TUCAN

TRIUMF Ultra Cold Advanced Neutron Collaboration

THE UNIVERSITY OF WINNIPEG

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

Thomas Hepworth

for the TUCAN collaboration

CAP Congress 2025, June 10th

thomashepworth12@gmail.com

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

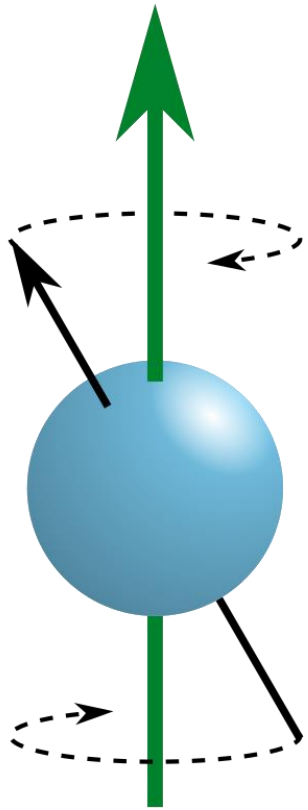
3. Discuss experiments to determine the material properties of DLC produced at UWinnipeg

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

- 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 $*10^{-26}$ $e \cdot cm$ (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?

- **U**ltra**c**old **N**eutrons: Neutrons moving at 5 – 14 m/s
  - Temperature of < 0.004 K --- COLD
  - Move so slowly they can bounce of surfaces – and be stored!
  - E < 350 neV

- Interactions of UCN with all the fundamental forces of Nature:
  - Gravity: $V = mgh$ = 100 neV/m
  - Magnetic: $V = -\mu \cdot B$ μ = 60 neV/T
  - Strong: $V = V_{eff}$ $V_{eff} < 335$ neV
  - Weak: $\tau_n = 886$ s = 15 mins.

- The ability to study a population of UCN for 100s of sec → excellent for EDM search!

A Global History of nEDM measurements

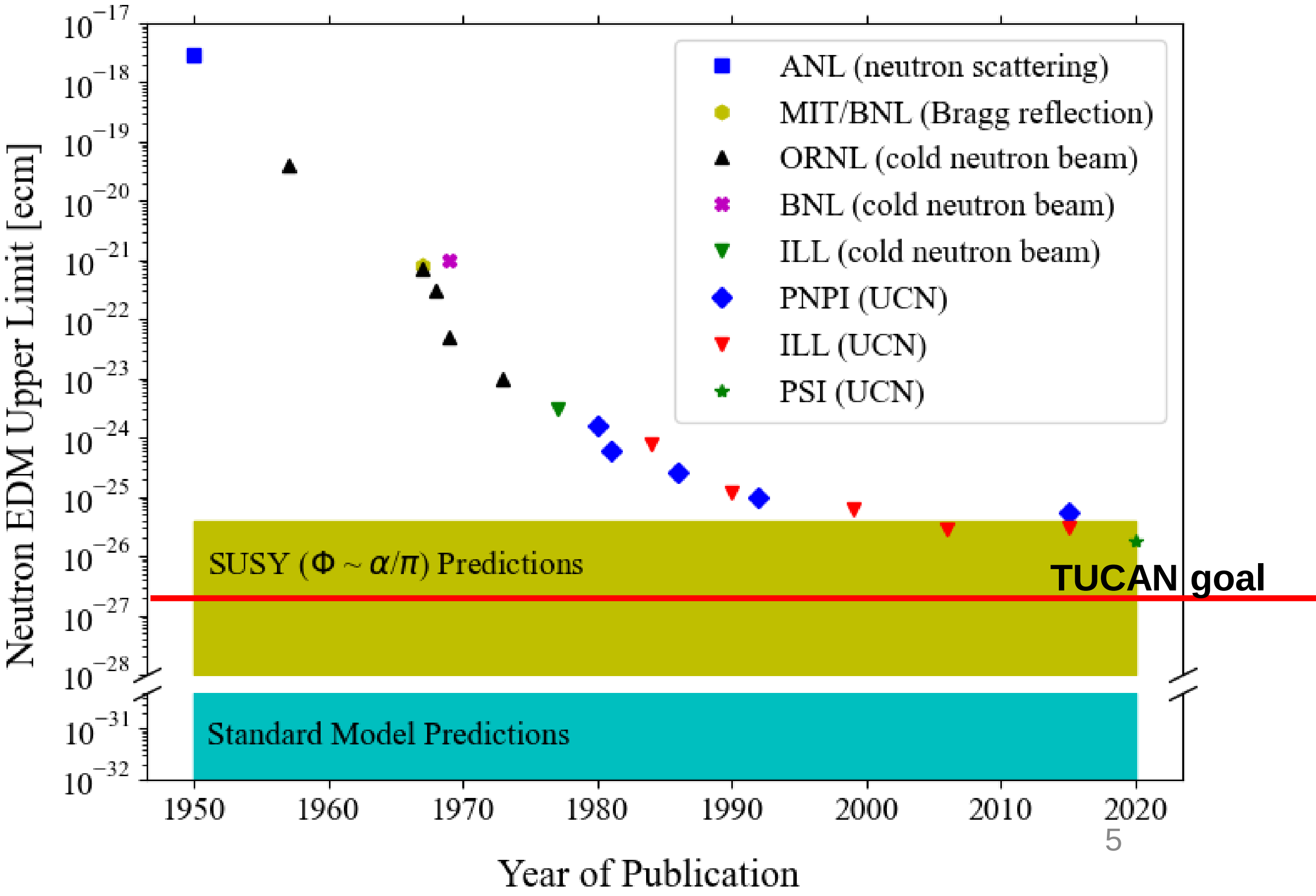
- Modern experiments are limited by the number of UCN they store (statistics)

- How do you increase statistics?
  - Powerful UCN sources
  - Maximally efficient UCN transport

- Statistical uncertainty:

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

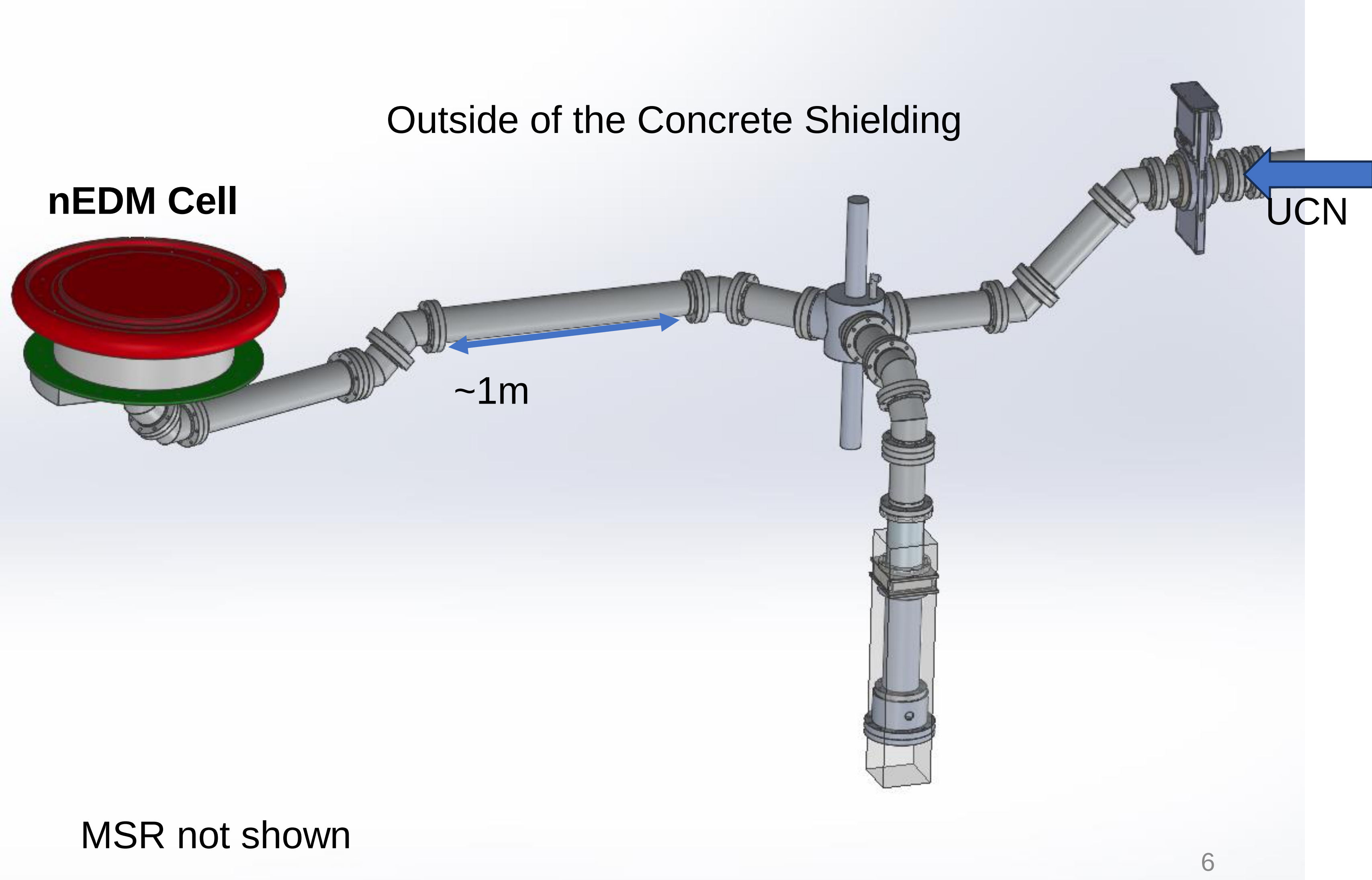
  - Many polarized UCN needed for precision measurements



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:

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

Material Potential:

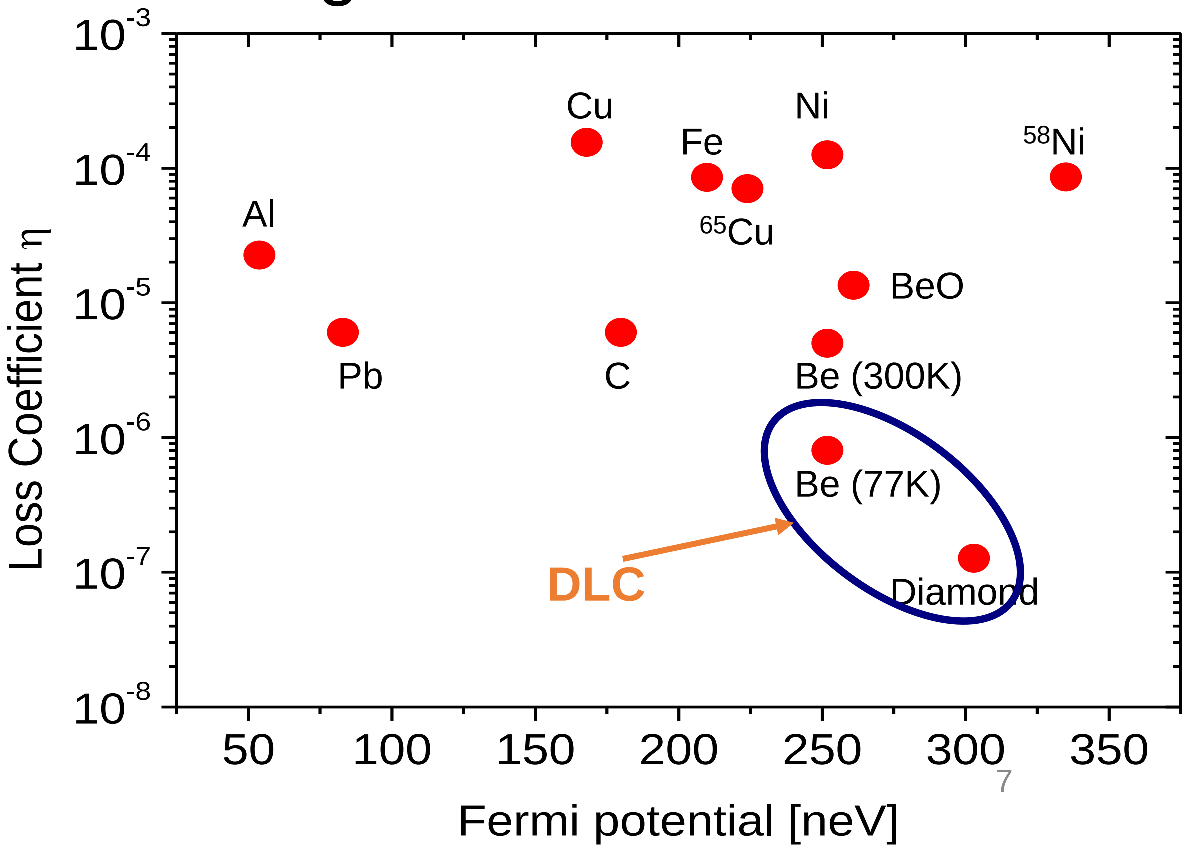
$$V = \frac{2\pi\hbar^2}{m} Nb$$

Maximum energy of stored UCN

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

V → CN Reflectometry

W → Storage Experiments



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_{DLC}

- Compare UCN in vs UCN out → understand UCN losses

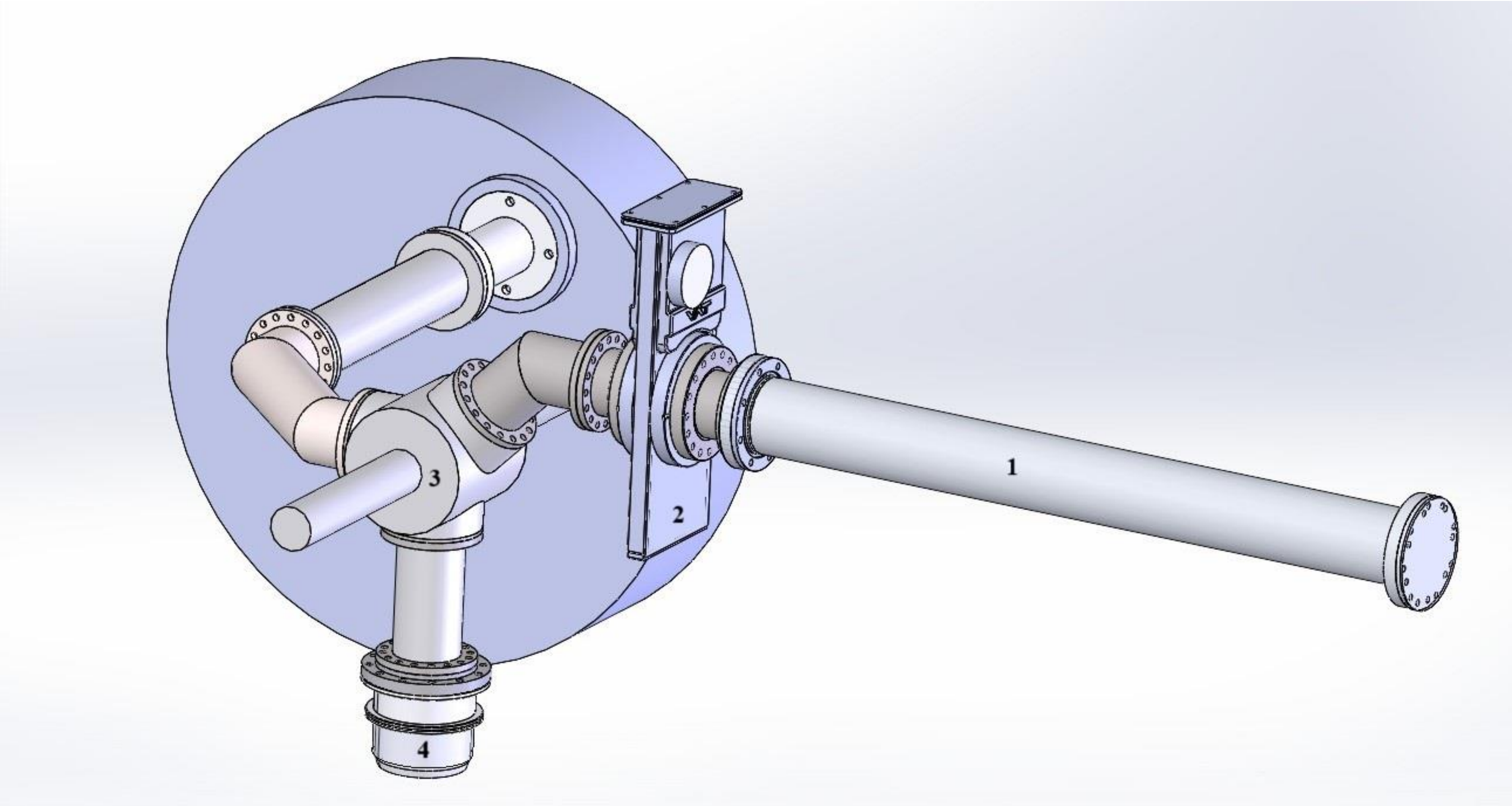
UCN Storage Experiment at JPARC

1: 1m long test guide

2: VAT Valve

3: Rotary Valve

4: Dunia 3He UCN detector



3D model of the experiment

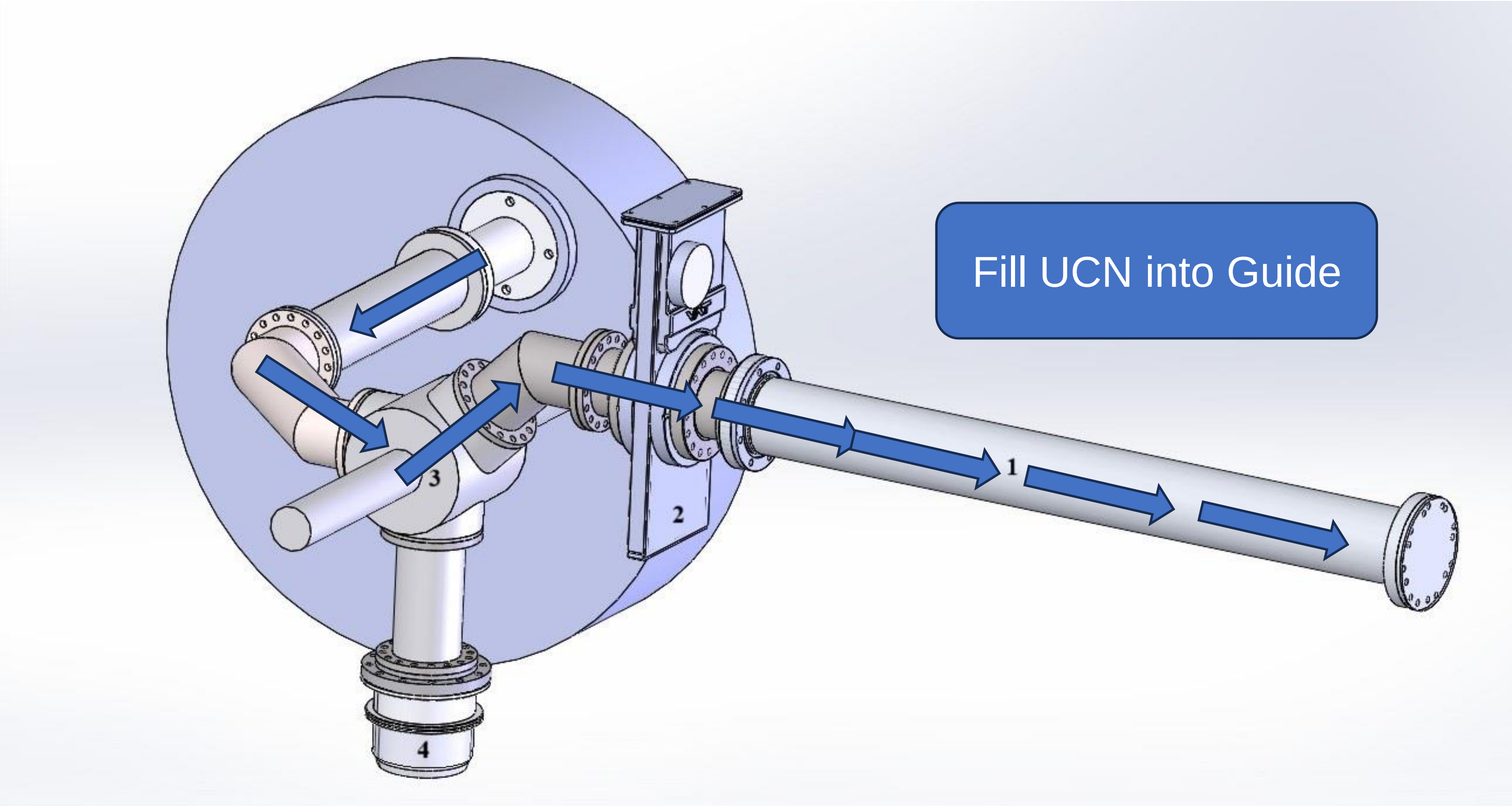
UCN Storage Experiment at JPARC

1: 1m long test guide

2: VAT Valve

3: Rotary Valve

4: Dunia 3He UCN detector



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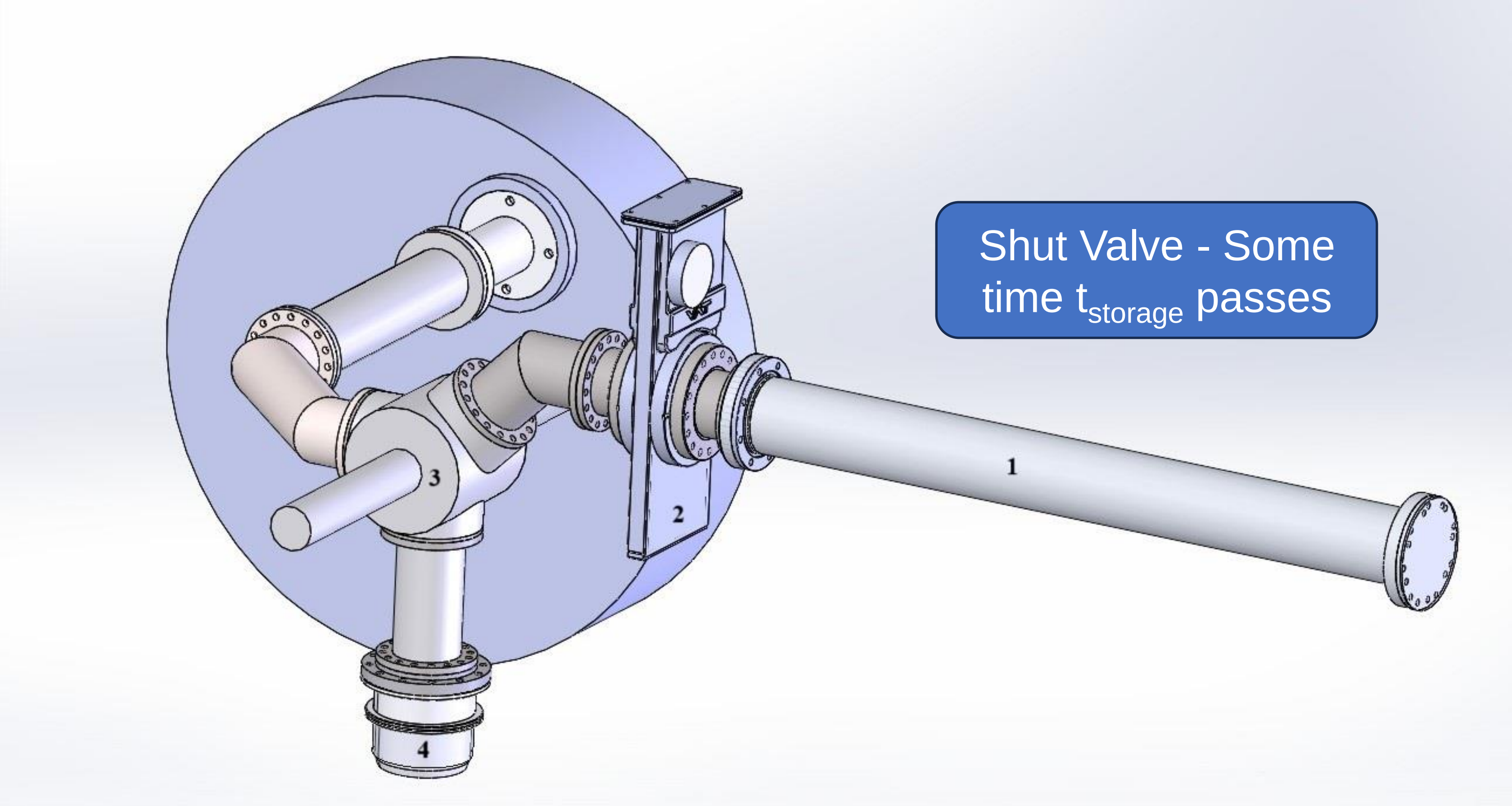

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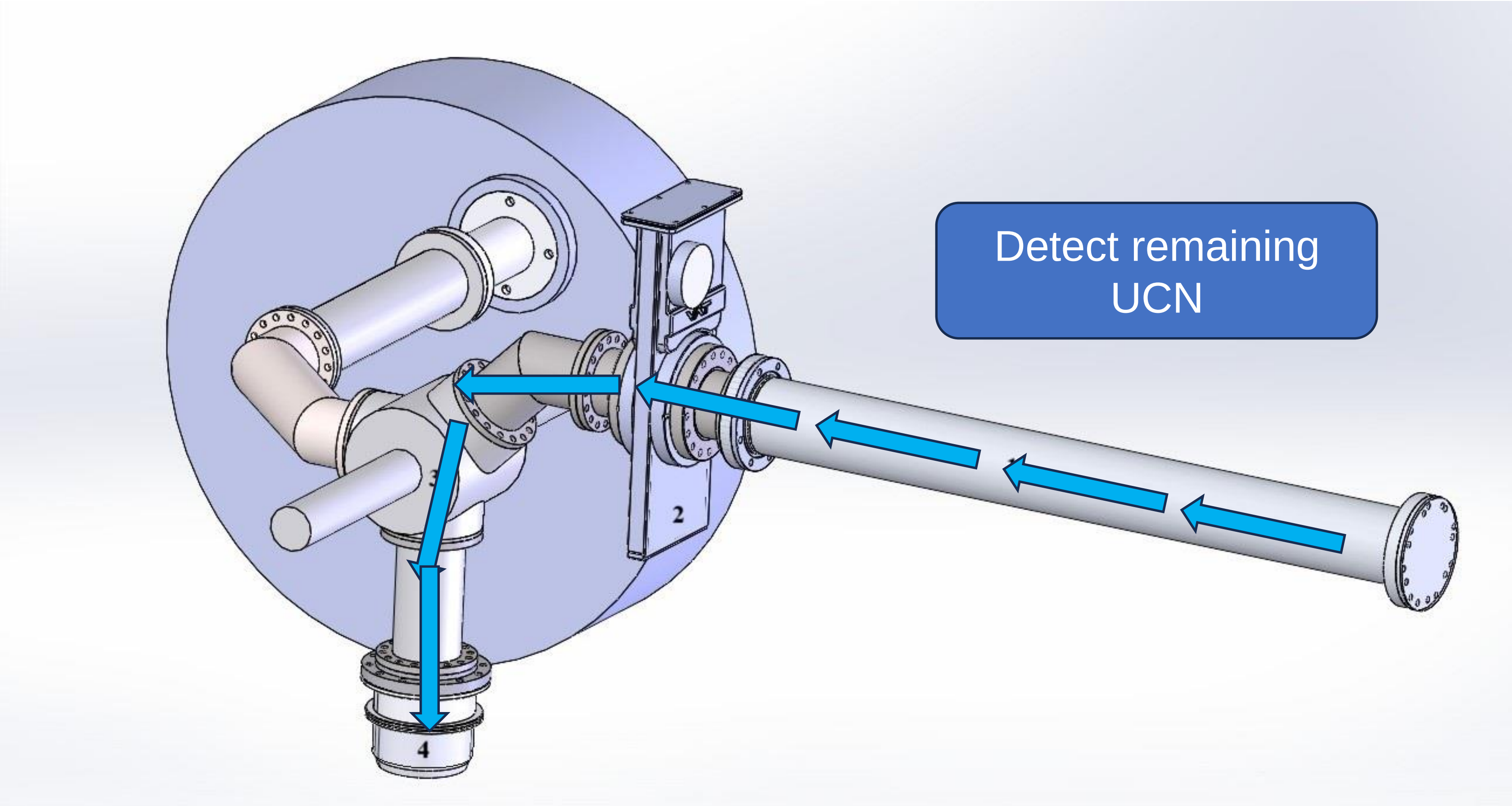


3D model of the experiment

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}, λ_i) parameter space

Other params of secondary interest

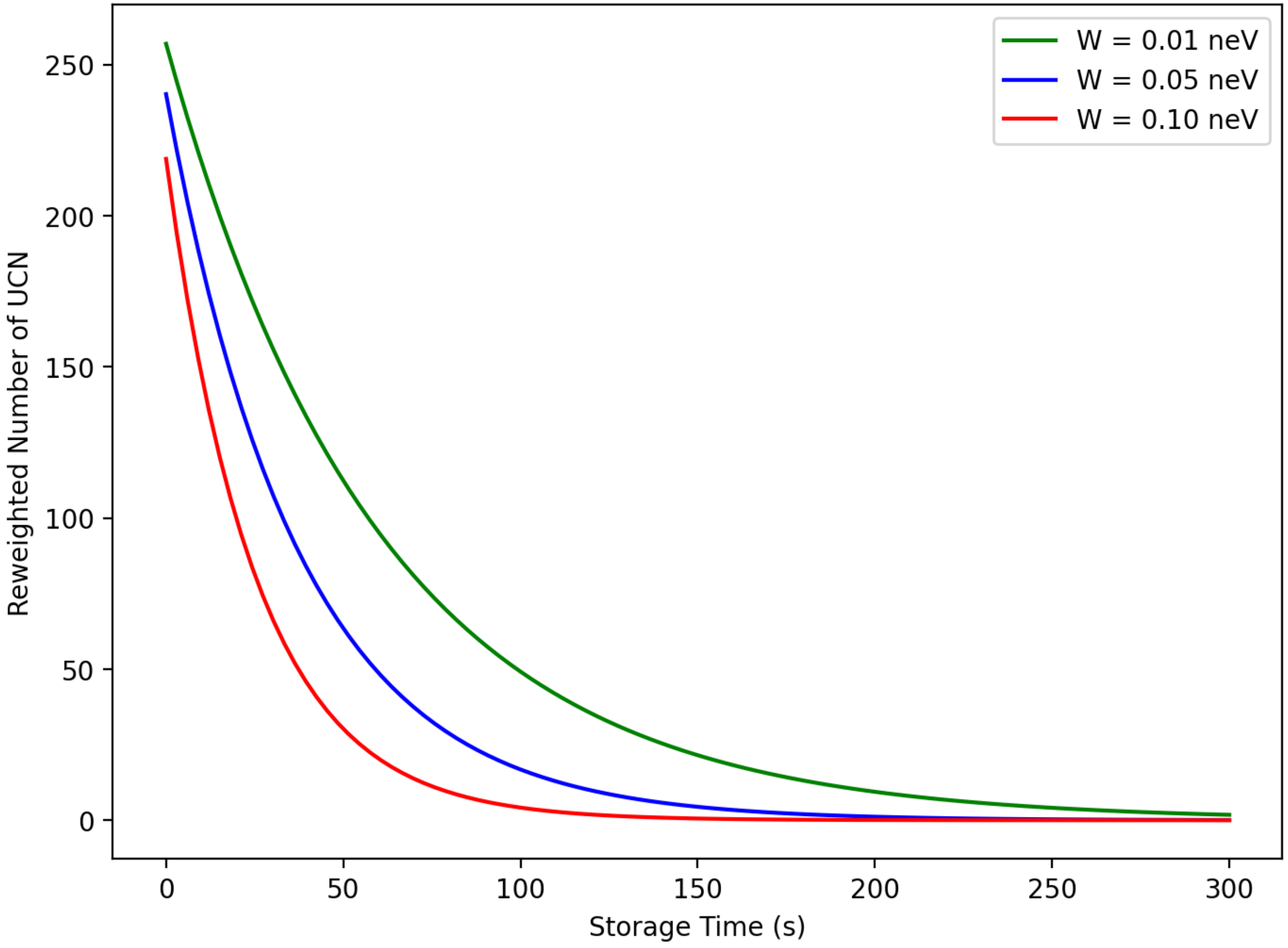
```
########################################################################
###                      Welcome to PENTrack,                        ###
### a simulation tool for ultracold neutrons, protons and electrons ###
########################################################################
```

J-PARC Simulation Goals

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

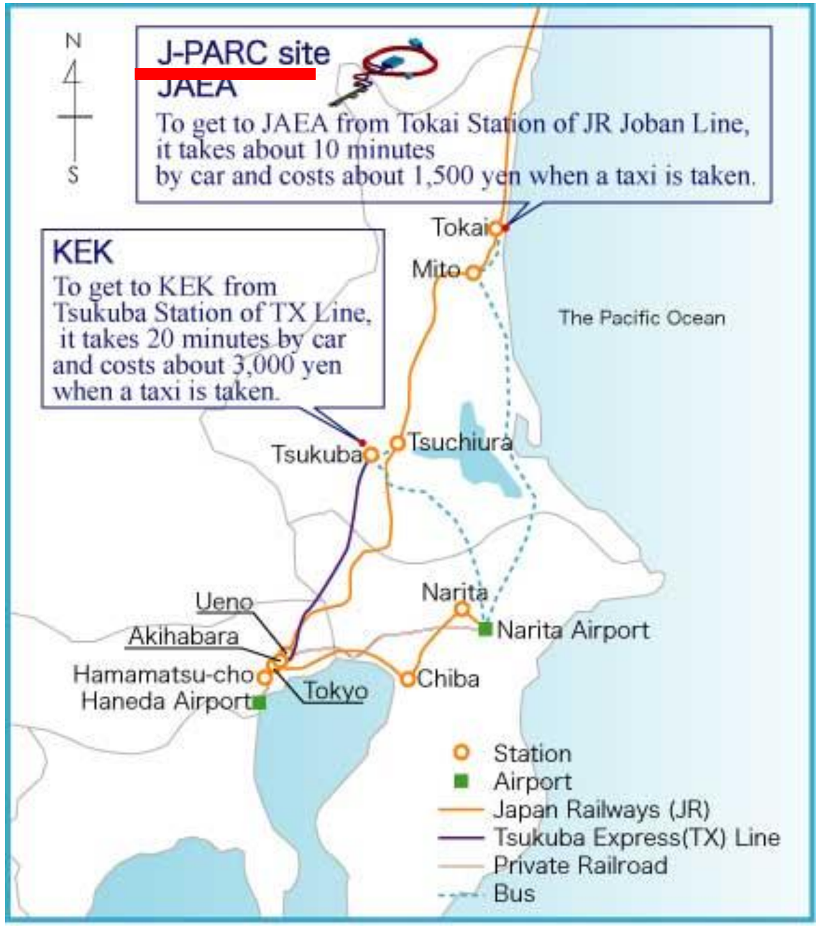
Building Our Reference Table

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



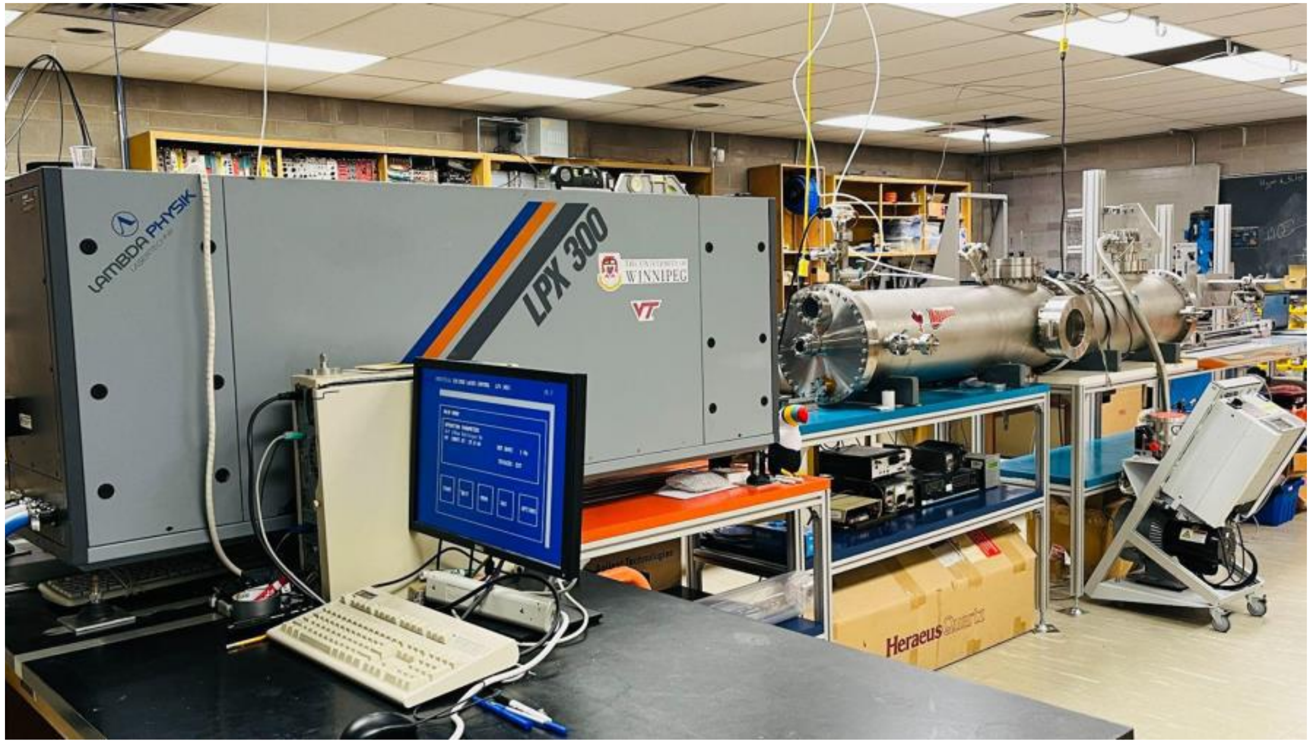
Future Work

- 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



thomashepworth12@gmail.com

Questions?



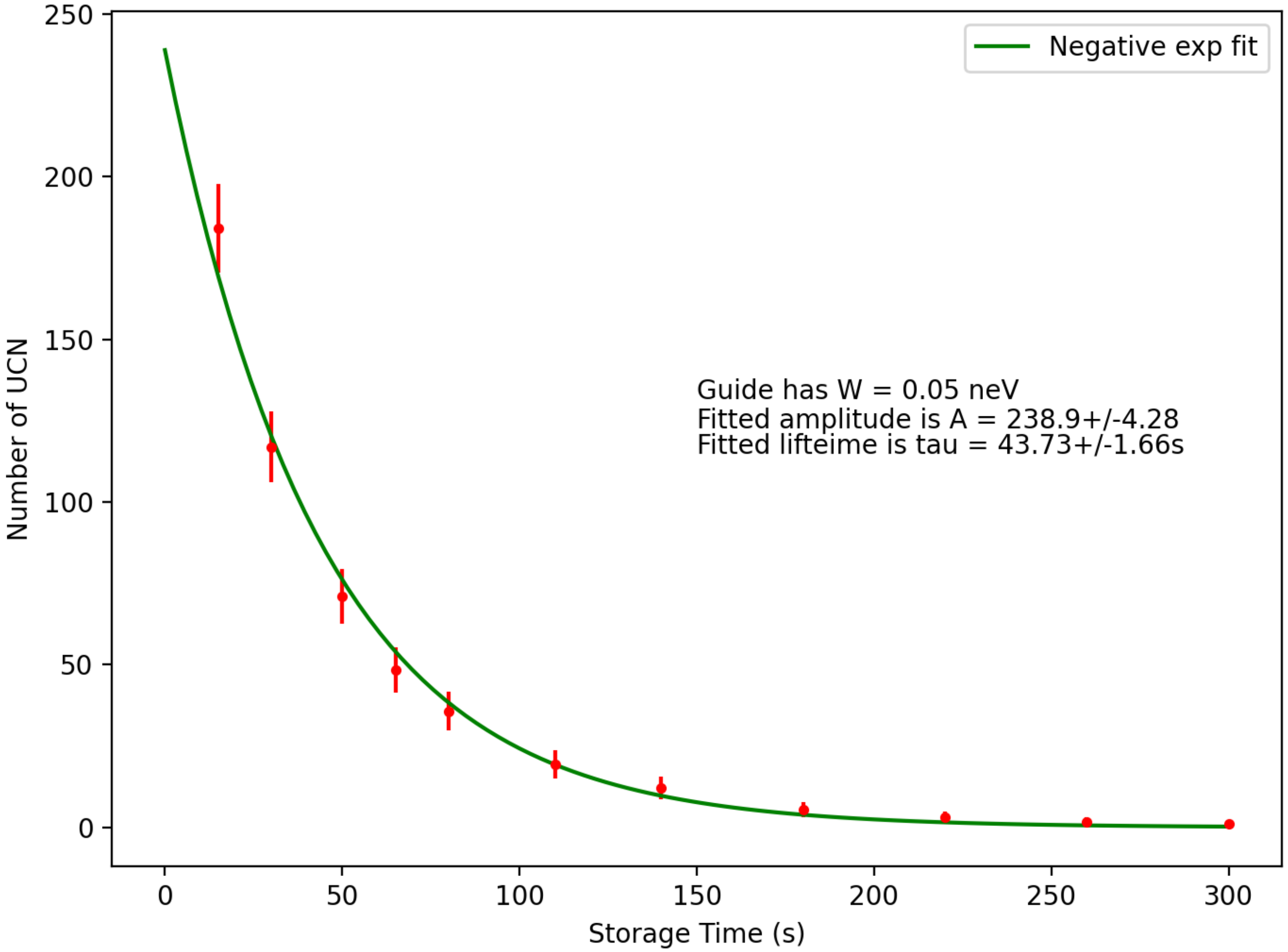
Update from
A. Brossard's Talk:

FIRST UCN EXPECTED AT TRIUMF IN MERE HOURS

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

Fig: UWinnipeg Guide Coating Facility

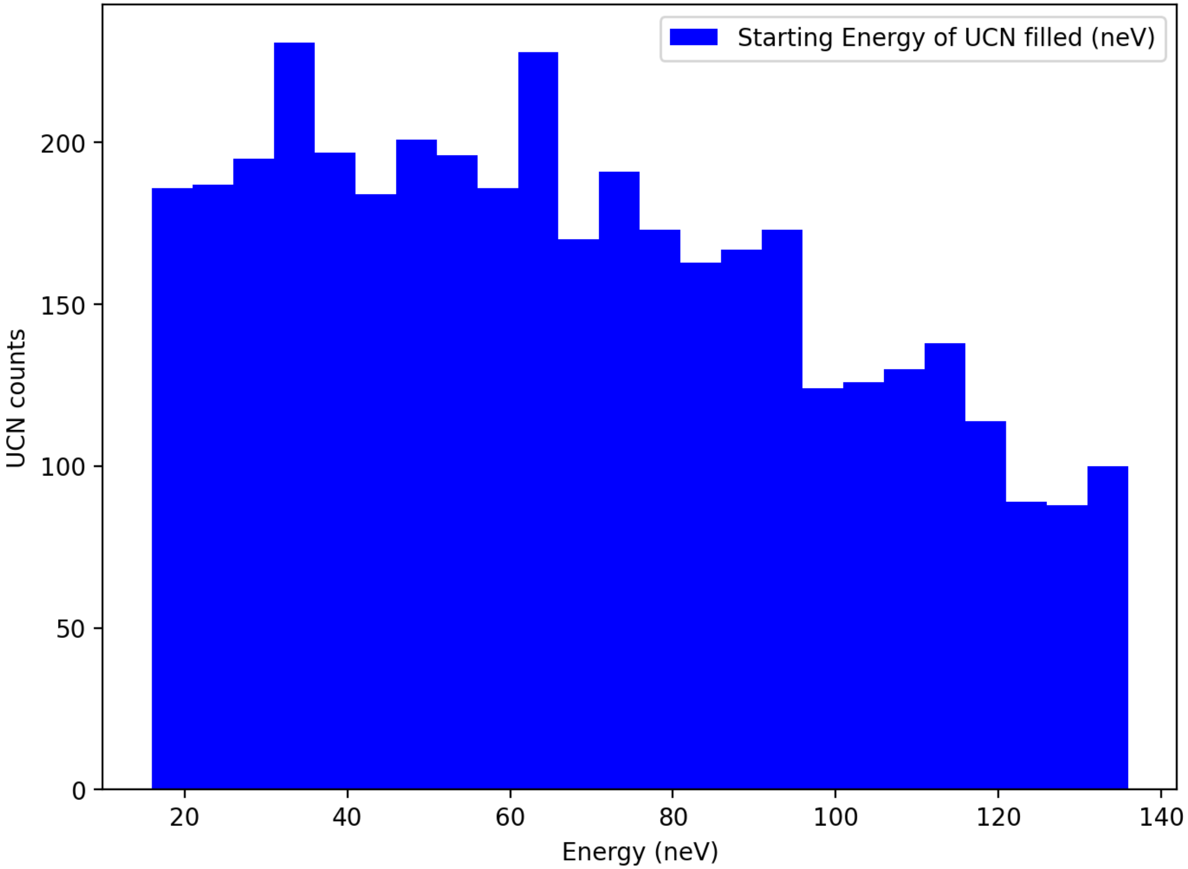
Backups

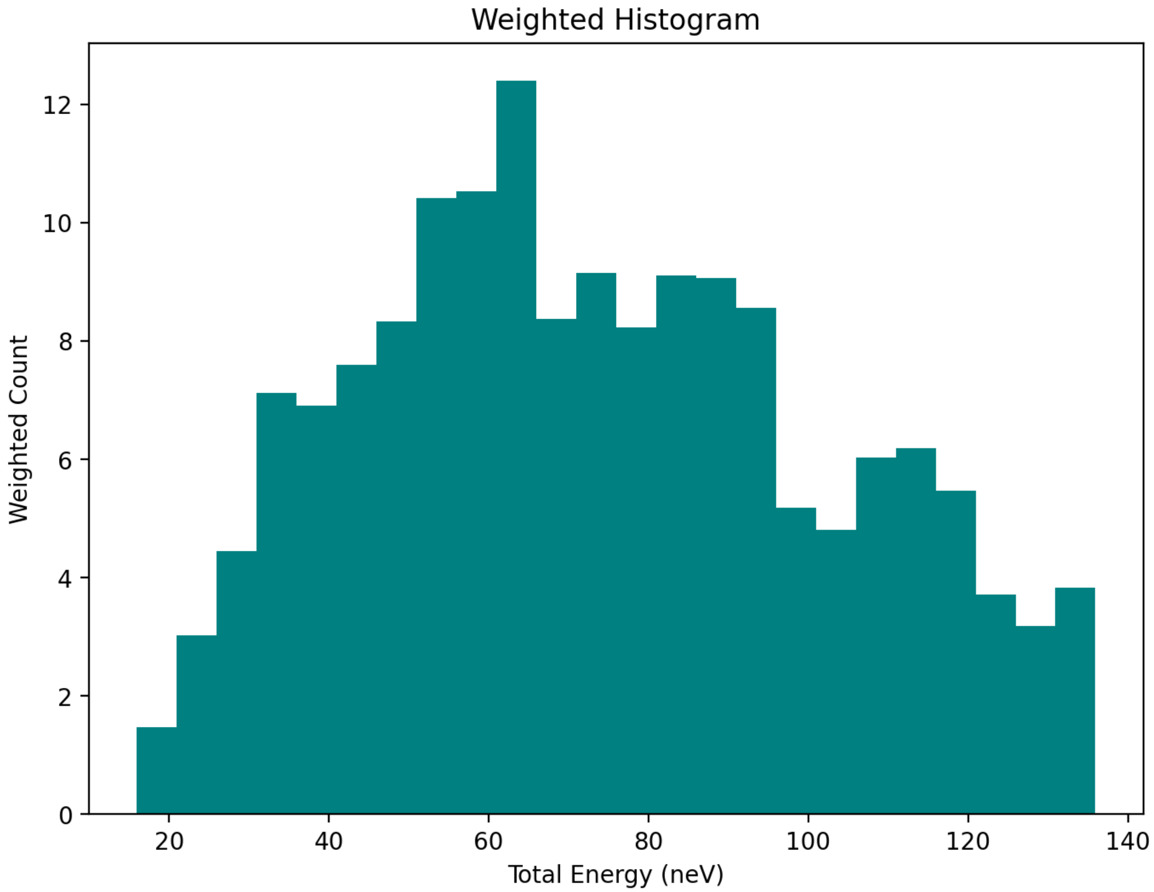

Negative exp fit
Guide has W = 0.05 neV
Fitted amplitude is A = 238.9+/-4.28
Fitted lifteime is tau = 43.73+/-1.66s
Number of UCN
Storage Time (s)
0
50
100
150
200
250
300

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:

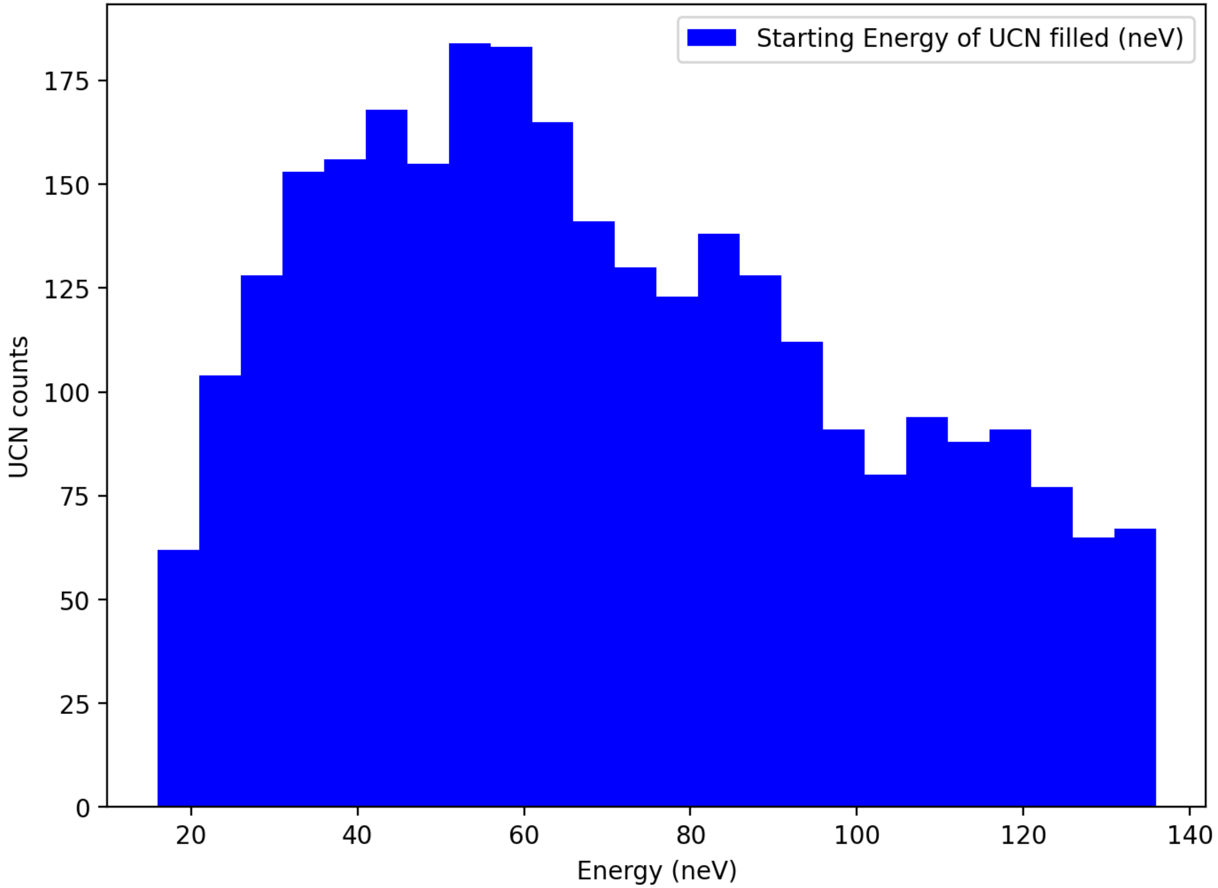




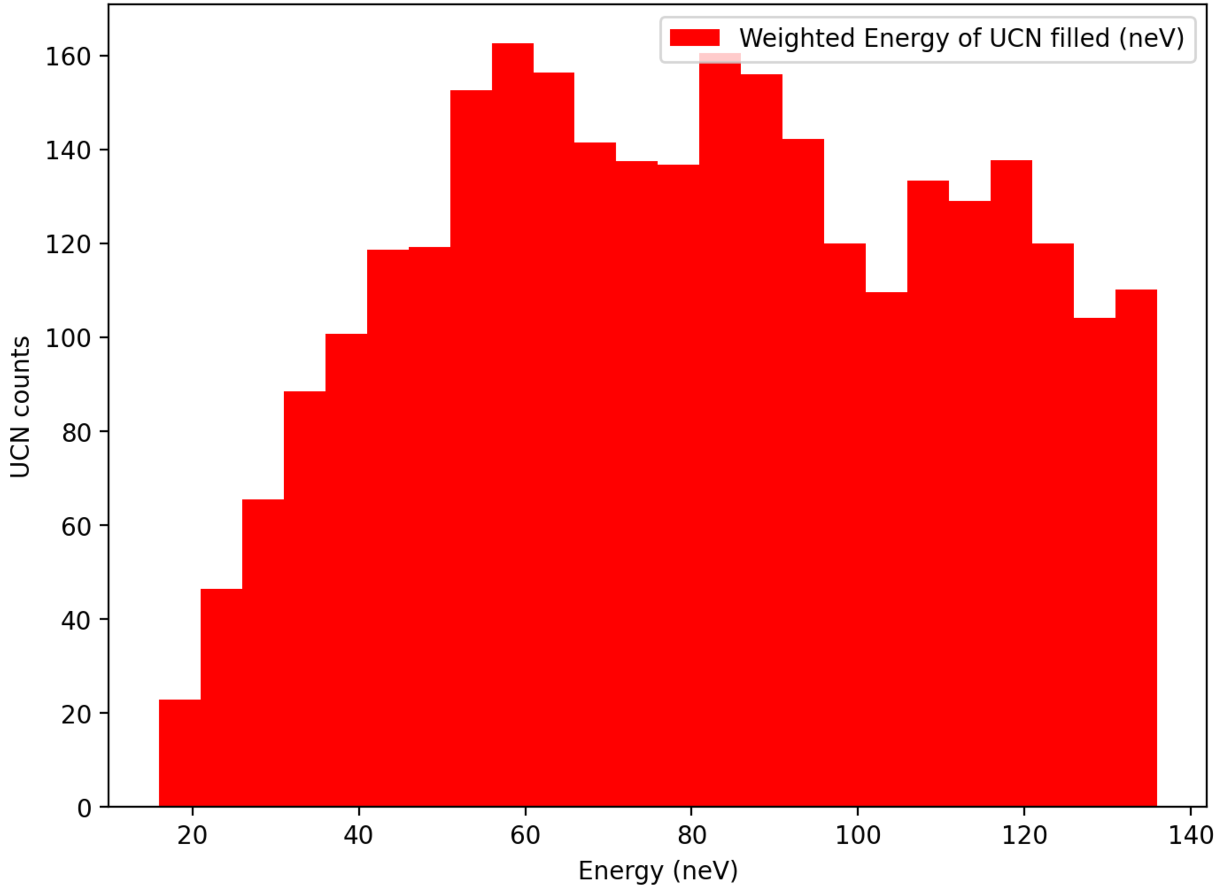
Sum the weighted counts in the plot on the right and get:

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

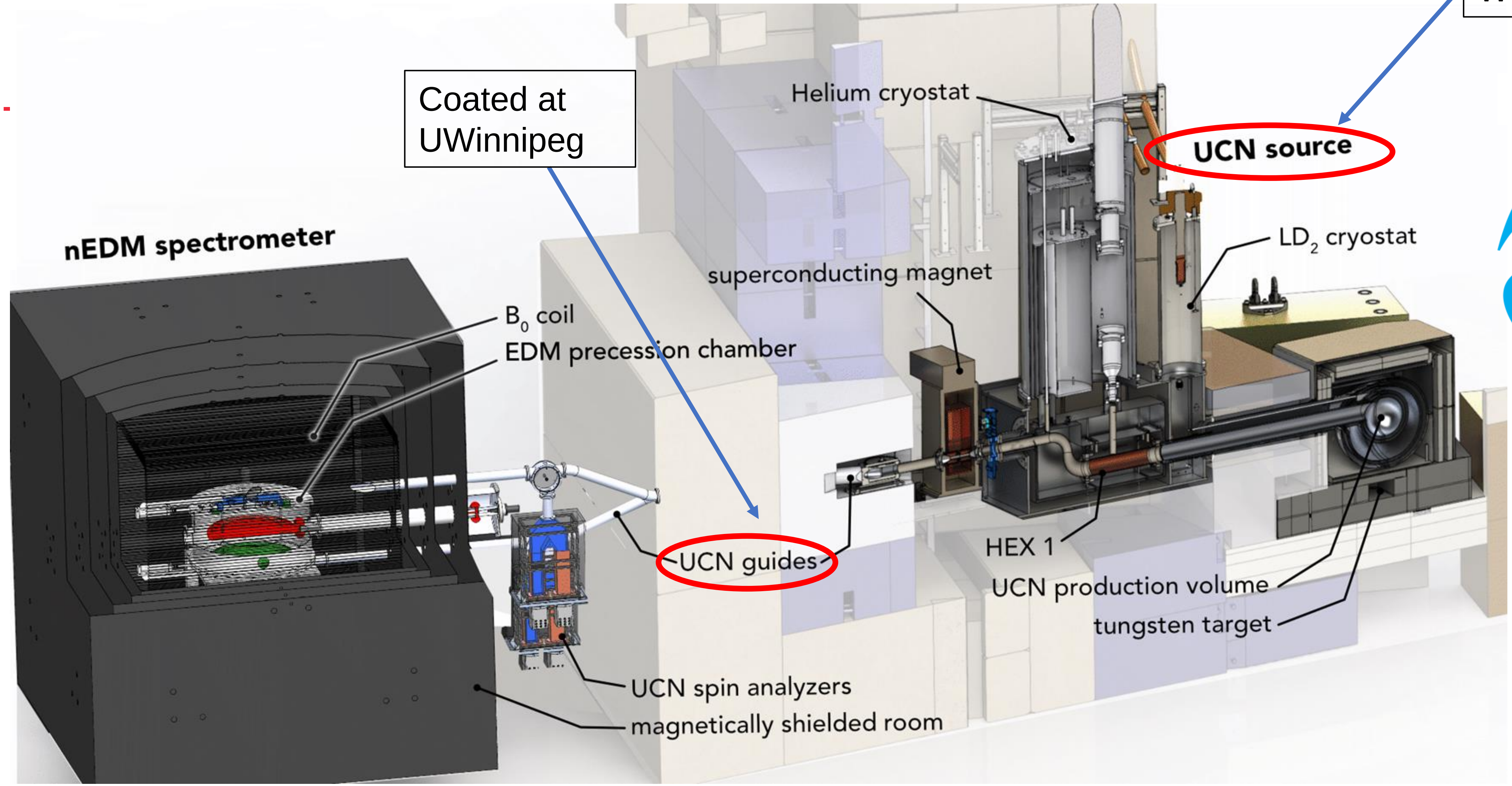
Simulation and Analysis Workflow

- PENTrack uses configuration files as inputs
  - Config files complete prescribe everything in a simulation
- I use scripts (Perl) to autonomously edit and adjust my template for each simulations (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

Coated at UWinnipeg



520 MeV Cyclotron

Key Principles of Experiment

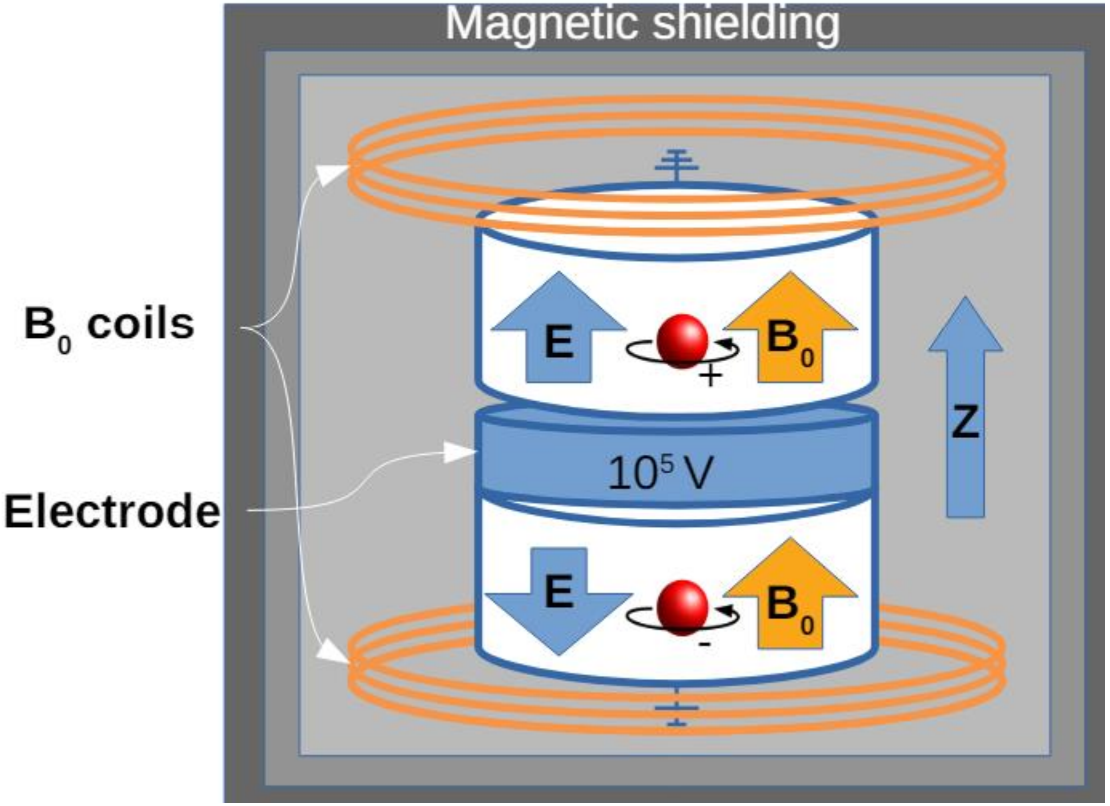
- Hamiltonian of neutron in an EM field (non-relativistic limit)

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

$\rightarrow \not{T} \rightarrow \not{CP}$

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

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



Benchmarking

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

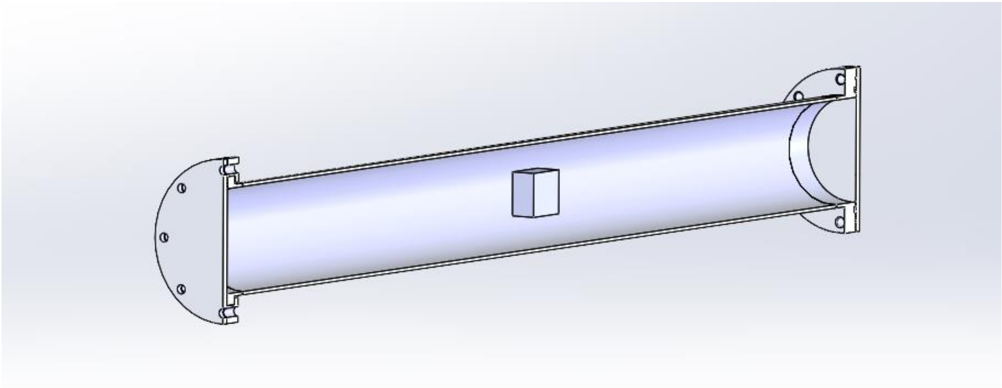
$$\tau^{-1}(H) = \frac{\sqrt{2H/m}}{4\gamma(H)} \int_a^b \frac{H - mgz}{H} \sum_i \frac{dA_i}{dz} \mu_i(H - mgz)dz + \tau_\beta^{-1}$$

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

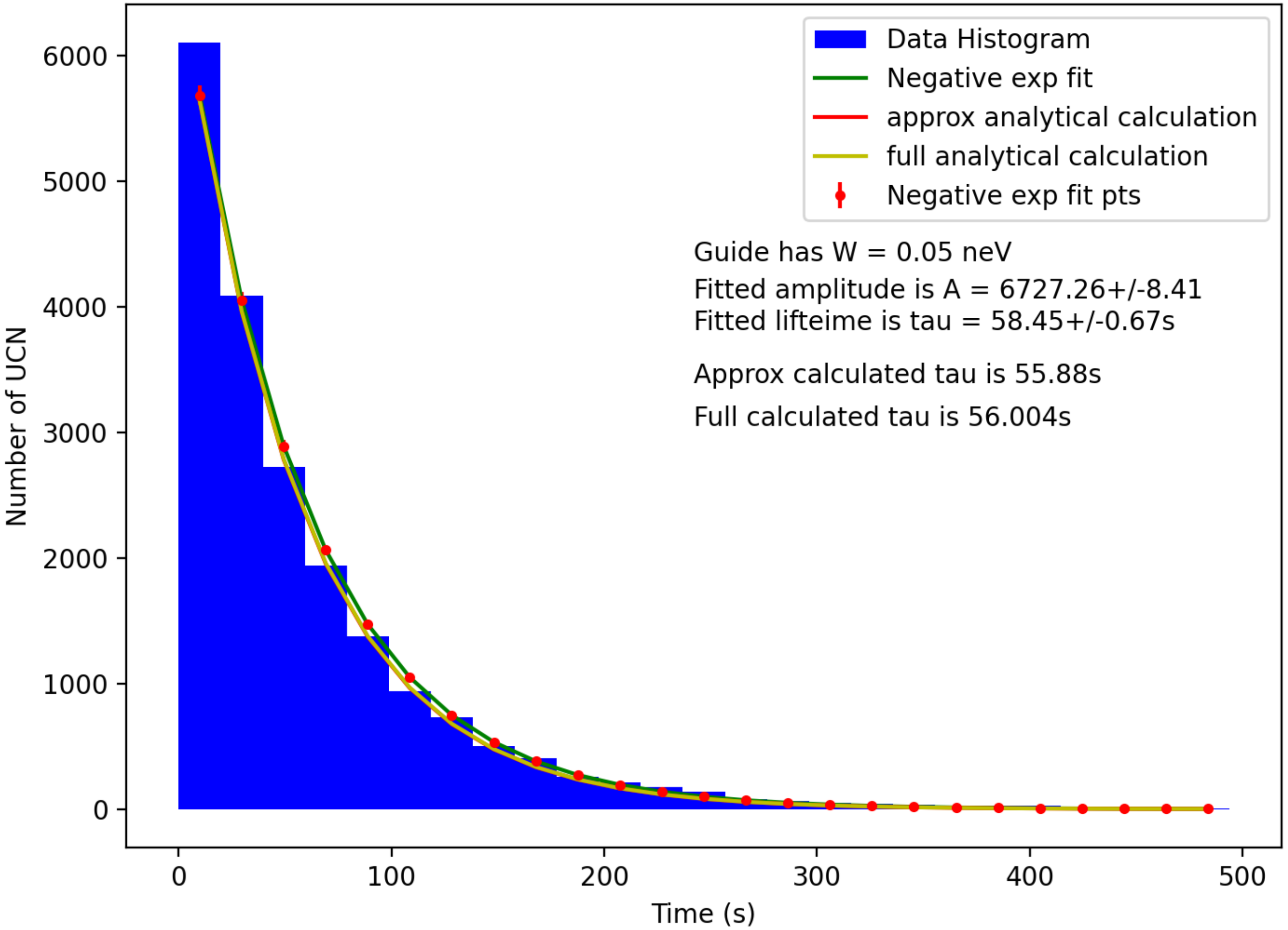
Calculate for Uniform energy spectrum

to the fit of the simulated data:

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



UCN leave cube with uniform energy and angular spectrum



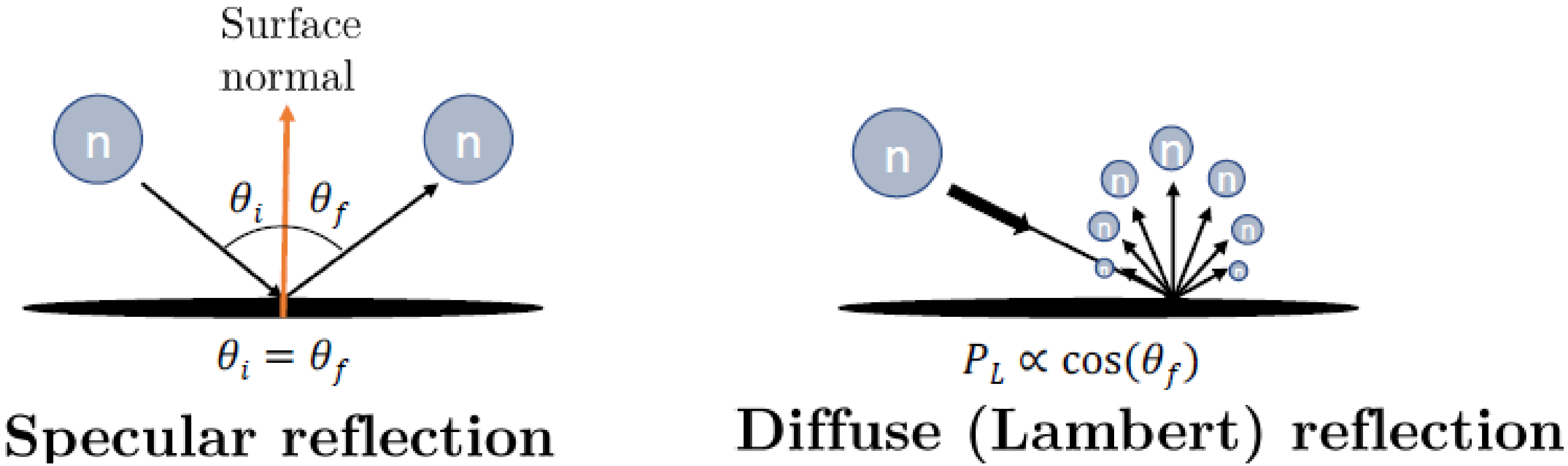
Weighted Uncertainty Calculation: Bin and Scale

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

Lambertian Scattering



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

Experimental Technique

ω: precession freq. of neutron
μ_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

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

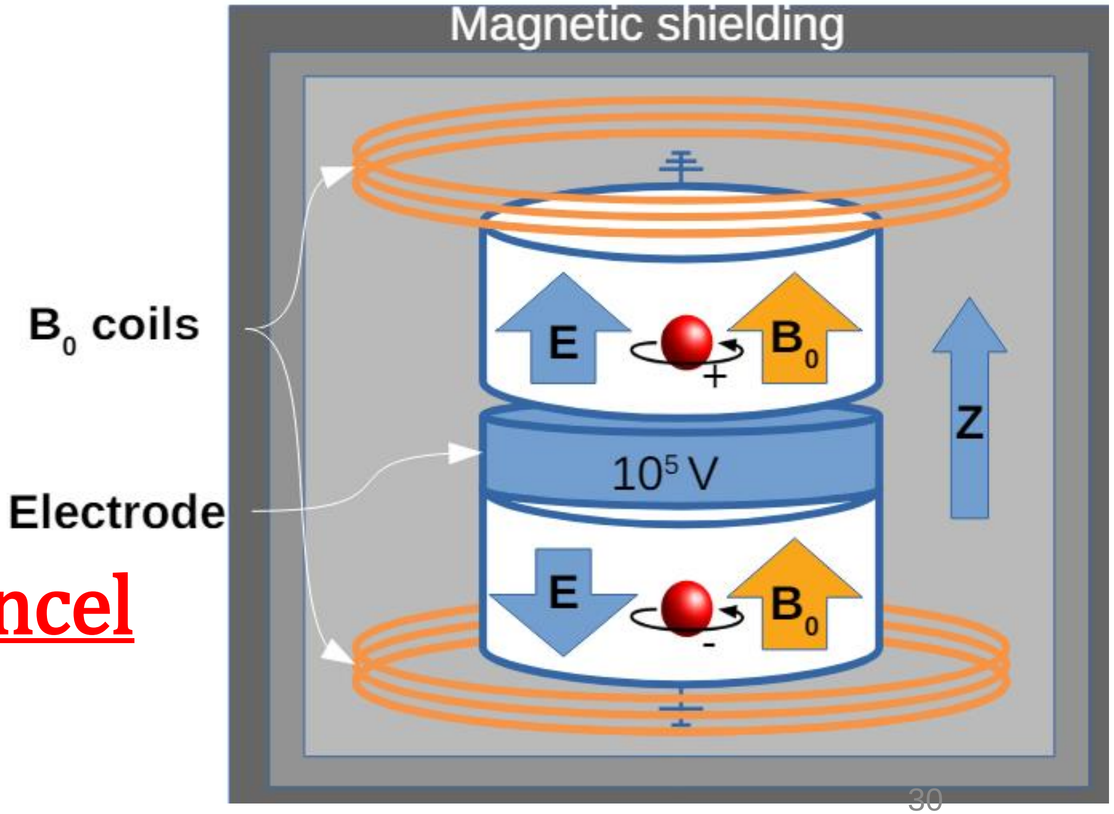
$$\hbar\omega = 2\mu_n B - 2d_n E$$

$\rightarrow$ = 0?

Subtract and we get:

$$d_{\mathrm{n}} = \frac{\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})}{4E}$$

→ **B must cancel**



EDM, CP violation, and basic technique

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

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

$\to \not{T} \to \not{CP}$

	P	T	C	CP	CPT
$\boldsymbol{\mu} \cdot \boldsymbol{B}$	+1	+1	+1	+1	+1
$d_n \cdot \boldsymbol{E}$	-1	-1	+1	−1	-1

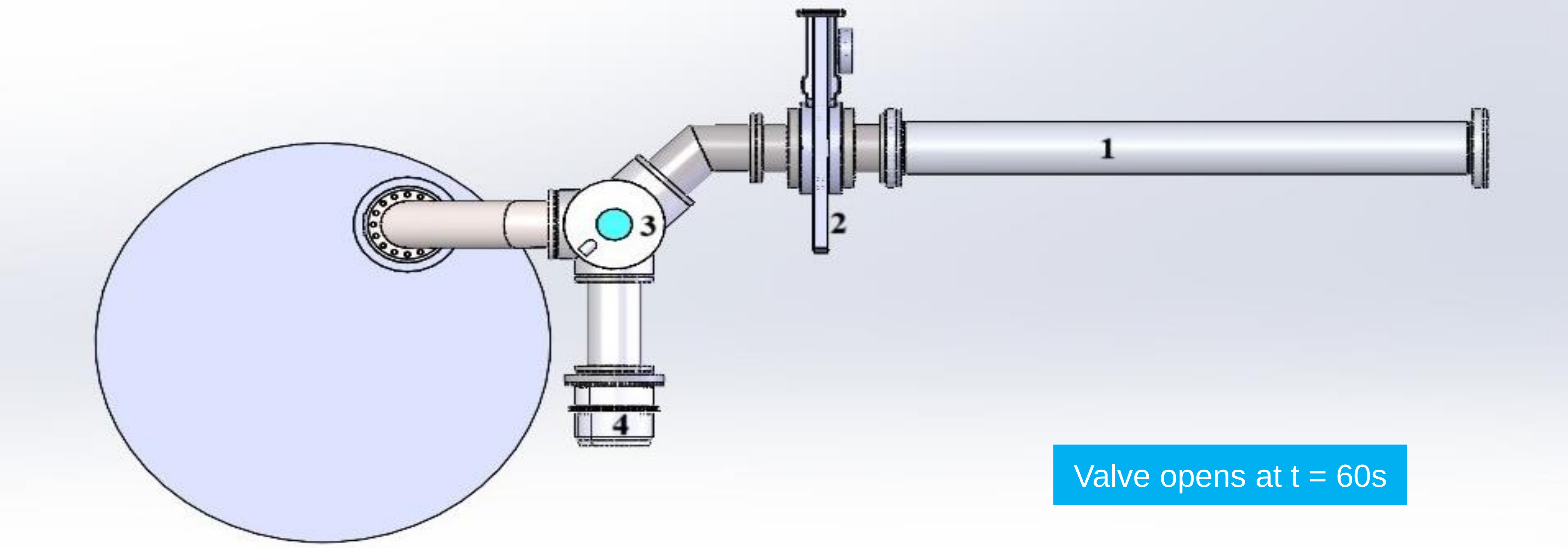
- Experiment: precise measurement of neutron spin precession frequency to determine d_n

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

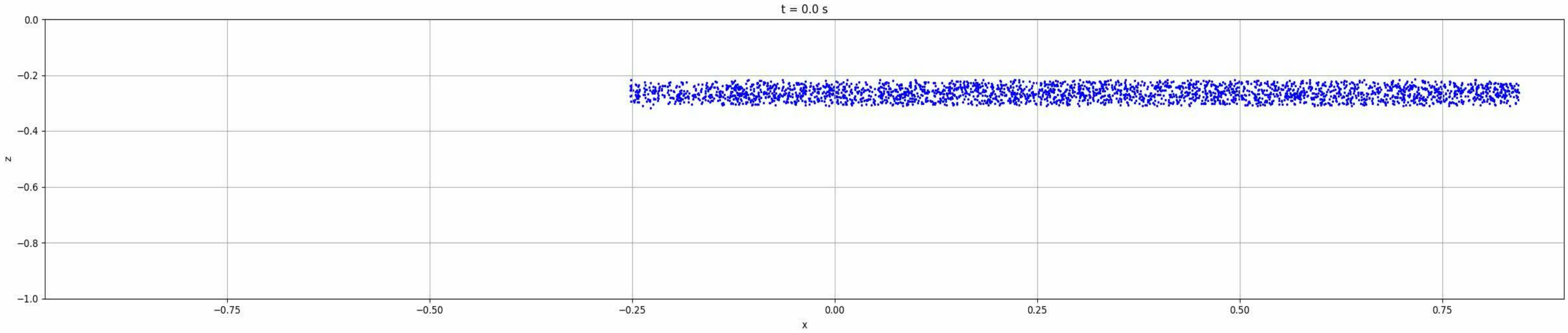
- Statistical uncertainty:

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

Precision frequency measurement requiring many polarized neutrons



Valve opens at t = 60s

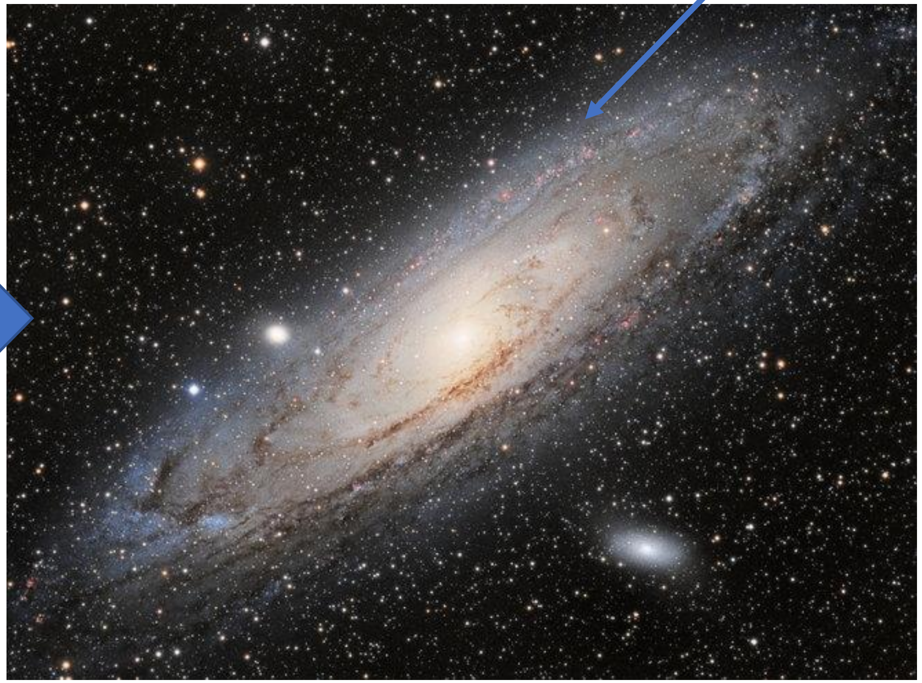


The Story of Our Universe

Just Regular Matter

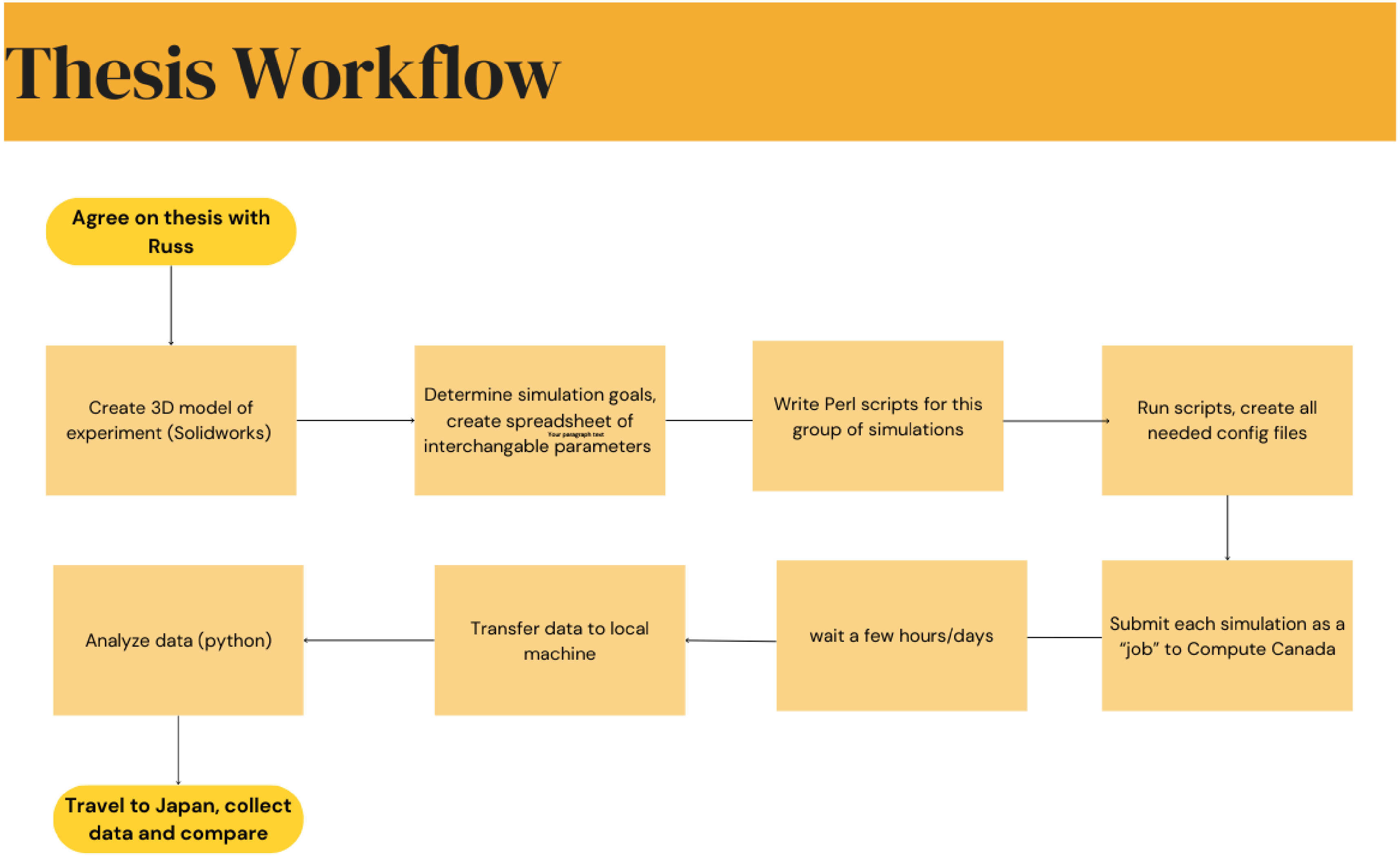
Big Bang (energy)

13.8 billion yr

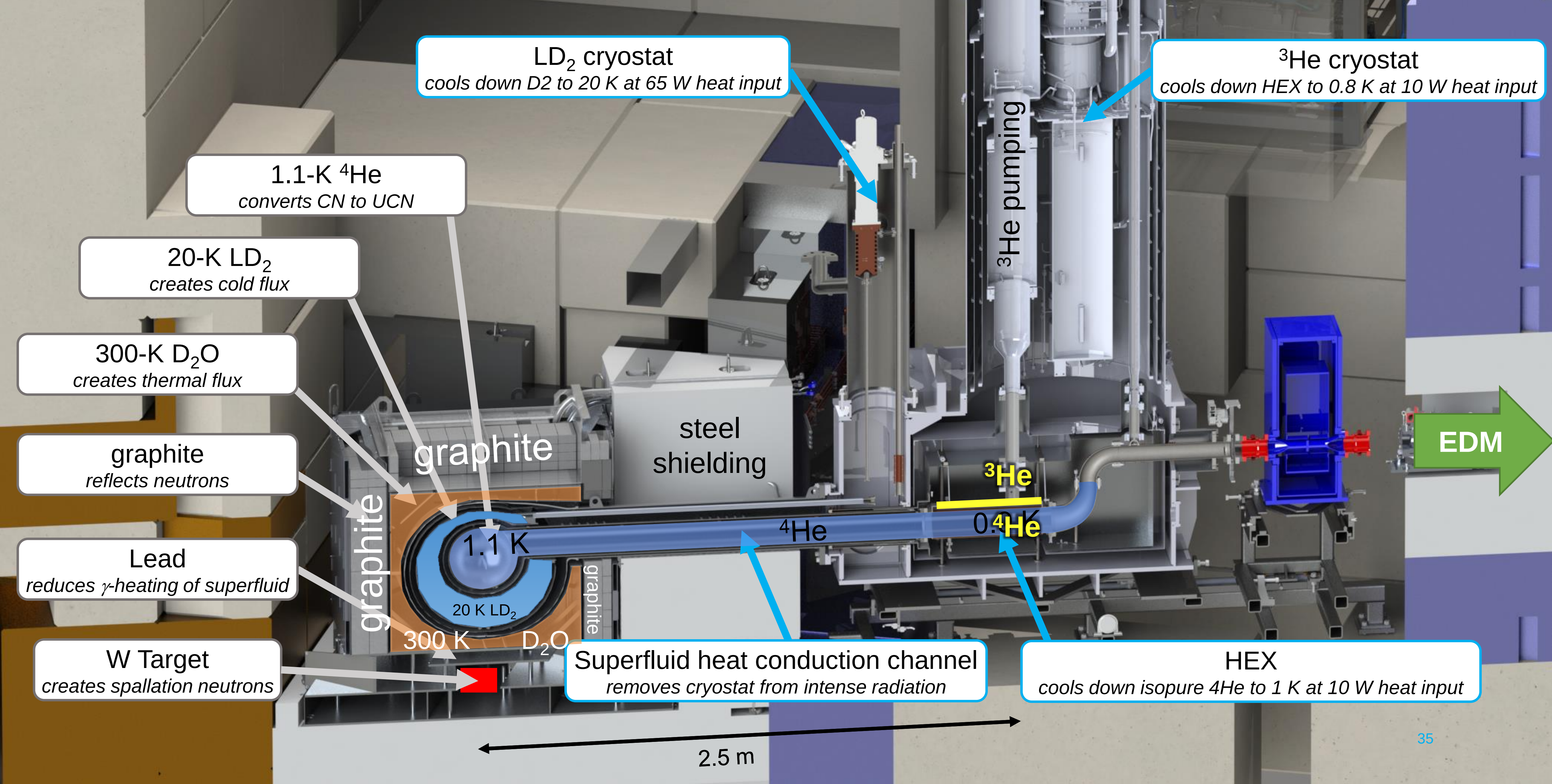


What Happened to all the antimatter?????

Si

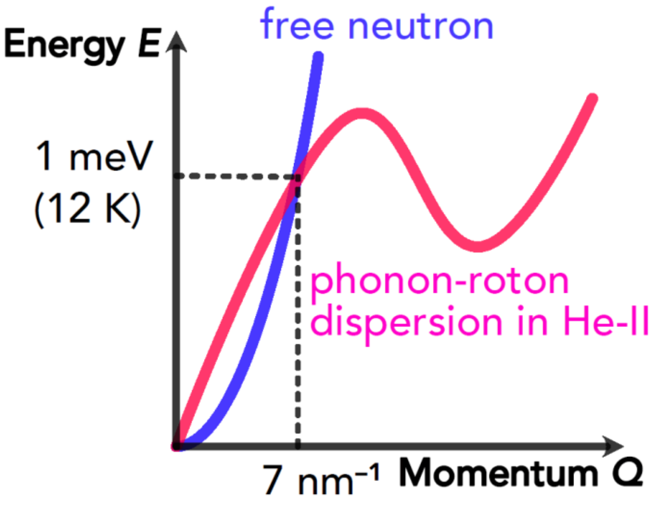

Thesis Workflow
Agree on thesis with Russ
Create 3D model of experiment (Solidworks)
Determine simulation goals, create spreadsheet of interchangable parameters
Write Perl scripts for this group of simulations
Run scripts, create all needed config files
Submit each simulation as a "job" to Compute Canada
wait a few hours/days
Transfer data to local machine
Analyze data (python)
Travel to Japan, collect data and compare

TUCAN UCN source components

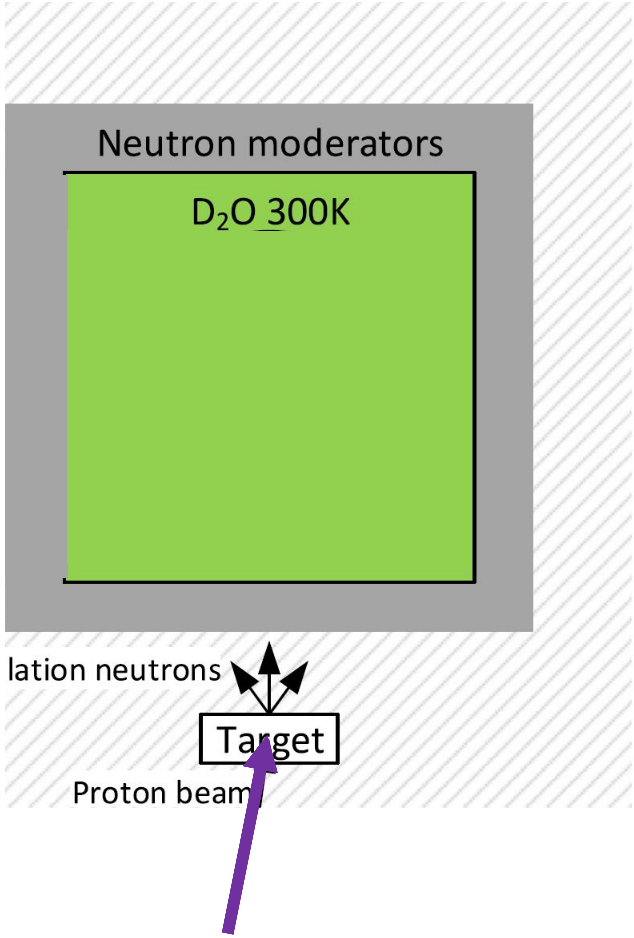


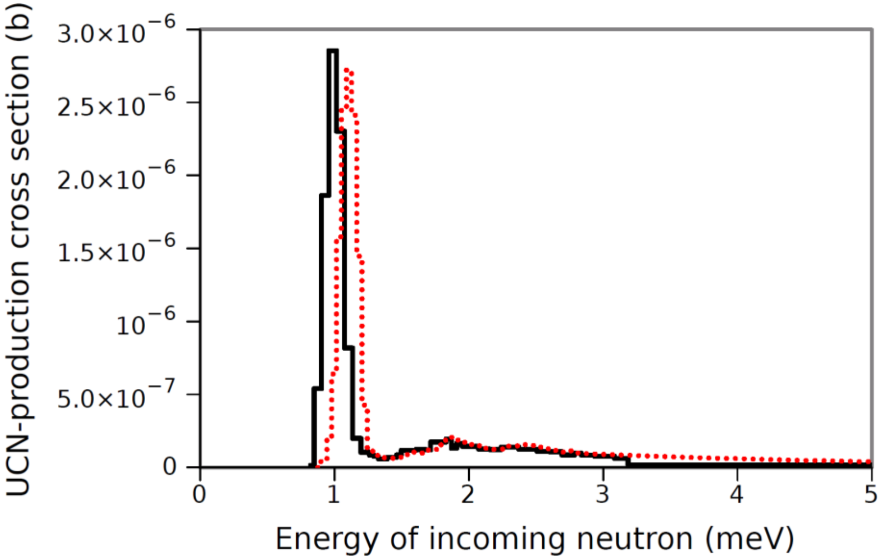
TUCAN source recipe

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. ^{4}He at around 1 K **converts** 1 meV (9Å) neutrons **to UCN** (< 215 neV)

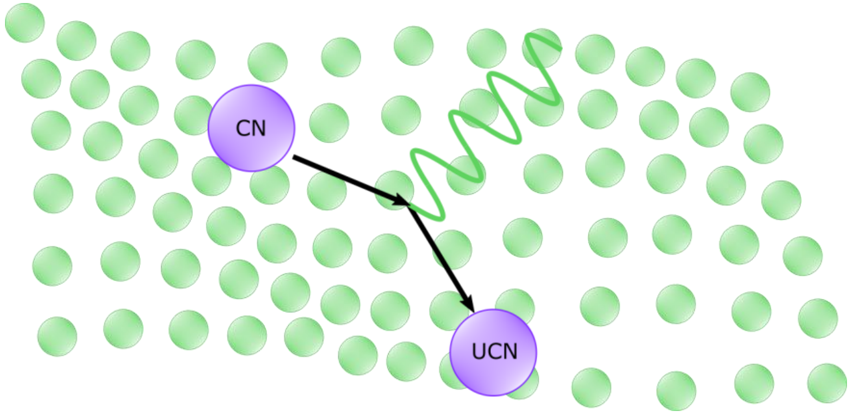


SF He and UCN dispersion rel.





UCN production cross section



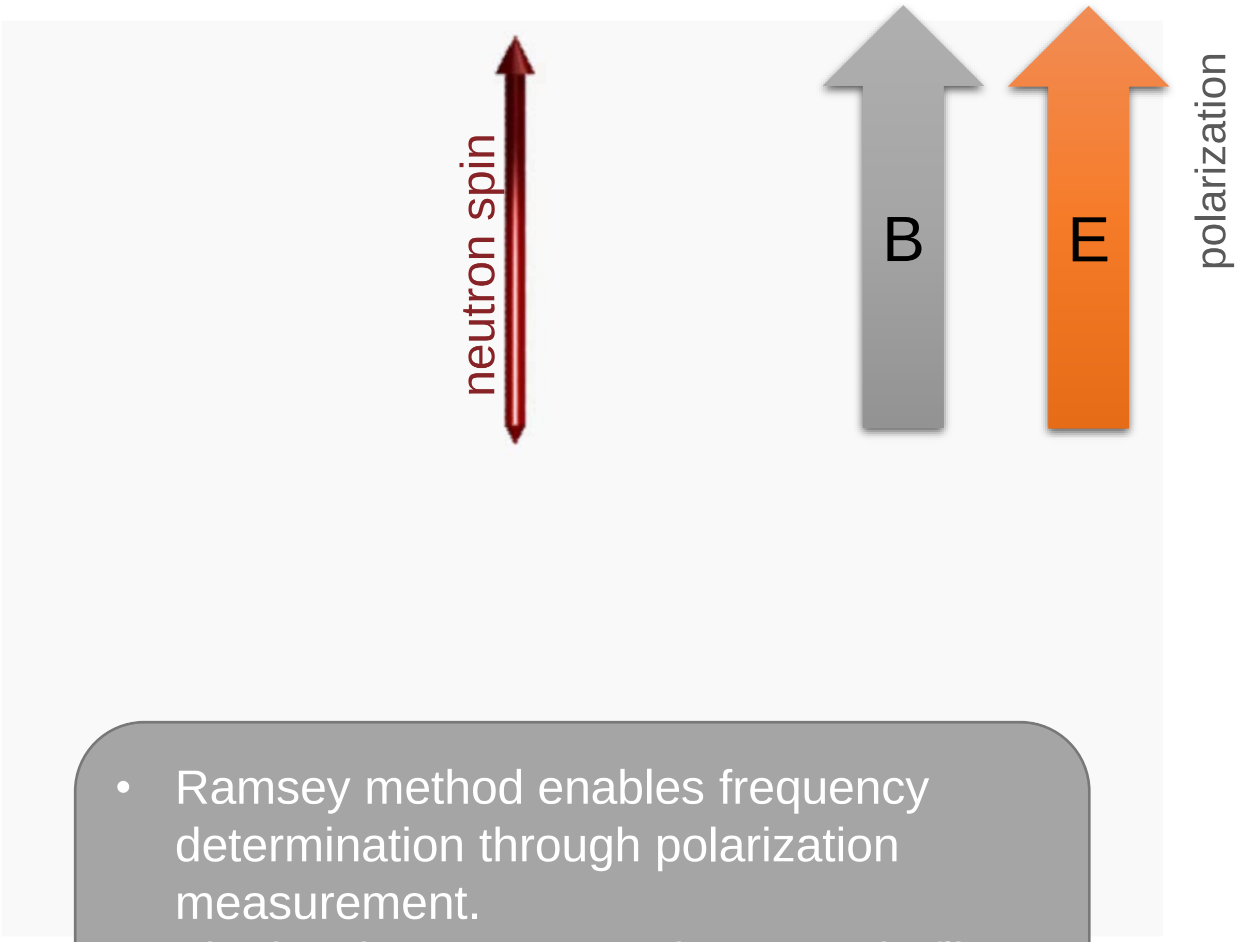
UCN conversion cartoon

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.

Ramsey method

37

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



- 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.

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

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

6. Flip E field and repeat

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

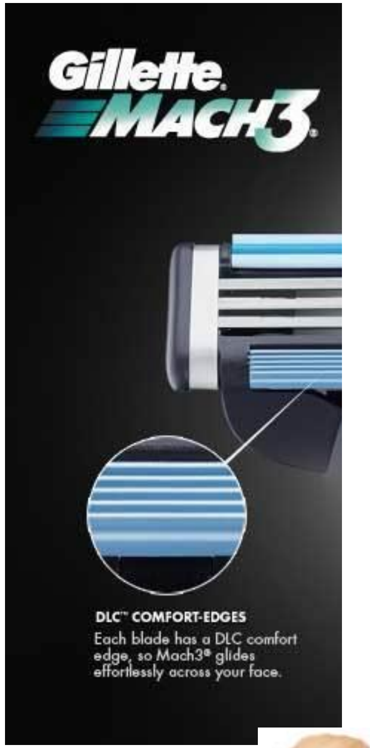
Future UCN guides

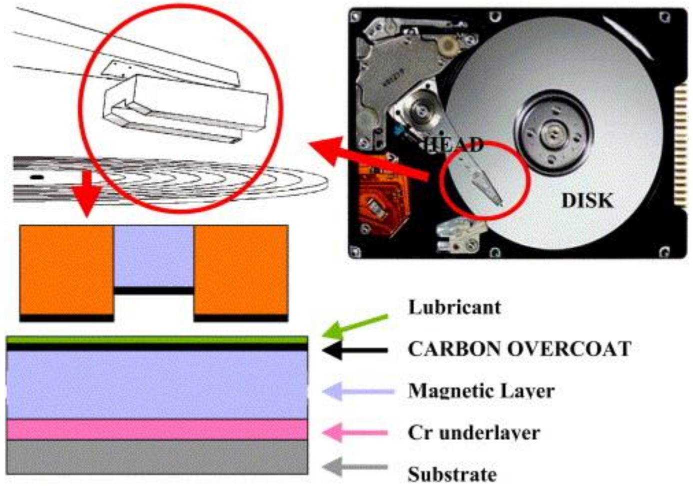
- Each individual UW DLC guide must be tested on its own before being installed in the experiment at TRIUMF

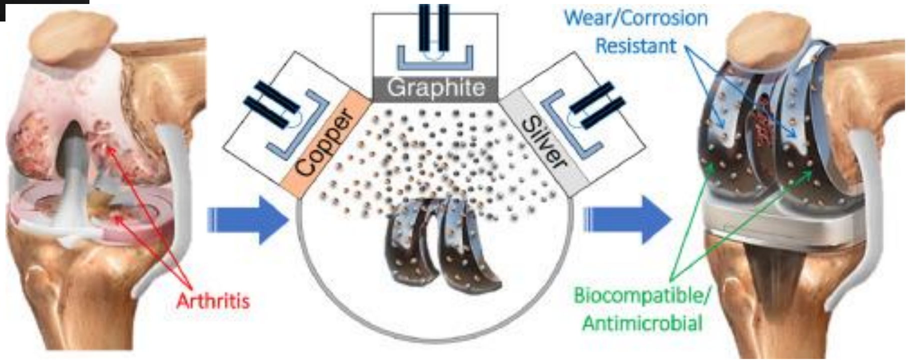
- These simulations can be used to test all future UW guides at the JPARC UCN source
  - Workflow can also be adapted to TRIUMF UCN source, once it is producing UCN (hopefully in July!)

  - **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 form 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