The University Of Sheffield.

Monitoring Reactors and Spent Nuclear Fuel with Neutrinos

Core of Advanced Test Reactor, Idaho National Laboratory
https://commons.wikimedia.org/w/index.php?curid=27024528

Mainz Physics Academy Retreat
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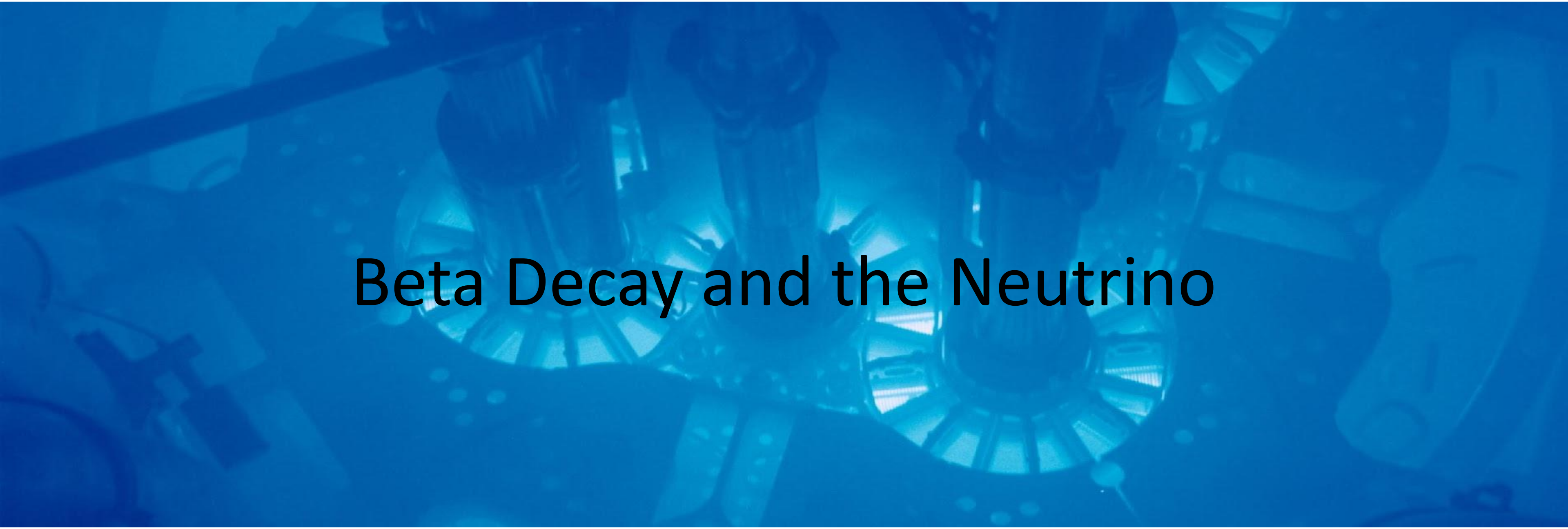
University of Sheffield

What I'll cover in this talk

1. Beta Decay and the Neutrino
2. Nuclear Reactors and the Monitoring Gap
3. Antineutrinos for Monitoring
4. Reactor Monitoring
5. Spent Nuclear Fuel Monitoring
6. CEvNS for safeguarding
7. Outlook

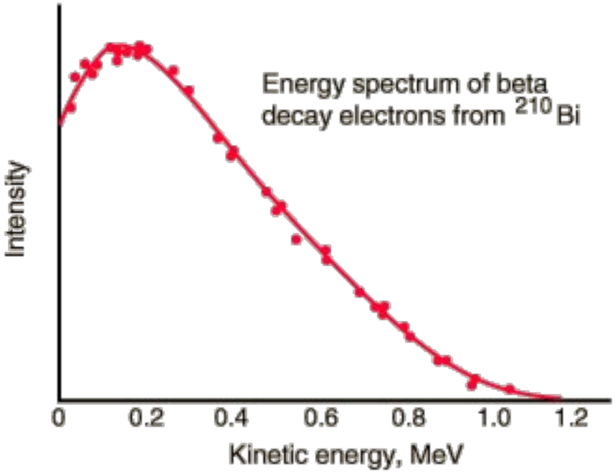
Beta Decay and the Neutrino



Pauli's Postulated Particle

The year is 1930. It's 16 years since James Chadwick identified a problem with β decay - it doesn't appear to conserve energy!

- α and γ are emitted with discrete spectra corresponding to the difference between the initial and final state nucleus.
- electrons from β decays are emitted with a continuous spectrum.



What's Wolfgang Pauli's solution?

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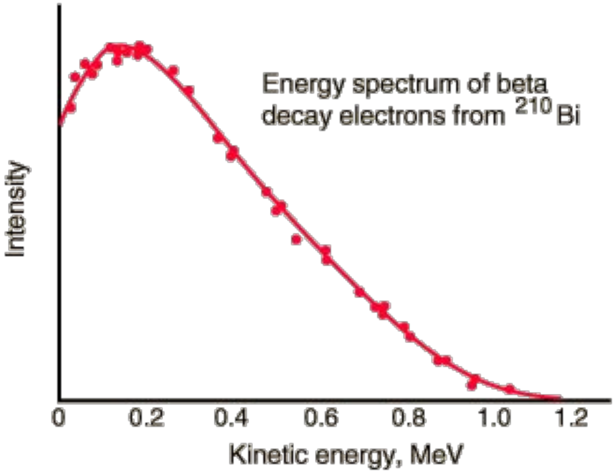

What's Wolfgang Pauli's solution?

Despite his better judgement, he "hit upon a desperate remedy" - a new particle.

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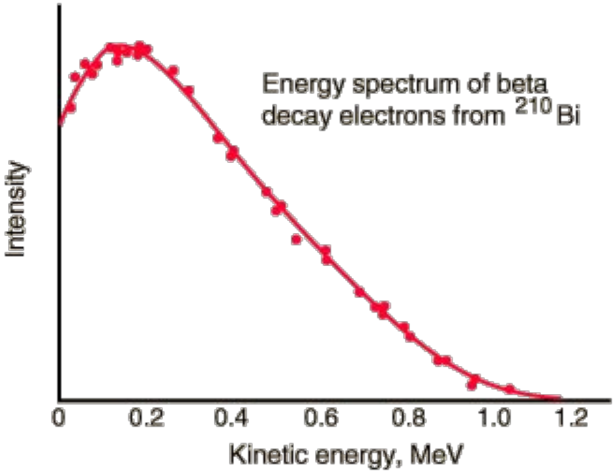


What's Wolfgang Pauli's solution?

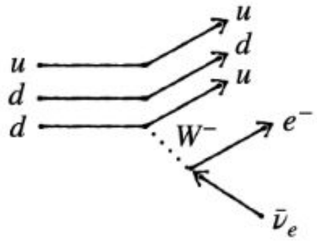
Despite his better judgement, he "hit upon a desperate remedy" - **a neutral, very light, spin ½ particle inside the nucleus, which "cannot be detected"**.

Fermi's theory for the new particle

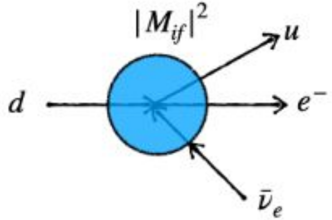
The neutrino (literally "little neutral one" in Italian) was cemented in theory by [Fermi theory of beta decay (1934)].

$$n \rightarrow p + e^- + \nu \quad \text{or} \quad (\mathrm{Z, A}) \rightarrow (\mathrm{Z, 1 + A}) + \mathrm{e}^- + \nu$$

Quark interaction



Matrix Element



Fermi's Golden Rule

Density of final states

$$\lambda_{if} = \frac{2\pi}{\hbar} |\mathcal{M}_{if}|^2 \rho_f$$

Decay rate

Matrix element

The strength of the interaction (GF) can be tuned using β decay data

$$M = \frac{G_F}{\sqrt{2}} [\overline{u_P} \gamma^\mu u_N][\overline{u_e} \gamma^\nu u_\nu]$$

Speculations too remote from reality

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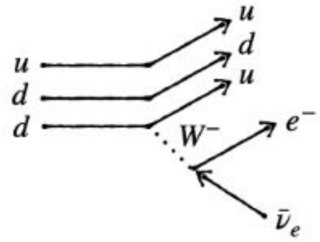
$$n \to p + e^- + \nu \quad \text{or} \quad (\mathrm{Z}, \mathrm{A}) \to (\mathrm{Z}, 1 + \mathrm{A}) + \mathrm{e}^- + \nu$$

Not ***everyone*** was impressed - Enrico Fermi's paper "contains speculations too remote from reality to be of interest to the reader" (*Nature*).

Quark interaction



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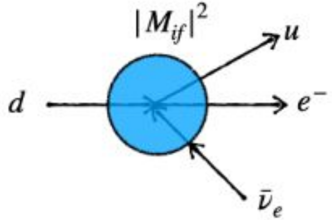

Precursor to the weak interaction

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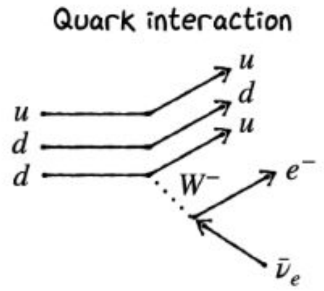
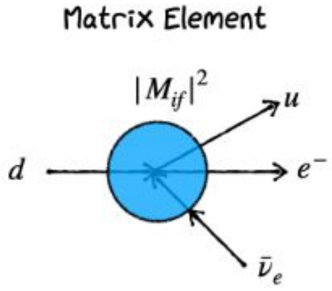


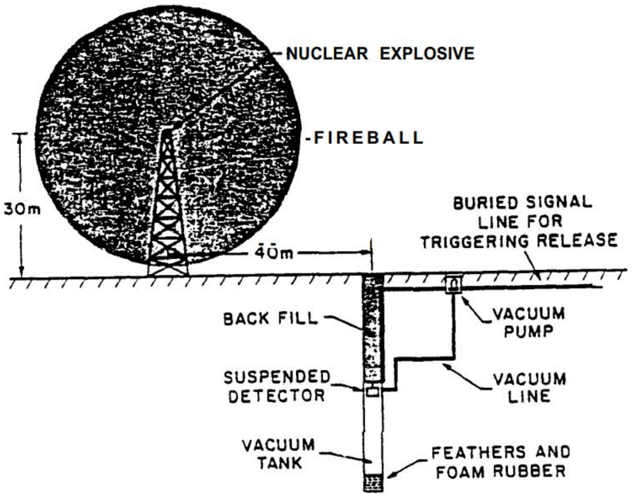


Not ***everyone*** was impressed - Enrico Fermi's paper "contains speculations too remote from reality to be of interest to the reader" (*Nature*).

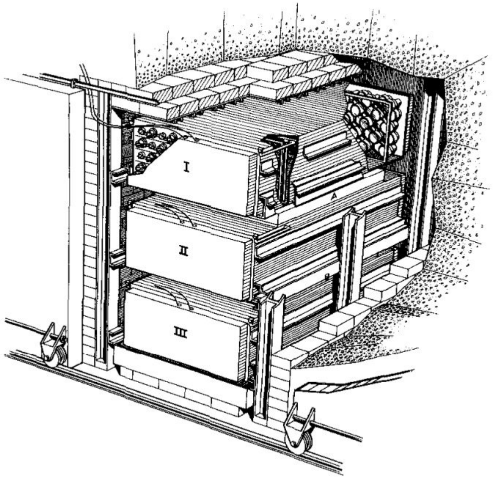
But Fermi had come up with a new fundamental interaction and his theory forms the basis of the weak interaction we know and love today.

The Neutrino: From Poltergeist to Particle

First idea from Reines and Cowan: controlled nuclear explosion to produce a sufficiently high antineutrino flux as to be detectable



Better and rather safer idea to detect the lower flux of antineutrinos from the Savannah River nuclear reactor:



Images from Reines' Nobel Lecture (1995)

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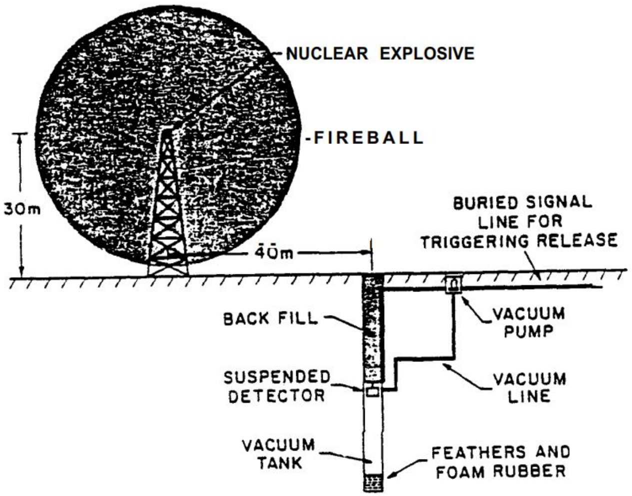

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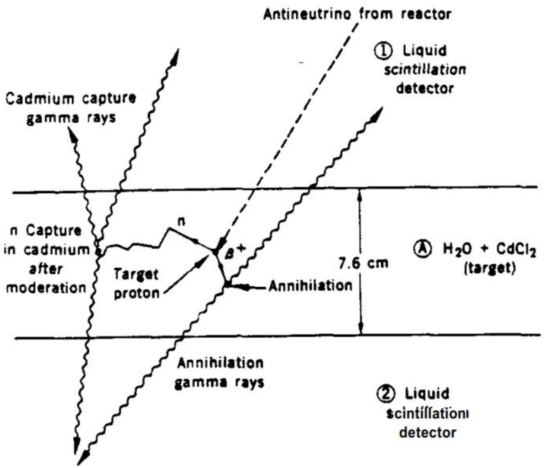

Antineutrinos detected via a positron and a neutron from inverse beta decay.

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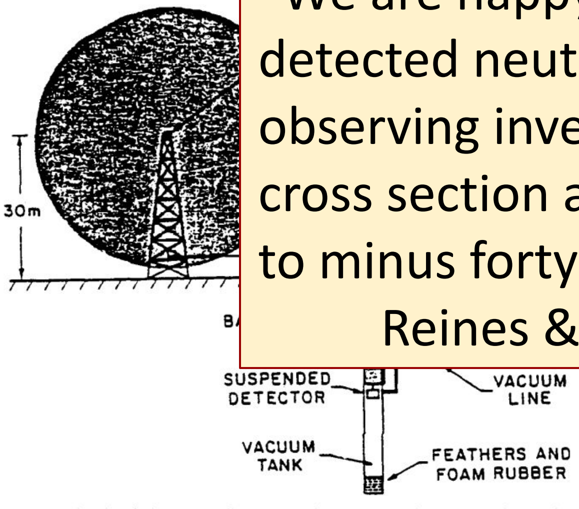

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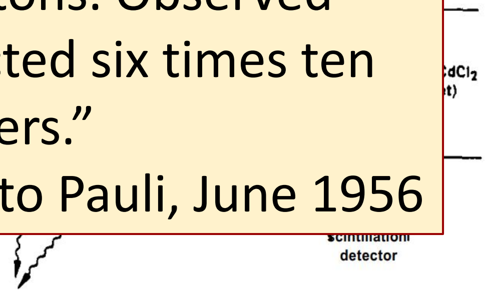
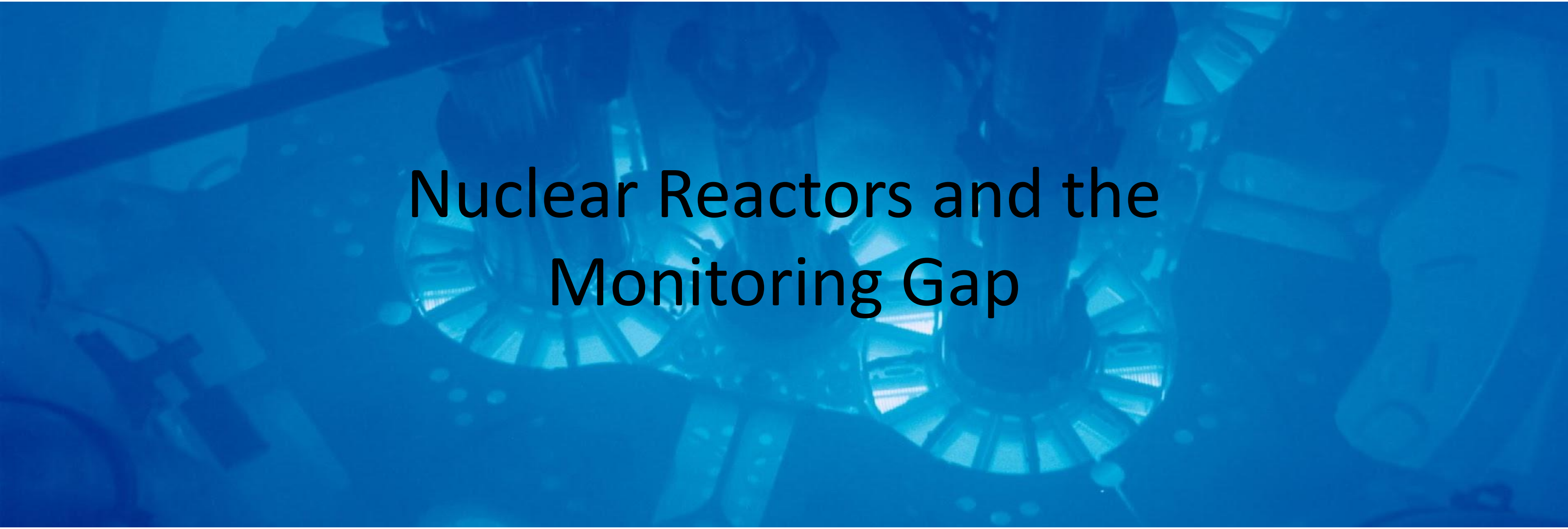


> "We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty four square centimeters."
>
> Reines & Cowan in a telegram to Pauli, June 1956

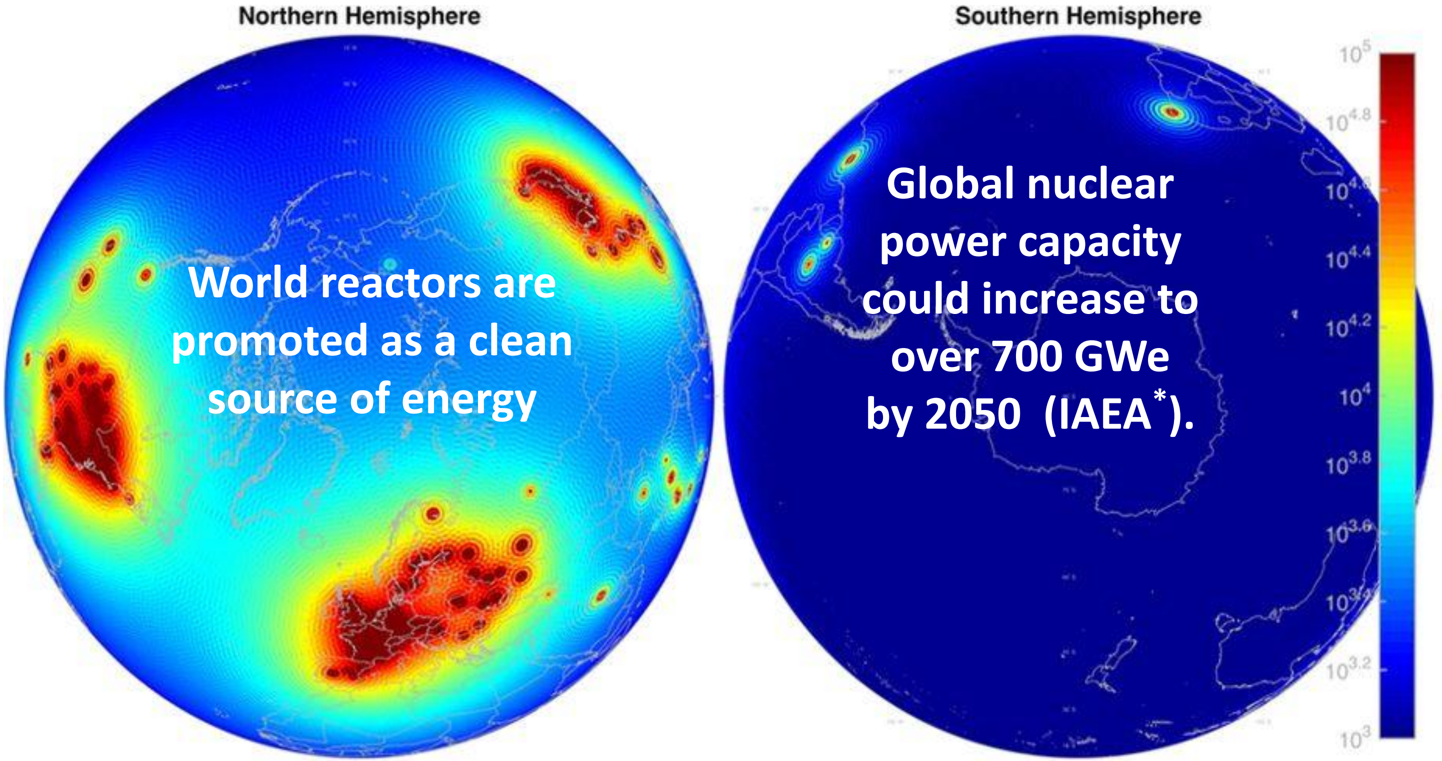
Antineutrinos detected via a positron and a neutron from inverse beta decay.

Images from Reines' Nobel Lecture (1995)

Nuclear Reactors and the Monitoring Gap



Nuclear power for energy security



World reactors are promoted as a clean source of energy

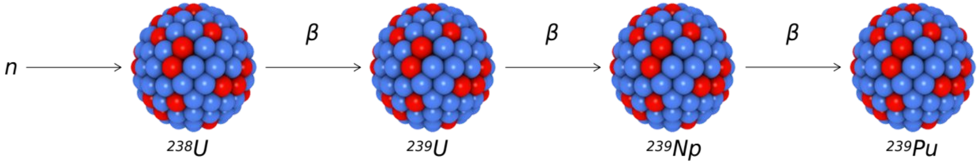
Global nuclear power capacity could increase to over 700 GWe by 2050 (IAEA*).

AGM2015

*International Atomic Energy Agency

Plutonium - a byproduct of nuclear energy

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



Plutonium can be extracted by chemical reprocessing.

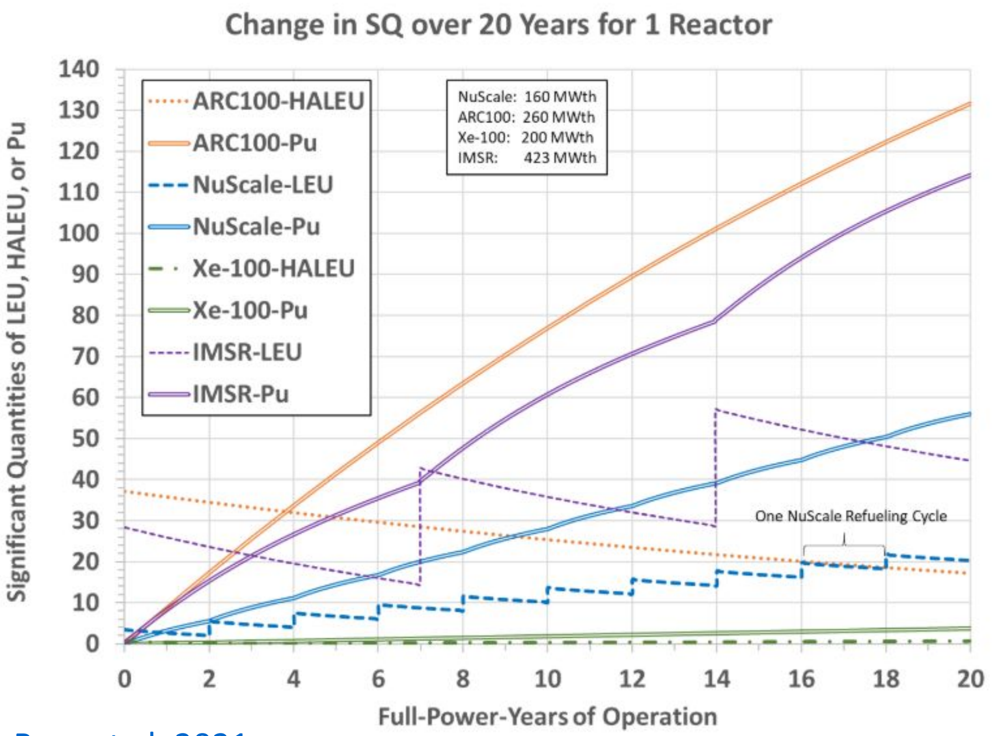
Weapons grade plutonium has >= 7% ^{239}Pu and <8% ^{240}Pu.

^{240}Pu and ^{241}Pu are produced from ^{239}Pu by neutron capture as irradiation progresses in the core.

Production reactor: early extraction (2-3 months of irradiation) yields higher concentrations of ^{239}Pu.

Fast breeder advanced reactors convert ^{238}U to ^{239}Pu.

Pu extracted by chemical reprocessing



Bays et al, 2021

HALEU: 5% < ^{235}U < 20%
LEU: < 5% ^{235}U

1 significant quantity:

- **8 kg of Pu ready for use within days (3 months for Pu in irradiated fuel)**
- 75 kg of ^{235}U (^{235}U < 20%) ready for use within 3 months to a year

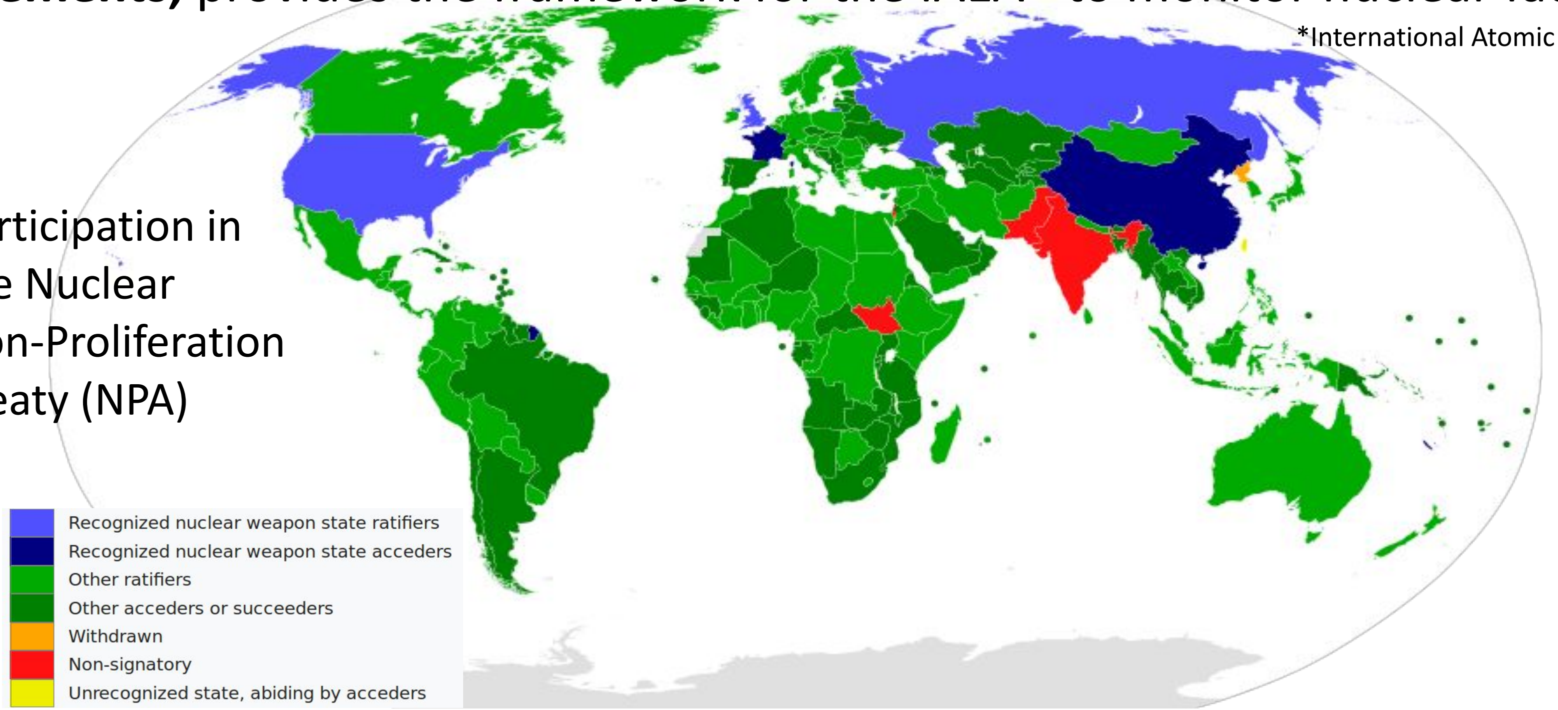
International Atomic Energy Agency (*IAEA*) Safeguards Glossary

Nuclear power requires careful monitoring

The **Non-Proliferation Treaty,** supported by **Comprehensive Safeguard Agreements,** provides the framework for the IAEA* to monitor nuclear facilities.

*International Atomic Energy Agency

Participation in the Nuclear Non-Proliferation Treaty (NPA)

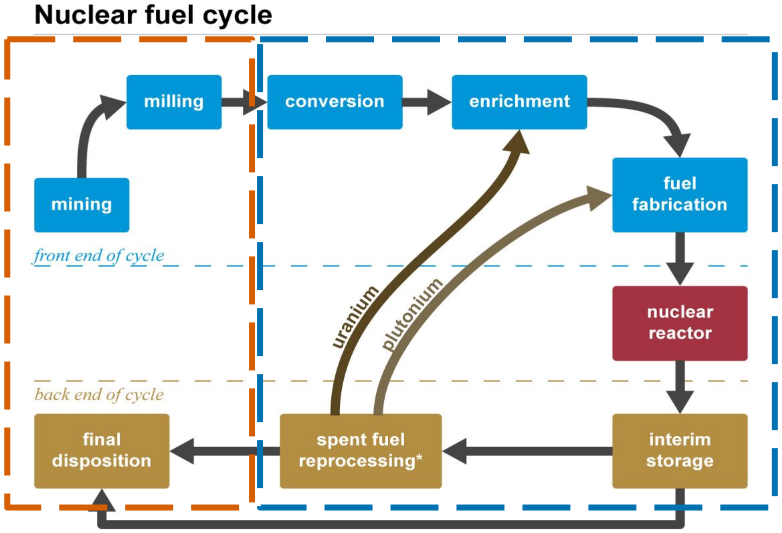


Additional protocol **extend the IAEA activities to include monitoring outside a nuclear facility.**

The monitoring challenge

International Atomic Energy Agency (IAEA) can monitor all stages of the nuclear fuel cycle.

Covered under Additional Protocol



Covered under Comprehensive Safeguards Agreements

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

Signatory states may perceive inspections as intrusion and threat to national security.

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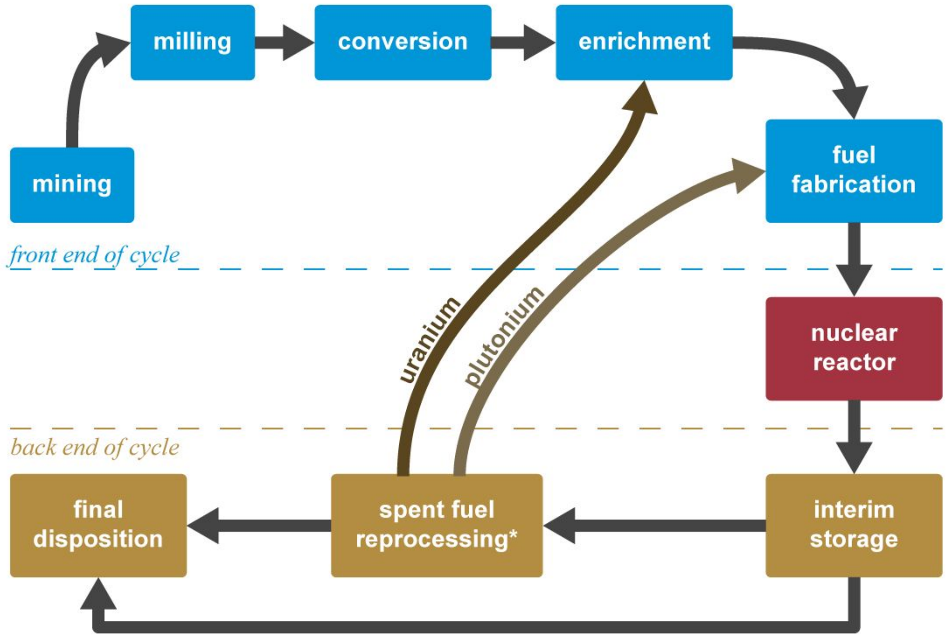

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1. Diversion of nuclear material
2. Undeclared production or processing of nuclear material
3. Undeclared nuclear material or facility

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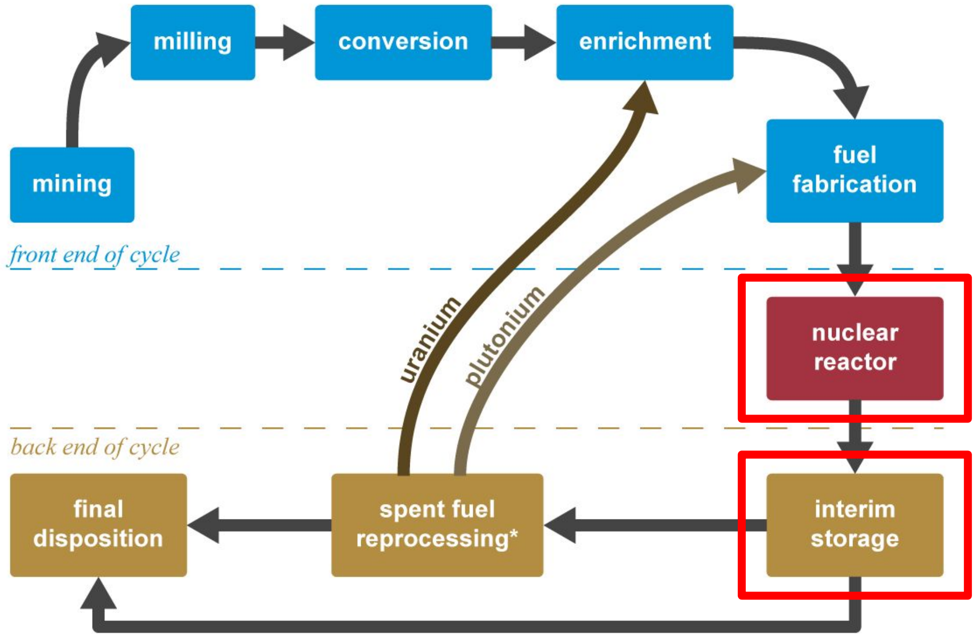

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Nuclear reactors - essential ingredients

To make nuclear power

Ingredients

Fuel e.g. 3-5% enriched Uranium.
Water or graphite moderator to thermalise neutrons.
Control rods (neutron absorber e.g. cadmium).
Coolant to transfer heat from core.
Steam generator powered by heat from coolant.

Method

Just add neutrons

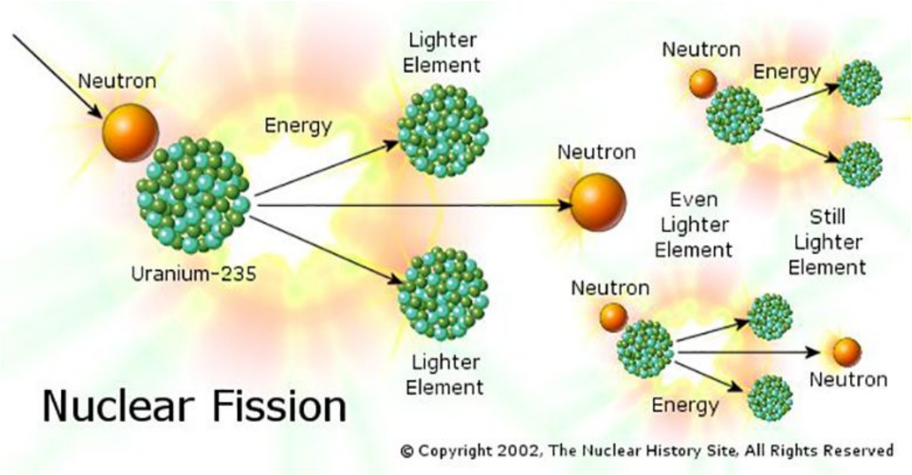
Take nuclear fuel and add neutrons

^{235}U undergoes induced fission after capturing a low-energy (thermal) neutron:

Adding a neutron to ^{235}U gives a total energy of

$$E(^{236}U^*) = [m_{U\text{-}235} + m_n - m_{U\text{-}236}]c^2$$
$$= [235.0439 + 1.0087 - 236.0456]c^2$$
$$= 6.5 \text{ MeV},$$

which is above the fission barrier of 6.2 MeV.



More neutrons from induced fission

~2.42 **prompt neutrons** per fission are emitted from compound nucleus of ^{235}U or its fission products.
~0.0162 **delayed neutrons** are emitted in the decays of daughter nuclei.

Neutrons released in ^{235}U fission can:

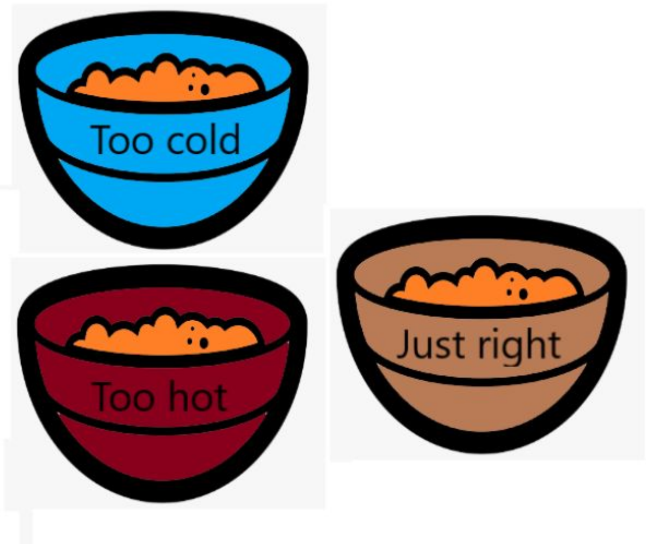
1. **Induce fission in another ^{235}U nucleus (desired effect). Increase with neutron moderator - slow neutrons down to thermal energies.**
2. **Absorbed in (n,γ) on ^{235}U or ^{238}U - produces fissile ^{239}Pu (byproduct). Increased in absence of moderator**.
3. Induce fission in ^{238}U (low probability).
4. Lost in other way e.g. (n,ɣ) on reactor components.

Stable chain reaction

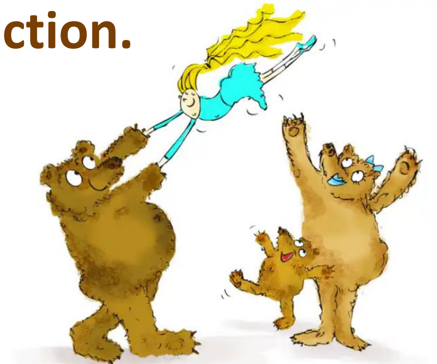
The goal is a controlled, self-sustaining chain reaction where each fission results in one additional fission on average.

Too cold (sub-critical)
< 1 additional fission

Too hot (super-critical)
> 1 additional fission



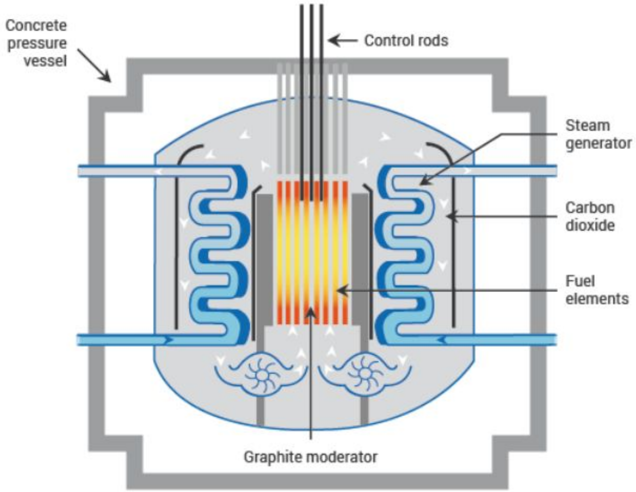
Just right(critical)
1 additional fission: self-sustaining chain reaction.



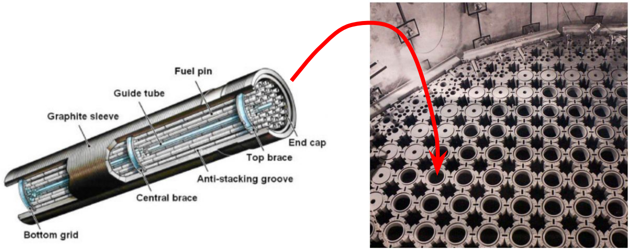
(=happy Goldilocks)

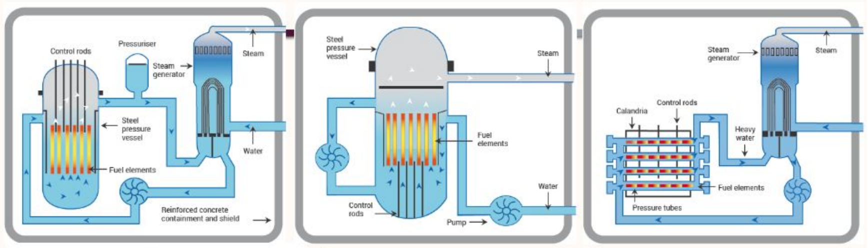
Keeping the reactor just sub-critical for prompt neutrons extends timescale of chain reaction and makes the reactor controllable.

Conventional nuclear reactor design



Advanced Gas-cooled Reactor (AGR)





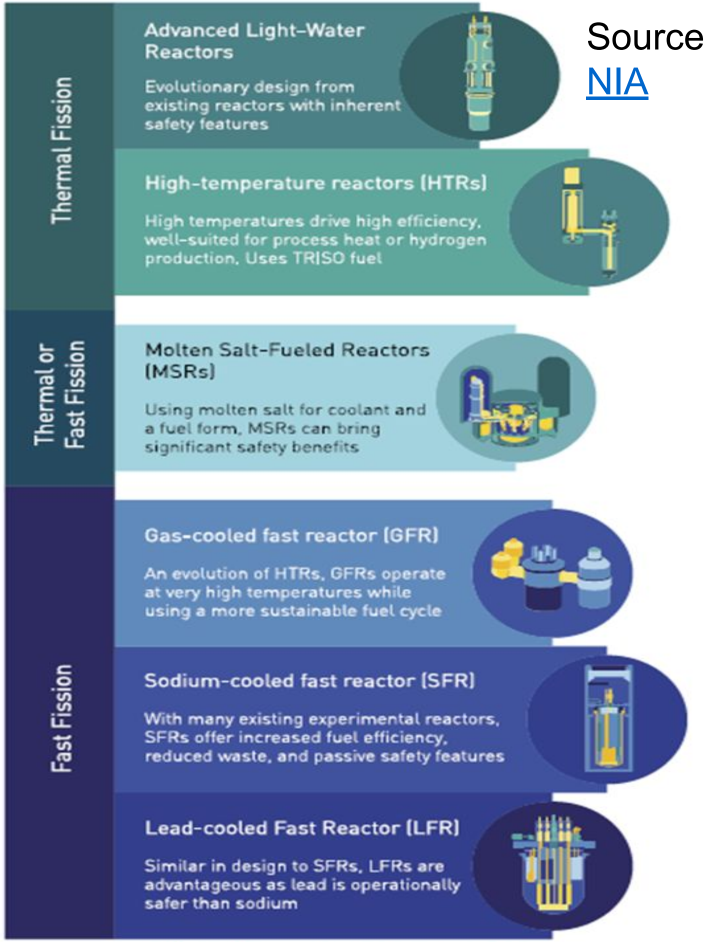
Pressurised Water Reactor (PWR), Boiling Water Reactor (BWR) and Canada Deuterium Uranium (CANDU) PWR.

Most conventional reactors use low-enriched uranium (3-5% ^{235}U).

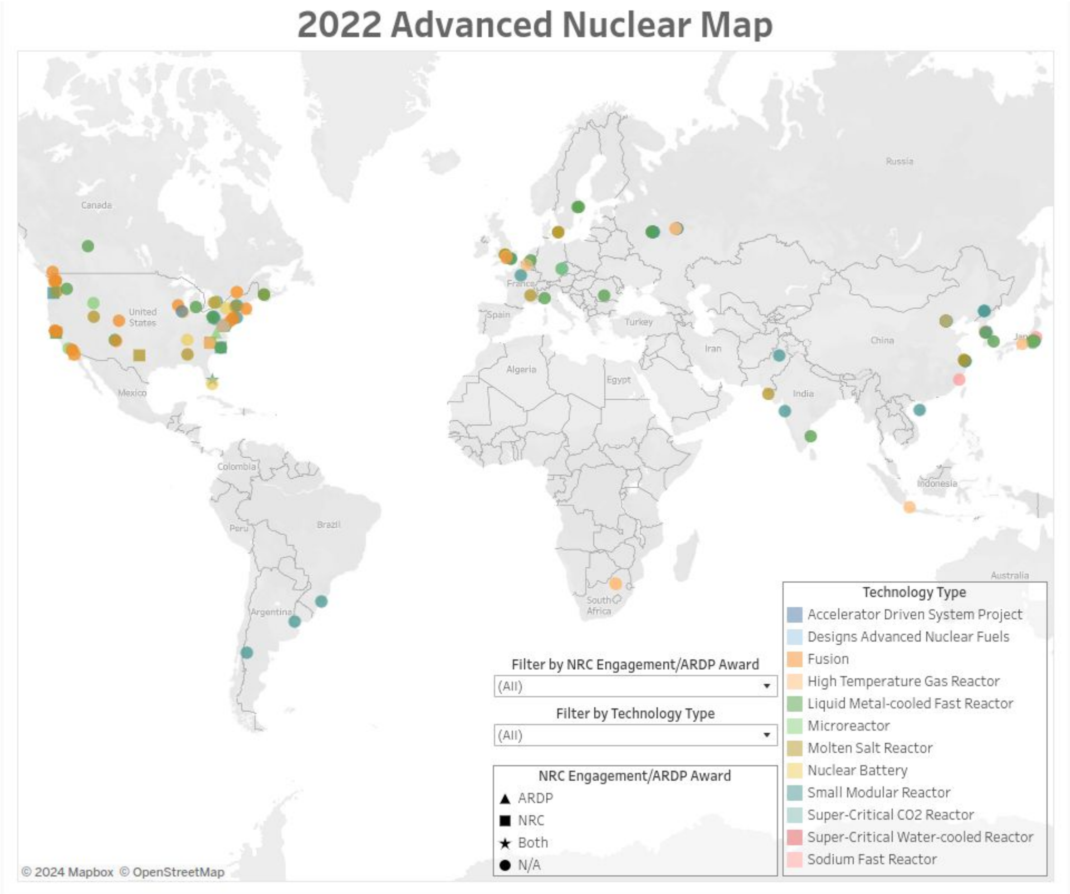
Require core shutdown for refuelling.

Monitoring presents issues when access to the core is restricted.

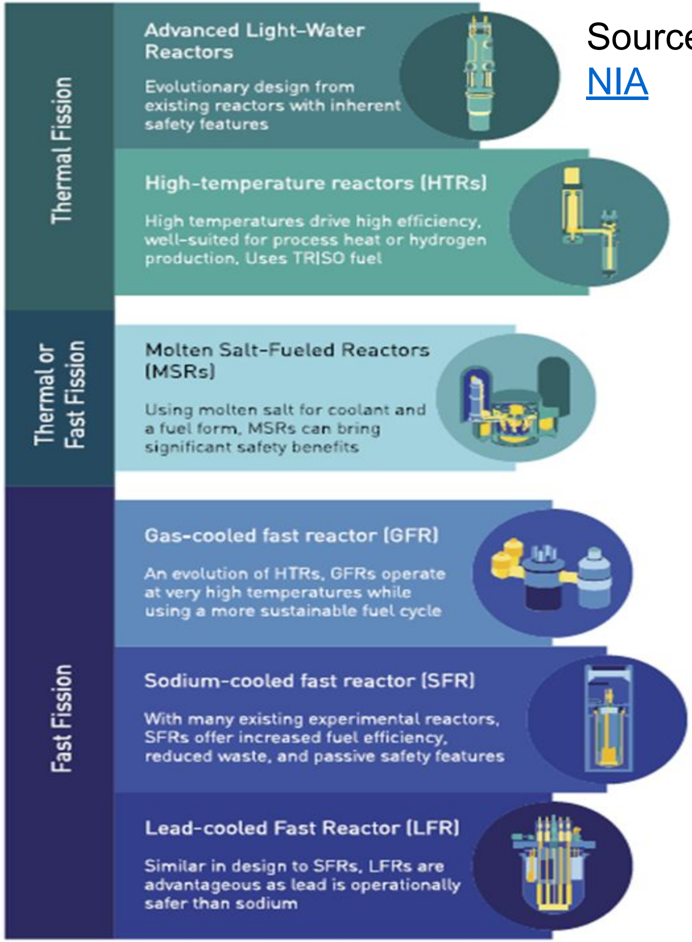
Advanced nuclear reactor development



Source: [NIA]



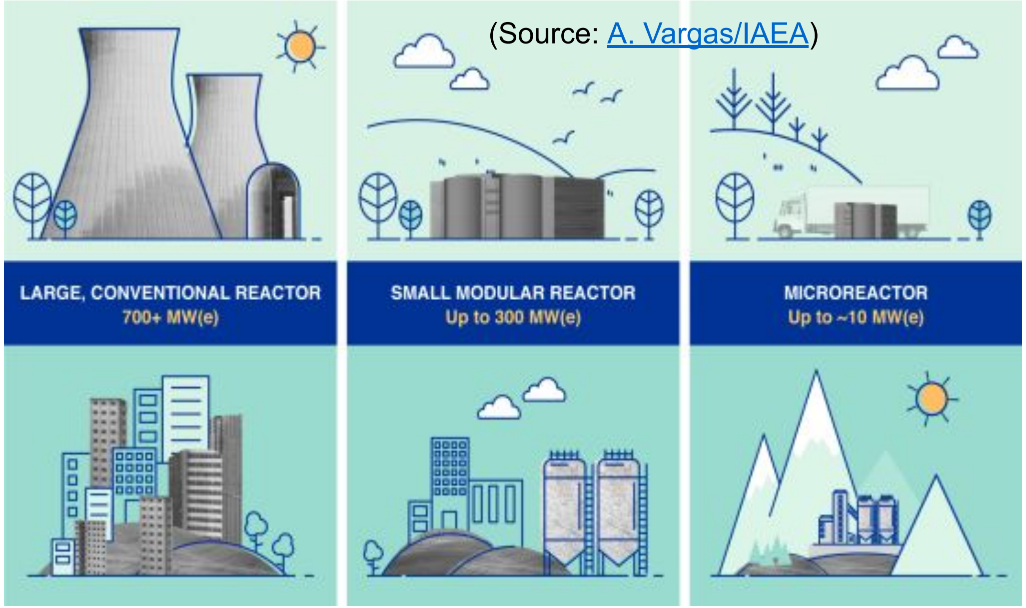
Greater efficiency, smaller size



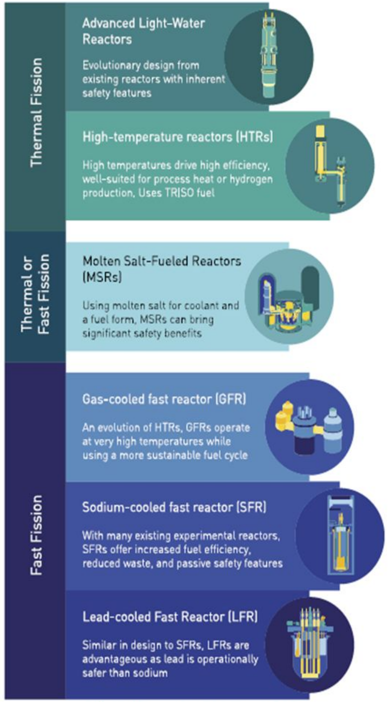
Source: NIA

Advanced reactor types and smaller sizes pose new monitoring challenges.

(Source: A. Vargas/IAEA)

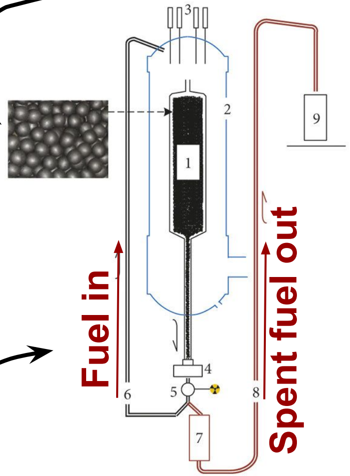


The monitoring gap - enter the neutrino



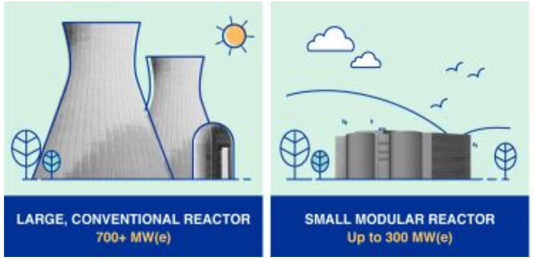
NIA

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.

Nuclear Reactors and the Monitoring Gap

- ^{239}Pu is a byproduct of nuclear power production, or produced in a production reactor.
- Conventional nuclear reactors produce power from induced fission of low-enriched uranium.
- Monitoring conventional reactors poses problems when access is restricted, requiring long-range monitoring.
- Advanced reactors offer greater efficiency, smaller sizes, but higher enrichment, difficult fuel accountancy, no access to core.
- Potential for near-field antineutrino detectors built into the design of advanced reactors, or mobile, above-ground detectors.

Questions?

Antineutrinos for Monitoring

Antineutrinos from fission fragments

In the induced fission of ^{235}U:

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$

X_1 and X_2 have average masses of A=94 and A=140 and have 142 neutrons between them.

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The stable nuclei with A=94 and A=140 are $^{94}_{40}Zr$ and $^{140}_{58}Ce$, which together have only 136 neutrons.

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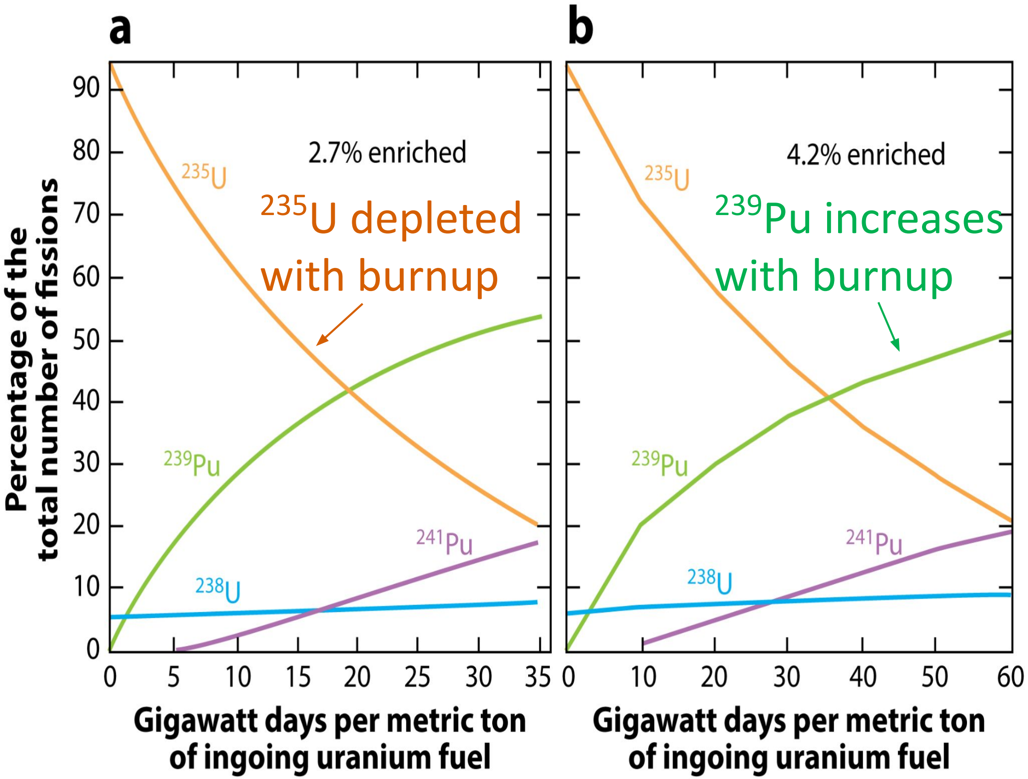
The stable nuclei with A=94 and A=140 are $^{94}_{40}Zr$ and $^{140}_{58}Ce$, which together have only 136 neutrons.

So as the fission fragments undergo beta decay to stability, we get **on average 6 electron antineutrinos per fission**.

Emitted antineutrino flux - insight into the core



Hayes, Vogel, 2016

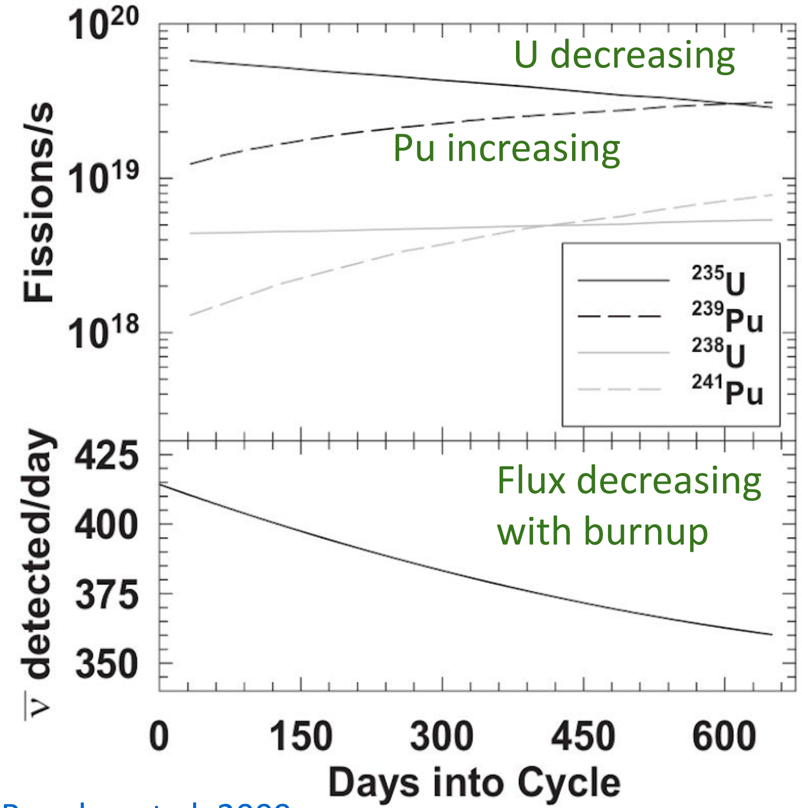
On average 6 antineutrinos are released per fission with energies up to ~10 MeV.

O(10^{20}) antineutrinos per GW_{th} per second with energies up to 10 MeV.

Antineutrino flux and spectrum depends on the fissioning isotopes.

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

Emitted antineutrino flux - insight into the core



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

Bowden et al, 2009

Emitted antineutrino spectral flux

The instantaneous antineutrino emission is given by:

$$\Phi_{\bar{\nu}_e,i}(E_{\bar{\nu}_e}) = P_{th} \frac{p_i \lambda_i(E_{\bar{\nu}_e})}{Q_i}$$

$$\lambda_i(E_{\bar{\nu}_e}) = \exp\left(\Sigma_{j=0}^{5} a_j E_{\bar{\nu}_e}^{j} \right)$$

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Thermal power of the core

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Emitted antineutrino spectral flux

The instantaneous antineutrino emission is given by:

Fraction of P_{th} from isotope *i*

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Average thermal energy per fission of isotope *i*

Thermal power of the core

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Emitted antineutrino spectral flux

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Fraction of P_{th} from isotope *i*

Antineutrino energy spectrum per fission of isotope *i*

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Average thermal energy per fission of isotope *i*

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$$\lambda_i(E_{\bar{\nu}_e}) = \exp\left(\Sigma_{j=0}^{5} a_j E_{\bar{\nu}_e}^{j}\right)$$

Emitted antineutrino spectral flux

The instantaneous antineutrino emission is given by:

$$\Phi_{\bar{\nu}_e,i}(E_{\bar{\nu}_e}) = P_{th} \frac{p_i \lambda_i(E_{\bar{\nu}_e})}{Q_i}$$

Fraction of P_{th} from isotope *i*

Antineutrino energy spectrum per fission of isotope *i*

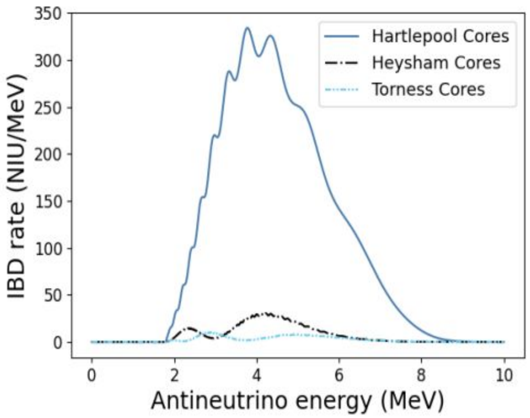
Average thermal energy per fission of isotope *i*

Thermal power of the core

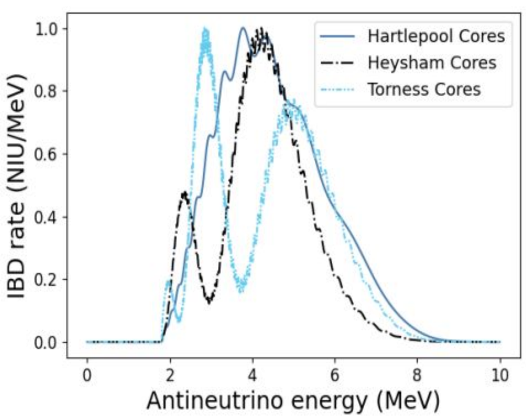
$$\lambda_i(E_{\bar{\nu}_e}) = \exp\left(\Sigma_{j=0}^{5} a_j E_{\bar{\nu}_e}^{j}\right)$$

Fit parameters from Huber, 2011 and Mueller, 2011

Detectable antineutrino spectrum



(a) Detectable IBD spectra.



(b) Normalised spectra showing effect of oscillations.

Kneale, 2023

$$R(E_{\bar{\nu}_e}) = \frac{N_p \sigma(E_{\bar{\nu}_e})}{4\pi d^2} \Phi_{\bar{\nu}_e}(E_{\bar{\nu}_e}) P(E_{\bar{\nu}_e}, d)$$

Dependent on the distance between the reactor and the detector.

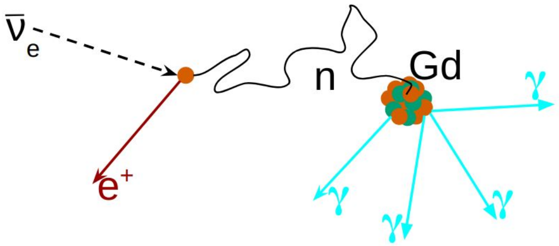
Detectable antineutrino spectrum

Dependent on the size and design of the detector and on the interaction.

$$R(E_{\bar{\nu}_e}) = \frac{N_p \sigma(E_{\bar{\nu}_e})}{4\pi d^2} \Phi_{\bar{\nu}_e}(E_{\bar{\nu}_e}) P(E_{\bar{\nu}_e}, d)$$

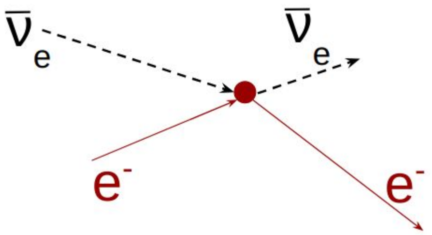
Reactor antineutrino interactions

Inverse beta decay (IBD)



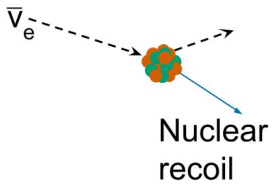
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Elastic scattering (ES)



$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

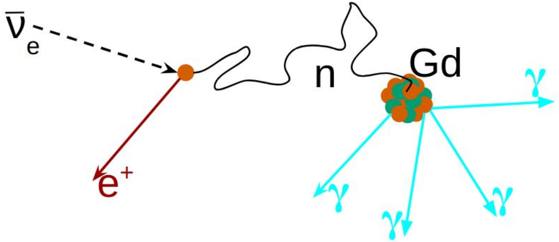
Coherent Elastic Neutrino Nucleus Scattering (CEvNS)

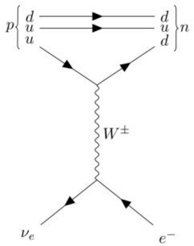


$$\bar{\nu}_e + N \rightarrow \bar{\nu}_e + N$$

Inverse beta decay for reliable detection

Inverse beta decay (IBD)

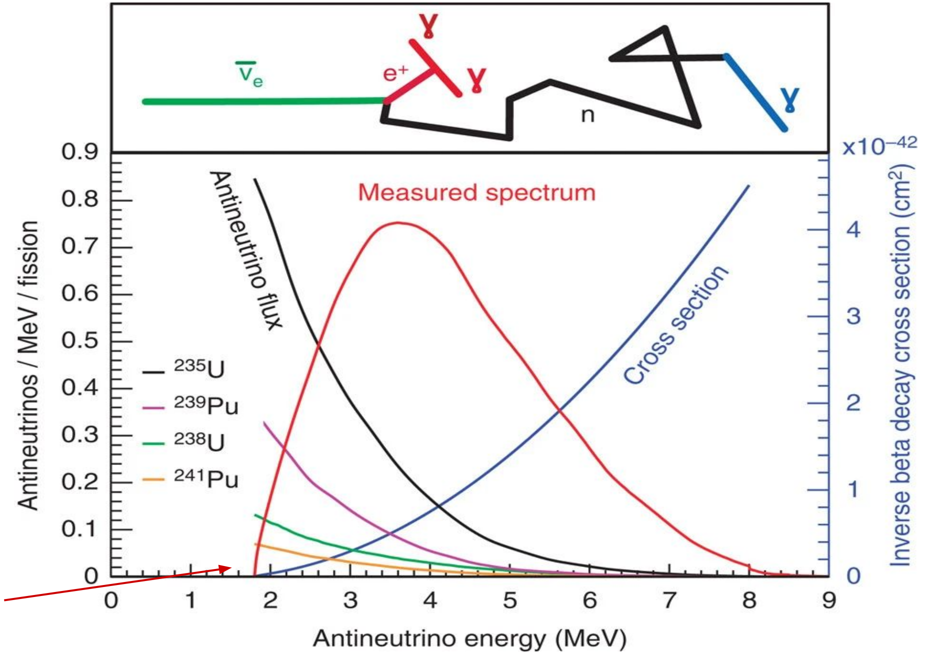




$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Background suppression with neutron tagging.

1.8 MeV threshold

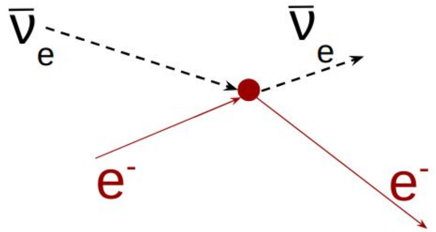


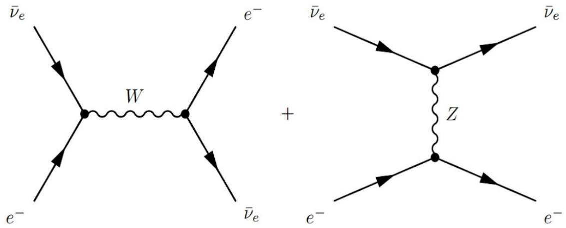
Inverse beta decay (IBD) tried and tested means of detection.

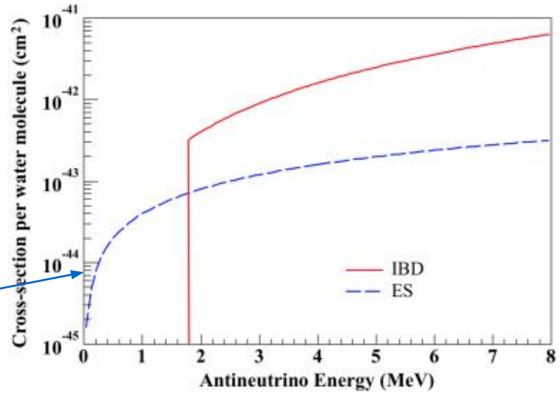
[Vogel, Wen, Zhang, 2015]

Elastic scattering to point to a reactor

Elastic scattering (ES)



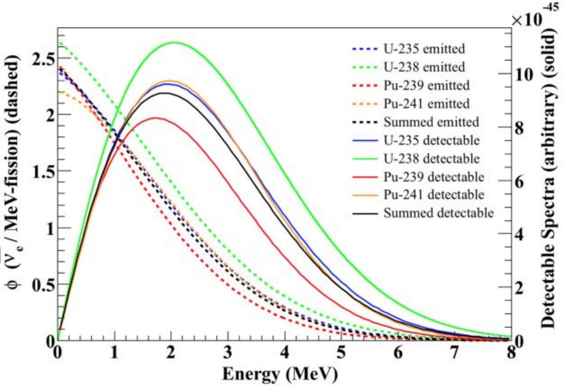


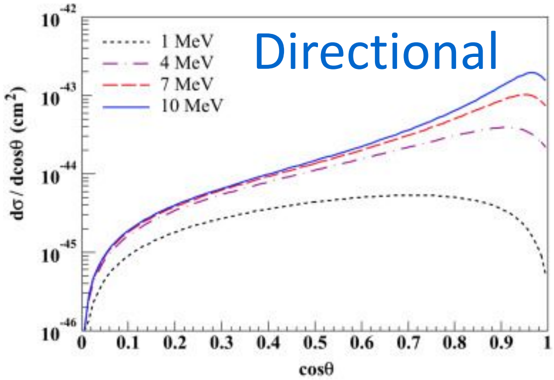


No threshold but lowest cross section

$$\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$$

- Pointing requires IBD rejection and very low radon levels.



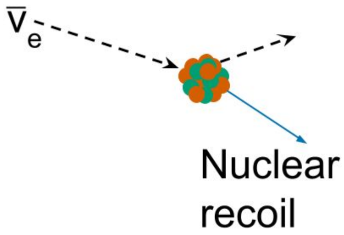


Directional

Plots from Hellfeld et al

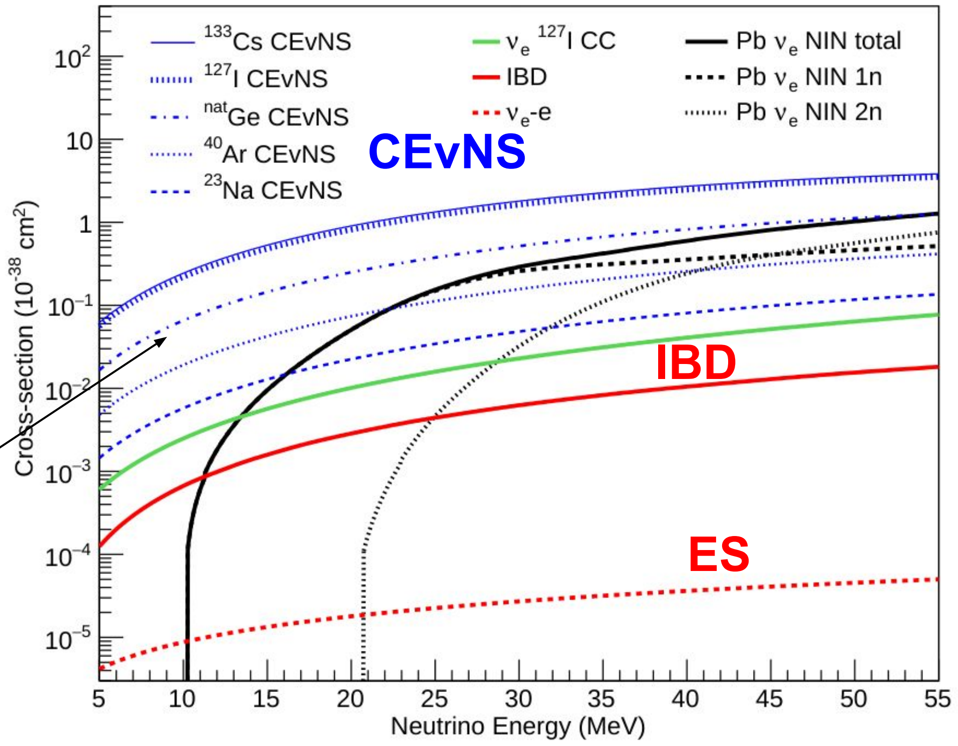
CEvNS for lowest-energy neutrinos

Coherent Elastic Neutrino Nucleus Scattering (CEvNS)



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

- **Largest cross section**
- No threshold
- Passive, small detectors (easy to deploy)



COHERENT

Neutrinos for non-proliferation

A neutrino detector offers a continuous, non-intrusive means of monitoring.

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

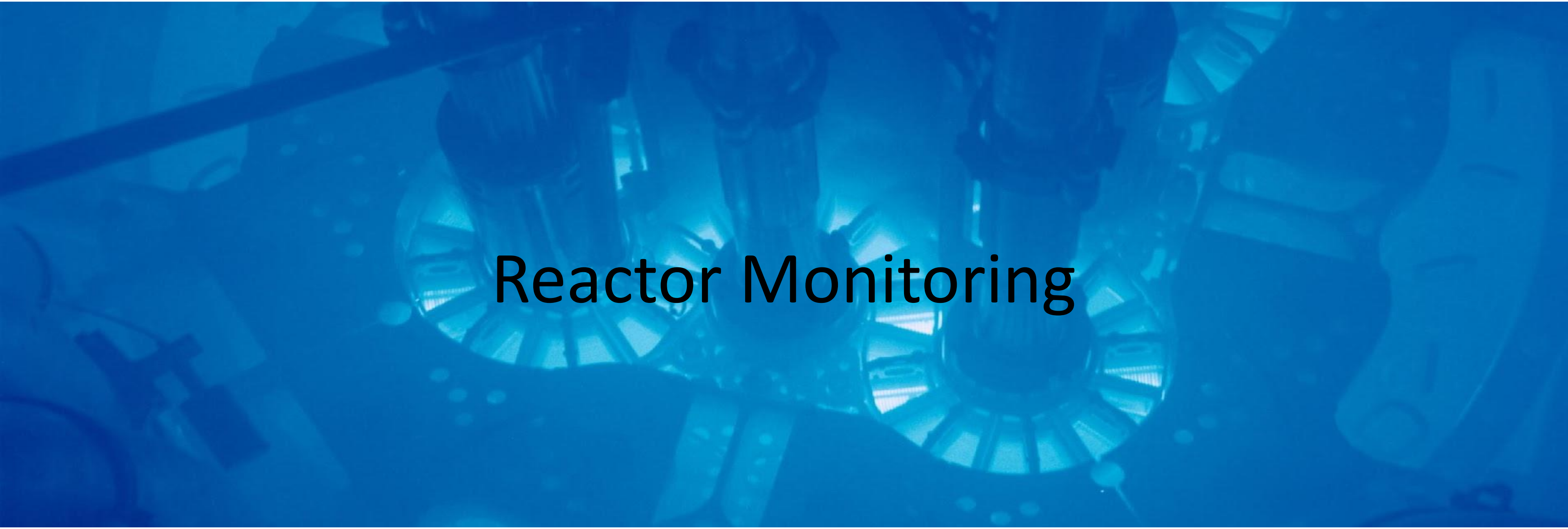
- reactor on/off cycle and power
- reactor distance (ranging)
- reactor direction (pointing)
- core composition and burn-up
- diversion of 1 SQ fissile material
- antineutrinos from nuclear waste

Antineutrinos for Monitoring

- Antineutrinos emitted through beta decay of fission fragments.
- On average 6 antineutrinos per fission in a reactor, $O(10^{20})$ per second per GW_{th} power output.
- Time-dependent antineutrino emission bears signature of the reactor power and core composition.
- Detectable antineutrino spectrum has additional distance and direction information.
- Reactor antineutrinos detectable via IBD, ES and CEνNS.
- Detecting IBD with neutron tagging is the most tried and tested method.
- Potential for continuous monitoring and additional information compared to traditional monitoring.

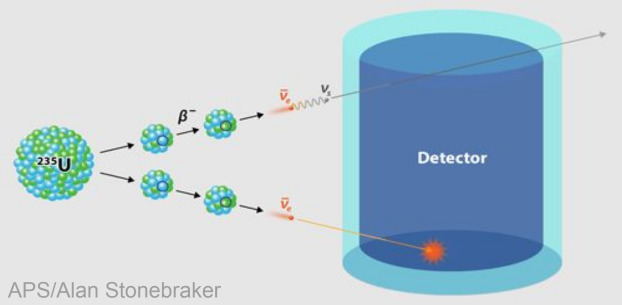
Questions?

Reactor Monitoring

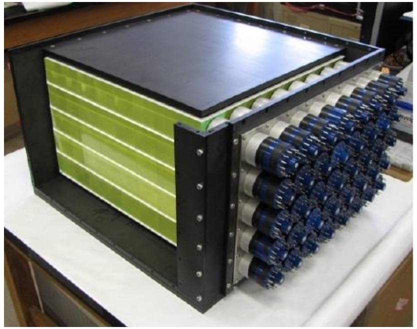


Reactor monitoring applications

Far-field monitoring (> ~10 km).



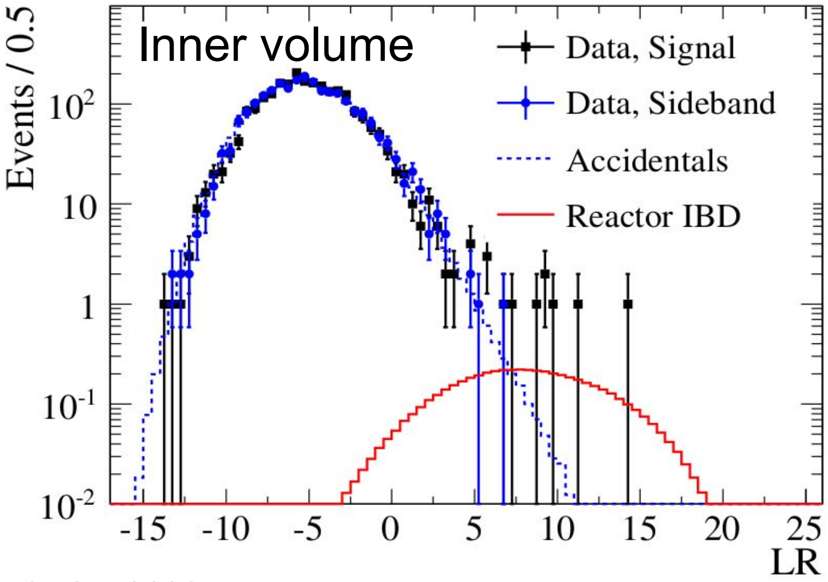
Near-field monitoring (< ~50 m)



Mid-field monitoring
O(1) km

Water-based far-field monitoring

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



SNO+, 2023

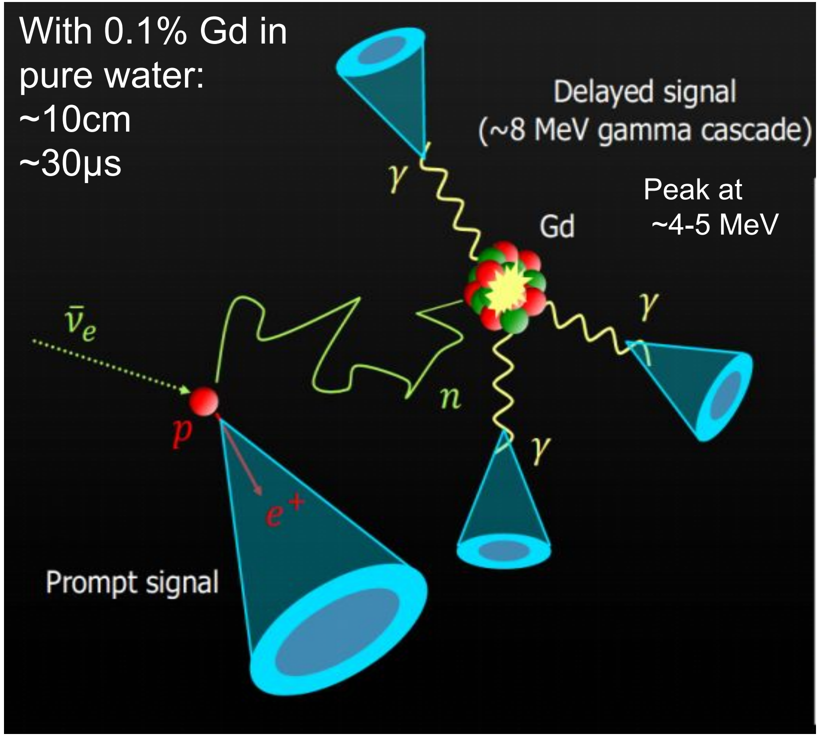
First antineutrinos have been seen in a pure water Cherenkov detector by SNO+ from reactors > 240 km away (composite reactor signal).

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

Neutron tagging with Gd

The positron is detected by a prompt Cherenkov cone and the neutron gives a delayed signal when it captures on a nucleus in the detector medium.



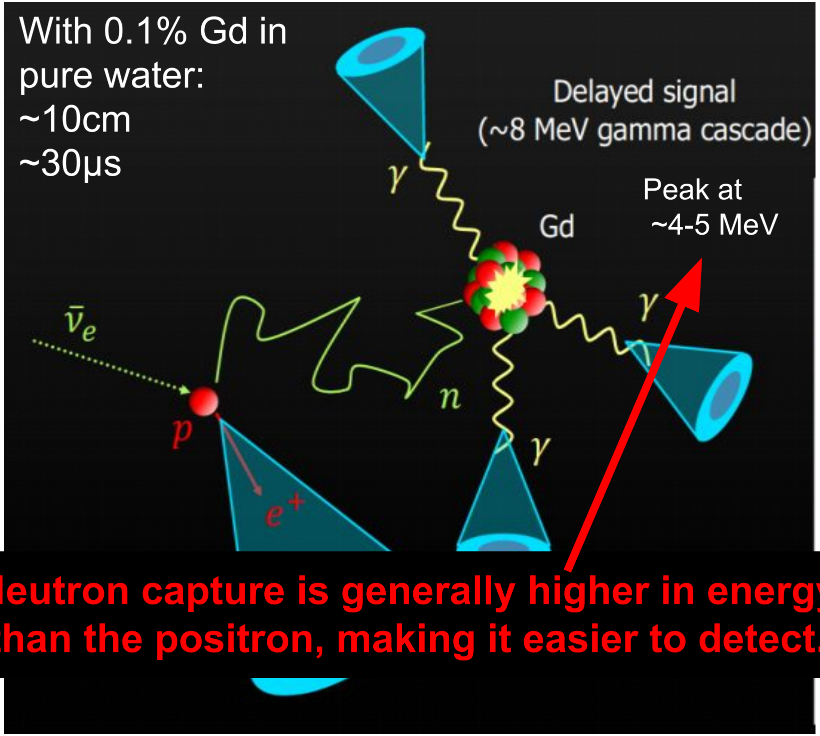
	H_2O	Gd-H_2O
σ	~0.3 b	~ 49,000 b
τ	~200 μsec	~30 μsec
E	2.2 MeV gamma	~8 MeV gamma cascade

Neutron-capture on Gd > 90% with 0.1% Gd
Demonstrated in EGADS and deployed in Super-K and ANNIE.

With gadolinium (Gd) loading, we can see the IBD as a pair of interactions.

Neutron tagging with Gd

The positron is detected by a prompt Cherenkov cone and the neutron gives a delayed signal when it captures on a nucleus in the detector medium.



Neutron capture is generally higher in energy than the positron, making it easier to detect.

	H_2O	Gd-H_2O
σ	~0.3 b	~ 49,000 b
τ	~200 μsec	~30 μsec
E	2.2 MeV gamma	~8 MeV gamma cascade

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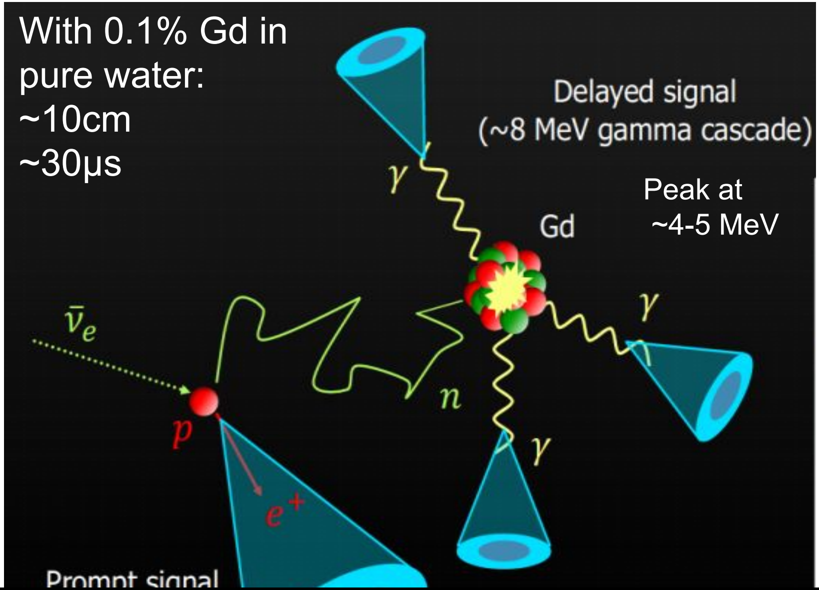


	H_2O	Gd-H_2O
σ	~0.3 b	~ 49,000 b
τ	~200 μsec	~30 μsec
E	2.2 MeV gamma	~8 MeV gamma cascade

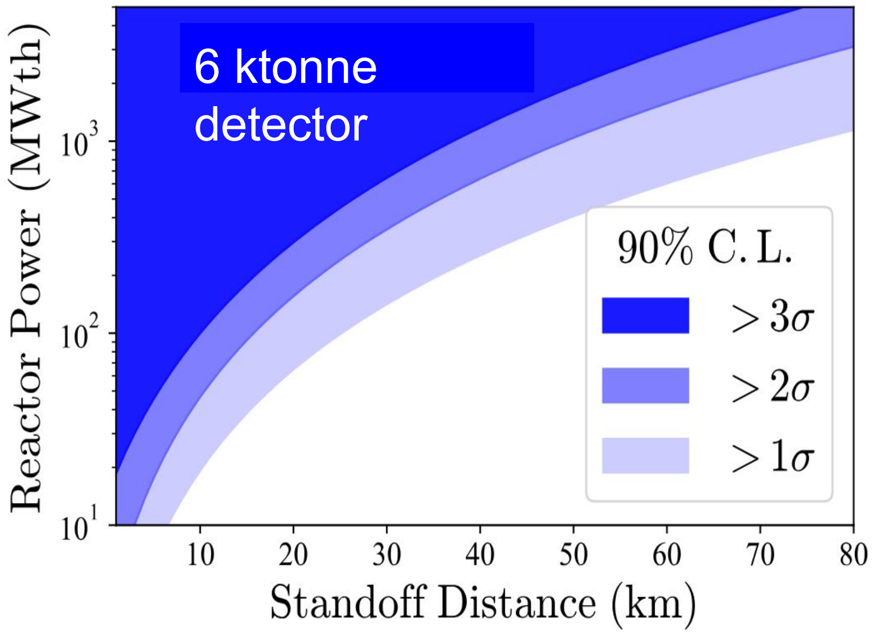
Neutron tagging of IBD positrons gives a *coincident* signal pair, which helps reject the majority of the reactor antineutrino backgrounds.

With gadolinium (Gd) loading, we can see the IBD as a pair of interactions.

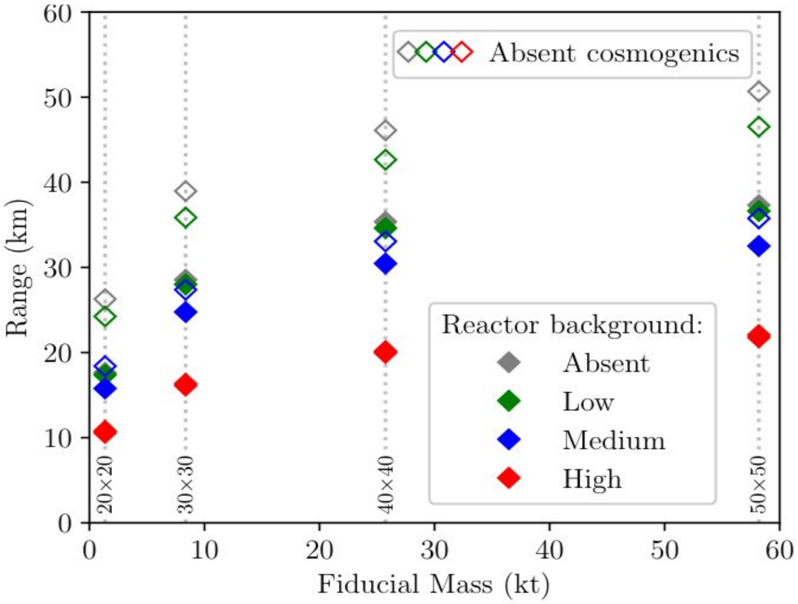
Neutron-capture on Gd > 90% with 0.1% Gd
Demonstrated in EGADS and deployed in Super-K and ANNIE.

Gd-water Cherenkov monitoring potential

Tagging the IBD neutron offers the best chance of resolving a single reactor.



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

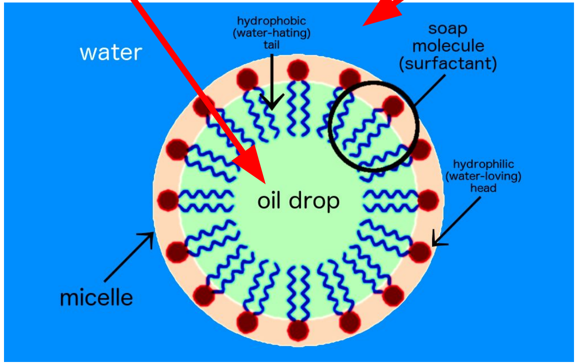


Scalability for true far-field monitoring limited by position resolution
Li et al, 2022

WbLS - best of water and scintillator

Scintillation Detectors:
✅ High light yield
✅ Low energy threshold
✅ Good energy and position resolutions
🚫 Limited in size by absorption and cost
🚫 No directionality

Cherenkov Detectors:
✅ Directional information
✅ Can be very large (low absorption)
✅ Particle ID at high energies
🚫 No access to physics below the Cherenkov threshold
🚫 Low light yield



Courtesy of Zara Bagdasarian U.C. Berkeley

Water-based liquid scintillator (WbLS)

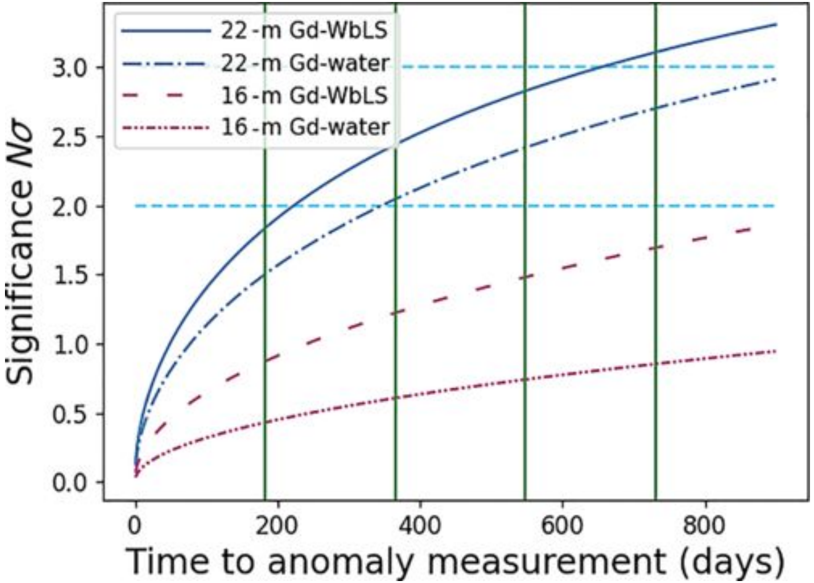
Deployment of WbLS already achieved in ANNIE.

WbLS cocktails are being refined for the best balance of Cherenkov and scintillation light.

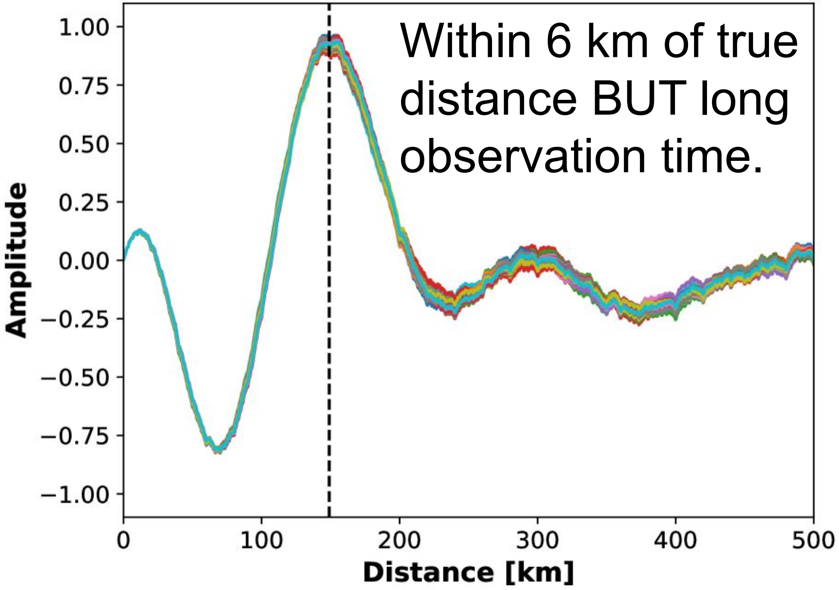
Gd-WbLS is under development.

Gd-WbLS monitoring potential

Additional light from 1% LS improves position and energy resolution.



Sensitivity to single reactor complex ~200 km away: **minimum requirement Gd-doped water-based liquid scintillator** ([Kneale, Wilson et al, 2023])

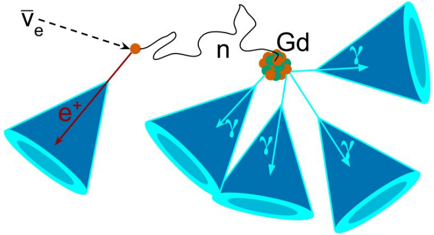


Ranging using Gd-doped WbLS: timely ranging limited by detector performance ([Wilson et al, 2024])

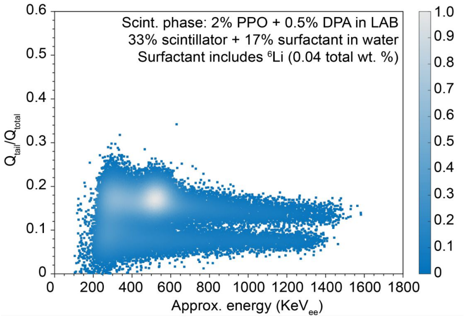
Maximise potential of WbLS

WbLS wishlist for single-reactor sensitivity with long-range monitoring:

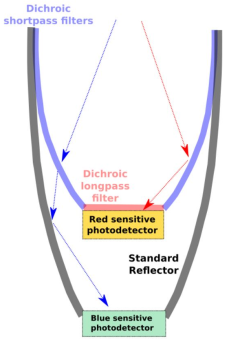
- Gd or Li-doping
- Pulse shape discrimination?
- Cherenkov/scintillation separation
- Tailored reconstruction/analysis

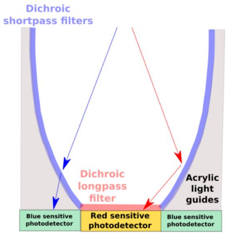


Gd/Li doping



Pulse-shape discrimination





Photon sorting + fast photosensors = Cherenkov/scintillation separation

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.

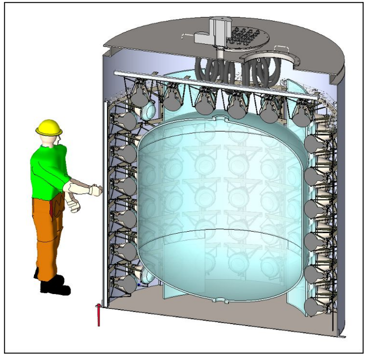
- Very low-background environment.
- Advanced photosensor technology.
- Novel fill materials e.g. water-based liquid scintillator (WbLS).

Final construction phase imminent.
Planning underway for BUTTON ~1 ktonne.

Hybrid detector for far-field monitoring

EOS

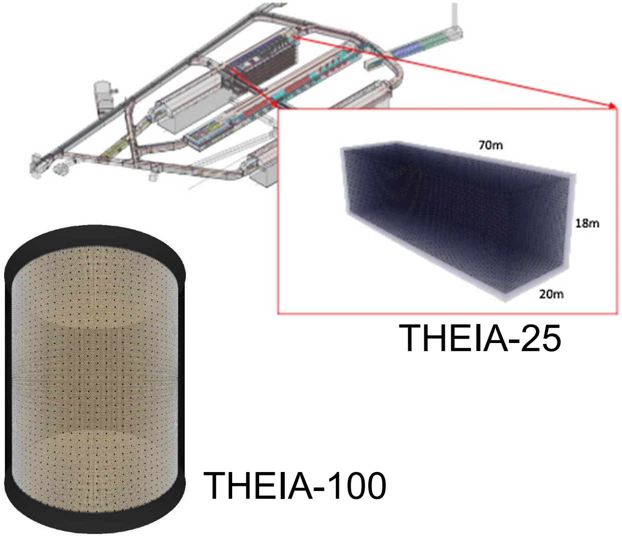
- 20 tonne (4-tonne ID)
- WbLS testbed
- Commissioning now!



Demonstration of:

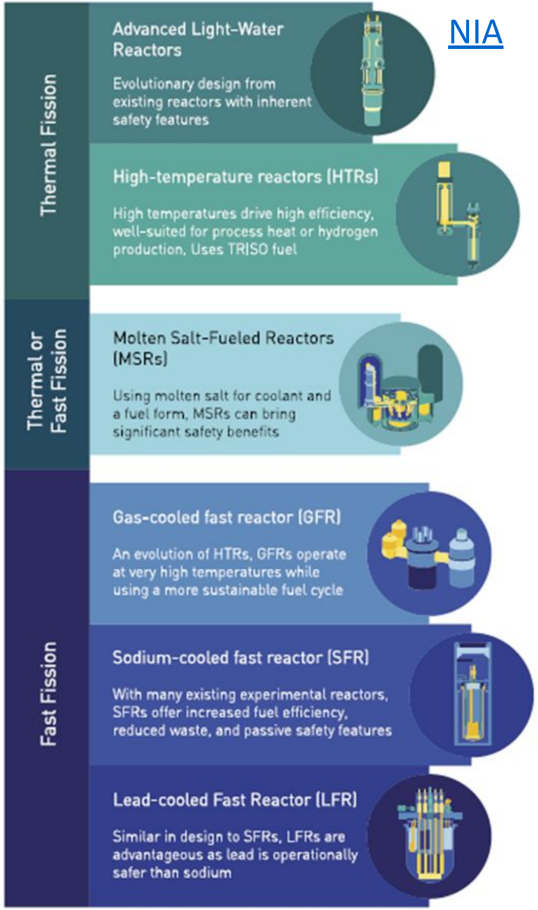
- Spectral sorting and ps photodetection for Cherenkov-scintillation separation.
- Direction reconstruction.

THEIA



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

Near-field reactor monitoring



NIA

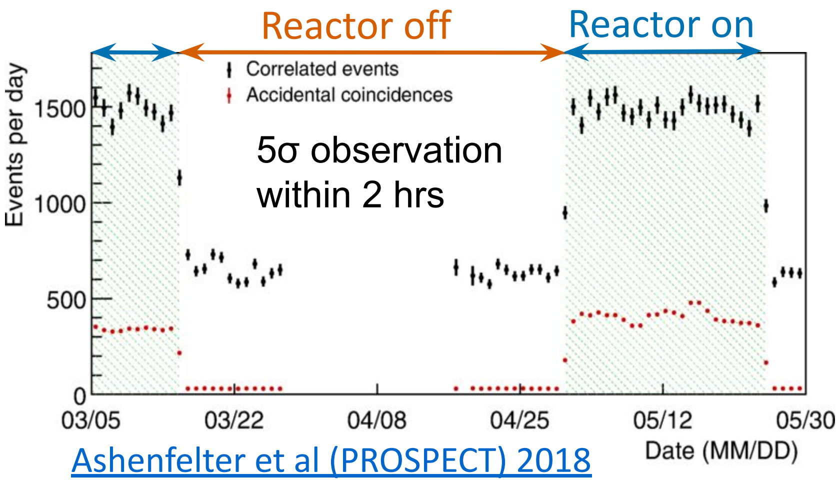
Near-field neutrino monitor can address new challenges of advanced reactor types and smaller sizes:

- Fuel accountancy difficult e.g. fuel pebbles.
- Fuel can have different irradiation histories.
- Continuous loading.
- Online reprocessing.
- Higher enrichment.
- Small modular reactors.

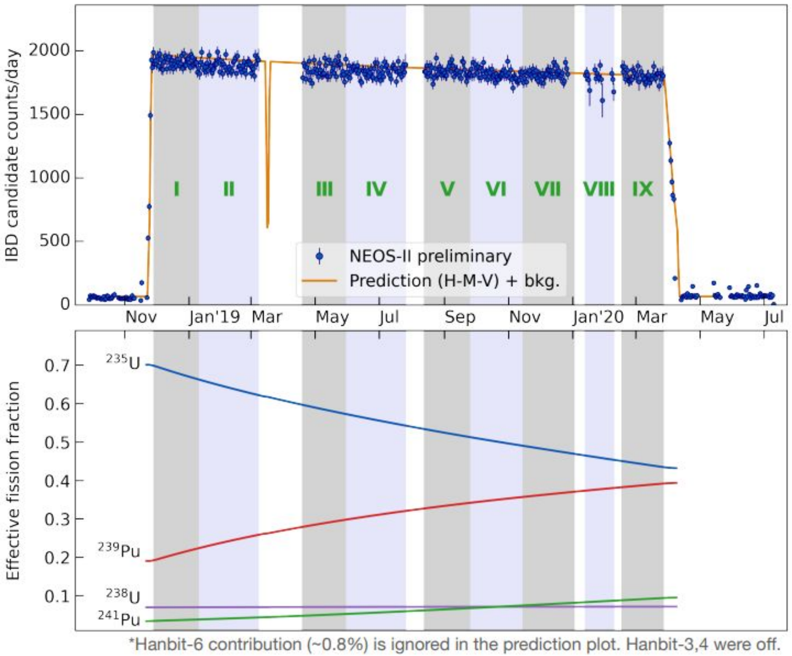
Need easy to install/move or mobile detectors: liquid or plastic scintillator.

Current very near-field capabilities

Reactor on/off cycle and core burnup



[Ashenfelter et al (PROSPECT) 2018]



PROSPECT

Segmented 4-tonne ^{6}Li-doped LS

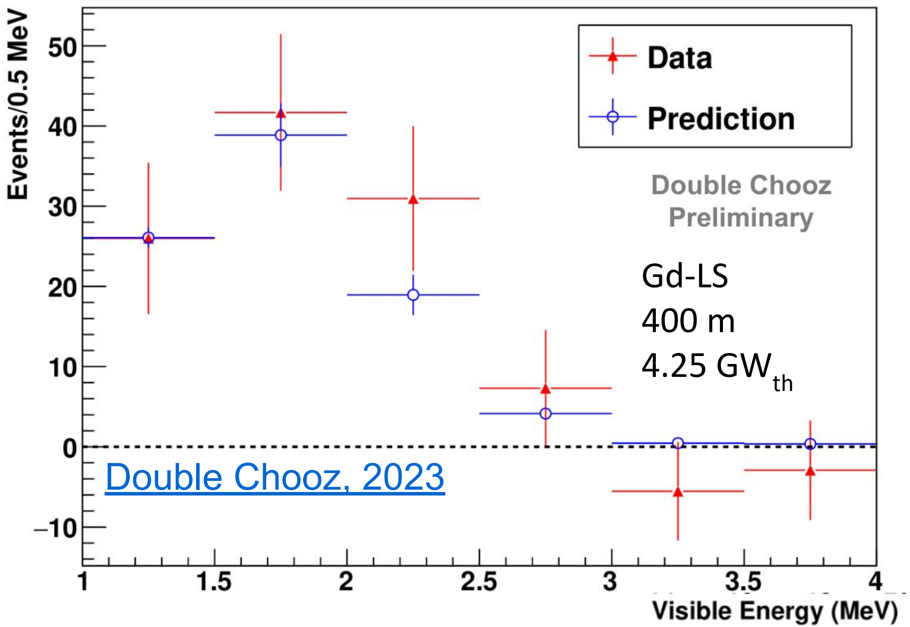
7-9 m from 85 MW HFIR core

[NEOS-II] Gd-LS

23.7 m from 2.8 GW Hanbit-5 core

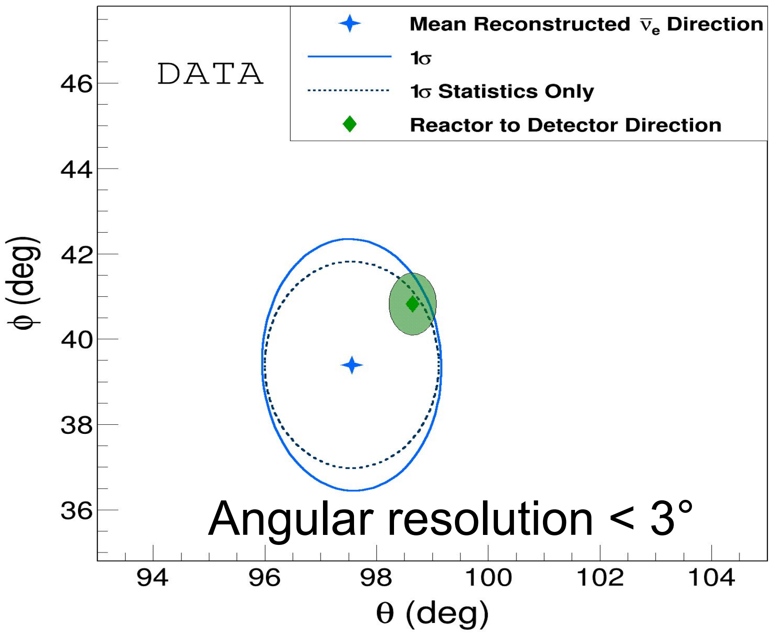
Current very-near-field capabilities

Residual antineutrinos



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

Reactor pointing

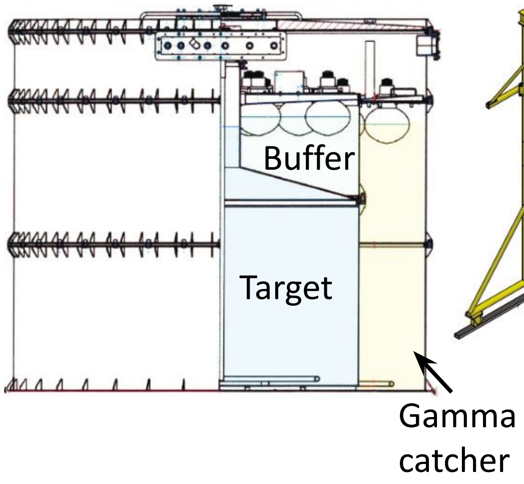


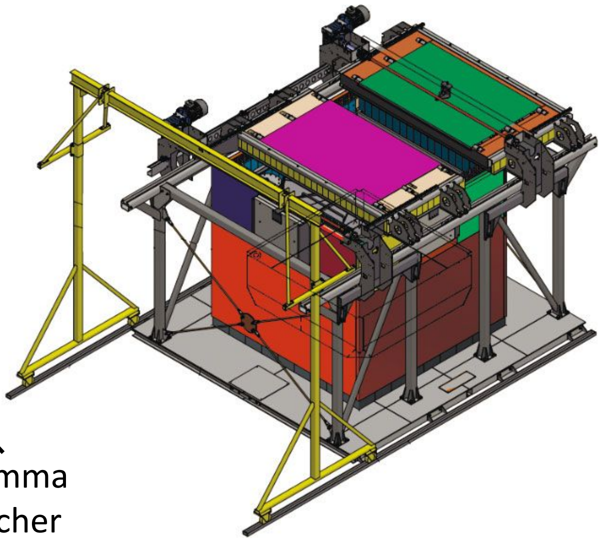
Andriamirado et al (PROSPECT), 2024

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

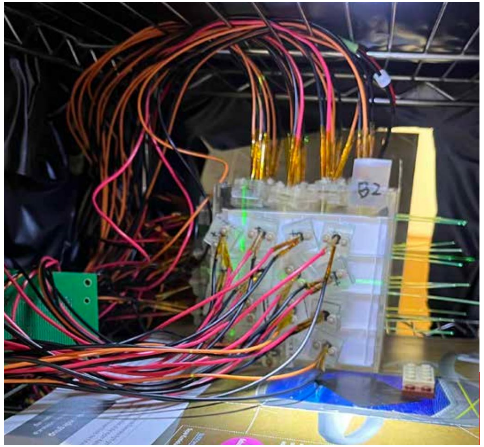


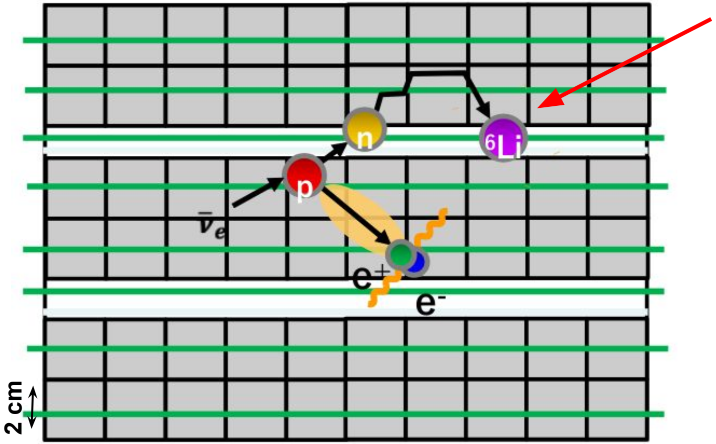


- Simple design.
- Active and passive shielding.
- Easy mounting.
- No need for daily maintenance.
- Remote control of all systems of the detector.

^{6}Li-doped plastic scintillator monitor

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





Li preferred as its single gamma is easier to distinguish from the back-to-back gammas from positron/electron annihilation than the Gd gamma cascade.

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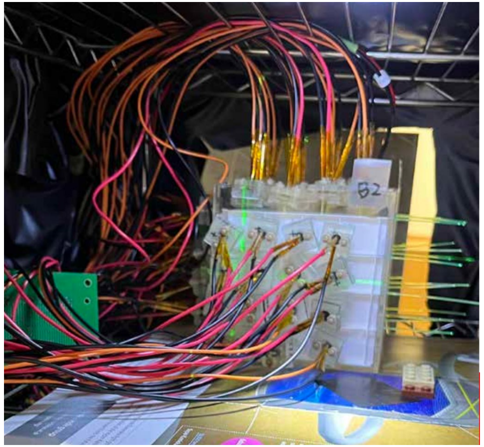
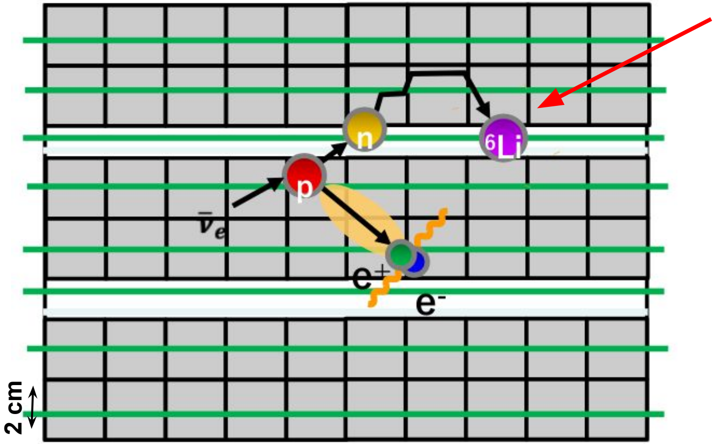


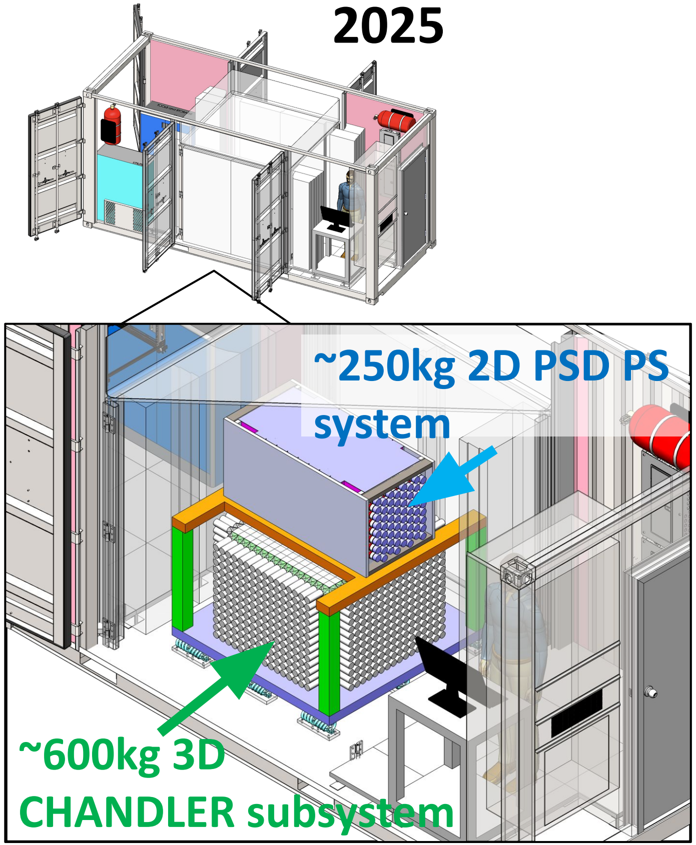


Li preferred as its single gamma is easier to distinguish from the back-to-back gammas from positron/electron annihilation than the Gd gamma cascade.

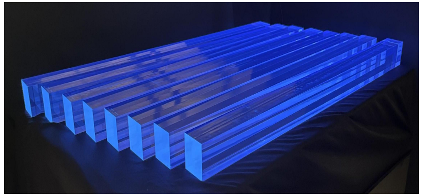
Prototype measured backgrounds 3 m from core at 20 MW JRR-3 research reactor in Japan (lower end of the range of power of SMRs).
Next phase: new location and more shielding.

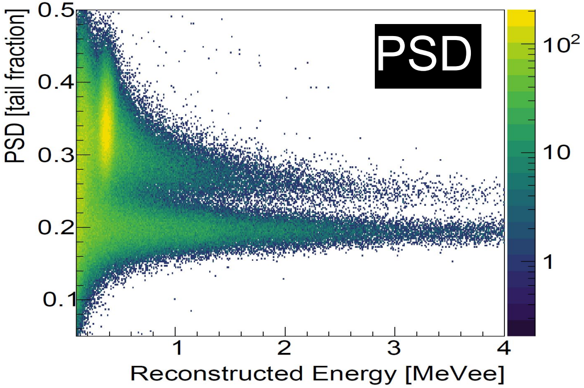
Mobile antineutrino detector

MAD - deployment in 2025

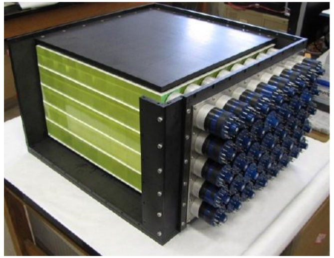


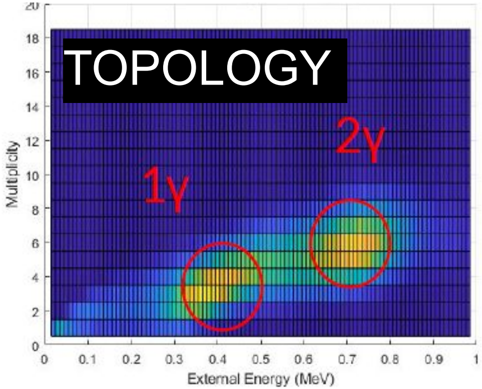
2D ^{6}Li-doped PS with pulse-shape discrimination





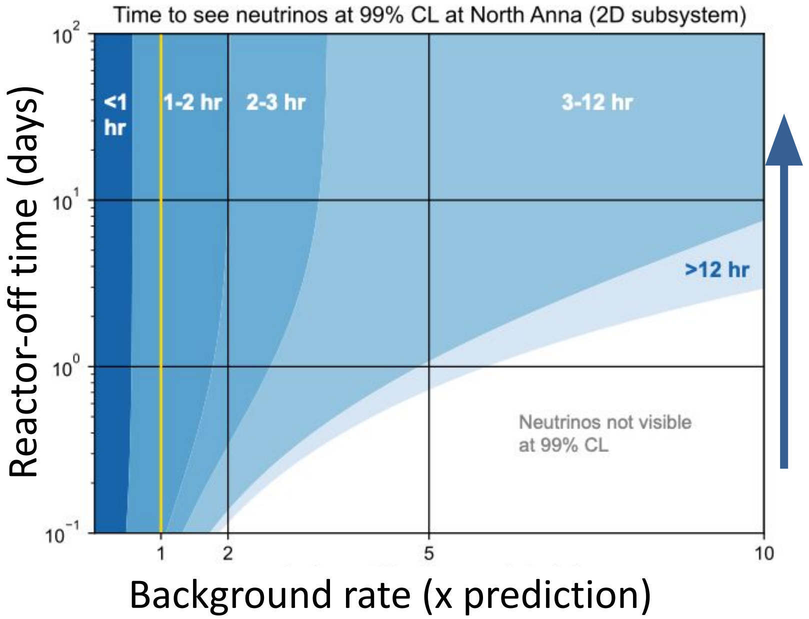
3D ^{6}LiZnS & WLS plastic (CHANDLER)



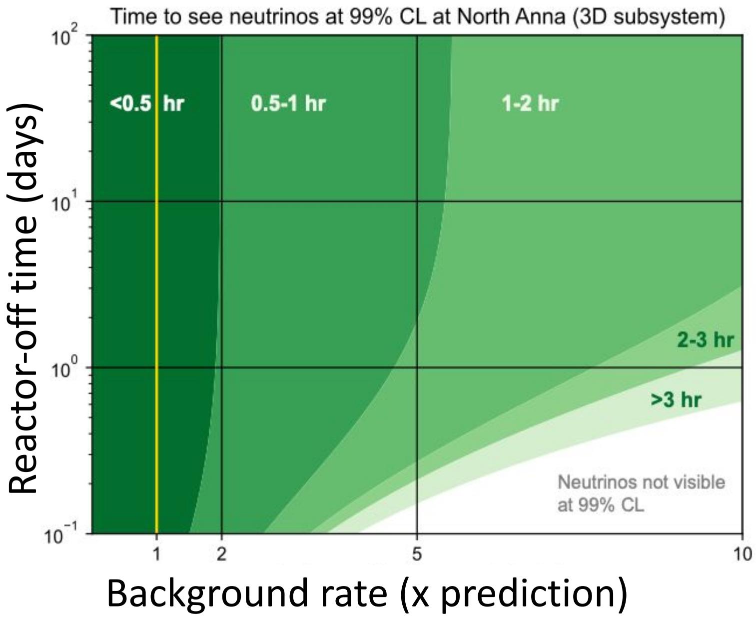


Mobile antineutrino detector

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



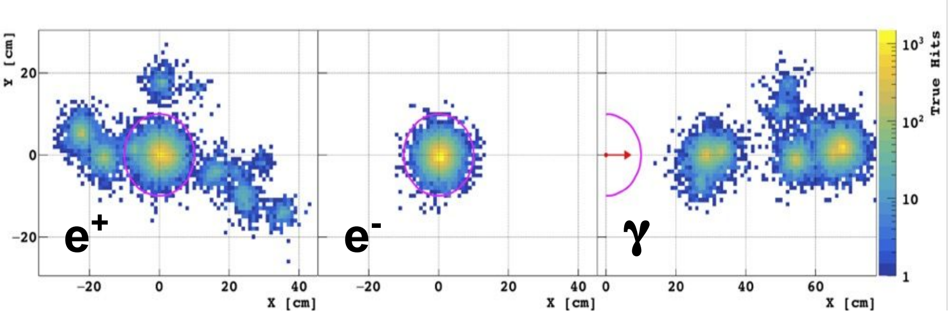
2D ^{6}Li-doped PSD PS system



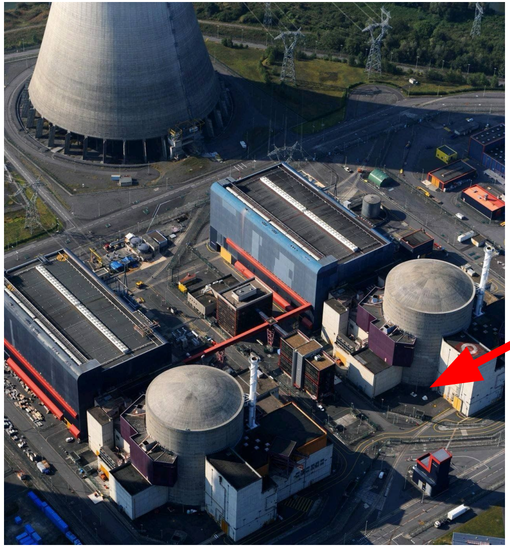
3D ^{6}LiZnS & WLS PS system

Opaque LS near-field monitor

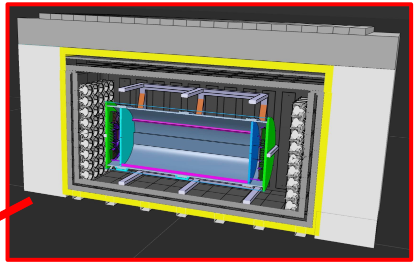
CLOUD near-field detector at Chooz with 5-10 tonne LiquidO (LiquidO Consortium 2021) opaque scintillator target.



Positron distinguishable from point-like electrons, protons and alphas in LiquidO.



~35 m from core
~3 m overburden



> 200 pe/MeV
sub-ns timing

CLOUD-I addresses primary goal of AntiMatter-OTech project to develop non-intrusive reactor monitoring.

Future mid-field monitor?

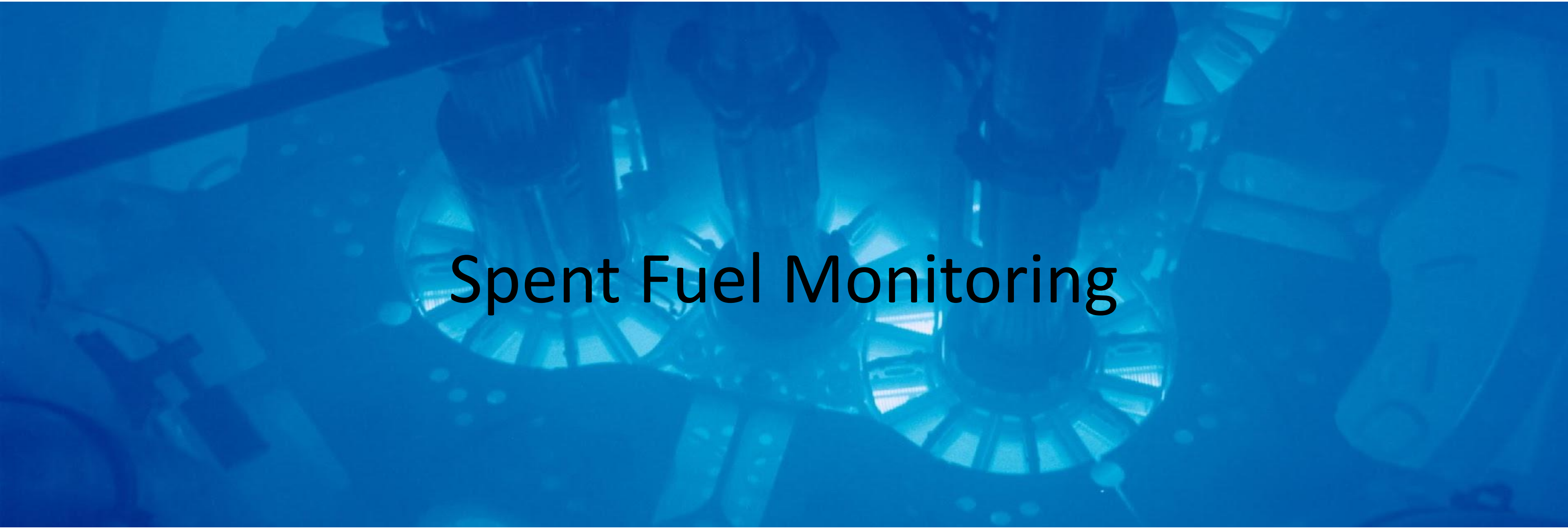
SuperChooz includes a mid-field 10 ktonne detector at ~1 km from core - potential for just-outside-the-fence monitoring.

10 million reactor antineutrino interactions per year.

Reactor Monitoring

- Water-based detectors for long-range monitoring are limited by energy threshold (currently ~3.5 MeV), time to construct, lack of suitable sites.
- Liquid scintillator (LS) detectors can be small and mobile and have powerful pulse-shape discrimination (PSD) but are highly flammable.
- Plastic scintillator loses some of the PSD of LS but detectors are mobile, easy to deploy and not flammable.
- LiquidO has particle ID, 4D time-space resolution for IBD coincidence and potential SuperChooz detector could demonstrate mid-field monitoring.
- Most promising application is for advanced reactors - built into the design or a mobile detector.

Questions?



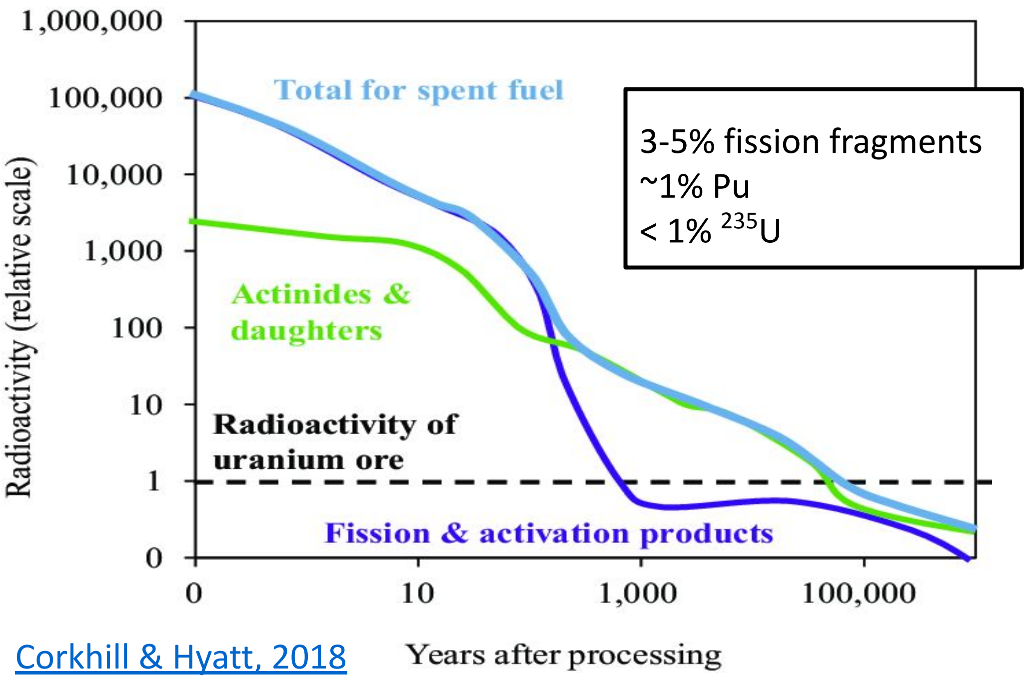
Spent Fuel Monitoring

Spent nuclear fuel monitoring

Spent nuclear fuel (SNF) is stored in interim facilities at nuclear power plants, and finally in geological repositories - decades to centuries of active management.

Composition dependent on reactor type and properties e.g. thermal power, burnup, fuel enrichment.

Most problematic waste from nuclear reactors.

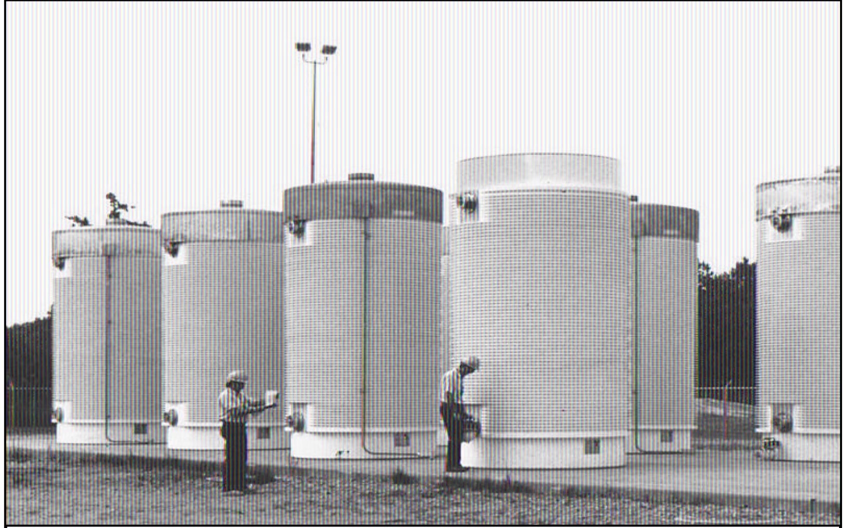


[Corkhill & Hyatt, 2018]

The problem with nuclear waste

Stored in Dry Casks at an interim nuclear storage facility.

- 1 dry cask = 15 tonnes of SNF.
- 32 PWR fuel assemblies (459 kg of U).
- 352 AGR fuel assemblies (0.0425 kg of U).



"Dry Storage of Spent Nuclear Fuel" by NRCgov is

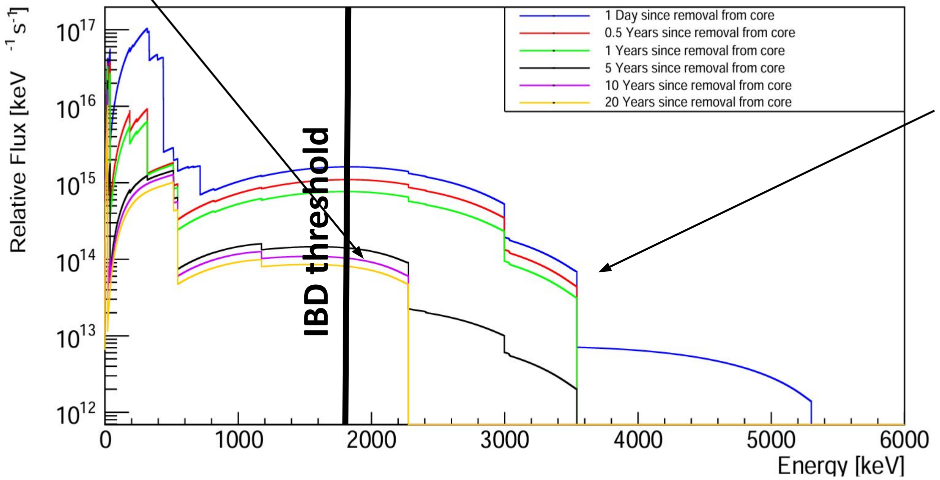
Many casks with different irradiation histories at a single site.

Current methods rely on neutron/gamma detection or visual surveillance. Measurements taken from within radiation shielding.

Neutrinos for spent nuclear fuel

Courtesy of Z. Leliwa, U. of Sheffield

Detectable antineutrinos above the IBD threshold are mainly emitted from the decay of ^{90}Y, especially after long cooling times.

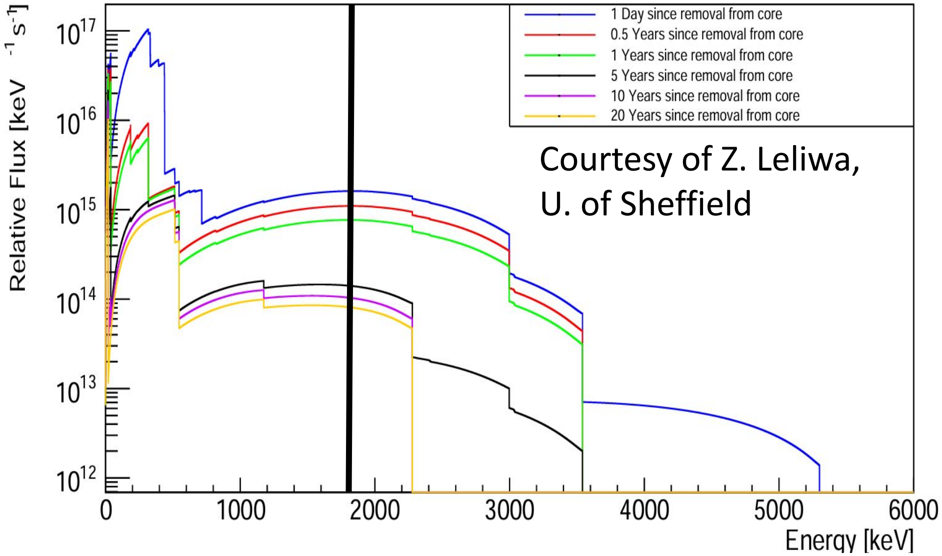


Isotopes emitting higher energy antineutrinos have shorter half lives.

Flux very low at high energies and long cooling times.

Antineutrino emission spectrum of one dry cask of SNF originating from the Hartlepool AGR, Z. Leliwa.

Neutrinos for spent nuclear fuel



Neutron and gamma detectors must be operated in high-radioactivity environment within radiation shielding.

A neutrino detector could perform:

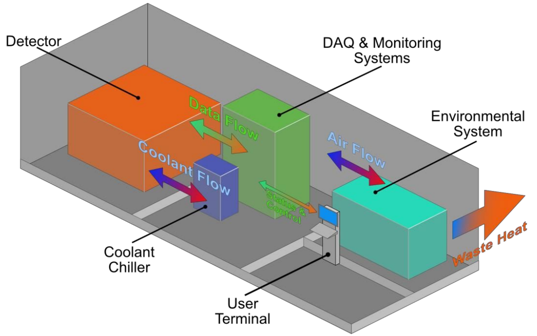
- cask-by-cask monitoring
- long-term monitoring
- detection of diversion of SQ Pu
- **remote monitoring from outside shielding**

Potential for observation of IBD from ^{90}Y (^{90}Sr decay chain)

1 SQ Pu results in 2 mol of ^{90}Sr.

Mobile spent nuclear fuel monitor

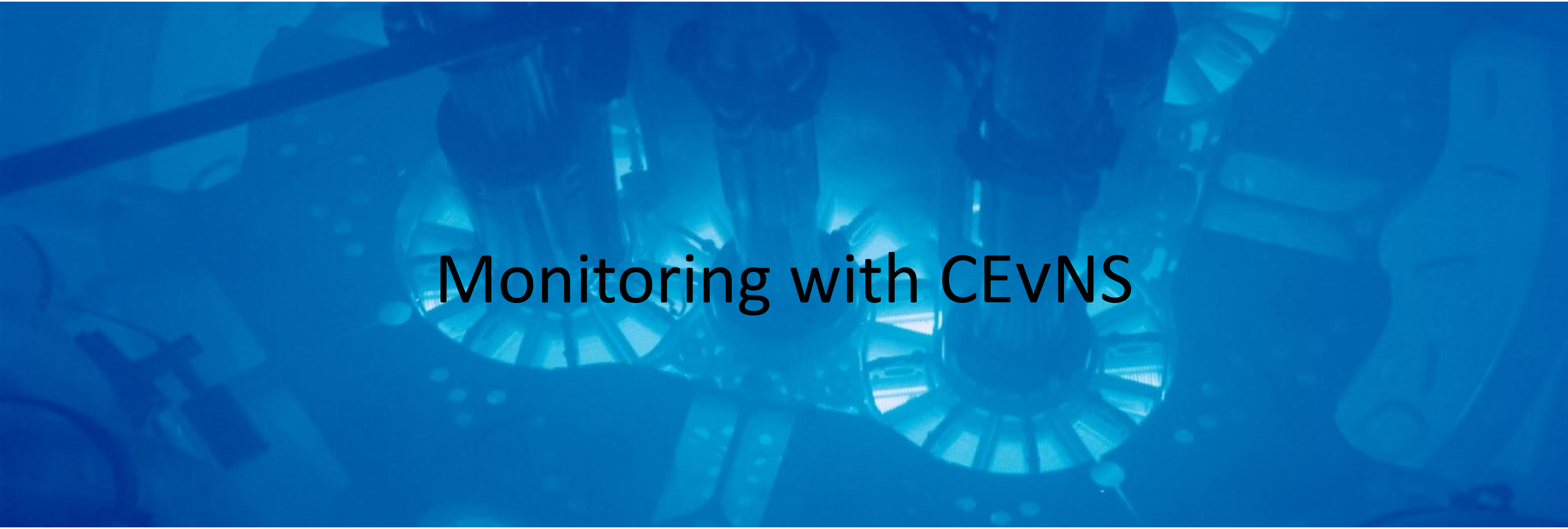
VIDARR is now running ~ 40 m from large store of spent nuclear fuel at Sellafield nuclear facility, UK



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

Positron annihilation + neutron capture coincident signal from IBD (^{90}Y decay).

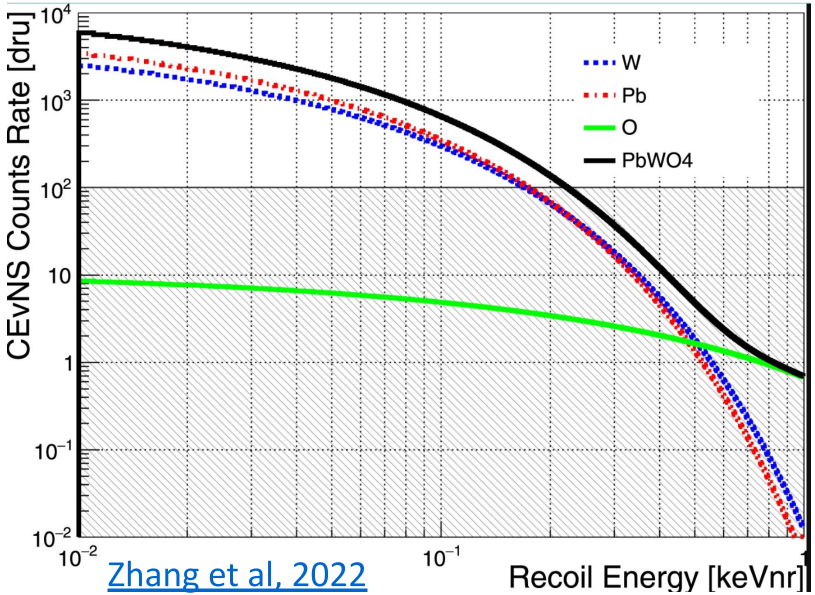
Expected ~10 antineutrino interactions/day (R. Mills NNL).



Monitoring with CEvNS

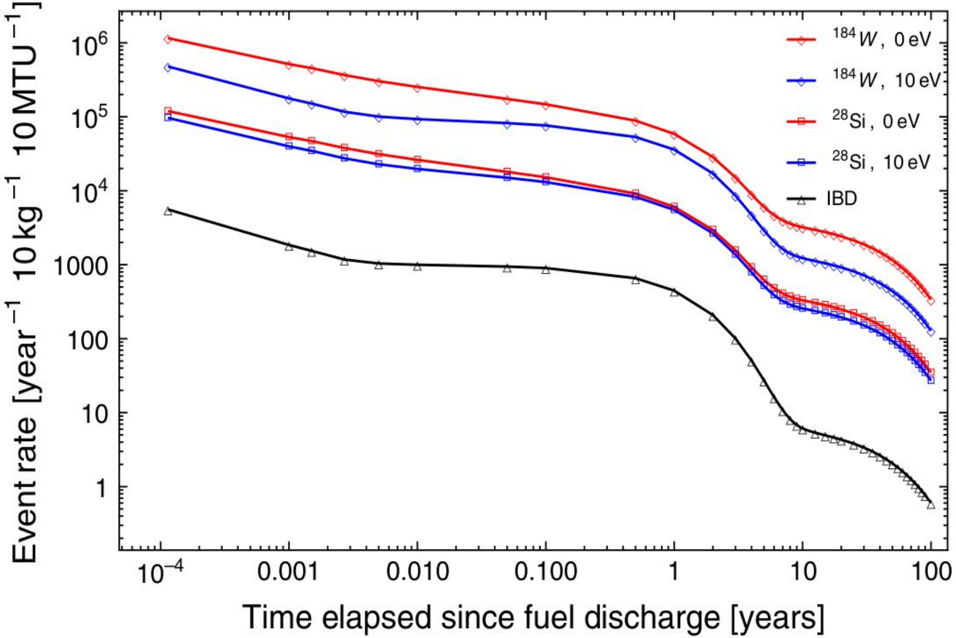
CEvNS for safeguarding

CEvNS rate in a detector 30 m from a 4.6 GW_{th} reactor core.



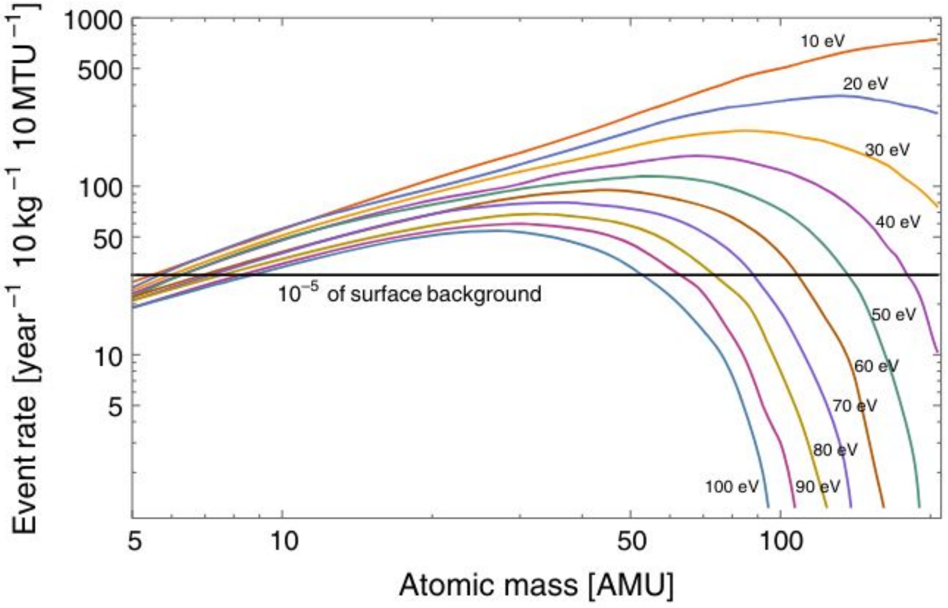
Zhang et al, 2022

CEvNS from spent nuclear fuel



Raesfeld, Huber 2022

CEvNS - choice of nucleus

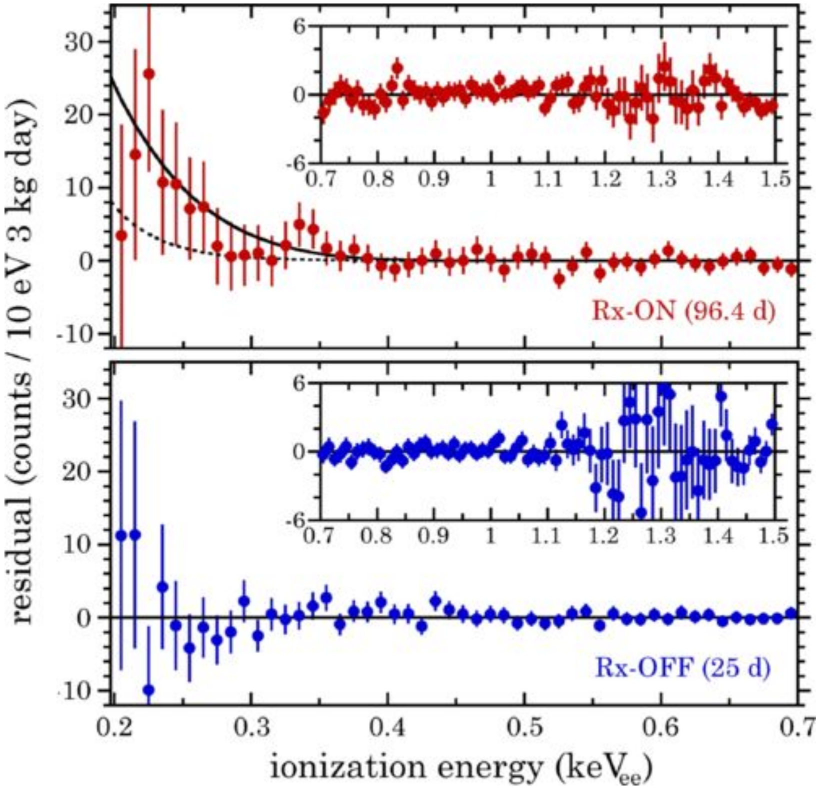


Raesfeld & Huber, 2022

CEvNS event rate depends on atomic mass and nuclear recoil threshold.

- High-mass isotopes have high event rates at low recoil thresholds
- Low mass isotopes perform best at high recoil thresholds.
- The higher the atomic mass, the more difficult to detect the nuclear recoil

CEvNS from reactor antineutrinos



Colaresi et al, 2022

- 96.4 day observation
- 3 kg ultralow noise Ge detector
- low 0.2 keV energy threshold
- compact shielding
- 8 m from Dresden-II 2.96 GW$_{th}$ core

- ~3.2σ preference for CEvNS from reactor fission

Many other projects at reactors and new technologies being explored.

Spent Fuel Monitoring & Monitoring with CEvNS

- Potential to monitor spent nuclear fuel through detection of IBD of antineutrinos from ^{90}Y.
- VIDARR currently operating at Sellafield nuclear waste site in the UK.
- IBD threshold cuts out most of the spectrum.
- Solution: combine with other technologies e.g. muon tomography and/or use a different interaction.

- CEvNS offers potential for monitoring reactor and spent nuclear fuel neutrinos at the lowest energies but CEvNS from reactor neutrinos has not been measured yet.

Questions?

Neutrinos for nuclear safeguards

Detector materials, technology and prototypes with potential to meet requirements already exist but more work is needed to demonstrate the technology and the application.

Strongest use cases are identified for advanced reactors:

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

What next?

Technology demonstration

Measurements of different reactors

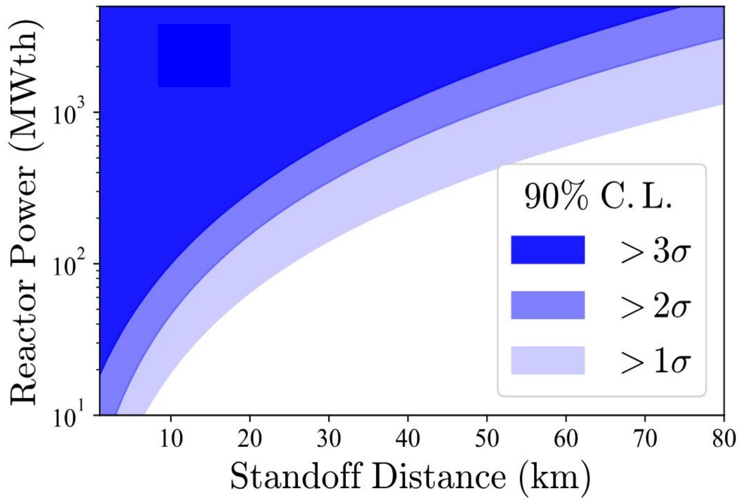
Measurements with different detectors (understand systematics)

Continue to develop use cases with end users

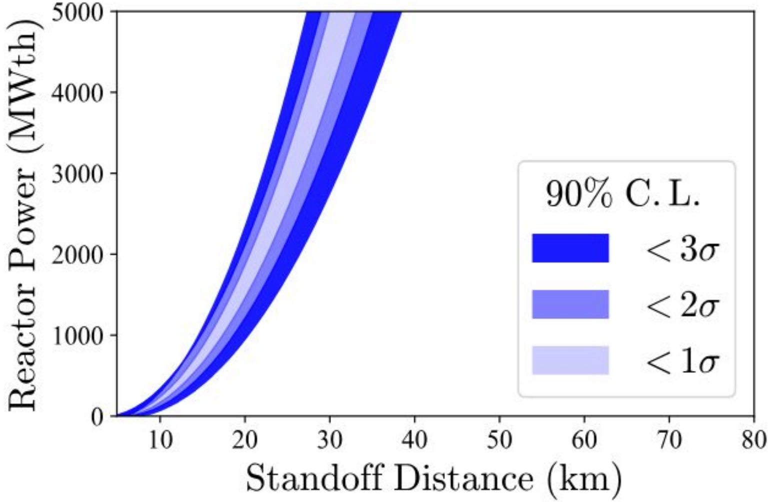
Backups and References

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.

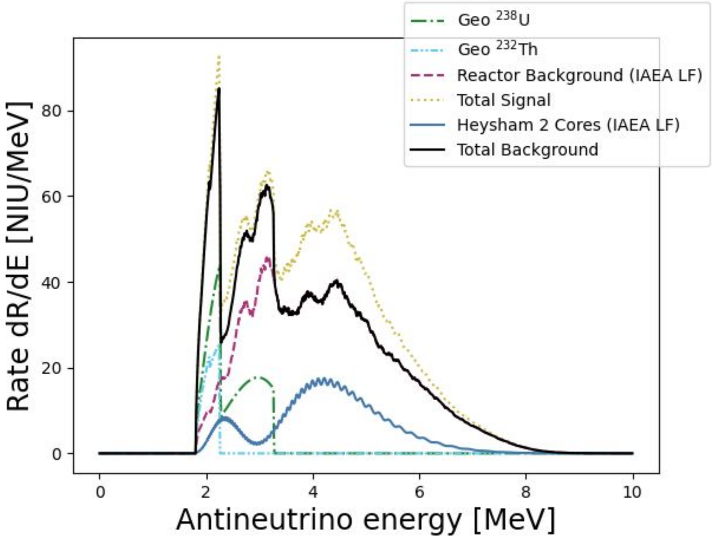


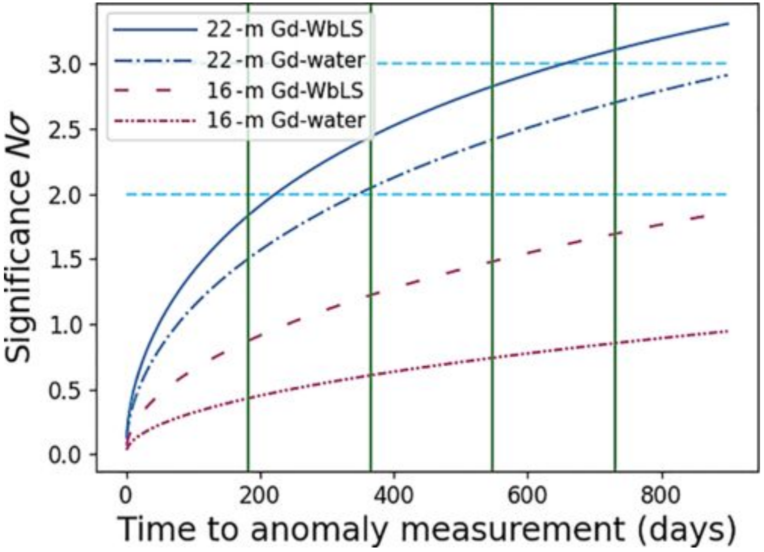
Confirmation of declared 3 GW_{th} reactor at 26 km standoff.

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.

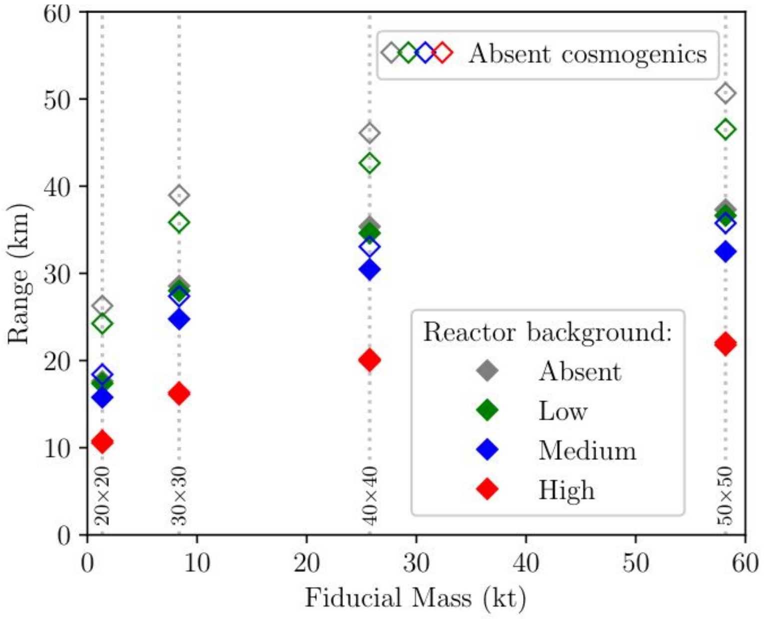




Sensitivity to single reactor complex up to 200 km away:
minimum requirement Gd-doped WbLS (Kneale, Wilson et al, 2023)

Water Cherenkov for far-field monitoring

Gd-doped detector with 40 % photocoverage



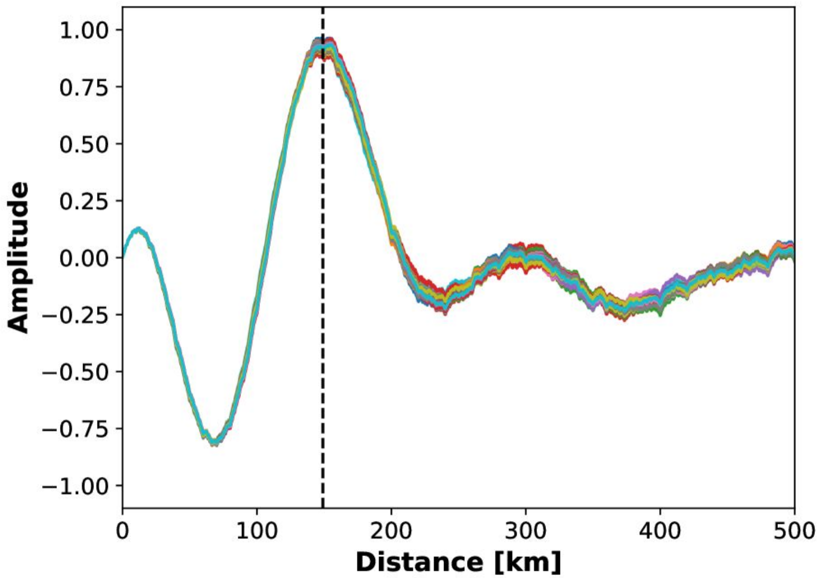
Different detector sizes evaluated for low, medium and high reactor background levels.

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)

Reactor CEvNS projects (not exhaustive!)

Experiment	Mass	Detector (energy threshold)	Reactor	Standoff
BULLKID	0.6 kg (Si) / 1.3 kg (Ge)	Si/Ge (100 eV)	/	/
CONNIE	8 g with new MCM	Si CCD (300 eV)	3.95 GW_{th} Angra 2	30 m
CONUS	4 4 kg	4 x PPC Ge (1 keV)	3.9 GW Brokdorf	17.1 m
Dresden-II	3 kg	PCGe (200 eV)	2.96 GW Dresden-II	8 m
MINER	10 g - 1.5 kg	Ge/Si (cryogenic) SuperCDMS iZips (100 eV)	Possibly at 85 MW HIFR	/
NEON	16.7 kg	NaI(Tl)	2.8GWth Hanbit	23.7m
NUCLEUS	10 g	$CaWO_4/Al_2O_3$ (cryogenic) (20 eV)	Chooz	Very Near Site
vGen	1.4 kg	HPGe PPC	3 GW_{th} Kalinin	11 m
RED-100	200 kg LXe (100 kg LAr)	LXe/LAr dual phase (1 keV)	3 GW_{th} Kalinin	18 m
Ricochet	38 g	Ge bolometers (55 eV)	ILL high-flux, Grenoble	
SBS		Scintillating bubble chamber	Possibly Lacuna Verde, Mexico	
TEXONO		p-PCGe/electro-cooled PPCS	2.9 GW_{th} KSNL	28 m