

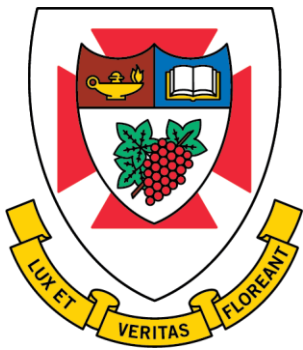
**TUCAN**

TRIUMF Ultra Cold  
Advanced Neutron  
Collaboration

# Determining Material Properties of DLC Coatings for a Neutron Electric Dipole Moment Experiment

Thomas Hepworth

for the TUCAN collaboration



THE UNIVERSITY OF  
**WINNIPEG**

CAP Congress 2025, June 10<sup>th</sup>

# Overview

In this talk I will:

1. Introduce the search for a non-zero neutron electric dipole moment (nEDM) at TRIUMF using ultracold neutrons (UCN)
2. Motivate the need for highly efficient UCN transport guides, and the use of Diamond-Like-Carbon (DLC) coatings
3. Discuss experiments to determine the material properties of DLC produced at UWinnipeg

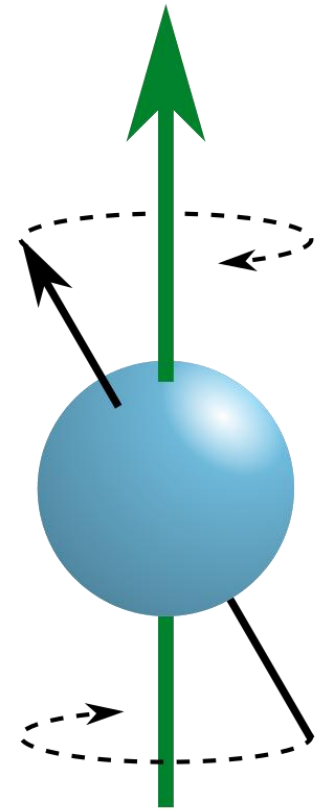
Other TUCAN talks this week:

- A. Brossard – TUCAN developments towards first UCN production and nEDM experiment – Monday
- M. Katotoka – Shim Coils and their importance in measuring the nEDM – Tuesday, 11:15 am

# Neutron Electric Dipole Moment Experiments

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- nEDM experiments are a CP and T violation search
- This could have profound implications on new physics scenarios
- The current world best limit on the nEDM is  $1.8 \cdot 10^{-26} e \cdot cm$  (90% CL)
  - Has always been measured to be zero. It shouldn't be, and we don't know why.
- TUCAN aims for a factor of 10 improvement on this measurement
  - We use ultracold neutrons to make these measurements



# What are UCN?

- **Ultracold Neutrons:** Neutrons moving at 5 – 14 m/s
  - Temperature of  $< 0.004$  K --- **COLD**
  - Move so slowly they can bounce off surfaces – and be stored!
  - $E < 350$  neV
- Interactions of UCN with all the fundamental forces of Nature:
  - Gravity:  $V = mgh = 100$  neV/m
  - Magnetic:  $V = -\mu \cdot B$   $\mu = 60$  neV/T
  - Strong:  $V = V_{\text{eff}}$   $V_{\text{eff}} < 335$  neV
  - Weak:  $\tau_n = 886$  s = 15 mins.
- The ability to study a population of UCN for 100s of sec  $\rightarrow$  excellent for EDM search!



# A Global History of nEDM measurements

- Modern experiments are limited by the number of UCN they store (statistics)

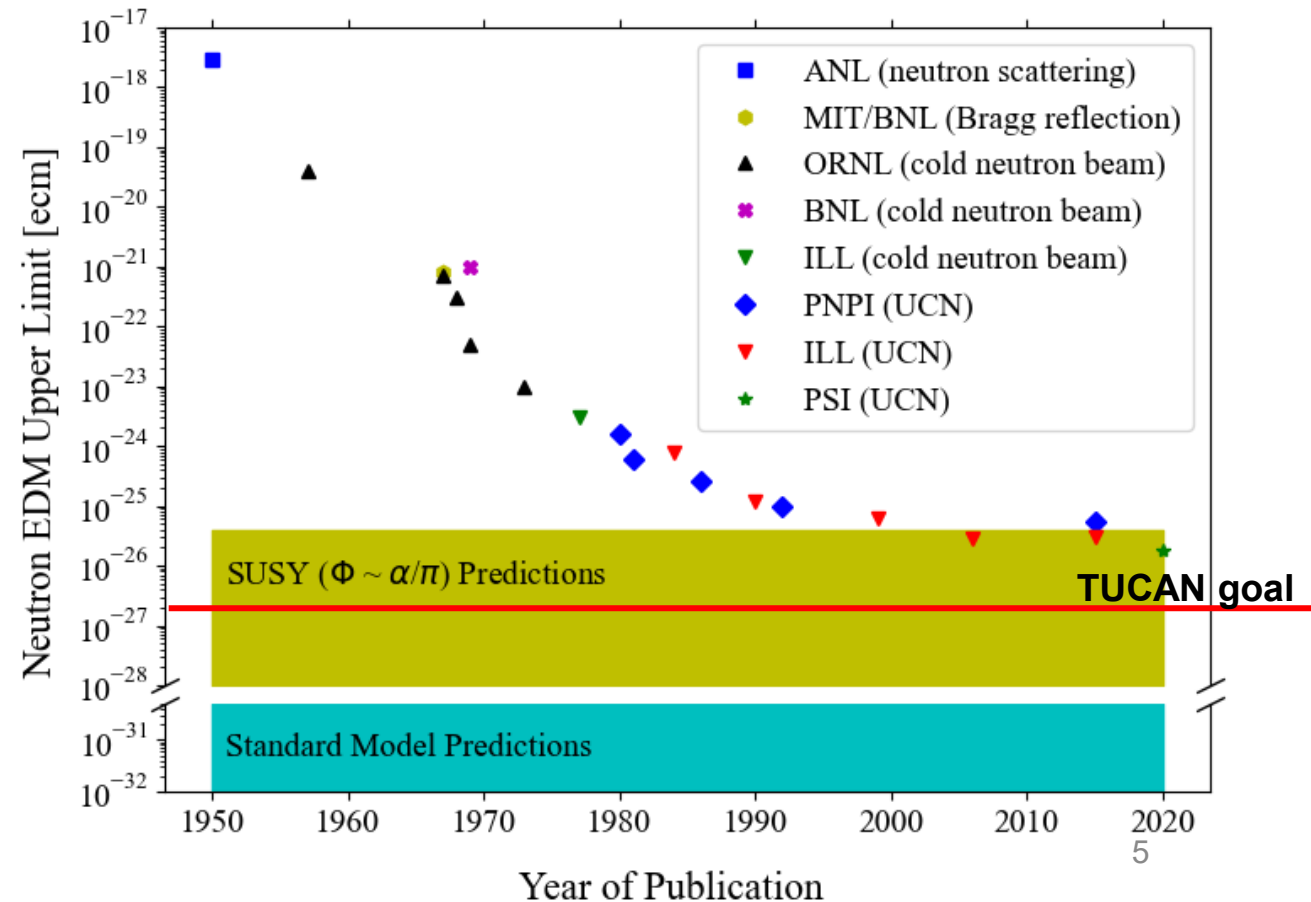
- How do you increase statistics?

- Powerful UCN sources
- Maximally efficient UCN transport

- Statistical uncertainty:

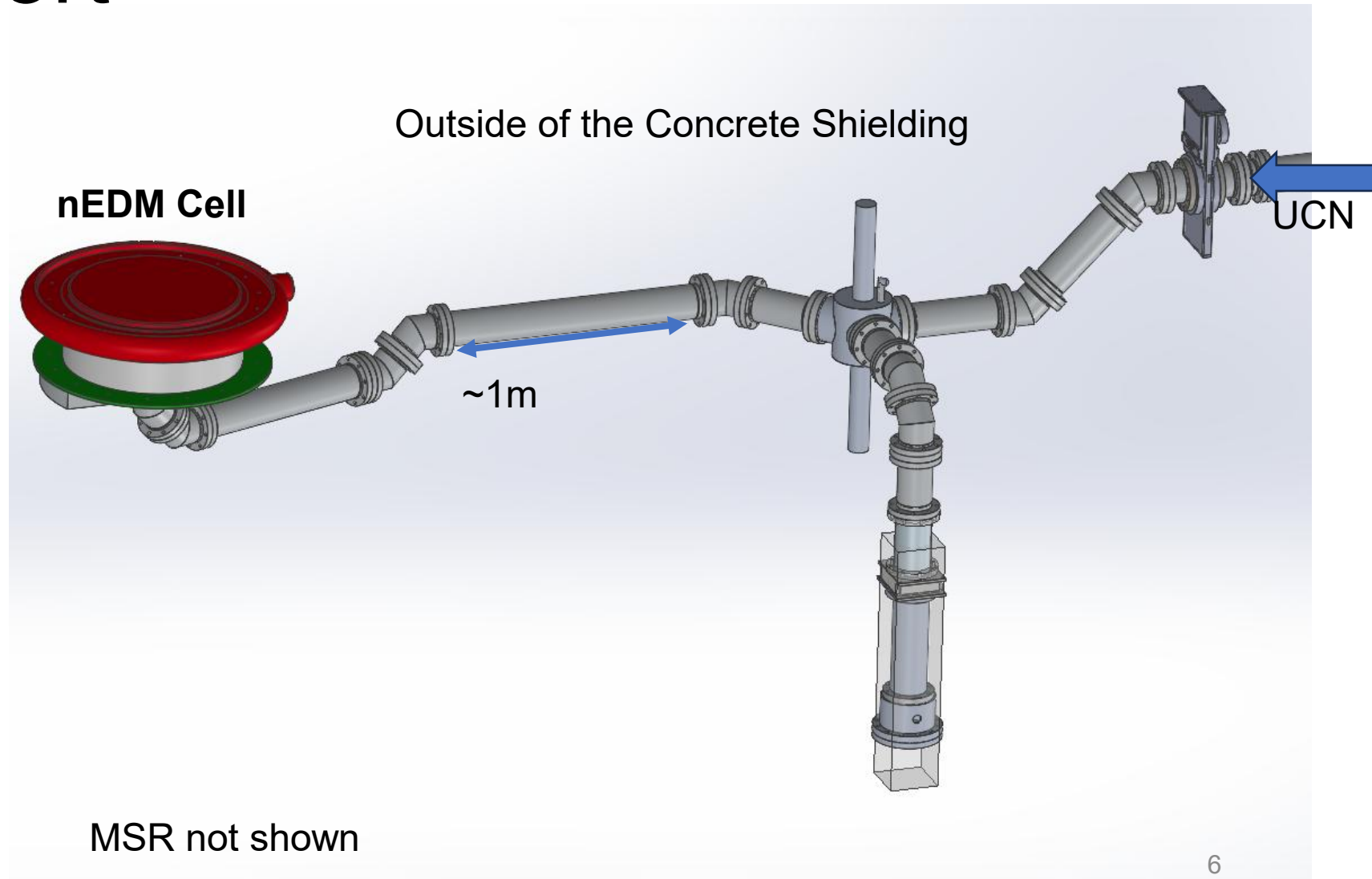
$$\sigma_d = \frac{\hbar}{2\alpha ET\sqrt{N}}$$

- Many polarized UCN needed for precision measurements



# UCN Transport

- Guides take UCN from source to experiment
- Without excellent UCN transport, TUCANs forecasted world best UCN source can't be utilized



# Diamond-Like Carbon (DLC)

- Simulations using published DLC values indicate a 40-100% increase in UCN delivered compared to next best coatings

UCN losses upon reflection:

$$V \Rightarrow U = V - iW, \quad \eta = W/V \ll 1$$

Material Potential:

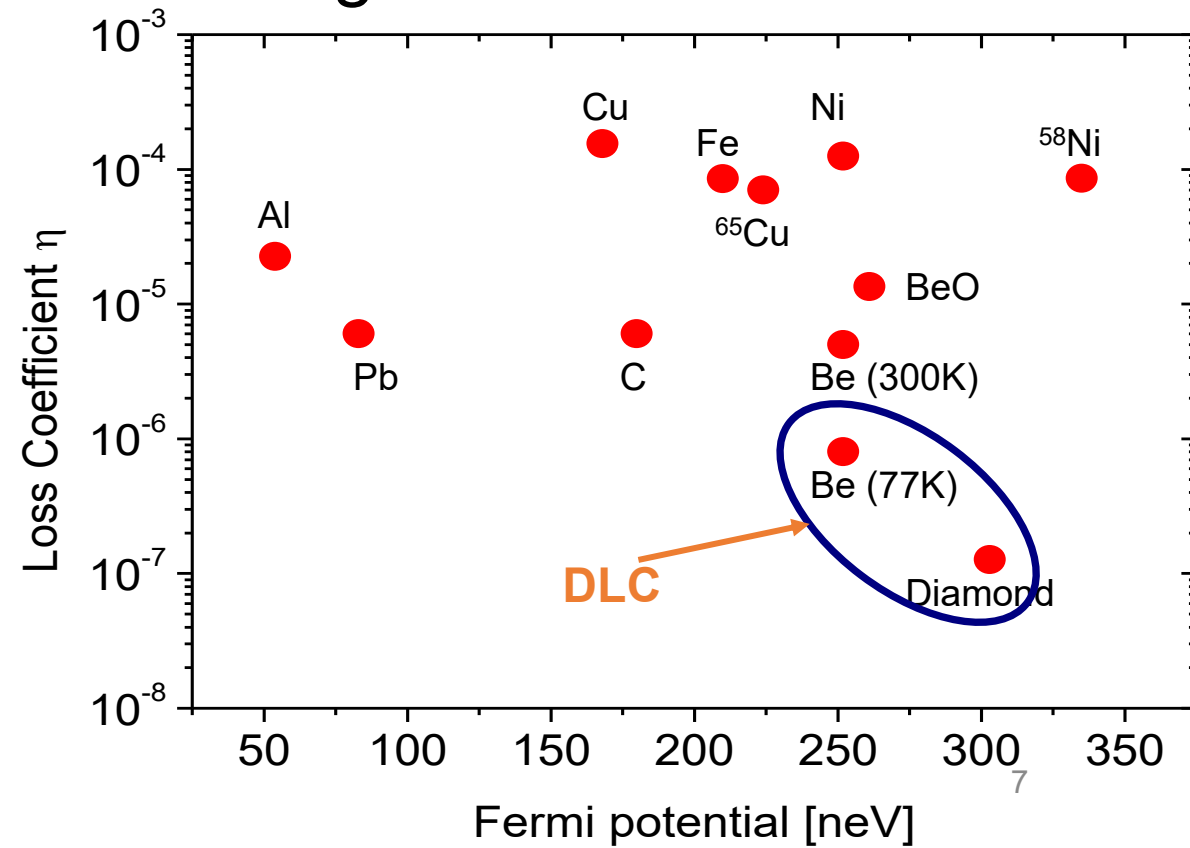
$$V = \frac{2\pi\hbar^2}{m} Nb$$

Maximum  
energy of stored  
UCN

To confidently connect any DLC guide to your UCN source, V and W must be understood

Storage Experiments

CN Reflectometry

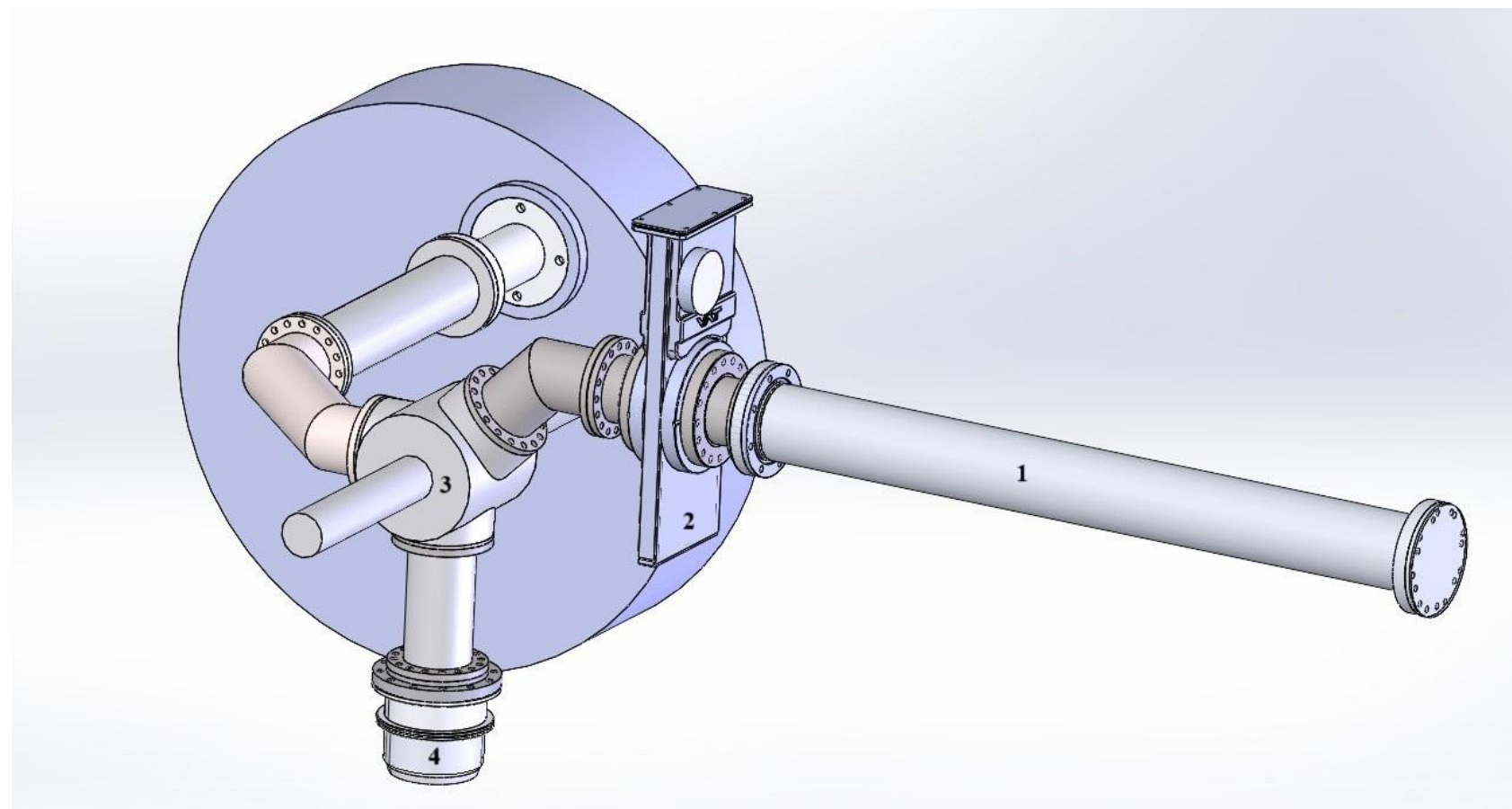


# Determining $W$ : UCN Storage Experiments

- We need to measure the transport efficiency of our DLC guides
  - Must be done for all guides produced at UW
    - Want a repeatable test procedure
- This mostly boils down to measuring  $W_{\text{DLC}}$
- Compare UCN in vs UCN out  $\rightarrow$  understand UCN losses

# UCN Storage Experiment at JPARC

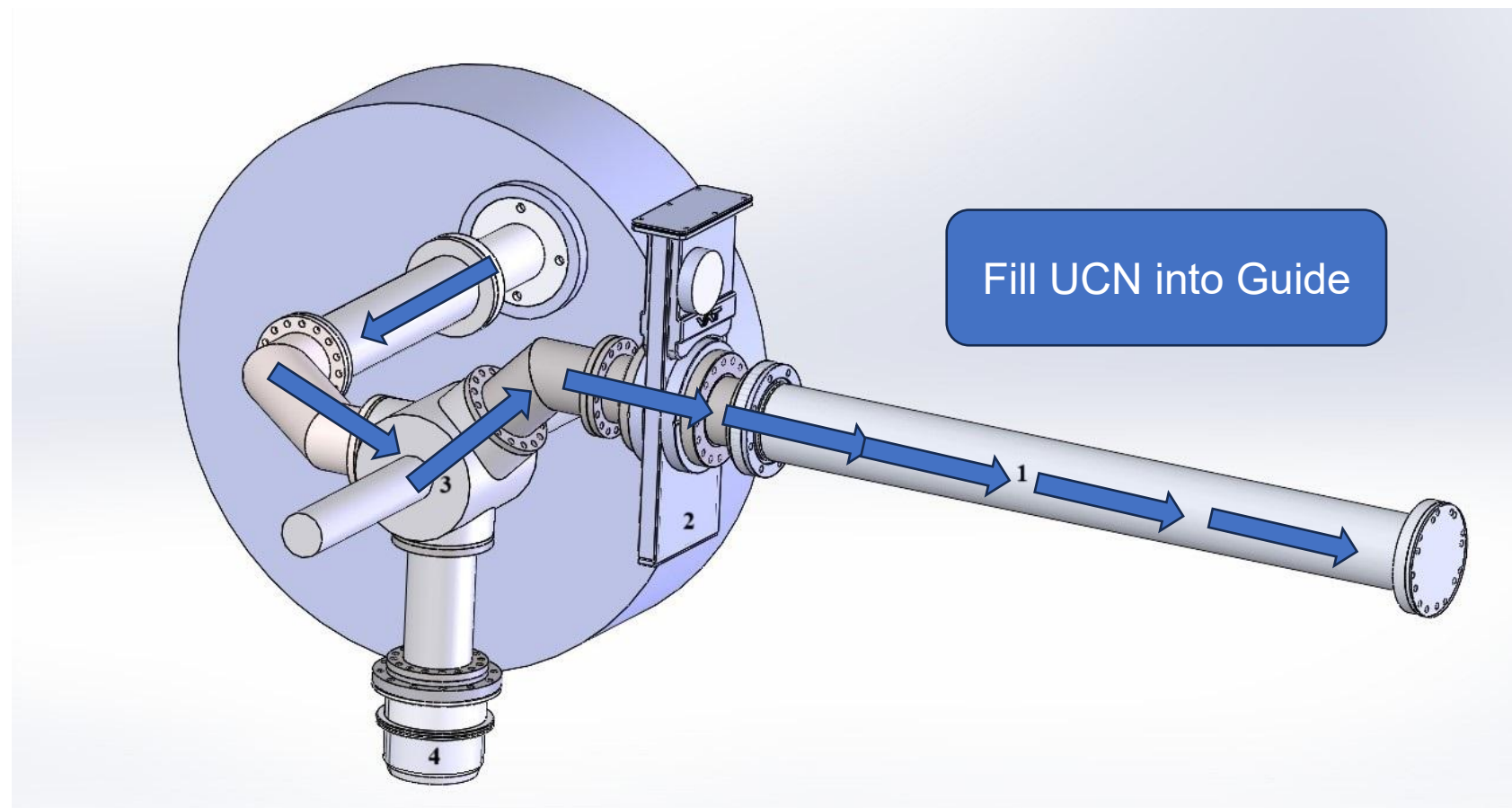
- 1: 1m long test guide
- 2: VAT Valve
- 3: Rotary Valve
- 4: Dunia 3He UCN detector



3D model of the experiment

# UCN Storage Experiment at JPARC

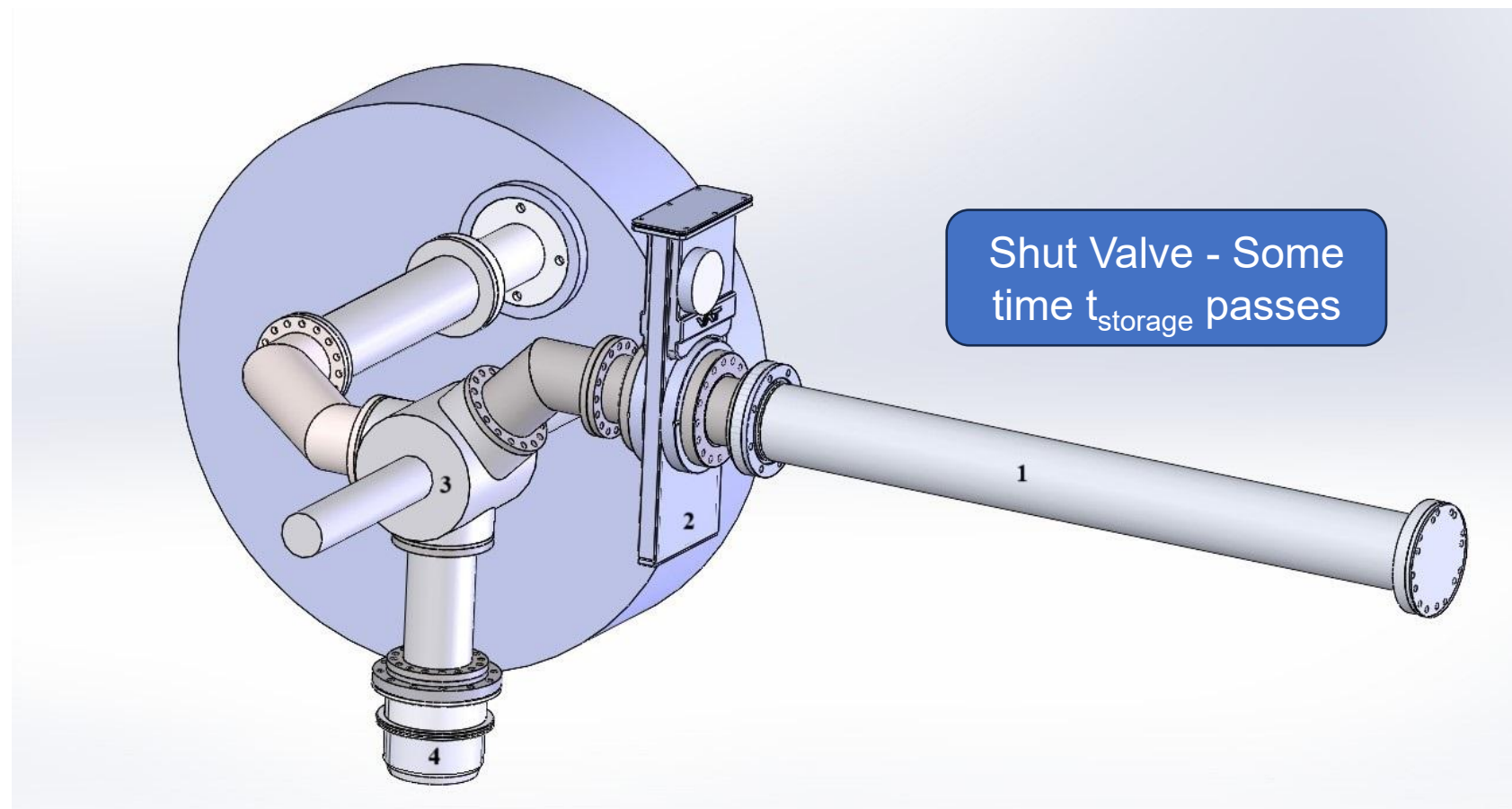
- 1: 1m long test guide
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3D model of the experiment

# UCN Storage Experiment at JPARC

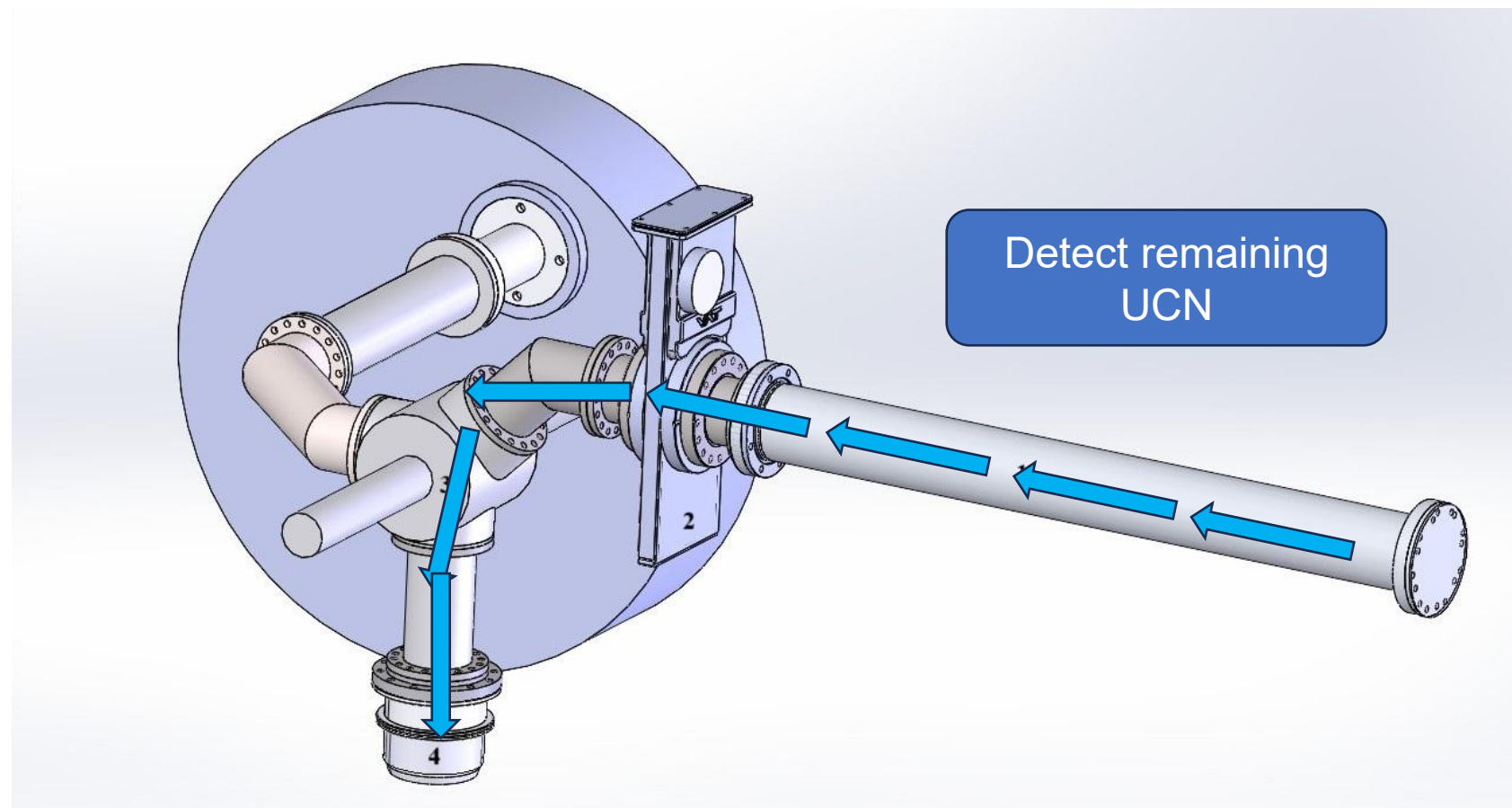
- 1: 1m long test guide
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3D model of the experiment

# UCN Storage Experiment at JPARC

- 1: 1m long test guide
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3D model of the experiment

# PENTrack

- PENTrack (Proton Electron Neutron Tracker) is a Monte Carlo particle tracking software package
  - Simulated trajectories of UCNs
- Uses a 3D model to define geometries whose materials you specify
- Allows us to perform simulations over a large ( $W_{DLC}$ ,  $\lambda_i$ ) parameter space
 

↳ Other params of secondary interest

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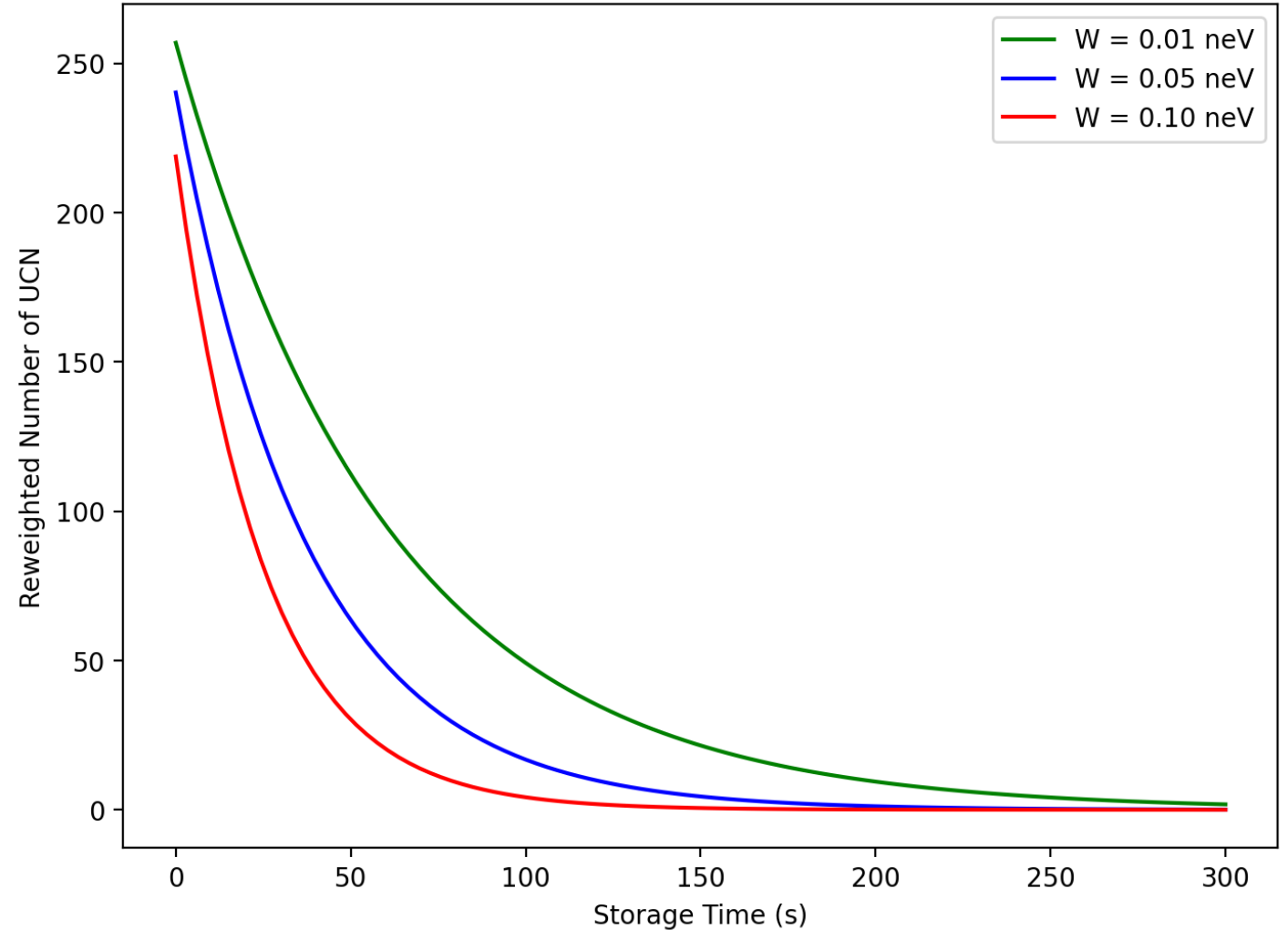
#####
###                               Welcome to PENTrack,                               ###
### a simulation tool for ultracold neutrons, protons and electrons ###
#####
  
```

# J-PARC Simulation Goals

- There is a large range of  $W_{\text{DLC}}$  values we could expect
  - Anywhere from 0.03 – 0.08 neV
- We simulate  $W_{\text{DLC}}$  within these boundaries, and determine the storage lifetime ( $\tau$ )
- When we collect data at JPARC, we compare  $\tau_{\text{experiment}}$  and  $\tau_{\text{simulated}}$  to extract a corresponding  $W_{\text{DLC}}$

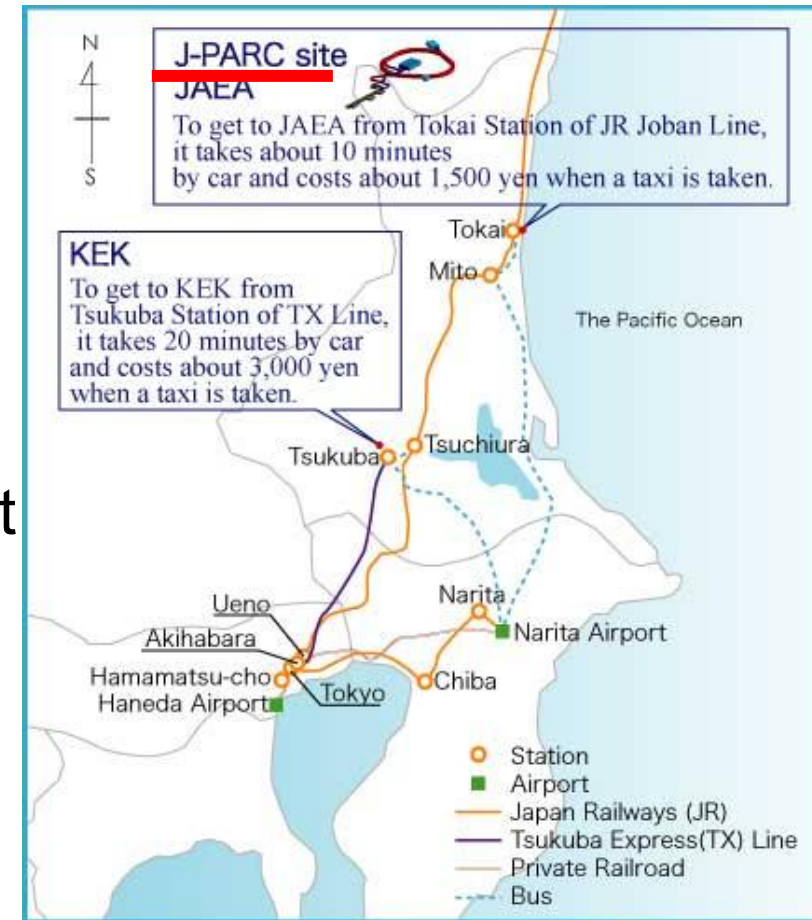
# Building Our Reference Table

- By fitting this curve to an exponential, we can extract our main metric  $\tau(W)$
- Many of these curves give us a large collection of possible  $\tau(W)$  to overlay on data



# Future Work

- Travel to Tokai, Japan to collect data:
  - 2026? Delayed from June 2025 due to MLF shutdown
- Analyze real data, compare to simulations
  - Likely need to run more simulations – not a huge effort
- Conclude a  $W_{DLC}$  for the tested guide: inform future DLC coating studies





# Questions?

Update from  
A. Brossard's Talk:

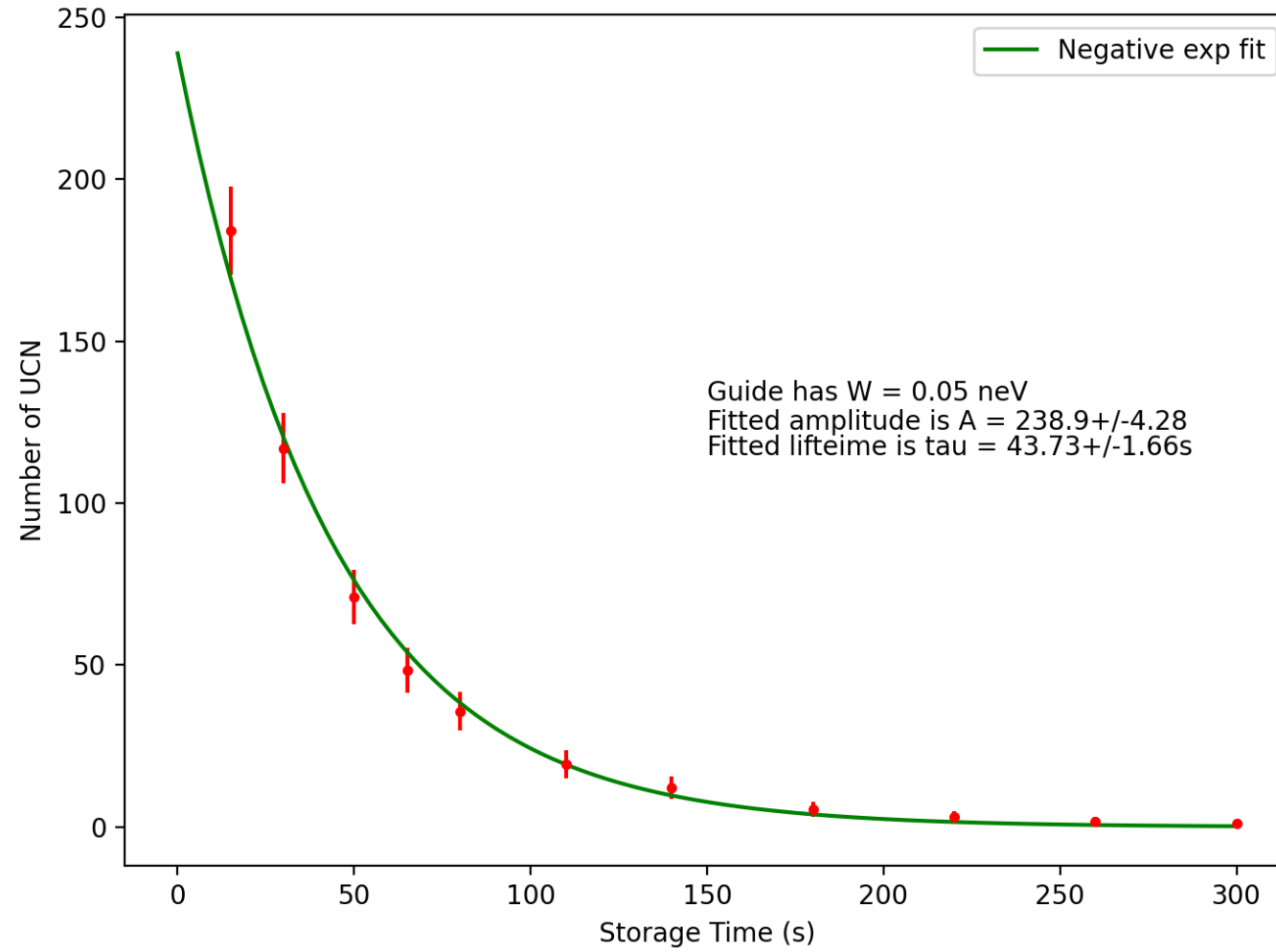
**FIRST UCN EXPECTED  
AT TRIUMF IN MERE  
HOURS**

Actively tuning beam, doing radiation surveys  
(literally right now as you read this!!!)



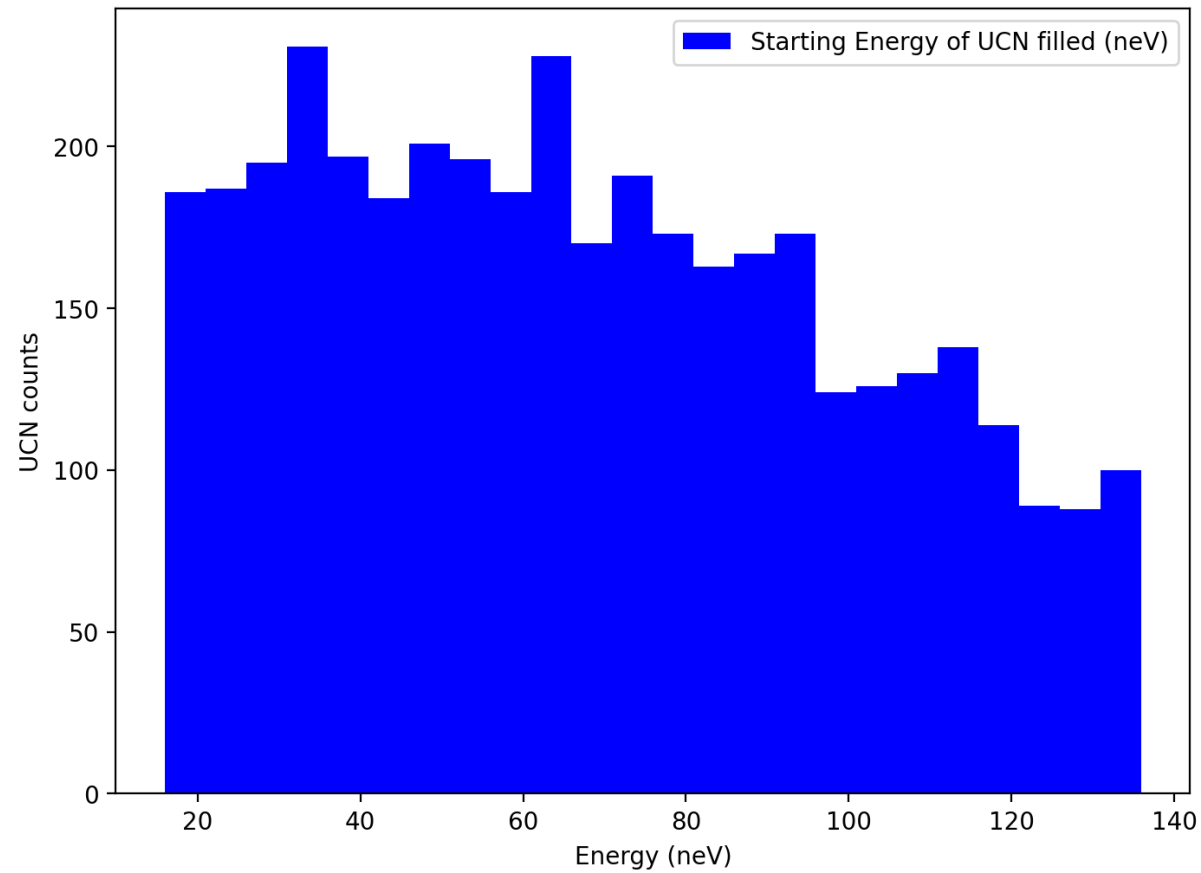
Fig: UWinnepeg Guide Coating Facility

# Backups

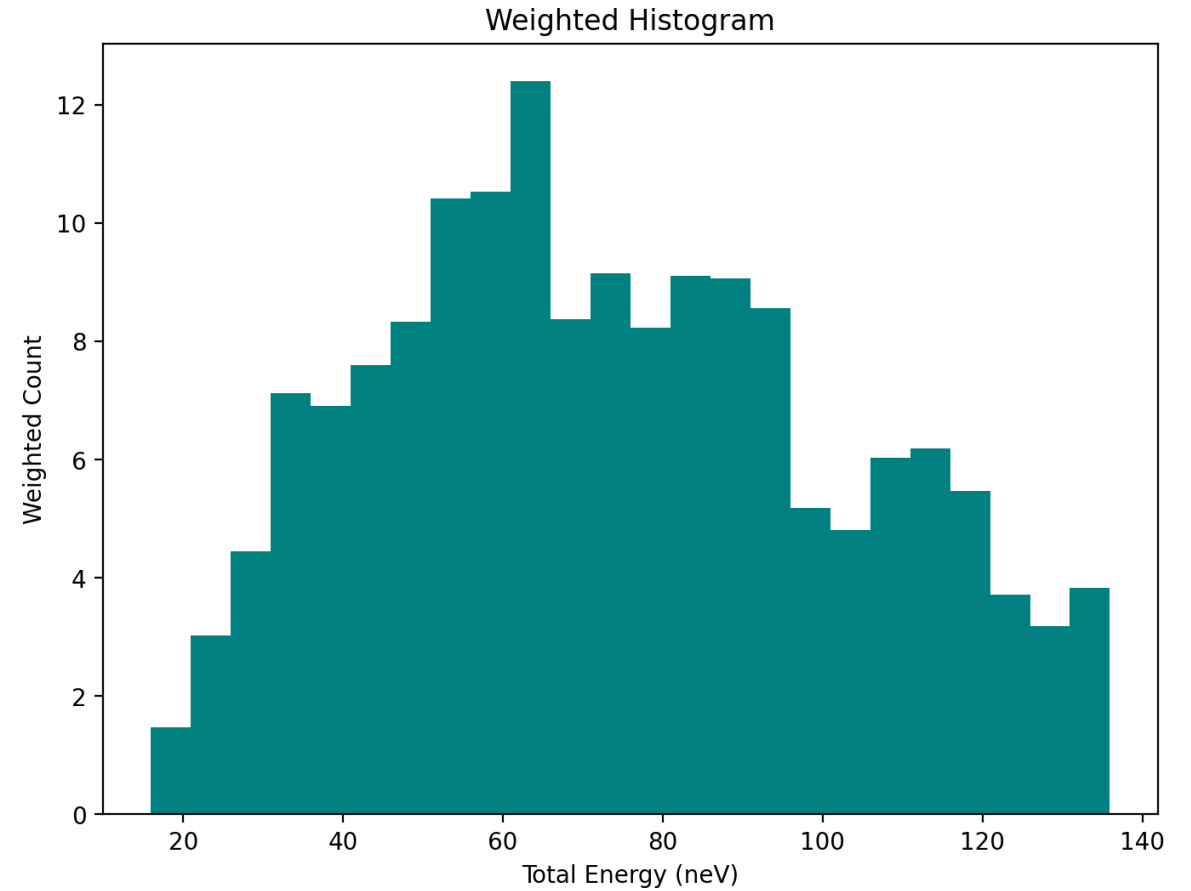


# Reweighting

- J-PARC sims are done with uniform energy spectrum
  - Certainly not will come out of the Doppler shifter
- We can Reweight storage curves for the measured energy spectra from the DS
- Simulations are separated into filling and then storage and draining.
  - 2 sims -> reweight twice



Reweight using Filled spectrum, filter which UCN hit detector and get:

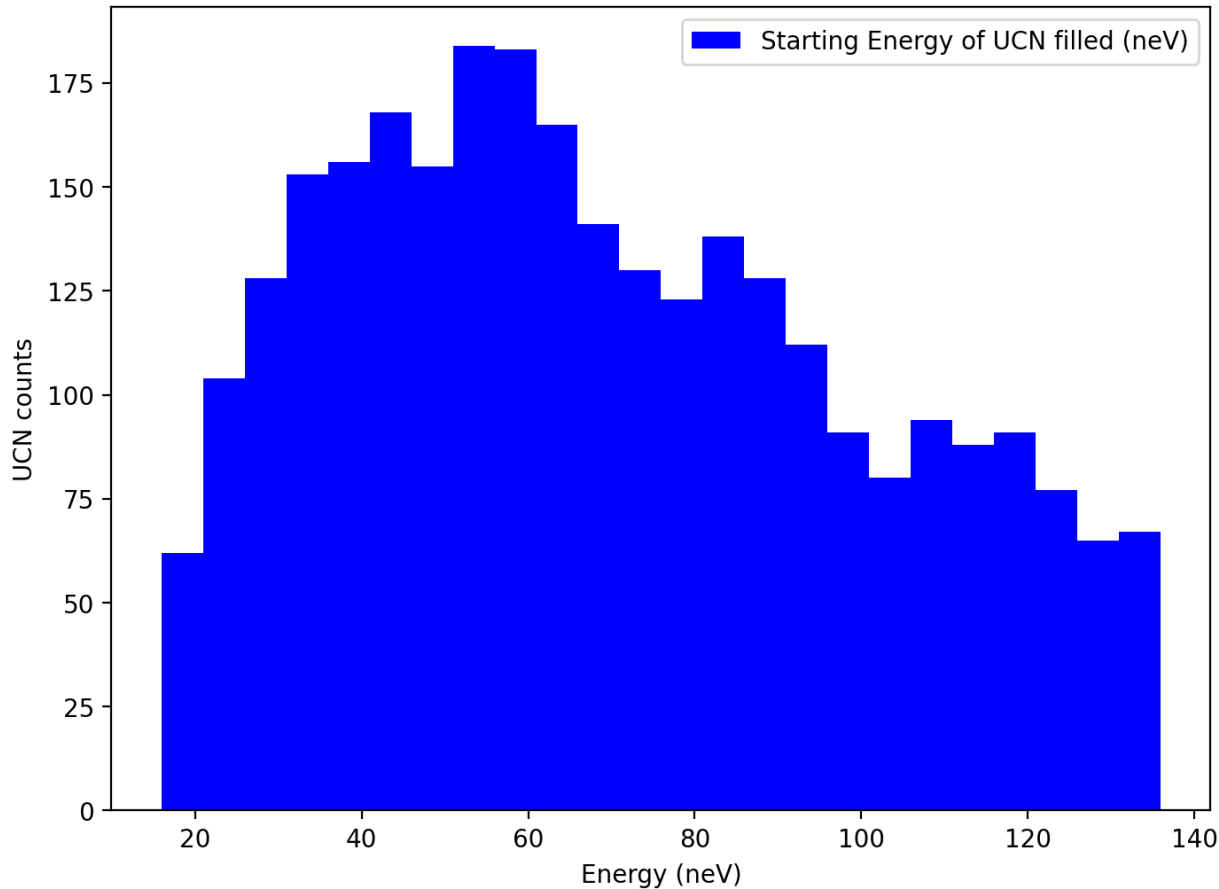


Sum the weighted counts in the plot on the right and get:

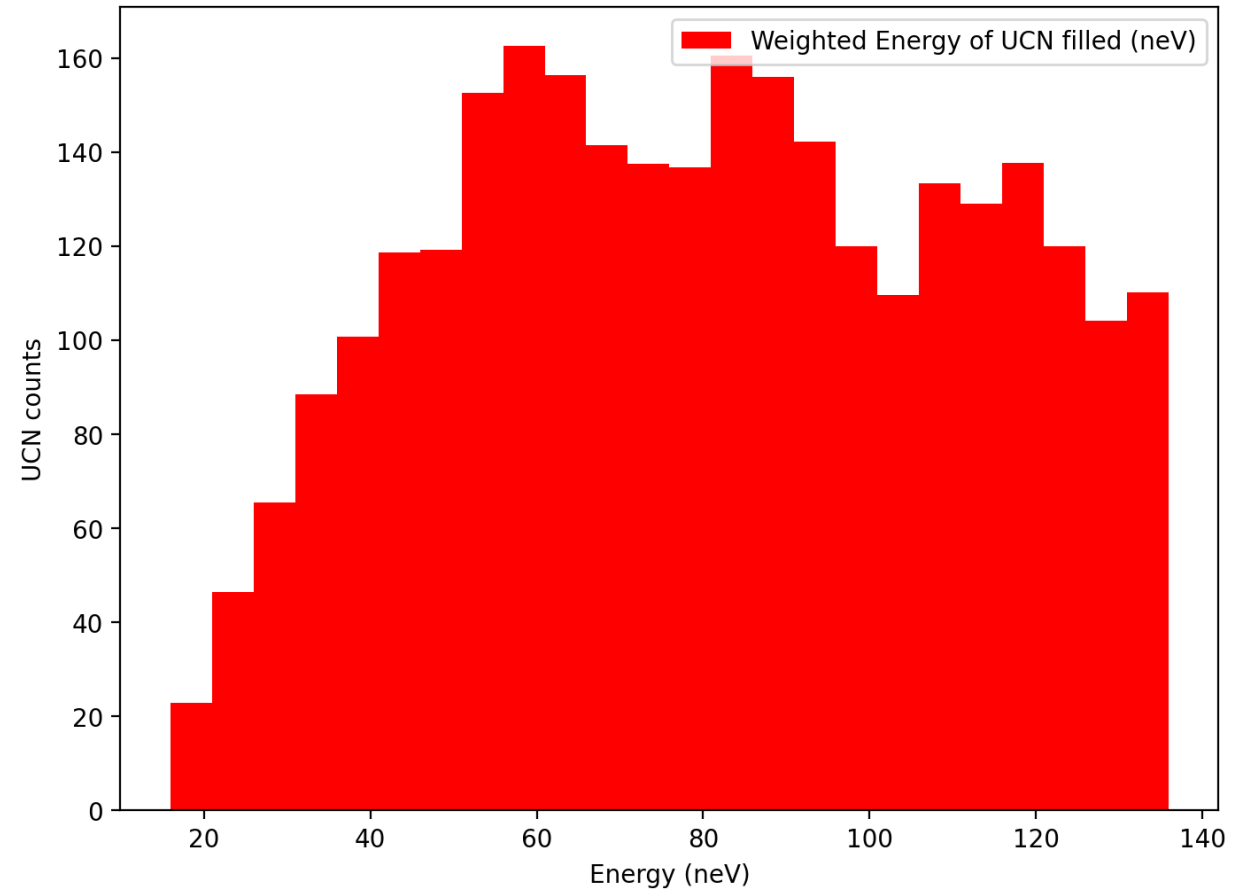
DS Spectrum Generalized Weibull (GW)

$$\left(\frac{x}{p_0}\right)^{p_2} e^{-\left(\frac{x}{p_0}\right)^{p_1}}$$

p0	p1	p2
383.6009	3.6262	0.7712



UCN energy that make it to guide



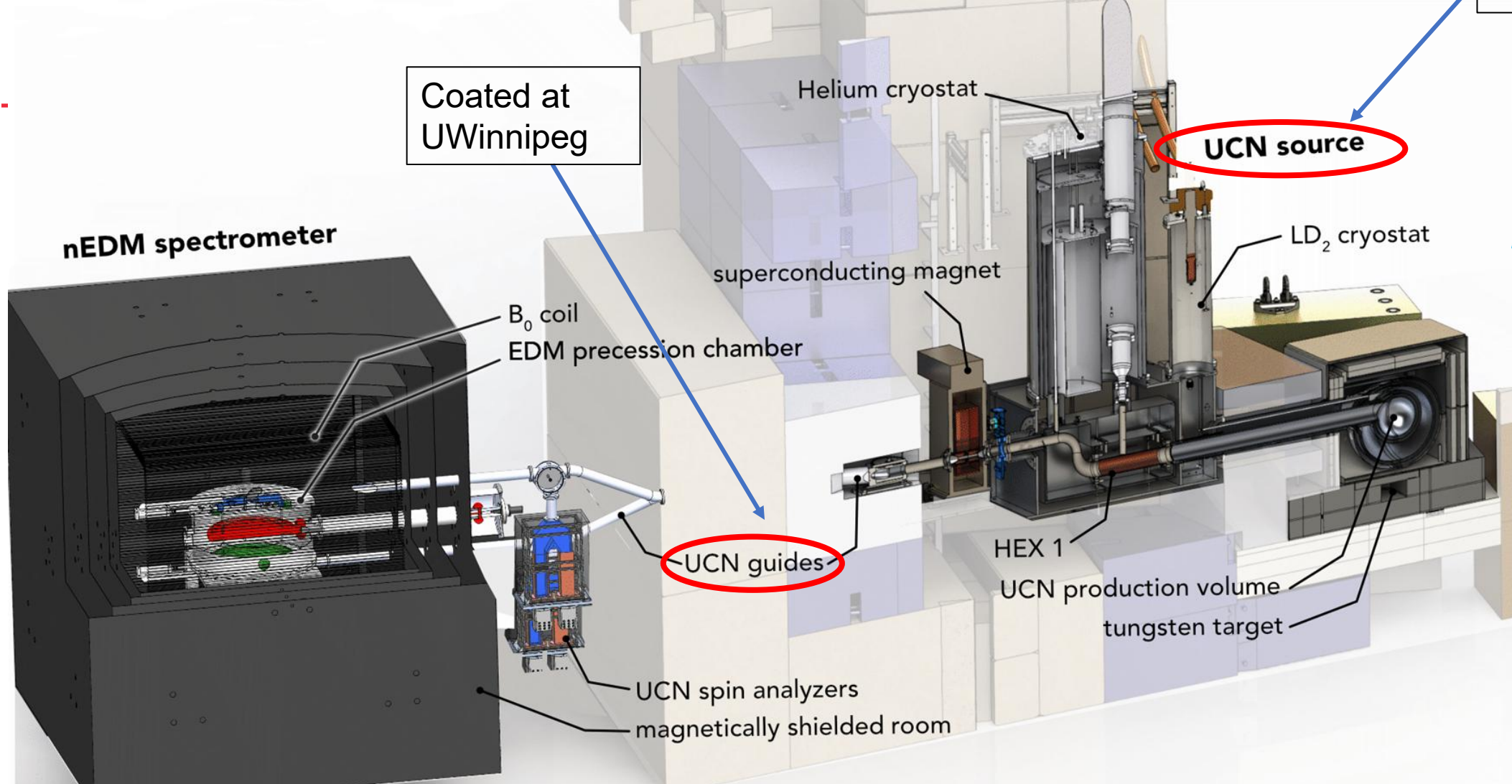
After reweighting to J-PARC spectra

# Simulation and Analysis Workflow

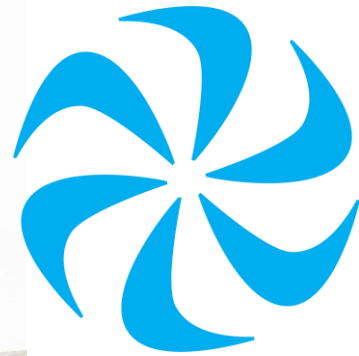
- PENTrack uses configuration files as inputs
  - Config files completely prescribe everything in a simulation
- I use scripts (Perl) to autonomously edit and adjust my template for each simulation (1000s)
- Simulations run on ComputeCanada servers at Simon Fraser University
  - I then download and analyze data when the simulations are completed (hours or days later)



# Ingredients for an nEDM measurement



Forecasted  
World Best



520 MeV  
Cyclotron

# Key Principles of Experiment

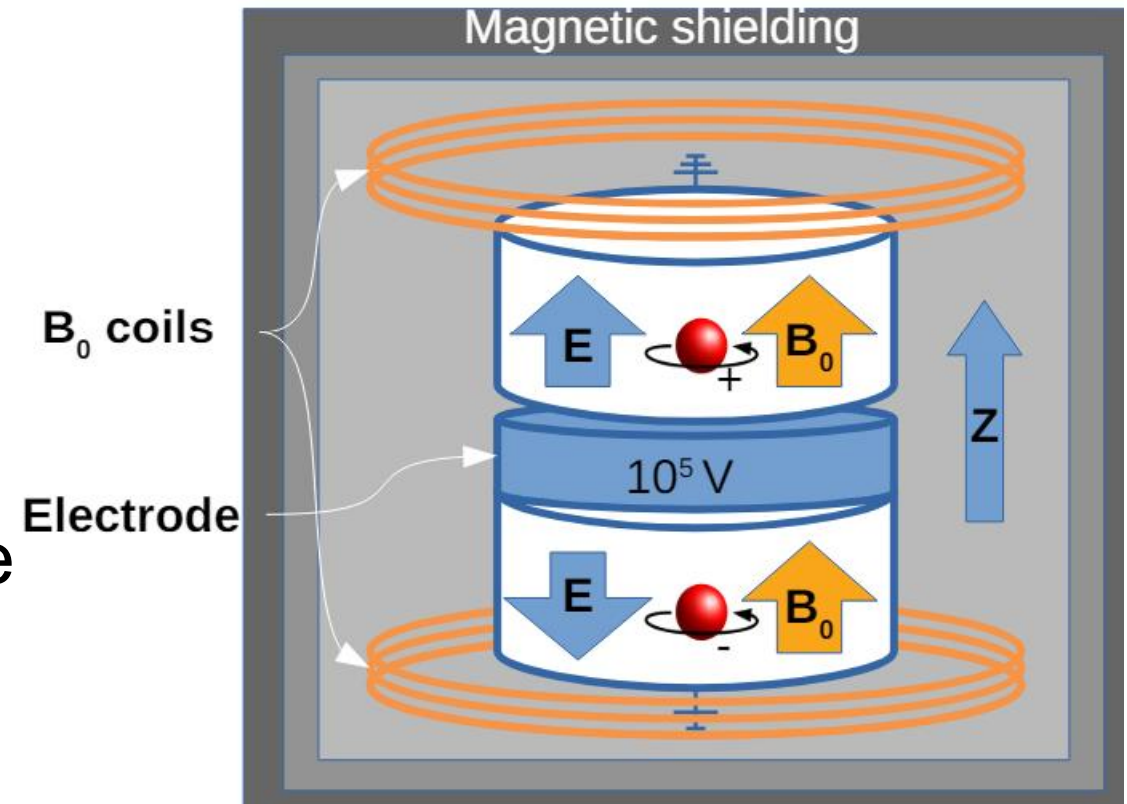
- Hamiltonian of neutron in an EM field (non-relativistic limit)

$$H = -\mu_n \vec{\sigma} \cdot \vec{B} - d_n \vec{\sigma} \cdot \vec{E}$$

$\swarrow \searrow$   
 $\mathcal{T} \rightarrow \mathcal{CP}$

- Experiment: precise measurement of neutron spin precession frequency to determine  $d_n$

$$\hbar\omega = 2\mu_n B \pm 2d_n E$$



# Benchmarking

- PENTrack results must be analytically verified by comparing the following:

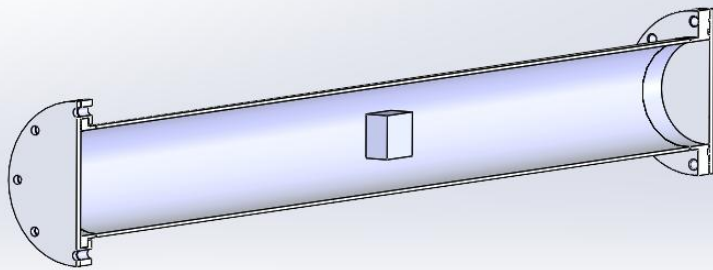
$$\tau^{-1}(H) = \frac{\sqrt{2H/m}}{4\gamma(H)} \int_a^b \frac{H - mgz}{H} \sum_i \frac{dA_i}{dz} \mu_i(H - mgz) dz + \tau_\beta^{-1}$$

$$\tau^{-1}(E) = \sqrt{\frac{2E}{m}} \sum_i \frac{A_i}{4V} \mu_i(E) + \tau_\beta^{-1}$$

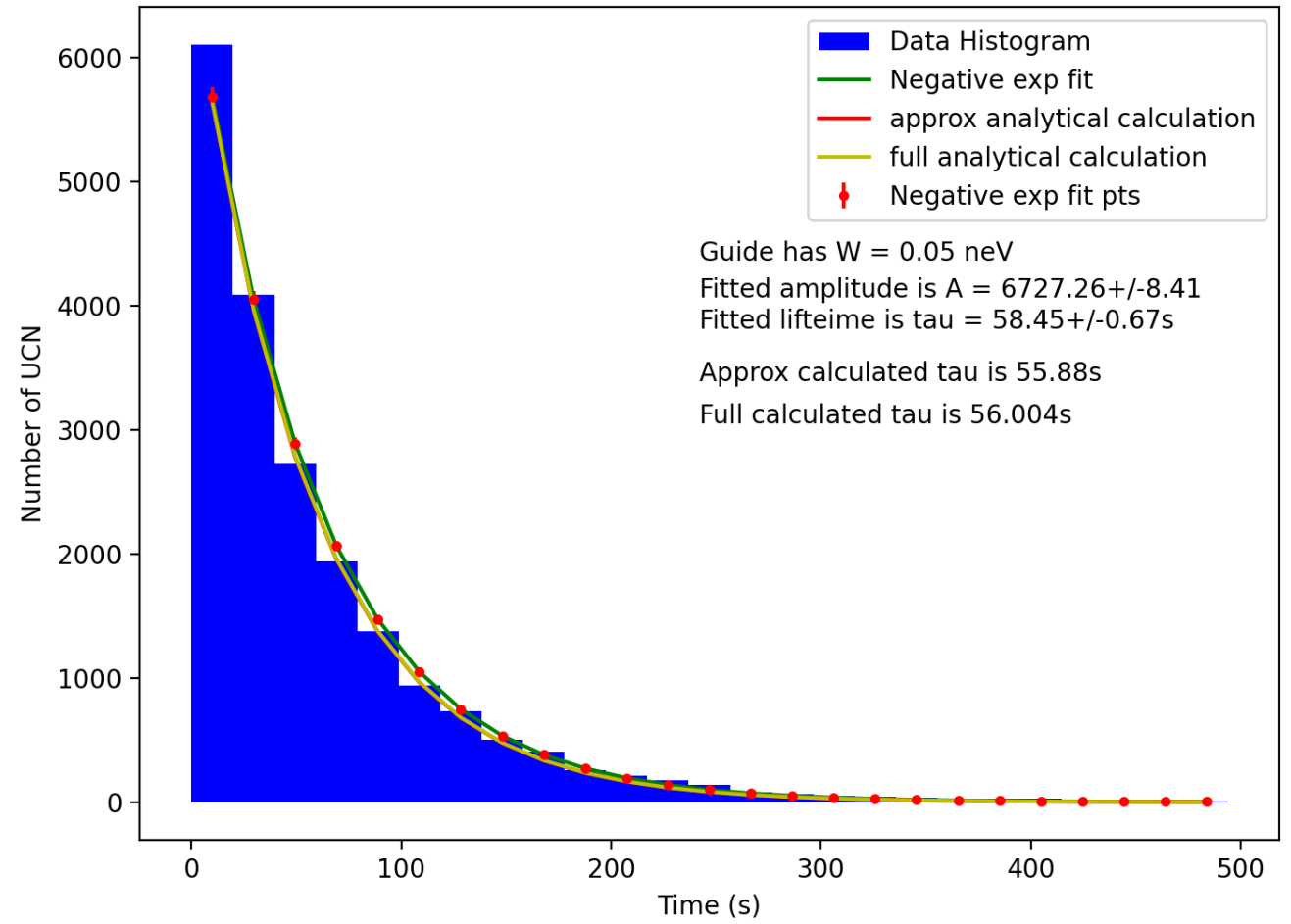
Calculate for Uniform energy spectrum

to the fit of the simulated data:

$$N(t) = N_0 e^{-t/\tau_{fit}}$$



UCN leave cube with uniform energy and angular spectrum



# Weighted Uncertainty Calculation: Bin and Scale

- Bin your simulated UCNs by the weighting parameter ( $H$ ), such that you have  $N_u(H, t)$
- Now,  $N_w = \sum_H w(H)N_u(H, t)$
- For a single bin, the uncertainty is  $w(H)\sqrt{N_u(H, t)}$

- Then the total uncertainty is obtained by error propagation

$$\sigma_w = \sqrt{\sum_H \left( w(H)\sqrt{N_u(H, t)} \right)^2}$$

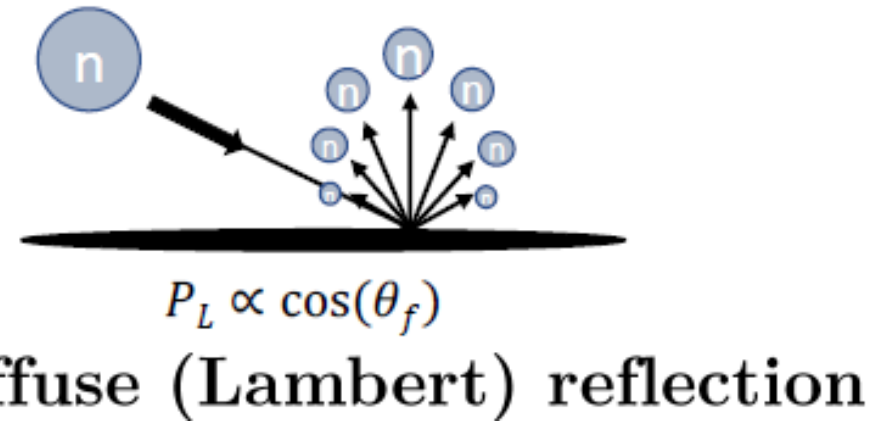
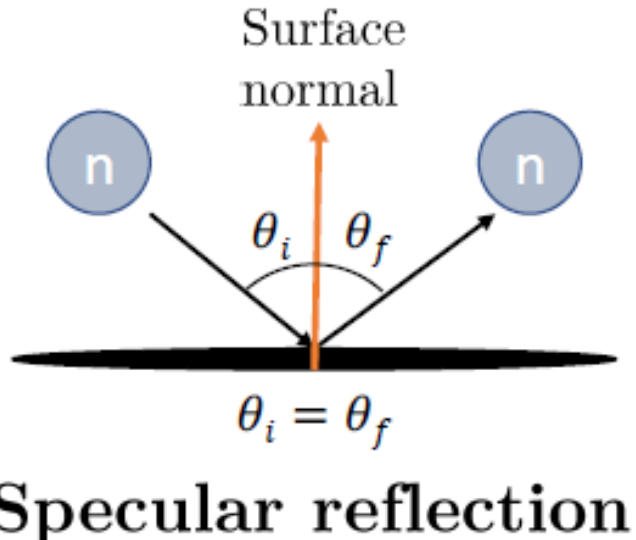
- For weighting of a filled spectrum with a function:

- $w_{filled}(H) = w(H)N_{filled}(H)$
- $\sigma(w_{filled}(H)) = w(H)\sqrt{N_{filled}(H)}$

- For weighting of storage results:

- $N_{stored,rw}(H) = w_{filled}(H)N_{stored,sim}(H)$
- $\sigma(N_{stored,rw}(H)) = N_{stored,rw}(H) * \sqrt{\frac{\sigma(w_{filled})^2}{w_{filled}^2} + \frac{\sigma(N_{stored,sim})^2}{N_{stored,sim}^2}} = N_{stored,rw}(H) * \sqrt{\frac{\sigma(w_{filled})^2}{w_{filled}^2} + \frac{1}{N_{stored,sim}}} = N_{stored,rw}(H) * \sqrt{\frac{1}{N_{filled}(H)} + \frac{1}{N_{stored,sim}(H)}}$
- $N_{stored,rw} = \sum N_{stored,rw}(H)$
- $\sigma(N_{stored,rw}) = \sqrt{\sum \sigma(N_{stored,rw}(H))^2}$

# Lambertian Scattering



The outgoing angle after a surface collision is randomized with a  $\cos(\theta)$  probability distribution. It's used to represent non-specular, elastic reflections from rough surfaces

# Experimental Technique

$\omega$ : precession freq. of neutron  
 $\mu_n$ : neutron magnetic moment  
 $B$ : magnetic field  
 $E$ : electric field  
 $d_n$ : neutron electric dipole moment

- $d_n$  is measured indirectly through the neutron's Larmor spin precession frequency

$$\hbar\omega = 2\mu_n B + 2d_n E$$

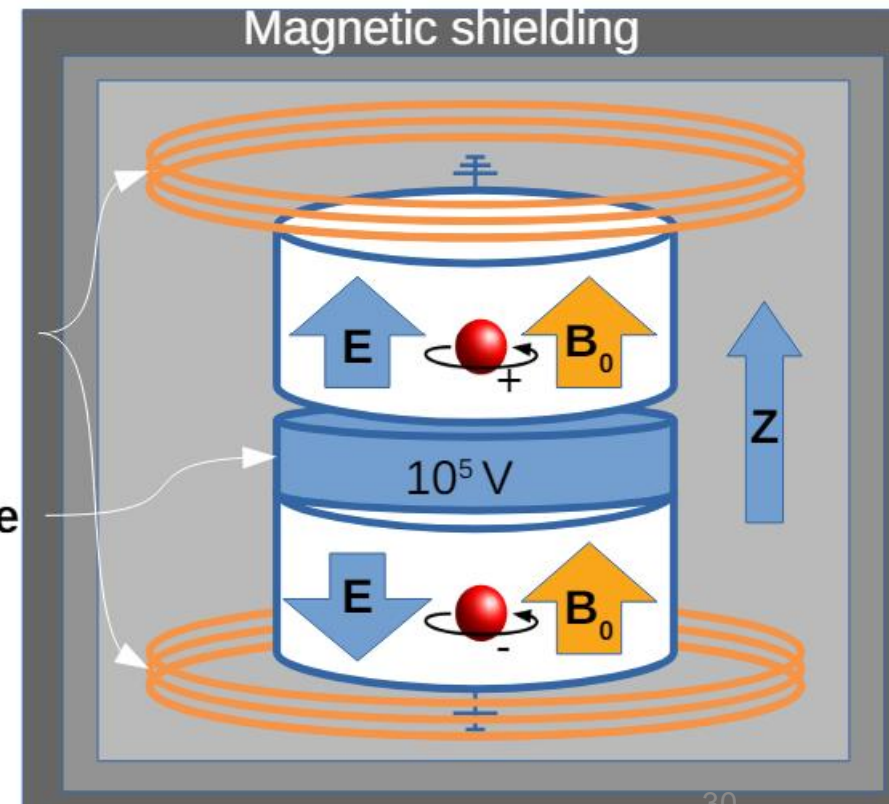
$$\hbar\omega = 2\mu_n B - 2d_n E$$

→ = 0?

Subtract and we get:

$$d_n = \frac{\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})}{4E}$$

→ **B must cancel**



# EDM, CP violation, and basic technique

- Hamiltonian of neutron in an EM field (non-relativistic limit)

$$H = -\mu_n \vec{\sigma} \cdot \vec{B} - \underbrace{d_n \vec{\sigma} \cdot \vec{E}}_{\mathcal{T} \rightarrow \mathcal{CP}}$$

	P	T	C	CP	CPT
$\mu \cdot B$	+1	+1	+1	+1	+1
$d_n \cdot E$	-1	-1	+1	-1	-1

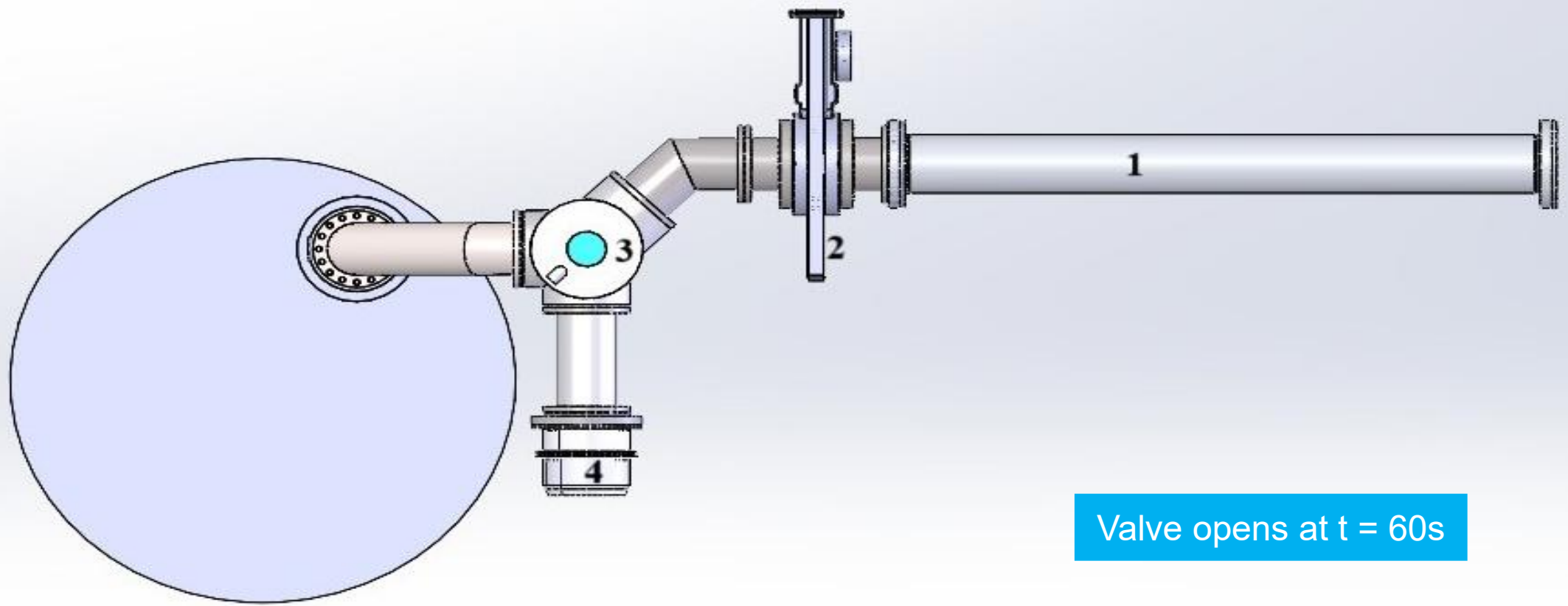
- Experiment: precise measurement of neutron spin precession frequency to determine  $d_n$

$$\hbar\omega = 2\mu_n B \pm 2d_n E$$

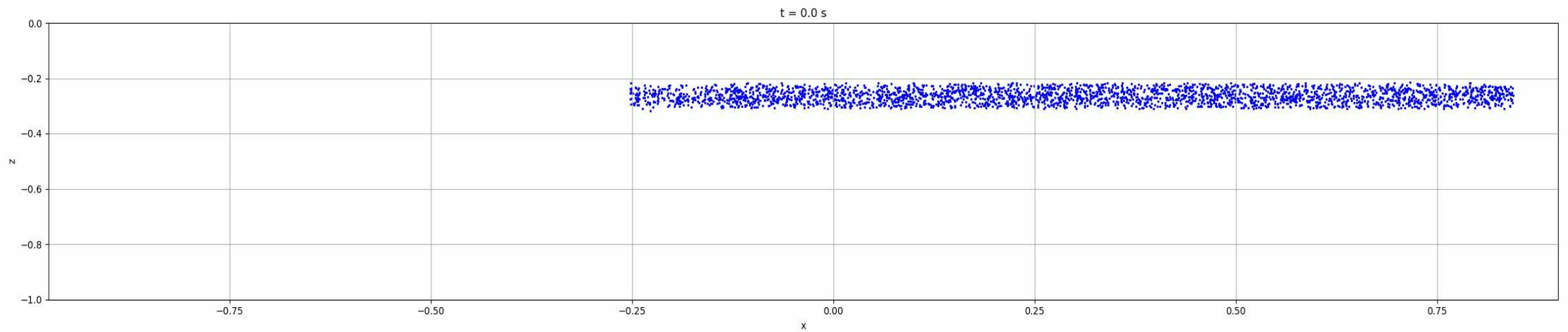
- Statistical uncertainty:

$$\sigma_d = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

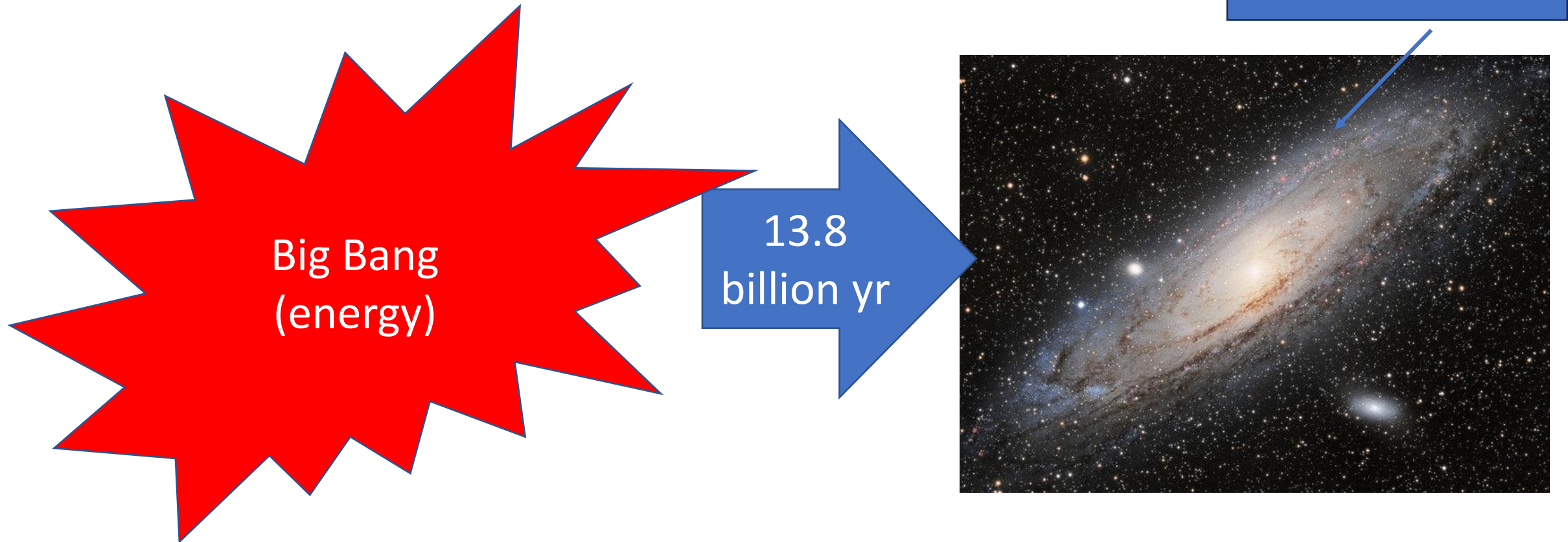
Precision frequency measurement requiring many polarized neutrons



Valve opens at  $t = 60s$



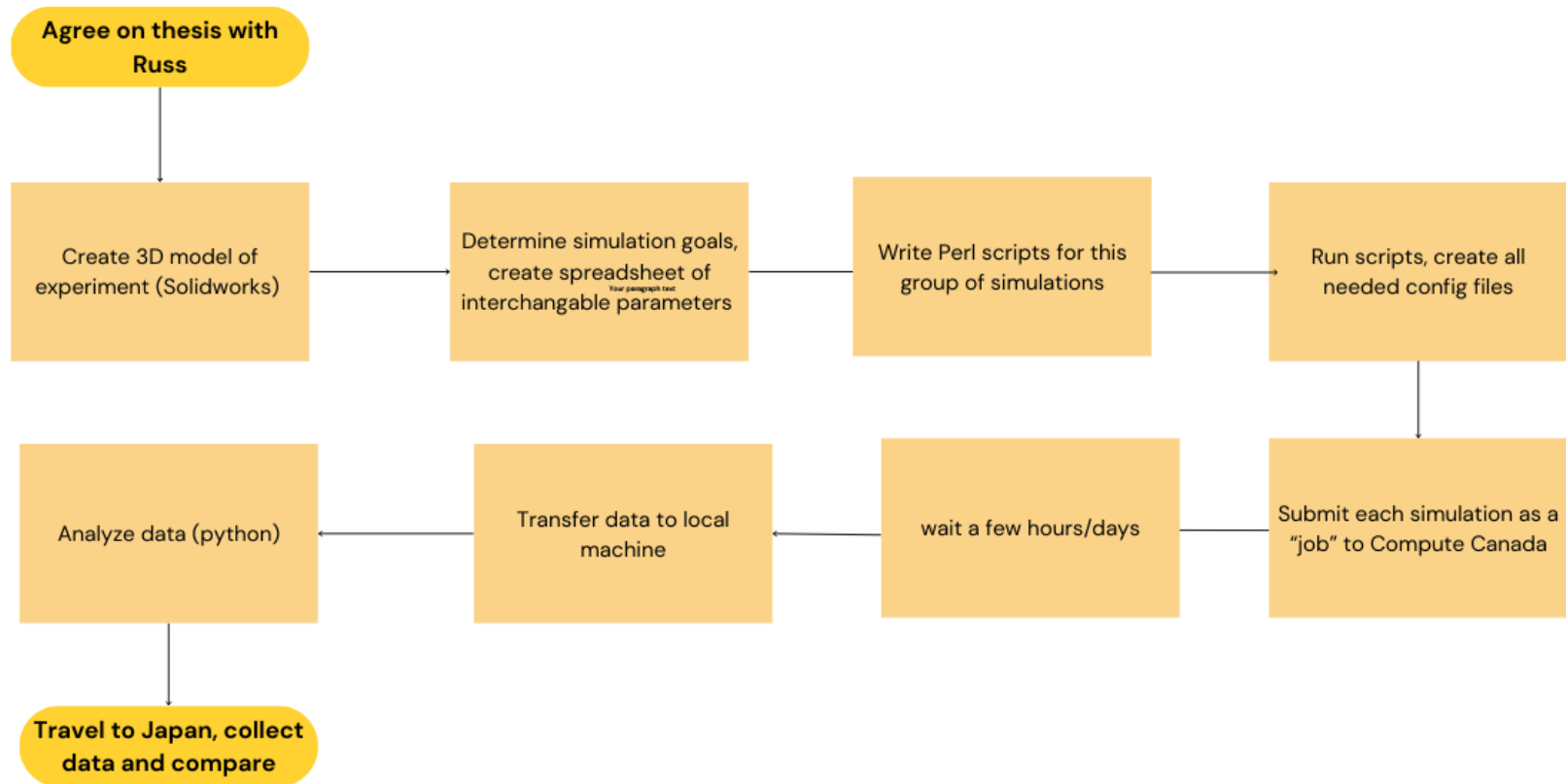
# The Story of Our Universe

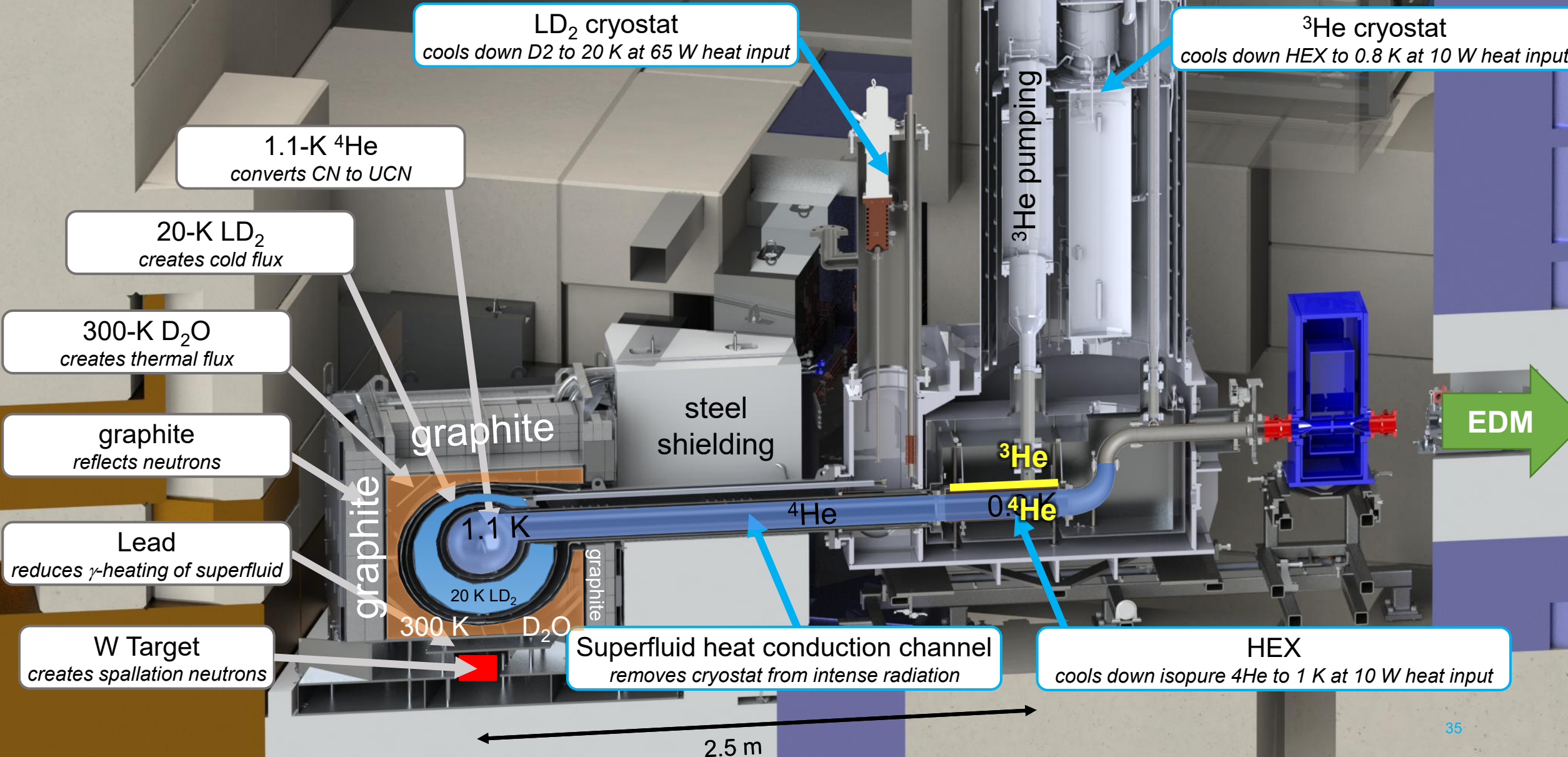


What Happened to all the antimatter?????

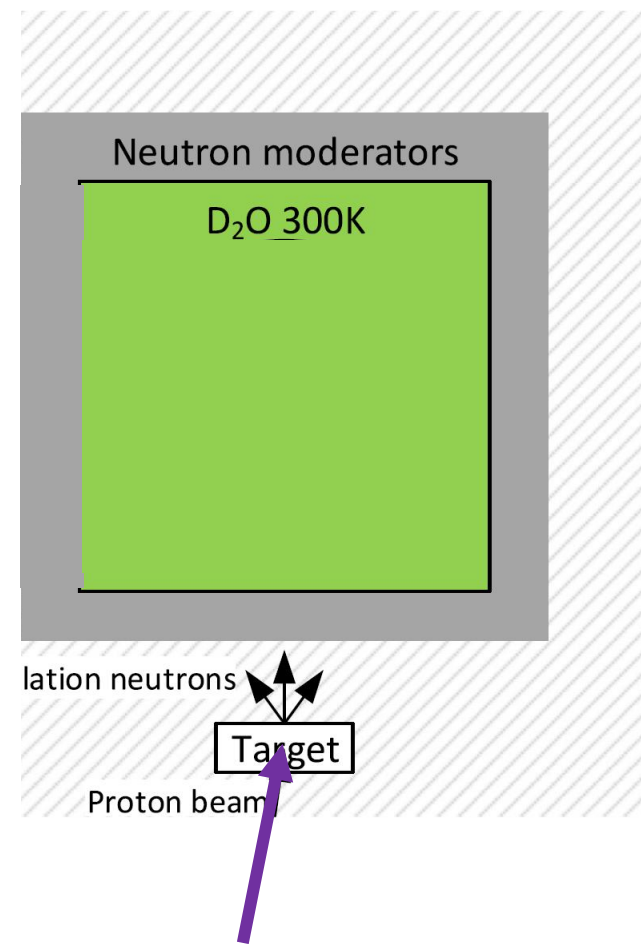
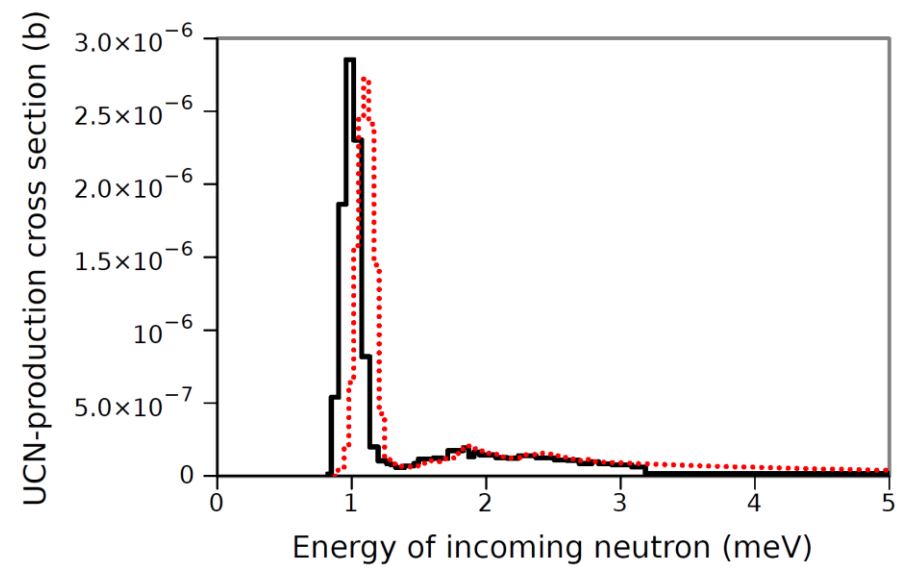
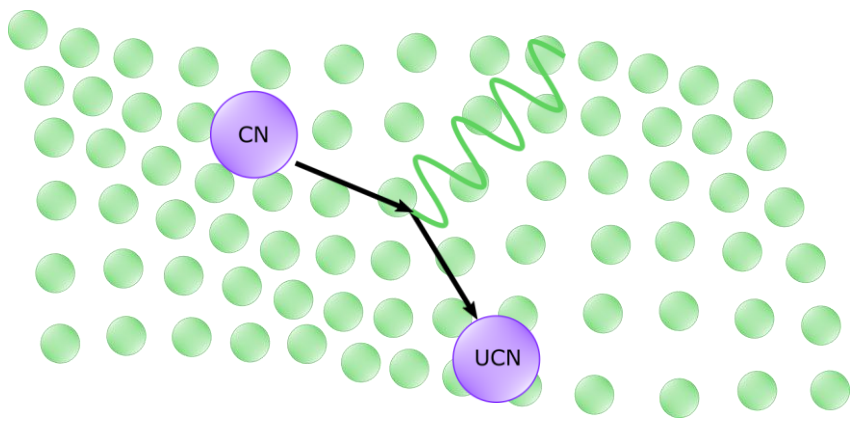
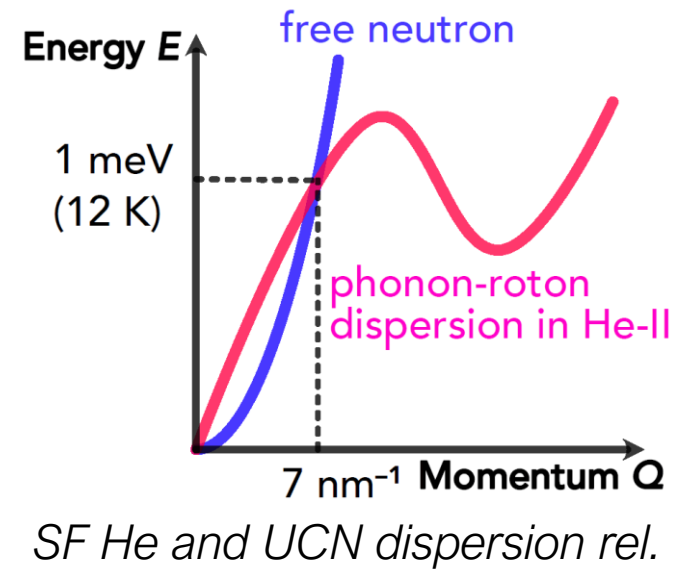
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# Thesis Workflow





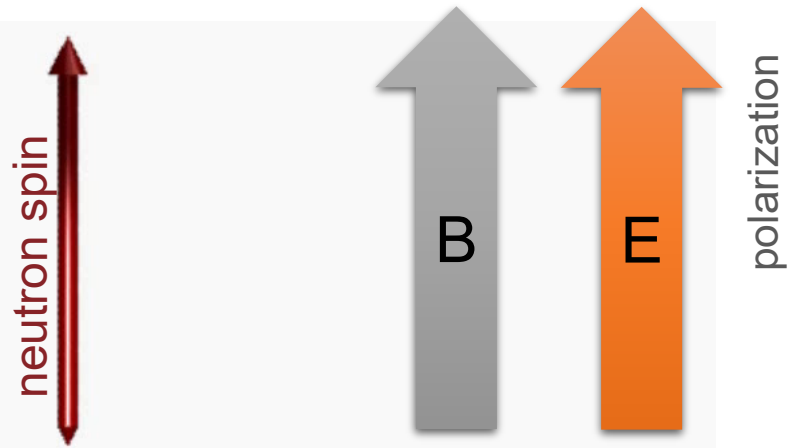
1. **480 MeV protons** on tungsten create **spallation neutrons**
2. lead, graphite and **heavy water** moderate fast neutrons (MeV) to thermal neutrons (25 meV)
3. **liquid deuterium** at 20 K moderates further to create a **large cold flux** (1 meV)
4. **<sup>4</sup>He** at around 1 K **converts** 1 meV (9Å) neutrons **to UCN** (< 215 neV)



*UCN production cross section*

E. Korobkina, R. Golub, B.W. Wehring, and A.R. Young. Physics Letters A, 301(5):462 - 469, 2002.  
P. Schmidt-Wellenburg, et al. Phys. Rev. C, 92:024004, Aug 2015.

N. F. Ramsey, Phys.Rev.76 996 (1949) ⇒ Nobel Prize 1989



1. prepare a sample of **polarized neutrons**
2. make a 90° spin flip (“**start clock**”)
3. allow **free spin precession** in static, parallel **B** and **E** fields
4. make another 90° spin flip (“**stop clock**”) in phase with first
5. Projection of neutron spin on **B** field vector ⇒ polarization



- Ramsey method enables frequency determination through polarization measurement.
- The key is to separate the two spin flips and give the spin enough time to pick up additional phase.

$$P = \frac{N_{\downarrow} - N_{\uparrow}}{N_{\downarrow} + N_{\uparrow}}$$

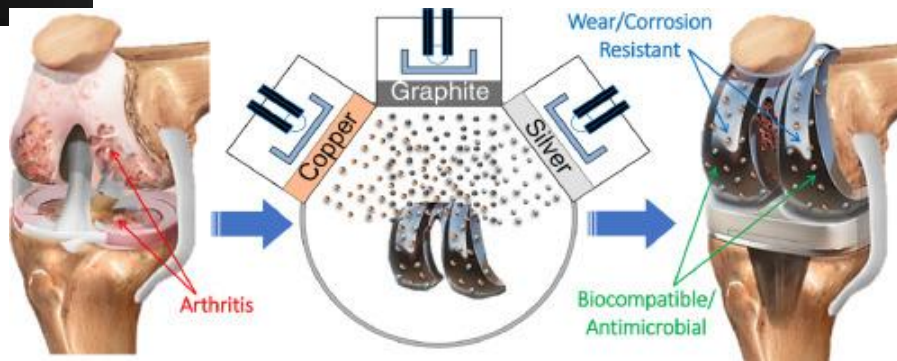
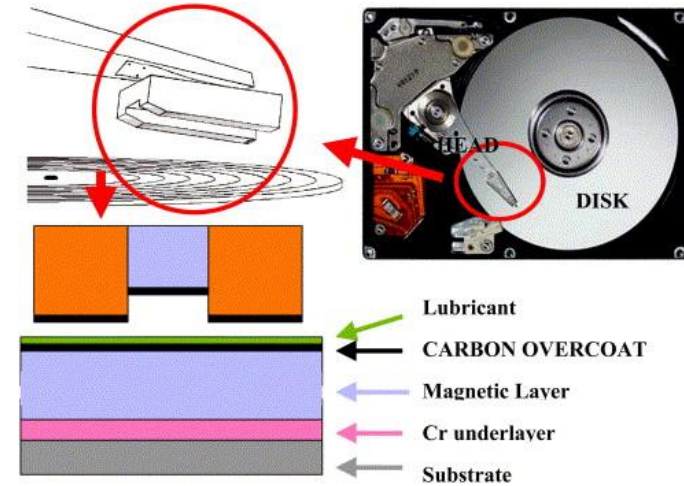
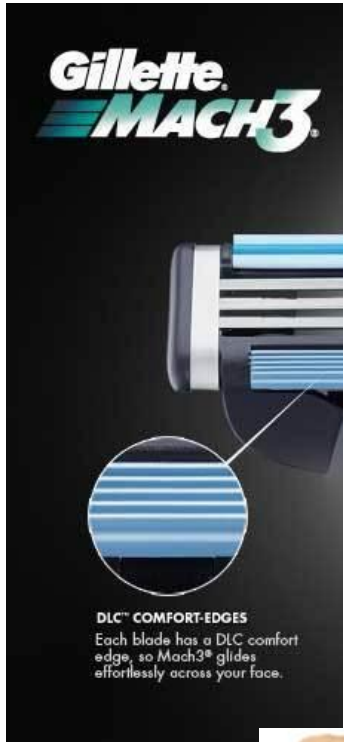
6. **Flip E field and repeat**

$$\Delta \varepsilon = h |\Delta \nu| = 4Ed_n$$

# Future UCN guides

- Each individual UW DLC guide must be tested on its own before being installed in the experiment at TRIUMF
- These simulations can be used to test all future UW guides at the JPARC UCN source
  - Workflow can also be adapted to TRIUMF UCN source, once it is producing UCN (hopefully in July!)
- **Need a picture in here**

# DLC in Industry



materialstoday

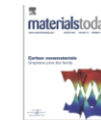
Volume 10, Issues 1–2, January–February 2007, Pages 44–53

Review

## Diamond-like carbon for data and beer storage

Cinzia Casiraghi ✉, John Robertson, Andrea C. Ferrari ✉

Show more ▾



# Benchmarking Goals

- Simulate simple storage experiment
- Analyze data statistically and analytically, comparing results to give us confidence in PENTrack simulations
- Develop a PENTrack workflow that can essentially be mirrored onto the JPARC experiment

# A General Simulation Workflow

- Specify material parameters which you want to vary
- Create a configuration file template and a corresponding batch file template
- Create a configuration generator file, that loops through desired material parameters and runs a unique simulation for each specified option – perl scripting
- Run simulations and analyze data – python scripts

# Analysis and Results

- Simulated 20,000 UCN, uniform angular and energy distribution
  - $W$  values ranging from 0.01 – 0.1 neV (0.01 neV steps)
- Statistical analysis compared with analytical model based on the kinetic theory of gas applied to UCNs
- Scripts developed to run from command line, so analysis can be done on Compute Canada servers if desired

# Templates, Scripting and Analysis

- All relevant templates have been created
- I must determine the desired material parameters to input
  - Need to determine what ranges of non DLC components I need to vary to inform error bars in the experiment
  - Consulting Sean Vanbergen (TRIUMF) next Monday
- Run simulations once this is completed (next two weeks)
- Analysis only requires minor tweaks from benchmarking analysis

# Identifying PENTrack issues

- I found that the micro-roughness diffuse scattering model was not working properly in PENTrack
  - I switched to Lambert scattering for my benchmarking
- I consulted Wolfgang Schreyer who identified this as a key issue that he must fix in the PENTrack software package