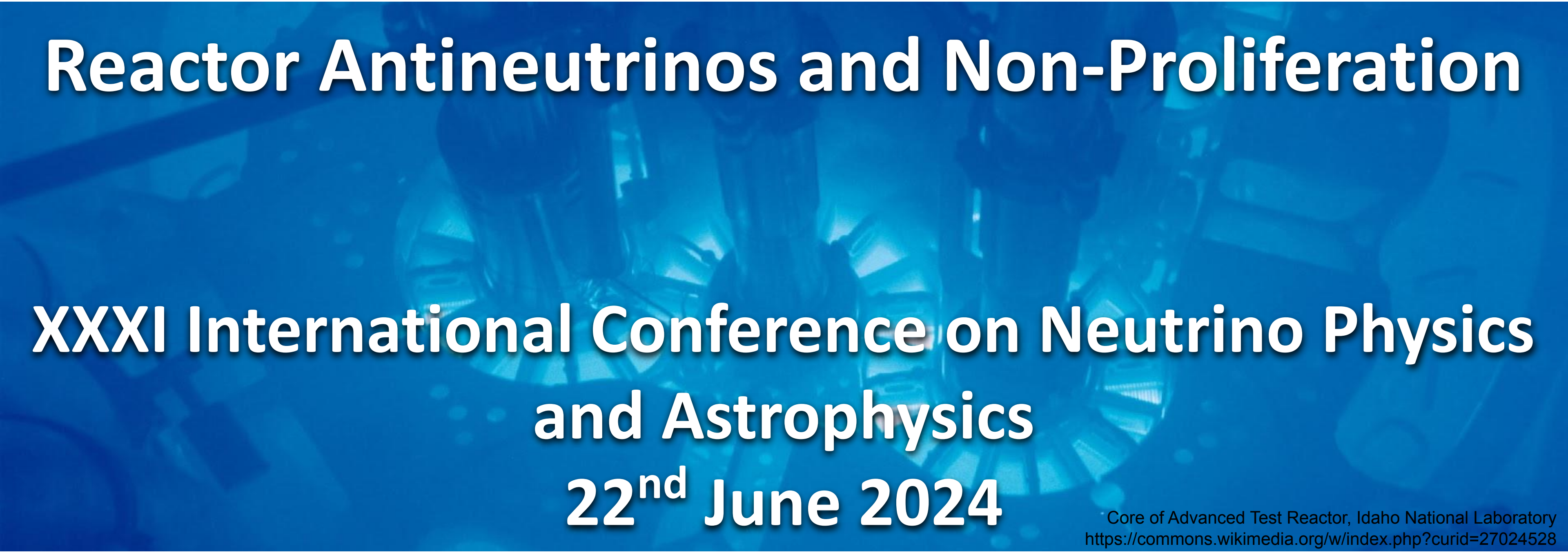
# Reactor Antineutrinos and Non-Proliferation

## XXXI International Conference on Neutrino Physics and Astrophysics

## 22nd June 2024



Core of Advanced Test Reactor, Idaho National Laboratory
https://commons.wikimedia.org/w/index.php?curid=27024528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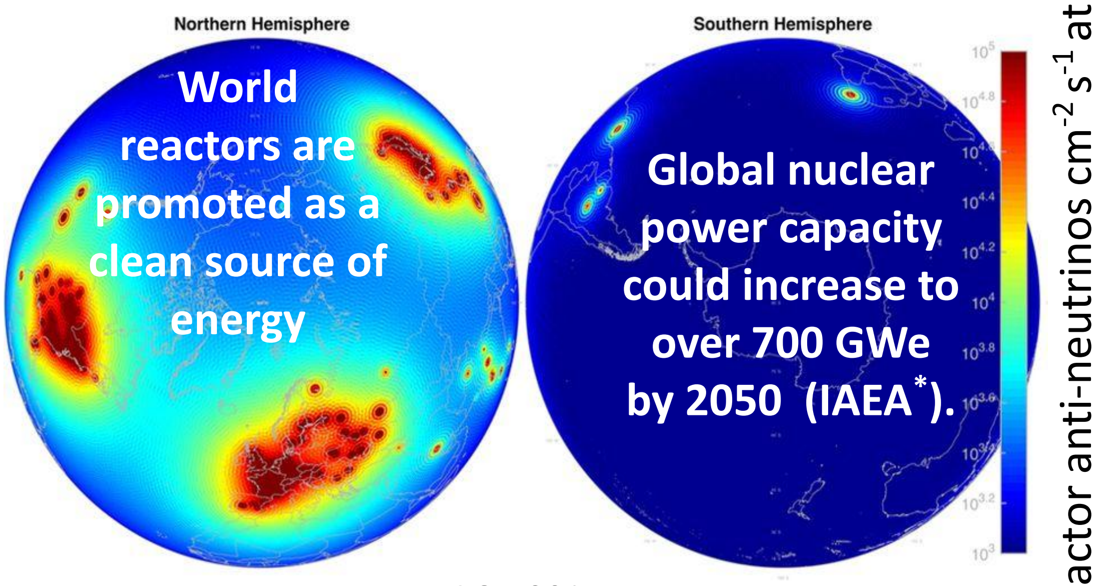
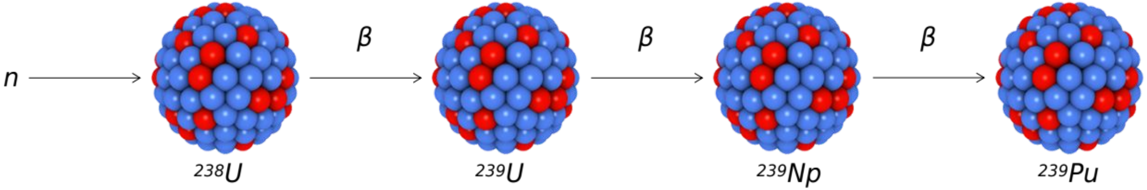
# Plutonium - a byproduct of nuclear energy




AGM2015



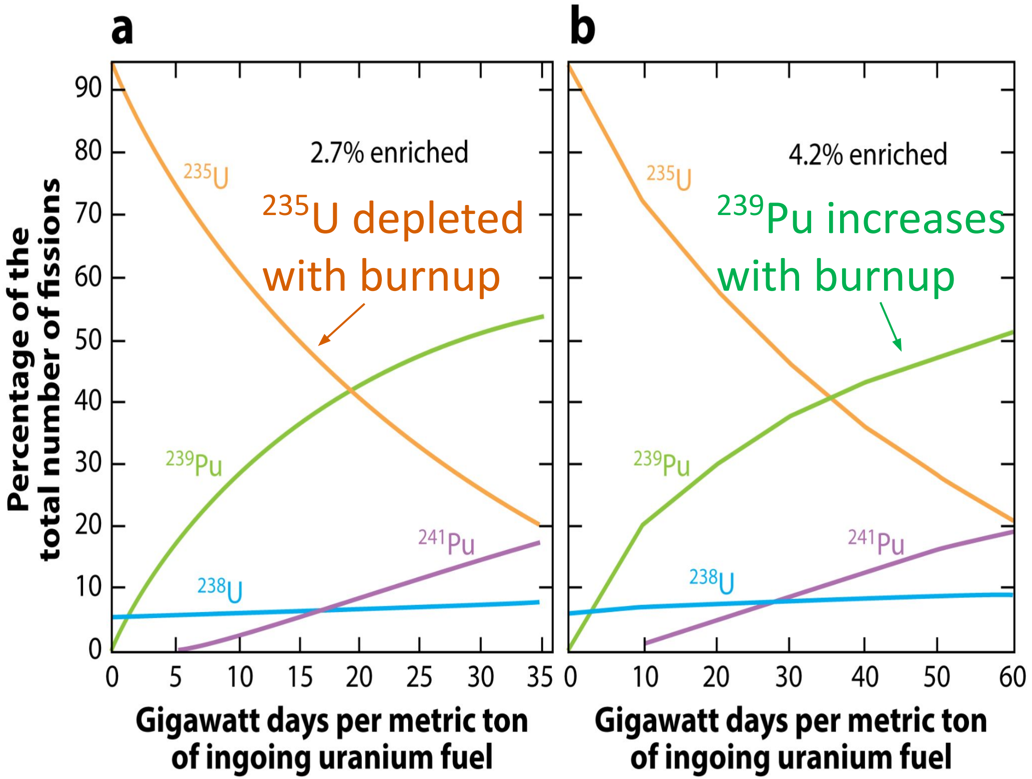

Most of the enriched $^{235}$U fuel in a reactor core is in fact $^{238}$U, which can be converted $^{239}$Pu.

Pu can be extracted via chemical reprocessing.

*1 significant quantity*:
**~8 kg of Pu ready for use within days (3 months for Pu in irradiated fuel)**

*International Atomic Energy Agency

# Antineutrino flux - insight into the core



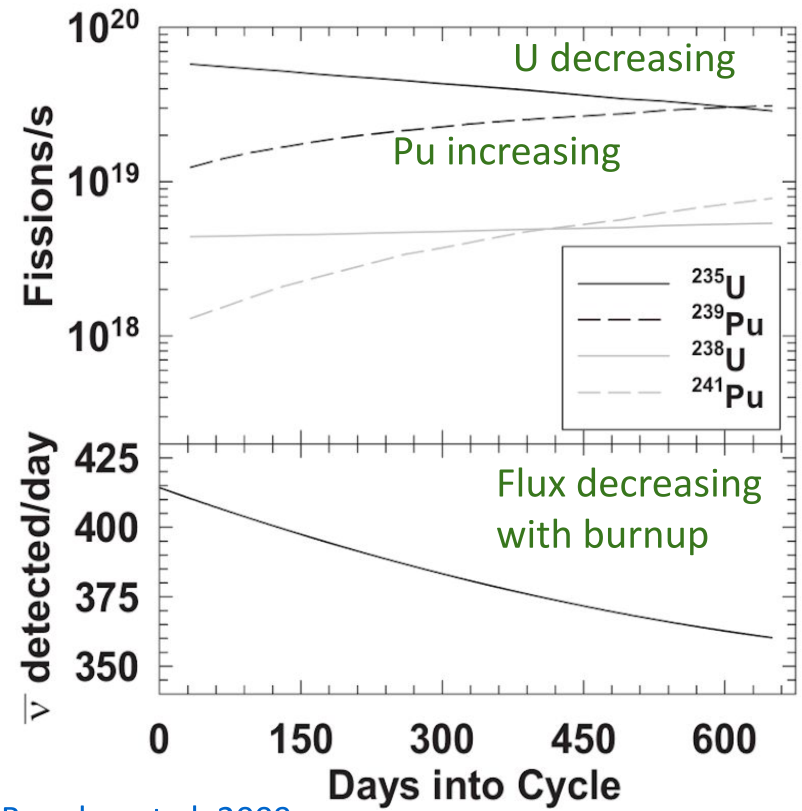

O($10^{20}$) antineutrinos per $GW_{th}$.

Antineutrino flux and spectrum depends on the fissioning isotopes.

Four main isotopes with time-dependent fission fractions in $^{235}$U-fuelled reactor.

Hayes, Vogel, 2016

# Antineutrino flux - insight into the core




[Bowden et al, 2009]

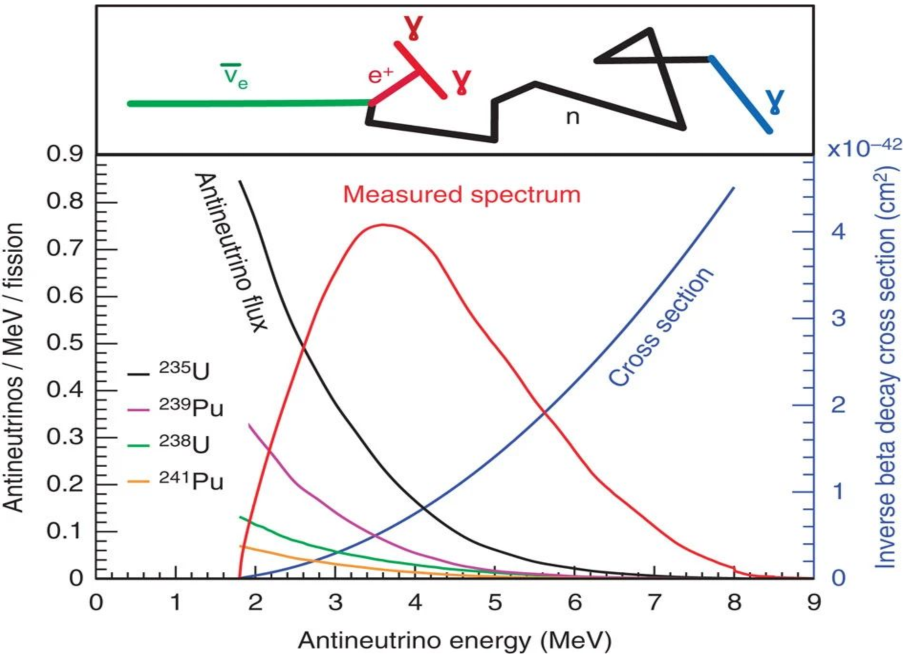
O($10^{20}$) antineutrinos per $GW_{th}$.

Antineutrino flux and spectrum depends on the fissioning isotopes.

Four main isotopes with time-dependent fission fractions in $^{235}U$-fuelled reactor.

Time-dependent antineutrino emission bears information about the reactor operating power and composition of the core.

# Neutrinos for non-proliferation




Inverse beta decay (IBD) tried and tested means of detection.

[Vogel, Wen, Zhang, 2015]

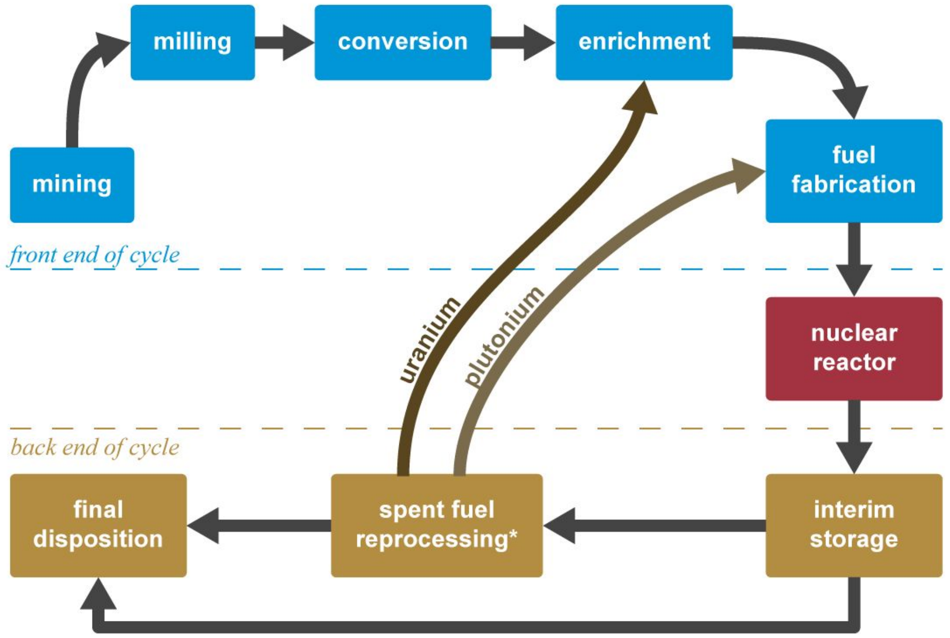
**Neutrinos offer a continuous, non-intrusive means of monitoring.**

Measurement of the antineutrino flux and spectrum has the potential to observe and verify:

- reactor on/off cycle and power
- reactor distance (ranging)
- reactor direction (pointing)
- core composition and burn-up
- diversion of 1 SQ fissile material
- antineutrinos from nuclear waste

# The monitoring challenge

**Non-Proliferation Treaties** provide the framework for the International Atomic Energy Agency (IAEA) to monitor all stages of the nuclear fuel cycle.




Source: Pennsylvania State University Radiation Science and Engineering Center (public domain)

1. Diversion of nuclear material
2. Undeclared production or processing of nuclear material
3. Undeclared nuclear material or facility

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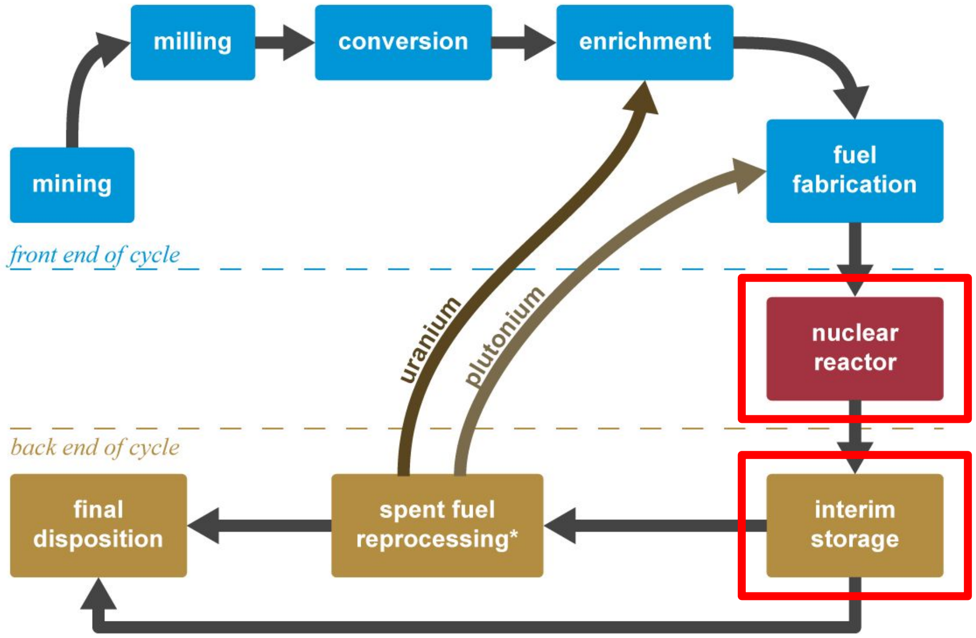


1. Diversion of nuclear material
2. Undeclared production or processing of nuclear material
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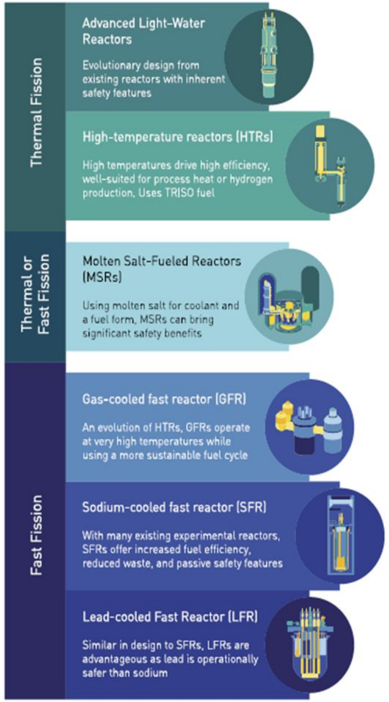
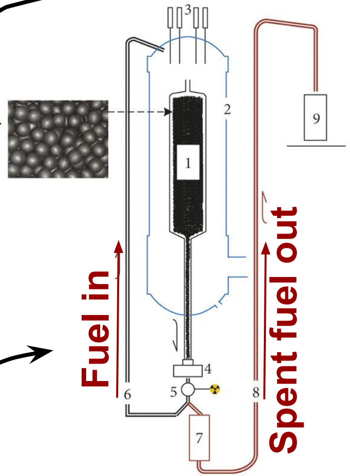
Source: Pennsylvania State University Radiation Science and Engineering Center (public domain)

# The monitoring gap - advanced reactors



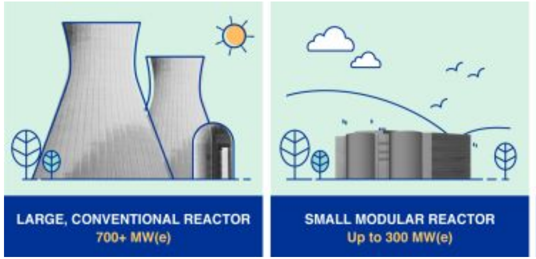

NIA

Non-homogenous fuel




HTR-PM, Wu et al,2022

Online loading and reprocessing



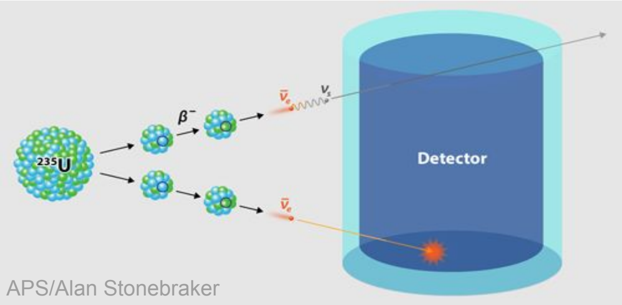

A. Vargas/IAEA

Small modular reactors: multi unit, low power (20-300 MW)

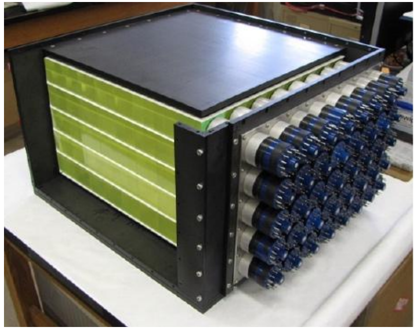
Neutrinos are fuel-form agnostic and do not require access to the core.
Interest in detectors built into the design of new reactors and mobile monitors.

# Monitoring applications in this talk

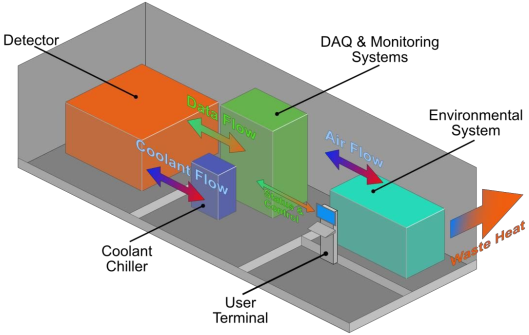
1. Far-field monitoring (> ~10 km).



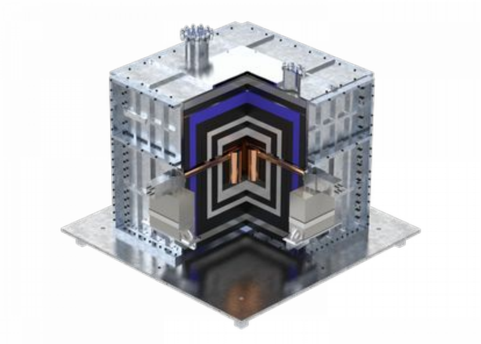

2. Near-field monitoring (< ~50 m)



3. Spent fuel monitoring

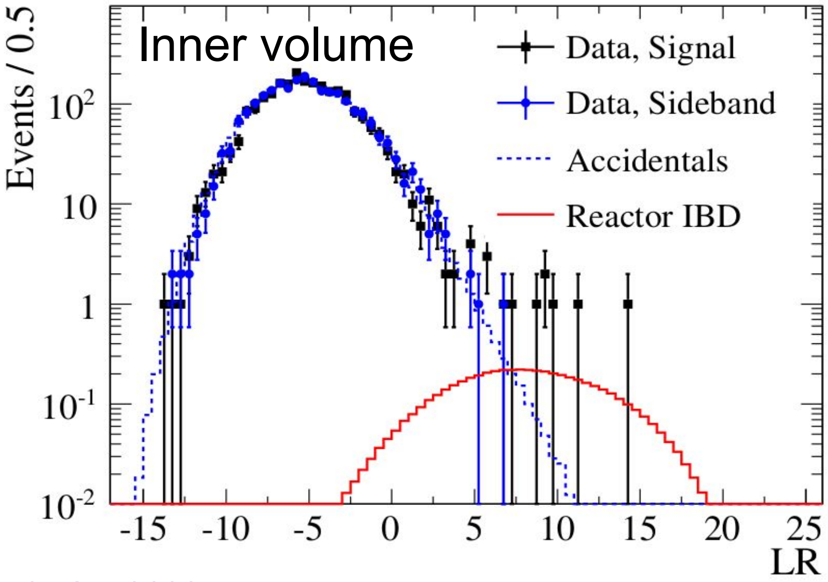



4. CEvNS for safeguarding



# Water-based far-field monitoring

Water-based detectors are scalable to very large sizes for far-field detection.




SNO+, 2023

First antineutrinos have been seen in a pure water Cherenkov detector by SNO+ from reactors > 240 km away (composite reactor signal).

**For far-field application we need more advanced technology to observe a single reactor in a complex reactor landscape:**

- reactor on/off cycle and power
- reactor distance
- reactor direction

# Water-based reactor monitor testbed

**BUTTON-30** 30-tonne low-background testbed for hardware and fill media, with a focus on low-energy antineutrino detection for non-proliferation.

Under construction in Boulby Mine.

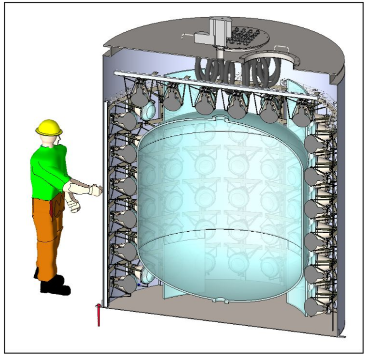
- Very low-background environment.
- Advanced photosensor technology.
- Novel fill materials e.g. water-based liquid scintillator (WbLS).

Final construction phase beginning in September 2024.
Planning underway for BUTTON ~1 ktonne

# Hybrid detector for far-field monitoring

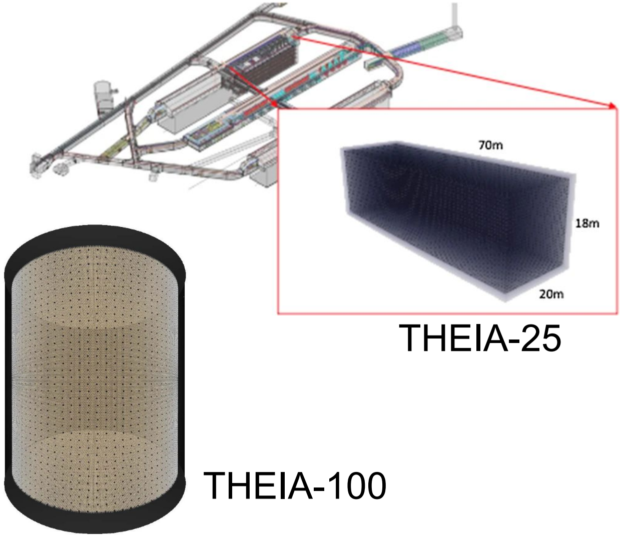
**EOS**

- 20 tonne (4-tonne ID)
- WbLS testbed
- Commissioning now!



→

**THEIA**



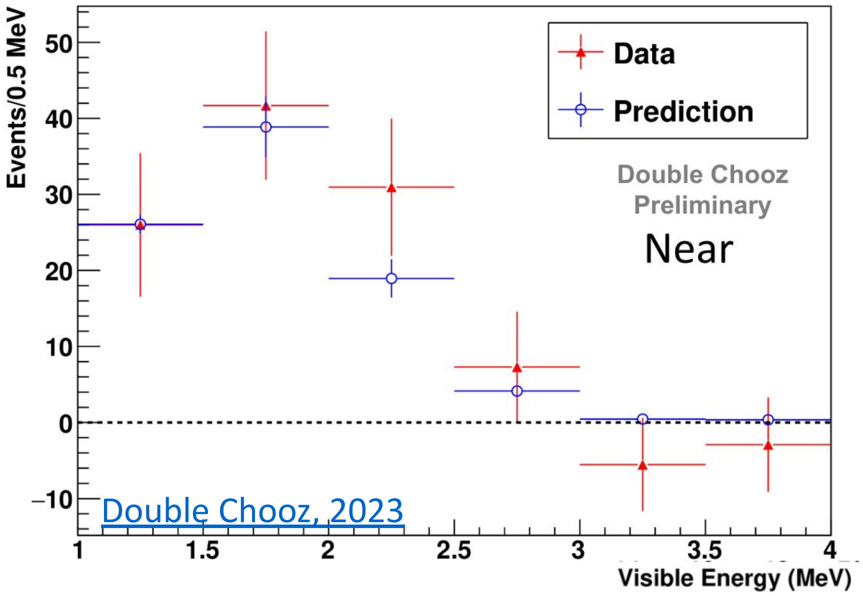

Demonstration of:

- Spectral sorting and ps photodetection for Cherenkov-scintillation separation.
- Direction reconstruction.

- 25 or 100 ktonne
- Reactor monitoring, **range** and **direction** at >1000 km

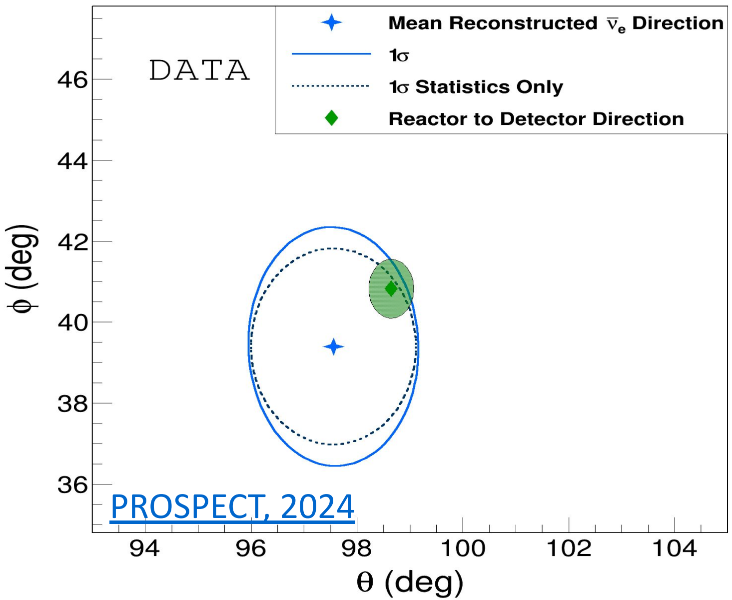
# Latest near-field capabilities

## Residual antineutrinos




- **spent fuel in the cooling pools**
- assemblies in the shut down reactor
- assemblies kept for the next cycle

## Reactor pointing

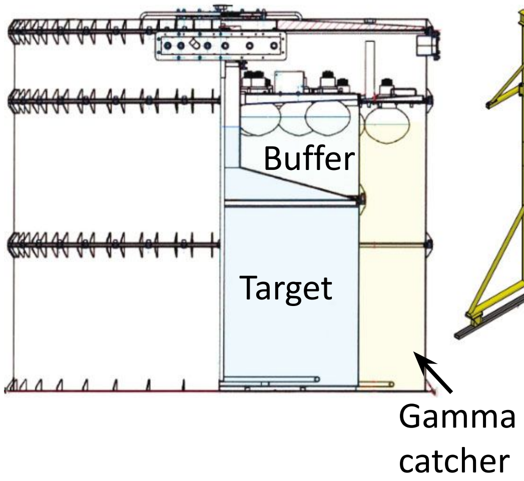


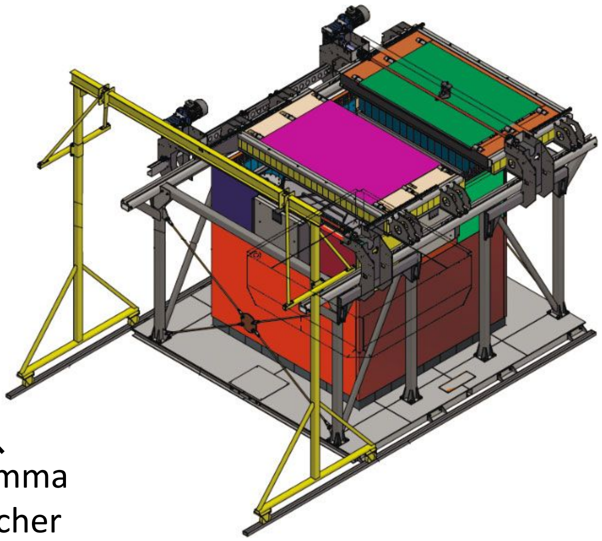

Angular resolution on reactor direction < 3°

# Gd-doped liquid scintillator monitor

The 1-tonne Gd-doped LS **iDREAM** detector at the Kalinin nuclear power plant (Russia) at ~20 m from the core.

Started taking data in spring 2021

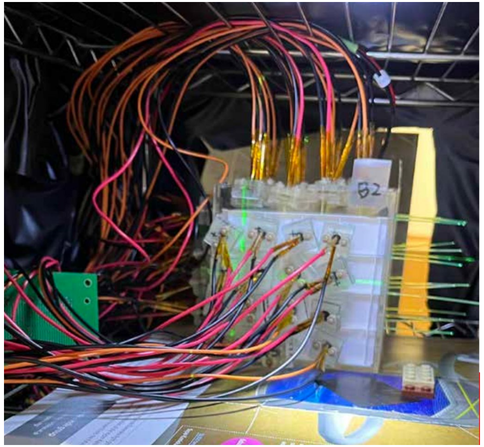


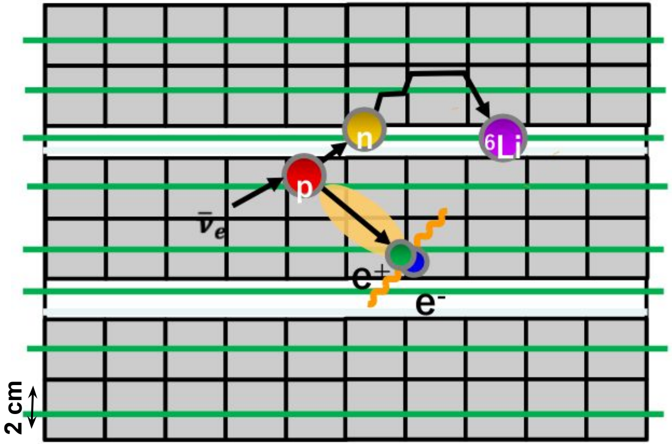



- Simple design.
- Active and passive shielding.
- Easy mounting.
- No need for daily maintenance.
- Remote control of all systems of the detector.

# $^6$Li-doped plastic scintillator monitor

**PANDA** is made of $^6$Li-doped plastic scintillator cubes with 3D segmentation and has topological particle ID.



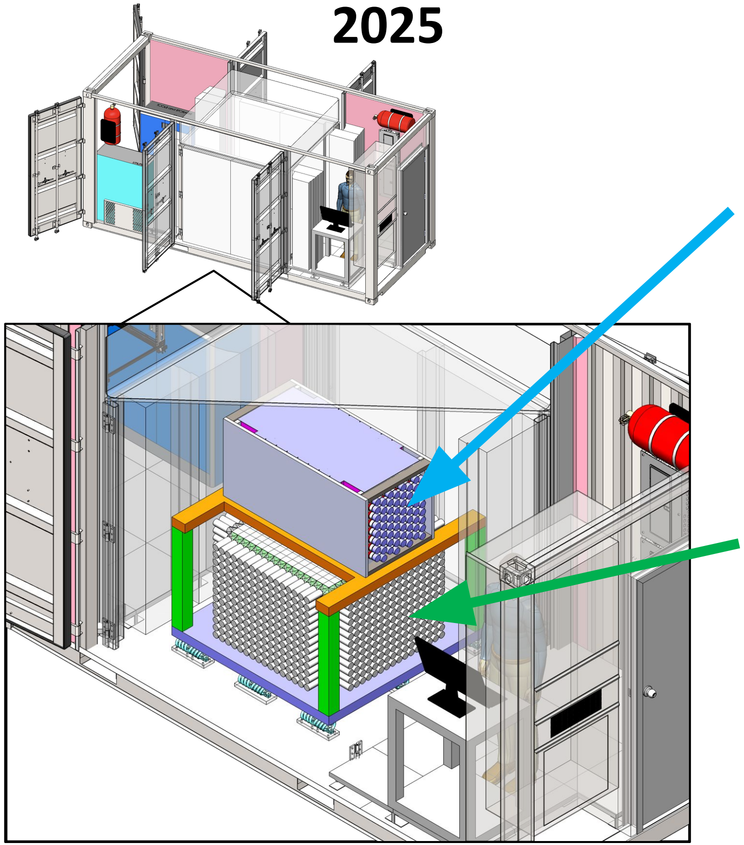

Next phase:

new location and more shielding.

Prototype measured backgrounds 3 m from core at 20 MW JRR-3 research reactor in Japan.

# Mobile reactor monitor

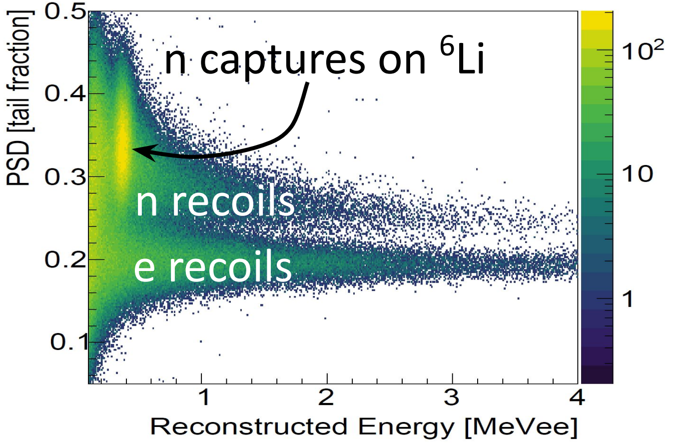
**MAD - deployment in 2025**

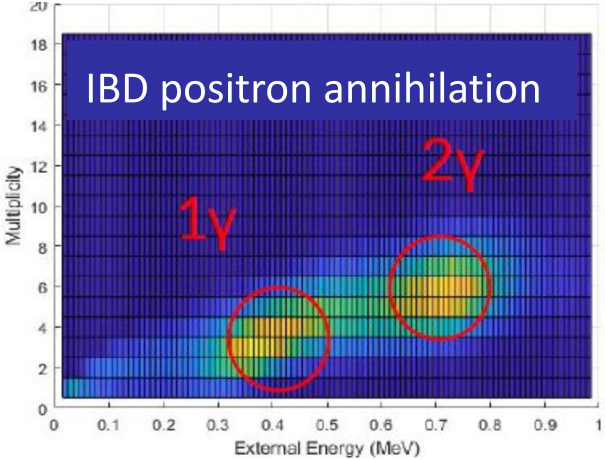


- 2D segmented
- ~250kg
- $^{6}$Li-doped PS
- pulse-shape discrimination

CHANDLER

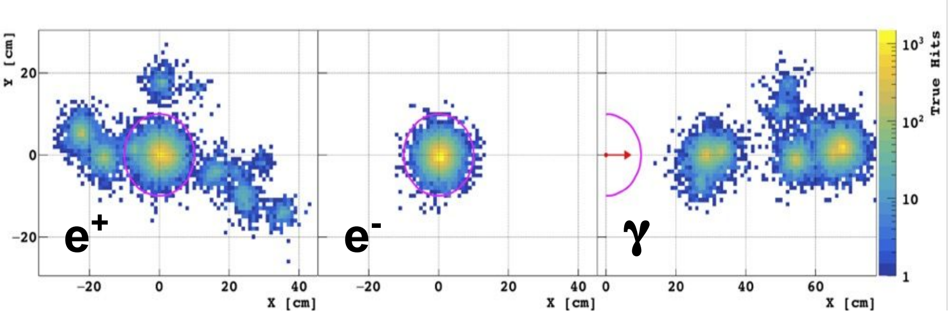
- 3D segmented
- 600 kg
- WLS PS cubes
- $^{6}$Li-doped ZnS
- topological PID



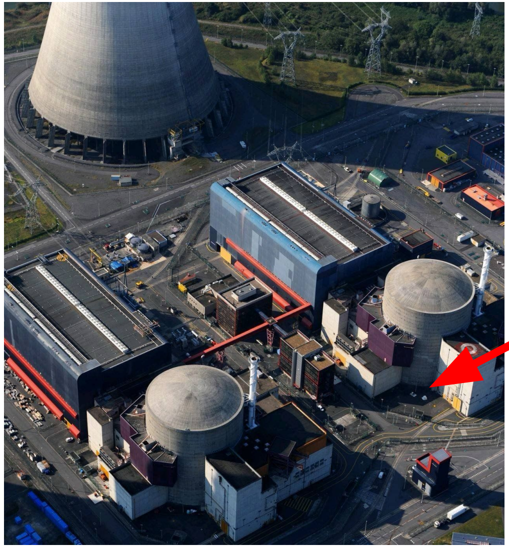



# Opaque liquid scintillator near-field detector

**CLOUD** near-field detector at Chooz with 5-10 tonne LiquidO (LiquidO Consortium 2021) opaque scintillator target.

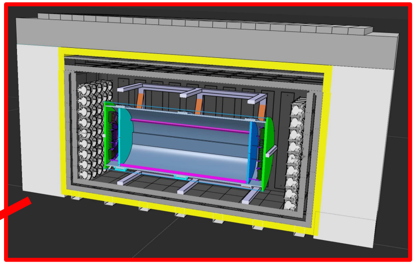



**~10 000 IBD interactions per day**



~35 m from core

~3 m overburden



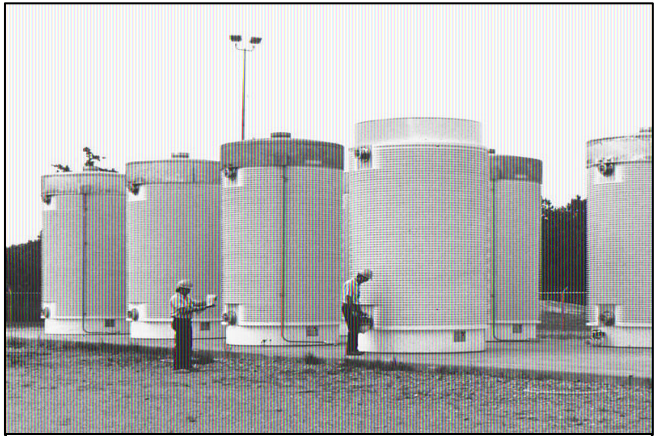
> 200 pe/MeV

sub-ns timing

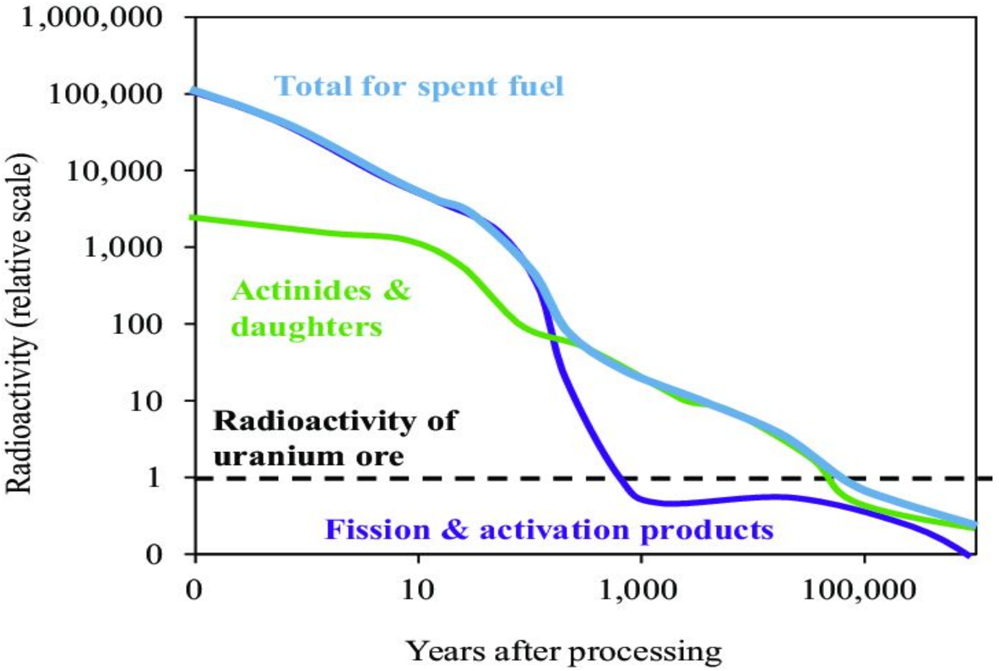
**CLOUD-I**: development of non-intrusive reactor monitoring.

# Spent nuclear fuel monitoring

Spent nuclear fuel (SNF) is stored in casks in interim facilities at nuclear power plants - requires decades of active monitoring.

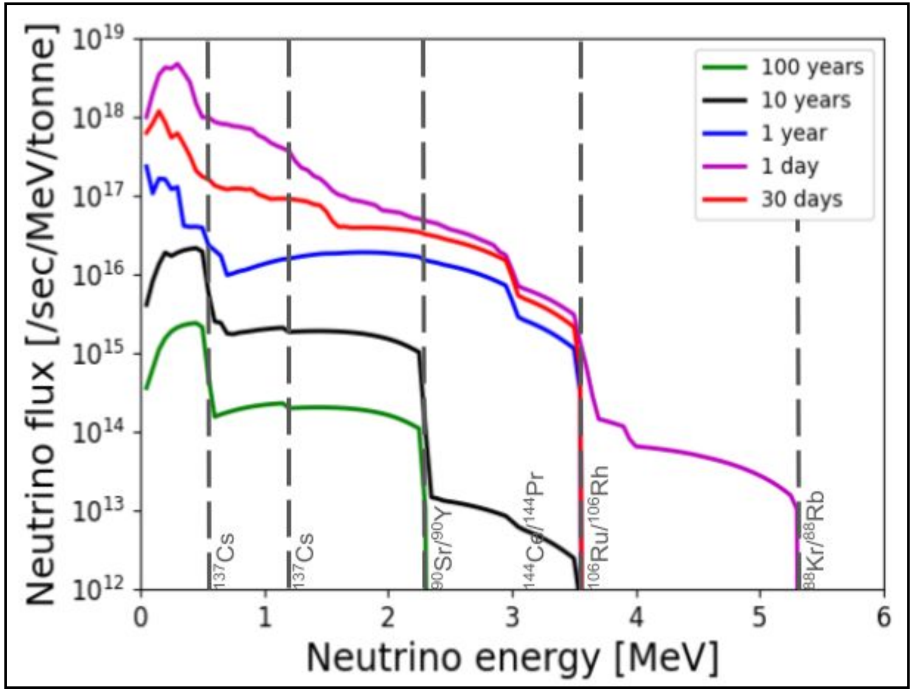


"[Dry Storage of Spent Nuclear Fuel]" by NRCgov is licensed under CC BY 2.0.




Corkhill & Hyatt, 2018

# Neutrinos for spent nuclear fuel monitor




Brdar et al, 2017

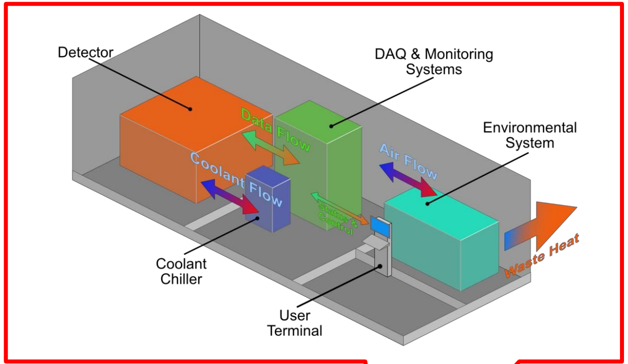
Potential for observation of IBD from $^{90}$Sr and $^{90}$Y (1 SQ Pu results in 2 mol of $^{90}$Sr).

A neutrino detector could perform:

- cask-by-cask monitoring
- long-term monitoring
- detection of diversion of SQ Pu
- **remote monitoring from outside shielding**

# Mobile spent nuclear fuel monitor

**VIDARR** is now running ~40 m from large store of spent nuclear fuel at Sellafield nuclear facility, UK

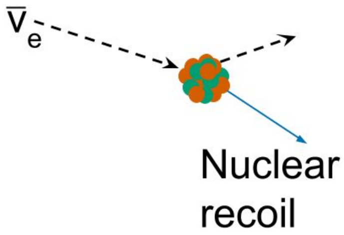



- 2 tonnes of PS bars
- Gd-doped mylar sheets between layers
- Energy threshold ~120 keV

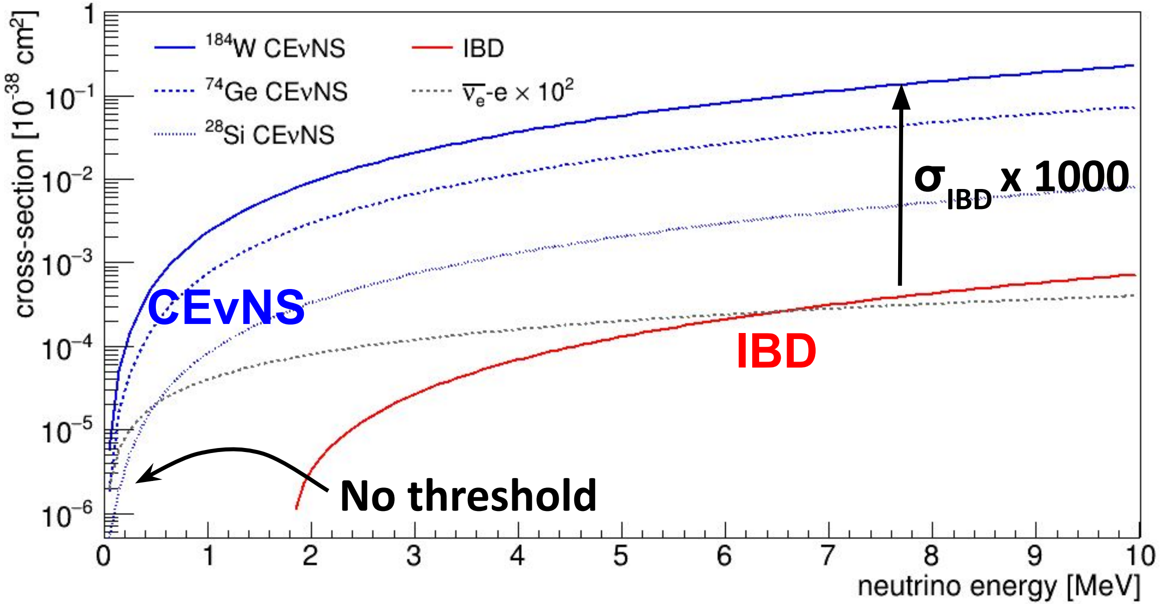
Expected rate ~10 antineutrino interactions/day (R. Mills NNL).

# CEvNS for safeguarding

**Coherent Elastic Neutrino Nucleus Scattering (CEvNS)**




$$\bar{\nu}_e + N \rightarrow \bar{\nu}_e + N$$




- Largest cross section
- Low-threshold detectors (keV)
- Small detectors

**Many projects ongoing at reactors and new technologies being explored (Talk by Irina).**

# Neutrinos for nuclear safeguards

Detector materials, technology and prototypes with potential to meet monitoring requirements probably already exist but…

…**more work is needed to demonstrate the technology and the application, and to perform more challenging monitoring such as burnup verification, monitoring outside the fence, and so on**.

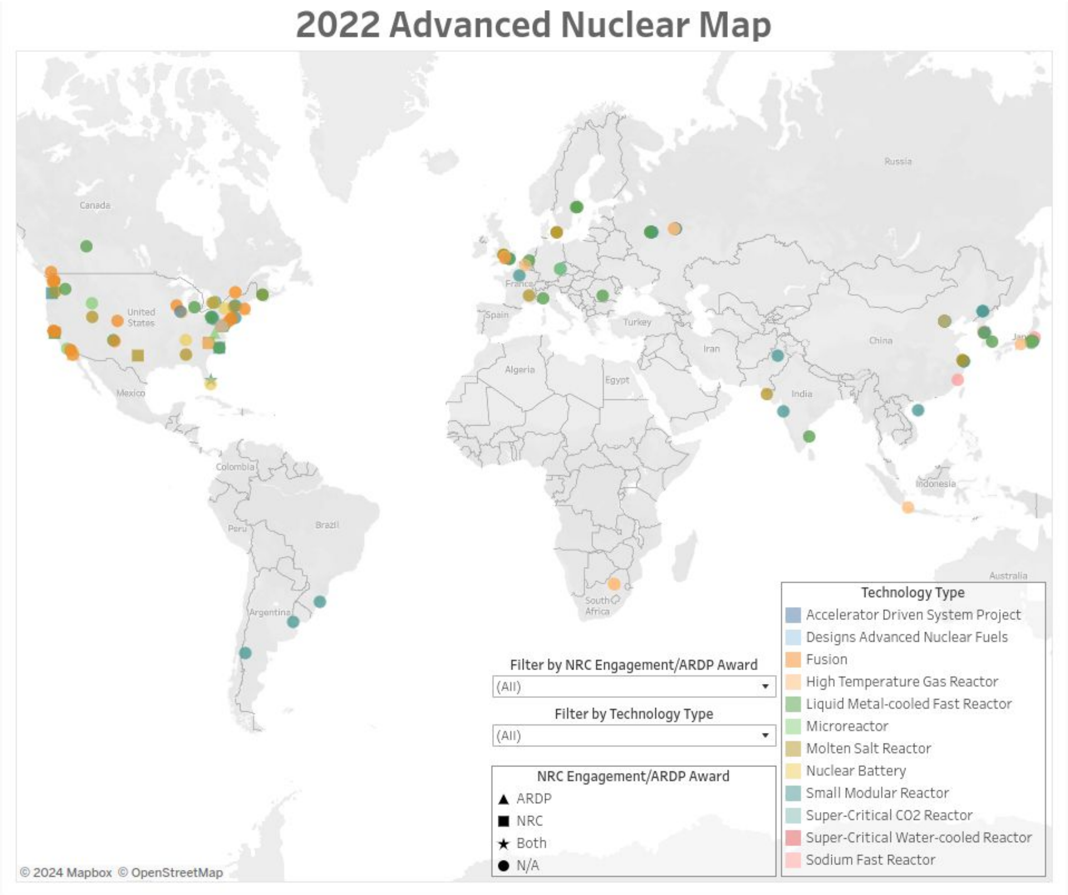
**Strongest use cases address the new challenges of advanced reactor types**:

- Safeguarding by design - detector built into reactor design
- Mobile, above-ground detectors

Strong **Applied Antineutrino Physics (AAP) community** meet annually to discuss reactor monitoring and other antineutrino applications - next meeting in Aachen 28th - 30th October this year!

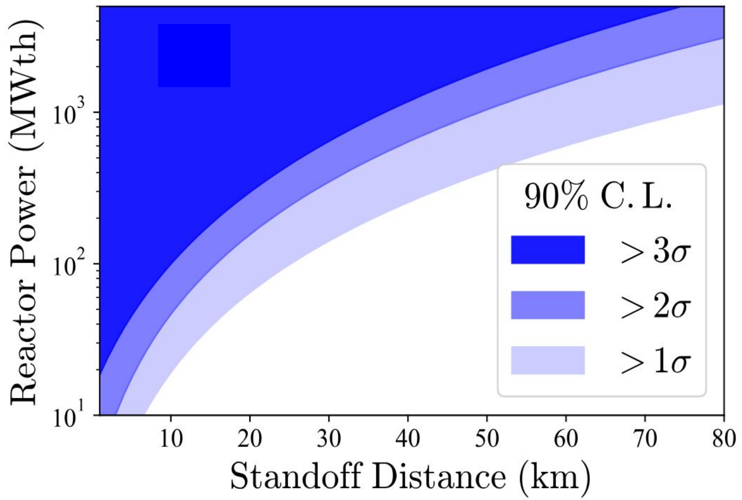
# Backups

# The monitoring gap - advanced reactors

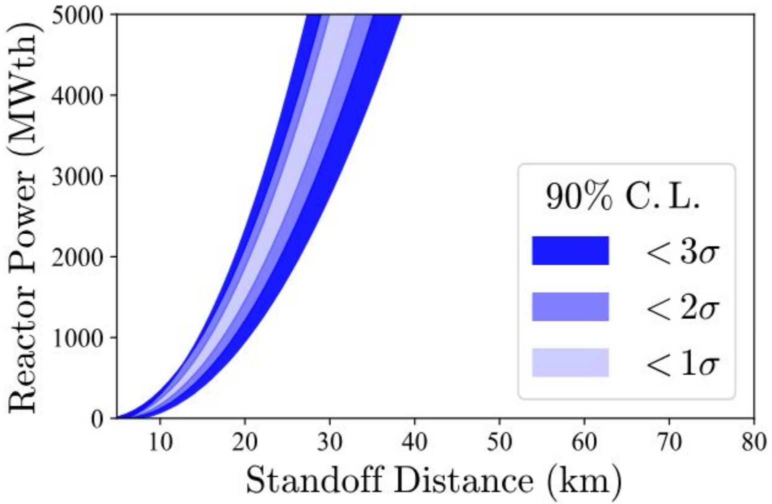



# Water Cherenkov: mid to far-field

6 ktonne Gd-doped detector with 20% photocoverage and active muon veto:




Exclusion of unknown reactor from a given region.

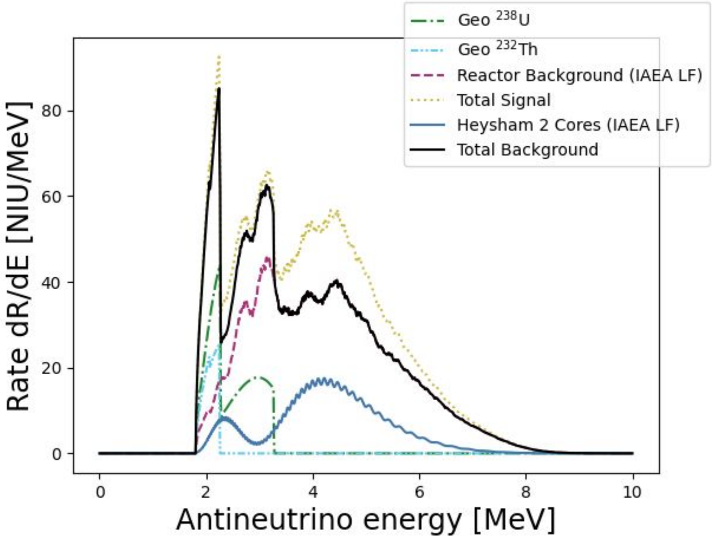


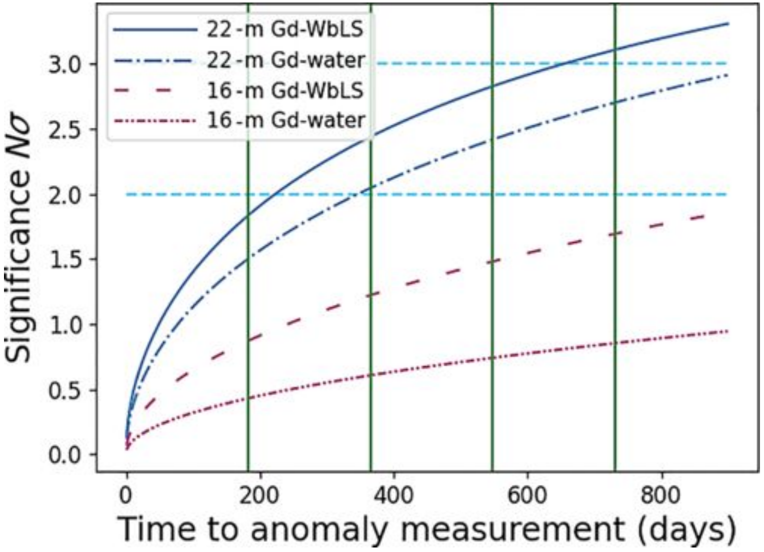

Confirmation of declared 3 $GW_{th}$ reactor at 26 km standoff.

Untangling degeneracy in reactor power and standoff: limited by energy resolution (Akindele et al, 2023).

# Water-based far-field monitor

Gd-water & Gd-WbLS, passive muon veto, 3 GWth reactor, 150 km standoff, known reactor landscape and other backgrounds.

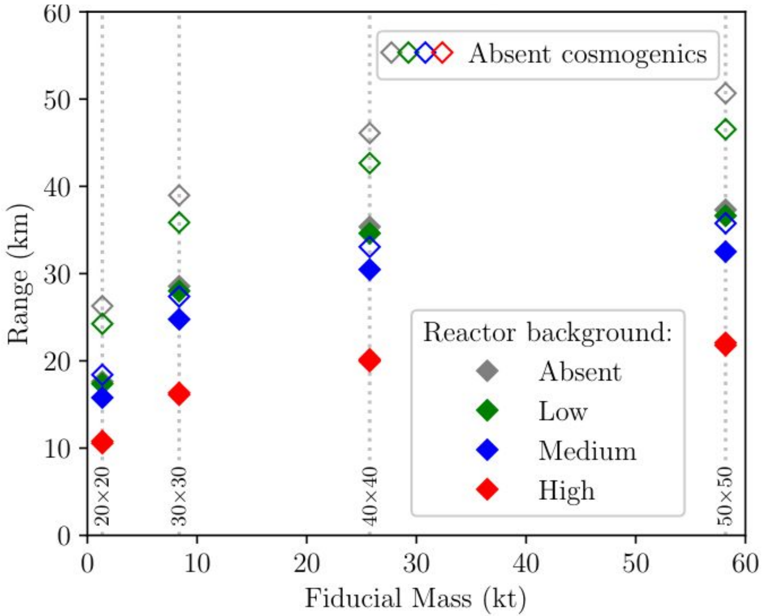



Sensitivity to single reactor complex up to 200 km away:
**minimum requirement Gd-doped WbLS** ([Kneale, Wilson et al, 2023])

# Water Cherenkov for far-field monitoring

Gd-doped detector with 40 % photocoverage



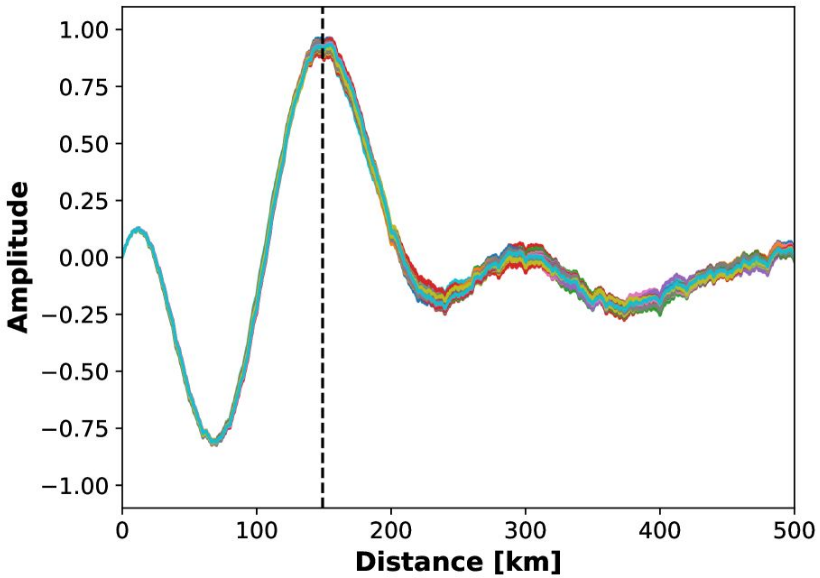

Different detector sizes evaluated for low, medium and high reactor background levels.

Detectable within 1 year, with no independent background measurement.

Scalability for true far-field monitoring:
Limited by position resolution (Li et al, 2022)

# Gd-WbLS for far-field monitoring

Gd-WbLS, passive muon veto, 3 GWth reactor, 150 km standoff, known reactor landscape and other backgrounds.




Fourier transform converts energy spectrum to distance to reactor.

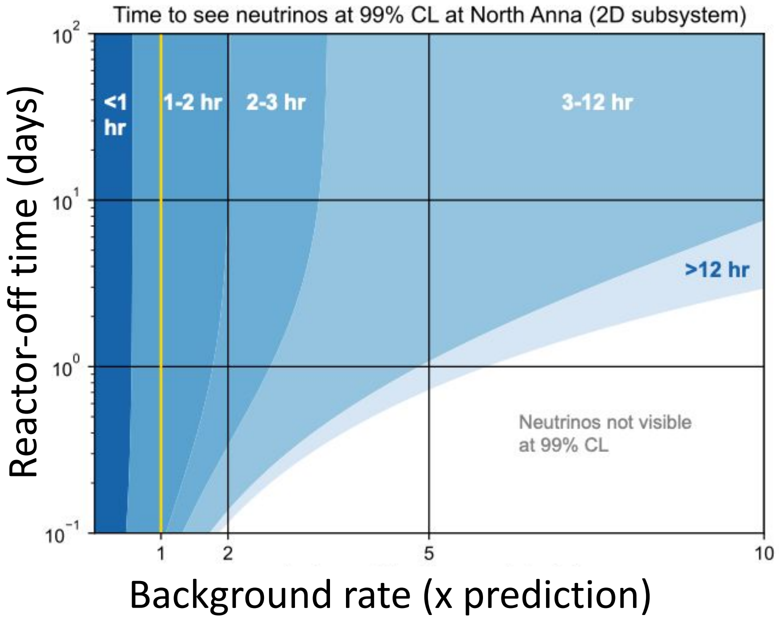
| True distance to reactor (km) | Reconstructed distance (km) |
|---|---|
| 149 | 155 +/- 5 |

**But decades of observation!**

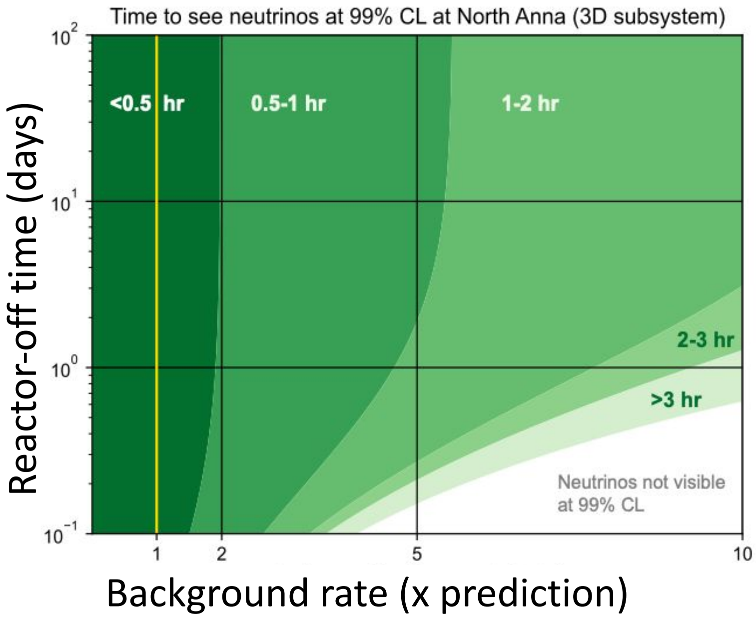
Ranging using Gd-doped WbLS:
timely ranging limited by detector performance (Wilson et al, 2024)

# Mobile reactor detector

The subsystems will observe **reactor on/off transition within hours** (3 $GW_{th}$ reactor from 25 m)




2D $^{6}Li$-doped PSD PS system




3D $^{6}Li$-ZnS & WLS PS system