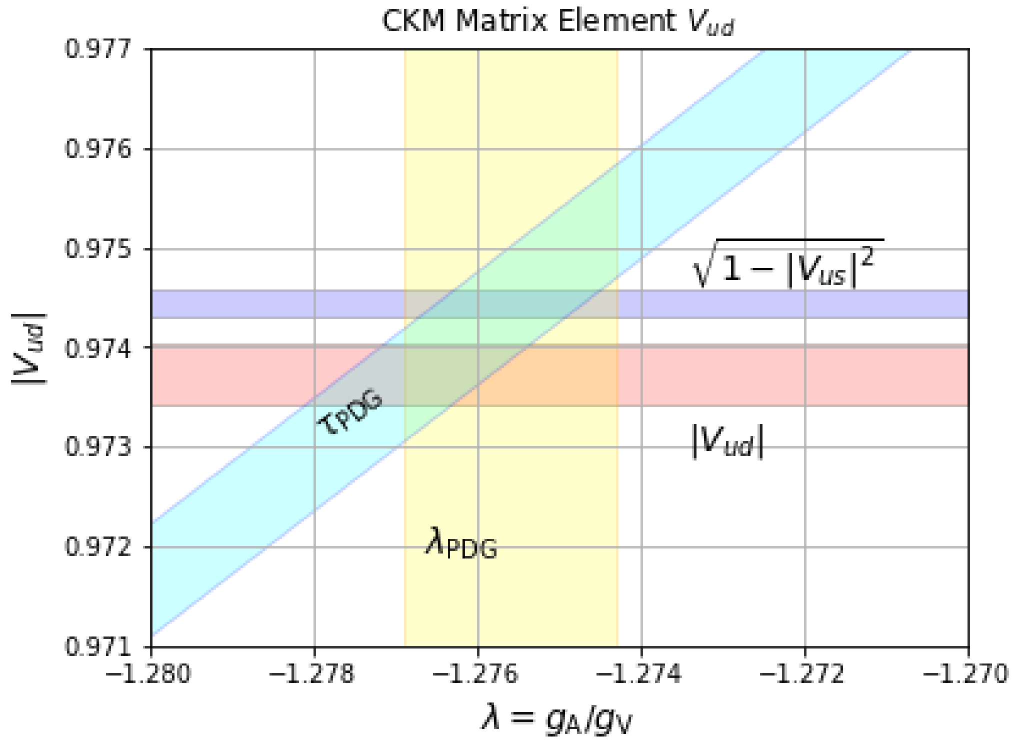


Data from:

- Workman, R. L. *et al*, Particle Data Group (2022)
- J. C. Hardy and I. S. Towner, Physical Review C 102, 045501 (2020)
- L. Hayen, Physical Review D 103, 113001 (2021)

Beta-Decay: Enter the Neutron

- Neutron decay:
  - $n \rightarrow p^+ + e^- + \bar{\nu}_e$
  - $|V_{ud}|^2 = \frac{5099.3\ \text{s}}{\tau_n\,(1+3\,\lambda^2)(1+\Delta_R)}$
- Experimentally Determine:
  - τ_n: Neutron Lifetime
  - $\lambda = g_A/\,g_V$: Ratio of coupling constants
- Theoretically Easier:
  - No nuclear structure corrections!
  - Inner radiative correction Δ_R
- To compete with $0^+ \rightarrow 0^+$ measurements:
  - $\Delta\tau_n/\,\tau_n < 3 \times 10^{-4}$ (or $\Delta\tau_n < 0.3$ s)
  - $\Delta\lambda/\lambda < 1 \times 10^{-3}$ (or $\Delta\lambda < 1 \times 10^{-3}$)



Data from:
- Workman, R. L. *et al*, Particle Data Group (2022)

Beta-Decay: What's Going On?

- Neutron decay:
  - $n \rightarrow p^+ + e^- + \bar{\nu}_e$
  - $|V_{ud}|^2 = \dfrac{5099.3\ \text{s}}{\tau_n\,(1+3\,\lambda^2)(1+\Delta_R)}$
- Experimentally Determine:
  - τ_n: Neutron Lifetime
  - $\lambda = g_A/\,g_V$: Ratio of coupling constants
- Theoretically Easier:
  - No nuclear structure corrections!
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- To compete with $0^+ \rightarrow 0^+$ measurements:
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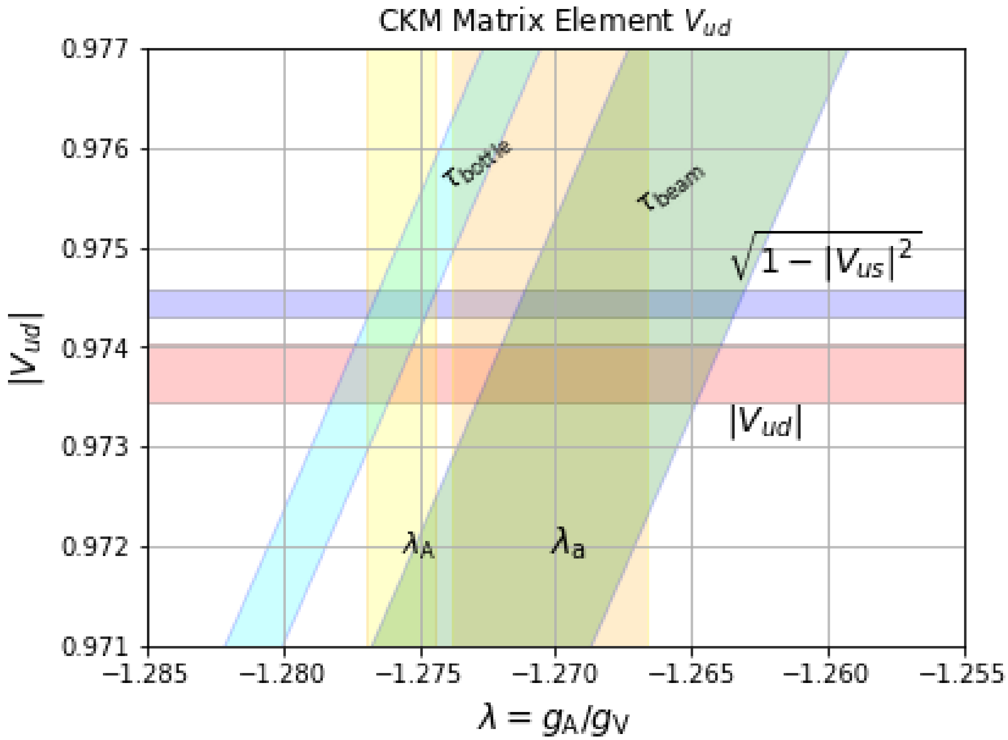
  - $\Delta\lambda/\lambda < 1 \times 10^{-3}$ (or $\Delta\lambda < 1 \times 10^{-3}$)

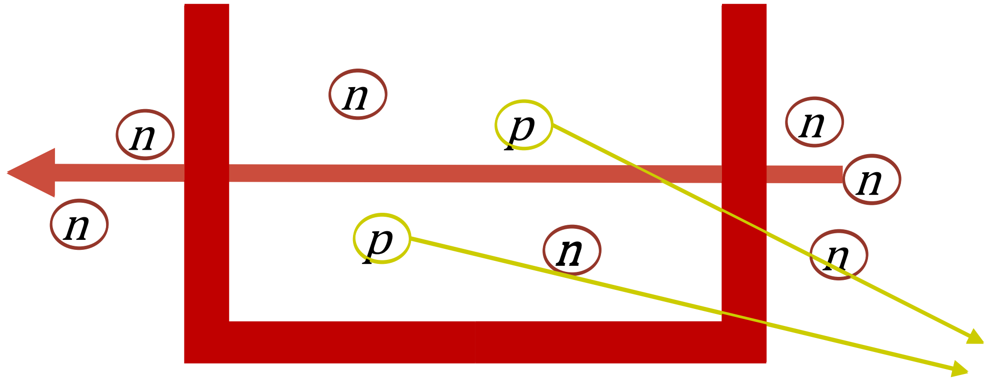


Tension between different methods of determining τ_n, λ!

Data from:
- Workman, R. L. *et al*, Particle Data Group (2022)

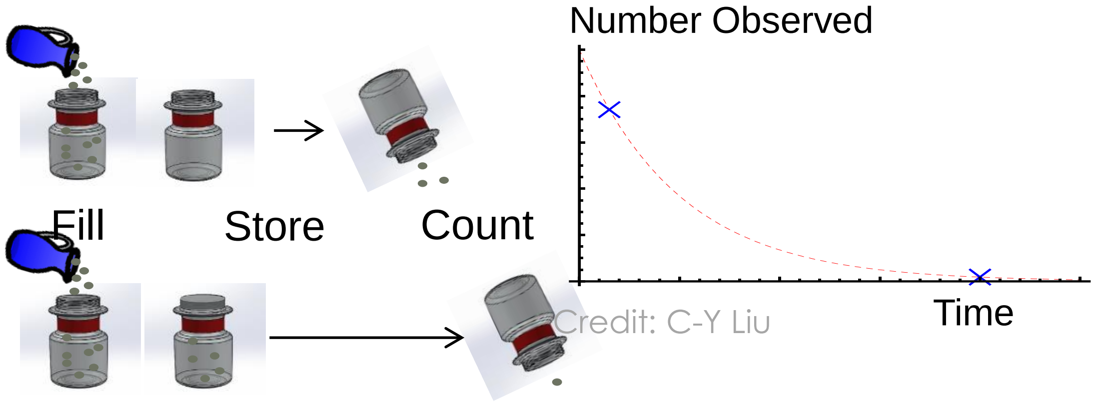
How to Measure a Lifetime?
Count the Dead or Count the Living

- “Beam experiment”:
  - Counting the ~~dead~~ decay products
  - $\tau_{beam} \sim \frac{\dot{N}_n}{\dot{N}_p}$



- Systematics:
  - Absolute measurements of p^+ and n rates
  - ***Need to calibrate two detectors***

- “Bottle experiment”:
  - Counting the ~~living~~ neutrons
  - $Y(t) = Y_0 e^{-t\,/\,\tau_{bottle}}$



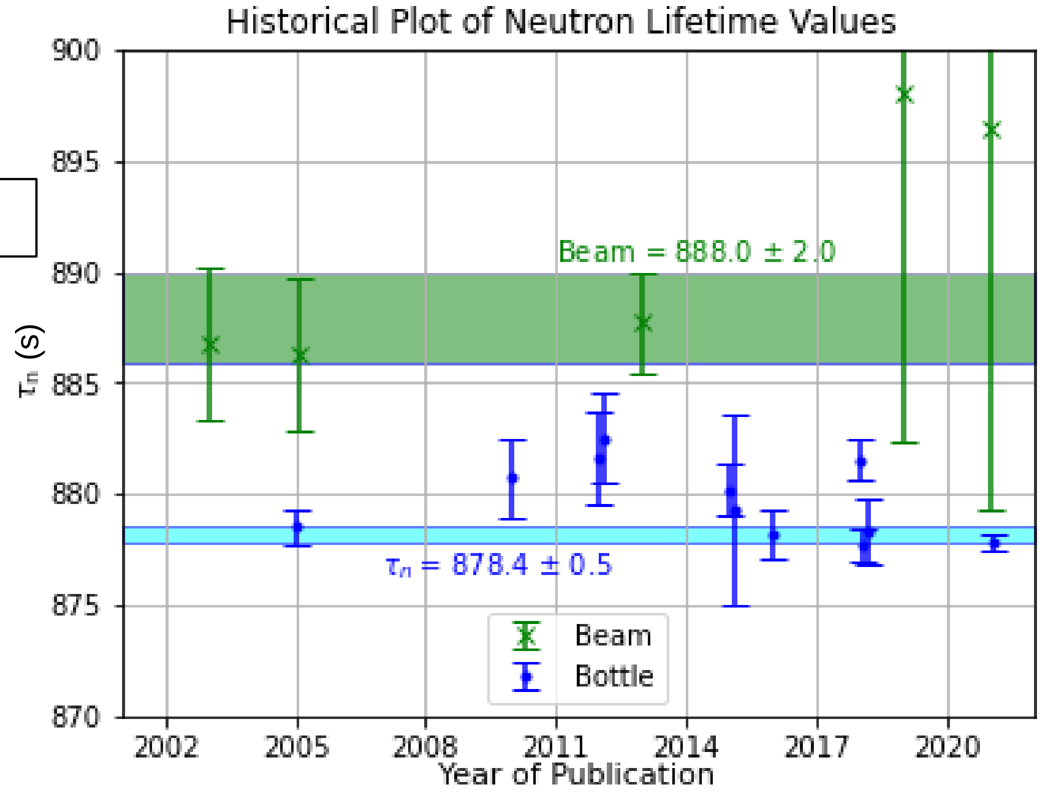
Credit: C-Y Liu

- Systematics:
  - Relative measurements of rates
  - ***Unaccounted for sources of loss give a lower lifetime!***

How to Measure a Lifetime?
Count the Dead or Count the Living

- “Beam experiment”:
  - Counting the ~~dead~~ decay products
- “Bottle experiment”:
  - Counting the ~~living~~ neutrons

Beam > Bottle (~4σ)



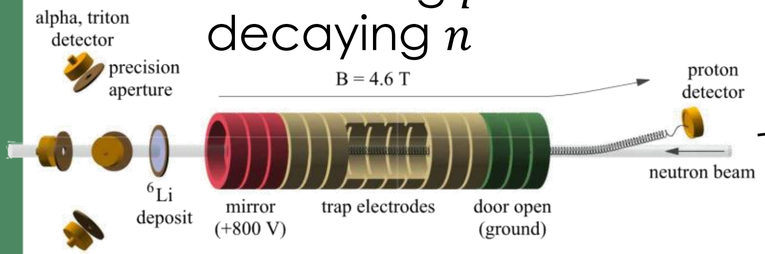
Can be explained if $n \rightarrow \chi$, where χ is not a proton

Data from:
- Workman, R. L. *et al*, Particle Data Group (2022)

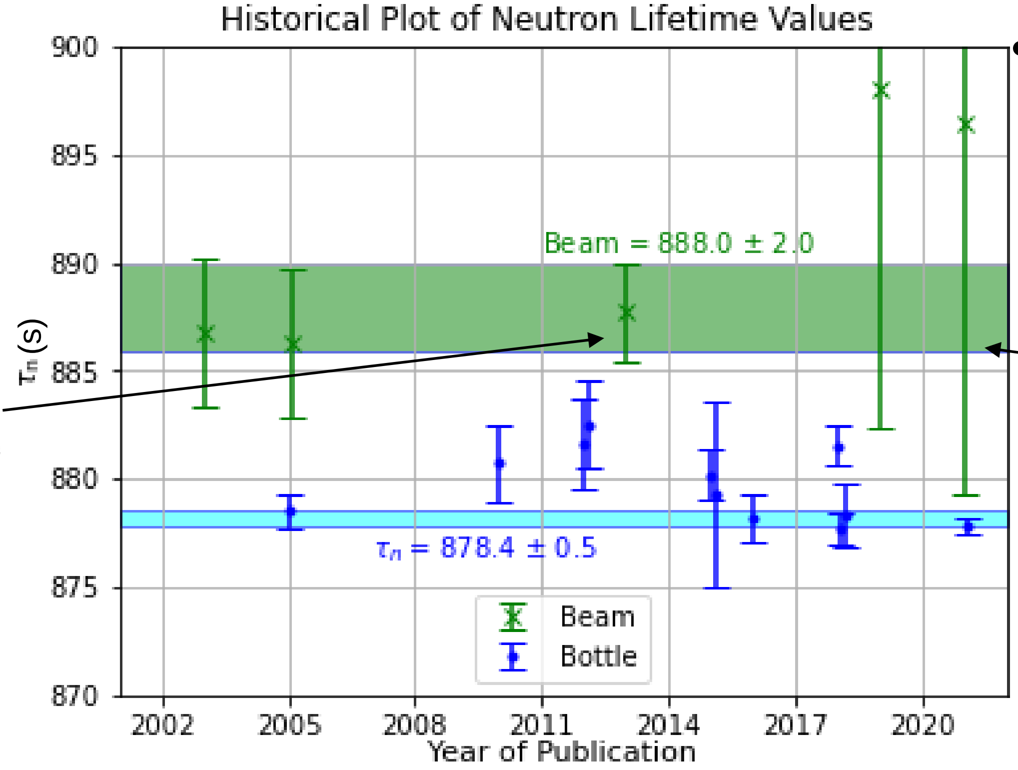
For more on n into dark matter:
- Fornal, B. and Grinstein, B. PRL 120, 191801 (2018)

Measuring τ_n: Beam Experiments

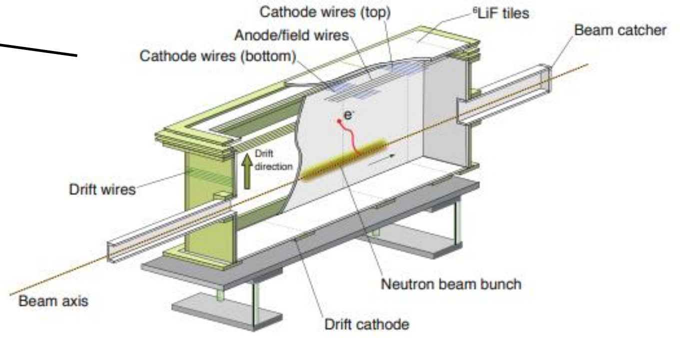
- NIST Beam Lifetime:
  - $\tau_n = 887.7 \pm 1.2_{stat} \pm 1.9_{sys}$
  - Measuring p^+ from decaying n



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



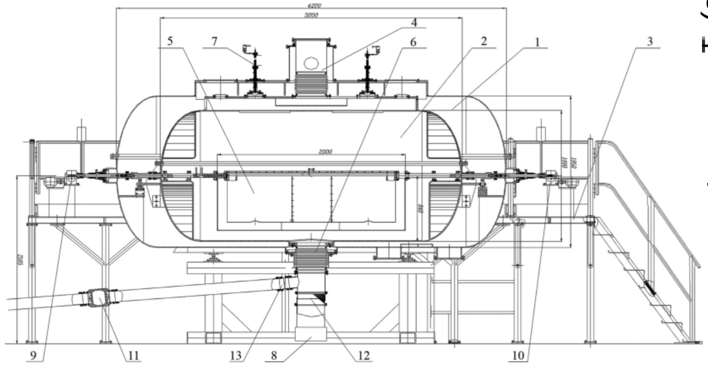
- JPARC Beam Lifetime:
  - $\tau_n = 898 \pm 10(stat)^{+15}_{-10}(sys)$
  - Measuring e^- from decaying n



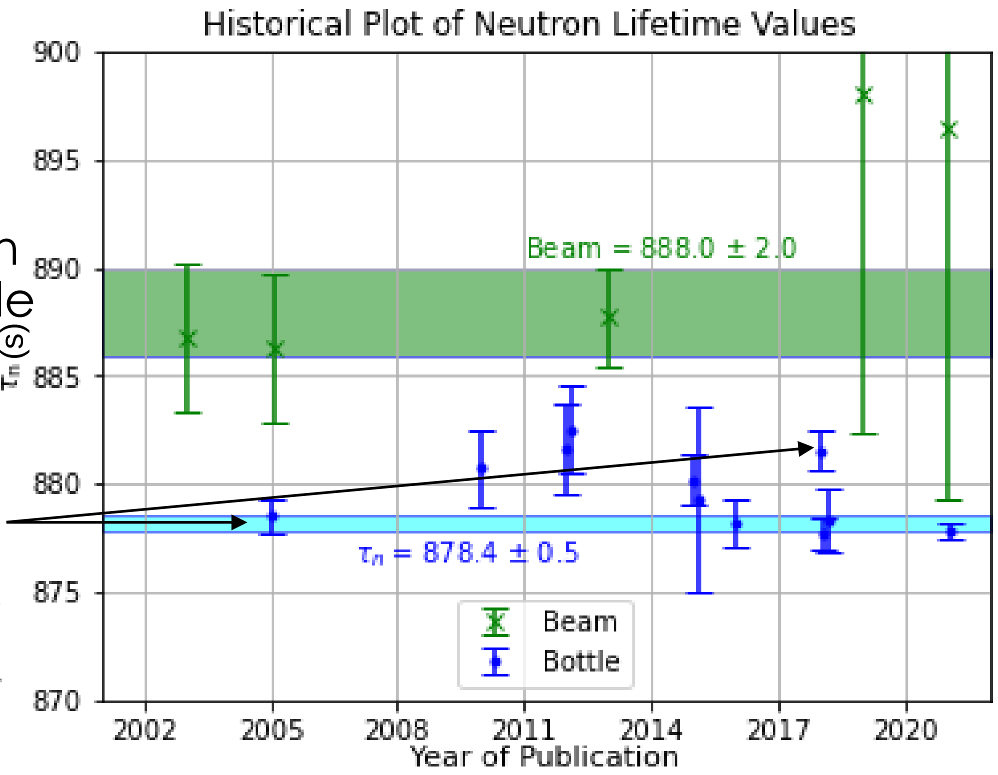
Sumi et al., JPS Conf. Proc. 33, 011056 (2021)

Measuring τ_n: Bottle Experiments

- Gravitrap:
  - $\tau_n = 878.5 \pm 0.7_{stat} \pm 0.3_{sys}$ *(2005)*
  - $\tau_n = 881.5 \pm 0.7_{stat} \pm 0.6_{sys}$ *(2018)*
  - Counting n after holding in variable size material bottle



[Serebrov et al., PRC 97, 055503 (2018)]



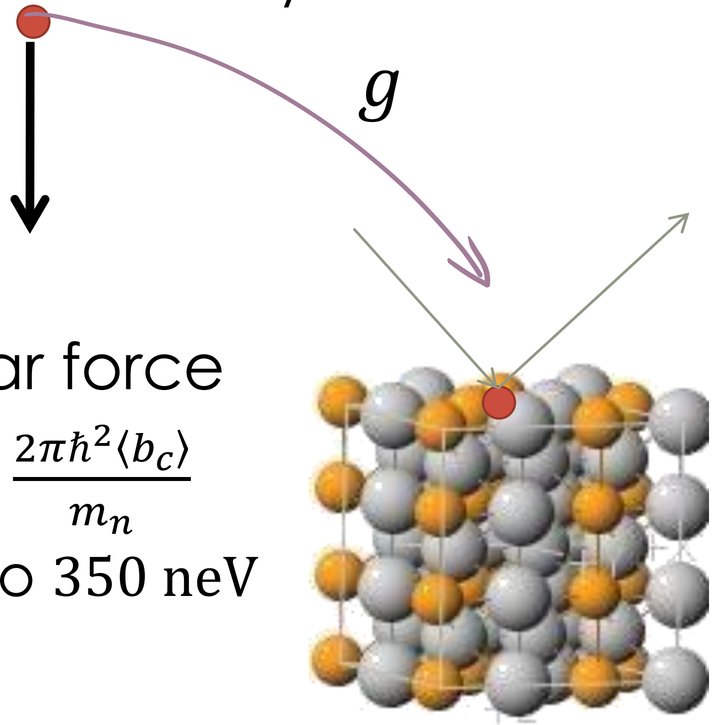
- Space!
  - $\tau_n = 883 \pm 17$
  - Counting n produced by cosmic rays hitting the moon or planetary atmospheres

NASA Lunar Prospector
Credit: [NASA/Ames]

[Wilson et al., PRC 104, 045501 (2021)]

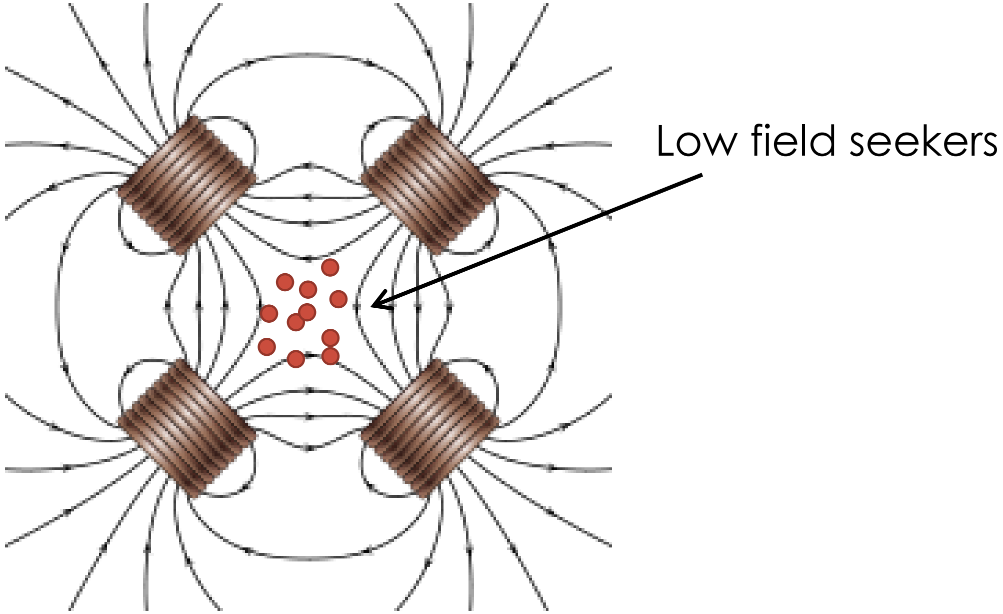
How Do You Make a Neutron Bottle? Ultracold Neutrons!

- Gravitational force
  - $E = m_n g\, h$
  - About $100\ \mathrm{neV/m}$



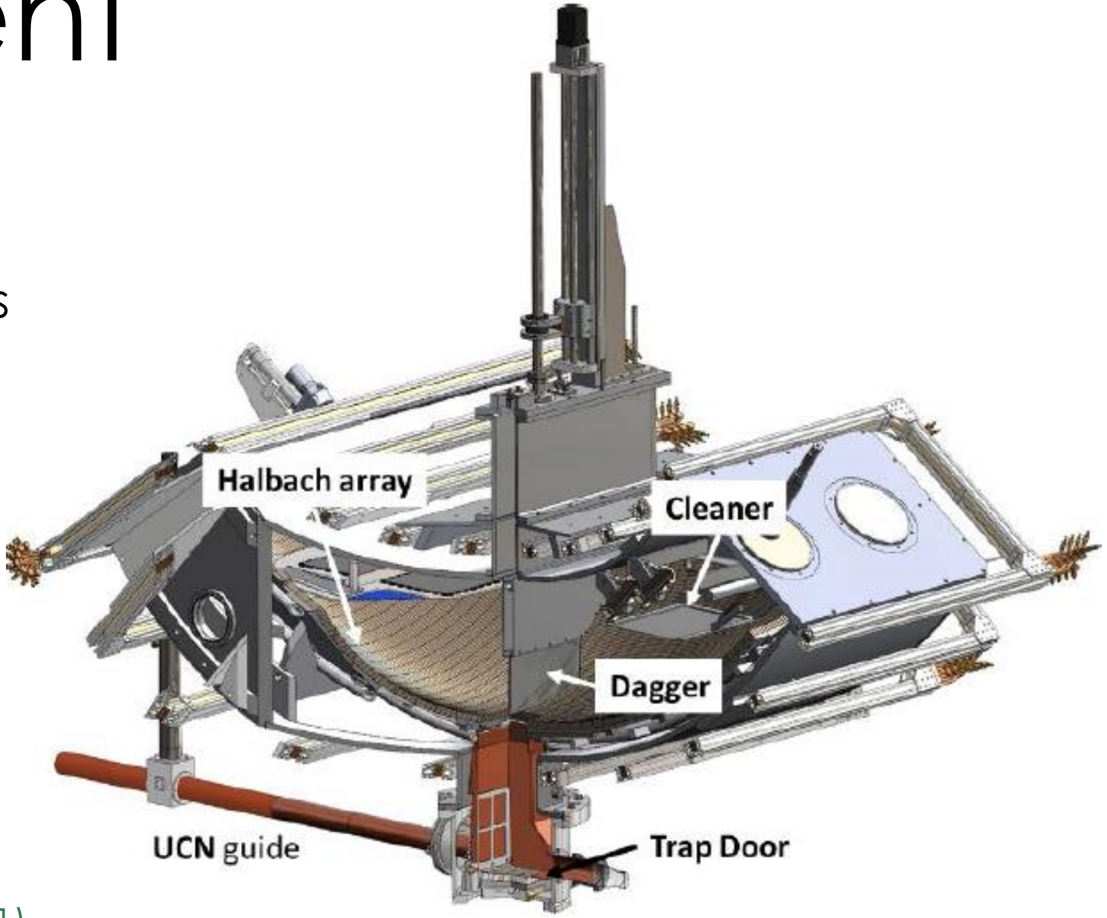
- Nuclear force
  - $V_f = \dfrac{2\pi\hbar^2\langle b_c\rangle}{m_n}$
  - Up to $350\ \mathrm{neV}$

- Magnetic Force
  - $\vec{F} = \overrightarrow{\mu_n} \cdot (\nabla \vec{B})$
  - About $60\ \mathrm{neV/T}$

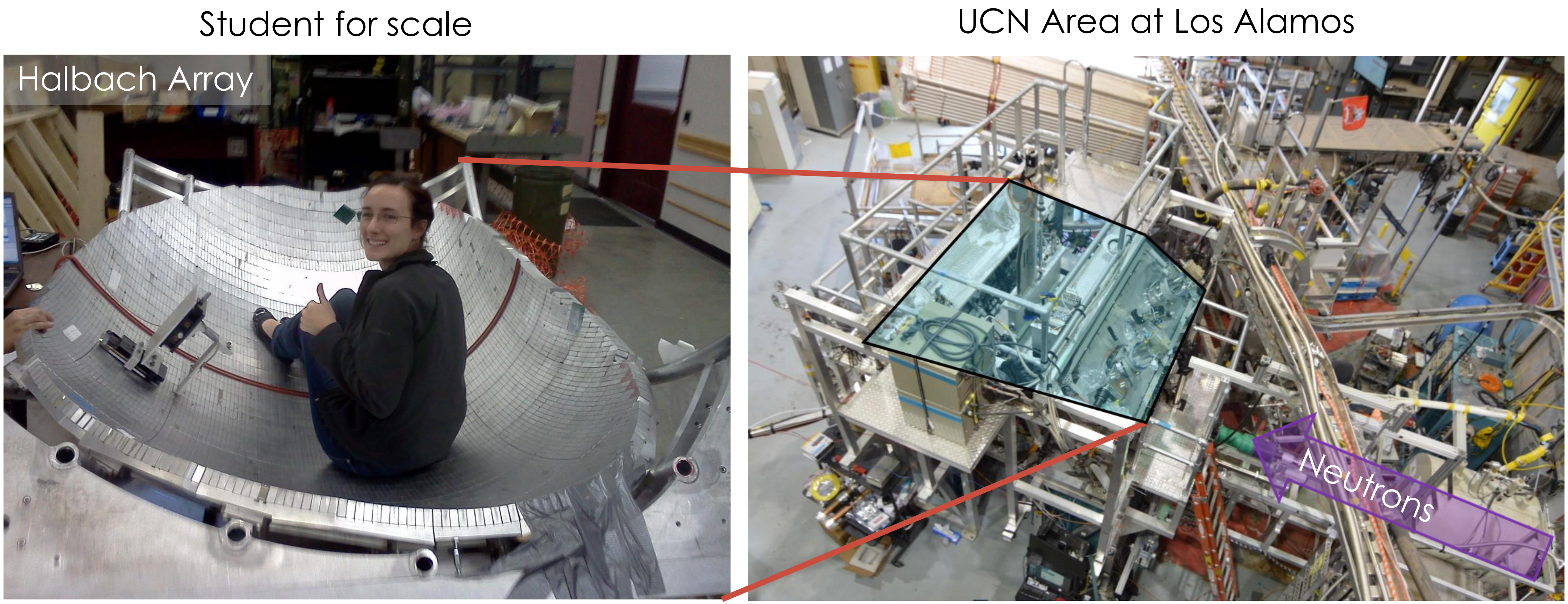


Measuring τ_n:
The UCNτ Experiment

- World's most precise measurement of the neutron lifetime
  - Traps Ultracold Neutrons with magnetic fields (and gravity!)
  - Minimizes material interactions
- Two precision results:
  - Data taken 2016, published 2018:
    - $\tau_n = 877.7 \pm 0.7(\text{stat.})\,^{+0.4}_{-0.2}(\text{sys.})$ s
    - Pattie Jr., R. W. *et al*, Science 360, 627 (2018)
  - Data taken 2017-2018, published 2021:
    - $\tau_n = 877.75 \pm 0.28(\text{stat.})^{+0.22}_{-0.16}(\text{sys.})$ s
    - Gonzalez, F. M. *et al*, Phys. Rev. Lett. 127, 162501 (2021)

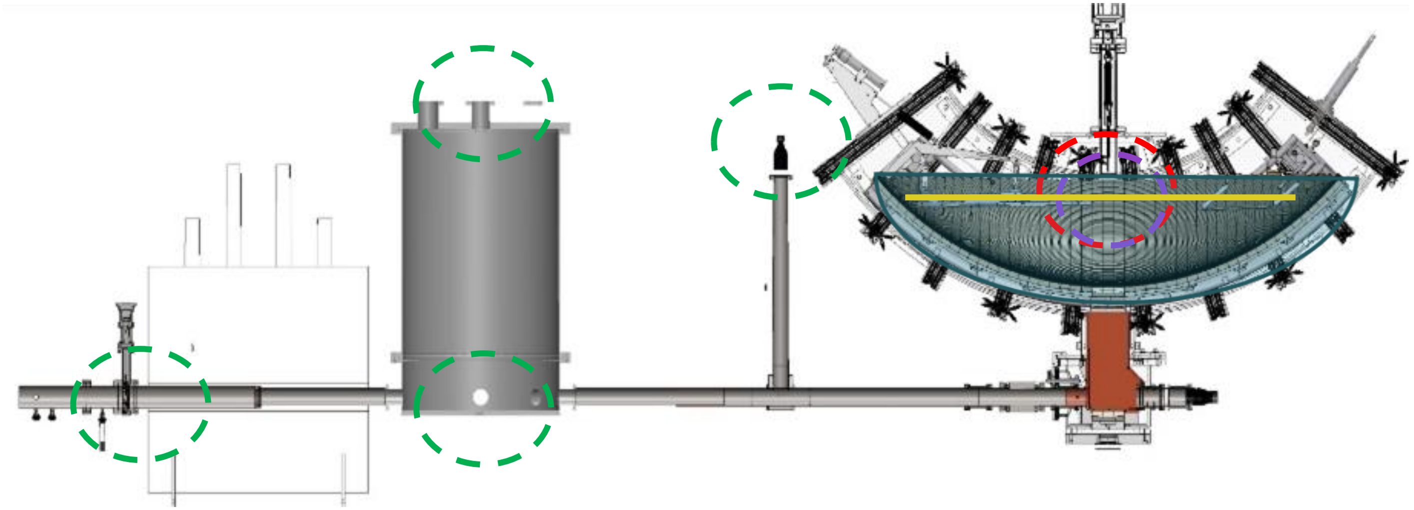


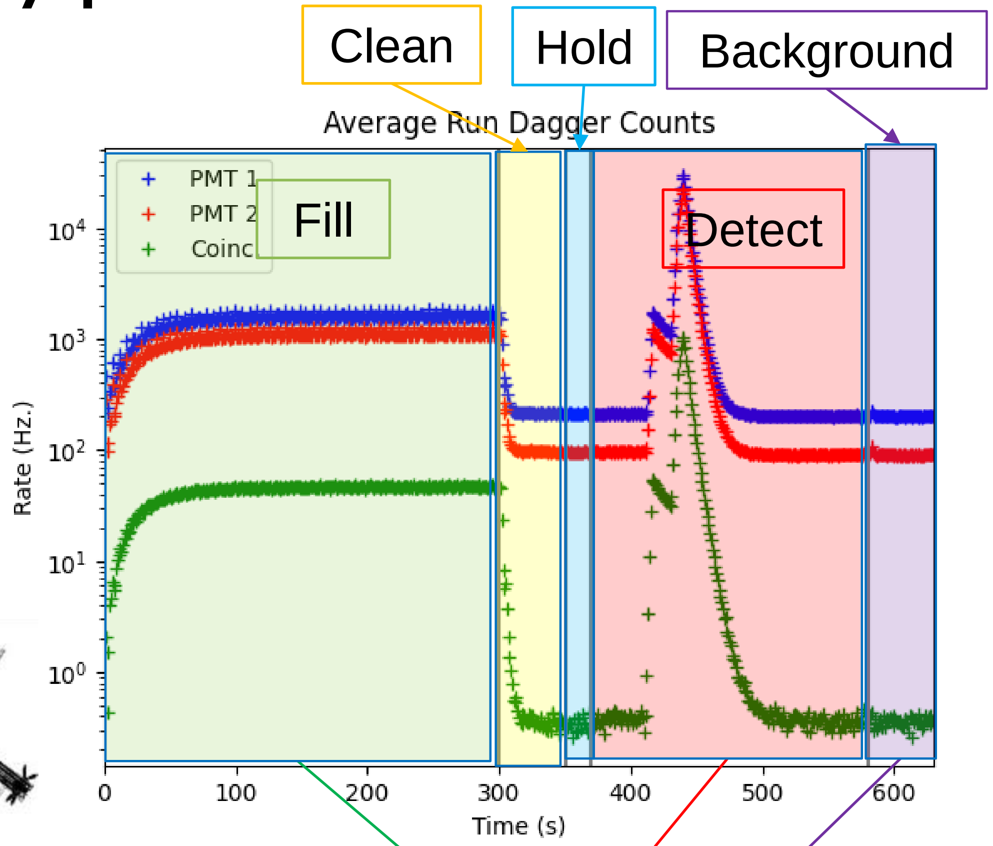
What does it look like in real life?



How to find a Bottle-Type Lifetime

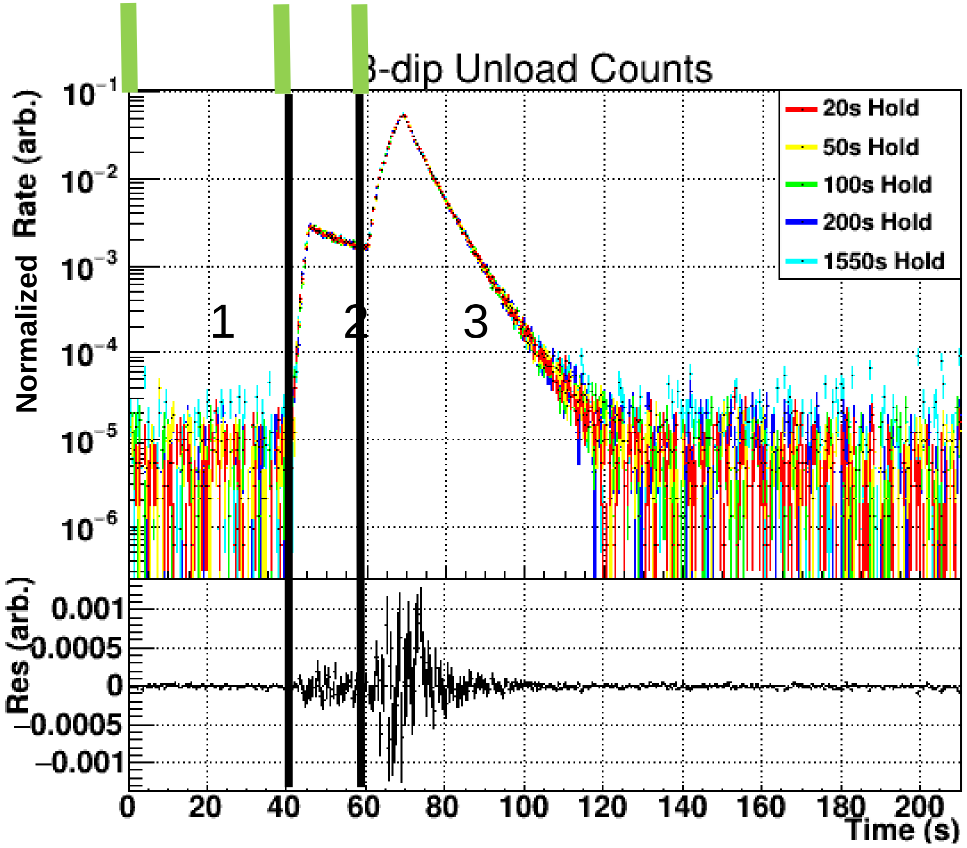
- For each run calculate “Normalized Yields” (Y_i)
  - Fill trap, and determine neutrons in trap $f(M_i)$
  - Clean (remove) untrappable neutrons
  - Hold for variable $(20\text{ s} < t_i < 5000\text{ s})$
  - Detect number of neutrons remaining (D_i)
  - Subtract Background counts (B_i)

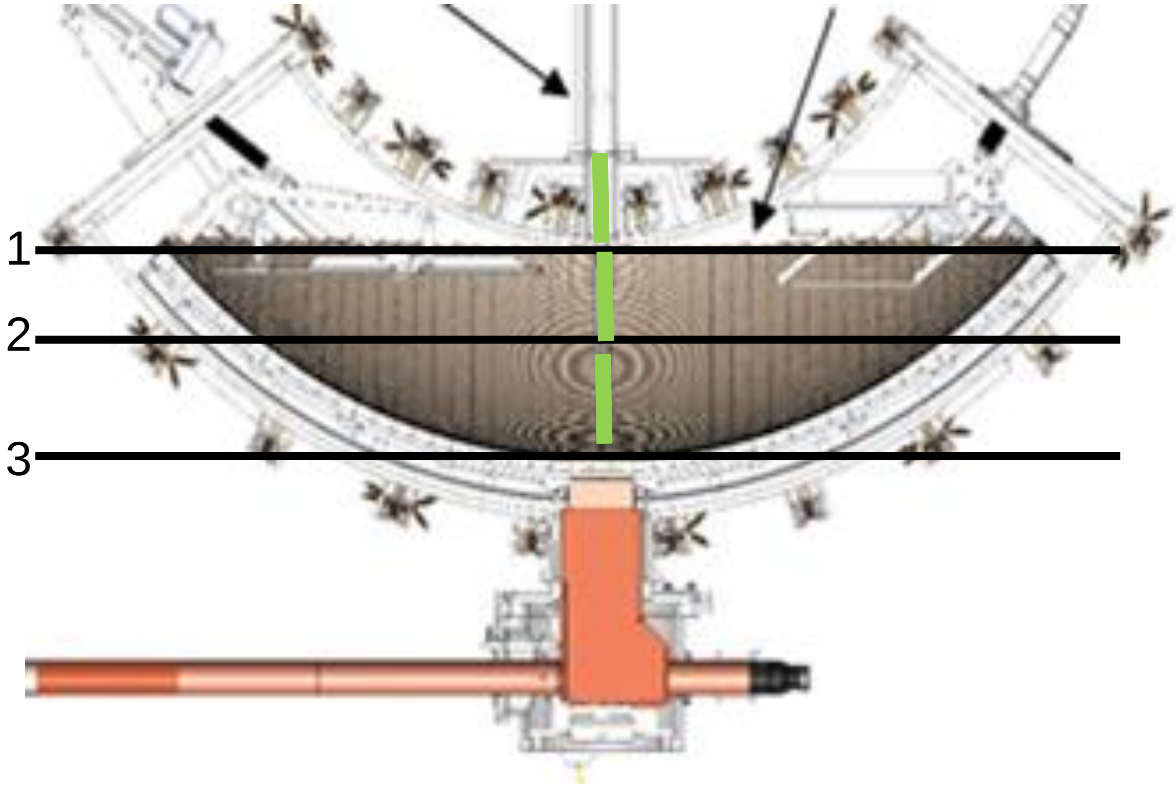




$$Y_i = \frac{D_i - B_i}{f(M_i)}$$

3-Step Unloads, using $E = m_n g h$





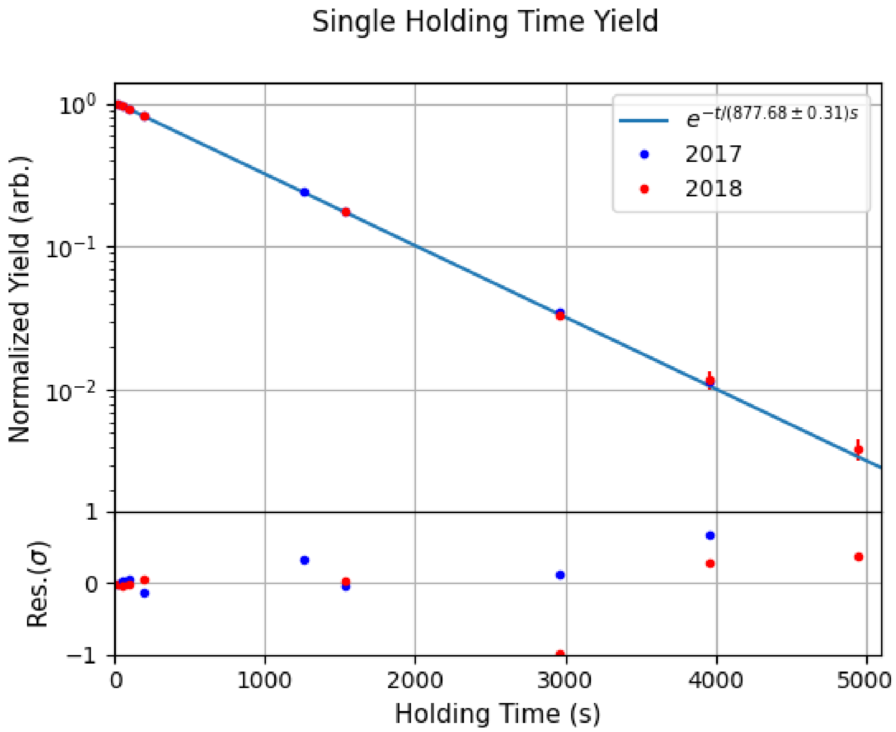
Neutron losses (or changes in detector efficiency) would have an energy dependence

Finding the Lifetime:

$$Y(t_i) = Y_i e^{-t_i/\tau_{meas}}$$

Effect	2021 Reported Value (s)
τ_{meas}	877.58 ± 0.28
UCN Event Definition	0 ± 0.13
Normalization Weighting	0 ± 0.06
Depolarization	$0 + 0.07$
Uncleaned UCN	$0 + 0.11$
Heated UCN	$0 + 0.08$
Al Block	0.06 ± 0.05
Residual Gas Scattering	0.11 ± 0.06
Sys. Total	$\mathbf{0.17^{+0.22}_{-0.16}}$
TOTAL	$\mathbf{877.75 \pm 0.28^{+0.22}_{-0.16}}$

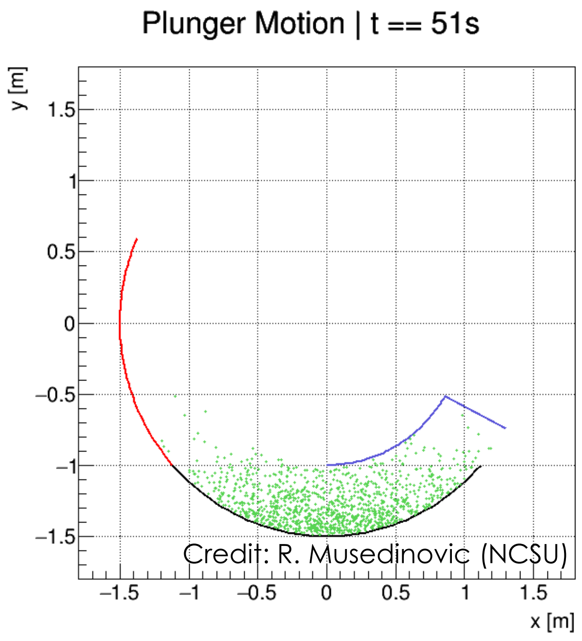
Gonzalez, F. M. *et al*, Phys. Rev. Lett. 127, 162501 (2021)



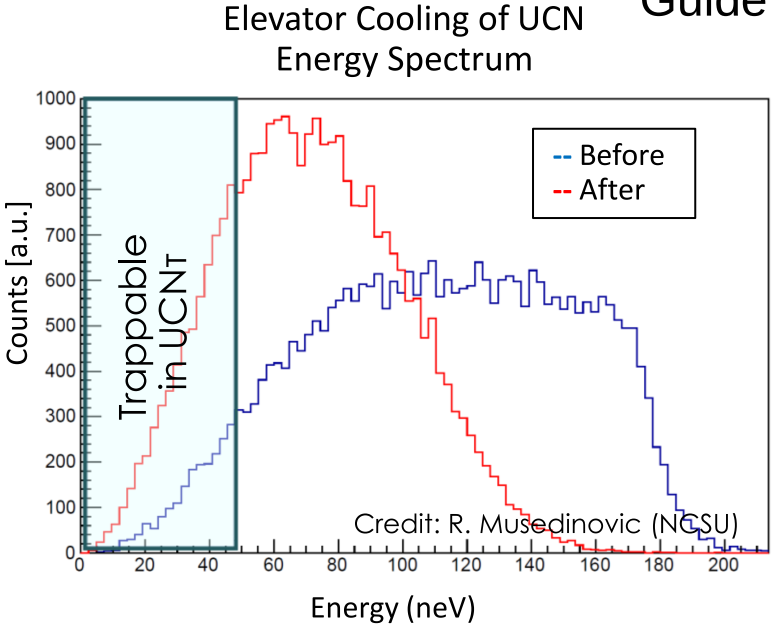
Corrections less than statistical uncertainty!

UCNτ+: Improving Statistics

- New "Elevator" Loading Mechanism to maximize statistics
  - Uses existing trap!
  - Anticipate $10\times$ counts over loading from bottom

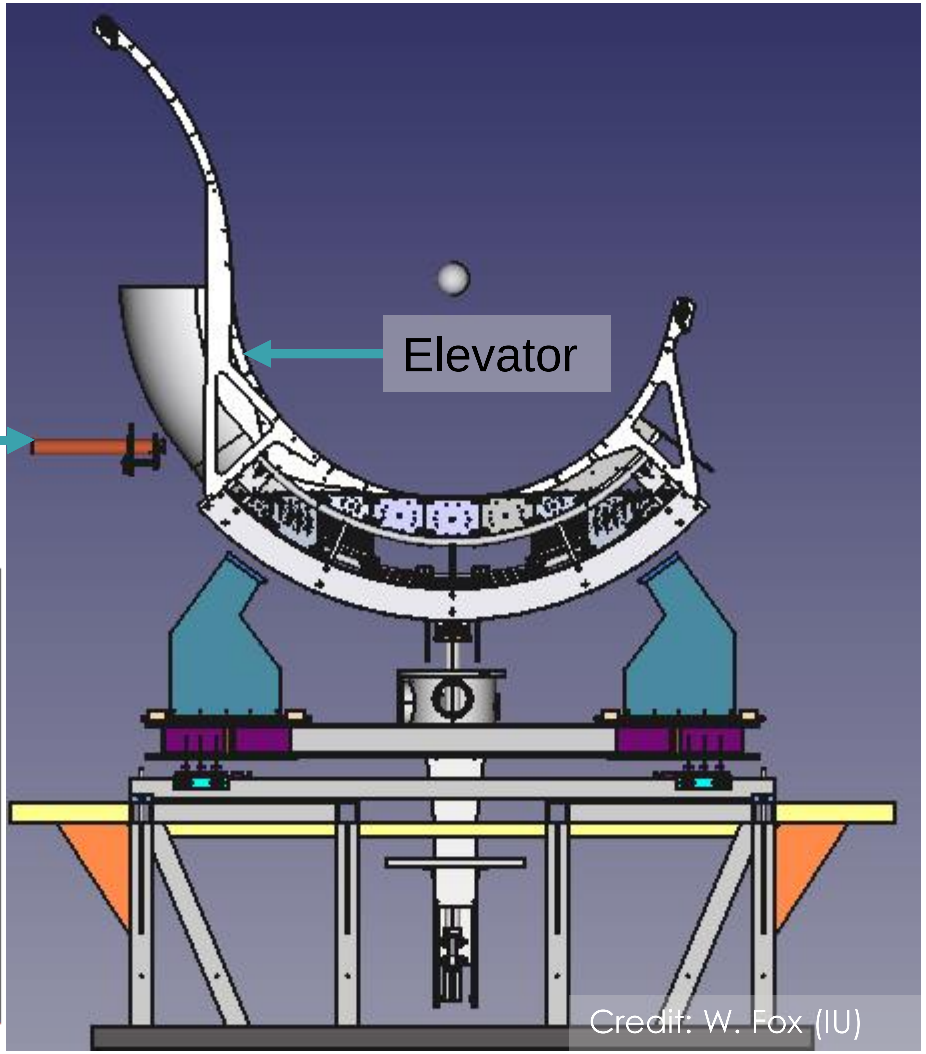


Credit: R. Musedinovic (NCSU)



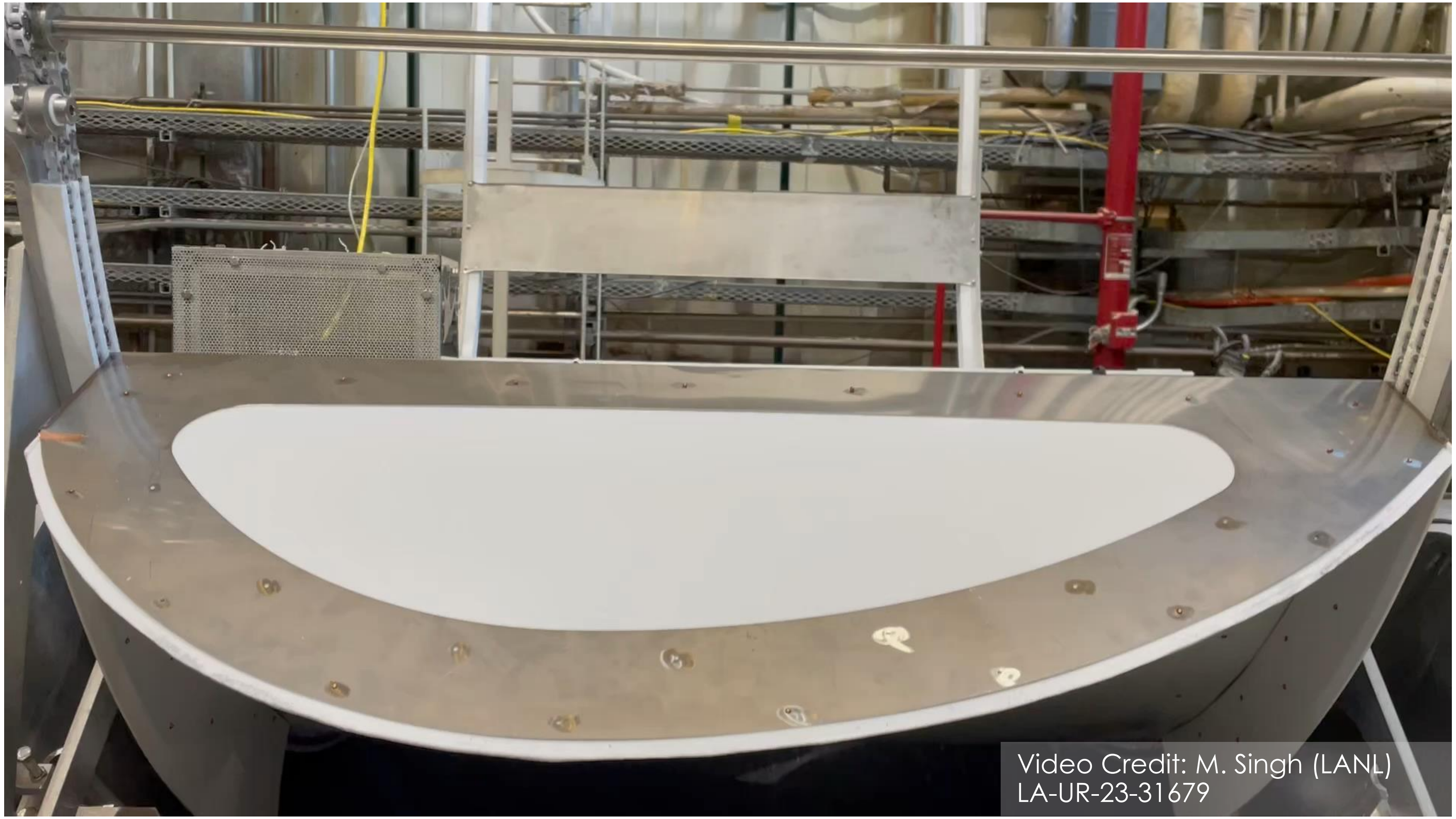
Credit: R. Musedinovic (NCSU)

UCN Guide



Credit: W. Fox (IU)

UCNτ+ Elevator In Action

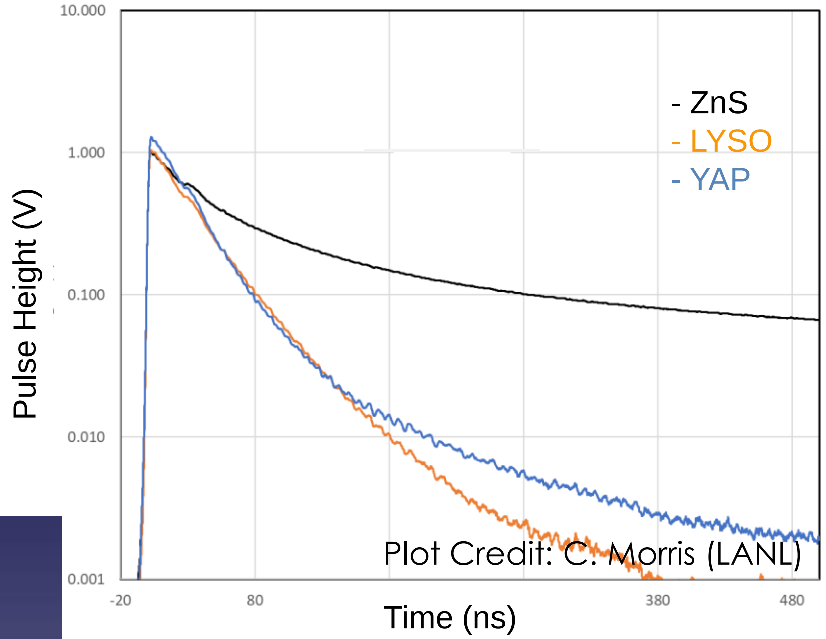


Video Credit: M. Singh (LANL)
LA-UR-23-31679

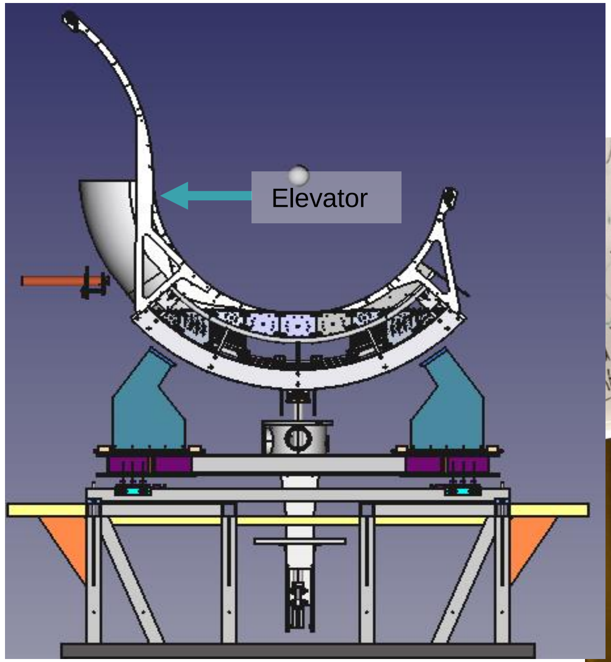
Near Future Improvements

- Developing new detectors to count UCN faster and mitigate Rate Dependent Effects
  - Faster scintillator (LYSO, plastic)
  - Segmented detector
- Higher Statistics due to improved loading
  - Elevator Under Construction Now!
- Bring UCNτ+ to a lifetime sensitivity of $\Delta\tau_n < 0.15$s:

$$\Delta\tau_n/\tau_n = 1 \times 10^{-4}$$



Plot Credit: C. Morris (LANL)



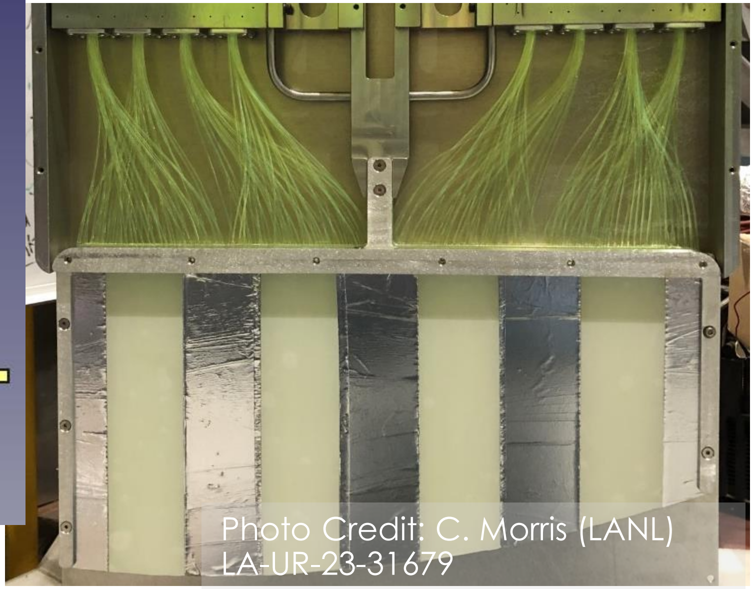


Photo Credit: C. Morris (LANL)
LA-UR-23-31679

The UCNτ Collaboration

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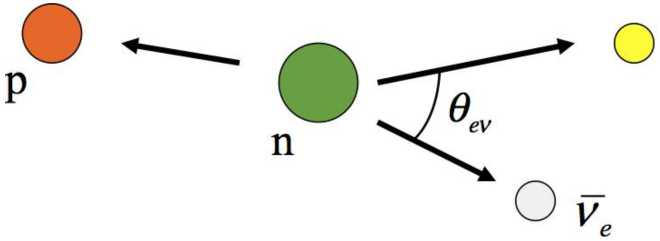
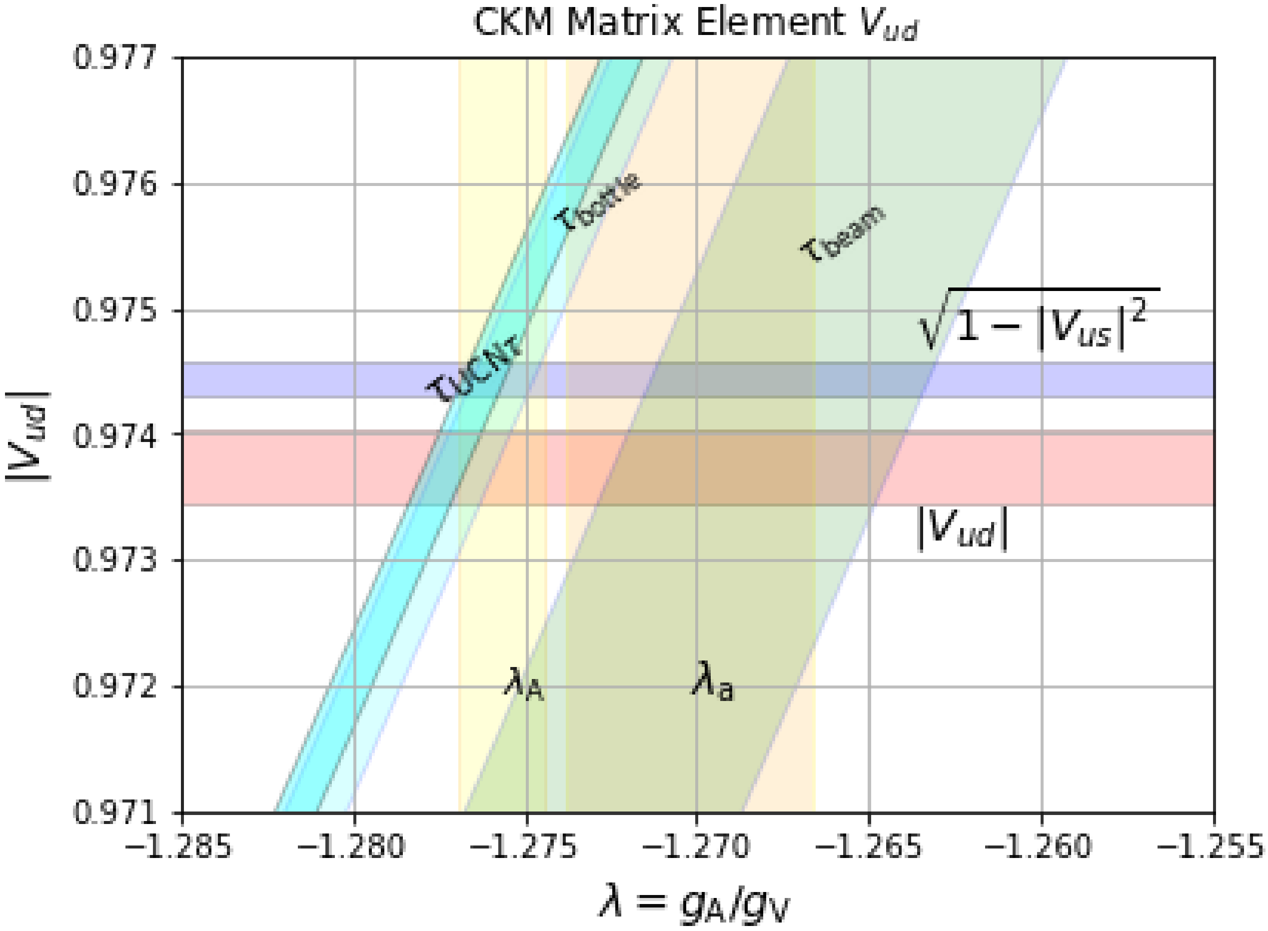
Back to Neutron Decay

- Recall:
  - $n \rightarrow p^+ + e^- + \bar{\nu}_e$
  - $|V_{ud}|^2 = \frac{5099.3\ \text{s}}{\tau_n\,(1+3\,\lambda^2)(1+\Delta_R)}$
- To compete with $0^+ \rightarrow 0^+$ measurements in finding V_{ud}:
  - $\Delta\tau_n/\,\tau_n < 3 \times 10^{-4}$ *(UCNτ)*
- Other observables in neutron decay:
  - Energies of p^+, e^-, and $\bar{\nu}_e$
  - Momenta (direction) of p^+, e^-, $\bar{\nu}_e$
- Use these to determine λ





Data from:

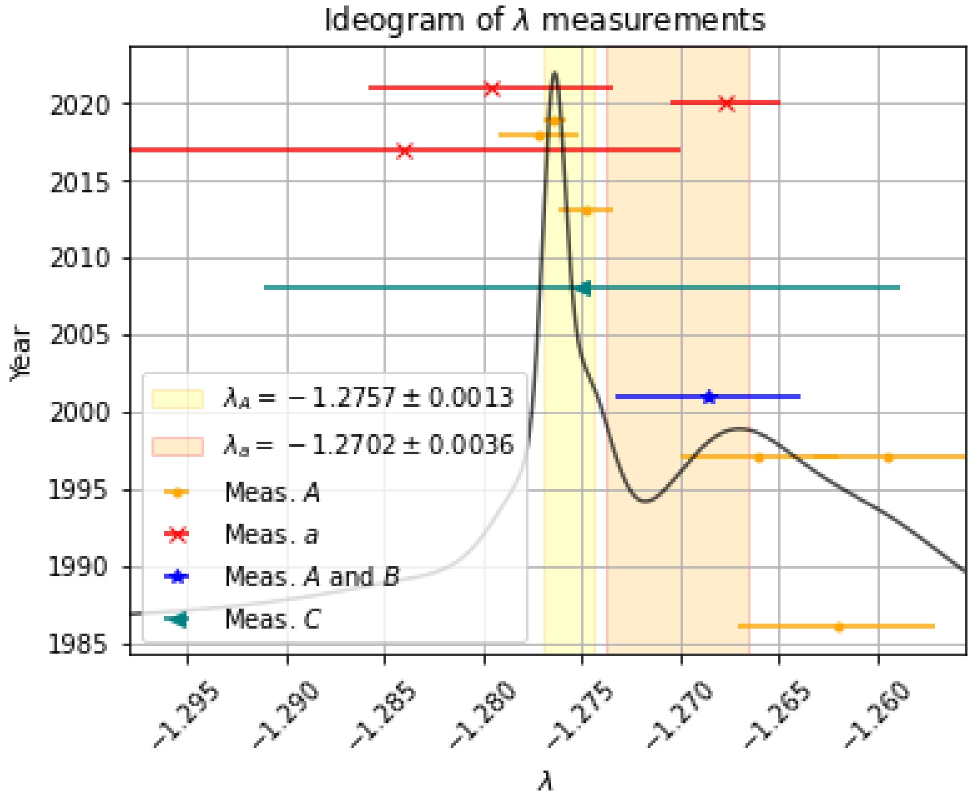
- Workman, R. L. *et al*, Particle Data Group (2022)

How to Measure $\lambda = g_A/g_V$?

Decay rate of the neutron is proportional to:

$$\frac{d\Gamma^3}{dE_e\, d\Omega_e\, d\Omega_\nu} \sim p_e E_e E_\nu^2 (1+3\lambda^2)\left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + \langle\vec{\sigma_n}\rangle\cdot\left(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu}\right) + \cdots\right]$$

- Correlation terms (asymmetries) relate to $\lambda = g_A/g_V$:
  - $a = \frac{1-\lambda^2}{1+3\lambda^2}$ ($\vec{p_e}$ vs. $\vec{p_\nu}$)
  - $A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2}$ ($\vec{p_e}$ vs. $\vec{\sigma_n}$)
- Fierz Interference term b couples to scalar (g_S), tensor (g_T) currents in weak interaction
  - Non-zero g_S, g_T is new physics

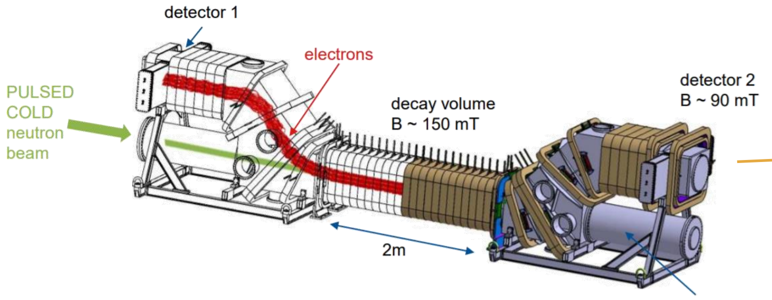


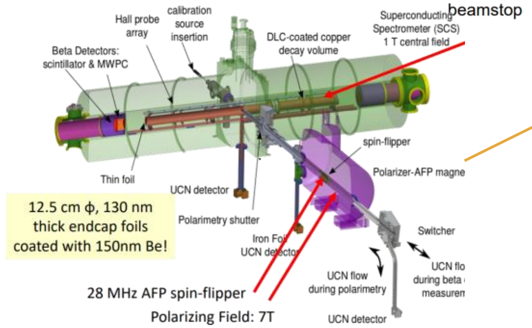
Data from:

- Workman, R. L. *et al*, Particle Data Group (2022)

Measuring λ: Recent Results

- PERKEO III (A):
  - $\Delta\lambda/\lambda = 4.4 \times 10^{-4}$
  - Polarized cold neutrons, measure e^- asymmetry



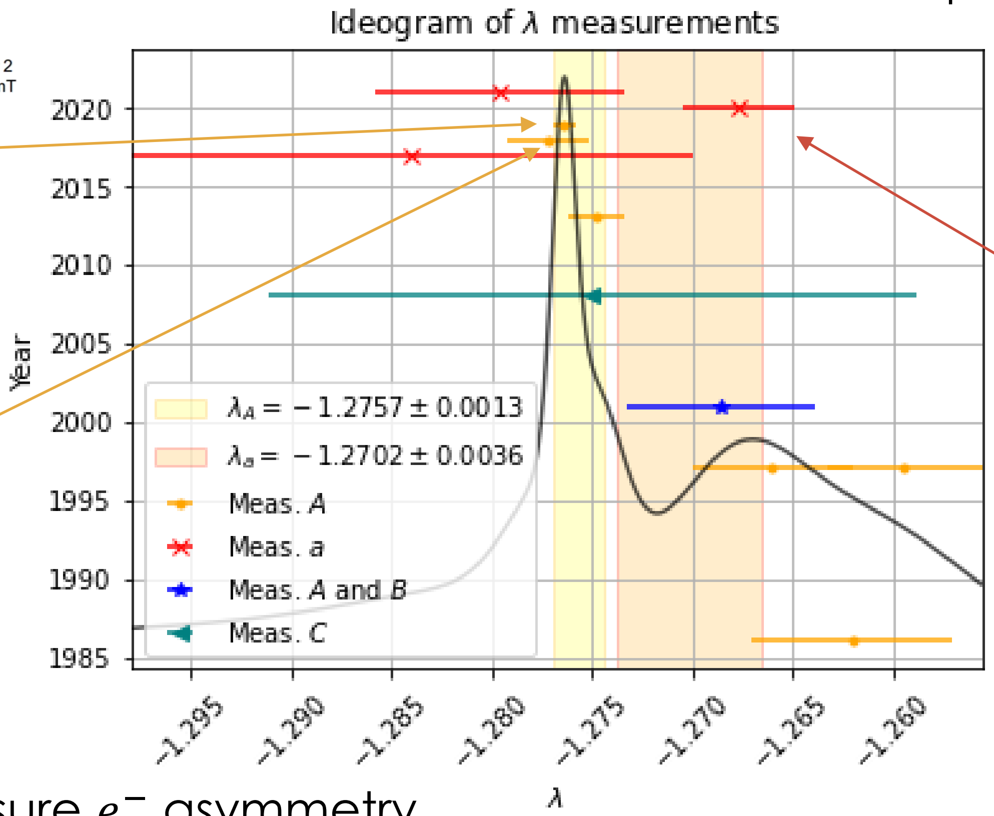


12.5 cm ϕ, 130 nm thick endcap foils coated with 150nm Be!

28 MHz AFP spin-flipper

Polarizing Field: 7T

- UCNA (A):
  - $\Delta\lambda/\lambda = 1.7 \times 10^{-3}$
  - Polarized UCN, measure e^- asymmetry

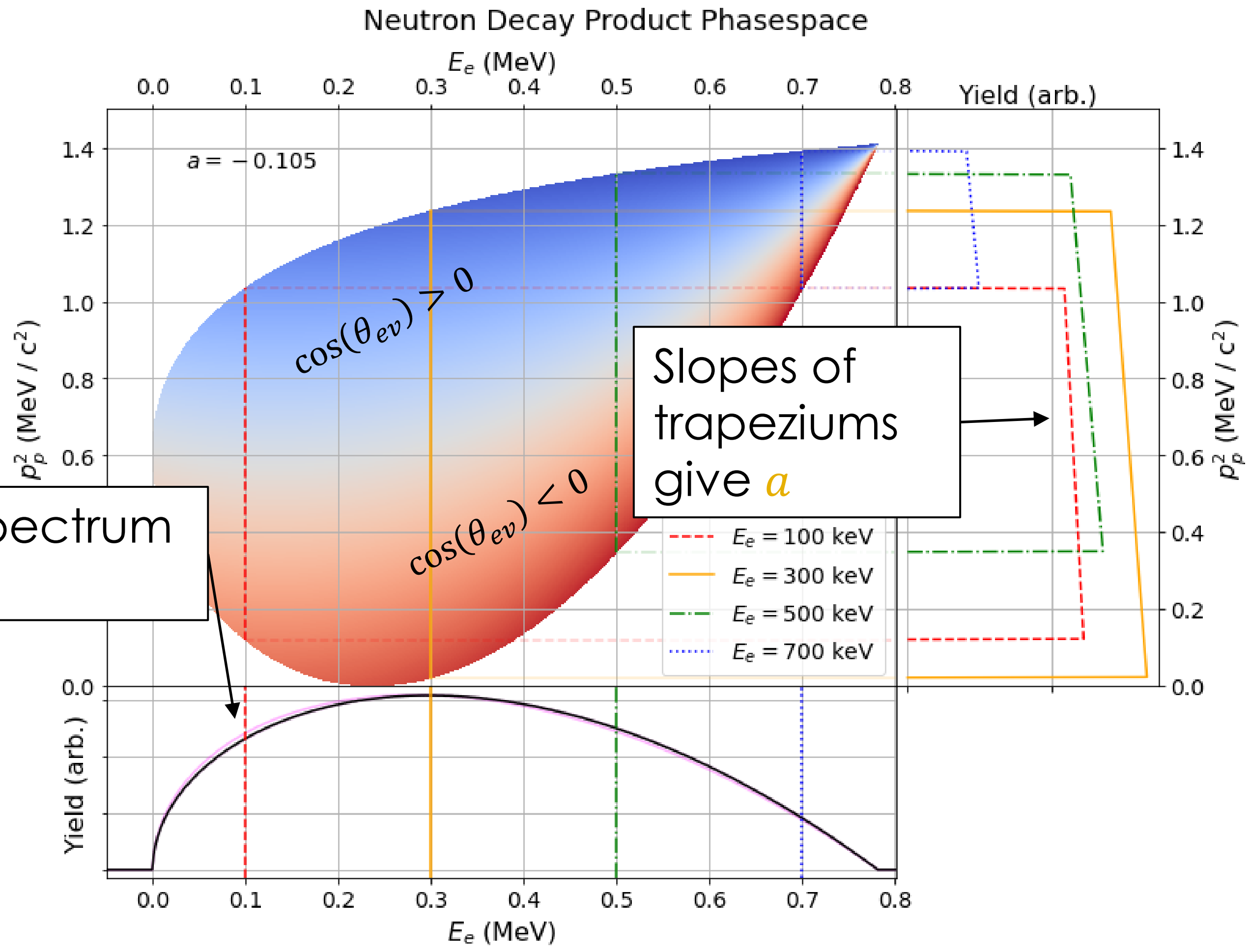


- aSPECT (a):
  - $\Delta\lambda/\lambda = 2.2 \times 10^{-3}$
  - Unpolarized cold n, measure p^+ spectrum

Brown et al., PRC 97, 035505 (2018)
Märkisch et al., PRL 122, 242501 (2019)
Beck, et al., PRC 101, 055506 (2020)

Kinematics of Unpolarized Neutron β-Decay

- For unpolarized neutrons:
  - $d\Gamma^3 \propto 1 + a\frac{|\overrightarrow{p_e}|\,|\overrightarrow{p_\nu}|}{E_e E_\nu}\cos(\theta_{e\nu}) + b\frac{m_e}{E_e}$
- Relativistic kinematics:
  - Relativistic Energy (for $i \in \{n, p^+, e^-, \nu\}$):
    - $E_i^2 = \overrightarrow{p_i}^2 + m_i^2$
  - Conservation of E:
    - $E_\nu = E_n - (E_e + E_p)$
  - Conservation of $\vec{p}$:
    - $\cos(\theta_{e\nu}) = \frac{\overrightarrow{p_p}^2 - \overrightarrow{p_e}^2 - \overrightarrow{p_\nu}^2}{2|\overrightarrow{p_e}||\overrightarrow{p_\nu}|}$
- After some algebra, find $d\Gamma^3(E_e, p_p^2)$
  - If we can reconstruct E_e, p_p^2 for each decay, we can extract a, b…



Shape of e^- spectrum gives b

Slopes of trapeziums give a

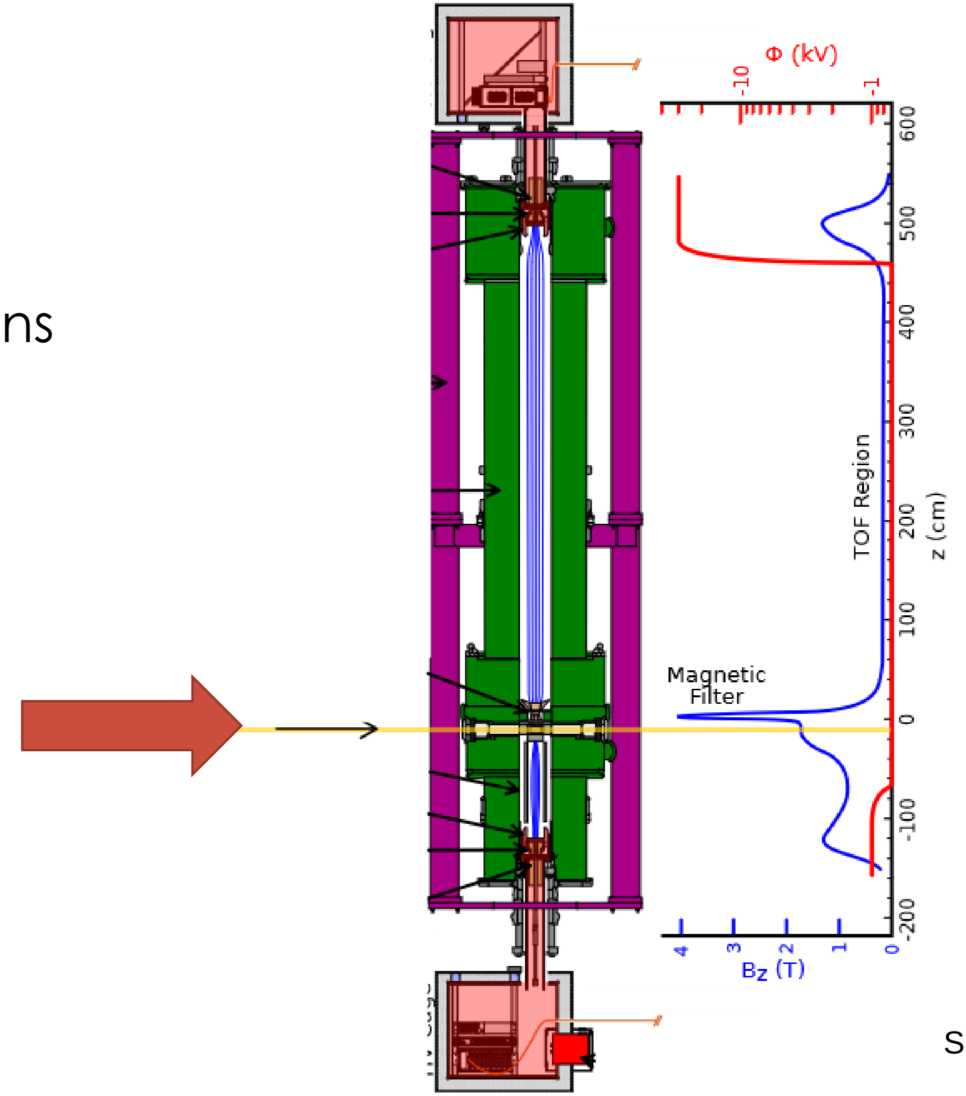
The Nab Experiment at Oak Ridge

World’s largest cryogen-free superconducting magnet!


gif credit: J. Fry, EKU

Reconstructing β-Decay Product Kinematics

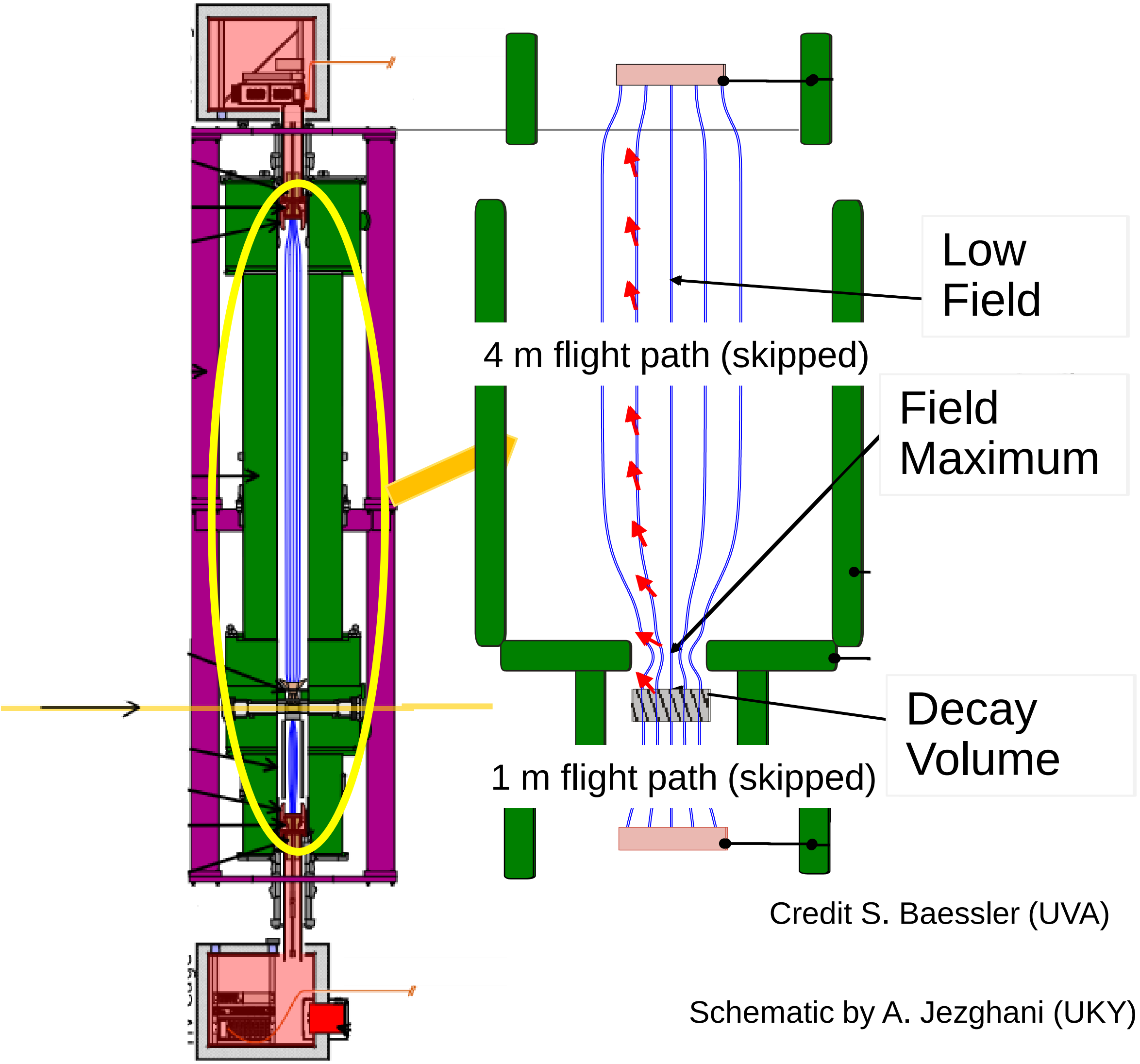
- Use an asymmetric (7m long) spectrometer
- Beam of cold spallation neutrons



Schematic by A. Jezghani (UKY)

Reconstructing β-Decay Product Kinematics

- Use an asymmetric (7m long) spectrometer
- Beam of cold spallation neutrons
- Magnetic fields guide decay products
  - High-field decay region
  - Low-field time of flight region longitudinalizes momentum

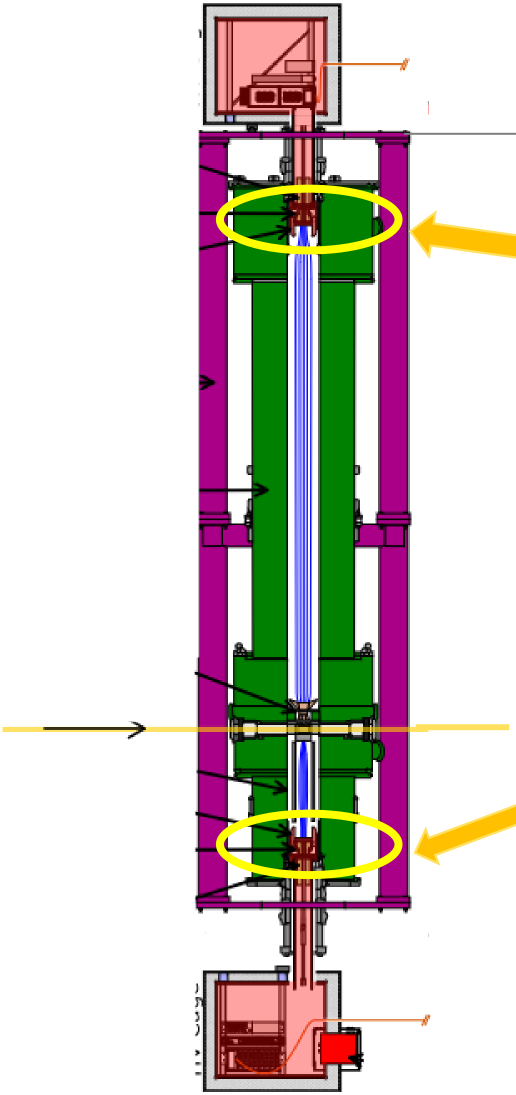


Credit S. Baessler (UVA)

Schematic by A. Jezghani (UKY)

Reconstructing β-Decay Product Kinematics

- Use an asymmetric (7m long) spectrometer
- Beam of cold spallation neutrons
- Magnetic fields guide decay products
  - High-field decay region
  - Low-field time of flight region longitudinalizes momentum
- Detect coincident p^+ and e^- at one of two silicon detectors
  - E_e measured in detector
  - $|\overrightarrow{p_p}|$ determined from proton time of flight



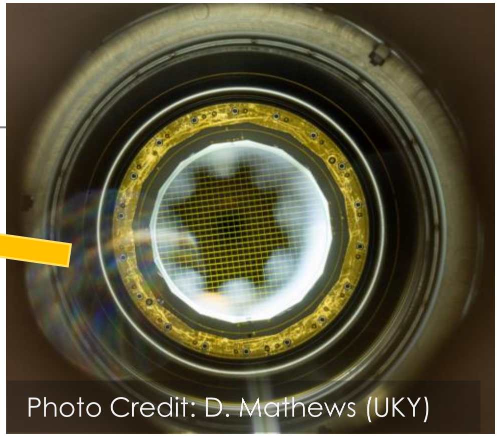


Photo Credit: D. Mathews (UKY)

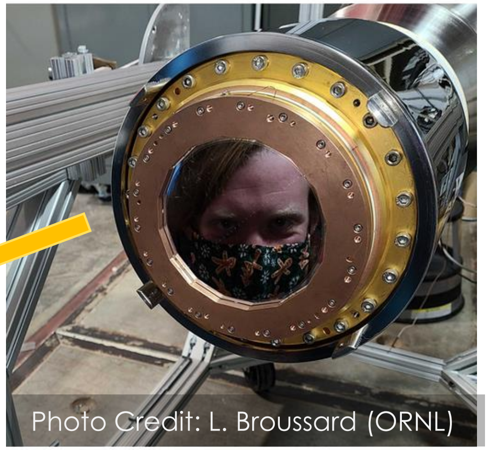


Photo Credit: L. Broussard (ORNL)

Schematic by A. Jezghani (UKY)

Extracting E_e with Silicon Detectors

- Segmented silicon detector (produced by Micron)
  - 127 hexagonal pixels for spatial resolution
  - Deadlayer ~ 100 nm
- Floats at 30 kV to see both p^+ and e^-

Photo Credit: Micron Semiconductor, Inc.

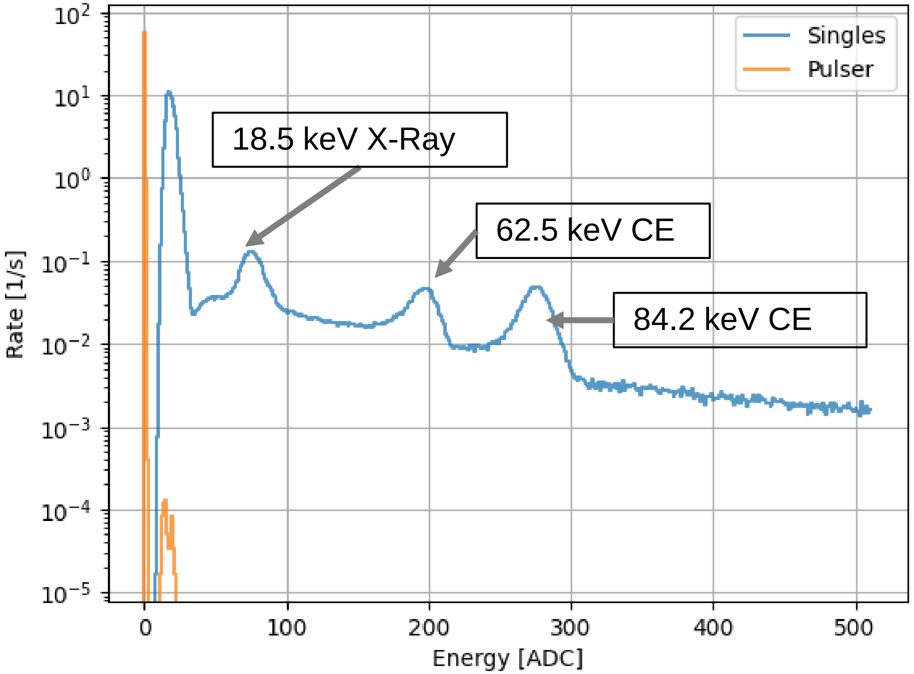
Photo Credit: L. Broussard (ORNL)

Detector Effects	Target Uncertainty	$(\Delta a\ /\ a)_{sys.}$
Electron Energy Calibration	$\Delta E_e < 0.2$ keV	2×10^{-4}
Shape of Electron Energy Response	fraction of events in tail to 1%	4.4×10^{-4}
Proton Trigger Efficiency	$\epsilon_p < 100$ ppm / keV	3.4×10^{-4}
TOF Shift due to Detector/Electronics	$\Delta t_p < 0.3$ ns	3.9×10^{-4}
SUM		7.1×10^{-4}

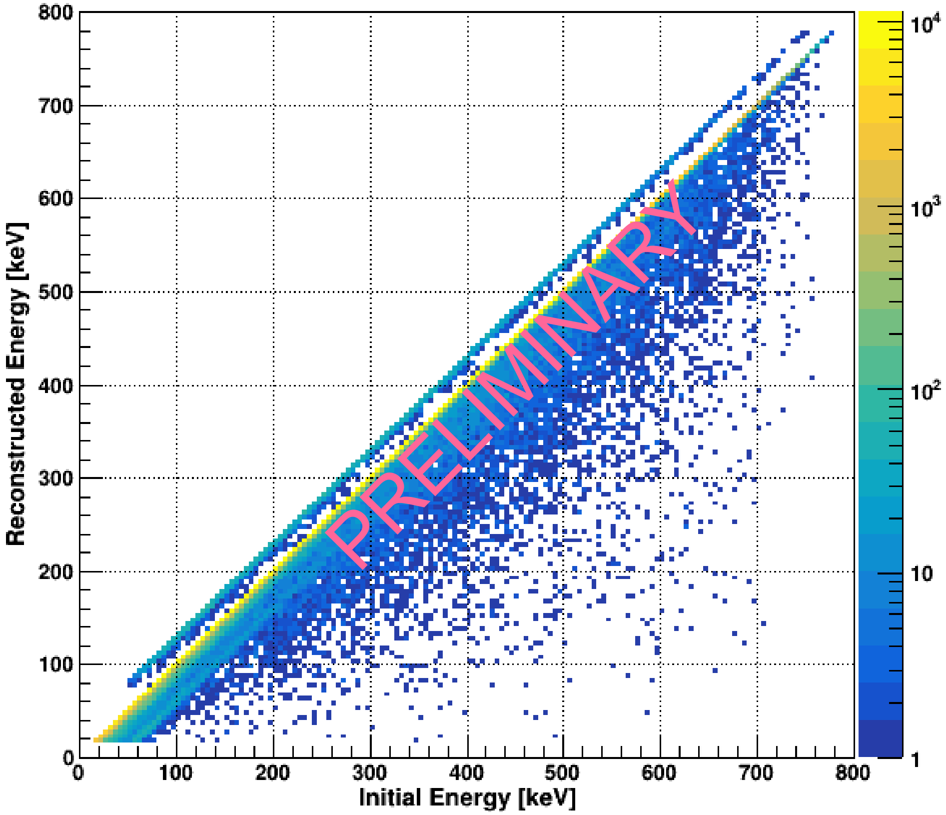
Electron Response Function

- Need to understand $E_{e,meas}$ for each E_e to 1%
  - Fast + Linear electronics response
  - Electron bounce history
  - Energy loss in detector due to Bremsstrahlung
- Simulate detector response and measure

^{109}Cd Energy Spectrum, One Detector

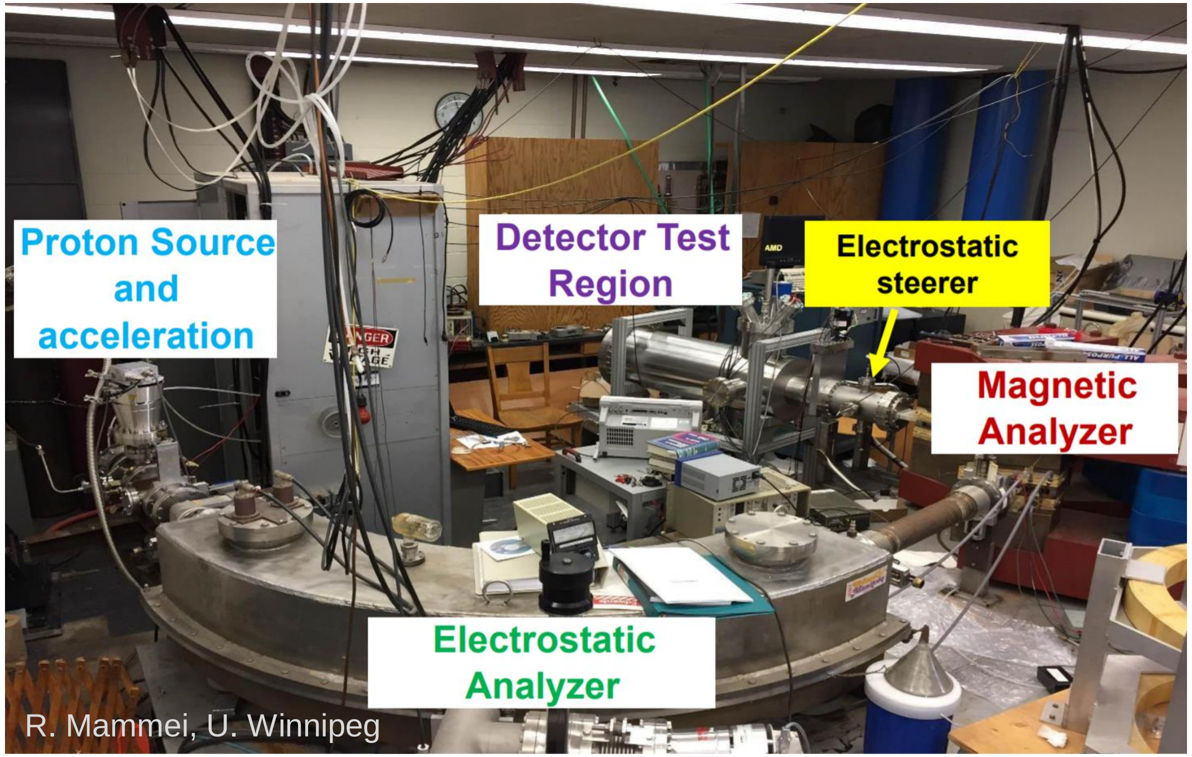


Simulated Electron Response



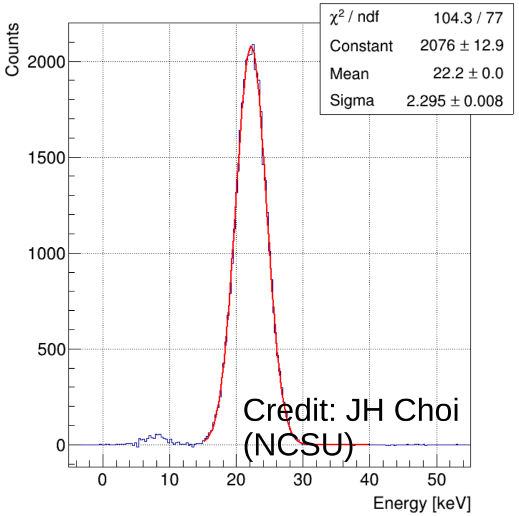
Manitoba II Proton Source

- Allows pixel-by-pixel mapping of detector
- Double focusing mass spectrometer
  - Penning ion gauge Hydrogen-Argon gas discharge source
  - Analyzer selects 30 kV p^+
  - Steerer guides p^+ onto detector



R. Mammei, U. Winnipeg

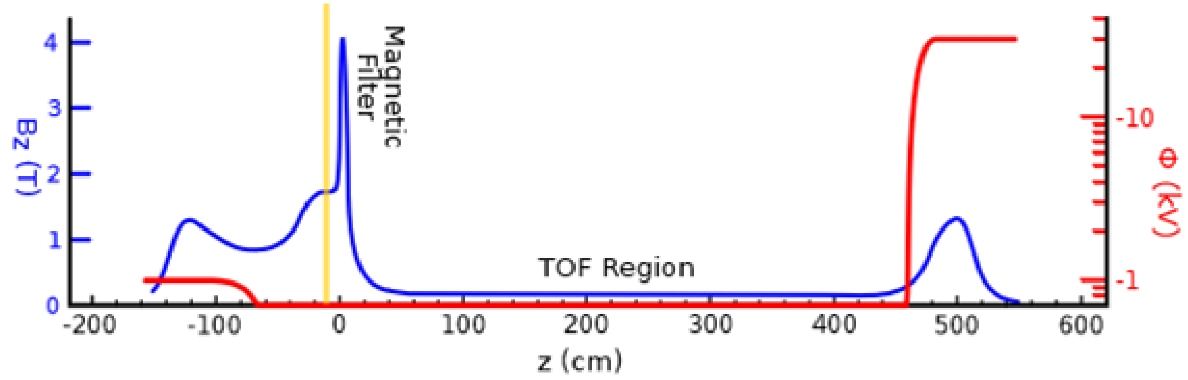
Calibrated Proton Spectrum



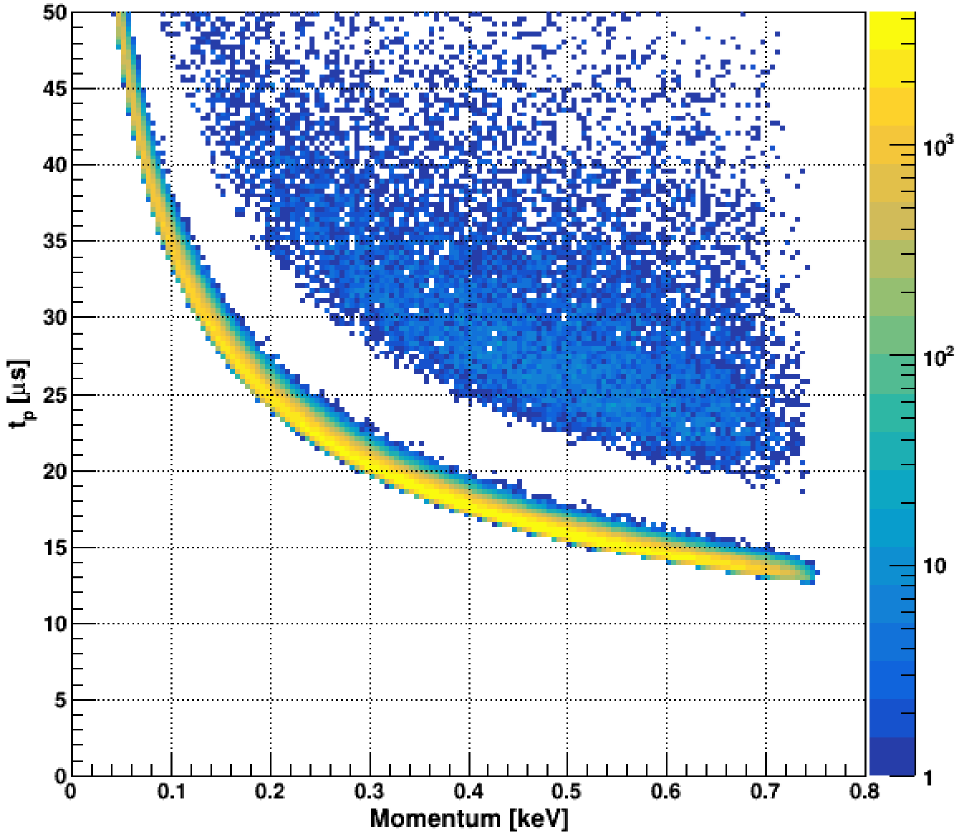
Credit: JH Choi (NCSU)

Determining p_p from Time of Flight

- Charged particle (p^+) moving through EM field:
  - $t_p = \frac{m_p}{p_p} \int_{z_0}^{L} \frac{dz}{\sqrt{1 - \frac{B(z)}{B_0} \sin^2(\theta_0) + \frac{q(V(z) - V_0)}{E_0}}}$
  - Smearing of response due to θ_0, z_0
  - High magnetic field rejects p^+ with:
    - $\cos(\theta_0) < \sqrt{1 - B_0/B_f} \sim 0.7$



Simulated Proton Response



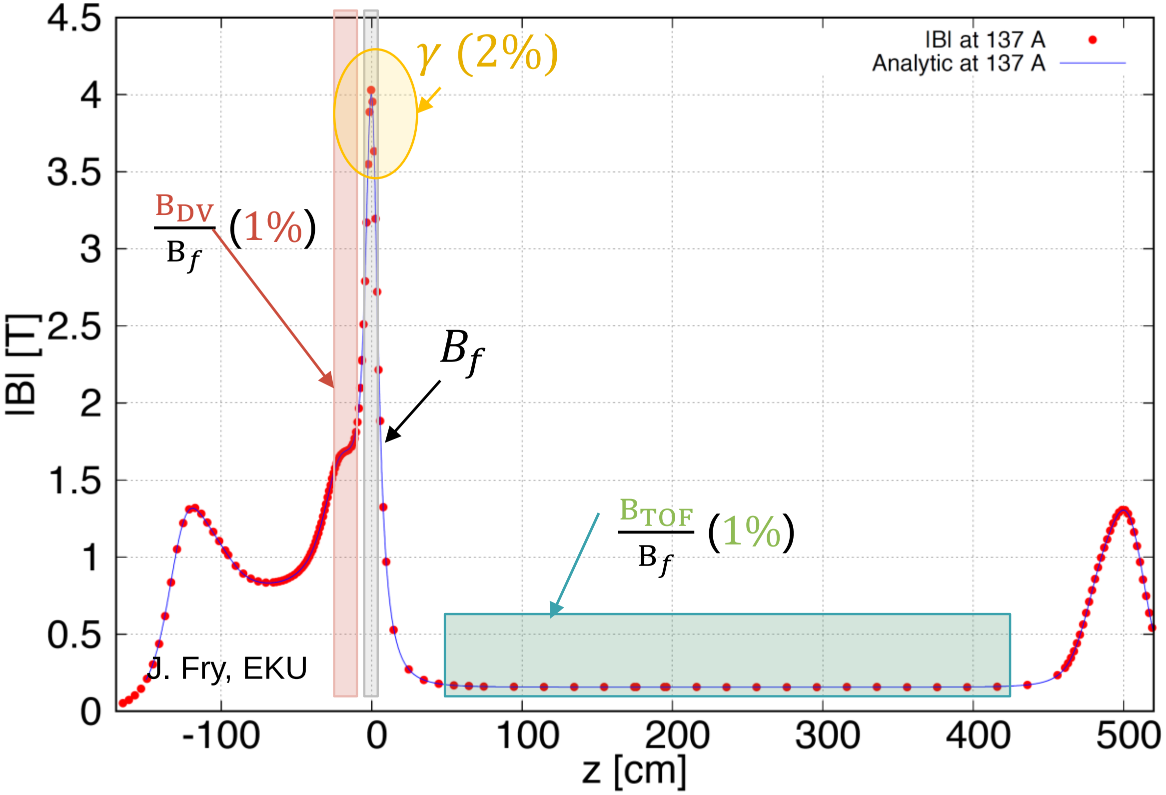
Fry et al. EPJ Web of Conferences 219, 04002 (2019)

Characterization of Magnetic Field

- Need to understand $B(z)$ to determine t_p
  - Have done measurements with Hall probe
  - Good agreement with simulation
- Analysis of magnetometry data ongoing

Magnetic Field	Target Uncertainty	$(\Delta a\ /\ a)_{sys.}$
Curvature at Pinch γ	$\Delta\gamma/\gamma = 2\%$	5.3×10^{-4}
Ratio $r_{B,\mathrm{TOF}} = B_{TOF}/B_f$	$(\Delta r_{B,\mathrm{TOF}})/r_{B,\mathrm{TOF}} = 1\%$	2.2×10^{-4}
Ratio $r_{B,DV} = B_{DV}/B_f$	$(\Delta r_{B,DV})/r_{B,DV} = 1\%$	1.8×10^{-4}
SUM		6.0×10^{-4}

$|B|$ vs. z



Target Uncertainties for a and b

- Leading uncertainties:
  - Magnetic Field (only a)
  - Detector Effects (both a and b)
  - Neutron Beam (only a)
- Goal precision:
  - $\Delta a/a \sim (1 \times 10^{-3})_{tot.}$
  - $\Delta\lambda/\lambda \sim (4 \times 10^{-4})_{tot.}$
  - $\Delta b \sim (3 \times 10^{-3})_{tot.}$
- Not statistically limited!

Experimental Parameter	$(\Delta a\ /\ a)_{sys.}$
Magnetic Field	6.0×10^{-4}
Electric Potential Inhomogeneity	5.5×10^{-4}
Neutron Beam	3.3×10^{-4}
Adiabaticity of Proton Motion	1×10^{-4}
Detector Effects	7.1×10^{-4}
Electron TOF	$< 1 \times 10^{-4}$
Residual Gas	3.8×10^{-4}
TOF in Acceleration Region	3×10^{-4}
Background/Accidental Coincidences	$< 1 \times 10^{-4}$
Length of the TOF Region	N/A
SUM	$1.2 \times\ 10^{-3}$

Troubleshooting Nab Magnet

- June 2022:
  - Upper coils of Magnet stop cooling at ~10K (should be ~4K)
  - Indicative of 20W heat load
- Leak? Detector touching bore? Compressor issue? Broken Coldhead?

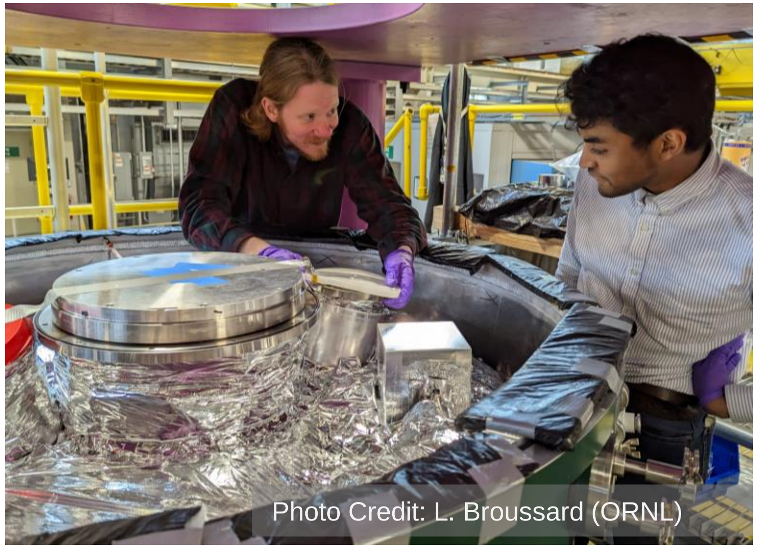


Photo Credit: L. Broussard (ORNL)

- Tie rods caught in the wrong place!
  - Pulls the bore tube ~1.5mm down
- April 26, 2023:
  - Modified alignment piece, successfully ramped

Before

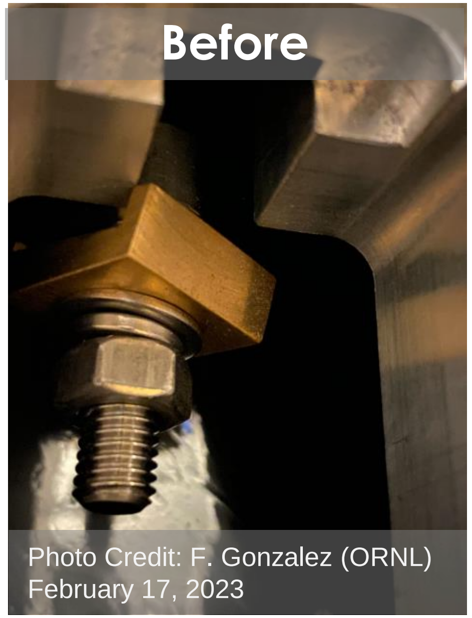


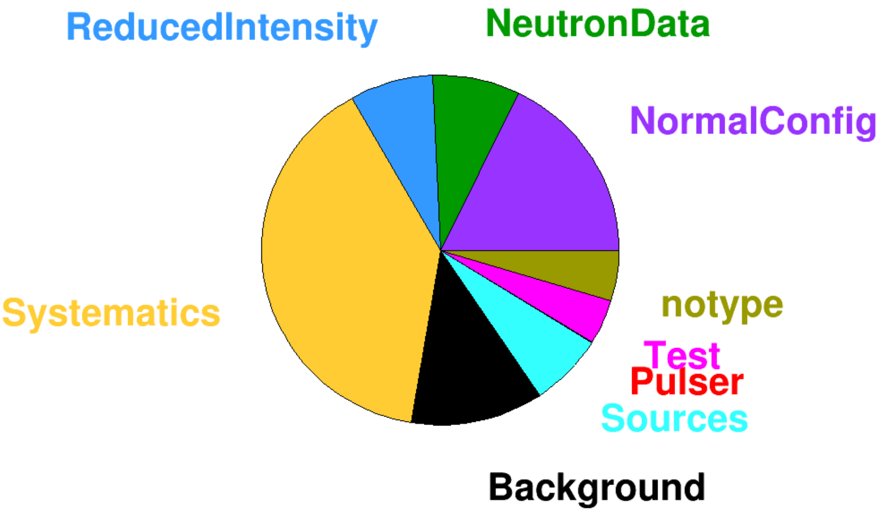
Photo Credit: F. Gonzalez (ORNL)
February 17, 2023

After


Photo Credit: F. Gonzalez (ORNL)
March 23, 2023

Summer Commissioning + Data Taking

- First time with 2 detectors in working magnet with high voltage and neutrons!



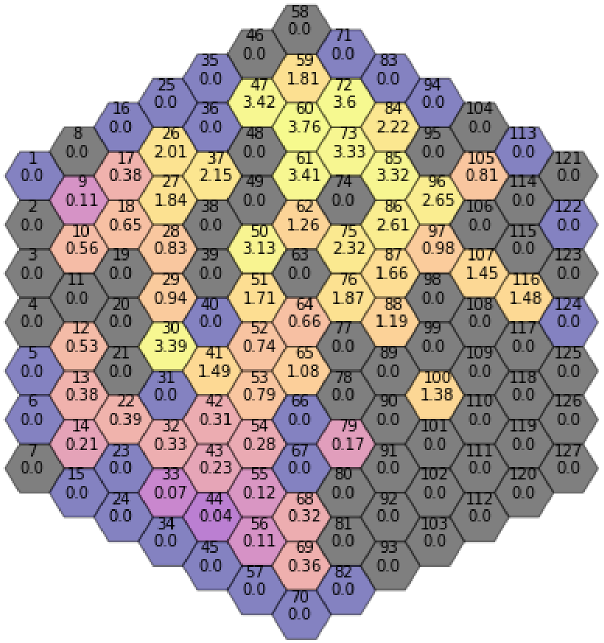
Data Taken per Run Type

- Normal Data Taking = 20%
- Systematics (+ Reduced Intensity) = 46.7%
- Background = 12.0%

Chart Credit: J. H. Choi (NCSU)

- Caveat: Electronics and Detector Issues
  - Electronics unstable
  - Parts of detector system unresponsive
  - Lower detector underdepleted

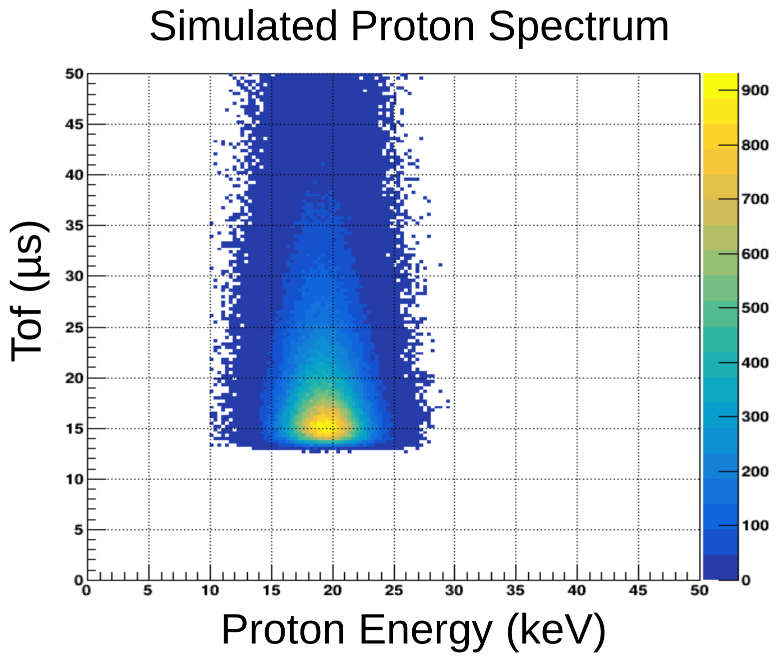
Detected Proton Rate

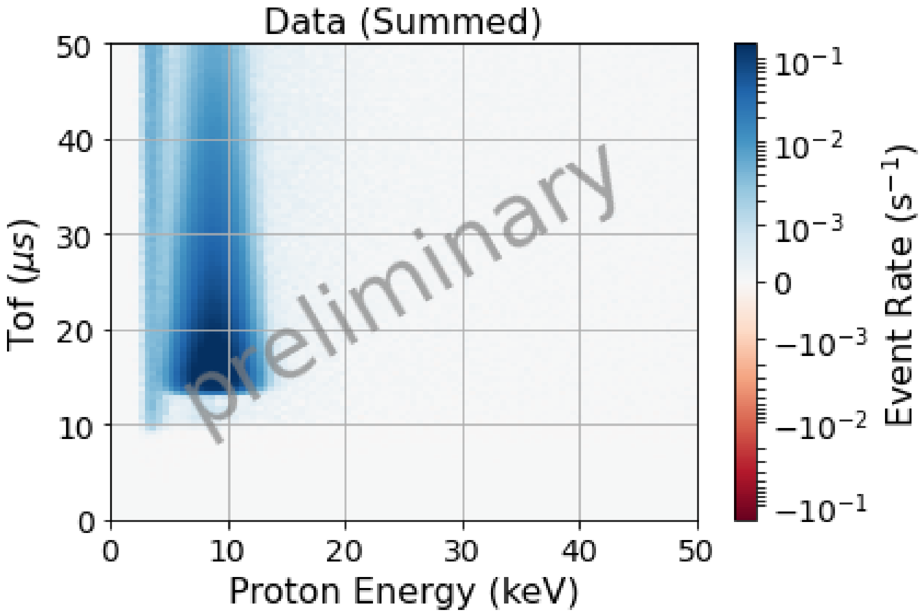


- Upgrade of detector system underway

Proton Response

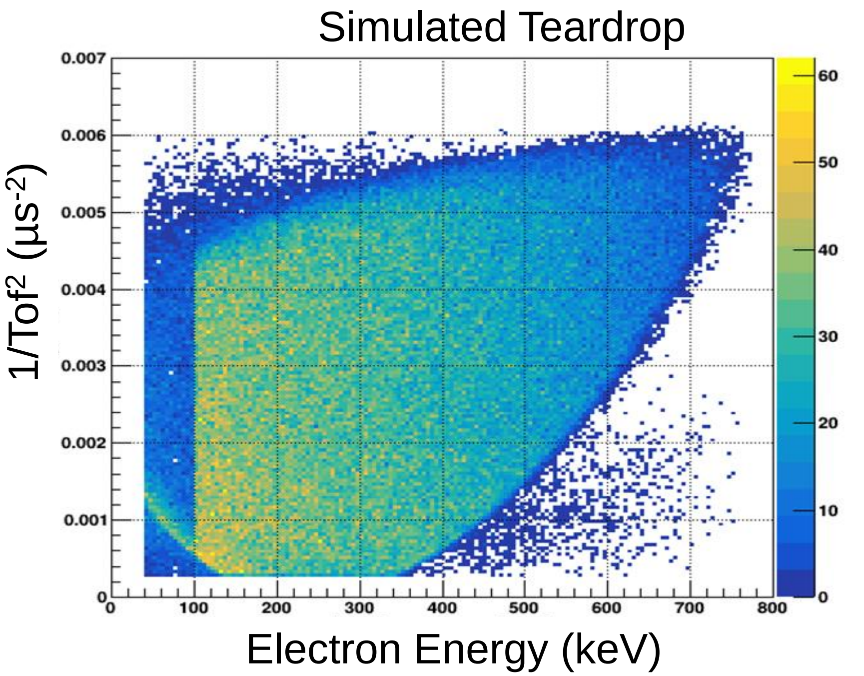
- We see protons!
  - Observed p^+, e^- coincidence rate in our detectors $\sim 50\ n/s$
- Proton peak energy lower than expected
  - Expected 20 keV for -30 kV detector voltage
  - See peak at ~10 keV, lower than expected

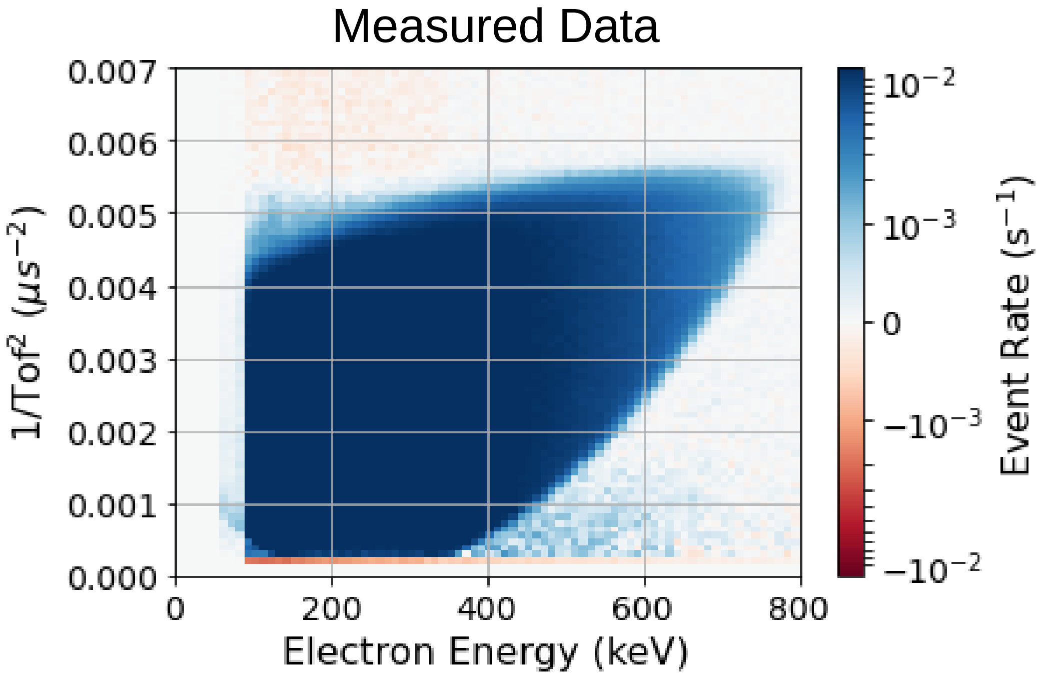




Neutron Decays!

- First Full-Phasespace Reconstruction of Neutron Decay!
- Measured 1.6e7 coincidences above background
  - Corresponds to $(\Delta a/a)_{stat} \sim 1.1 \times 10^{-2}$
  - Detector response leads to significant (presently unquantified) systematic shifts





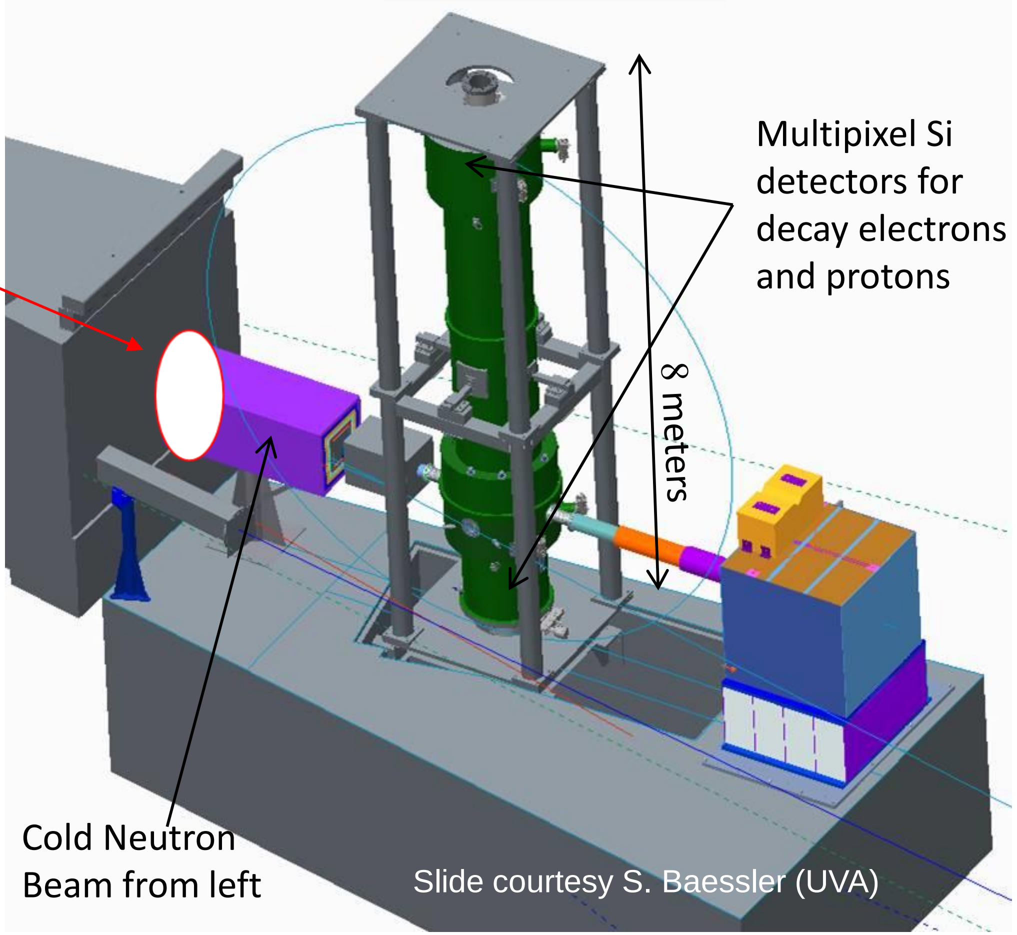
Preparations for Upcoming Beamtime

- Detector System Improvements
  - Upgrade of detector electronics
  - DAQ timing and stability improvements
- Detector characterizations
  - Studies of detector deadlayer
  - Linearity, temperature, and calibration studies
- Polarimetry studies at HFIR and SNS

Photo Credit: L. Broussard (ORNL)

Looking Forward: pNab

- Use the same apparatus to measure A, B
  - Add a neutron beam polarizer
    - Crossed supermirrors or ^{3}He
  - Goals:
    - $\Delta A/A \leq 10^{-3}$
    - $\Delta B/B \leq 10^{-3}$
- Knowledge of uncertainties from Nab a and b:
  - Competitive Statistics
  - High detector energy/time resolution
  - Coincidence detection to suppress background
- Different systematics to other A, B measurements!



Slide courtesy S. Baessler (UVA)

The Nab Collaboration

- Nab Collaborating Institutions:

Oak Ridge National Laboratory
Los Alamos National Laboratory
University of Virginia
The University of Tennessee Knoxville
Arizona State University
NC State University
Massachusetts Institute of Technology
University of Kentucky
University of Michigan
Eastern Kentucky University
The University of Tennessee Chattanooga
Universidad Nacional Autónoma de México
University of Manitoba
The University of Winnipeg
WKU
Universität Karlsruhe (TH)
Forschungsuniversität • gegründet 1825
University of South Carolina

Main Project Funding:

NSF
U.S. Department of Energy Office of Science
Oak Ridge National Laboratory
University of Virginia

Summary

- 1) Interested in V_{ud} to resolve tensions in CKM unitarity
- 2) Most precise value of τ_n
  - UCNτ+ coming online soon
- 3) Measuring λ
  - Nab commissioning now!
- Neutron soon competitive with other probes of V_{ud}!