Supplement of Saf. Nucl. Waste Disposal, 2, 203–203, 2023
https://doi.org/10.5194/sand-2-203-2023-supplement

Supplement of

Antineutrino detection concepts for safeguarding spent nuclear fuel

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ANTINEUTRINO DETECTOR CONCEPTS FOR SAFEGUARDS MONITORING OF SPENT NUCLEAR FUEL

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safeND 2023: Interdisciplinary Research Symposium on the Safety of Nuclear Fuel Disposal Practises
Berlin | 13th September 2023

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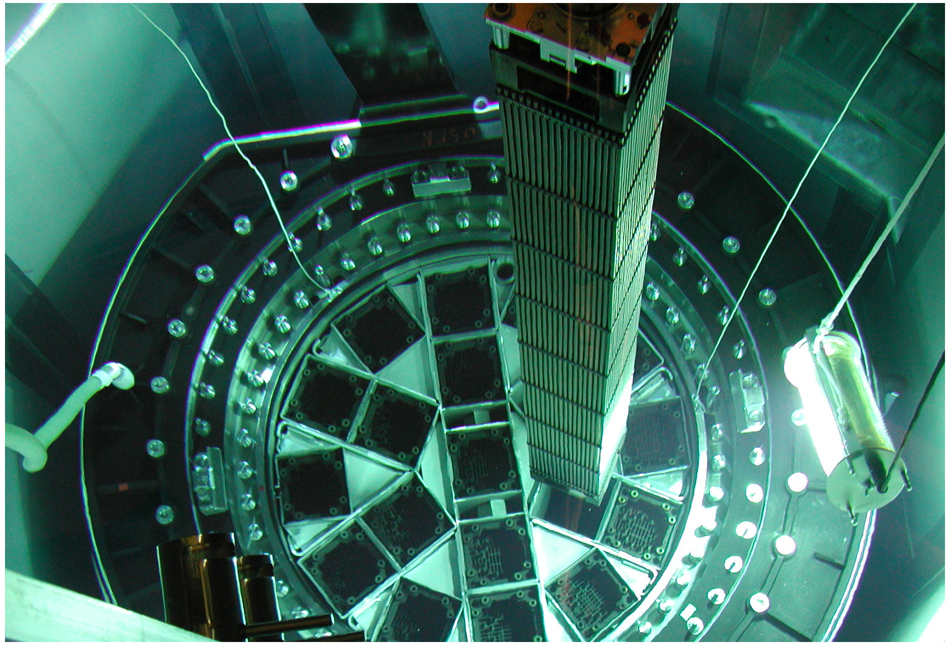
Introduction: Spent Nuclear Fuel

- 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**

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

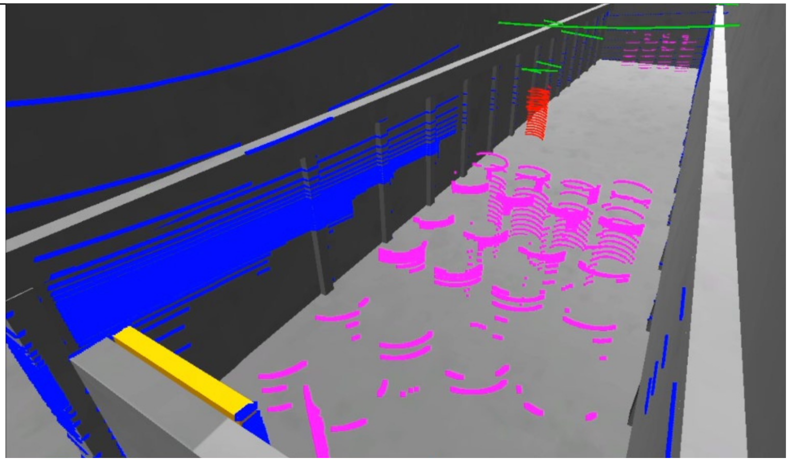
Safeguards R&D for SNF Storage

- Safeguards impact on facility operation
  - Inspections require **access** and **radiation exposure**
  - Re-establishing CoK ("re-verification") in case of discrepancies or incident requires **huge effort & time**

- Safeguards R&D aims
  - **Lessening** operational burden (automated/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



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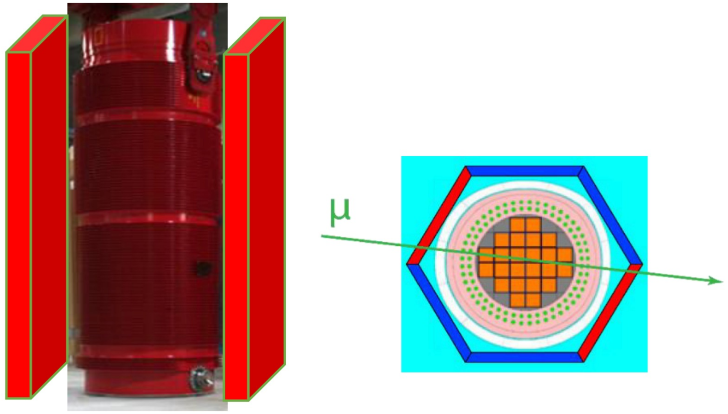

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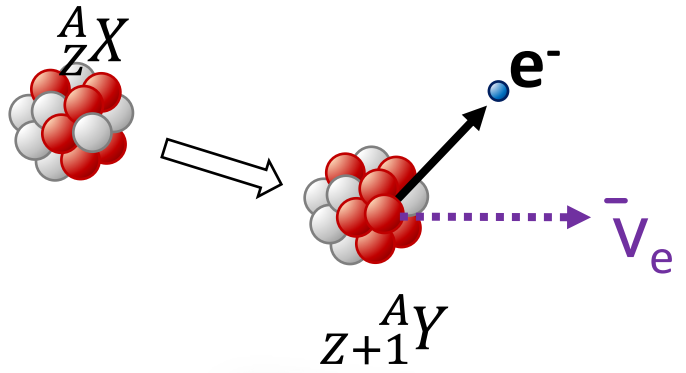
Antineutrinos as Reactor Safeguards Tool

- Concept originally proposed for **reactor safeguards**
  - Several active experiments, prototypes and groups
  - Physics community interested in **practical applications**
    → NuTools report, annual Applied Antineutrino Physics workshops

- During beta-decay: emission of electron antineutrinos $\bar{\upsilon}_e$
  - Spectra and flux depend on isotope
  - Fission fragments rich in beta-decaying isotopes

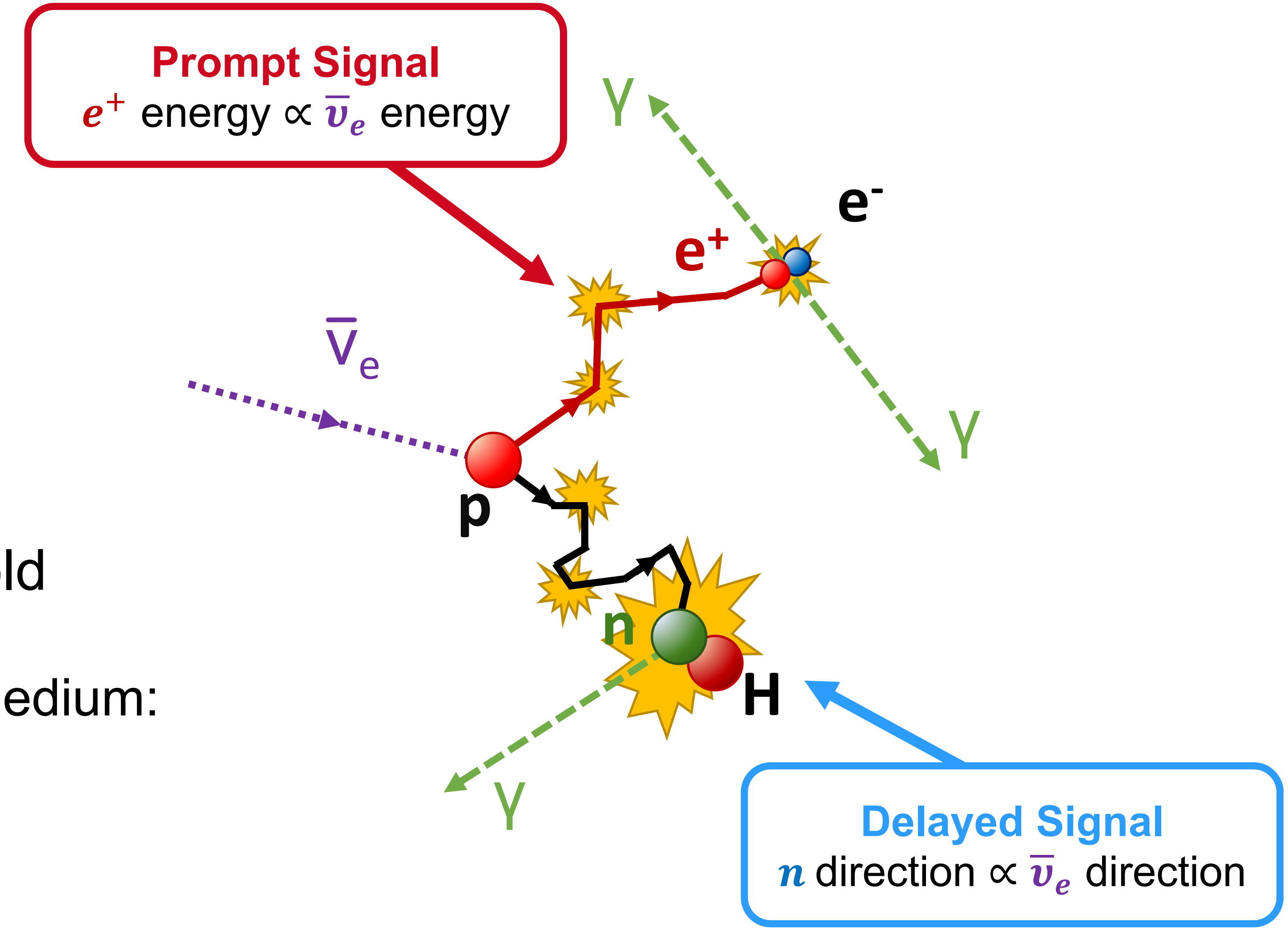
- Unique to antineutrinos: **cannot be shielded**
  - Signal even penetrates heavy shielding
  - Unique signal: nuclear decays main source of antineutrinos
  - Emission spectrum correlated with decaying isotope
  - But also: **very low** interaction rates

- Most approaches: detection via Inverse Beta-Decay (IBD)



Antineutrino Detection: Inverse Beta Decay

- Inverse Beta-Decay (IBD)
  - Main channel of interest
  - Process: $\bar{\nu}_e + p \rightarrow e^+ + n$
- Double coincidence time structure:
  → powerful **background rejection**
- Kinematics impose energy threshold
  - **1.806 MeV** for (semi-)free protons
  - Require **hydrogen-rich** detection medium: scintillators, organic media



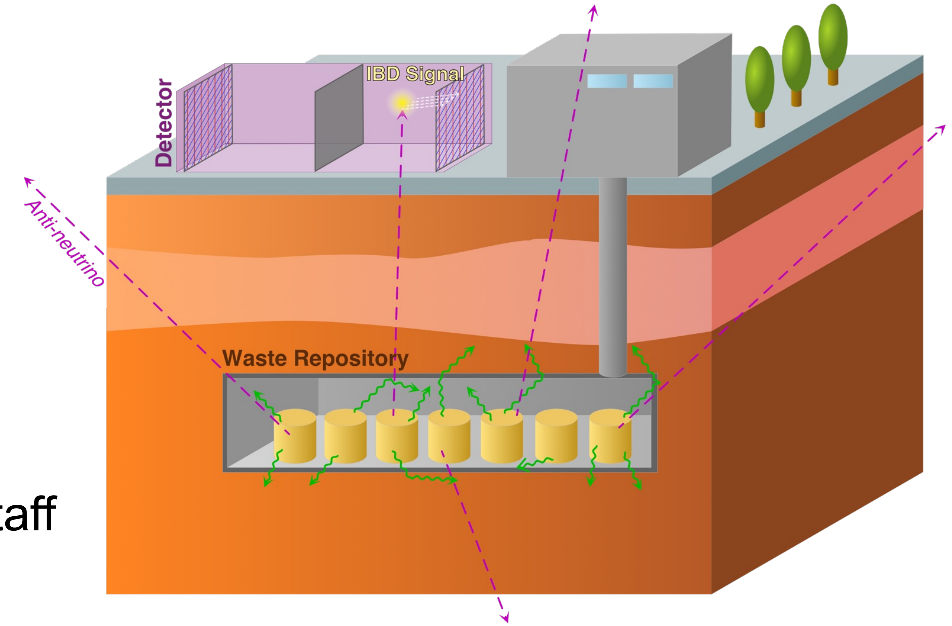
Antineutrino Detection as SNF Safeguards Tool

- From reactor measurements to SNF safeguards
  - Fission fragments in SNF continue to beta-decay for decades/centuries
  - Lower **energy**, lower **flux** than reactors
  - Main detectable isotope: **^{90}Sr**

- Advantages apply to SNF as well
  - Signal penetrates containment
  - Direct measure of content **complementary** to muon (density) or n/ɣ measurements

- Complementary characterisation of SNF
  - Ongoing decays → **continuous** monitoring
  - No need for direct physical access → **no radiation exposure** for staff

- NU-SAFEGUADS project investigates several candidate technologies
  - LAB, PVT scintillators + TMS time-projection chambers
  - Investigate several storage scenarios

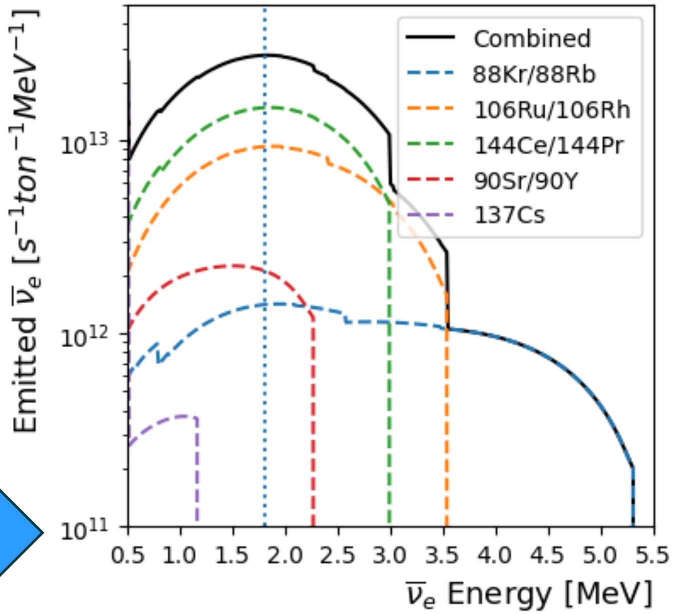


Antineutrino Flux Modelling: Understanding the SNF Signal

Fuel Simulation

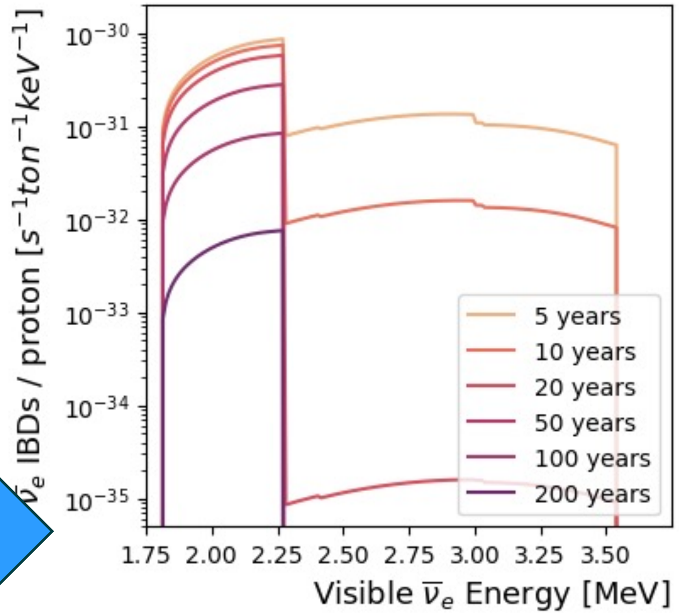
- **ONIX**: simulate fuel assemblies
  - Example: GKN II fuel assembly at 54 MWd/kg burn-up
- Tally isotopic contents after burn-up

Antineutrino Spectrum



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

Detectable Signal



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

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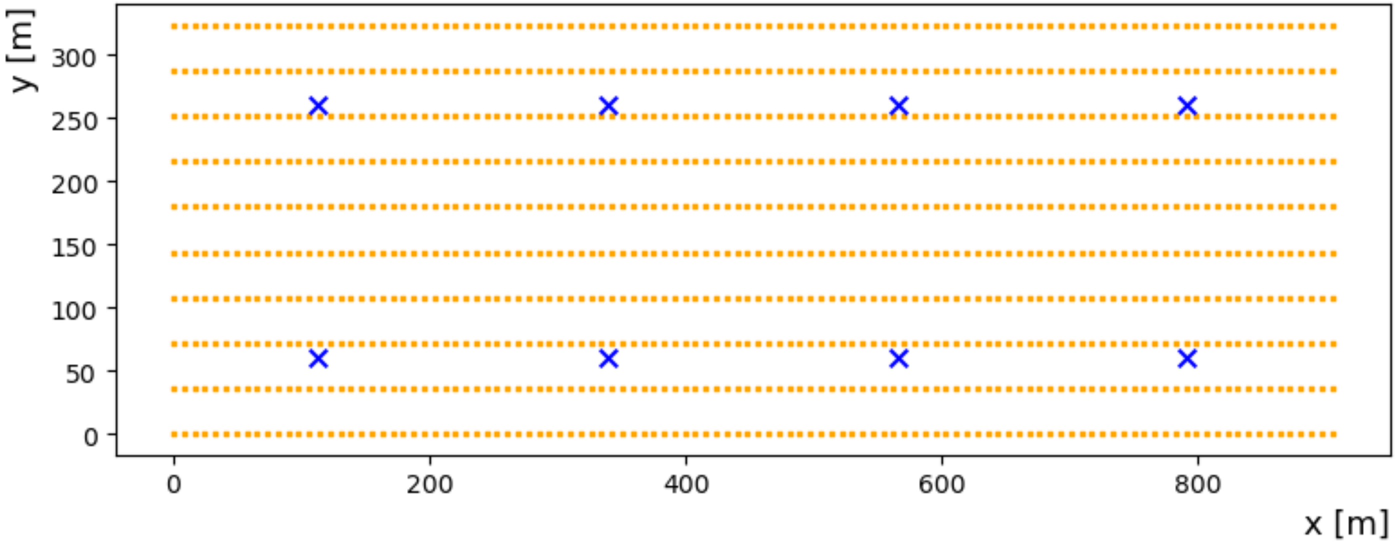
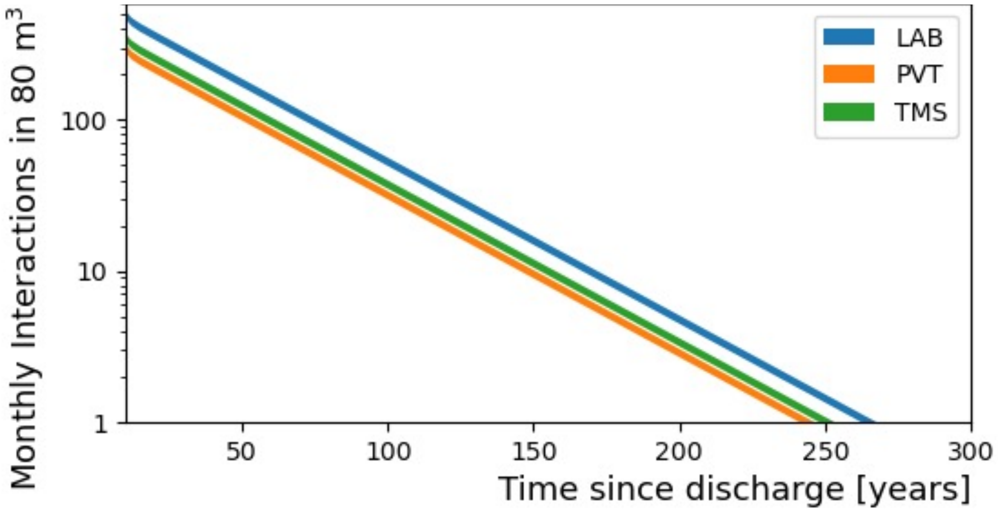
Example Geological Repository: Layout & Interaction Rates

- 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





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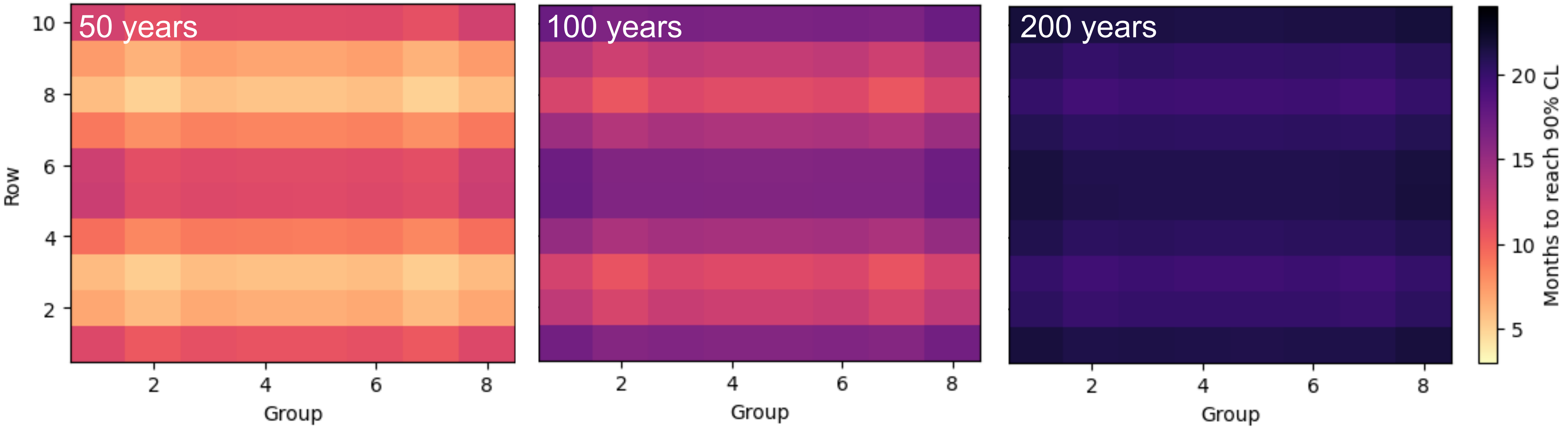
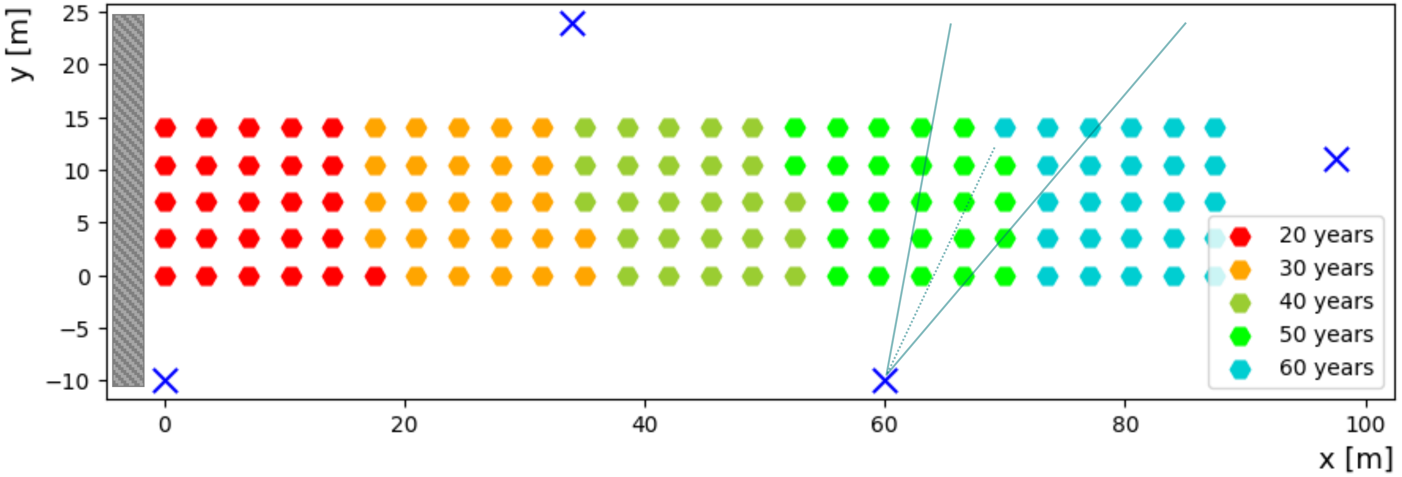
Example Geological Repository: Expected Sensitivity



- 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

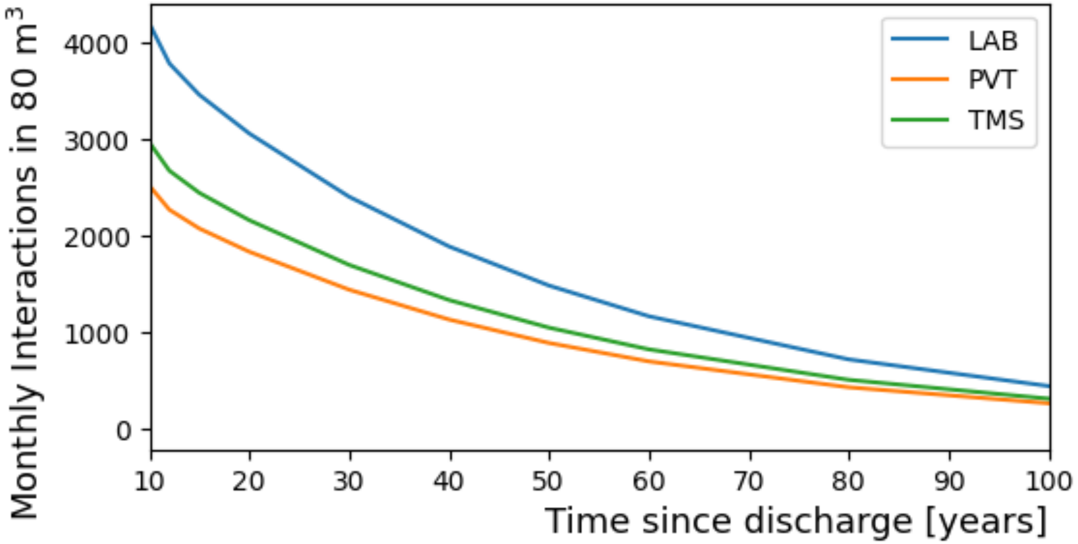
Example Interim Storage Facility: Layout & Interaction Rates

- Modelling sensitivity of idealised 80m³ detectors (no background)
  - **Four locations**:
    - 10m distance from casks
    - One side (left) service building/access
    - Iterative optimisation of locations

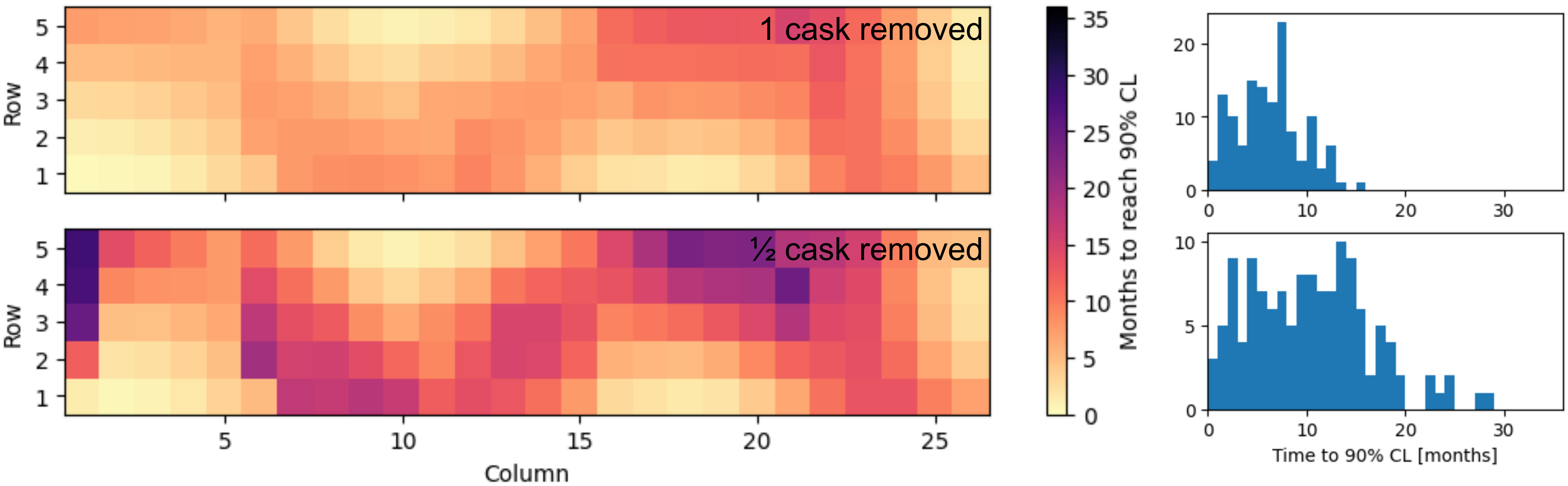


- Simplified interim storage
  - 130 fuel casks x 19 fuel assemblies
  - SNF stored 20-60 years ago

- 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

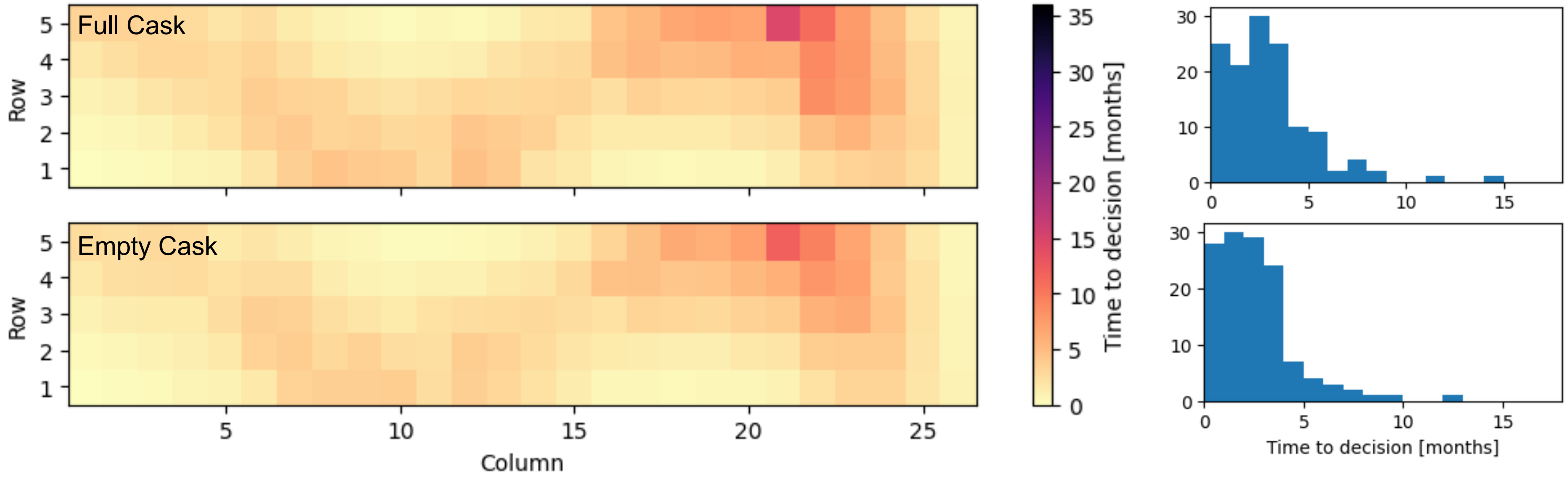


Example Interim Storage Facility: Expected Sensitivity



- 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

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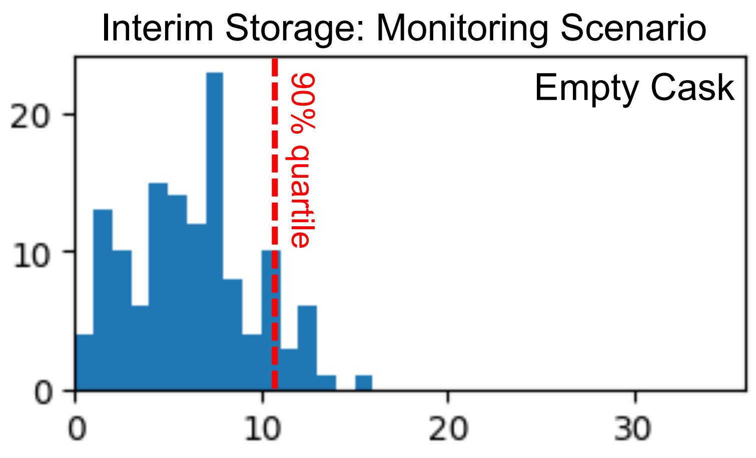
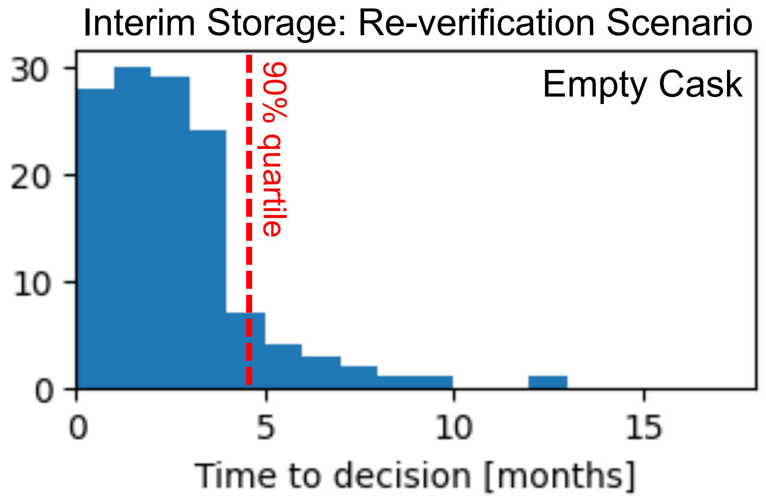
Conclusions

- Antineutrino detection for safeguards
  - **Attractive** features: reduce need for direct (staff) access & unique signal for SNF
  - Information complementary to density or n/ɣ measurements
  - But: **challenging** signal rates in any scenario
- Geological repositories
  - Long-term monitoring (100+ years) difficult: **limited by ^{90}Sr half-life** of ~30 years
  - Monitoring during filling: better signal rate but hard to cover whole repository
- 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





Summary & Outlook

- **NU-SAFEGUARDS**: studying feasibility of antineutrino detection as safeguards for SNF

- 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 to investigate:
  - Embedding application for antineutrino monitoring in overall safeguards concepts & use cases
  - Understand properties & background rates for each detector technology

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