Cryogenic UCN storage, super-thermal production, and live spin analysis for measurements of static nEDMs, oscillating EDMs, and the neutron magnetic moment

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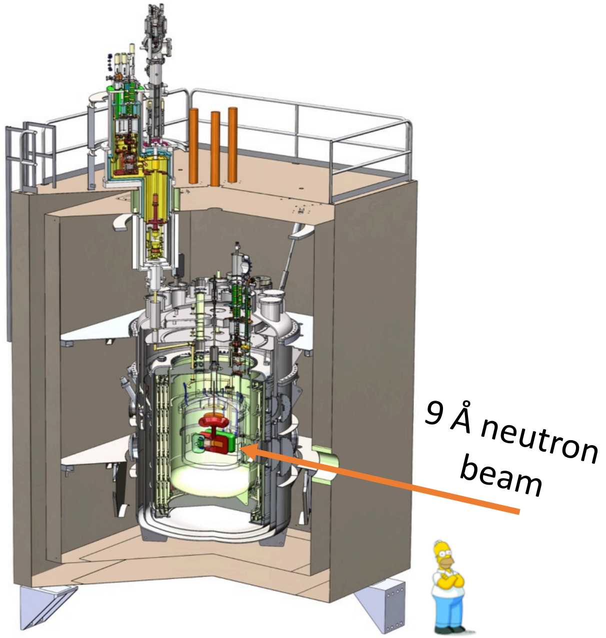
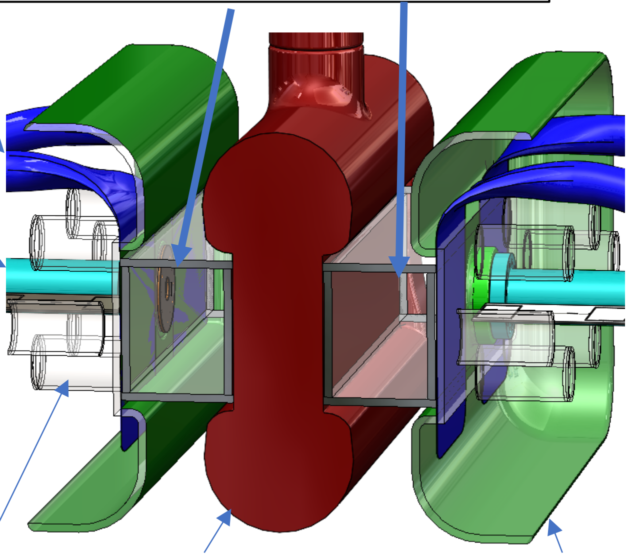
“Les Houches” nEDM2021 workshop, 2021-02-16

The nEDM@SNS experiment



2x measurement cells:
inner 7.5 cm (W), 10 cm (H), 40 cm (D)
filled with UCN, ~ 0.4 K sf4He, and 3He ~ 10^{-10}



Golub & Lamoreaux’s technique: polarized **UCN** + polarized ^{3}**He** atoms + superfluid ^{4}**He**

Statistical “shot noise” limit: $$\sigma(d_n) \sim \frac{\hbar}{2\alpha E T \sqrt{N}}$$

$E = \text{electric field}$ (75 kV/cm thanks to sf-^{4}He. See Ito, Riley, Blatnik, Korsch talks.)

$\alpha = \text{polarization contrast}$ (UCN polarization ~ 98%)

$T = \text{precession time}$ (goal to use 1000 sec if wall loss times low enough)

$N = \text{no. detected neutrons}$ (high density from in-situ super-thermal production & accumulation. Density increases with $\tau_{storage}$. No need to transport. But “filling” time is ~ 1000 sec)

Polarized ^{3}He (~ 98%) serves as in-situ & live UCN spin analyzer (new type of signal!)

Low temperature (~ 0.4 K): SQUIDs and superconducting magnetic shielding

^{3}He + SQUIDs as co-magnetometer. Small changes of sf^{4}He temperature causes large changes (~ $T^{7.5}$) of ^{3}He mean-free-path as dominated by ^{3}He-phonon scattering. Great for co-magnetometer systematic checks .

Overview

- Measurement cells: UCN storage and reduction of neutron beam-induced activation
- *in-situ* & live UCN spin analysis: a new type of precession signal (simulations)
- Advantages in searching for time-oscillating nEDMs & extraction of γ_{n}/γ_{3He}

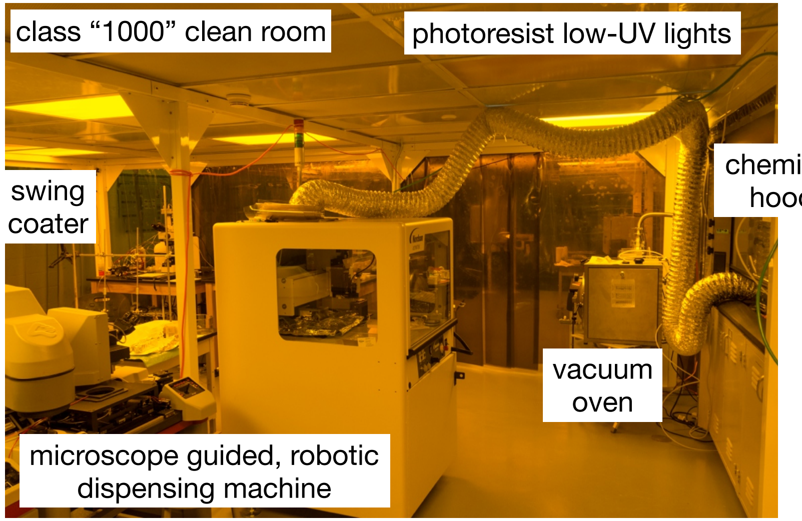
Central themes: UCN storage, measurement cells, super-thermal production in 4He, and signal analysis

Measurement cells

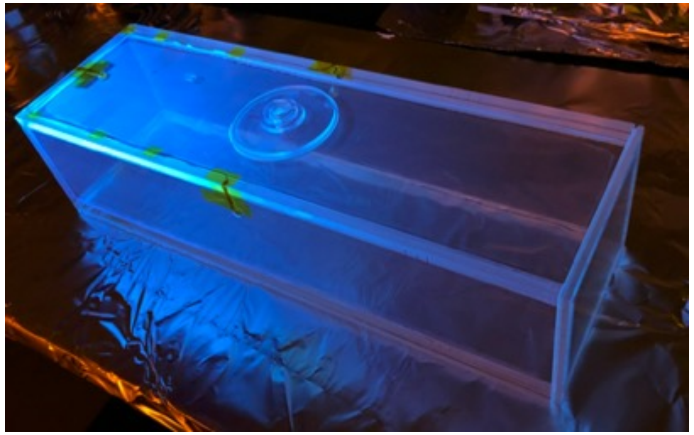
- Dimensions optimized for statistics and systematics. (e.g. E-field, diffusion-limit L^{-4} dependence of T_2 time & L^2 dependence of false EDM, magnetic field gradients, etc.).
- Cells separate from electrodes (cooling needed for heat flush)

Inner coating	~ 1 um thick d-TPB embedded in d-PS matrix	Non-magnetic and not electrically conductive. Deuteration for high Fermi potential (165 neV from neutron reflectometry). TPB for detection of 80 nm ^{4}He scintillation light (see Ito, Cianciolo, Loomis talks)
Side walls	~ 1 cm thick p-PMMA plates	Optical photon transmission, mechanical strength, and purity. “Swing coating” on flat plates produce surface finish ~ 5 nm RMS roughness (AFM measured)
End windows	~ 5 mm thick d-PMMA	reduce activation caused by scattering of 9 Å beam
Sealed cell	deuterated solvent cemented	to separate 10^{-10} polarized ^{3}He inside cell from unpolarized natural-abundance ^{3}He
Cell hole	~ 1 cm opening	initial 4He filling then loading/unloading 3He via heat flush. Low UCN loss.

Cell production facilities in clean room



Full-sized test measurement cell (illuminated by 360 nm UV lamp). Temperature sensors embedded from outside for tests.



*p- & d- refers to “protonated” or fully-deuterated versions of a material.

PMMA = poly(methyl methacrylate), more commonly-known by tradenames acrylic or plexiglass.

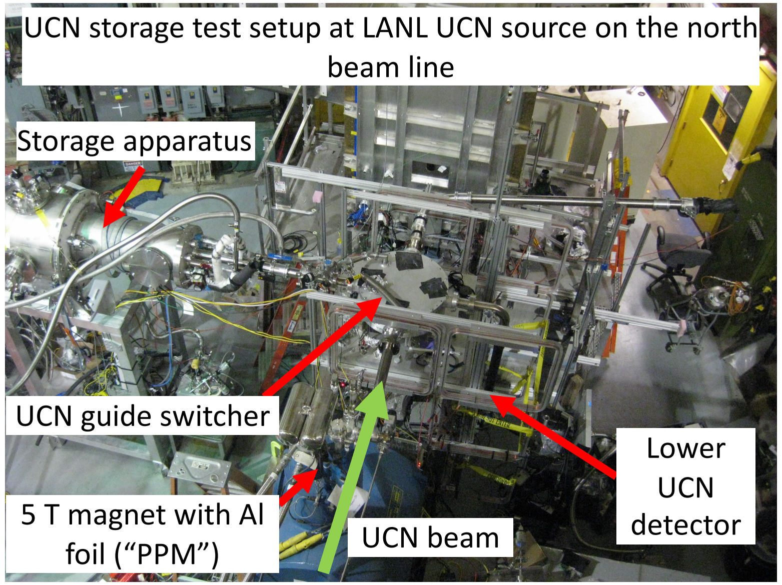
PS = polystyrene.

TPB = tetraphenyl butadiene, an electroluminescent dye

Cryogenic UCN storage tests with external UCN source

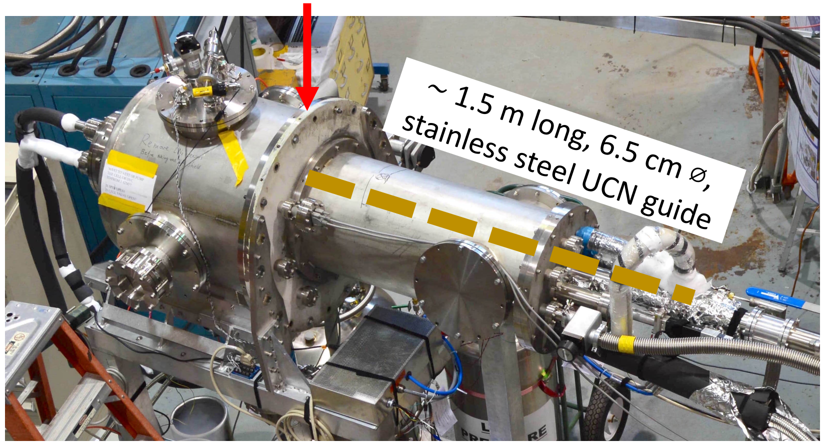
Thanks to collaborators: Cianciolo, Clayton, Cooper, Curie, Golub, Griffith, Huffman, Ito, Korobkina, Makela, McDonald, O'Shaughnessy, Pentilla, Ramsey, Smith, Stanislaus, Tang, Weaver, Wei

- A **cryogenic UCN storage apparatus** used with the **Los Alamos National Lab. solid-D_2 UCN source**.
- **Standard fill-and-empty setup** with cell valve & UCN guide switcher to connect (1) UCN source to cell or (2) cell to lower UCN detector
- **Cells cooled by spring-loaded cooling plates coupled to flowing L^4He line**. Cells reach nominal 30 K in ~ 3 days (but can reach 15 K with high L^4He rate).
- Dry & clean vacuum system: in vacuum outside cell, P ~ 5 x 10^{-7} mbar before starting to cool cell. Outgassing dominated by plastic.
- Pumping inside cell restricted due to 1-cm cell hole & UCN guides. Put UCN guide switcher in "intermediate" position for increased cell pumping speed.
- **Cells are heated** to 50 degC (coating limit) and **pumped for 10-14 days** before cooling.
- The input L4He flow is split, **a region of stainless steel UCN guide ~20 cm away from the cell is maintained to be coldest point in the system** (nominally > 20 K colder than cell). This SS surface **acts as a cryopump** for pumping out cell and **traps condensable-contamination** from reaching inside cell.

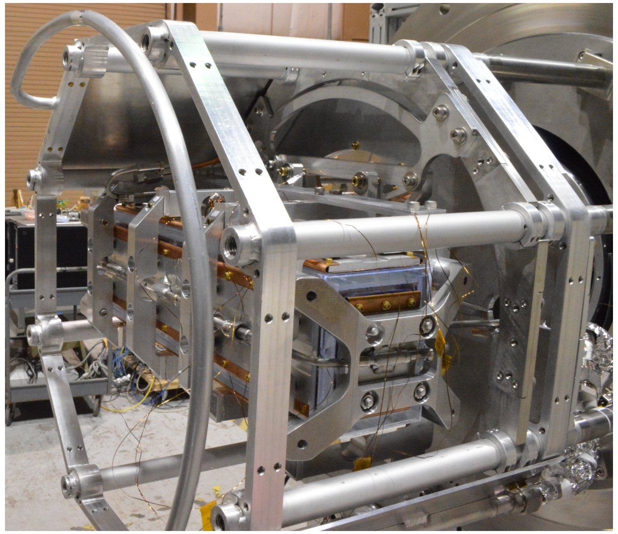


UCN storage test setup at LANL UCN source on the north beam line

Slide-openable vacuum vessel with flowing LN_2 radiation shield (80 K & ~ 3π sr coverage)



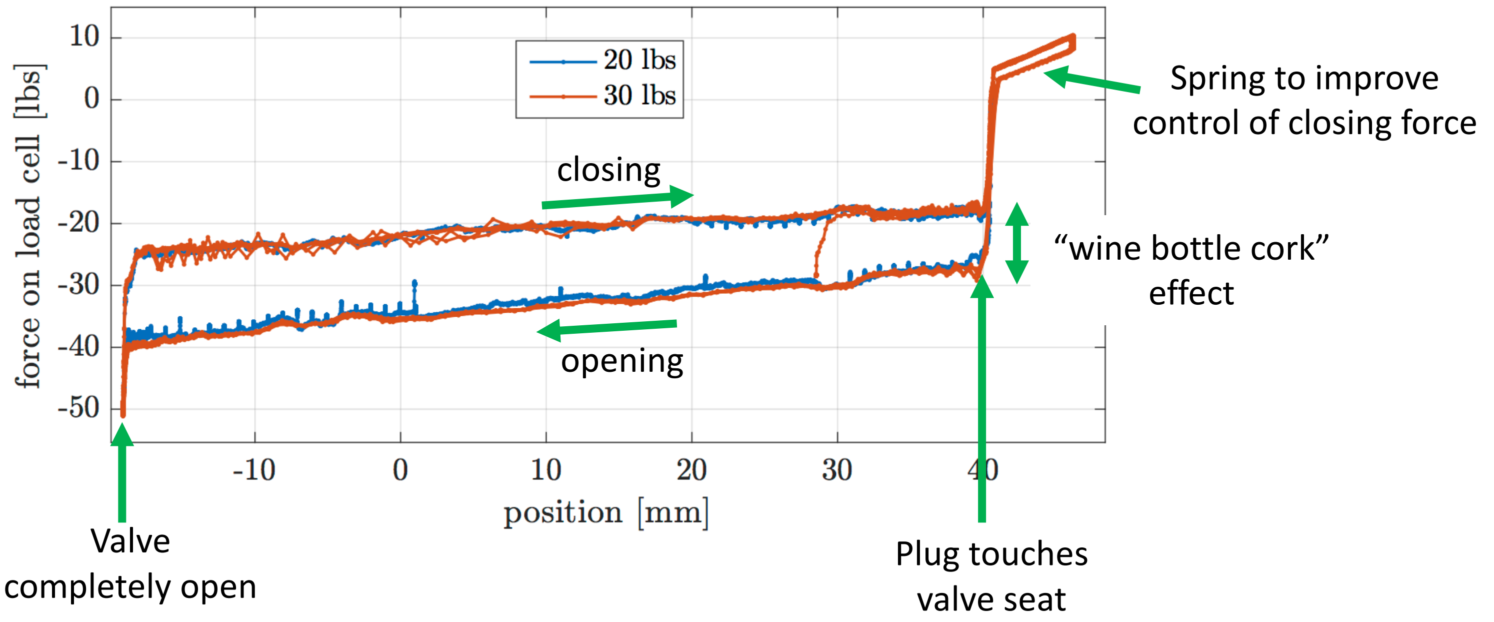
Spring loaded cooling plates used to maintain contact with cell
Return L4He cools another radiation shield (50 K)

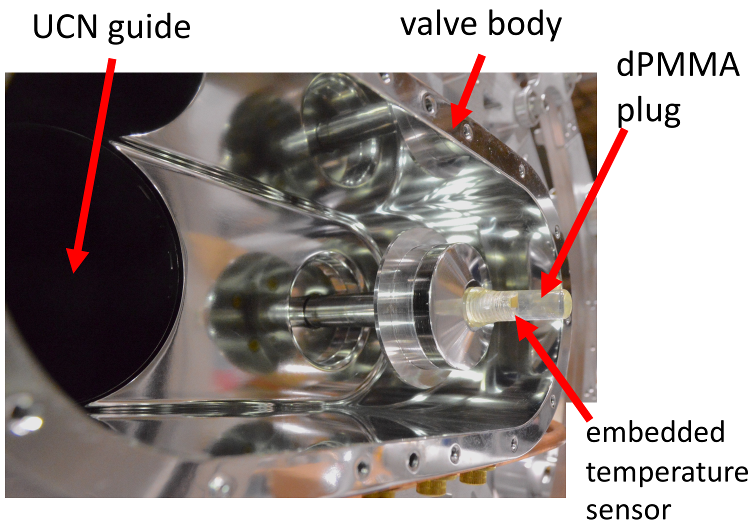


Deuterated plastic cell valve

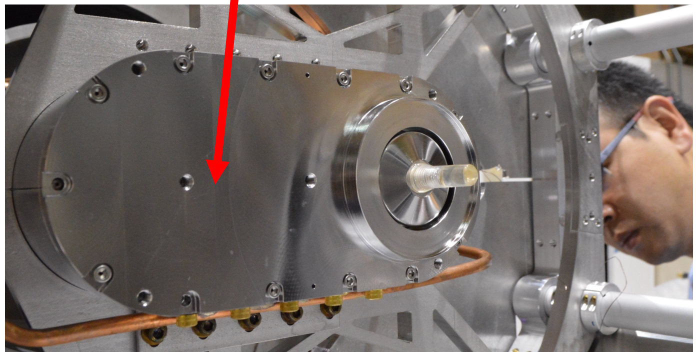
- The cell-valve body is stainless steel 180 neV (eventually it will be plastic)
- Valve **plug is bulk-dPMMA** & **valve seat is bulk-dPMMA ring** solvent-welded to cell.
- Linear motion controlled by servo-motor actuator with optical encoder (< 0.1 mm precision). Force is measured with a load cell. **Precise control of position, force, and speed of the valve.**

Force on valve actuator vs actuator position





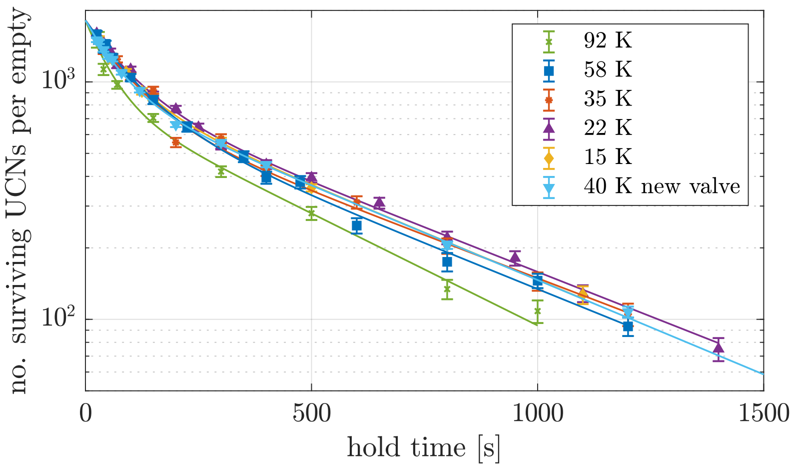
SS plate closing off valve body



UCN storage results

(Data normalized so number of UCNs at t=0 extrapolated with double exponential fit are matched. The value chosen at t=0 is average of the different storage curves with same cell, measured over consecutive days)

2nd generation cell #2

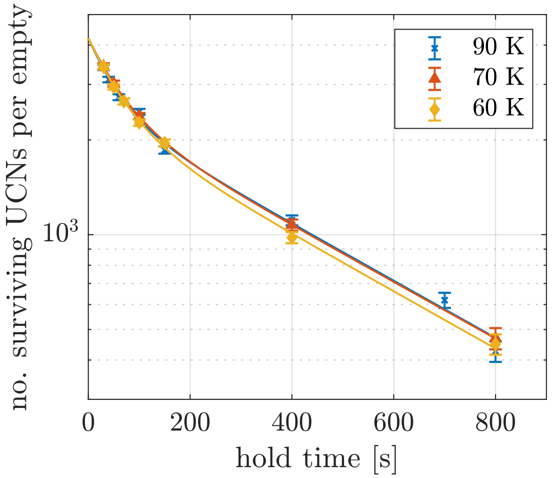


- Beam position: behind UCNτ
- Measured with old and new valve systems

Fitting 40 K data:

N_{short} = (50 ± 2) % , τ_{short} = (73 ± 7) s
N_{long} = (50 ± 2) %, τ_{long} = (546 ± 16) s

2nd generation cell #3

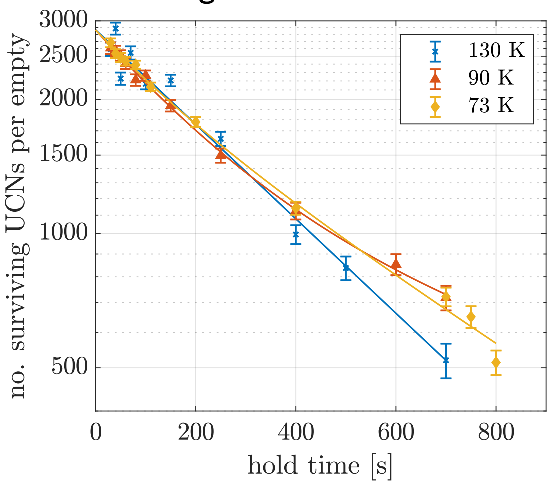


- Beam position: north beam line
- dPMMA valve system

Fitting 60 K data:

N_{short} = (45 ± 4) % , τ_{short} = (66 ± 16) s
N_{long} = (55 ± 4) %, τ_{long} = (477 ± 47) s

2nd generation cell #4



- Beam position: north beam line
- dPMMA valve system
- Reduced dust contamination during cell production

Fitting 73 K data:

N_{short} = (24 ± 28) % , τ_{short} = (170 ± 190) s
N_{long} = (76 ± 28) %, τ_{long} = (590 ± 190) s
OR
$\tau_{single\text{-}exp}$ = (490 ± 11) s

- Either sum of two exponential decays ("long" and "short") or single-exponential fit.
- When sum of two exp decays, strong correlations between fitted parameters
- When cell not cooled, $\tau_{single\text{-}exp}$ = (130 ± 5) s
- Storage times here are β-decay + cell wall losses

Interpretation of results

- High quality set of cryogenic UCN storage data with a new type of deuterated polymer coated surface (V_F = 165 neV, fluorescent, ^{3}He polarization friendly) exhibiting excellent UCN storage properties. Cell #4 with $\tau_{single\text{-}exp}$ = (490 ± 11) s => **loss per reflection ~ 2 x 10^{-5}**

- **Standard UCN-energy-dependent wall loss theory** (i.e. f = W/V_F description) **insufficient** for describing data exhibiting **strong double-exponential decay**.

- From crude information on UCN spectrum, we deduce it is the higher-energy UCNs in the τ_{short} component. Commonly explained away by above-trapping threshold UCNs but the time scales here are very long for our rectangular cells.

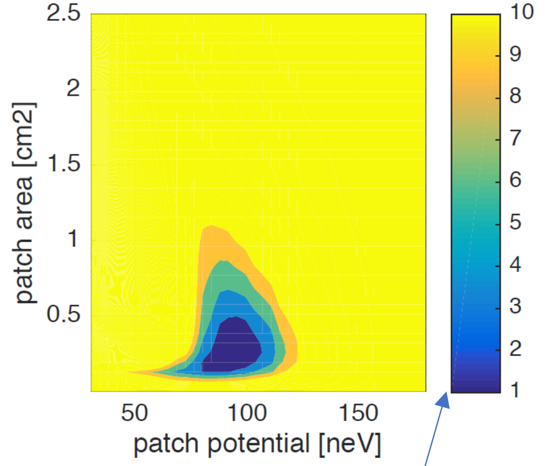
- Most promising **<u>model</u> found so far has been fitting with a small area "patch"** (~ 0.3 cm^2) with **low V_F** (~ 100 neV) exposed to UCNs

- Patch parameters very similar between cells #2 & #3

- Possible theories for cell #4:
  - (1) τ_{short} component very short, so not visible since shortest hold time is 25 sec (patch area > 3x larger)
  - (2) τ_{short} component very long or non-existent (difficult to fit for. Would need patch 5x smaller)
  - (3) higher UCN energies not loaded into the cell in the first place.

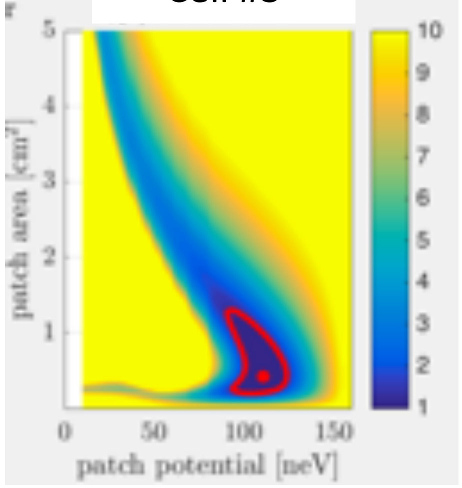
- Currently developing UCN tracking simulations to increase understanding. Possibly use UCN spectrometer in future experiments.

Cell #2



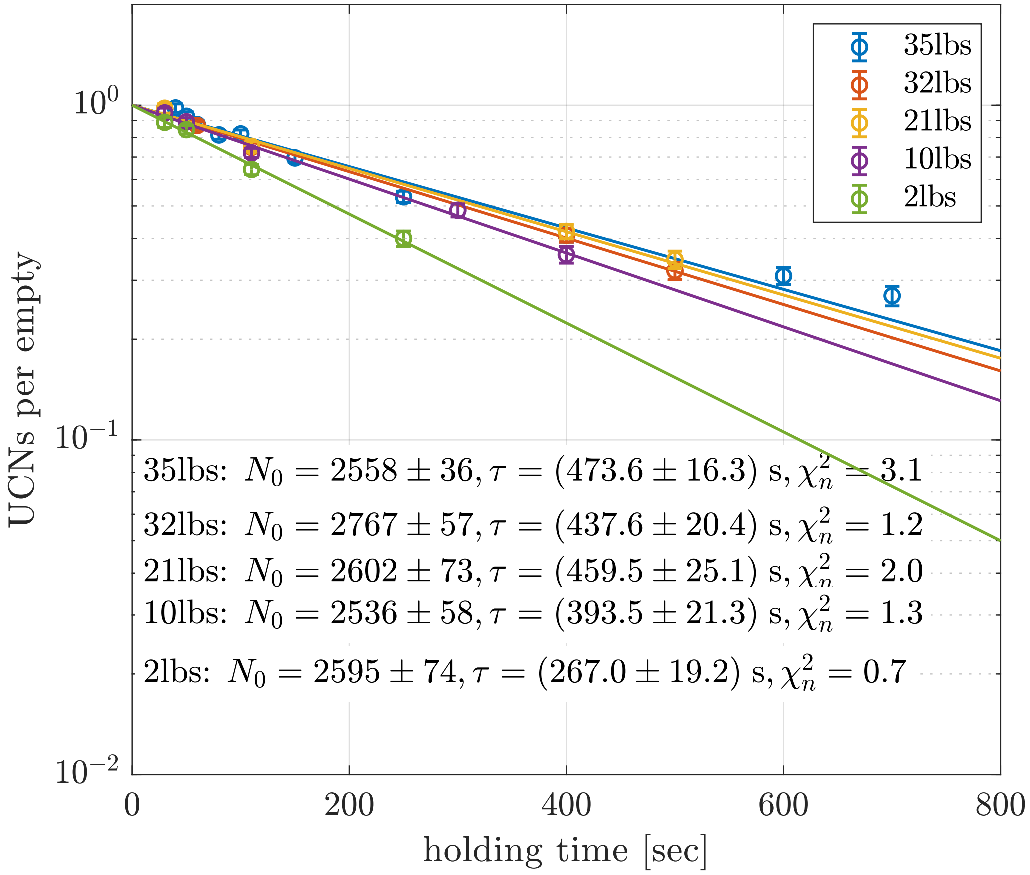
χ^2/dof contours

Cell #3



dPMMA UCN cell valve results

- These results show we have **learned to implement a UCN valve with negligible UCN loss**
- The leak tightness of the valve is more stringent for containing ^{3}He inside the cell in final experiment (v ~ 30 m/s)



9 Å neutron beam induced cell activation in final experiment

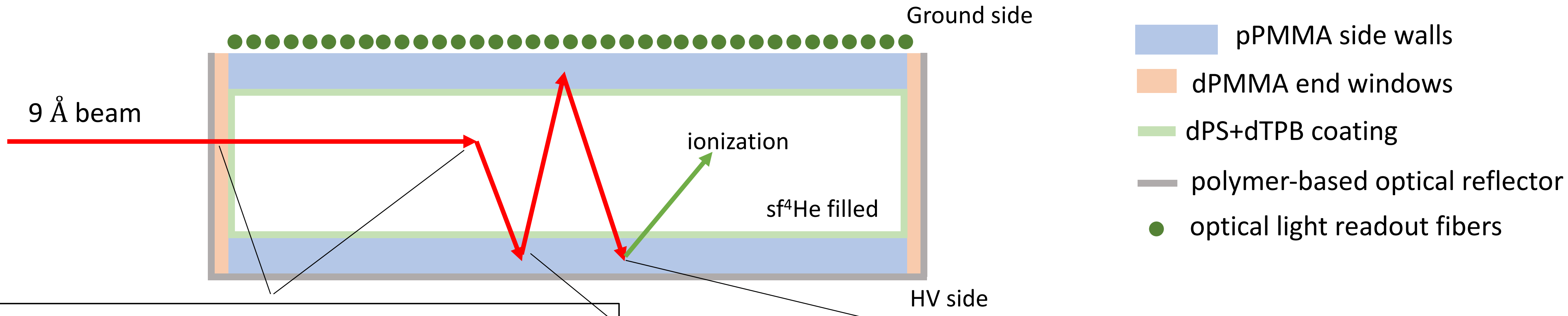
- In-situ UCN production via super-thermal production in sf^{4}He by 9 Å beam (via choppers) offers many advantages:

High UCN density ~ 150 UCN/cm^3 after 1000 s of "filling time"

No UCN or depolarization loss from transport

Spatial spread of beam and filling time reduces phase-space evolution at start of precession measurements

- The beam intensity is 5 x 10^5 s^{-1} in each cell (UCN production P = 0.31 UCN/cm^3/s), so T_{fill} = 1000 s -> 5 x 10^5 neutrons incident



Scattering in sf4He (coherent inelastic scattering).
Mean-free-path = 20 m, 40 cm cell, 2%.
OR
Scattering in dPMMA windows (mix coherent elastic scattering & incoherent elastic scattering). ~ 1% depending on window thickness
OR
Direct activation of impurities in dPMMA with decay chains

Cold neutrons bounce around via incoherent elastic off ^{1}H

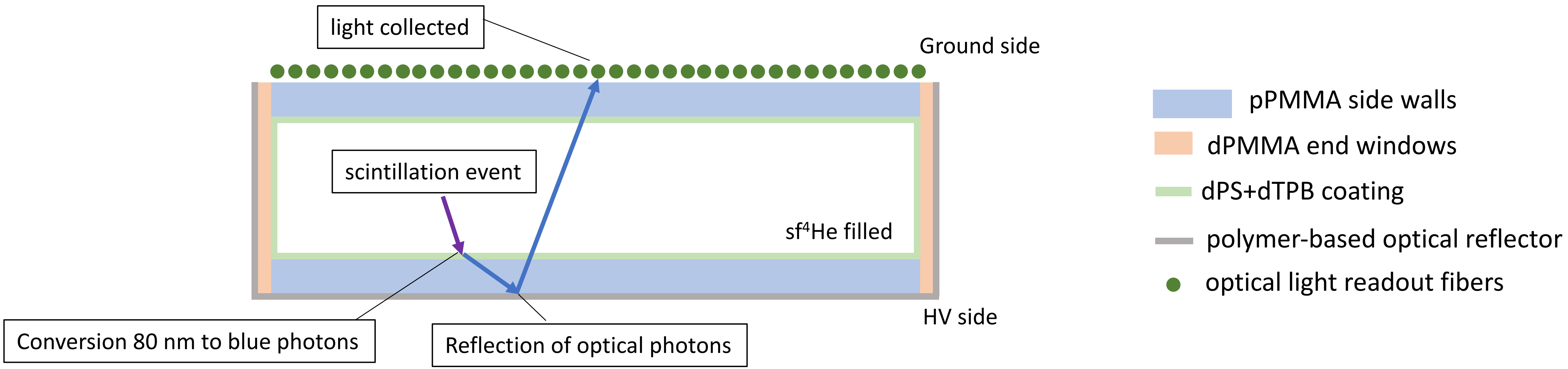
Eventually n+p -> D + γ (2.2 MeV) + other prompt-reactions => can produce free charge in cell
OR
n + contaminant -> short or long lived decay chain => delayed background scintillation events

(see Korsch & Loomis talks)

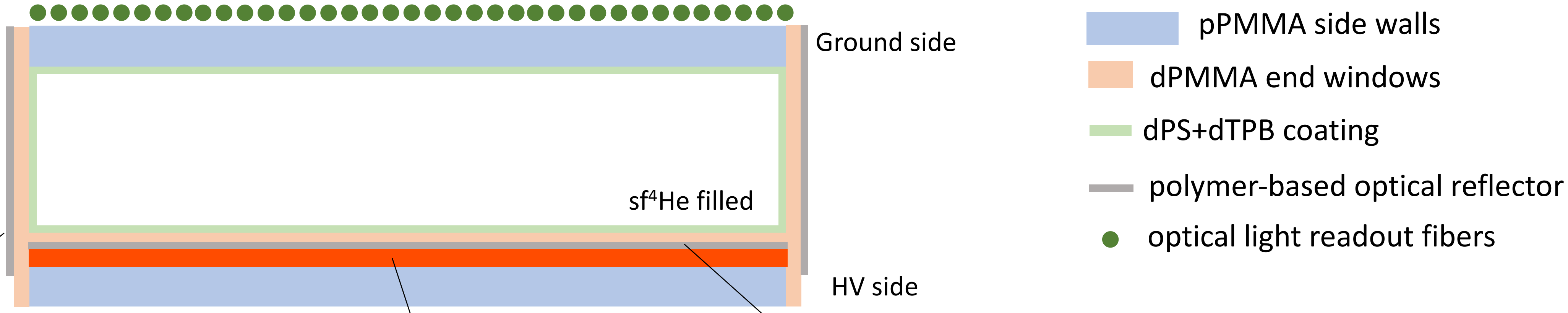
Note: we developed L^{4}He MCNP neutron scattering kernels to 4 K. (Thanks to C. Lavelle from Johns Hopkins!)

How scintillation light is collected in measurement cell

(see Cianciolo talk)



Solution to problem

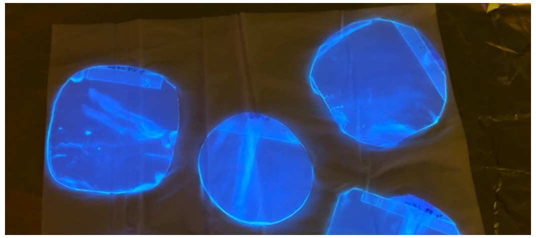


Make dPMMA end windows thin (~ 0.5 - 1 mm) & very pure

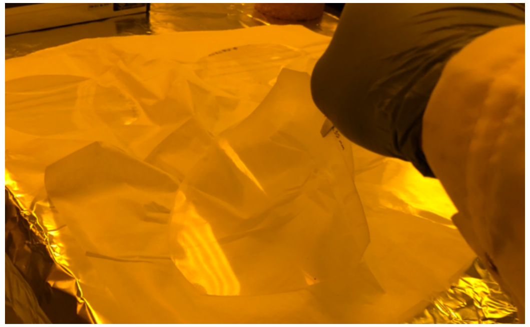
Embed ^{6}Li cold neutron absorbing layer (1-2mm thick) close to inside of cell (but UCNs can't reach)

Place optical reflector between dPS+dTPB coating and (non-optically transparent) n-absorbing layer

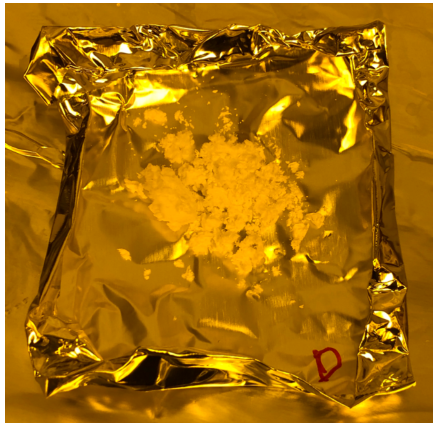
Coated thin end PMMA windows



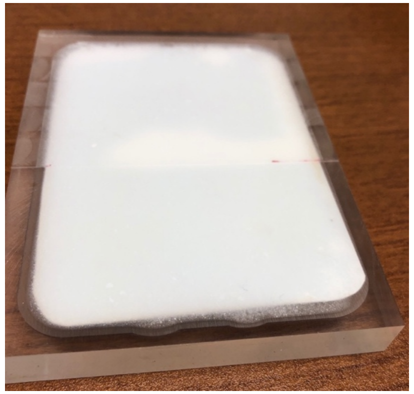
LN2 dunk and strength tests

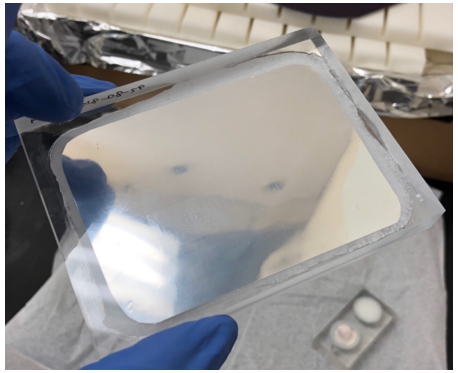


In-house synthesis of high-purity dPMMA



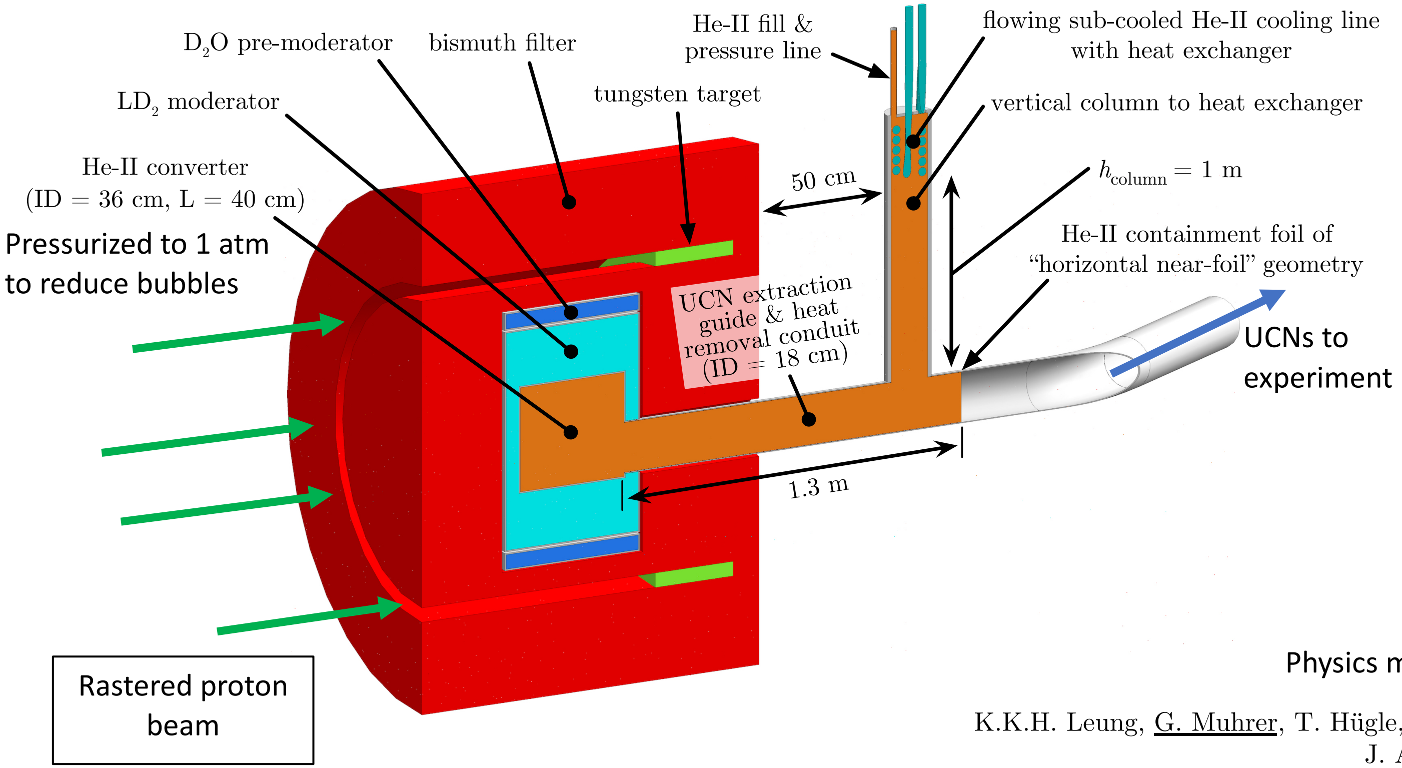
1/3rd scale prototype side wall with embedded LiOH absorber and optical reflector





High UCN-current, "inverse spallation target geometry", sf-^{4}He source (small digression)

- Take **1 MW proton beam** @ 800 MeV energy (available SNS/LANL/Fermilab)
- 40 L sf-^{4}He bath with **100 W @ 1.6 K using sub-cooled helium technology** (e.g. common at LHC, JLab, SNS, Fermilab, ESS)
- At 1.6 K, up-scattering $\tau_{up} \approx$ 3 s, **optimize for a maximum current UCN source (pessimistically assume single passage transport only)**
- **Raster proton beam** on "ring" shaped tungsten spallation target allows **edge water cooling**
- Total UCN production rate in sf-^{4}He is **1.8 x 10^9 UCN/s**.
- UCN delivery, **5 m away in 18 cm diameter guide**, from UCN simulations is **5 x 10^8 UCN/s** (1-passage efficiency 28%. Foil ~ 68% transmission.)



*^{58}Ni cut-off potential & unpolarized

Delivered equilibrium UCN density to external bottle with 18 cm hole:

V_{bottle} (l)	5	50	500	5×10^3	5×10^4
ρ_{bottle} ($\times 10^4$ UCN cm^{-3})	1.12	1.11	1.05	0.80	0.31
τ_{bottle} (s) (Filling time)	0.11	1.1	10	80	315

(pessimistically assume if UCN leaves volume then it is lost)

- Density doesn't drop until extremely large volumes
- If filling restricted by a small hole (e.g. 1 cm Ø => 200 s fill time) then need 1 **MW beam needed at ~ 10% duty**

Physics model (w/ minor engineering considerations) published in:

K.K.H. Leung, G. Muhrer, T. Hügle, T.M. Ito, E.M. Lutz, M. Makela, C.L. Morris, R.W. Pattie, A. Saunders, A.R. Young
J. Appl. Phys. 126, 224901 (2019). doi:10.1063/1.5109879

a new type of UCN precession signal:

***in-situ* & live spin analysis**

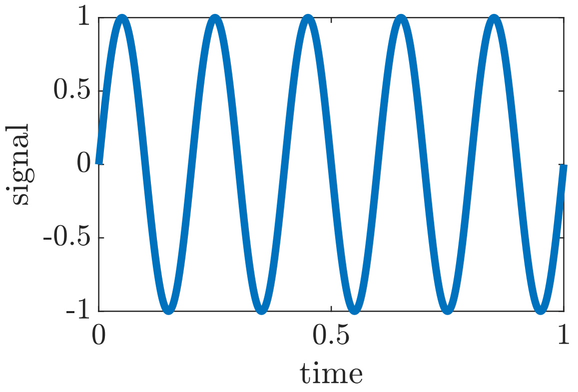
Difference between measuring phase vs frequency

- **Ramsey technique's observable is final phase (via UCN count, which is an amplitude):** $\phi_{nf} \equiv \phi_n(T_f) = \phi_{n0} + \int_{t'=0}^{T_f} \omega_n(t')\,\mathrm{d}t'$

Can only deduce *average* frequency: $\bar{\omega}_n = (\phi_{nf} - \phi_{n0})/T_f$

Can only tell you frequency with time if frequency is constant
(i.e. B-field & other systematics are constant within precession time)

- **"Always measure frequency…"** (Rabi? Ramsey? Wieman?) Why?

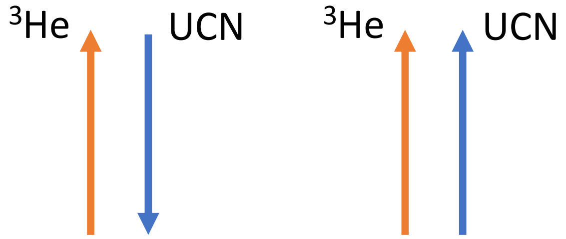


Changes of signal over short times suppresses drifts in system.

Don't need absolute signal size.

- **Live and in-situ UCN spin analysis with polarized ^{3}He:** measures throughout precession phase difference between ^{3}He analyzer & UCNs:

n + ^{3}He -> p + ^{3}H + 800 keV



$\sigma_{\uparrow\downarrow} \approx 800\,\mathrm{kb}$ $\quad$ $\sigma_{\uparrow\uparrow} \lesssim 0.02\,\sigma_{\uparrow\downarrow}$

$$\dot{N}_3(t) = \frac{N_n(t)}{\bar{\tau}_3}\left[1 - P_n(t)\,P_3(t)\,\cos\phi_{3n}(t)\right]$$

500 s is our optimum ~10^{-10} ^{3}He concentration

$$\phi_{3n}(t) \equiv \phi_3(t) - \phi_n(t)$$

$\phi_3(t)$ measured with SQUIDs
(^{3}He is a co-magnetometer also.)

<u>The spirit of frequency measurement lives!</u>
(via derivative)

Free-precession mode scintillation light

- After $\pi/2$ pulse, UCN & ^{3}He free precession: $\phi_{3n}(t) = \left[(|\gamma_3| - |\gamma_n|)B_0 \pm \frac{2d_n|E|}{\hbar}\right] t + \phi_{3n0}$ (ignoring shifts & drifts for now)

$$= \omega_{3n}^{\pm} t + \phi_{3n0}$$ ($\omega_3/(2\pi) \approx 100\,\mathrm{Hz}$ & $\omega_{3n}/(2\pi) \approx 10\,\mathrm{Hz}$ @ 30 mG)

acceptance probabilities 0.33 & 0.93

Background rate
(could be time-dependent)

- "accepted" rate of scintillation light events: $\dot{N}_{\mathrm{ac-s}}(t) = N_n(t)\left(\frac{\epsilon_\beta}{\tau_\beta} + \frac{\epsilon_3}{\bar{\tau}_3}\{1 - P_3(t)P_n(t)\cos[\theta_{3n}(t) + \phi_{3n0}]\}\right) + R_{\mathrm{BG}}$

no. UCNs in cell

recall: 500 s

polarizations

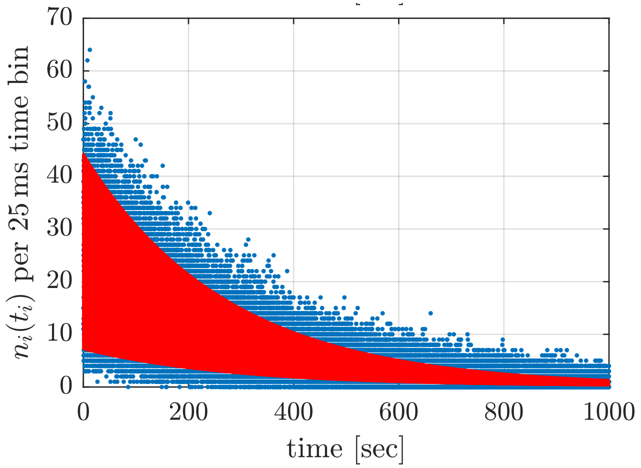
$$P_3(t)P_n(t) = P_{30}P_{n0}\exp(-t/T_{2,\mathrm{tot}}) \approx (0.98)(0.98)\exp(-t/[10,000\,\mathrm{s}])$$

UCN spectrum

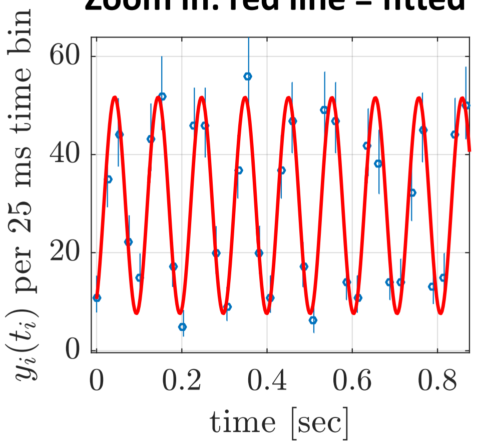
$$N_n(t) = \int_0^{E_{\max}} \mathrm{d}E\, n_{n0}(E)\exp\left[-\frac{t}{\tau_{\mathrm{cell}}(E)} - \frac{t}{\bar{\tau}_\beta} + \frac{P_n(t)P_3(t)}{\bar{\tau}_3}\int_0^t \cos\phi_{3n}(t')\mathrm{d}t'\right]$$

Oscillating term due to previous
n-^{3}He absorption

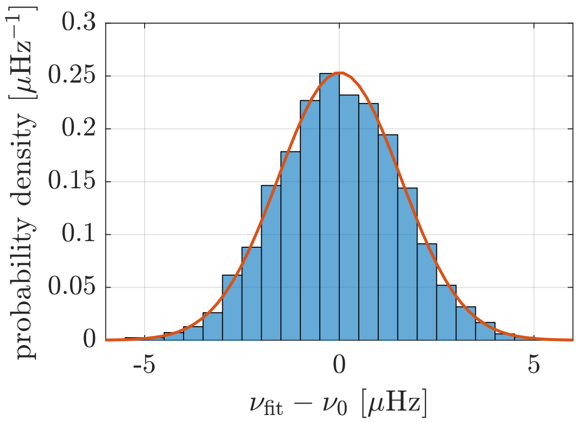
Simulated signal 1-cycle (accepted events)



Zoom in: red line = fitted



Repeat generation & fit:



Generated "full statistics" data set with constant B_0

From distribution: 1σ error bar = 1.8 μHz

- Free precession mode 300 live days data taking (e.g. 2-3 years) **1σ nEDM error = 3×10^{-28} *e*.cm**

Dressed-spin mode gives **1.6×10^{-28} *e*.cm**

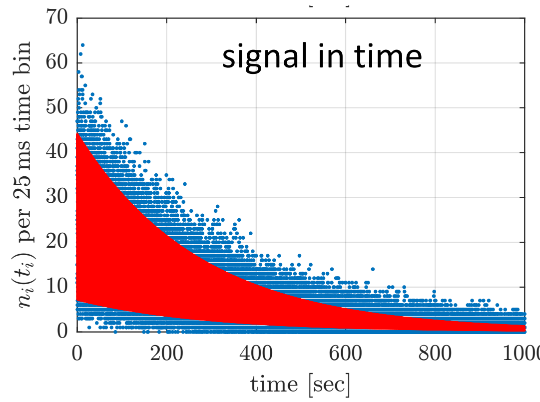
Data analysis simulations

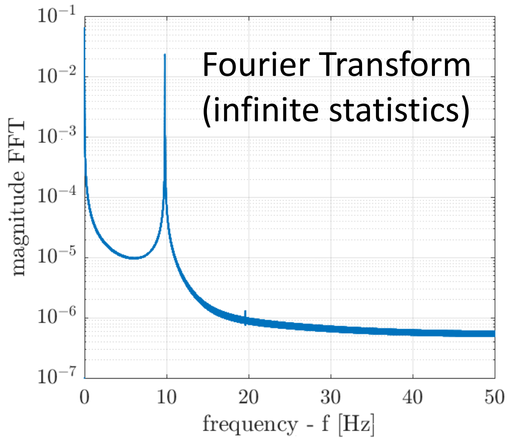
We (re-)launched a team to study statistics and systematic effects in our data analysis.
Effects studied or under-study:

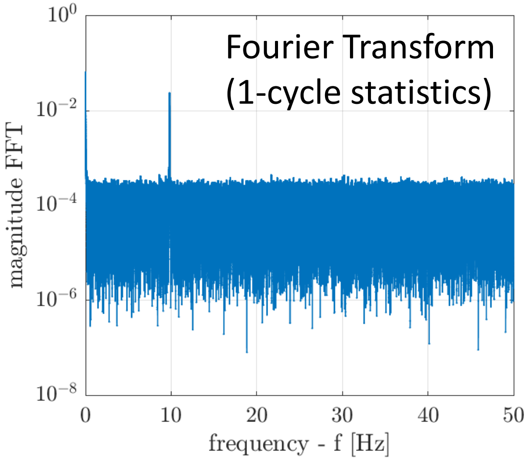
- Neutron decay **β-asymmetry** (Plaster)
- **Spatial-variation scintillation light** detection efficiency (see talks Cianciolo, Loomis, Leggett)
- **Oscillation in N_n(t)** due to history of n-^{3}He absorption (moi)
- Difficult to analytically-fit **UCN energy-dependent wall loss** (moi)
- Generation of scintillation light data with **magnetic field drifts** (moi & Cianciolo)
- Generation of SQUID **^{3}He signal with noise and drifts** (Behzadipour, Cianciolo, Plaster, Clayton)
- **Magnetic field noise** in spin-dressing mode (see talks Swank and Tat)
- UCN spin-tracking on **Graphics Processing Units** (Broussard, Kline, Matthews)
- UCN center-of-mass **gravitational offset time-evolution** (moi)

Data analysis techniques being developed:

- Maximum likelihood fitting time-binned counts and **un-binned counts**
- Markov Chain Monte Carlo random walk fitting techniques
- **Fourier Transform** analyses, digital filtering and **matched-filter** techniques







Handle field drifts in free-precession mode

- Highlight work led by Mojtaba Behzadipour (U. Kentucky grad student) **simulation of SQUID 3He signal with white+pink electronic noise** (based on data) and **B-field slow drifts and jumps** (based on magnetic shielding specs)
- Advantage of live UCN spin analysis is do not necessarily need to throw away data if field jump
- With live & in-situ UCN spin analysis the **time-dependent B(t) from the (co-)magnetometers needed**. (In Ramsey technique need to think a bit about this too if there's a statistics versus time variations in B-field extraction from magnetometers due to relaxation)
- General procedure under development: approximate B(t) with 2nd order polynomial:

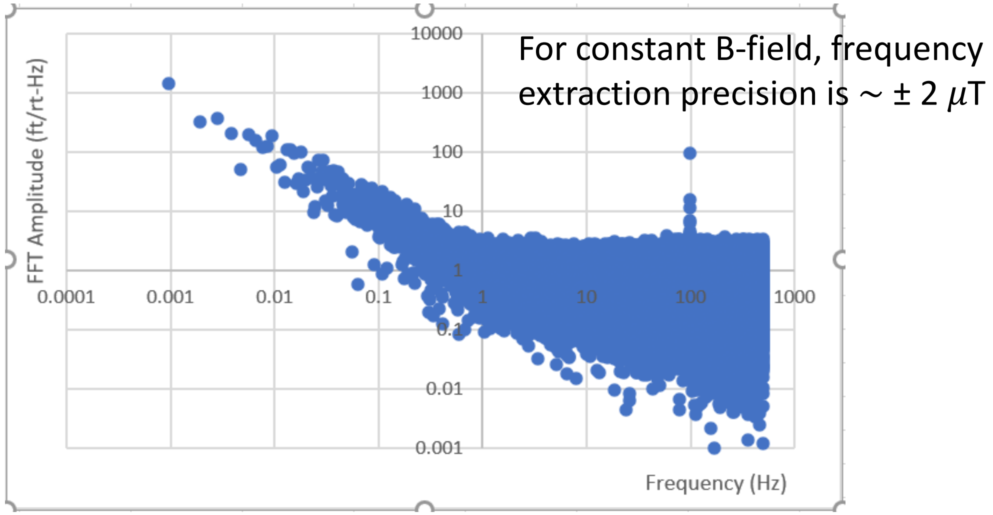
$$B(t) = B(0)(1 + \epsilon_1 t + \epsilon_2 t^2) \longrightarrow$$

SQUID signal from superconducting pick-up coils

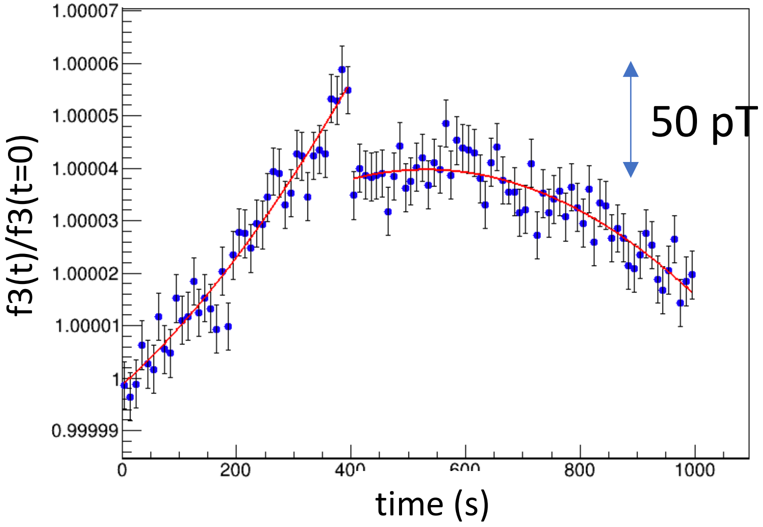
$$S(t) = \underline{A_0} \exp(-t/T_{2,3\mathrm{He}}) \cos\left[|\gamma_3|\underline{B(0)}(t + \frac{1}{2}\underline{\epsilon_1} t^2 + \frac{1}{3}\underline{\epsilon_2} t^3) + \phi_{30}\right]$$

(1) fit B(0), ε_1 and ε_2 from ^{3}He comagnetometer and then used these values fixed in scintillation light fitting, OR
(2) "Global" fit of 3He and scintillation light signal

Simulated FFT signal from SQUID for 1000 s, with SQUID noise based on data from LANL (1 fT/rt-Hz, 1 Hz cross-over frequency)



Split signal into 10 s windows and extract frequency in each



Advantages in alternative physics extraction with live & in-situ UCN phase information

Searching for time-oscillating nEDM signals

- Axion-like particles can induce an oscillating nEDM signal [Abel et al., Phys. Rev. X 7, 041034 (2017)]:

$$\omega_n(t) = |\gamma_n| B_0 \pm \frac{2d_n|E|}{\hbar} + \frac{2|E|\alpha_{\rm ax}}{\hbar}\cos(\omega_{\rm ax}t + \phi_{\rm ax})$$

Amplitude of oscillation (units: e.cm)

phase (free parameter in fit)

- Sensitivity scales with nEDM sensitivity. nEDM@SNS every measurement cycle (2400 s) get a 1 σ precision of ± 4 x 10^{-26} e.cm. Expected 1-2 orders-of-magnitude improvement in "standard" base-line search technique.

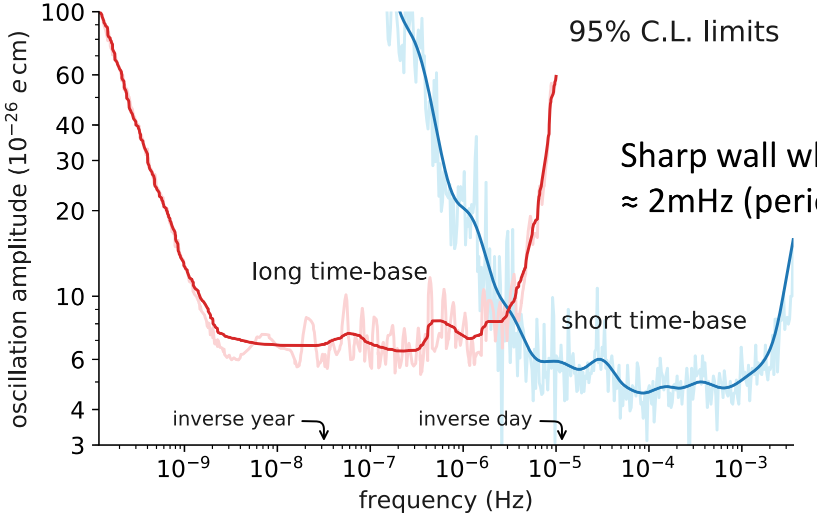
Ultra-short time-base search:

- ϕ_n(t) information allows searches for oscillating nEDM signal at frequencies higher than the measurement cycling:

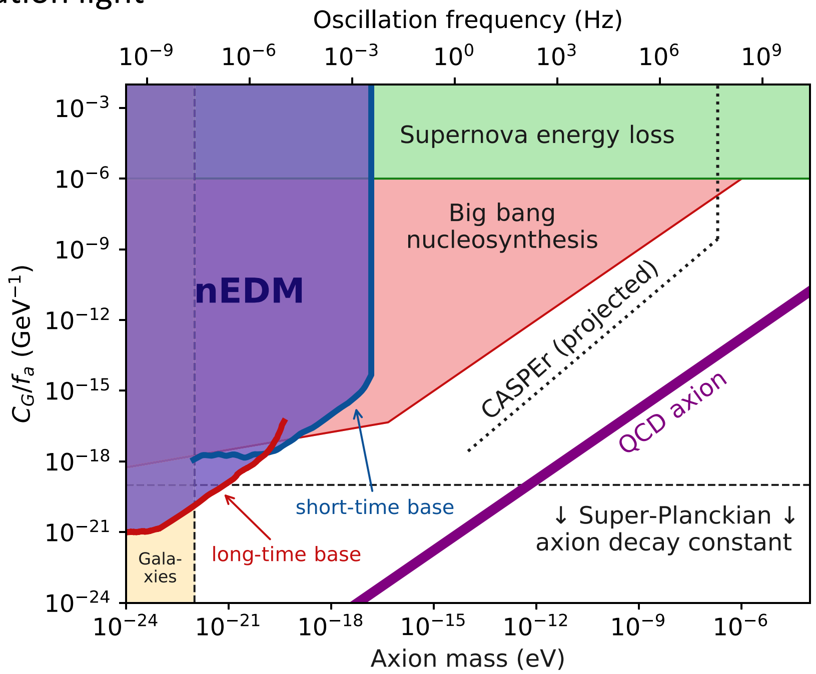
$$\phi_{3n}(t) = \left[(|\gamma_3| - |\gamma_n|)B_0 \pm \frac{2d_n|E|}{\hbar}\right]t + \frac{2|E|\alpha_{\rm ax}}{\hbar\omega_{\rm ax}}\left[\sin(\omega_{\rm ax}t + \phi_{\rm ax}) - \sin\phi_{\rm ax}\right] + \phi_{3n0}$$

determines n-3He scintillation light

From Abel et al.:



Sharp wall when frequency ≈ 2mHz (period 500 sec)



High-precision measurement of the ratio γ_n/γ_{3He}

- Only minor improvements in knowledge of the neutron magnetic moment over the past 5 decades

PHYSICAL REVIEW D VOLUME 20, NUMBER 9 1 NOVEMBER 1979

Measurement of the neutron magnetic moment

G. L. Greene* and N. F. Ramsey
Harvard University, Cambridge, Massachusetts 02138

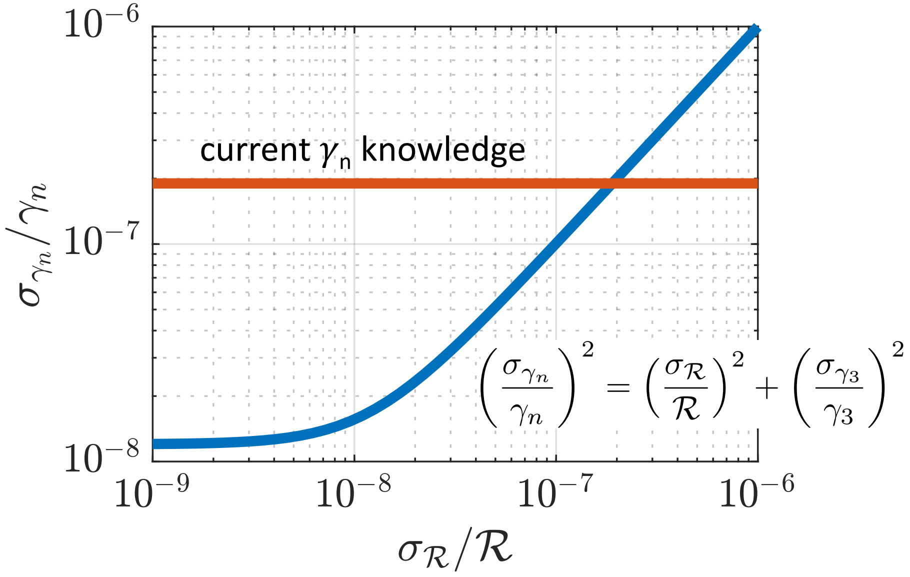
+ et al.

$$\frac{\sigma_{\gamma_n}}{\gamma_n} = 0.24\,\mathrm{ppm} \text{ via } \frac{\gamma_\mathrm{n}}{\gamma_\mathrm{p}}$$

Afach et al., Phys. Lett. B 739 (2014) -> $\frac{\sigma_{\gamma_n}}{\gamma_n} = 0.19\,\mathrm{ppm}$ via $\frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}$

- In nEDM@SNS, we measure: $\mathcal{R} \equiv \frac{\gamma_n}{\gamma_{3\mathrm{He}}}$

CODATA 2018: $\frac{\sigma_{\gamma 3\mathrm{He}}}{\gamma_{3\mathrm{He}}} = 1.2 \times 10^{-8}$



STATISTICAL ERROR:

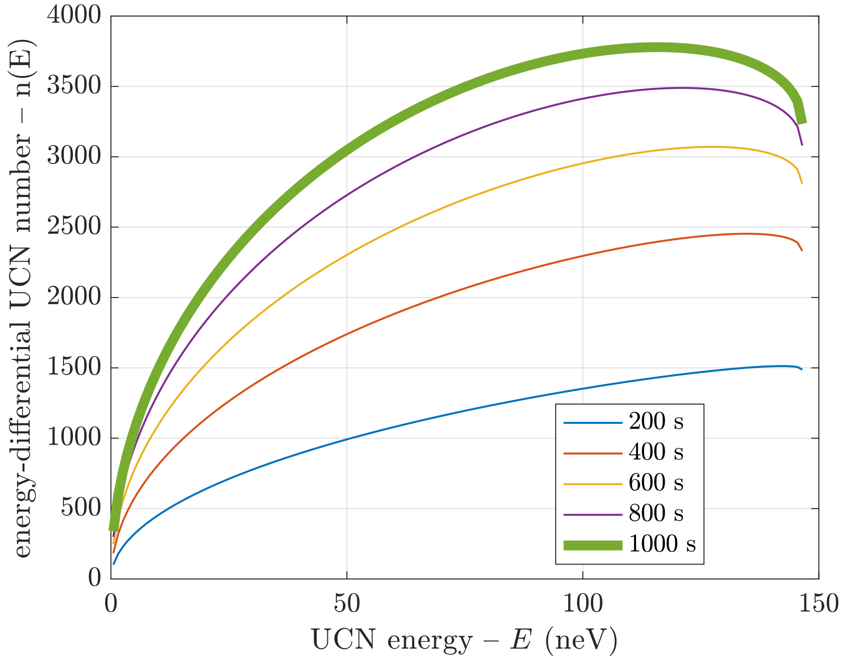
- In one measurement cycle: $\frac{\sigma_\mathcal{R}}{\mathcal{R}} \approx \frac{\sigma_{\omega 3\mathrm{n}}}{\omega_{3\mathrm{n}}} \approx \frac{1.8\,\mathrm{uHz}}{10\,\mathrm{Hz}} = 2 \times 10^{-7} (0.2\,\mathrm{ppm})$
- To reach ± 0.01 ppm (~ 20 x improvement in γ_n) need 11 days of statistics

KEY SYSTEMATIC: UCN center-of-mass gravitational offset effect

Evolution of UCN spectrum during filling and precession

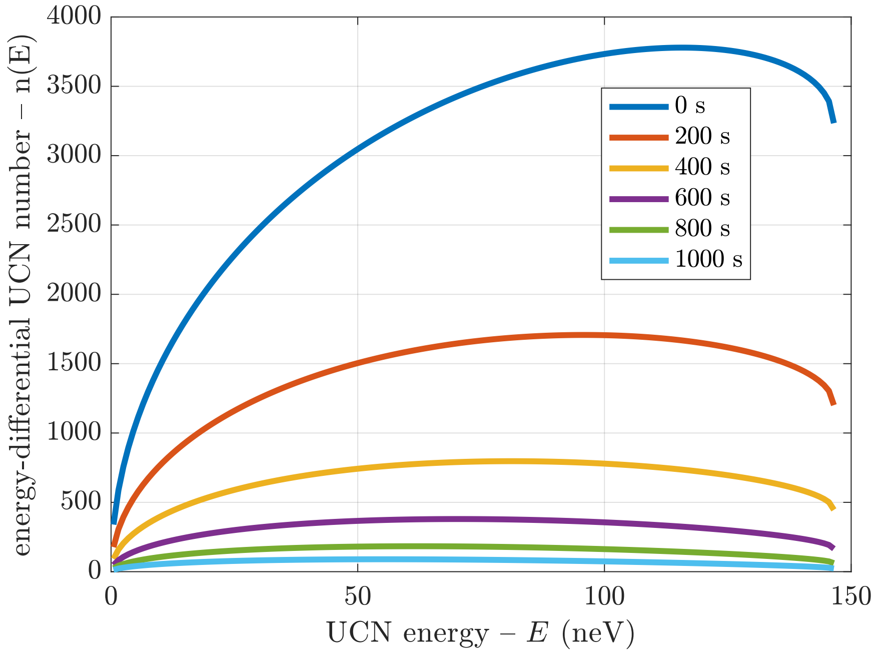
Example: used f = W/V = 0.8 x 10^{-5}

UCN spectrum during “filling” (low ^{3}He absorption)



Statistically optimized T_{fill} = 1000 s:

UCN spectrum evolution during free precession measurement time (includes τ_3 = 500 s)



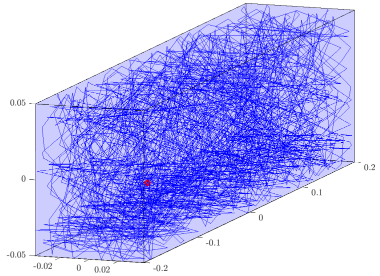
- Produced **UCN spectrum in sf^{4}He is well-described**. Transport in guides not so much.
- Above assumes mechanical equilibrium. **Phase-space evolution will be small in nEDM@SNS** (3 L cell, with UCNs produced with approximately isotropic momentum and close to uniformly throughout cell, filled over 1000 s). Next step is to confirm with simulations
- These are the UCN spectra inside the cell. **Since spin analysis is in-situ, no need to correct for UCN-energy dependent transport loss** (and depolarization loss) during transport to interpret any UCN spectral measurements
- Change filling time (with reduction on statistics) to change initial UCN spectrum slightly for systematics

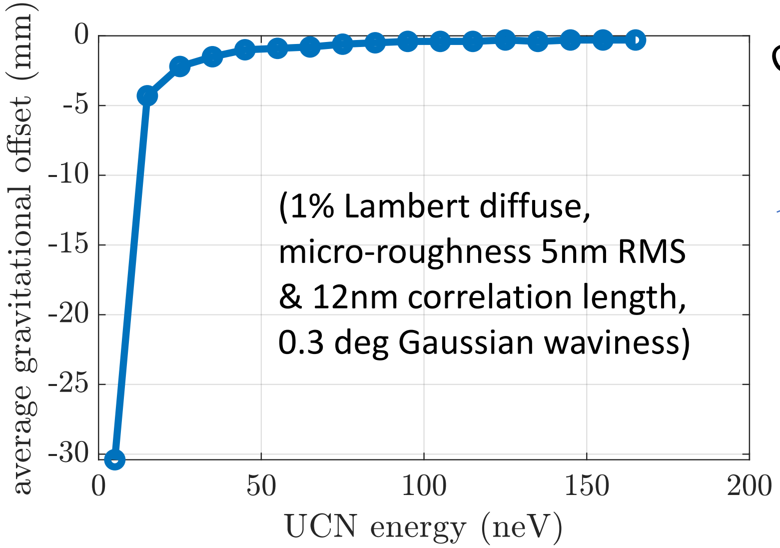
Use time-evolution of UCN gravitational offset to study UCN spectrum

UCN tracking simulations:

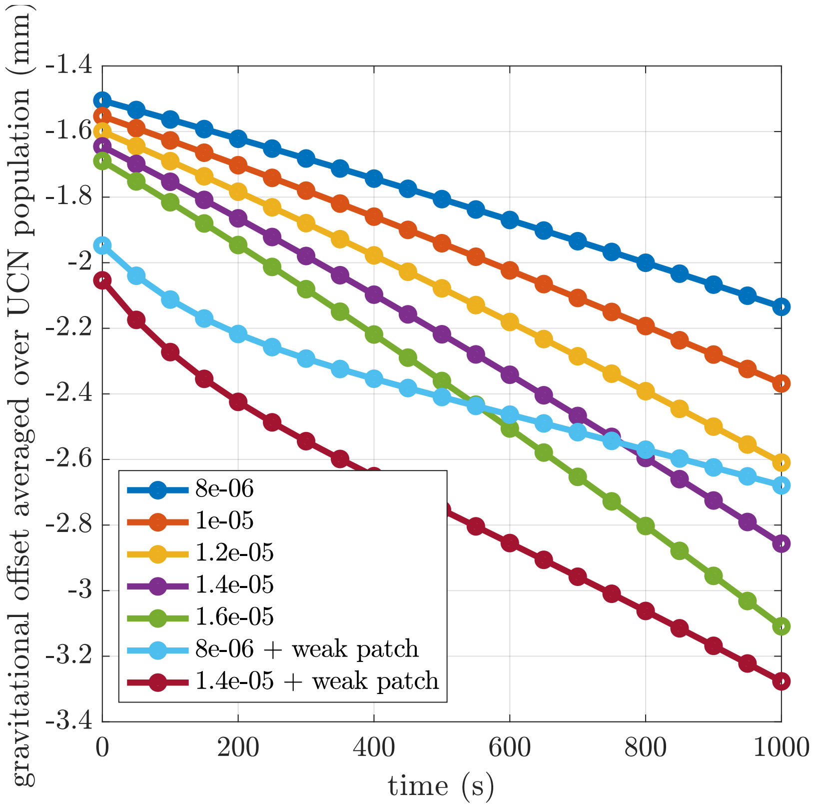
Shown E = 100 neV

Straight lines between wall collisions displayed.





Combine with UCN spectral evolution from previous slide



UCN center-of-mass offset when averaged over UCN population

$$f_n = \frac{\gamma_n}{2\pi}\left(B_0 + \frac{d|B|}{dz} h_{\mathrm{off}}(t)\right)$$

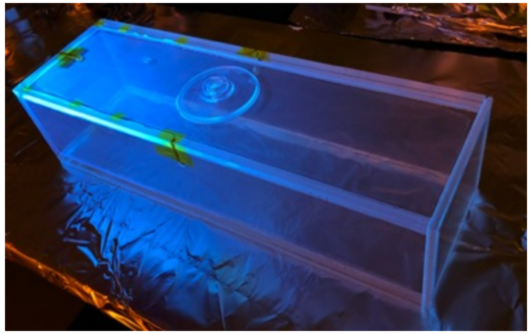
Vertical gradient

$(B_0 \to \text{from } ^3\text{He})$

- Apply **known gradient, measure $f_n(t)$** to **get information on the time-evolution of average UCN energy** during precession.
- **Combine with total number UCN storage time measurement**: just watch β-decay without loading ^{3}He.
- More direct than spin-echo since since measuring precession frequency
- Phase-space evolution (which will impact this systematic effect as well as others!) less in the nEDM@SNS experiment
- A good chance for controlling this important systematic effect! Currently in early days of development still.

Summary

- Below a **"warm" 90 K, UCN storage improves by > 4 times compared to room temperature**
- Very **long UCN storage times for multiple full-sized cells**: $\tau_{\text{single-exp}}$ = (490 ± 11) s or $\tau_{\text{long}} \approx$ 550 s
- In-situ superthermal UCN production ^{4}He offers many advantages (no need to transport, high density, phase-space evolution reduction)
- However, there is **activation caused by the 9 Å neuton beam**. Need to add neutron absorber, vikuiti reflector, and thin and pure dPMMA end windows. (*Should* not affect UCN storage.)
- Polarized **^{3}He used as a co-magnetometer and live and in-situ UCN spin analyzer** allows the **continuous measurement the neutron phase.** (In order to "measure frequency": this is the way…)
- This is a new type of signals in nEDM experiments. **Detailed simulations are being performed to understand how to best analyze** this data
- **ϕ_n(t) information allows a new way for studying UCN spectral evolution** inside the cell by coupling to the UCN center-of-mass gravitational offset coupling to an applied B-gradient



Simulated signal 1-cycle (accepted events)