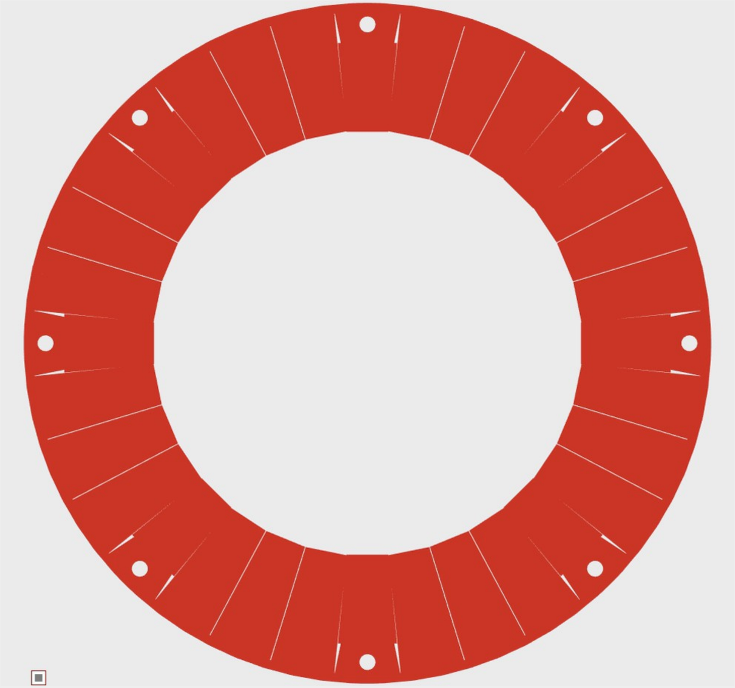
Simulating ultra cold neutron storage and lifetime measurement in a fully magnetic trap



Sylvain Vanneste (svannest@uni-mainz.de)
for the τSPECT collaboration

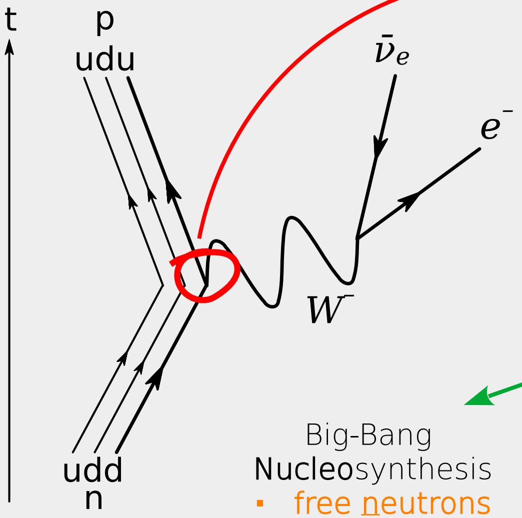
GRD-inf 2024

PRISMA+

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

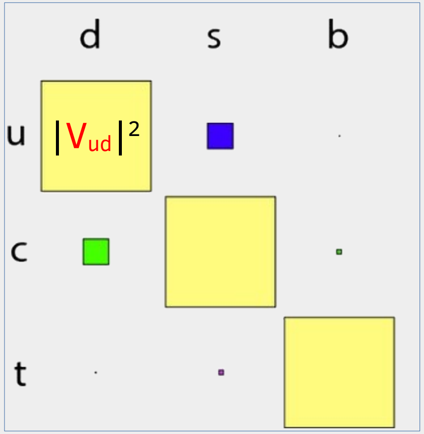
The free neutron lifetime τ_n quantity

Beta decay
neutron → proton



$d \rightarrow u$ quark flavour changing probability $\propto |V_{ud}|^2$
Free neutron lifetime $\tau_n \propto 1 / |V_{ud}|^2$

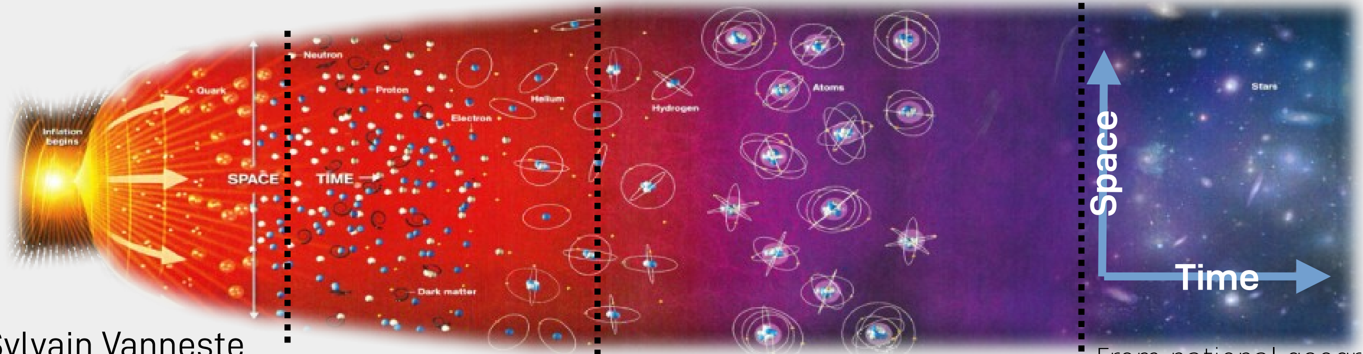
Cabibbo–Kobayashi–Maskawa (CKM) matrix



Big-Bang Nucleosynthesis
- free neutrons
- free protons

1^{st} atoms:
Hydrogen (p) vs Helium (p+n)

1^{st} large sturctures



From national geography

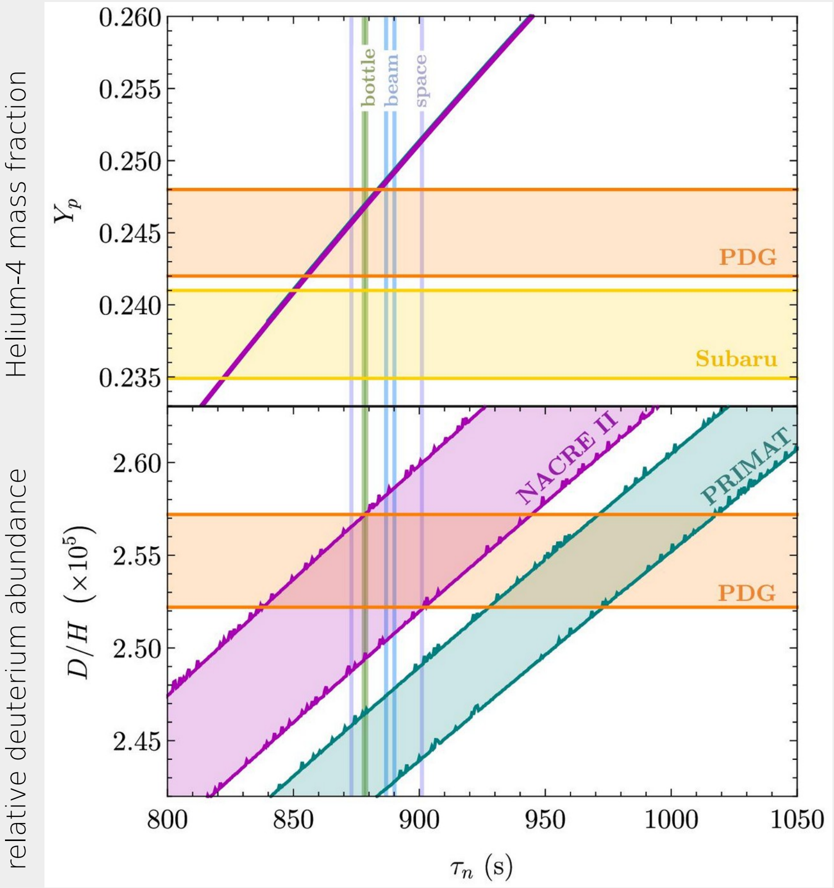
Unitarity: $\sum$ probabilities = 1
$\rightarrow |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$
Test for Standard Model deviation

Sylvain Vanneste

DOI:10.1088/1742-6596/631/1/012005

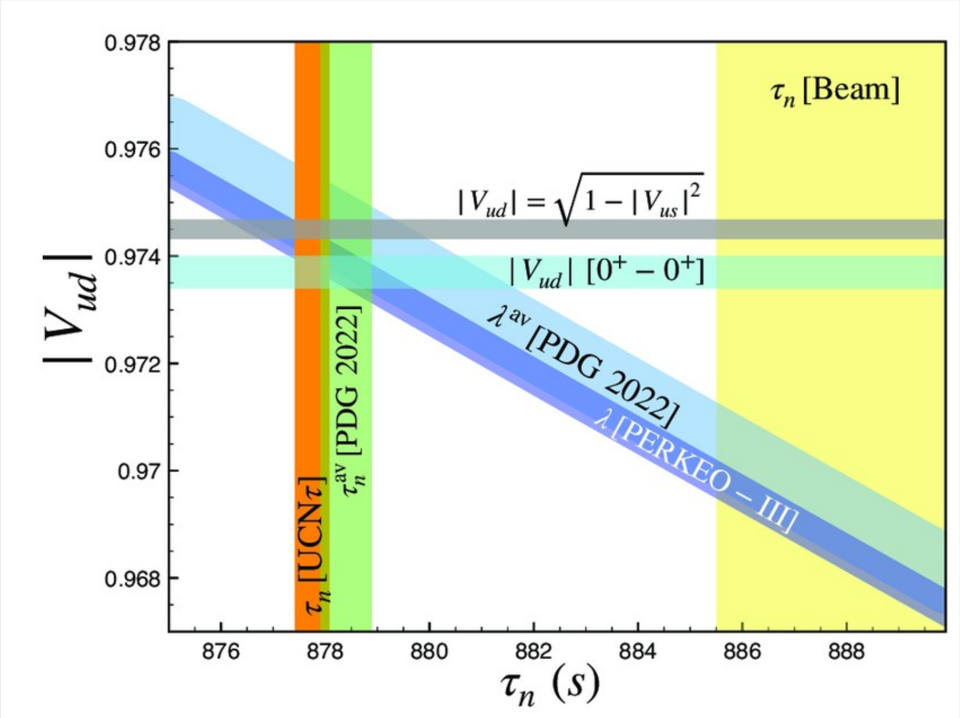
Hot motivations for the free neutron lifetime τ_n measurement

Primordial element in early Universe



https://doi.org/10.1139/cjp-2023-0188

u ↔ d quark flavor mixing amplitude



10.3390/universe9090422

$$\lambda \equiv g_A/g_V$$

- g_A axial coupling constant
- g_V vector coupling constant

$$|V_{ud}|_n^2 \propto \frac{1}{\tau_n(1+3\lambda^2)}$$

Experimental methods

Two experimental methods :

- Beam : counting the dead
  ($n \rightarrow p + e + \nu_e$)

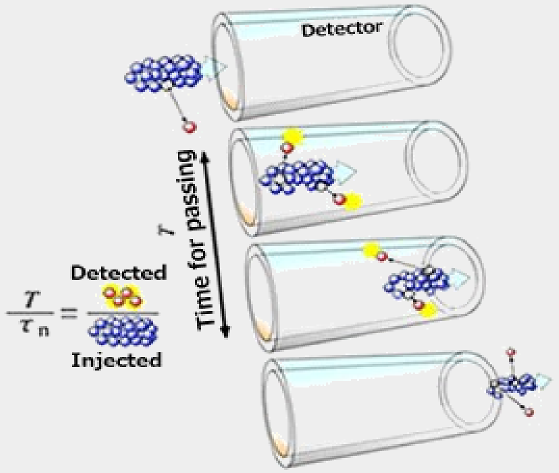
- Bottle : counting the survivors

Methods disagree → *Neutron lifetime puzzle*

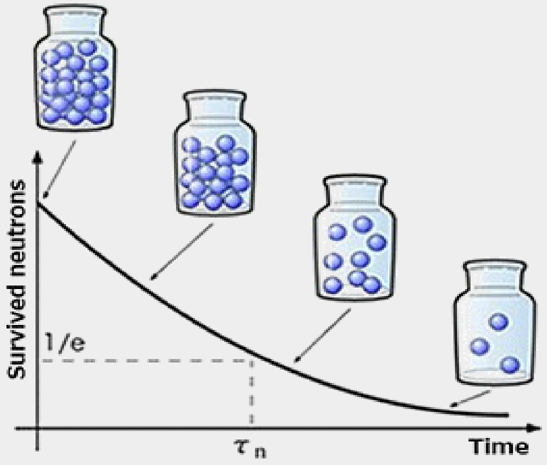
- Unknown systematic error(s) ?

- Exotic neutron decays ?

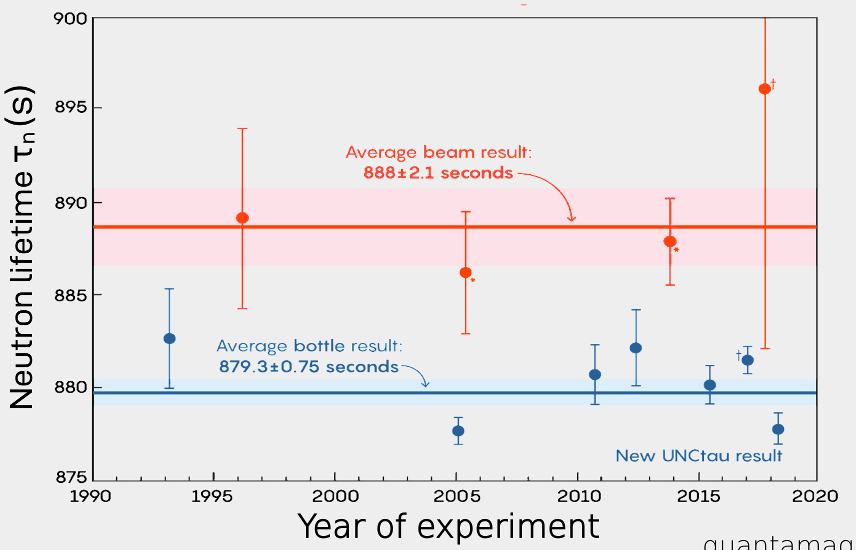
Beam method



Bottle method



icepp.s.u-tokyo.ac.jp

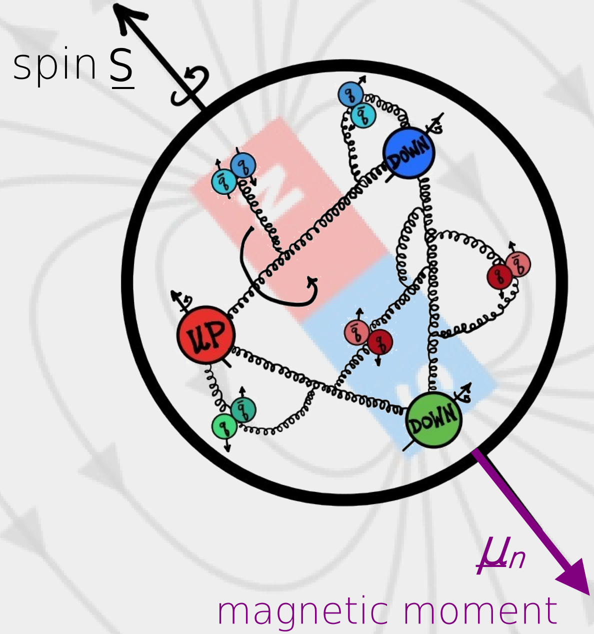


quantamagazine.org

Master of the four interactions

www-nsd.lbl.gov

Ultra Cold Neutron (**UCN**) : speed $v \lesssim 8$ m/s → Kinetic Energy $E_k \lesssim 350$ neV



Weak interaction :

Lifetime : $\tau_n \simeq 880$ s

Strong interaction :

Coherent interaction with nuclei

→ effective optical "Fermi" potential V_F

Material	V_F (neV)
Al	54
Steel	183
NiMo	300

Gravitational interaction :

$F_g = g \cdot m_n$ $\rightarrow \Delta E \simeq \Delta z \cdot 102$ neV/m

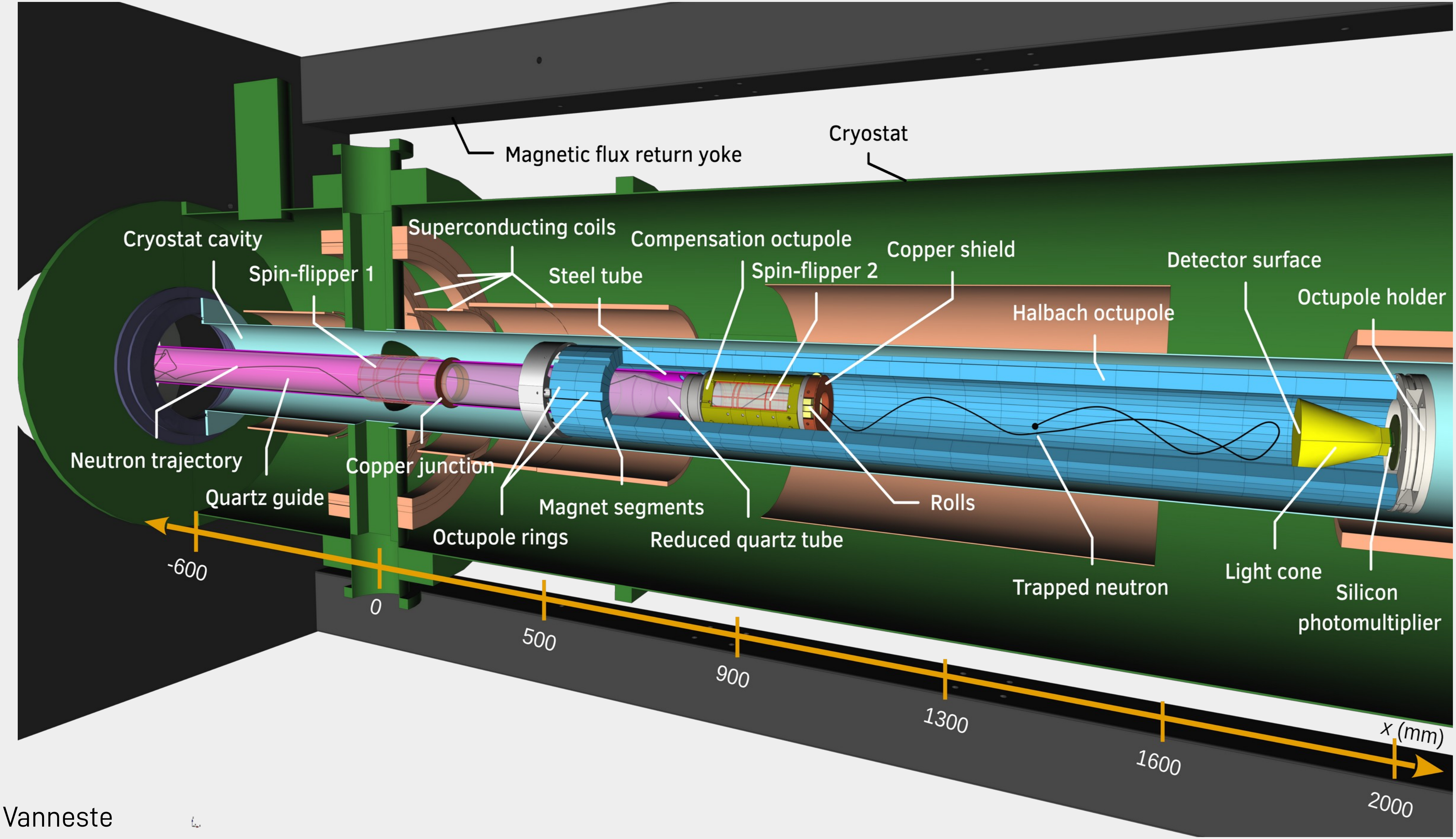
Electromagnetism interaction :

$F_m = p \cdot \mu_n \cdot \nabla|\underline{B}|$ $\rightarrow \Delta E \simeq \Delta|B| \cdot 60$ neV/T

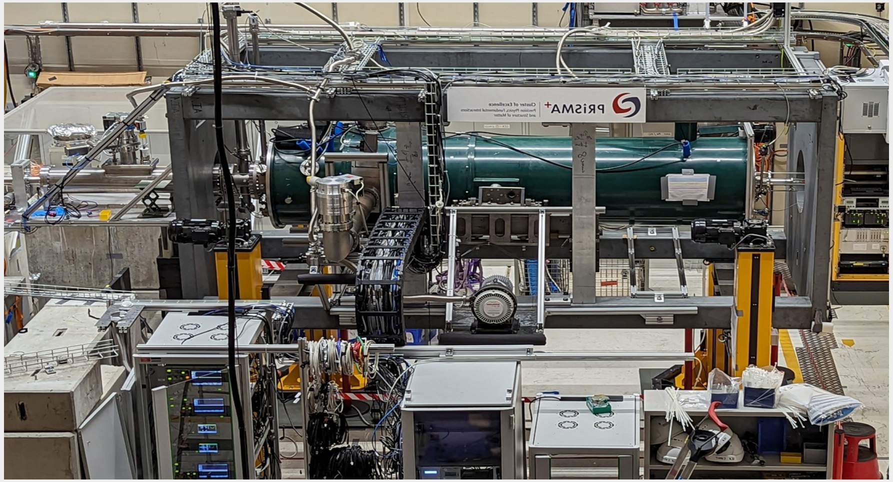
↳ polarization $p = \text{sign}(\underline{S} \cdot \underline{B})$

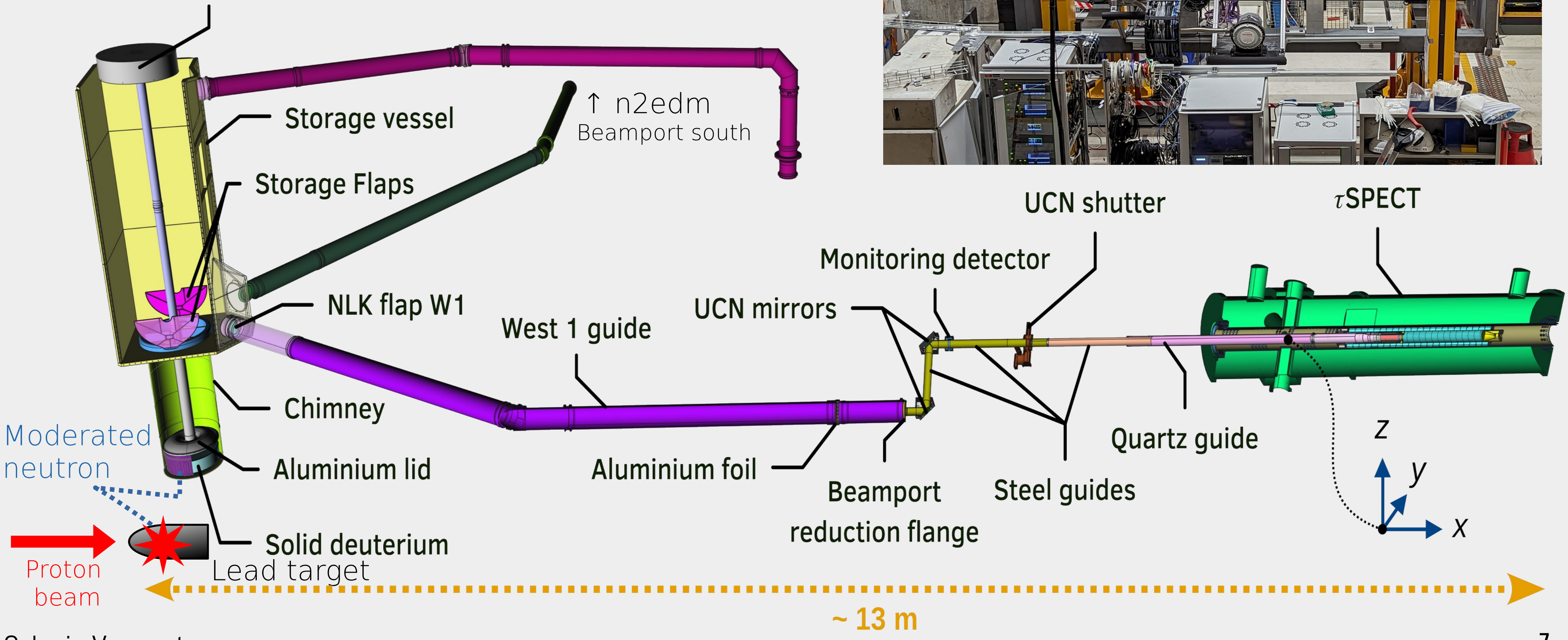
- High Field Seeker (HFS) : $\underline{S}\uparrow\downarrow\underline{B}$ → $p = -1$
- Low Field Seeker (LFS) : $\underline{S}\uparrow\uparrow\underline{B}$ → $p = +1$

τSPECT cut view

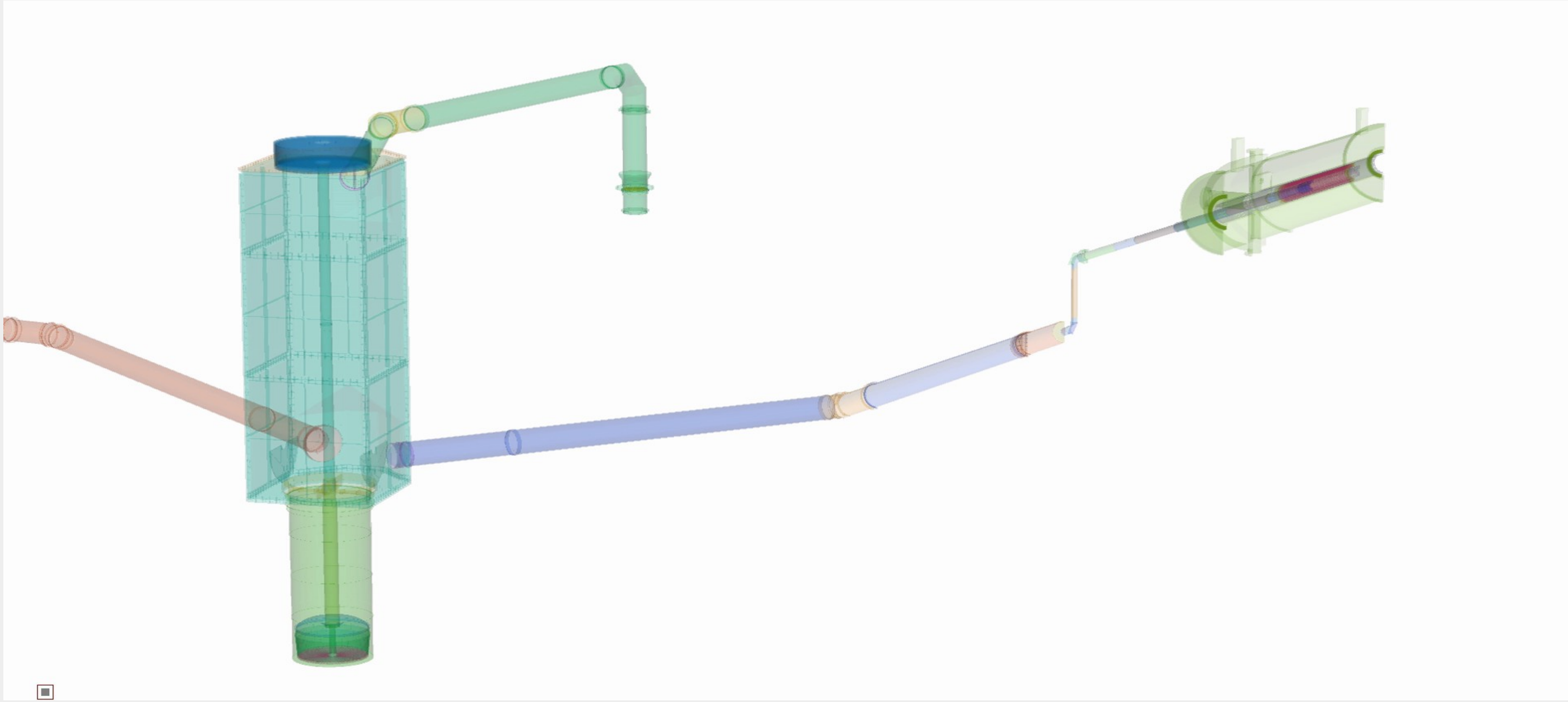


τSPECT & UCN source at PSI





Measurement cycle



→ https://gitlab.rlp.net/tauSPECT/penplot

Simulation framework receipe

UCN MC simulation : PENTrack (C++):

(http://dx.doi.org/10.1016/j.nima.2017.03.036 & https://github.com/wschreyer/PENTrack)

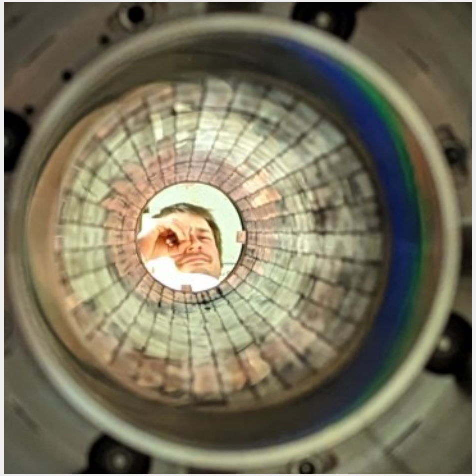
- Computes:
  - Trajectories of UCN + decay products.
  - Spins precession in EM fields.
  - Interaction with matter (Fermi potential) + diffuse scattering models.

- Input:
  - UCN initial distributions : energy, time, position ...
  - Geometries : freeCAD https://www.freecad.org/
  - Fields : open source python package magpylib https://doi.org/10.1016/j.softx.2020.100466
    - Meshes contains *B* value and relevant derivatives for tricubic interpolation

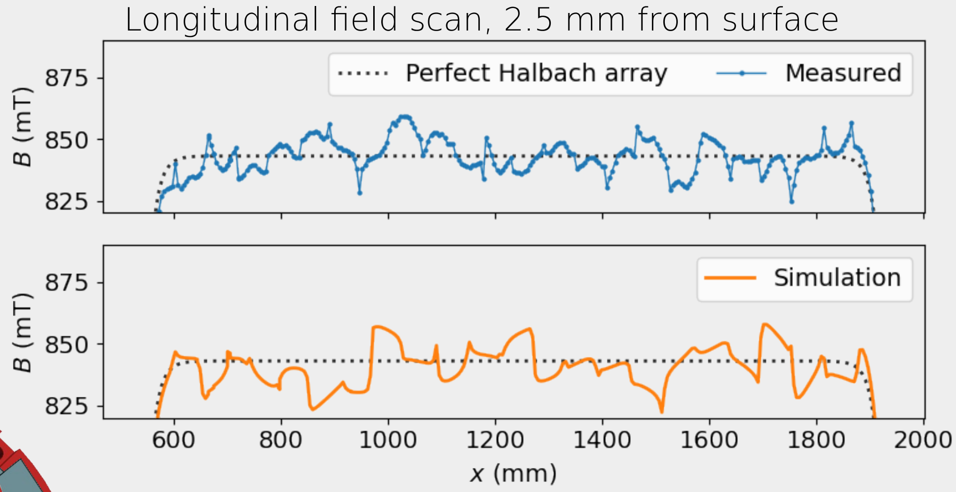
Compagnions modules (python):

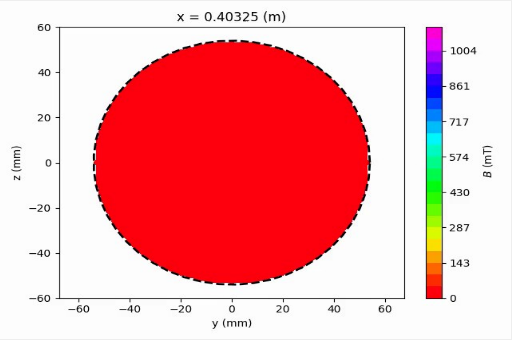
- penconf: manage configuration files for pentrack. https://gitlab.rlp.net/tauSPECT/penplot
- penplot: data manipulation, 3d plots, and animations. https://gitlab.rlp.net/tauSPECT/penconf

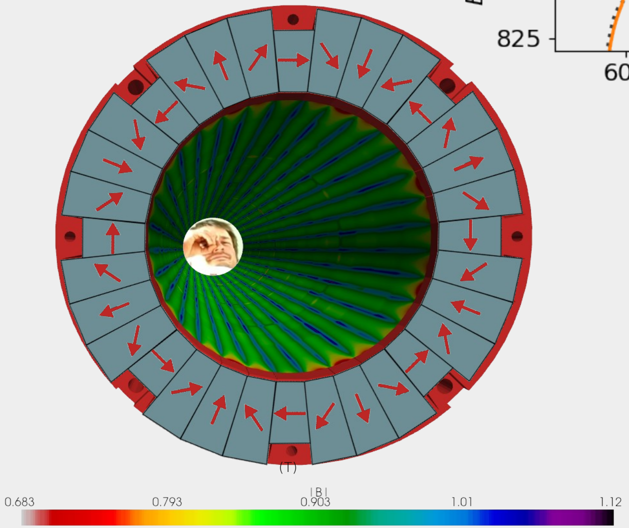
Halbach octupole



- 32 permanent magnet segments in a ring (Sm_2Co_{17}),
- 24 rings,
- 54 mm inner radius
- 1380 mm long







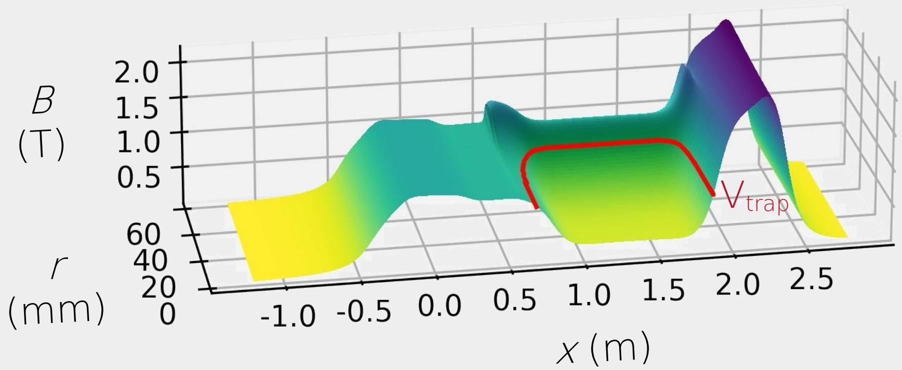
Random perturbation of each segment's

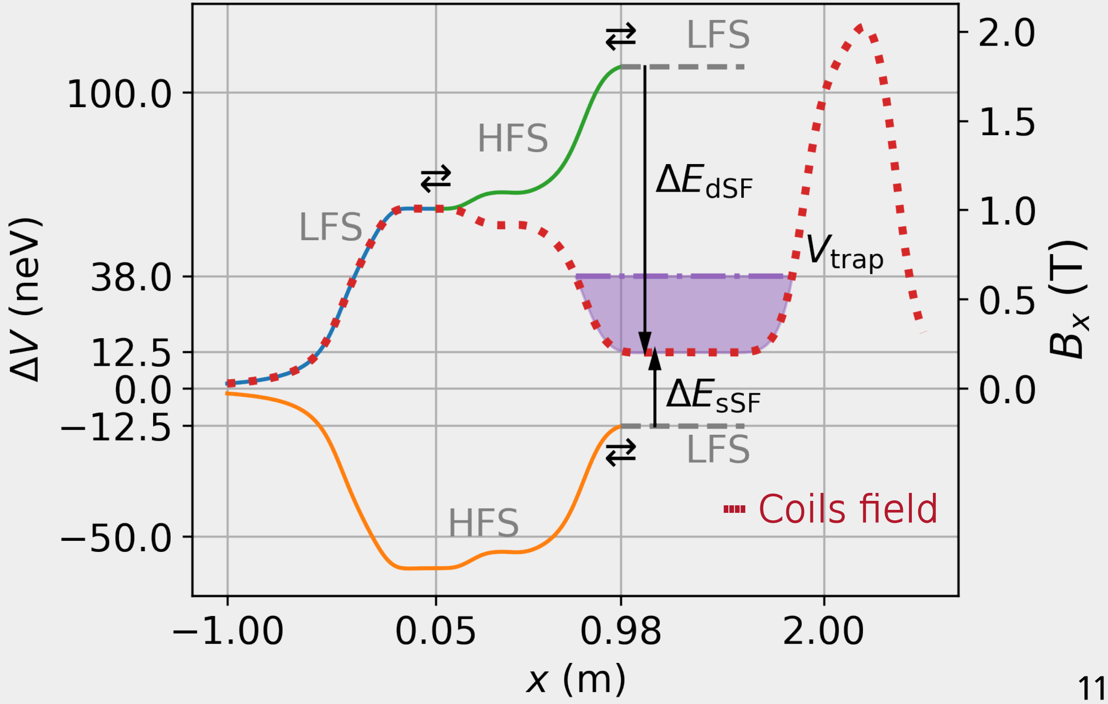
- magnetisation orientation and amplitude,
- position,
- dimensions

Sylvain Vanneste

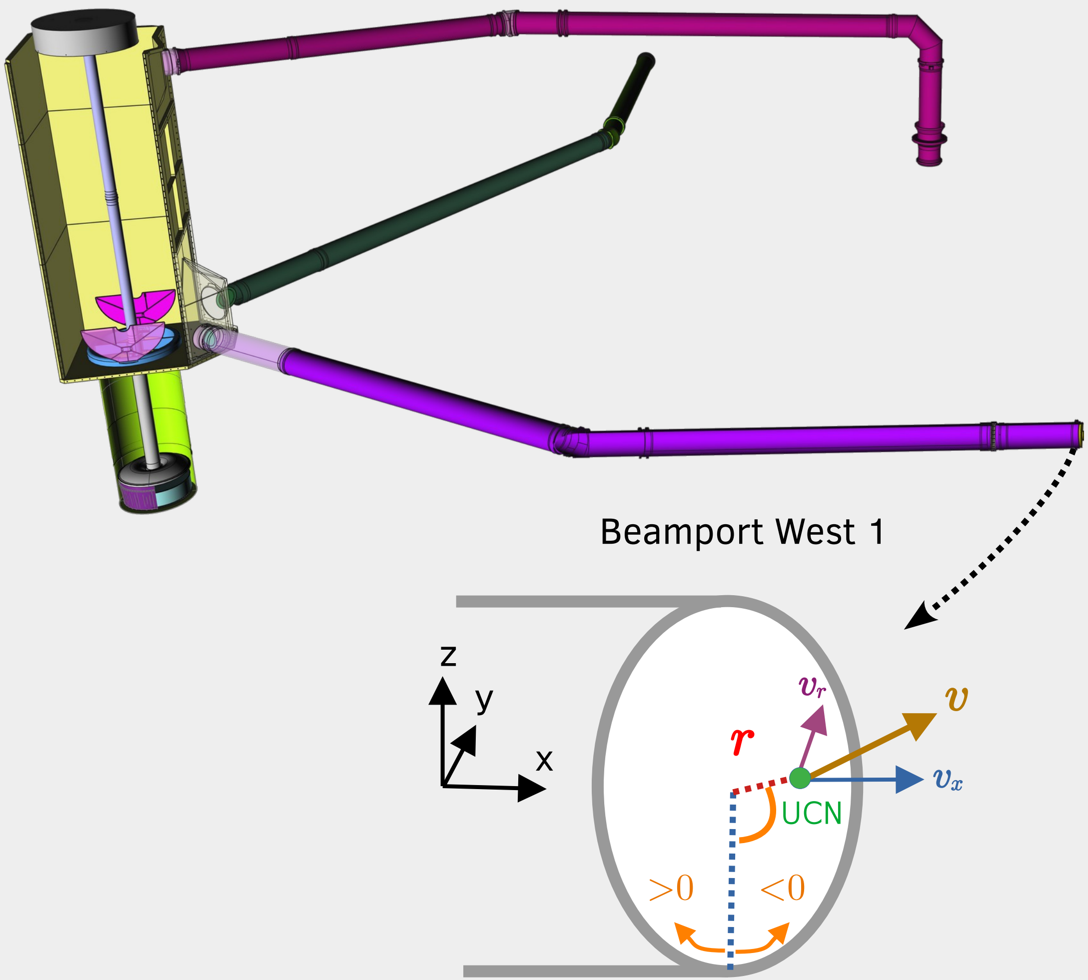
Spin-flip & energy acceptance

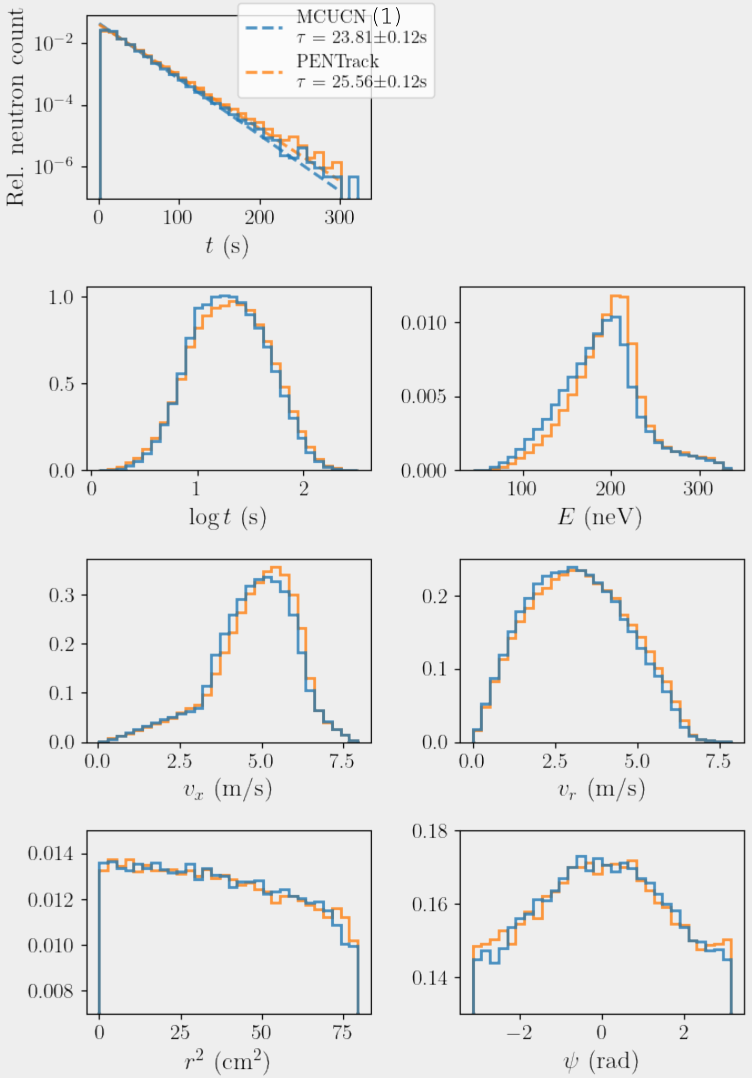
- Trap potential depth : $V_{\mathrm{trap}} = \min(V_{\mathrm{magnetic}} + V_{\mathrm{gravity}})|_{r=R_i} \simeq \underline{38\,\mathrm{neV},}$
- Storable neutrons with **single spin-flip** (sSF), total energy : $H_{\mathrm{sSF}} \in [0, V_{\mathrm{trap}} - \Delta E_{\mathrm{sSF}}] \simeq \underline{[0, 13]}\,\mathrm{neV}.$
- For **double spin-flip** (dSF) : $H_{\mathrm{dSF}} \in [\Delta E_{\mathrm{dSF}}, V_{\mathrm{trap}} - \Delta E_{\mathrm{dSF}}] \simeq \underline{[96, 134]}\,\mathrm{neV}.$





UCN distribution at PSI beamport W1



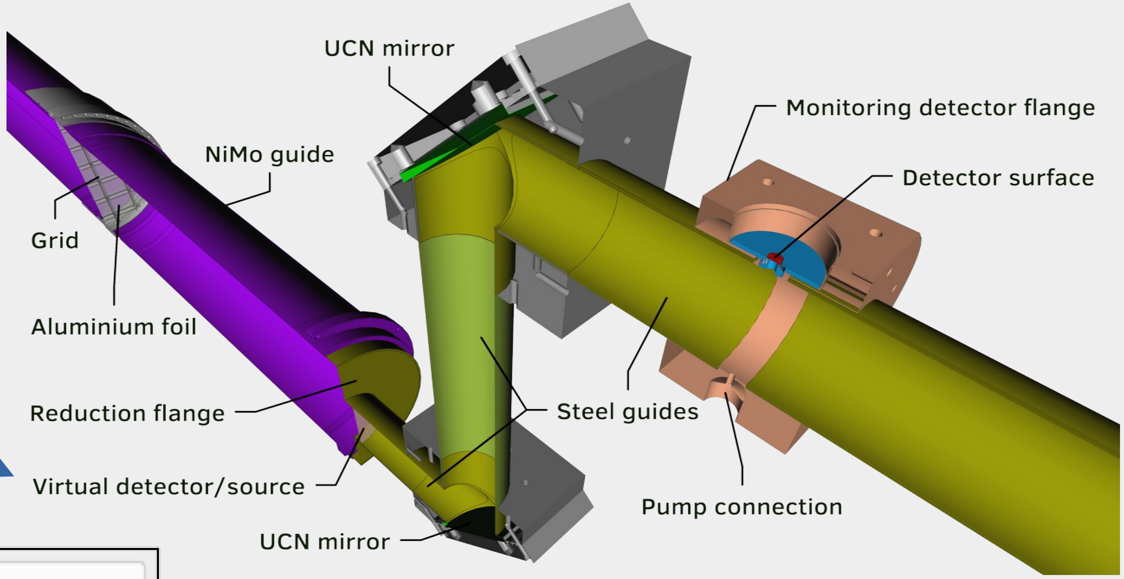


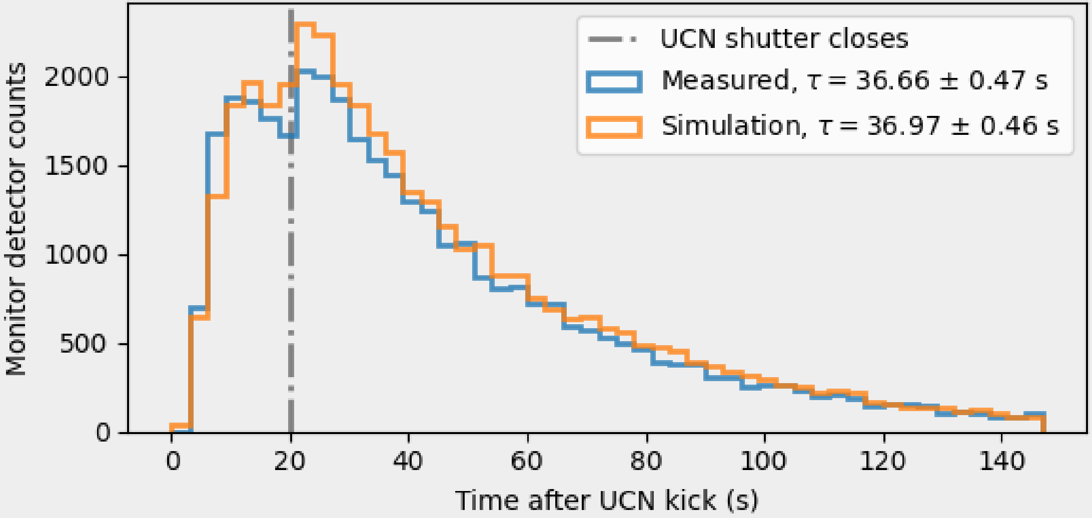
(1) https://doi.org/10.1016/j.nima.2017.10.065

Sylvain Vanneste

Monitor detector

Start τSPECT simulation from virtual source (save computation time)

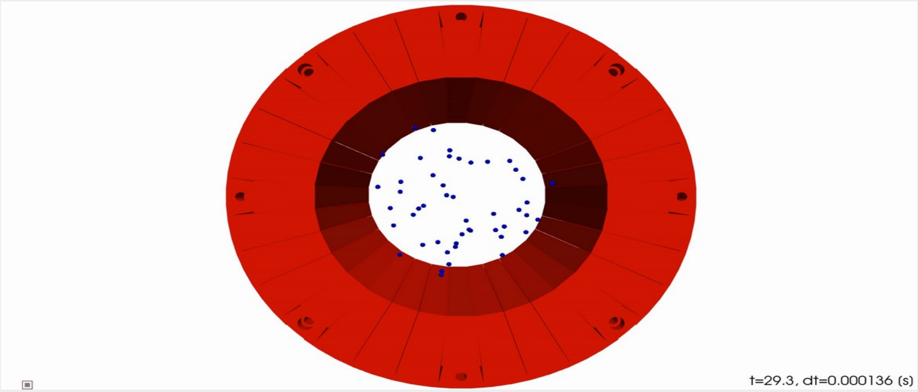


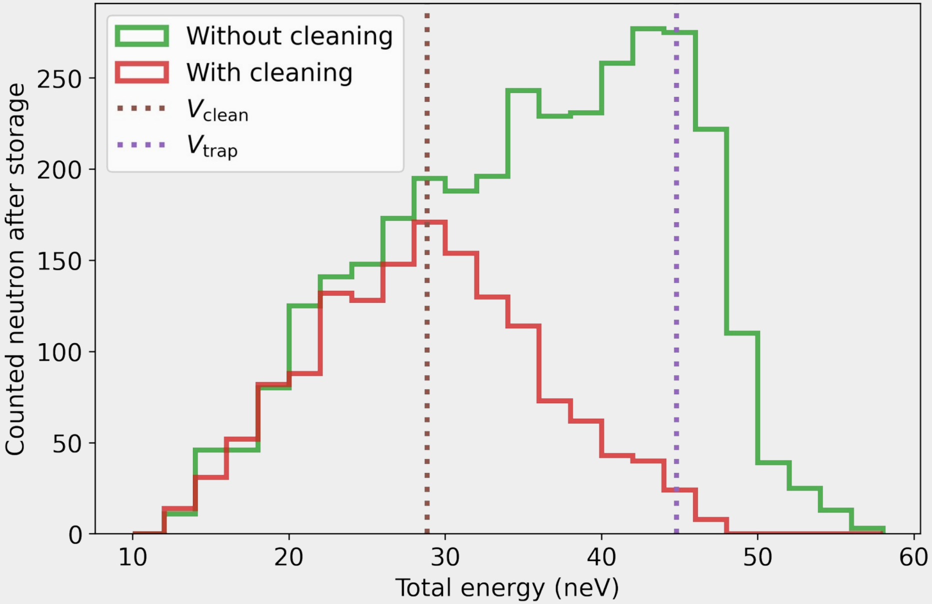


Trapped UCNs

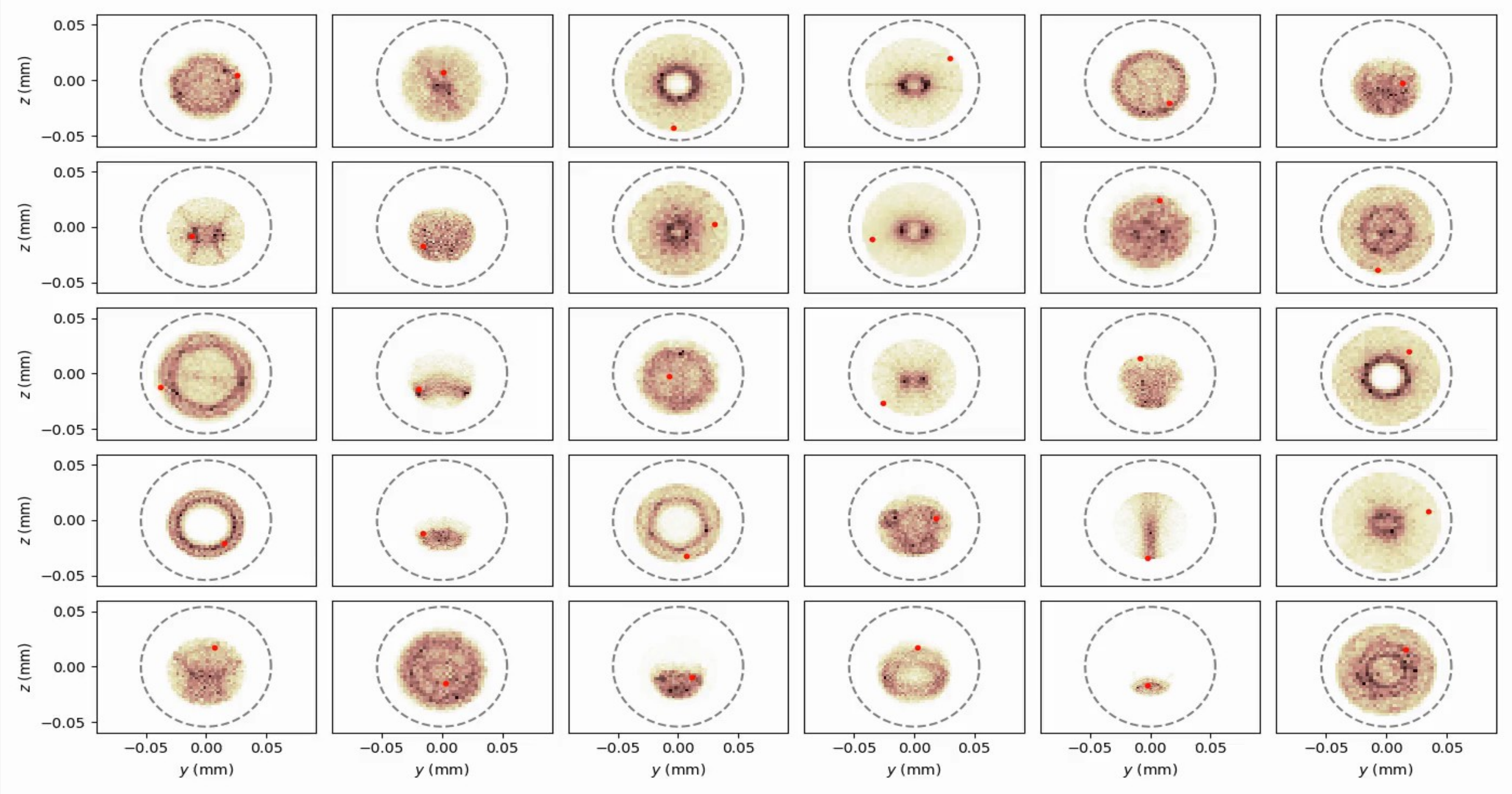
Maginally trapped UCN :

- Total energy above trap potential V_{trap}
- Can still survive very long in the trap → bias the measured neutron lifetime.
- Need to be removed → **cleaning** phase : detector is partially inserted in the trap

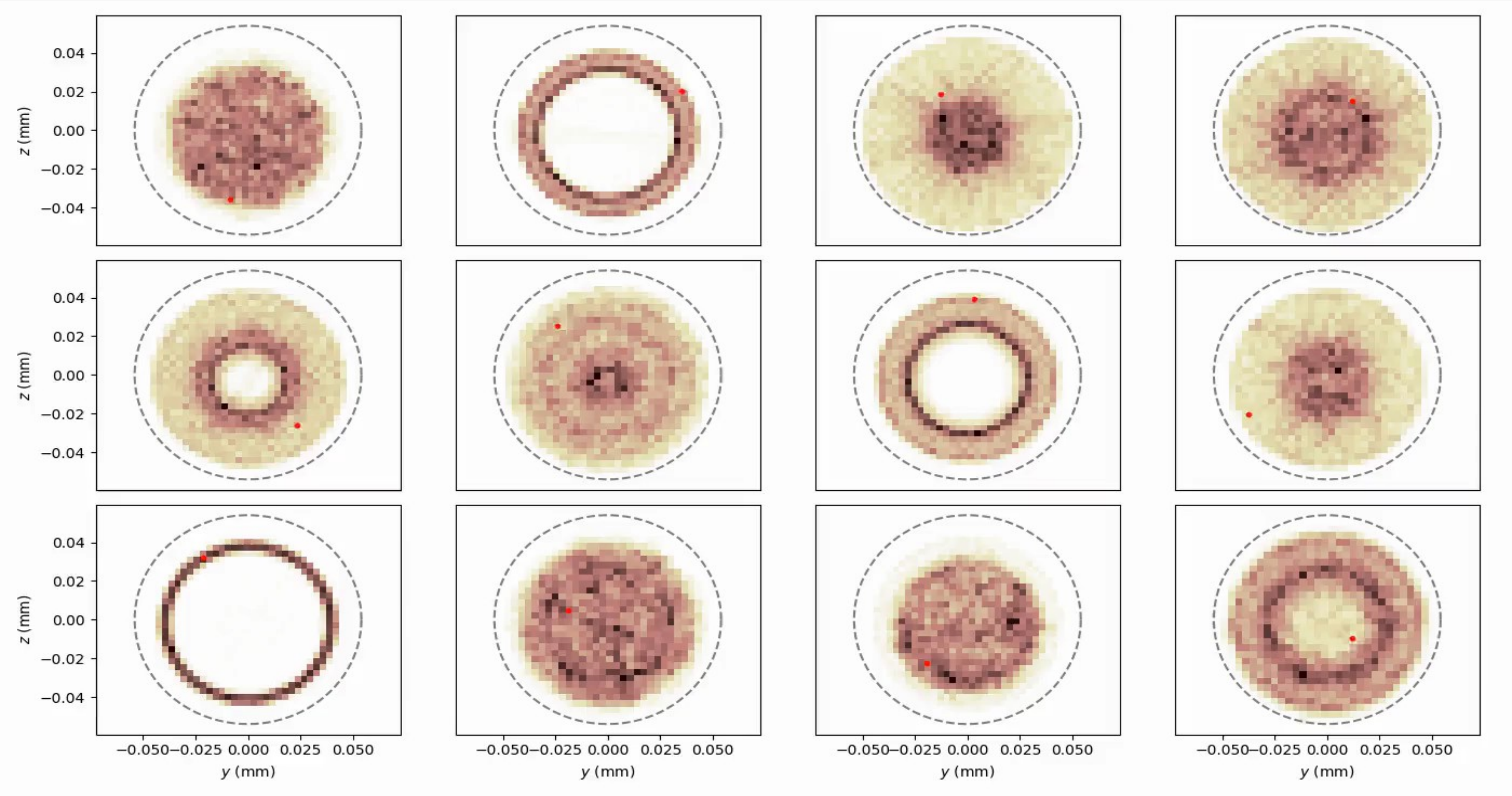




Orbits
Storable



Orbits
Marginal



UCN detector upgrades

Radial detector

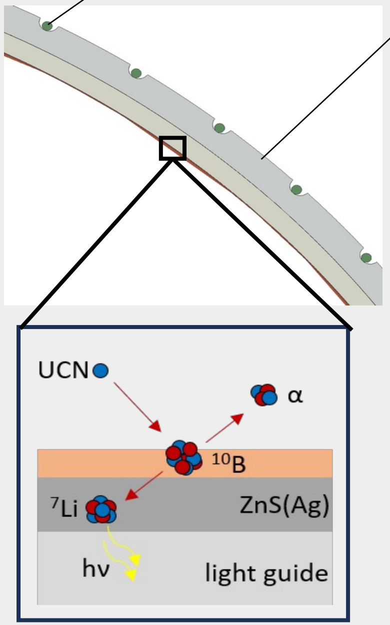
- Counts radially escaping UCNs
- Upgrade : counts electron/protons

Segmented UCN detector :

- Spatially resolves UCN counts
- Better background signal control

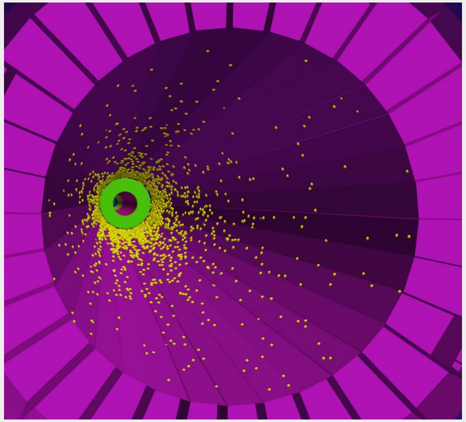
Wave length shifting fibers

Acrylic glass cylinder

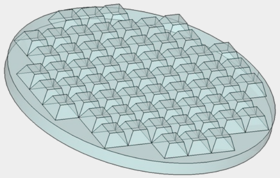


^{10}B coated scintillator foil

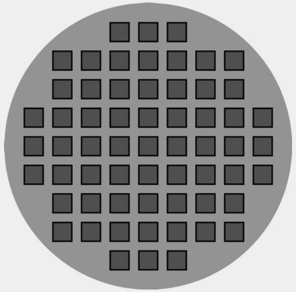
Simulated absorption on octupole



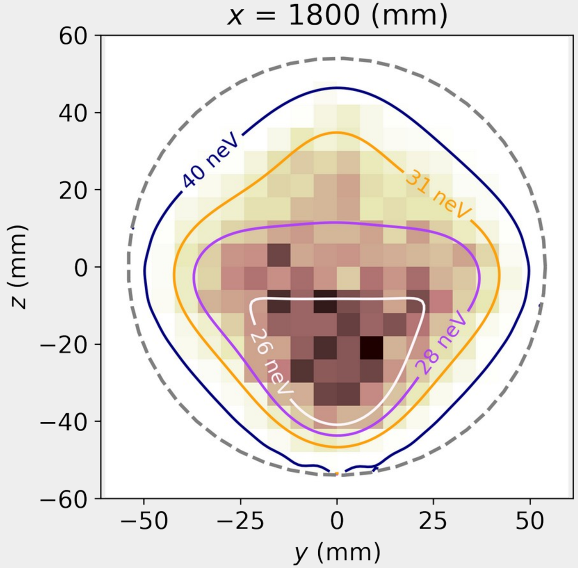
Light guides



SiPM grid

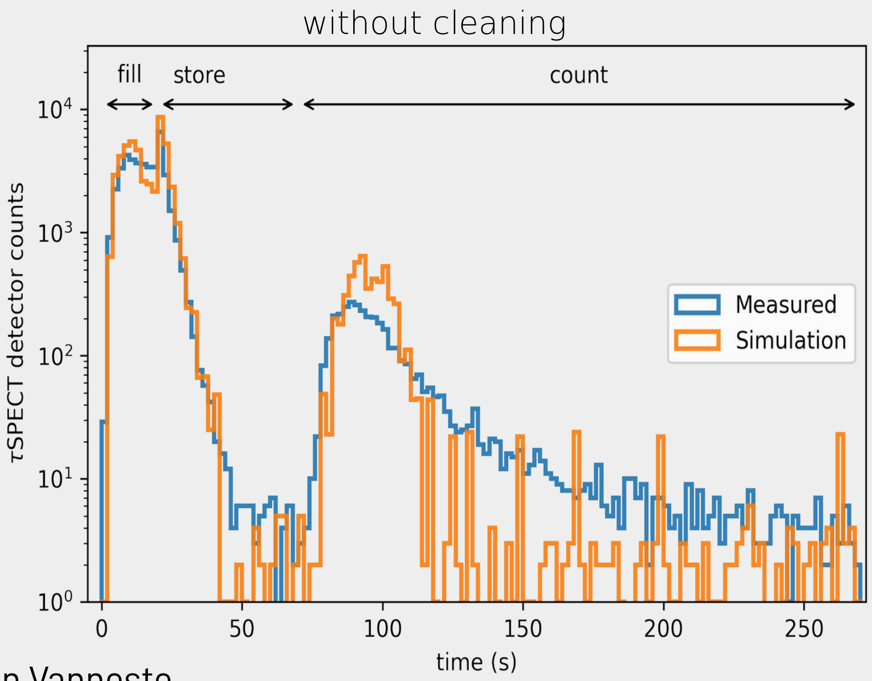


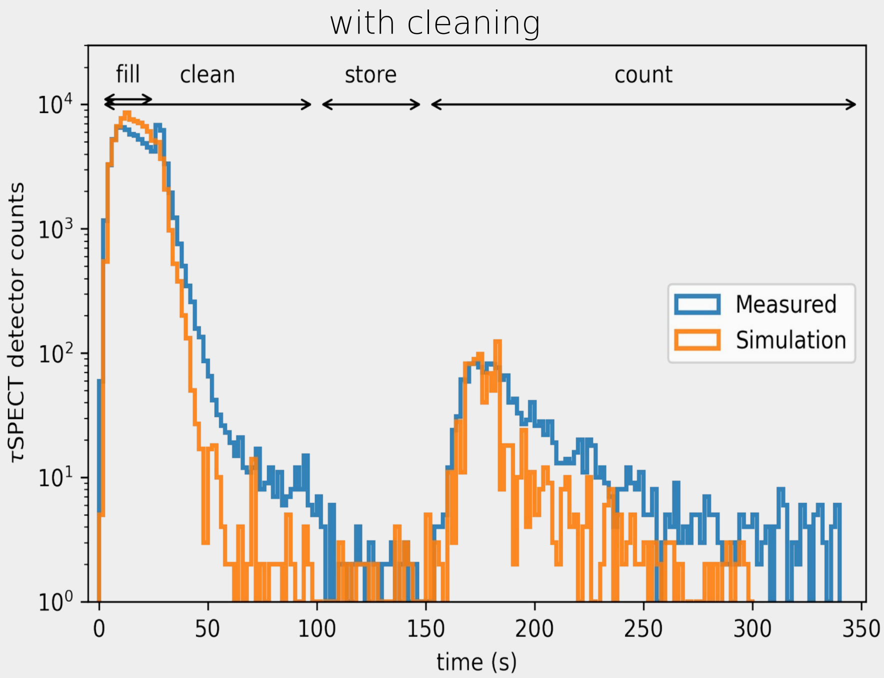
Simulated count position distribution during cleaning



Detector spectrum

- The framework can already simulate a whole measurement cycle.
- UCN simulations are never perfect,
  - Huge uncertainty on material properties
  - Needs precise mapping of octupole field





Simulation summary & outlook

Status :

- End-to-end UCN MC simulation framework for τSPECT.
- Consistent results with subsystems.
- Helps to better understand the experiment.

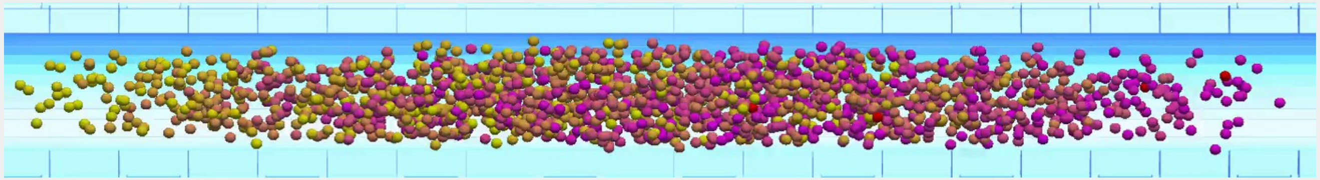
Short term :

- Speed up simulations, improve statistics, port to computer cluster.
- More accurate moving geometries, and octupole field mapping.
- Compare and fine-tune with recent comissionning data at PSI.

Long term :

- Optimize data taking,
- Guide analysis pipline.
- Identify systematic uncertainties.
- Guide future upgrades and next-generation of experiment

PRiSMA+



JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Sylvain Vanneste (svannest@uni-mainz.de)
for the τSPECT collaboration
GDR-inf 2024

Spin-flipping units