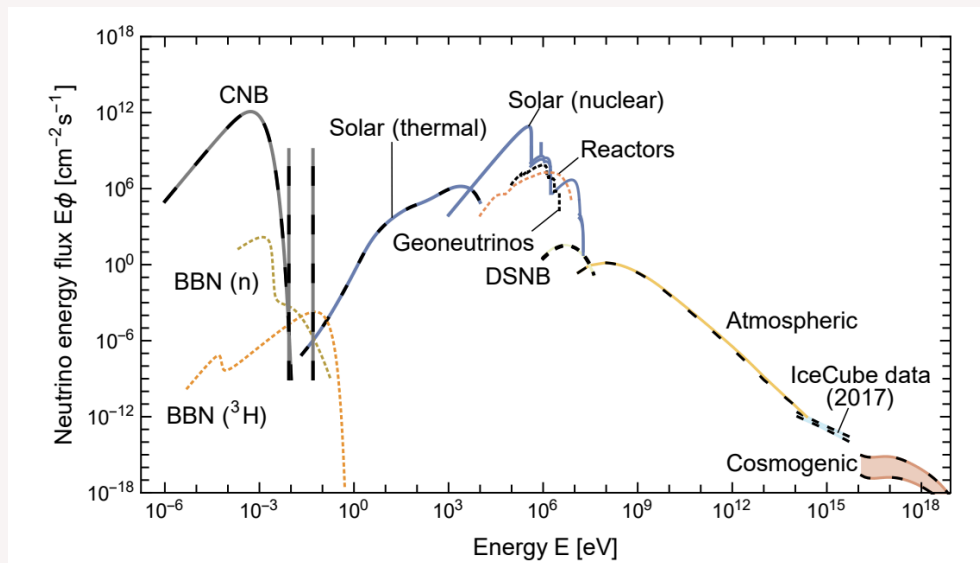


Neutrino ~~Theory~~ Applications & Quantum Sensing

Patrick Huber — Center for Neutrino Physics, Virginia Tech

MOTIVATION

The Grand Unified Neutrino Spectrum



Only half is measured — everything below ~ 1 MeV — the CNB, the thermal solar flux, most of the reactor flux — is inferred

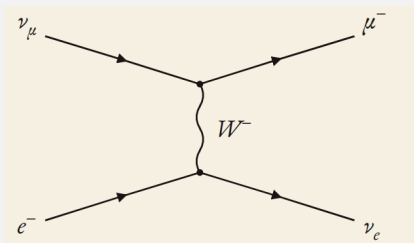
Not a flux problem — the fluxes are enormous; the obstacle is threshold

Source — Vitagliano, Tamborra & Raffelt, [arXiv:1910.11878](https://arxiv.org/abs/1910.11878)

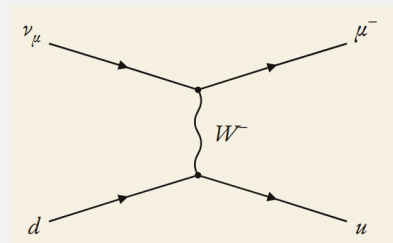
MOTIVATION

Neutrino Interactions in the Standard Model

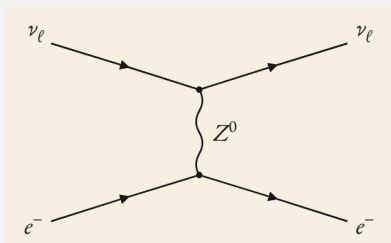
CHARGED CURRENT — LEPTONIC



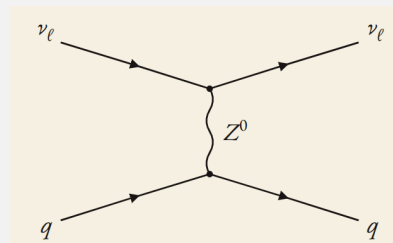
CHARGED CURRENT — QUARK



NEUTRAL CURRENT — ELECTRON



NEUTRAL CURRENT — QUARK



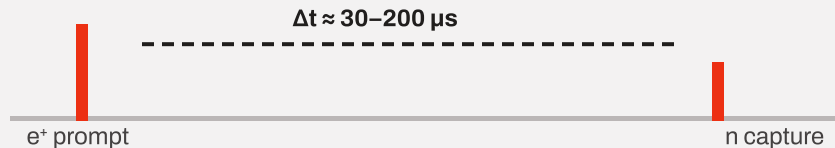
At low energy most charged-current channels are kinematically shut. Neutral current survives — plus bound-state channels such as induced tritium decay.

Inverse Beta Decay



A free proton is the target; the outgoing positron carries almost all the energy, so the visible energy tracks the neutrino spectrum directly.

DELAYED COINCIDENCE



Two flashes in a fixed time window: annihilation, then a 2.2 MeV γ on hydrogen or ~ 8 MeV on gadolinium. That pair is worth orders of magnitude in background rejection — it is why IBD detectors work at the surface.

$$E_{\text{thr}} = 1.806 \text{ MeV}$$

Set by kinematics: the neutron is 1.293 MeV heavier than the proton, and the positron costs another 0.511 MeV.

$$\sigma \approx 10^{-43} \text{ cm}^2$$

At a few MeV, growing roughly as E_ν^2 — small, but the coincidence makes it usable at tonne scale.

1956

This reaction was used to discover the neutrino, by Cowan and Reines at the Savannah River reactor.

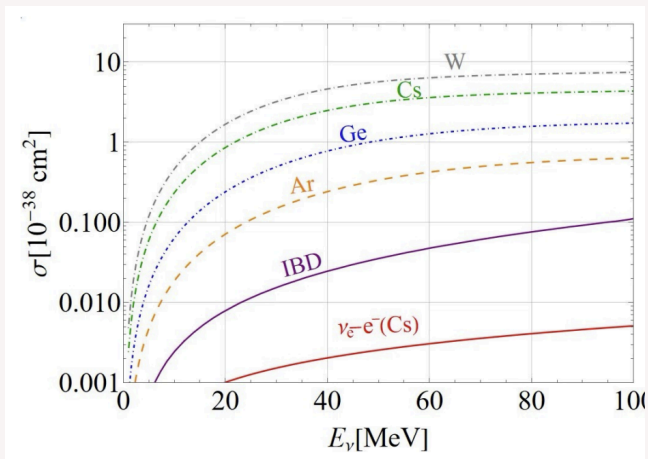
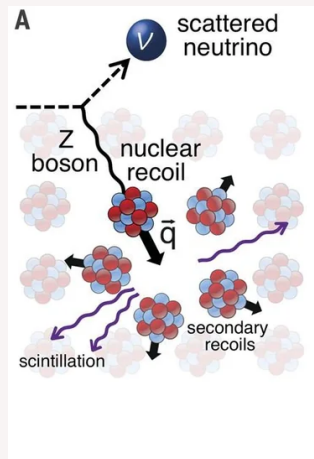
MOTIVATION

Coherent Elastic Neutrino–Nucleus Scattering

$$d\sigma/dT = (G_F^2 M/4\pi) \cdot Q_W^2 \cdot [1 - MT / 2E_\nu^2]$$

Point-like nucleus, no form factor.

$$Q_W = N - (1 - 4\sin^2\theta_W)Z \approx N$$

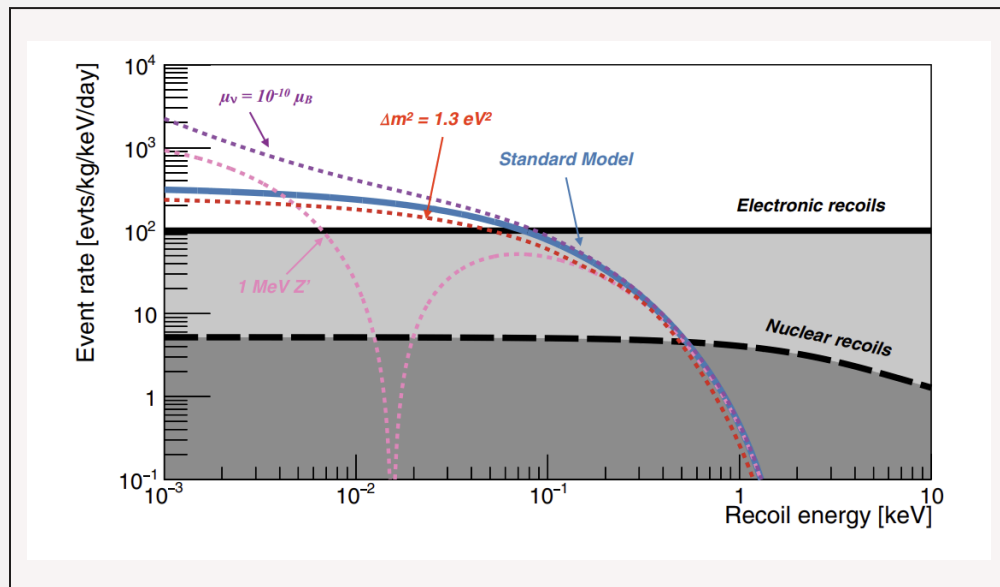


$\sigma \propto N^2$ — $1 - 4\sin^2\theta_W \approx 0.04$, so the protons drop out and the N neutrons add in phase

Orders of magnitude above IBD — at reactor energies the rate advantage is large

Paid for in threshold — the only observable is a recoil, cut off at $T_{\max} = 2E_\nu^2/M$

BSM at Low Energies



Magnetic moment

$\mu_V = 10^{-10} \mu_B$ lifts the rate steeply at the lowest recoils.

Sterile states

$\Delta m^2 = 1.3 \text{ eV}^2$ suppresses the rate below the Standard Model curve.

Light mediators

A 1 MeV Z' interferes with the SM amplitude and carves a dip into the spectrum.

Fermion portal to a dark sector

Neutrino mixing with a neutral dark state — CEvNS-like recoils, wrong spectrum.

All of it below $\sim 0.5 \text{ keV}$ — above that the scenarios converge on the Standard Model, so the discrimination lives entirely in the threshold region, on top of the electronic- and nuclear-recoil floors.

Figure: Billard, Johnston & Kavanagh, JCAP **11** (2018) 016, [arXiv:1805.01798](https://arxiv.org/abs/1805.01798) · portals: Berryman et al., [arXiv:2203.01955](https://arxiv.org/abs/2203.01955)

PART I B

Applications

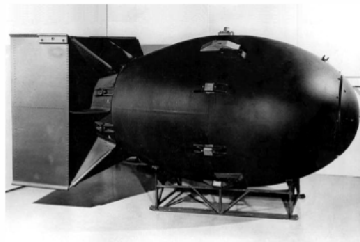
Nuclear security & neutrino science

Special Nuclear Materials

ISOTOPE	HALF-LIFE	NATURAL ABUNDANCE
^{235}U	700 million years	0.72%
^{233}U	160,000 years	0%
^{239}Pu	24,000 years	0%
^{241}Pu	14 years	0%

Only a handful of isotopes sustain a fast-neutron chain reaction — and essentially none of them exists in nature.

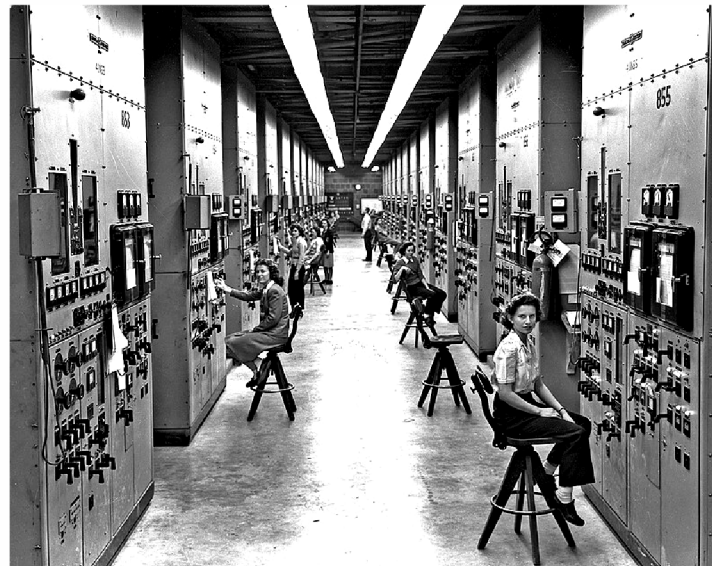
Obtaining the material is the major barrier to a weapon.



Enrichment Is an Industrial Undertaking



Gaseous diffusion — thousands of cascade stages over acres of plant, drawing power on the scale of a city



Electromagnetic separation — calutrons — slow, labour-intensive, but a working route to weapons-grade material

Why it matters for safeguards — both are large and visible; the diversion risk sits downstream, in the material

The Plutonium Route



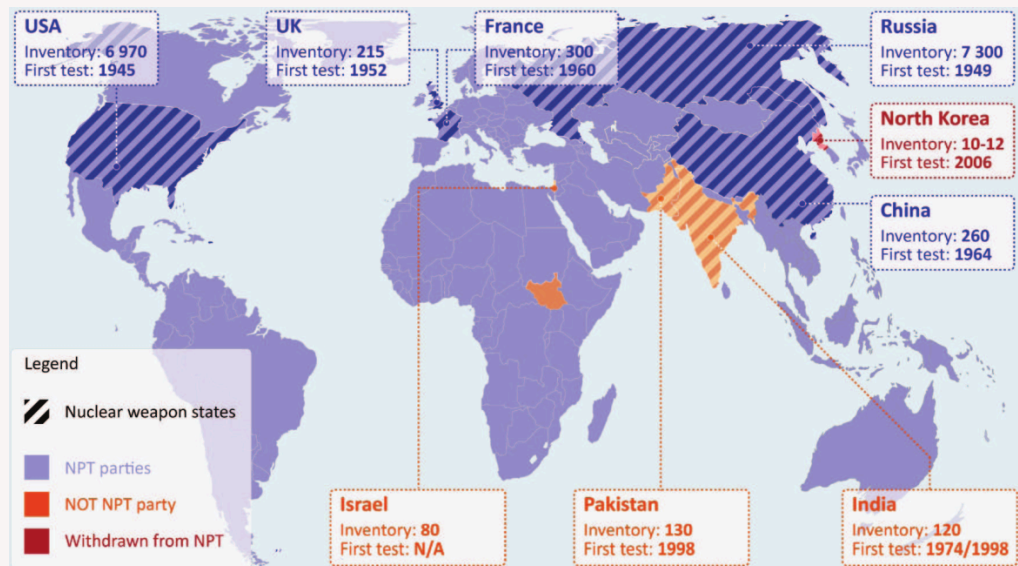
No enrichment required — breed ^{239}Pu in a reactor, then separate it chemically



The safeguards problem moves — from the enrichment plant to the reactor and the reprocessing line

Which is the use case for neutrinos — the only signal that leaves an operating core carrying its fuel composition

The Non-Proliferation Regime

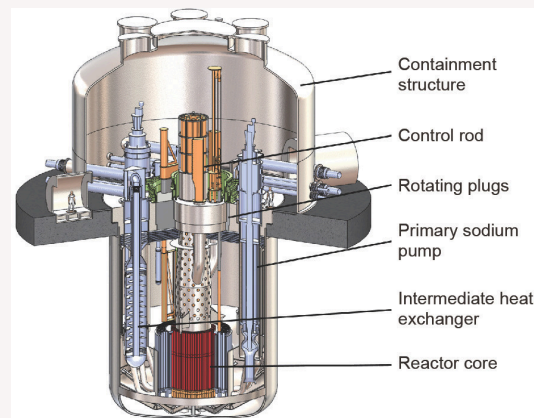
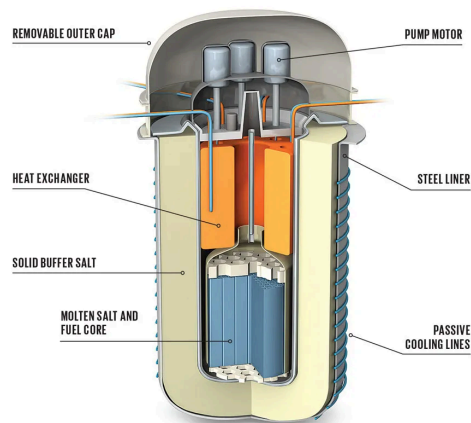
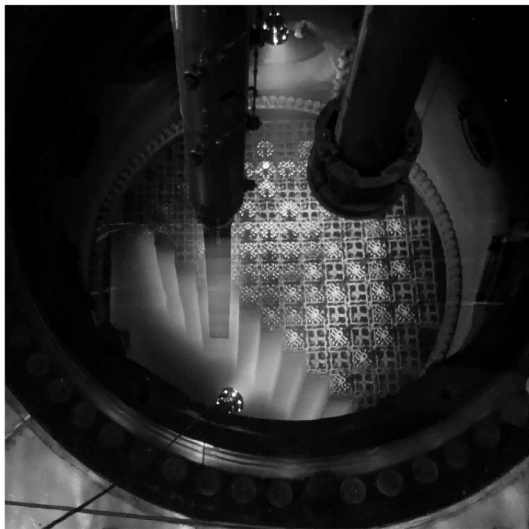


Verification, not trust — safeguards are the treaty's instrument — inspectors measure what operators declare

Declared civilian facilities — that is where the instruments have to work, on the operator's schedule

The gap — inventory of fissile material is inferred from bookkeeping, not measured directly

Advanced Reactors Break Item Accountancy



Item accountancy assumes — itemizable fuel assemblies, a transparent coolant, and frequent refuellings at which to count.

Advanced designs supply none of that — non-itemizable fuel (molten salt, pebble bed), opaque sodium coolant, lifetime cores, on-site reprocessing. Each invalidates some current practice.

MOTIVATION — WHERE THE NEUTRINOS COME FROM

The Brightest Neutrino Source on Earth

A cross section of 10^{-42} cm^2 is beaten with two large numbers.

01 10^{24} targets, for free

Avogadro's number: a mole is 6×10^{23} , so a kilogram-scale target is already 10^{24} nuclei.

02 You still need a colossal flux

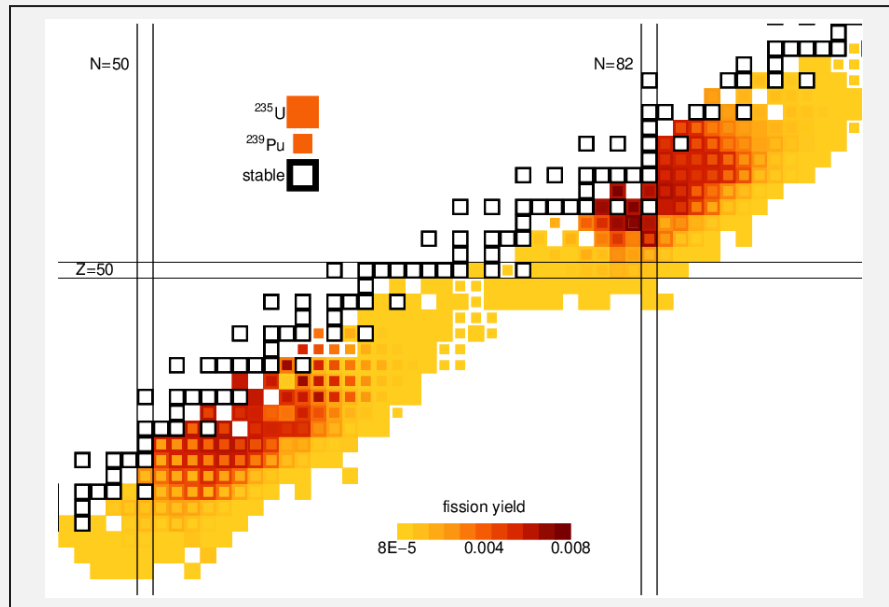
Order 10^{18} decays per second to make 10^{-42} cm^2 countable. Nothing human-made comes close to a reactor.

03 $\sim 6 \bar{\nu}$ per fission

One fission gives two neutron-rich fragments and $\sim 200 \text{ MeV}$; each fragment β -decays several times on the way back to stability.

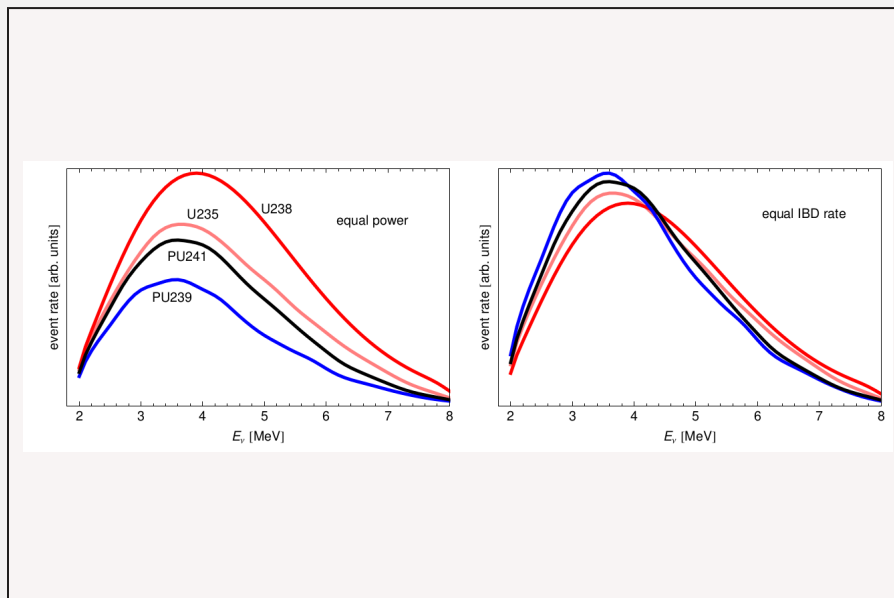
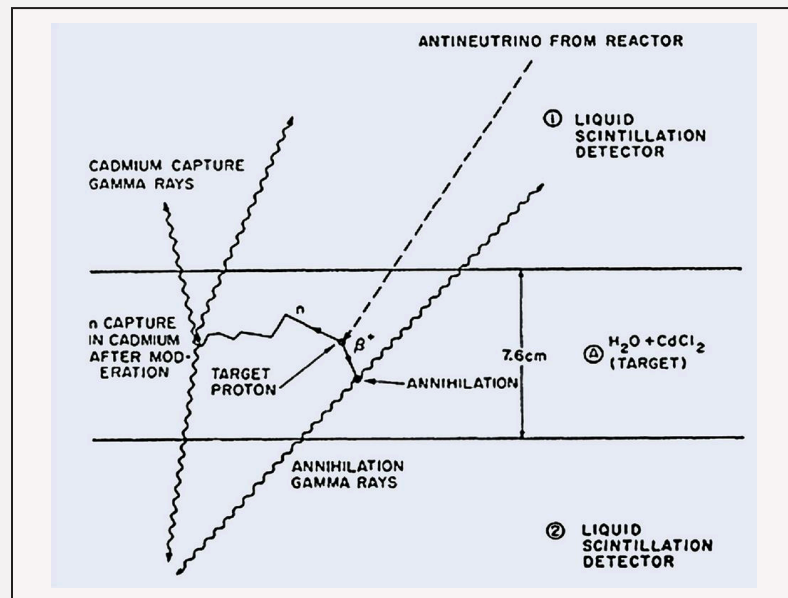
$10^{24} \bar{\nu}$ per kg of ^{235}U fissioned

A GW-scale core runs $\sim 10^{20} \bar{\nu}$ per second — and it comes free with the power.



Fission yields sit off the stable line — every coloured square β -decays its way back, and each step emits an antineutrino.

Neutrinos for Reactor Safeguards

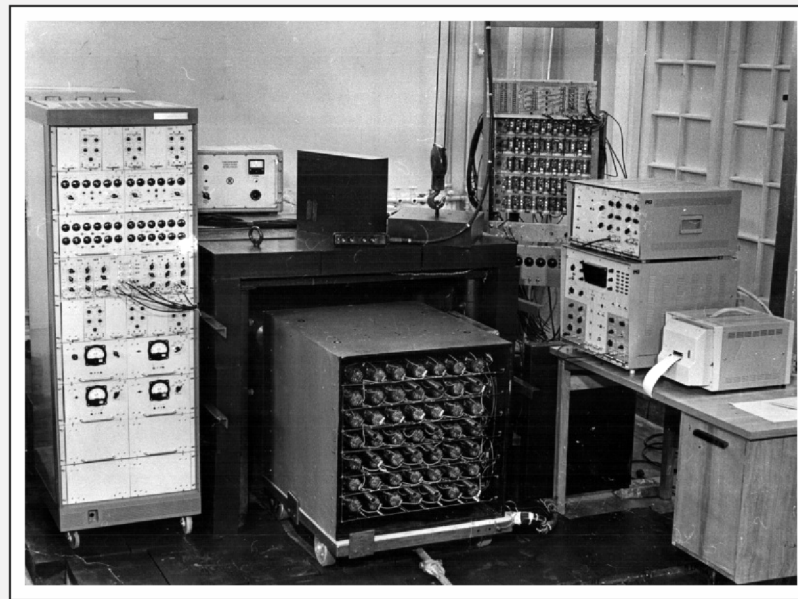
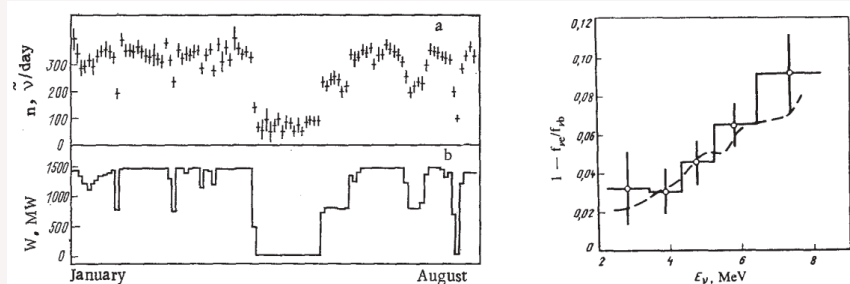


Reactor power — the rate is proportional to it, continuously and without entering the plant

Undeclared production — a direct handle on fissile material being made, not declared

Burn-up verification — the spectrum shifts as the fuel evolves — independent of the operator's books

Pioneering Work



Mikaelyan, late 1970s — the first serious programme on applied antineutrino measurements

Rovno detector — reactor power and fuel burn-up tracked from the antineutrino rate — Korovkin et al. 1988, Klimov et al. 1994

Active IBD Detectors Today

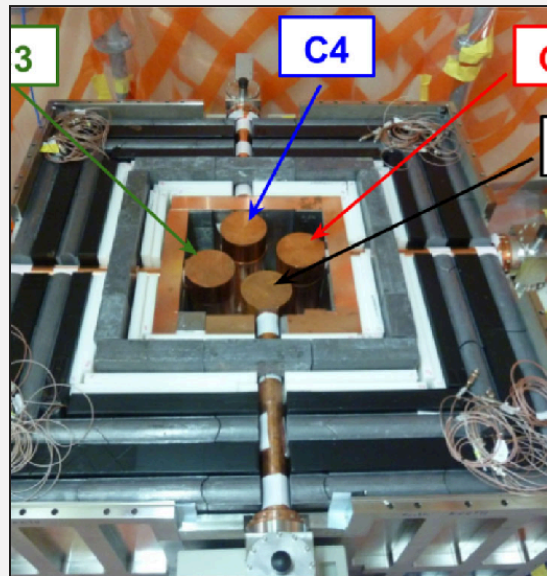
They work. They are also complex and expensive compared with anything else in the safeguards toolkit.



PROSPECT — segmented liquid scintillator at HFIR; a tonne of detector under assembly.



miniCHANDLER — a mobile solid-scintillator demonstrator, plus the rack of electronics that goes with it.



CONUS+ — germanium detectors inside their shield.

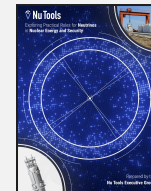
Active neutrino detectors are very big and complicated compared to other IAEA technology. An inspector carries a gamma spectrometer, not a tonne of scintillator — which is the argument for passive detectors.

APPLICATIONS

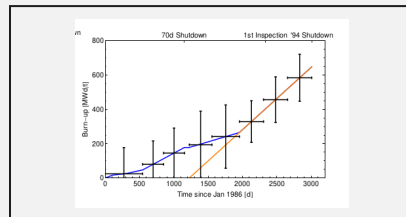
Case Studies

Surveyed end-to-end in the **Nu Tools** study —
Exploring Practical Roles for Neutrinos in
Nuclear Energy and Security, NNSA DNN R&D,
2021.

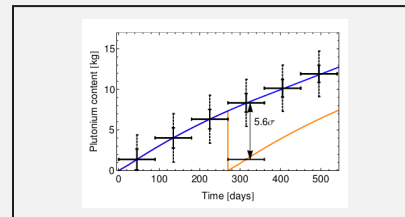
nutools.ornl.gov



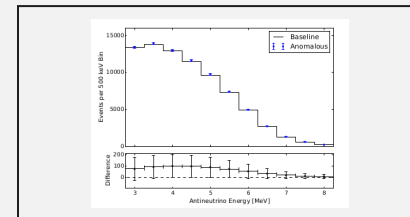
Yongbyon: the 5 MWe reactor and the ELWR.



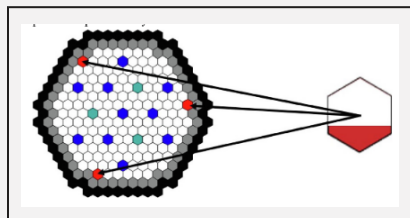
DPRK 1995 — reconstructing burn-up history after the fact.



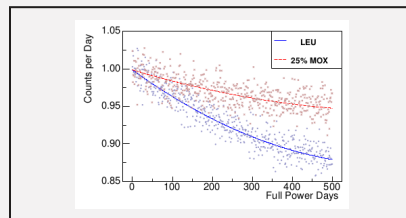
DPRK 2018 — plutonium content vs time; a diversion shows at 5.6σ .



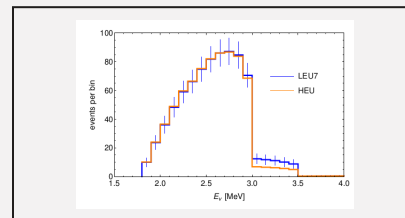
Iran — baseline vs anomalous antineutrino spectrum.



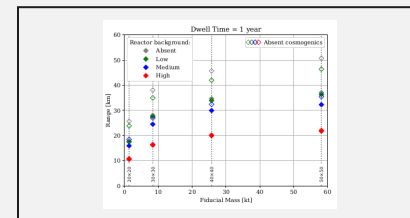
Fuel-assembly level: which pins were replaced.



Advanced reactors — LEU vs 25% MOX burn-up signature.



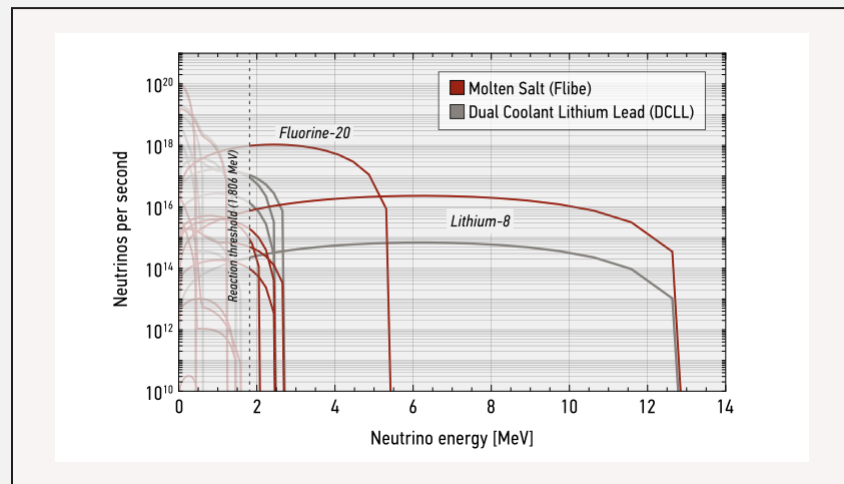
Naval reactors — LEU vs HEU from the spectrum.



Large water Cherenkov — standoff range vs fiducial mass.

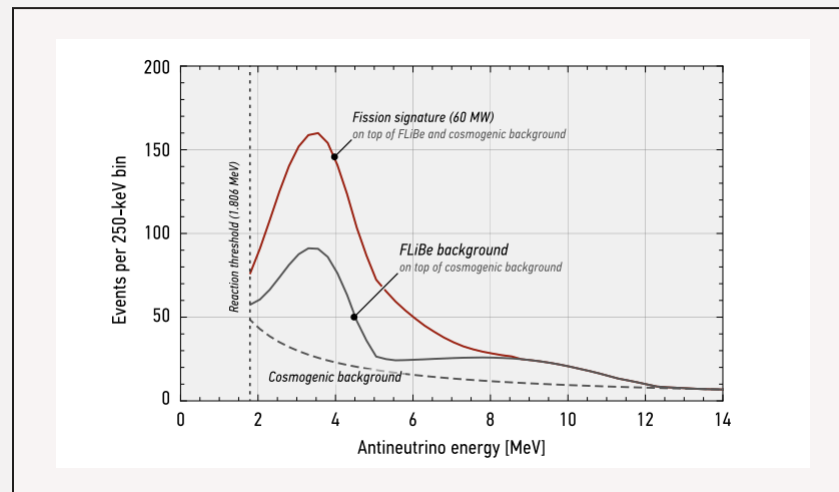
Safeguarding Fusion Plants

A fusion plant can breed plutonium: put fertile ^{238}U in a blanket region with intense neutron flux.



The blanket glows on its own. Activation of the coolant — ^{20}F and ^8Li — is the irreducible background

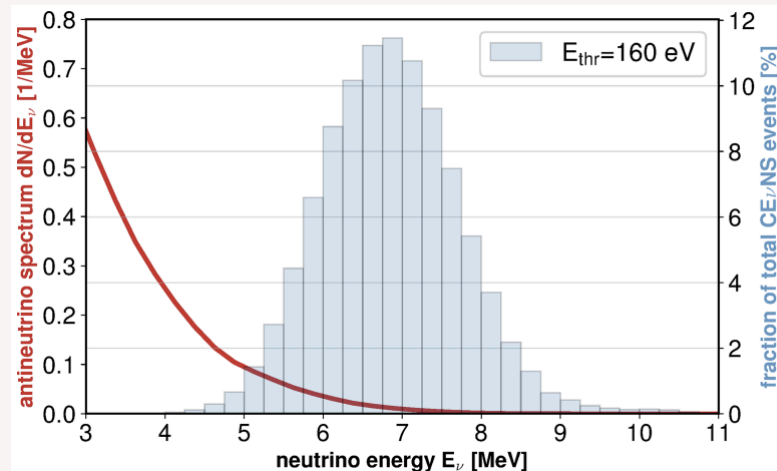
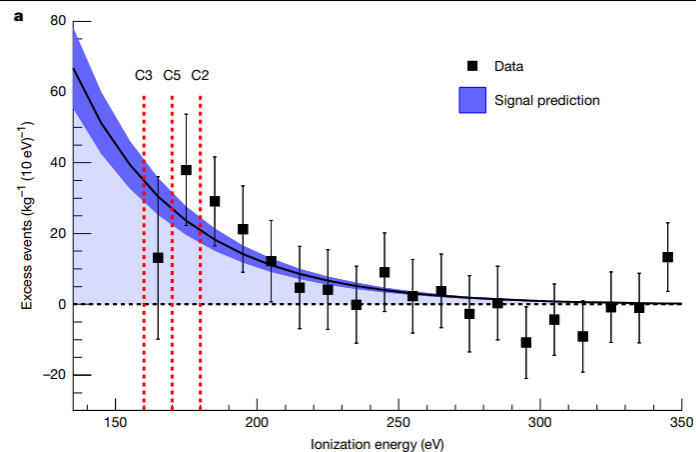
A few kilograms of plutonium over 30 days — detectable with a relatively small onsite detector, despite the activation and cosmogenic backgrounds.



A covert 60 MW fission signature stands clear of it in the 2–6 MeV window, on top of both the FLiBe and cosmogenic backgrounds.

Glaser, Huber & Goldston, *Detecting covert fissile material production in fusion power plants*, arXiv:2508.16358 (2025)

Reactor CEvNS, 2025



CONUS+ — a 3.2 kg germanium diode, 20.7 m from a 3.6 GW reactor.

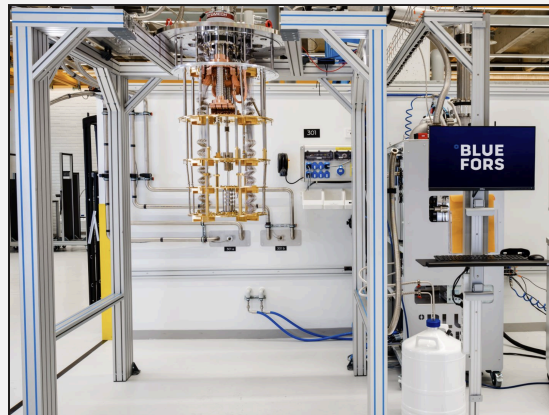
$E_{\text{thr}} = 160 \text{ eV}$ — which restricts sensitivity to neutrinos above $\sim 3.5 \text{ MeV}$: a sliver of the flux, and none of the breeding component.

Source — CONUS+ Collaboration, Nature **643** (2025) 1229.

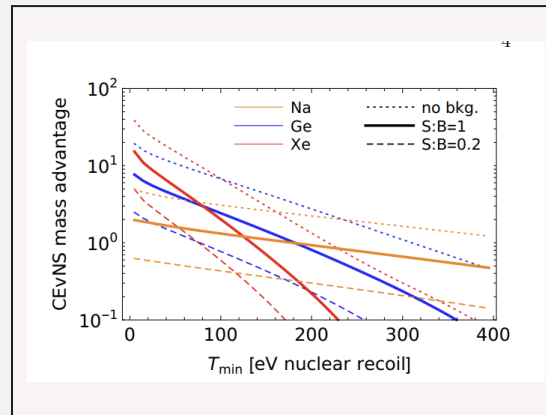
CEvNS vs Inverse Beta Decay



miniCHANDLER — 80 kg of solid scintillator in a trailer, operating at a reactor at room temperature.



A dilution refrigerator — a eV threshold requires millikelvins and continuous attention.



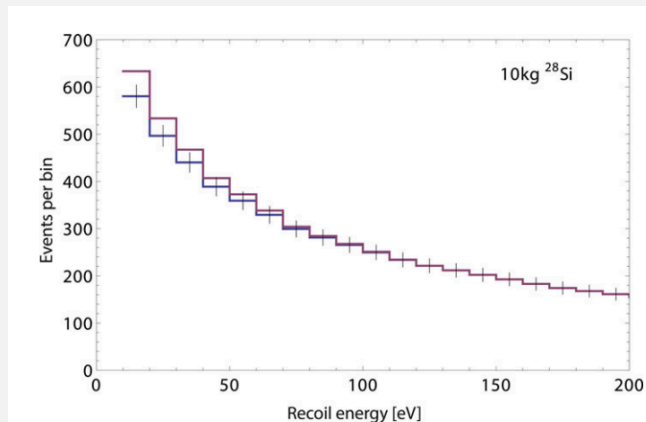
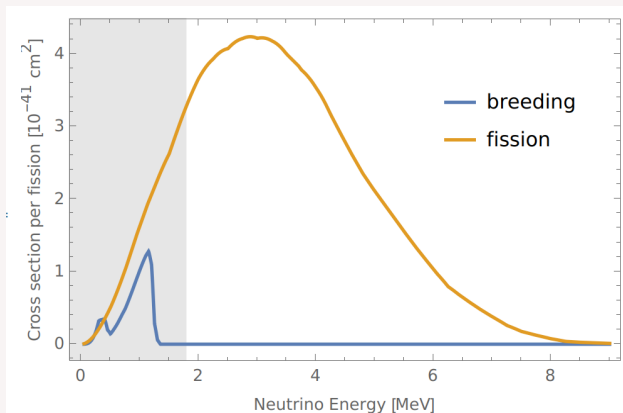
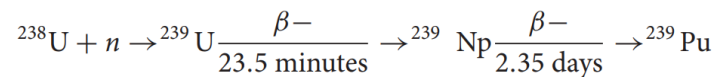
The trade — CEvNS only wins on target mass once the recoil threshold drops below ~ 100 eV.

Below ~ 100 eV — only then does the cross-section advantage become a mass advantage

Source — M. Bowen & P. Huber, Phys. Rev. D **102**, 053008 (2020)

MOTIVATION

Why Go Below 1.8 MeV



A direct SNM signature — the breeding chain itself emits antineutrinos

Below the IBD threshold — almost all of it lands under 1.8 MeV — the grey band

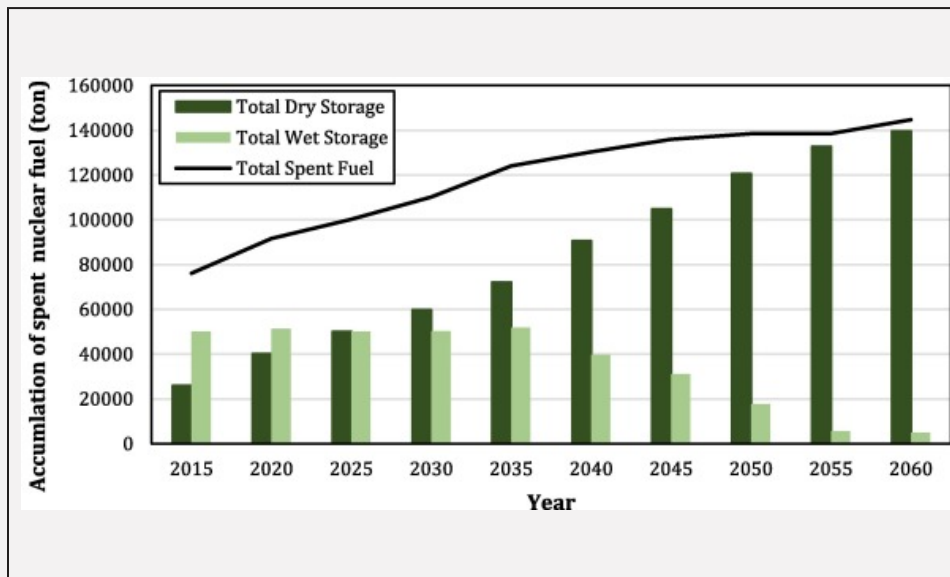
Source — Cogswell & Huber, Science & Global Security **24** (2016) 2, 114

Spent Nuclear Fuel

Once fuel is in a sealed dry cask, conventional verification is continuity of knowledge — not measurement.



Dry storage casks — sealed, passive, and effectively opaque to conventional re-verification.

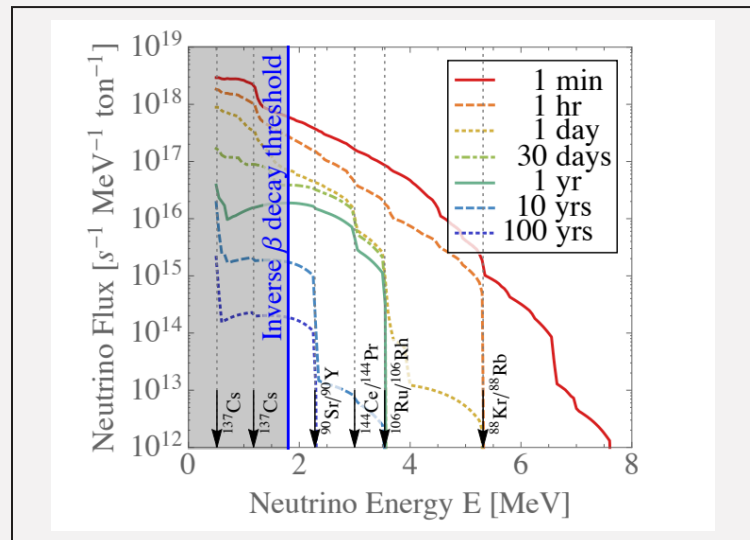


Dry storage overtakes wet entirely while the total keeps climbing. Elshazli et al., Nuclear Engineering and Design **414** (2023) 112632.

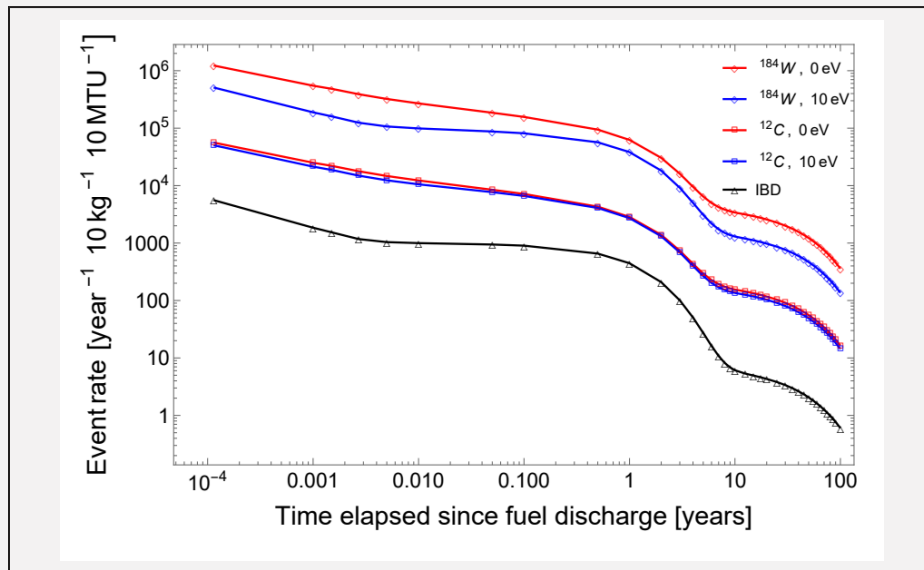
More and more fuel will be in dry storage — very difficult to re-verify with conventional methods. Antineutrinos do not respect a seal. Akindele, ..., Huber et al., arXiv:2112.12593.

Spent Fuel: IBD vs CEvNS

As fuel cools, the surviving flux drops below the IBD threshold
— which is exactly where CEvNS still counts.



Flux vs cooling time. After a year nearly everything left is inside the grey band, below threshold. Huber & v. Raesfeld, Phys. Rev. D **105** (2022) 056002.



CEvNS on ^{184}W or ^{12}C sits 2–3 orders of magnitude above IBD, and the gap widens as the fuel cools. Brdar, Huber & Kopp, Phys. Rev. Applied **8** (2017) 054050.

And it has been measured: Double Chooz extracted the spent-fuel IBD contribution over 17.2 days, isotope by isotope — ^{144}Pr and ^{106}Rh carry it, and it dies above ~ 3 MeV. Double Chooz, arXiv:2510.04869.

PART II

The why and how to of phonon detection

MOTIVATION

Recoil Energy vs Neutrino Energy

$$T_{\max} = 2E_{\nu}^2 / M$$

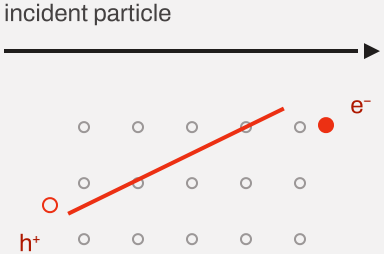
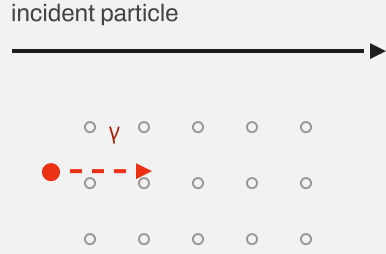
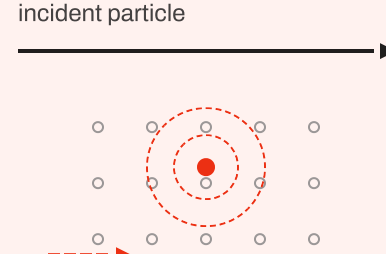
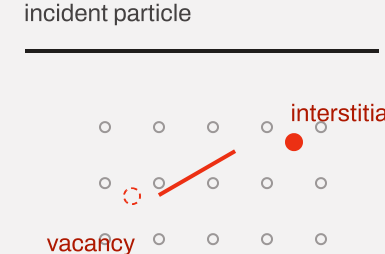
Elastic recoil off a heavy target: quadratic in neutrino energy, inversely proportional to nuclear mass. The mean recoil is about $\frac{1}{3}$ of $T_{\max}$.

E_{ν}	TARGET	$T_{\max}$
2 MeV	Ge (A = 73)	~120 eV
1 MeV	Ge (A = 73)	~30 eV
1 MeV	W in CaWO_4 (A = 184)	~12 eV

Sub-1.8 MeV breeding neutrinos therefore land in the tens of eV and below — which is exactly the regime the rest of this talk is about.

MOTIVATION

Particle Detection 101

 Ionization Electrons freed from bound states, drifted to electrodes. quantum $\approx 3\text{--}20\text{ eV}$ $\epsilon_{\text{pair}}(\text{Si}) = 3.6\text{ eV}$	 Scintillation Excited states de-excite radiatively; photons are counted. quantum $\approx 1\text{--}10\text{ eV}$ $\approx 10\text{--}40\text{ }\gamma\text{ / keV}$	 Phonons Lattice vibrations read out as a temperature rise or a phonon burst. quantum $\approx 1\text{--}10\text{ meV}$ $\theta_{\text{D}}(\text{Ge}) = 374\text{ K}$	 Defect formation Atoms knocked off-site, leaving persistent lattice damage. threshold $\approx 10\text{--}50\text{ eV}$ E_{d}: displacement energy
---	--	---	---

The quantum sets the floor: at tens of eV of recoil, ionisation and scintillation run out of quanta to count — phonons offer three orders of magnitude more.

The Organizing Axis

AXIS 1

Where you intercept

Anywhere along the down-conversion cascade — from prompt THz phonons to full thermal equilibrium.

AXIS 2

How you read it out

Analog — a continuous, noise-limited variable. Or digital — a quantum jump you count.

Those two choices predict the threshold, the scaling with target mass, and the failure mode.

TERMS, FIRST USE

Phonon — a quantum of lattice vibration: the crystal's sound field, quantized.

Nuclear recoil — a particle kicks a whole nucleus; the kick is what becomes phonons.

Threshold — the smallest deposit a detector can claim above its own noise.

The Down-Conversion Cascade

t = 0 Nuclear recoil  Broadband spectrum peaked near the Debye frequency.	~ns Prompt THz phonons  Ballistic, still athermal. Families 2, 3 and 4 intercept here.	~μs Anharmonic decay  Energy fragments into more, softer phonons; position information is lost.	~ms Thermal equilibrium  The crystal is simply warmer. Family 1 intercepts here.
---	--	--	--

TERMS, FIRST USE

Athermal — the phonon population is still far from a thermal distribution.

Debye frequency — the highest vibration a lattice supports; ~10 THz in silicon.

Ballistic — travelling in straight lines, without scattering.

THE FOUR FAMILIES

The Four Families

01 — Equilibrium calorimeters

02 — Athermal collection

03 — Quasiparticle counting

04 — Quantum acoustics

Equilibrium Calorimeters

Measure ΔT after the deposit has fully thermalized. The absorber and the thermometer are one system.

SENSORS IN USE

NTD-Ge thermistors (CUORE, EDELWEISS) · TES in the thermal regime (CRESST-III, NUCLEUS) · metallic magnetic calorimeters

THERMODYNAMIC BOUND

$$\sigma_E \approx \sqrt{(\xi k_B T^2 C)}$$

with $C \propto M T^3$ for a dielectric

$\sigma_E \propto \sqrt{M}$ is the hard wall

TERMS, FIRST USE

Calorimeter — a detector that measures energy as a temperature rise.

TES — transition-edge sensor: a superconducting film biased on its sharp resistive transition.

Heat capacity C — energy needed to warm the absorber by 1 K; it grows with mass, so ΔT shrinks.

MMC — metallic magnetic calorimeter: reads ΔT as a change in magnetisation.

NTD-Ge thermistor — doped germanium whose resistance depends steeply on temperature.

Where the Thermal Numbers Sit

EXPERIMENT, SENSOR	ABSORBER	BASELINE σ_E , DETECTOR	NOTE
CUORE — NTD-Ge on TeO ₂	750 g crystal	~5 keV FWHM	Built for MeV-scale resolution in $0\nu\beta\beta$, not for threshold
EDELWEISS — NTD-Ge on Ge	33.4 g	~18 eV	Best thermal Ge result at tens of grams
CRESST-III — TES on CaWO ₄	24 g	~4.6 eV	σ giving a ~30 eV nuclear-recoil threshold
Ricochet — CryoCube (NTD-Ge), Q-Array	18 × 42 g = 0.75 kg Ge	sub-keV_{nr}	8.8 m from the 58 MW ILL reactor; heat + ionisation for NR/ER discrimination; science phase since July 2025
NUCLEUS — TES on CaWO₄	~7 g (4 crystals)	2.8 eV	Lowest threshold in the family — CEvNS ROI 10–200 eV, at Chooz; 4.7 σ projected in one year of the physics run

Athermal Phonon Collection

Intercept the prompt $\sim$ THz phonons at the surface, before thermalization. Superconducting collection fins — usually aluminium — concentrate quasiparticles into a small-heat-capacity sensor. This is the QET architecture.

Resolution is set by sensor noise and the phonon collection efficiency ϵ , **not** by total absorber mass.

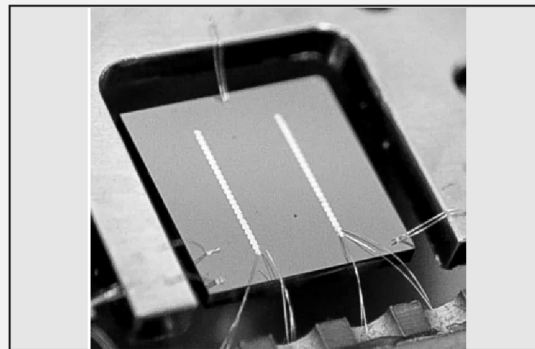


Fig. 1 of [arXiv:2503.03683](https://arxiv.org/abs/2503.03683) — TESSERACT 1 cm² Si detector, two QET channels (photo: M. Sargent / LBNL).

TERMS, FIRST USE

Cooper pair, gap Δ — below T_C electrons bind in pairs; breaking one costs 2Δ .

Quasiparticle — the unpaired electron left behind; this is what a phonon creates in the fin.

QET — quasiparticle-trap-assisted TES: aluminium fins funnelling into one small sensor.

Collection efficiency ϵ — fraction of deposited energy that actually reaches the sensor.

Where the Numbers Sit

DEVICE	TARGET	BASELINE σ_E , DETECTOR	NOTE
TESSERACT / SPICE, 2-channel	0.233 g Si	361.5 meV	Best athermal result to date; above-ground
SuperCDMS HVeV, latest gen	~1 g Si	~612 meV	Group webpage figure, not peer-reviewed — provisional
SuperCDMS CPD	10.6 g Si	3.86 eV	Shows the ϵ -versus-mass penalty
KIPM, MKID readout	1 g Si	320 eV	2.1 eV on energy reaching the sensor, divided by ~1% collection efficiency
MINER — sapphire + charge amplification	gram-scale array	sub-100 eV thr.	Mixed readout, not a pure TES; moving to HFIR for ~100× flux

TERMS, FIRST USE

MKID — microwave kinetic inductance detector: quasiparticles shift a resonator's frequency.

KIPM — kinetic-inductance phonon-mediated detector: MKIDs on a large substrate.

Substrate-equivalent — the threshold restated as energy in the crystal, after dividing by ϵ .

Collection Efficiency, Not Sensor Physics

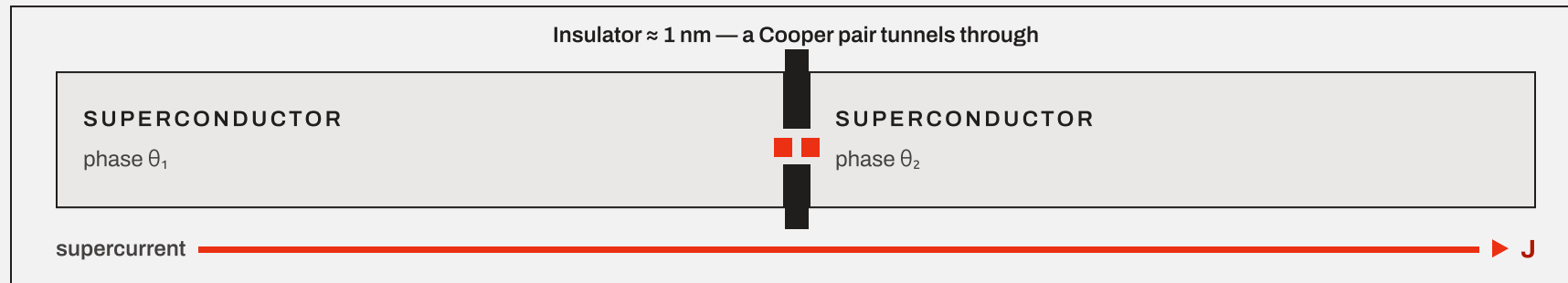
150x

the gap between what the KIPM sensor
resolves and what the detector resolves

Energy absorbed by the sensor	2.1 eV
Phonon collection efficiency ϵ	~1%
Substrate-equivalent threshold	320 eV

Whoever solves ϵ at kilogram scale wins. Ranking approaches by sensor σ_E alone will mislead you.

The Josephson Junction



$$I = I_c \sin \phi$$

Current with zero voltage, set only by the phase difference $\phi = \theta_1 - \theta_2$.

$$L_J = \hbar / (2e I_c \cos \phi)$$

An inductance that depends on its own current — and dissipates nothing below 2Δ .

TERMS, FIRST USE

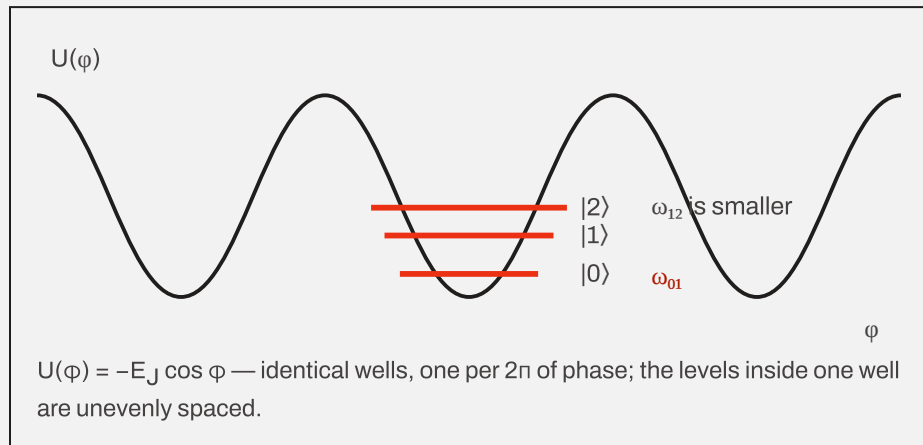
Critical current I_c — the largest supercurrent the junction carries before a voltage appears.

Josephson energy E_J — $\hbar I_c / 2e$: how strongly pair tunnelling locks the phases together.

The Energy Landscape

$$H = 4E_C(\hat{n} - n_g)^2 - E_J \cos \hat{\phi}$$

Conjugate variables, $[\hat{\phi}, \hat{n}] = i$: the charging term is diagonal in $\hat{n}$, the Josephson term in $\hat{\phi}$. **Which one wins is the only design choice** — it decides which variable is sharp.



Cosine, not parabola

A parabola's levels are evenly spaced, so one drive climbs the whole ladder. Here the spacing shrinks with height, so $|0\rangle \rightarrow |1\rangle$ can be driven alone — that is the qubit.

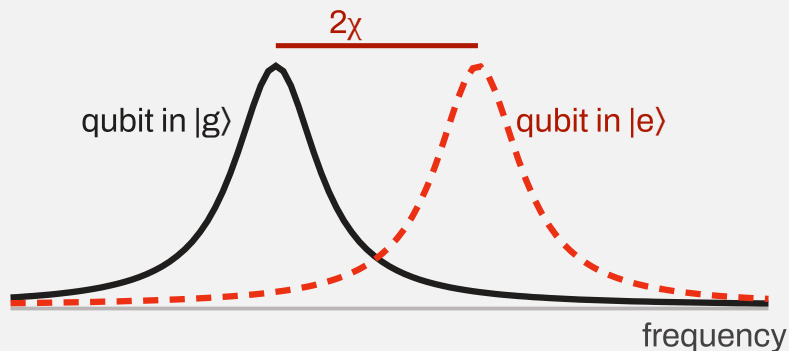
Shallow: $E_C \gg E_J$

The charging term dominates: $\hat{n}$ is sharp, $\hat{\phi}$ is smeared. States are pair-number states — the Cooper-pair box, sensitive to one electron.

Deep: $E_J \gg E_C$

The Josephson term dominates: $\hat{\phi}$ is sharp, $\hat{n}$ is smeared — so the energy stops depending on n_g and charge noise averages away. The transmon — coherent for $\sim 100 \mu\text{s}$.

Dispersive Readout



The resonator sits at a different frequency for each qubit state, so one tone's phase tells you which.

$$\tan \theta = 2\delta\omega / \kappa$$

The familiar driven-oscillator result: drive a resonator of linewidth κ off resonance by $\delta\omega$ and the response comes back phase-shifted by θ . Here the qubit state *is* the detuning — $\delta\omega = \pm\chi$ — so the reflected tone returns with phase $\pm 2 \arctan(2\chi/\kappa)$. No energy is exchanged with the resonator; only the phase carries the answer: quantum non-demolition measurement.

Quantum Acoustics

Step 1 Build a high-Q mechanical mode — an hBAR or bulk acoustic resonator.	Step 2 SWAP its excitation into a transmon.	Step 3 Read the qubit.
--	--	---

The only family that is genuinely quantum-limited: it admits QND repeated measurement, back-action evasion and squeezing.

Note the trade: you give up broadband acceptance for quantum-limited readout of one mode.

TERMS, FIRST USE

hBAR — high-overtone bulk acoustic resonator: a thin crystal holding one long-lived GHz mode.

Quality factor Q — how many cycles the mode rings before its energy leaks away.

SWAP — a resonant pulse that hands one excitation from the mode to the qubit.

QND — quantum non-demolition: a measurement that leaves the state intact, so you can repeat it.

The Mode-Matching Problem

A recoil produces a broadband athermal spectrum peaked near the Debye frequency. A qc-hBAR listens to one ~GHz mode.

The overlap factor is brutal unless something upstream funnels energy into the resonant band. No public, defensible number for that integral exists — if you evaluate this family, that is the quantity to demand.

AND IT MAY TURN OUT IMPOSSIBLE

Liouville's theorem

Funnelling a broadband flux into one mode is a compression of phase-space density. No passive, linear element can do that — so any funnel has to be dissipative, and dissipation costs the very quanta you are trying to count.

Convert Before Sensing

Quantum evaporation

A phonon reaching the surface of superfluid ^4He ejects a free atom, which is then adsorbed on a calorimeter and gives back its van der Waals binding energy — a built-in gain stage. **HeRALD** — Hertel et al., Phys. Rev. D **100**, 092007 (2019), [arXiv:1810.06283](#); Lyon et al., Phys. Rev. D **109**, 023010 (2024).

Optical phonon → IR photon

In a polar crystal, an optical phonon converts to a single infrared photon that a photon counter can see. GaAs and sapphire — Knapen et al., Phys. Lett. B **785**, 386 (2018), [arXiv:1712.06598](#); Griffin et al., Phys. Rev. D **98**, 115034 (2018), [arXiv:1807.10291](#).

Defect creation

Colour centres record the recoil permanently and are read out later by fluorescence microscopy. Formation energies ~ 25 eV set the threshold, and 10 g would suffice for reactor CEvNS. **PALEOCENE** — Cogswell et al., Phys. Rev. Applied **16**, 064060 (2021), [arXiv:2104.13926](#); Alfonso et al., Eur. Phys. J. C (2026).

TERMS, FIRST USE

Quantum evaporation — a phonon reaching a liquid-helium surface ejects a free atom.

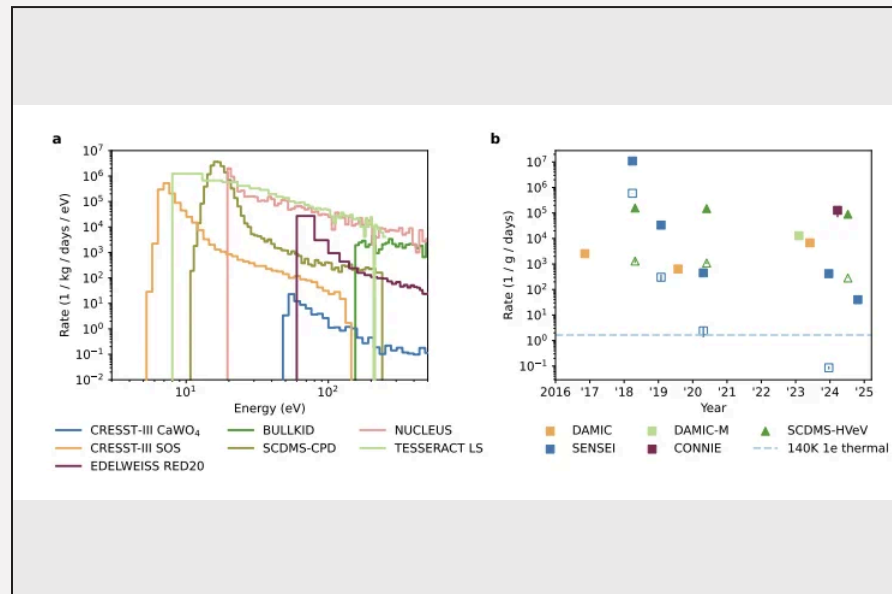
Optical phonon — a lattice mode where neighbouring ions move oppositely; in polar crystals it couples to light.

Colour centre — a lattice defect that traps charge and can be read out later, warm.

WHERE THE FIELD MEETS THE REAL WORLD

The Low-Energy Excess

The Low Energy Excess Is Universal



YEAR	OBSERVATION
2017	NUCLEUS — first cryogenic LEE in the literature, recognised only in hindsight.
2019	EDELWEISS — 33.4 g Ge, 6-day surface run: excess above a flat $\sim 10^3$ dru radiogenic rate down to 60 eV.
2019	CRESST-III — 23.6 g CaWO ₄ at LNGS, 3.64 kg-day: significant excess below 200 eV, 30 eV threshold.
since	Charge detectors too — SuperCDMS-HVeV, SENSEI, DAMIC, EDELWEISS-HV: single-electron rates far above prediction.

Below ~ 100 eV, everyone sees it — a steeply rising rate with falling energy, in every technology.

No common origin — a single explanation, dark matter included, is inconsistent with the data; phonon-side and charge-side causes are distinct.

Source — Baxter et al., [arXiv:2503.08859](https://arxiv.org/abs/2503.08859); the EXCESS workshop series.

Some possible causes of the Excess

PHONON SIDE — 01

Stress

Differential thermal contraction stores energy at crystal-holder and crystal-film interfaces, released later as discrete events. TESSERACT measured up to **100× more LEE** in a glued crystal than one suspended on bond wires — but CRESST varied its holding schemes and saw no difference, so stress is not the whole story.

PHONON SIDE — 02

Defect states

Lattice reconfigurations and the annihilation of radiation-induced defects release ~ 10 eV apiece; hundreds of eV needs many atoms moving at once, and no detailed description of that yet exists.

PHONON SIDE — 03

Excess quasiparticles

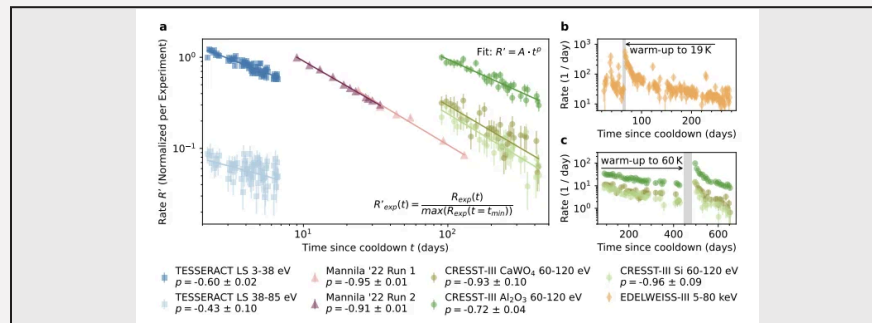
Vibration, environmental radioactivity, IR photons through antenna modes, cosmic rays in the substrate.

Charge side: a different list

Cherenkov and transition radiation from cosmic-ray secondaries crossing dielectrics and surfaces, plus fundamental backgrounds — not the same physics as the phonon excess.

The same problem as qubits?

Quasiparticle-tunnelling rates in qubits and TES data share a time dependence.



A Concrete Case: Shared vs Singles

Every low-threshold calorimeter sees the Low Energy Excess. TESSERACT resolves it into two distinct populations:

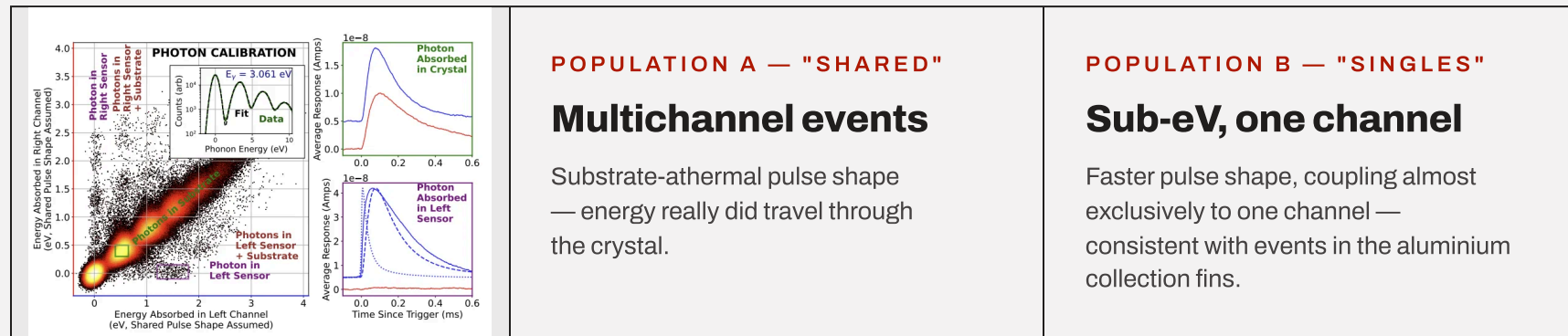


Fig. 2 of [arXiv:2410.16510](https://arxiv.org/abs/2410.16510)

TERMS, FIRST USE

Low Energy Excess — an unexplained event rate just above threshold, seen by every low-threshold calorimeter.

Pulse shape — the time profile of the sensor signal; it encodes where and how the energy arrived.

Further Reading

Golwala & Figueroa-Feliciano, *Novel Quantum Sensors for Light Dark Matter and Neutrino Detection*, Annu. Rev. Nucl. Part. Sci. 72, 419 (2022) — still the best single-source taxonomy, and deliberately qualitative.

Bui et al. (TESSERACT), [arXiv:2503.03683](#) — the 361.5 meV two-channel result and its detector figure.

Essig et al., Snowmass2021, [arXiv:2203.08297](#) — the landscape of low-threshold direct detection.

Anthony-Petersen et al., [arXiv:2410.16510](#) — low-energy backgrounds and excess noise; the shared/singles split.

Temples et al., [arXiv:2509.25544](#) — KIPM consortium status, with the honest discussion of ϵ .

Linehan et al., [arXiv:2404.04423](#) — transmon relaxation and correlated errors as a phonon probe.

Further Reading, Continued

Quantum parity detector engineering, [arXiv:2509.18637](#); passive defect registration, [arXiv:2104.13926](#).

Baxter et al., *Low-Energy Backgrounds in Solid-State Phonon and Charge Detectors*, [arXiv:2503.08859](#) — the LEE review.

Billard, Johnston & Kavanagh, JCAP **11** (2018) 016, [arXiv:1805.01798](#) — new physics in reactor CEvNS; the BSM recoil-spectrum figure.

DARPA QuSeN proposers-day slides (2024-11) — the program metrics: multi-kg, high-N absorbers, meV thresholds, no evolutionary improvements.

Berryman et al., [arXiv:2203.01955](#) — neutrino portals to dark sectors (Snowmass).

QuSeN at a Reactor



What QuSeN Actually Demands

REQUIREMENT 01

The interaction

Detectors using neutrino–matter interactions that produce low-energy nuclear recoils and athermal phonons — not ionisation, not scintillation.

REQUIREMENT 02

High neutron number

Absorbers with high N , because the CEvNS coherence gain is $\sigma \propto N^2$. The target material is part of the specification.

REQUIREMENT 03

(Multi)-kilogram scale

Not a gram-scale demonstrator. Kilograms of instrumented absorber, which is where every thermal architecture hits the $\sqrt{M}$ wall.

REQUIREMENT 04

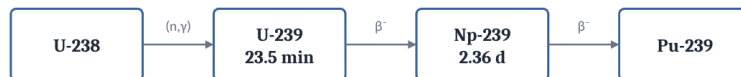
sub-eV thresholds

Three orders of magnitude below where reactor CEvNS sits today — and the reason the counting architectures are on the table at all.

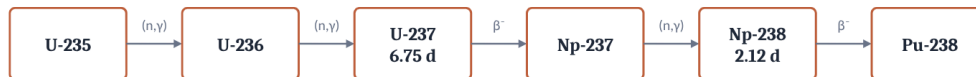
Multi-kg $\times$ meV threshold — the programme is written around that arithmetic.

Neutrino Yields: A New Contribution to the Flux

Pu-239 chain — one (n,γ) on U-238



Pu-238 chain — three captures starting from U-235 (Route B)



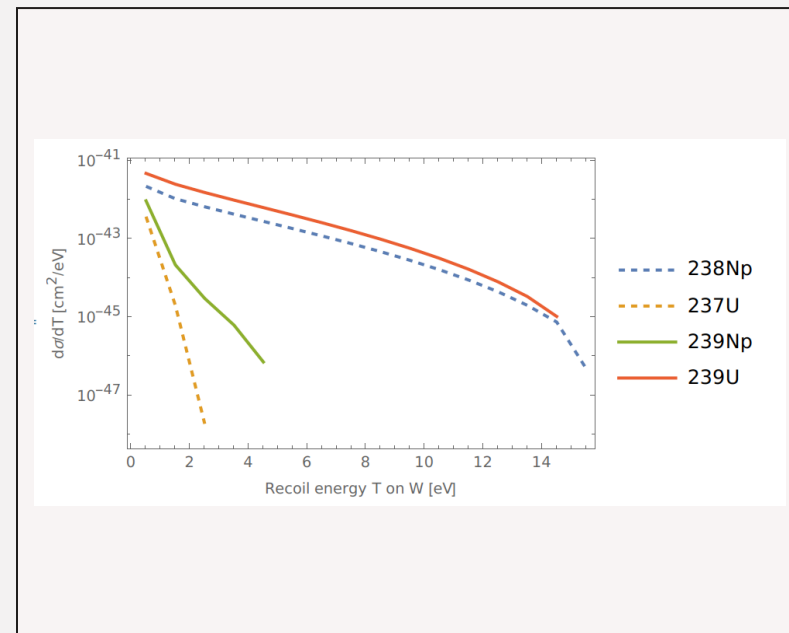
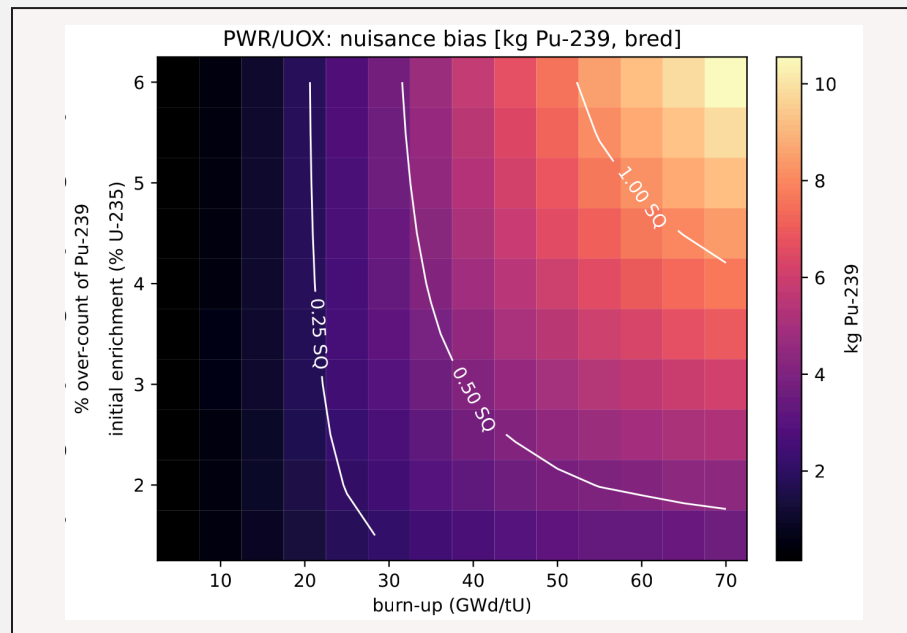
Route A (fast, threshold): U-238 (n,2n) → U-237 → ... → Pu-238 · σ_c(Np-237) = 158 b thermal, RI = 660 b

Fission flux — weak dependence on enrichment,
linear in fluence

Breeding flux — direct dependence on
enrichment, cubic in fluence

Pu-238 — well characterised from
RTG applications

Does It Help or Hinder?

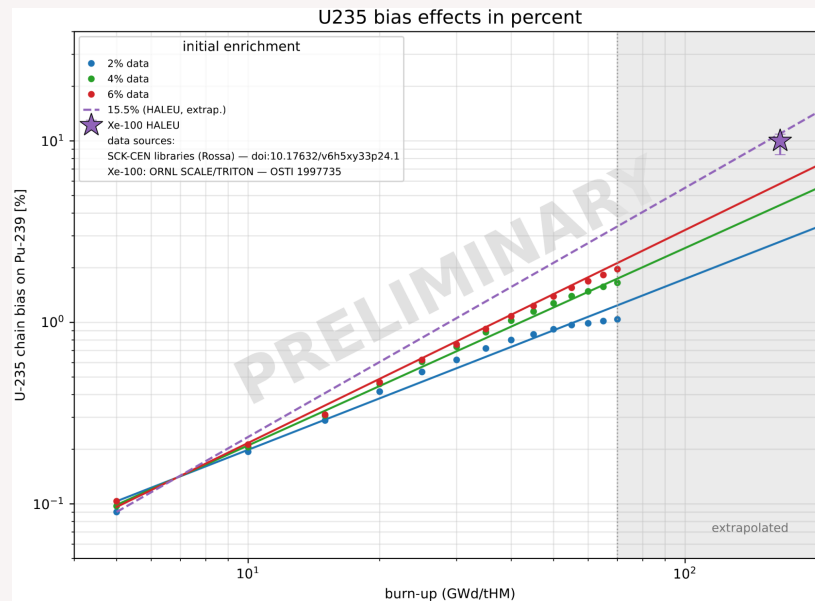


Too similar to separate — shape alone will not distinguish the components

So: does it track Pu-239? — or does it bias the inference — that is the real question

Method — published SCK-CEN fuel libraries to estimate the Pu-239 bias

Lessons Learned and Path Forward



High burn-up makes it worse — future designs exacerbate the bias

End goal — a full likelihood analysis, not a spectral cut

The KPI — Pu inventory accuracy for a deployed kg-scale experiment

CEvNS Rates at HFIR

Event counts vs recoil threshold — U-235 only, 85 MW_{th}, 24.5-day cycle, 1 kg target

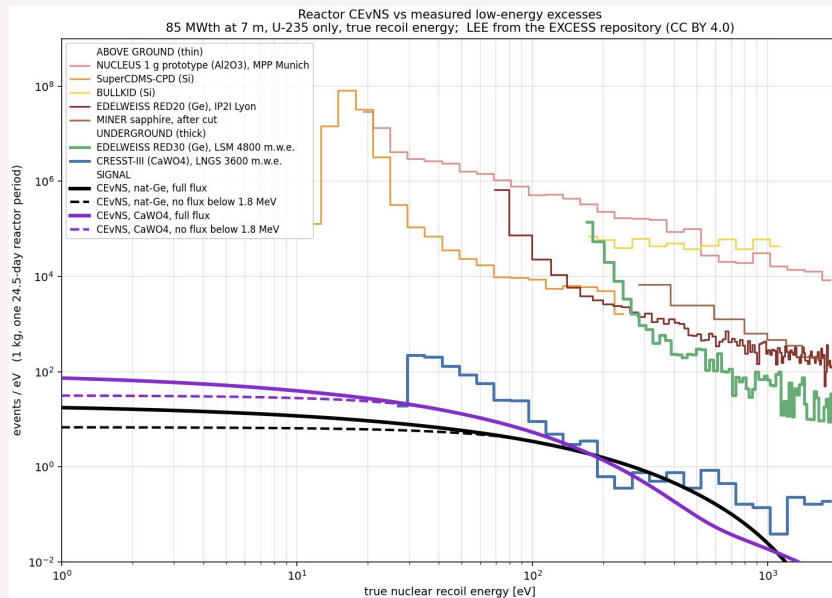
TARGET	DISTANCE	0 eV	1 eV	10 eV	100 eV
nat-Ge	7 m	1186	1168	1042	495
nat-Ge	9 m	717	706	630	300
CaWO ₄	7 m	2295	2215	1748	437
CaWO ₄	9 m	1389	1340	1058	264

Confirmed parameters — standoff 7–9 m, 85 MW_{th}, 24.5-day reactor cycle.

What threshold costs — 1 eV → 100 eV throws away half the Ge events and four fifths of the CaWO₄ events.

Still preliminary — reactor systematics in progress; fluxes below 1.8 MeV not finalised.

The CEvNS Spectrum at HFIR

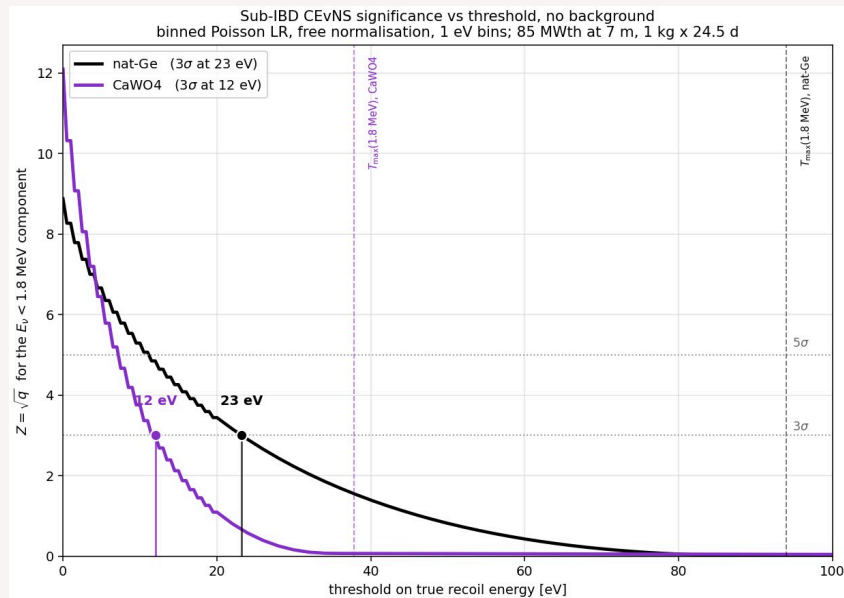


1186 events — on Ge, 1 kg at 7 m, one 24.5-day cycle

2295 events — on CaWO_4 , same exposure

The catch — the rates are quite good — the problem will be backgrounds

Sub-IBD Events



~15% of events — come from below the 1.8 MeV IBD threshold

3σ thresholds — 23 eV on natural Ge; 12 eV on CaWO₄

Assuming zero backgrounds — read it as a ceiling — see the low-energy-excess discussion

Non-Phonon Technologies

Skipper-CCD Inside a Reactor

2.2 g silicon, 12 m from the core of the 2 GW_{th}
Atucha II reactor. Depaoli et al., arXiv:2401.07885.

A RECOIL IN THE PIXEL

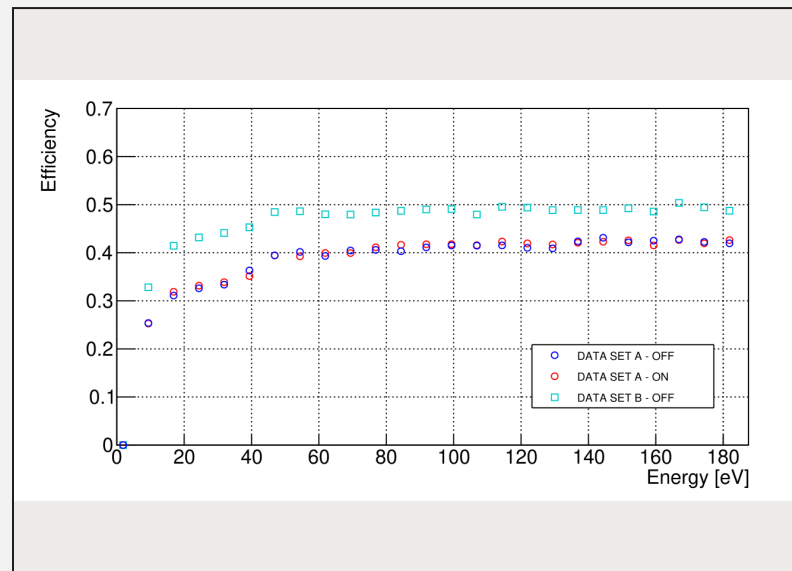
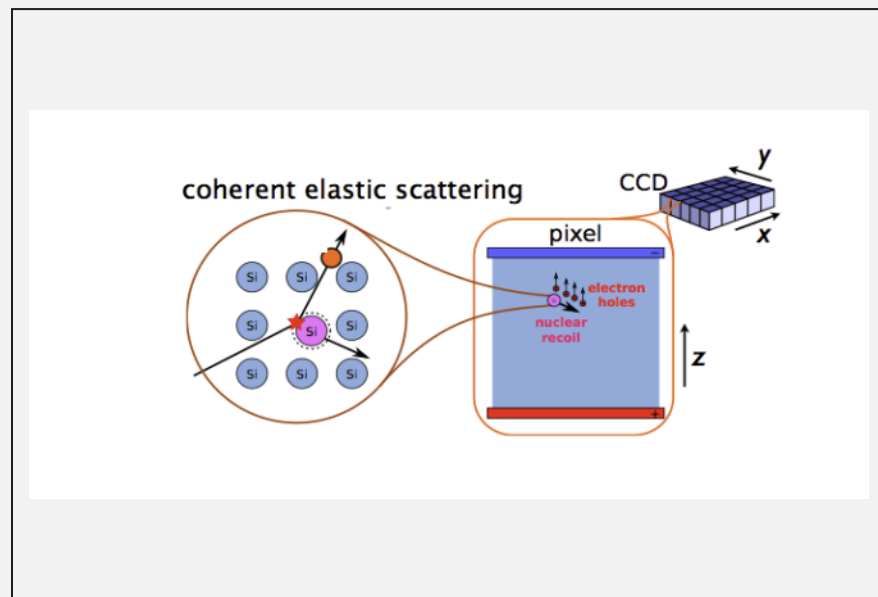


Fig. 7 — reconstruction efficiency vs. energy. Flat above 12 e⁻ (45 eV) at 0.49: the collection-efficiency problem, in charge rather than phonons.

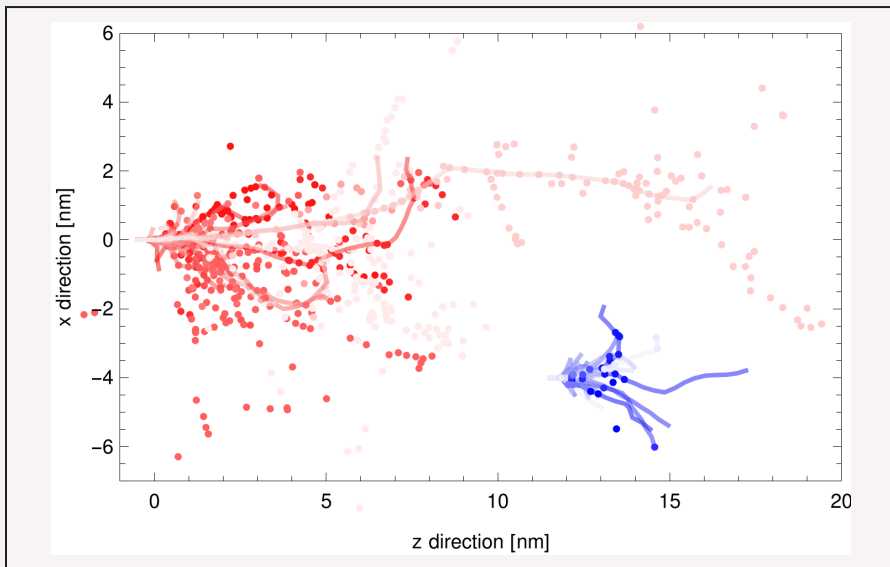
Threshold is set by pair creation — 3.75 eV per e⁻, not meV phonons.

But imaging buys cuts — cluster shape, hot columns and edges are all rejectable.

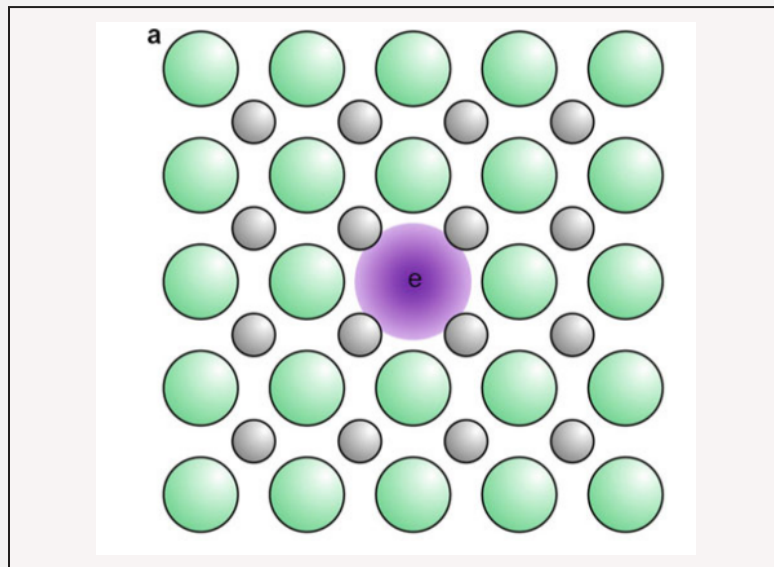
No ON–OFF difference yet down to 120 eV; background flat to 45 eV at ~35 kdru.

Why Colour Centres?

A recoil need not be read as it happens. It can be read as the damage it leaves behind.



TRIM simulation in NaI — the recoil cascade is nanometres across. Cogswell, Goel, Huber, Phys. Rev. Applied **16**, 064060.



An F centre: an anion vacancy in the lattice traps an electron. R. Tilley, Encyclopedia of Color Science and Technology, Springer 2013.

Formation energies ~10 eV — the damage threshold sets the detection threshold.

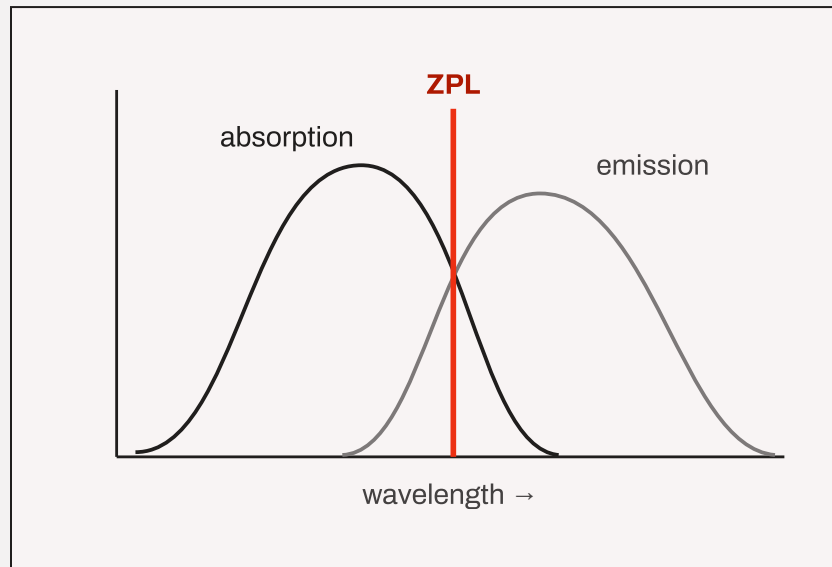
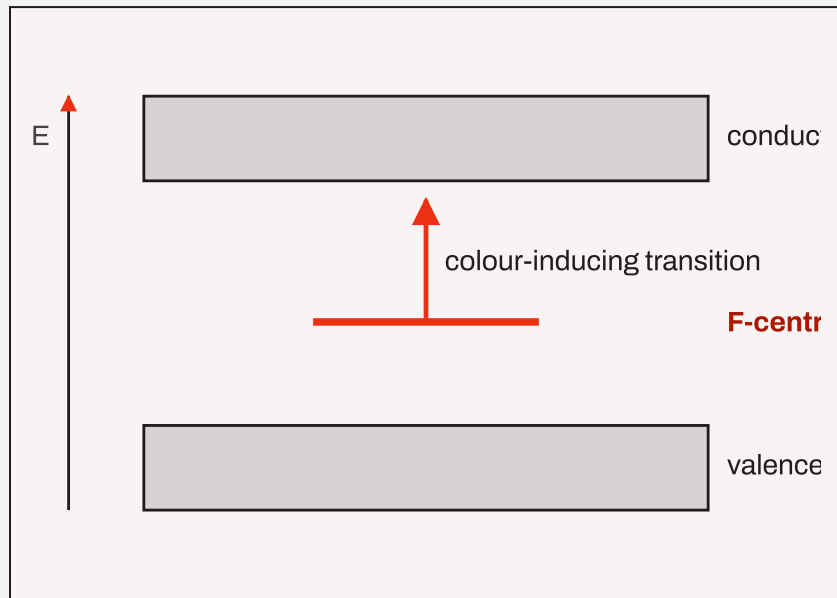
The defect is permanent — a passive detector that integrates, read out later and non-destructively.

Colour centres carry structure — the signature says something about the event that made it.

The Optical Signature

Levels in the gap mean the crystal absorbs and emits where the pristine material is transparent.

A level inside the gap, where the pristine crystal has none.



Broad absorption and emission bands meeting at the zero-phonon line. After Fedorov et al., Appl. Phys. Lett. **79**, 2318 (2001).

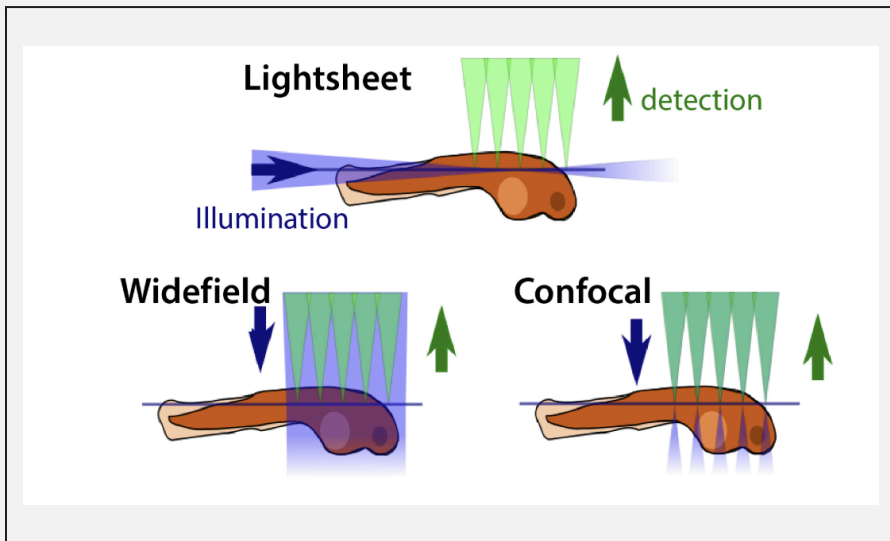
The zero-phonon line — the transition that emits no phonon; the wings are its phonon sidebands.

Readout is fluorescence — illuminate, look at the emission wavelength, count what is there.

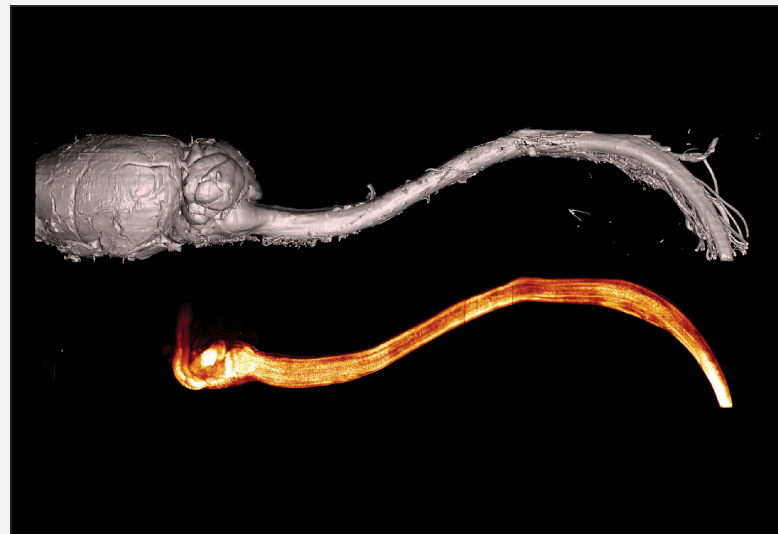
Non-destructive — nothing in the measurement consumes the defect. Read the crystal again.

SPIM: Light-Sheet Microscopy

Illumination and detection at right angles: excite one thin plane, photograph it edge-on, step through the volume.



"Comparison of Different Microscopy Illumination Modalities" by JKrieger, CC BY-SA 3.0, Wikimedia Commons (2013).



A whole mouse central nervous system — brain and spinal cord, GlyT2::EGFP, X-CLARITY — in one dataset. mesospim.org

Widefield floods the sample and collects everything, in focus or not.

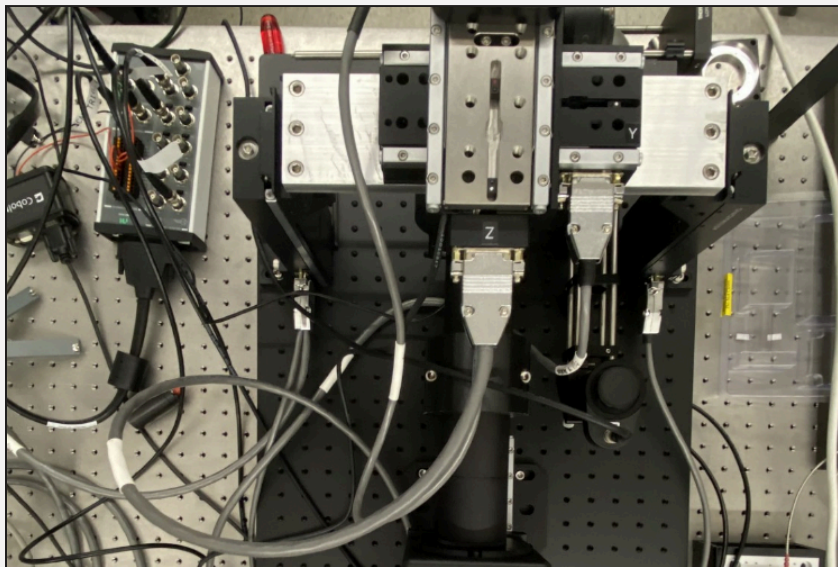
Confocal rejects the rest with a pinhole — clean, but point by point, and the whole cone is still excited.

Light-sheet excites only the plane it images: almost no bleaching, and a volume is a stack of camera frames.

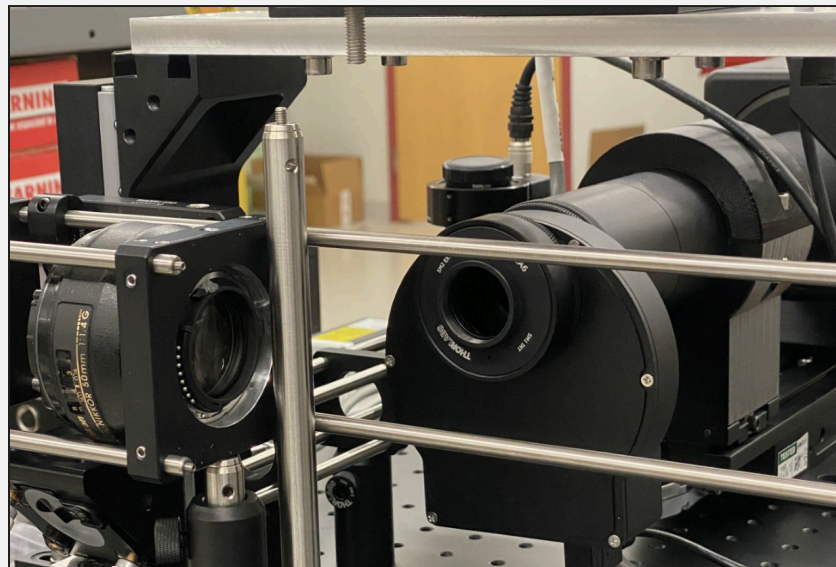
READING THE DAMAGE OUT

mesoSPIM @ VT

Light-sheet fluorescence microscopy — image the crystal volume plane by plane and find the defects.



The instrument: excitation arm, sample stages and detection path on one breadboard.



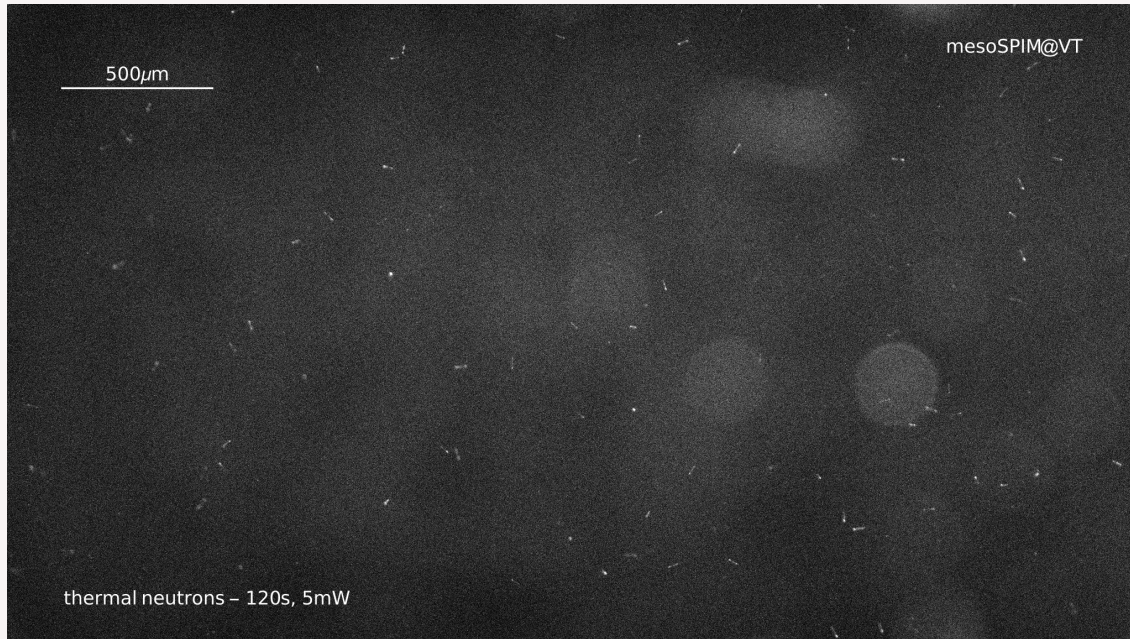
Detection path — the low-noise qCMOS camera is what makes single-defect counting possible.

Major difference to existing mesoSPIM instances — a low-noise qCMOS camera, the Hamamatsu ORCA Quest 2.

First light July 2025.

Thermal-Neutron Tracks

One 120 s exposure at 5 mW. Every streak is a track left in the crystal.



Scale bar 500 μm — tracks are tens of microns long, so they are counted individually and their orientation survives in the crystal.

Towards Reactor CEvNS with LiF

Why a passive crystal detector is the right fit.

Passive detectors

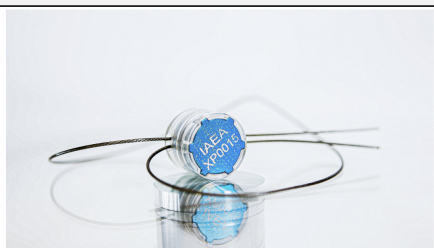
Nothing runs during the exposure — simpler shields, and much reduced gamma sensitivity.

Attractive for non-proliferation

A detector that can sit unattended in an awkward place and be read out later is what safeguards actually want.

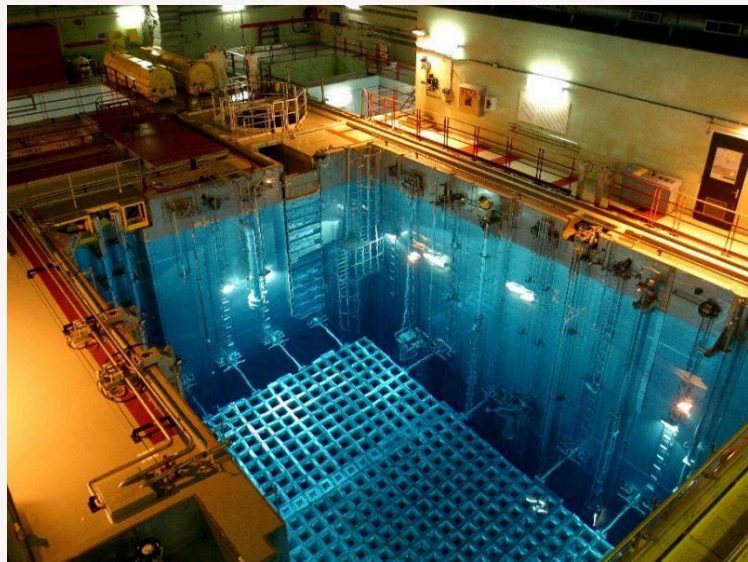
Light nuclei reach below 1.8 MeV

Low mass means more recoil energy per neutrino — access to the sub-IBD part of the spectrum albeit not to breeding neutrinos.



The new field verifiable passive seal does not require any tools to apply or maintenance while deployed.

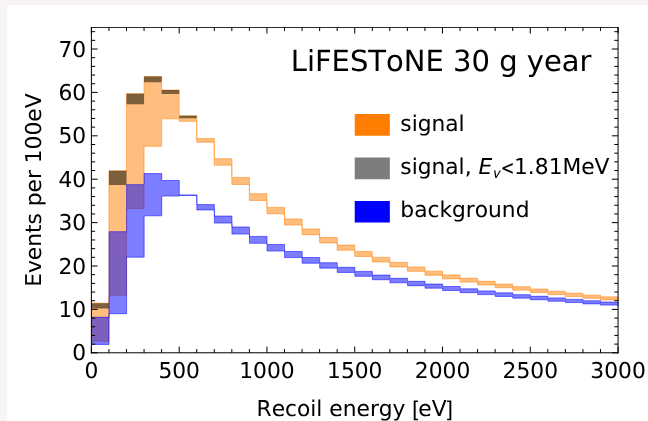
Precedent: the IAEA's field-verifiable **passive seal** — no tools to apply, no maintenance while deployed. Passive instruments are the mainstay in safeguards today.



A spent-fuel pool: maybe the ideal place for a passive detector.

LiFESToNE at CONUS+

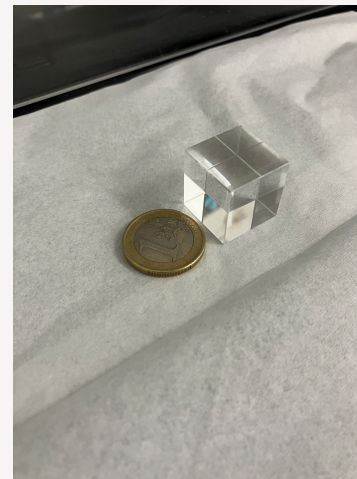
Projected 30 g·year reach, and the crystals going to the reactor now.



Signal, the sub-1.81 MeV component of it, and background — all of it inside the first few hundred eV of recoil energy.



Test LiF detectors will be deployed at the CONUS+ site for background studies.



A $2 \times 2 \times 2$ cm crystal is already **21 g** — under test now, behind a 60 cm water shield.

Summary & Outlook

Takeaways

Applications drive the push to low energy

The case for sub-MeV sensitivity comes from safeguards and reactor monitoring, not from curiosity about the spectrum alone.

Quantum sensing is promising

But collection efficiency at kilogram-scale targets is the hard part, and no one has demonstrated it.

The low-energy recoil problem is shared

Identical detector physics underlies light dark matter searches — see the other lectures this week.

Everything today is gram-scale

Every approach on the table uses gram-scale absorbers. It is unclear whether classic or quantum sensing methods will deliver a first sub-IBD measurement.

AND DON'T FORGET

For applications the SWaP (and cost) of the **deployed** system matters. Systems need to operate unattended over many months.

**And the low-energy excess is a problem for almost all sub-IBD technologies considered here.
Real show stopper if it remains unsolved.**