Fundamental neutron physics at Los Alamos National Laboratory

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Outline

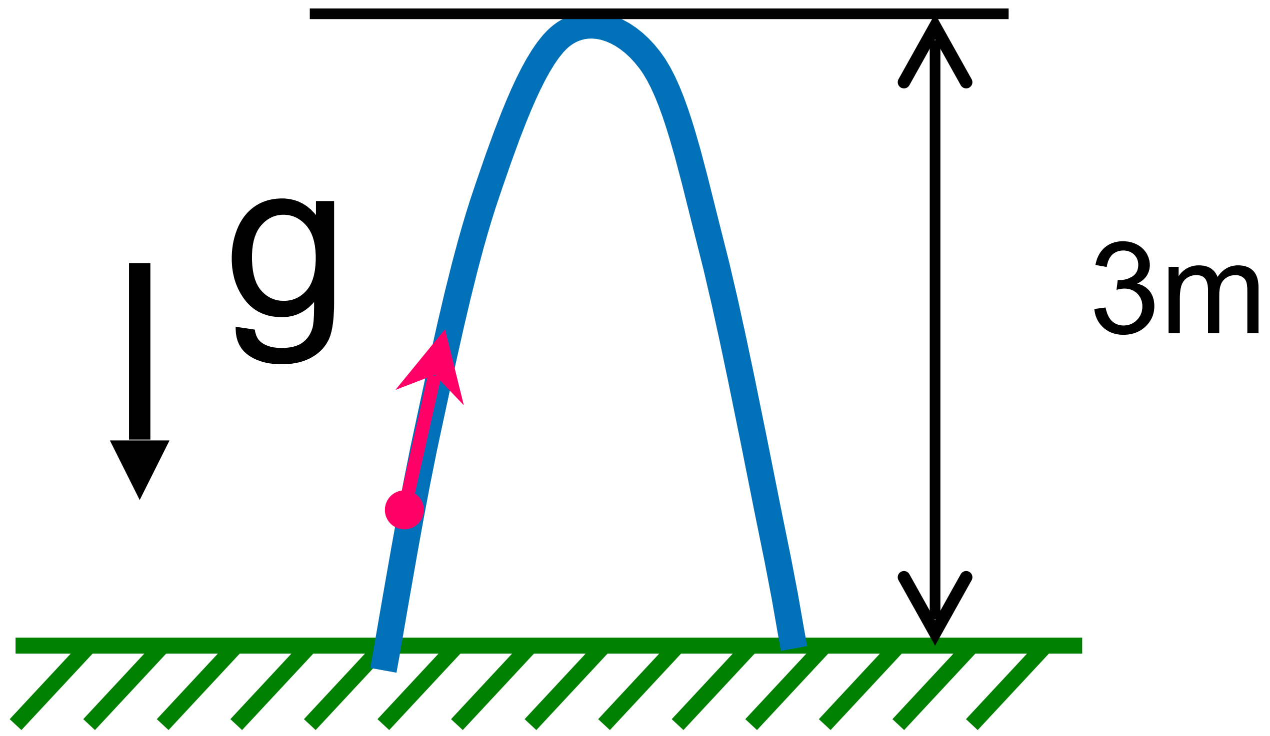
- Fundamental neutron physics
- Ultracold neutrons and ultracold neutron sources
- Test of the unitarity of the CKM matrix
- Neutron electric dipole moment search
- Summary and conclusion

Fundamental neutron physics

- What is it?
  - Tests of the consistency of the standard model of particle physics and searches of physics beyond it through precision measurement of neutron properties and interactions
- Possible experiments/observables
  - Neutron β decay correlations
  - Neutron lifetime
  - Search for neutron EDM
  - Search for neutron-antineutron oscillation
  - Bound quantum states in gravitational field
- Neutron sources used
  - Cold neutron beam
  - Ultracold neutrons (UCN)
- Facilities used
  - ILL, PSI, LANL, SNS, TRIUM, J-Parc…

Ultracold neutrons

- Very slow neutrons (v < 8 m/s)
- Can be confined in material and magnetic bottles
  - **Serves as a unique probe for both basic and applied sciences.**
- Typical parameters:
  - velocity < 8 m/s
  - Kinetic energy < 300 neV
  - Wavelength > 500 Å
- Kinetic energy ~ gravitational energy ~ magnetic energy
  - Gravitational potential: 100 neV/m
  - Magnetic potential: 60 neV/T

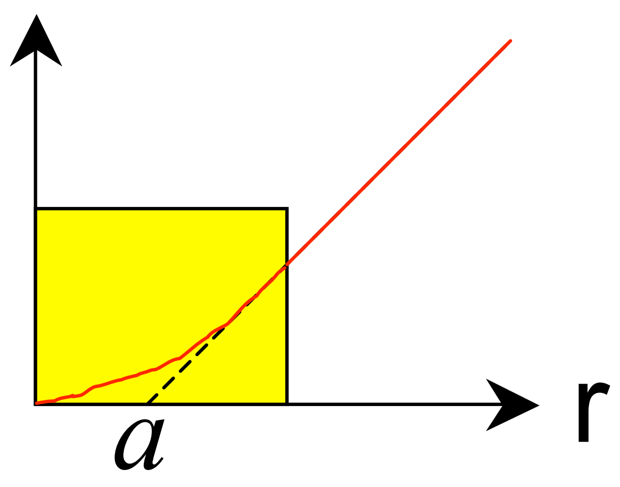


- Some characteristics of UCN give clear advantage over cold neutron beam experiments for some class of experiments (eg. nEDM, lifetime). For other classes of experiments, UCN and cold neutron experiments are complementary (eg decay correlation)

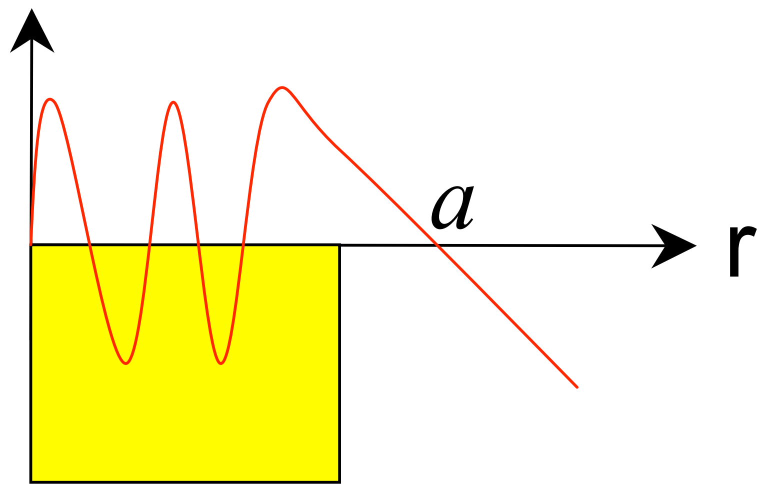
Ultracold neutrons — Fermi potential

- Low-energy neutron nucleus interaction described by scattering length a.

$\sin(kr+\delta)\quad (k \to 0)$



$a > 0$ for repulsive and strong attractive pot.
$a < 0$ for weak attractive pot.

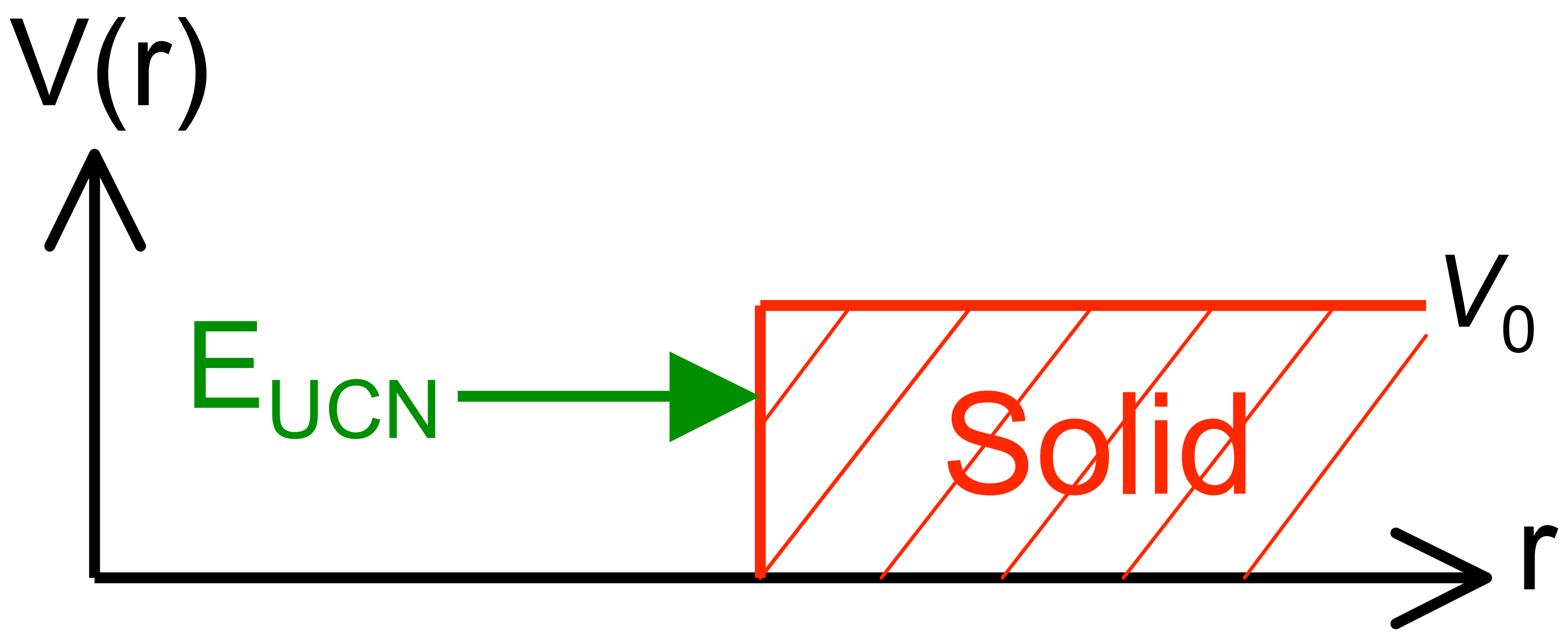


Note:
For heavy nuclei $a < 0$ is unlikely.

- Can use $V(r) = \frac{\hbar^2}{2m} 4\pi a \delta(\vec{r} - \vec{r}')$ (Fermi's pseudo-potential)
- For many nuclei in a solid, λ ≫ d (~1Å).

$$V(r) = \frac{\hbar^2}{2m} 4\pi \sum_i a_i \delta(\vec{r} - \vec{r}'_i)$$
$$= \frac{4\pi\hbar^2 a}{2m} N_0 \int \frac{d^3 r'}{V} \delta(\vec{r} - \vec{r}')$$
$$= V_0 \vartheta(\vec{r} \in V)$$

$$V_0 = \frac{2\pi\hbar^2 n_0 a}{m}$$



Material	V_0 (neV)
^{58}Ni	346
SS	188
DLC	282
dPS	165

Ultracold neutrons — where to find them

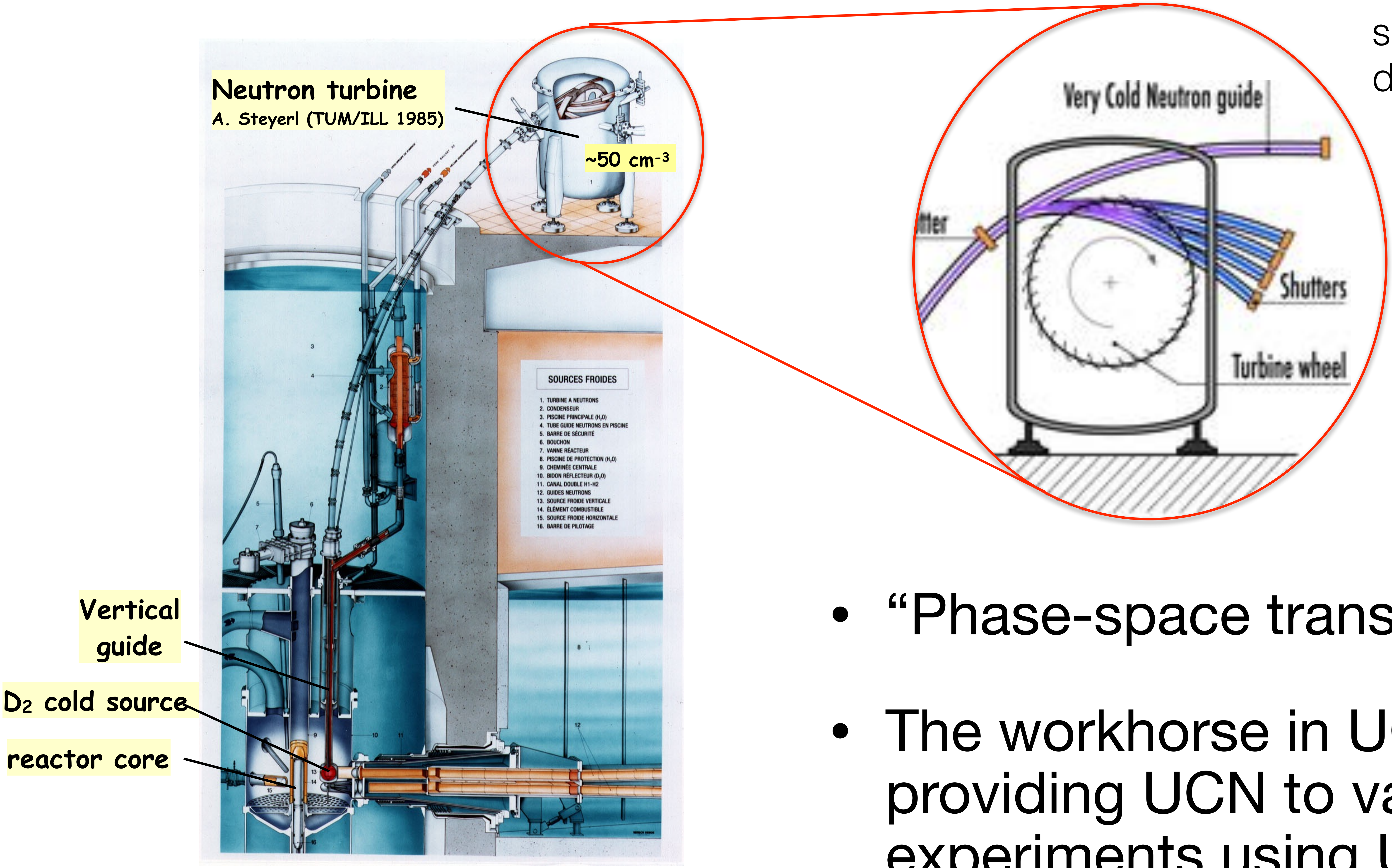
- What if we cool reactor neutrons with a moderator?

➡ The fraction of UCN in the Maxwellian spectrum is very small

$f \sim 3\text{x}10^{-8}$ at 300K
$f \sim 10^{-6}$ at 20K (liquid H_2 or D_2 source)

- Need a "trick" for a more efficient production of UCN
  - Turbine or doppler shifter
  - Superthermal converter

ILL Turbine source



Receding blades
slow neutrons
down

- “Phase-space transformer”
- The workhorse in UCN physics, providing UCN to various important experiments using UCN for decades.

Superthermal process

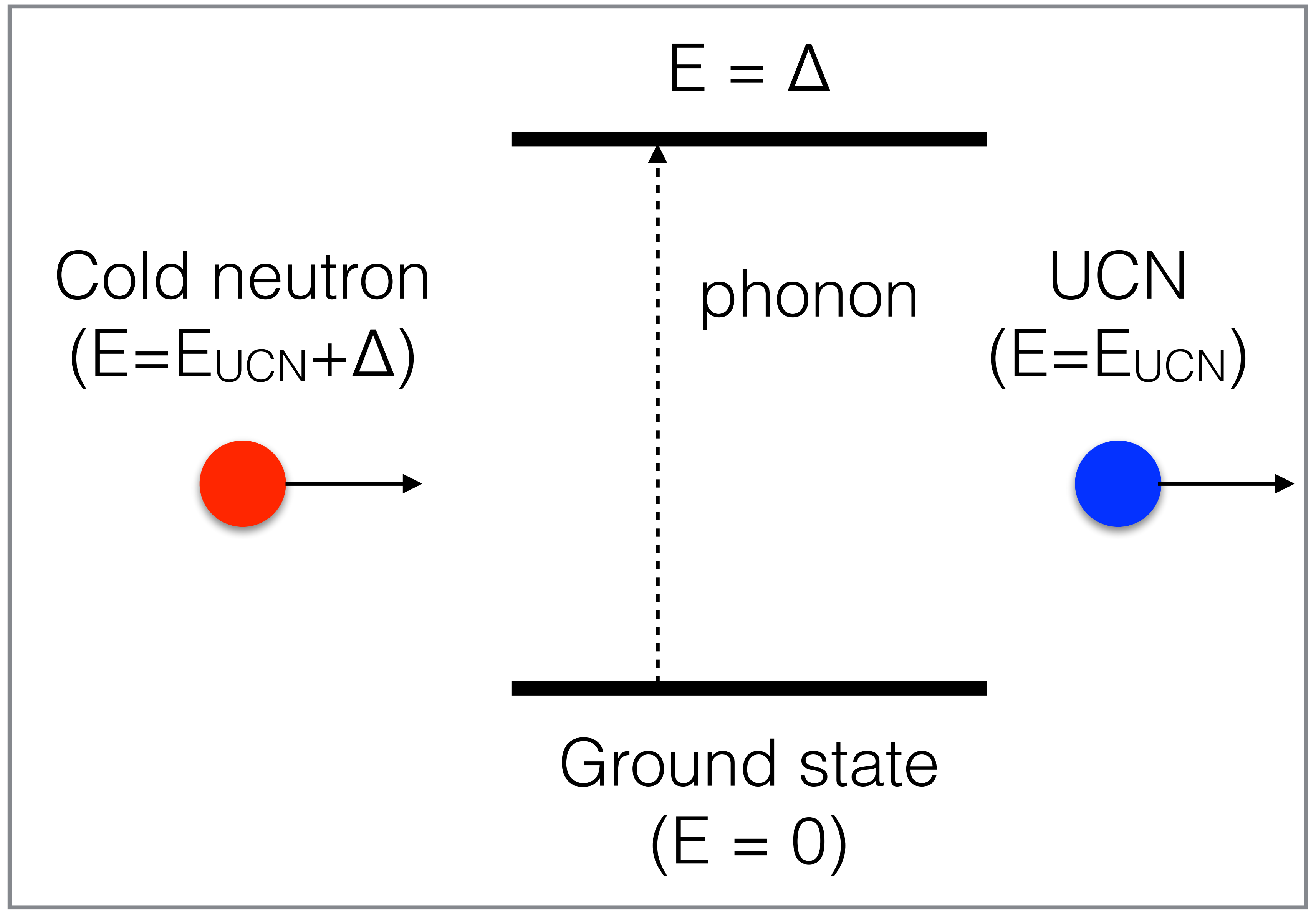
- No thermal equilibrium between the neutron “gas” and the scattering system
- Neutrons lose energy by creating photons in the “converter” (down-scattering)
- “Up-scattering” is suppressed by the Boltzmann factor

$$\sigma_{up} = \frac{E_{UCN} + \Delta}{E_{UCN}} e^{-\frac{\Delta}{kT}} \sigma_{down}$$

$$\Rightarrow \text{For } \Delta \gg kT \gg E_{UCN}, \ \sigma_{up} \ll \sigma_{down}$$

Golub and Pendlebury (1975)

Down-scattering



E = Δ

Cold neutron
(E=E_{UCN}+Δ)

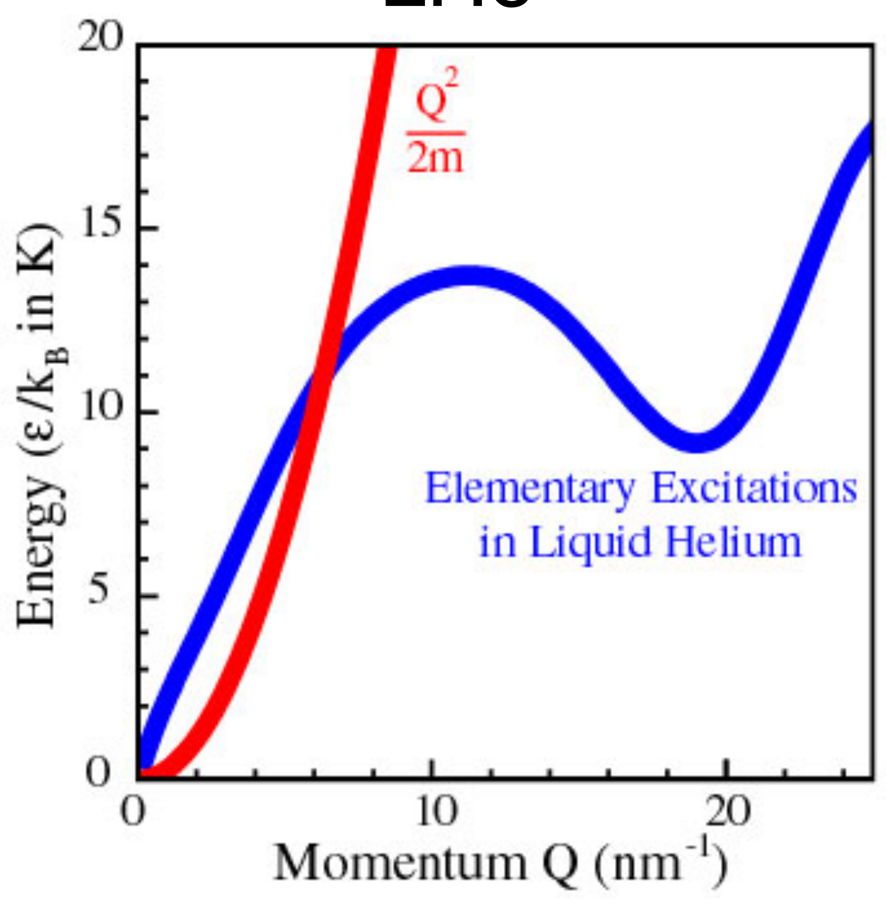
phonon

UCN
(E=E_{UCN})

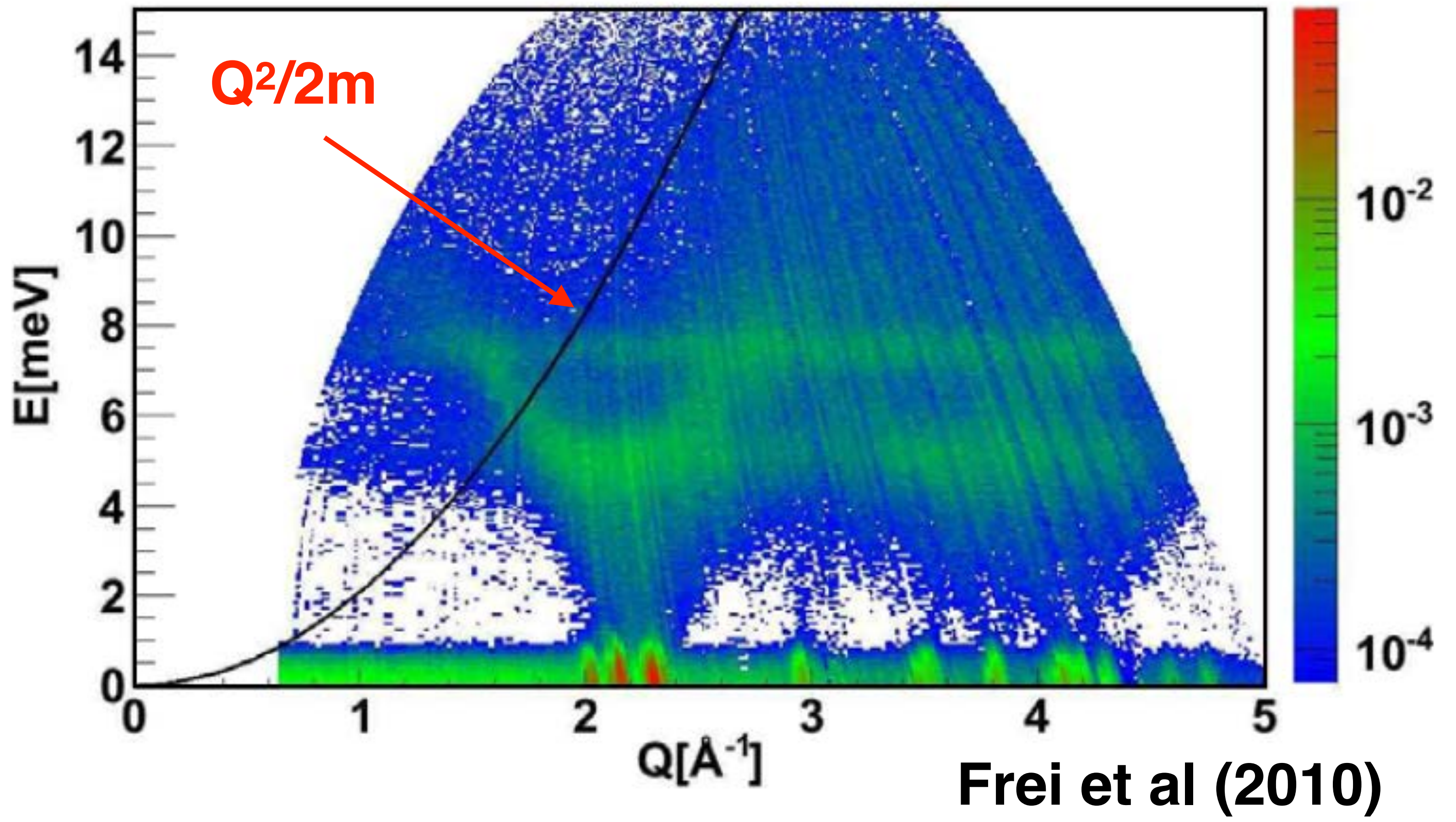
Ground state
(E = 0)

- Two commonly used converter materials:
  - LHe
  - SD2

LHe

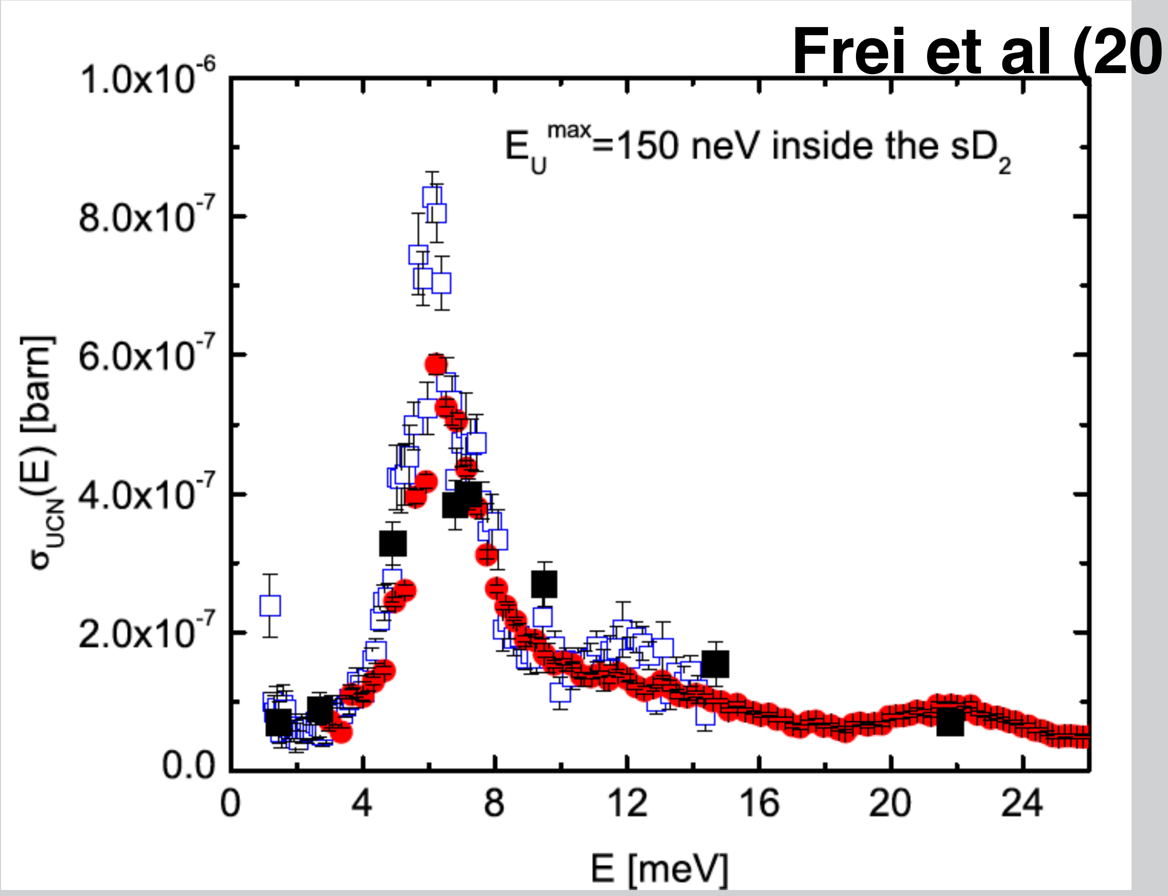
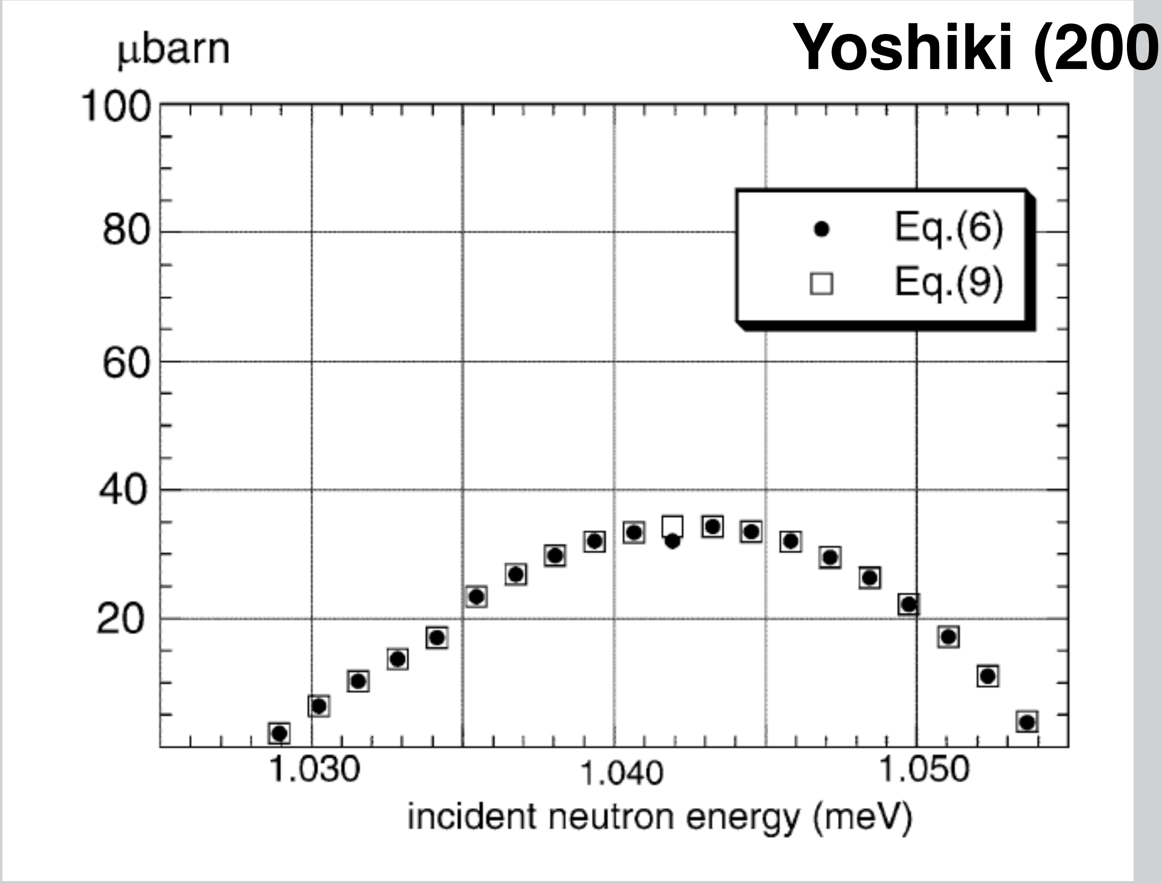


SD₂ S(Q,E)

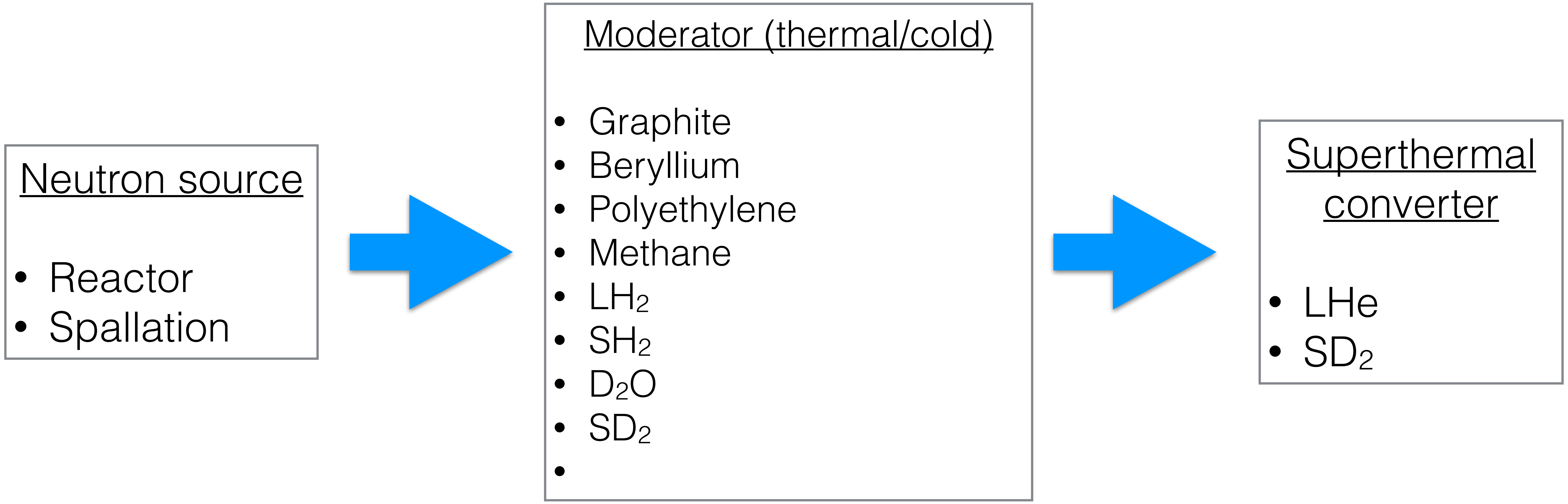


Frei et al (2010)

SD_2 vs LHe

	SD_2	LHe
UCN production	 **Frei et al (2010)** $\int\sigma(SD_2)dE \sim 10 \times \int\sigma(LHe)dE$	 **Yoshiki (2003)**
Up scattering	τ_{abs} ~ 150 ms at 5 K	τ_{up}~T^7, and ~1000 s at 0.7 K (multiphonon process)
Nuclear absorption	τ_{abs} ~ 150 ms	0
Other losses	• Absorption by H contamination (τ_{abs}~150 ms at 0.2% HD) • Up-scattering by para-D2 (τ_{up}~150 ms at 1.0% para)	Absorption by ^{3}He (τ_{abs}~500 s at X=10^{-10})

UCN sources based on superthermal converter



Neutron source

- Reactor
- Spallation

Moderator (thermal/cold)

- Graphite
- Beryllium
- Polyethylene
- Methane
- LH_2
- SH_2
- D_2O
- SD_2
-

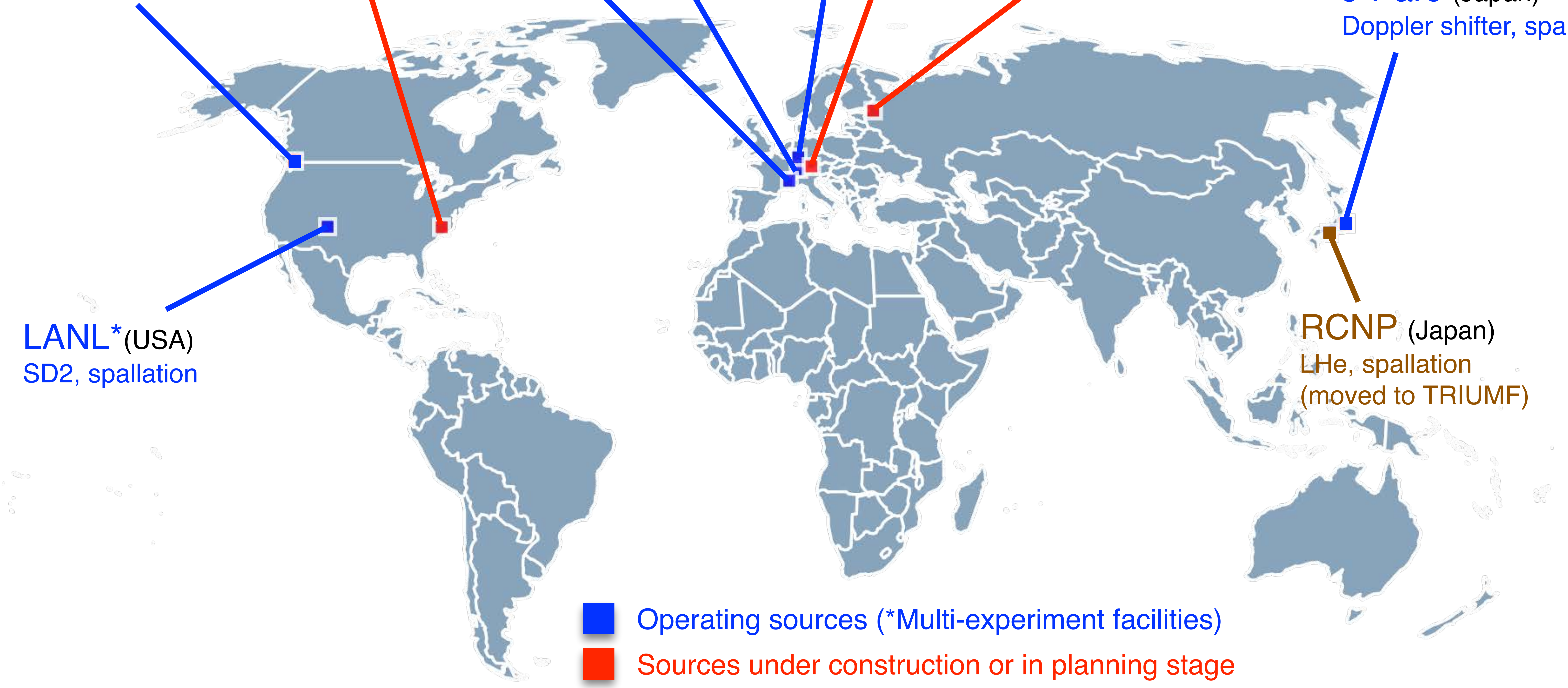
Superthermal converter

- LHe
- SD_2

It is important to optimize the entire system:

- Spectrum of the cold neutrons
- Coupling of the cold moderator to the UCN converter.

UCN sources around the world



Mainz* (Germany)
SD2, reactor

PSI (Switzerland)
SD2, spallation

NCSU (USA)
SD2, reactor

TUM (Germany)
SD2, reactor

ILL* (France)
Turbine, reactor
LHe, reactor

PNPI (Russia)
LHe, reactor

TRIUMF (Canada)
LHe, spallation

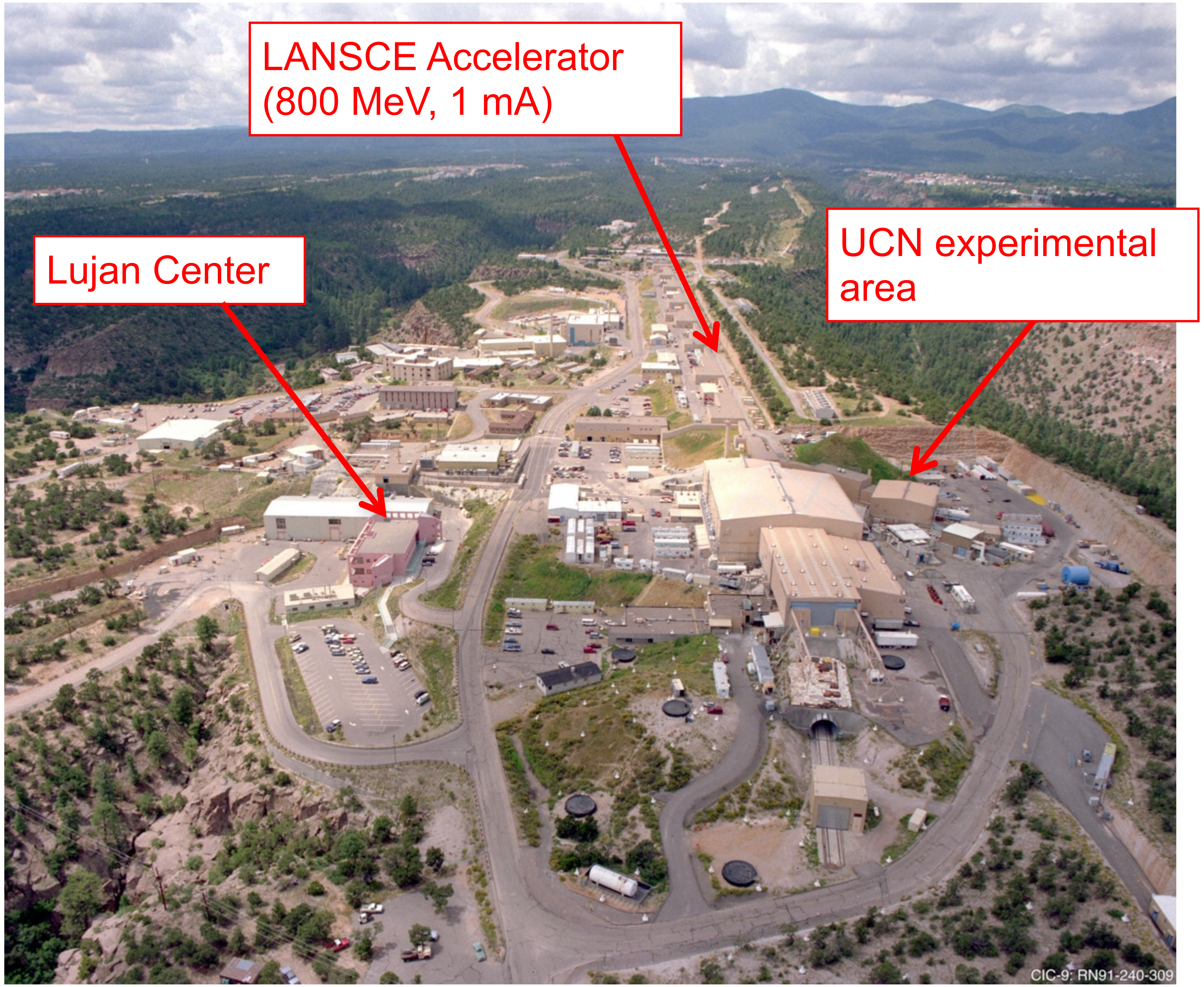
J-Parc (Japan)
Doppler shifter, spallation

LANL*(USA)
SD2, spallation

RCNP (Japan)
LHe, spallation
(moved to TRIUMF)

- 🟦 Operating sources (*Multi-experiment facilities)
- 🟥 Sources under construction or in planning stage
- 🟫 Sources no longer in operation

Los Alamos Neutron Science Center (LANSCE)

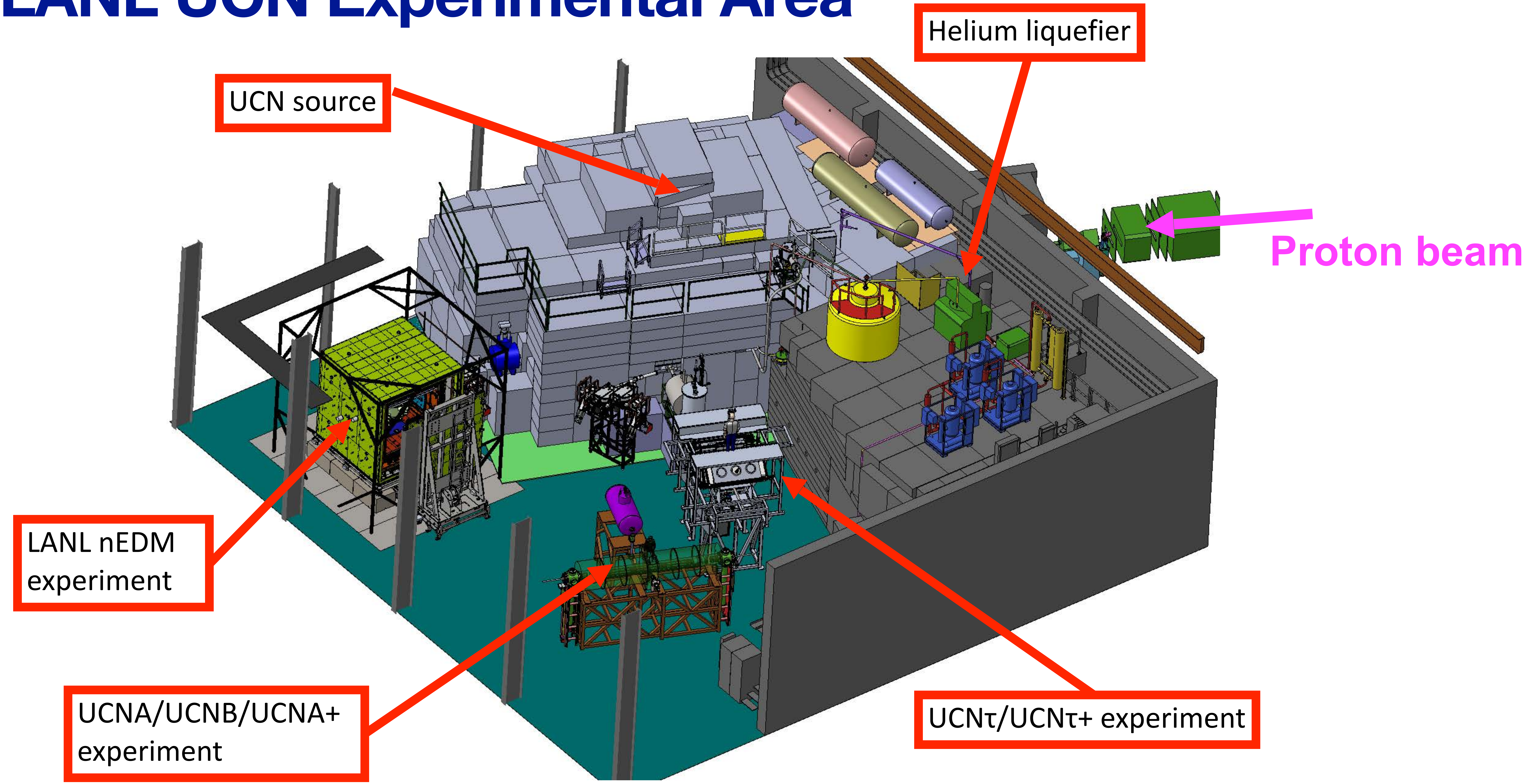


LANSCE Accelerator (800 MeV, 1 mA)

Lujan Center

UCN experimental area

LANL UCN Experimental Area



Helium liquefier

UCN source

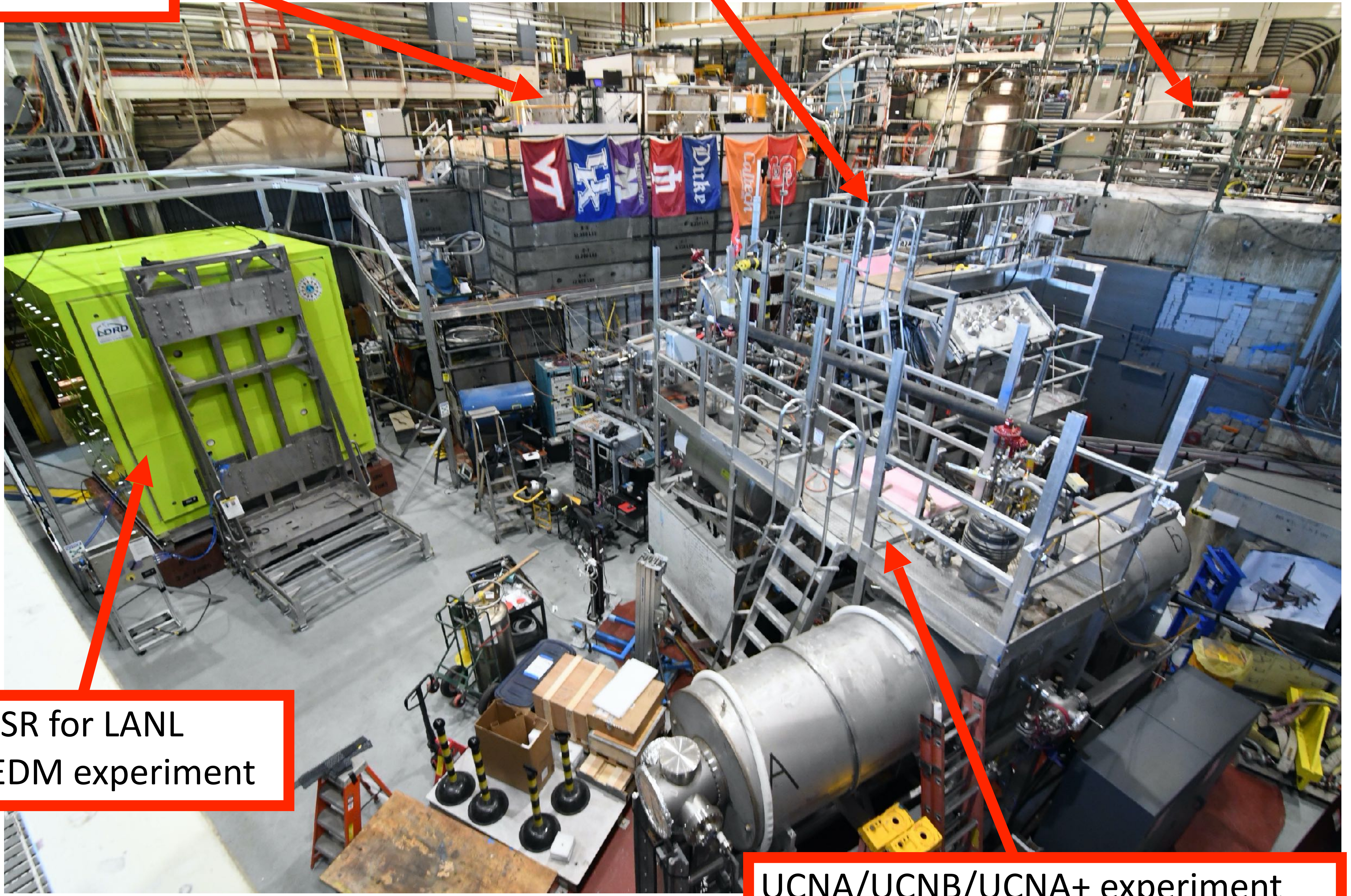
Proton beam

LANL nEDM experiment

UCNA/UCNB/UCNA+ experiment

UCNτ/UCNτ+ experiment

LANL UCN Experimental Area



UCN source

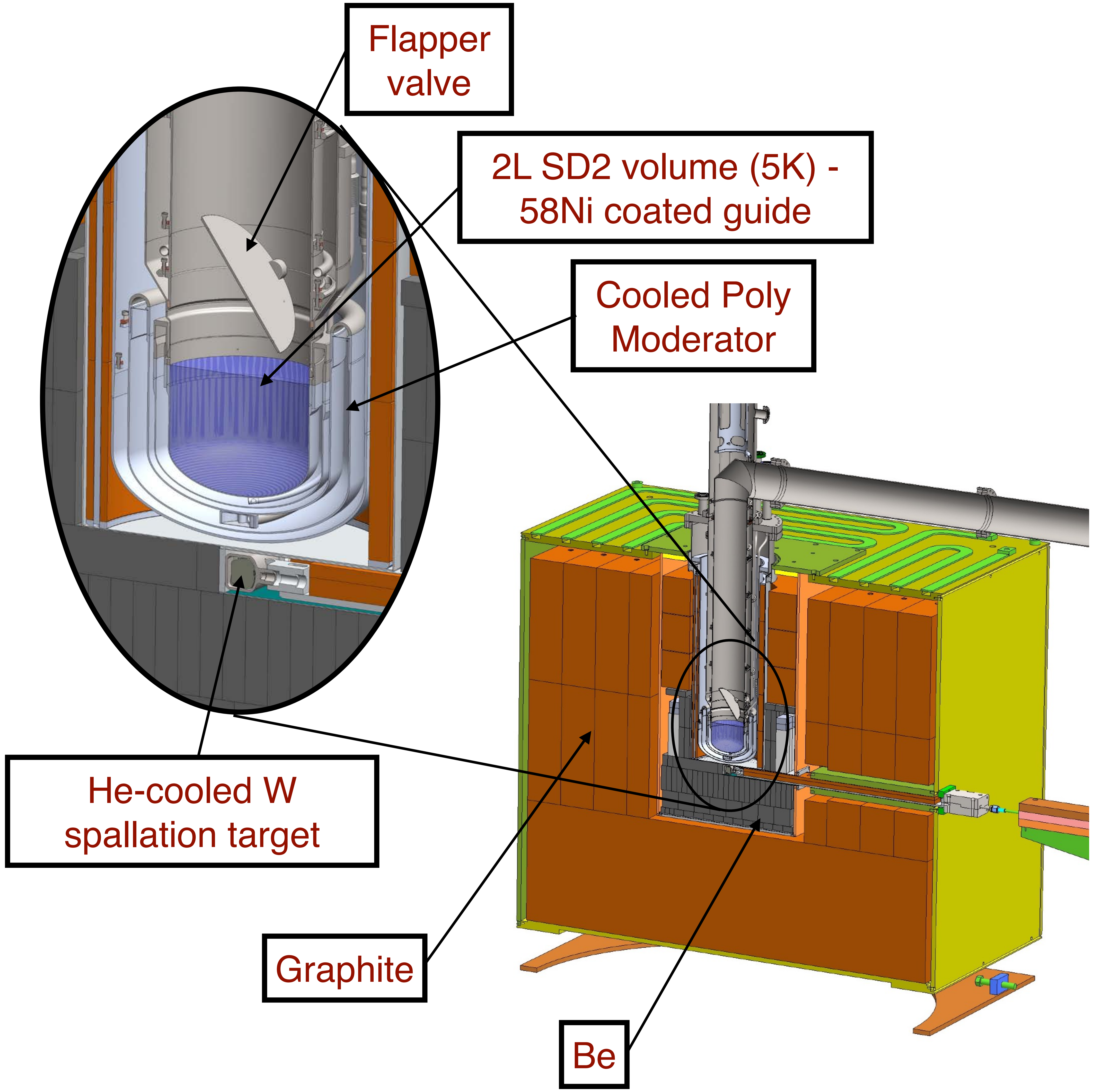
UCNτ/UCNτ+ experiment

Helium liquefier

MSR for LANL nEDM experiment

UCNA/UCNB/UCNA+ experiment

LANL UCN Source



Spallation neutrons from W target
~ 2 MeV

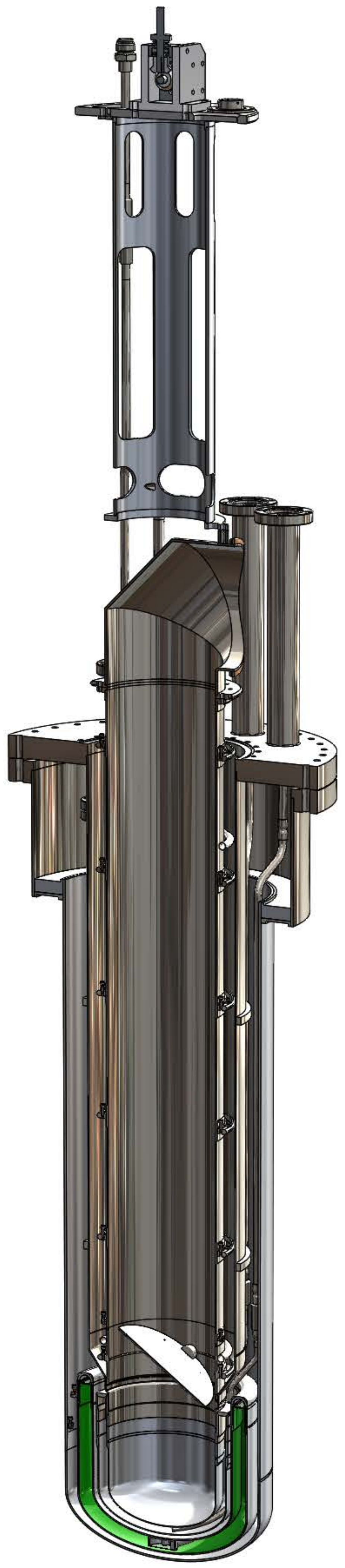
Thermal neutrons in Be and graphite moderator
~ 25 meV

Cold neutrons in polyethylene cold moderator
~ 6 meV

Ultracold neutrons in SD2 converter
~ 100 neV

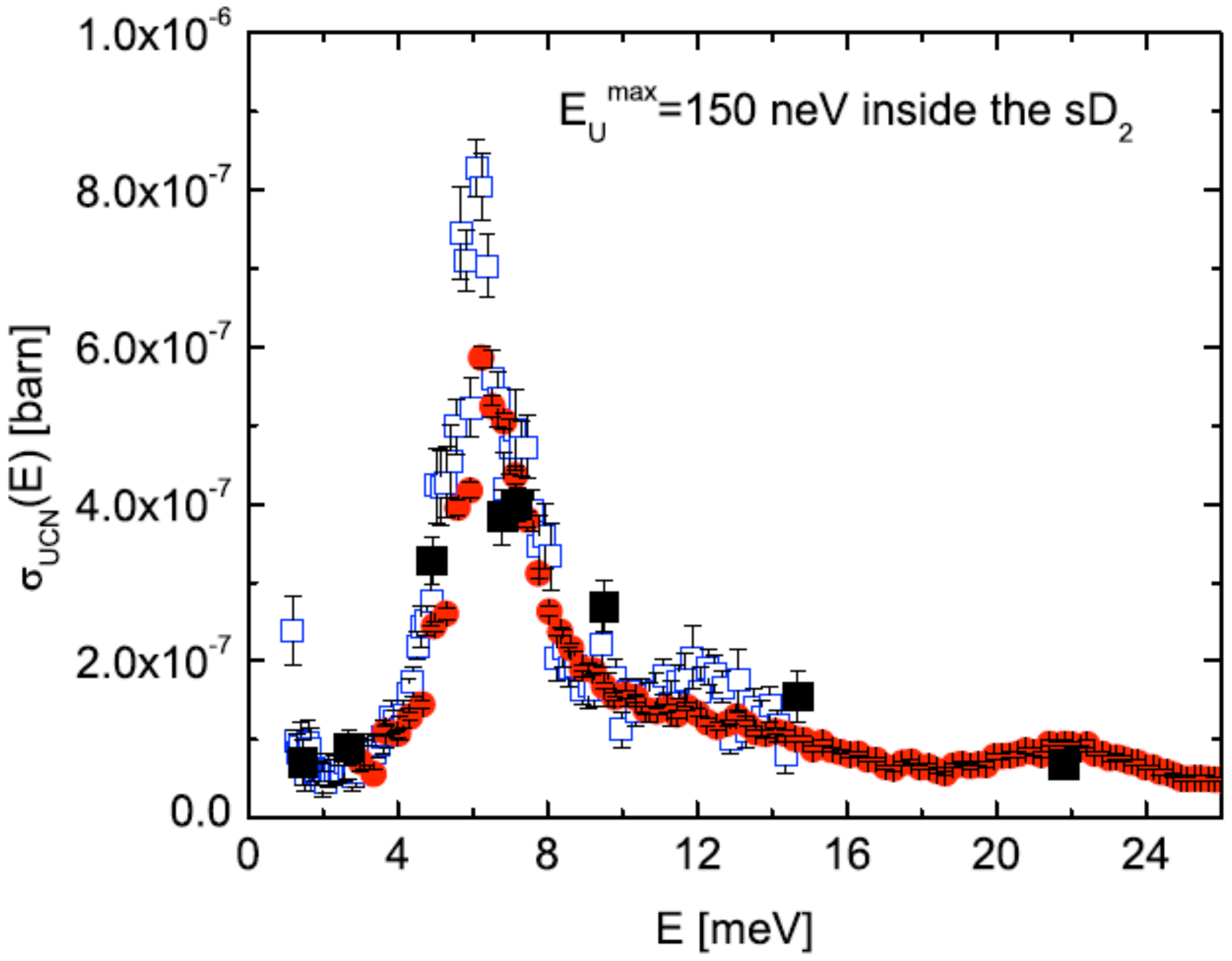
LANL UCN Source upgrade (FY14-17)

- New source cryostat
  - New design based on previous UCN Source cryostat, which had been successfully operating since 2004.
  - Optimize source cryostat and moderator geometry to improve UCN output (based on simulation that is benchmarked against the current source).
  - Replaceable moderator
- New flapper valve design based on previous successful version
  - Most recent model has surpassed 1M cycles
  - Tightly integrated with source cryostat design
  - Flapper drive components moved outside the UCN volume
  - Modify tee geometry for improved UCN flow and reduced loss



Optimization of UCN production

- UCN production cross section taken from Frei et al. (2010).



Includes data from Atchison et al. (2007)

UCN production peak @ ~ 7 meV ~ 80 K

- UCN production rate is given by:

$$P_{UCN} = \sigma_{SD2} \int \Phi_{CN} \sigma_{UCN} dE$$

D2 molecule number density

CN flux

UCN production cross section

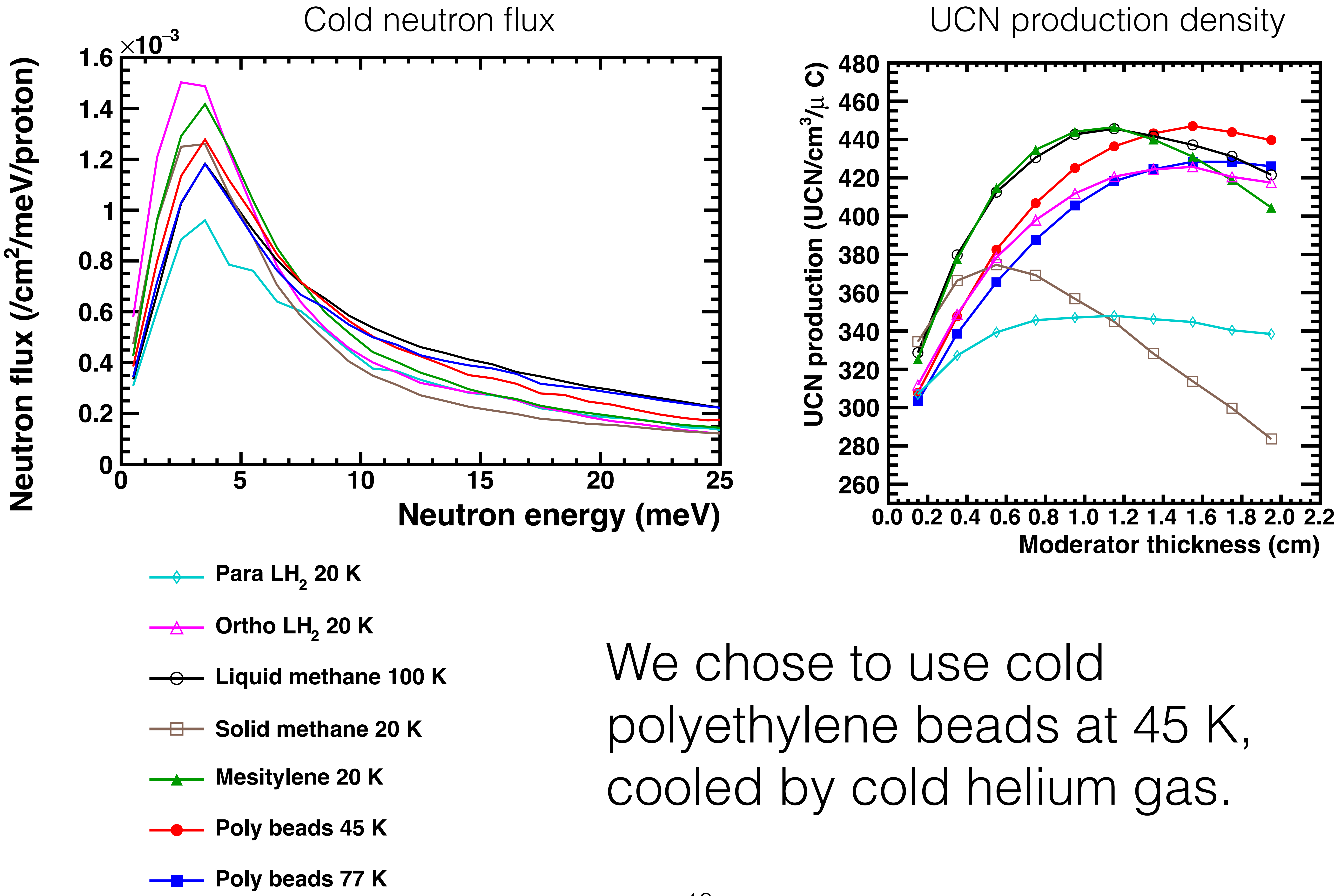
The UCN source design was optimized by varying:

- Moderator geometry
- Moderator material
- Source and guide geometries

Tools used include:

- MCNP6 with additional S(α, β) files:
  - Ortho SD2 at 5K from R. Granada
  - Polyethylene at 5K, 77K, and 293 K from C. Lavelle
  - Solid methane at 20K from D. Baxter
- In-house developed UCN transport code

Optimization of moderator material and temperature



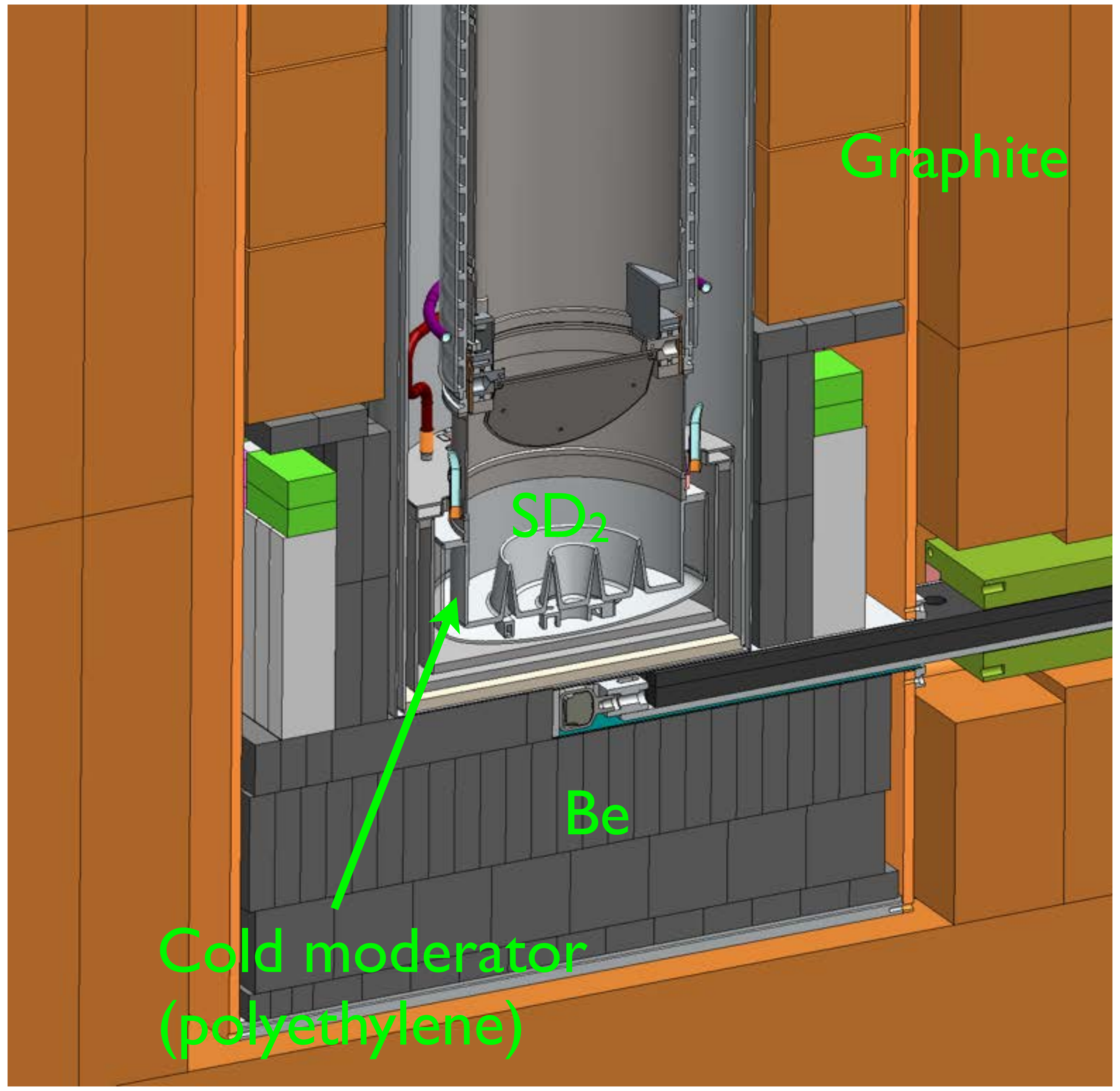
Cold neutron flux

UCN production density

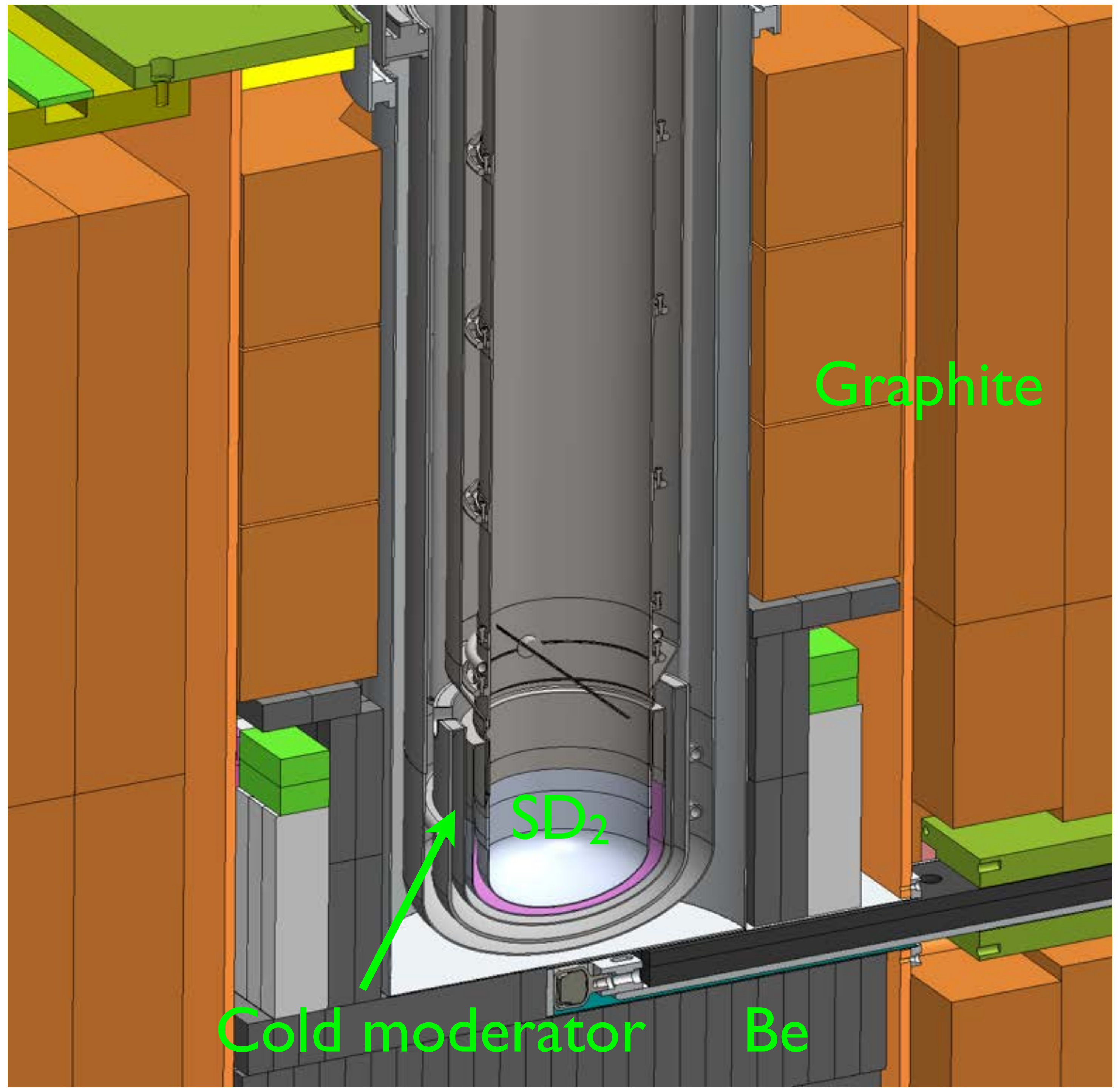
We chose to use cold polyethylene beads at 45 K, cooled by cold helium gas.

Previous and new sources (bottom part)

Previous

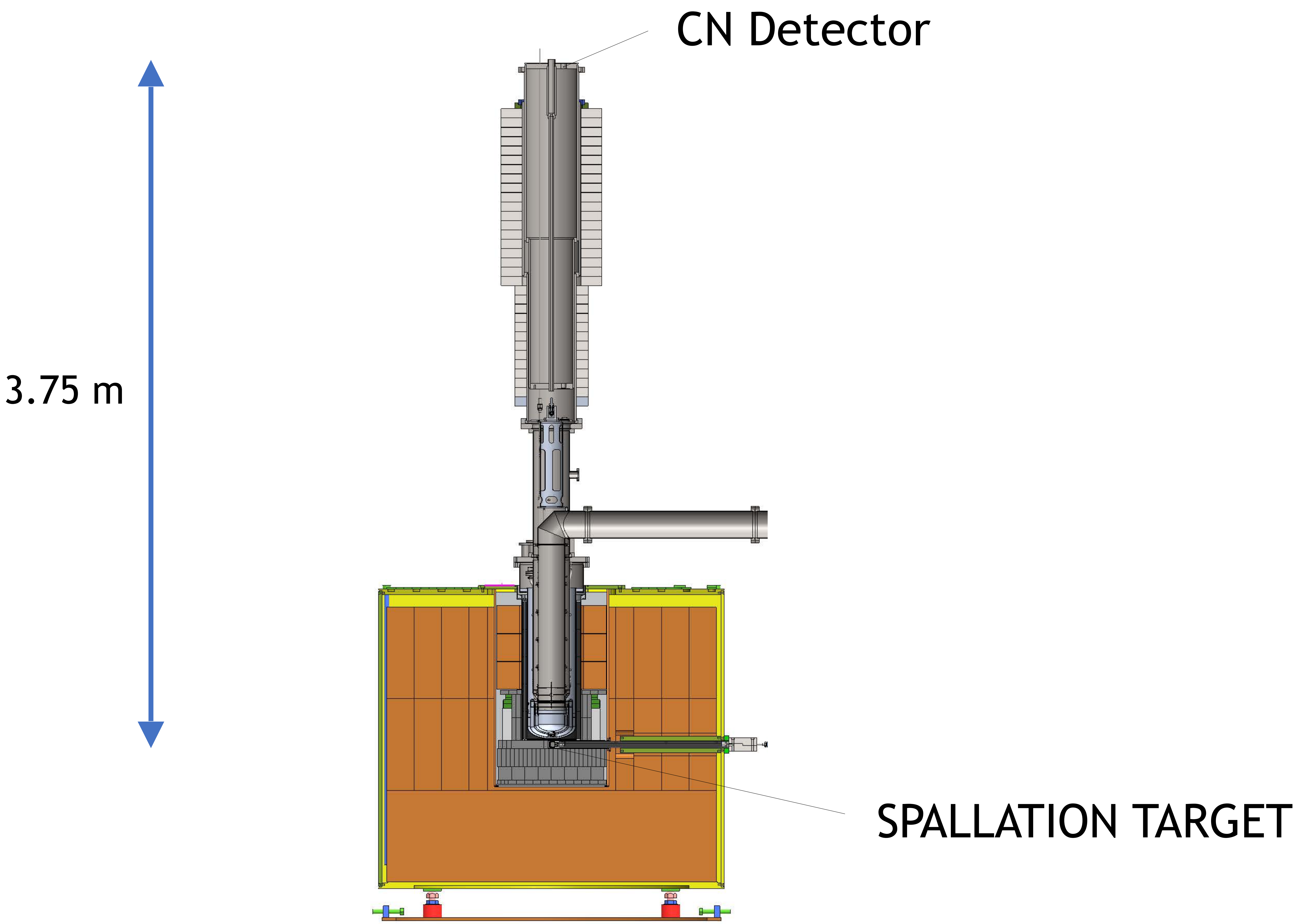


New

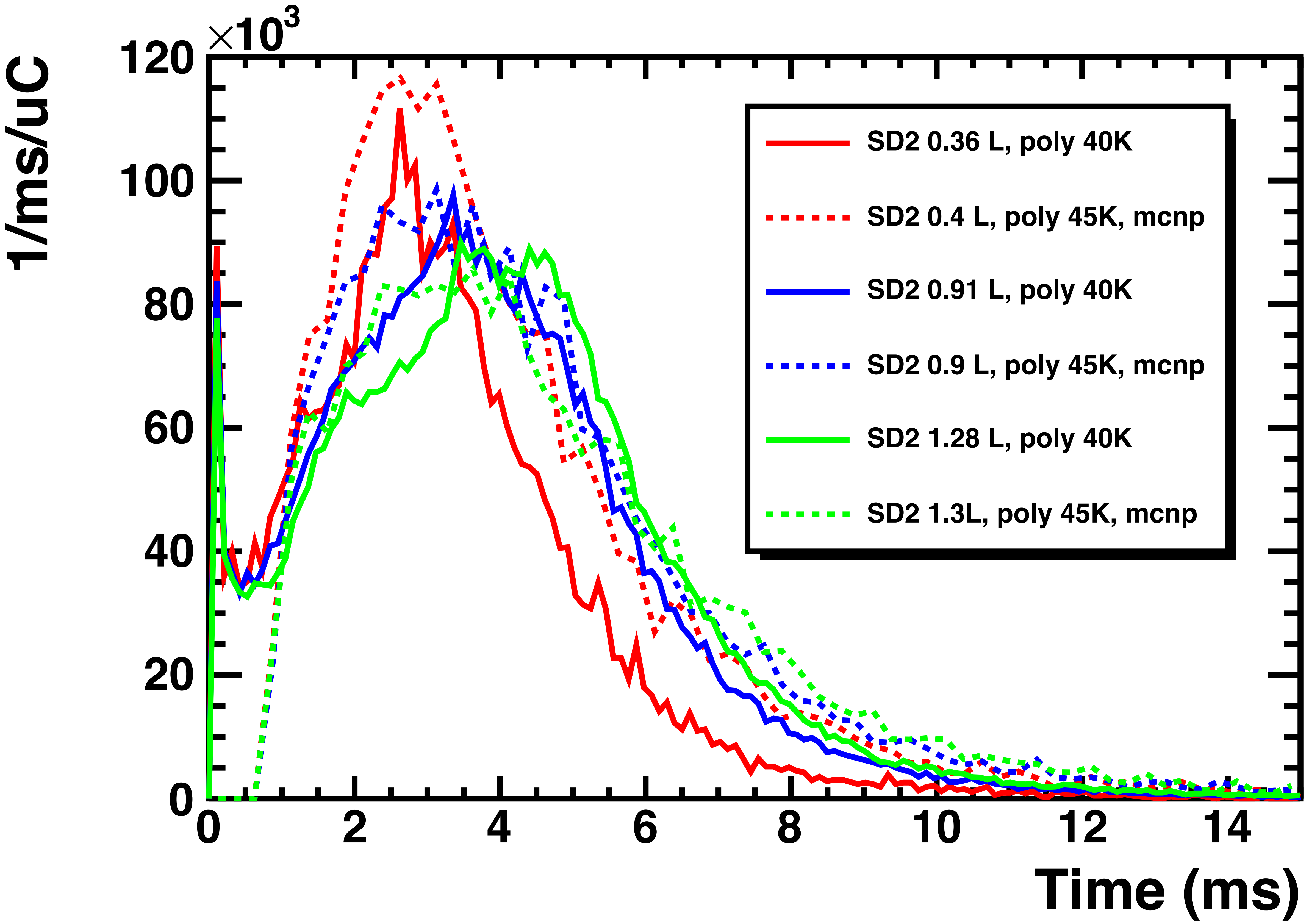


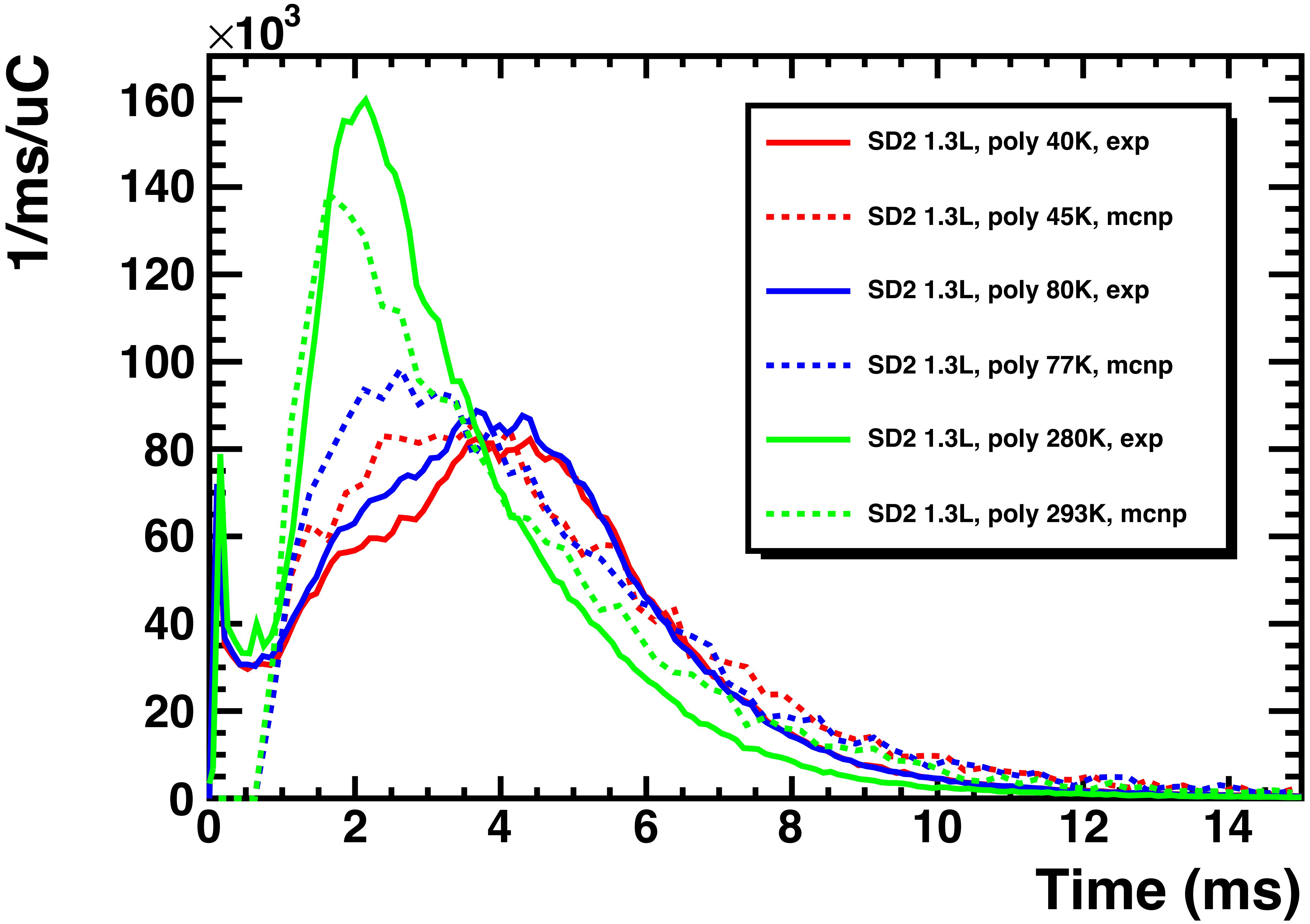
- A smaller UCN source diameter (15.24cm compared to 20.32 cm) achieved a more optimized balance between UCN production density and UCN transport out of the vertical UCN source volume.

Cold neutron (CN) measurement



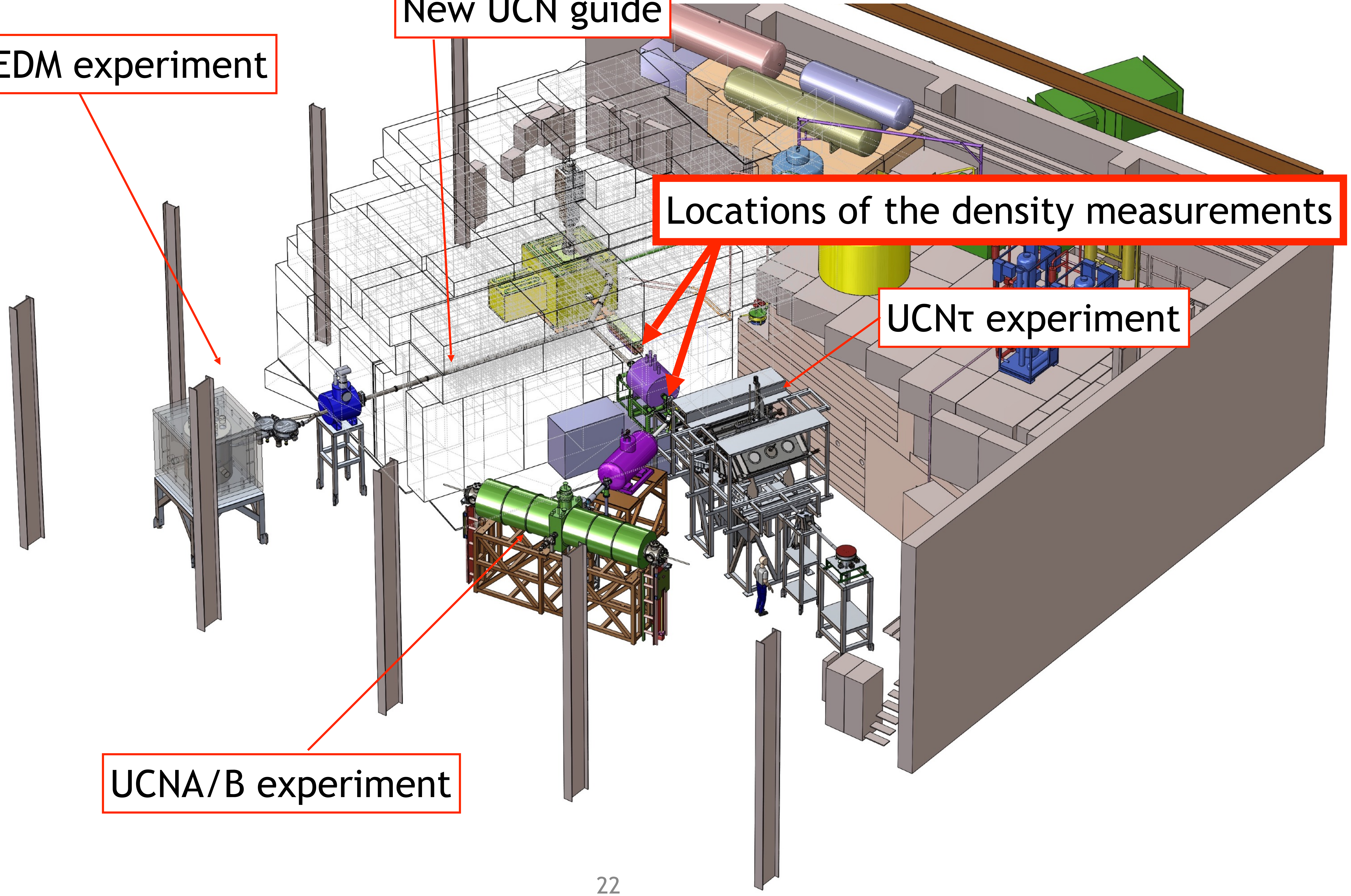
CN TOF distributions





Note: MCNP6 results are scaled by 0.5 to account for the CN detector efficiency

Locations of the UCN density measurements



New UCN guide

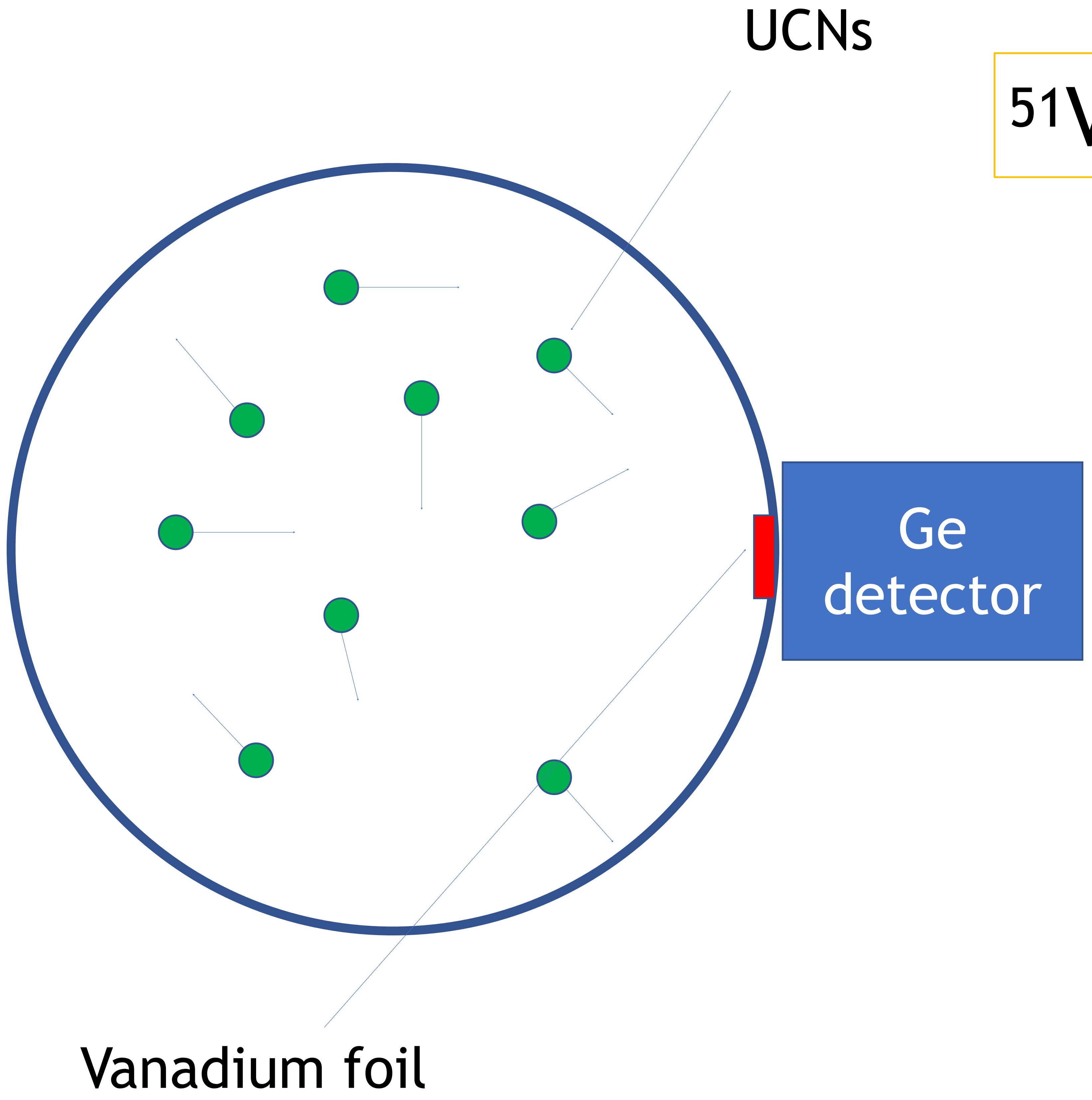
New nEDM experiment

Locations of the density measurements

UCNτ experiment

UCNA/B experiment

UCN density measurement based on vanadium activation

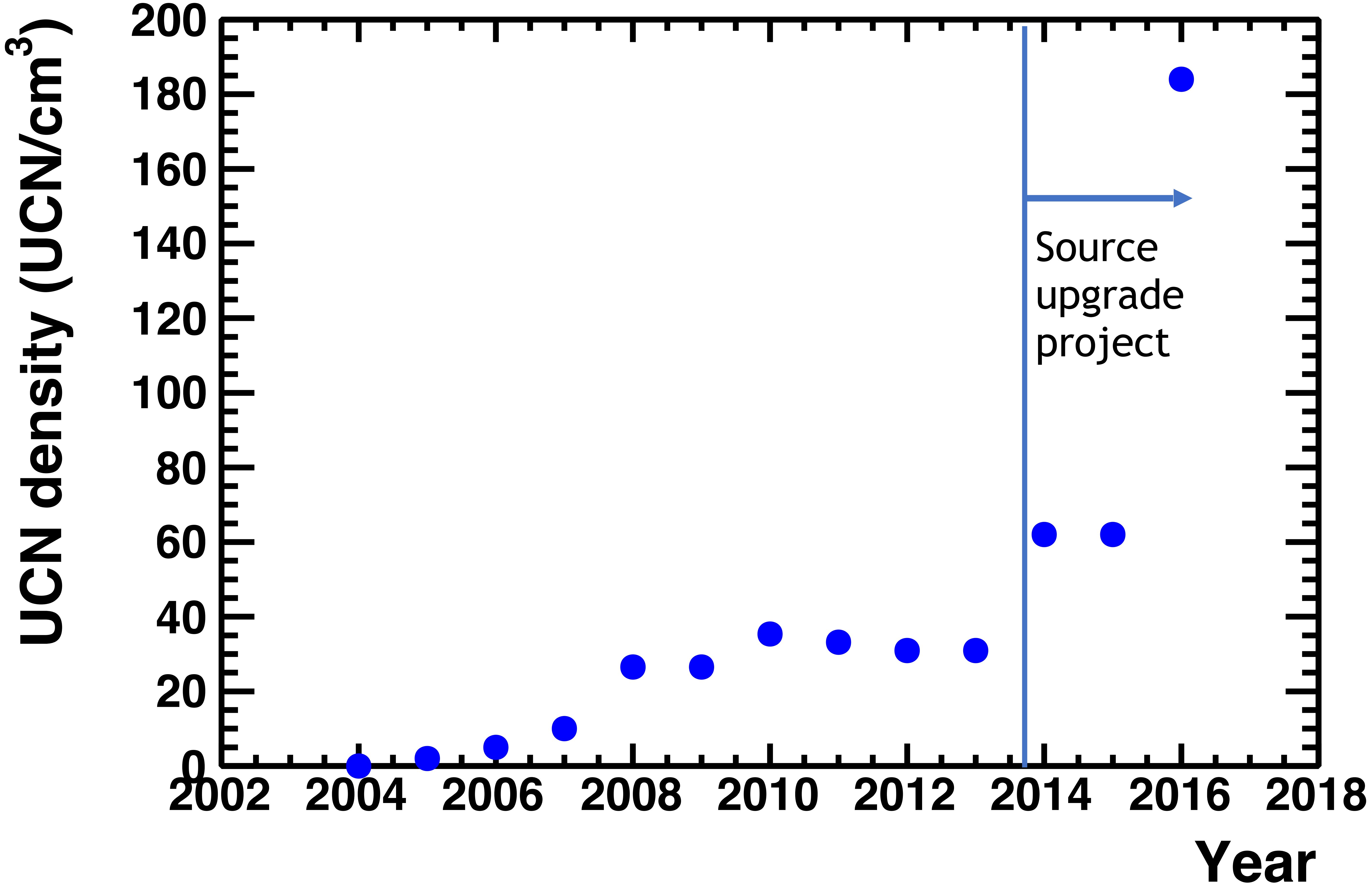


$^{51}V + n \rightarrow {}^{52}V \rightarrow {}^{52}Cr + \beta + \gamma$ (1.4 MeV)

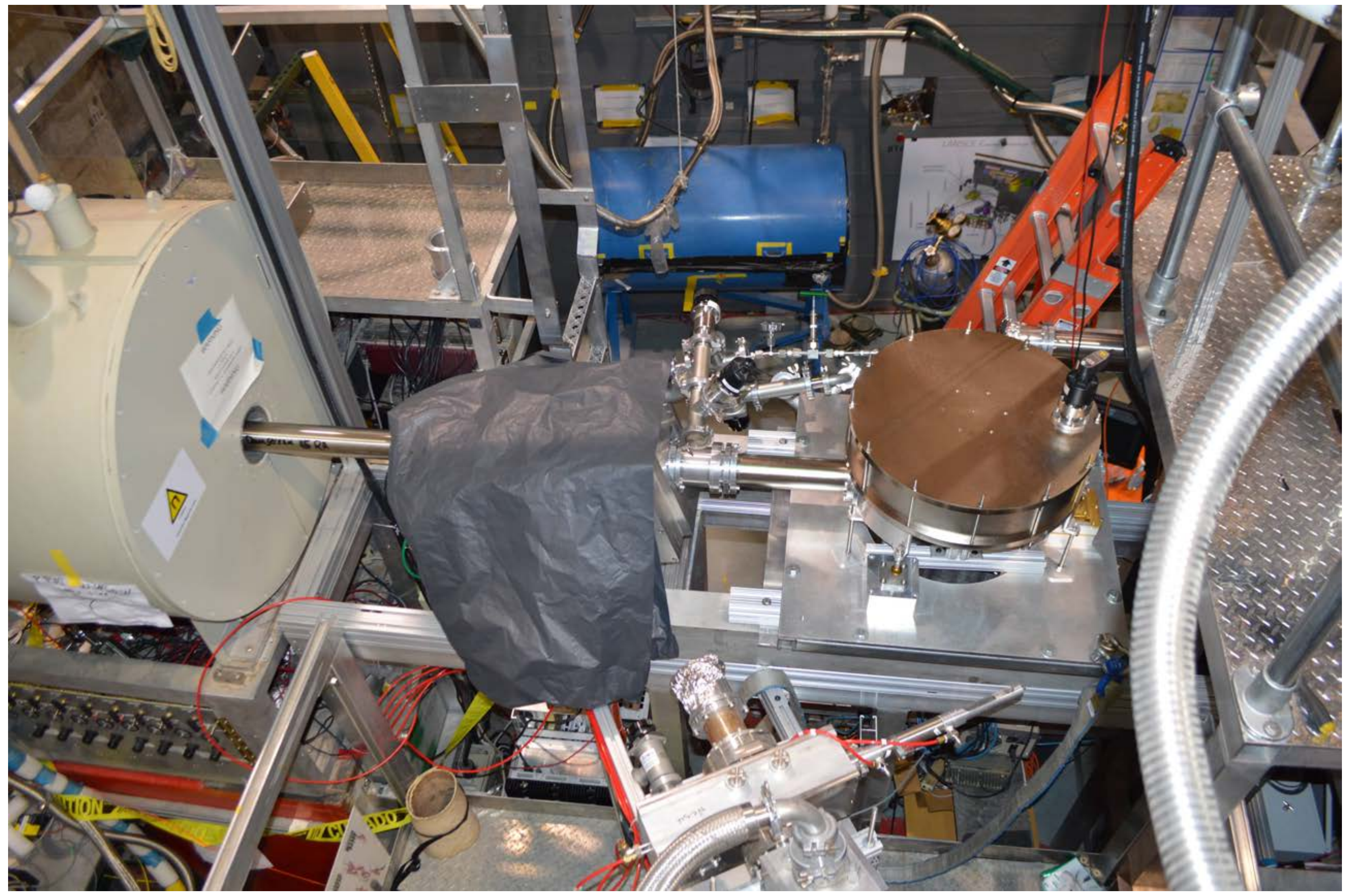
- Detecting the 1.4 MeV gammas with a Ge detector determines the UCN capture rate by the vanadium foil.
- The Ge detector can be calibrated (for the efficiency and solid angle product) by placing a calibrated ^{60}Co source at the location of the vanadium foil.
- UCN density can be determined from:

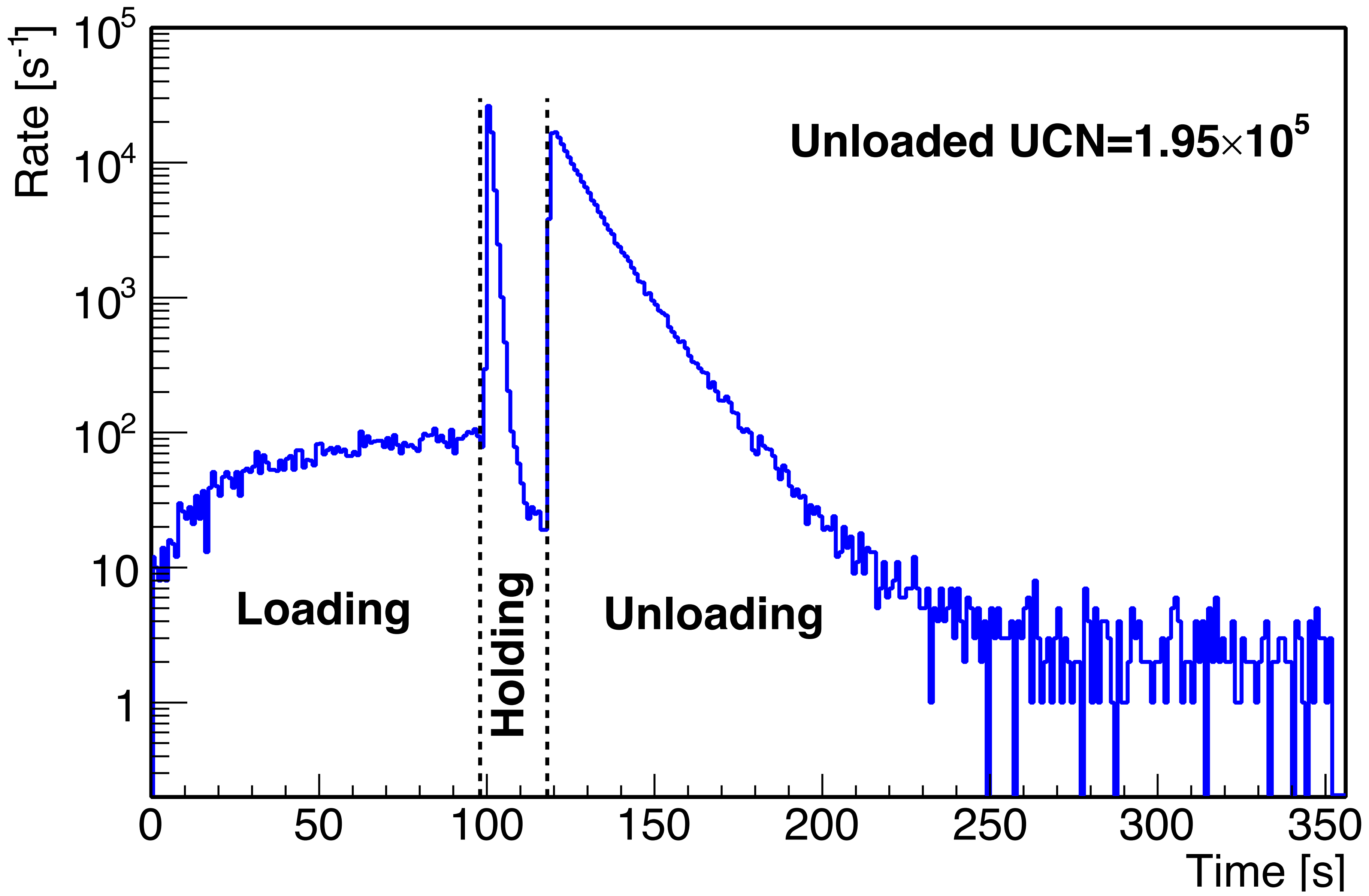
$$R = \frac{1}{4} v A \rho$$

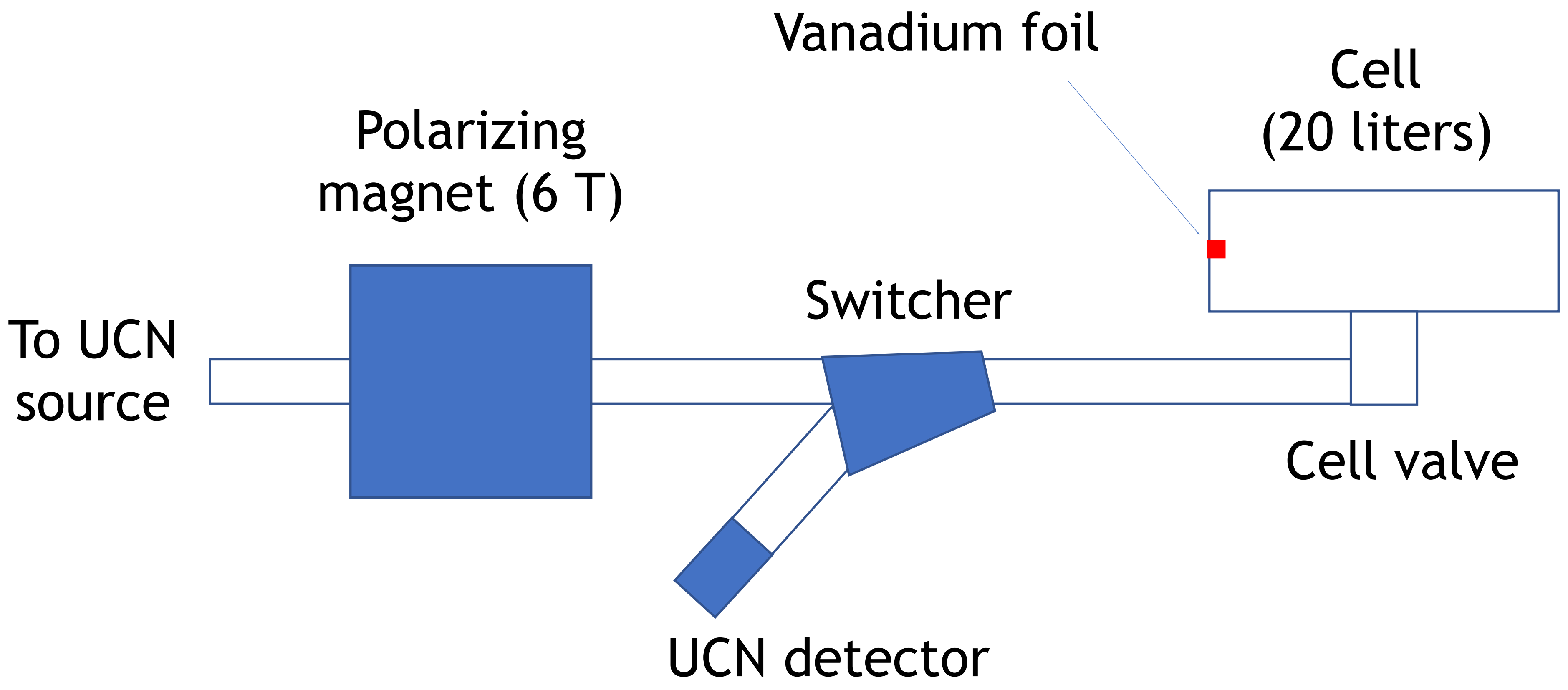
UCN density at the exit of the biological shield



Polarized UCN density in a dummy nEDM cell







Polarized UCN density (E < 170 neV) at t=0

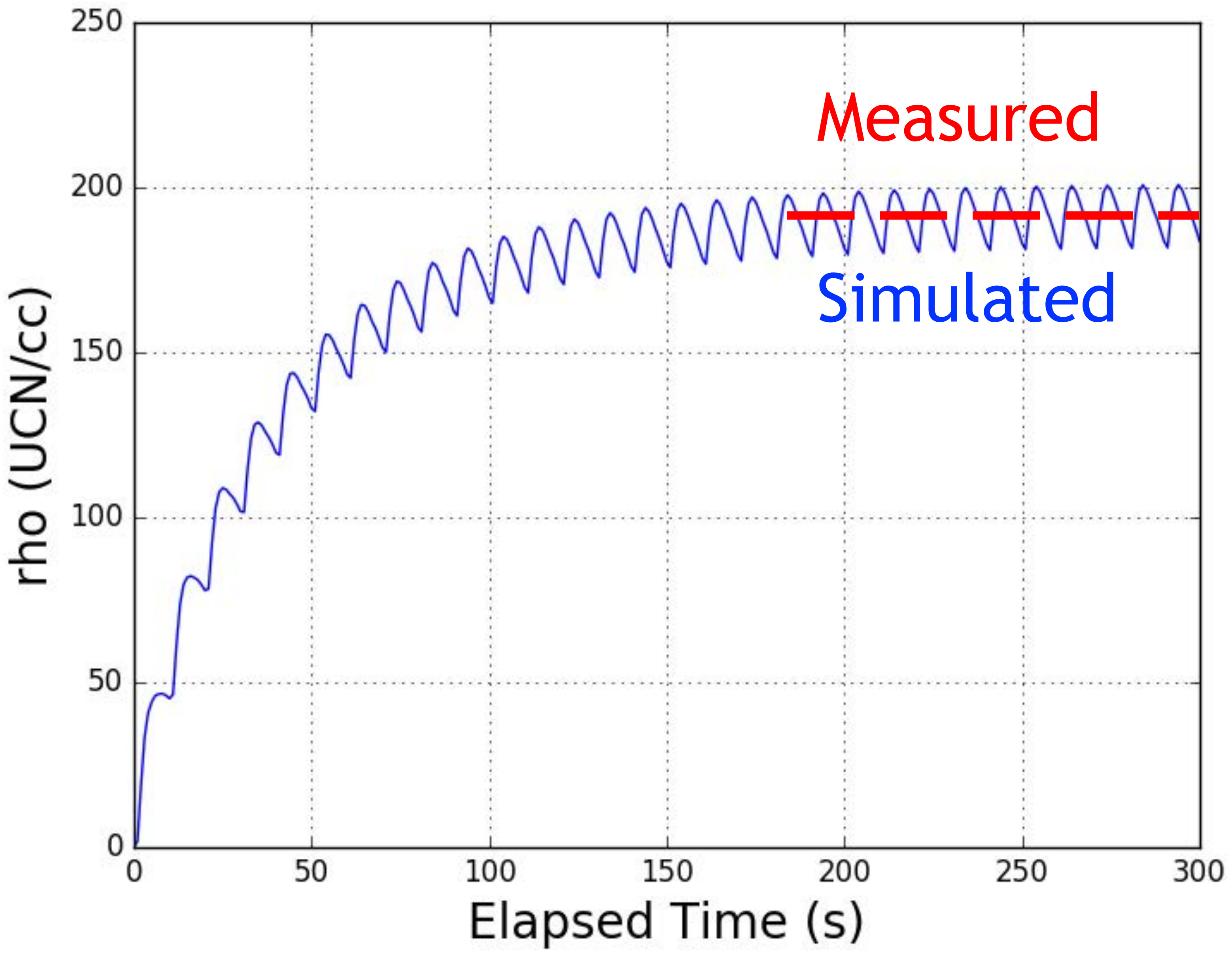
- 12 UCN/cc from the fill and dump measurement (was 2.5 UCN/cc before the source upgrade)
- 36 UCN/cc from vanadium foil activation measurement

The difference can be attributed to loss in the switcher and the finite detection efficiency.

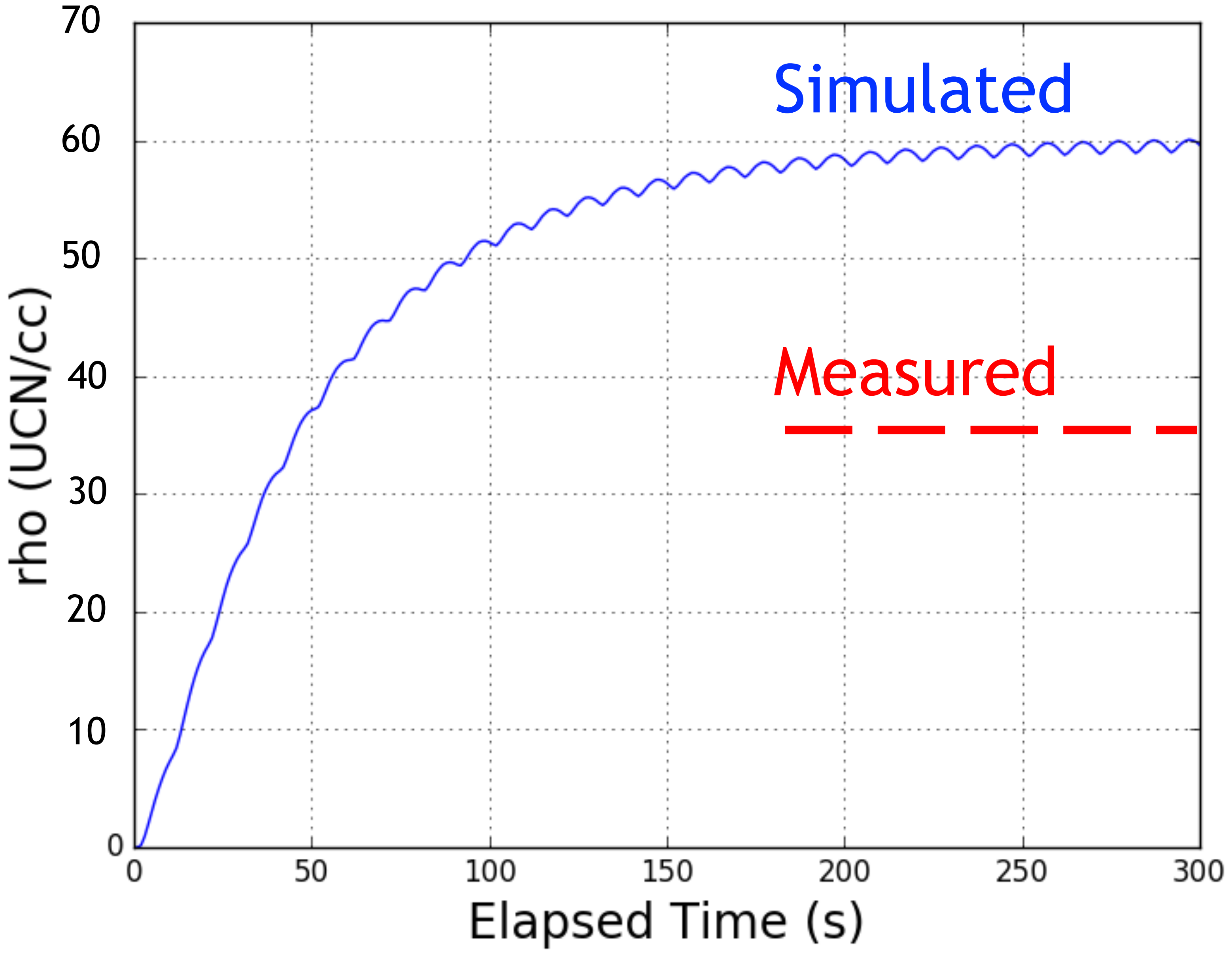
T. M. Ito et al., Phys, Rev. C **97**, 012501(R) (2018)

Comparison with expectation

Simulated UCN density at the exit of the biological shield



Simulated polarized UCN density at the cell



The simulation assumes the following parameters:

- guide non-specularity = 0.06, guide loss per bounce = 150E-6, τ_{SD2} = 49 ms, λ_{SD2} = 4 cm

The difference between the measured and simulated stored cell density could be attributed to the transport downstream of the exit of the biological shield.

Test of the Unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) Matrix

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

Weak states

CKM mixing matrix

Mass eigenstates

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

From β decay

From K decay

Negligibly small

- Traditionally, nuclear β decay has provided the most precise determination of V_{ud}.
- With improvement experiments, neutron β decay can provide a determination of Vud free from theoretical uncertainty associated with nuclear structure.

$$|V_{ud}|^2 = \frac{5099.3(4)\mathrm{s}}{\tau_n(1+3g_A^2)(1+RC)}$$

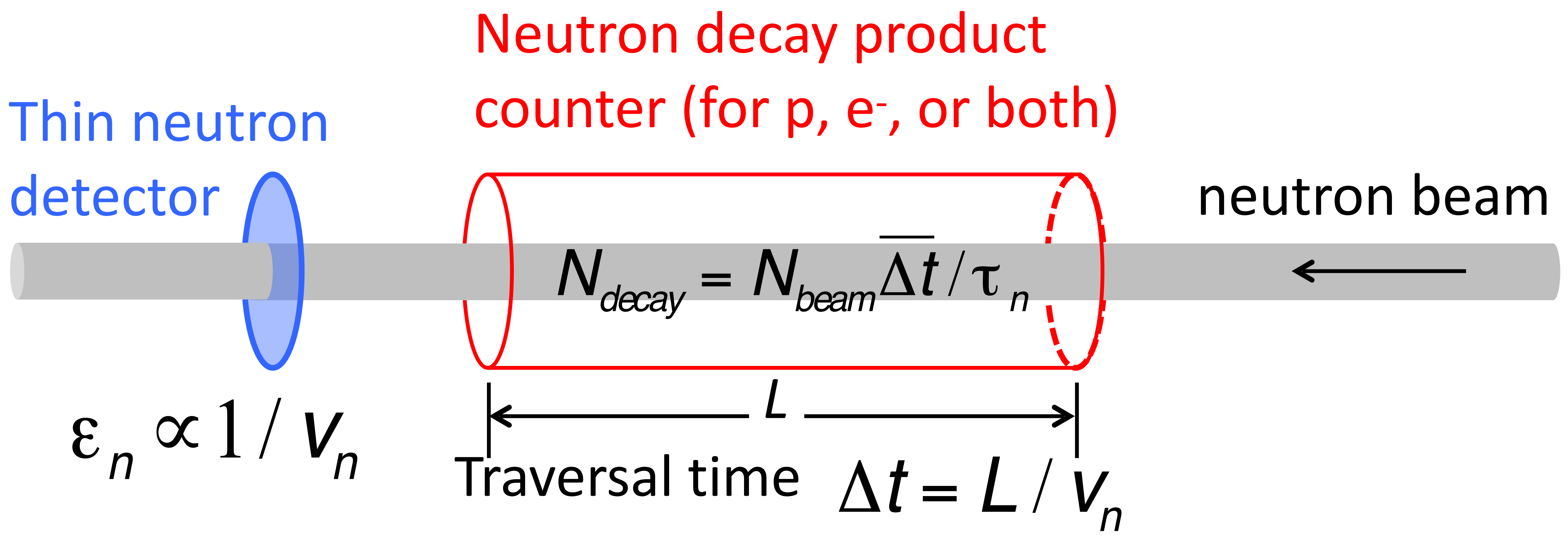
Neutron lifetime

Axial charge of the neutron

Radiative correction

Two techniques are used to measure τ_n

Cold Neutron Beam



Thin neutron detector

Neutron decay product counter (for p, e-, or both)

neutron beam

$N_{decay} = N_{beam}\overline{\Delta t}/\tau_n$

$\varepsilon_n \propto 1/v_n$

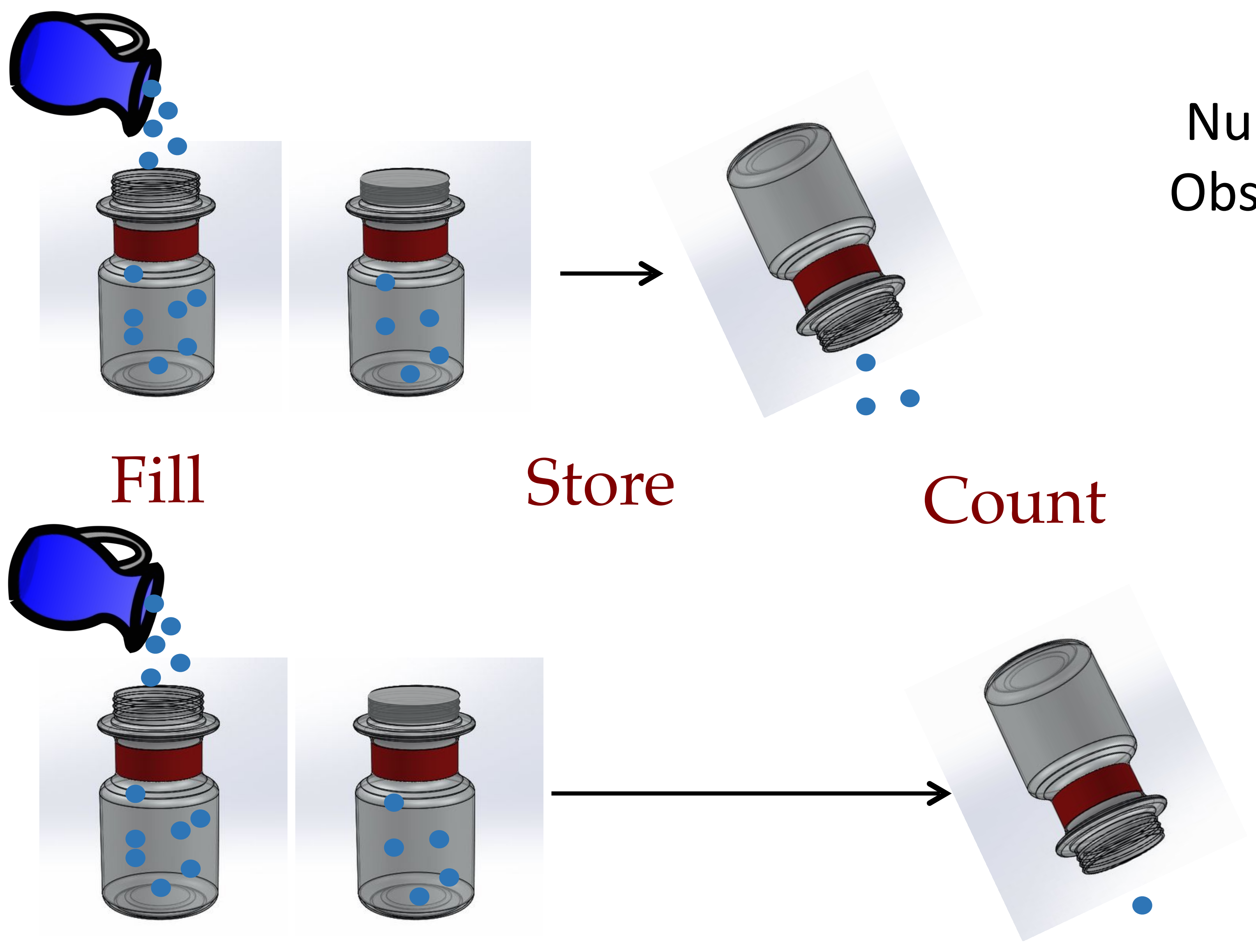
L

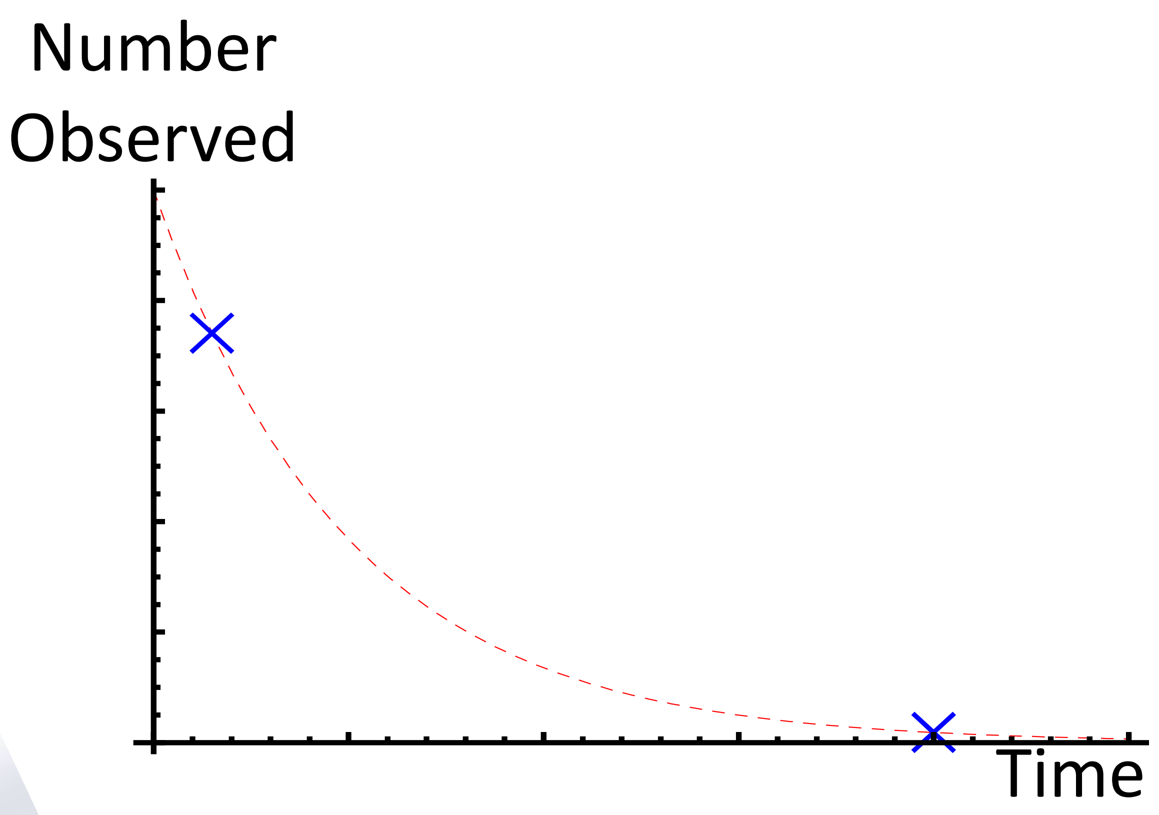
Traversal time $\Delta t = L/v_n$

Principal difficulties

- Need to know the absolute neutron flux must be measured very accurately
- Need to know the absolute proton detection efficiency must be known very accurately

Ultracold Neutron (UCN) Bottle (Material or magnetic trap)



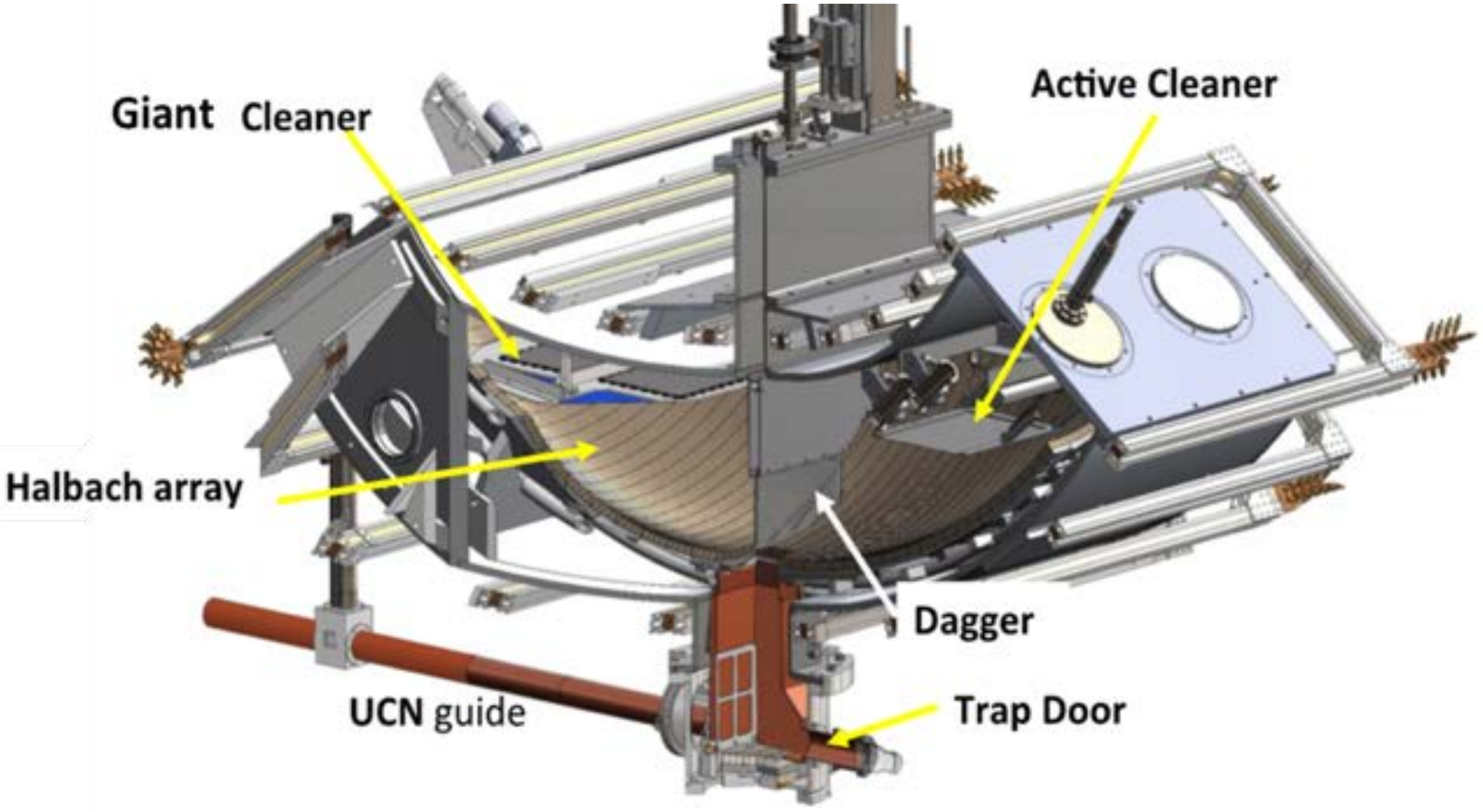


Could also detect decay products…

Principal difficulties

- UCN loss due to interaction with the wall (for material trap).
- Phase space evolution (mainly for material trap for which neutrons are drained and counted).
- Marginally trapped neutrons.

UCNτ experiment



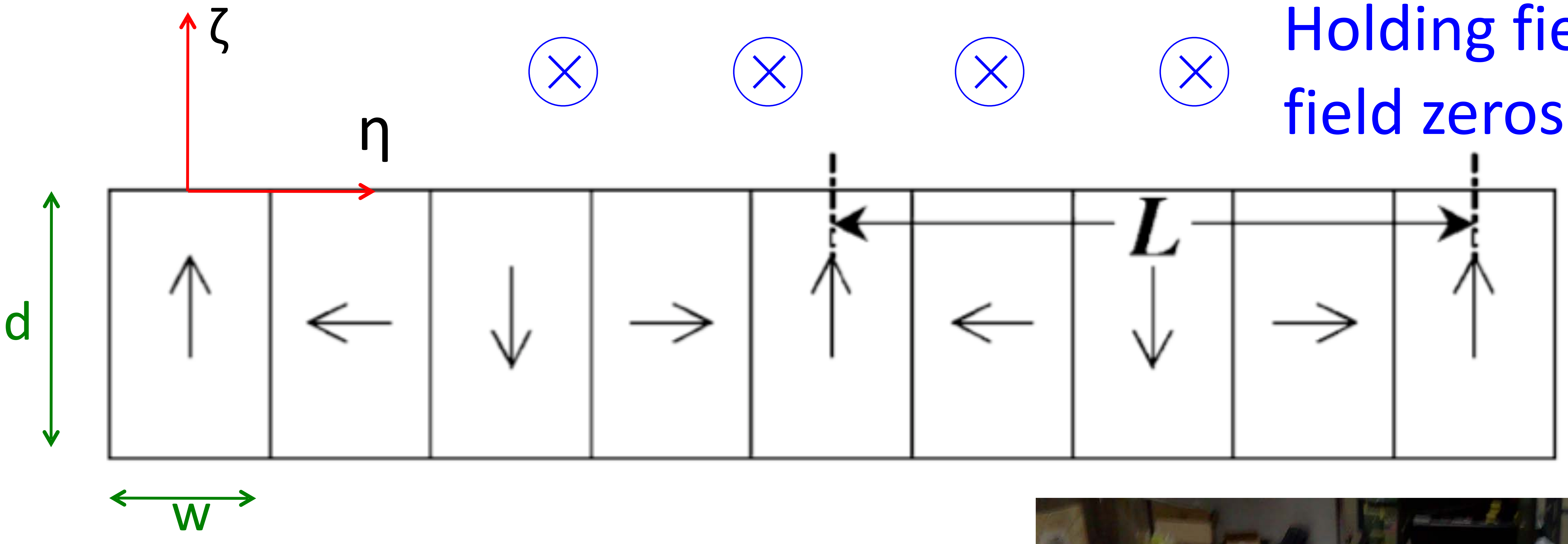
UCN stored in magneto-gravitational trap are counted by in-situ detector

- High statistics are achievable
  - Upgraded LANL UCN source
  - Large volume
  - In-situ counting of UCN with an efficient detector

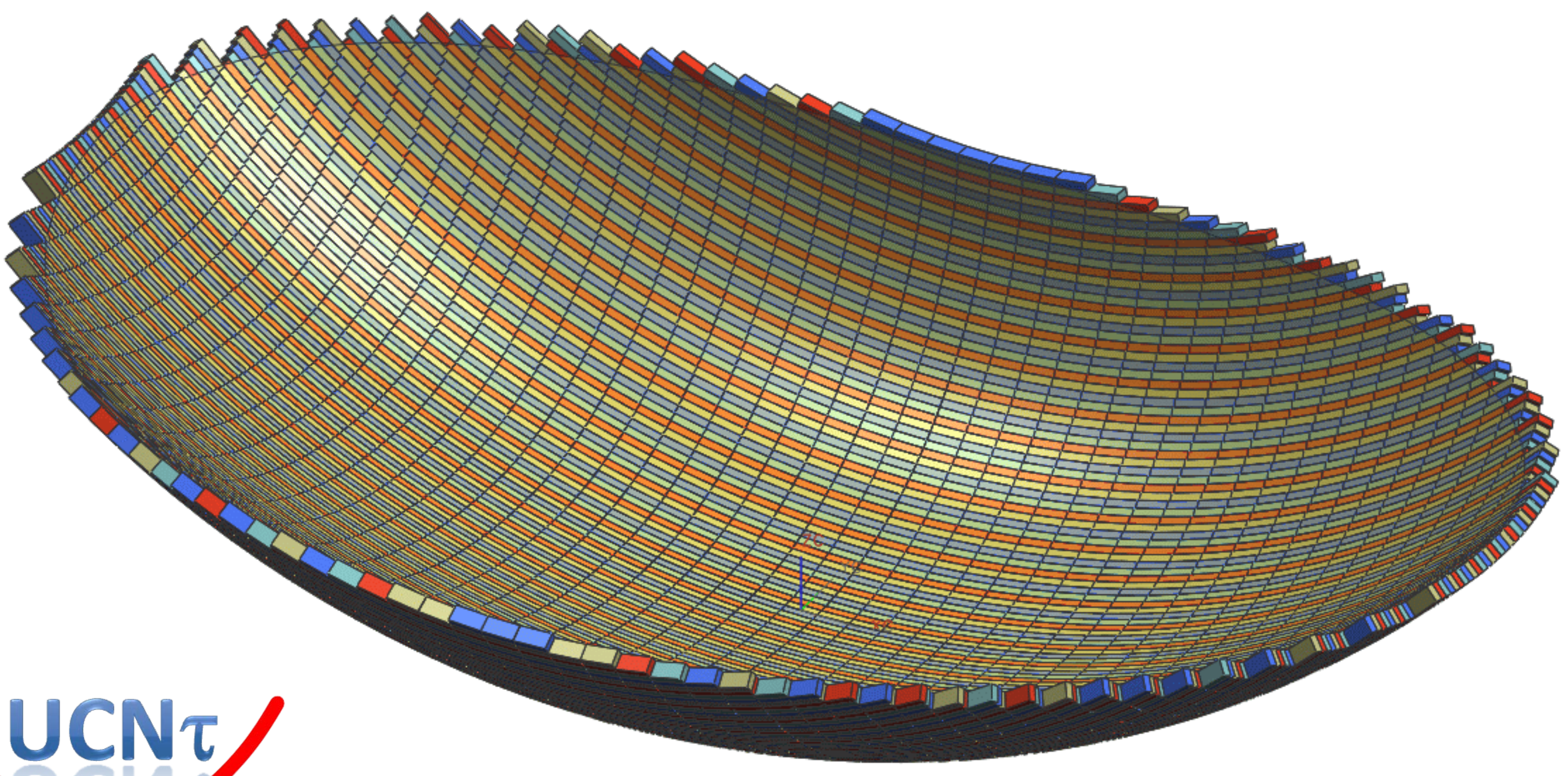
- Designed to eliminates all the known systematic effects of the previous “bottle” neutron lifetime experiments
  - Magneto-gravitational trap → no wall loss
  - Fast removal of quasi-bound UCNs through trap asymmetry and field ripple
  - In-situ counting removes effects due to phase space evolution

Halbach Array + Holding Field

$$|\mathbf{B}| = B_{\mathrm{rem}}(1 - \mathrm{e}^{-kd})\mathrm{e}^{-k\zeta}$$ (if continuous rotation of M)



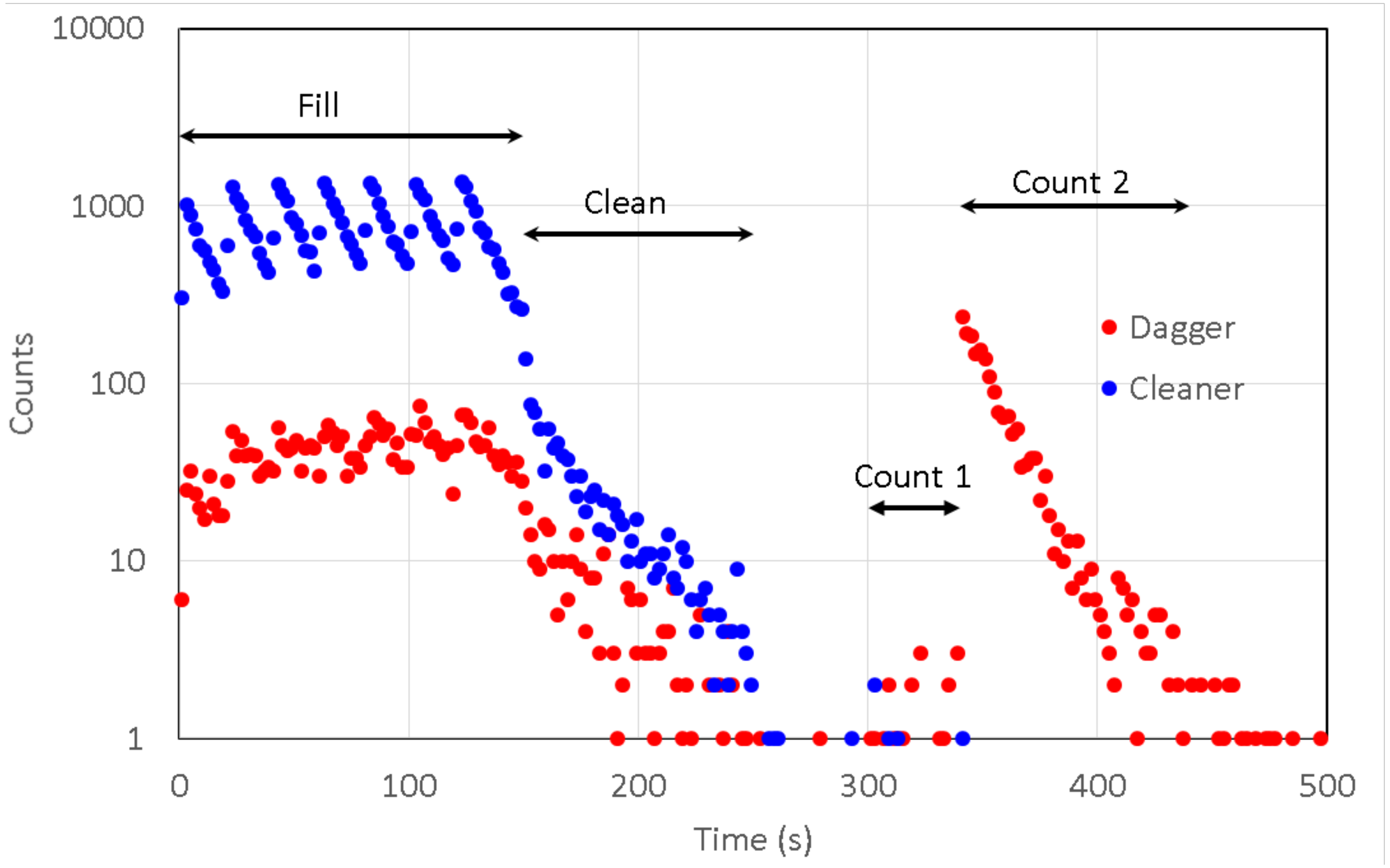
Holding field eliminates field zeros

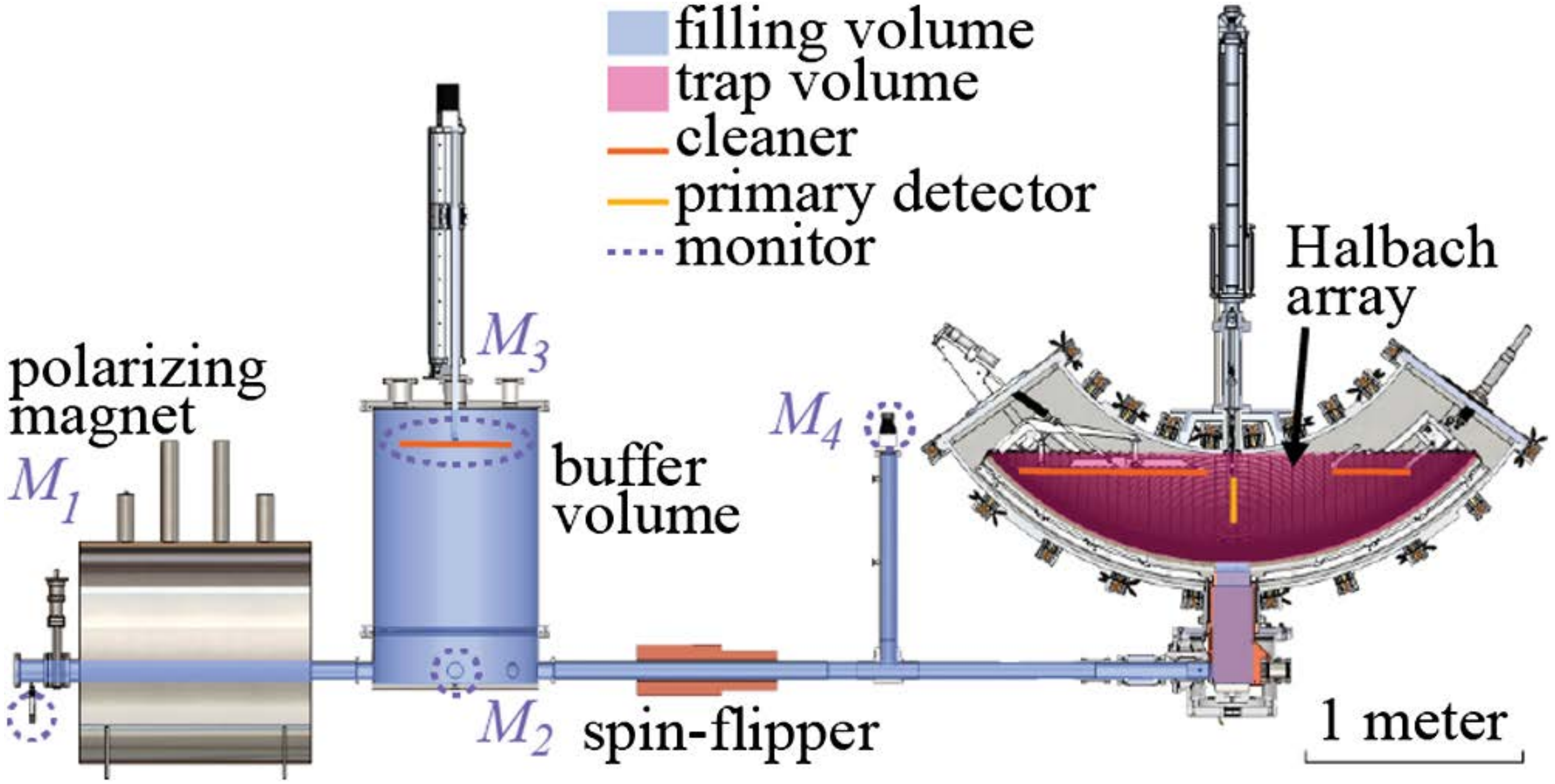


UCNτ

Measurement Cycle

1. Load the trap
2. Close the trap door
3. Remove quasi-bound UCNs (lower absorber, wait, raise absorber)
4. Hold UCNs in the trap for time *t*
5. Count the surviving UCN population *N*





Using two different cycles with holding times t_1 and t_2,

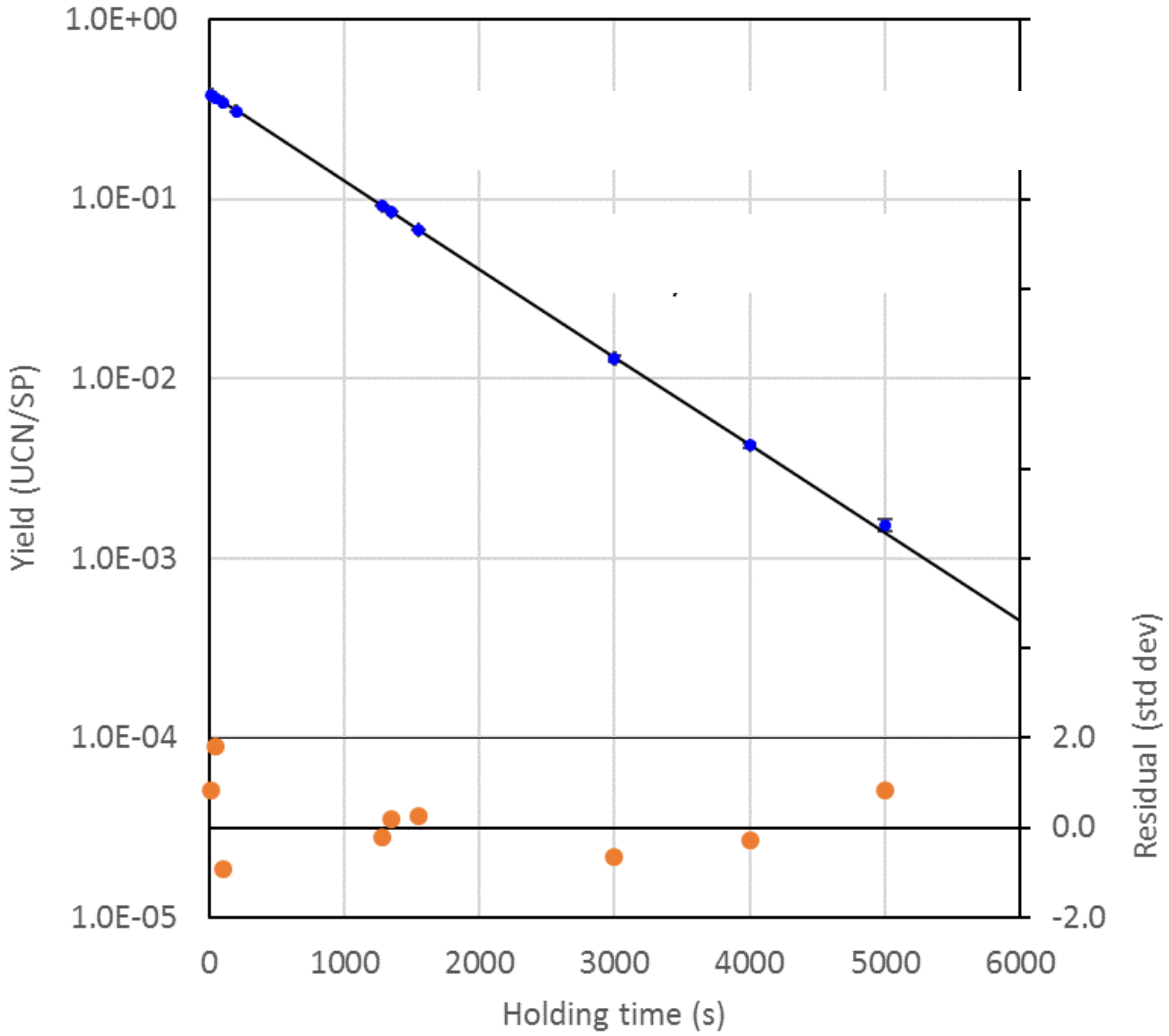
$$\tau_n = -(t_2 - t_1)/\log(\frac{N_2}{N_1})$$

New result from UCNτ

τ_n = 877.75±0.28$_{\text{stat}}$ +0.22/−0.16$_{\text{syst}}$ s

Phys. Rev. Lett. **127**, 162501 (Oct. 13, 2021)

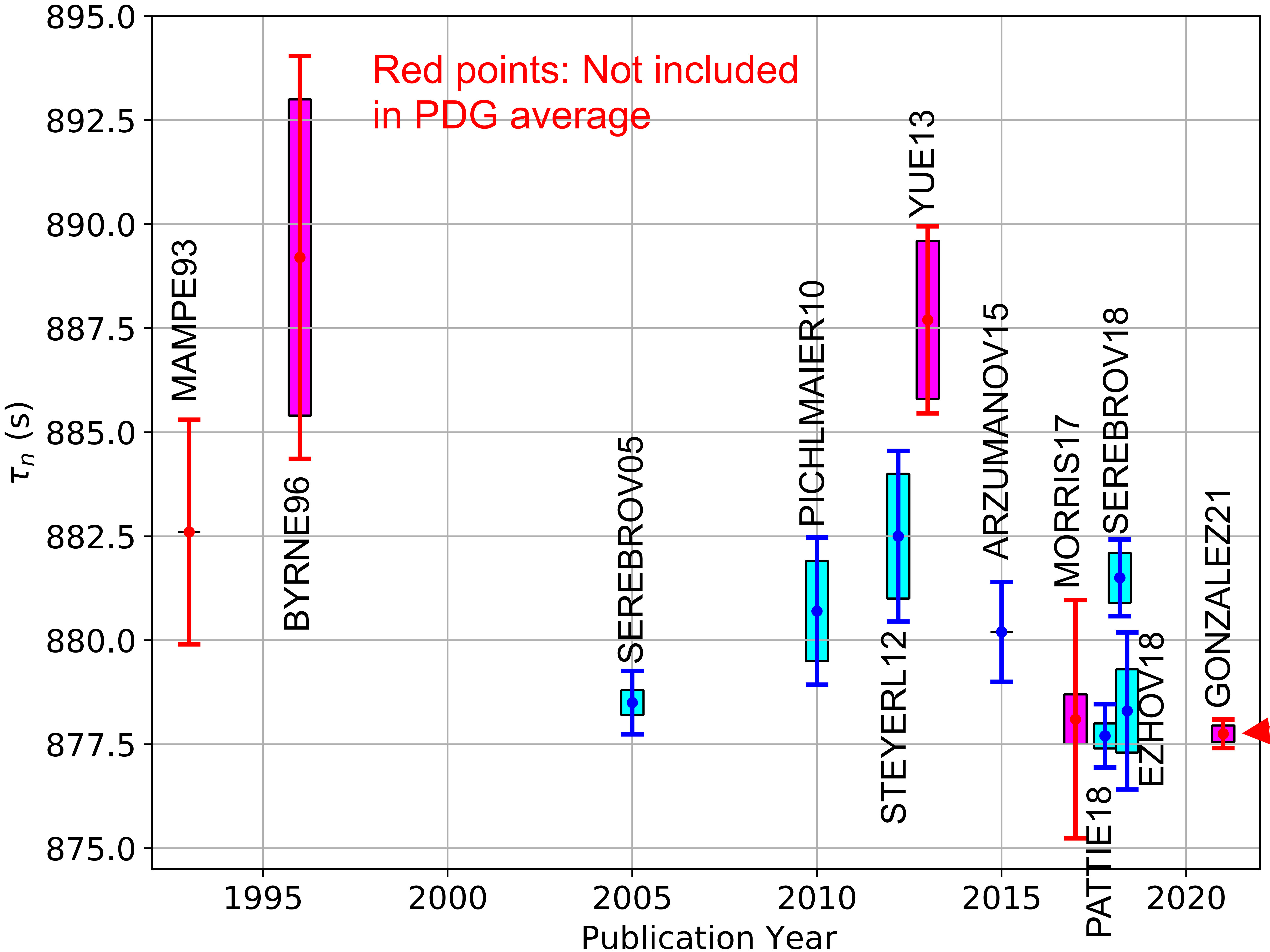
2017-2018 Run Campaigns:

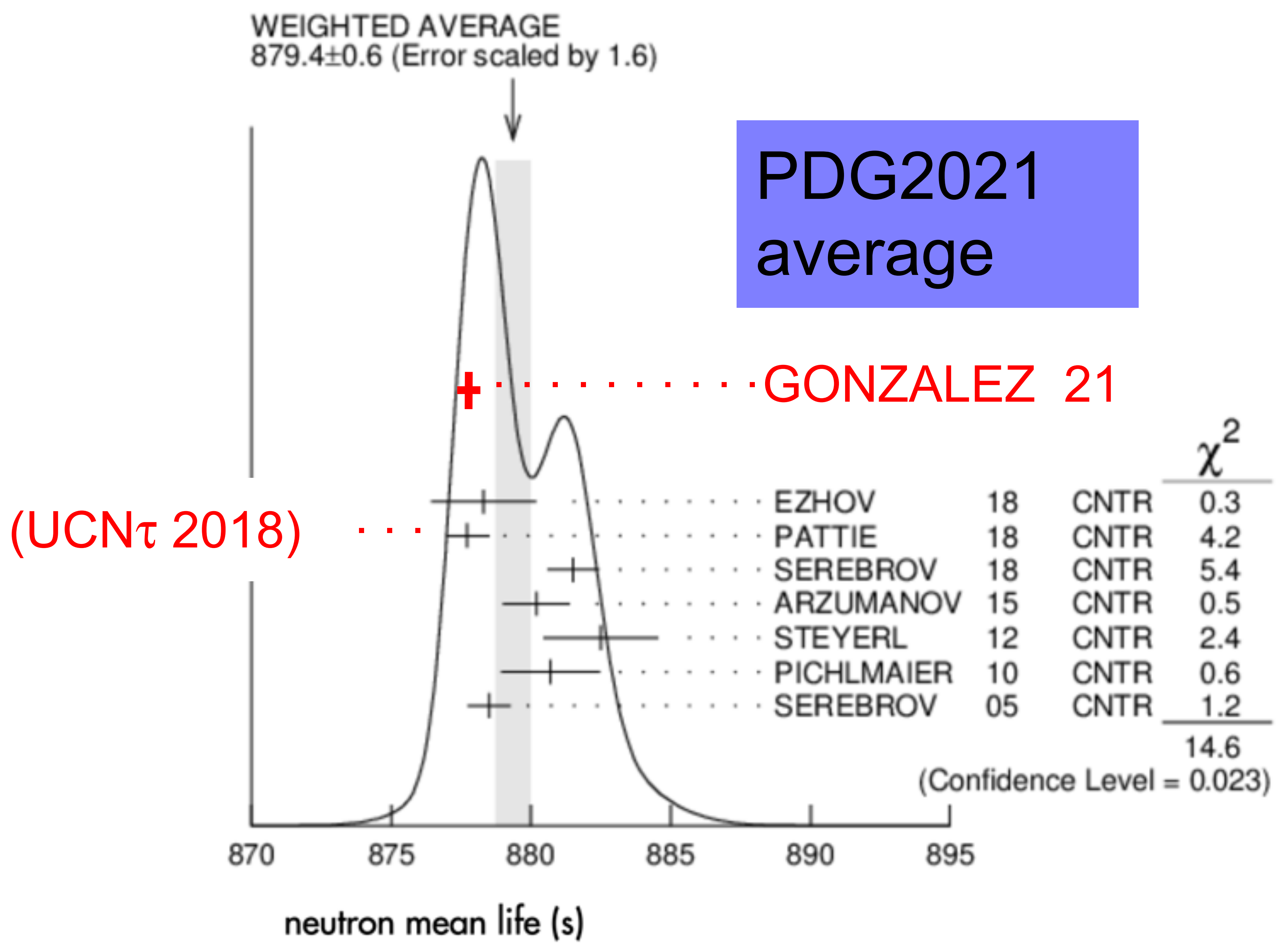


Final systematics table (2017-2018)

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

World data on τ_n including UCNτ2021

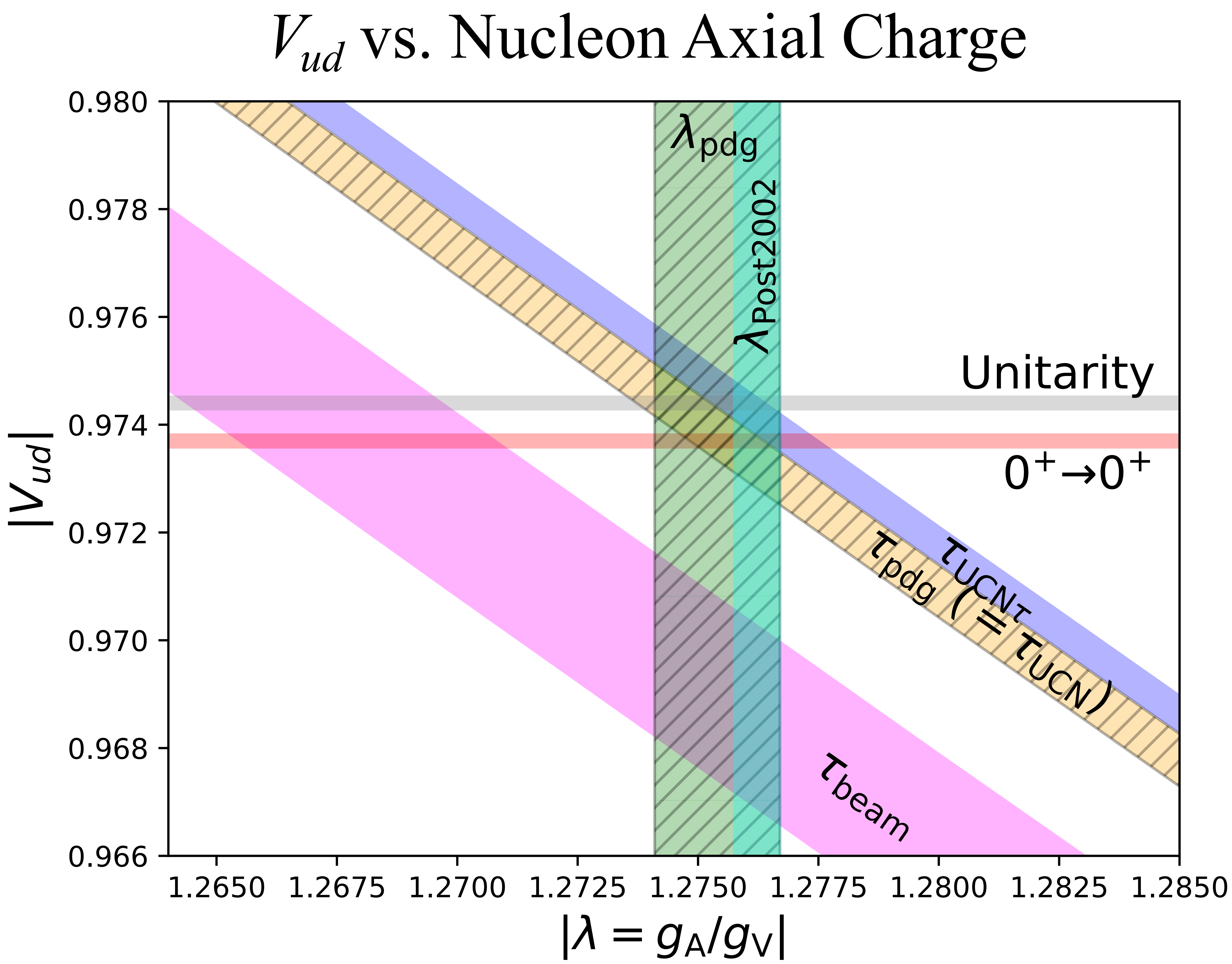




UCNτ2021

Gonzalez et al. PRL**127**, 162501 (2021)

Can we test the CKM unitarity with V_{ud} from neutrons?

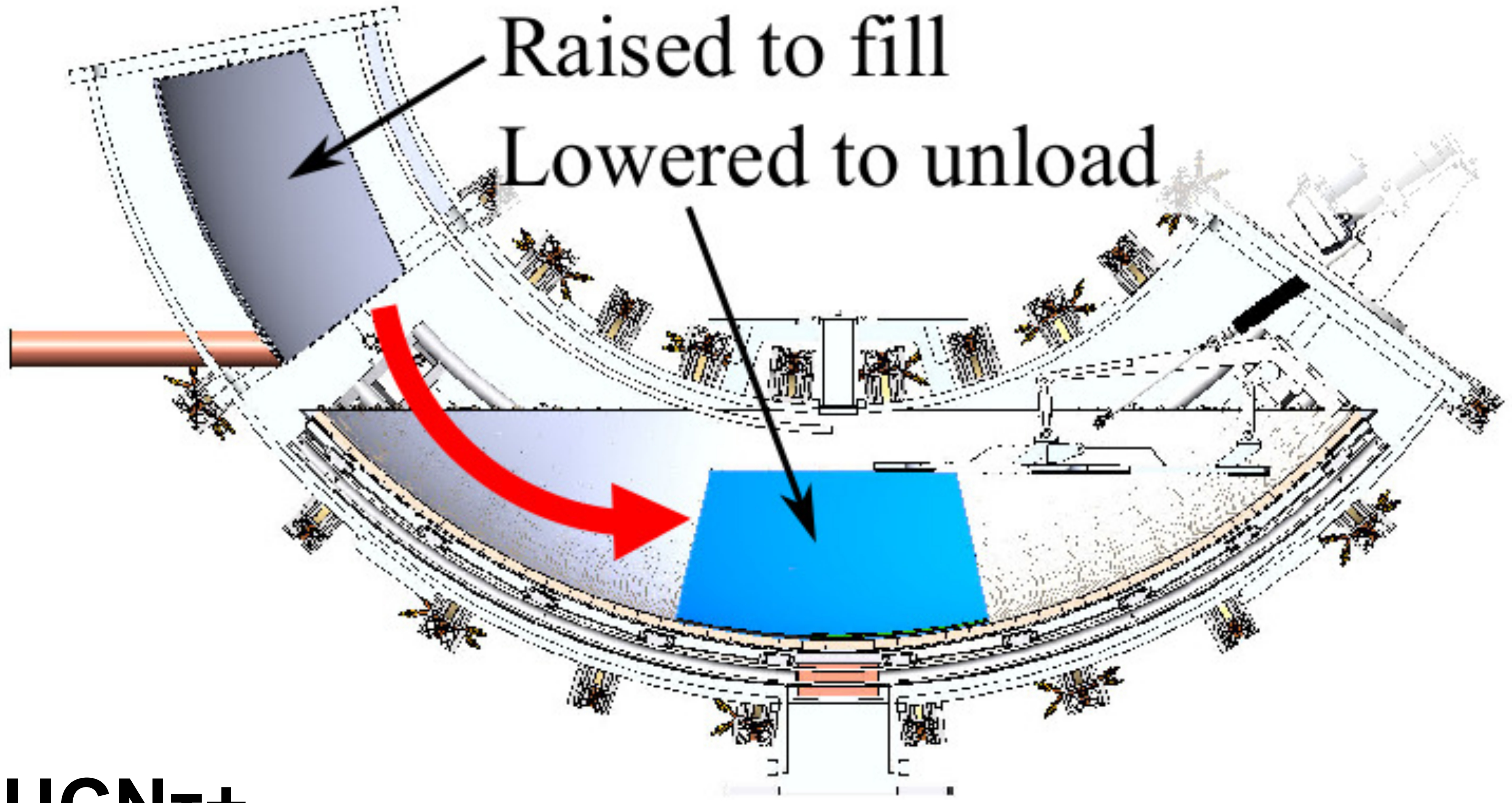


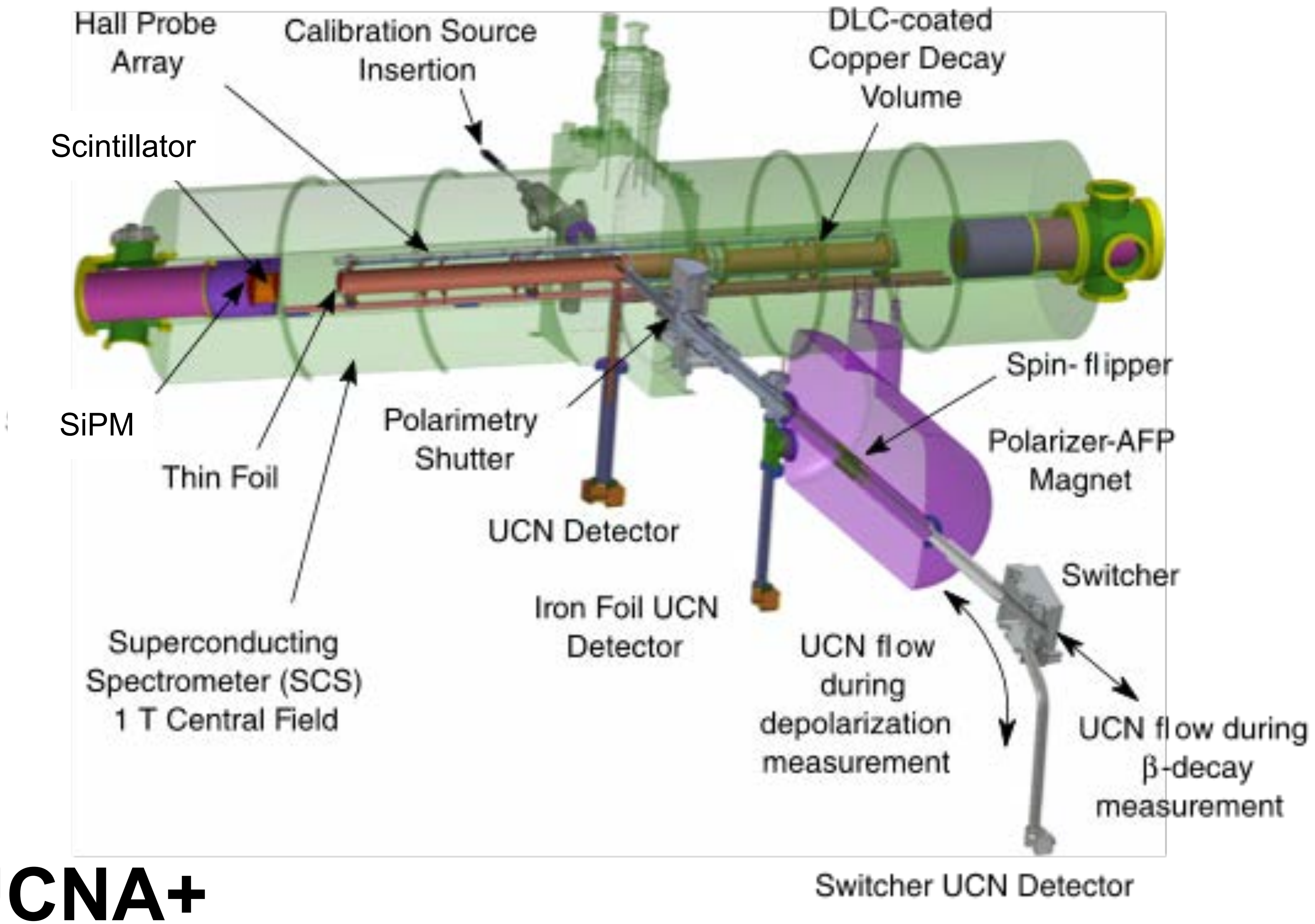
Neutron decay master formula:

$$|V_{ud}|^2 = \frac{5099.3(4)\mathrm{s}}{\tau_n(1+3g_A^2)(1+RC)}$$

Using RC from Seng et al., PRL **121**, 241804 (2018).

UCNτ+ and UCNA+ experiments





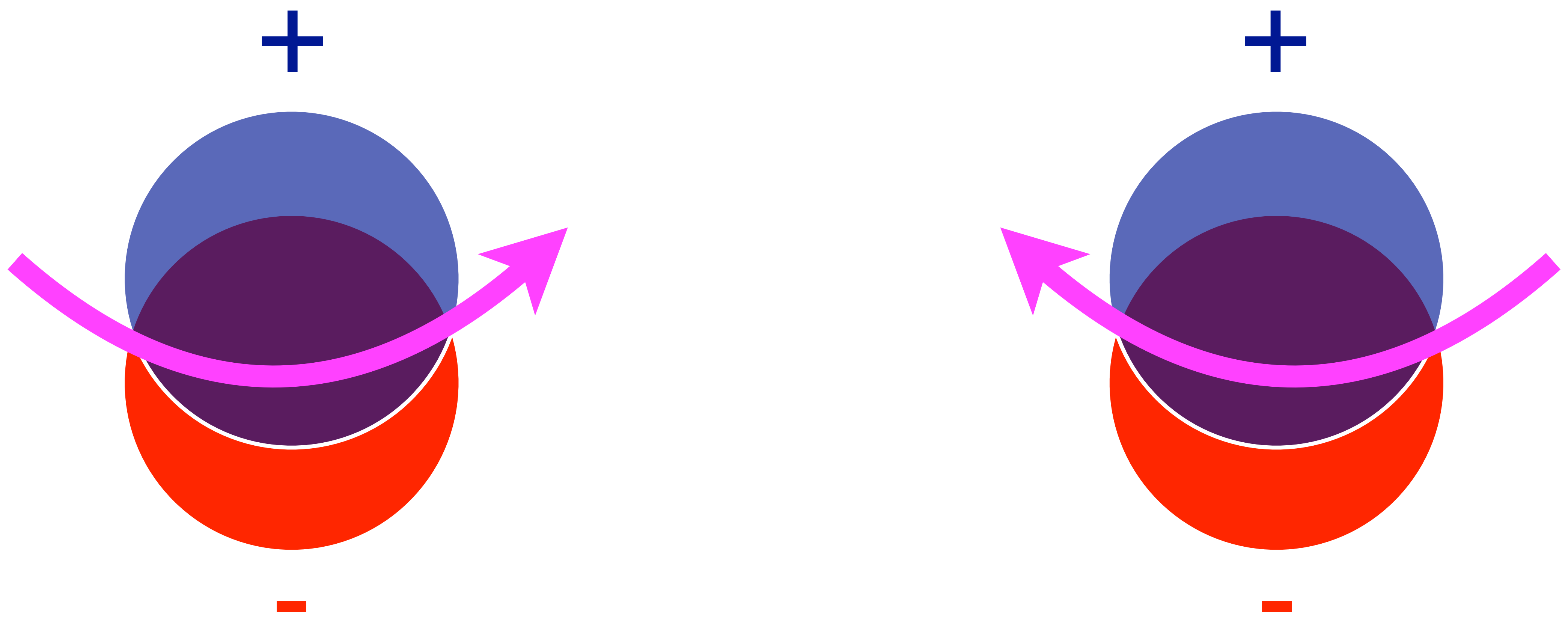
UCNτ+

- New elevator loading of UCN give 10x higher statistics
- Upgrade the detector for higher rate
- Currently development is funded by LDRD
- Goal: $\delta\tau_n < 0.1$ s

UCNA+

- Upgraded UCN source gives 3x higher statistics
- New β detector and improved calibration system
- Currently development is funded by LDRD
- Goal: $\delta A/A \sim 0.2\%$

Electric dipole moment



P or T reversed state

- Nonzero EDM violates both P and T (therefore CP) symmetries.
- Sensitive probe of new sources of CP violation, a key ingredient for dynamical generation of the cosmic matter and antimatter asymmetry.
- Current limit: $d_n < 1.8 \times 10^{-26}$ e-cm (90% C.L.) set by an experiment at PSI.
- Search for nEDM is an active field of research with strong international competition.

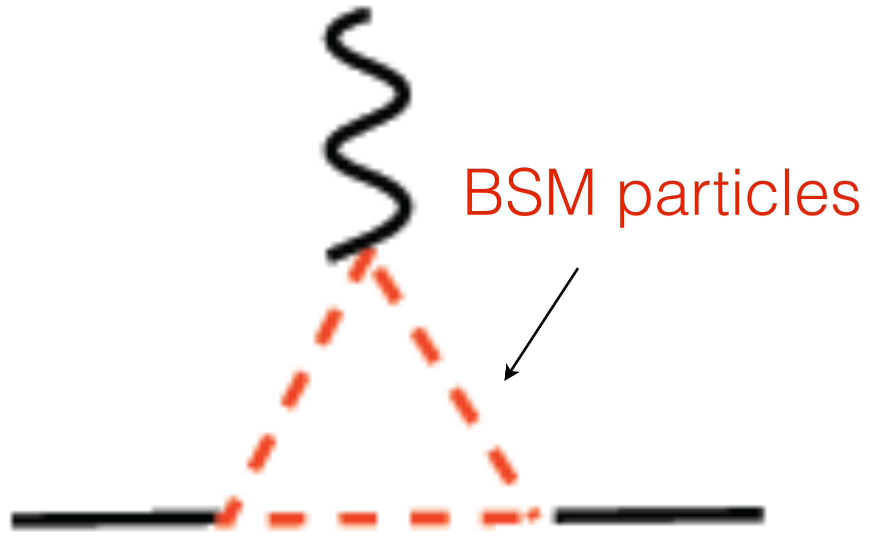
Motivations for nEDM search

- nEDM is a sensitive probe of new sources of CP violation
  - EDM due to the SM (CKM) is small because in the SM, CP violation only occurs in quark flavor changing processes to the lowest order
  - Many extension of the SM naturally produces larger EDMs because of additional CP violating phases associated with additional particles introduced in the model
- Strong CP problem
  - The limit on the CP violating term in QCD Lagrangian (from nEDM) is very small
  - One proposed remedy, Peccei-Quinn symmetry, predicts axions. However, axions have not been observed.
- Baryon Asymmetry of the Universe provides additional motivation.
  - Baryogenesis requires new sources of CP violation

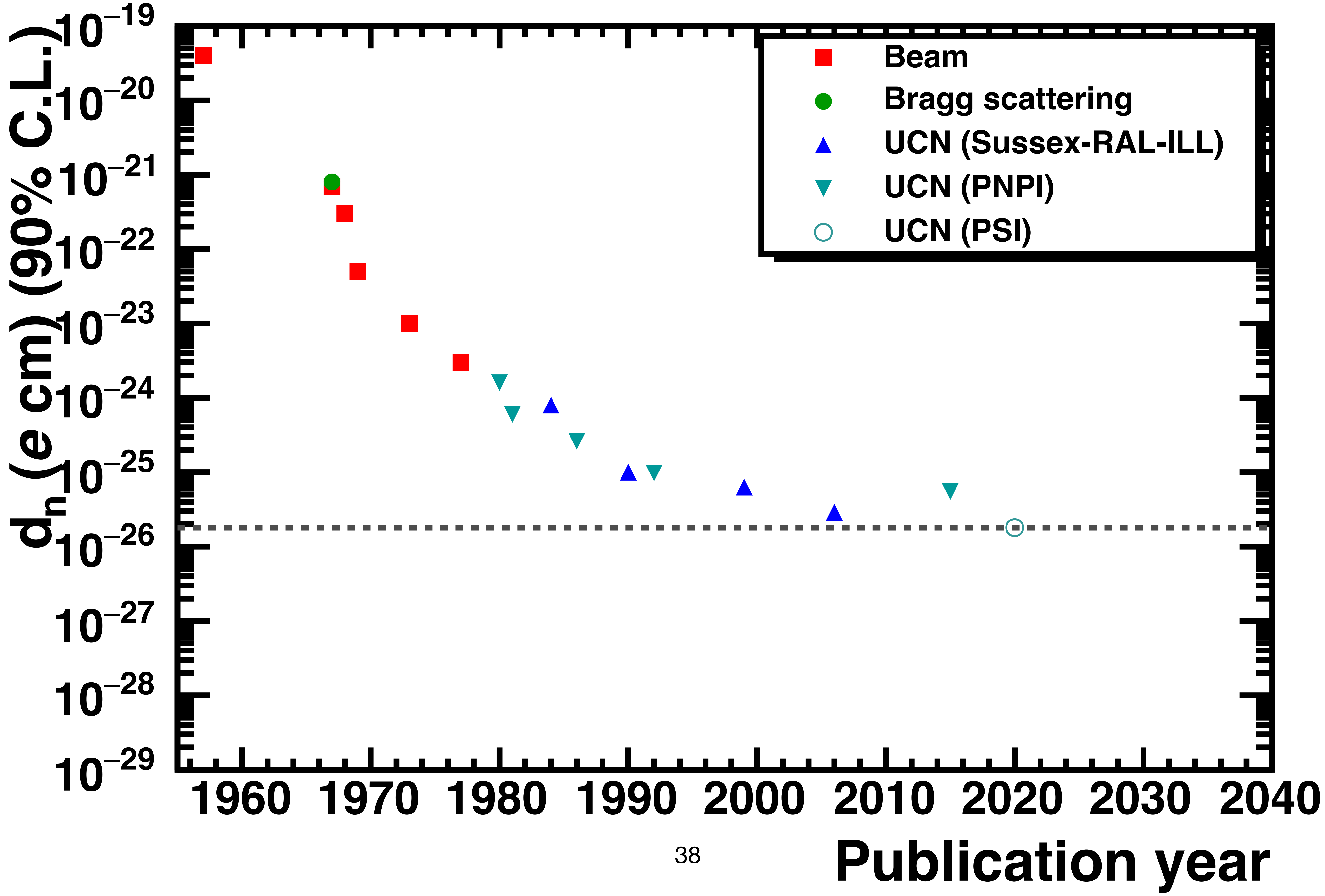
Evolution of nEDM experiments

- EDMs probe high scale BSM physics

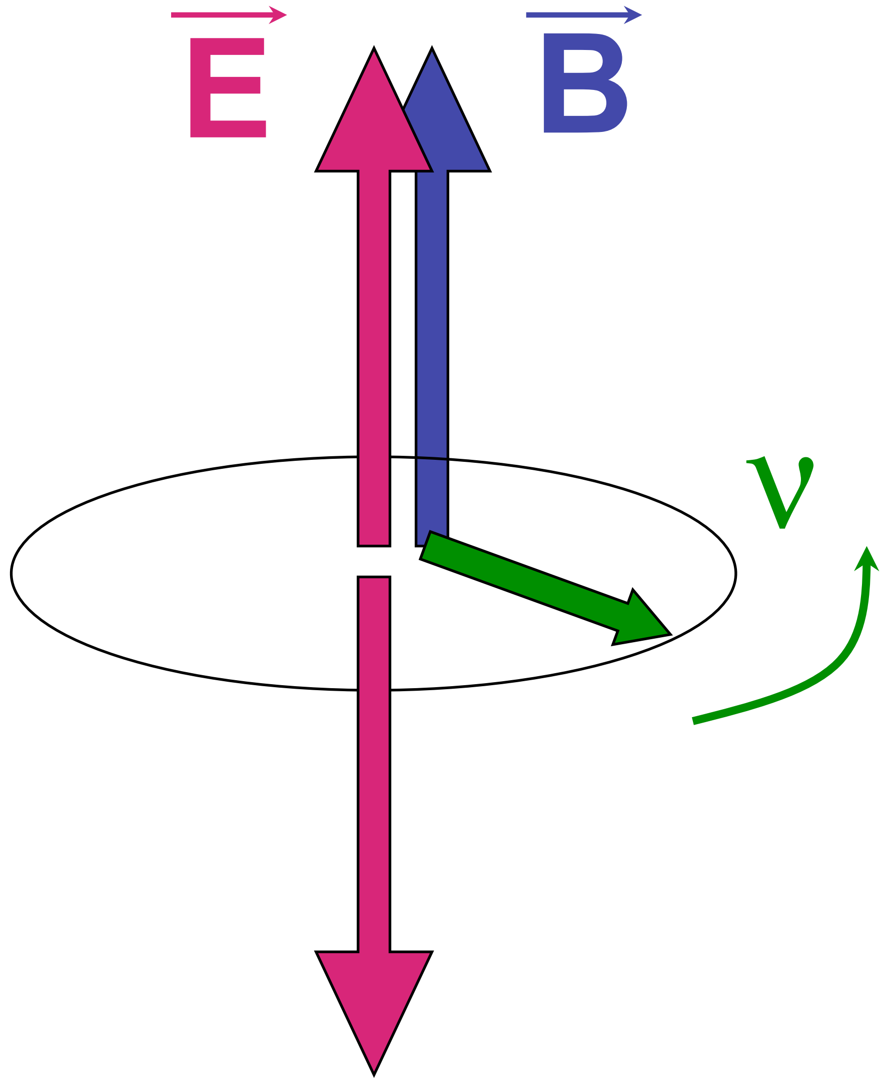
$$\boxed{d_i \propto \frac{m_i}{\Lambda^2}\ \sin(\phi_{\mathrm{CP}})}$$



- Current limits: $\Lambda \sim 100$ TeV, for $\phi_{\mathrm{CP}} \sim O(1)$



nEDM measurement principle



$$\nu = \left(2\mu_n B \pm 2d_n E\right)/h$$

$$\Delta\nu = 4d_n E/h$$

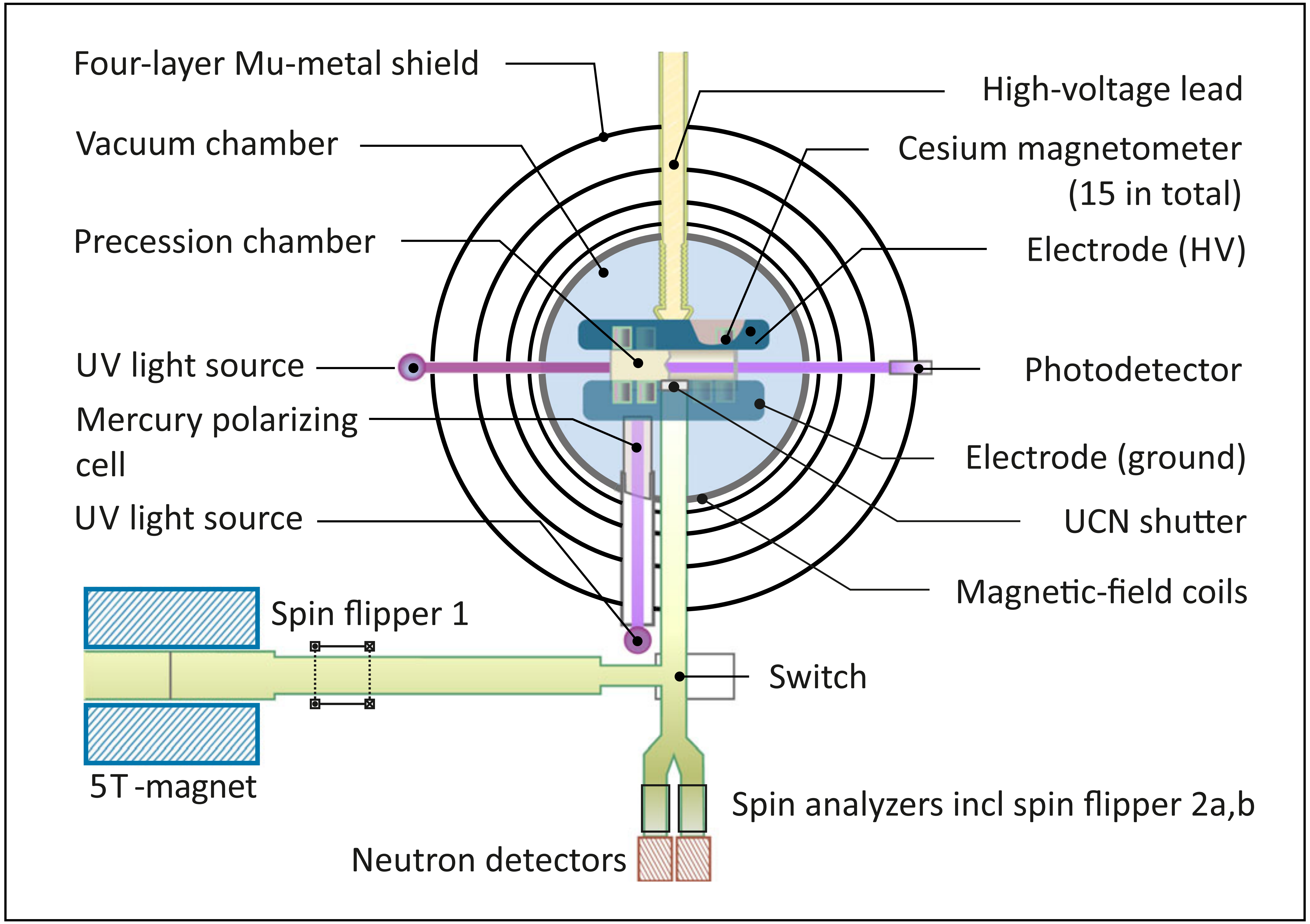
$$\delta d_n = h\frac{\delta\Delta\nu}{4E}$$

For B ~ 10 mG, ν = 30 Hz.
For E = 10 kV/cm and $d_n = 3\times10^{-27}$ e-cm, Δν=0.03 μHz. → comagnetometer essential

For each measurement, the statistical sensitivity goes as

$$\delta d_n \propto \frac{1}{ET\sqrt{N}}$$

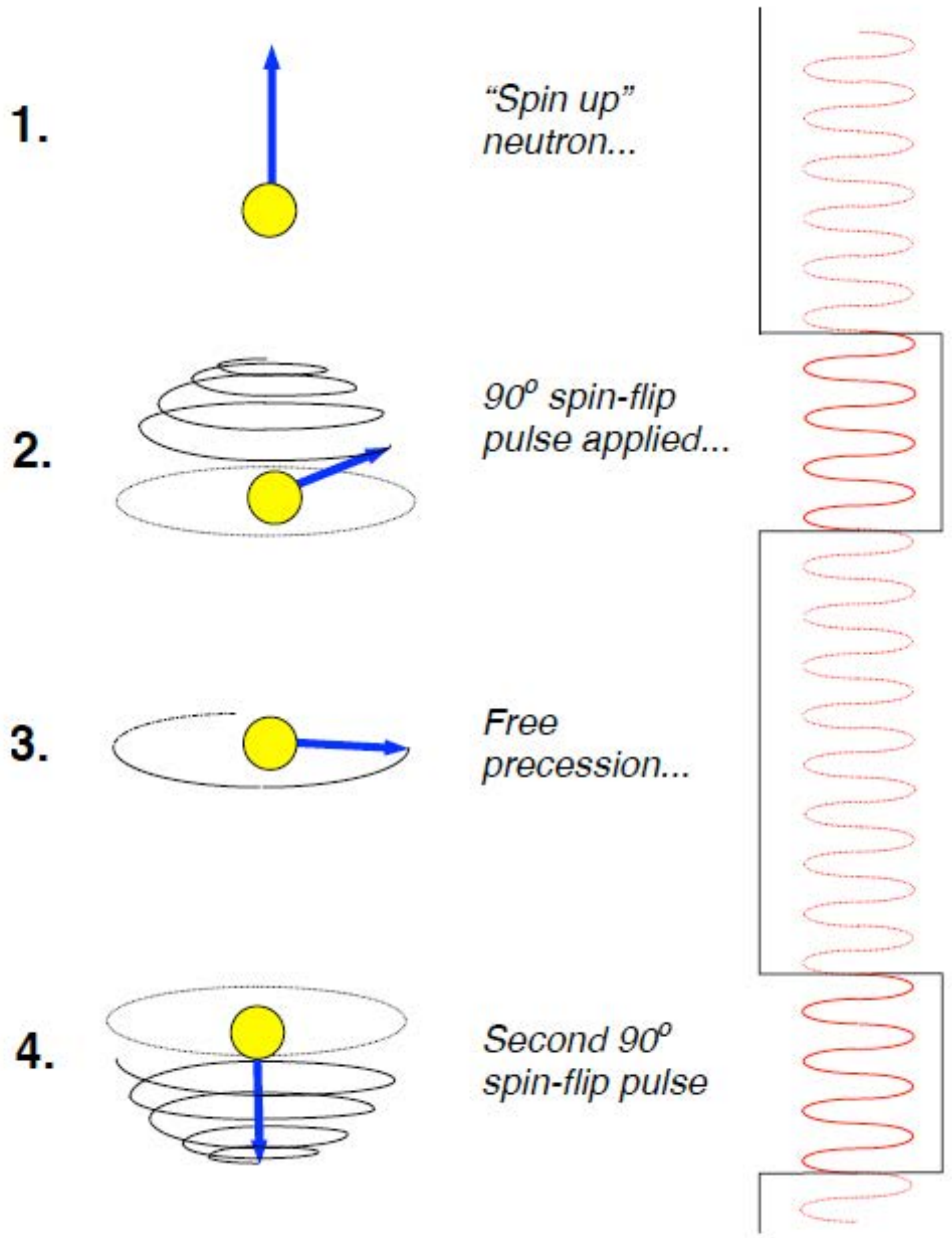
PSI experiment

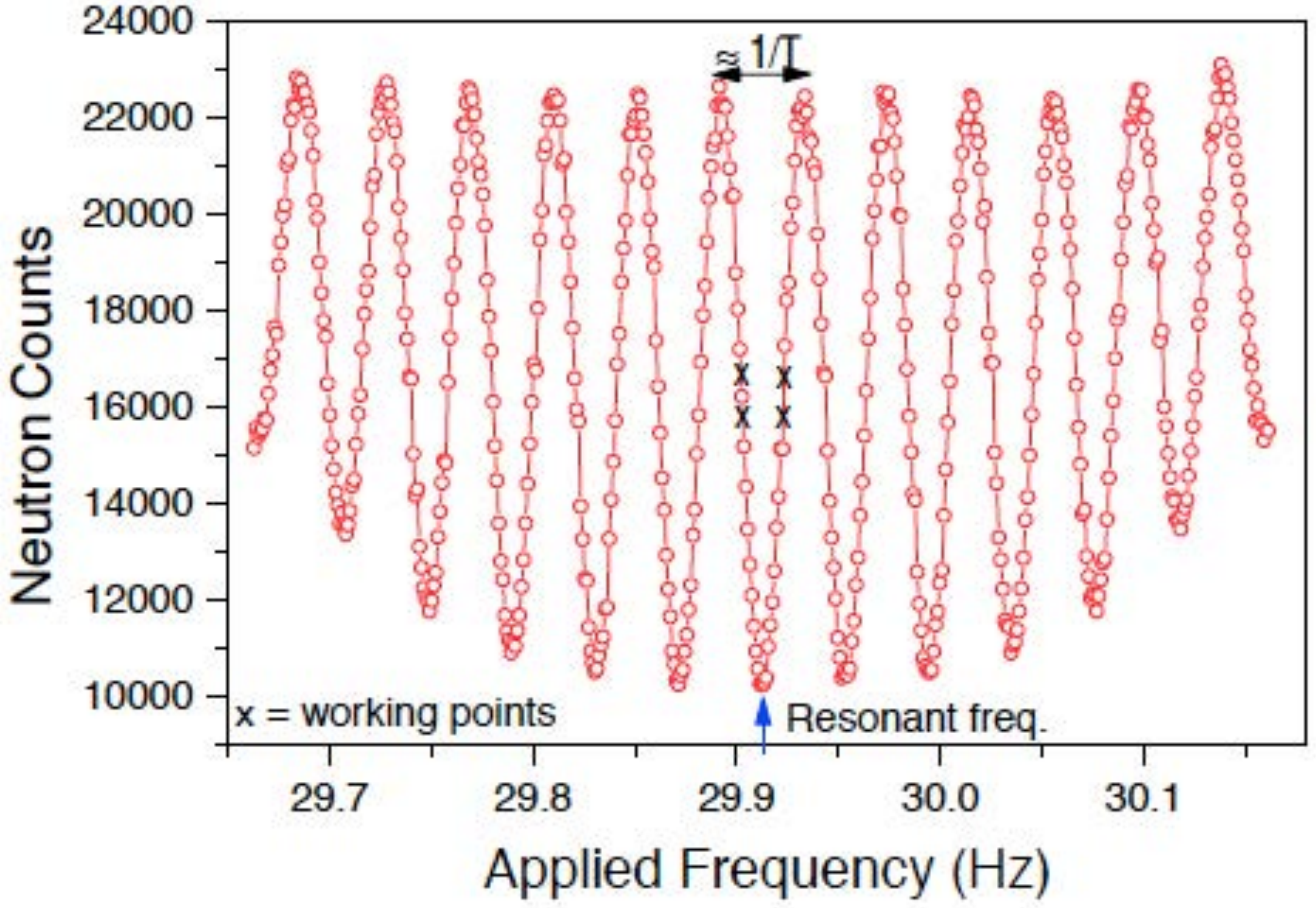


- Precession measurement
  - Ramsey's separated oscillatory fields
- Magnetometry
  - Cs magnetometers
  - ^{199}Hg comagnetometer
- Selected parameters
  - $E = 11$ kV/cm
  - $T = 180$ s
  - $N = 11400$
- Results
  - $d_n < 1.8 \times 10^{-26}$ e-cm (90% C.L.)

C. Abel, et al., Phys. Rev. Lett. 124, 081803 (2020).

Ramsey method of separated oscillatory fields

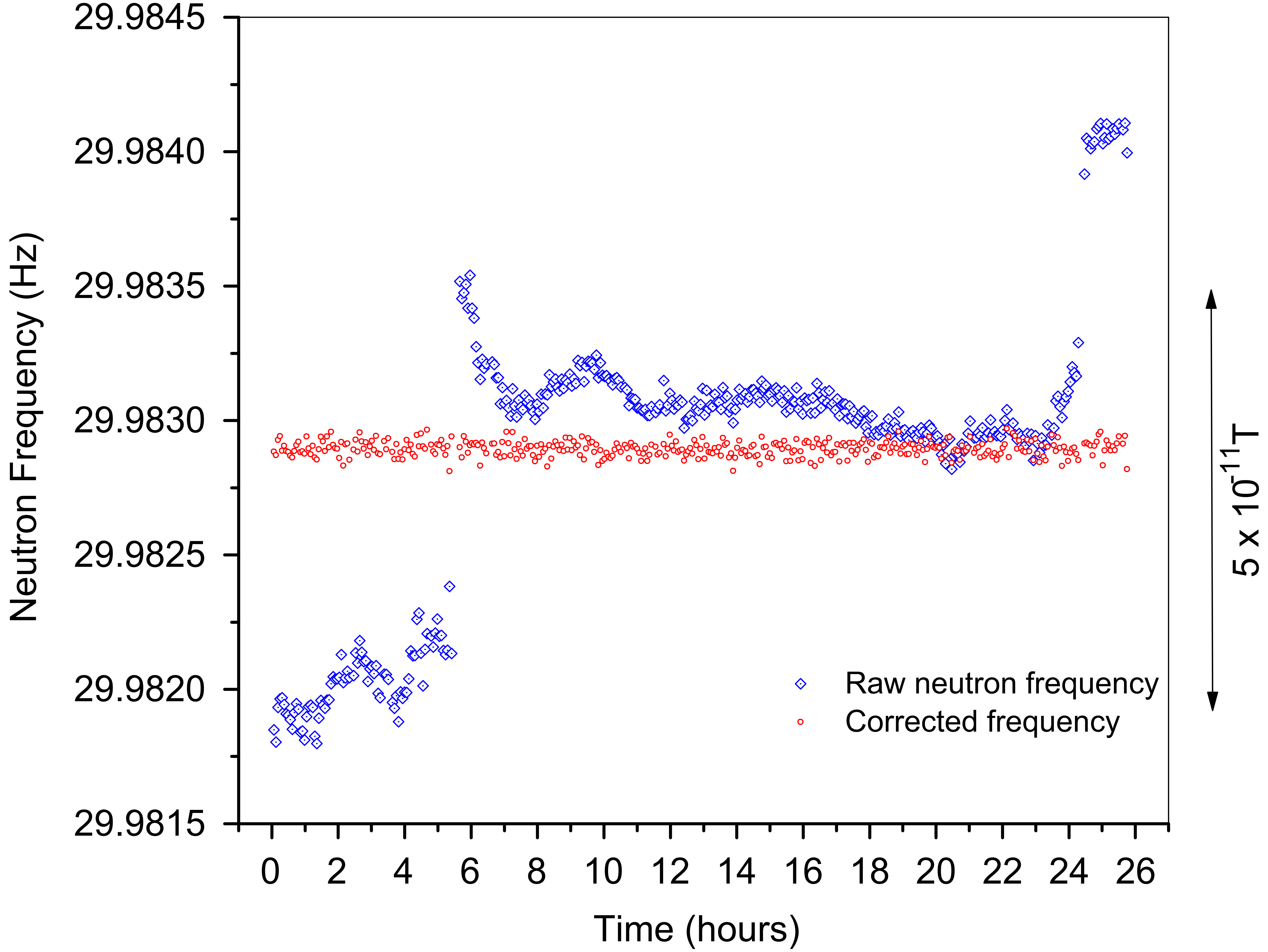




Baker et al, NIMA 736, 184 (2014) (arXiv:1305.7336)

^{199}Hg comagnetometer

Comagnetometer: Magnetometer that occupies the same volume over the same precession time interval as the species on which an EDM is sought



Baker et al, NIMA 736, 184 (2014) (arXiv:1305.7336)

Experimental considerations

- Statistical sensitivity:

$$\delta d_n \propto \frac{1}{ET\sqrt{N}}$$

- Therefore we need:
  - Higher *E*
  - Longer *T*
  - Larger *N*

- Systematics
  - vxE (motional magnetic field) effect
  - Leakage currents
  - Non-uniformity and instability of magnetic field
  - Geometric phase effects

Note:

- Drastically higher *E* and *T* are difficult for room temperature UCN-based experiments.
- Improved source of UCN can provide a larger *N*.

nEDM experiments being developed

Experiment	Location	UCN Source	Features	90% C.L. (10^{-28} e-cm)
n2EDM	PSI	Spallation, D2	Ramsey method, double cell, ^{199}Hg comagnetometer	< 20
PanEDM	ILL	Reactor, LHe	Ramsey method, double cell, (^{199}Hg comagnetometer)	< 20
LANL nEDM	LANL	Spallation, D2	Ramsey method, double cell, ^{199}Hg comagnetometer	< 30
TUCAN	TRIUMF	Spallation, LHe	Ramsey method, double cell, ^{199}Hg comagnetometer	< 20
nEDM@SNS	SNS at ORNL	In-situ production	Cryogenic, double cell, 3He comagnetometer, 3He as the spin analyzer	< 3

Estimated statistical sensitivity of an nEDM experiment at LANL UCN Source

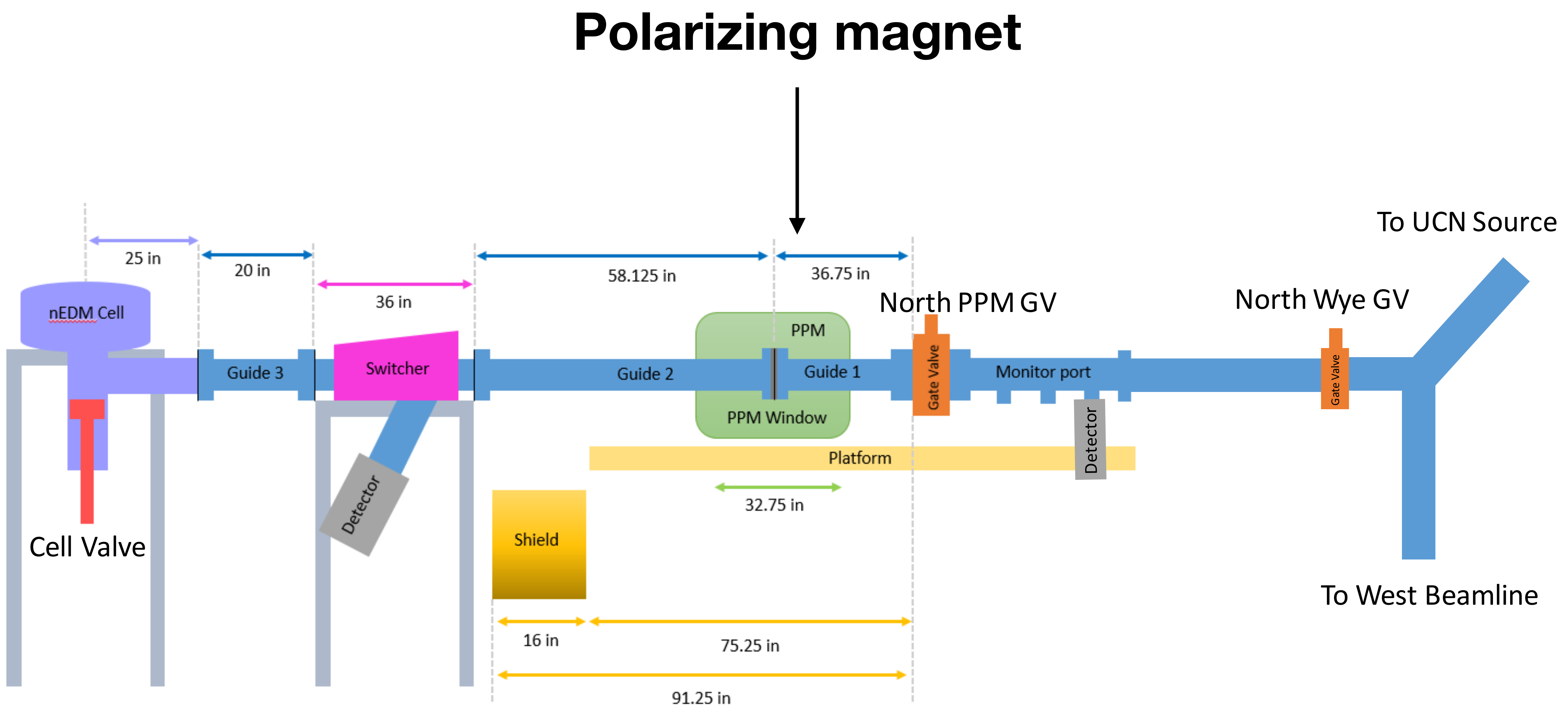
Parameters	Values
E(kV/cm)	12.0
N(per cell)	39,100
T_{free} (s)	180
T_{duty} (s)	300
α	0.8
σ/day/cell (10^{-26} e-cm)	5.7
σ/day (10^{-26} e-cm) (for double cell)	4.0
σ/year (10^{-27} e-cm) (for double cell)	2.1
90% C.L./year (10^{-27} e-cm) (for double cell)	3.4

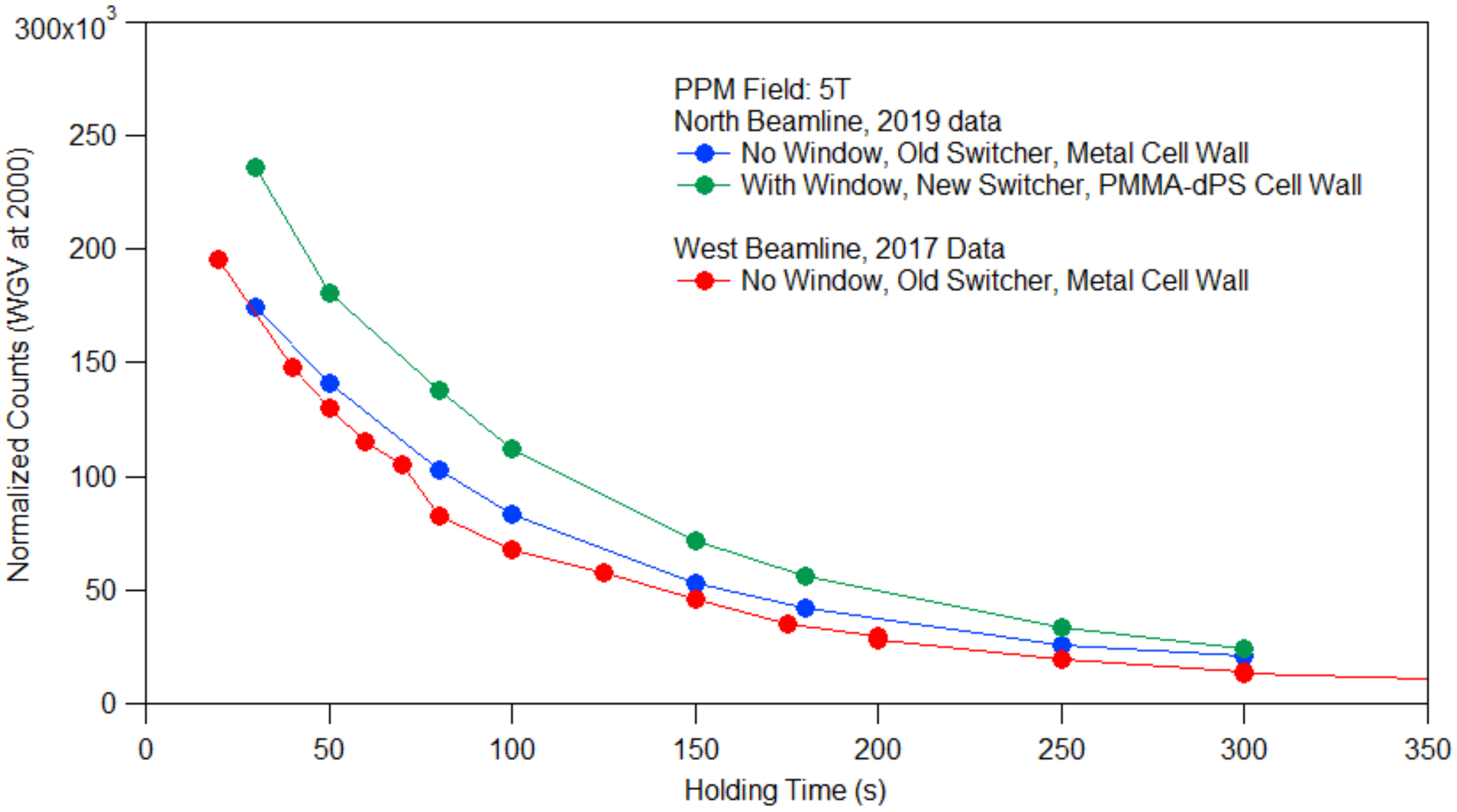
This estimate is based on the following:

- The estimate for E, T_{free}, T_{duty}, and α is based on what has been achieved by other experiments.
- The estimate for N is based on the actual detected number of UCN from our fill and dump measurement at a holding time of 180 s. Further improvements are expected (new switcher and new detector).

* "year" = 365 live days. In practice, it will take 5 calendar years to achieve this with 50% data taking efficiency

Neutron transport and storage test

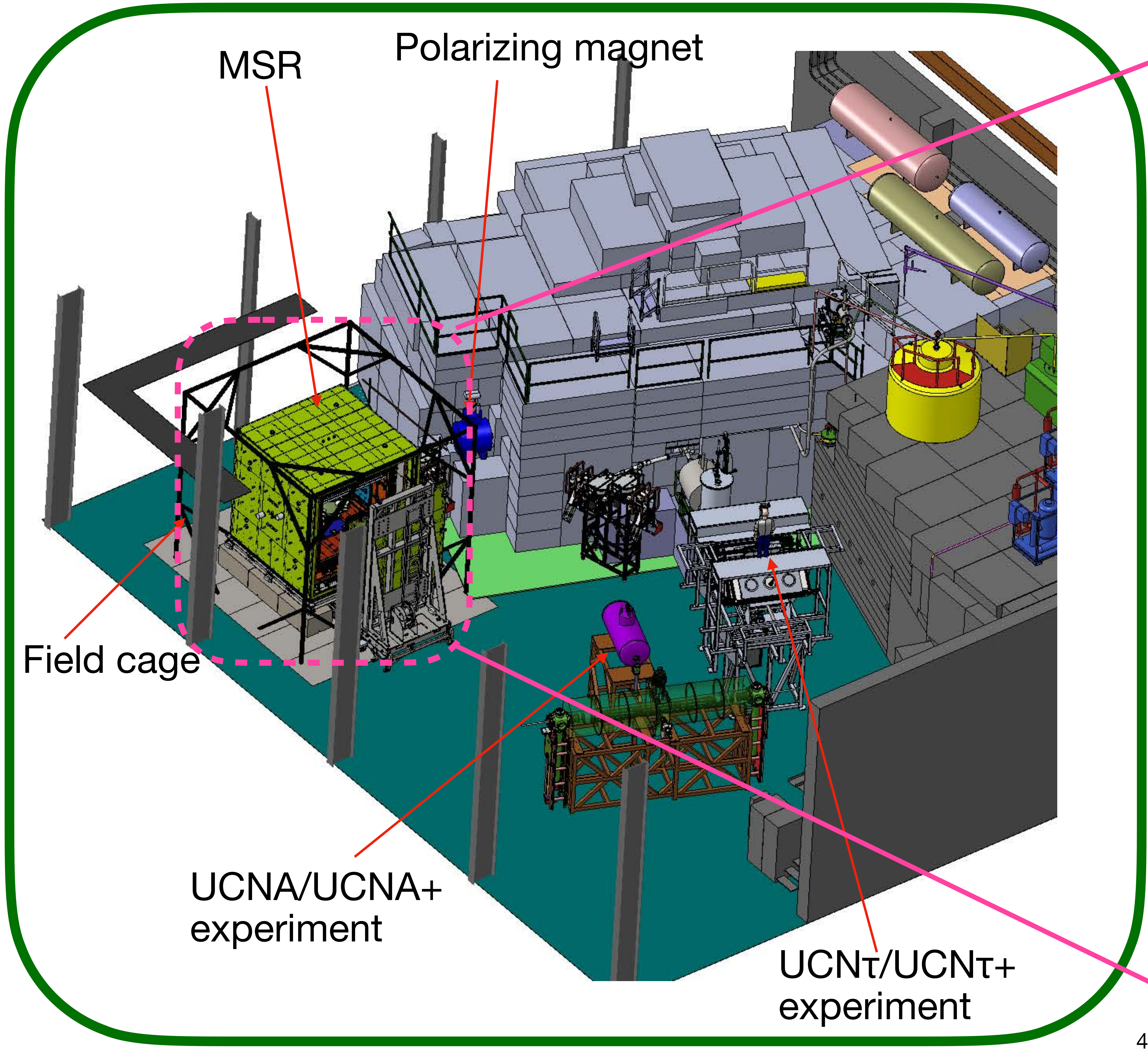




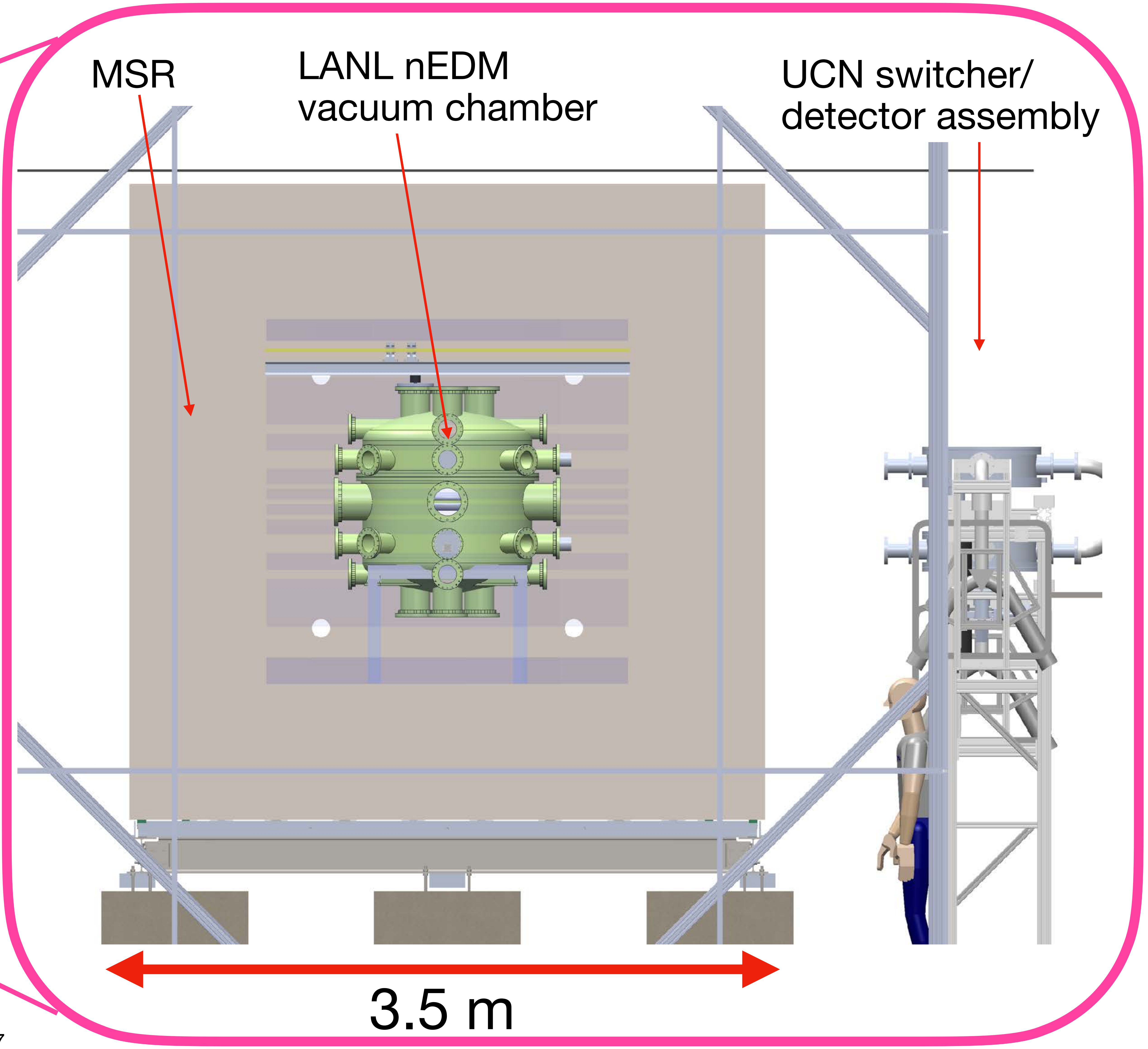
Measurement corresponds to ~70,000 detected UCN @ 2000 Hz GV rate after 180 s when a dPS coated cell wall was used with the new switcher

LANL nEDM expriment

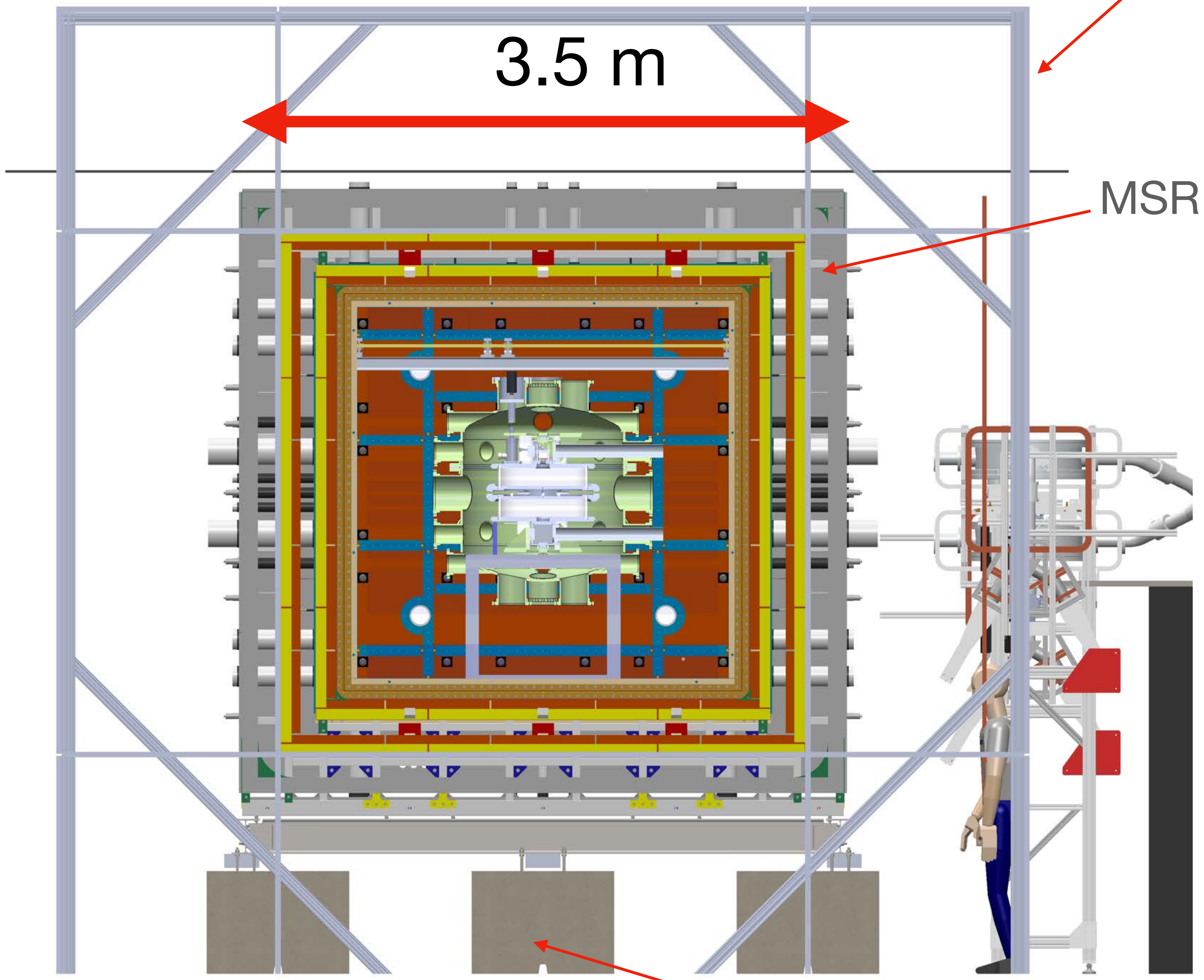
TA-53 Area B (UCN Experimental Hall)



LANL nEDM experiment



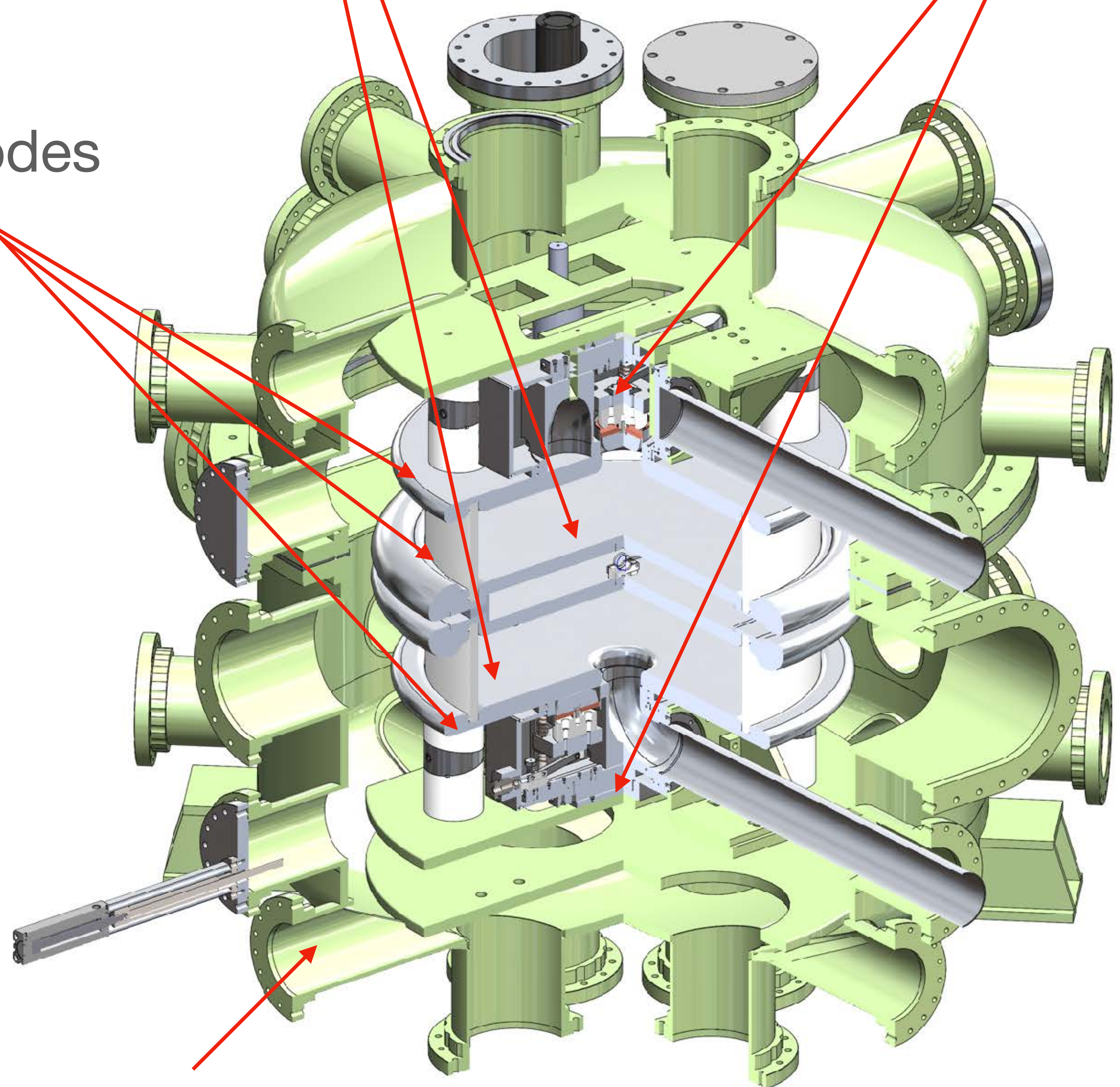
Experiment design



Field cage

MSR

MSR support structure



Precession chambers (50 cm diameter)

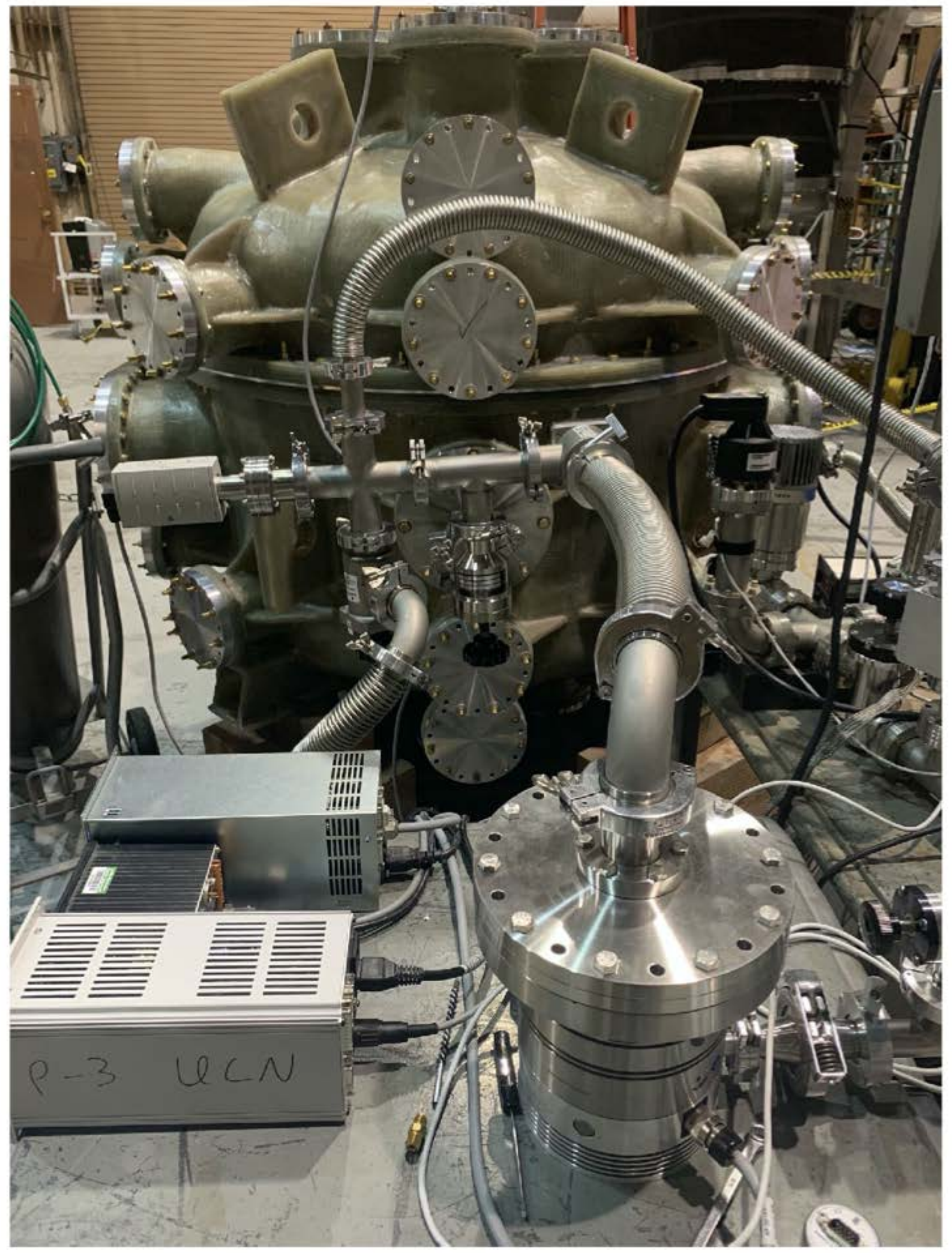
UCN valves

Electrodes

Vacuum chamber (made of composite material to avoid magnetism).

LANL nEDM expriment: status

Magnetically shielded room with a shielding factor of 10^5.



Non-magnetic vacuum chamber

½ scale prototype of the B_0 coil

- Takes advantage of the LANL UCN source. Uses well established Ramsey’s method at room temperature.
- Current development is funded by LDRD and NSF, with a goal sensitivity of $\delta d_n = 3\times10^{-27}$ e-cm.
- First engineering run planned for summer of 2022.

Summary

- Precision measurements of neutron properties and interactions provide unique and important information for tests of the consistency of the standard model and searches for physics beyond it.

- The recent upgrade of the LANL ultracold neutron source enabled new experiments.

- Recent results from UCNτ experiment have brought us a step closer to testing the CKM first row unitary using V_{ud} from neutrons. Upgrades of UCNA and UCNτ are being developed.

- LANL nEDM experiment, which takes advantage of the UCN density provided by LANL UCN Source, is being developed with a sensitivity goal of $\delta d_n = 2\times10^{-27}$ e-cm.