



# Neutrino applications within nonproliferation

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## Nonproliferation mission and neutrinos

- Nuclear nonproliferation remains a critical international security priority.
- "Prevent state and non-state actors from developing nuclear weapons or acquiring weapons-usable nuclear or radiological materials" - NNSA statement
- Nuclear fission produces vast quantities of neutrinos that cannot be practically shielded, providing a unique signature for nuclear monitoring and verification applications.
- Can we use neutrino detection, hybrid technology, and advanced analysis techniques to assist in this mission?
- Three potential applications of neutrino detection for nuclear nonproliferation are investigated:



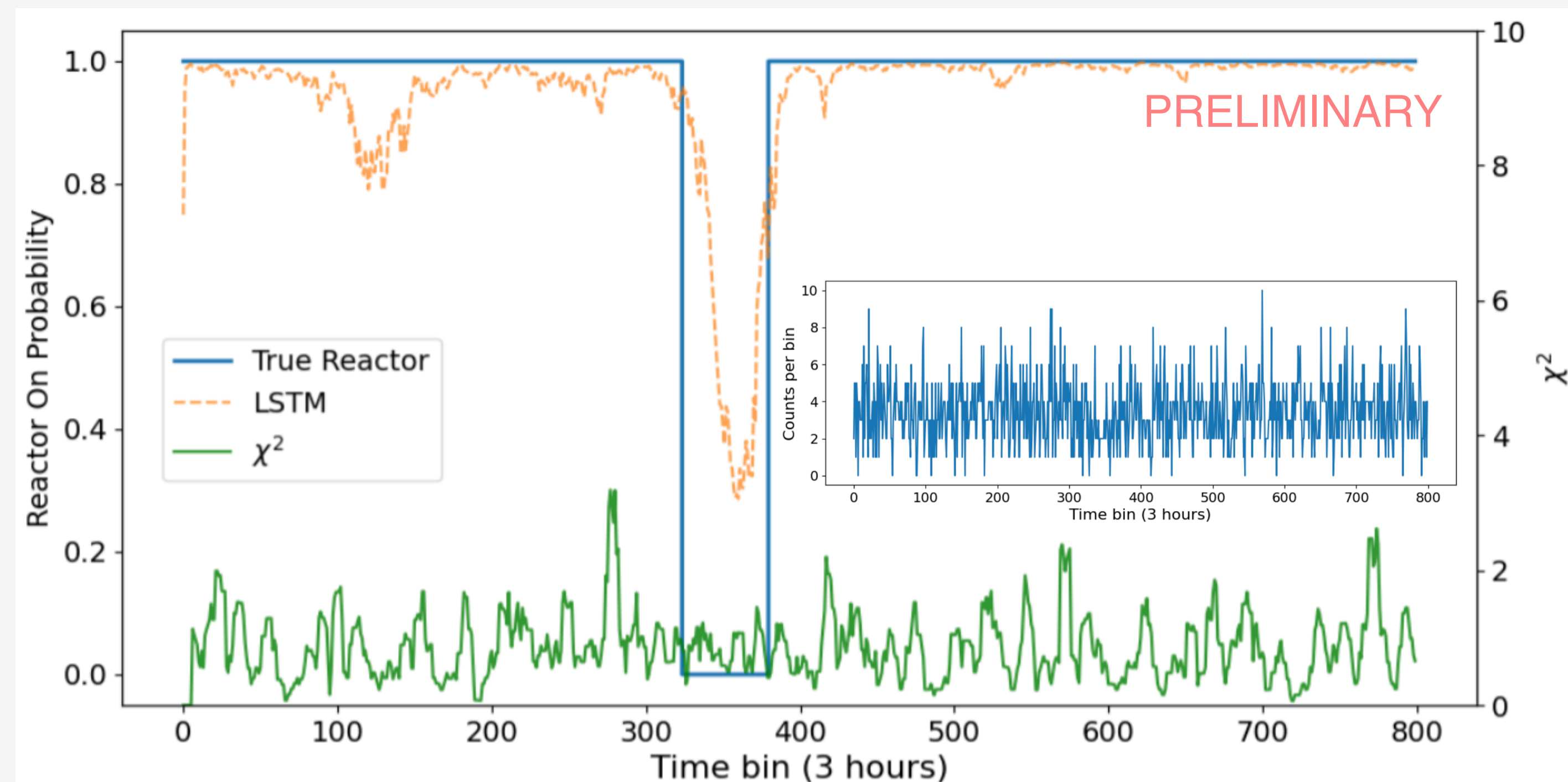
Test site transparency

Maritime monitoring

Lunar reactor observations

## Machine learning techniques

- Verifying reactor states is an essential tool for minimizing the potential proliferation of weapons-usable nuclear materials
- $\chi^2$  hypothesis testing of inverse beta decay rates in a neutrino detector is a valid approach for monitoring reactor on/off cycles
- However, recurrent neural networks are excellent at searching for discrepancies in long-term datasets
- Long Short-Term Memory (LSTM) networks provide a powerful framework for modeling temporal reactor signatures
- For a given detector, will a well-trained LSTM outperform  $\chi^2$  hypothesis testing?

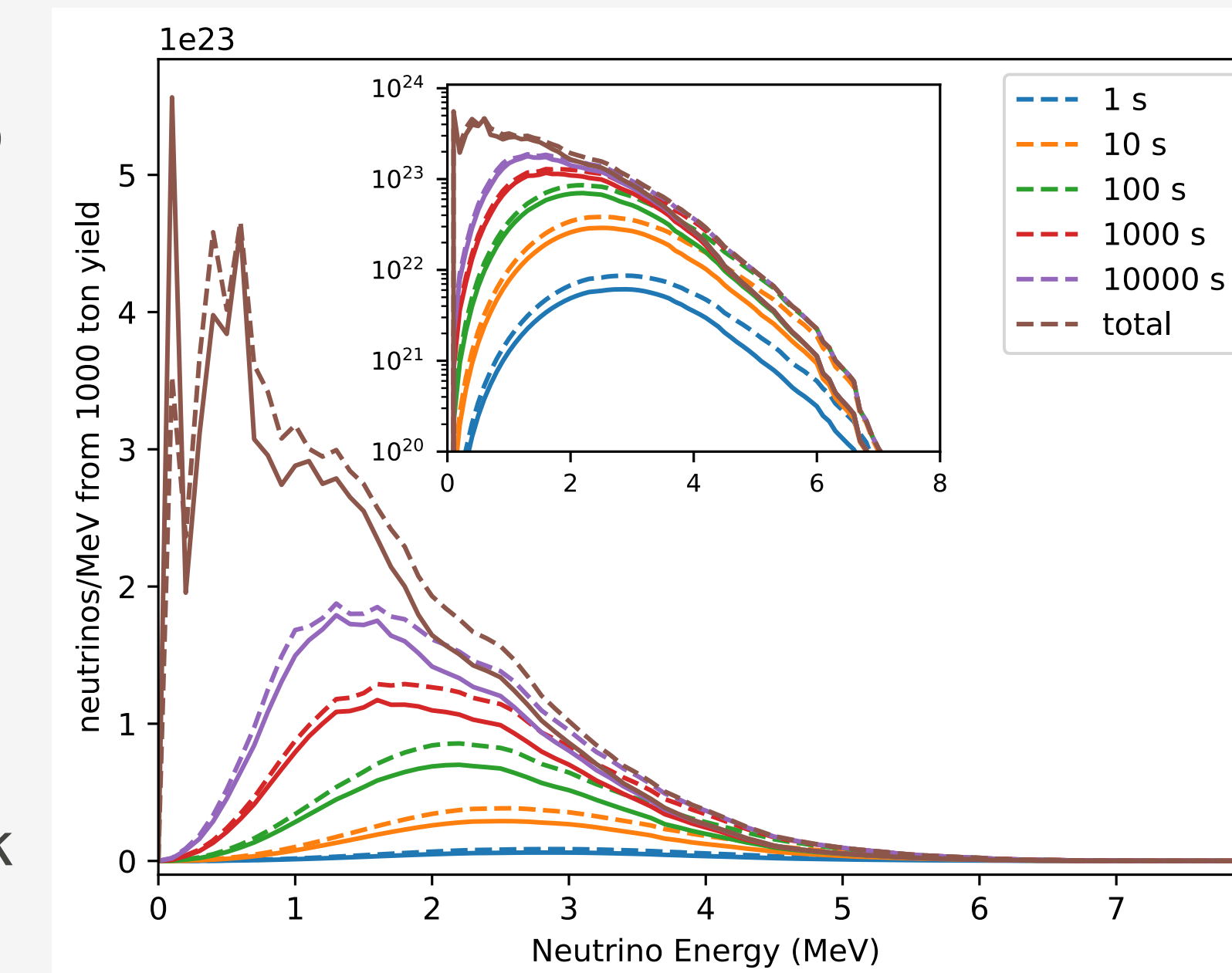


Simulation of a 7-day reactor outage for a 25 MW reactor located 100 m from a 1-ton detector. While the  $\chi^2$  method fails to identify the outage, the LSTM correctly determines when the reactor is powered down.

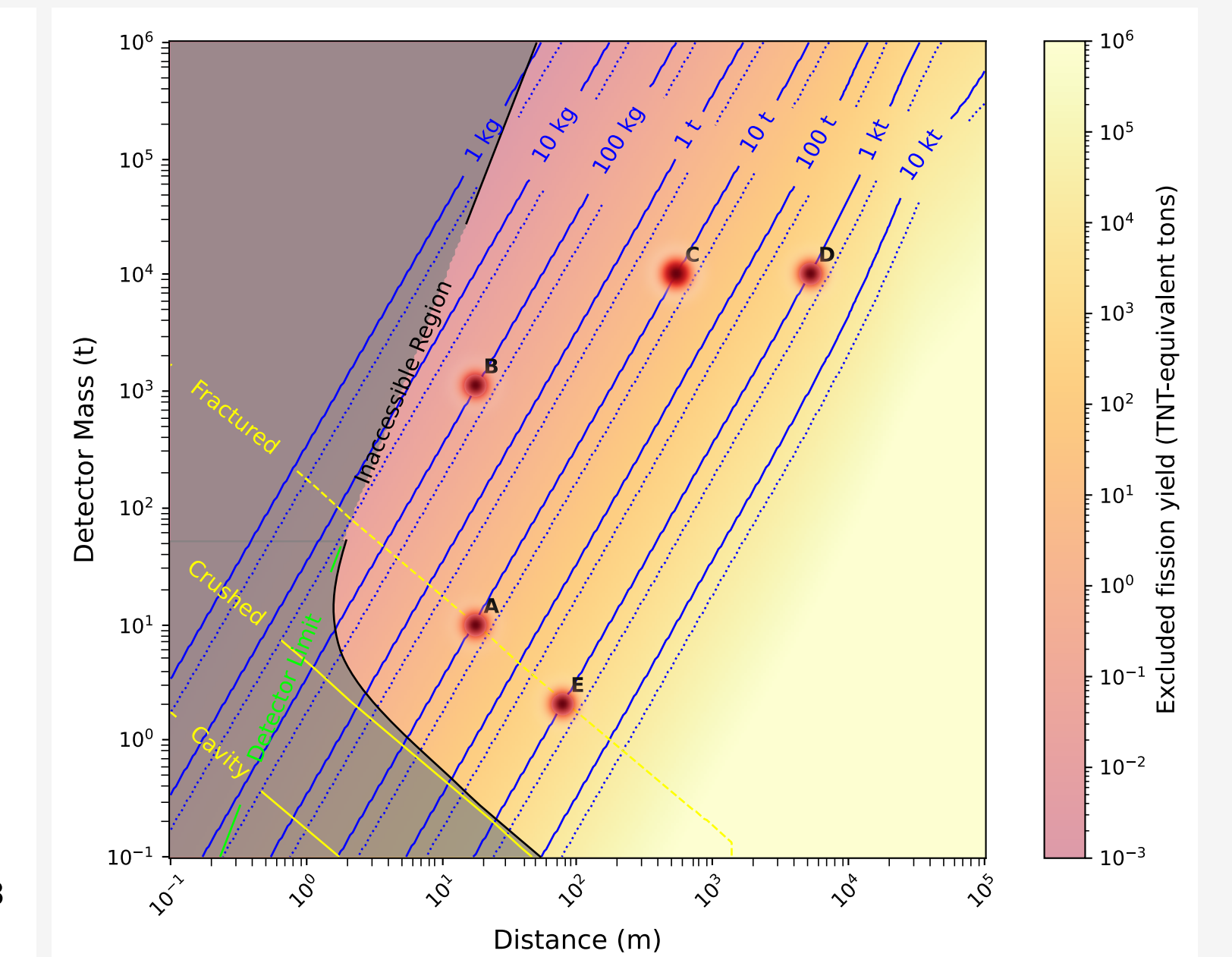
- Ongoing work focuses on optimizing performance through detector design, batch size selection, hyperparameter tuning, realistic background modelling, and multi-reactor monitoring scenarios.

## Test site transparency

- Nuclear fission produces large quantities of neutrinos. The absence of a detected neutrino signal can therefore be used to constrain the fission yield of a nuclear explosion.
- This capability could provide an independent means of verifying compliance with agreed limits on nuclear fission yield at former nuclear test sites.
- Aim: quantify neutrino detector masses required to set fission yield limits at source-to-detector distances up to 100 km, assuming detection by inverse beta decay.
- CONFLUX (Calculation Of Neutrino FLUX) software framework was used for anti-neutrino flux predictions
- Neutrino technology as a means for monitoring detonations for fission yields  $\geq 10\text{kg}$  is feasible

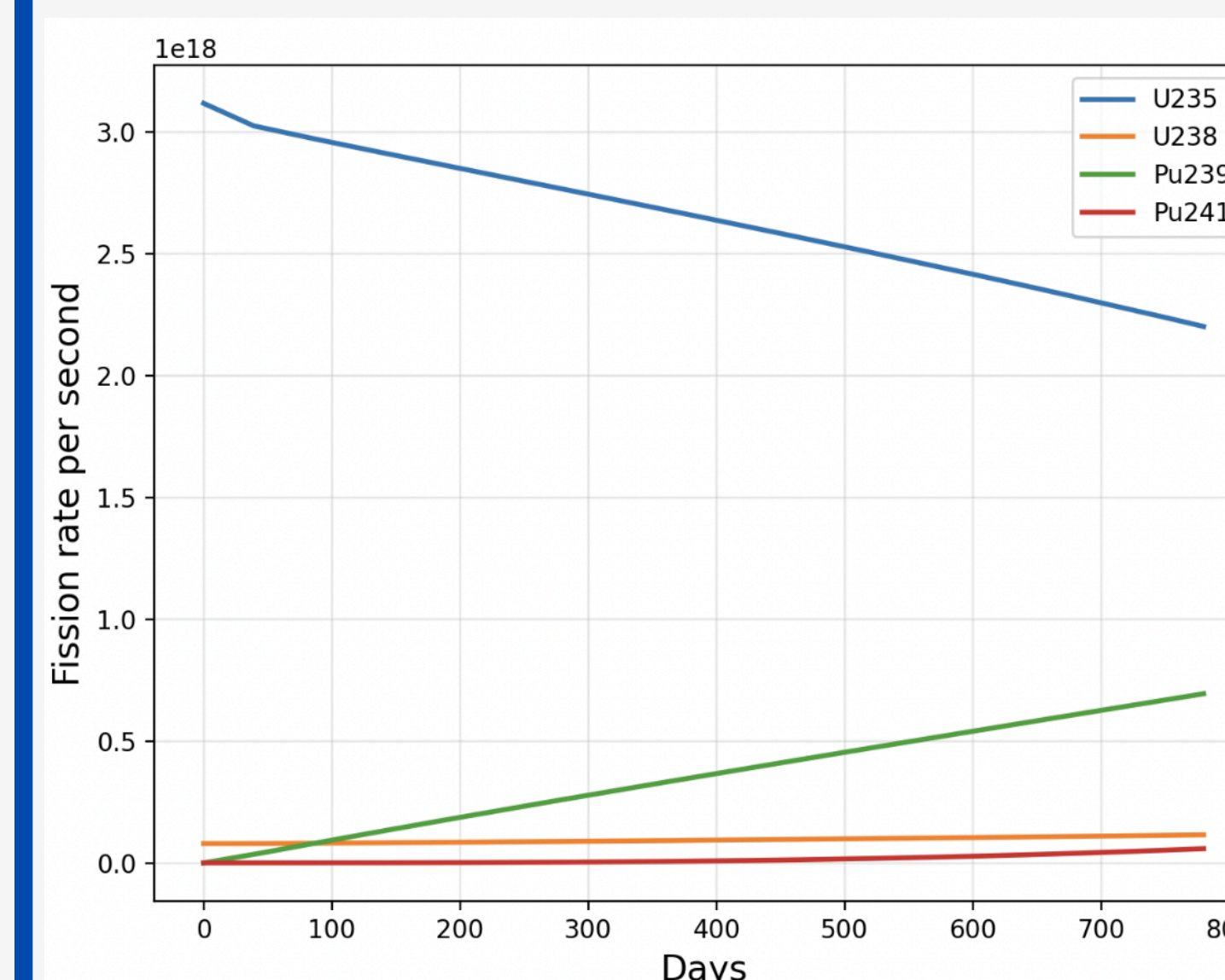


Antineutrino flux predictions for multiple post-detonation observation windows. This analysis uses a 10 s detection interval to establish a background-less detector scenario.

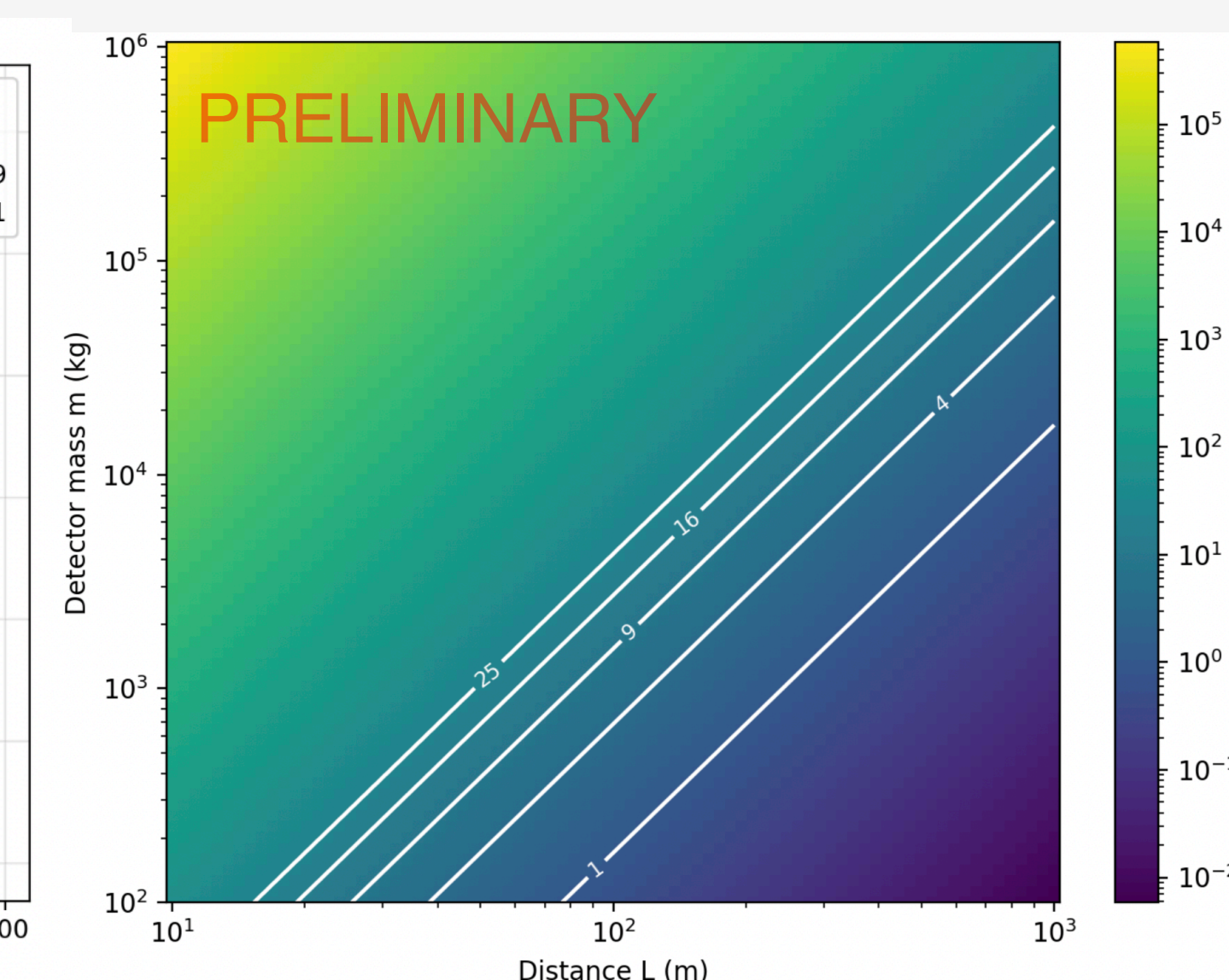


Excluded fission yield in a monitored explosion, at 95% confidence level, as a function of neutrino detector mass and distance between the explosion and detector center

## Maritime reactor verification

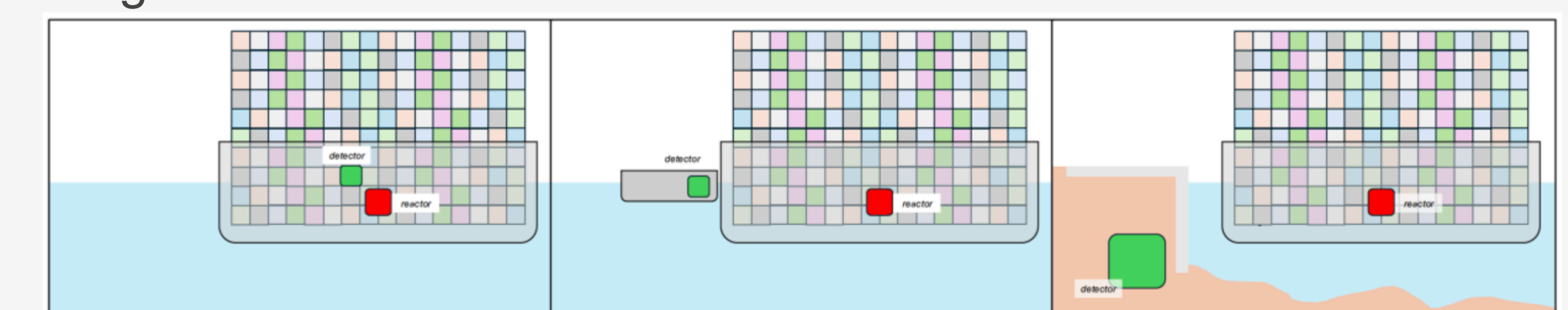


Evolution of the U-235, U-238, Pu-239, and Pu-241 fission rates for the 100 MW Light Water Reactor (LWR) used in this study.



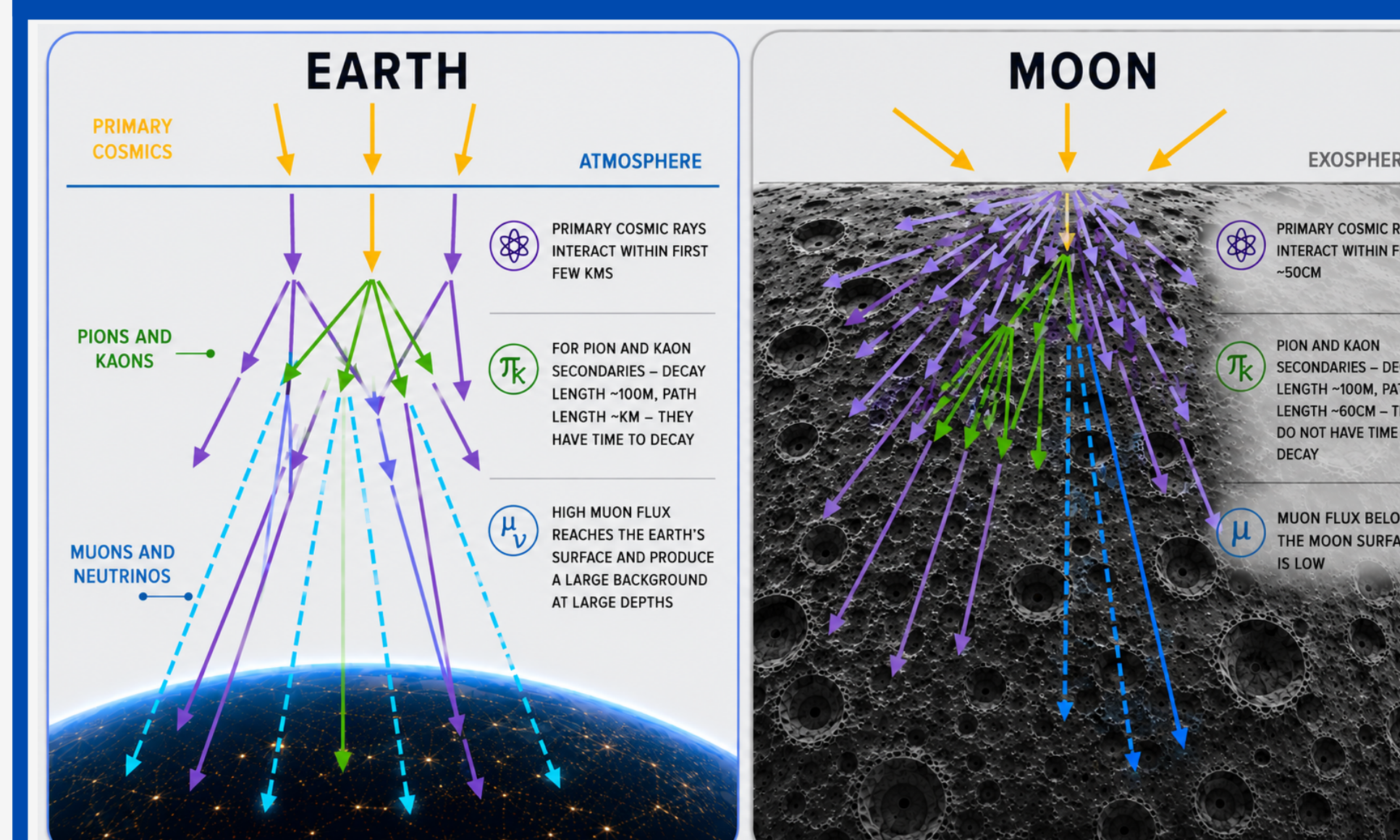
Minimum time to observe a statistically significant difference (binned  $\chi^2 = 9$ ) between early- and mid-cycle neutrino signals. No backgrounds or systematic uncertainties are included.

- Renewed interest in commercial nuclear vessels and floating nuclear power plants motivates exploration of new monitoring techniques
- Neutrino systems could take data on a semi-autonomous basis, yielding information about reactor power and fuel composition
- Initial studies examine potential use cases for neutrino-based monitoring
- After the production of one IAEA significant quantity of Pu-239, is a neutrino detector sensitive to flux reductions and spectral changes?
- This framework evaluates the detectability of reactor replacement scenarios using neutrino observations



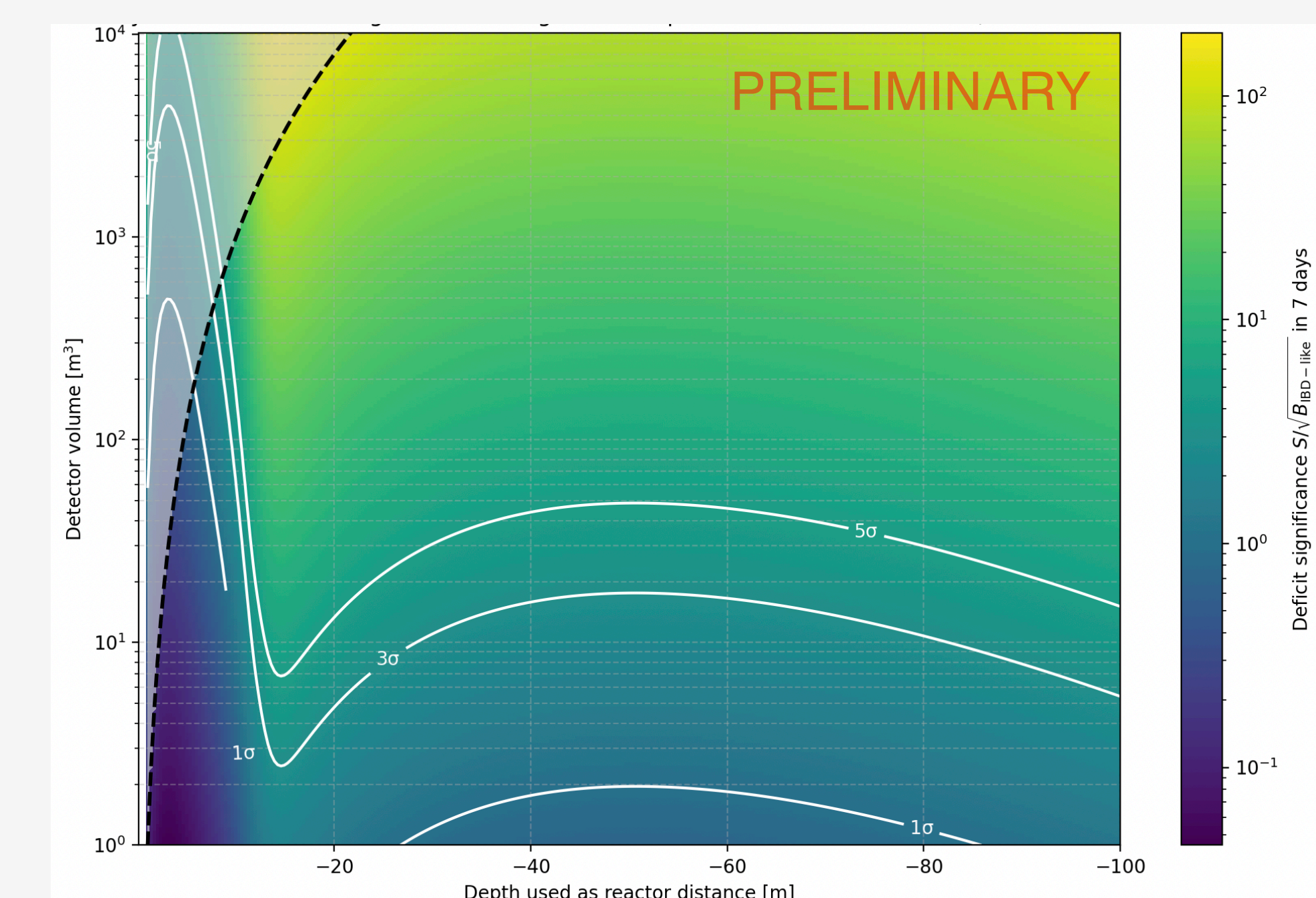
Potential use cases for monitoring maritime nuclear reactors

## Lunar reactor monitoring



To characterize backgrounds, GEANT4 simulations of primary cosmic rays interacting within the lunar regolith have been performed. These simulations provide depth-dependent estimates of the inverse beta decay (IBD) background rate. Owing to the hadronic nature of cosmic-ray showers at the lunar surface, detector deployments at substantially shallower depths than those required on Earth may be feasible.

- Exploring the feasibility of neutrino-based reactor monitoring in a lunar environment
- Many countries are undergoing research to produce lunar deployed nuclear reactors with the earliest to be deployed in 2030!
- Compared with terrestrial nuclear activities, international regulatory frameworks for lunar reactors remain relatively undeveloped - monitoring will be essential
- More challenging than terrestrial reactors - no atmosphere, smaller reactor designs, and it's on the moon!



Detection significance for a 7-day reactor outage as a function of detector volume and depth for a 10 MW surface-deployed reactor.