Antineutrino Safeguards for Spent Nuclear Fuel

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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

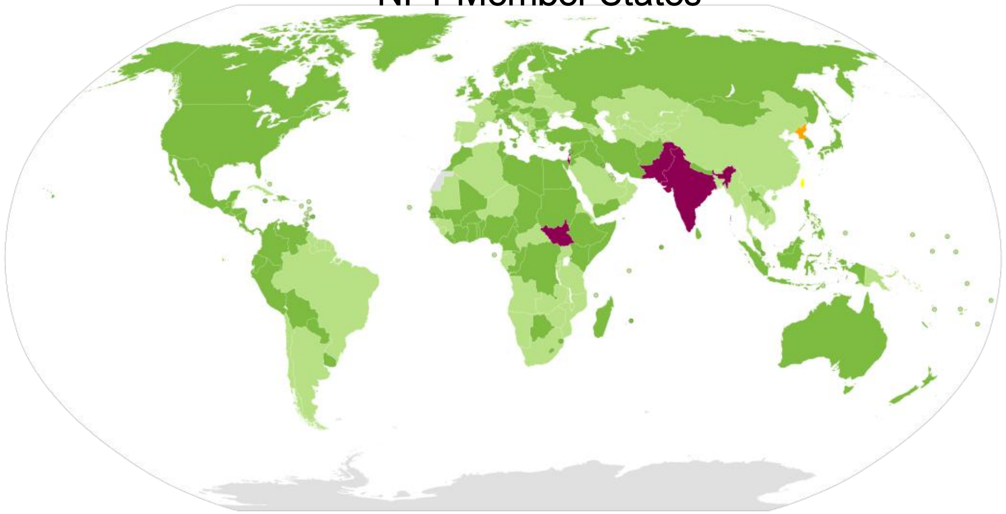
Introduction: Safeguards & Spent Nuclear Fuel

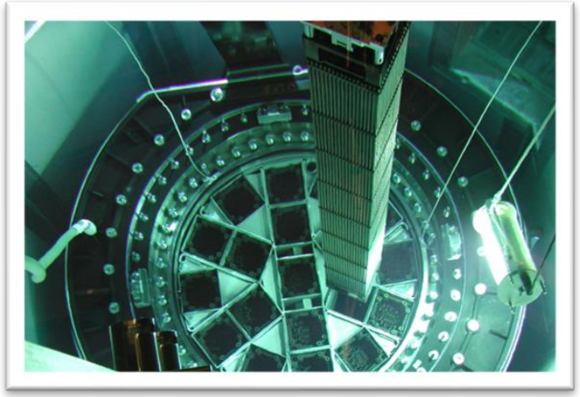
- Fissile material (e.g. ^{235}U, ^{233}U, Pu): **safeguards**
  - Timely detection of (clandestine) diversion of fissile material
  - Applied by IAEA, Non-Proliferation Treaty (NPT): **legal obligation** to declare material

- Spent Nuclear Fuel (SNF) produced by reactors
  - Total global SNF: ~300,000 t HM* + ~7,000 t HM annually
  - Mostly ^{238}U (93-96%), but also: <1% ^{235}U, ~1% Pu
    → interim storage & final disposal **subject to safeguards**

- Discharged SNF after refuelling goes to:
  - **Spent fuel ponds** (several years), **Interim storage** facilities (several decades) or reprocessing, **geological repository** (none yet – Onkalo starting '25, ~100 years operation)

NPT Member States





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

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Safeguarding Spent Nuclear Fuel

- Even without operating reactors:
  - **Decades to centuries** of actively managing SNF

- 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

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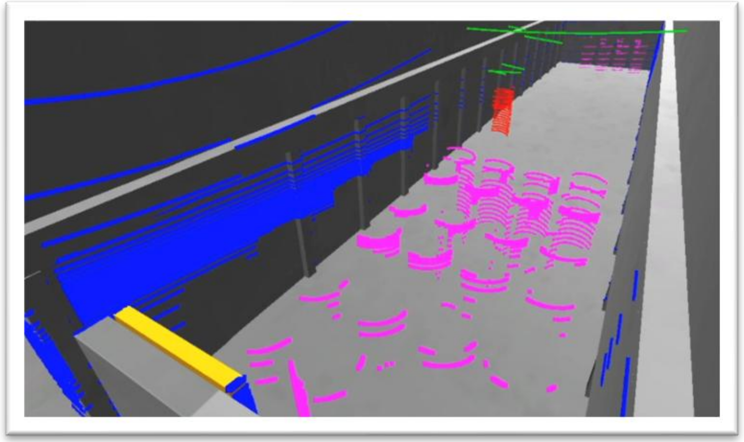
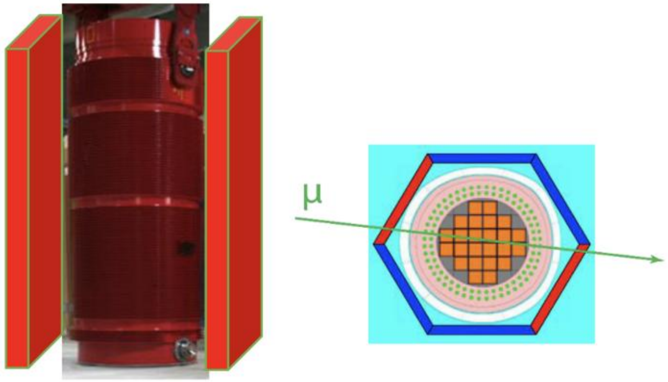
Safeguards R&D for Storage Facilities

- 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



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.

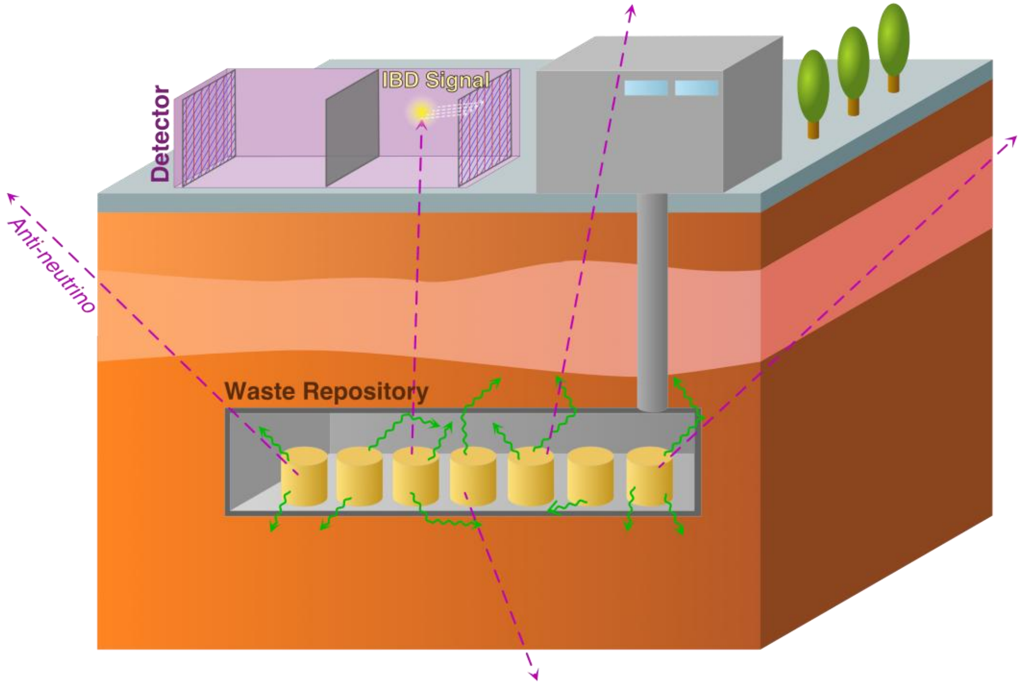
Antineutrino Detection for SNF

- 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/γ measurements

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

- **NU-SAFEGUADS** project investigates:
  - LAB, PVT scintillators + TMS time-projection chambers
  - Current technologies: detection via **Inverse Beta-Decay (IBD)**



Detector Technologies

- Applied antineutrino detection: active R&D in past two decades
  - Focussed on reactor anti-neutrinos
  - 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/

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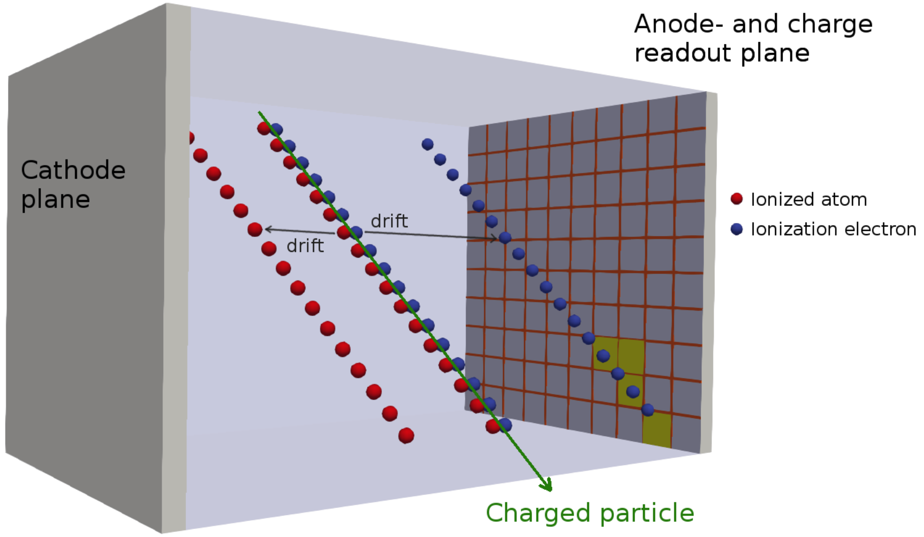
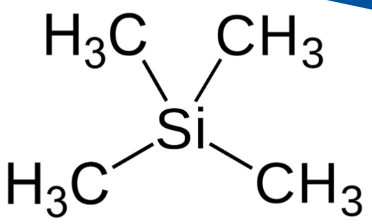
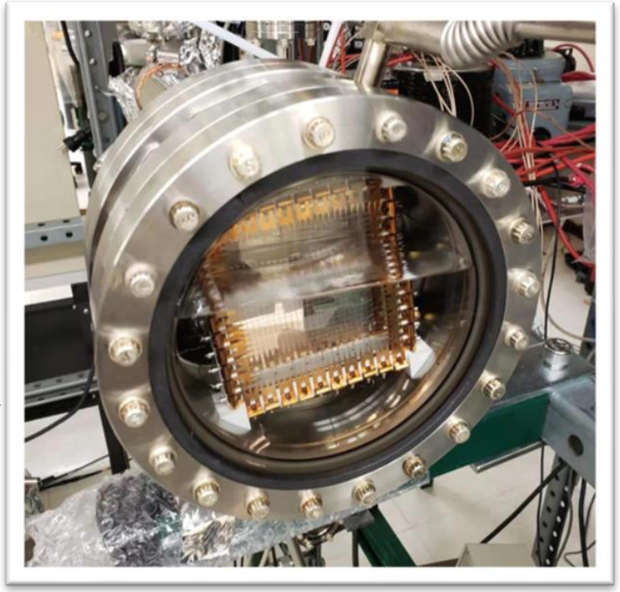
Detector Concept: LOr-TPC



- TPCs provide good **reconstruction of particle positions** and/or trajectories
  → useful for particle ID and directionality
  → but most TPC media not dense / low in hydrogen

- Concept: Liquid Organic TPC (LOr-TPC)
  - **Tetramethylsilane** (TMS): $Si(CH_3)_4$
  - Contains **hydrogen** for IBD: 5.3 x 10^{22} H atoms per cm^3
  - Basic feasibility investigated by S. Wu *et al*. at Stanford
  - However: drift over larger distances unproven



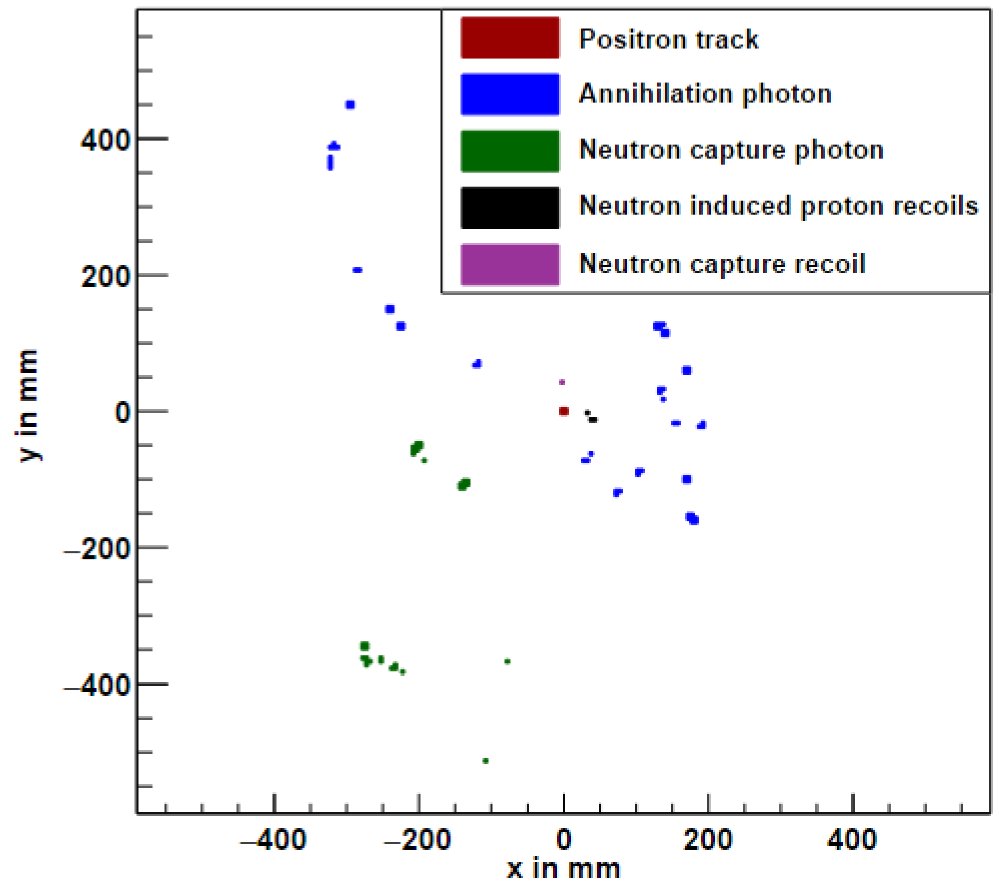


https://arxiv.org/abs/1911.12887

T. Radermacher et al, "Liquid-organic time projection chamber for detecting low energy antineutrinos". Nucl. Instr. Meth. A, vol. 1054, 168426 (2023).

Simulation of IBD in LOr-TPCs

- Initial GEANT4 simulations of 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 $\bar{\nu}_e$ direction with <10° deviation

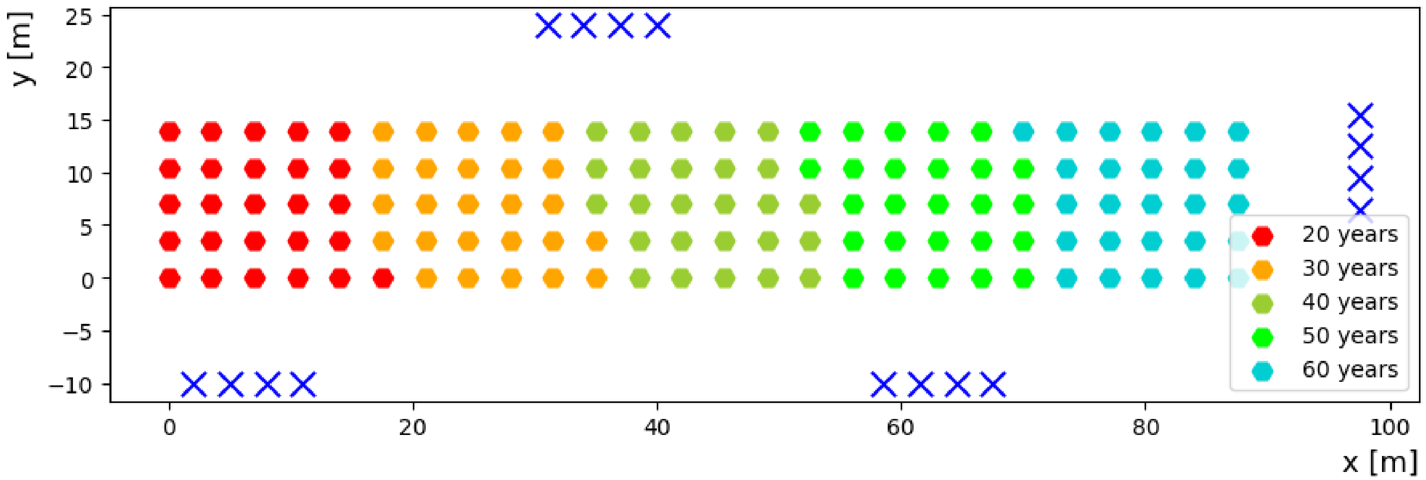


T. Radermacher et al, "Liquid-organic time projection chamber for detecting low energy antineutrinos". Nucl. Instr. Meth. A, vol. 1054, 168426 (2023).

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

Example Study: Interim Storage Facility

- Modelling sensitivity of 80m^3 detectors
  - Four locations:
    - 10m distance from casks
    - Split into four 20m^3 sub-units
  - Concentrate on TMS as medium
- Simplified interim storage
  - 130 fuel casks x 19 fuel assemblies
  - SNF stored 20-60 years ago



Facility Monitoring

- 90% confidence level (CL) test of null hypothesis H_{full} against:
  - Diversion of 1 cask (~10.6 t HM)
  - Diversion of ½ cask (~5.3 t HM)
- Monitoring of whole facility

Re-verification

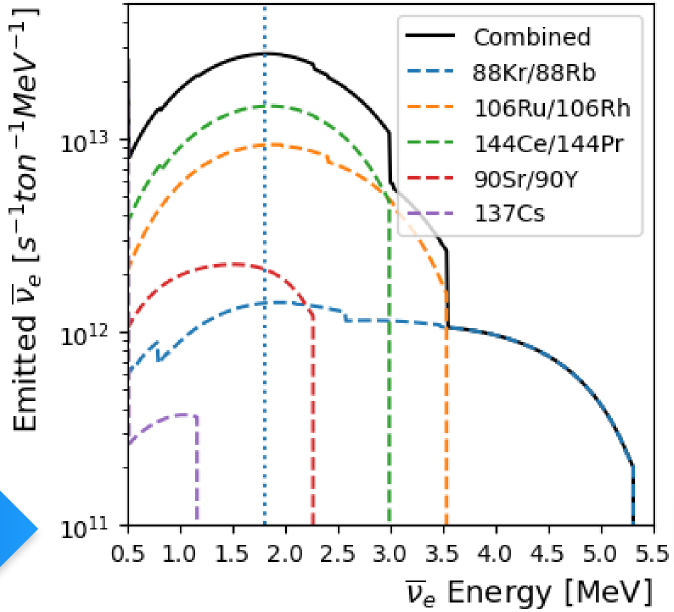
- Verify/reject **single** cask as full/empty
- Directional selection (30º cone)
- Sequential Probability Ratio Test (SPRT): optimal verification/rejection time*
- Allow for asymmetric error:
  - 20% type I error (false positive)
  - 10% type II error (false negative)

Signal: Antineutrino Flux from SNF

Fuel Simulation

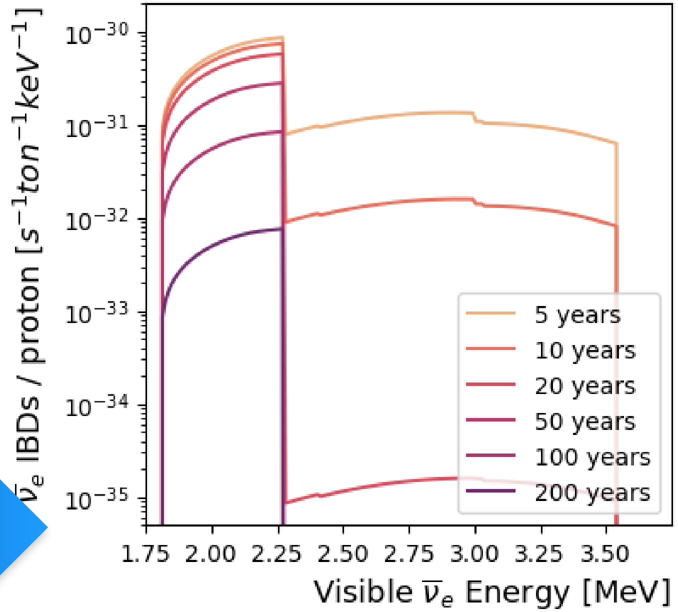
- **ONIX**: simulate fuel assemblies
  - Example: GKN II fuel assembly at 54 MWd/kg burn-up
- Tally isotopic contents after burn-up

Antineutrino Spectrum



- Select main contributing isotopes (high $\overline{\nu}_e$ energy + long half-lives)
- NDS ENDSF database/BetaShape for beta & $\overline{\nu}_e$ 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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[1] First Search for Short-Baseline Neutrino Oscillations at HFIR with PROSPECT (https://doi.org/10.1103/PhysRevLett.121.251802)
[2] PROSPECT-II physics opportunities (https://doi.org/10.1088/1361-6471/ac48a4)
[3] Sterile Neutrino Search at the NEOS Experiment (https://doi.org/10.1103/PhysRevLett.118.121802)

Dominant Background: Cosmogenic Fast Neutrons

- Surface facilities exposed to cosmic rays
  - Spallation of ^{12}C → production of ^{9}Li / ^{8}He
  - Produce **fast neutrons** after decay
  - Fast neutron + accidental prompt from radioactivity
    → **fake IBD signal**

- Use knowledge from reactor antineutrino experiments:
  - Based on PROSPECT[1], PROSPECT-II predictions[2], NEOS[3]
  - Highly segmented detectors using liquid scintillator (LS)

- Estimated background events: 53 events/day per ton
  - Adjusted for ^{12}C content and SNF energy range (1 MeV window):
    - Liquid Scintillator (LAB): c. 7.1 events per day per m^3
    - Plastic Scintillator (PVT): c. 8.5 events per day per m^3
    - LOr-TPC (TMS): c. 3.4 events per day per m^3

Conservative

- No further assumptions

→ 272 events / day per detector

Directional

- Rejection of any events not coming from facility

→ 27.2 events / day per detector

Directional + Enhanced

- Rejection of any events not coming from facility
- 0.5 MeV window
- 50% reduction through e+/e- ID

→ 6.8 events / day per detector

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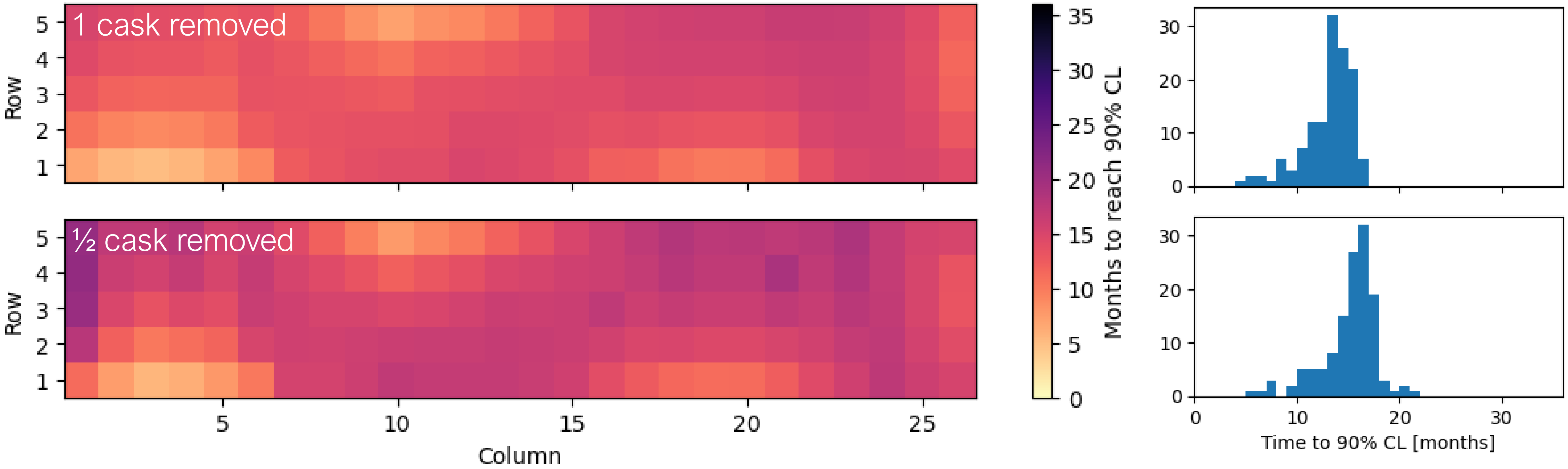
Facility Monitoring: "Conservative Background"



- Time t_{CL90} to reach 90% CL for both scenarios for each cask location
  - Scenario 1 (1 cask): $\tilde{t}_{CL90}$ **(median) = 13.6 months** (5.0-16.5 months), 90% quantile = 15.6 months
    - No bkg (1 cask): $\tilde{t}_{CL90}$ **(median) = 8.5 months** (1.4-11.0 months), 90% quantile = 11.4 months
  - Scenario 2 (½ cask): $\tilde{t}_{CL90}$ **(median) = 15.7 months** (5.6-22.0 months), 90% quantile = 17.6 months
    - No bkg (½ cask): $\tilde{t}_{CL90}$ **(median) = 11.3 months** (1.7-21.1 months), 90% quantile = 14.2 months

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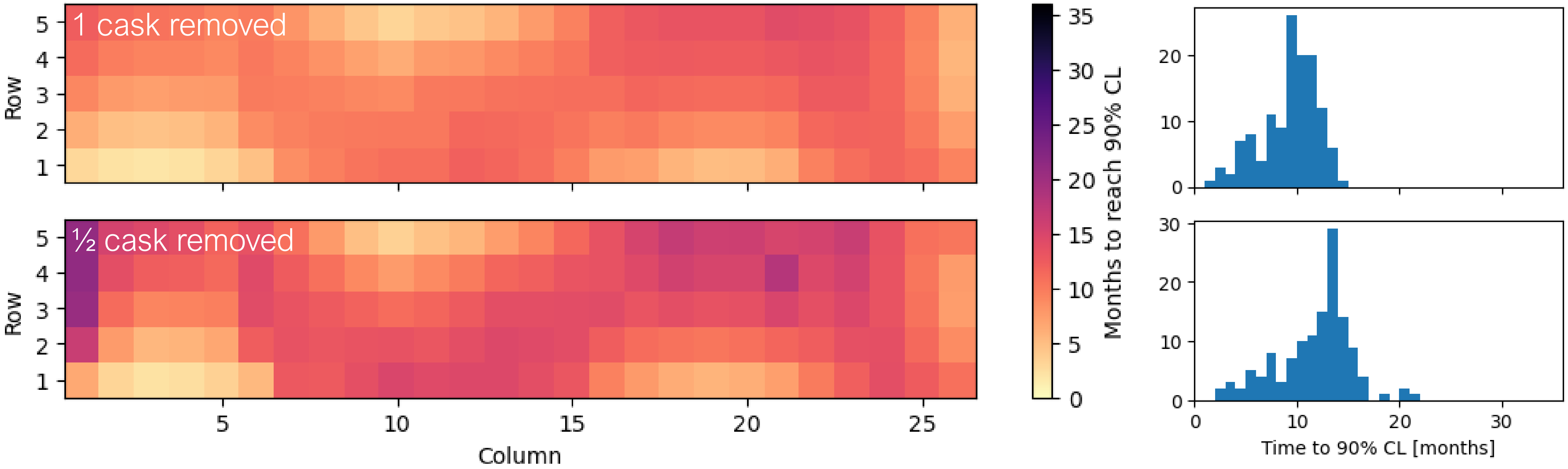
Facility Monitoring: “Directional Rejection”



- Time t_{CL90} to reach 90% CL for both scenarios for each cask location
  - Scenario 1 (1 cask): $\tilde{t}_{CL90}$ (median) = **9.3 months** (1.9-14.1 months), 90% quantile = 12.5 months
    - No bkg (1 cask): $\tilde{t}_{CL90}$ (median) = **8.5 months** (1.4-11.0 months), 90% quantile = 11.4 months
  - Scenario 2 (½ cask): $\tilde{t}_{CL90}$ (median) = **11.8 months** (2.2-21.4 months), 90% quantile = 15.4 months
    - No bkg (½ cask): $\tilde{t}_{CL90}$ (median) = **11.3 months** (1.7-21.1 months), 90% quantile = 14.2 months

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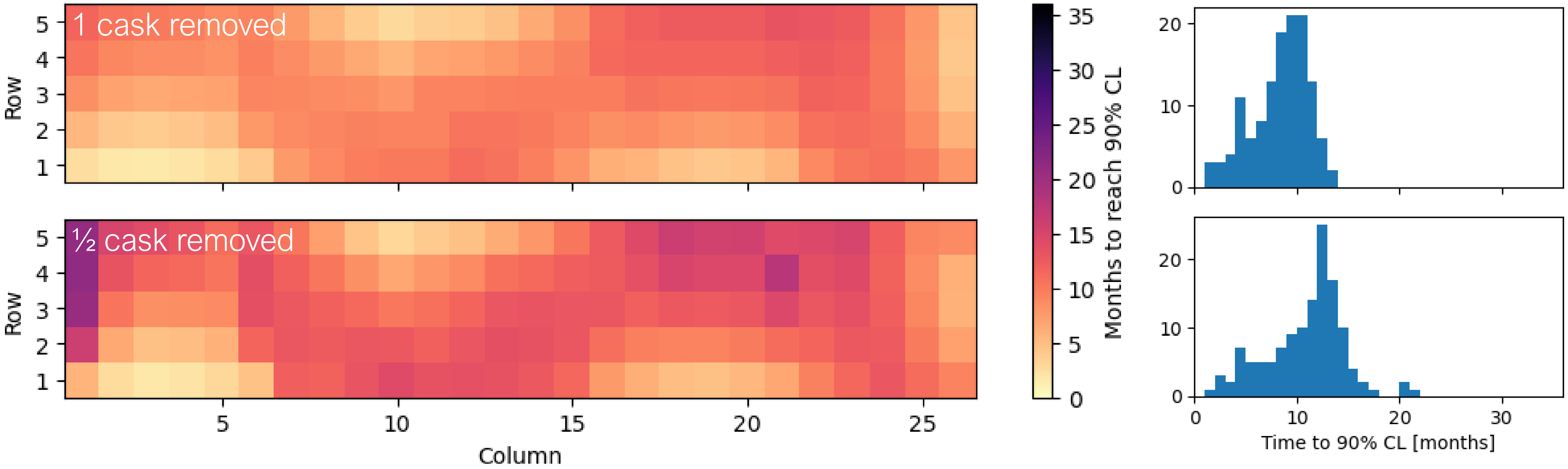
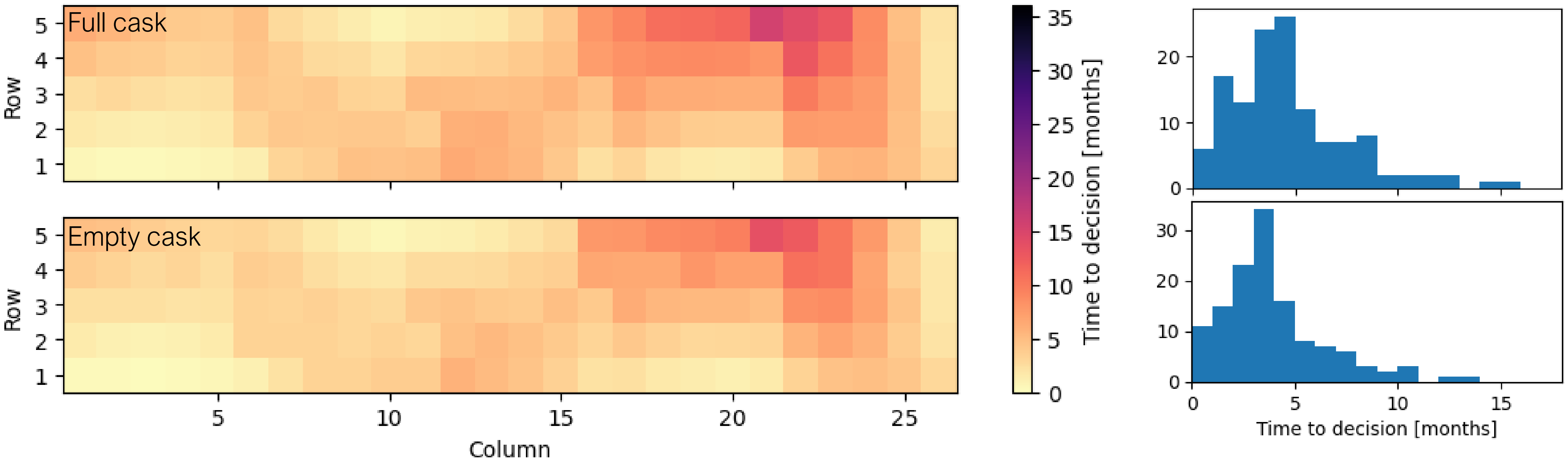
Facility Monitoring: “Directional + Enhanced Rejection”



- Time t_{CL90} to reach 90% CL for both scenarios for each cask location
  - Scenario 1 (1 cask): $\tilde{t}_{CL90}$ **(median) = 8.9 months** (1.6-13.3 months), 90% quantile = 11.7 months
    - No bkg (1 cask): $\tilde{t}_{CL90}$ **(median) = 8.5 months** (1.4-11.0 months), 90% quantile = 11.4 months
  - Scenario 2 (½ cask): $\tilde{t}_{CL90}$ **(median) = 11.8 months** (1.8-21.2 months), 90% quantile = 14.6 months
    - No bkg (½ cask): $\tilde{t}_{CL90}$ **(median) = 11.3 months** (1.7-21.1 months), 90% quantile = 14.2 months

Re-Verification: “Directional + Enhanced Rejection”



- Re-verification of single cask of interest: verify full or declare empty cask with SPRT
- Time t_{SPRT} to verify/reject a cask (30° selection cone)
  - Full Cask: $\tilde{t}_{SPRT}$ (median) = 4.1 months (0.3-15.6 months), 90% quantile = 8.6 months
    - No bkg: $\tilde{t}_{SPRT}$ (median) = 2.6 months (0.3-14.6 months), 90% quantile = 5.6 months
  - Empty Cask: $\tilde{t}_{SPRT}$ (median) = 3.3 months (0.3-13.5 months), 90% quantile = 7.8 months
    - No bkg: $\tilde{t}_{SPRT}$ (median) = 2.2 months (0.2-10.6 months), 90% quantile = 4.7 months

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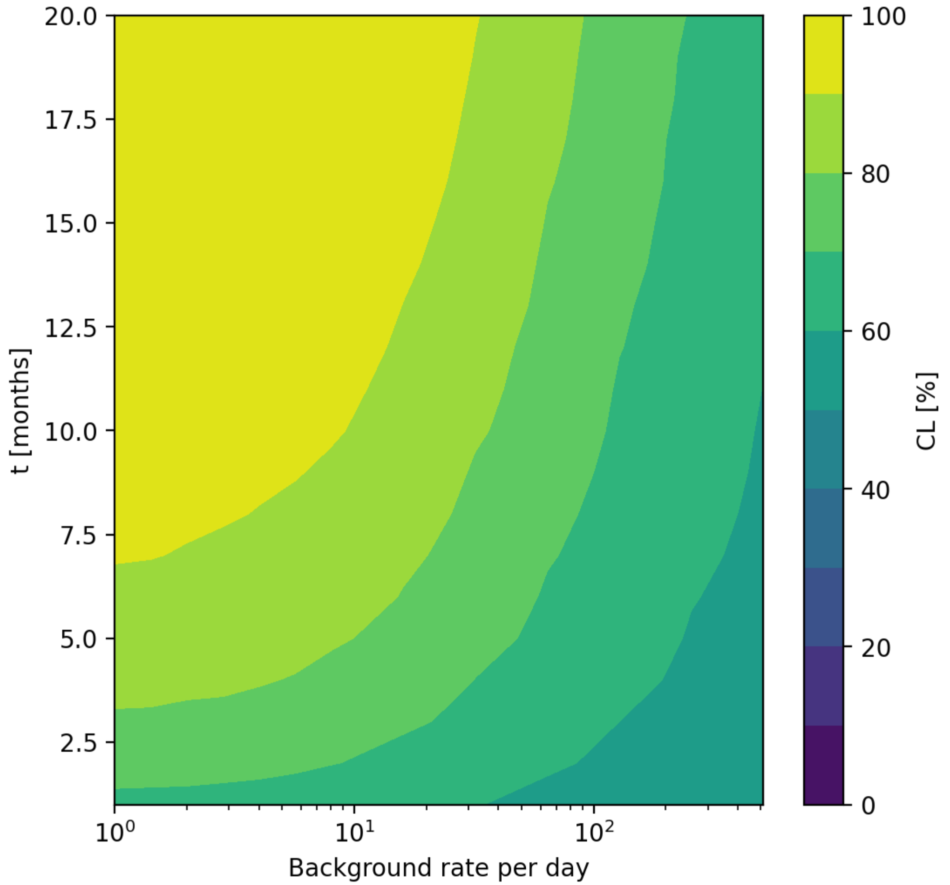
“Pick your CL”

- Repeat facility monitoring procedure for:
  - Background rate from 1/day – 500/day
  - Calculate median CL for range 1 – 20 months

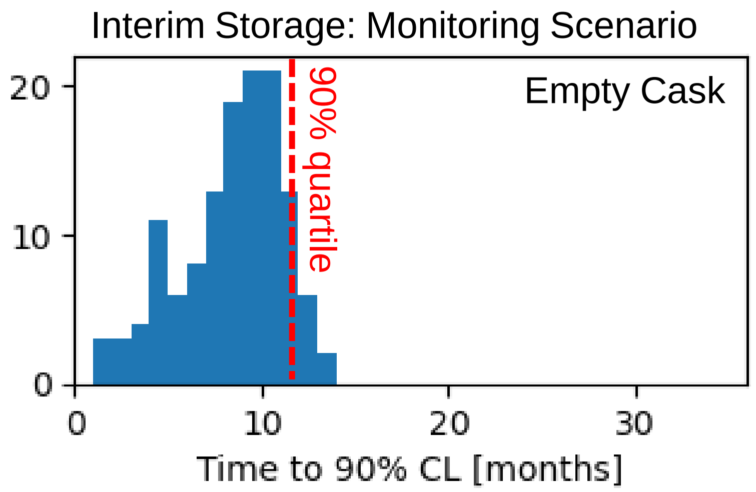
- Determine required background suppression based on…
  - Required timeliness (depends on monitored material)
  - Acceptable CL

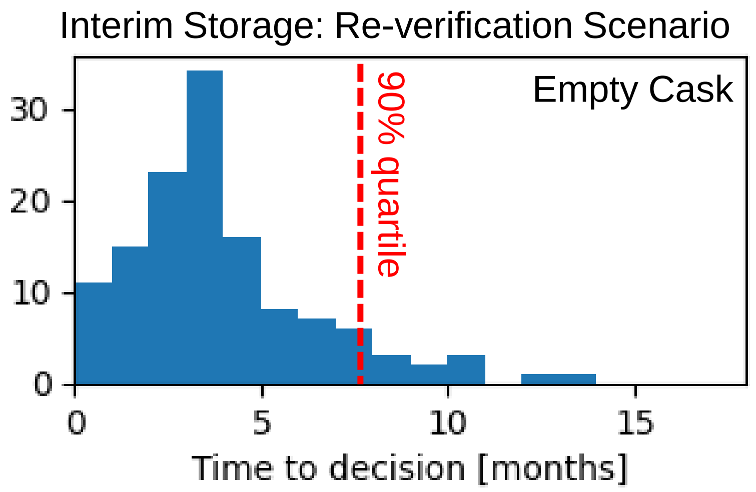
- Required CL varies by task
  - “Gold standard” at 90%
  - For certain re-verification / complementary as low as 50%



Conclusions

- Antineutrino detection for safeguards
  - **Attractive** features: reduce need for direct (staff) access & unique signal for SNF
  - Information complementary to density or n/γ measurements
  - But: **challenging** signal rates in any scenario
- Interim storage facility
  - Newer SNF & lower stand-off distances: **sufficient signal rates**
  - Cosmogenic background challenging:
    - Directionality greatly enhances sensitivity
    - **Need** for detector R&D to be feasible
  - **General monitoring**: < 1 year to detect removal
  - **Re-verification**: few months required





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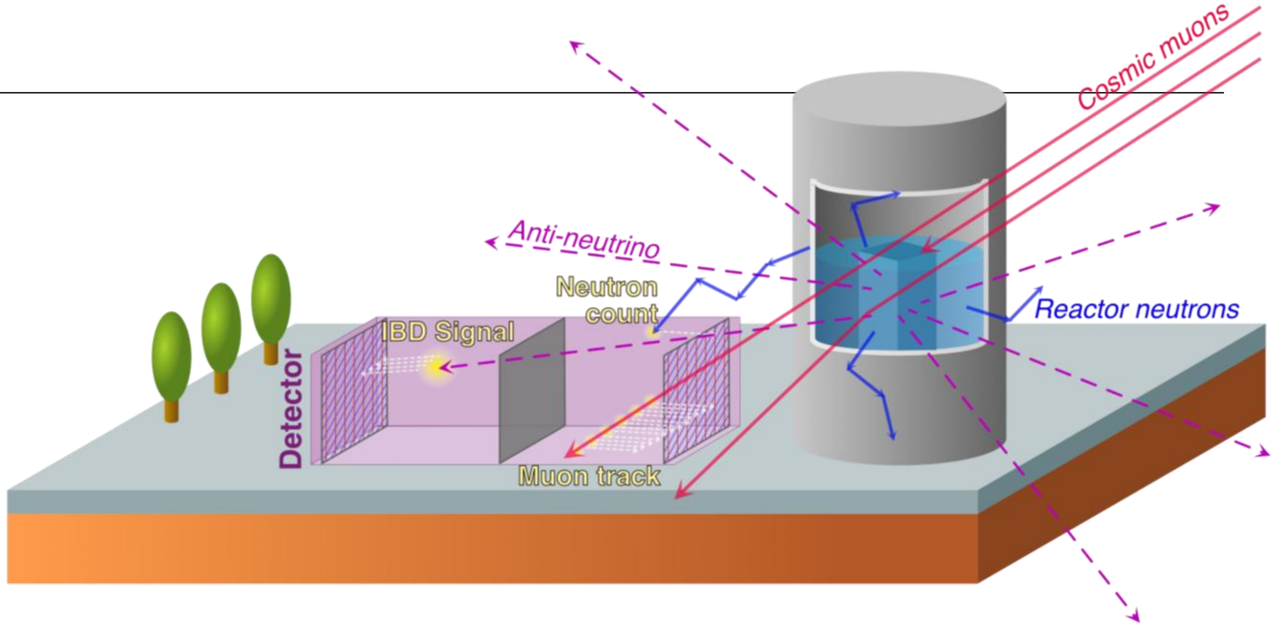
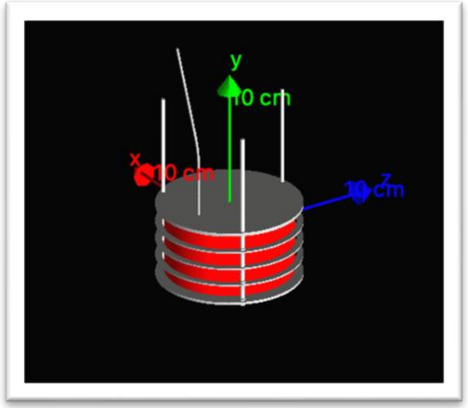
Ongoing & Future Work

- Expanding studies with **nuSENTRY**
  - Project on antineutrino-based safeguards for future reactors (SMRs, Gen 4+, HALEU etc)
  - Combination with other channels of interest
  - Includes detector development:
    - Scaling for LOr-TPC with TMS: test of readout with up to 10 cm drift distance
    - Custom TMS purification & cooling system for LOr-TPC system





DN100CF Cube

Summary & Outlook

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

- Continued studies with **nuSENTRY**
  - Embedding application for antineutrino monitoring in overall safeguards concepts & use cases for new reactors (advanced, SMR, HALEU)
  - LOr-TPC R&D

- Collaboration with the **Peace Research Institute Frankfurt (PRIF)**
  - Affiliated with the Science for Nuclear Diplomacy group (https://www.cntrarmscontrol.org/snd)
  - Using experimental physics + computational physics to support non-proliferation, arms control, verification and disarmament of nuclear weapons

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Thank you for your attention!

…any questions?

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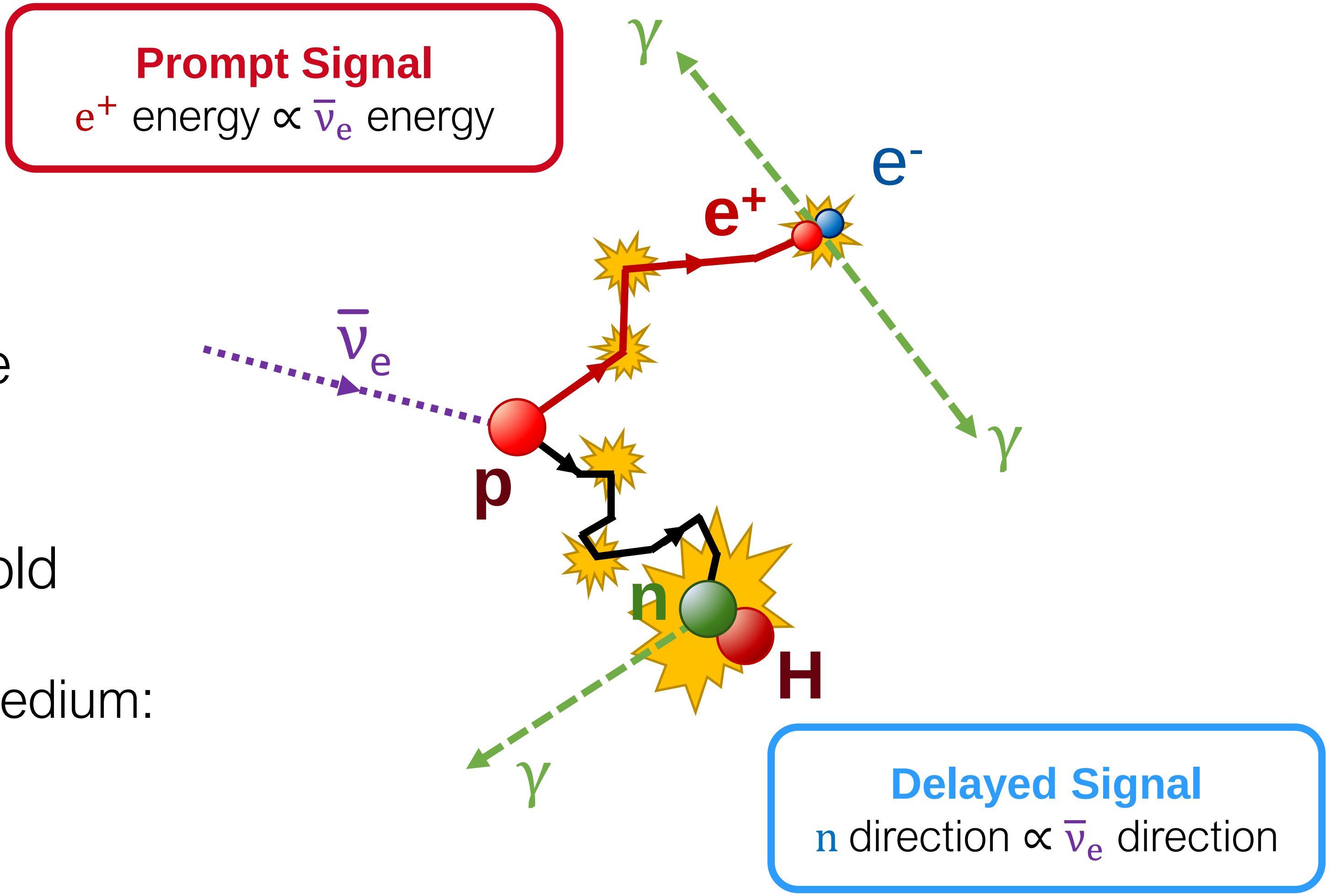
Backup Slides

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: organic scintillators, organic media



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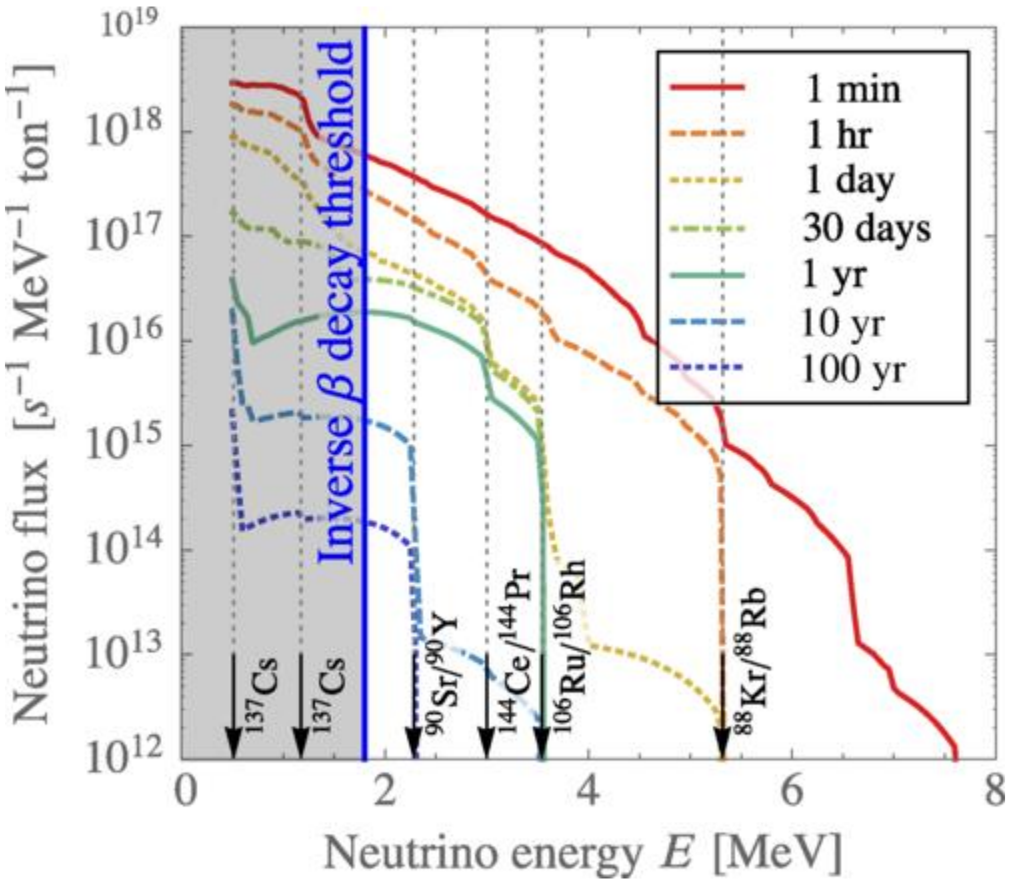
Antineutrino Monitoring Concept Paper

- 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



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Significant Quantities

- "Timely" dependent on isotope and form
- Detection time dependent on ease of extraction

Material	Quantity
Plutonium ^{233}U	8 kg 8 kg
Highly enriched uranium (20+% ^{235}U)	25 kg
Low enrichment uranium (<20% ^{235}U) Natural uranium Depleted uranium	75 kg 10 t 20 t
Thorium	20 t

Material	„Timely“
Fresh Plutonium / ^{235}U	1 Months
Irradiated Plutonium / ^{235}U	3 Months
Indirectly useable material	3-12 Months

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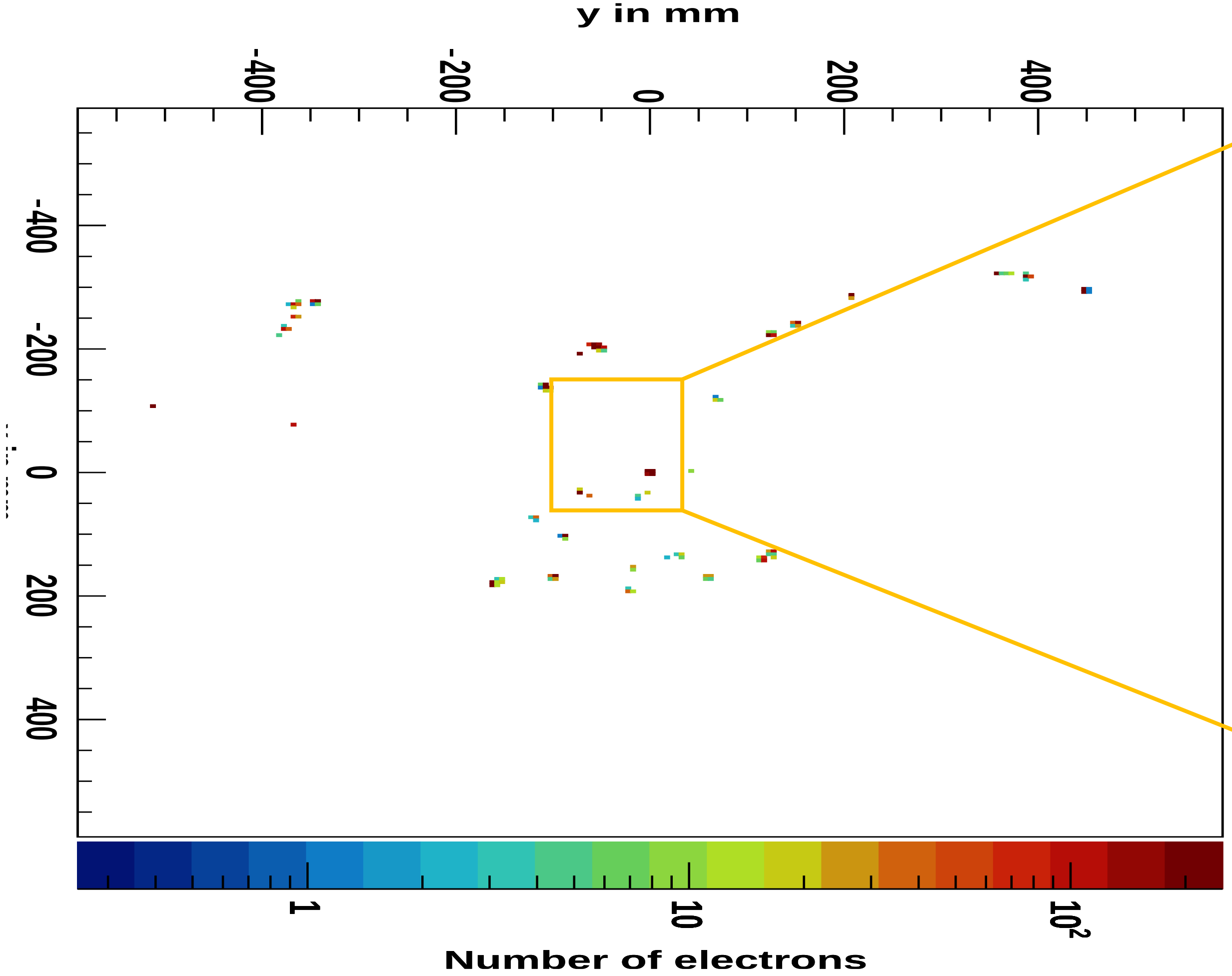
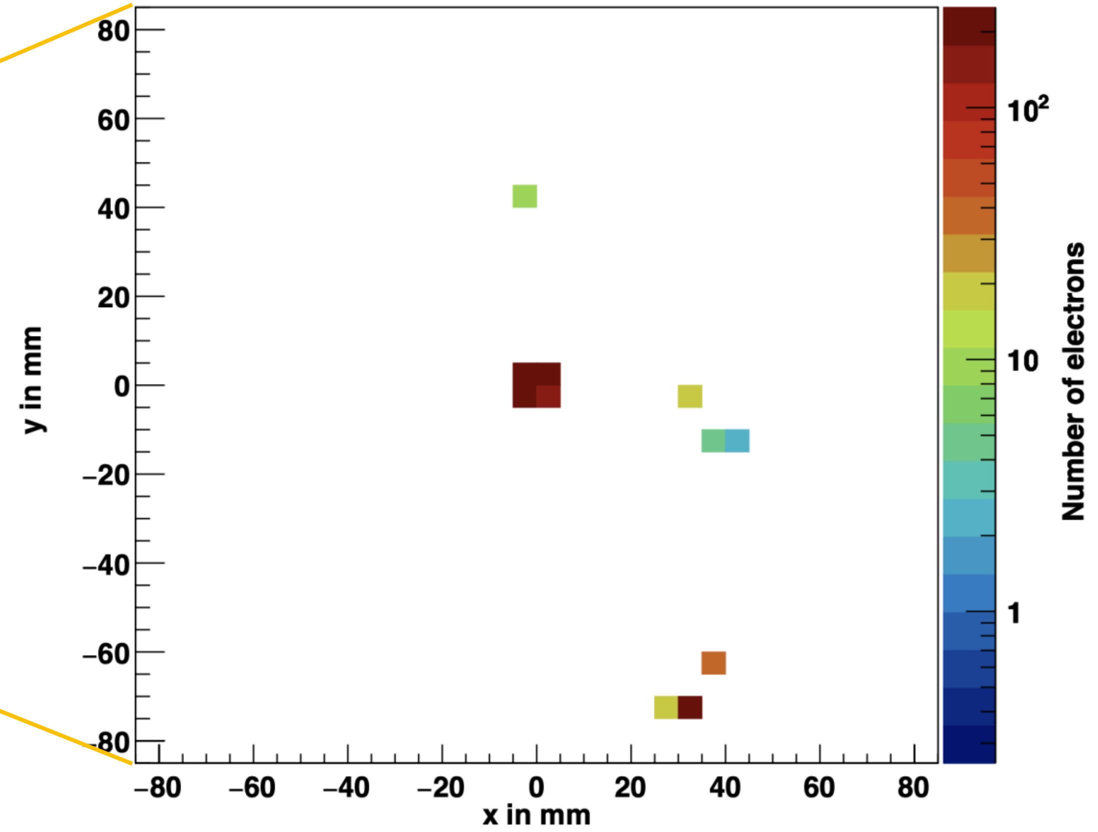
IBD Event in LOr-TPC (Electron Yield)

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





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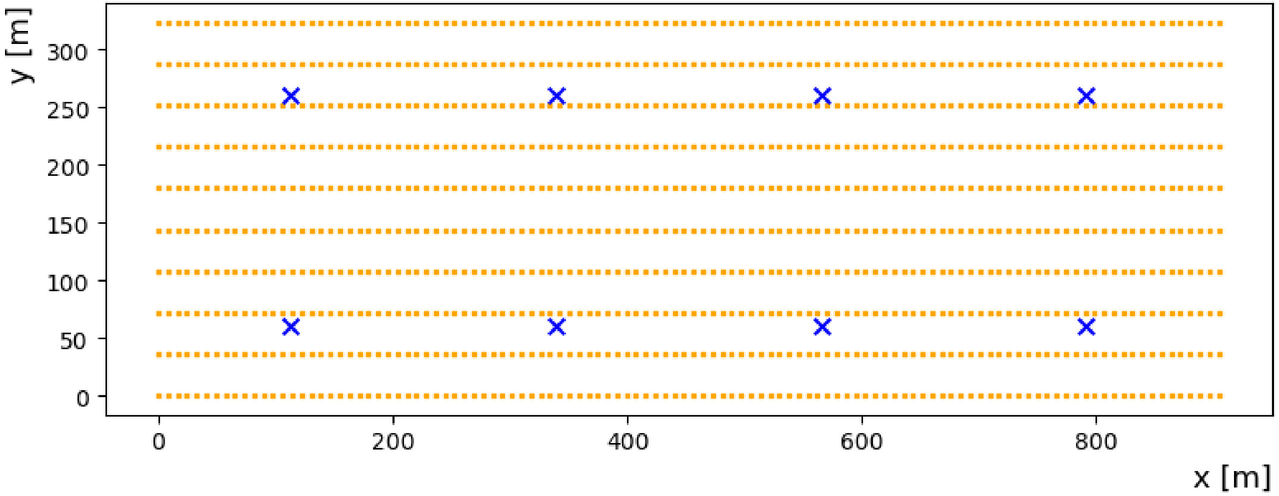
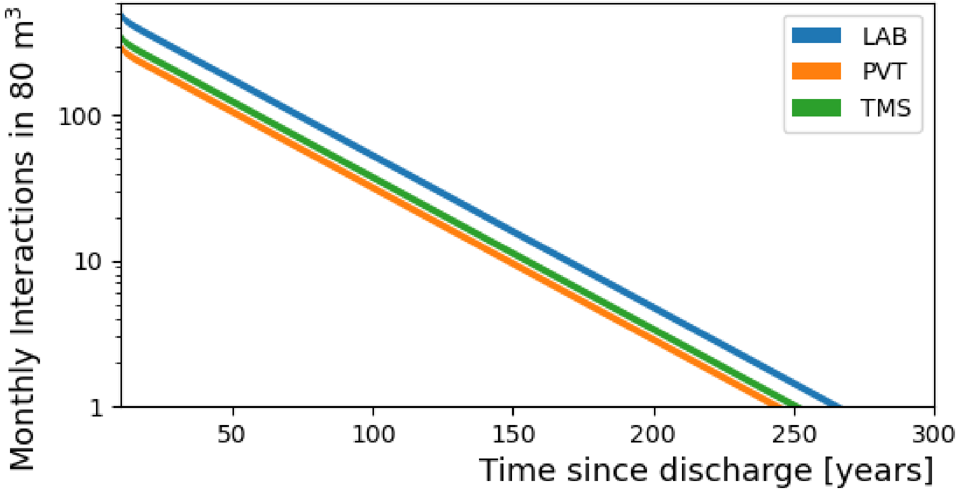
Example: Geological Repository - Layout

- 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





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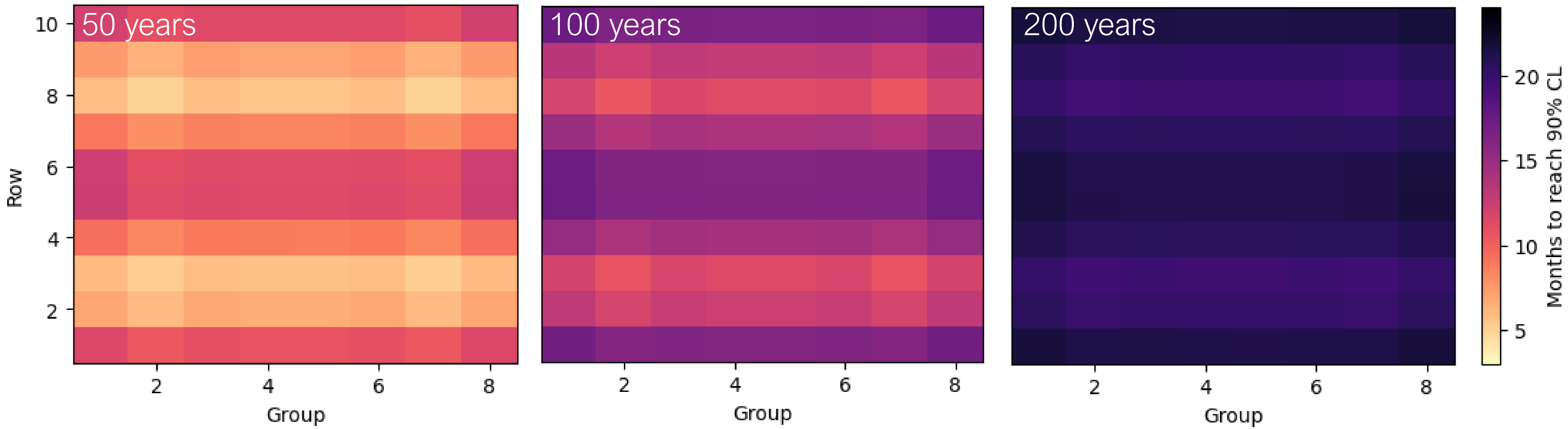
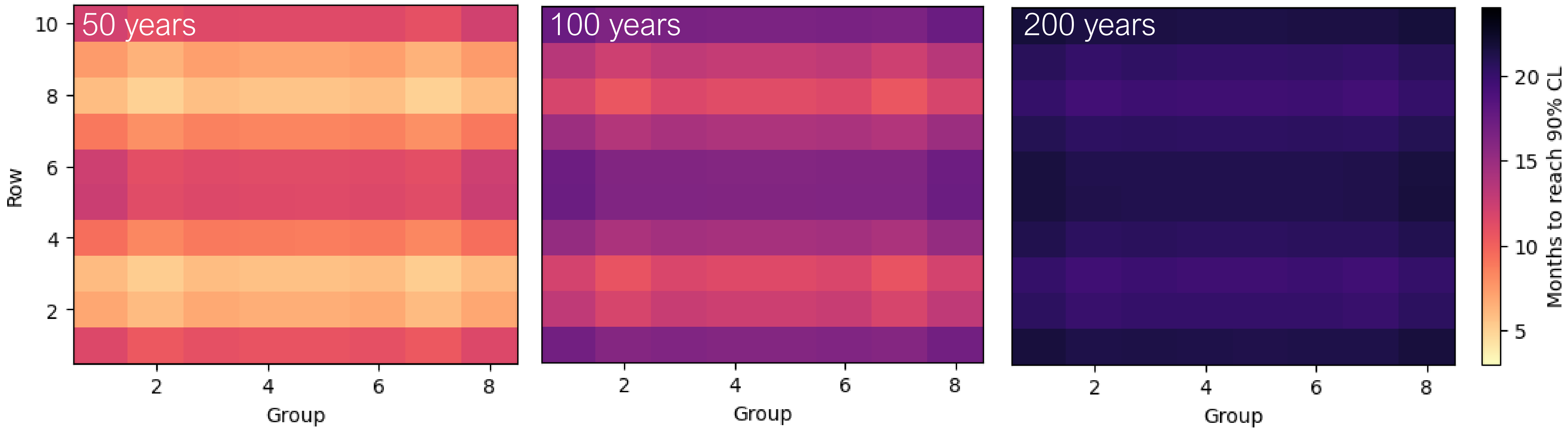
Example: Geological Repository – Sensitivity



- Criterion for detection: 90+% CL that diversion occurred

- Time t_{CL90} to reach 90% CL for all scenarios for removed group (no background)
  - 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: Geological Repository – Sensitivity



- Conclusion for geological repositories
  - Long-term monitoring (100+ years) difficult:
    - **Limited by ^{90}Sr half-life** of ~30 years
    - **Need to cover large area**

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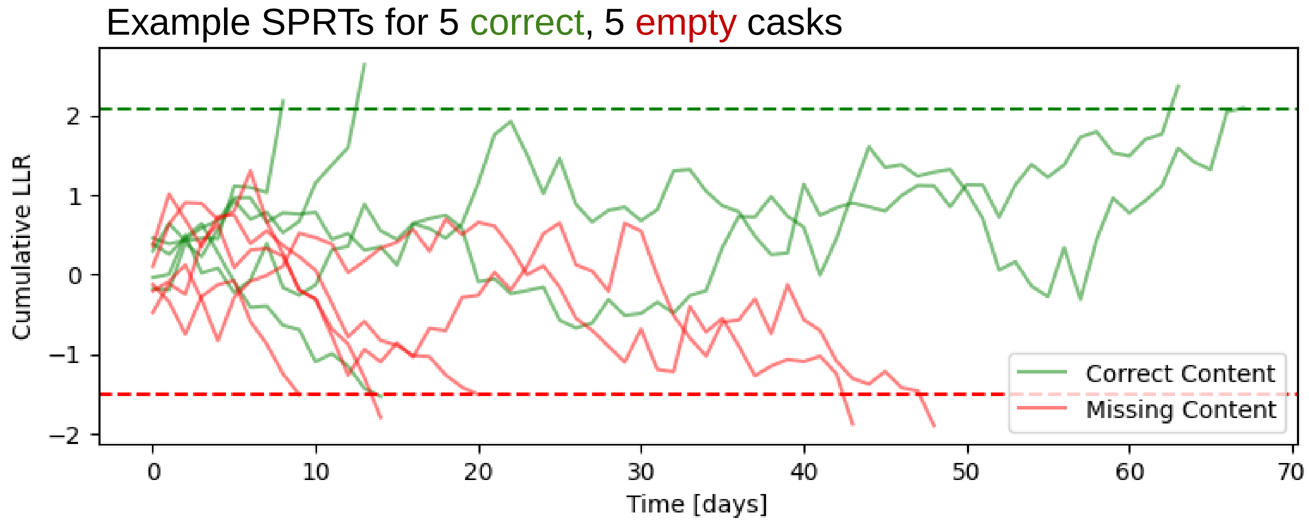
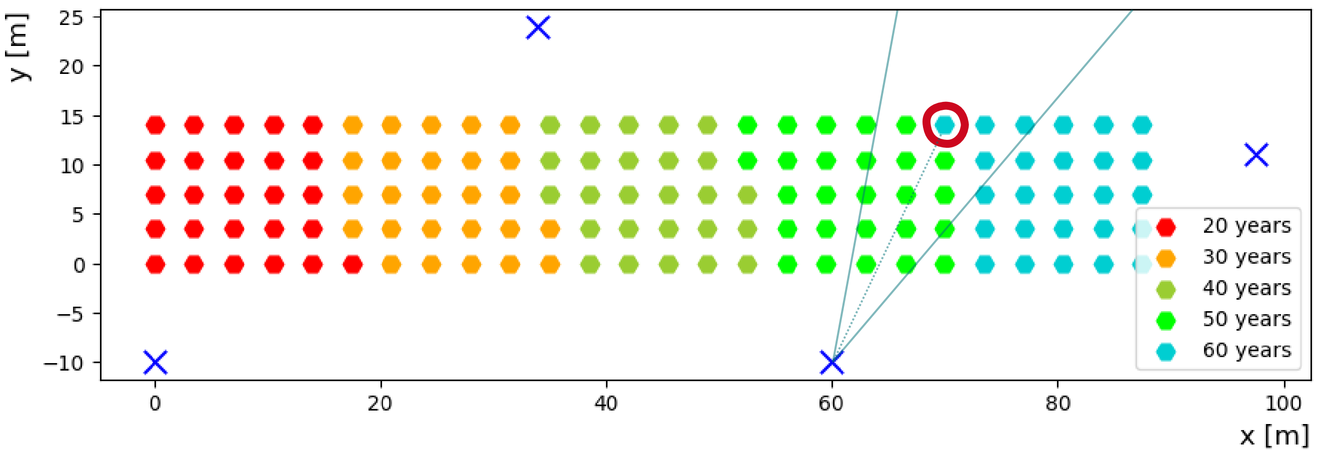
Sequential Probability Ratio Test





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TMS Purification System