The nEDM @ Spallation Neutron Source experiment: our novel approach and other physics reach

Kent Leung (on behalf of the nEDM@SNS collaboration)

ECT* neutron electric dipole moment: from theory to experiment (August 2022). Trento, Italy

nEDM @SNS

MONTCLAIR STATE UNIVERSITY

(public-R2 in New Jersey, 20 km from Manhattan)

NC STATE UNIVERSITY

Duke UNIVERSITY

TUNL TRIANGLE UNIVERSITIES NUCLEAR LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF National Science Foundation

How it all started.

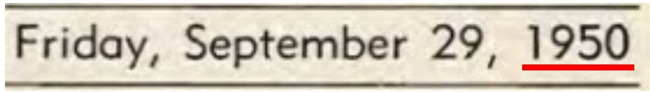
Vol. 3—No. 13 OAK RIDGE, TENNESSEE

HARVARD UNIVERSITY SPONSORS PROGRAM HERE — James H. Smith, Harvard University graduate student in physics, is shown as he adjusts a neutron beam apparatus at the south face of the Oak Ridge Pile. Using the Pile as a source of neutrons, Mr. Smith is engaged in a project jointly sponsored by Harvard University and Oak Ridge National Laboratory for the purpose of determining if neutrons have permanent electric dipole moments.

Harvard University Conducts Important Research at ORNL

The growing importance of Oak Ridge National Laboratory as a research center is manifested particularly in its assistance to universities and technical schools on various projects in which nuclear research is involved. An example of such relationship is its present collaboration with Harvard University in an investigation to determine if neutrons have permanent electric dipole moments.

The work of the project is under the direction of Professors E. M. Purcell and Norman F. Ramsey of the Harvard University Physics Department and is being conducted on the Laboratory area by James H. Smith, a graduate student at Harvard. Dur-



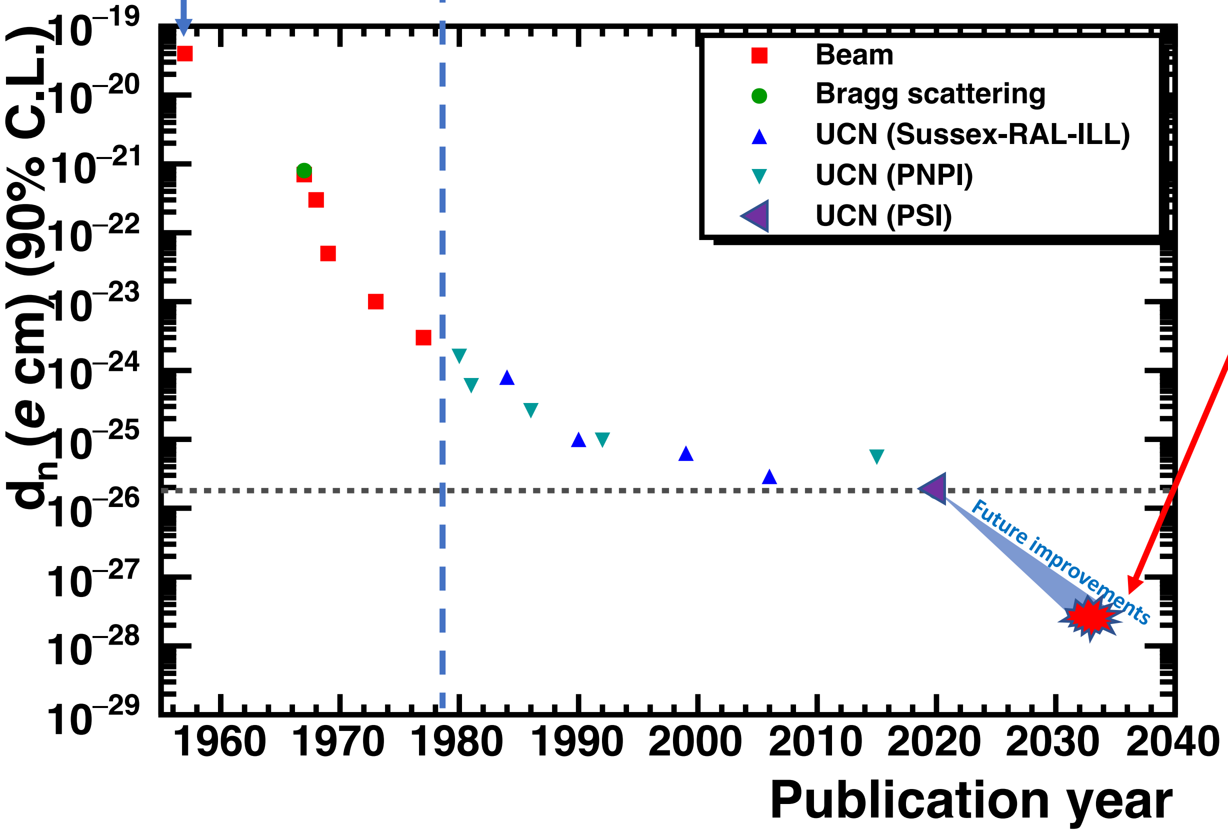
Friday, September 29, 1950

- Oak Ridge National Laboratory's X-10 pile went critical in 1943, and civilian research began in 1945.
- Wu & Ambler's P-violation experiment in 1957
- nEDM Result published in 1957 by *Smith, Purcell & Ramsey:* $D=(-0.1\pm 2.4)\times 10^{-20}$ cm,

nEDM experimental trend

ORNL experiment

Ultracold neutrons take over field



From: Electric dipole moments and the search for new physics (community white paper) arxiv:2203.08103

Experiment	Location	UCN source	Features
n2EDM	PSI	Spallation, SD_2	Ramsey method, double cell, ^{199}Hg comagnetometer
PanEDM	ILL	Reactor, LHe	Ramsey method, double cell, ^{199}Hg comagnetometer
LANL nEDM	LANL	Spallation, SD_2	Ramsey method, double cell, ^{199}Hg comagnetometer
Tucan	TRIUMF	Spallation, LHe	Ramsey method, double cell, ^{129}Xe comagnetometer
nEDM@SNS	ORNL	In-situ production in LHe	Cryogenic, double cell, ^{3}He comagnetometer, ^{3}He as the spin analyzer

+ beam EDM (see talk from F. Piegsa)

$$\hat{H} = -\frac{1}{2}\left(\mu_n \vec{I}\cdot\vec{B} + d_n \vec{I}\cdot\vec{E}\right)$$

CODATA: $\mu_n = -0.966\,236\,50(23) \times 10^{-26}\,\mathrm{J\,T^{-1}}$

$$\mu_n \times (0.5\,\mathrm{Gauss}) \sim 10^{-13}\,\mathrm{eV}$$

Earth's B-field

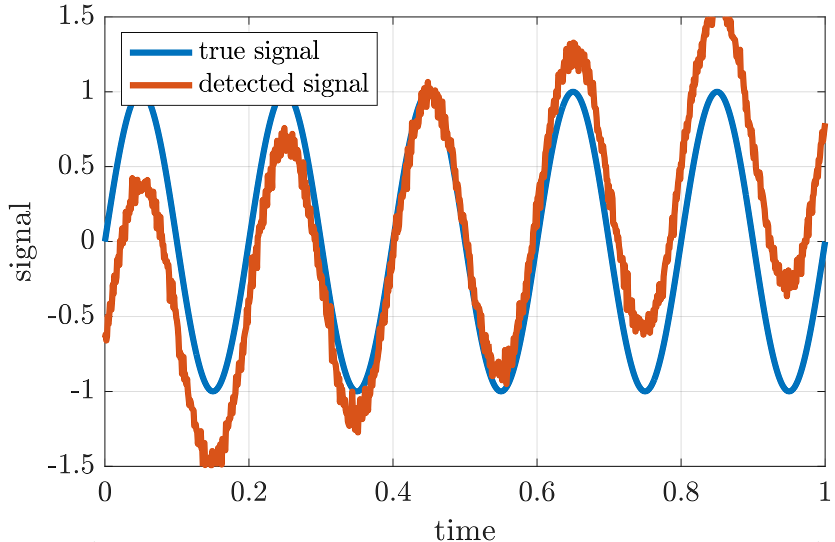
$$(10^{-20}\,e.\mathrm{cm}) \times 100\,\mathrm{kV/cm} \sim 10^{-15}\,\mathrm{eV}$$

~ largest lab E-field

Maxim for precision experiments:

“Always measure frequency…” (Rabi? Ramsey? Wieman?)

- Control and measurements of time can be done to a high precision
- Determined by relative change in signal amplitude over short times
- Drifts in signal detection amplitude on time-scales > a few oscillations are suppressed.

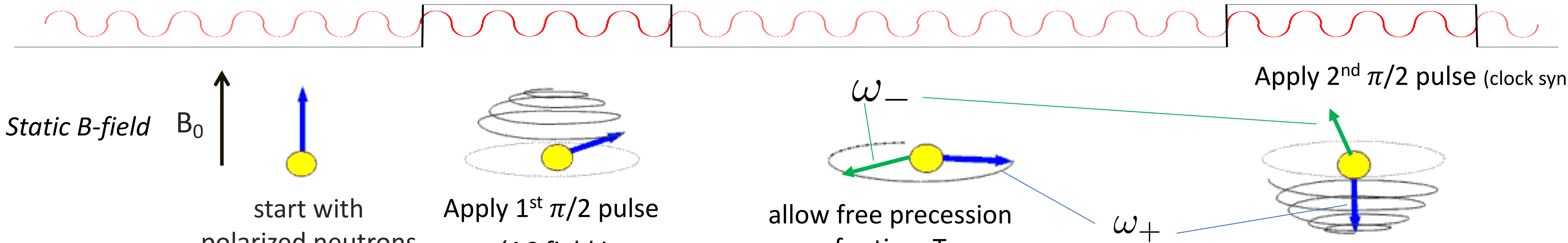


(dummy generated plots with arbitrary units to illustrate point only)

Ramsey's technique of separated oscillatory fields

- Picture used in the field: "net spin vector" ➞ the *macroscopic* (net) spin polarization vector obeying Bloch's (NMR) equations.
- **Ramsey Separated Oscillatory Fields technique** (on neutron beam or UCNs):

Clock at close to Larmor frequency: $\omega_0 = \gamma_n B_0$



Apply 2nd $\pi/2$ pulse (clock sync'd)

start with
polarized neutrons

Apply 1st $\pi/2$ pulse

(AC field in transverse plane)

allow free precession
for time T

Perform spin analysis along B_0:
➞ count number neutrons spin down N_{down}
➞ measures *final phase* of neutrons

(modern experiments also measure N_{up} for normalization)

(1) Apply E-field parallel: ↑ $\omega_+ = \omega_0 + 2 e d_n E/\hbar$

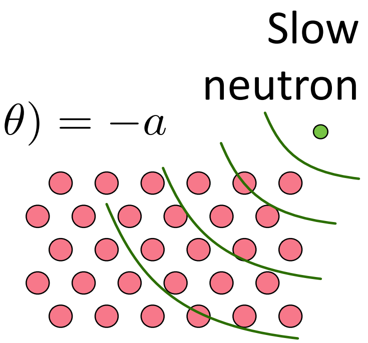
(2) Repeat w/ E-field anti-parallel: ↓ $\omega_- = \omega_0 - 2 e d_n E/\hbar$

$\text{If } d_n \neq 0 \rightarrow \Delta\omega \neq 0 \rightarrow \Delta N_{\text{down}} \neq 0$

I argue this is not a *frequency measurement:*

- if N_{down} detection efficiency changes (typically ~ 100 s apart for UCNs), then directly shifts *deduced average frequency*
- cannot tell what frequency at a specific time during free precession (due to numerous reasons, it is not constant)

Ultracold neutrons (UCNs)



- Slow neutrons undergo **scattering** from a nuclei via strong force: $\psi(\mathbf{r}) \propto \exp(i\mathbf{k}\cdot\mathbf{r}) + f(\theta)\,\frac{\exp(ikr)}{r} \longrightarrow$ s-wave: $f(\theta) = -a$
- Coherent scattering off collection of nuclei: $\psi(\mathbf{r}) = \exp(i\mathbf{k}_0\cdot\mathbf{r}) - \int \beta(\mathbf{r}')\,\psi(\mathbf{r}')\,\frac{\exp(ik_0|\mathbf{r}-\mathbf{r}'|)}{|\mathbf{r}-\mathbf{r}'|}\,\mathrm{d}^3r'$
- Apply Born approximation, where nuclei can be treated as δ-functions (nuclei size ~ 1 fm, where as slow neutron λ > 1 Å)
- Volume average gives **effective neutron "optical" potential:**

$$V_{\text{opt}} = \frac{2\pi\hbar^2}{m}\sum_i n_i b_i$$

nuclei-number density

bound coherent scattering length $b = \frac{m_n}{m}a$

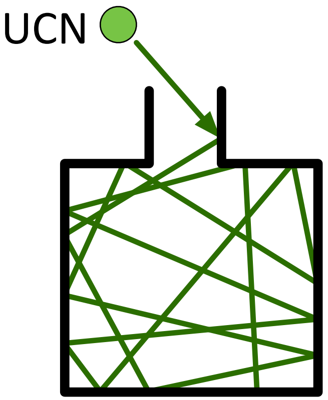
sum over nuclear species in a material

Material	**V$_{\text{opt}}$**
^{58}Ni	335 neV
Be	252 neV
Fluorocarbons	~100 neV
Al	54 neV
polyethylene	-9 neV
d8-polystyrene	160 neV

If **energy below V$_{\text{opt}}$ of a material** => **total *external* reflection at all incident angles**
=> **<u>Ultracold neutrons</u>** can be **stored in a material "bottle"**

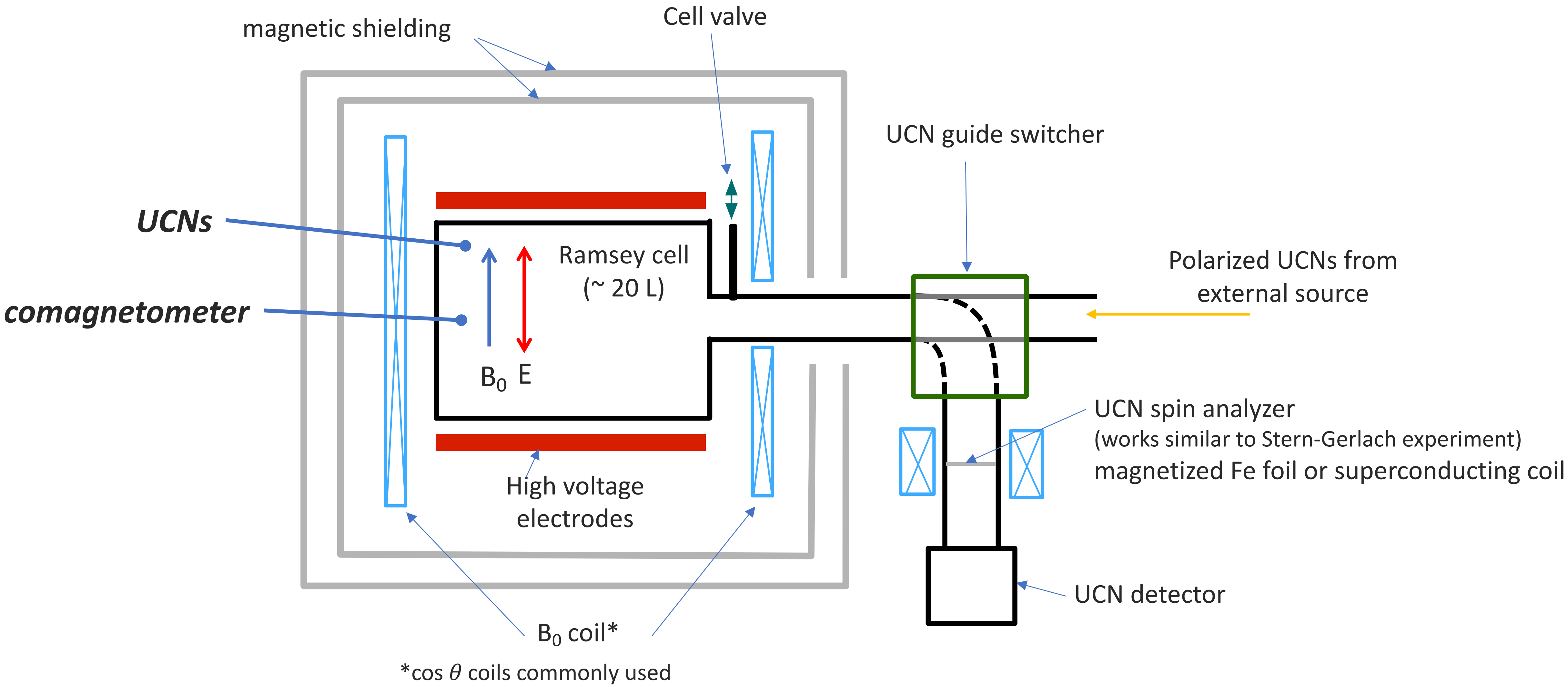
$$E \lesssim 300\,\text{neV}, \lambda \gtrsim 60\,\text{nm}, v \lesssim 7\,\text{m/s}, \text{"temperature"} \lesssim 2\,\text{mK}$$

Idea: Fermi (1946); Published: Zeldovich (1959);
Realization: Shapiro et al., Dubna (1968) & Steyerl et al., Munich, (1969)



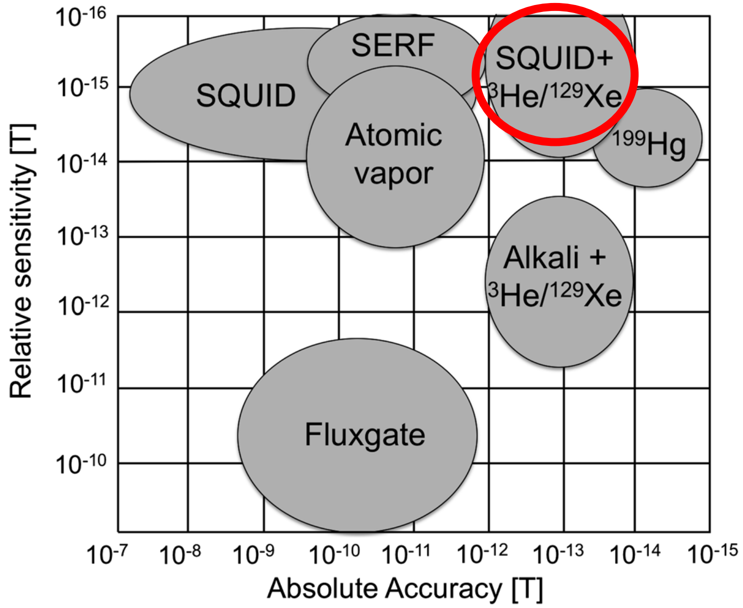
- ○ **Typically 10^{-4} loss probability per reflection** $\Rightarrow R_{\text{reflect}} \approx (vA_{\text{walls}})/(4\times\text{Volume})$
- ○ Store UCNs with time constant (including β-decay loss) $\tau_{\text{tot}} \lesssim$ 100 - 600 s

“Traditional” Ramsey nEDM experiment with UCNs schematic



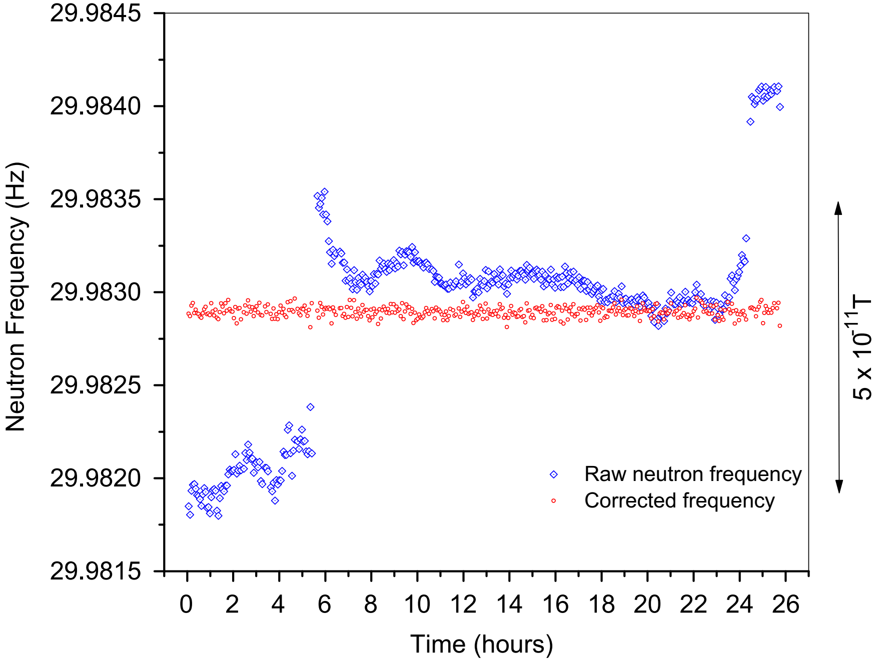
The comagnetometer

- A magnetometer species (typically a gas) that “cohabits” the same volume as the UCNs experience.
- Need sufficient comagnetometer atoms for precision; too high can cause electric breakdowns & UCN loss (~ 10^{-6} mbar)



Chupp et al. RMP (2019)

Harris et al. PRL (1999)



“sensitivity” ➞ the response of the sensor to changes in the magnetic field
“accuracy” ➞ the absolute accuracy for measuring fields/a measure of stability

- nEDM experiments ultimate measure relative to comagnetometer’s EDM (usually “Schiff suppressed”)
- However, the two species still experiences **different net magnetic fields** because of **differences in motion:**
  - UCNs have such low speeds, they “sag” in gravity a few mm.
  - Relativistic $\vec{E} \times \vec{v}$ motional-field related effects are different. One produces a *false* EDM (most serious systematic error)

Polarized ^{3}He as comagnetometer AND *live and in-situ* UCN spin analyzer

Golub & Lamoreaux, Phys. Rep. (1994)

- Polarized ^{3}He gas cells widely used as neutron beam spin analyzers (count survivors)
- Relies on the strongly spin-dependent capture cross-section: $^3\overrightarrow{\mathrm{He}} + \vec{\mathrm{n}} \rightarrow \mathrm{p} + {}^3\mathrm{H} + 764\,\mathrm{keV}$

  Anti-parallel spins: $\sigma_{\downarrow\uparrow,\mathrm{thermal}} \approx 11\,\mathrm{kb}$ Parallel spins: $\sigma_{\uparrow\uparrow,\mathrm{thermal}} \lesssim 0.1\,\mathrm{kb}$

- Capture reaction rate for polarized UCNs and ^{3}He in same volume :

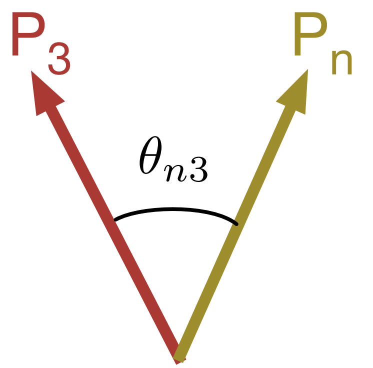
$$\dot{N}_3 = N_{\mathrm{UCN}}\,\bar{\tau}_3^{-1}\,(1 - P_n P_3 \cos\theta_{n3})$$

number of UCNs polarizations angle between spins

where $\bar{\tau}_3^{-1} \approx [n_3\,\sigma_{\downarrow\uparrow,\mathrm{thermal}} \times (2200\,\mathrm{m/s})]/2$

3He number density

- Detect the 760 keV as generated ➞ in-situ and live UCN spin analyzer
- Want ^{3}He-n capture rate to be similar to UCN loss time in cell, i.e. $\bar{\tau}_3 \approx 500\,\mathrm{s}$
- Want $n_3 \approx 2 \times 10^{12}\ \mathrm{cm}^{-3}$ with near $P_3 \approx 100\%$ ➞ Achievable with atomic beam source!
- This n_3 produces ~ fT fields ➞ detectable by SQUIDs! (Superconducting Quantum Interference Device)



UCNs + ^{3}He + superfluid ^{4}He: nEDM@SNS collaboration

Spokespeople: Brad Filippone (Caltech) & Vince Cianciolo (ORNL)

Arizona State University

Brown University

California Institute of Technology

Duke University

Harvard University

Indiana University

University of Illinois Urbana-Champaign

University of Kentucky

Los Alamos National Laboratory

Massachusetts Institute of Technology

MIT Bates Laboratory

Montclair State University

Universidad Nacional Autonoma de Mexico

Mississippi State University

North Carolina State University

Oak Ridge National Laboratory

Simon Fraser University

University of Tennessee

Tennessee Technological University

Triangle Universities Nuclear Lab

Valparaiso University

University of Virginia

Yale University

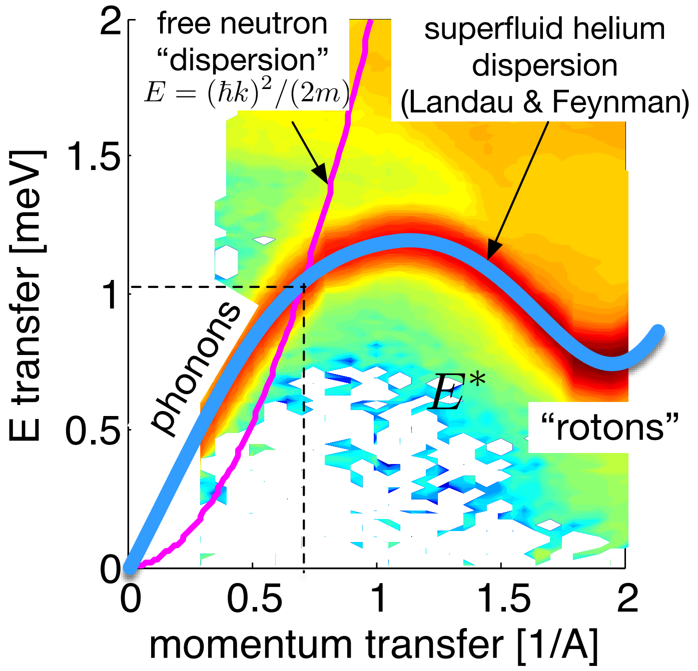
nEDM@SNS overview

Super-thermal down-conversion of cold neutrons to UCNs

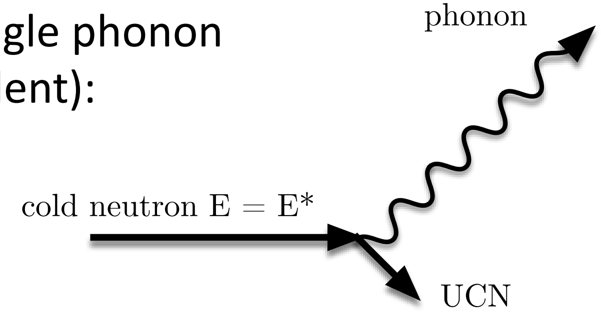
- **Scattering off phonons** in superfluid ^{4}He to **convert cold neutrons to UCN energy range**.

[Golub & Pendlebury, Physics Letters A (1977)]

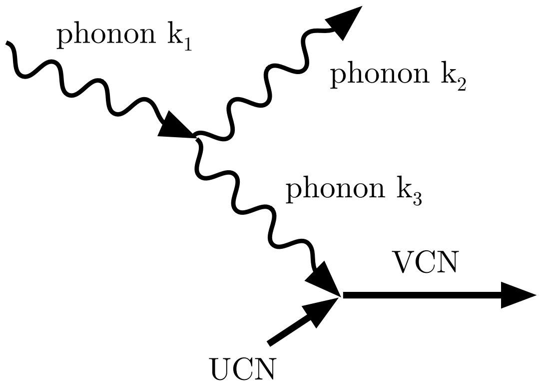
Log contour plot of dynamic structure factor of He-II @ 1.2K
from [Andersen et al. J. Phys. Condens. Matter (1994)]



Down-scattering from single phonon
(~ temperature independent):



Most dominant UCN up-scattering process is two-phonon scattering:



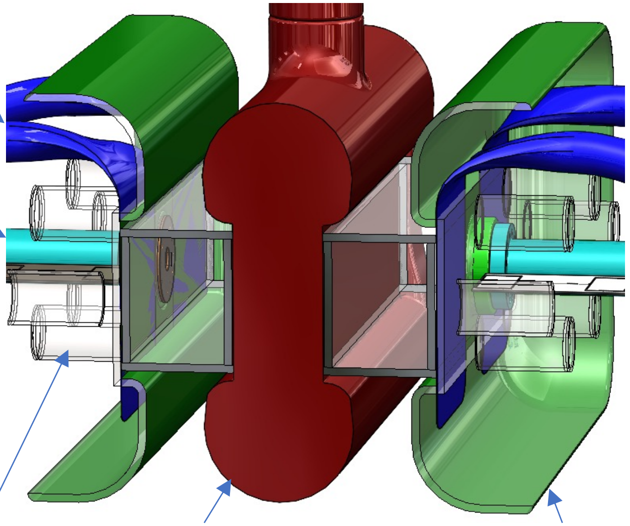
$$\tau_{\mathrm{up,2-phonon}} = (100\,\mathrm{s\,K^7})\,T^{-7}$$

- "Super-thermal" because UCNs are not in equilibrium with superfluid medium
- For **T = 0.4K, up-scattering (or "thermalization") time constant ≈ 20 hours**. Neutron absorption by ^{4}He is zero, but need isotopic purity.
- Superfluid helium also scintillates at ~ 80 nm ("Vacuum" or "Extreme" ultraviolet) ➞ detect n-^{3}He capture events
- ^{3}He atoms also scatter off phonons ➞ temperature has strong affect on mean-free-path ➞ important for systematics control

nEDM scheme: UCNs + ^{3}He + superfluid ^{4}He bath

All inside another superfluid ^{4}He bath

Based on Golub & Lamoreaux, Phys. Rep. (1994)



Scintillation light collection fibers

^{3}He plumbing & cell ”plug” valve

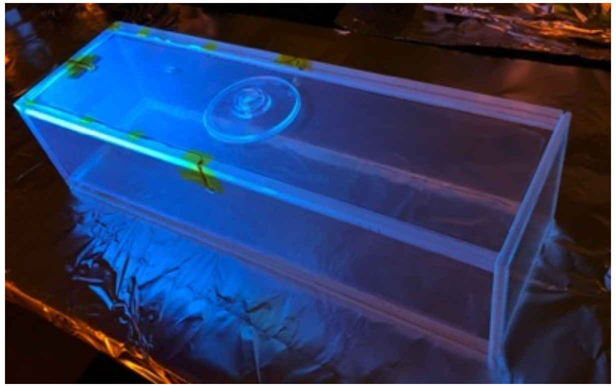
$B_0 = 30\,\mathrm{mG}$

SQUID magnetometers coils

High-voltage electrode

GND electrodes (2x)

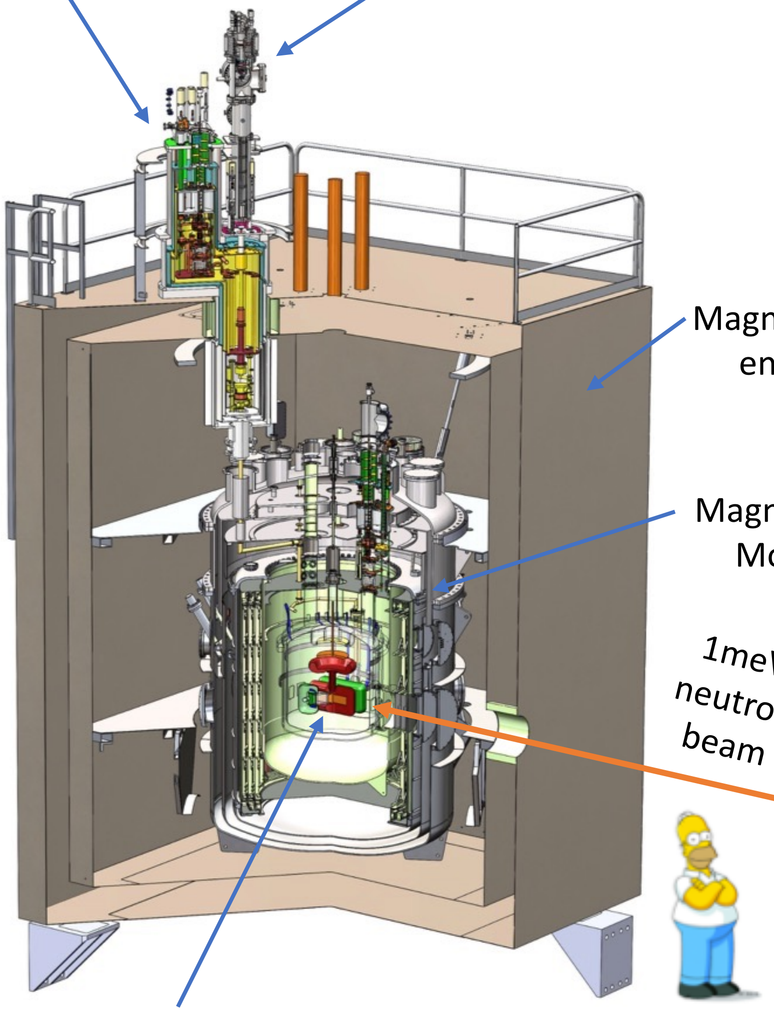
Full-sized prototype measurement cell illuminated by 300 nm UV lamp



2x measurement cells: 7.5 cm (W), 10 cm (H), 40 cm (D)
Fill with ~ 0.4 K superfluid ^{4}He

- **Double cell** set up with E-field relative to B-field opposite in each cell
- **In-situ super-thermal UCN production** and accumulation in **superfluid ^{4}He with polarized 1 meV cold neutron beam**
- Cryogenic UCN storage => **low wall loss** due to suppression of up-scattering loss (design goal $\tau_{\mathrm{walls}} \approx 2{,}000$ s). Goal UCNs storage time (wall loss + neutron β-decay) with **time constant ≈ 600 s**
- Goal accumulated equilibrium **polarized UCN density of ~ 180 UCN/cm^3** => ~ 500,000 UCNs per cell at start
- **Latest cell** tested at LANL with (cell loss + β-decay) time constant of 560 ± 20 s. Only single exp-decay observed. Some UCN spectrum uncertainties due to cryogenic guides. Adding UCN gravitational spectrometer for energy analysis

The nEDM@SNS experiment



^{3}He services cryostat

Polarized ^{3}He atomic beam source

Magnetic shield enclosure

Magnet Field Module

1meV neutron beam

Central detector system (with cells and electrodes)

- Atomic beam source produces P_3 ~ 98% ^{3}He atoms.
- ^{3}He services transports in to (and out of) cell via “heat flush”. Concentration in cell ~ 10^{-10} atom fraction
- Magnetic (mu-metal) shield enclosure & internal Pb superconducting shield to control spatial and temporal B-field changes
- Magnet Field Module produces B_0 and AC field

Statistical “shot noise” figure of merit: $\sigma(d_n) \sim \dfrac{\hbar}{2\alpha E T\sqrt{N}}$

$E = \text{electric field}$ 75 kV/cm in superfluid ^{4}He @ ~ 2 atm pressure vs ~ 10 kV/cm

$\alpha = \text{polarization contrast}$ (UCN & ^{3}He polarization ~ 98%)

$T = \text{precession time}$ (design goal to use 1000 sec vs ~ 200 s)

$N = \begin{matrix}\text{no. detected}\\ \text{neutrons}\end{matrix}$ Number similar to other new generation experiments but high-density in small cell reduces systematics (see next)

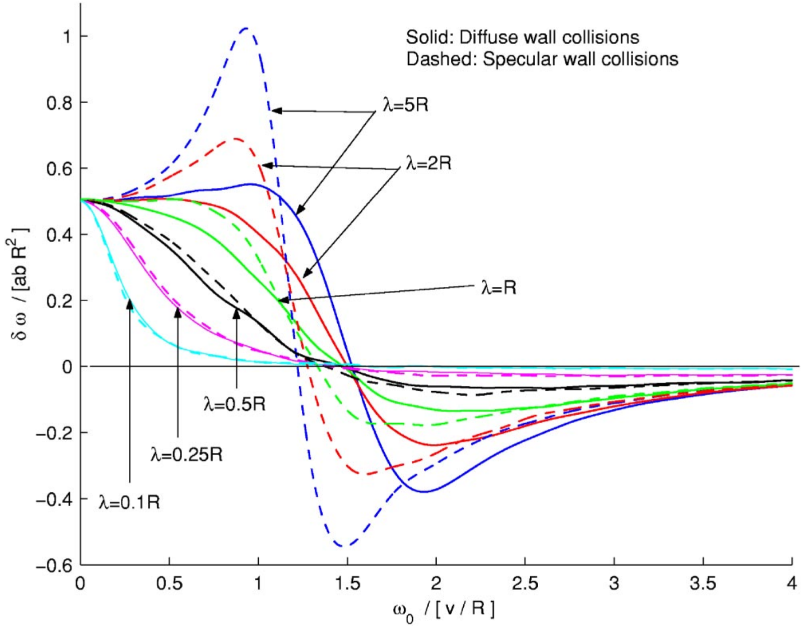
False EDM systematic effect

- Recall: nEDM is measured relative to the comagnetometer’s EDM. Most effects cancel out with opposite E-field.
- Comagnetometer’s EDM suppressed by Schiff screening but **can experience a false EDM**
- From *interaction* between the $\vec{E} \times \vec{v}$ motional field and magnetic field gradients (“geometry-phase induced false EDM”)
- “Discovered” in the nEDM field, false EDM for comagnetometer: $$d_{af} = \frac{J\hbar}{4}\left(\frac{\partial B_{0z}}{\partial z}\right)\frac{\gamma^2 R^2}{c^2}\left[1-\frac{\omega_0^2}{\omega_r^{\dagger 2}}\right]^{-1}$$ Pendlebury et al. Phys. Rev. C (2004)

(Simplified cylindrical cell but general relationships hold. Rectangular cell work by Swank & Golub Phys. Rev. A **93**, 062703 (2016))

- Can change ^{3}He-phonon scattering mean-free-path by changes in superfluid temperature: $$\lambda_{3\mathrm{He}} \approx 0.077\,\mathrm{cm} \times \left(\frac{0.45\,\mathrm{K}}{T}\right)^{15/2}$$

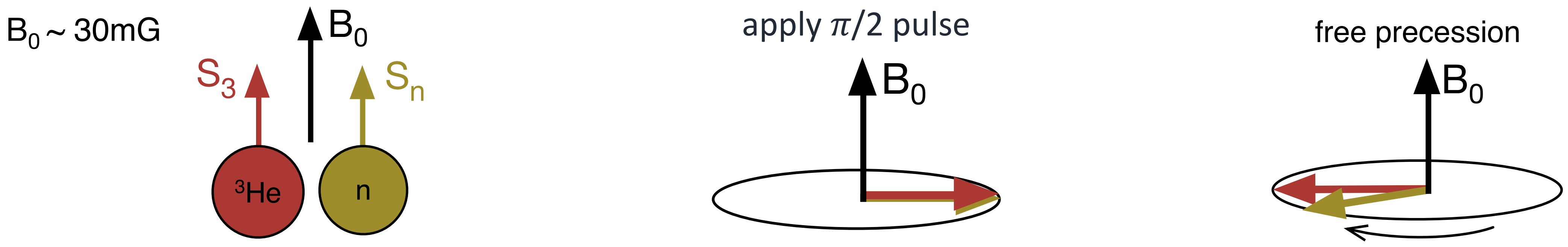
Numerical calculations from Golub:



Can tune temperature to make false EDM zero by scanning T!

The two measurement modes of nEDM@SNS

Double free precession mode



- Time evolution of angle: $\theta_{3n}(t) = \theta_3(t) - \theta_n(t) = \left[(\gamma_n - \gamma_3) B_0 \pm \frac{2 d_n |E|}{\hbar} \right] t + \phi_0 \equiv \omega_{3n}^{\pm} t + \phi_0$,
- With B_0 = 30 mG $\gamma_3 B_0 / (2\pi) \approx 100\,\mathrm{Hz}$ $\gamma_3 \approx 1.1\,\gamma_\mathrm{n}$ $|\gamma_n - \gamma_3| B_0 / (2\pi) \approx 10\,\mathrm{Hz}$

- The transverse spin coherence time (wall depolarization + gradient depolarization), T_2 ~ 10,000 s

- Flipping high-voltage electrode often with known sequences to suppress 1st order drifts (e.g. + - - + - + + -) and analysis as a ”super-asymmetry"

Free precession signal

Acceptance probability for β-decay events (~0.33)

Acceptance probability for n-^{3}He capture (~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

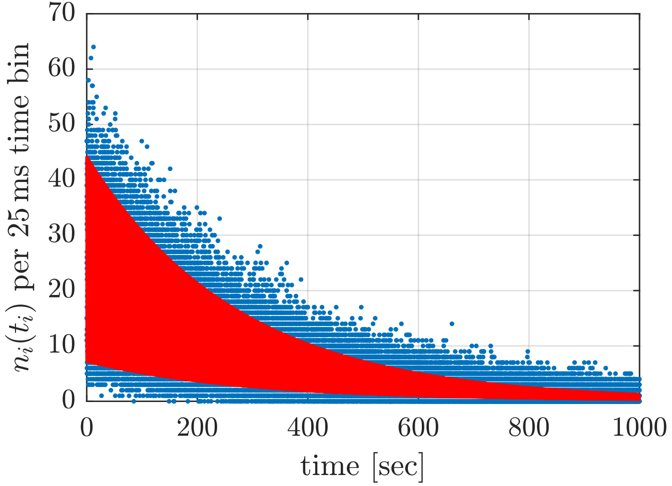
$$P_3(t)P_n(t) = P_{30}P_{n0}\exp(-t/T_{2,\mathrm{tot}}) \approx (0.98)(0.98)\exp(-t/[10,000\,\mathrm{s}])$$

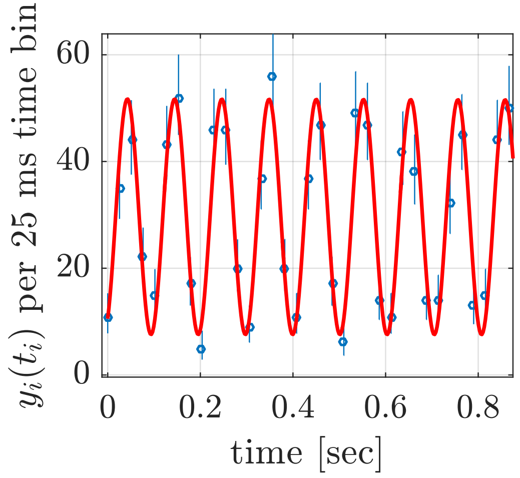
UCN spectrum

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

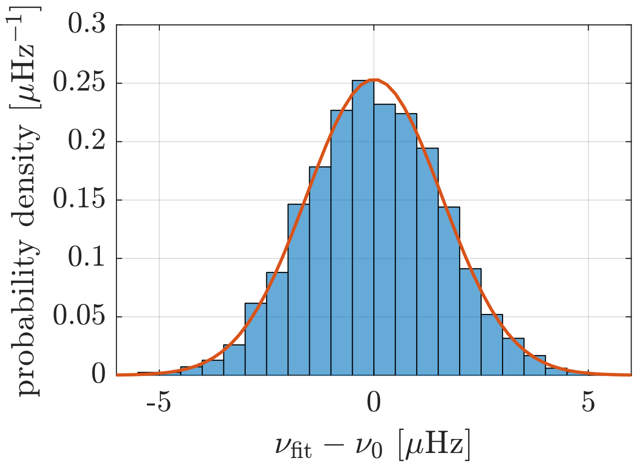
Oscillating term due to previous n-^{3}He absorption

Accepted events in time bins:





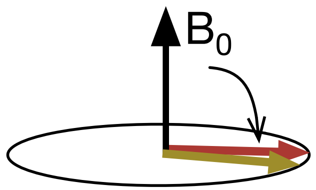
Repeat generation & fit:



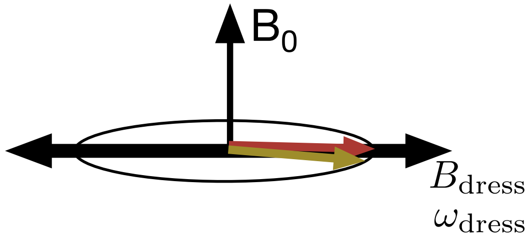
- ➢ Continuously measuring the UCN phase (relative to ^{3}He) ➞ **continuous frequency measurement** (via derivative)!
- ➢ 300 live days of running (expected to take 3 years), get **1σ nEDM error = 3 x 10^{-28} *e*.cm** (see JINST paper)

Dressed-spin mode

apply $\pi/2$ pulse



apply strong off-resonance dressing field perpendicular to B_0 to alter precession of **both species**



Cohen-Tannoudji:

$$\hat{H} = -\gamma B_0 \hat{S}_z + \hbar\omega_d \hat{a}^\dagger \hat{a} + \lambda \hat{S}_x (\hat{a} + \hat{a}^\dagger)$$

$$\lambda = \gamma B_d / 2\sqrt{\bar{n}},$$

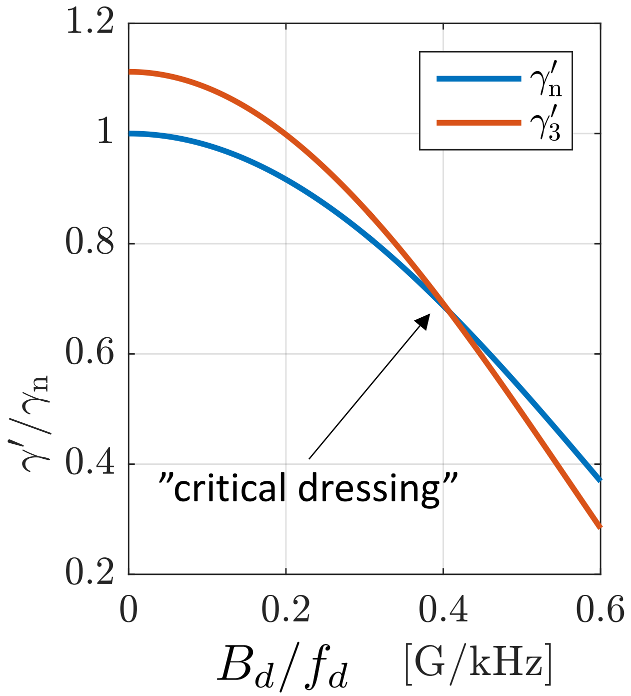
In the limit $B_{\mathrm{dress}} \gg B_0$

effective gyromagnetic ratio

0^{th} order Bessel function

$$\gamma' = \gamma \, J_0\left(\frac{\gamma B_{\mathrm{dress}}}{\omega_{\mathrm{dress}}}\right)$$

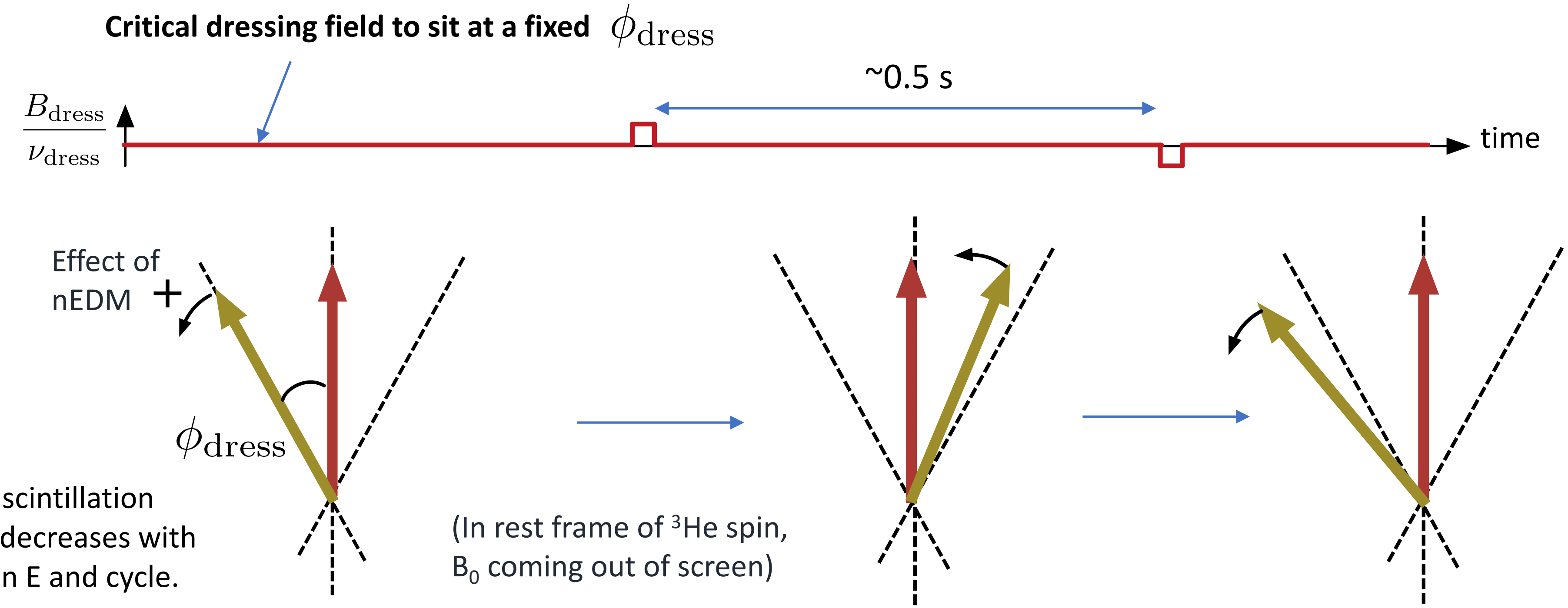
original



- Specific value of B_d/ν_d can make $\gamma'_3 = \gamma'_n$
- For instance, if $B_d = 1\,\mathrm{G}$ is chosen, then $f_d \approx 2.5\,\mathrm{kHz}$ is needed
- If above or below critical dressing condition, then **can make neutrons precess faster or slower than ^{3}He as needed**.

Critical modulated dressed-spin mode

- The effect of **neutron EDM** with spin dressing: $\gamma'_{\mathrm{n}} B_0 \pm \dfrac{2ed_n E J_0(\gamma_{\mathrm{n}} B_{\mathrm{dress}}/\omega_{\mathrm{dress}})}{\hbar}$
- Example of modulation with **"square wave pulses".** Many other modes possible.



Critical dressing field to sit at a fixed ϕ_{dress}

If there's a nEDM scintillation light increases or decreases with time depending on E and cycle.

(In rest frame of ^{3}He spin, B_0 coming out of screen)

- Can treat as asymmetry measurement or nEDM signal occurring at f_{mod} , both growing with time (main signal at $2f_{\mathrm{mod}}$)

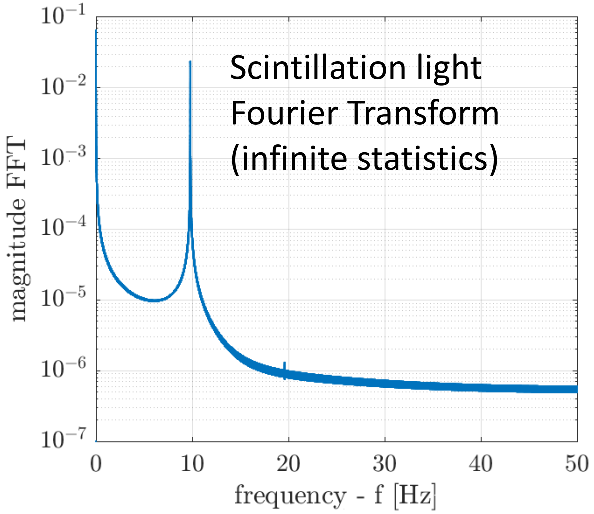
Predicted sensitivity: 300 live days of data (e.g. 3 years running) $\sigma(d_n) = 1.7 \times 10^{-28}\ e{\cdot}\mathrm{cm}$

- Less sensitive to static field in-homogeneities. Quality and control dressing field is main systematic.

Data analysis simulations

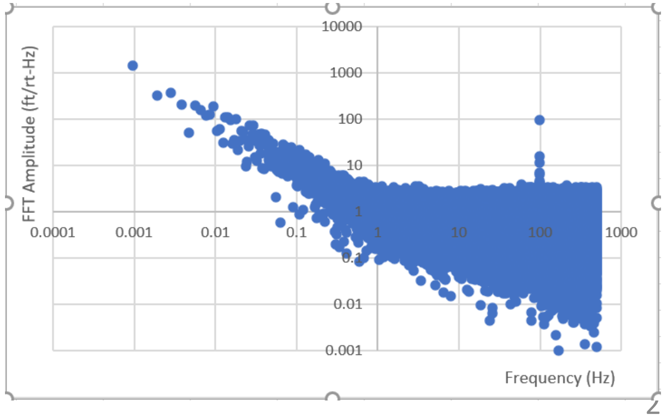
We have a team to study statistics and systematic effects in our data analysis. Effects studied or under-study:

- Neutron decay β**-asymmetry**
- **Spatial-variation scintillation light** detection efficiency
- **Oscillation in $N_n(t)$** due to history of n-^{3}He absorption
- **Reduced parameter ”contrast” fitting** to handle UCN energy-dependent wall loss
- Generation of scintillation light data with **magnetic field drifts**
- Generation of SQUID **^{3}He signal with noise and drifts** (UKy student: Mojtaba Behzadipour)
- **Simultaneously fitting SQUID signal and scintillation light** signal with global likelihood parameter (UKy student: Mojtaba Behzadipour)
- Fit **temporal field drifts** with **orthogonalized polynomials**
- **Particle-by-particle neutron** scintillation data generation code
- **Magnetic field noise** in spin-dressing mode
- **Novel** spin dressing field modulation modes (Caltech grad: Raymond Tat)
- UCN spin-tracking on **Graphics Processing Units**
- UCN center-of-mass **gravitational offset time-evolution**



Scintillation light Fourier Transform (infinite statistics)

SQUID signal with noise



Searching for axions with nEDM@SNS

time-oscillating nEDM-like signals and axions

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

Amplitude of oscillation (units: e.cm)

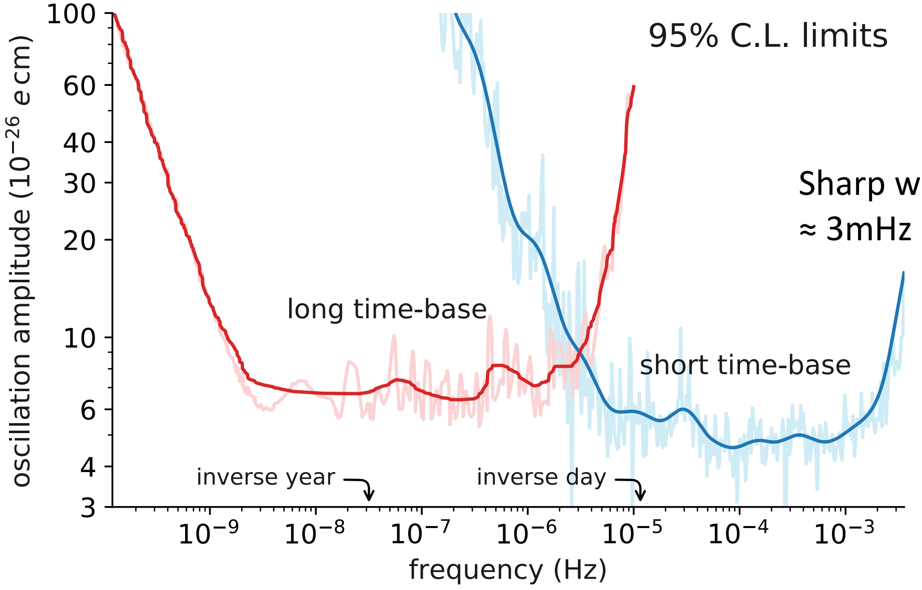
phase (free parameter in analysis)

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

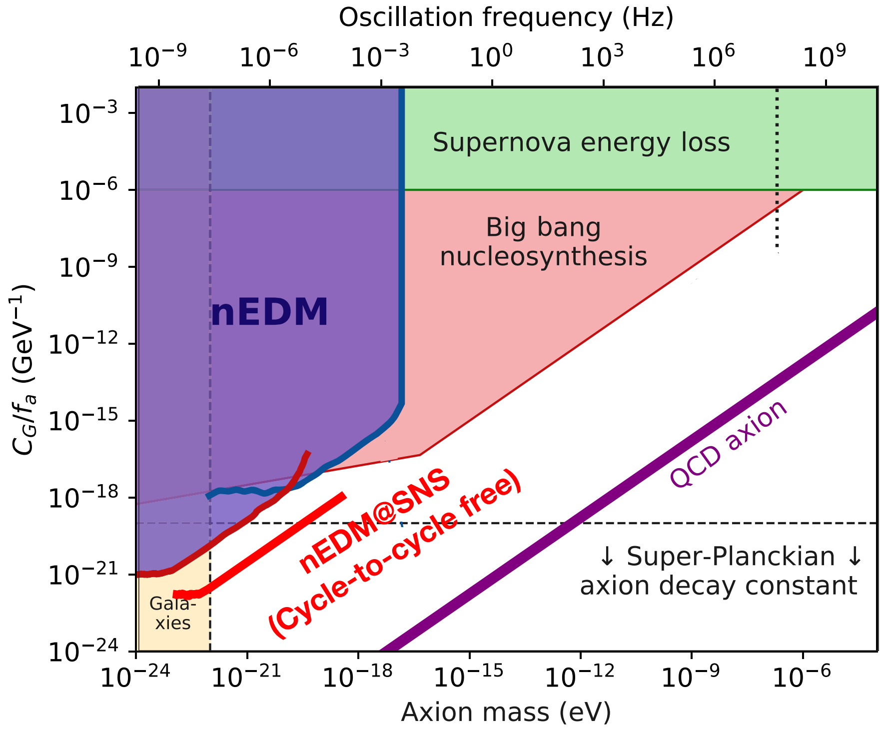
$\omega \approx m_a c^2/\hbar$, Axion-field coherently oscillates:

- 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.

From Abel et al.:



Sharp wall when frequency ≈ 3mHz (period 300 sec)



nEDM@SNS's ultra-short baseline searches

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

In free-precession mode
(can search up to 10 Hz)

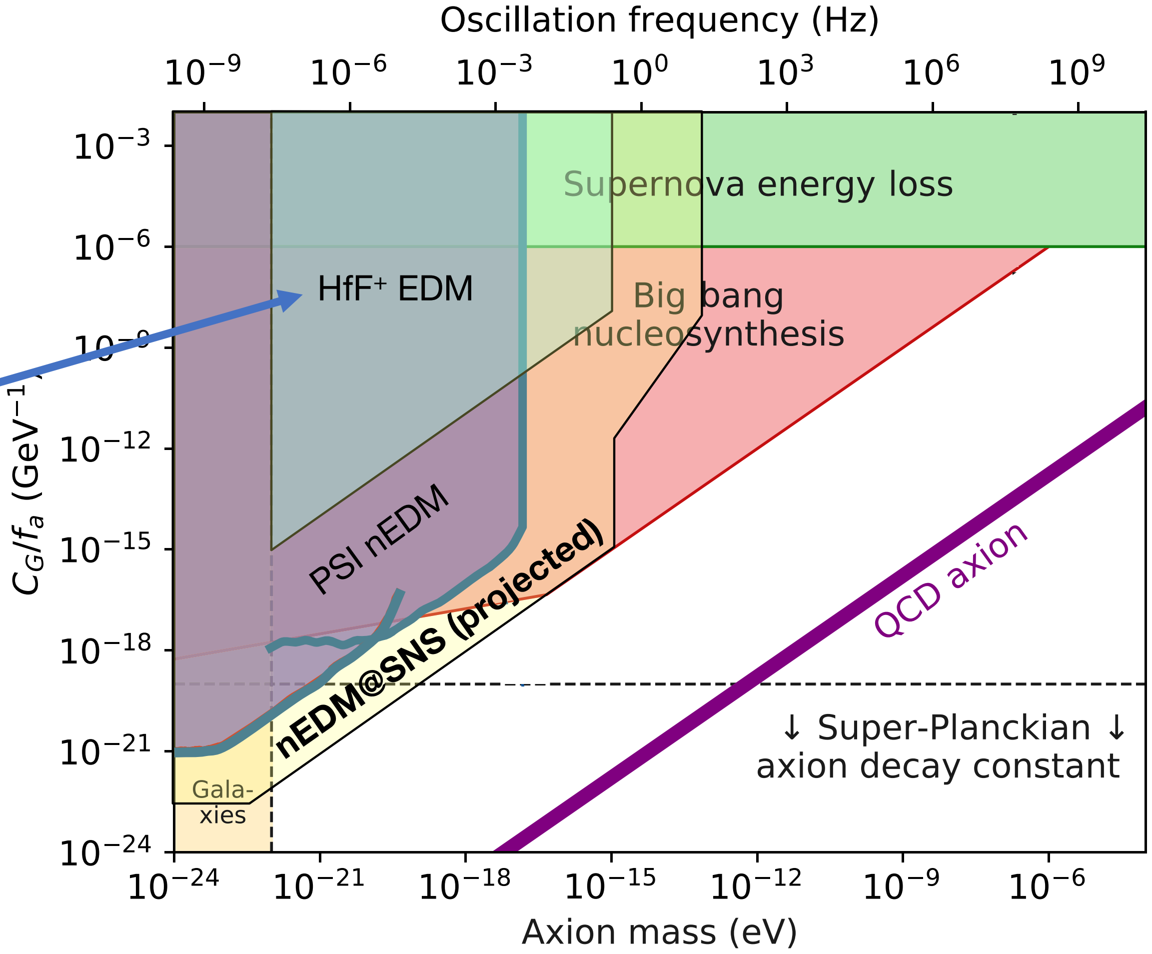
$$\phi_{3n}(t) = \left[(|\gamma_3| - |\gamma_n|)B_0 \pm \frac{2d_n|E|}{\hbar}\right] t + \frac{2|E|\alpha_{\mathrm{ax}}}{\hbar\omega_{\mathrm{ax}}} \left[\sin(\omega_{\mathrm{ax}} t + \phi_{\mathrm{ax}}) - \sin\phi_{\mathrm{ax}}\right] + \phi_{3n0}$$

determines n-3He scintillation light

In dressed-spin mode: each modulated cycle is like an asymmetry to extract nEDM. Can search up to 1 Hz.

"Experimental Constraint on Axionlike Particles over Seven Orders of Magnitude in Mass"

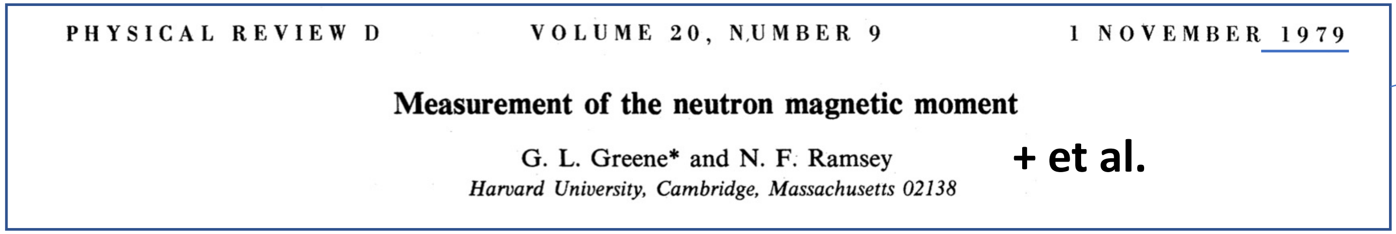
Roussy, Cornell, et al. PRL 2021



Improve the neutron magnetic moment precision with nEDM@SNS

Measurement of γ_n/γ_{3He} to improve γ_n

- 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

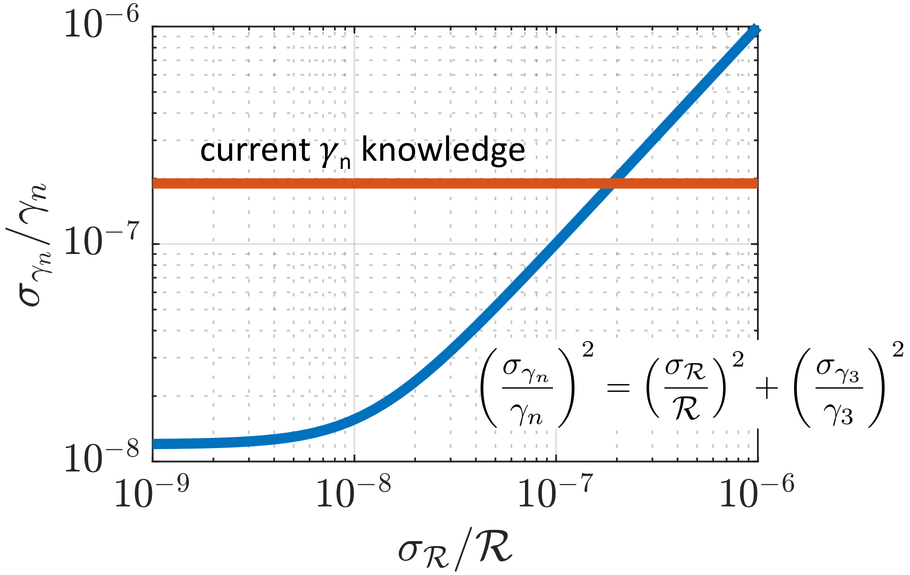
+ et al.

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

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

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

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



$$\left(\frac{\sigma_{\gamma_n}}{\gamma_n}\right)^2 = \left(\frac{\sigma_\mathcal{R}}{\mathcal{R}}\right)^2 + \left(\frac{\sigma_{\gamma_3}}{\gamma_3}\right)^2$$

STATISTICAL ERROR:

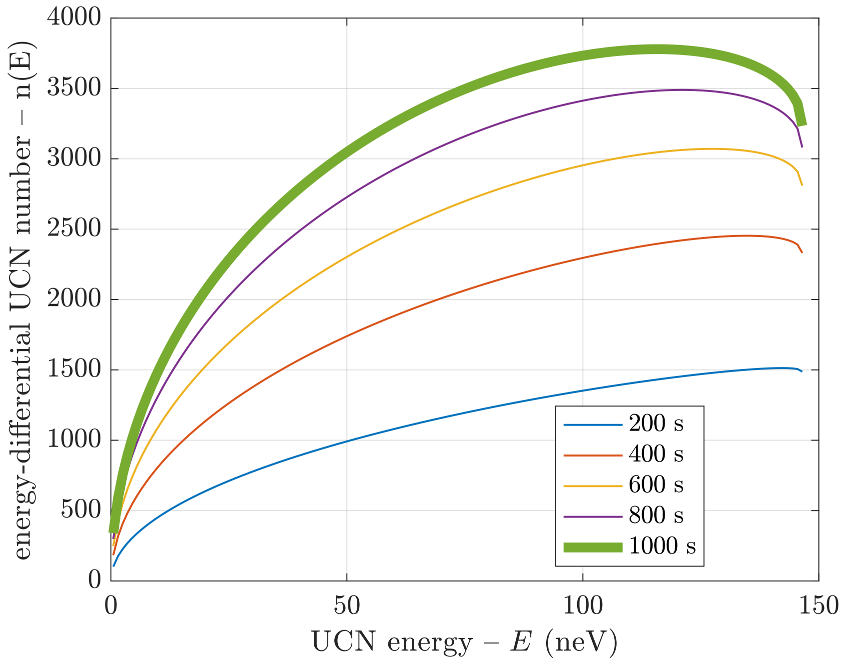
- In one measurement cycle: $\frac{\sigma_\mathcal{R}}{\mathcal{R}} \approx \frac{\sigma_{\omega_\text{3n}}}{\omega_\text{3n}} \approx \frac{1.8\,\text{uHz}}{10\,\text{Hz}} = 2 \times 10^{-7}(0.2\,\text{ppm})$
- To reach ± 0.01 ppm (~ 20 x improvement in γ_n) need 11 days of statistics

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

Evolution of UCN spectrum during filling and precession

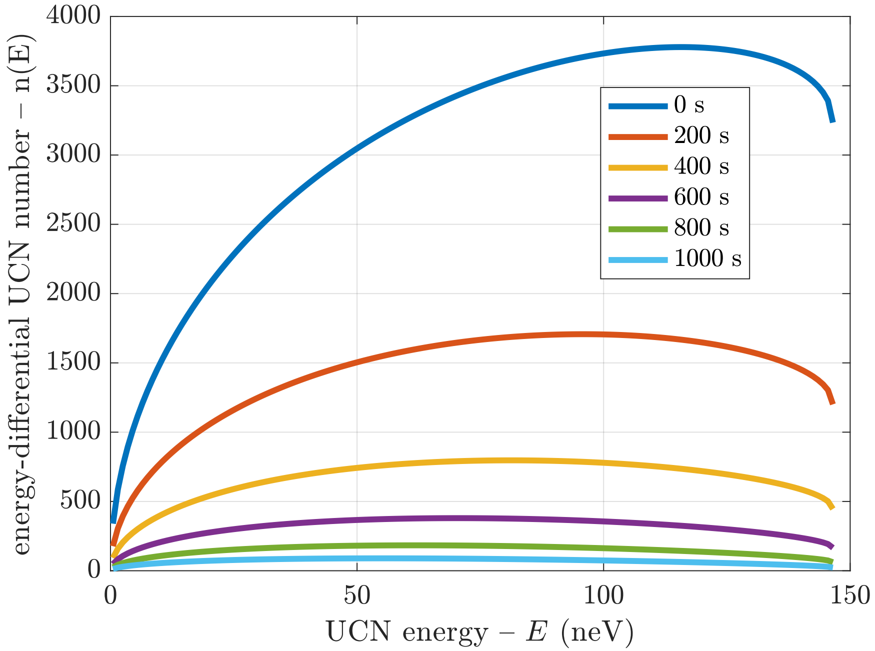
Example: used f = W/V = 0.8 x 10^{-5}

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)



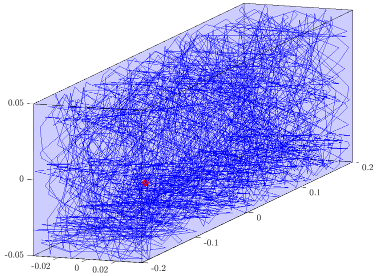
- Produced **UCN spectrum in sf^{4}He is well-described**. Transport in guides not so much.
- Above assumes mechanical equilibrium. **Phase-space evolution will be small in nEDM@SNS** (3 L cell, with UCNs produced with approximately isotropic momentum and close to uniformly throughout cell, filled over 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

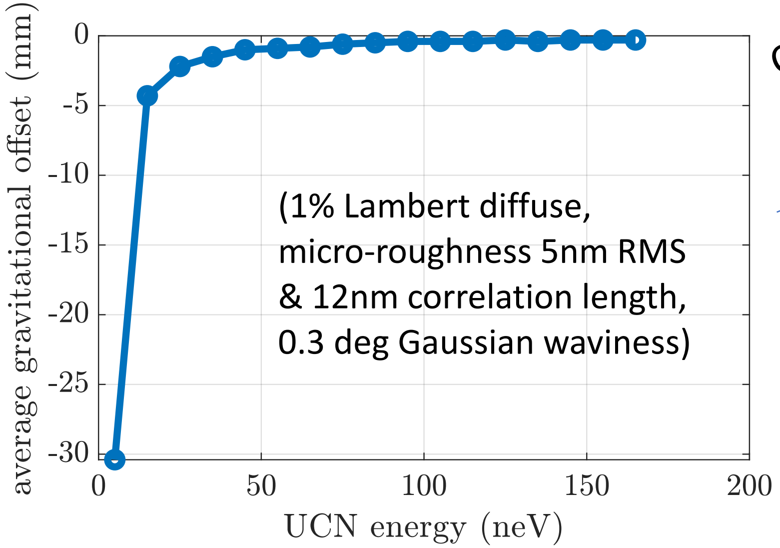
Use time-evolution of UCN gravitational offset to study UCN spectrum

UCN tracking simulations:

Shown E = 100 neV

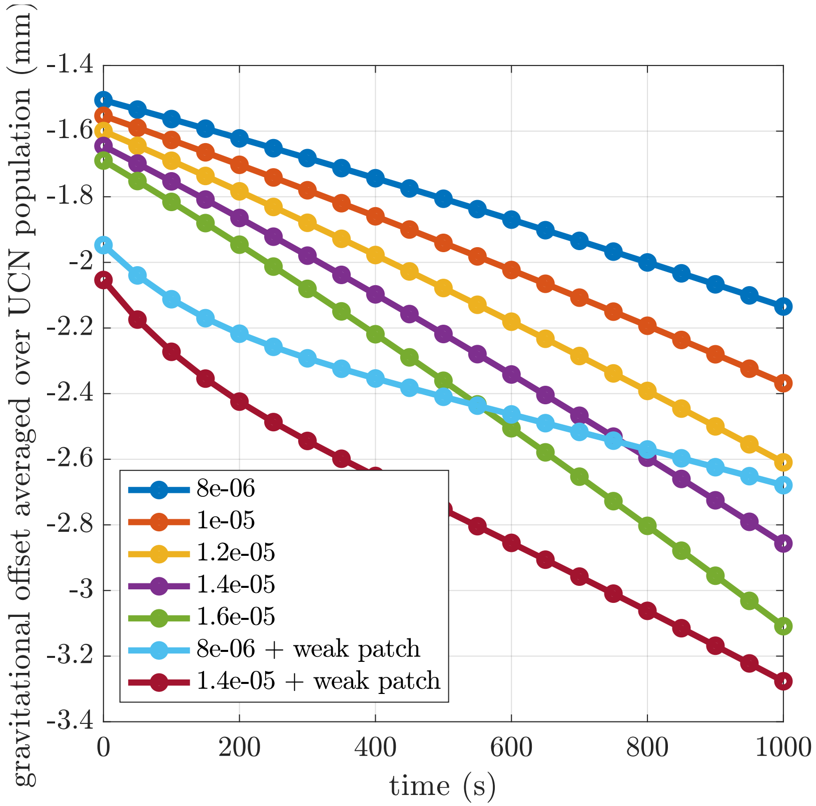
Straight lines between wall collisions displayed.





(1% Lambert diffuse, micro-roughness 5nm RMS & 12nm correlation length, 0.3 deg Gaussian waviness)

Combine with UCN spectral evolution from previous slide



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

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

Vertical gradient

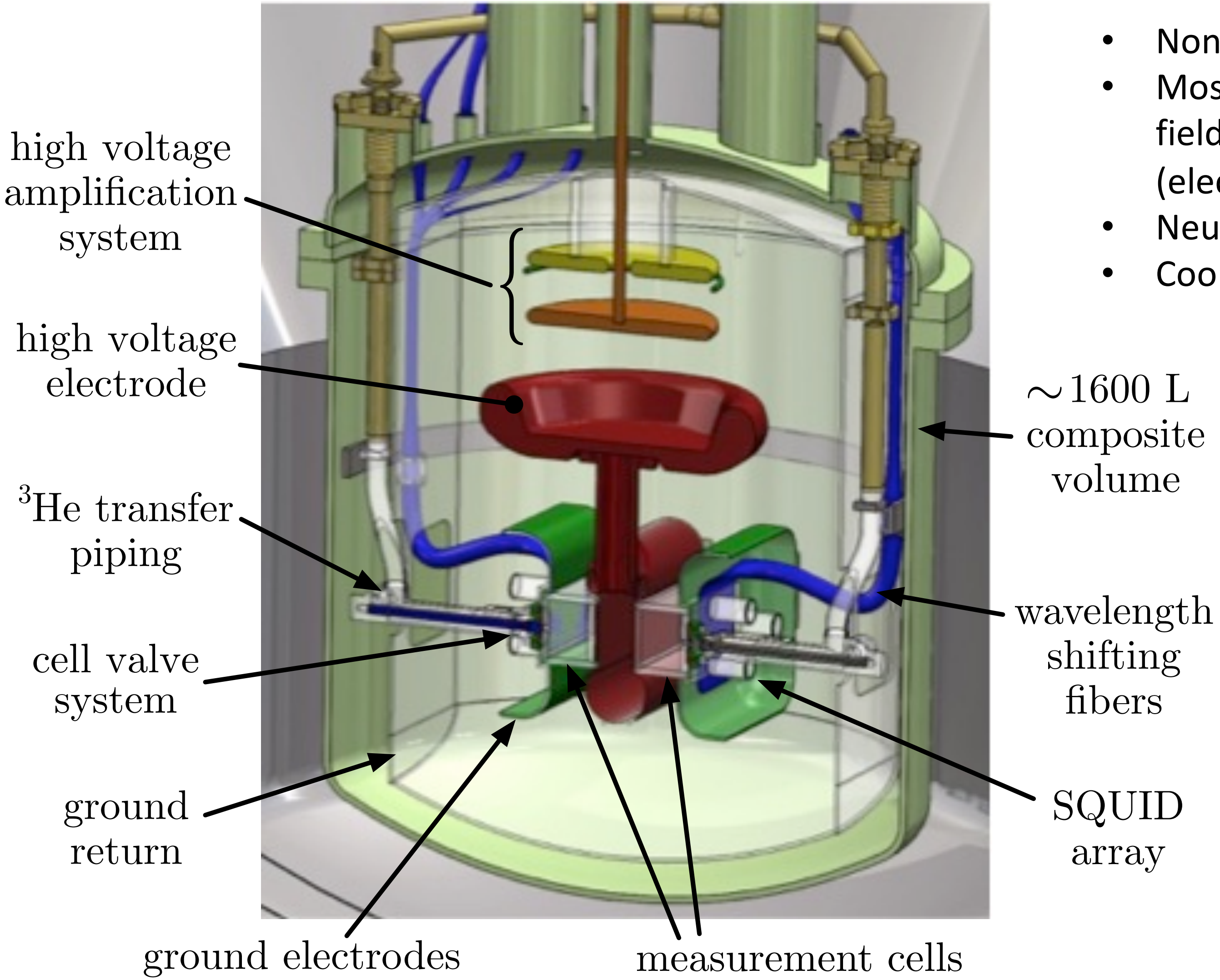
$(B_0 \to \text{from } {}^3\text{He})$

- 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.

Construction of the nEDM@SNS experiment

The central detector system

- Neutron beam going into screen. E & B0 field left to right

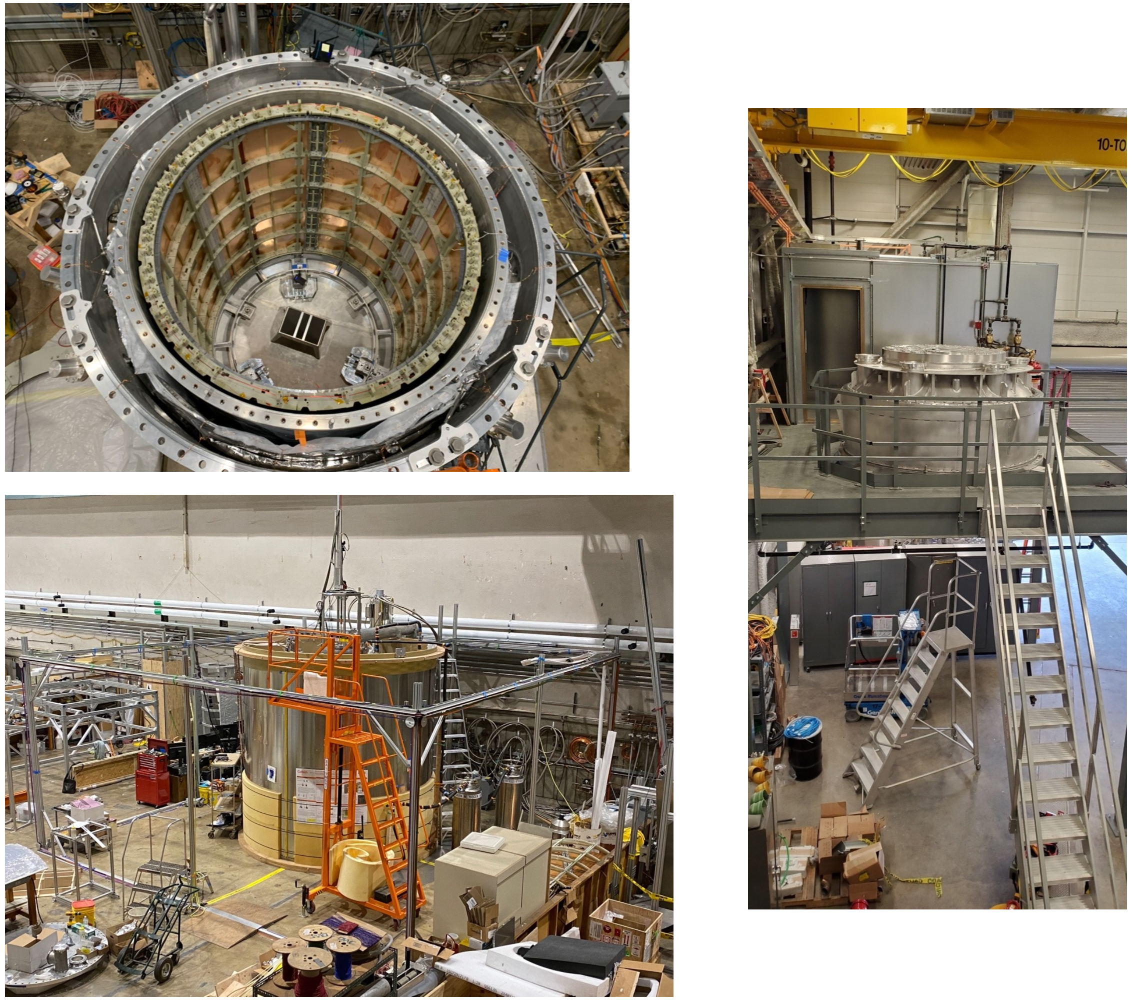


- Non-magnetic cryogenics.
- Mostly non-conductive (to not distort AC fields), but sometimes need conductivity (electrodes)
- Neutron activation friendly
- Cool to 300 mK

Large-scale integration

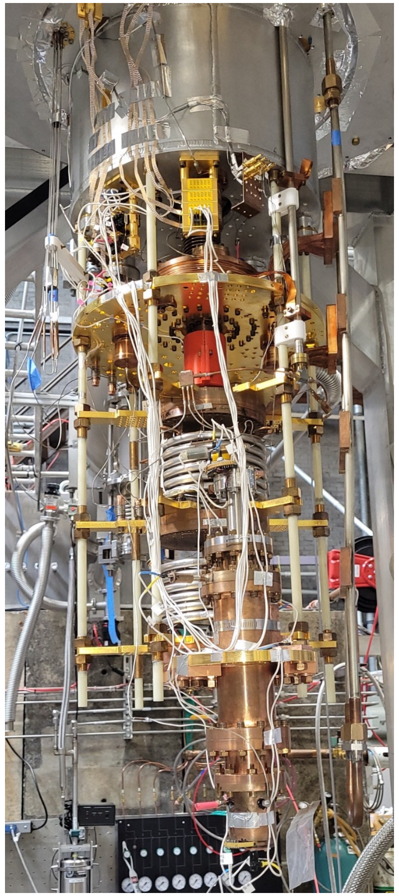
- From 2012-2018 in the Critical Component Demonstration phase.
- In 2018 transitioned to Large-scale integration and installation at SNS (with some on-going R&D)

  - Magnet module: Caltech ➞ ORNL

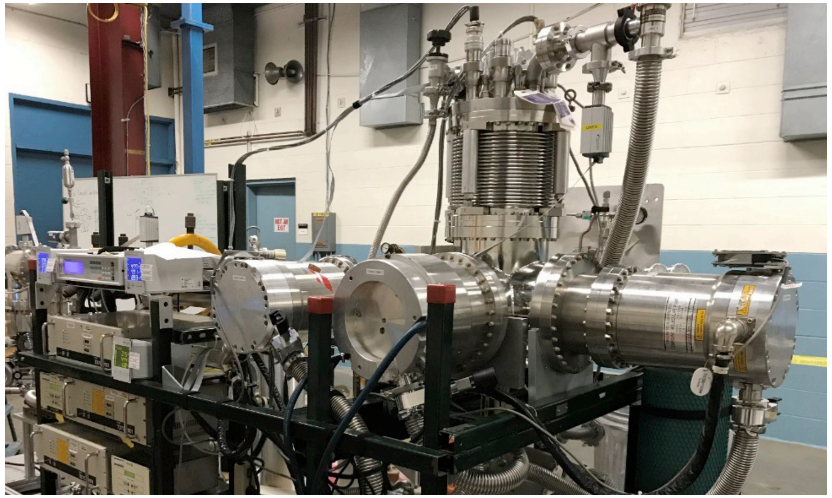


  - Magnetic shield enclosure @ Swiss company

- 3He services dilution refrigerator at UIUC



- ^{3}He Atomic beam source @ MIT



- Cavallo voltage multiplier & electrode testing

- Systematics and Operation Studies test apparatus (like a “mini” nEDM apparatus) @ NCSU

Moving into EB1 at SNS

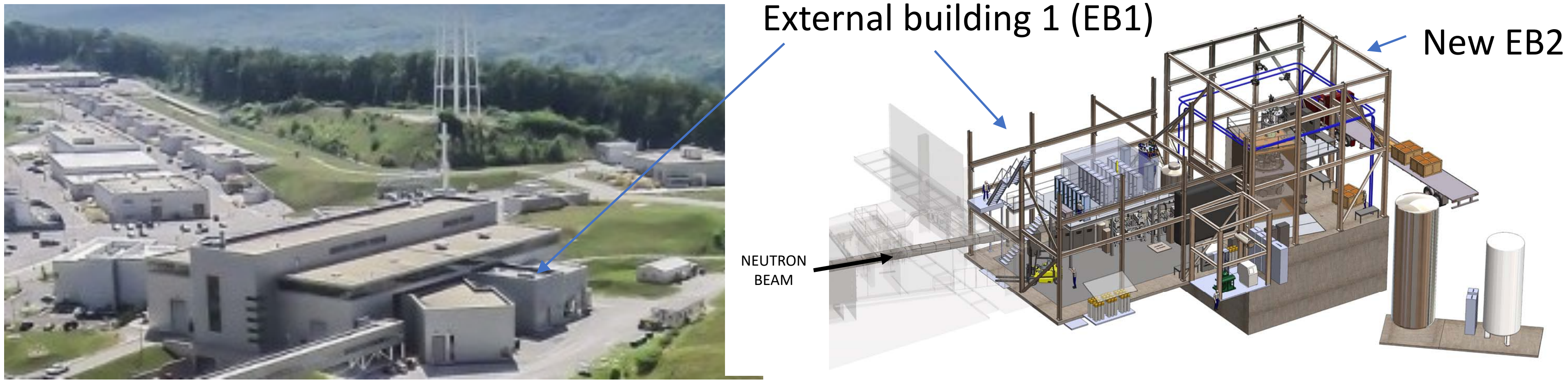


Photo from last week inside EB1:

Summary

- There is a lot from the collaboration to cover, I apologize if I missed something for time’s sake.
- The **cryogenic UCN + ^{3}He + superfluid** scheme offers many advantages to **reach 10^{-28} e.cm**
- In-situ produced UCN in **small cell with high-density and long storage times**
- Supports high **electric field**, **SQUIDs** and **superconducting magnetic shielding**
- Can vary motion of our ^{3}He magnetometer with **small T changes to study key systematic effects**
- **Two measurement modes** with different systematic effects for **self-checking our own results**
- The live and in-situ UCN spin analysis is **a true frequency measurement**
- **New type of signals for the field**, on-going extensive work to understand its analysis
- Yielded new **ultra-short baseline axion search to reach higher mass**
- Our large-scale experiment is being constructed and moving “on the floor” at SNS


Important Research at ORNL