TUCAN

TRIUMF Ultra Cold
Advanced
Neutron source

The TRIUMF Ultra Cold Advanced Neutron source and EDM experiment

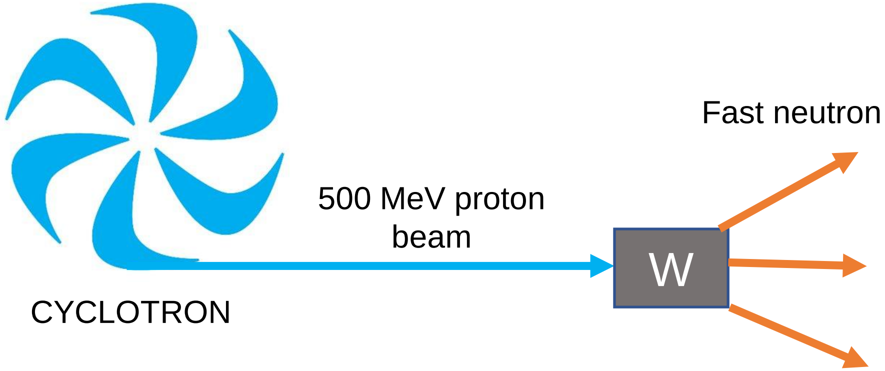
Alexis Brossard
On behalf of the TUCAN collaboration

Exploring the Dark Side of the Universe Tools 2024 – 5th World Summit
Noirmoutier Island June 7th, 2024

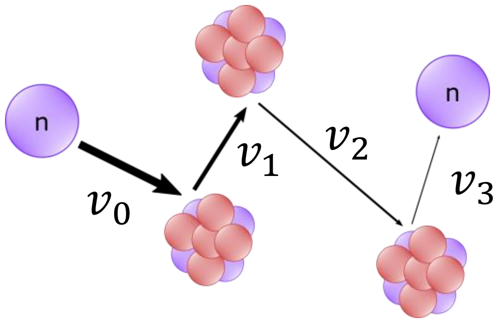
Ultracold Neutron

Neutron production, cooling and ultra-cooling:

- Spallation source:

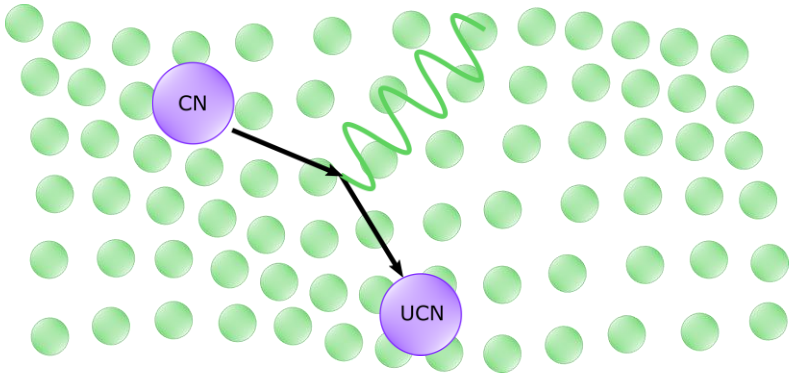


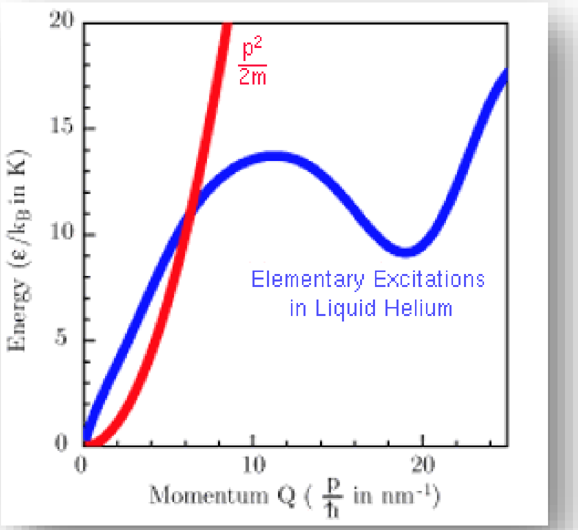
- Cooling with thermal moderator:



$$v_3 < v_2 < v_1 < v_0$$

- Phonon emission in superfluid He-4

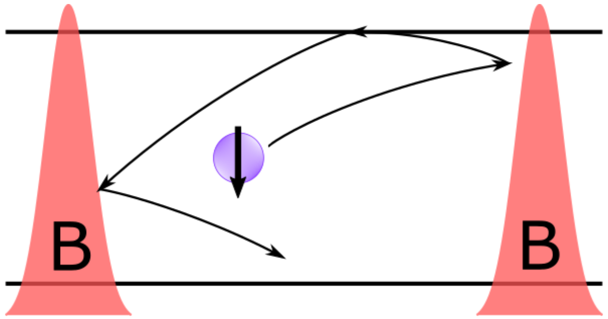




UCN confinement

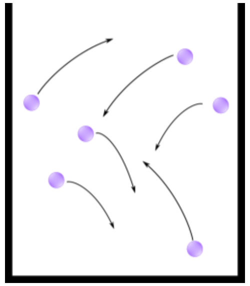
- Magnetic Field:

$$\mu_N = 60.3\ \frac{\text{neV}}{\text{T}}$$



- Gravity:

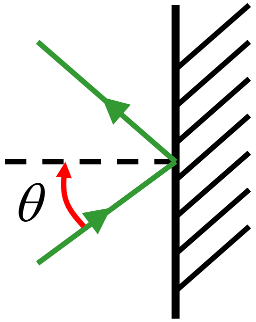
$$V_g = m_n g z = \left(102.5\ \frac{\text{neV}}{\text{m}}\right) z$$



- Strong force:

$$V(\vec{r}) = \frac{4\pi\hbar^2}{2m} \sum_i a_i \delta(\vec{r} - \vec{r}_i')$$

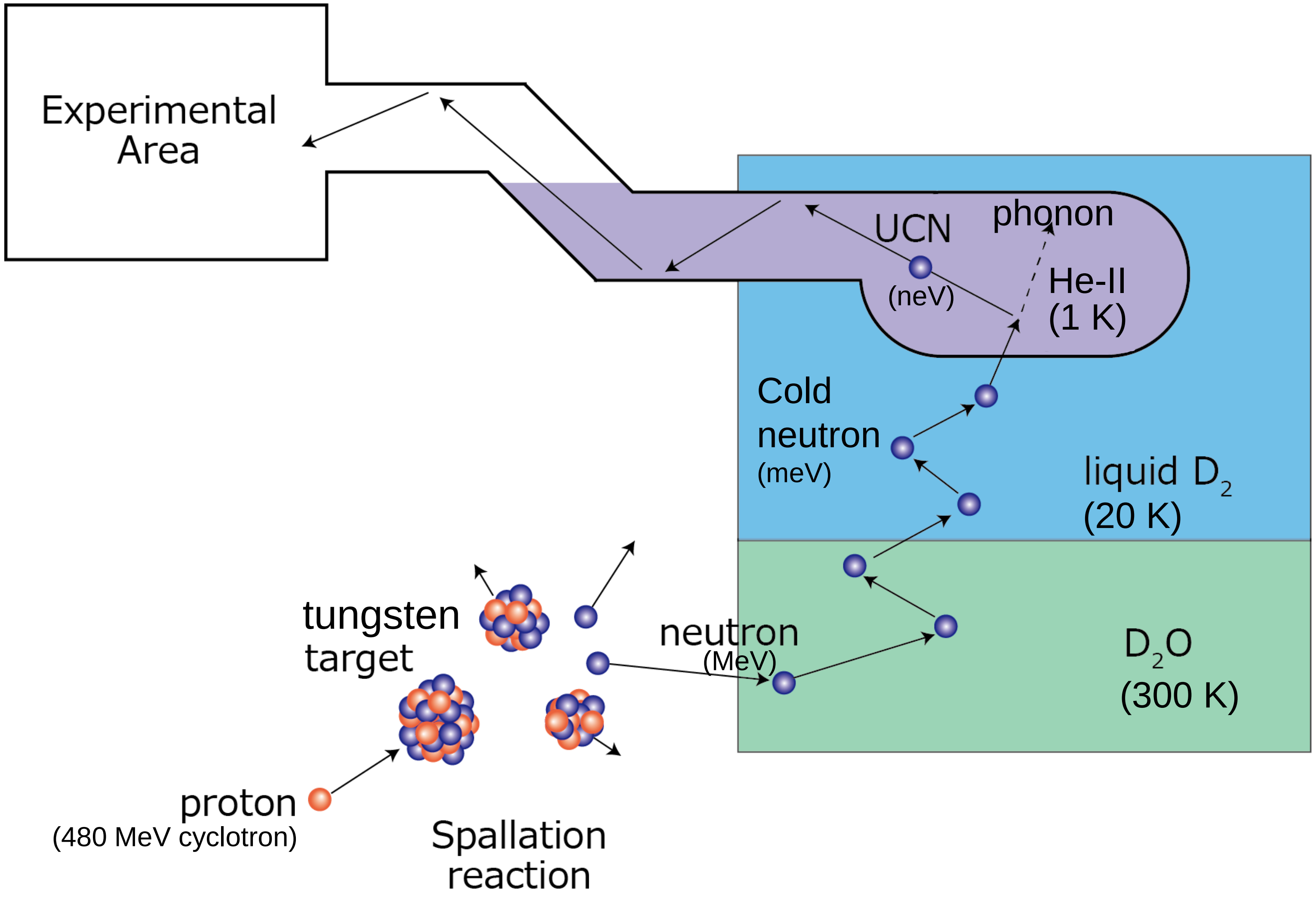
$$E_{kin} < V_F :$$



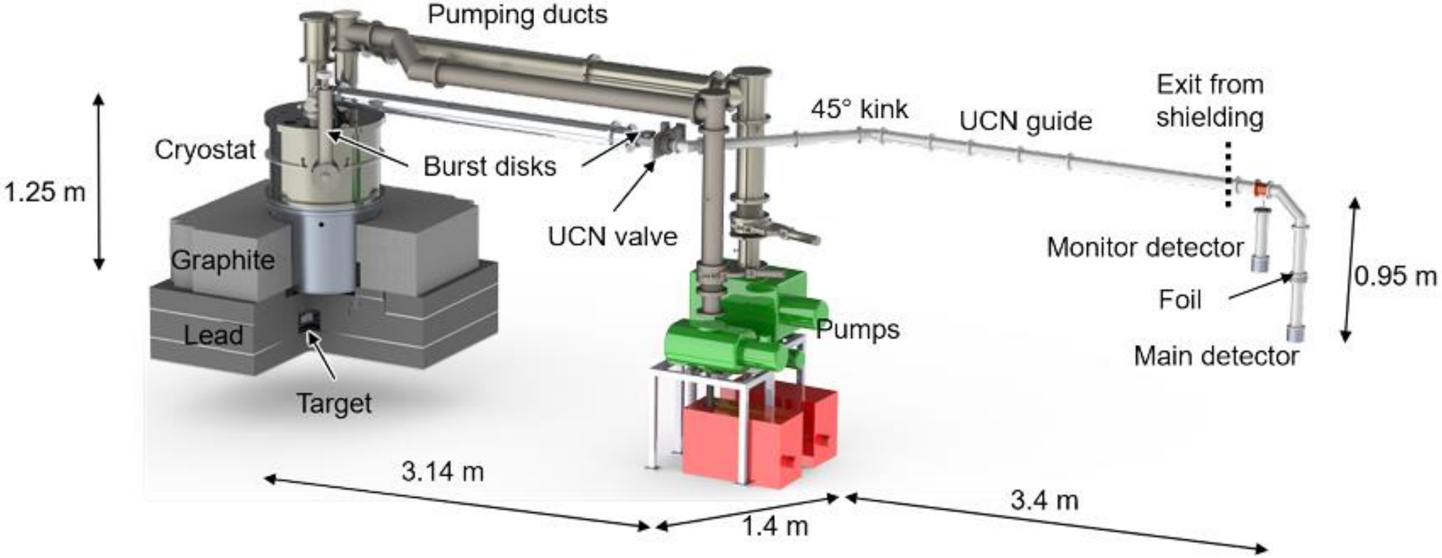
Material	V_F (neV)	v (m/s)
Al	54	3.2
^{58}Ni	350	8.2
Graphite	180	5.9
Stainless Steel	188	6
DLC	282	7.3

UCN can be stored

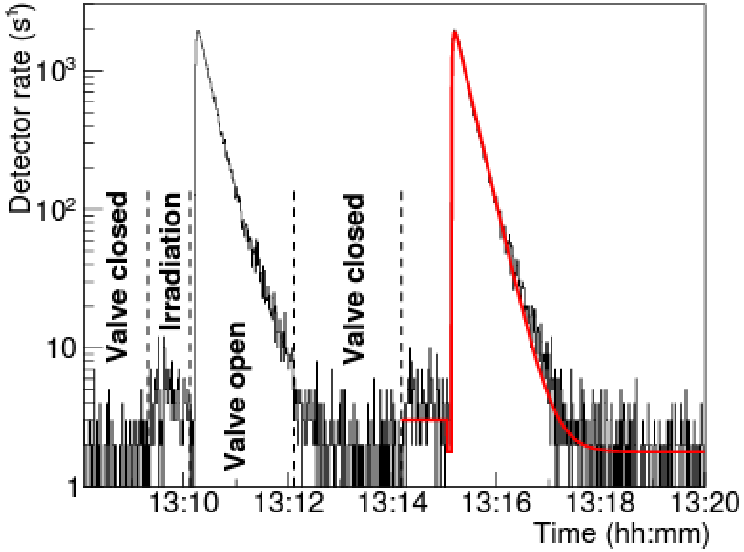
TUCAN method

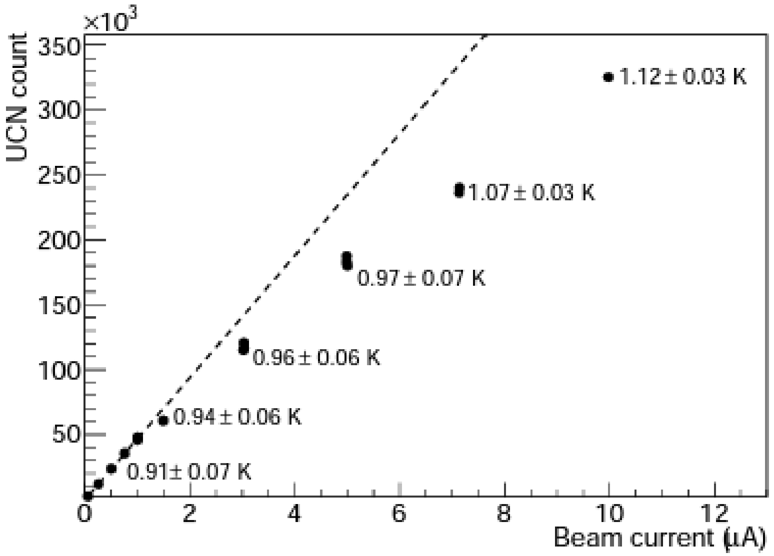


TUCAN first prototype:

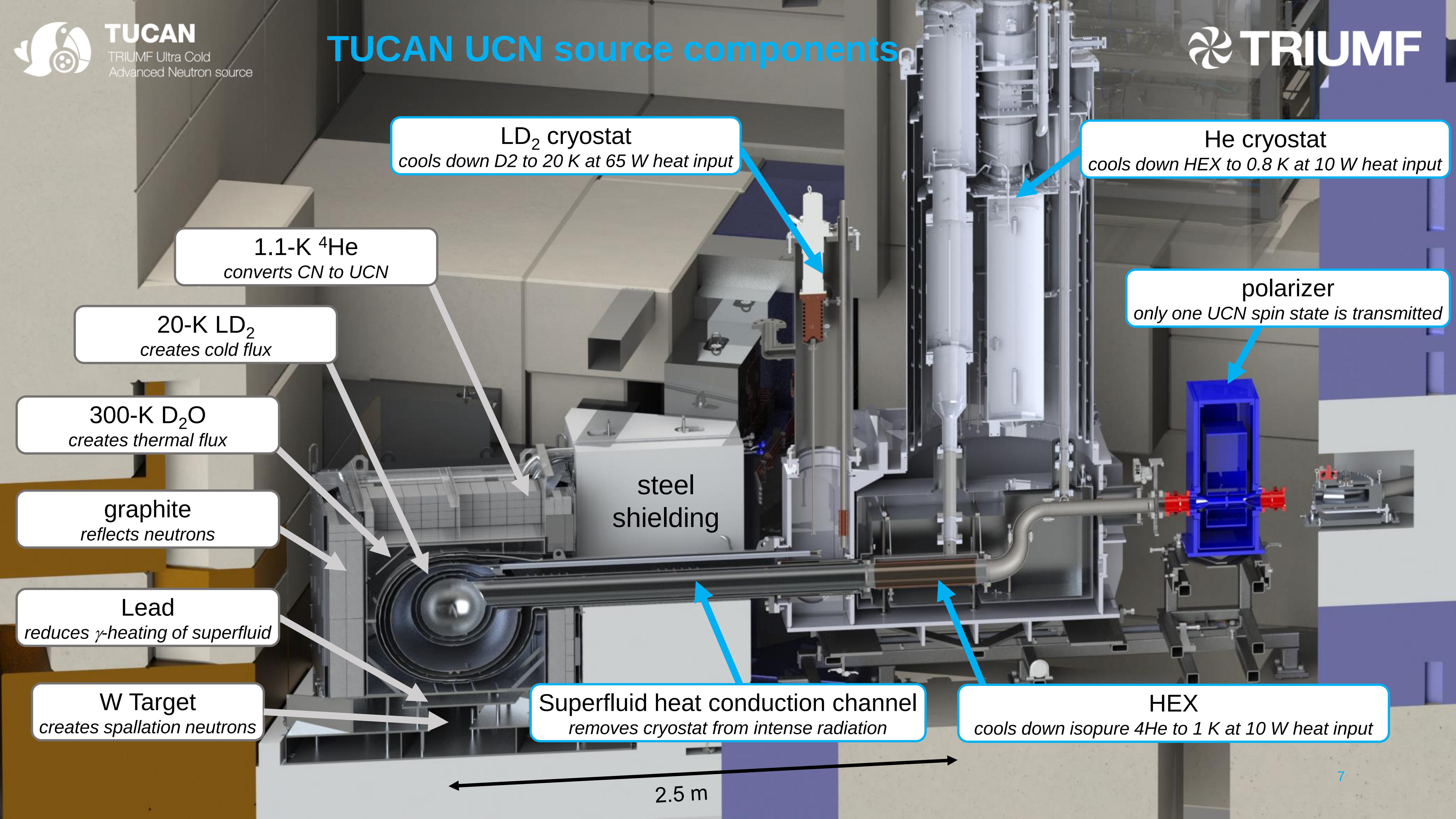


- First UCN on November 13, 2017
- 2 10^4 UCN/s
- Decommissioned in 2019
- Validate components and simulation for the new source
- Gives first operational experience





TUCAN UCN source components

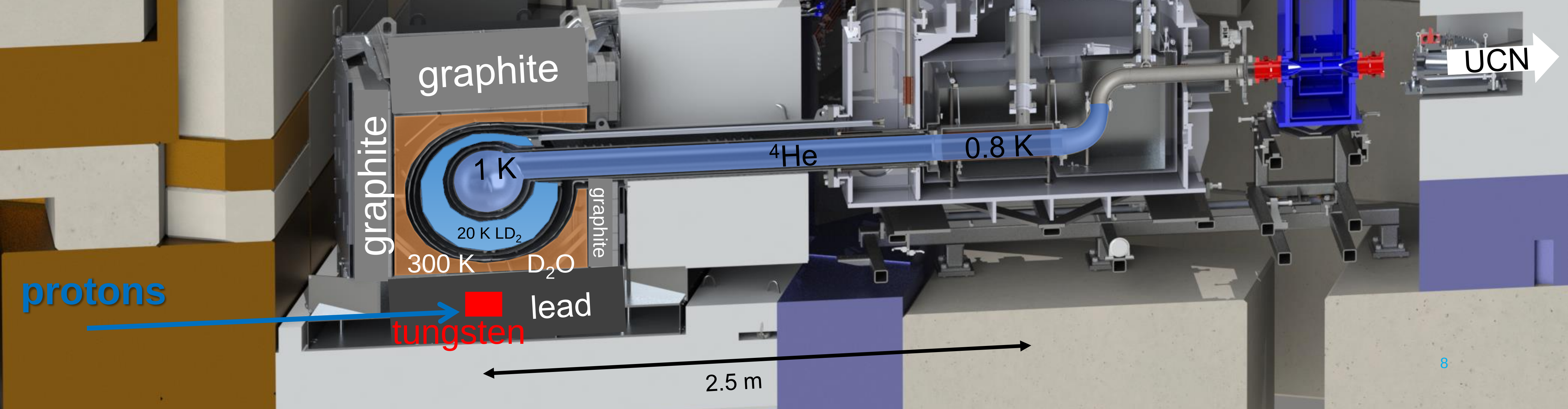


TUCAN
TRIUMF Ultra Cold Advanced Neutron source

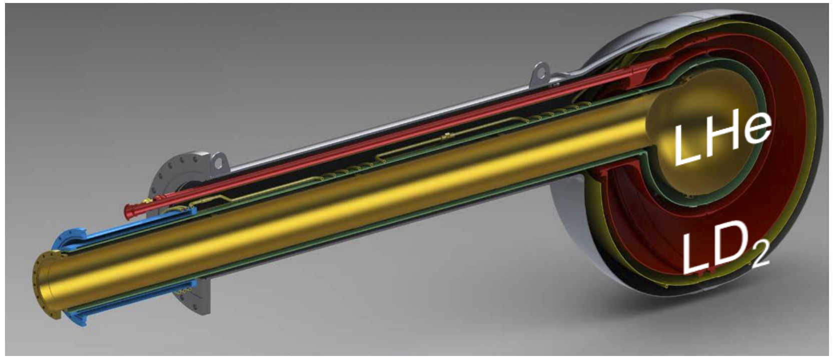
TUCAN UCN source recipe

TRIUMF

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)
5. **Extraction** to experiments via material guides



Keeping 27 liters of isopure Helium-4 at 1K under 10-Watt heat load

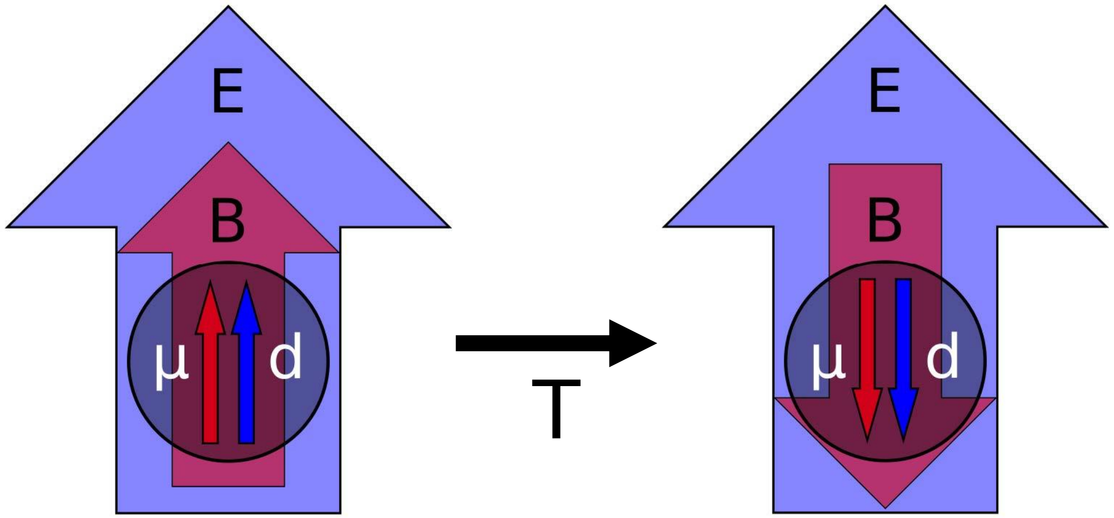


Source in commissioning phase. First UCN production this fall. Full source next summer.
World leading source 1.6 x 10^7 UCN/s

Neutron electric dipole moment measurement

Neutron Electric Dipole Moment violates CP symmetry

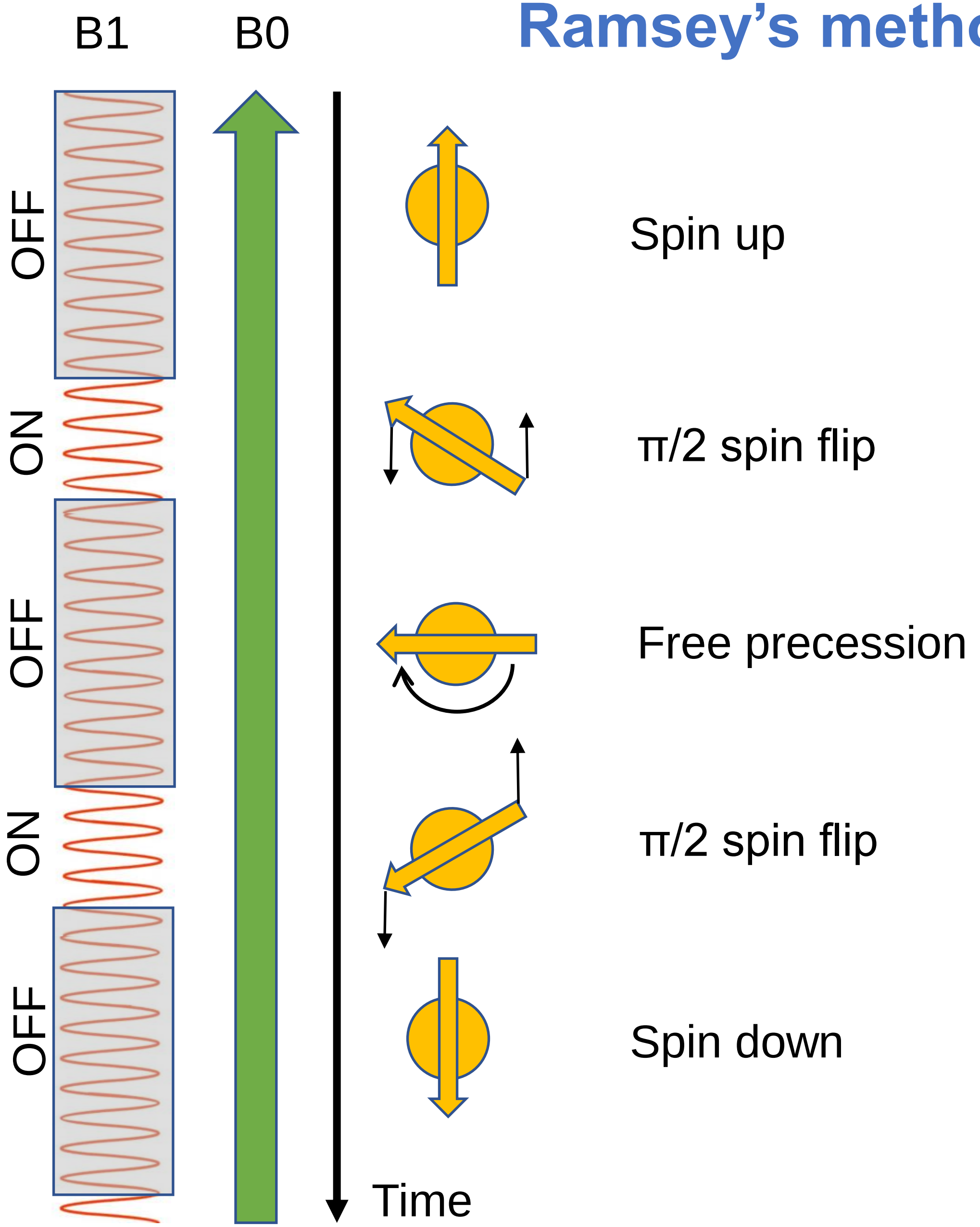
- Violates T & CP symmetry
- Test of beyond-Standard Model theories
- Can be detected by measuring precession frequency in electric and magnetic field
- Ultracold neutron (E<300 neV) are suitable for such measurement.

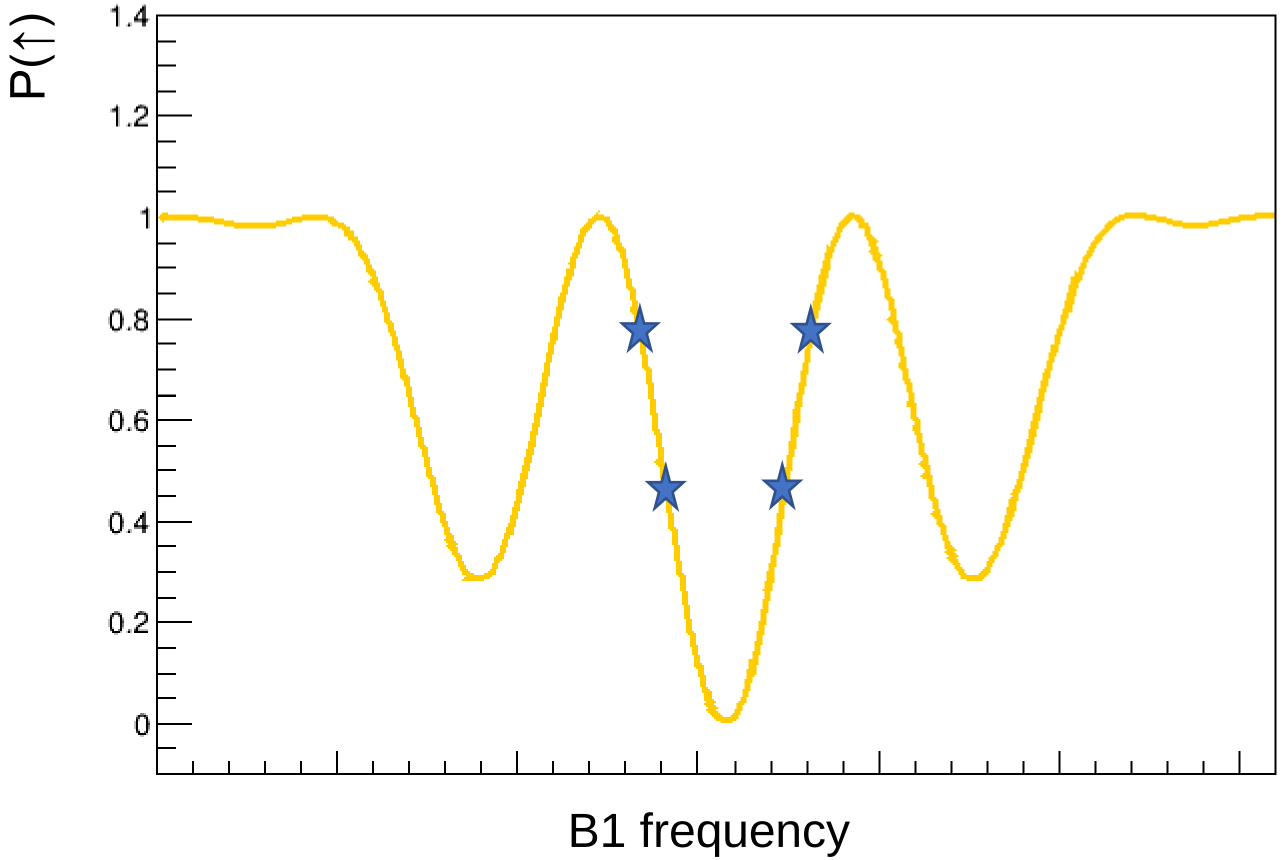


$$H = -\mu \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \vec{B} - d \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \vec{E} \neq -\mu \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \left(-\vec{B}\right) - d \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \vec{E}$$

Figures by D. Ries
https://www.youtube.com/watch?v=QBKPQFUdDB0

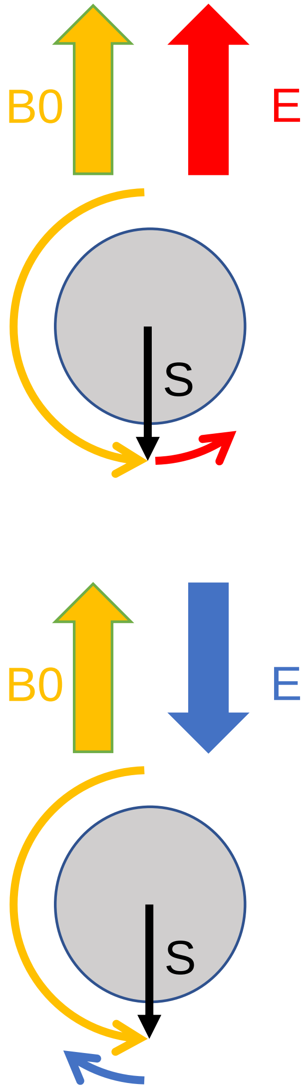
Ramsey's method of separated oscillatory fields





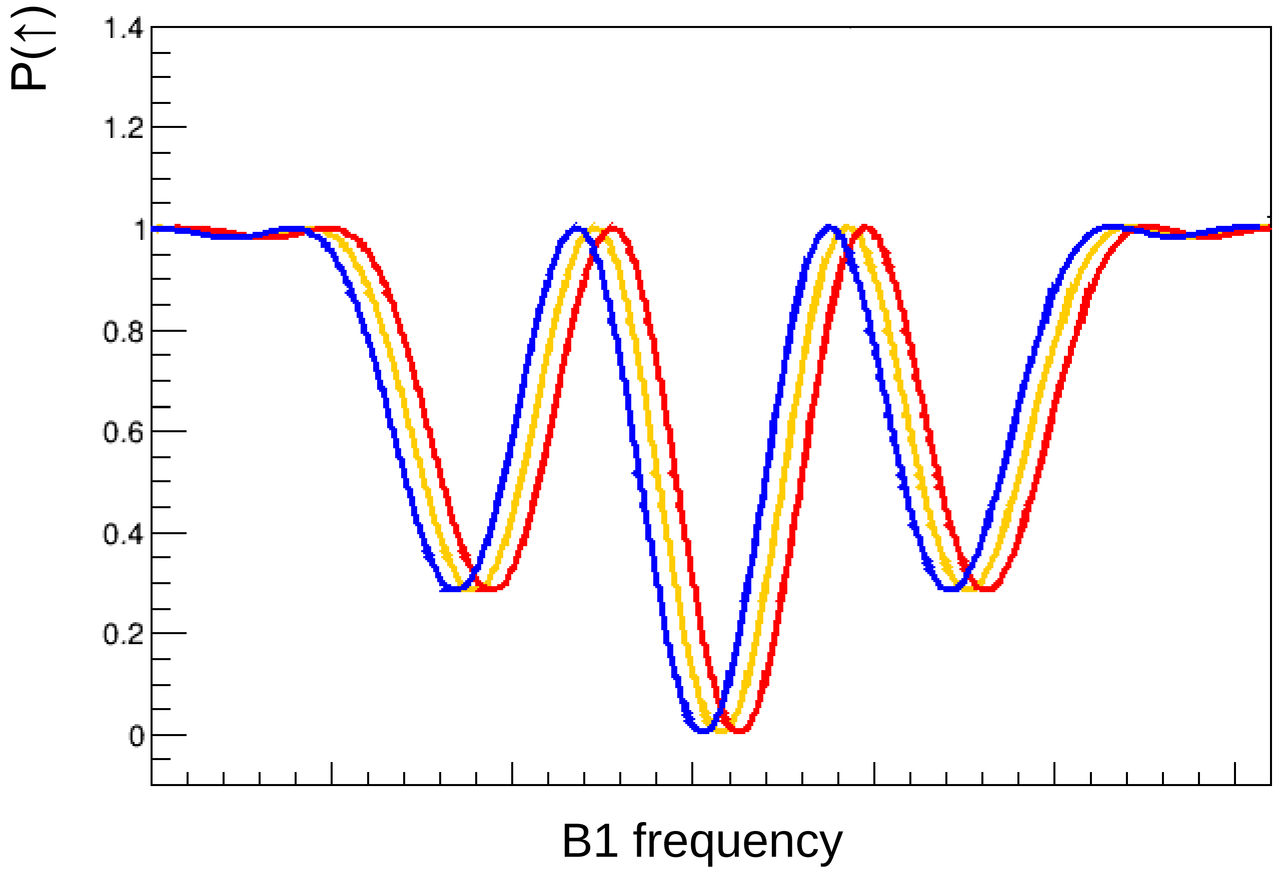
Resonance frequency: $2\pi f = \frac{2\mu_n}{\hbar}\mathrm{B}$

Effect of the E field:



$$2\pi f = \frac{2\mu_n}{\hbar}\mathrm{B} + \frac{2d_n}{\hbar}E$$

$$2\pi f = \frac{2\mu_n}{\hbar}\mathrm{B} - \frac{2d_n}{\hbar}E$$



EDM will cause shift in precession frequency

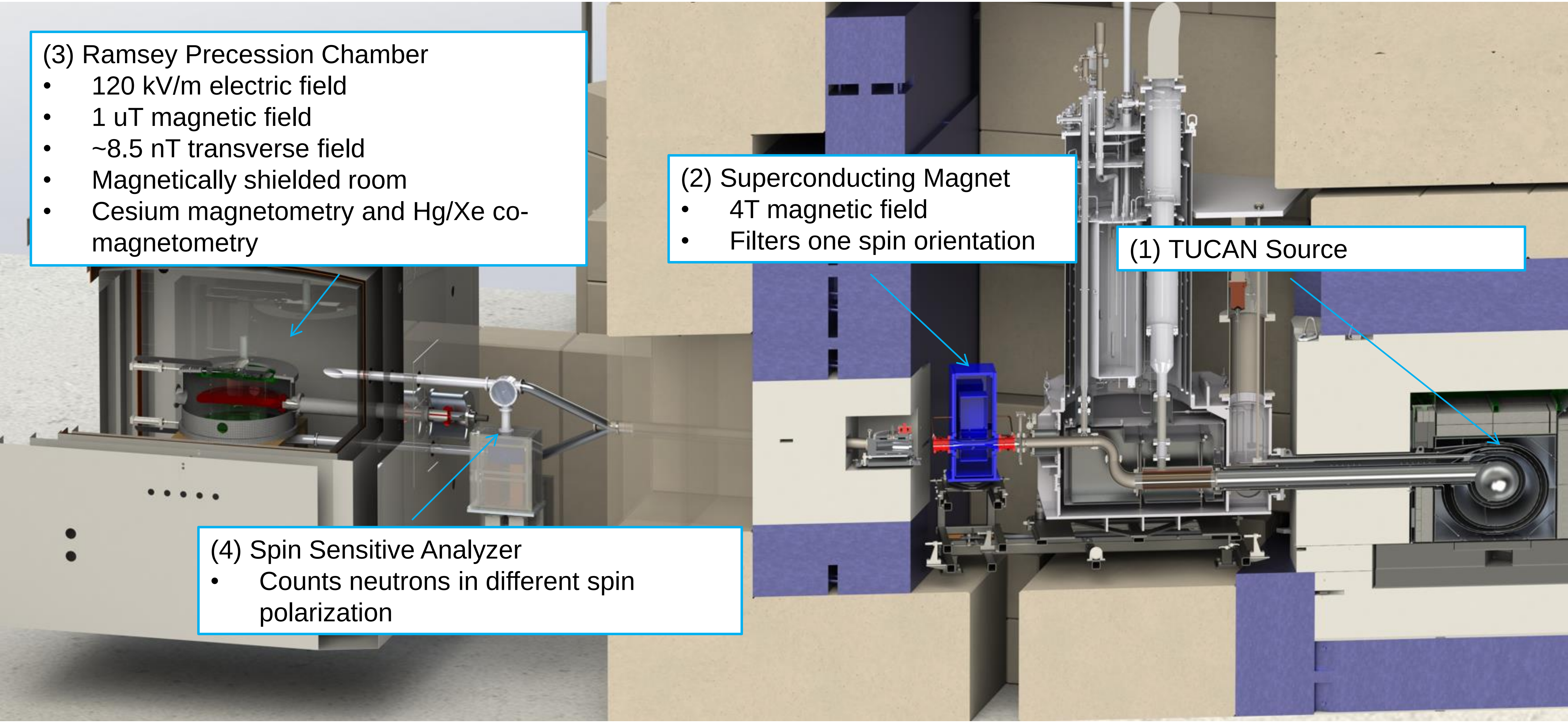
$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = \frac{2\pi}{\hbar}d_n E$$

Statistical uncertainty:

$$\sigma_d = \frac{1}{2\alpha E T\sqrt{N}}$$

- α: Visibility, neutron polarization. Account for polarization at the beginning of the cycle, depolarization during the cycle and efficiency of the spin analyzer.
- *E:* Electric field strength. Limited by the cell breakdown voltage
- *N*: Number of neutron detected, needs for high efficiency at few 100 kHz detection rate
- *T:* Free precession time, must be optimized considering neutron decay, absorption, storage lifetime, de-polarization…

TUCAN METHOD:



(3) Ramsey Precession Chamber
- 120 kV/m electric field
- 1 uT magnetic field
- ~8.5 nT transverse field
- Magnetically shielded room
- Cesium magnetometry and Hg/Xe co-magnetometry

(2) Superconducting Magnet
- 4T magnetic field
- Filters one spin orientation

(1) TUCAN Source

(4) Spin Sensitive Analyzer
- Counts neutrons in different spin polarization

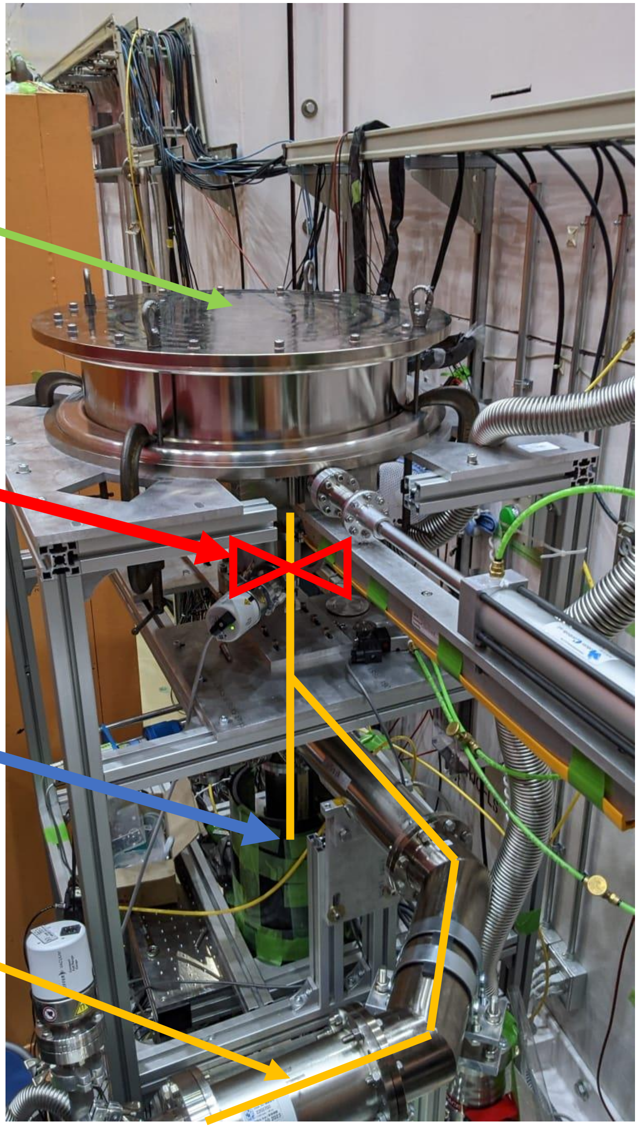
Cell lifetime measurement

UCN Cell

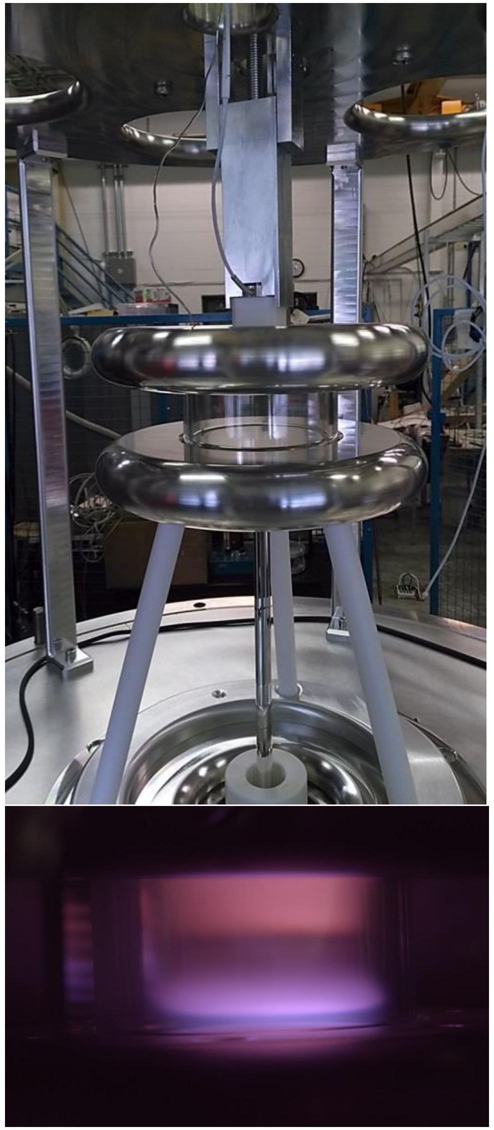
UCN Valve

^{3}He detector

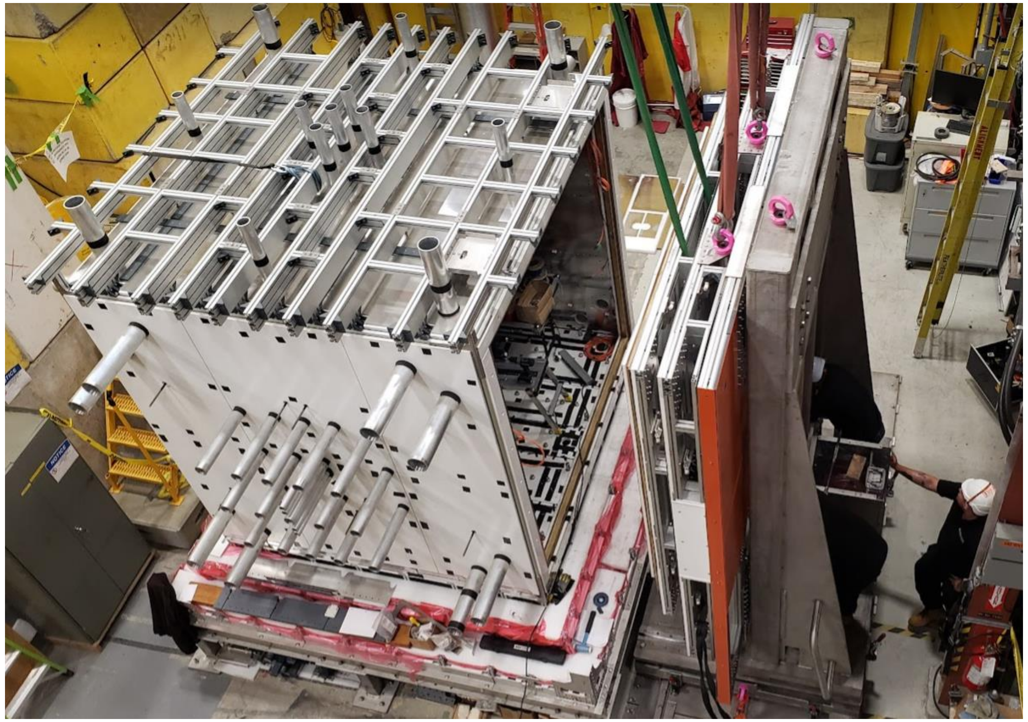
UCN



Cell HV test



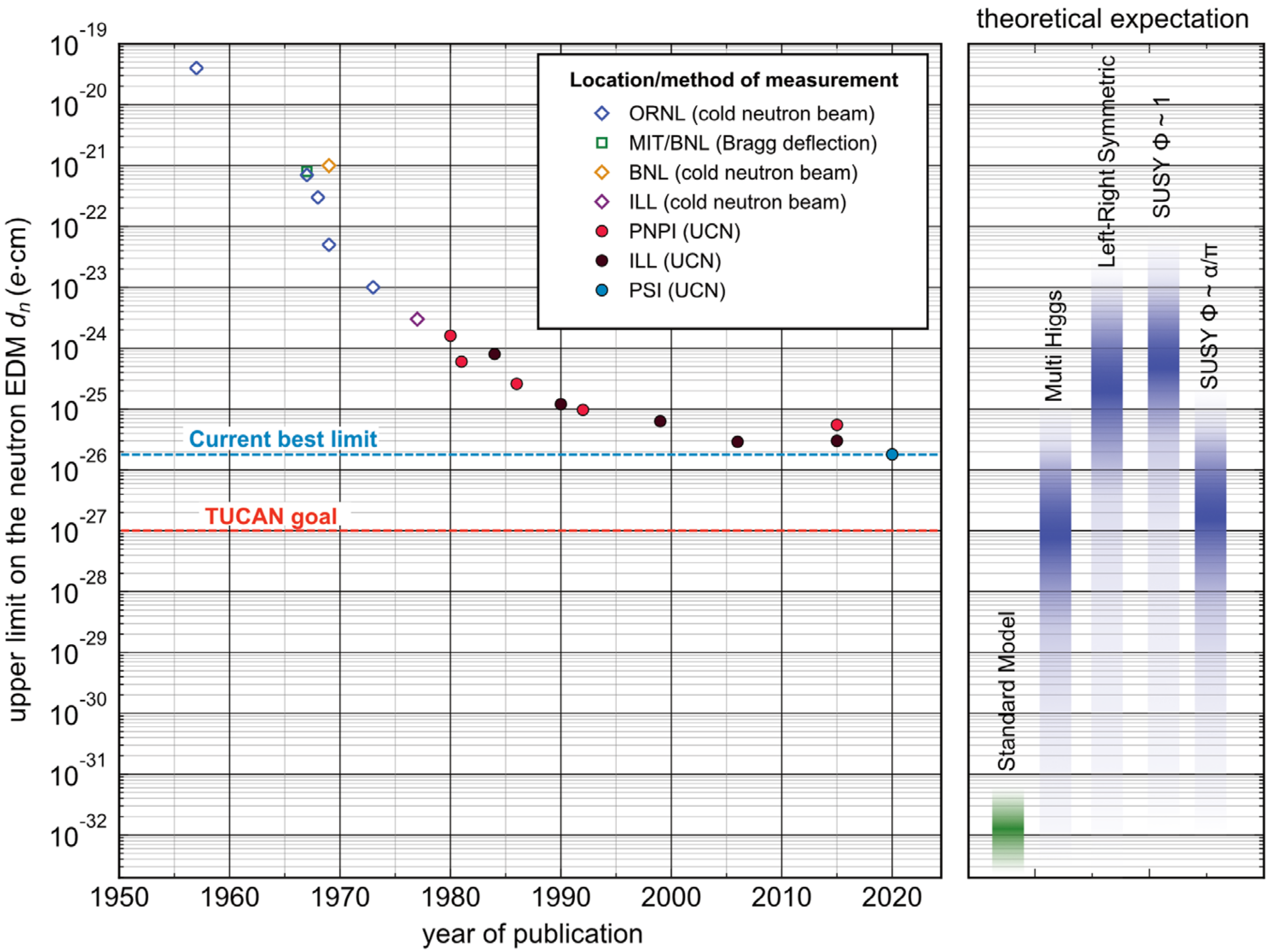
Magnetically shielded room



Magnetometry

Time to reach 10^{-27} ecm = 281 ± 16 days

S. Sidhu et al, 2022: https://doi.org/10.1051/epjconf/202328201015



T. Higuchi on behalf of the TUCAN collaboration EPJ Web of Conferences 262, 01015 (2022)

- $d_n < 1.8 \times 10^{-26}$ ecm (90% C.L.)
  C. Abel et al., Phys. Rev. Lett. 124, 081803 (2020)
- Many groups pursuing ~ 10^{-27} ecm measurement as next step

You?

UCN source

nEDM experiment

TRIUMF UBC UNBC SFU University of Manitoba The University of Winnipeg NC State University University of Saskatchewan

TUCAN

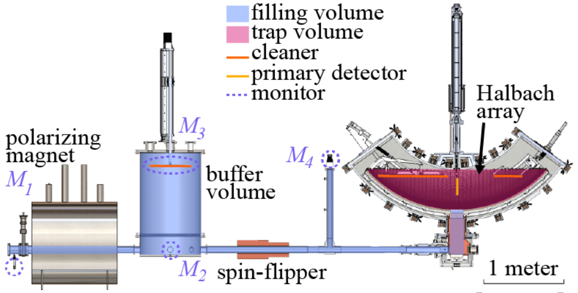
TRIUMF Ultra Cold
Advanced Neutron source

February 2024 Collaboration Meeting, Winnipeg

KEK RCNP Nagoya University Japan Society for the Promotion of Science NSERC CRSNG INNOVATION.CA Canada Foundation for Innovation Fondation canadienne pour l'innovation

UCN for neutron radioactive period measurement

- **UCN Bottle Measurements**
- Store UCN in a container
- Count how many UCN are left over after waiting for some time

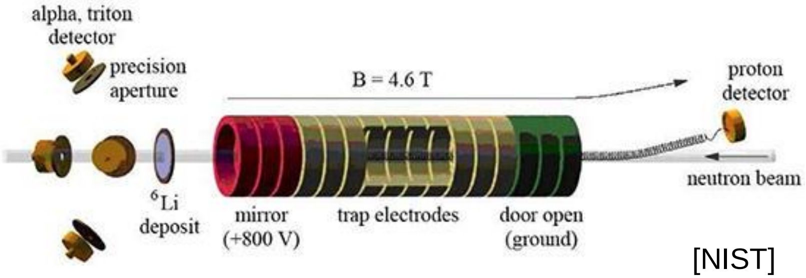


[UCNτ]

- 7/8 best measurements: Ezhov, Pattie, Serebrov, Arzumanov, Steyerl, Pichlmaier, Serebrov
- $\tau_n = 879.4 \pm 0.6$ s

Neutron Beam Measurements

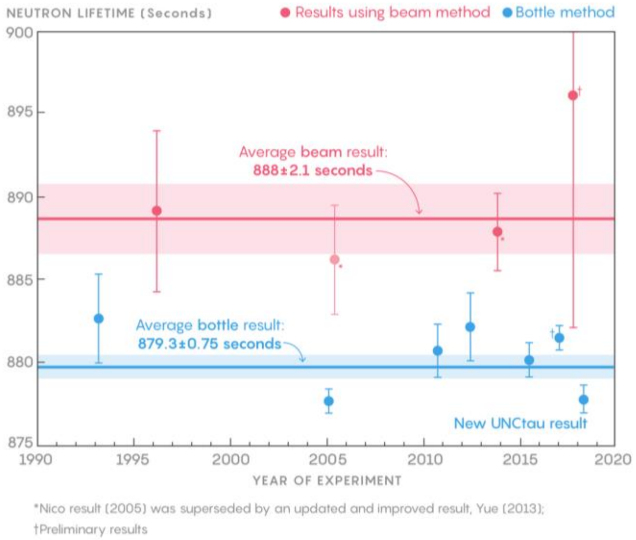
- Direct a beam of cold neutrons down a long volume
- Capture decay protons using magnetic fields and count them



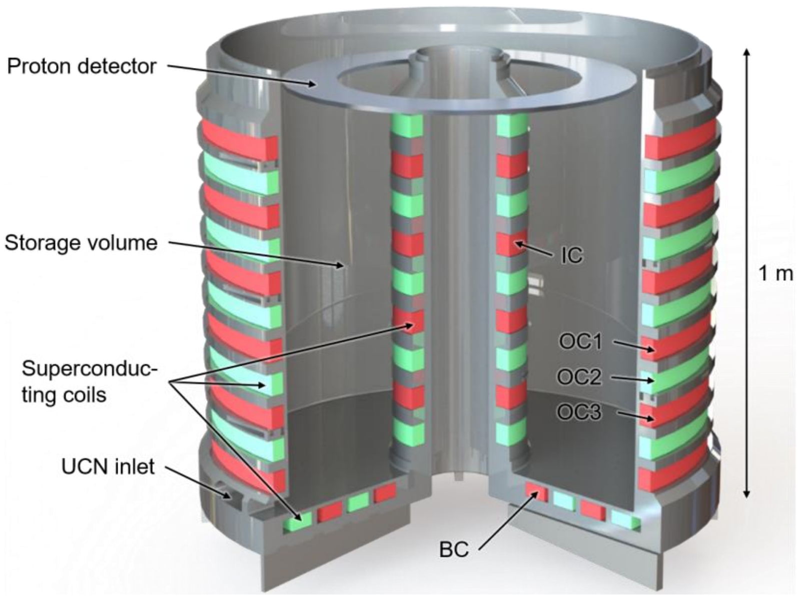
[NIST]

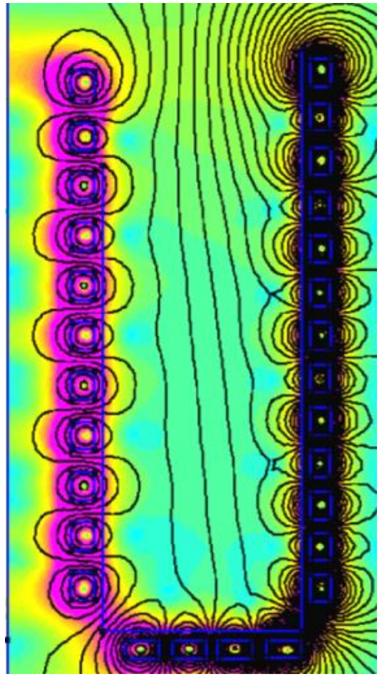
1/8 best measurements: Yue

$$\tau_n = 887.7 \pm 2.2 \text{ s}$$



PEnELOPE

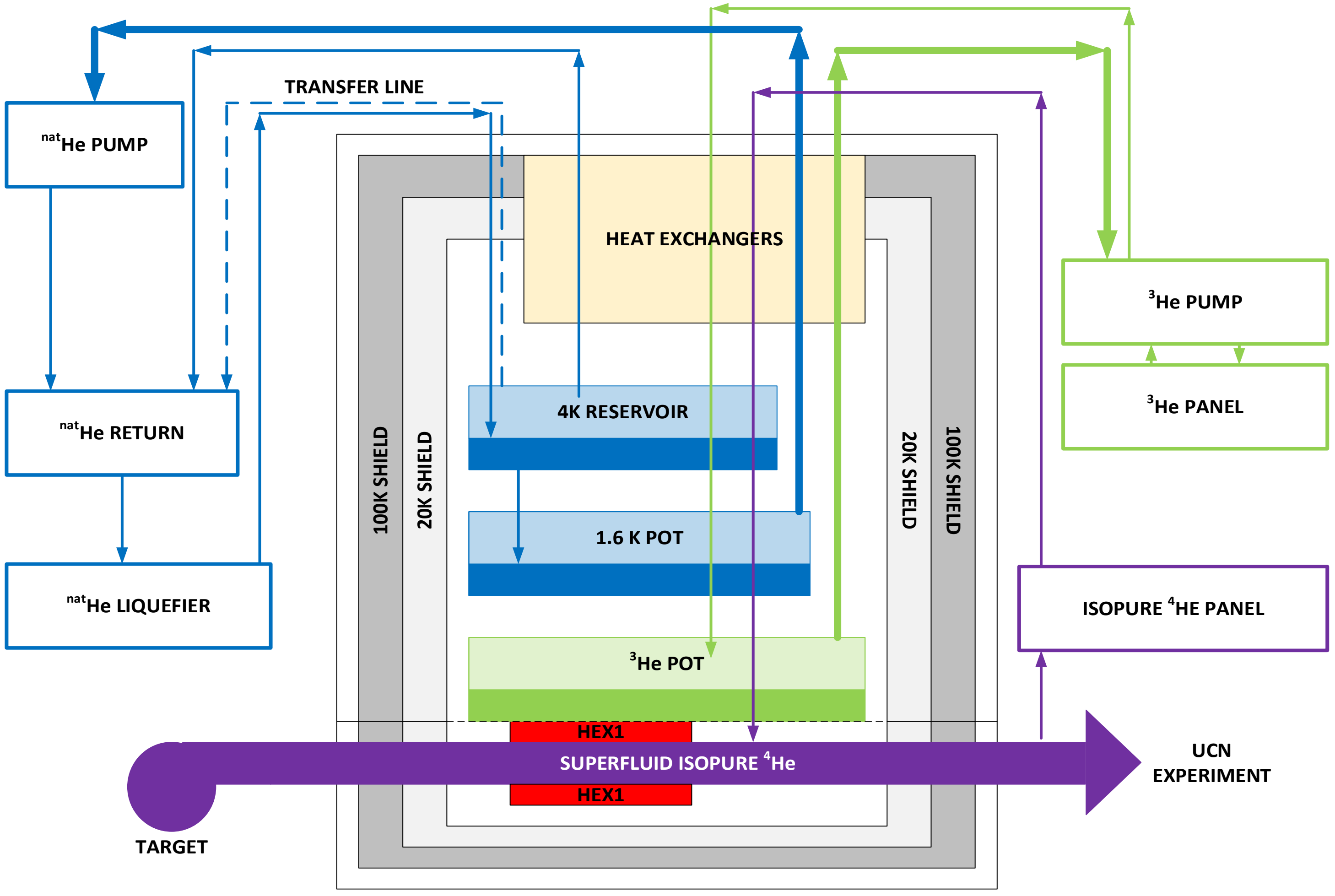




Store UCN into a magneto-gravitational trap.

Detect proton from neutron decay and surviving UCN.

Keeping 27 liters of isopure Helium-4 at ~1 K under 10-Watt heat load

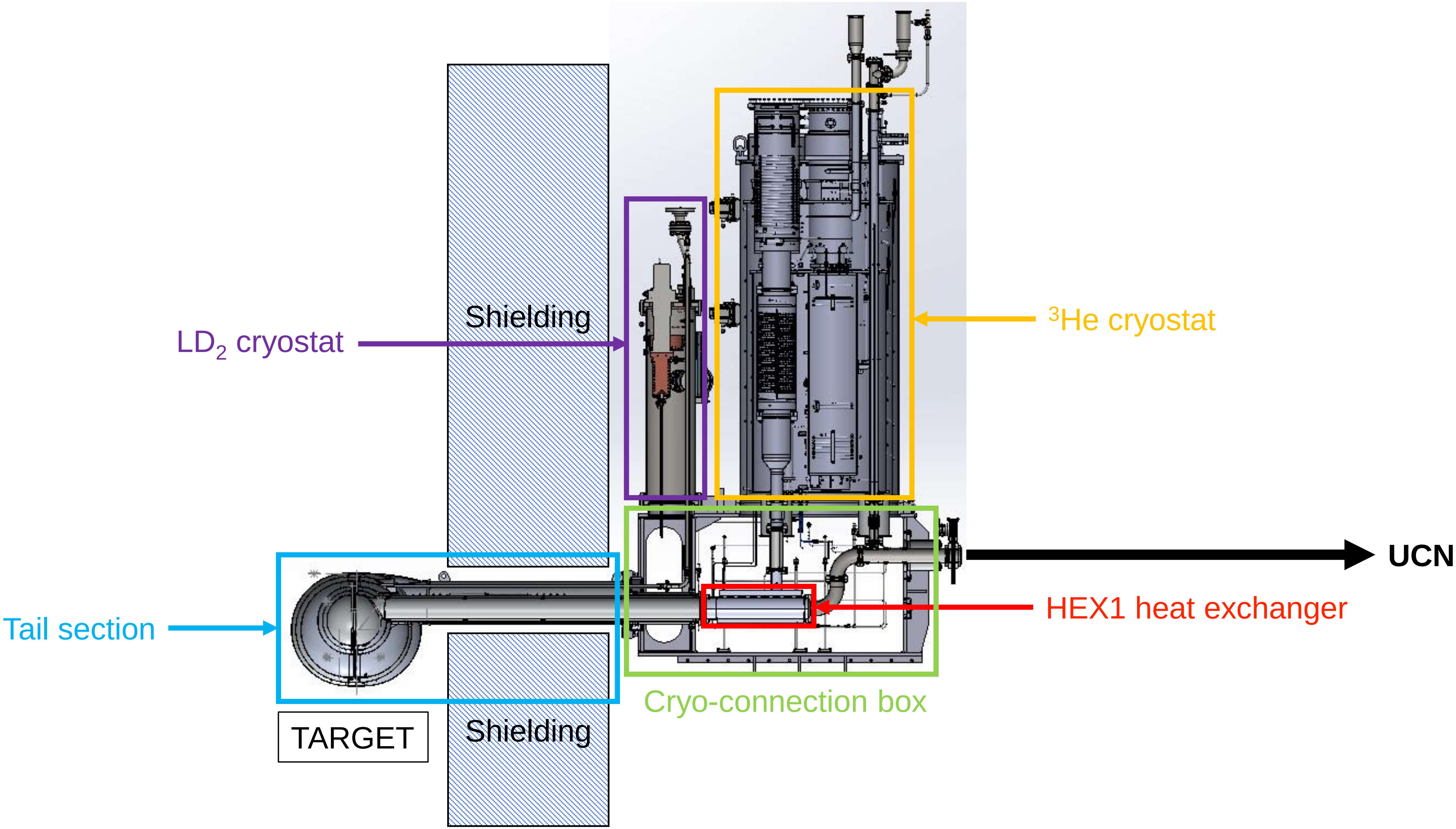


Three gases:

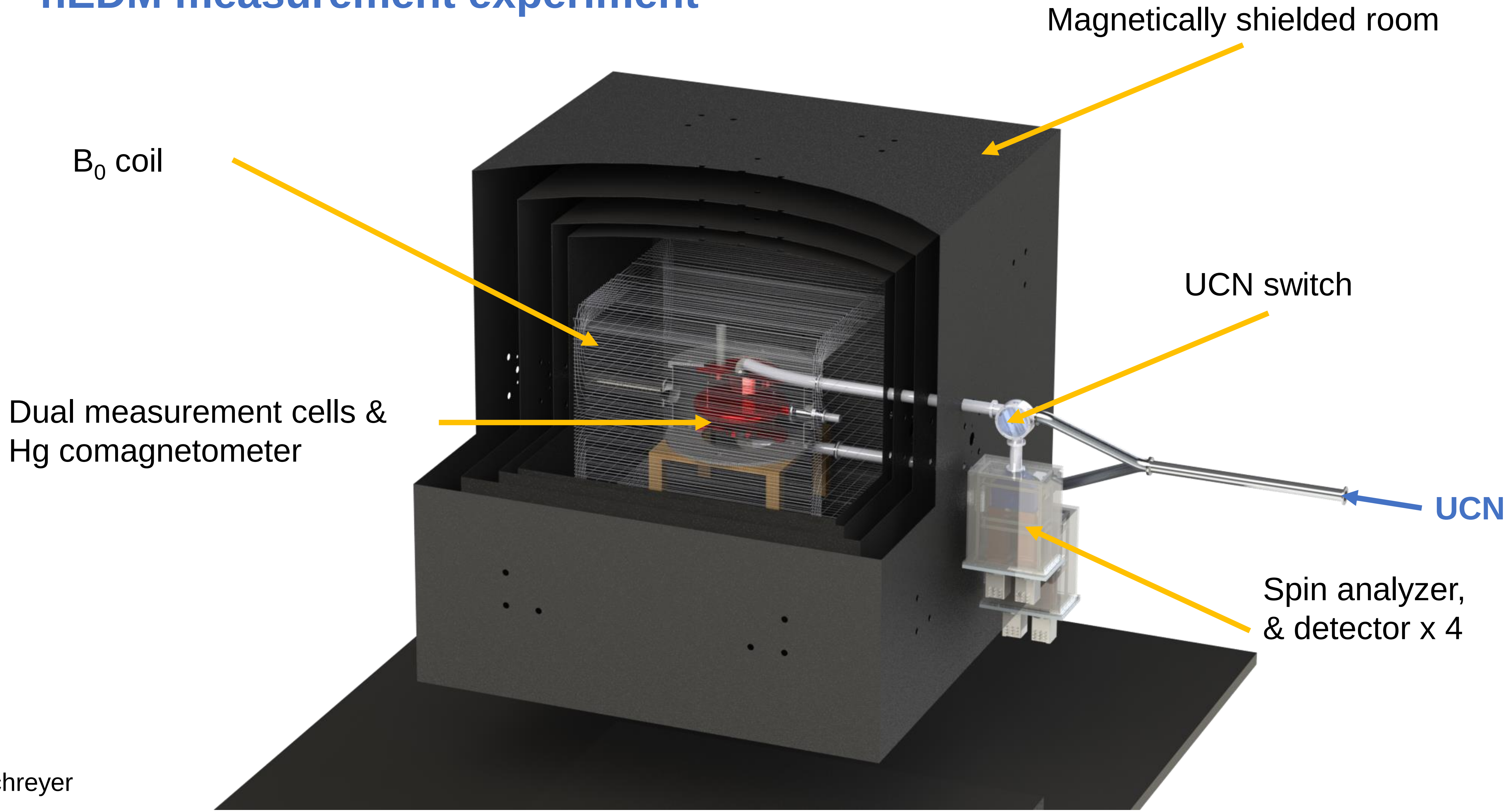
- Natural Helium
- Helium-3
- Isopure Helium-4

This challenge implies state-of-the-art:

- Cryostat
- ^{nat}He liquefier
- Liquid ^{nat}He transfer line
- Cryostat
- Heat exchanger
- Pump
- ^{3}He and ^{4}He gas handling
- …


Shielding
LD₂ cryostat
³He cryostat
UCN
HEX1 heat exchanger
Tail section
Cryo-connection box
TARGET
Shielding

nEDM measurement experiment



W. Schreyer

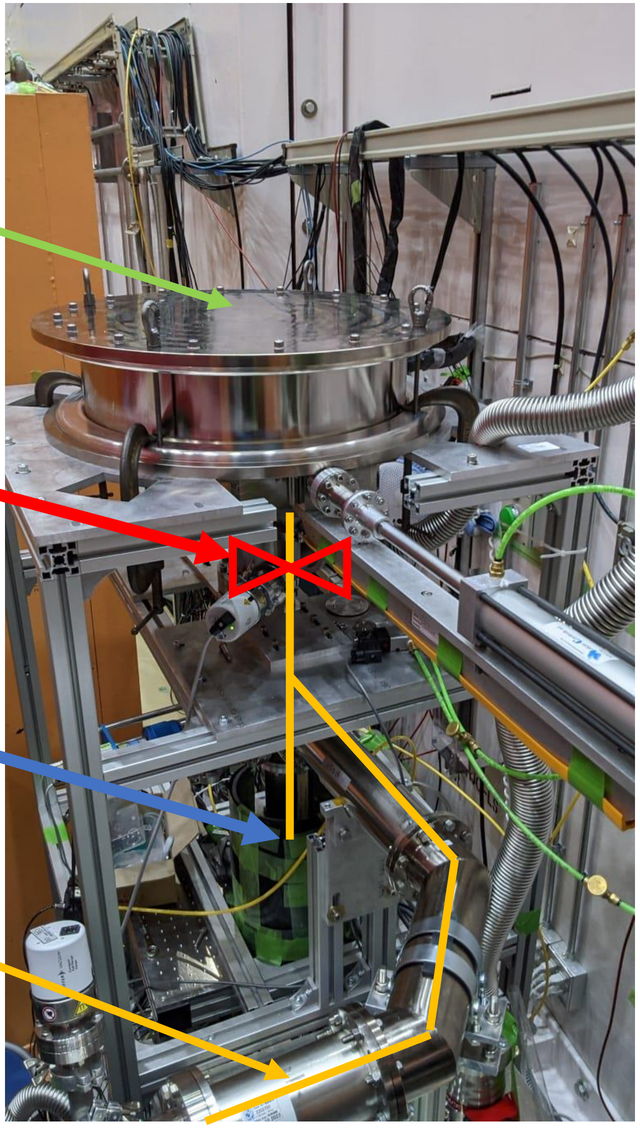
Precession cell: UCN storage test

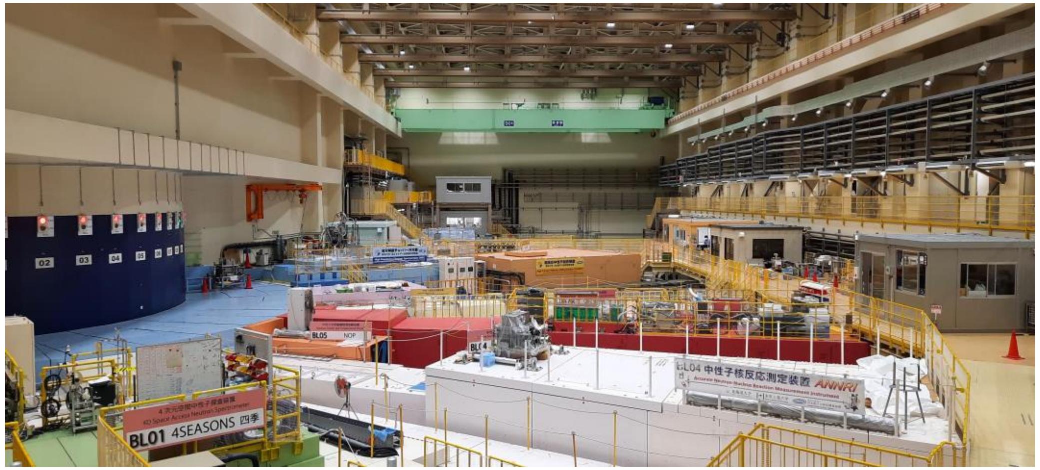
UCN Cell

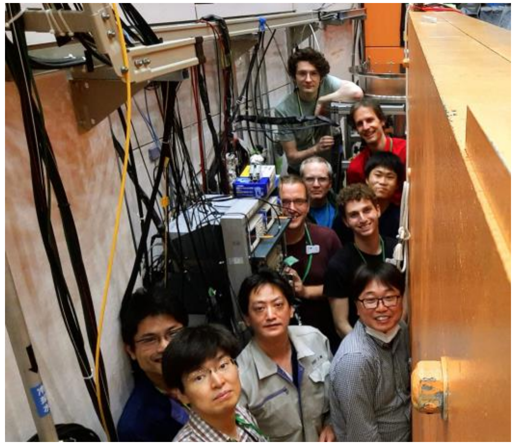
UCN Valve

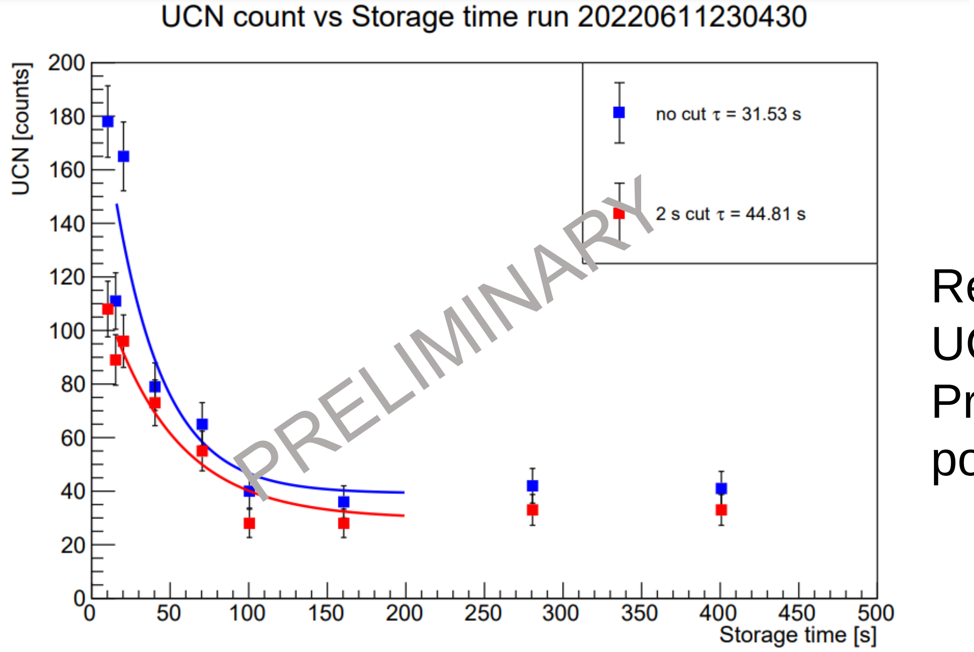
^{3}He detector

UCN



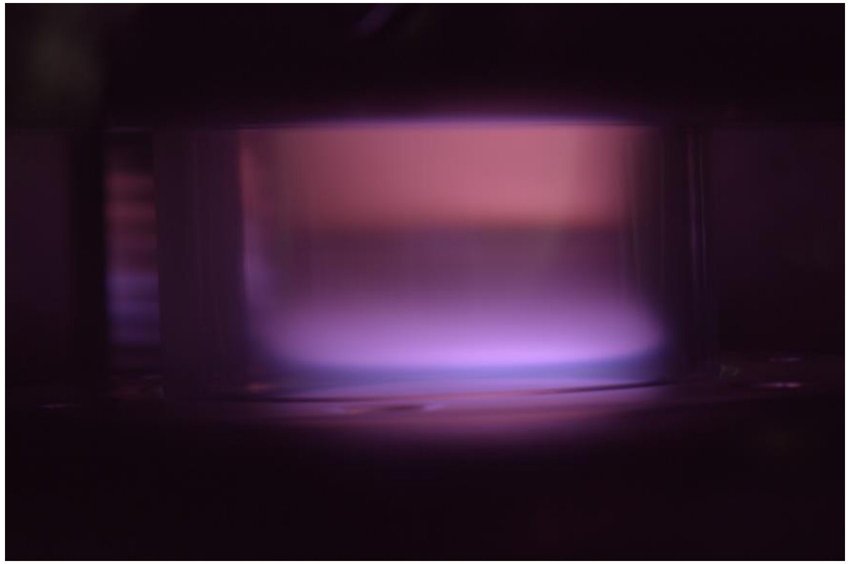


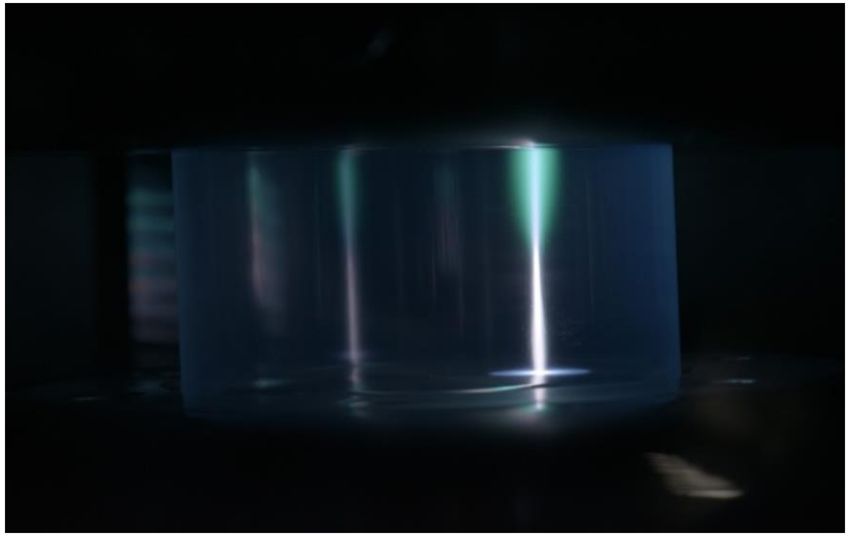




Recently tested at J-PARC UCN source:
Prototype cell & valve, polarizers, detectors

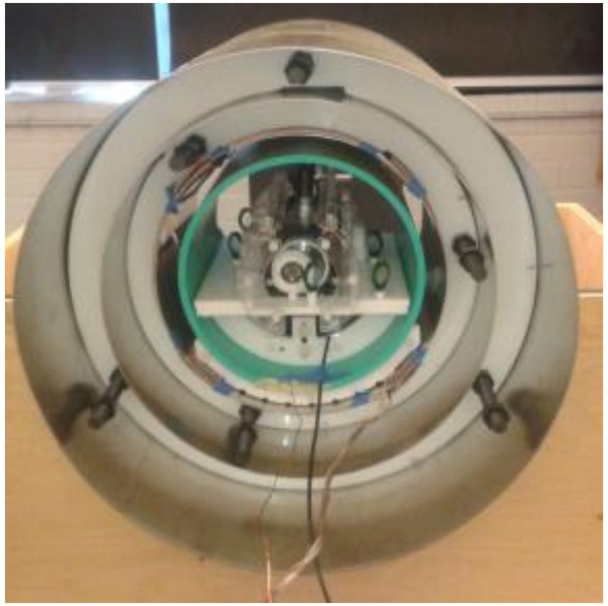
Precession cell: Electrical properties:

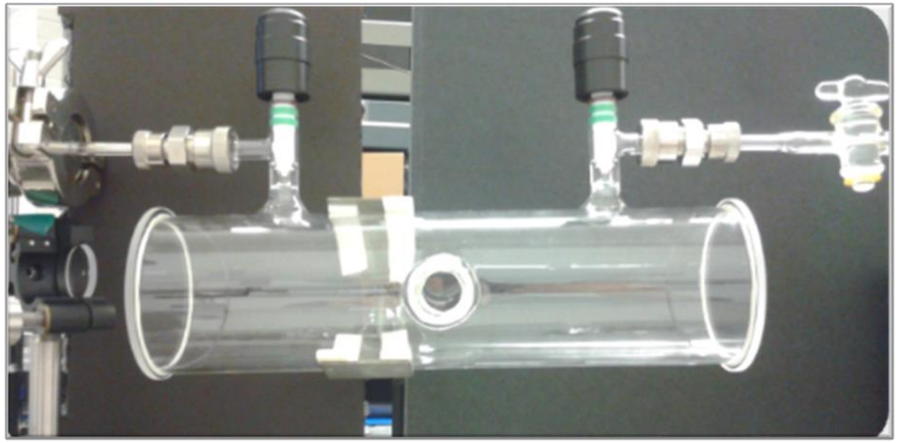




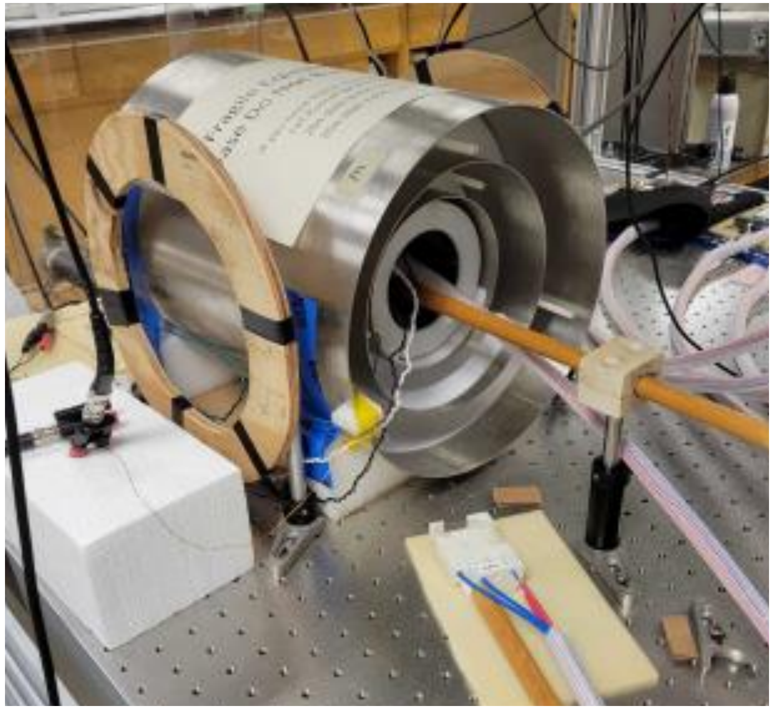
HV discharge testing of electrodes, insulators, coatings, comagnetometer gases.

Magnetometry

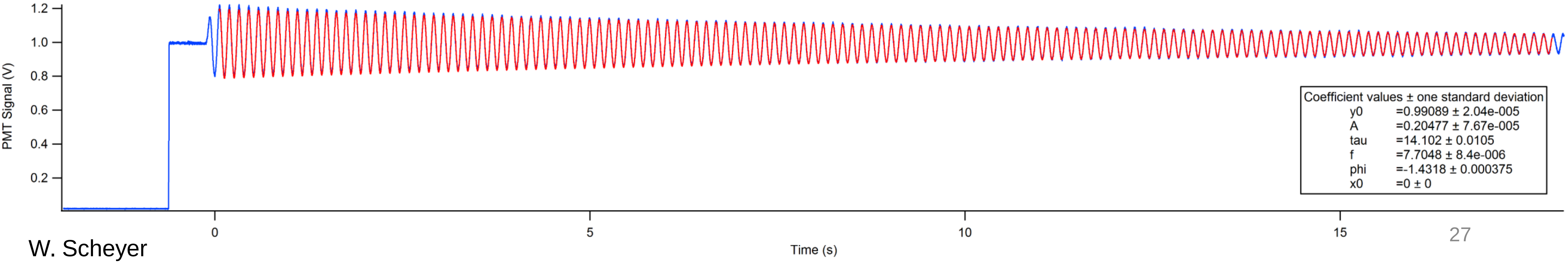




Hg comagnetometer prototype achieved 10s free precession, 1 pT resolution
Goal: 10 fT

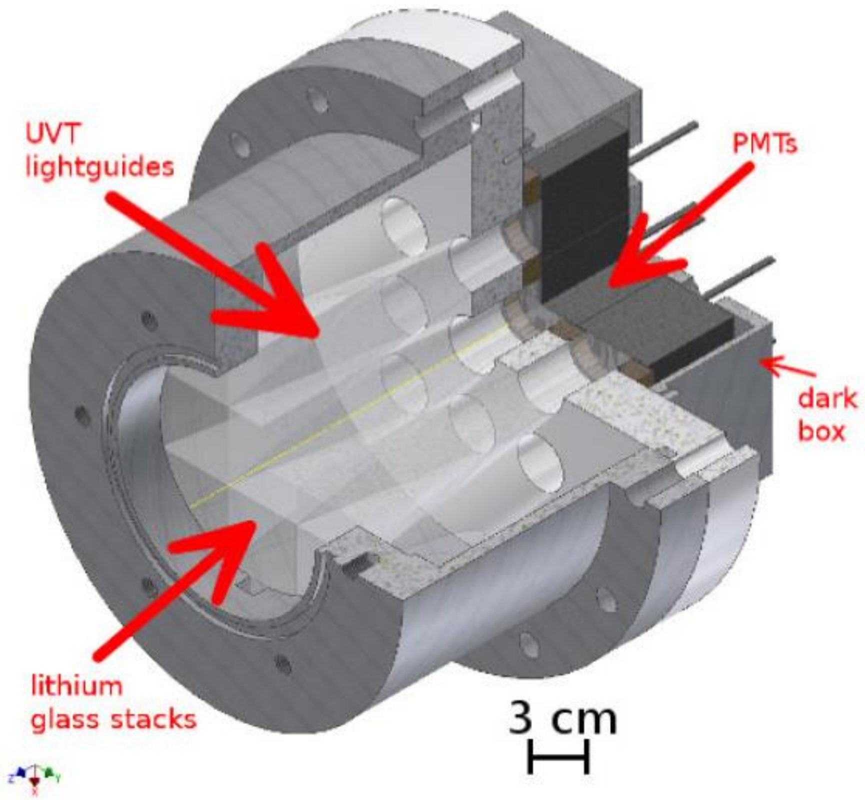


Operating 5 optical Cs magnetometers & 5 more on order



W. Scheyer

UCN detection



Scintillating stacks Lithium detector:

^{6}Li + $n \rightarrow \alpha$(2.05MeV) + t(2.73MeV)

The upper layer is 60 μm thick depleted ^{6}Li glass (0.01 %), and the lower layer is 120 μm thick doped ^{6}Li (95 %) glass. Ensure energy deposition in scintillating glass.

Fast signal 6 ns rise time 55 ns fall time allows for MHz detection.
89.7 % efficiency