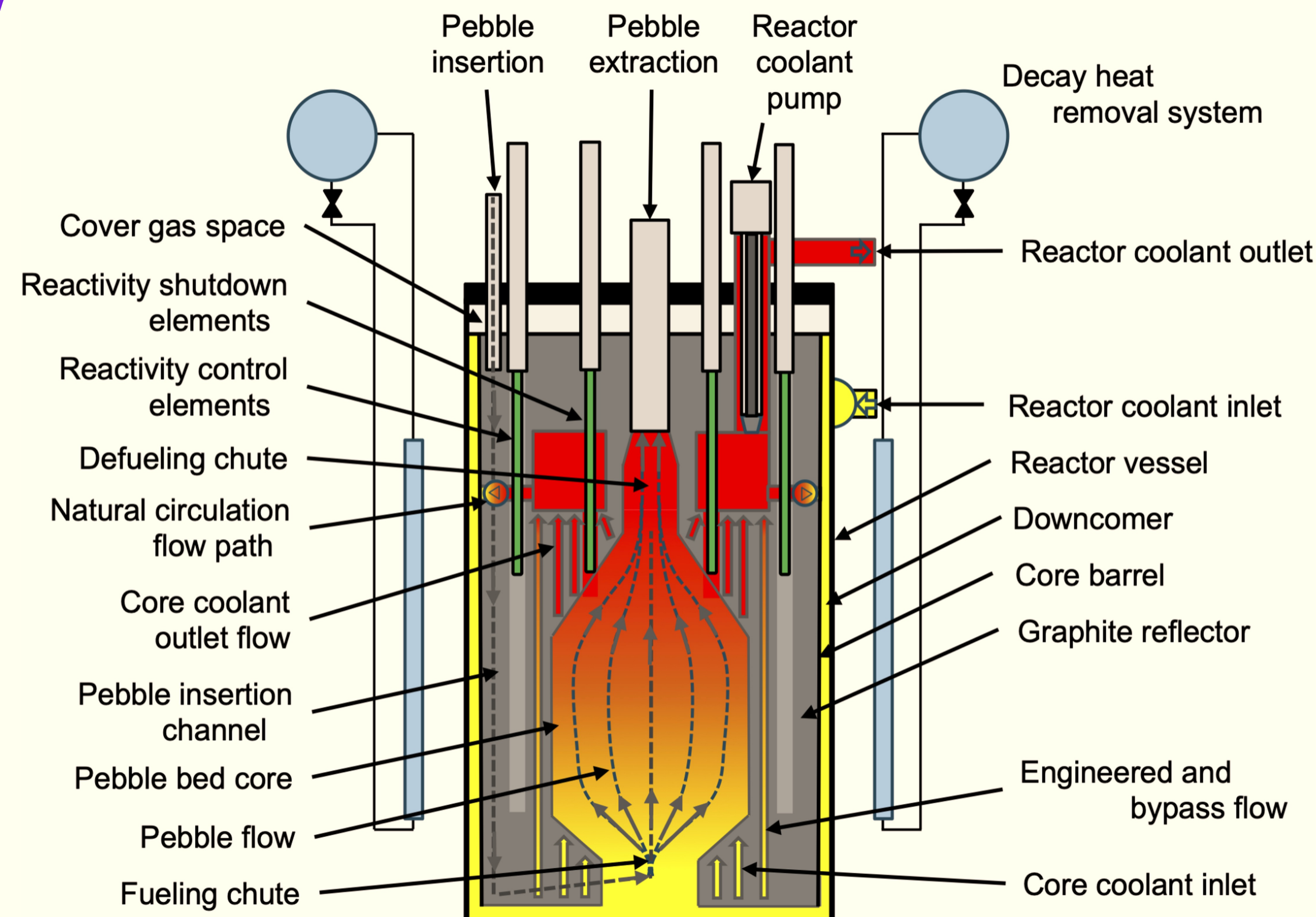


# Enhancing Nuclear Proliferation Safeguards with Neutrino Detection

## 1. Why this matters

- Global energy demand is expected to **significantly increase** in the coming decades.
- Many governments and private businesses plan to meet demand with **nuclear energy**.
- Small modular reactors, especially those with **continuous fuel cycles** (see §2), are becoming more popular.
- Current safeguards regimes **do not sufficiently protect** against Plutonium-239 diversion from these reactors.
- Pu-239 can be used to build nuclear weapons, so diversion poses a proliferation risk.
- Neutrinos pose a potential solution for monitoring.**

## 2. How the continuous fuel cycle works

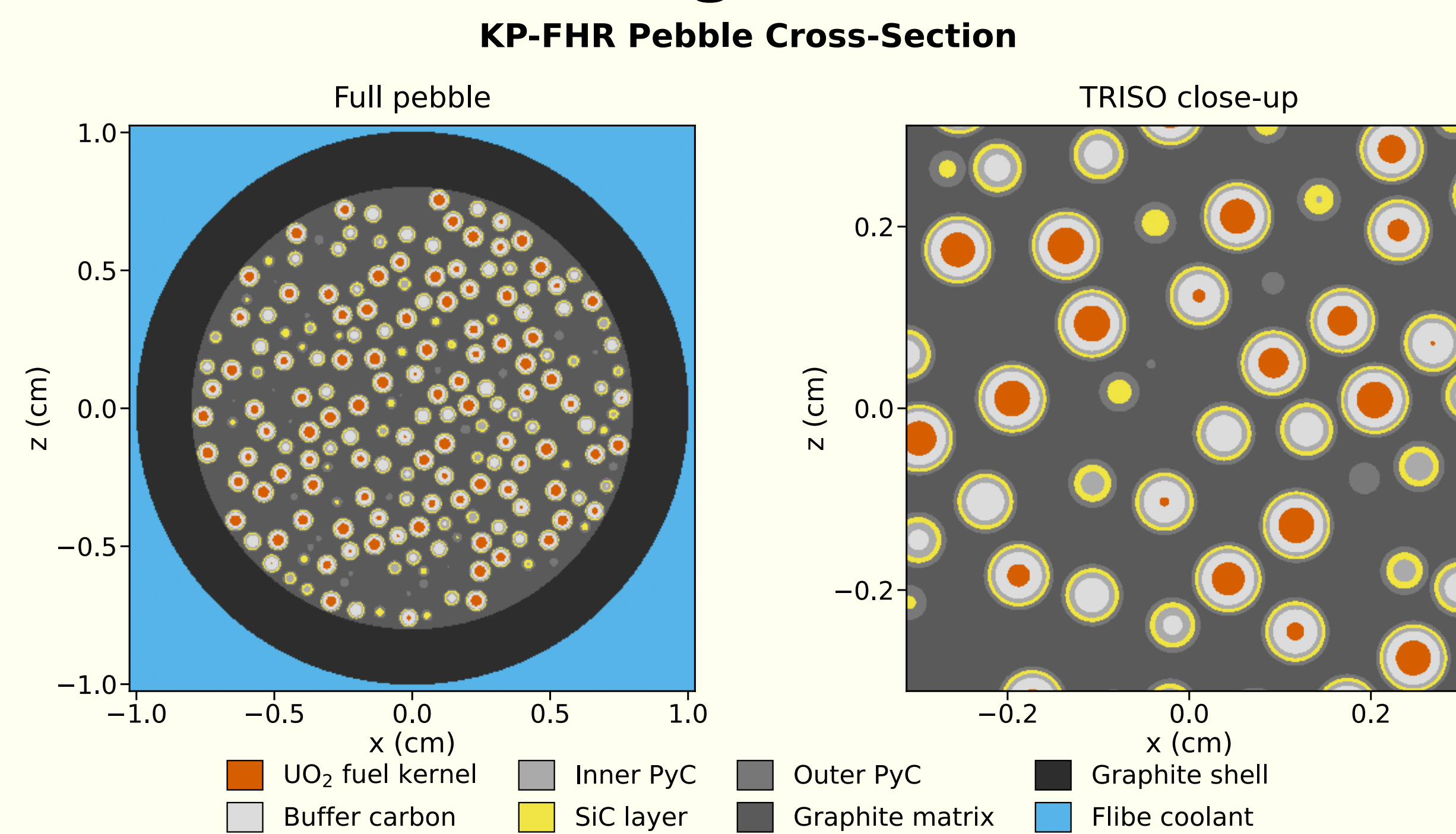


- In general, continuous fuel cycles cycle nuclear fuel in, through, and out of the reactor continuously.
- This could allow for diversion of fuel that is not possible with current reactor designs.
- The Kairos Power fluoride salt-cooled high-temperature reactor (KP-FHR; pictured here in image from [1]) was used in this analysis.
- It is a pebble-bed-style reactor, but the analysis is transferable to other continuous fuel cycles.
- TRi-structural ISOtropic particle (TRISO) high-assay low-enriched uranium (HALEU) fuel was considered for this analysis and is a broadly popular pebble fuel type.
- This new avenue for fuel diversion is **not currently captured** by existing safeguards, and a new solution is needed.

## 3. A solution for detection

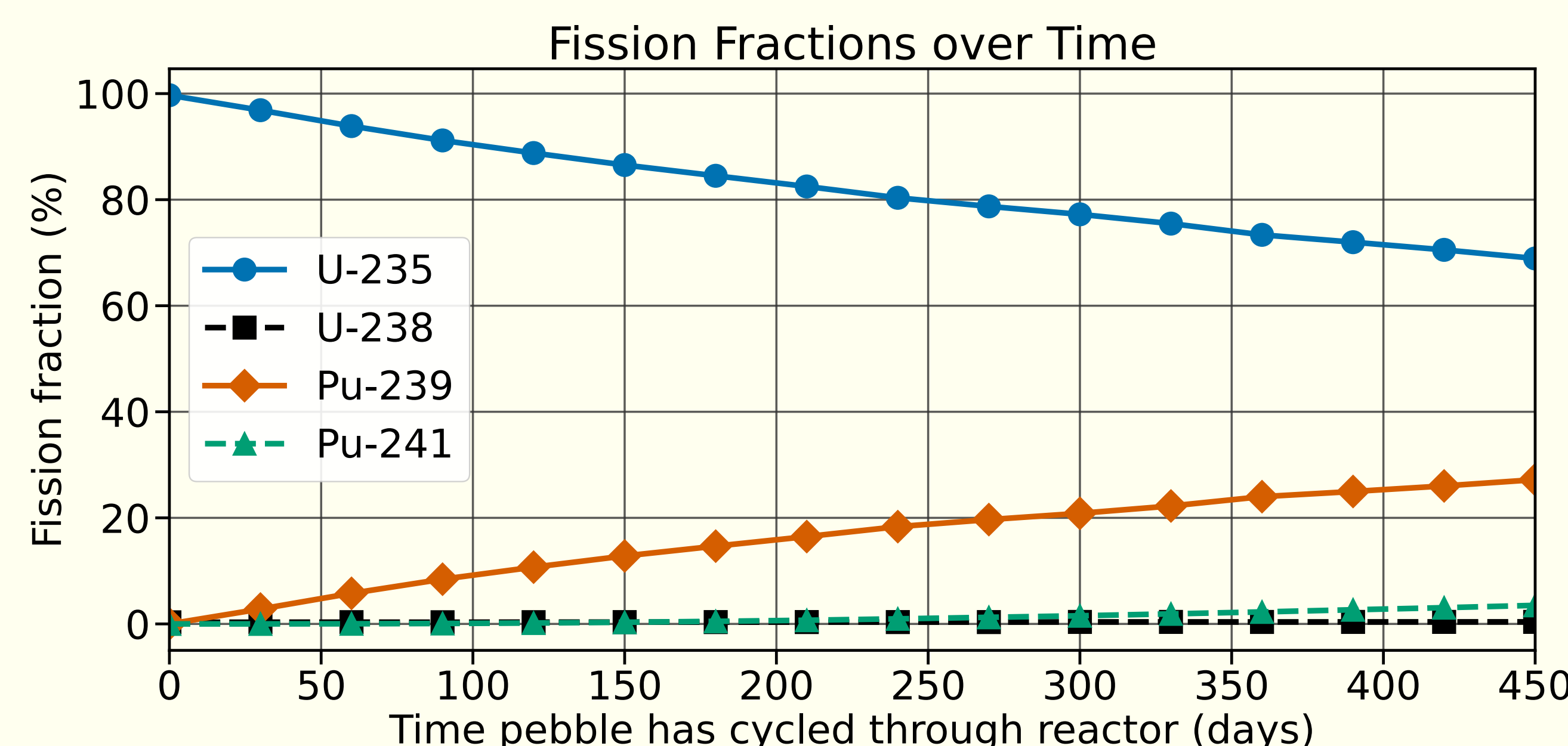
- Neutrino detectors may be useful for this problem!
- The CHANDLER detector, currently under development at Virginia Tech, serves as the prototype for this project.
- CHANDLER is a solid plastic scintillator detector technology that detects neutrinos via inverse beta-decay (IBD)  $\bar{\nu}_e + p \rightarrow e^+ + n$  through detection of coincident positron- and neutron-like events.
- In 2017, a scale-prototype of CHANDLER, MiniCHANDLER, was deployed to North Anna Nuclear Generating Station, located 25 m from the core, and reported a measurement of reactor neutrinos at  $5.5\sigma$  significance [2].
- The detector considered here is a 1000 kg scaled-up version of MiniCHANDLER** assuming [2,3]:
  - A 35% increase in efficiency due to improved event reconstruction,
  - A signal:background ratio of 1:1 due to vastly improved light collection and improved shielding,
  - A further 52% increase in efficiency due to the reduction of dead-time from 40  $\mu$ s to  $<1$   $\mu$ s, and
  - The same signal region of 0.5 — 8 MeV.

## 4. Simulating fuel evolution



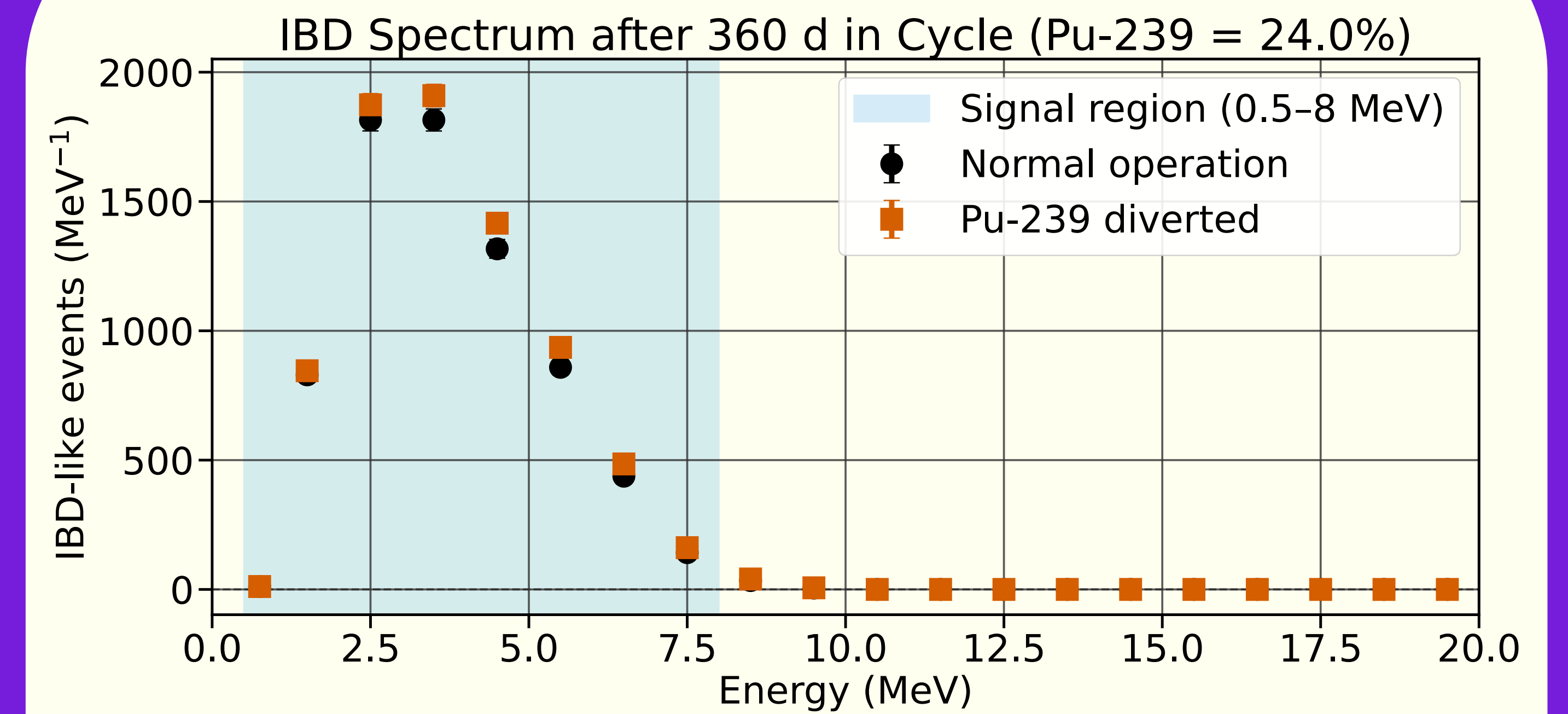
- Reactor depletion/burnup for a continuous fuel cycle reactor, the Kairos Power KP-FHR [1,4] was modeled in OpenMC [5], an open-source Monte Carlo neutron and photon transport code.
- This figure shows a single fuel pebble containing many TRISO particles. The reactor was simulated by using reflective boundary conditions, representing tessellating fuel pebbles.

## 5. How the fuel evolves over time



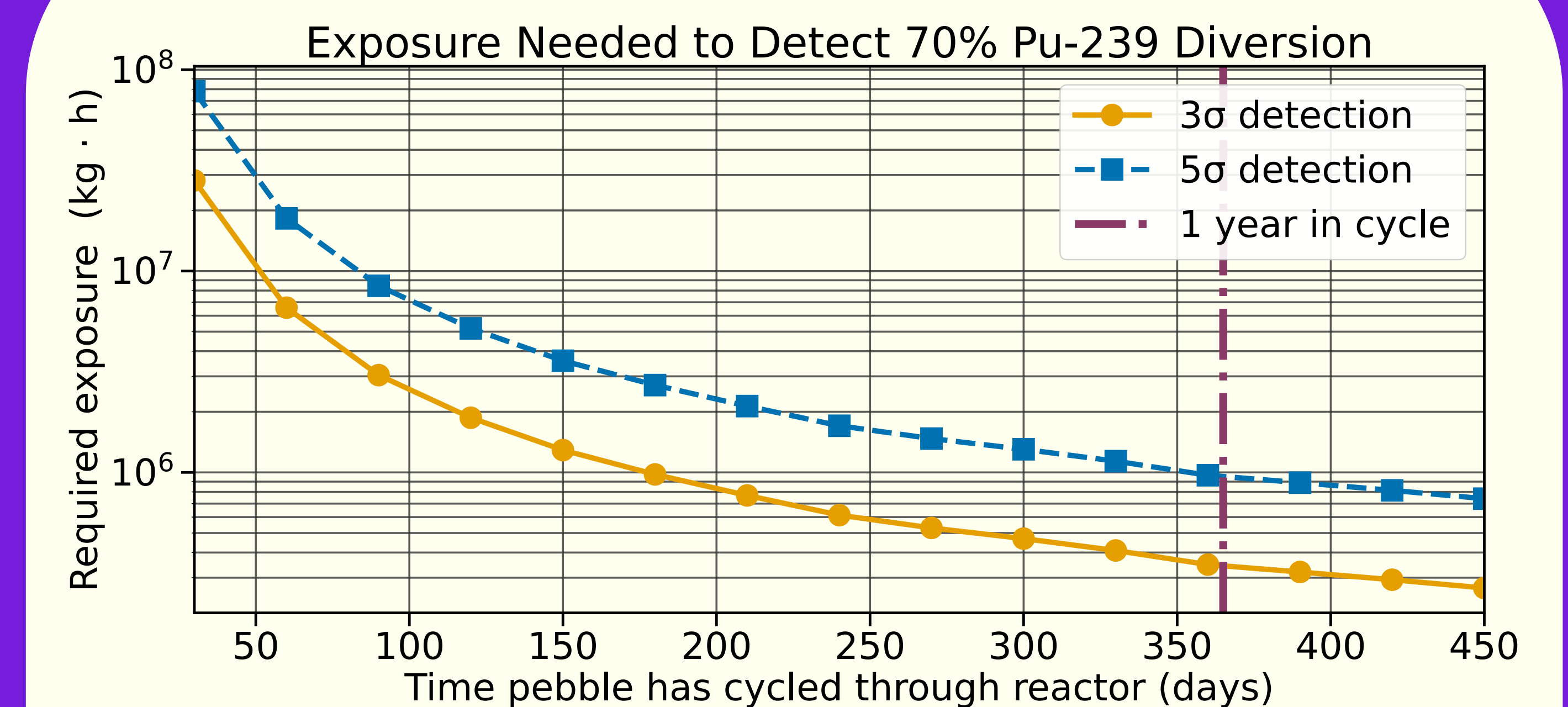
The fission fraction evolution was extracted from the OpenMC reactor simulation to find the fraction of Pu-239 bred over time.

## 6. What does this look like in the detector?



The IBD spectra for the prototype detector were calculated using CONFLUX [6] for every time-step for both normal operation and a plutonium diversion scenarios. Shown here is 360 days of breeding.

## 7. So, can we see it?



The normal operation and plutonium diversion spectra were then compared using a binned  $\chi^2$  fit. This result shows the exposure required to detect diversion after the specified period of operation. **After one year of breeding, a 3 $\sigma$  detection of plutonium diversion can be made in 14.5 days** (intersection of purple and orange lines).

## 8. What to do next

- This research shows that **it is feasible** to use a CHANDLER-like IBD neutrino detector to monitor Pu-239 diversion from continuous fuel cycle reactors.
- As more of these types of reactors are built in the coming years, **it is important to continue this research and deploy the technology to reactor facilities.**
- Implementing such systems has the potential to **strengthen nuclear proliferation safeguards.**

## References

- [1] Kairos Power, "KP-FHR Core Design and Analysis Methodology," KP-TR-024-NP (2025).
- [2] A. Haghighat, et al., *Phys. Rev. Appl.* **13**, 034028 (2020).
- [3] J. Link (personal communication, March 5, 2026).
- [4] Y. Sun & K. Kurosaki, arxiv:2504.02599 (2025).
- [5] P. K. Romano, et al., *Ann. Nucl. Energy* **82**, 90–97 (2015).
- [6] Zhang, et al., arxiv:2503.18966 (2025).