NUCLEAR SAFEGUARDS:
MONITORING OF SPENT NUCLEAR FUEL

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Nuclear Verification and Disarmament

III. Physikalisches Institut B

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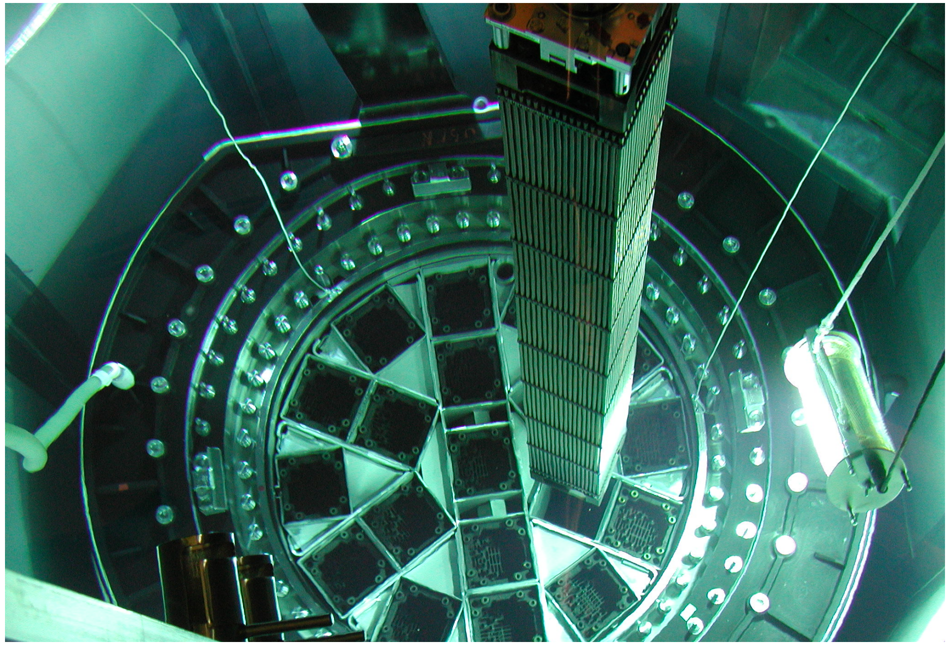
*Nuclear Technology Review 2021, GC(65)/INF/2, IAEA Report, https://www.iaea.org/sites/default/files/gc/gc65-inf2.pdf

Introduction: Spent Nuclear Fuel

- Spent Nuclear Fuel (SNF) produced by reactors
  - Total global SNF: ~300,000 t HM* + ~7,000 t HM annually
- Discharged SNF after refuelling goes to:
  - **Spent fuel ponds** (several years)
  - **Interim storage** facilities (several decades) or **reprocessing**
  - Ultimately: **geological repository** (none yet – Onkalo starting ’25, ~100 years operation)
- Even without operating reactors:
  - **Decades to centuries** of actively managing SNF



Fuel assembly containing SNF being loaded into a cask
https://www.gns.de/language=de/21562/behaelterbeladung

Safeguarding Spent Nuclear Fuel

- SNF requires safeguards:
  - Mostly ^{238}U (93-96%), but also: <1% ^{235}U, ~1% Pu
    → interim storage & final disposal **subject to safeguards**

- Current safeguards often rely on **Continuity of Knowledge** (CoK)
  - Nuclear material accountancy
  - Containment/Surveillance (C/S)
  - Design information verification (DIV)

- Declarations verified by **regular inspections**
  → Operational/radiological burden on facility operators/staff
  → Interested in methods to fulfil obligations with less intrusion

Material	In SNF
^{238}U	93-96%
^{235}U	<1%
Fission fragments (e.g. ^{90}Sr)	3-5%
Pu	~1%
Minor actinides	<1%

ZWILAG Zwischenlager Würenlingen AG

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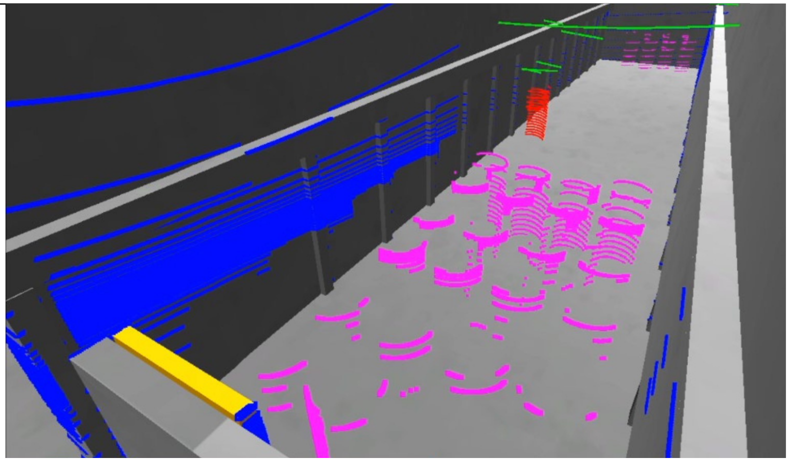
Ongoing Safeguards R&D for SNF Facilities

- Re-establishing CoK (“re-verification”) in case of discrepancies or incident requires **huge effort & time**
  → Better techniques for re-verification desired!

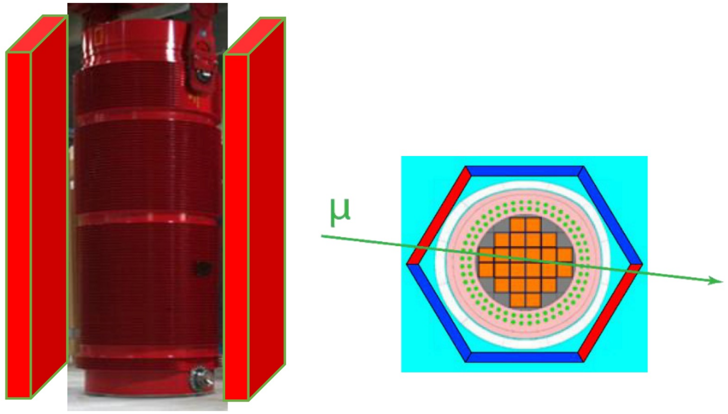
- Safeguards R&D aims
  - **Lessening** operational burden (automated/continuous/remote systems)
  - **Complement** existing methods

- Under development for interim storage facilities
  - **Improved C/S** techniques (e.g. “laser curtains”)
  - **Muon tomography** of casks (measuring content density)

- Under development for geological repositories
  - **Muon tomography** for design information verification



V. Sequeira et al., “Laser Curtain for Containment and Tracking”. Proceedings of the INMM & ESARDA Meeting 2021.

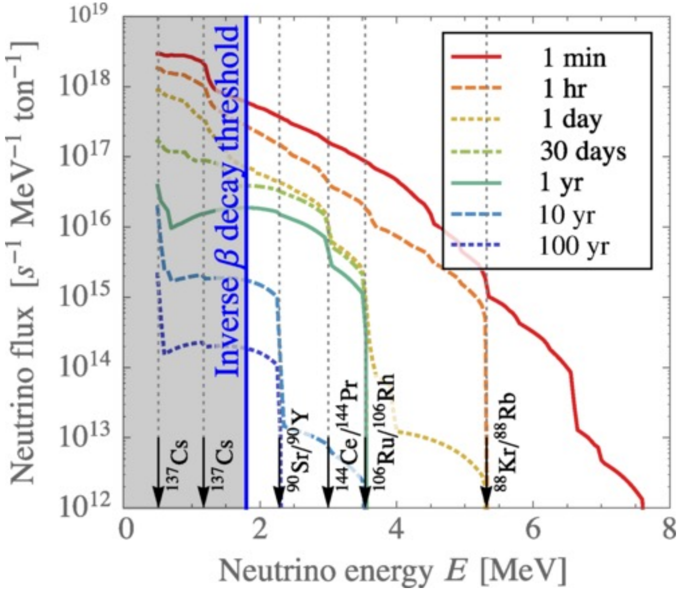


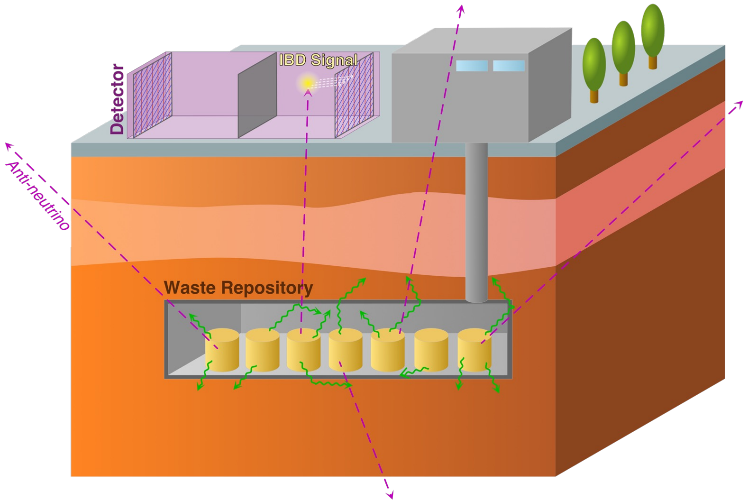
D. Ancius et al., “Muon tomography for dual purpose casks (MUTOMCA) project”. Proceedings of the INMM & ESARDA Meeting 2021.

Brdar, V. and Huber, P. and Kopp, J., “Antineutrino Monitoring of Spent Nuclear Fuel”,
Phys. Rev. Applied, vol. 8, issue 5, pg 054050 (2017).
DOI: https://doi.org/10.1103/PhysRevApplied.8.054050

Antineutrino Detection as SNF Safeguards Tool

- Antineutrino monitoring concept has been proposed and investigated by V. Brdar, P. Huber and J. Kopp in 2017
- Transfer reactor safeguards concepts to SNF
  - Fission fragments in SNF continue to beta-decay for decades/centuries
  - Lower **energy**, lower **flux** than reactors
  - Main detectable isotope for IBD: **^{90}Sr/^{90}Y**
- **Complementary** to other SNF safeguards R&D concepts
- Investigating several candidate technologies (IBD-based)
  - LAB, PVT scintillators + TMS time-projection chambers
  - Investigate several storage scenarios





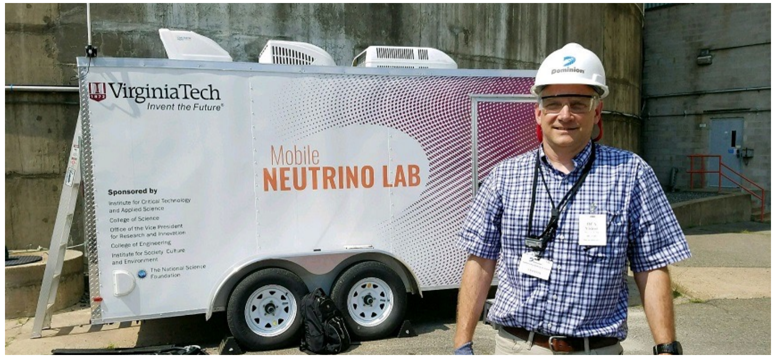
Detector Technology Comparison

- Applied antineutrino detection: active R&D in past two decades
  - Focussed on reactor antineutrinos
  - No "best" technology: ongoing R&D + use case-dependent

- Main technologies
  - **Scintillators (liquid, crystal, plastic)**
  - Cherenkov tanks
  - Radiochemical
  - **Time projection chambers (TPCs)**

- For ideal detector:
  - Good scaling (small/large, flexible geometries)
  - Localised information (segmentation/good reconstruction)
  - Sensitivity near IBD threshold (1.8 MeV)
  - Continuous, autonomous readout
  - *Final state reconstruction (particle ID: e^+ vs e^-)*
  - *Antineutrino direction*

PROSPECT (liquid scintillator-based)
Nucl. Instrum. Meth. A 922 (2019), pg. 287



MiniCHANDLER (plastic scintillator-based)
http://cnp.phys.vt.edu/chandler/

Example Medium	Density [g/cm3]	H atoms /cm3
LAB (liquid scintillator)	0.86	7.5×10^{22}
PVT (plastic scintillator)	1.10	4.5×10^{22}

T. Radermacher et al, “Liquid-organic time projection chamber for detecting low energy antineutrinos”. Nucl. Inst. Meth. A 1054(2023).
DOI: https://doi.org/10.1016/j.nima.2023.168426

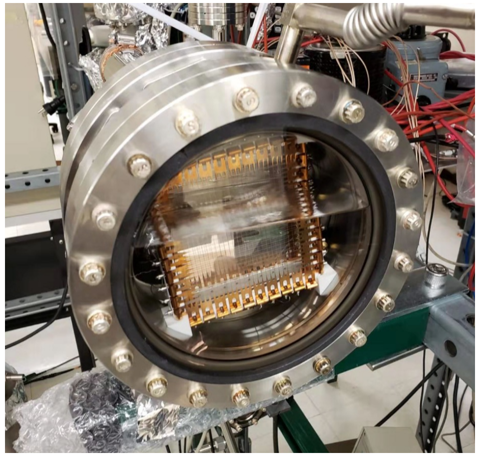
Liquid Organic Drift Media for Time Projection Chambers (TPCs)

- TPCs provide good **reconstruction of particle positions** and/or trajectories
  → additional information for particle ID and directionality
  → previous work looked at LAr-TPCs

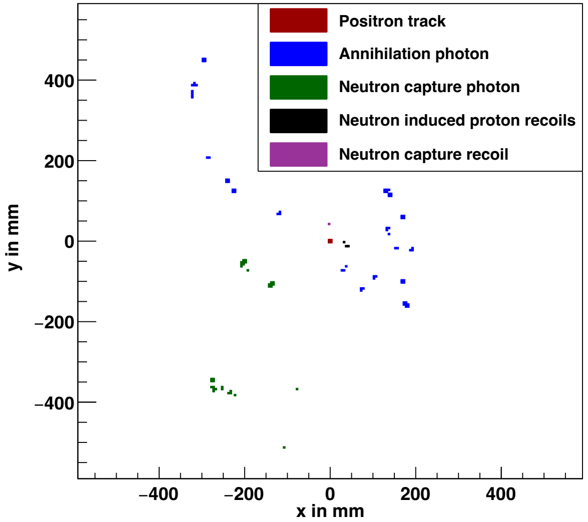
- Current approach: Liquid Organic TPC (LOr-TPC)

- “New” medium under investigation
  - **Tetramethylsilane** (TMS): $Si(CH_3)_4$
  - Contains **hydrogen** for IBD: 5.3×10^{22} H atoms per cm^3
  - Basic feasibility investigated by S. Wu *et al*. at Stanford
  - However: drift over larger distances challenging and unproven

- GEANT4 simulation of SNF antineutrinos:
  - Positron track, annihilation photons and neutron capture
  - Majority of events: can reconstruct **original $\overline{\nu}_e$ direction with <10° deviation**


https://arxiv.org/abs/1911.12887

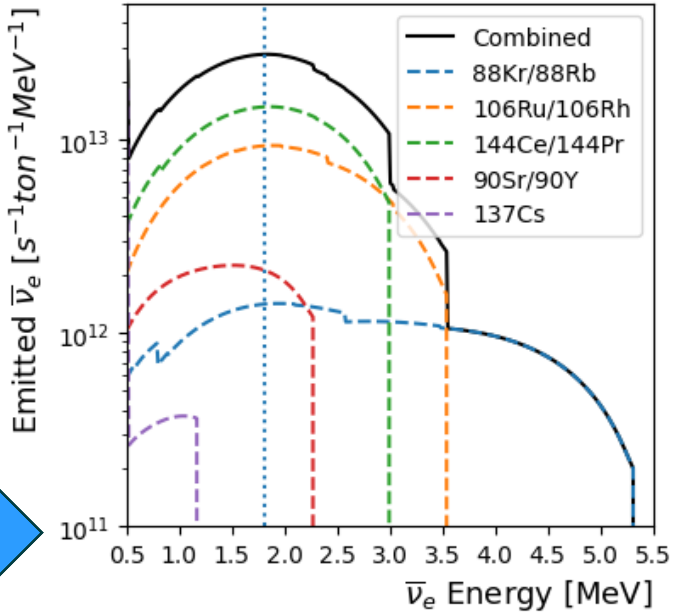
Half-filled cell showing wire chamber through viewport



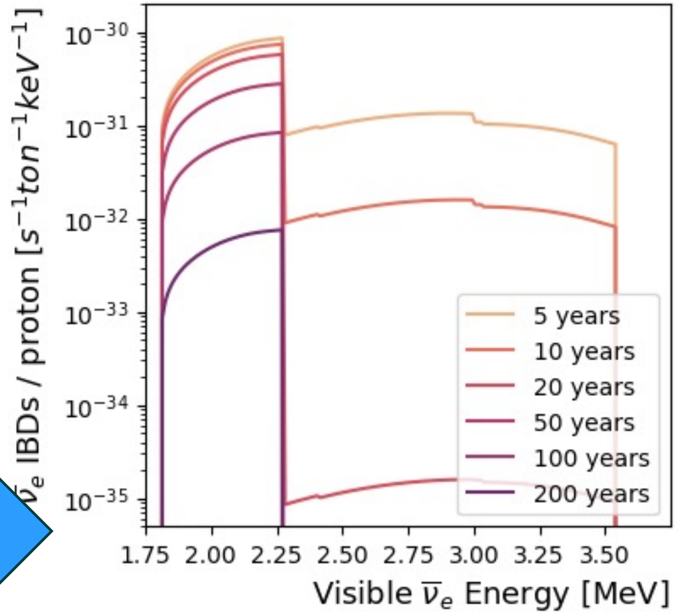
Antineutrino Flux Modelling: Understanding the SNF Signal

Fuel Simulation

Antineutrino Spectrum



Detectable Signal



- **ONIX**: simulate fuel assemblies
  - Example: GKN II fuel assembly at 54 MWd/kg burn-up
- Tally isotopic contents after burn-up

- Select main contributing isotopes (high $\overline{\upsilon}_e$ energy + long half-lives)
- NDS ENDSF database/BetaShape for beta & $\overline{\upsilon}_e$ energy spectra

- Convolve with IBD cross-section
- Determine interaction rate per ton of SNF
- Repeat for different SNF ages

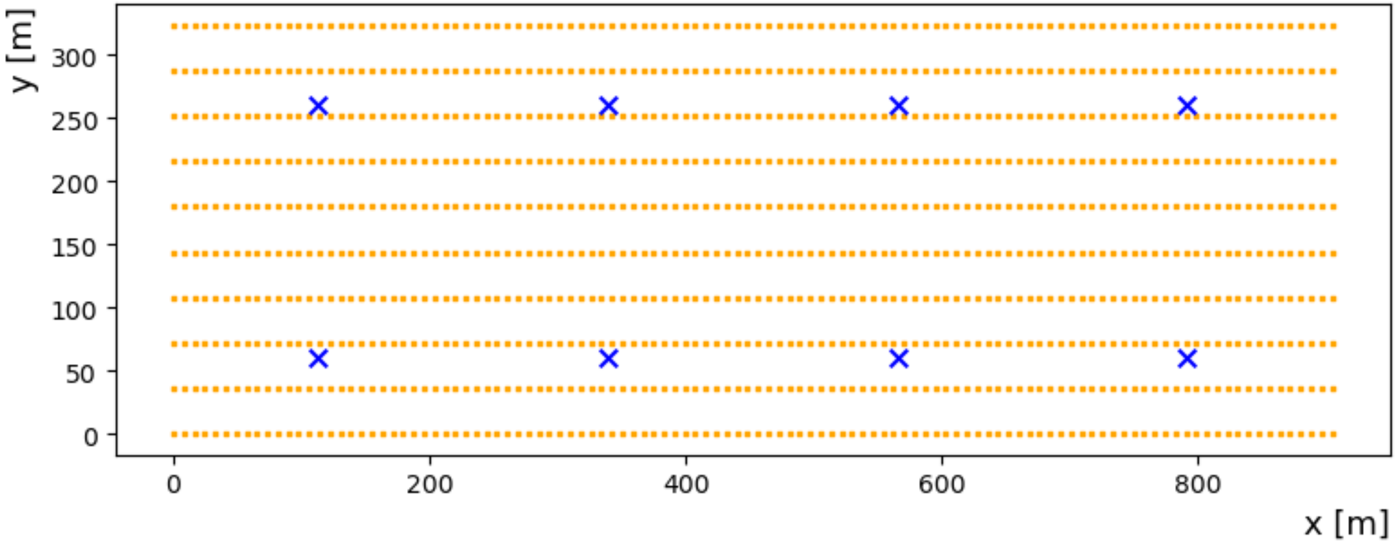
Example Geological Repository: Layout & Interaction Rates

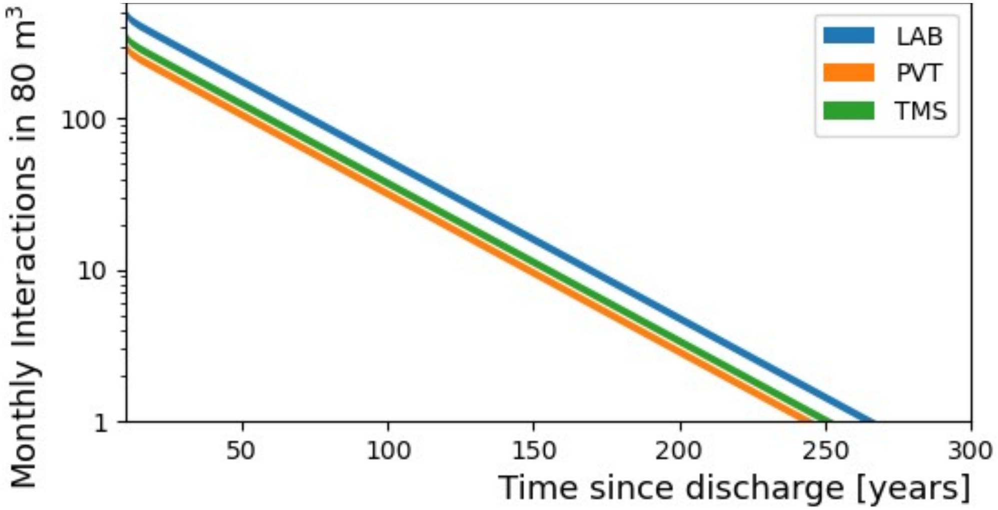
- Modelling sensitivity of idealised 80m^3 detectors (no background)
  - **Eight locations**: 50m above casks

- Simplified geological repository
  - 1,120 **canisters** x 10 fuel assemblies
  - Uniform age for all canisters (50, 100 or 200 years)

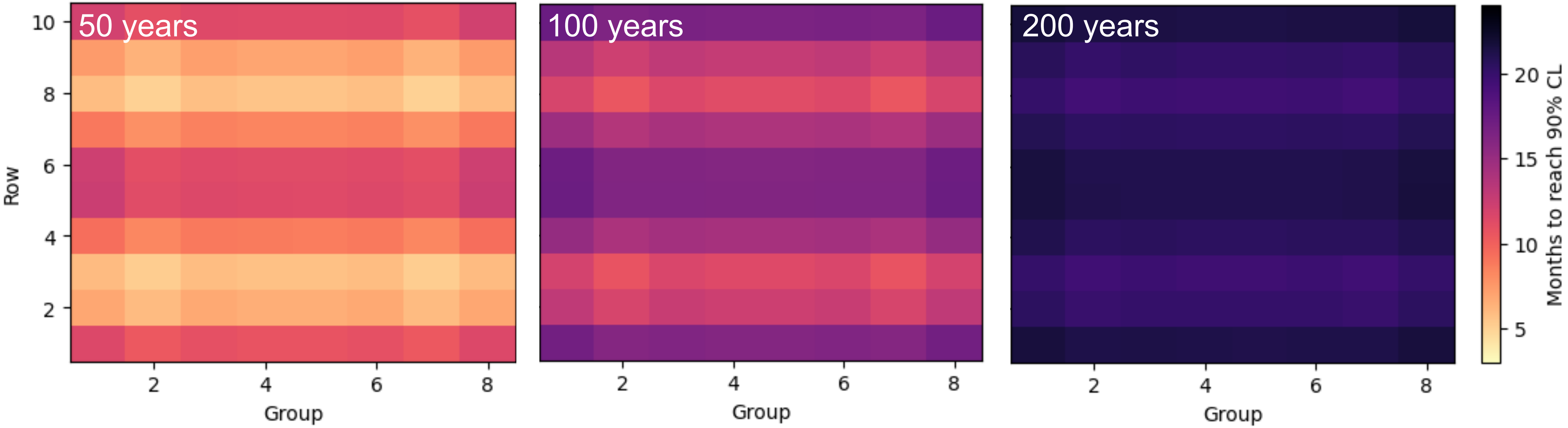
- Modelled diversion of 1.25% of content (14 canisters: ~78.4t HM)

- Three detection media compared – all similar overall performance
  - Use TMS as example medium





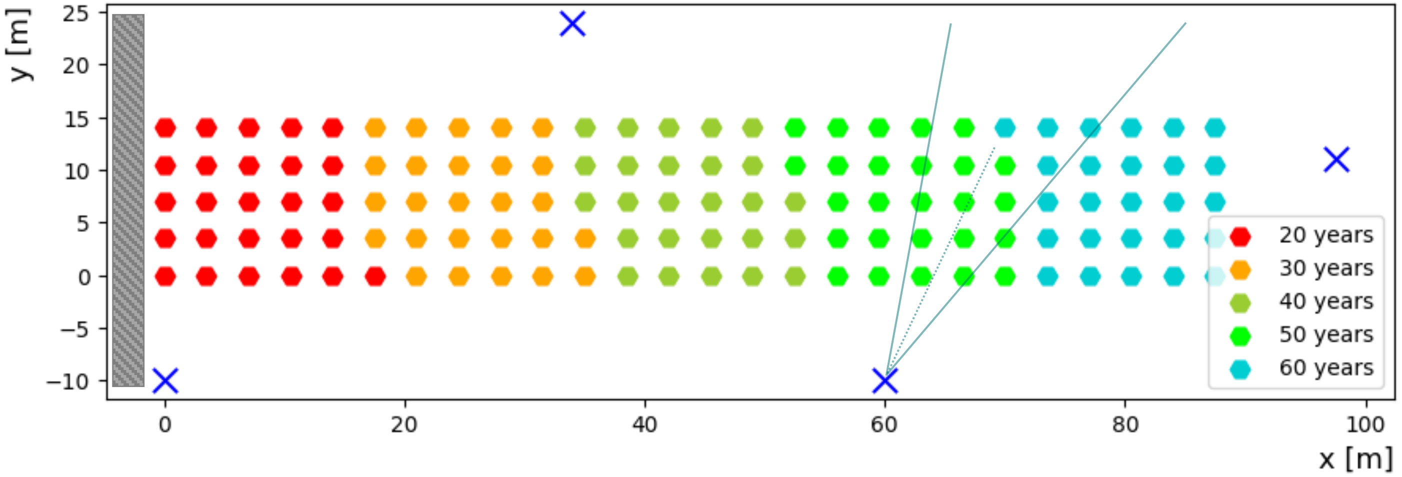
Example Geological Repository: Expected Sensitivity



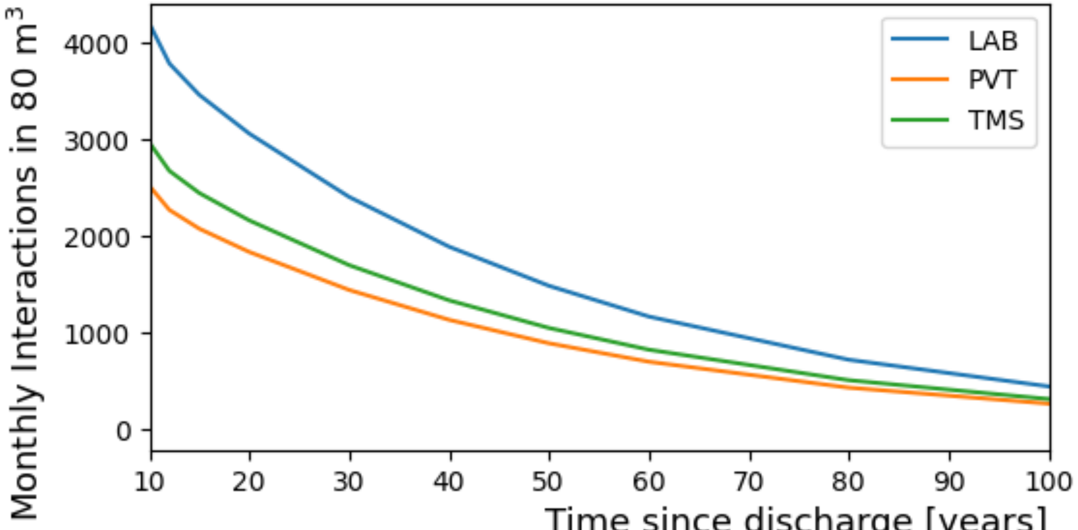
- Criterion for detection: 90+% CL that diversion occurred
- Time t_{CL90} to reach 90% CL for all scenarios for removed group
  - Scenario 1 (50 years): $\tilde{t}_{CL90}$ **(median) = 8.6 months** (5.0-12.5 months), 90% quantile = 11.5 months
  - Scenario 2 (100 years): $\tilde{t}_{CL90}$ **(median) = 14.2 months** (10.6-17.3 months), 90% quantile = 16.7 months
  - Scenario 3 (200 years): $\tilde{t}_{CL90}$ **(median) = 20.6 months** (19.4-21.8 months), 90% quantile = 21.6 months

Example Interim Storage Facility: Layout & Interaction Rates

- Modelling sensitivity of idealised 80m^3 detectors (no background)
  - **Four locations**:
    - 10m distance from casks
    - One side (left) service building/access
    - Iterative optimisation of locations

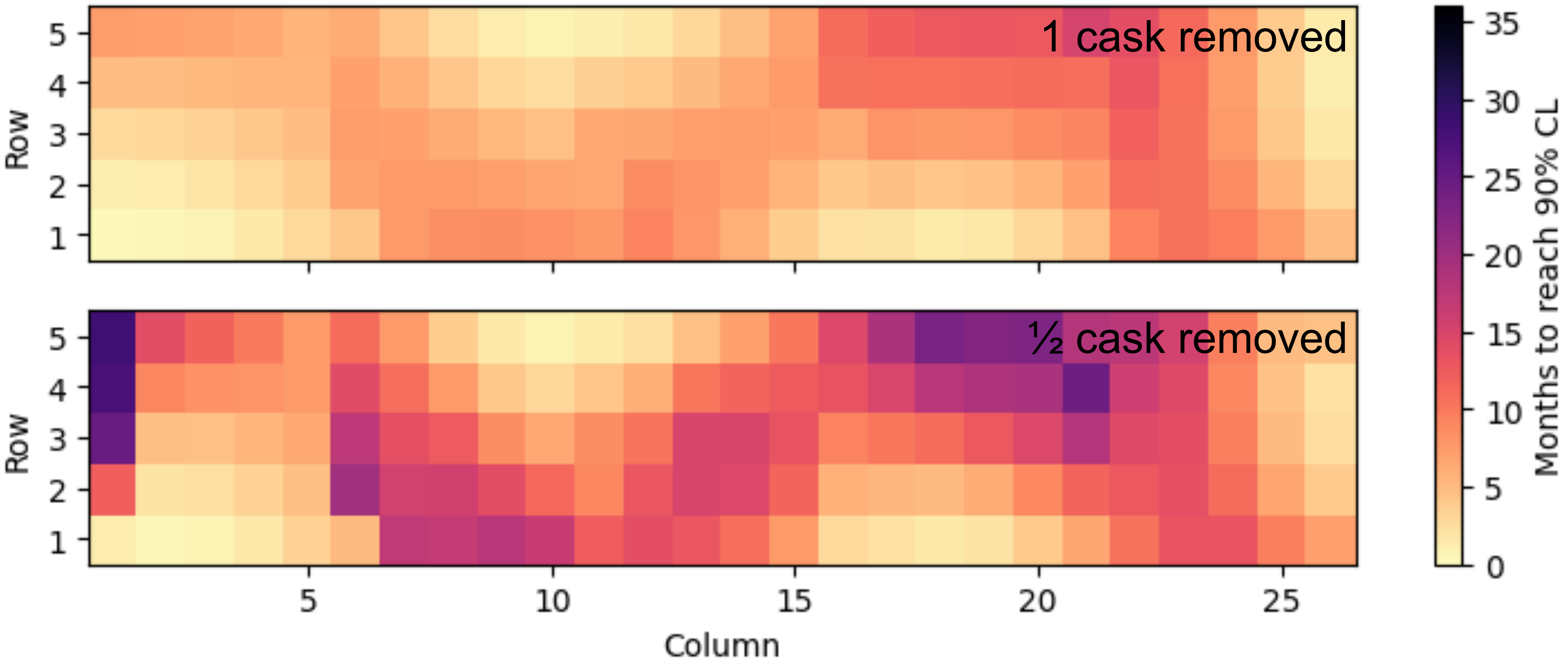


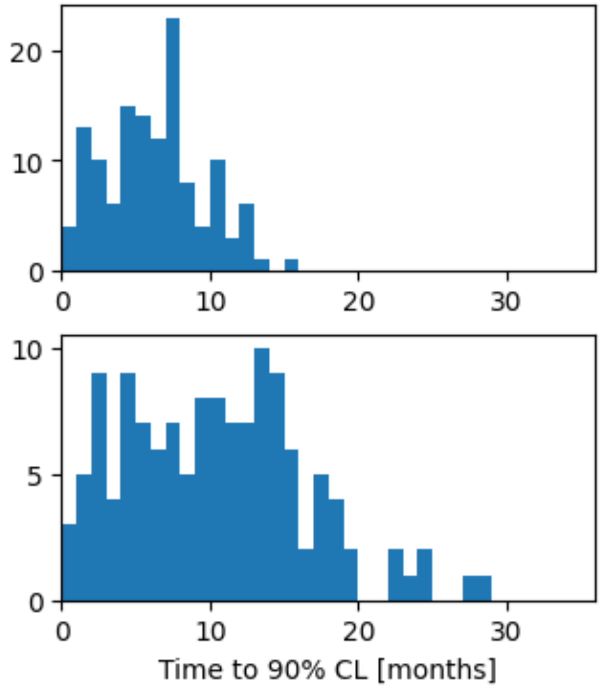
- Simplified interim storage
  - 130 fuel casks x 19 fuel assemblies
  - SNF stored 20-60 years ago



- Modelled following scenarios:
  - Diversion of 1 cask (~10.6 t HM)
  - Diversion of ½ cask (~5.3 t HM)
  - Re-verification of 1 cask w/ directional capability

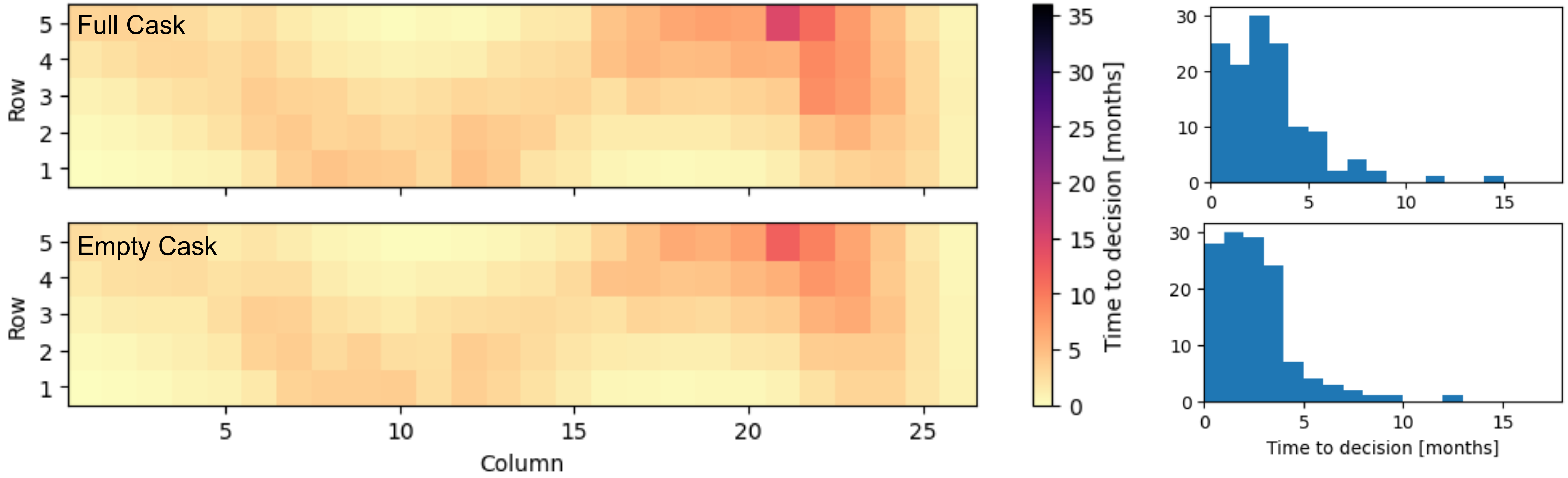
Example Interim Storage Facility: Expected Sensitivity





- Criterion for detection: 90+% CL that diversion occurred
- Time t_{CL90} to reach 90% CL for both scenarios for each cask location
  - Scenario 1 (1 cask): $\tilde{t}_{CL90}$ **(median) = 6.4 months** (0.4-15.2 months), 90% quantile = 10.9 months
  - Scenario 2 (½ cask): $\tilde{t}_{CL90}$ **(median) = 10.3 months** (0.6-28.4 months), 90% quantile = 18.1 months

Example Interim Storage Facility: Re-verification with 30º Directional Capability



- Re-verification of **single cask of interest**: verify full or declare empty cask
  - Use Sequential Probability Ratio Test (SPRT) - allow 10% false negatives, 20% false positives (can be tuned)
  - Assume 30º directional selection for incoming antineutrinos (angular resolution is technology dependent)
- Time t_{SPRT} to verify/reject a cask (30º selection cone)
  - Full Cask: $\tilde{t}_{SPRT}$ **(median) = 2.6 months** (0.1-14.6 months), 90% quantile = 5.6 months
  - Empty Cask: $\tilde{t}_{SPRT}$ **(median) = 2.2 months** (0.1-10.6 months), 90% quantile = 4.7 months

von Raesford, C. and Huber, P., “Use of CEvNS to Monitor Spent Nuclear Fuel”,
Phys. Rev. D 105, pg 056002 (2022).
DOI: https://doi.org/10.1103/PhysRevD.105.056002

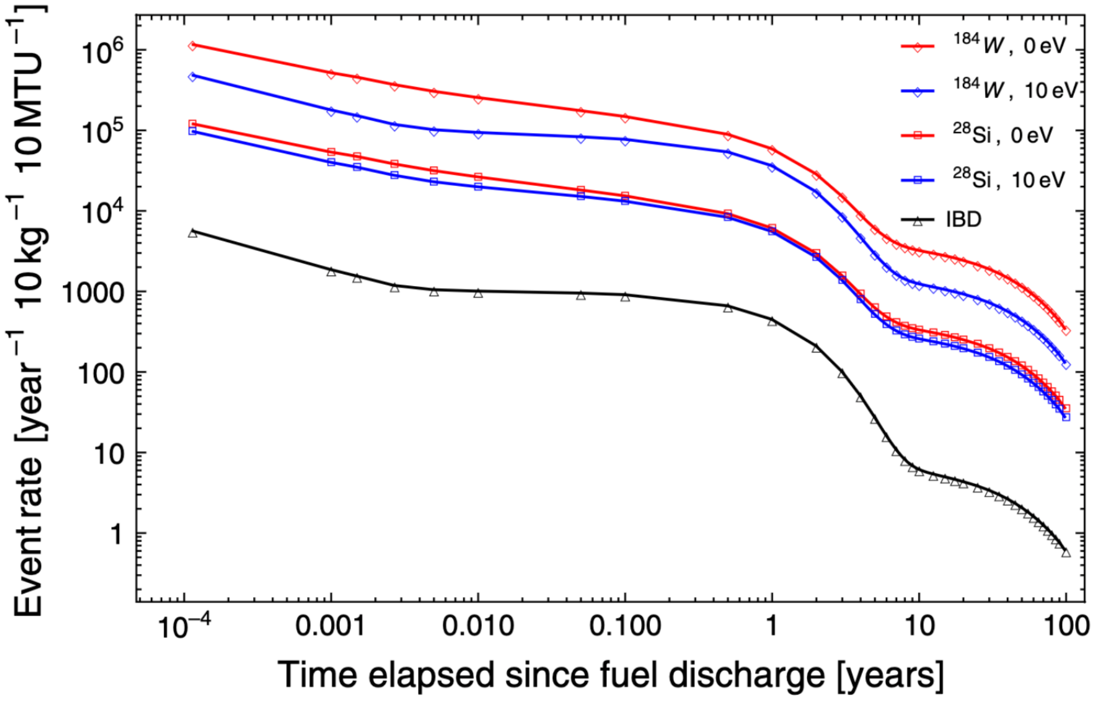
Monitoring & Verification using CEvNS

- Proposal & study by C. von Raesford & P. Huber:
  - Coherent Elastic neutrino-Nucleus Scattering (CEvNS)
  - Exploit higher cross-section for smaller detector

- Example scenario investigated
  - 10 t HM of SNF
  - 10 kg detector mass
  - 3m stand-off distance

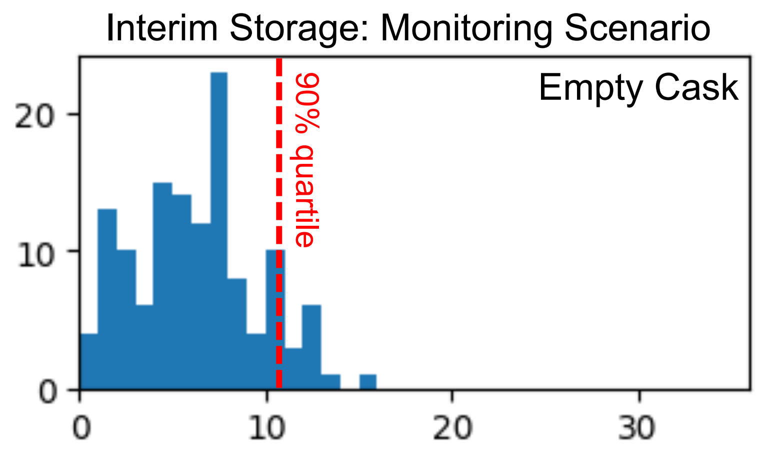
- Expectation for 1 year data collection
  - 100+ events
  - Potential sensitivity: single fuel element removal with <10% error

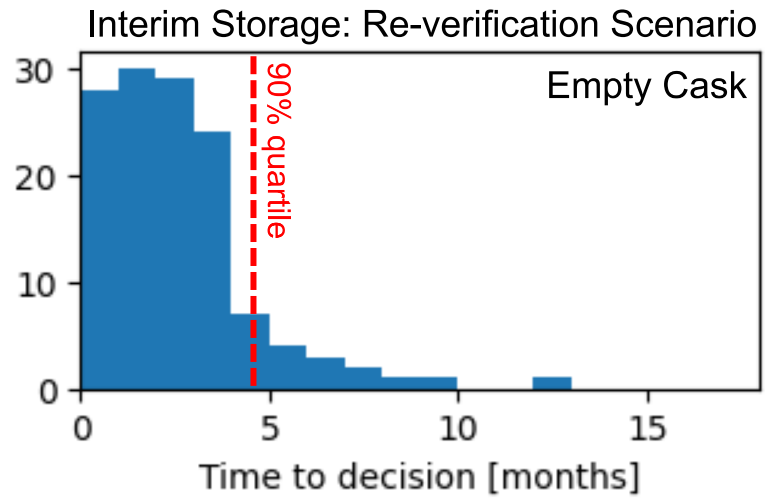
- Results from reactor CEvNS experiments will determine feasibility



Conclusions

- Antineutrino detection for safeguards
  - Reduce operational burden – **desirable** by facilities
  - Complementary to density or n/ɣ measurements (ongoing R&D)
  - Potential for **re-verification** to re-establish CoK
- Geological repositories
  - Long-term (100+ years) difficult - **limited by ^{90}Sr half-life**
- Interim storage
  - Newer SNF & lower stand-off distances: **high signal rates**
  - **General monitoring**: < 1 year to detect removal
  - **Re-verification** with directional detector: < 5 months required
- CEvNS also proposed as re-verification approach
  - Highly dependent on results of CEvNS research





Summary & Outlook

- Sensitivity analysis of two model SNF storage sites
  - Ideal conditions: signal within few months
  - Statistical tests can be tuned to specific use cases
  - Directionality can speed up re-verification
- Ongoing project NU-SAFEGUARDS project investigates:
  - Embedding application for antineutrino monitoring in overall safeguards concepts & use cases
  - Technology comparison for low energy antineutrinos (close to IBD threshold)

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Thank you for your attention!

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BACKUP SLIDES

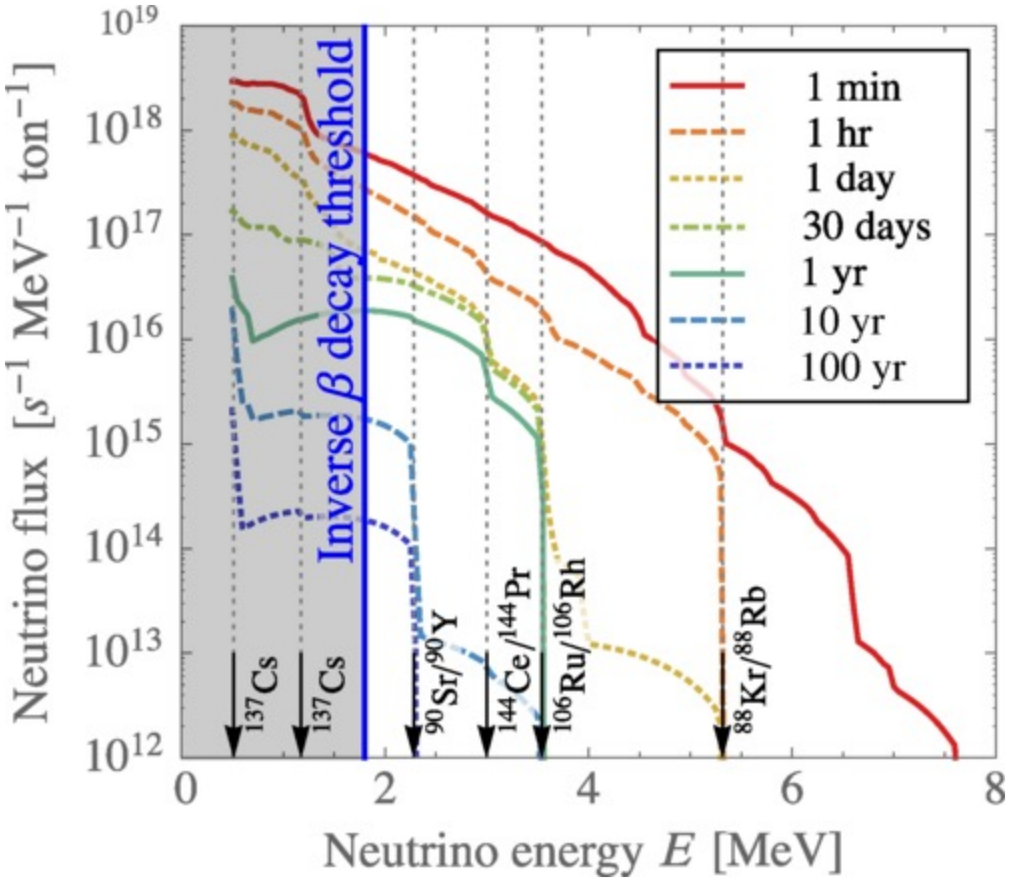
Antineutrino Monitoring Concept Paper

- Antineutrino monitoring concept has been proposed and investigated by V. Brdar, P. Huber and J. Kopp in 2017

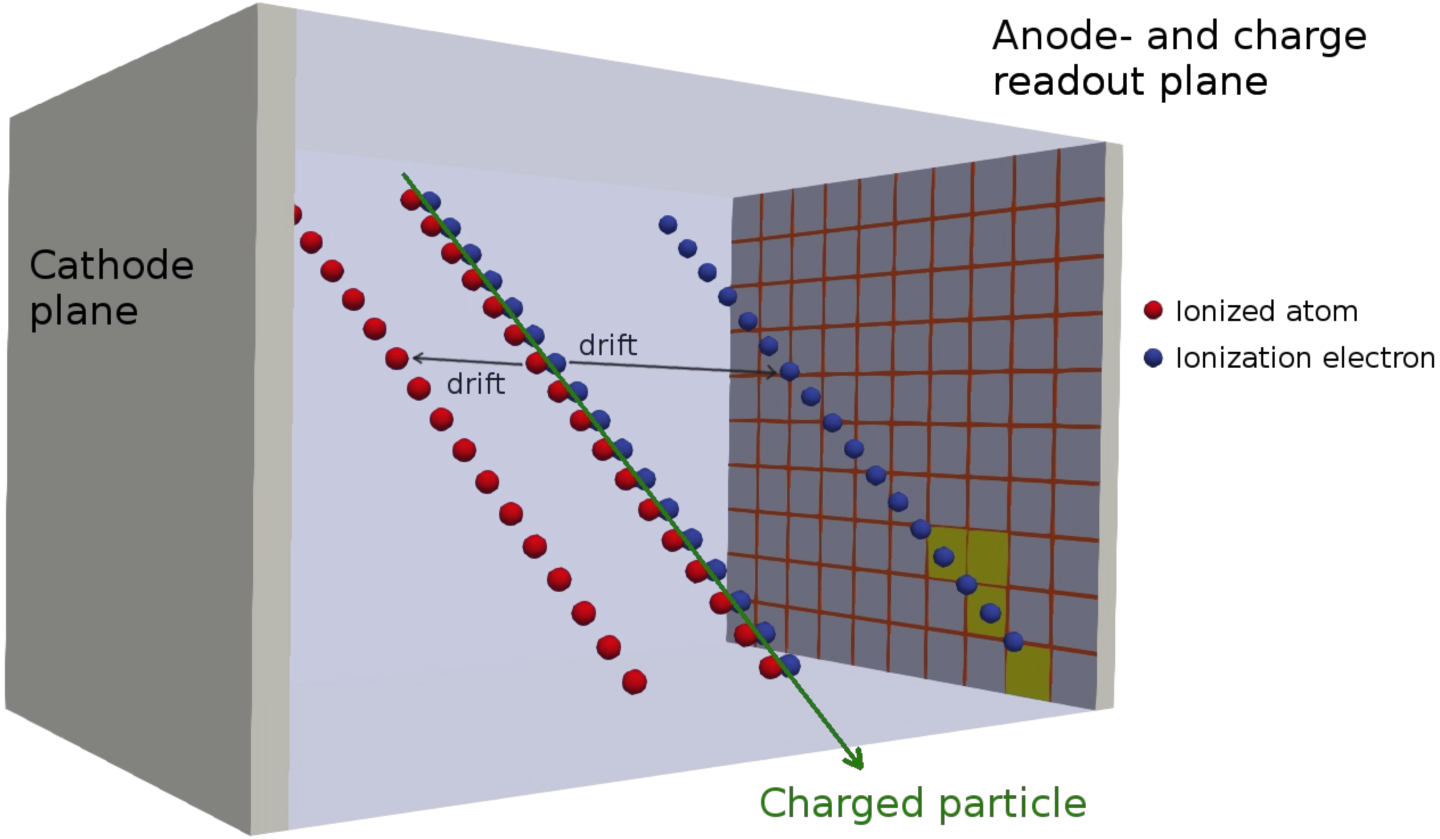
- Paper calculates antineutrino flux for all isotopes
  - ^{88}Kr dominates after a few hours
  - ^{90}Sr dominates after 10 years

- Does **not** make technological recommendations
  - But points out that current technology insufficient (except for detecting "cataclysmic" spills)
  - Recommends directional resolution **O(10 degrees)**

Brdar, V. and Huber, P. and Kopp, J., "Antineutrino Monitoring of Spent Nuclear Fuel", Phys. Rev. Applied, vol. 8, issue 5, pg 054050 (2017). DOI: https://doi.org/10.1103/PhysRevApplied.8.054050



Detection Principles: TPC



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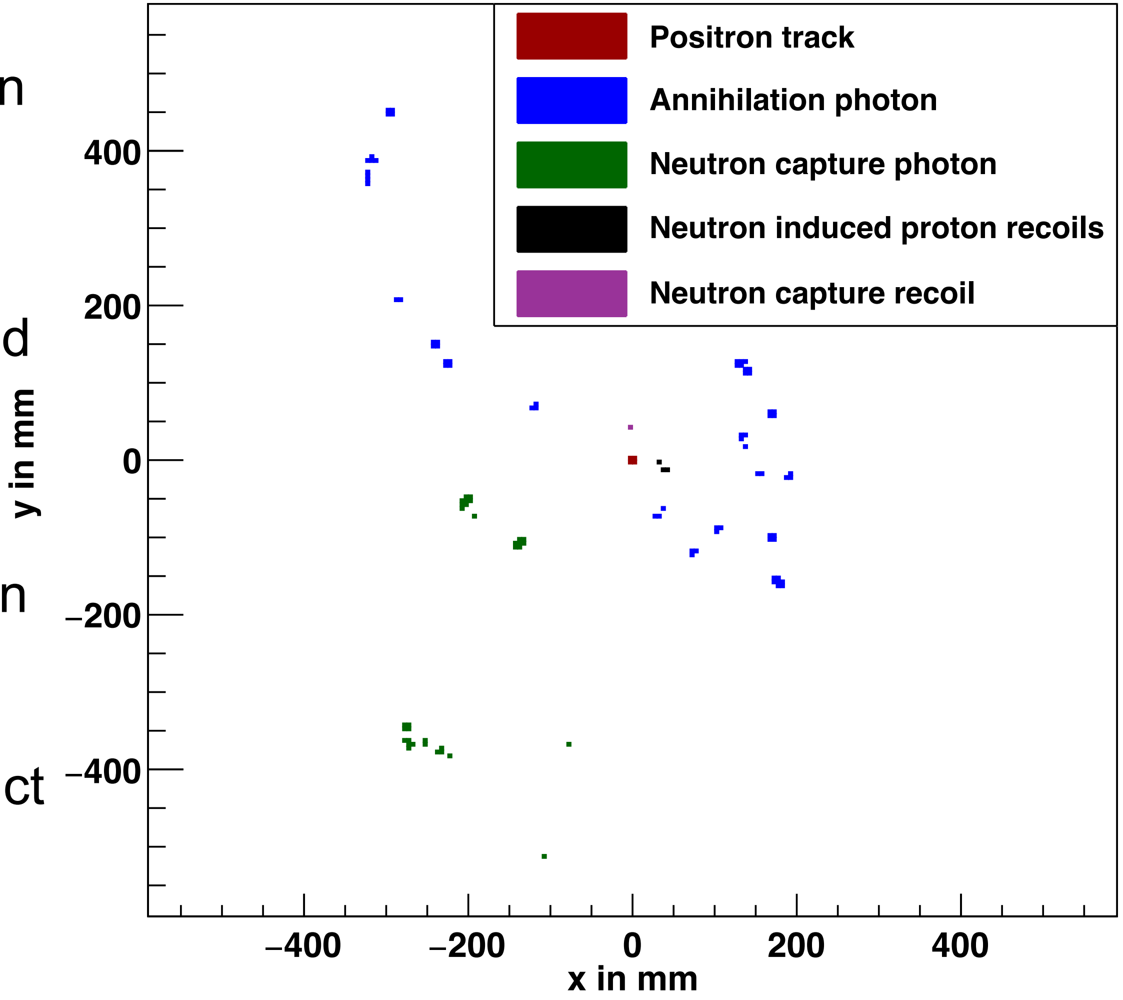
DOI: https://doi.org/10.1016/j.nima.2023.168426

Preliminary IBD Simulation in LOr-TPC

- Initial GEANT4 simulations of ^{90}Sr/^{90}Y IBD events in TMS
  - Includes preliminary model of electron drift
- Can resolve positron track, annihilation photons and neutron capture
  → additional **background rejection**
- Neutron recoil produces separate energy deposition
  → could be used to infer **antineutrino direction**
- Majority of events: enough information to reconstruct **original $\bar{\upsilon}_e$ direction with <10° deviation**



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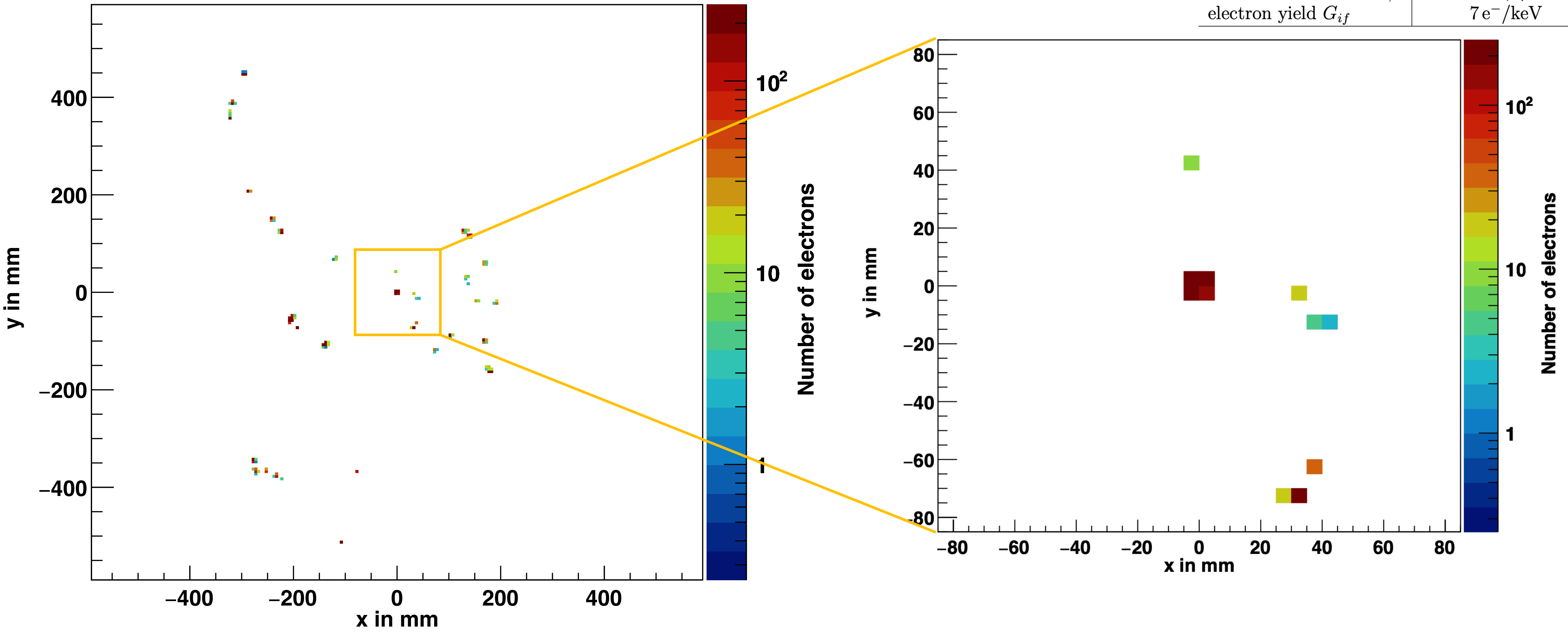
IBD Event in LOr-TPC – Electron Yield

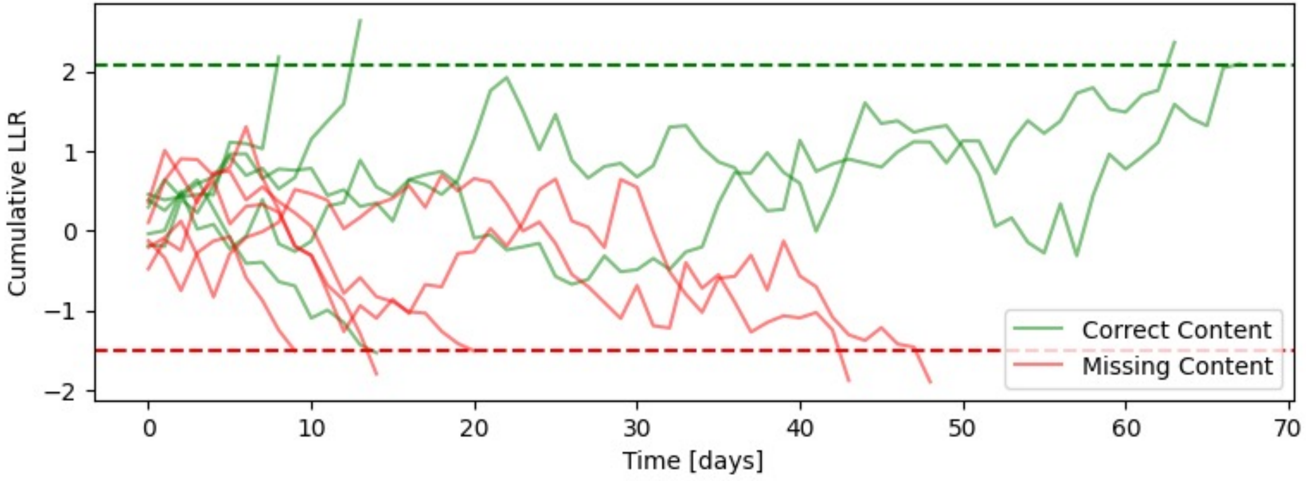
	Detector configuration 1
maximum drift length l	$1\,\mathrm{m}$
electric field E	$5.0\,\mathrm{kV/cm}$
drift velocity v_d	$5.5\,\mathrm{\mu m/ns}$
diffusion coefficient $d_{L,T}$	$60\,\mathrm{\mu m}/\sqrt{\mathrm{cm}}$
electron yield G_{if}	$7\,\mathrm{e^-/keV}$

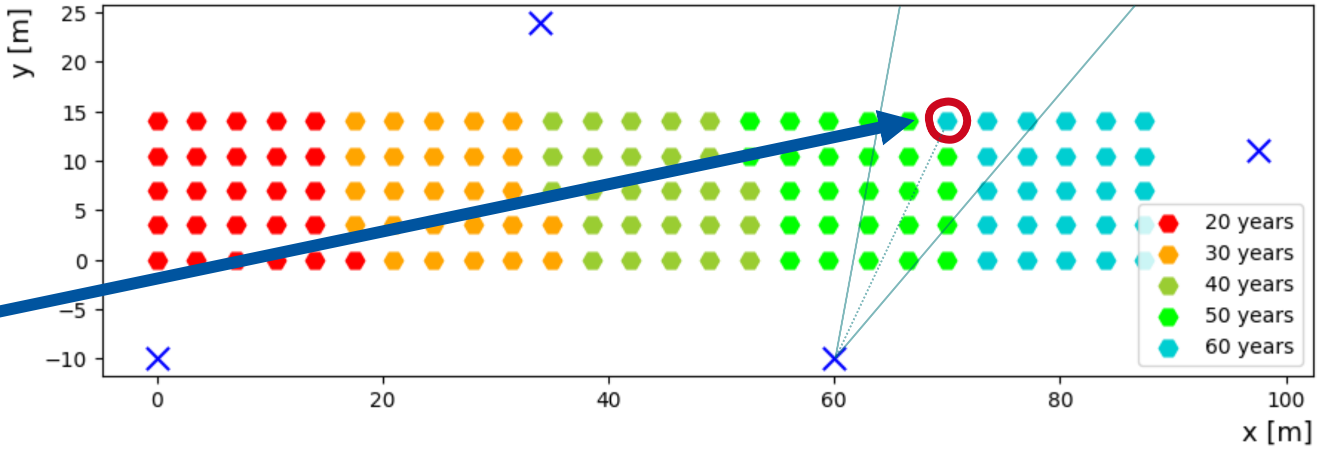


Re-verification at Interim Storage Facility: Sequential Probability Ratio Testing

- Use for Re-verification:
  - Check of (individual) units for anomalies
  - Different tolerance for type I (**false positive**) and type II (**false negative**) errors
  - Complementary to other tools
- Sequential Probability Ratio Test (SPRT):
  - Either verify cask contents are correct or missing (this example: full or empty cask)
  - Optimal time to verification/rejection decision*
  - Choose: **20% type I errors**, **10% type II errors**
  - Note: error **per** cask, not for whole facility!
- For TMS (and certain scintillators): **directional** information available
  - For re-verification: focus on area-of-interest
  - Selection cone of 30°

Example SPRTs for 5 correct, 5 empty casks





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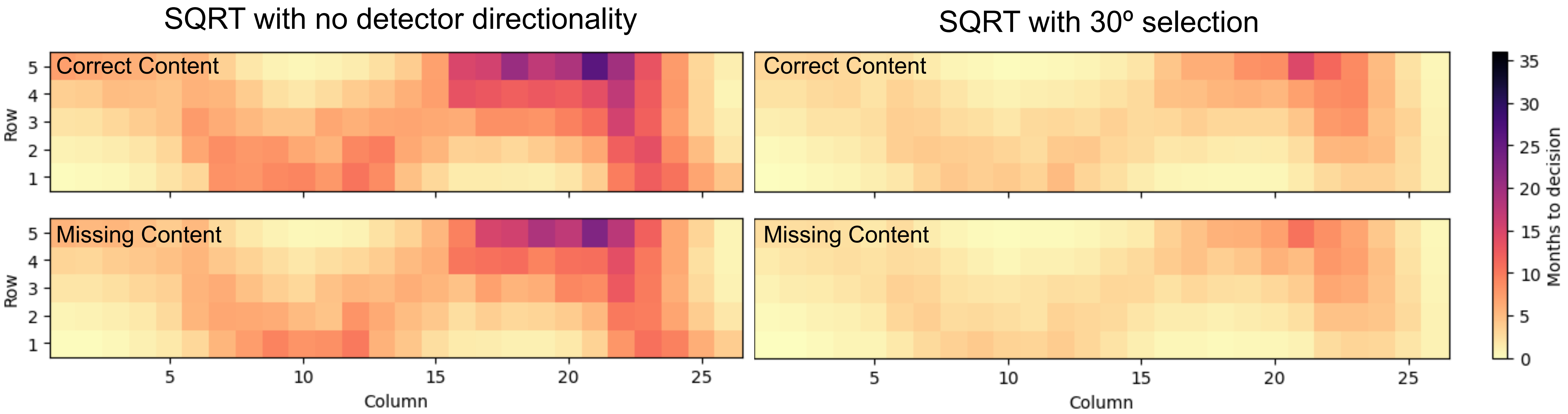
*A. Wald, J. Wolfowitz, “Optimum Character of the Sequential Probability Ratio Test“. Ann. Maths. Stats. 19(3), pg. 326-339 (1948).

Example Interim Storage Facility: Re-verification using SPRT


SQRT with no detector directionality

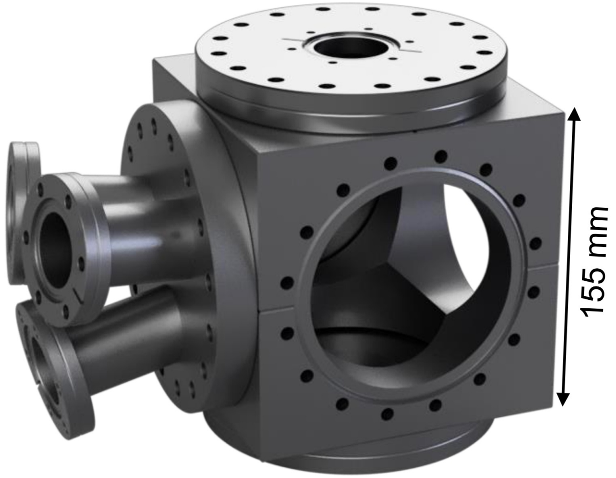
SQRT with 30º selection

- Time t_{SPRT} to verify/reject a cask
  - Correct Content: $\overline{t_{SPRT}}$ **= 6.5 months** (0.2-26.0 months)
  - Missing Content: $\overline{t_{SPRT}}$ **= 5.4 months** (0.2-22.7 months)
- Time t_{SPRT} to verify/reject a cask (30º)
  - Correct Content : $\overline{t_{SPRT}}$ **= 3.1 months** (0.1-14.6 months)
  - Missing Content : $\overline{t_{SPRT}}$ **= 2.5 months** (0.1-10.6 months)

TMS Prototype Developments

- Construction of small-scale prototype underway to investigate TMS properties
  - Test of purification system
  - Test of drift behaviour and readout with radioactive sources (*γ*- and *n*-emitters)

- Prototype simulation studies are done in parallel using GEANT4 + electron drift simulation
  - Characterise energy deposition by test sources within medium
  - Prototype measurements will allow improved modelling of drift behaviour
  - Will be used to predict TMS performance in large-scale system (tonne-scale)



DN100CF Cube