Neutrons III

III.1 A, a, and τ_n… and the importance of systematics

III.2 Responses to the Lifetime Puzzle

III.3 Beyond β-decay

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36th National Nuclear Summer School, July 2024
Indiana University, Bloomington

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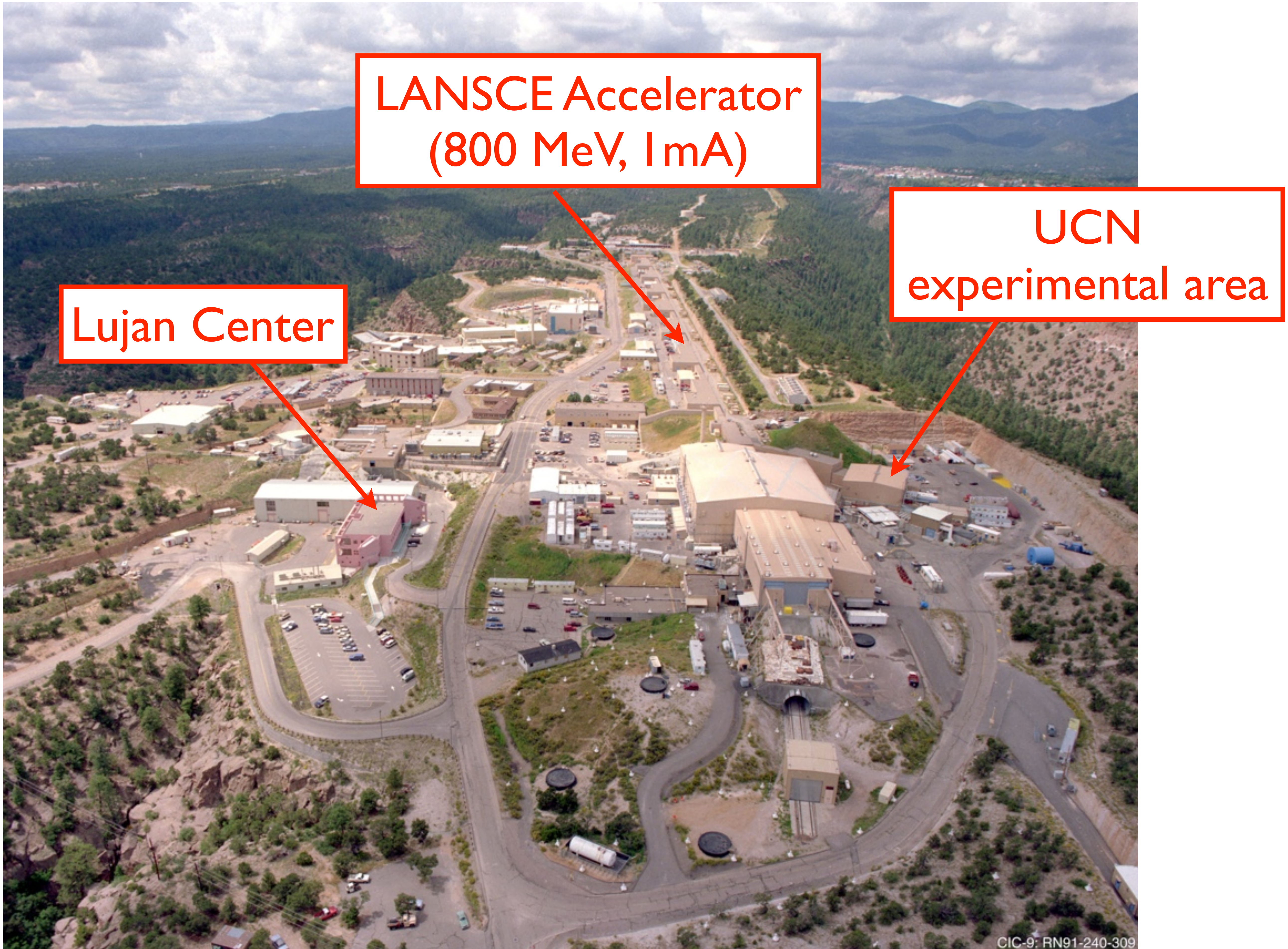
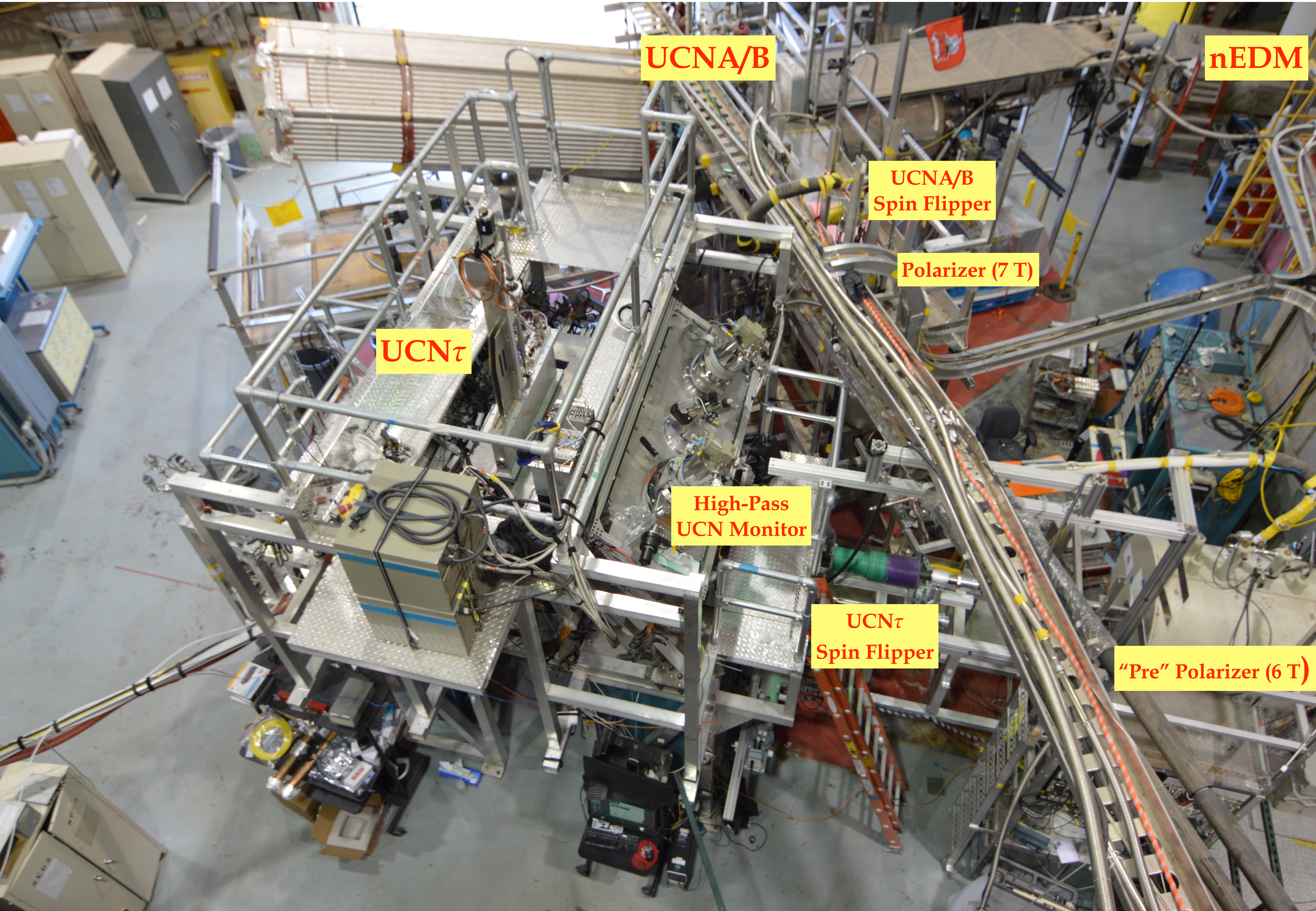
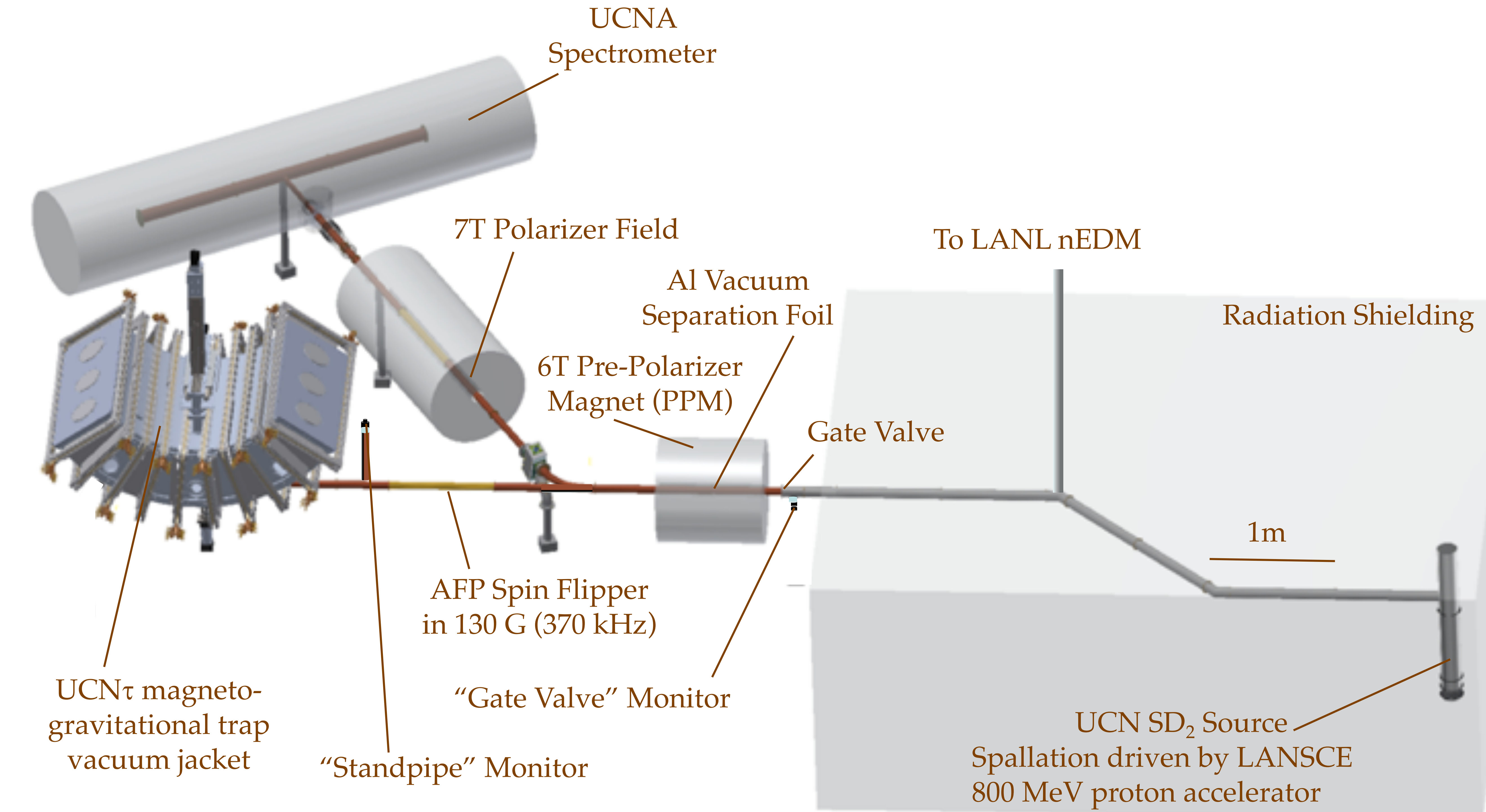


Area B



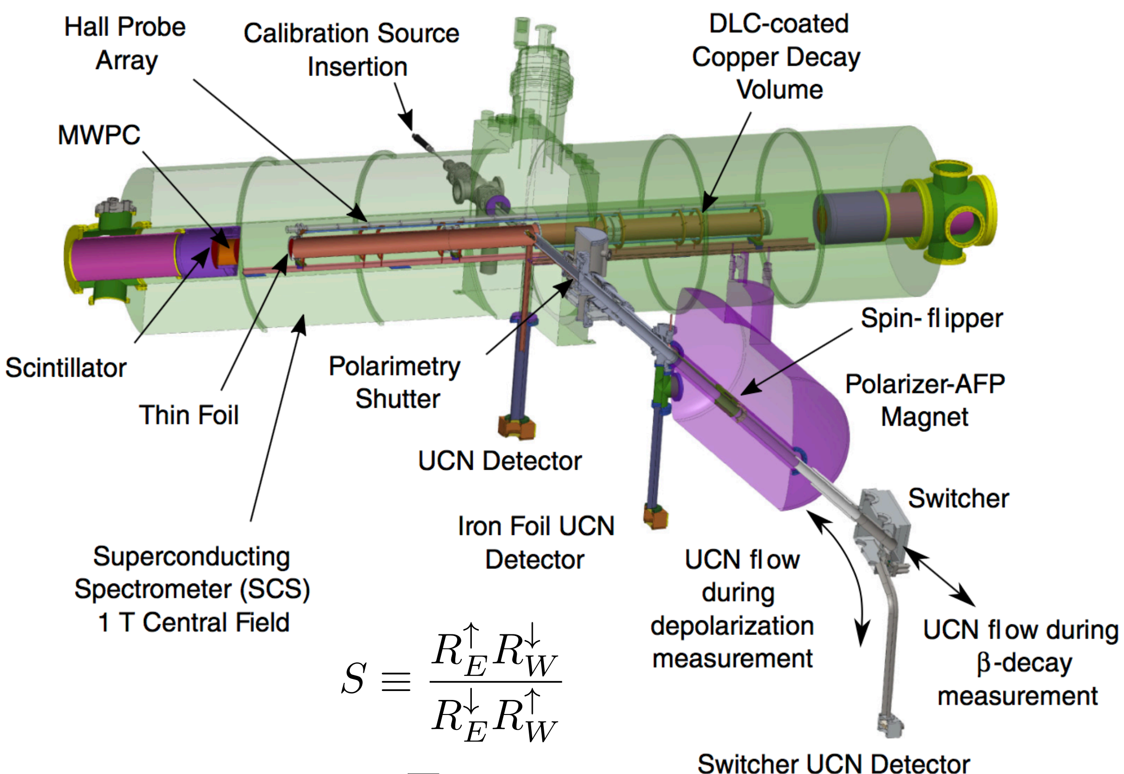
UCNA/B
nEDM
UCNA/B Spin Flipper
Polarizer (7 T)
UCNτ
High-Pass UCN Monitor
UCNτ Spin Flipper
"Pre" Polarizer (6 T)

Area B: UCNτ / UCNA / nEDM



Area B: UCNA

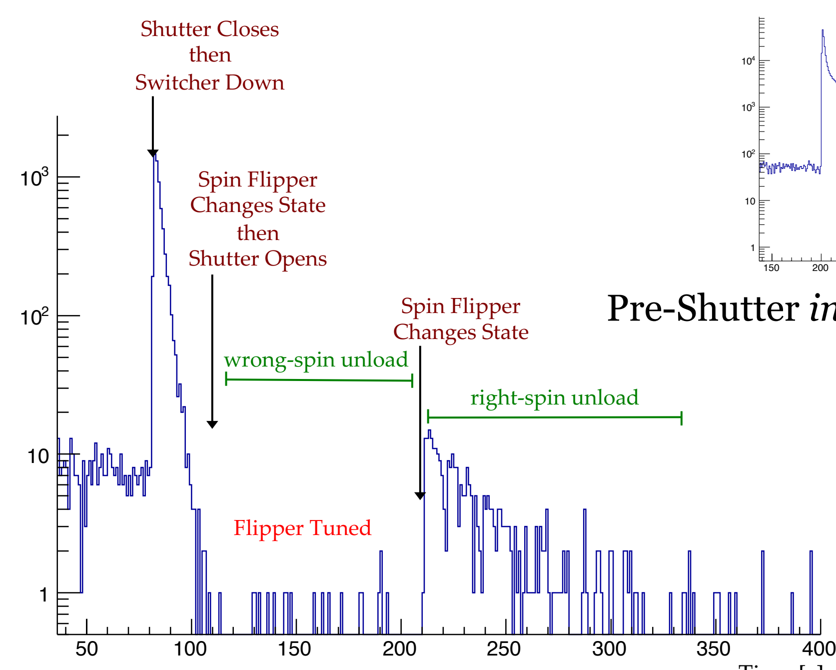
UCNA

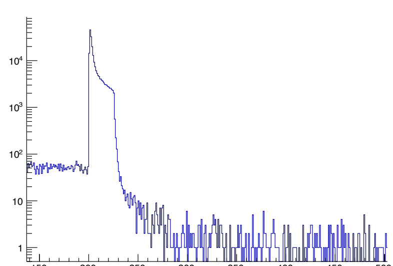


$$S \equiv \frac{R_E^{\uparrow} R_W^{\downarrow}}{R_E^{\downarrow} R_W^{\uparrow}}$$

$$A_{\rm meas}(E_e) = \frac{1-\sqrt{S}}{1+\sqrt{S}} = \langle P_n \rangle A \beta \langle \cos\theta \rangle$$

Typical Shutter Polarimetry *in situ* cycle





Pre-Shutter *in situ* Polarimetry cycle

The "Nutrition Label"

M. P. Mendenhall *et al.*, *Phys. Rev.* C **87**, 032501(R) (2013)

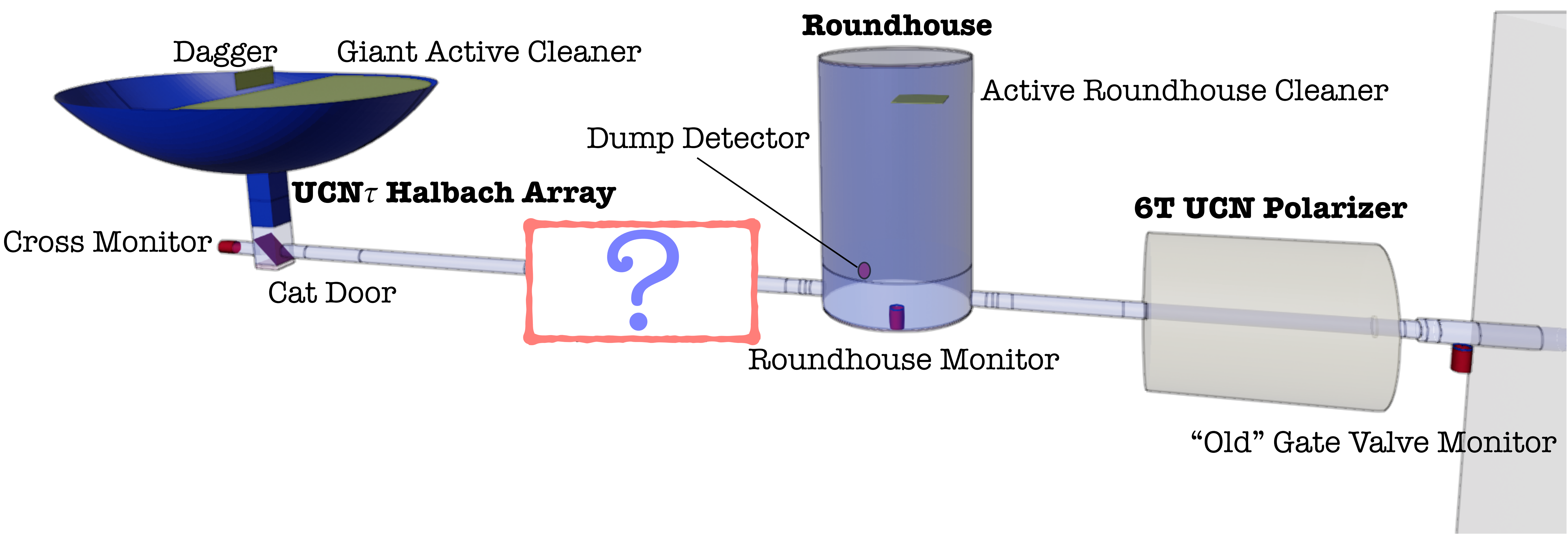
Systematic	Corr. (%)	Unc. (%)
Polarization	+0.67	± 0.56
$\Delta_{\rm backscattering}$	+1.36	± 0.34
$\Delta_{\rm angle}$	−1.21	± 0.30
Energy reconstruction		± 0.31
Gain fluctuation		± 0.18
Field non-uniformity	+0.06	± 0.10
$\epsilon_{\rm MWPC}$	+0.12	± 0.08
Muon veto efficiency		± 0.03
UCN-induced background	+0.01	± 0.02
$\sigma_{\rm statistics}$		± 0.46

M. A.-P. Brown *et al.*, *Phys. Rev.* C **97**, 035505 (2018)

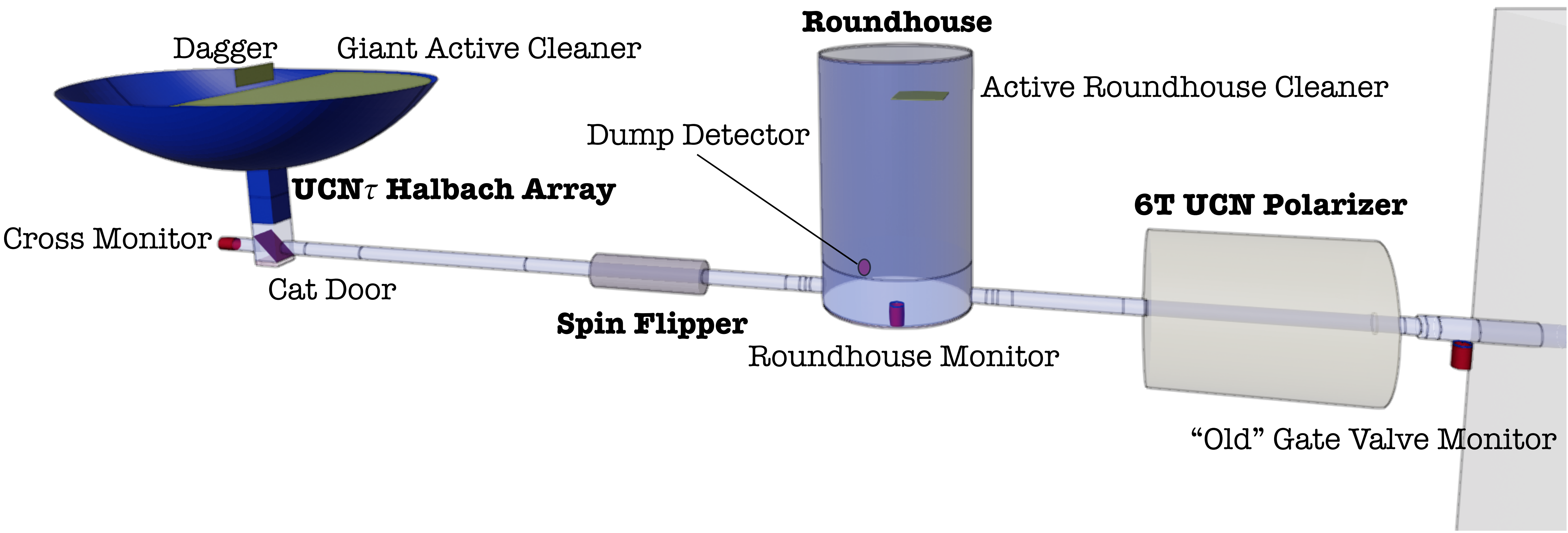
$$\frac{\delta\lambda}{\lambda} \sim \frac{1}{4}\frac{\delta A}{A}$$

	% Corr.		% Unc.
	2011–2012	2012–2013	
$\Delta_{\cos\theta}$	− 1.53	− 1.51	0.33
$\Delta_{\rm backscattering}$	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

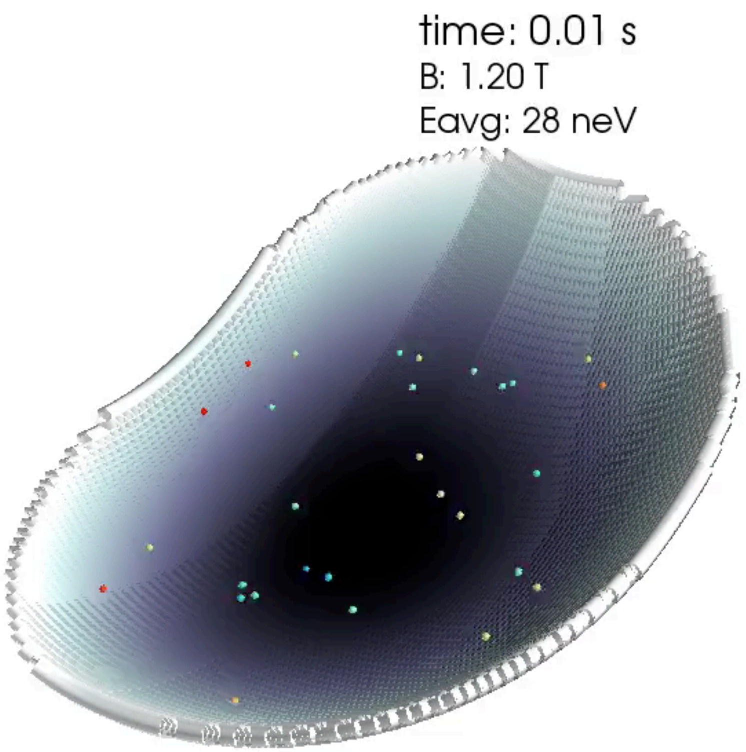
Area B: UCNτ

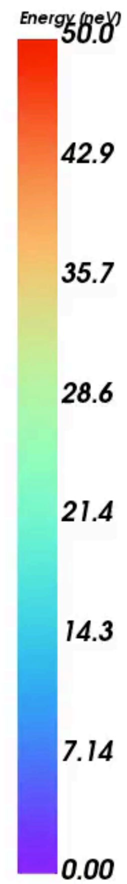

Roundhouse
Dagger
Giant Active Cleaner
Active Roundhouse Cleaner
Dump Detector
UCNτ Halbach Array
6T UCN Polarizer
Cross Monitor
?
Cat Door
Roundhouse Monitor
"Old" Gate Valve Monitor

Area B: UCNτ

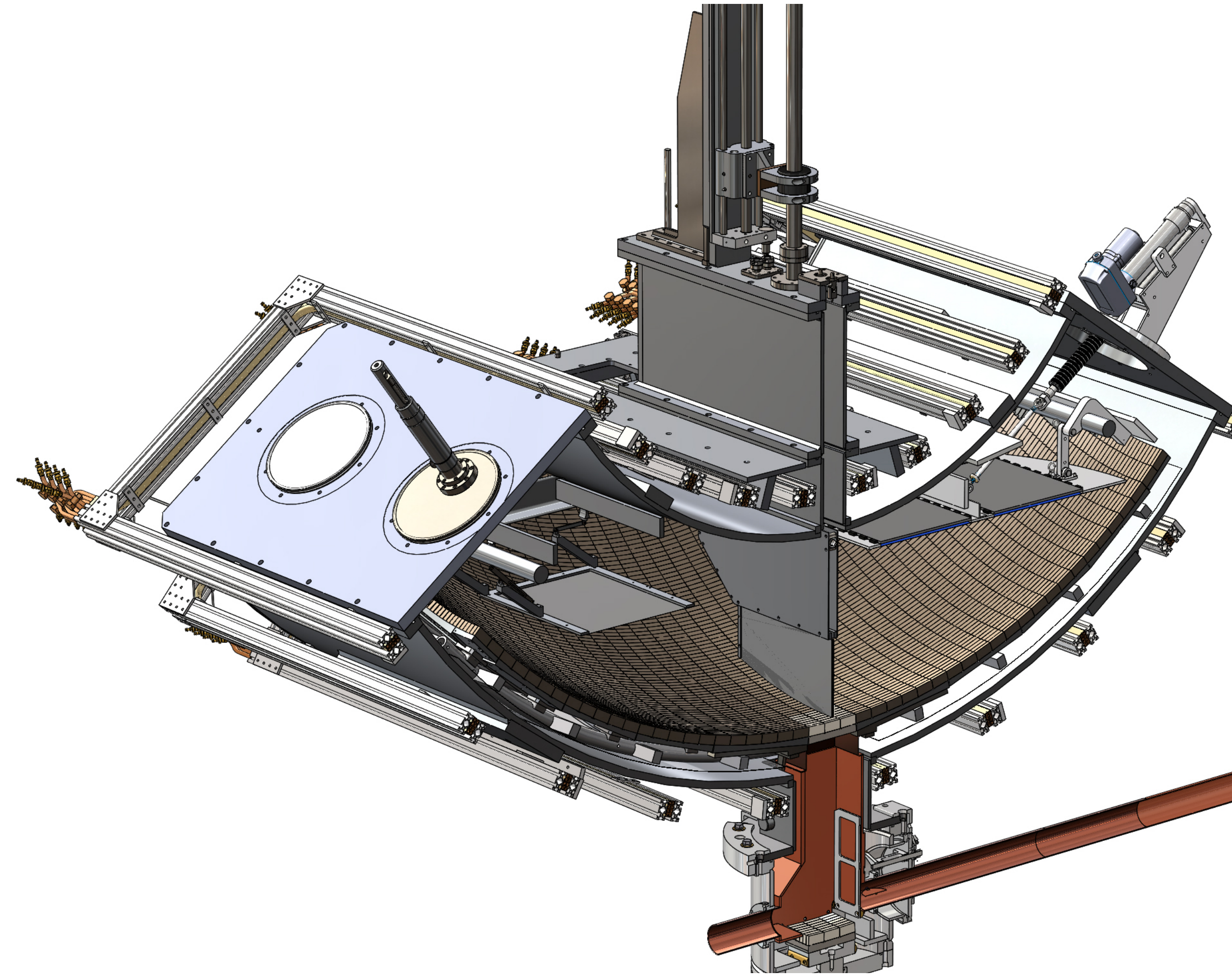


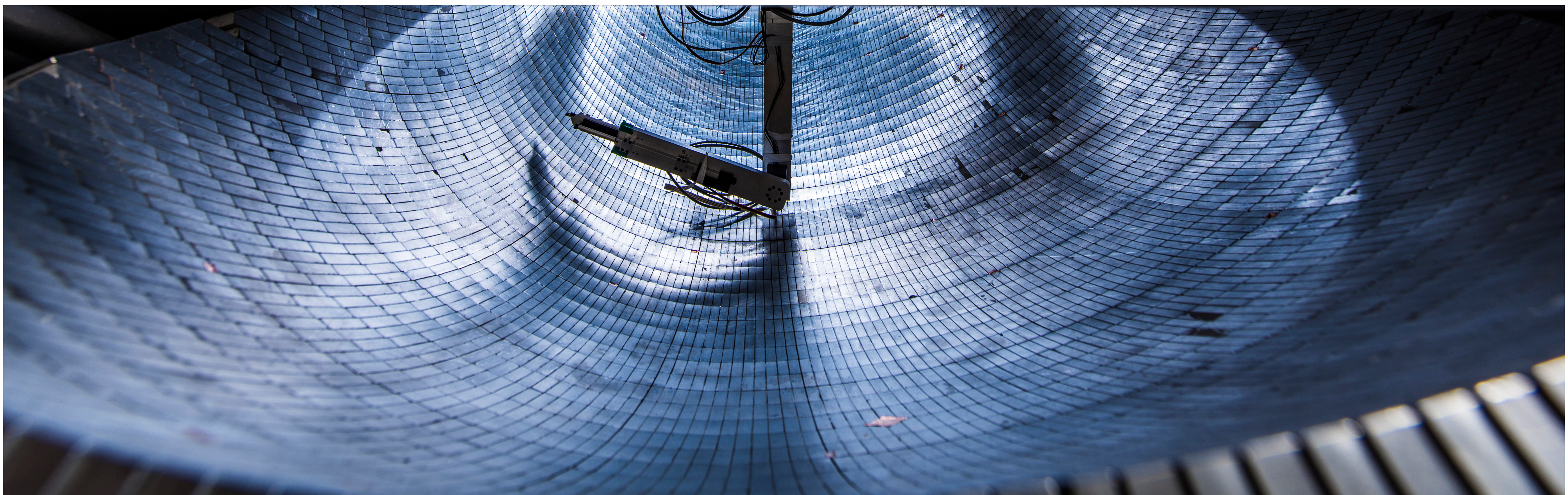
UCNτ: Halbach Array



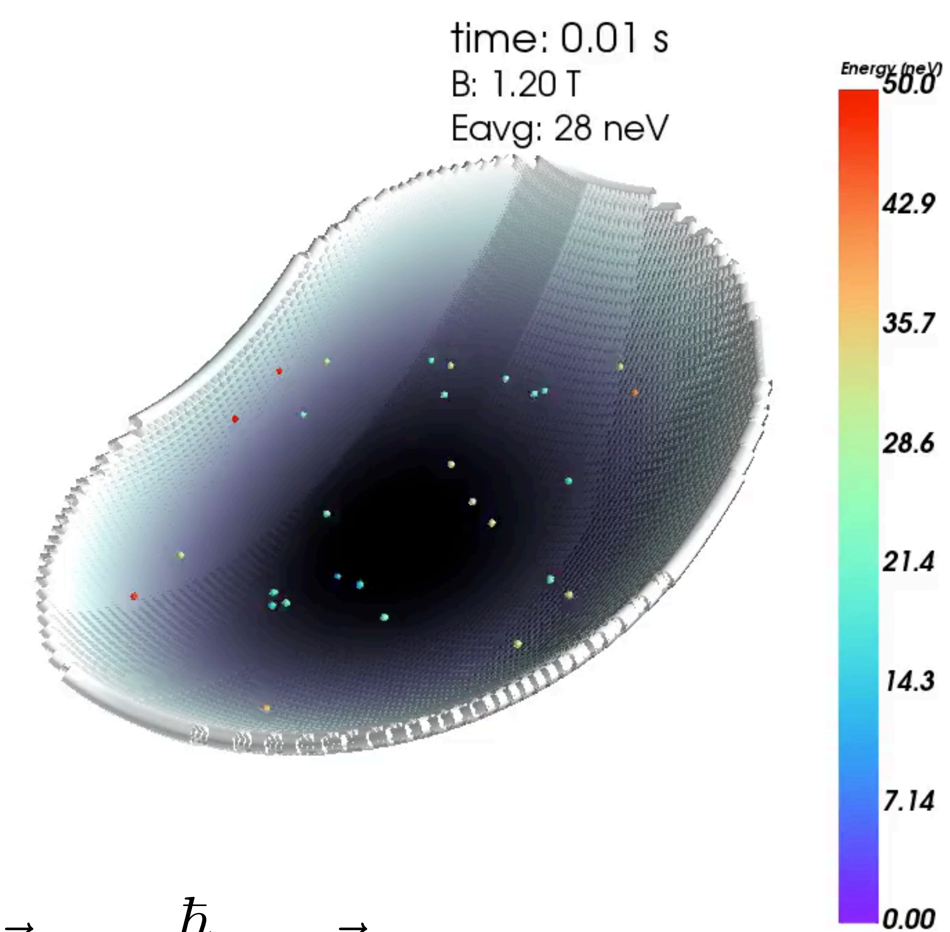


$$\vec{F} = \pm\frac{\hbar}{2}|\gamma_n|\vec{\nabla}|B| - m_n g$$

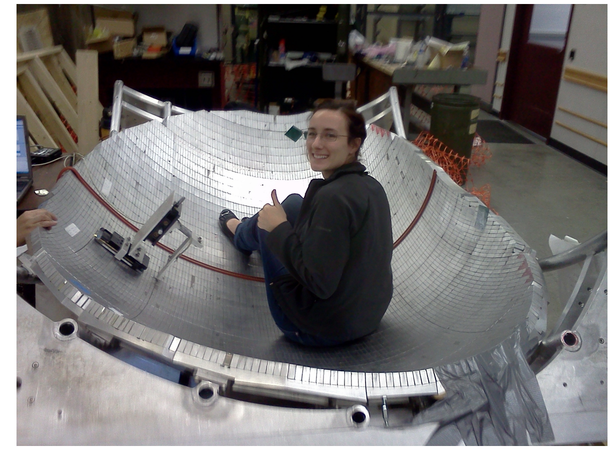


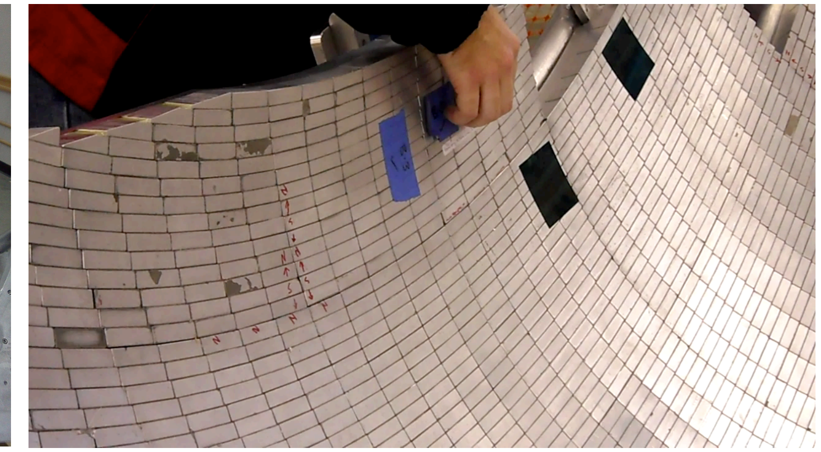


UCNτ: Halbach Array

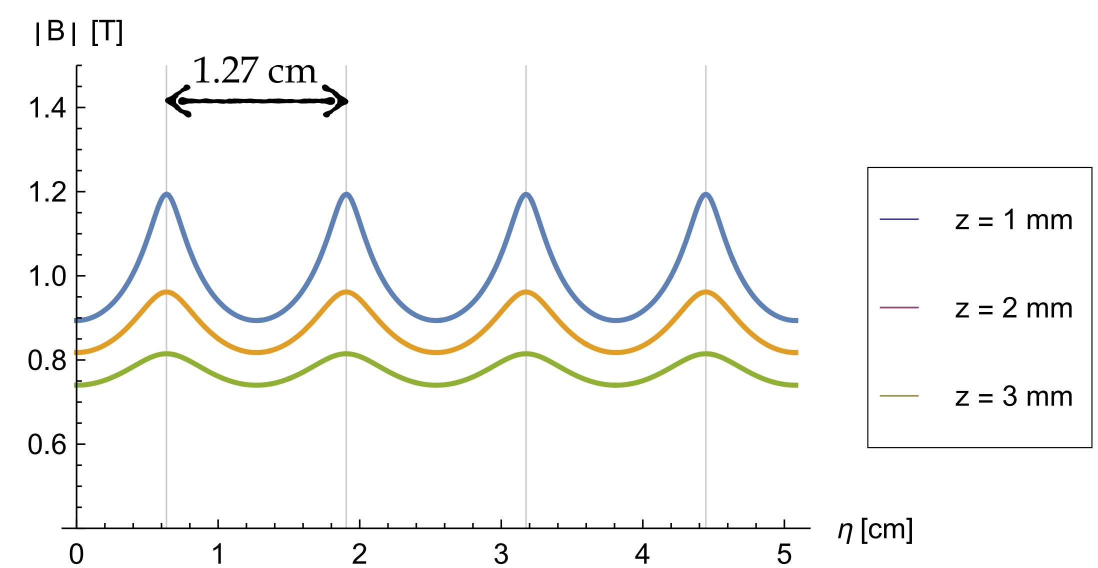


$$\vec{F} = \pm\frac{\hbar}{2}|\gamma_n|\vec{\nabla}|B| - m_n g$$





Discrete Halbach Field Magnitude.
Vertical Lines are magnet edges.

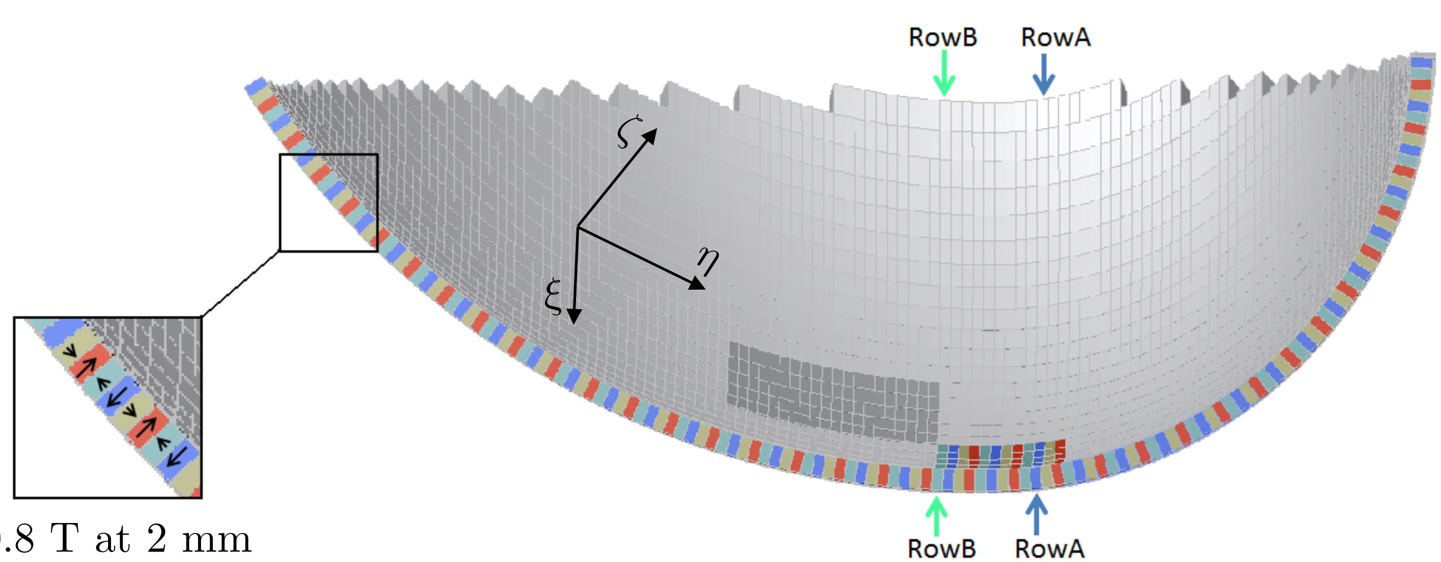


$$\vec{B} = \frac{4B_{\text{rem}}}{\pi\sqrt{2}}\sum_{n=1}^{\infty}\frac{(-1)^{n-1}}{4n-3}(1-e^{-k_n d})e^{-k_n\zeta}\left[\sin(k_n\eta)\,\hat{\eta} + \cos(k_n\eta)\,\hat{\zeta}\right] + B_0\frac{a+R}{\rho}\hat{\xi}$$

Halbach Field

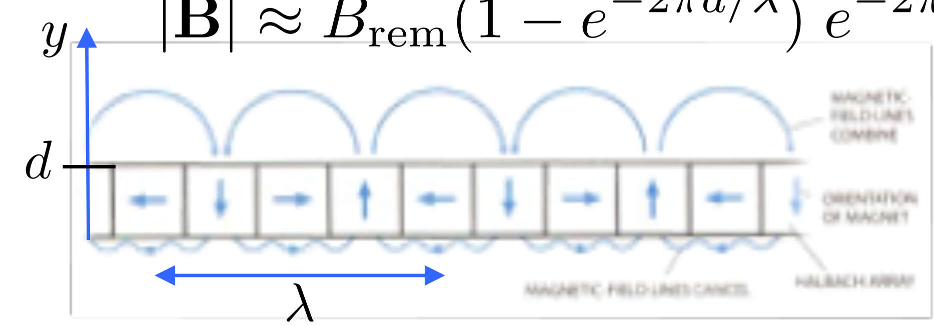
Holding Field

P. L. Walstrom, et al., NIMA, 599 (2009)



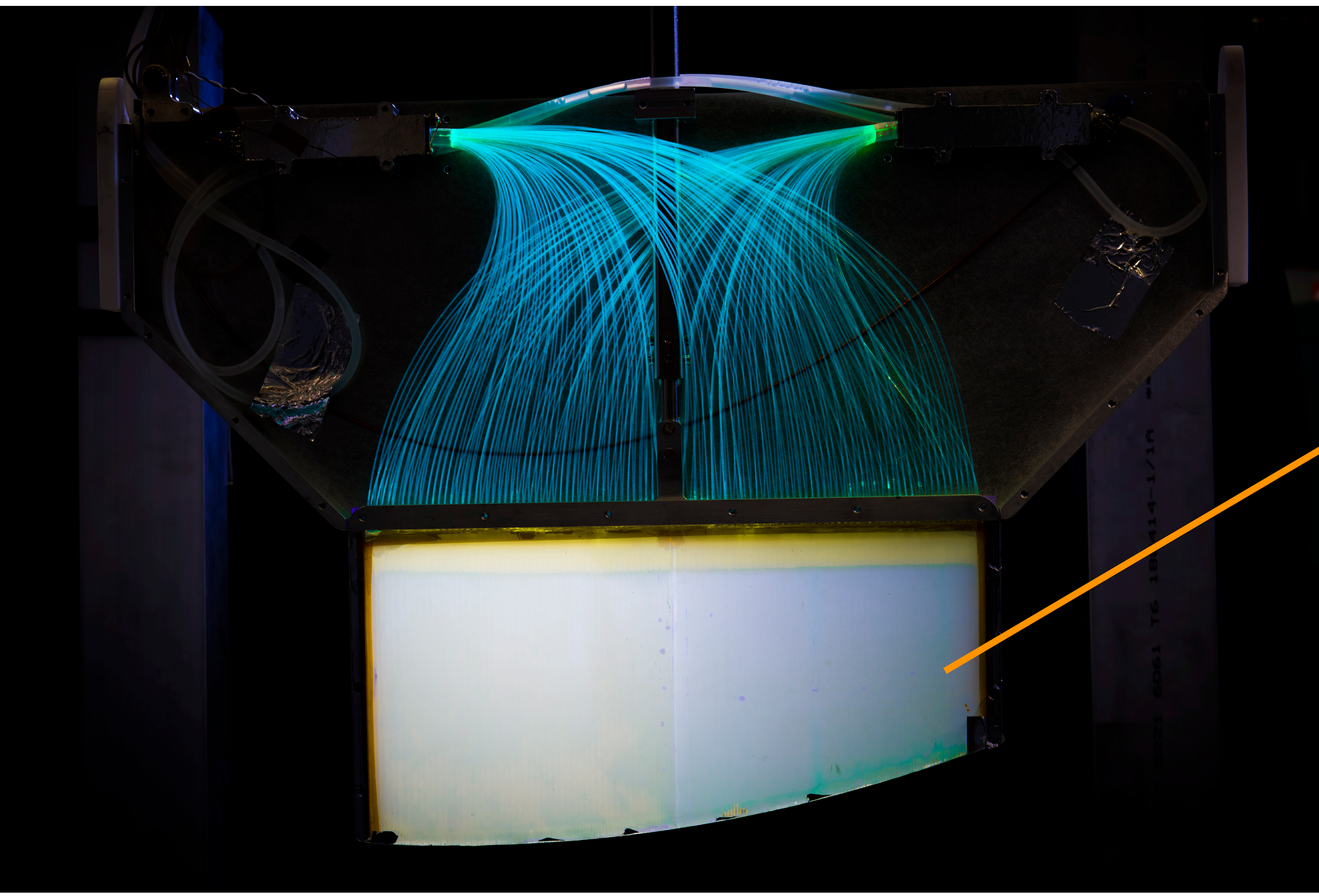
~ 0.8 T at 2 mm

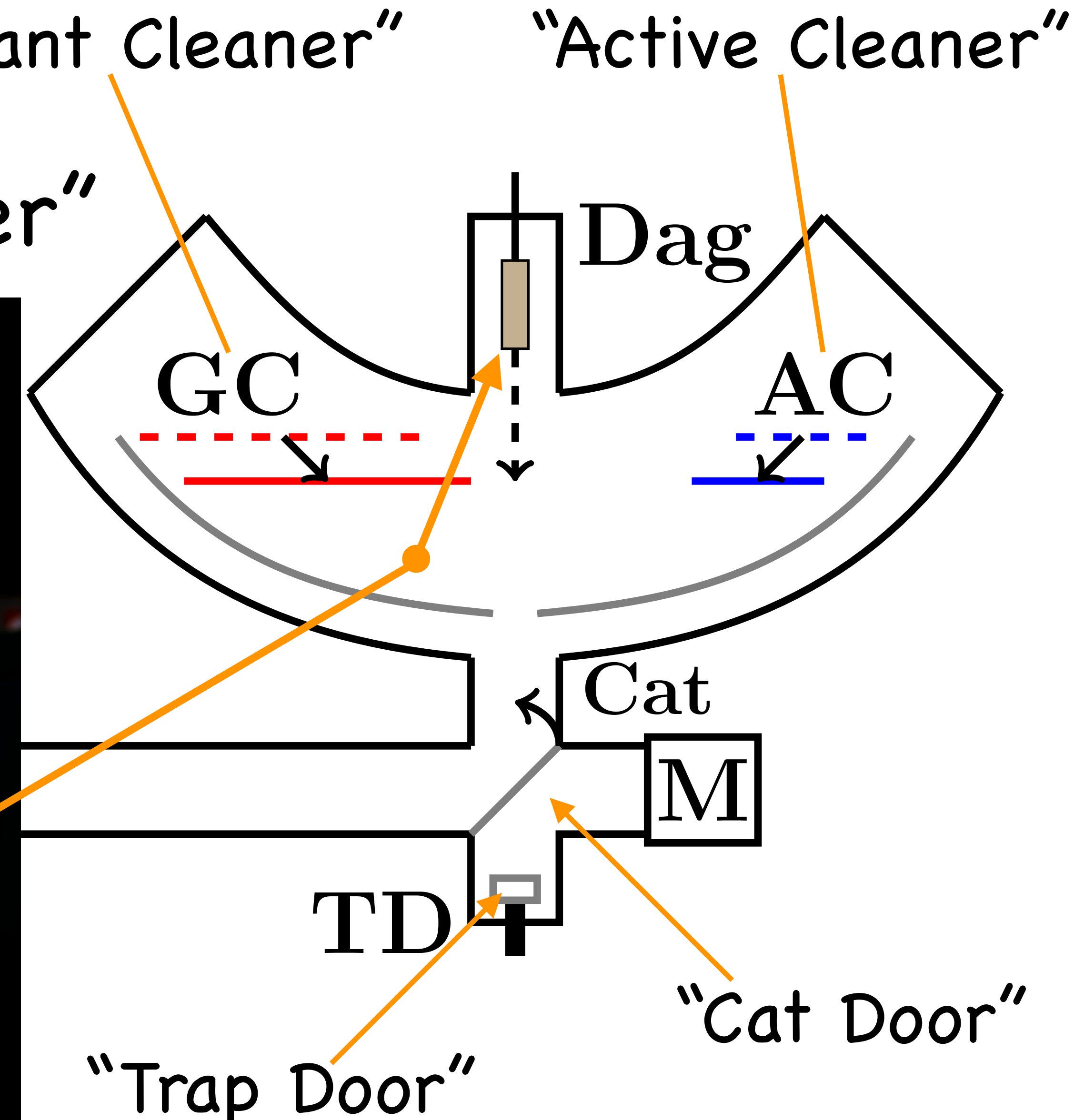
$$|\mathbf{B}| \approx B_{\text{rem}}(1 - e^{-2\pi d/\lambda})\; e^{-2\pi y/\lambda}$$



UCNτ: "Dagger" Detector

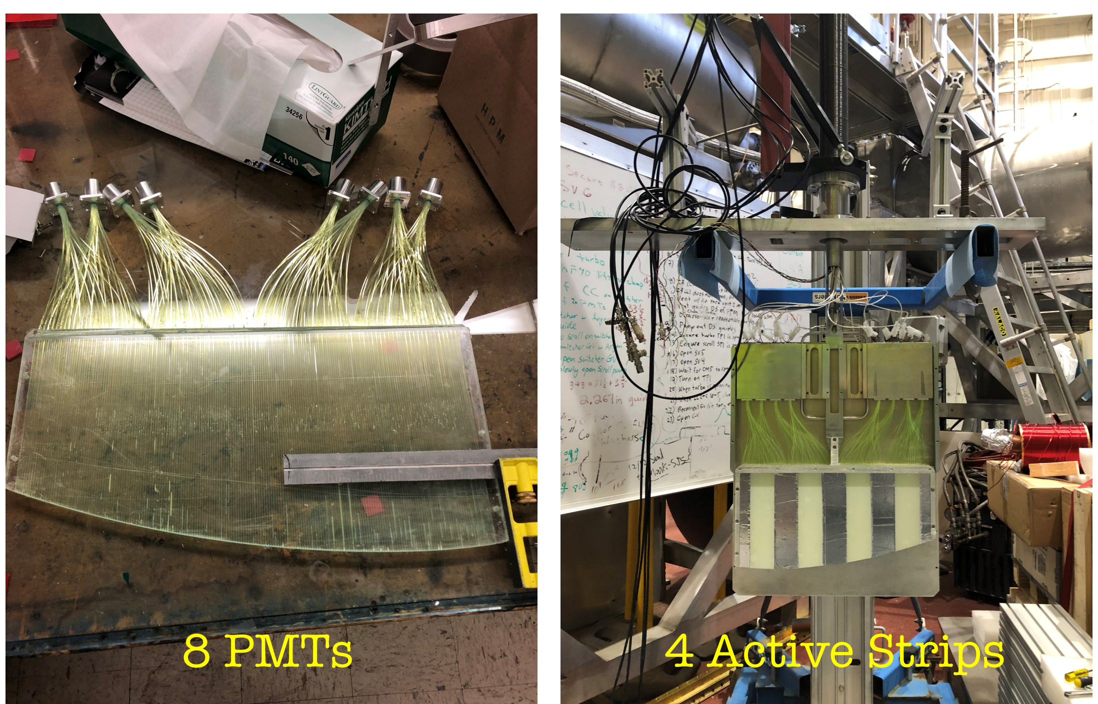
Neutron Detector, a.k.a the "Dagger"



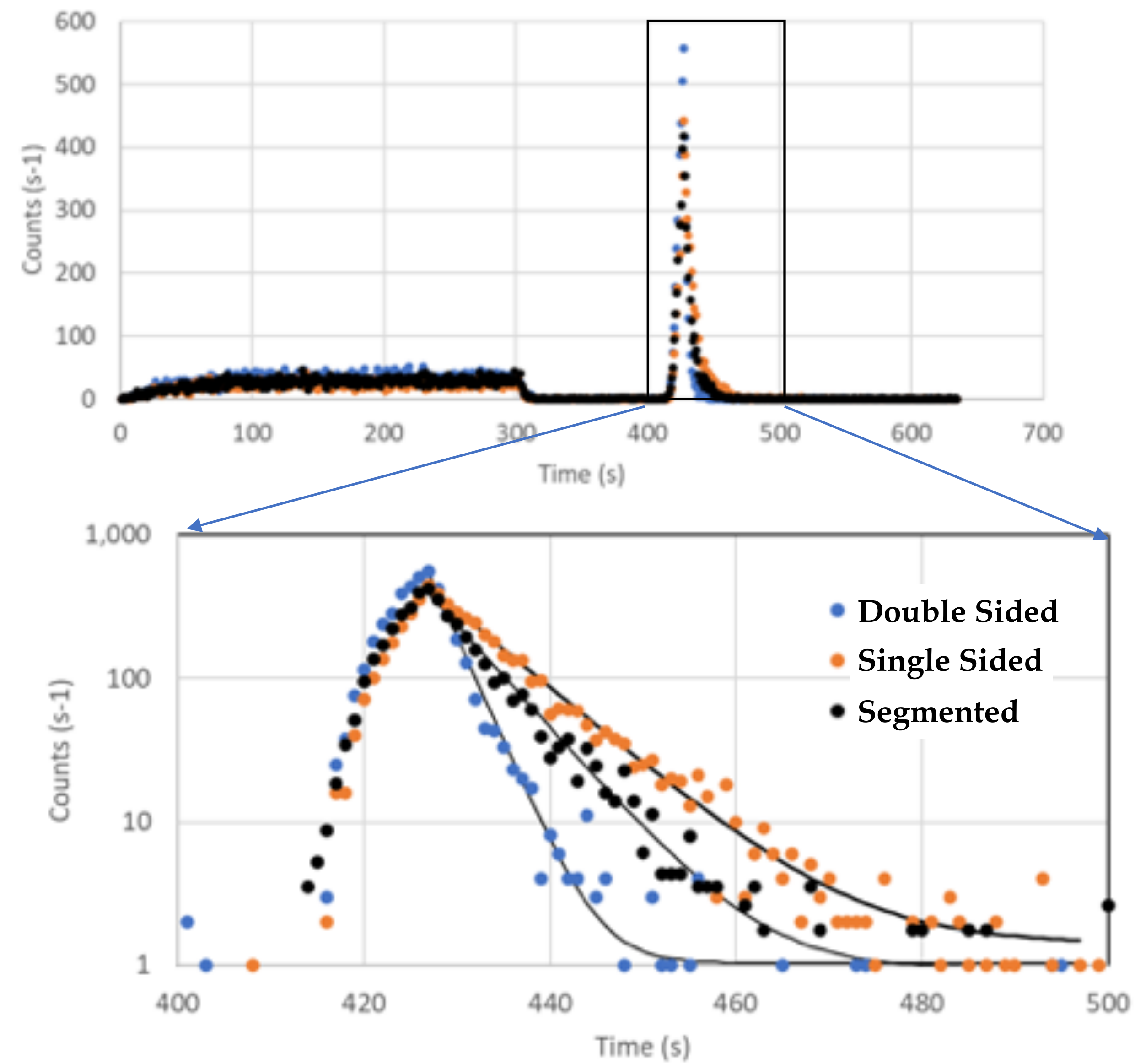


UCNτ: “Dagger” Detector

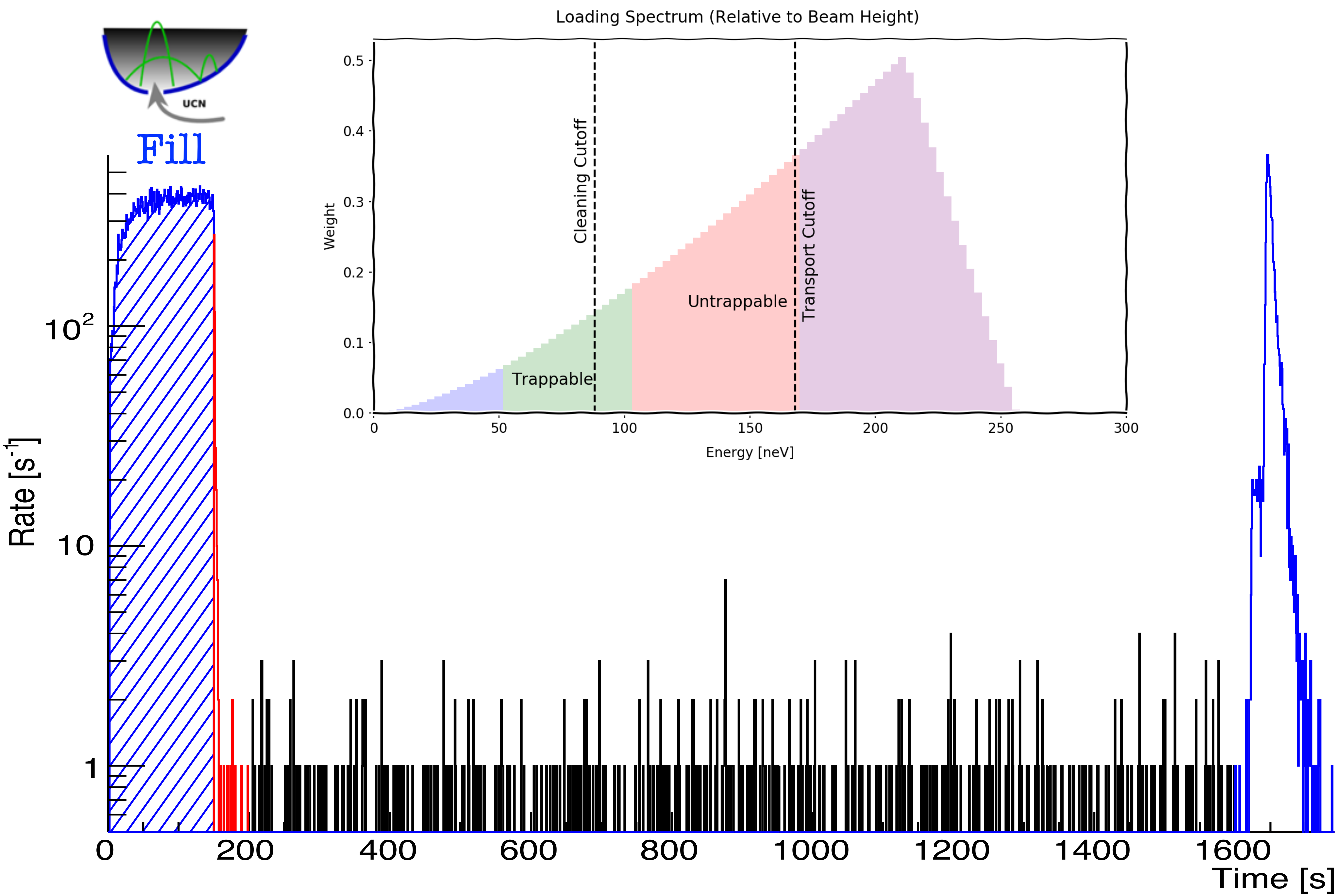
Single Sided



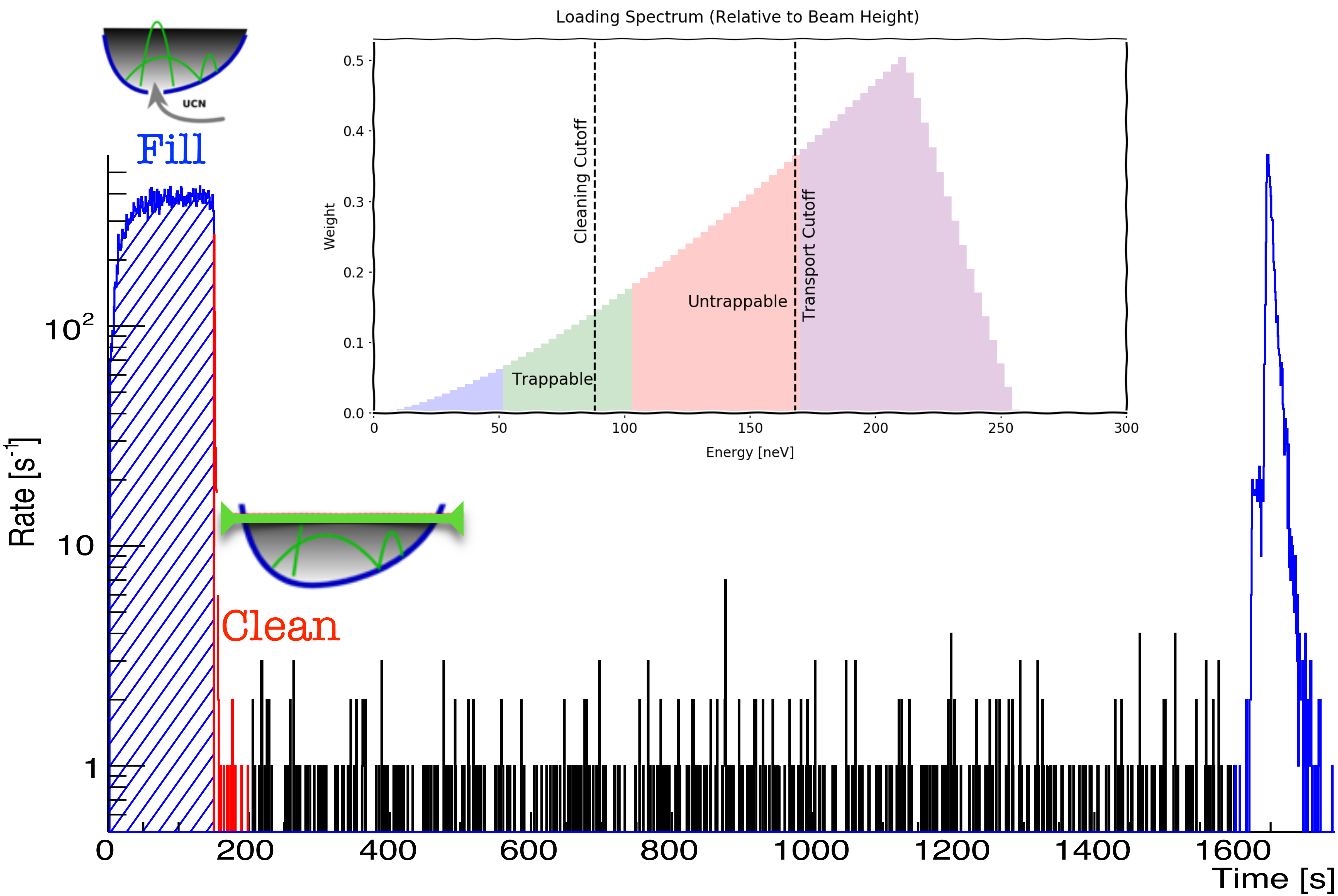
Segmented



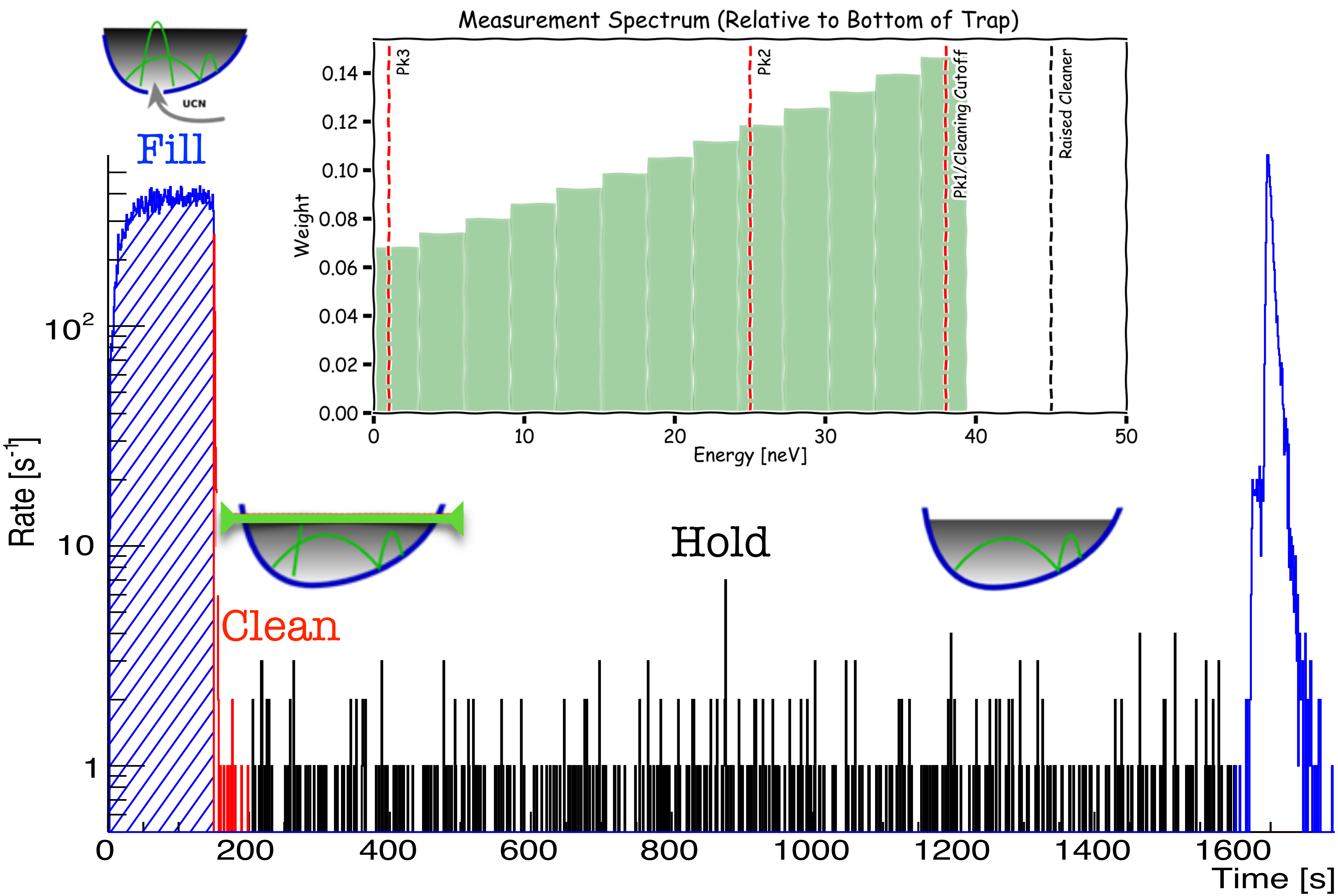
UCNτ: Measurement Cycle



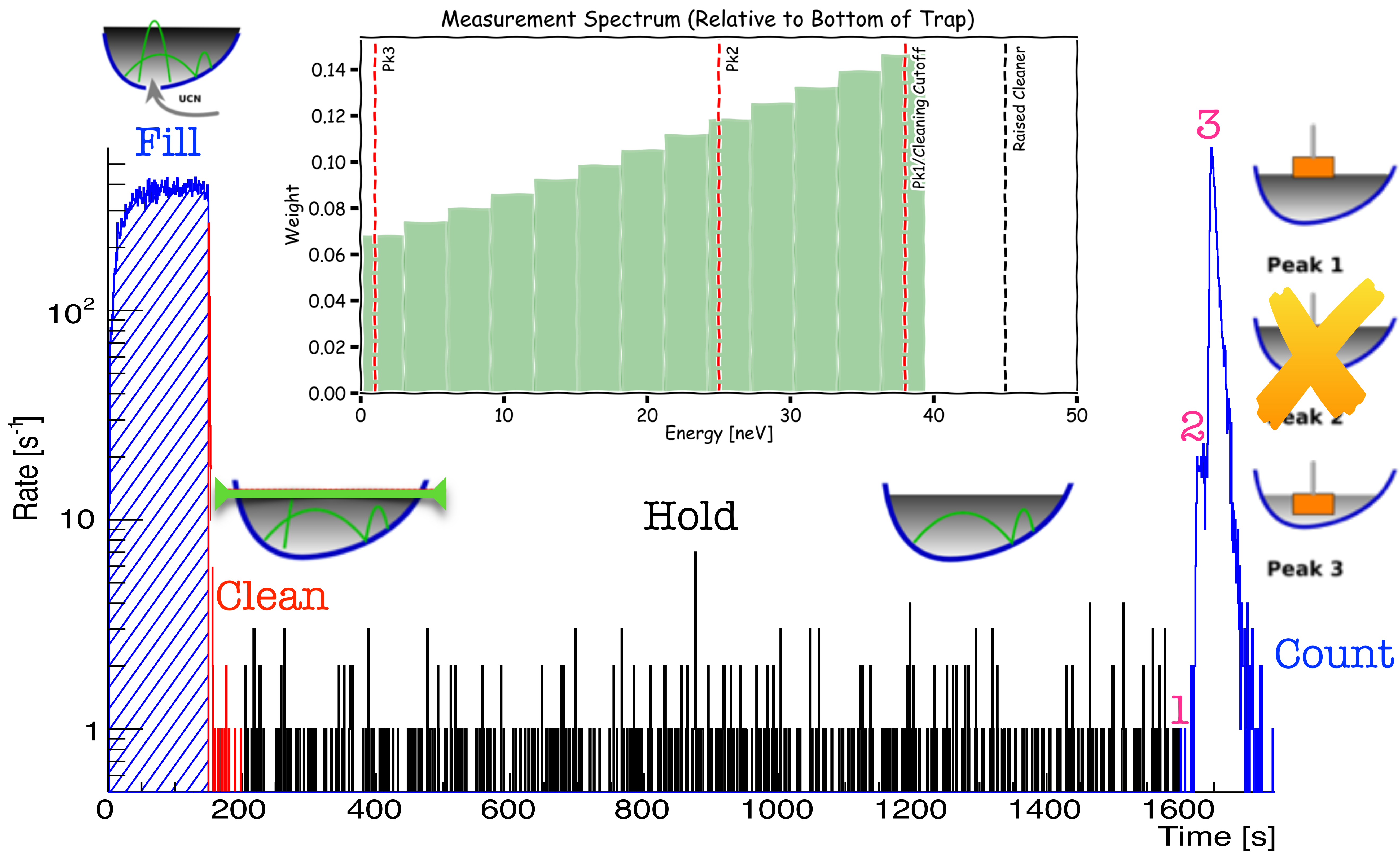
UCNτ: Measurement Cycle



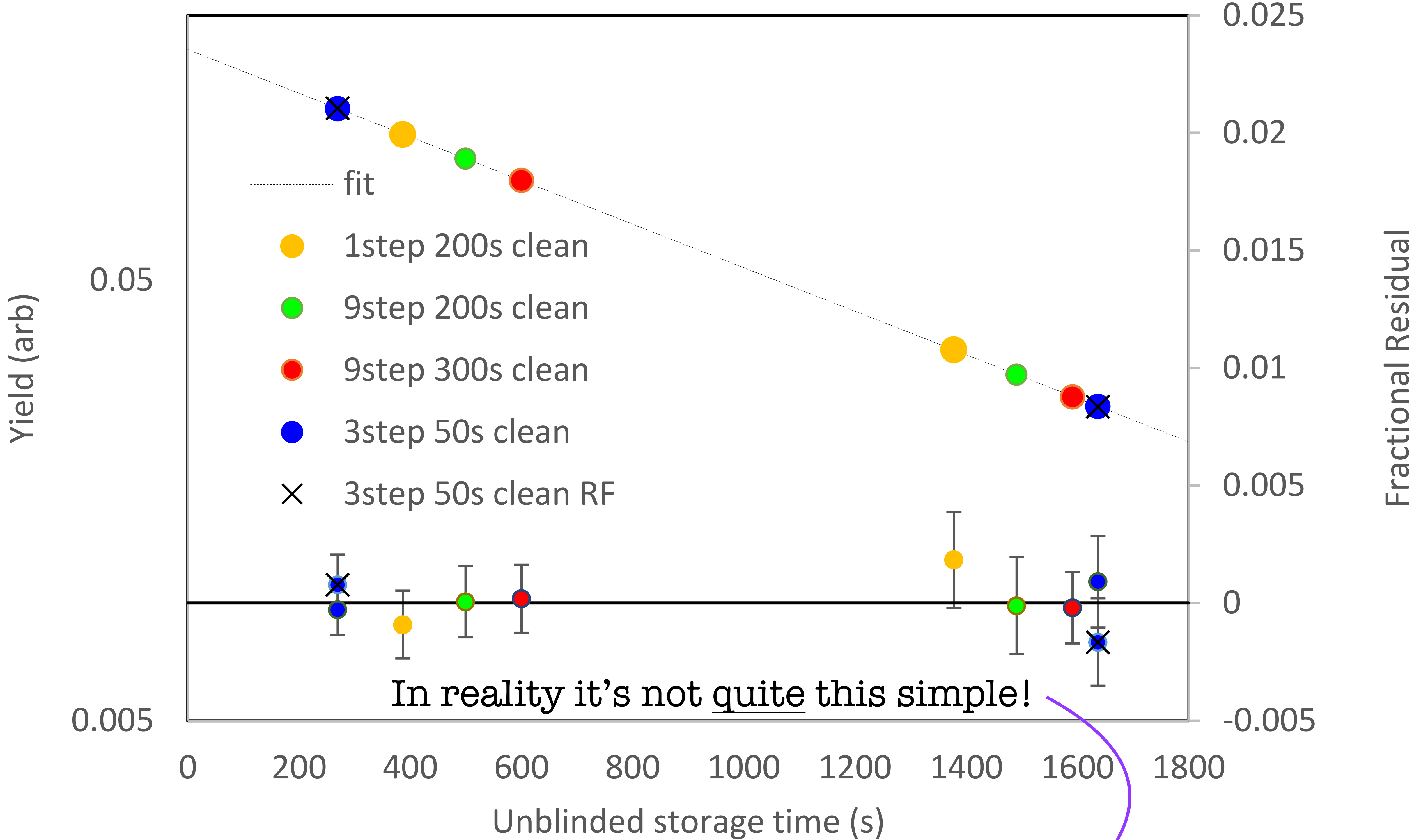
UCNτ: Measurement Cycle

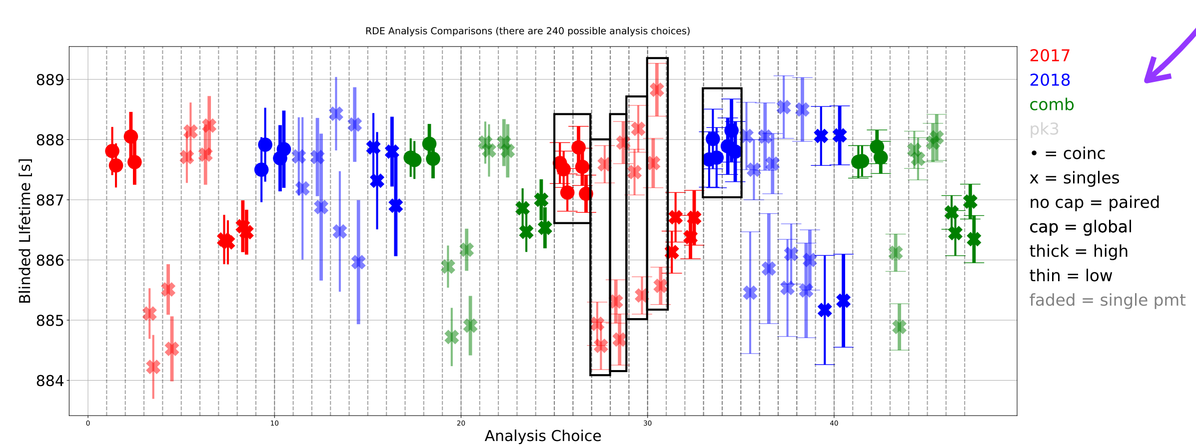


UCNτ: Measurement Cycle



Neutron Lifetime



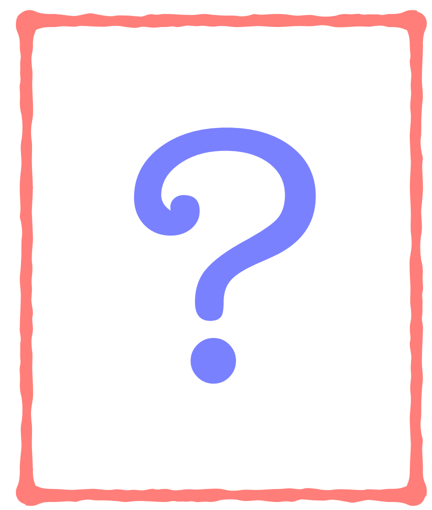


UCNτ: Systematic Effects

Non β-decay losses must be well-measured or have a small loss rate.

$$\left(\frac{\Delta\tau_n}{\tau_n}\right)_{\text{loss}} = \left(\frac{\tau_n}{\tau_{\text{loss}}}\right)\cdot\left(\frac{\Delta\tau_{\text{loss}}}{\tau_{\text{loss}}}\right)$$

Effect	**Direction**
Normalization	
Uncleaned UCNs	
Heated UCNs	
Depolarization	
Residual Gas Scattering	
Phase Space Evolution	



UCNτ: Systematic Effects

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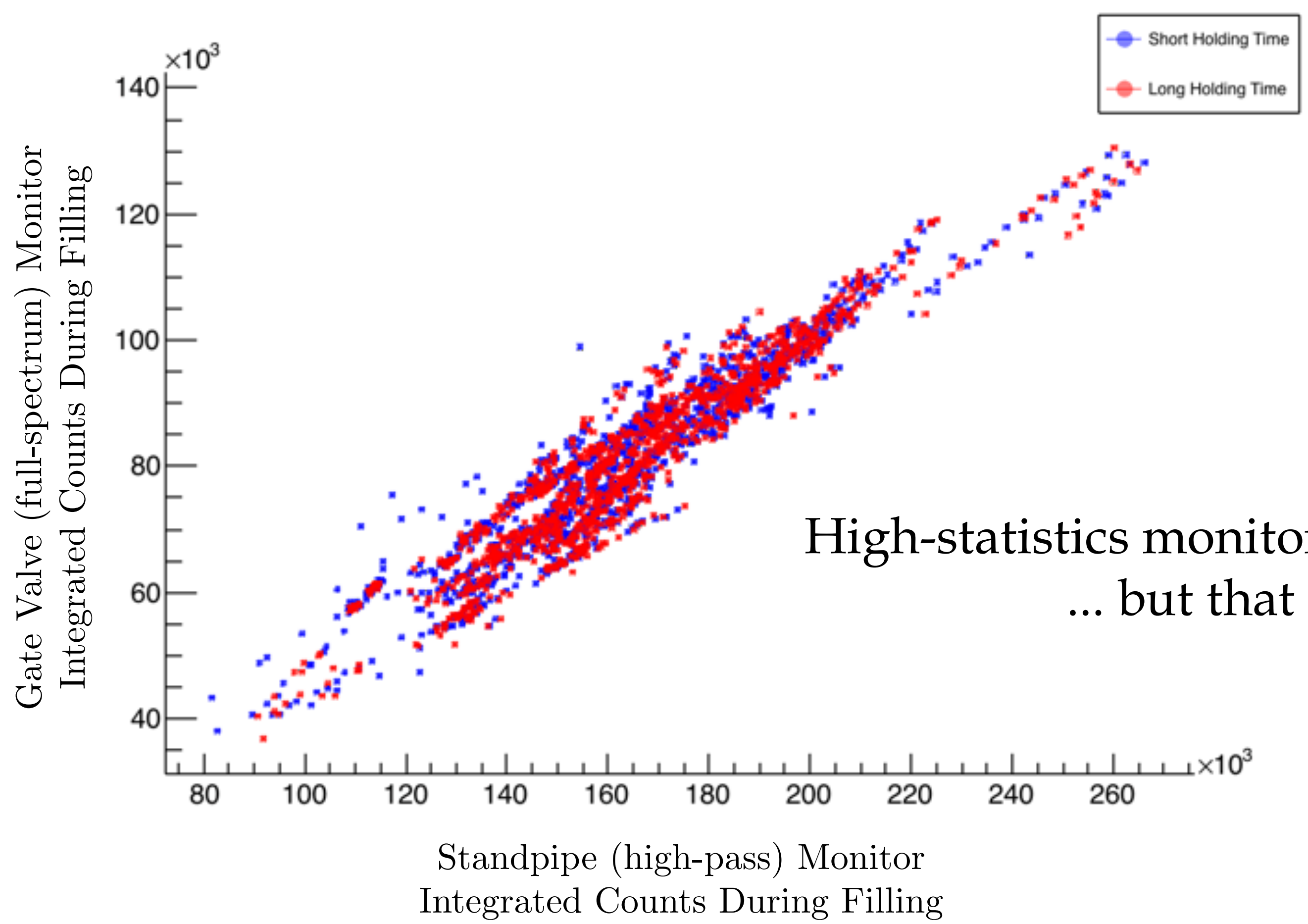
$$\left(\frac{\Delta\tau_n}{\tau_n}\right)_{\text{loss}} = \left(\frac{\tau_n}{\tau_{\text{loss}}}\right)\cdot\left(\frac{\Delta\tau_{\text{loss}}}{\tau_{\text{loss}}}\right)$$

Effect	Direction
Normalization	
Uncleaned UCNs	−
Heated UCNs	−
Depolarization	−
Residual Gas Scattering	−
Phase Space Evolution	

$$\frac{1}{\tau_{\text{n}}} = \frac{1}{\tau_{\text{trap}}} - \frac{1}{\tau_{\text{not }\beta}}$$



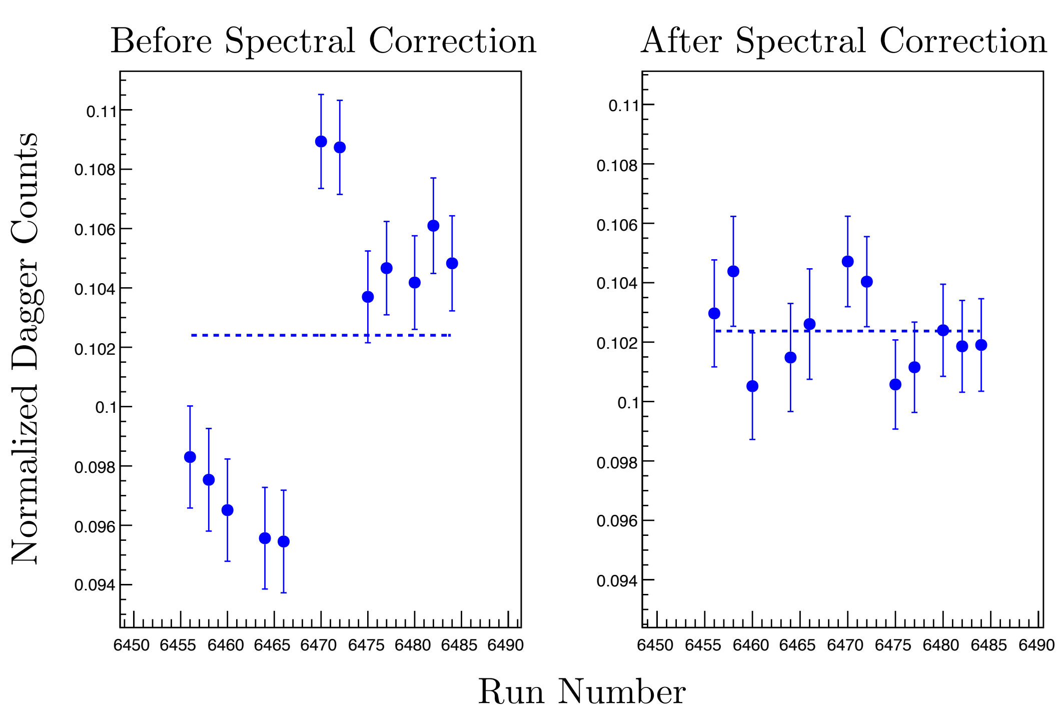
The bottle technique is a <u>relative</u> measurement, but normalization is necessary due to fluctuations in production.

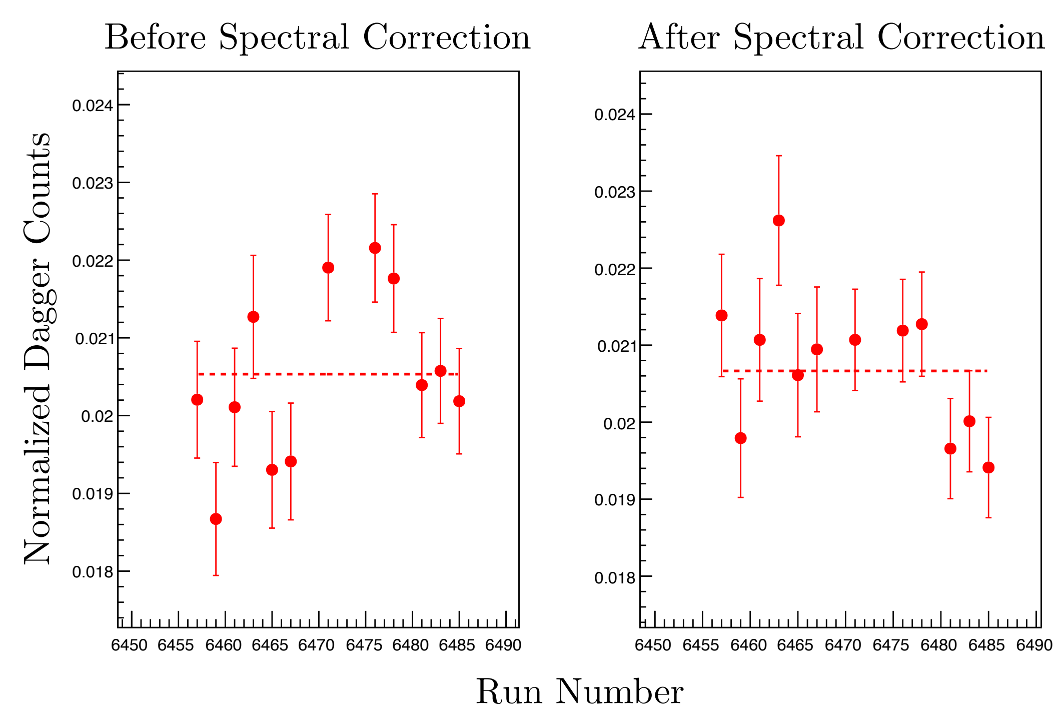
$$\frac{1}{\tau_{\mathrm{trap}}} = \frac{1}{T_{\mathrm{L}} - T_{\mathrm{S}}} \ln\left[\frac{N_{\mathrm{S}}}{N_{\mathrm{L}}}\frac{\eta_{\mathrm{L}}}{\eta_{\mathrm{S}}}\right]$$

High-statistics monitor = High-pass monitor

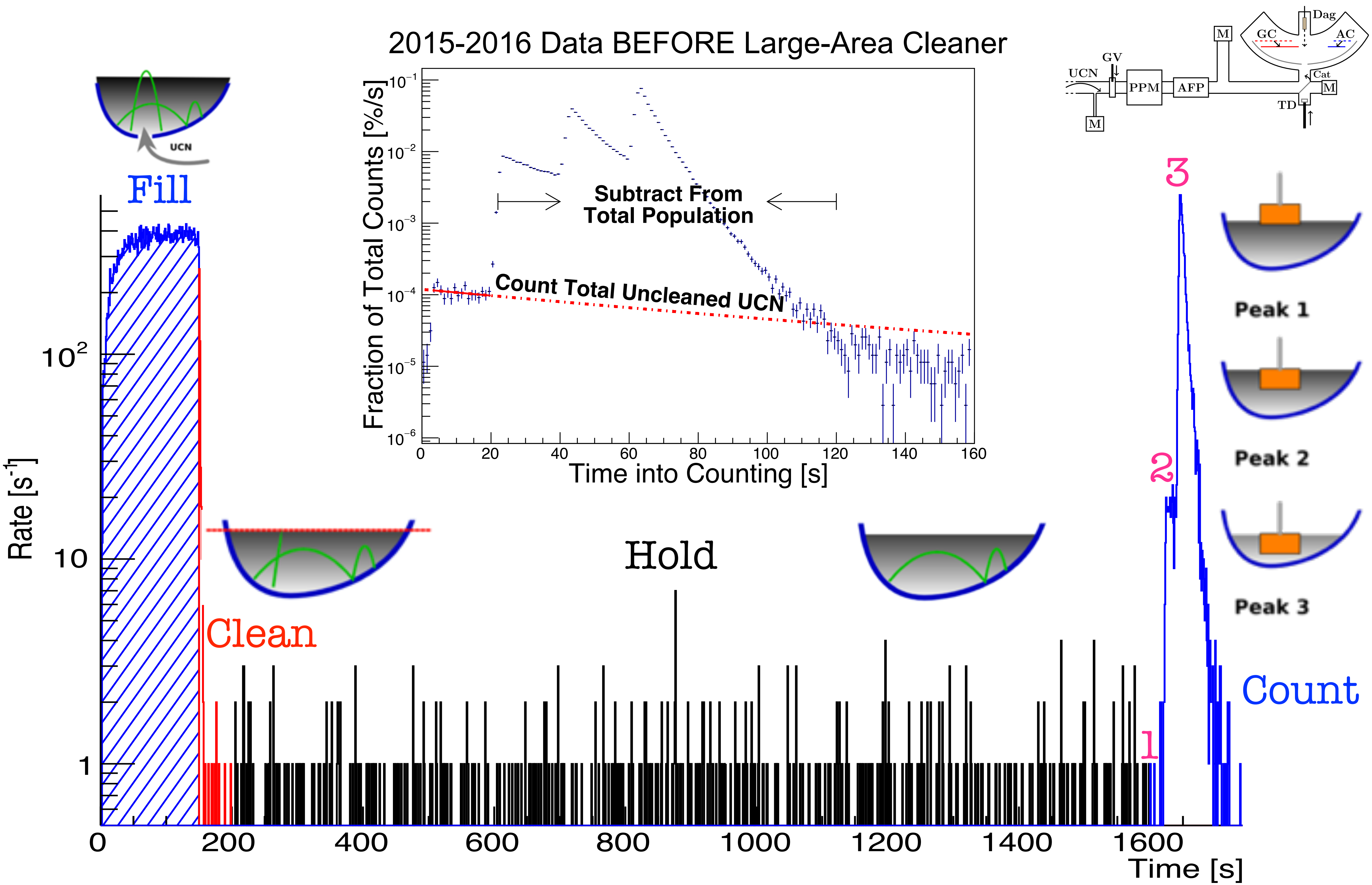
... but that requires corrections for spectral variations.

$$\hat{\eta} = [1 + \rho_{\mathrm{min}}(\overline{\sigma} - \sigma)] \times \int_0^{T_{\mathrm{load}}} \mathscr{D}_{\mathrm{sp}}\ \mathrm{d}t$$



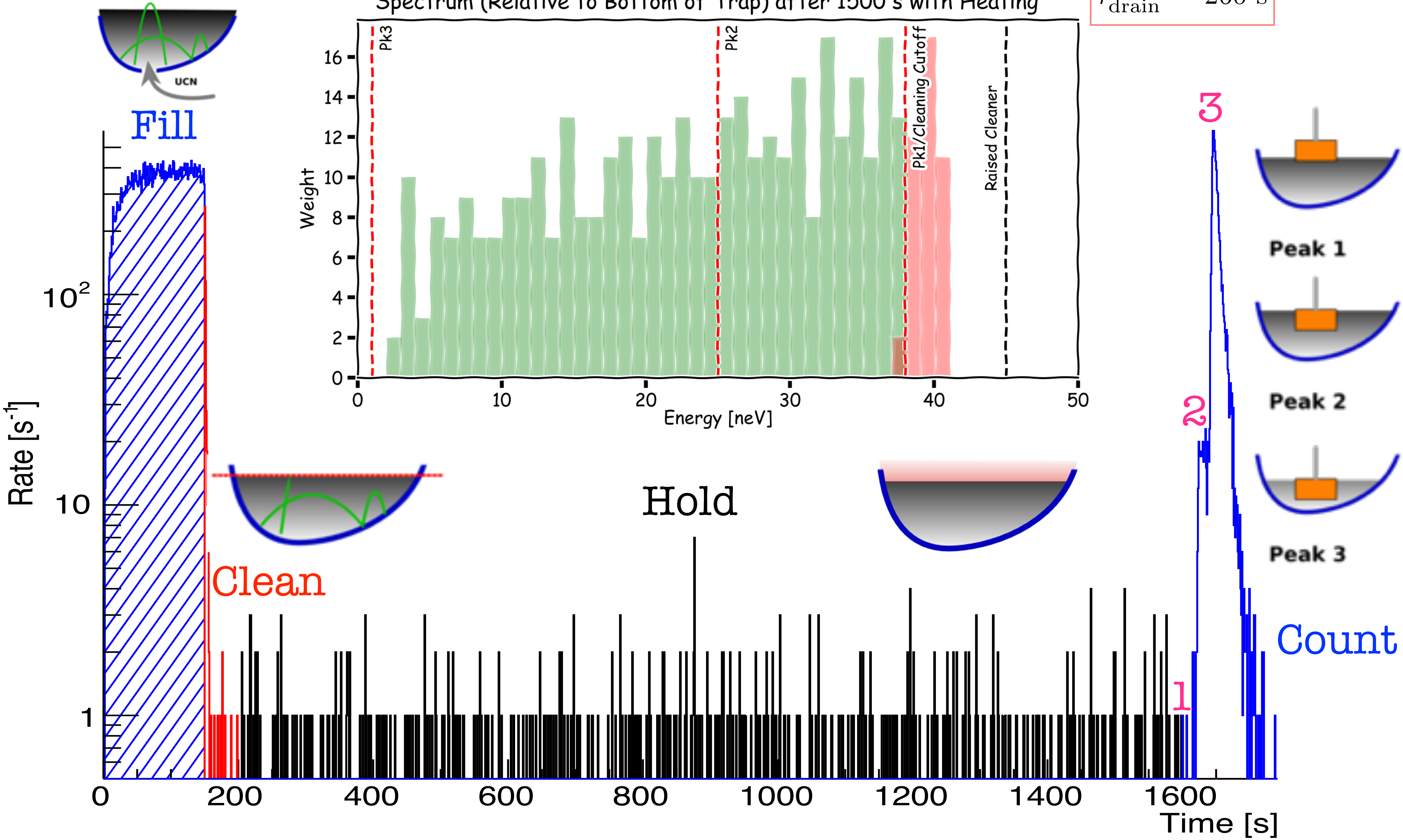


Systematics: Cleaning

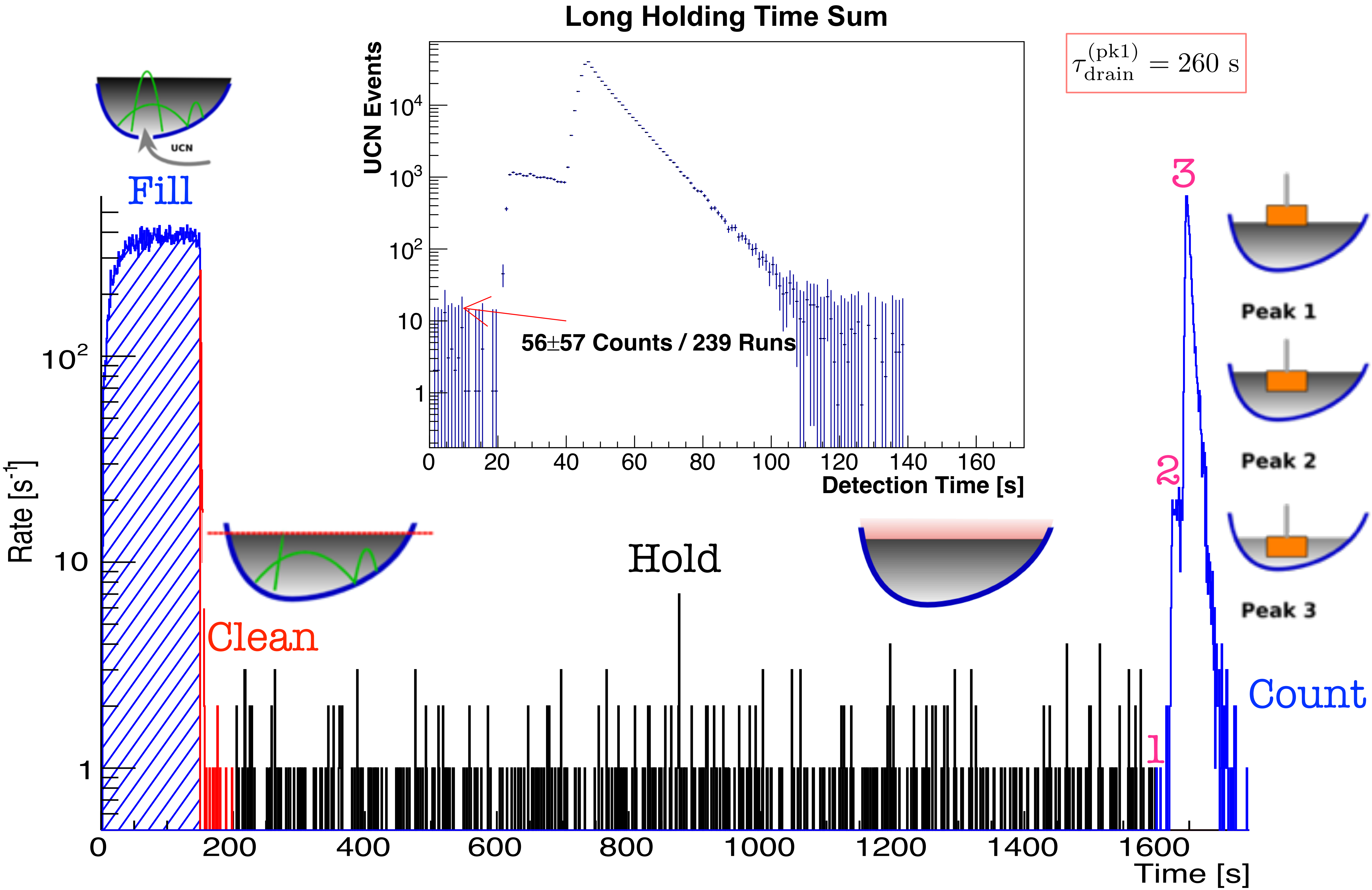


Systematics: Heating

$\tau_{\text{drain}}^{(\text{pk1})} = 260\ \text{s}$

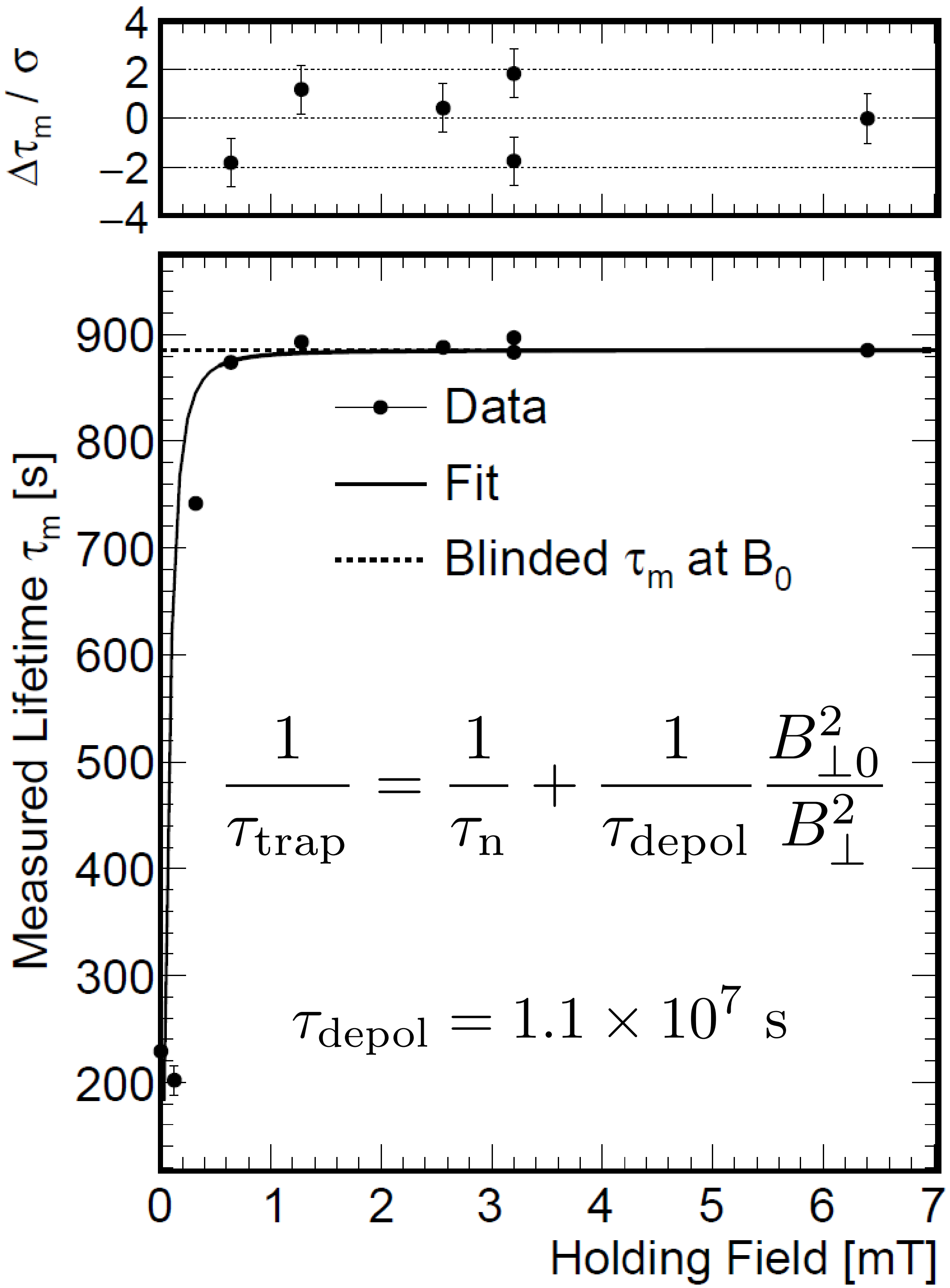


Systematics: Heating



Systematics: Depolarization

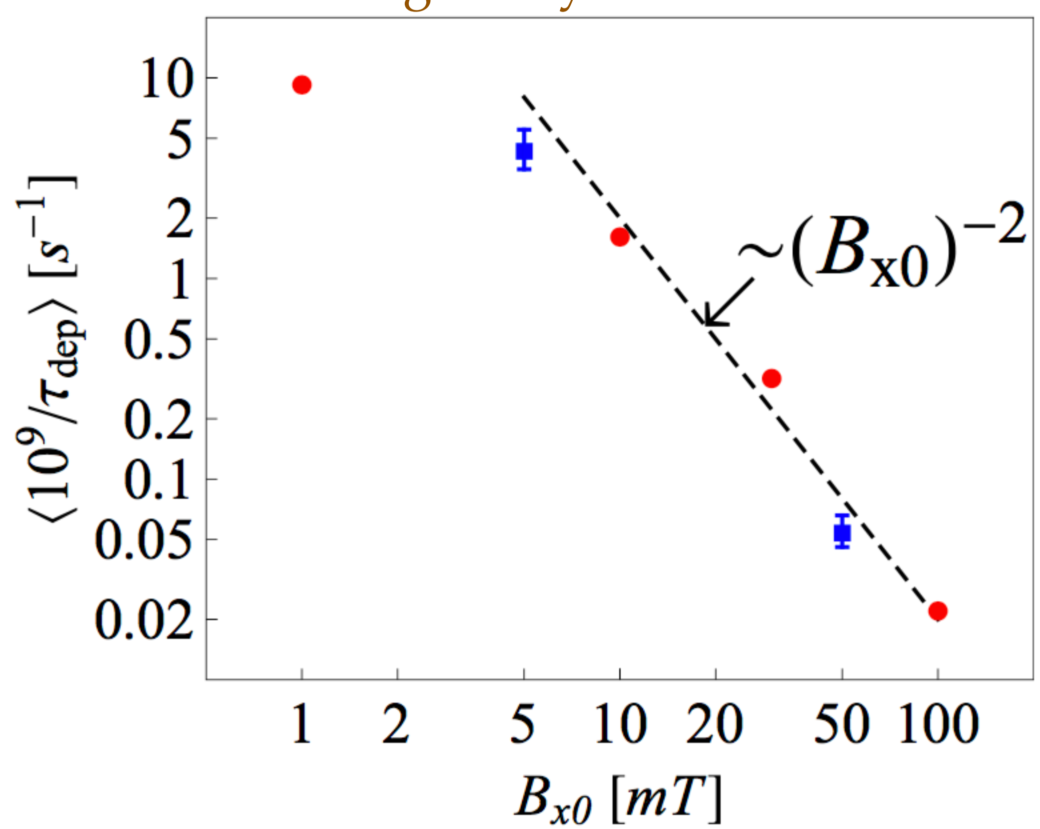
Effect	Correction	Uncertainty
UCN event definition	···	±0.13
Normalization weighting	···	±0.06
Depolarization	···	+0.07
Uncleaned UCNs	···	+0.11
Heated UCNs	···	+0.08
~~Al block~~	~~+0.06~~	~~±0.05~~
Residual gas scattering	+0.11	±0.06
Uncorrelated sum	$0.17^{+0.22}_{-0.16}$ s	



Three things to check:

1. Where to assess spin flip probability.
2. Scaling behavior at low holding field.
3. Ideal vs. actual magnetic field.

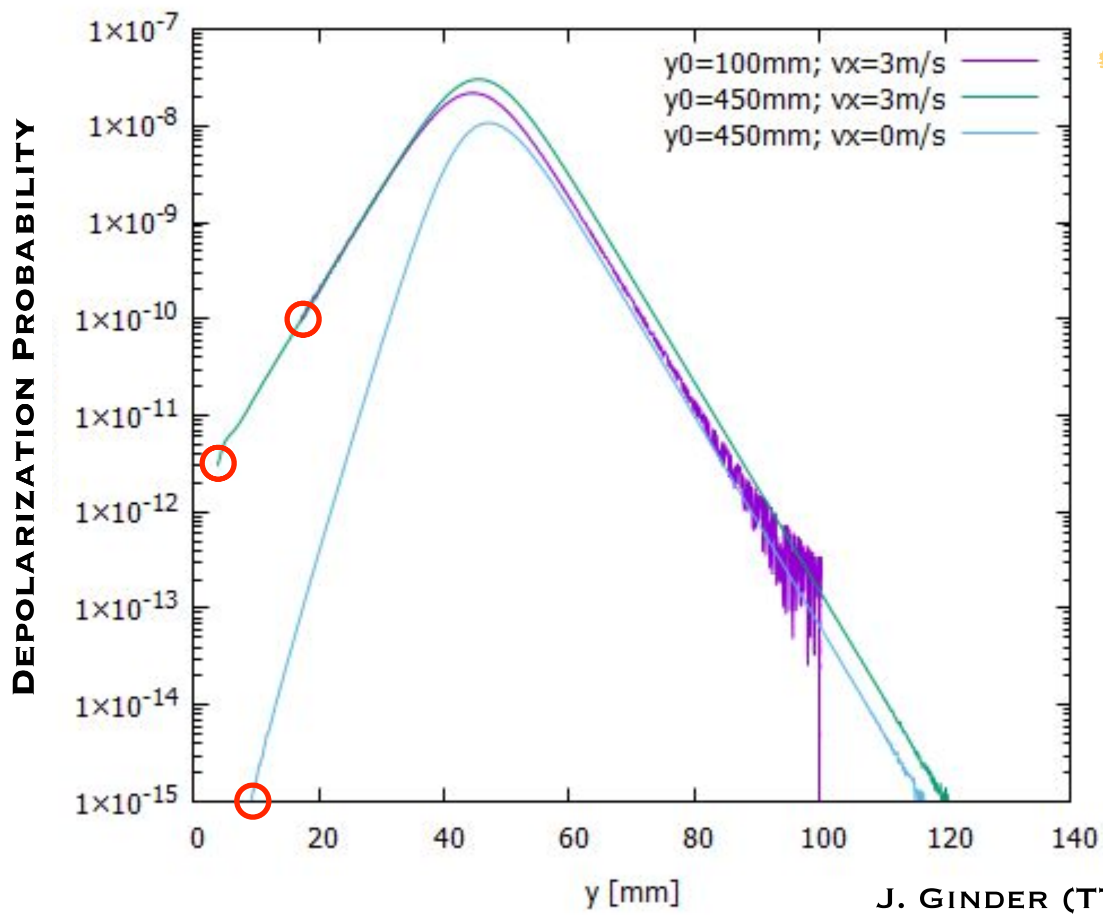
Using Analytic Field Profile



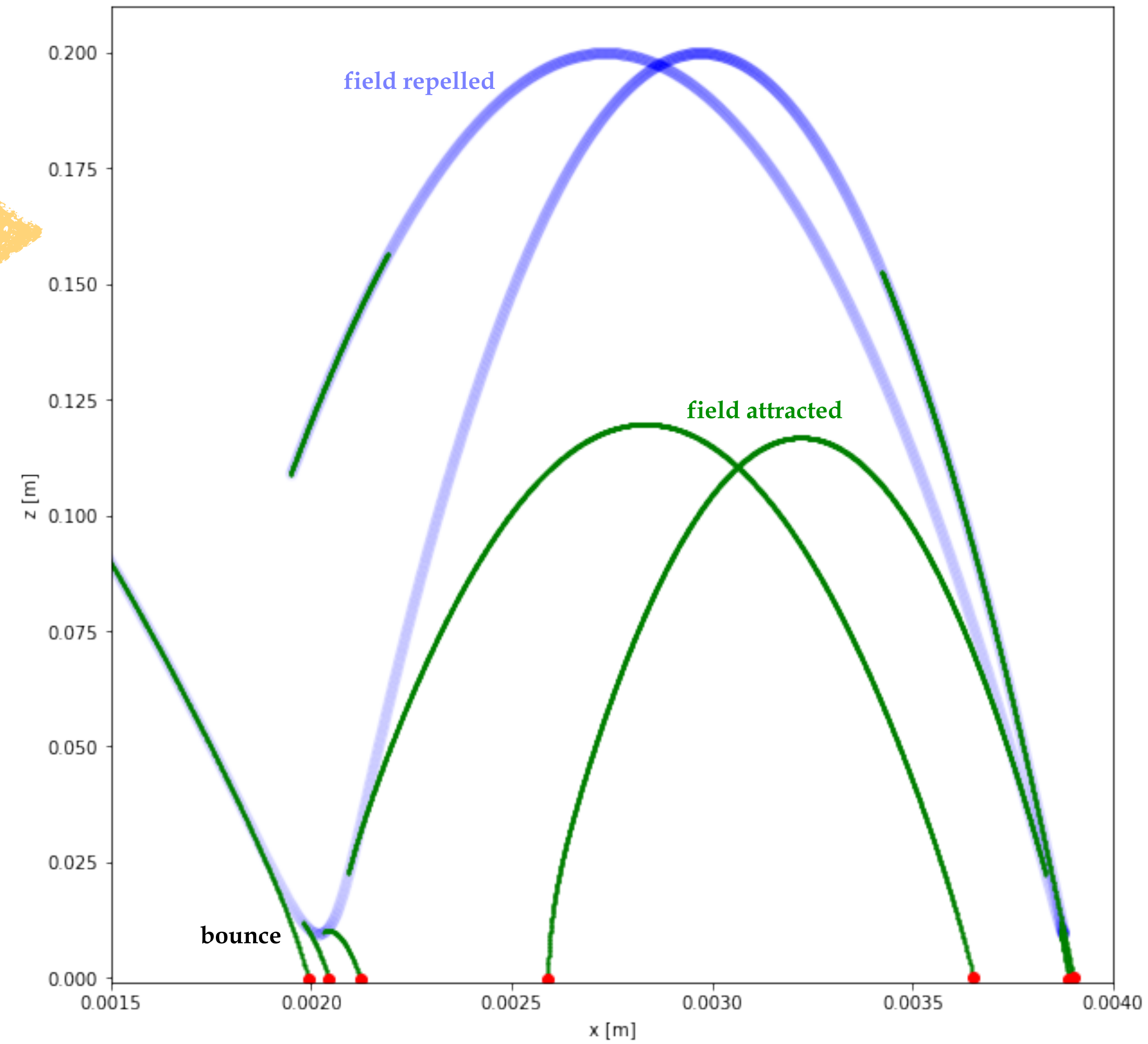
A. Steyerl et al, Phys Rev C 95 (2017)

Systematics: Depolarization

3D Spin Dynamics MC Simulation
Semiclassical Split Symplectic/RK45 (space/Bloch)

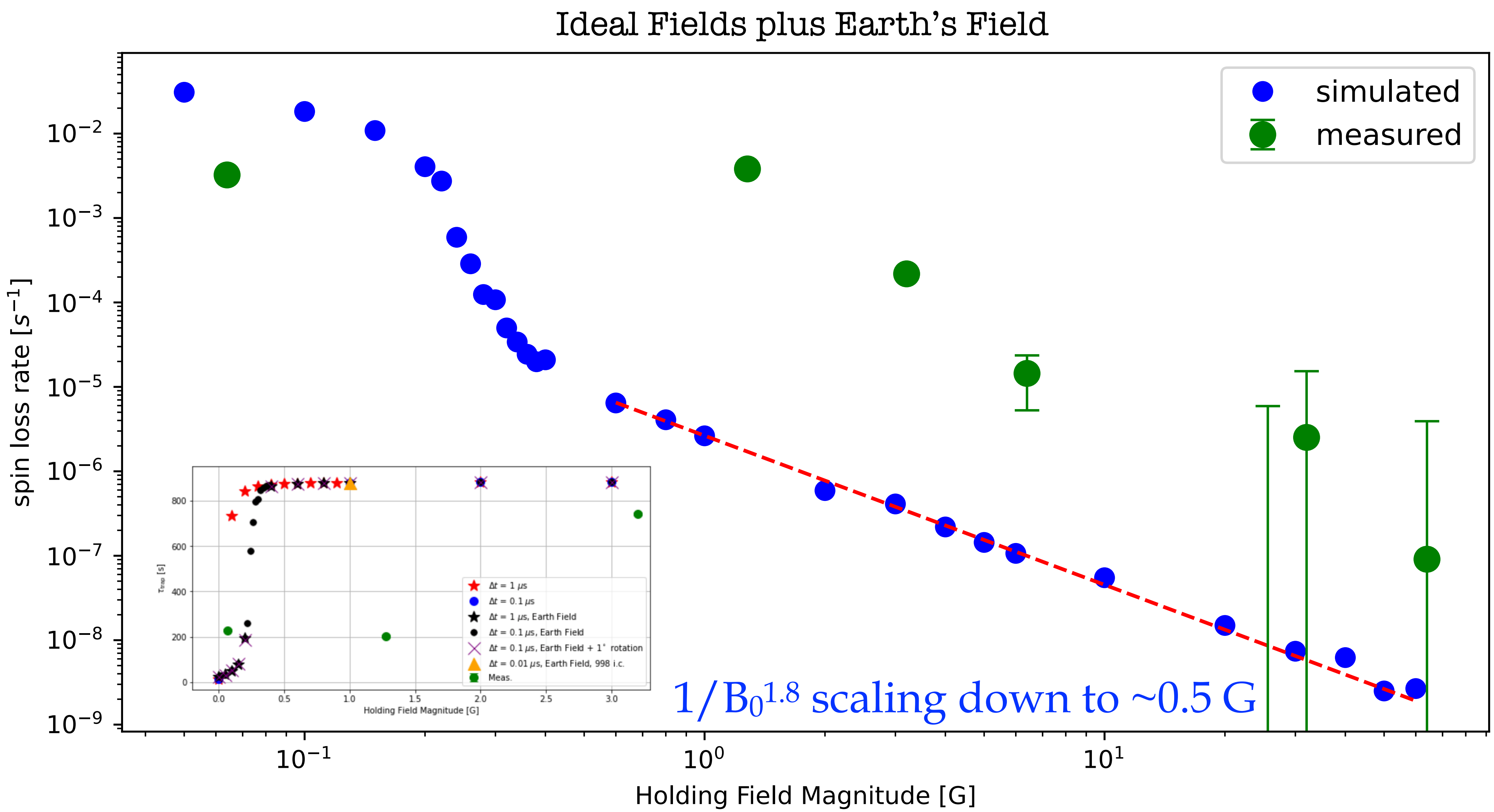


J. Ginder (TTU)



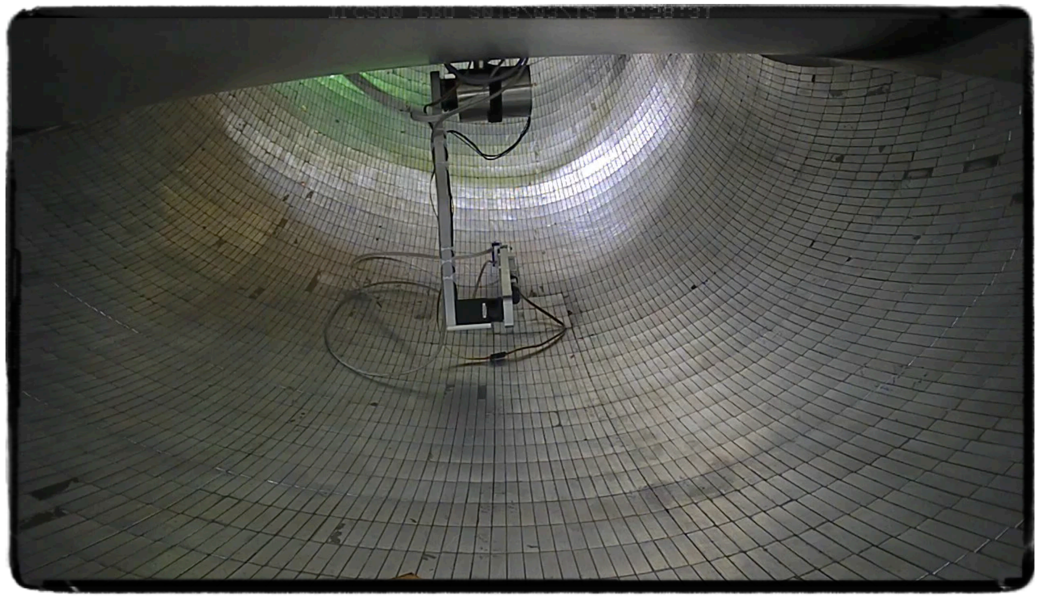
Dual Tracking Semiclassical Split Symplectic/Unitary (space/spinor) with adaptive spin stepper:

- Initialize two spinors X_{lfs} and X_{hfs} as spin up along local field direction.
- X_{lfs} is tracked using field-repelled component and X_{hfs} is tracked using the field-attracted component.
- Assume rapid decoherence of spatial entanglement. When the field-attracted spinor encounters the array, find $P_+ = |\langle X+|X_{lfs}\rangle|^2$ and $P_- = |\langle X-|X_{hfs}\rangle|^2$. Reset both spinors as spin up.
- Accrue the loss fraction for each reset over the course of the simulation.
- Average loss rate is determined by averaging loss per bounce and bounces per second over many simulations with different initial conditions.
- For a single process with a 0.1 μs time step, 1 simulation second ~ 400 wall clock seconds.

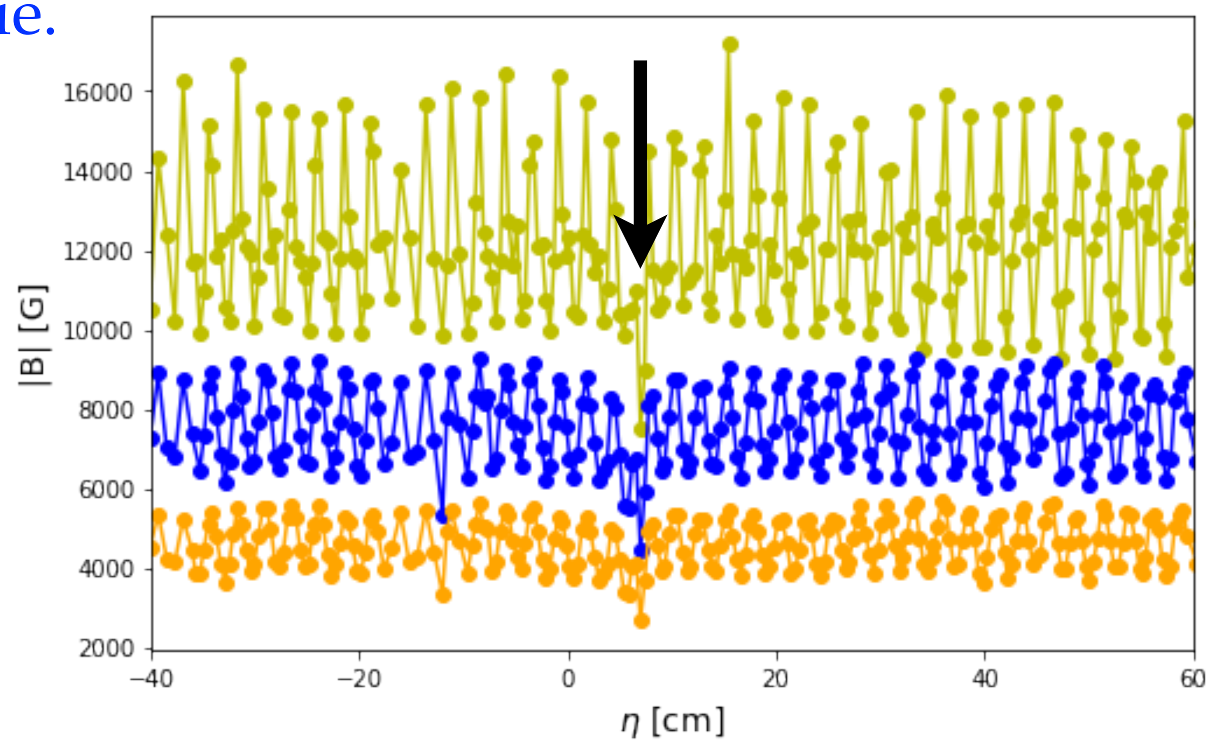


- Behavior at small holding fields affected by external fields.
- Details of the physical Halbach array (e.g. magnet coating or defects) affect the measured behavior at larger fields.
- Understanding the cause will enhance the precision with which the depolarization loss rate is determined.

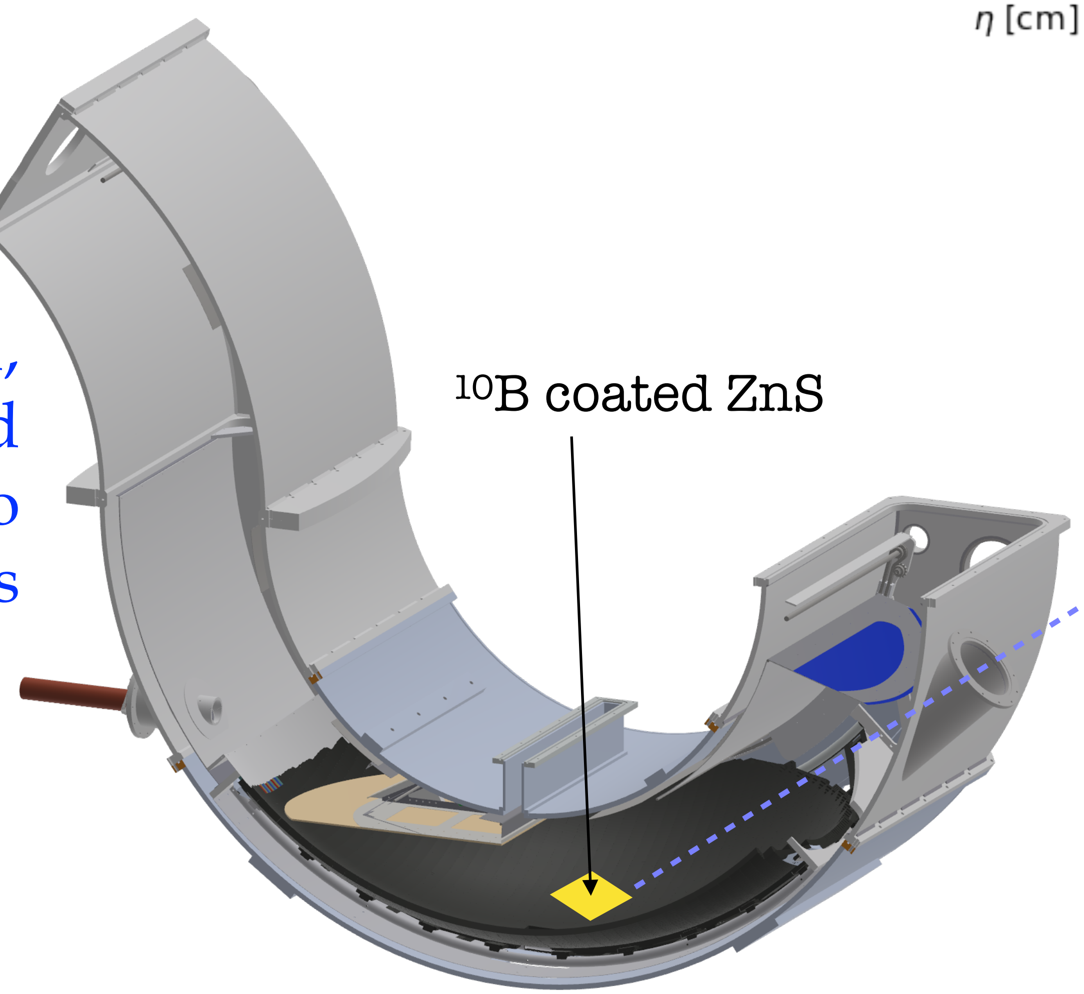
Our ongoing mapping effort has recently characterized trap defects after fixing a position calibration issue.



$\xi \sim 1.0$ cm

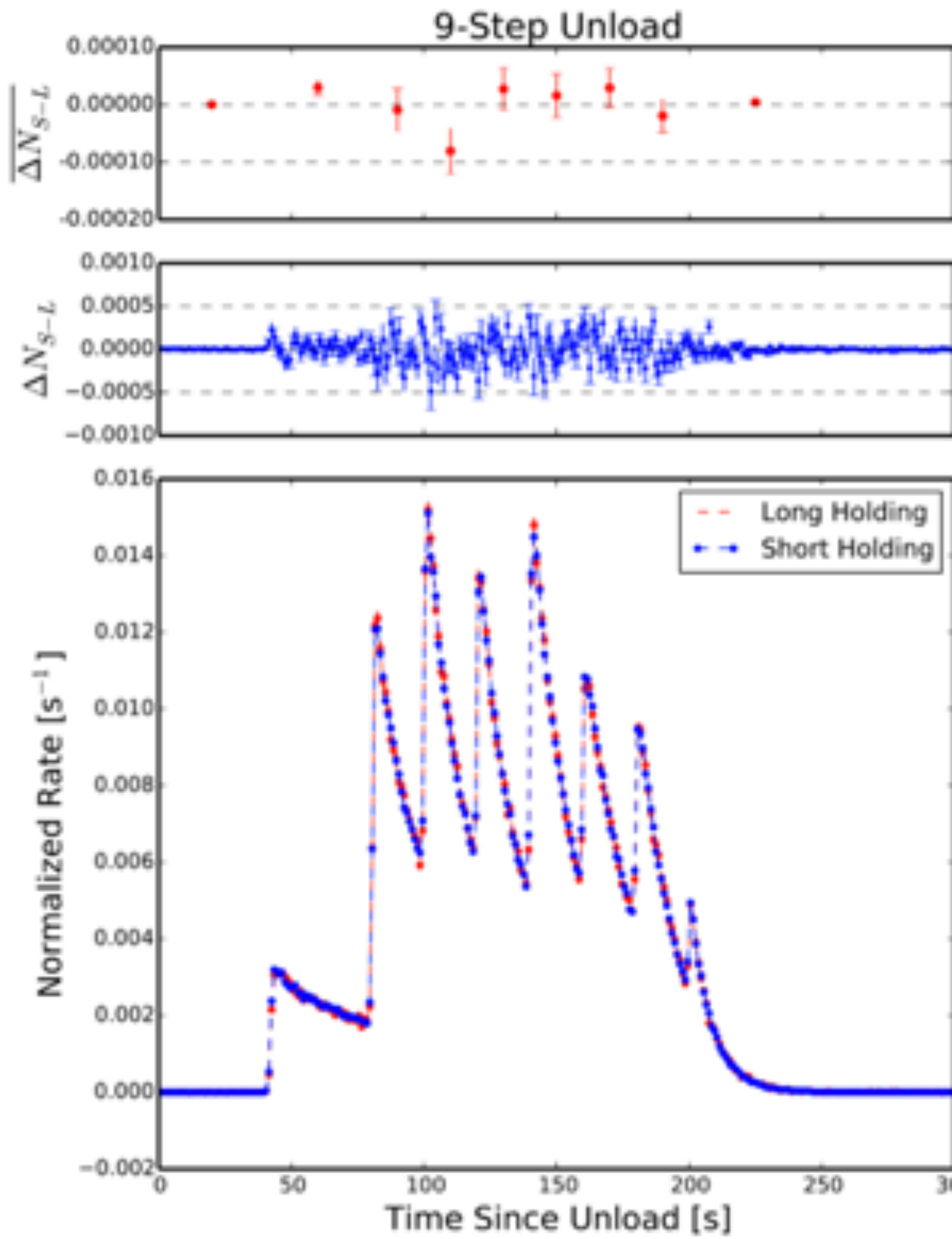


Aquadaq to reduce light background, more loaded UCN, and a dedicated port provide the possibility to directly observe depolarization loss in UCNτ+.

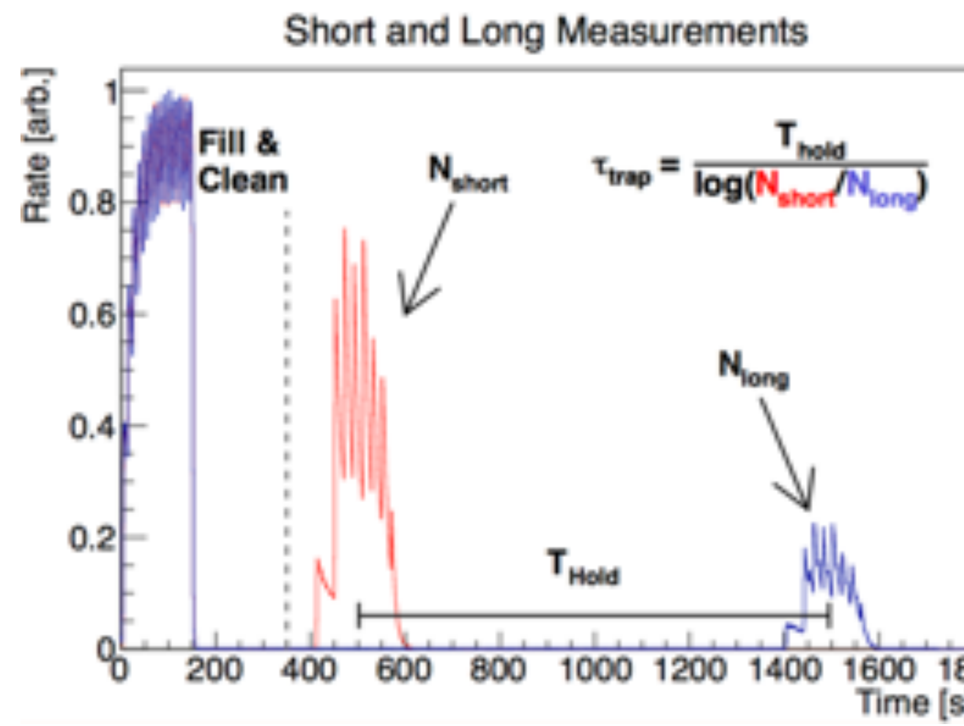


Systematics: Phase Space Evolution

Phase Space Evolution would alter the shape of the arrival time distribution…



R. W. Pattie



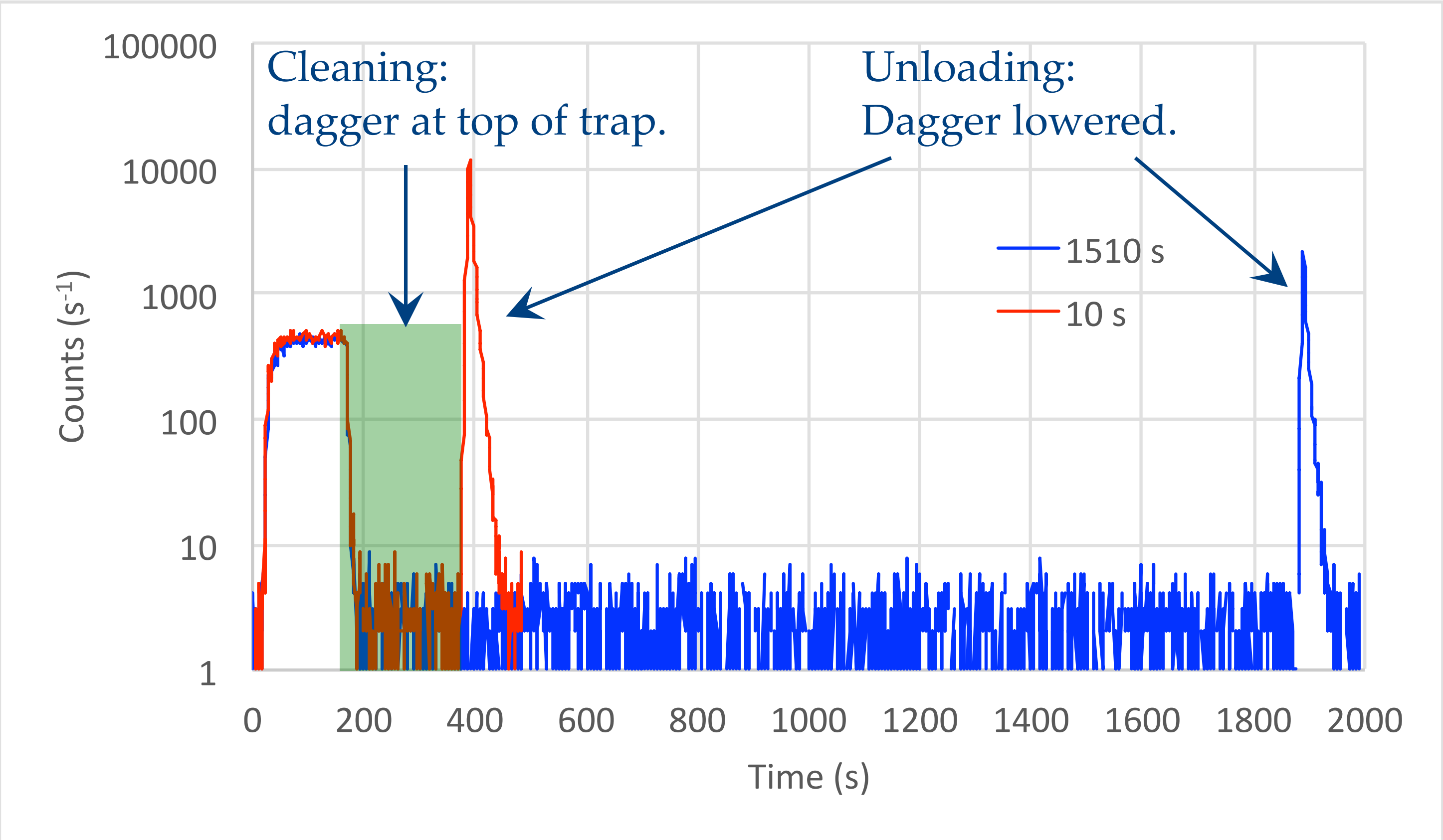
N.B. Callahan

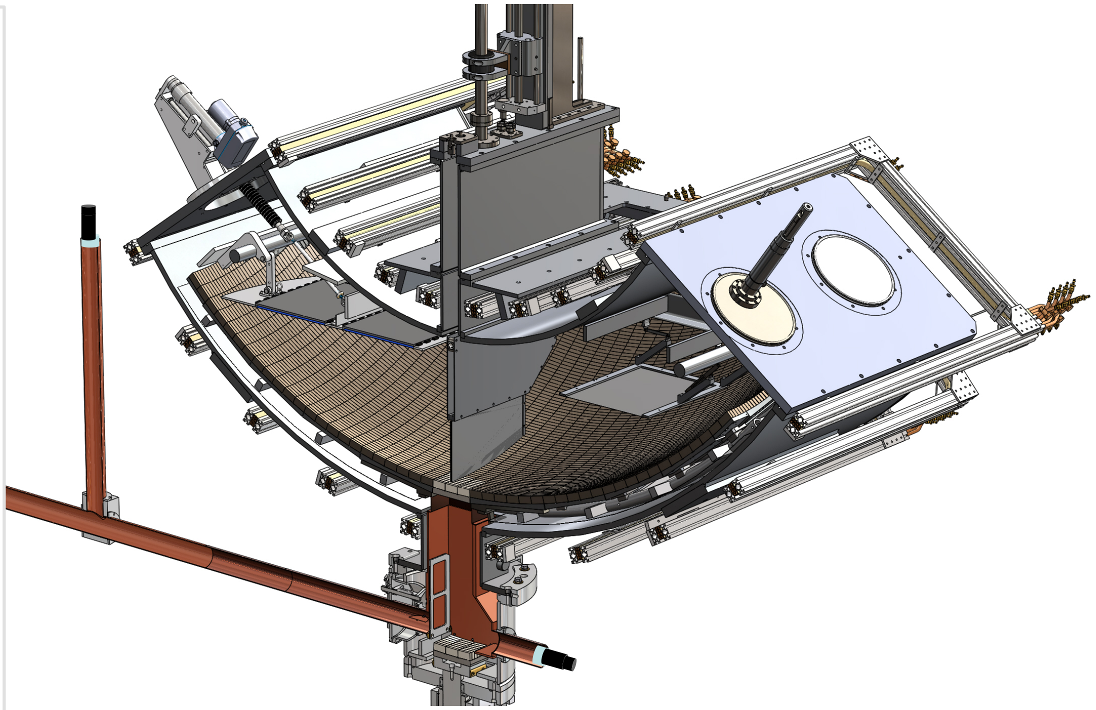
Use difference between mean arrival times

$$\overline{T} = \frac{\sum N_i t_i}{\sum N_i}$$

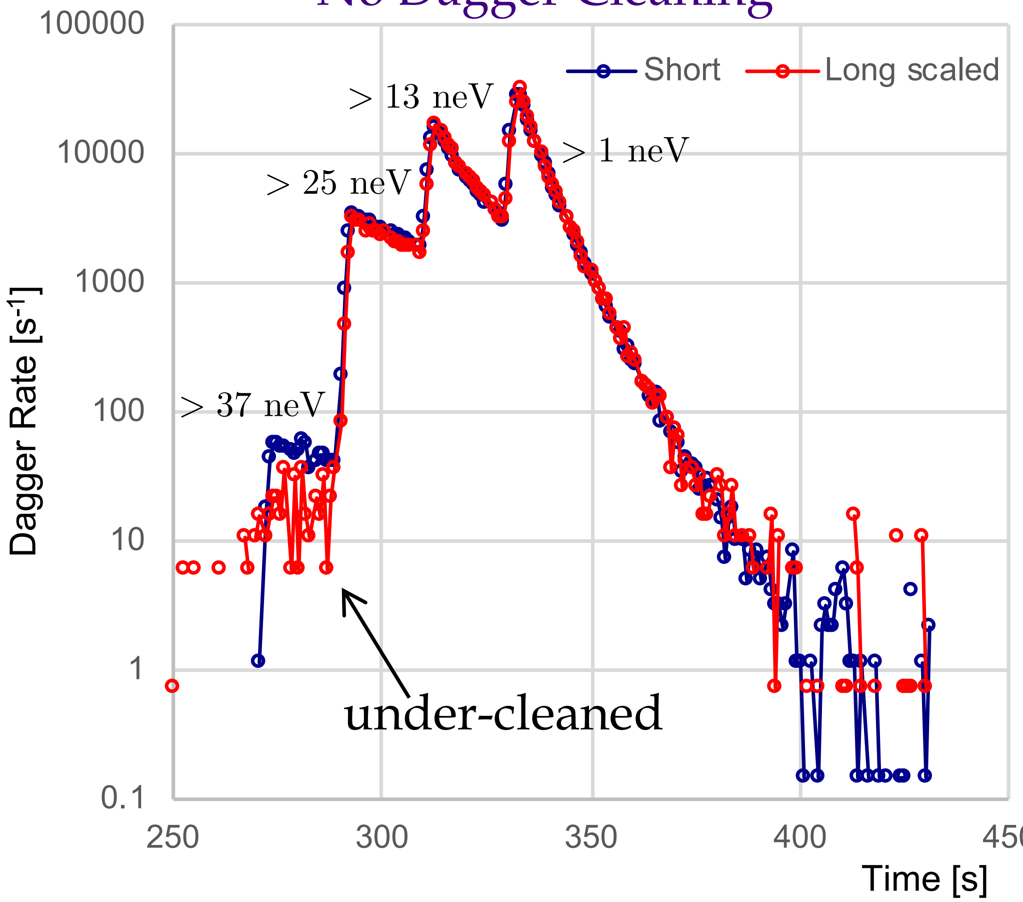
as T_{hold}. Difference between this and the programmed holding time sets the phase space evolution bound.

Systematics: Observing Phase Space Evolution

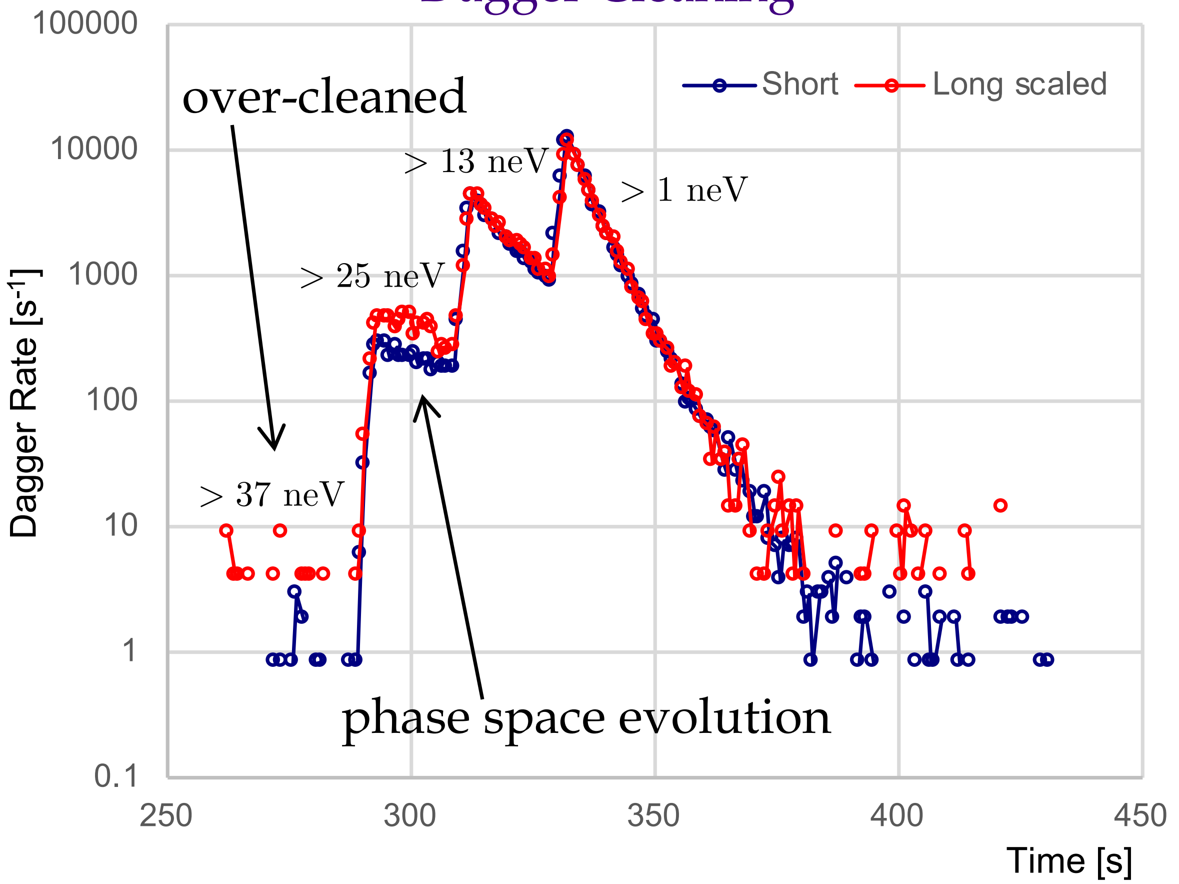




No Dagger Cleaning

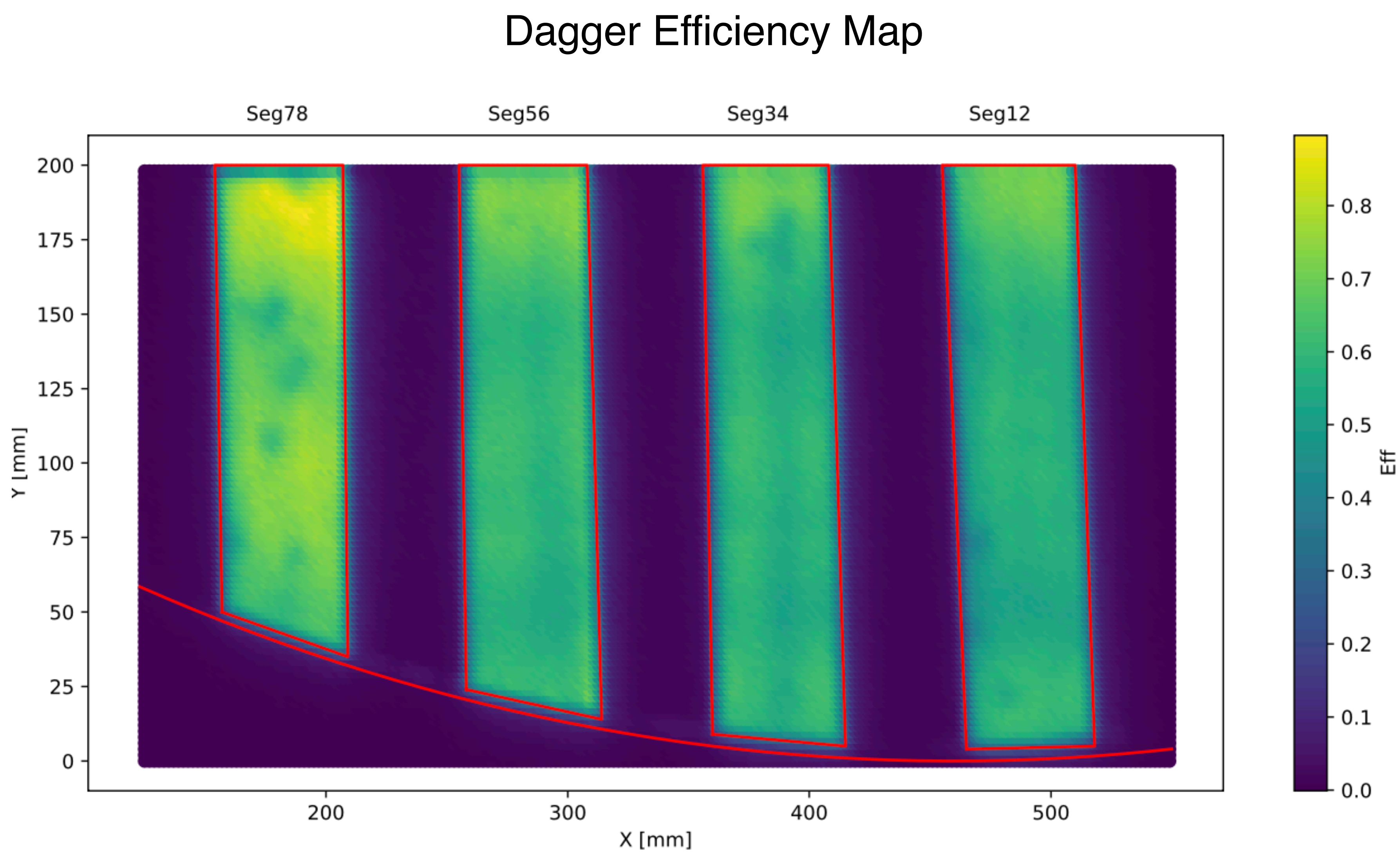


Dagger Cleaning



Systematics: Phase Space Evolution

- Lifetimes extracted from individual segments are significantly different.
- This seems to demonstrates “horizontal” evolution of the UCN phase space.
- In reality the effect seems to be dominated by a vertical shift in the UCN centroid.
- These kind of changes cause a systematic effect when coupled to inhomogeneities in the dagger efficiency.



Region	τ_n (Blinded)
Segment Sum	876.7 ± 0.6 s
Segment 1/2	880.1 s
Segment 2/3	878.0 s
Segment 3/4	876.2 s
Segment 4/5	871.1 s

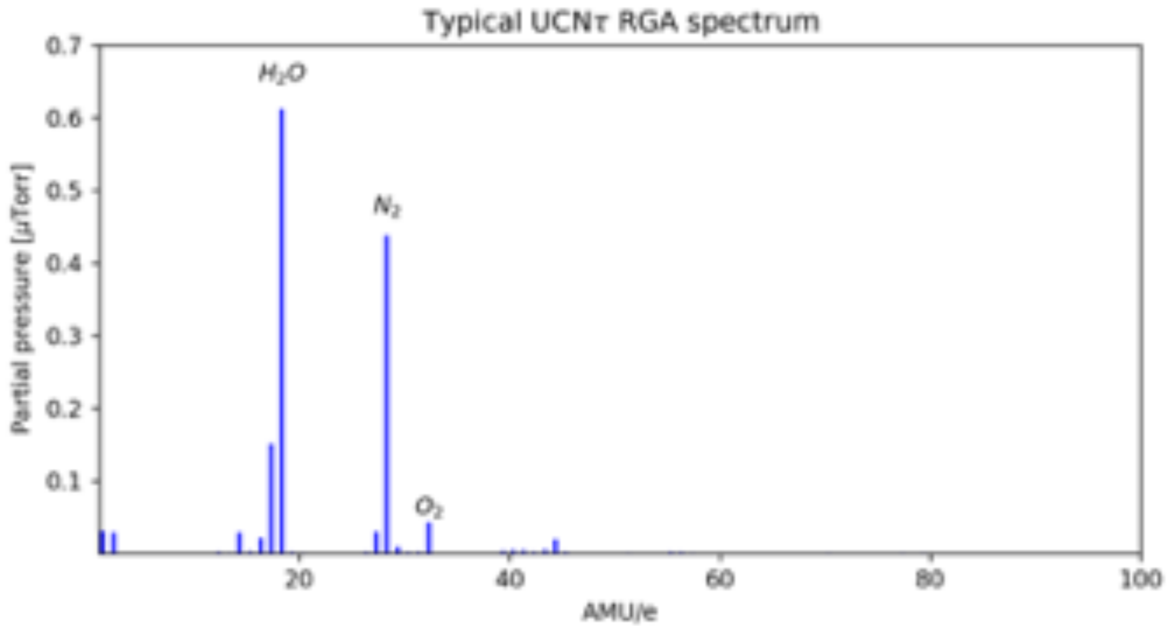
Systematics: Residual Gas Scattering

Residual Gas: Measured the UCN upsacttering cross sections in residual gasses.

Allowable pressures for $\left(\frac{\Delta\tau_n}{\tau_n}\right)_{\text{loss}} \leq 1 \times 10^{-4}$

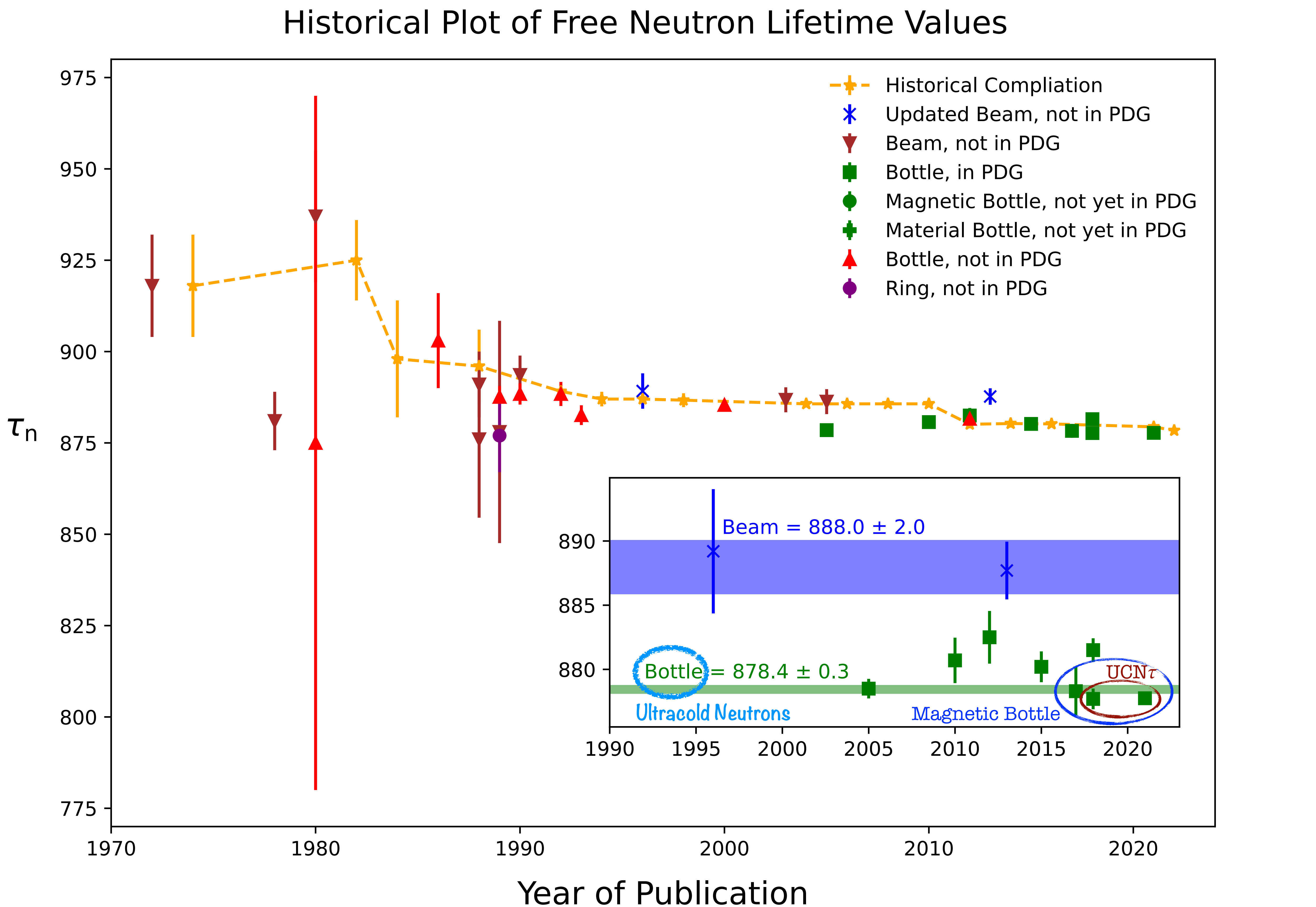
RGA and continuous vacuum monitoring.
Currently achievable pressure ~5e-8 Torr.

Gas	Max. Pressure [Torr]
Ne	2.0×10^{-5}
Ar	1.8×10^{-5}
CF_4	1.6×10^{-6}
D_2	1.5×10^{-6}
Xe	6.5×10^{-7}
H_2	2.9×10^{-7}
Water	2.6×10^{-7}
C_4H_{10}	7.1×10^{-8}
^{3}He	3.0×10^{-9}



S.J. Seestrom *et al.*, *Phys. Rev. C* ***95*** 015501 (2017)

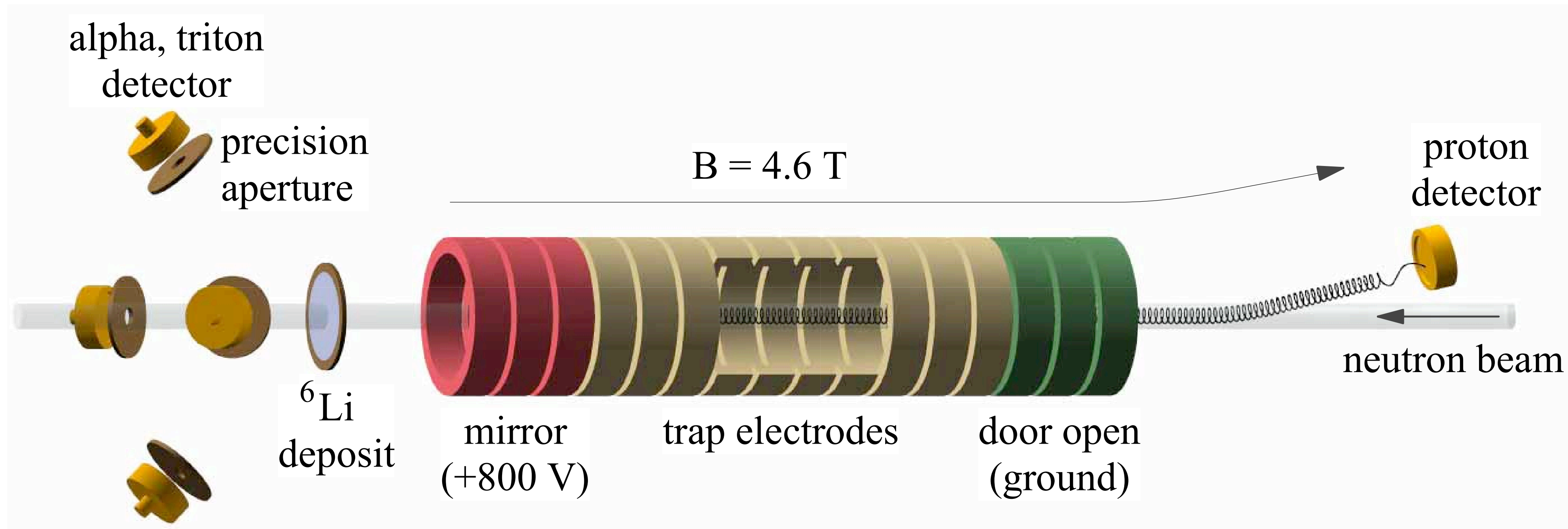
The Neutron Lifetime Puzzle



The Neutron Lifetime Puzzle

Cold Neutron Beam

- Neutron Fluence
- Beam Halo
- Trap non-linearity
- Statistics!

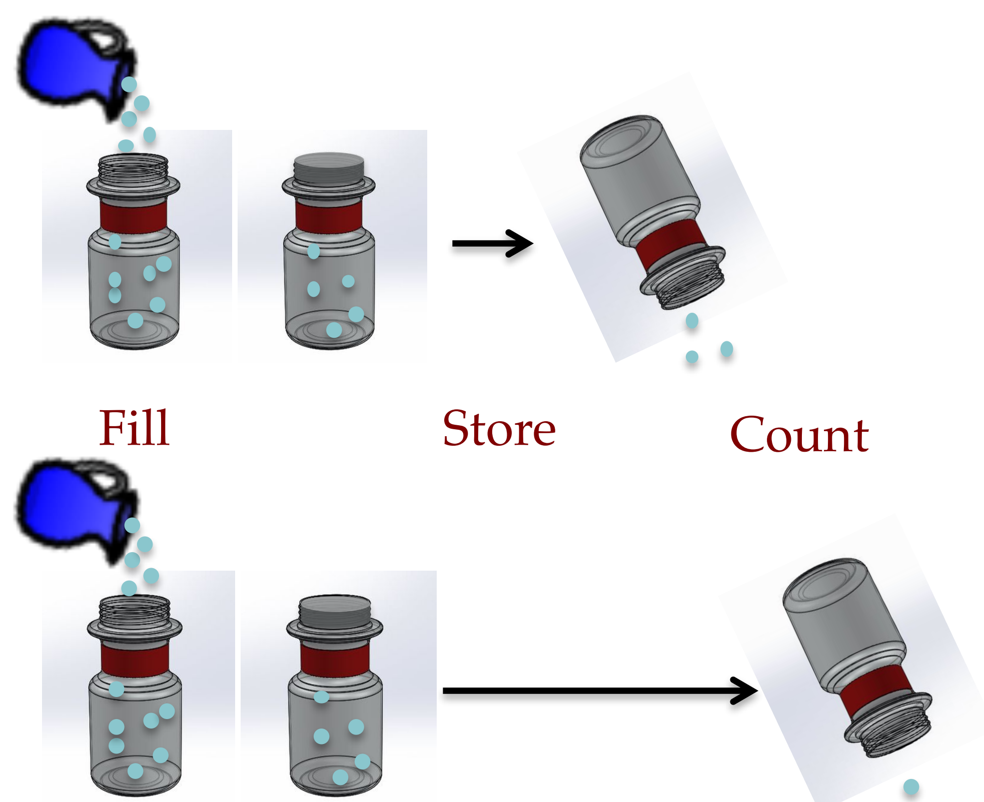


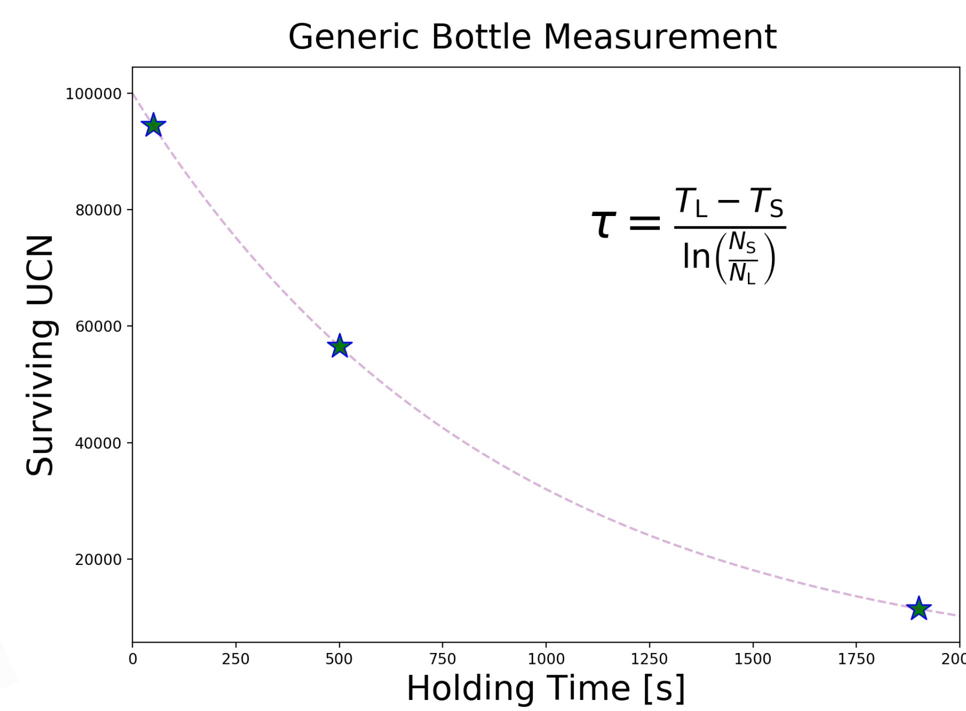
J.S. Nico *et al.*, *Phys. Rev.* C **71**, 055502 (2005)

Ultracold Neutron Bottle

- Cleaning
- Heating
- Phase Space Effects
- Detector Effects
- ~~Material Loss~~ Depolarization
- Normalization and Statistics!

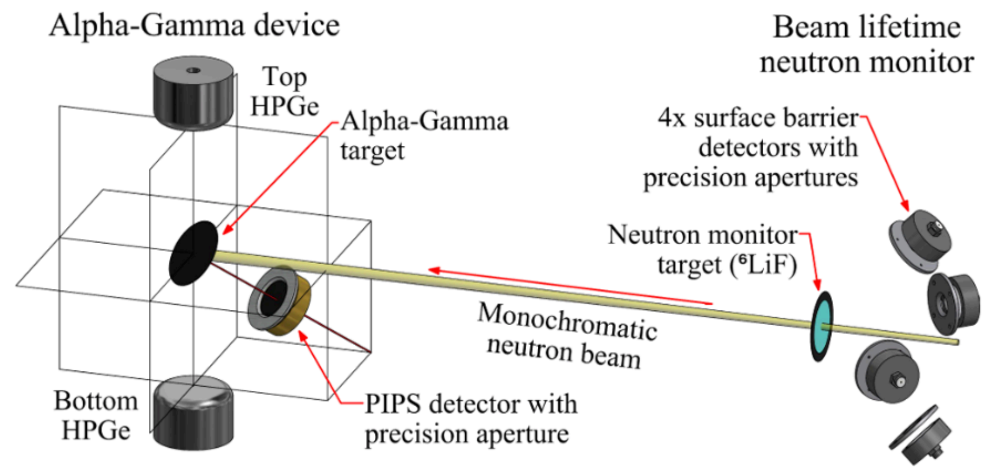
$$\frac{1}{\tau_{\rm n}} = \frac{1}{\tau_{\rm trap}} - \frac{1}{\tau_{\rm not\ \beta}}$$

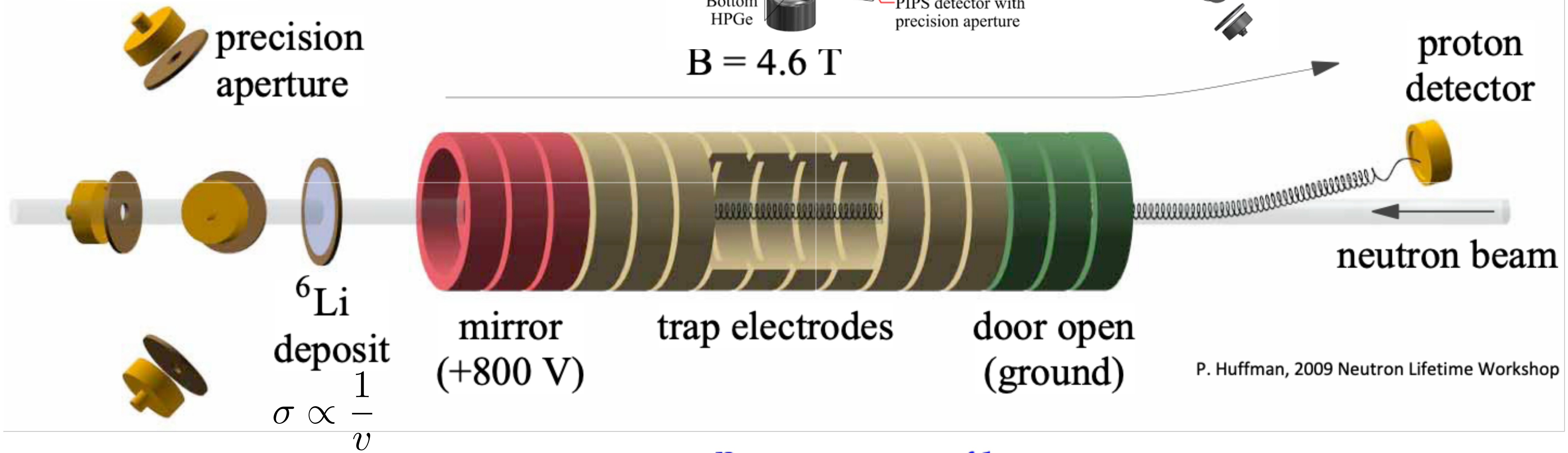




The Neutron Lifetime Puzzle

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





$$\text{Decay Rate} = \frac{\mathcal{F} \cdot A \cdot L}{v \cdot \tau_{\text{n}}}$$

$\frac{\text{n}}{s \cdot cm^2}$

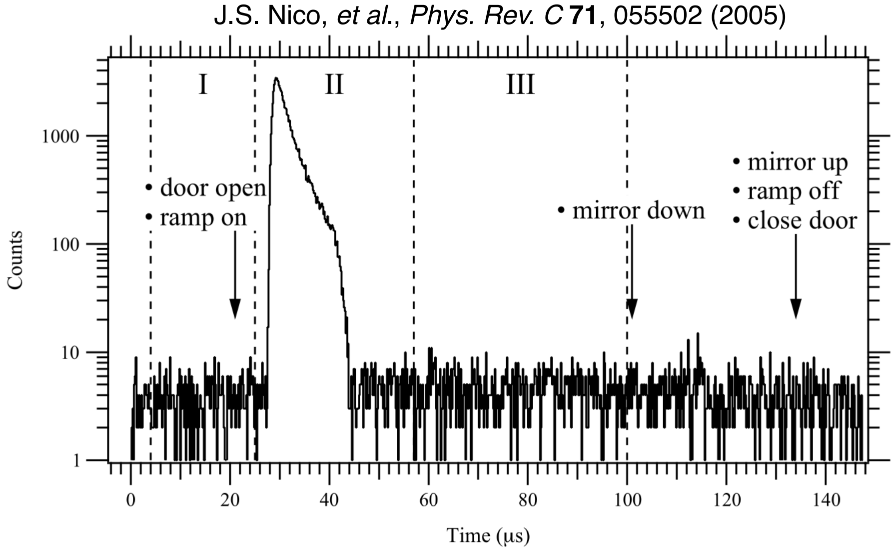
area of beam

length of decay volume

neutron speed

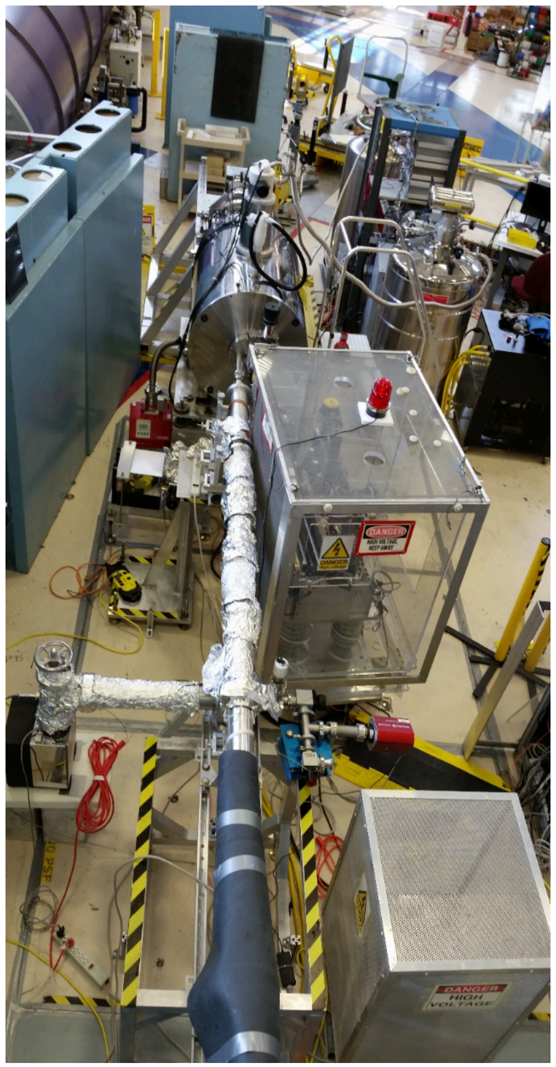
neutron lifetime

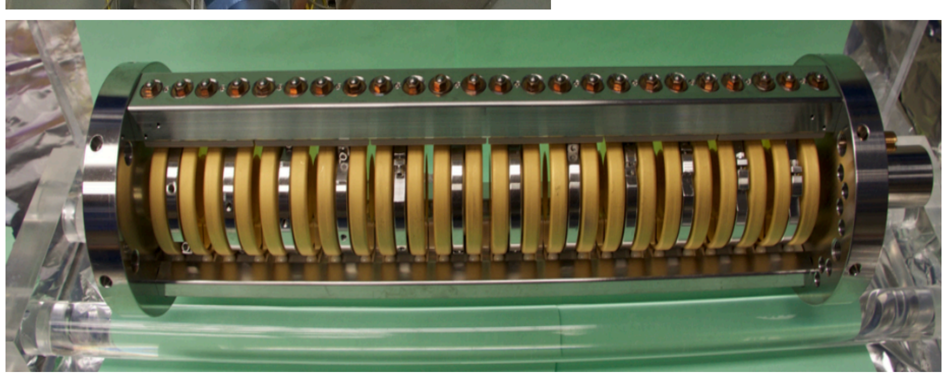
J.S. Nico, *et al.*, *Phys. Rev. C* **71**, 055502 (2005)



The Neutron Lifetime Puzzle

Beam Lifetime 2 ($\delta\tau_n$ ~1s)

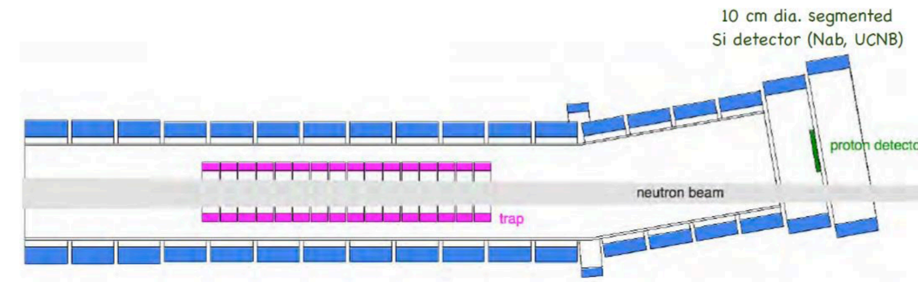




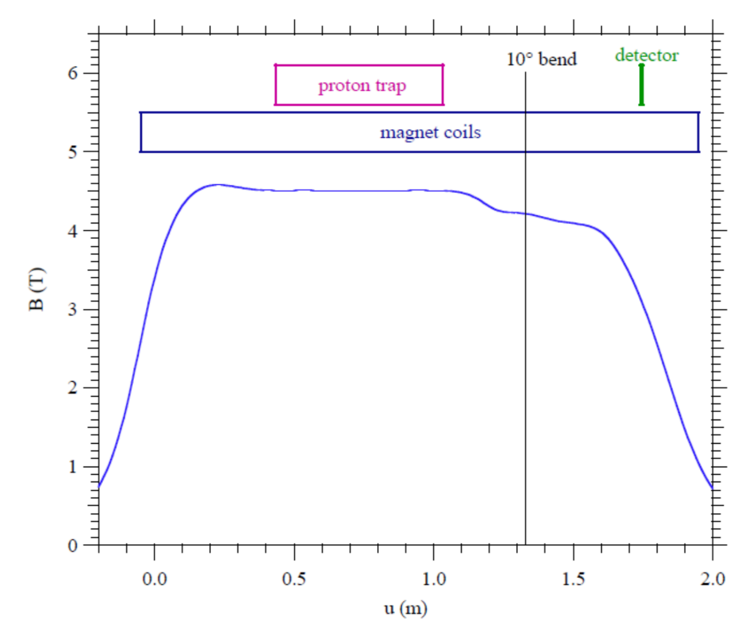
S. Hoogerheide

- Beam Fluence: alpha-gamma device
- Beam Halo: runs with larger p detector
- Trap Non-Linearity: shorter traps
- Statistics: NG-C, NCNR source upgrade

Beam Lifetime 3 ($\delta\tau_n$ <0.3 s)

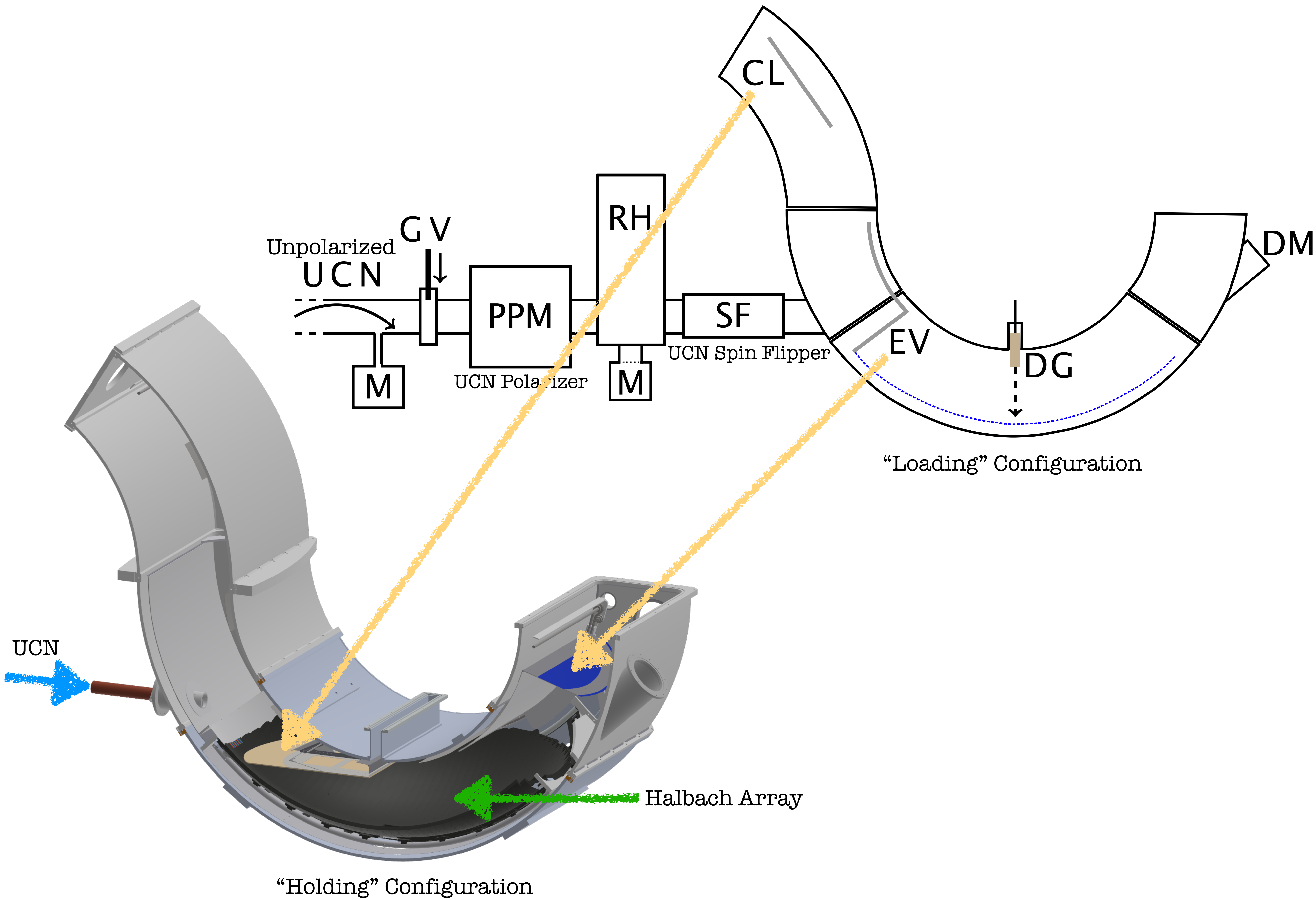


- Larger proton detector (x30) and position sensitivity
- Better, and controllable, field uniformity (<0.01%)
- Precision neutron spectral flux measurement
- improved use of alpha-gamma geometry and independent flux calibrations

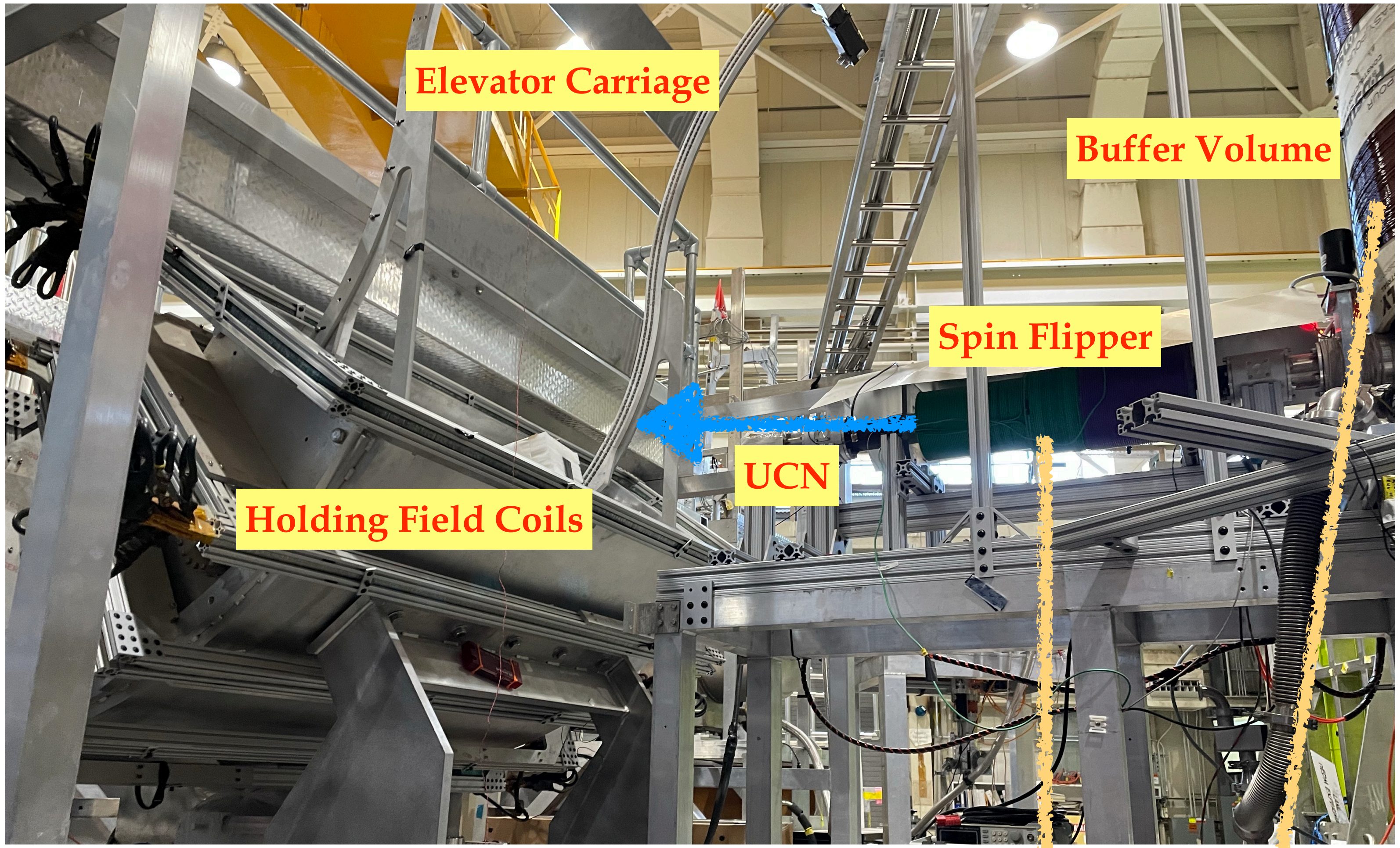


M. Scott Dewey

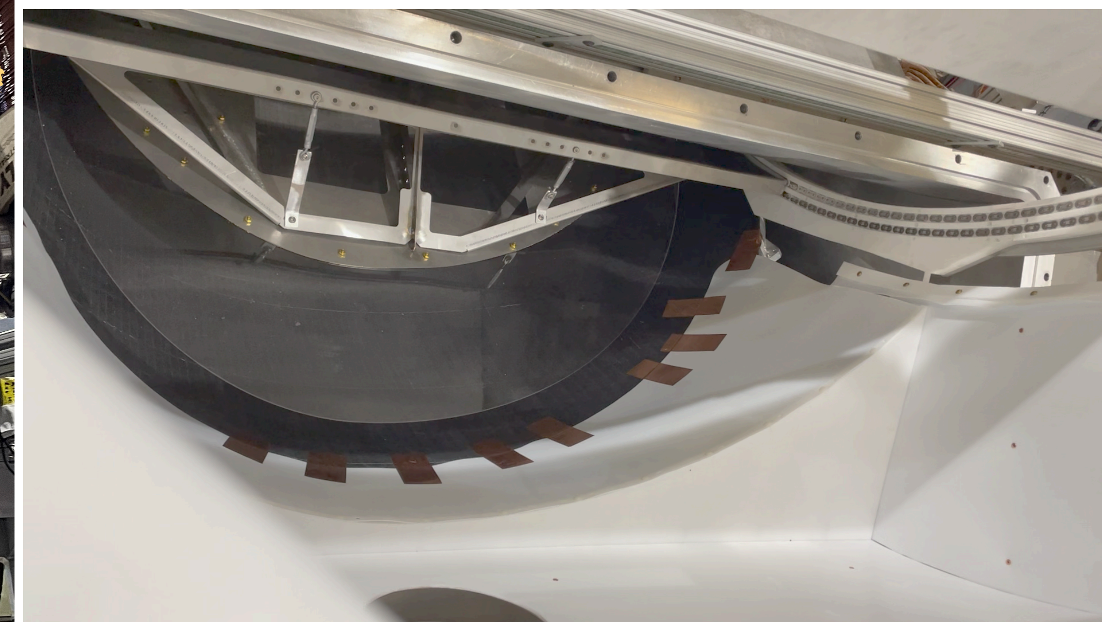
UCNτ+


CL
Unpolarized
UCN
GV
PPM
RH
SF
DM
EV
DG
M
M
UCN Polarizer
UCN Spin Flipper
"Loading" Configuration
UCN
Halbach Array
"Holding" Configuration

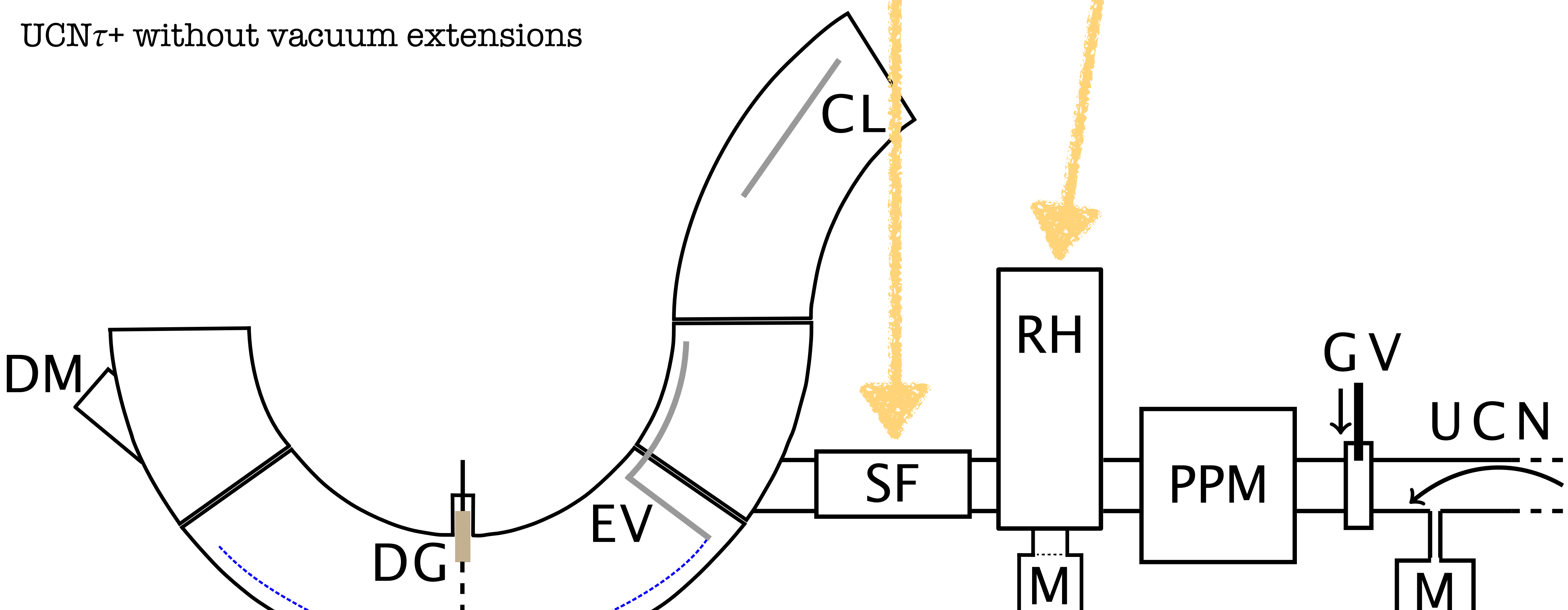
UCNτ+



UCNτ+ without vacuum extensions

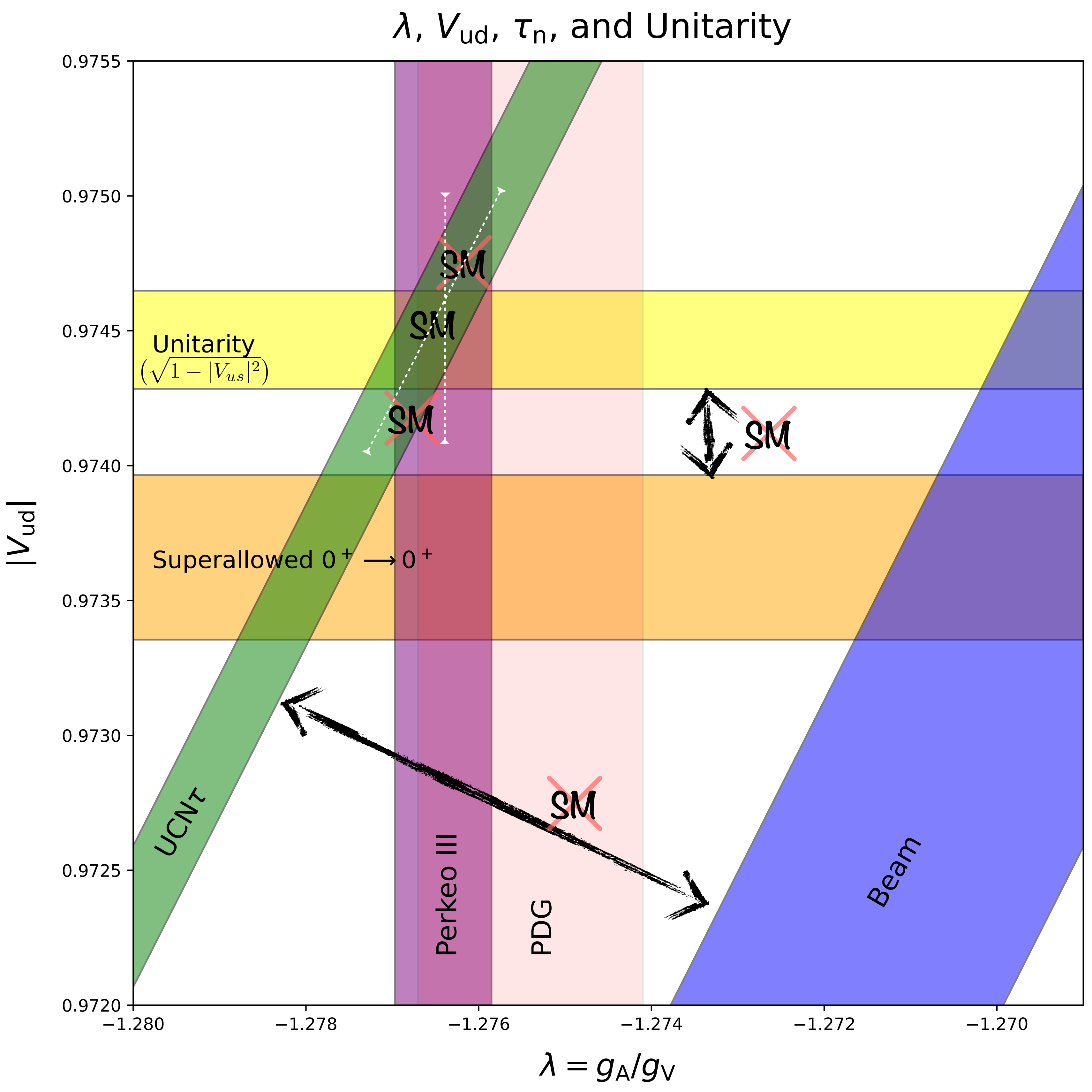


Elevator Motion



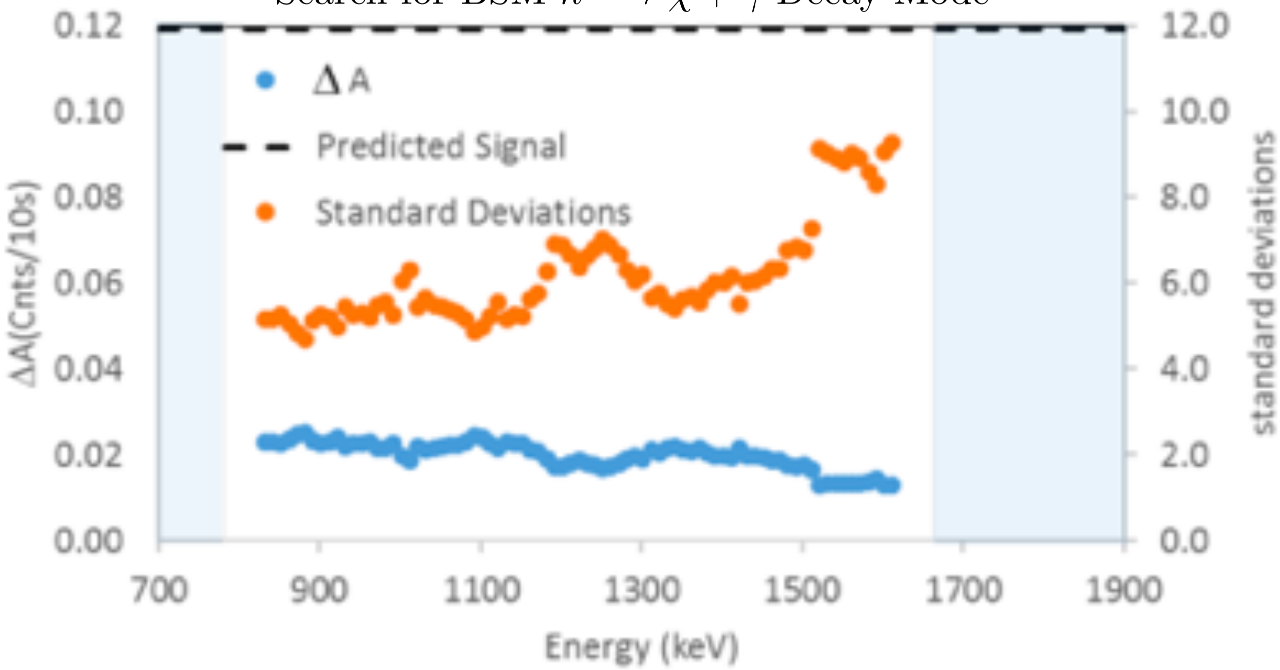
“Loading” Configuration

But if it wasn't systematics…

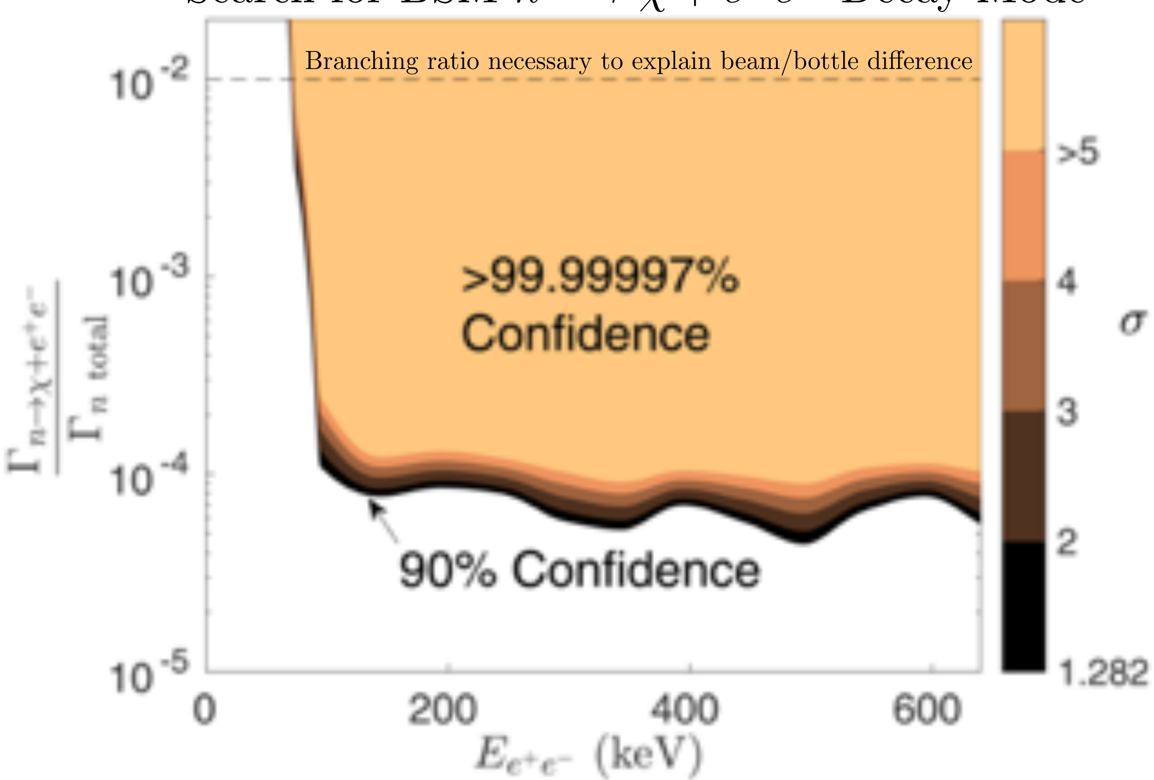


The Neutron Lifetime Puzzle: BSM - Dark Decay

Search for BSM $n \longrightarrow \chi + \gamma$ Decay Mode



Search for BSM $n \longrightarrow \chi + e^+e^-$ Decay Mode



Constrained theoretically by:

- Stability of nuclei
- neutron star stability
- stability of H atom

B. Fornal and B. Grinstein, *Dark Matter Interpretation of the Neutron Decay Anomaly*, Phys. Rev. Lett. 120, 191801 (2018)

Z. Tang et al, *Search for the Neutron Decay n → X + γ where X is a dark matter particle*, Phys. Rev. Lett. 121, 022505 (2018)

A. Czarnecki, W. Marciano, and A. Sirlin, *The Neutron Lifetime and Axial Coupling Connection*, Phys. Rev. Lett. 120, 202002 (2018)

A.P. Serebrov et al. (PNPI Gatchina, Russia) *Neutron lifetime, dark matter and search for sterile neutrino*, arXiv:1802.06277

D. McKeen, A.E. Nelson, S. Reddy, and Da. Zhou, *Neutron stars exclude light dark baryons*, arXiv:1802.08244

G. Baym, D. H. Beck, P. Geltenbort, and J. Shelton, *Coupling neutrons to dark fermions to explain the neutron lifetime anomaly is incompatible with observed neutron stars*, arXiv:1802.08282

T. F. Motta, P. A. M. Guichon, and A. W. Thomas, *Implications of Neutron Star Properties for the Existence of Light Dark Matter*, arXiv:1802.08427

M. Pfützner and K. Riisager, *On the possibility to observe neutron dark decay in nuclei*, Phys. Rev. C 97, 042501 (2018)

James M. Cline and Jonathan M. Cornelly, *Dark decay of the neutron*, arXiv:1803.04961

X. Sun et al., *Search for dark matter decay of the free neutron from the UCNA experiment: n → χ + e^+e^-*, Phys. Rev. C 97, 052501 (2018)

S.K. Lamoreaux, *Stored Ultracold Neutron Lifetime Experiments: Non-Inertial Frame Effects on the Neutron Velocity Spectrum*, arXiv:1804.01087

George K. Leontaris and John D. Vergados, *neutron - antineutron oscillations and the neutron lifetime*, arXiv:1804.09837

Georgios K. Karananas and Alexis Kassiteridis, *Small-scale structure from neutron dark decay*, arXiv:1805.03656

The Neutron Lifetime Puzzle: BSM - DM Blobs

$$\tau_n = \frac{\Delta T}{\ln N_S - \ln N_L}$$

$$20,000 \times e^{-1550/878} = 3422$$

$$\frac{1550 \text{ s}}{\ln(20000) - \ln(3422)} = 877.93 \text{ s}$$

$$\frac{1550 \text{ s}}{\ln(20000) - \ln(3421)} = 877.79 \text{ s}$$

S. Rajendran and H. Ramani, *Phys. Rev. D*, **103**, 035014 (2021)

Could DM scattering be responsible?

DM must have mass similar to n.
There must be a significant density of DM in the trap.

Galactic DM doesn't fit these criteria

↓

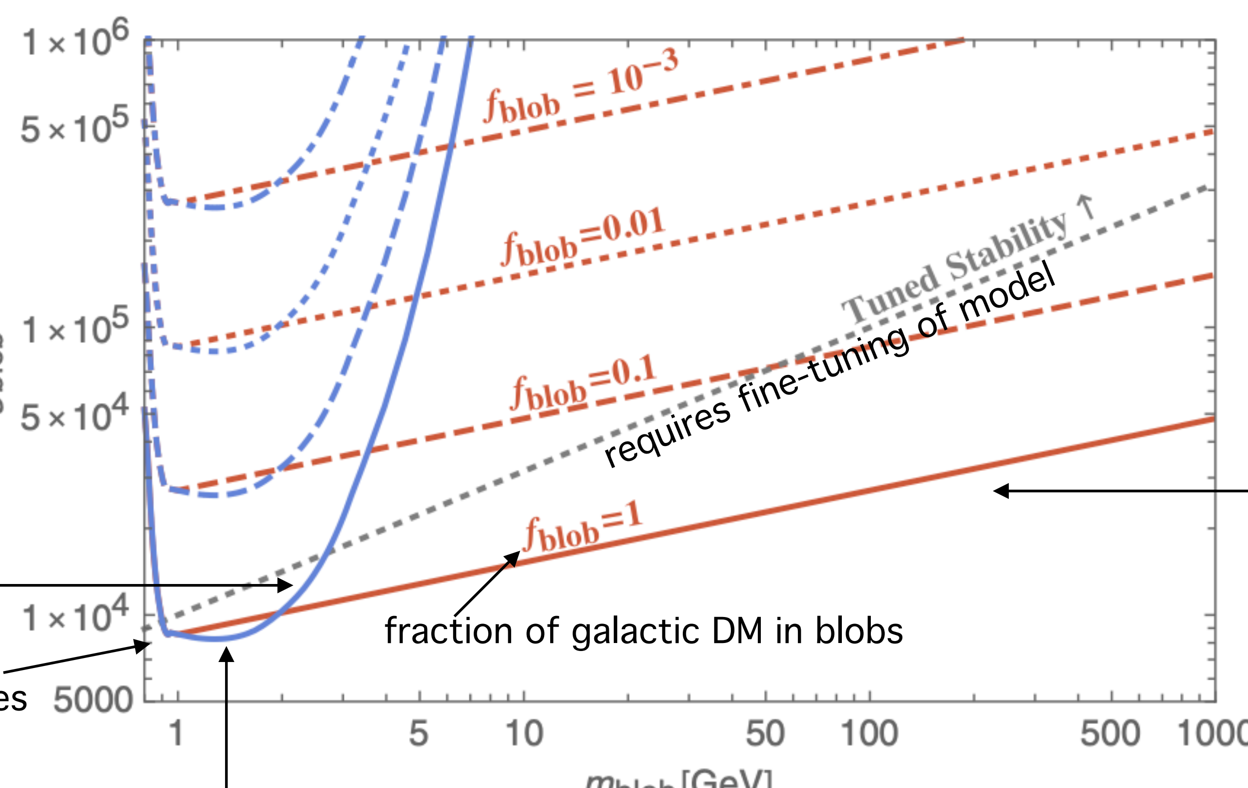
Composite DM: Blobs

- dark parton (f) blob: large dark charge, ~ µm range 5th force
- blobs can be captured in the earth —> self-scattering leads to more capture
- Distribution of blob masses —> significant lighter blob density at earth's surface
- Long range and thermalization suppresses signals from standard DM detectors
- Couples with strength g_f via a neutron dark electric dipole moment.

Blob Dark Charge for $\Delta\tau_{\text{beam/bottle}}$

surface density smaller than terrestrial density (set by evaporation)

< 1 GeV evaporation produces no viable parameter space



blobs sink leaving low surface density => larger required coupling as mass increases

age of earth ≈ 10^{10} years

$$\langle n_{\text{DM}}^{\text{terr}} \rangle = \frac{\pi r_E^2}{\frac{4}{3}\pi r_E^3} n_{\text{DM}}^{\text{vir}} v_{\text{vir}} \approx \frac{10^{15}}{\text{cm}^3} \frac{T_E}{10^{10} \text{ year}} f_{\text{blob}} \frac{\text{GeV}}{m_{\text{blob}}}$$

surface density equals terrestrial density. Valid for small enough mediator mass. Blob-Blob repulsion prevents sinking.

The Neutron Lifetime Puzzle: BSM - Excited Neutrons

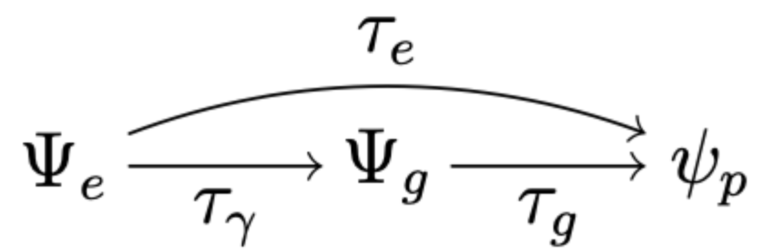
B. Koch and F. Hummel, arXiv:2403.00914v3 [hep-ph] 15 May 2024

What if... neutron has excited states inaccessible while bound in a nucleus:

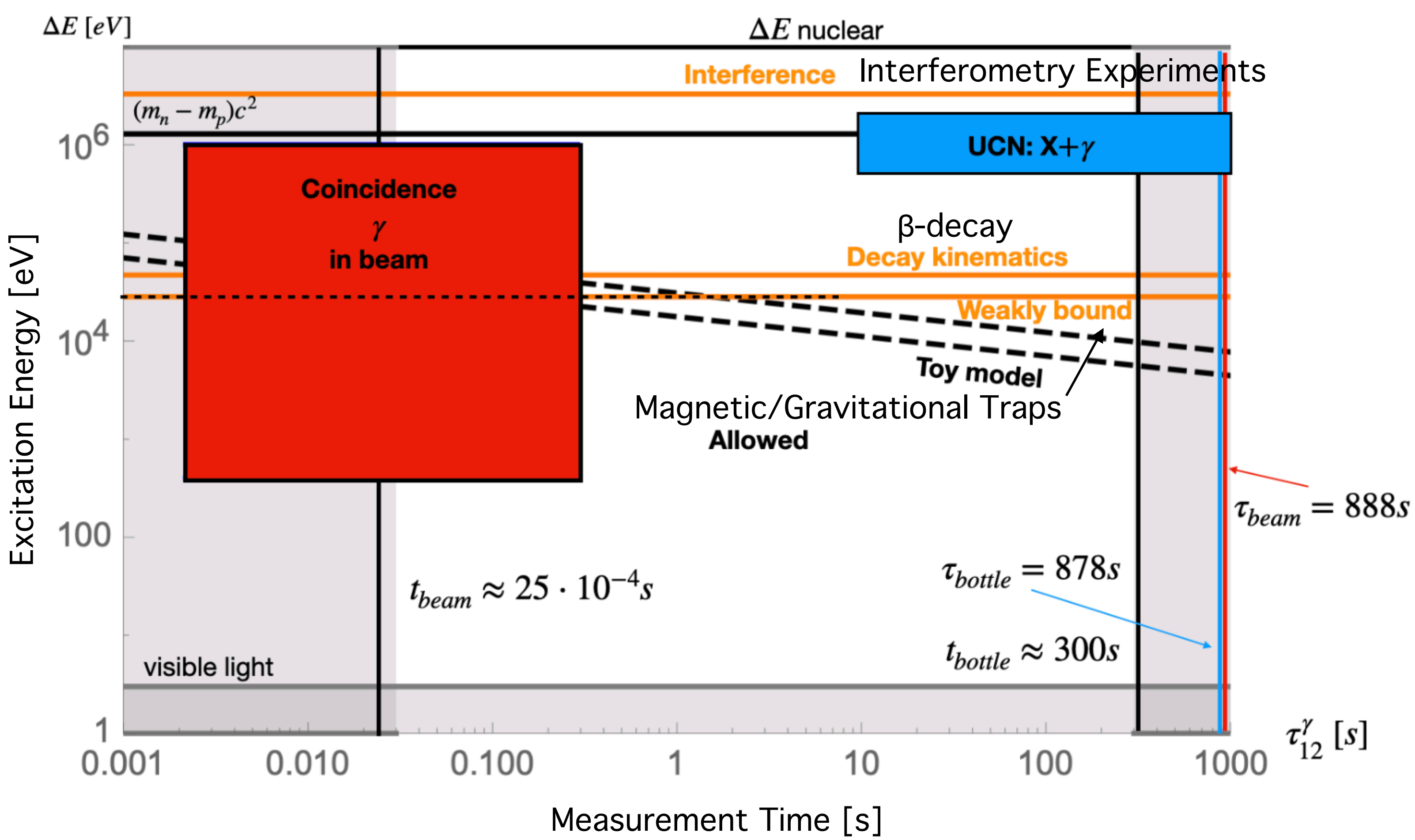
ground state ψ_g with β-decay lifetime τ_g

excited state ψ_e with β-decay lifetime τ_e

Suppose $\psi_e \longrightarrow \psi_g + \gamma$ with decay time τ_γ.

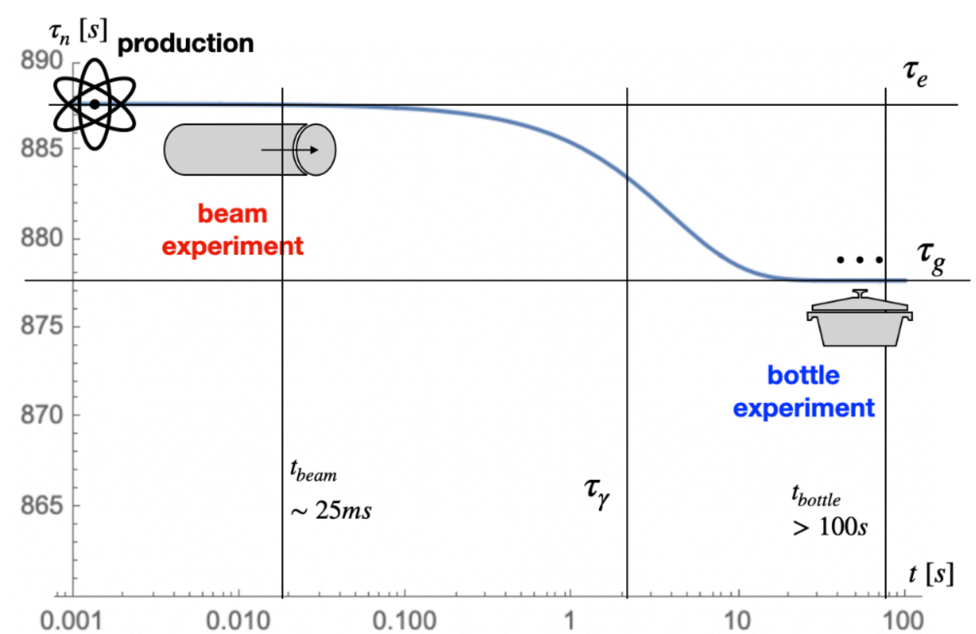


$$\dot{n}_e = -n_e\tau_\gamma^{-1} - n_e\tau_e^{-1}$$
$$\dot{n}_g = +n_e\tau_\gamma^{-1} - n_g\tau_g^{-1}$$



If the the γ is unobserved $n_n = n_g + n_e$

If $t_{\text{beam}} \ll \tau_\gamma \ll t_{\text{bottle}} < \tau_g < \tau_e$
~ 25 ms $\qquad > 300$ s



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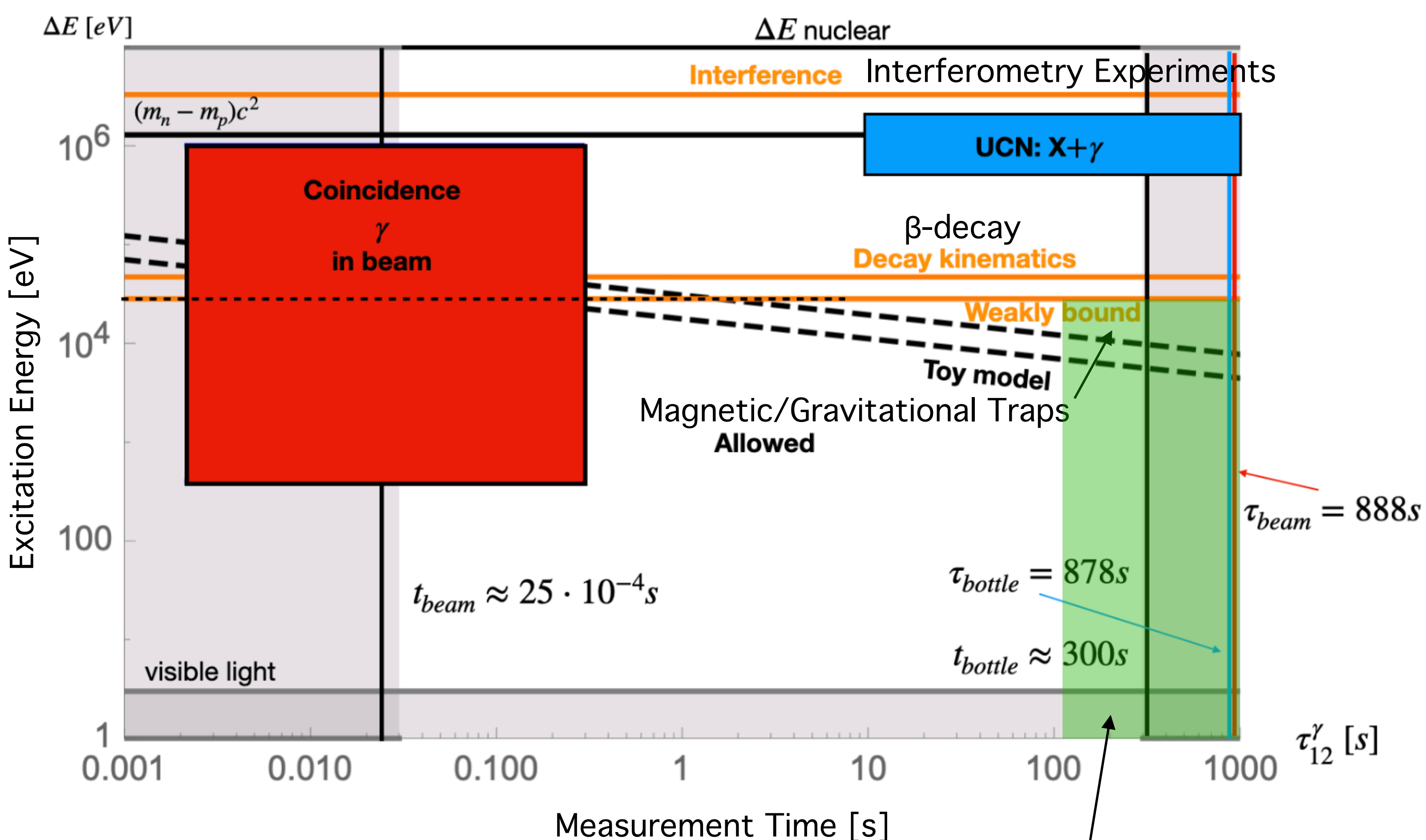
Suppose $\psi_e \longrightarrow \psi_g + \gamma$ with decay time τ_γ.

$$\Psi_e \xrightarrow{\tau_\gamma} \Psi_g \xrightarrow{\tau_g} \psi_p, \qquad \Psi_e \xrightarrow{\tau_e} \psi_p$$

$$\dot{n}_e = -n_e\tau_\gamma^{-1} - n_e\tau_e^{-1}$$

$$\dot{n}_g = +n_e\tau_\gamma^{-1} - n_g\tau_g^{-1}$$



Excluded by UCNτ data with holding times varying from 300 s to 2000 s

If the the γ is unobserved $n_n = n_g + n_e$

If $t_{\text{beam}} \ll \tau_\gamma \ll t_{\text{bottle}} < \tau_g < \tau_e$
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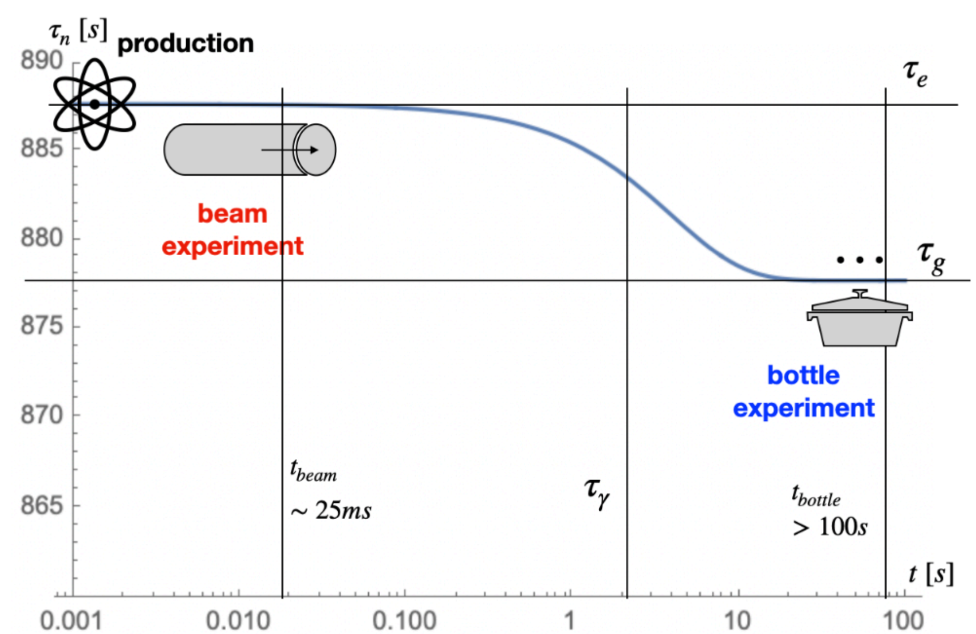
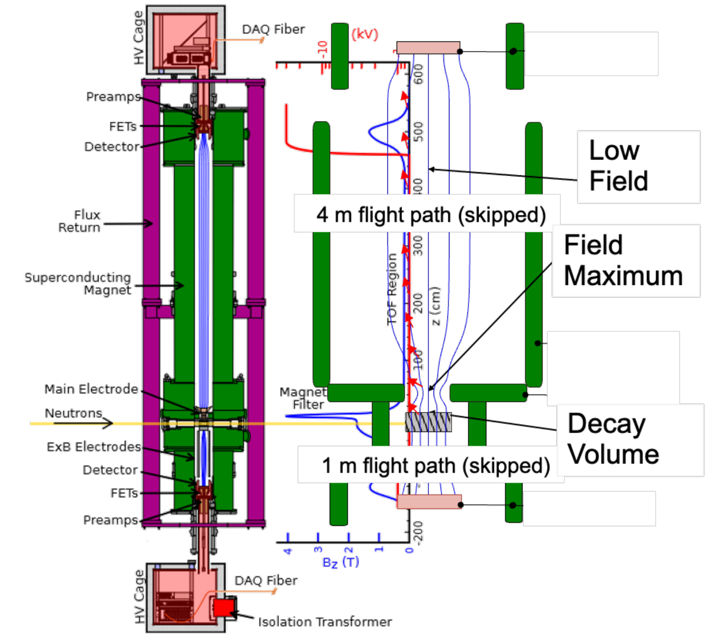


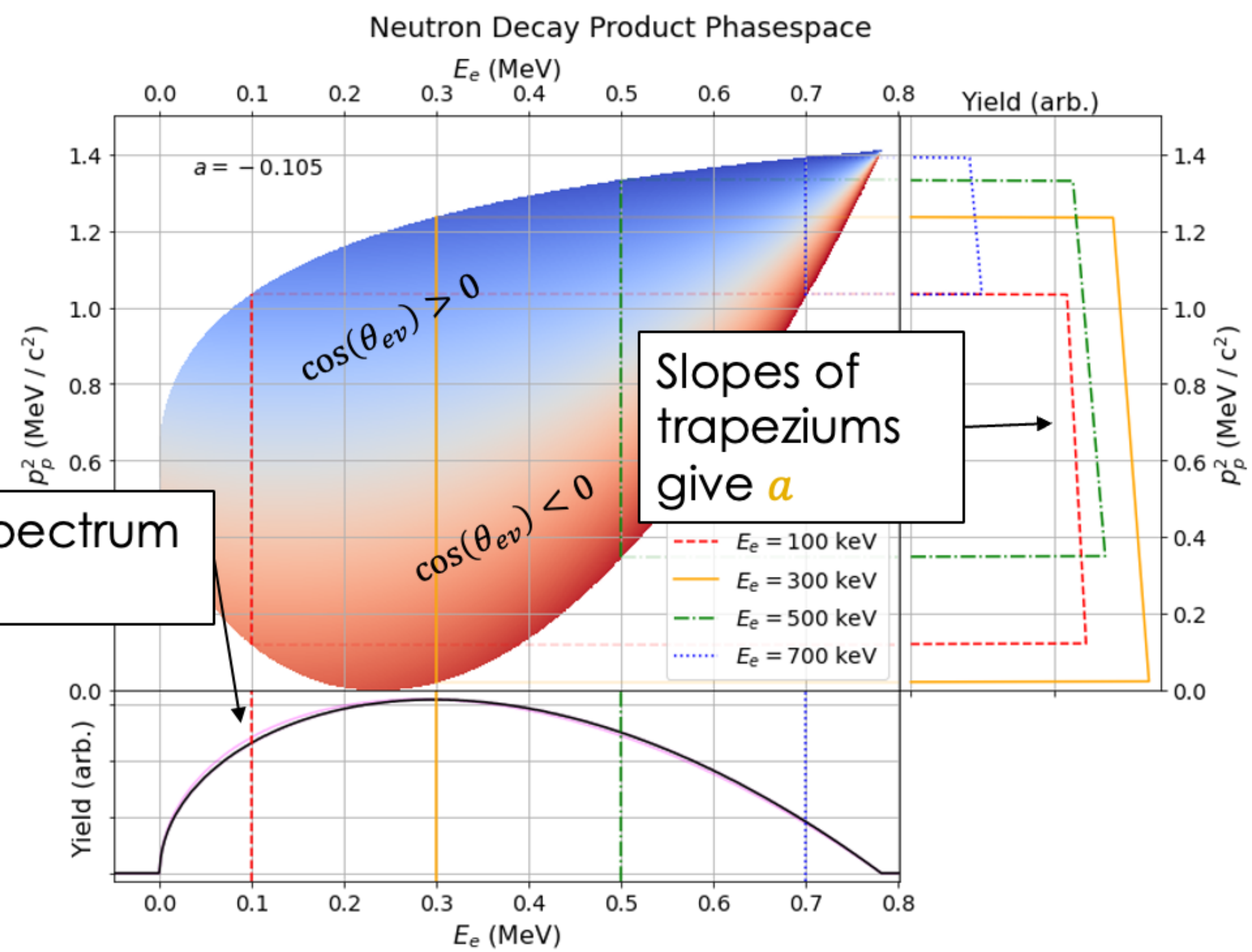
Nab (Oak Ridge National Lab)



Kinematics of Unpolarized Neutron β-Decay

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



Thanks to Frank Gonzalez for this slide!

New physics is expected, but elusive. The field of fundamental neutron physics is characterized by an exciting assortment of experiments and techniques.

https://www.jigidi.com/user/okieclem/

Slow Neutrons

Ultracold Neutrons

Decay Experiments ✓

Non-Decay Experiments

Matter/Antimatter Asymmetry

How do we know there is an asymmetry?

No X-ray and γ-ray signals observed.

Cosmic rays don't contain much antimatter.

Matter/Antimatter Asymmetry

How do we know there is an asymmetry?

No X-ray and γ-ray signals observed.

Cosmic rays don't contain much antimatter.

How could this happen? —> Sakharov Conditions

Baryon Number Violation $B = \frac{1}{3}(n_q - n_{\overline{q}})$

$$B_i^{\text{universe}} = 0, \text{ antimatter asymmetry } \implies B_f^{\text{universe}} \neq 0.$$

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CP & C Violation

$$\Gamma_{X_L \longrightarrow q_R q_L} \overset{C}{\leftrightarrow} \Gamma_{\overline{X}_L \longrightarrow \overline{q}_R \overline{q}_L}$$

$$CP$$

$$\Gamma_{X_R \longrightarrow q_L q_R} \underset{C}{\leftrightarrow} \Gamma_{\overline{X}_R \longrightarrow \overline{q}_L \overline{q}_R}$$

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$$CP$$

$$\Gamma_{X_R \longrightarrow q_L q_R} \underset{C}{\leftrightarrow} \Gamma_{\overline{X}_R \longrightarrow \overline{q}_L \overline{q}_R}$$

A deviation from thermal equilibrium

$$\langle B \rangle = 0 \text{ in thermal equilibirum}$$

i.e. $qq \longrightarrow X$ and $\overline{qq} \longrightarrow \overline{X}$ will cancel a generated asymmetry.

Matter/Antimatter Asymmetry

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No X-ray and γ-ray signals observed.

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Baryon Number Violation $B = \frac{1}{3}(n_q - n_{\overline{q}})$

$$B_i^{\text{universe}} = 0, \text{ antimatter asymmetry } \implies B_f^{\text{universe}} \neq 0.$$

CP & C Violation => T violation assuming CPT symmetry

$$\Gamma_{X_L \longrightarrow q_R q_L} \overset{C}{\leftrightarrow} \Gamma_{\overline{X}_L \longrightarrow \overline{q}_R \overline{q}_L}$$

CP

$$\Gamma_{X_R \longrightarrow q_L q_R} \underset{C}{\leftrightarrow} \Gamma_{\overline{X}_R \longrightarrow \overline{q}_L \overline{q}_R}$$

WHERE? →

SM
QCD ("strong CP problem")
CKM matrix has P-violating phase

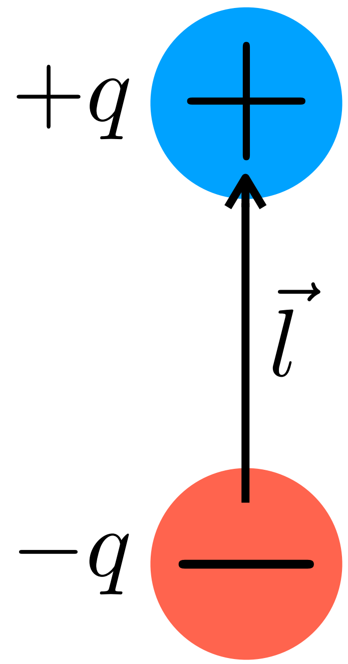
Not enough!

A deviation from thermal equilibrium

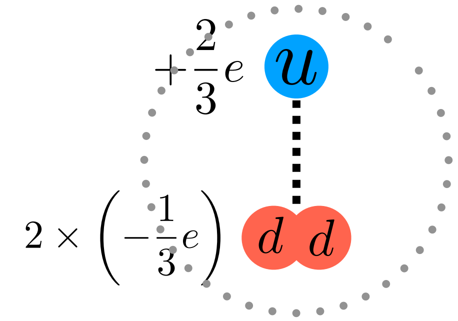
$$\langle B \rangle = 0 \text{ in thermal equilibirum}$$

$$\text{i.e. } qq \longrightarrow X \text{ and } \overline{qq} \longrightarrow \overline{X} \text{ will cancel a generated asymmetry.}$$

Search for a neutron Electric Dipole Moment (nEDM)



$$\vec{d} = q\vec{l}$$



$d_n^{\mathrm{SM}} \sim 10^{-32}$ e · cm

$d_n^{\mathrm{meas}} < 1.8 \times 10^{-25}$ e · cm

↓

$l \sim 2.7 \times 10^{-12}$ fm

($\sim 22\mu$m if a neutron was the size of the earth.)

Finding a non-zero nEDM immediately signals new physics!

$$\vec{\mu} = \mu \frac{\vec{J}}{J}$$

$$\vec{d} = d \frac{\vec{J}}{J}$$

$$\widehat{C}\psi_p = \psi_{\overline{p}}$$

$$\widehat{P}\,\psi_p(x,y,z) = \psi(-x,-y,-z)$$

$$\widehat{T}\,\psi_p(y) = \psi(-t)$$

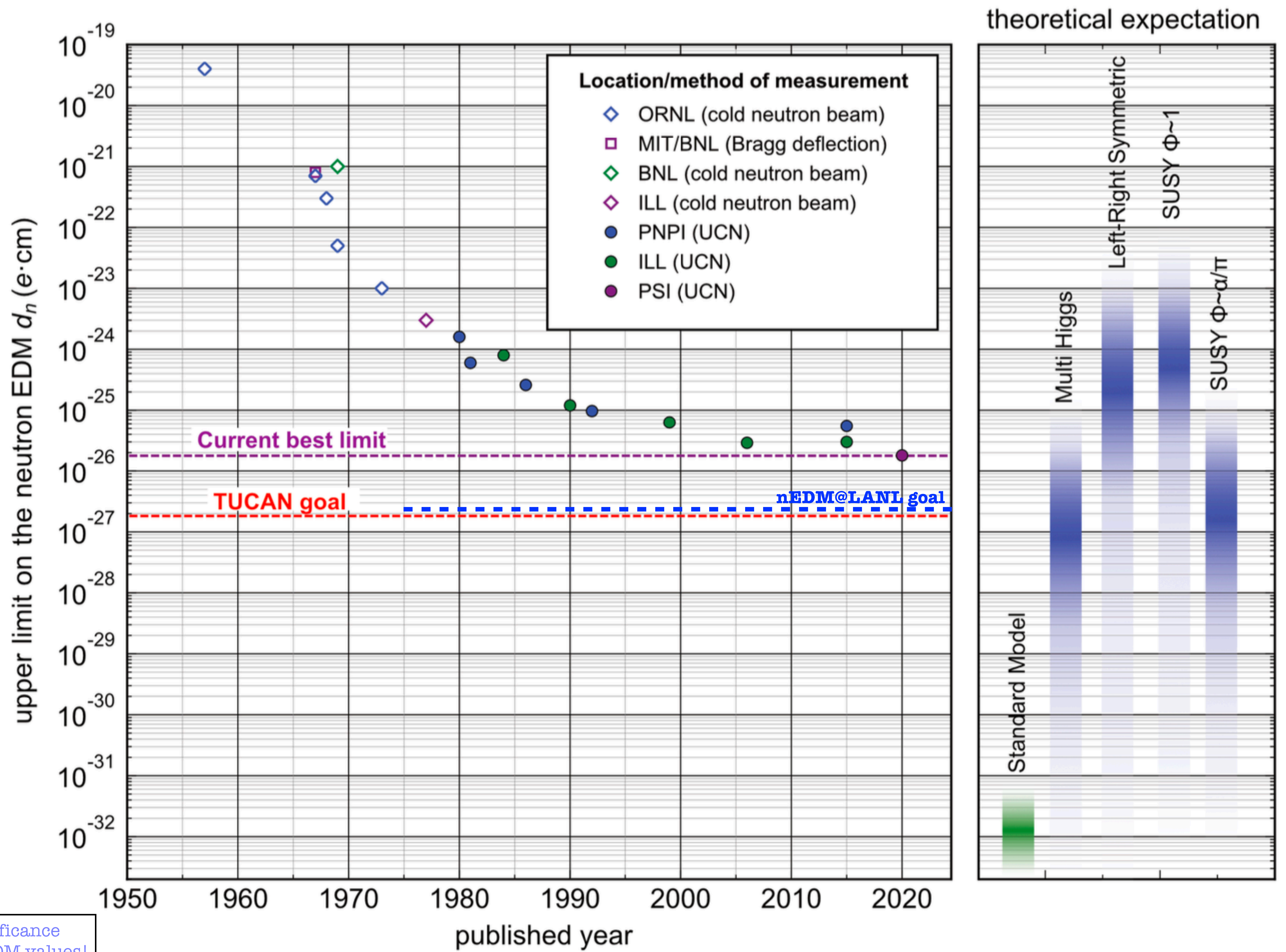
$$H = -\underbrace{\vec{\mu}\cdot\vec{B}}_{} - \underbrace{\vec{d}\cdot\vec{E}}_{}$$

$\vec{\mu}\cdot\vec{B}$	$\vec{d}\cdot\vec{E}$
C-even	C-even
P-even	P-odd
T-even	T-odd

$\Longrightarrow\ d \neq 0$ violates T and CP symmetry

	C	P	T
$\vec{\mu}$	−	+	−
$\vec{d}$	−	+	−
$\vec{E}$	−	−	+
$\vec{B}$	−	+	−
$\vec{J}$	+	+	−

Search for a neutron Electric Dipole Moment (nEDM)



NB Watch out for the significance level when comparing nEDM values!

S. Sidhu, *Improving the statistical sensitivity reach* of the TUCAN neutron electric dipole moment experiment, M.Sc. Simon Frasier University, 2023

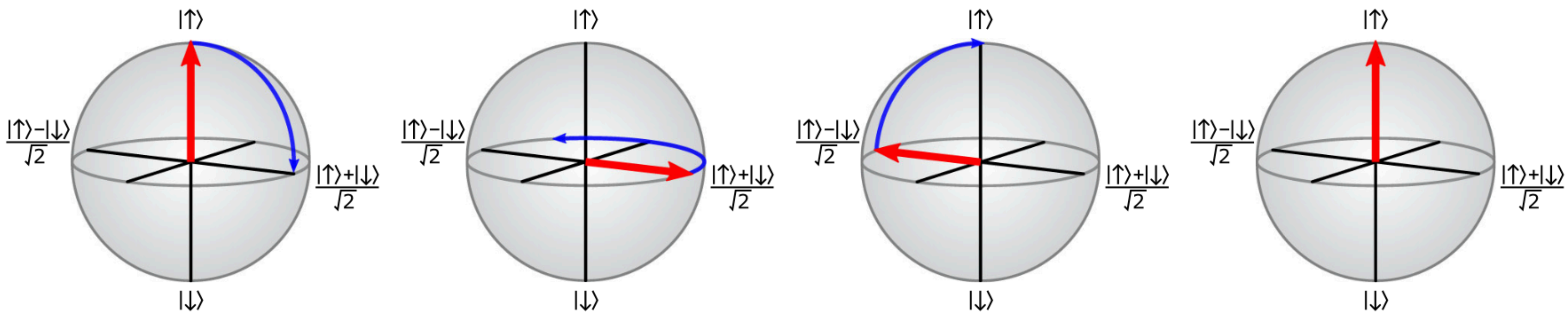
nEDM: "Ramsey Separated Oscillating Fields"

Highest precision measurements currently use UCN

$B_1 \approx 1\ \mu\mathrm{T} \Longrightarrow \omega_L \sim 30$ Hz

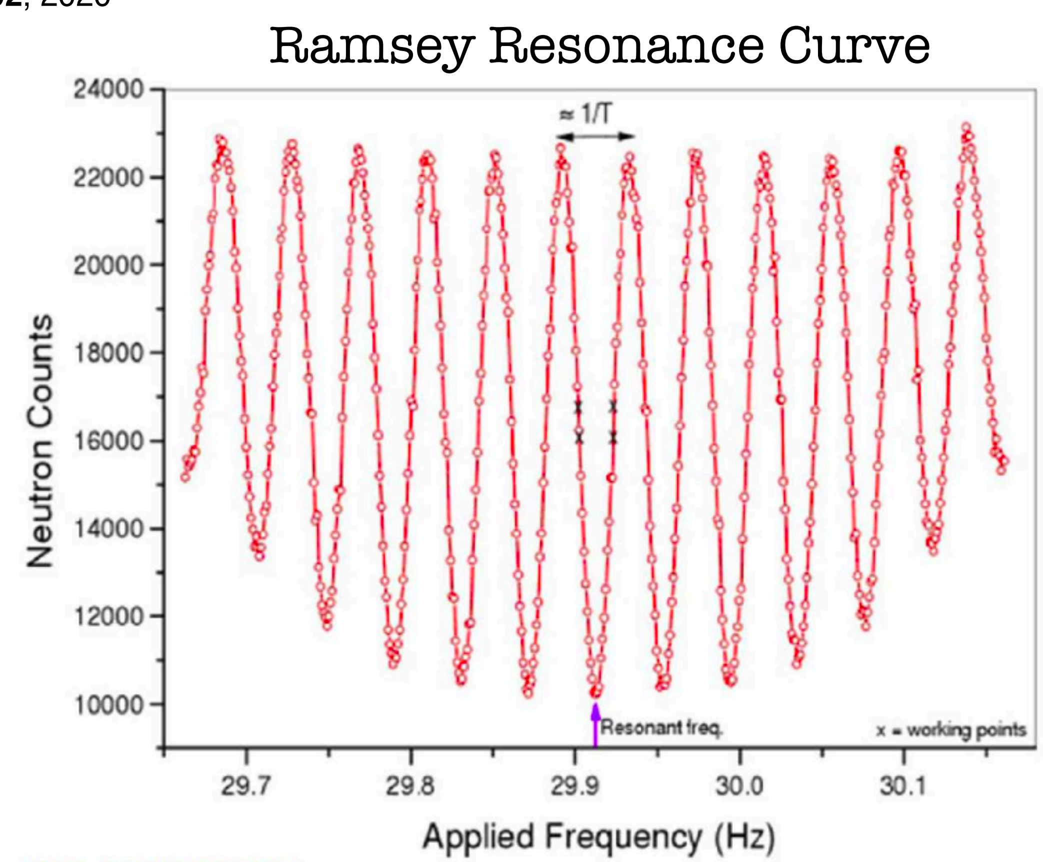
$T_{\mathrm{free}} \sim 180$ s

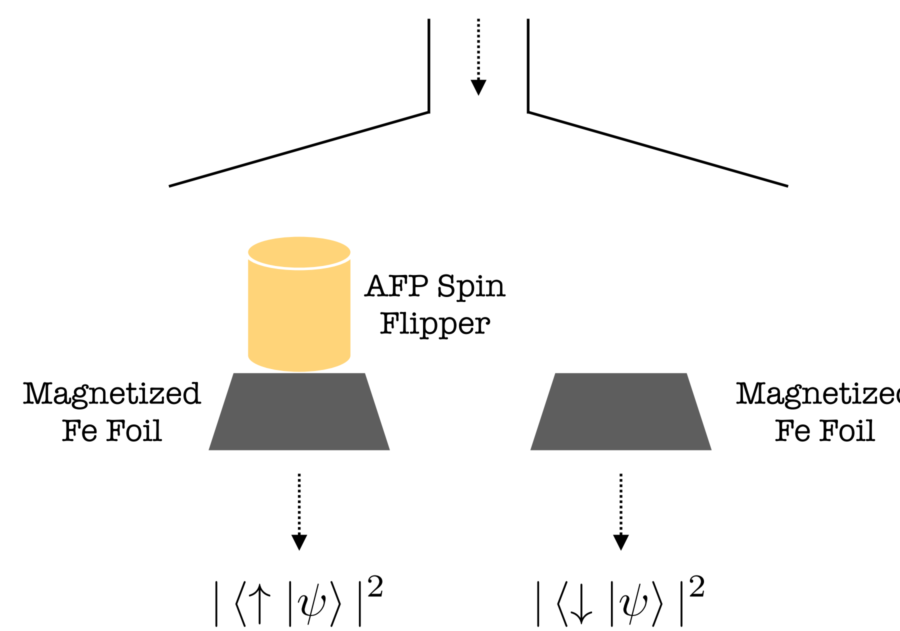
Initial π/2-pulse	Free precession inverval τ	Final π/2-pulse	Spin state readout
$B_{\mathrm{rf}} \sim 4$ nT, $T_{\mathrm{rf}} \sim 2$ s			$B_{\mathrm{rf}} \sim 4$ nT, $T_{\mathrm{rf}} \sim 2$ s



$B_1 \approx 1\ \mu\mathrm{T} \Longrightarrow \omega_L \sim 30$ Hz

J. Barry, et al., *Reviews of Modern Physics*, **92**, 2020

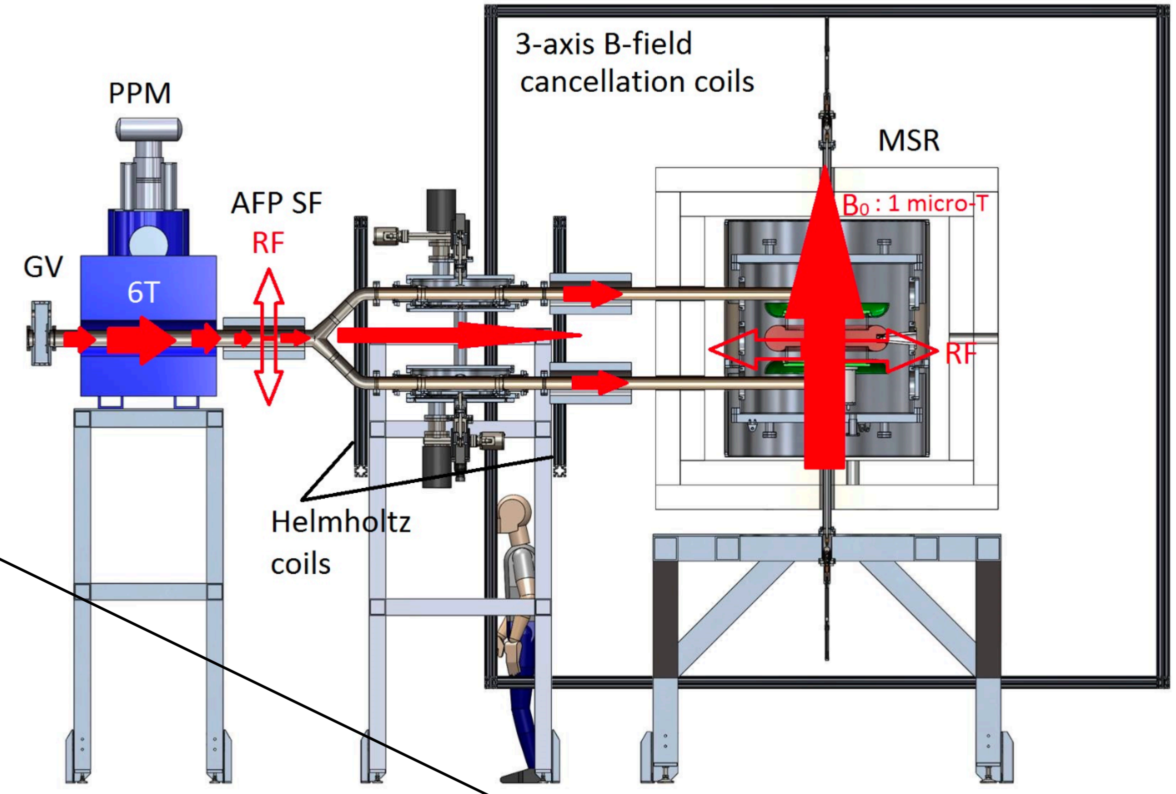




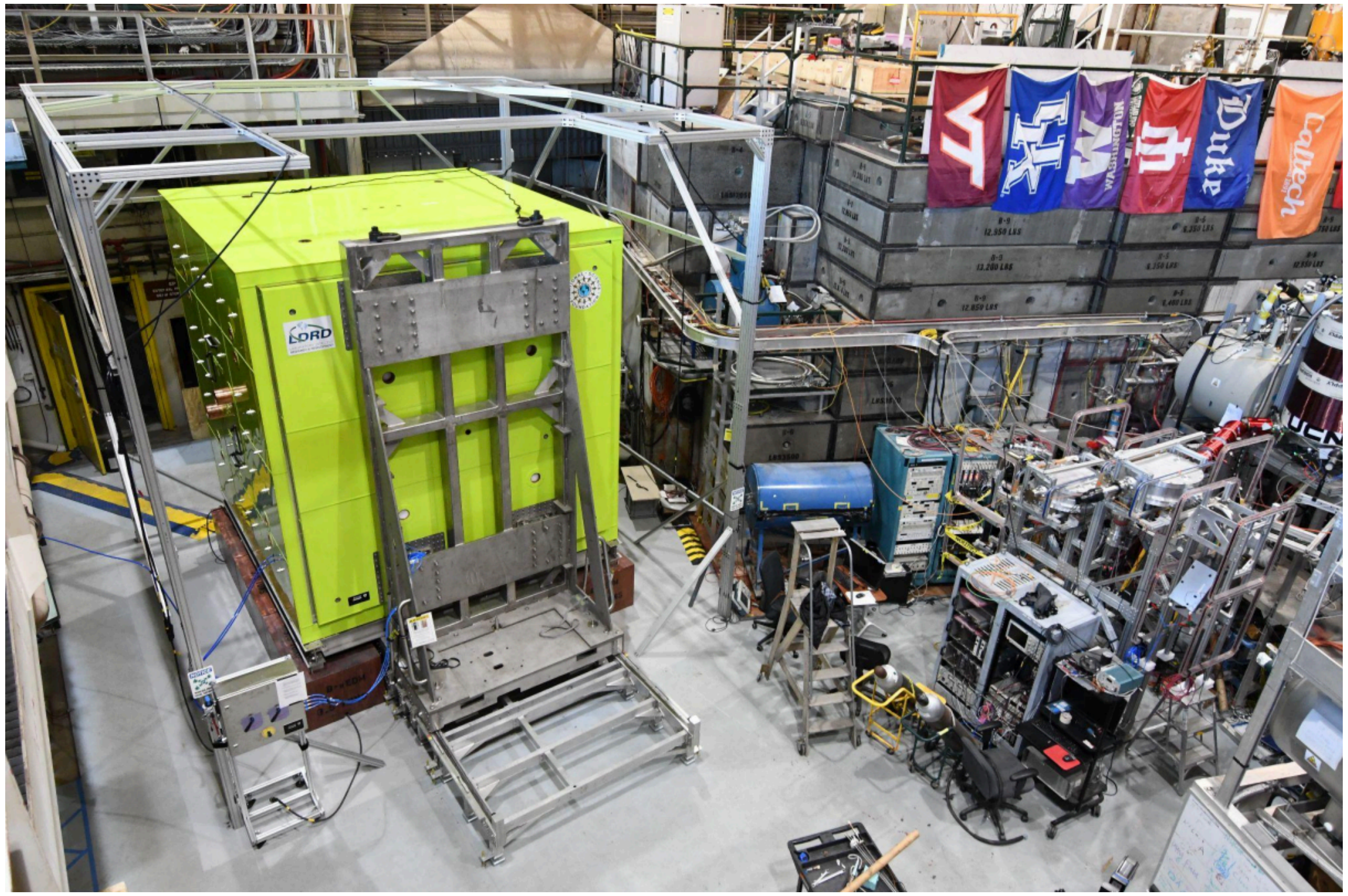
nEDM at LANL

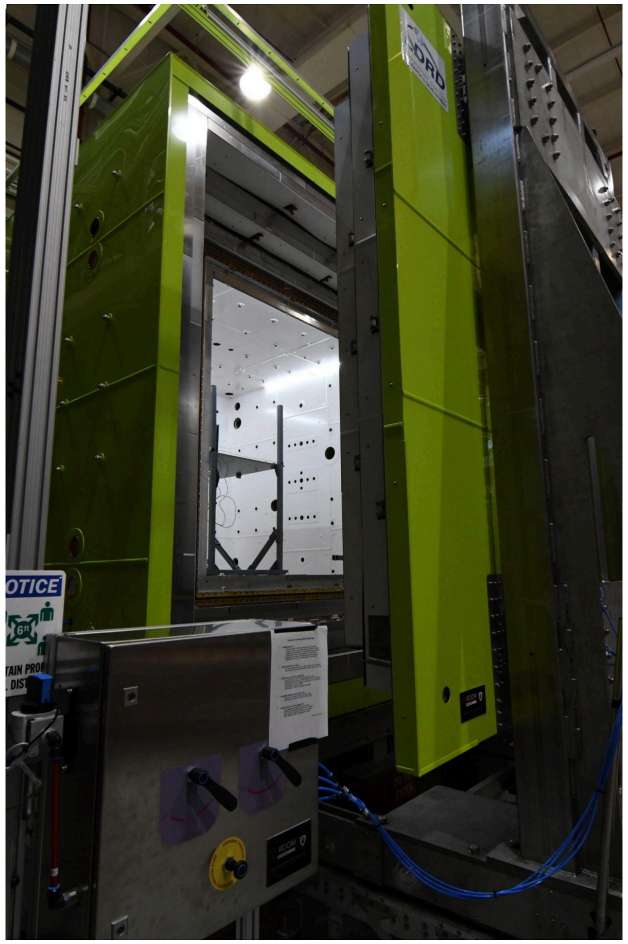
Parameter	Symbol	Units	Values
Electric field	E	kV/cm	12
UCN per chamber	N		39,000
Free Precession Time	T_{free}	s	180
Cycle Time	T_{cycle}	s	300
Polarization Product	$\alpha = AP_0$		0.8
Magnetic gradient	∇B	(nT/m)	0.3
Magnetic stability	ΔB	(fT/500 s)	50

$$\delta d_n = \frac{\hbar}{2\sqrt{2}} \cdot \frac{1}{AP} \cdot \frac{1}{E} \cdot \frac{1}{T_{\text{free}}} \cdot \frac{1}{\sqrt{N}}$$

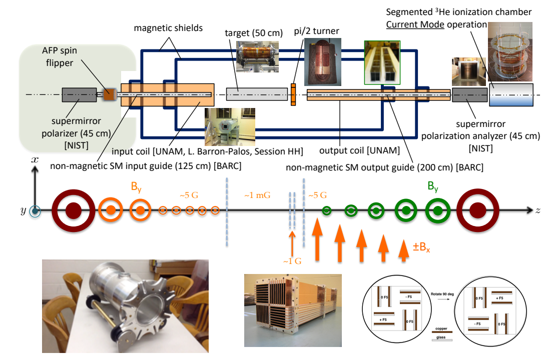


$B_r \propto |\vec{v} \times \vec{E}|$
+
"geometric phase"





Many More Non-Decay Experiments!



C. Haddock, et al., Physics Letters B **783** (2018) 227-233

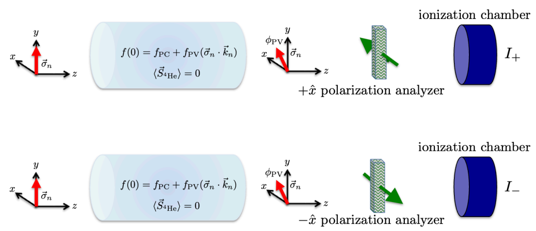
- Exotic spin-dependent force from vector boson exchange

$$V_{AA} \propto g_A^2\, \vec{\sigma} \cdot (\vec{v} \times \hat{r}) \left(\frac{1}{\lambda} + \frac{1}{r}\right) \frac{e^{-r/\lambda}}{r}$$

- Hadronic Weak Interactions

Probe low-energy QCD with Weak Interaction

$$f(0) = f_{\rm PC} + f_{\rm PV}(\vec{\sigma}_n \cdot \vec{k}_n)$$



Parity Violating Spin Rotation

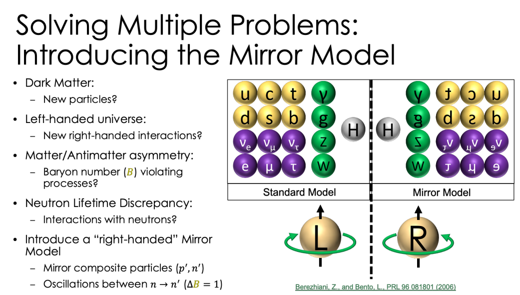
W.M. Snow, et al., Rev. Sci. Instrum., **86**, 055101 (2015)

- Cold and ultracold neutrons
- High flux neutron sources
- Optical Potential
- Neutron "spin gymnastics"
- Systematics!
- "Simple" detector systems
- Also epithermal neutrons… which means resonances!

} NR QM

- Mirror Neutrons

Dark Matter, B-violation, Lifetime ~~X~~ Puzzle

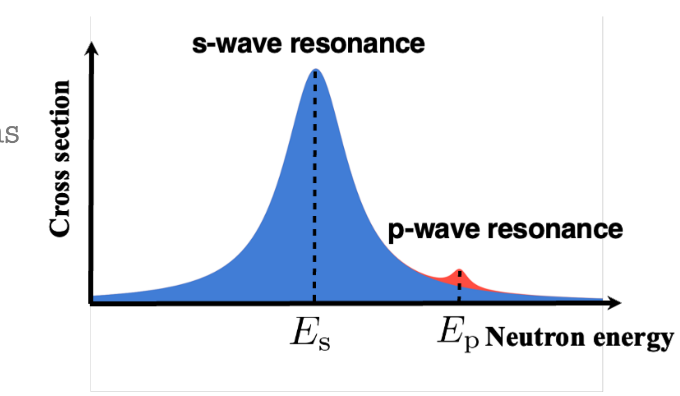


F. Gonzalez, et al., arXiv:2402.15981v1 [hep-ex] 25 Feb 2024

- NOPTREX: Neuton Optical Parity and Time-Reversal EXperiment

P-odd/T-even, P-odd/T-odd, P-even/T-odd nucleon-nucleon interactions in polarized neutron optics
Enhancement from compound p-wave nuclear resonances in polarized heavy nuclei with polarized epithermal neutrons

W. M. Snow, C. Haddock, and B. Heacock, **Searches for Exotic Interaction Using Neutrons**, invited paper, Special Issue: The Neutron Physics - Dark Matter Connection: Bridge Through the Baryon Symmetry Violation, Symmetry **14**, 10 (2021)



- Short Range Forces: Neutron Interferometry

Yukawa-Modified Gravity (20 pm - 10 nm)

B. Heacock et al., Science, **373**(6560), 1239-1243