Evaluating Antineutrino-Based Safeguards using the RETINA System

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2023 LANNS Symposium-2

LANNS
LABORATORY FOR ADVANCED NUCLEAR NONPROLIFERATION AND SAFETY

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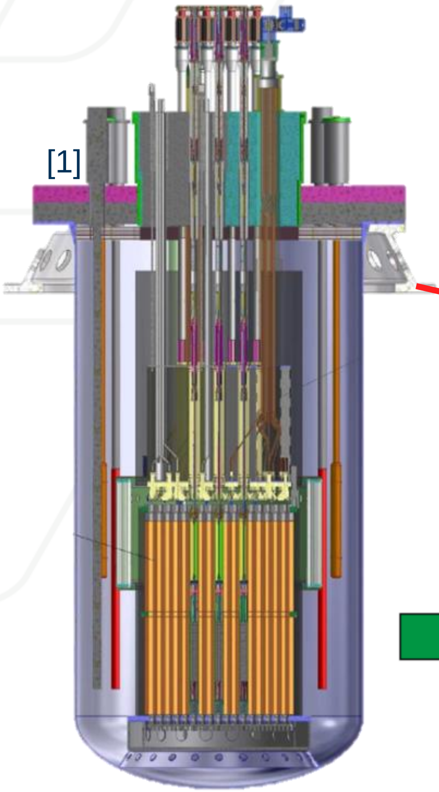
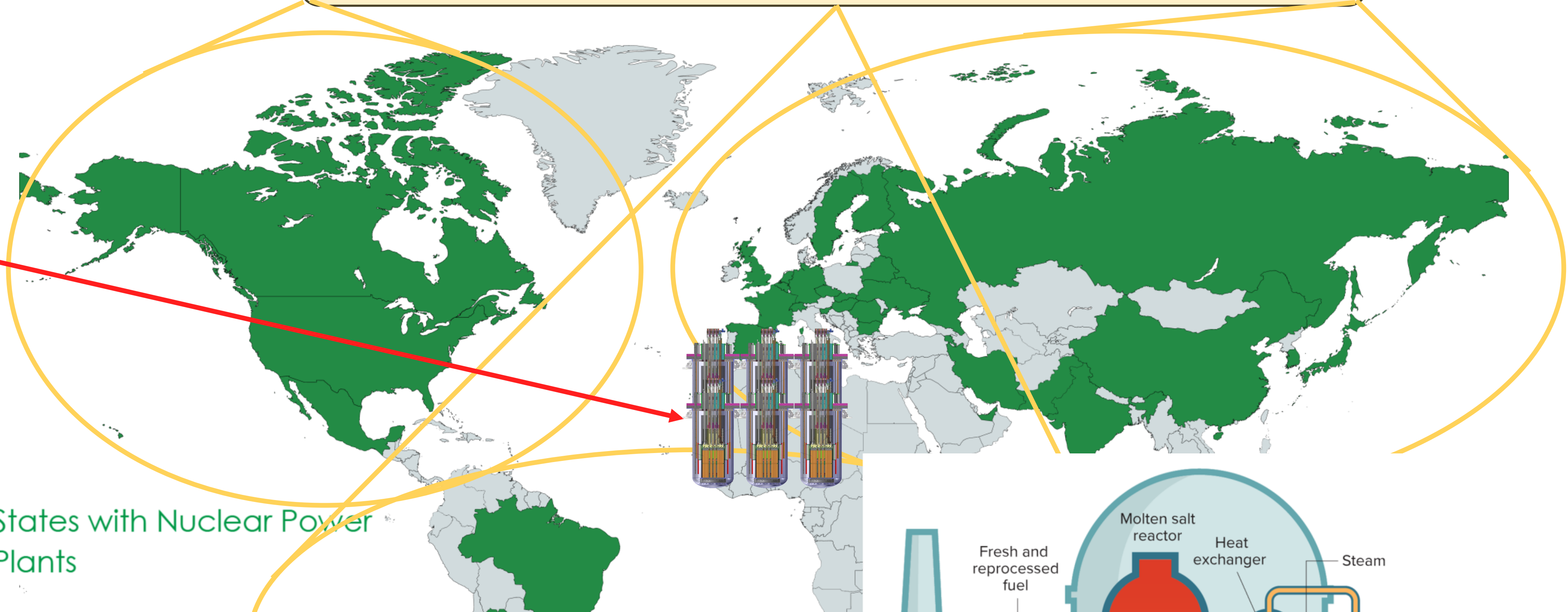
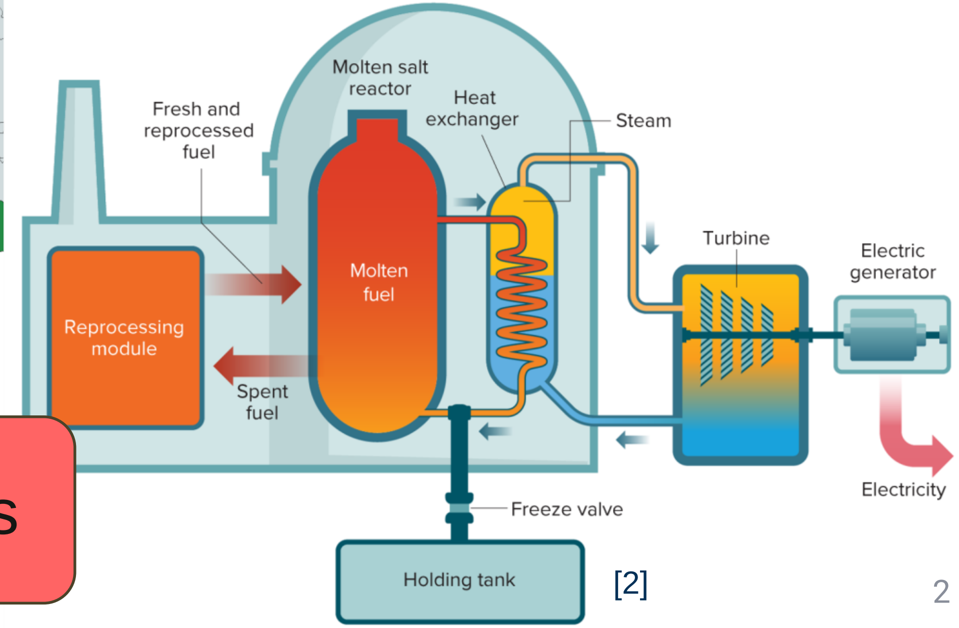
Introduction

The International Atomic Energy Agency (IAEA)

[1]







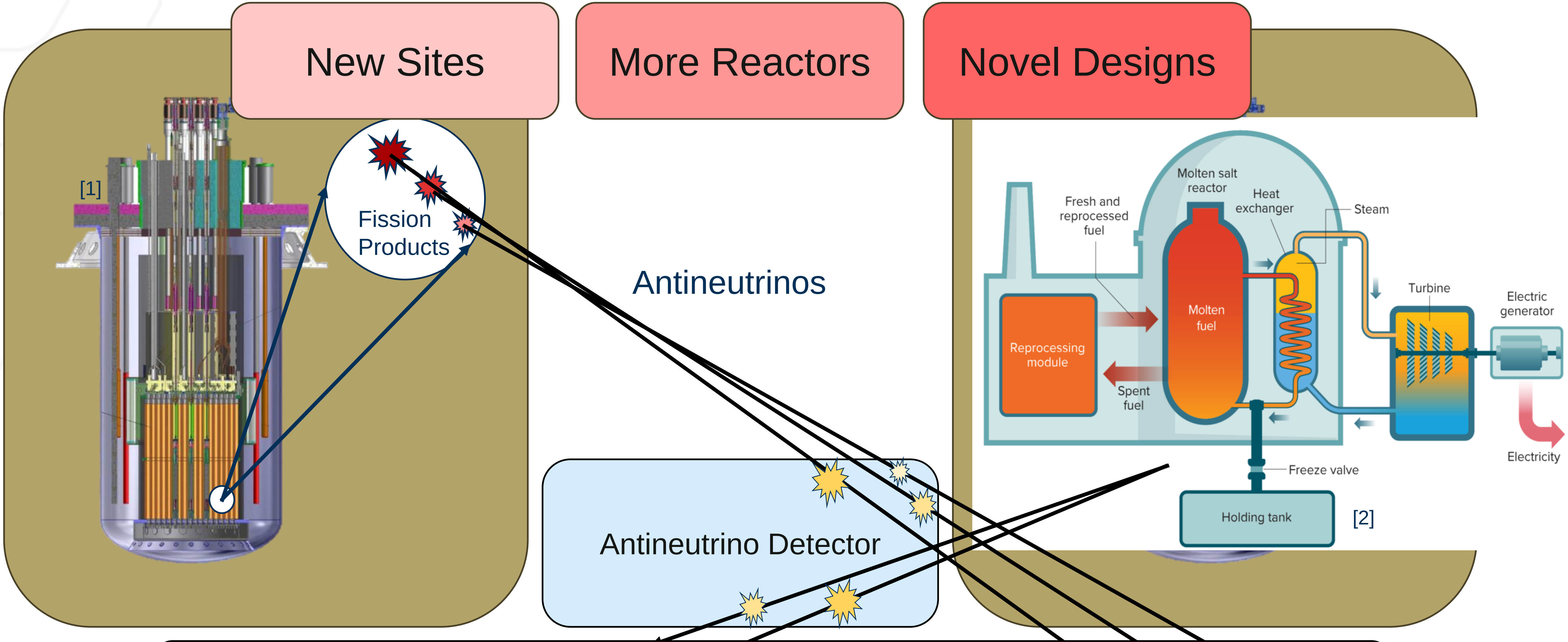
[2]

New Sites

More Reactors

Novel Designs

Motivation



How do we know reactors are operating as declared?

Background

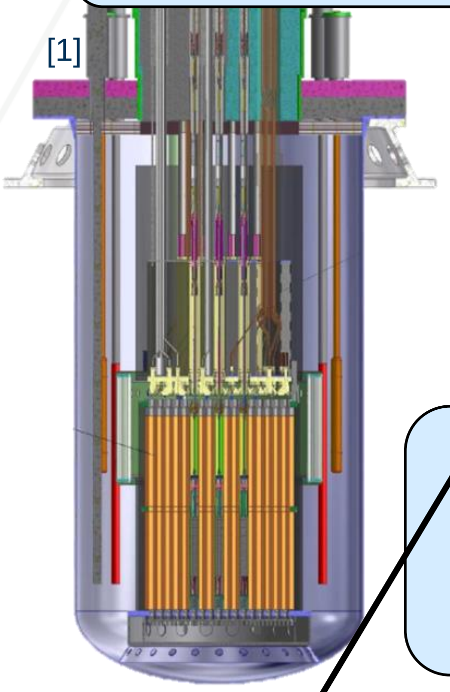
The Reactor Evaluation Through Inspection of Near-field Antineutrinos (RETINA) System

Design relevant environments

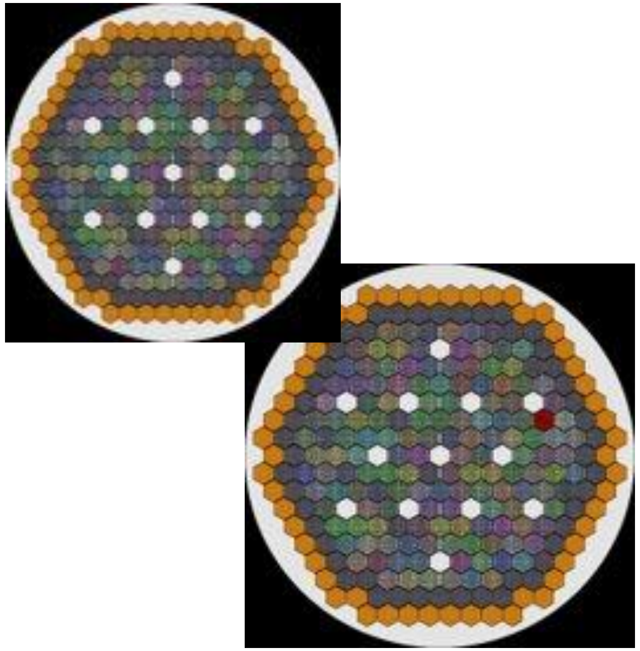
Simulate potential reactor conditions

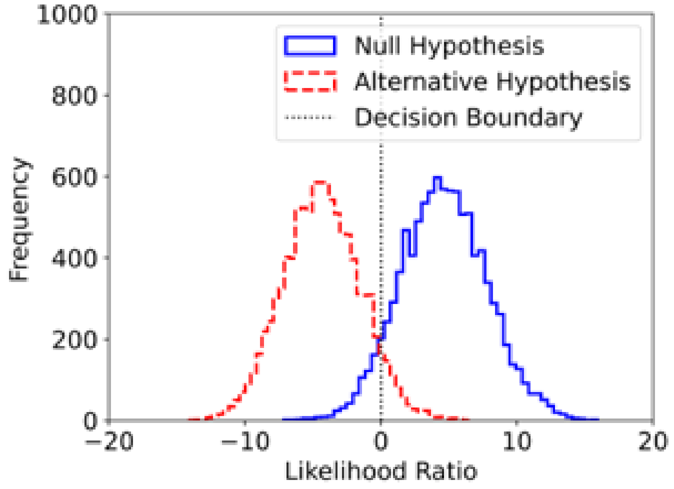
Deduce the current reactor state

[1]

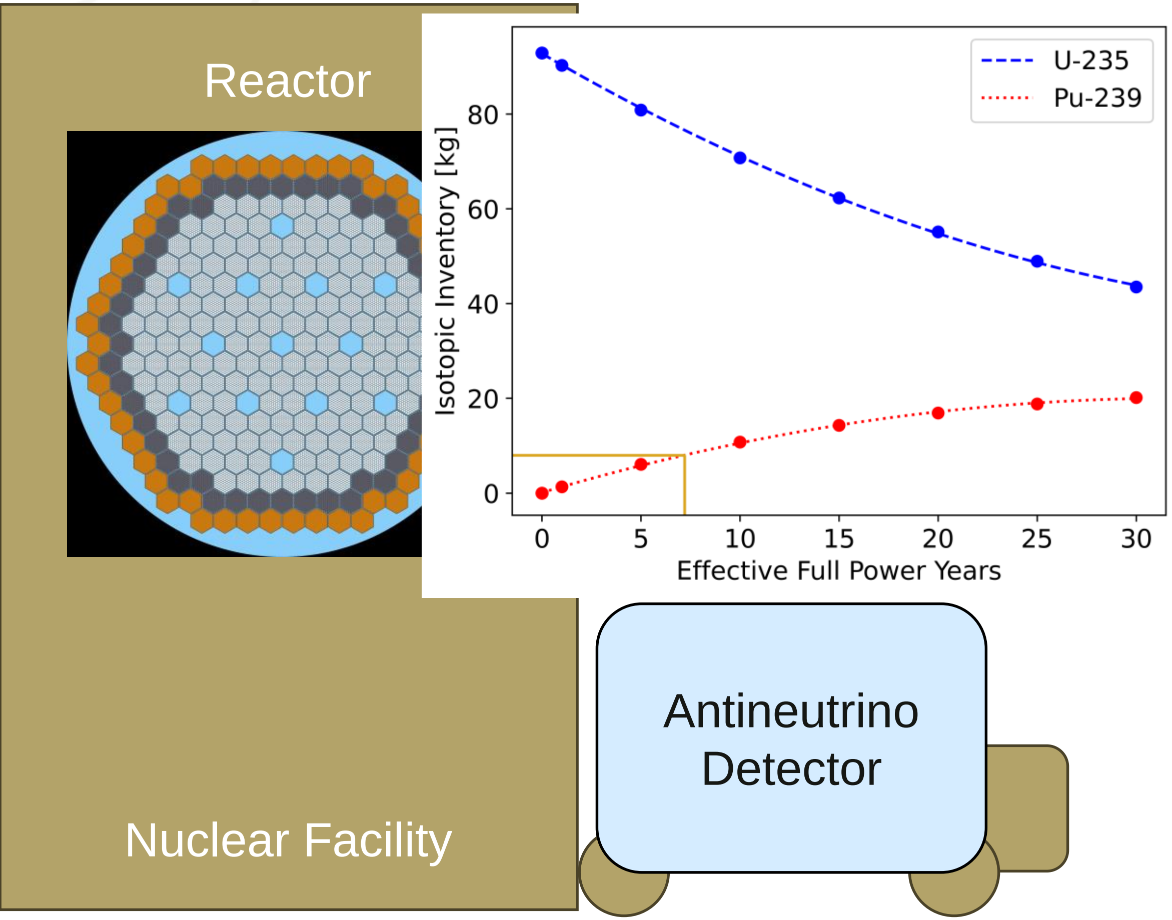


Antineutrino Detector





Evaluating Antineutrino-Based Safeguards



	Log In Declaration	Log In Alternative
Reactor Age [EFPYs]	7.2	0
Reactor Power [MWth]	250	250
Standoff Distance [m]	17	17
Background Knowledge [events]	Simulated bkgd collection	Simulated bkgd collection
Collection Period [days]	30	
Probability of Detection	62.4%	

Scenario Sensitivity Challenges

Assessing Sensitivity with ML Processing

Assessing Sensitivity for Specific Scenarios

(Old Results)	Individualized Models (Detection Probability)	Unseen Models (Detection Probability)
Diverted 1 Assembly	2.28%	1.40%
Diverted 2 Assemblies	0.27%	< 0.01%
Diverted 3 Assemblies	0.15%	< 0.01%

Does not work well for "unseen" scenarios

Limited computational resources means there will always be unseen scenarios

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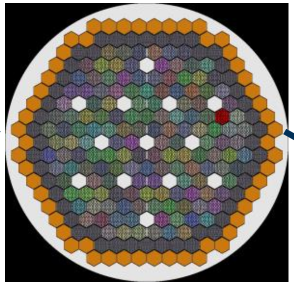
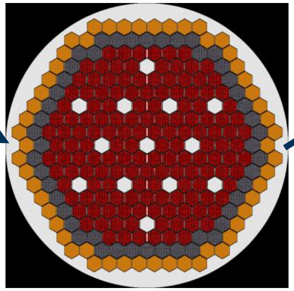
Future Work

Temporal Difference Learning

Test and Learn from Unseen Scenarios

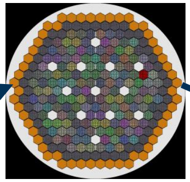
Scenario Selection Agent

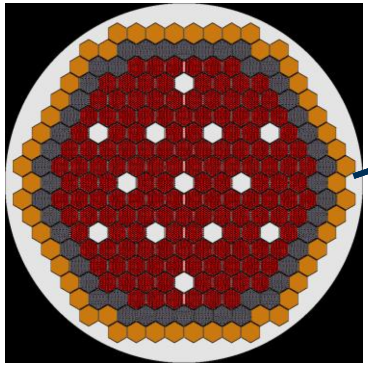




The RETINA System

- Customized detector modeling with the Mobile Antineutrino Demonstrator (MAD) project – led by **Lawrence Livermore National Laboratory**





Memory Feedback Agent

The system will converge to a **global diversion detection sensitivity** using the most **robust model**

Acknowledgement

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Thank you

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References

1. Office of Nuclear Energy. “Advanced Reactor Technologies.” *Energy.gov*
2. Waldrop, M. M. *Nuclear goes retro - with a much greener outlook*. Knowable Magazine | Annual Reviews

Extra Slides

Detection Probability Objective Functions

We've created a methodology for guiding detection objectives using **State-Specific Factors (SSFs),** or safeguards relevant factors used by the IAEA to develop State-level safeguards approaches

SSF-1	SSF-2	SSF-3	SSF-4	SSF-5	SSF-6
Safeguards Agreement	Fuel Cycle Capabilities	SSAC Capabilities	Implementing Safeguards	State Cooperation	Experience with State

$$\text{Detection Probability}_{Scenario} = \alpha^*DP_{SSF\text{-}1} + \beta^*DP_{SSF\text{-}2} + \gamma^*DP_{SSF\text{-}3} + \delta^*DP_{SSF\text{-}4} + \varepsilon^*DP_{SSF\text{-}5} + \zeta^*DP_{SSF\text{-}6}$$

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Technical Approach

The Reactor Evaluation Through Inspection of Near-field Antineutrinos (RETINA) System

Spectra Simulation

Customizable Objects
- Reactors
- Detectors
- Scenarios

Modular Configuration
- Plug-in inputs from outputs
- Multiple reactors and detectors allowed

System Sensitivity

Spectra Processing
- Null and Alternative Spectra from User-Input Objects

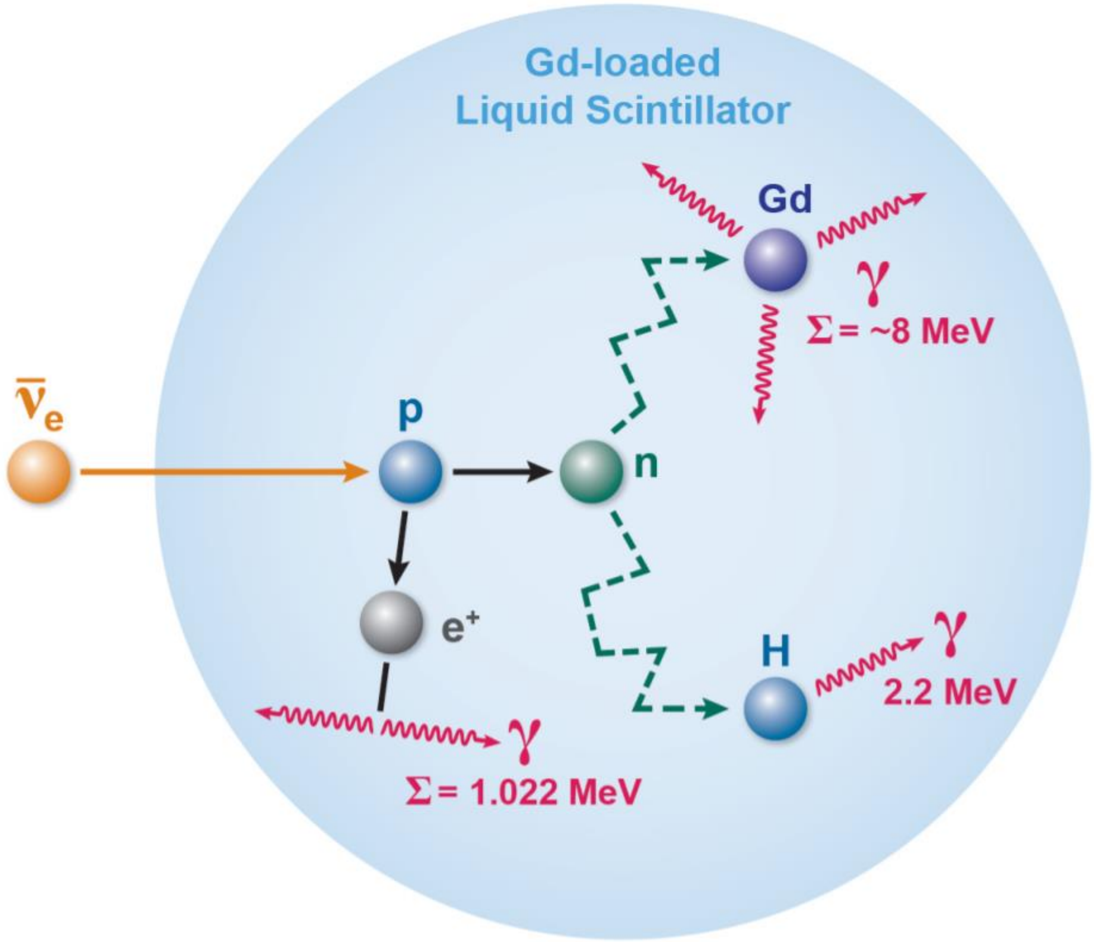
Profile Construction for Parameter Convergence
- Detection Probability
- Verification Collection Period
- Boundaries

Diversion Simulation

Customizable Reactor Inventories
- High-fidelity diversion modeling with customizable diversion assemblies, elements, quantities, and replacement fuel


End users can **evaluate** potential use cases and **develop** strategic system improvements

Antineutrino Detection



Inverse-Beta Decay: $\bar{\nu}_e + p = e^+ + n$

https://arxiv.org/pdf/1801.05386.pdf

Profile Construction

Generate Sample Detection Spectra

$$y_{i,0} \sim N(Counts_{Bkgd,i}, \sigma_{Counts_{Bkgd,i}})$$

$$x_{i,0} \sim Pois(y_{i,0} \mid y_{i,0} \in W)$$

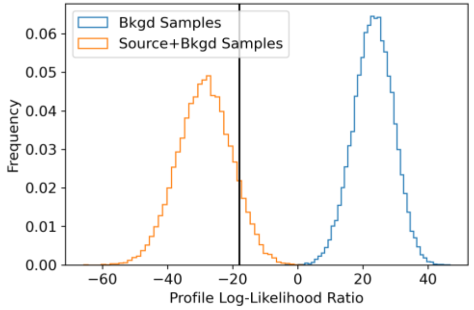
$$y_{i,1} \sim N(Counts_{Tot,i}, \sigma_{Counts_{Tot,i}})$$

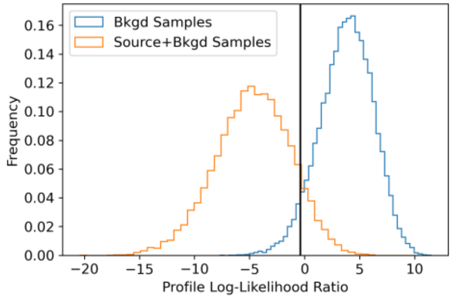
$$x_{i,1} \sim Pois(y_{i,1} \mid y_{i,1} \in W)$$

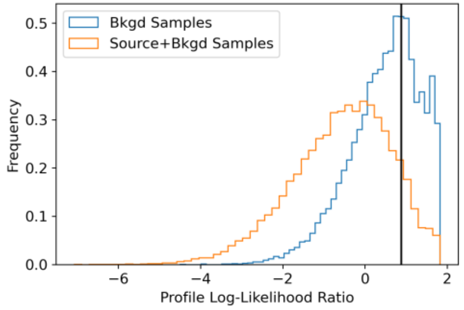
Determine Likelihood Values and Form Ratio Profiles

$$\lambda_0 = \ln\left(\frac{\prod_{i=0}^{15} L\left(x_{i,0} \in X_{i,0}\right)}{\prod_{i=0}^{15} L\left(x_{i,0} \in X_{i,1}\right)}\right) \qquad \lambda_1 = \ln\left(\frac{\prod_{i=0}^{15} L\left(x_{i,1} \in X_{i,0}\right)}{\prod_{i=0}^{15} L\left(x_{i,1} \in X_{i,1}\right)}\right)$$

Repeat Until Reaching our Desired Statistics







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