Erice: INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, 47th COURSE
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Search for CEνNS with Cryogenic Sapphire Detectors at MINER

Dipanwita Mondal*, Varchaswi Kashyap, Bedangadas Mohanty, Rupak Mahapatra

(on behalf of MINER collaboration)

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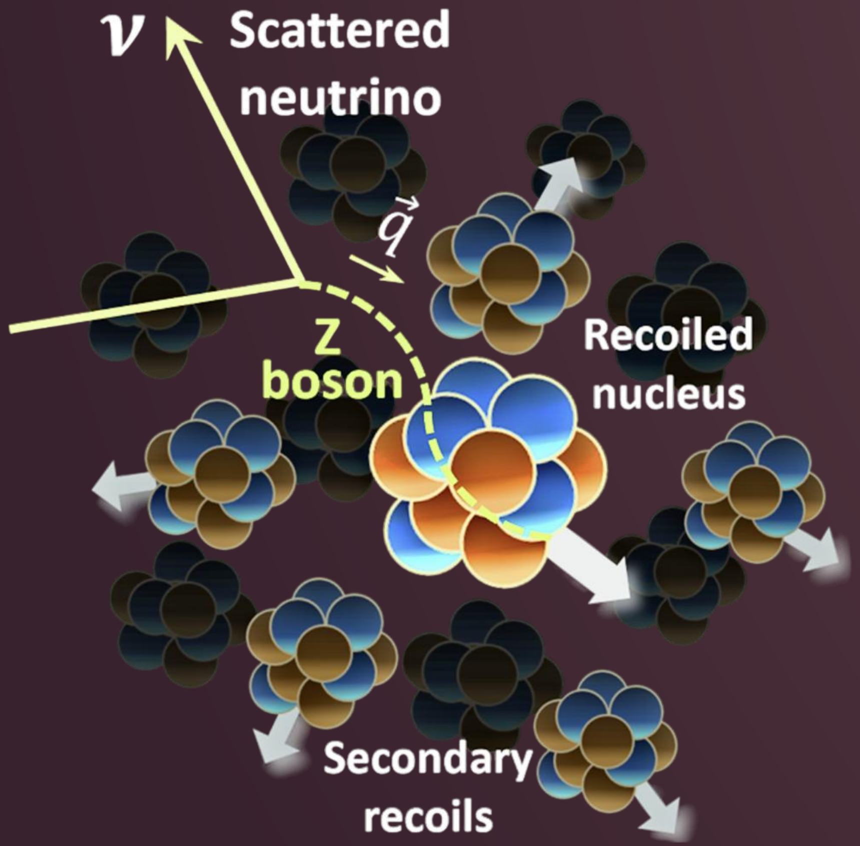
- Introduction
- MINER experiment
- Low energy excess
- Prospects

WHAT IS CEνNS?

CEνNS: Coherent Elastic Neutrino Nucleus Scattering



- First predicted in 1974 by D. Freedman
- Neutrino scatters off the entire nucleus
- Low momentum transfer $|\vec{\mathrm{q}}| \leq 1/\mathrm{R}_{\mathrm{nucleus}}$
- Flavor independent neutral current process
- The SM cross-section scales as N^2,

$N \rightarrow$ neutron number

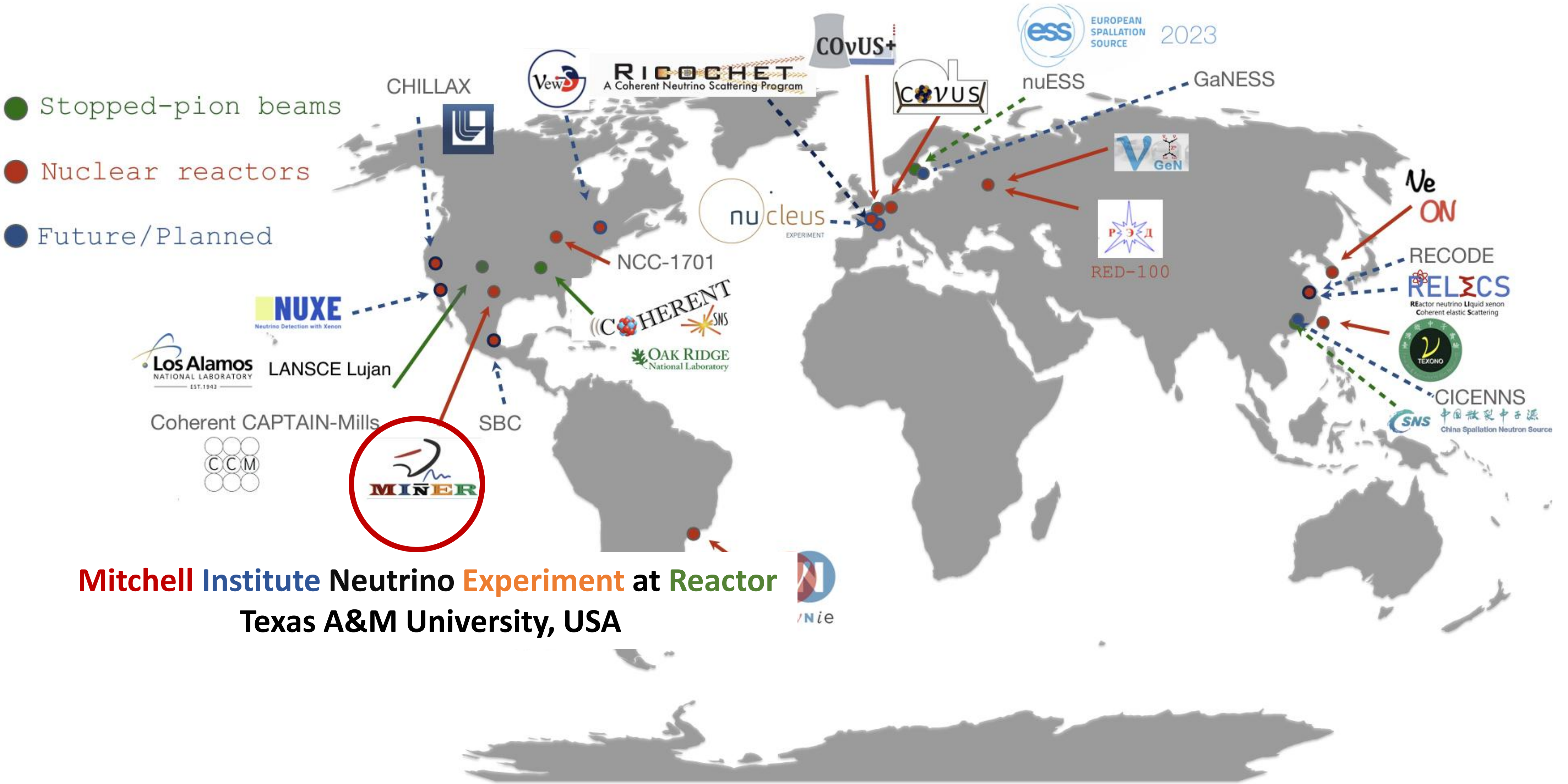
  - Enhanced for heavy nuclei but recoil energy reduces

- Recoil energy $\mathcal{O}(10 - 1000\ \mathrm{eV})$
- Offers sensitivity to both SM and BSM physics.

CEνNS EXPERIMENTS

Adapted from C. Bonifazi, Neutrino 2022

CEνNS EXPERIMENTS

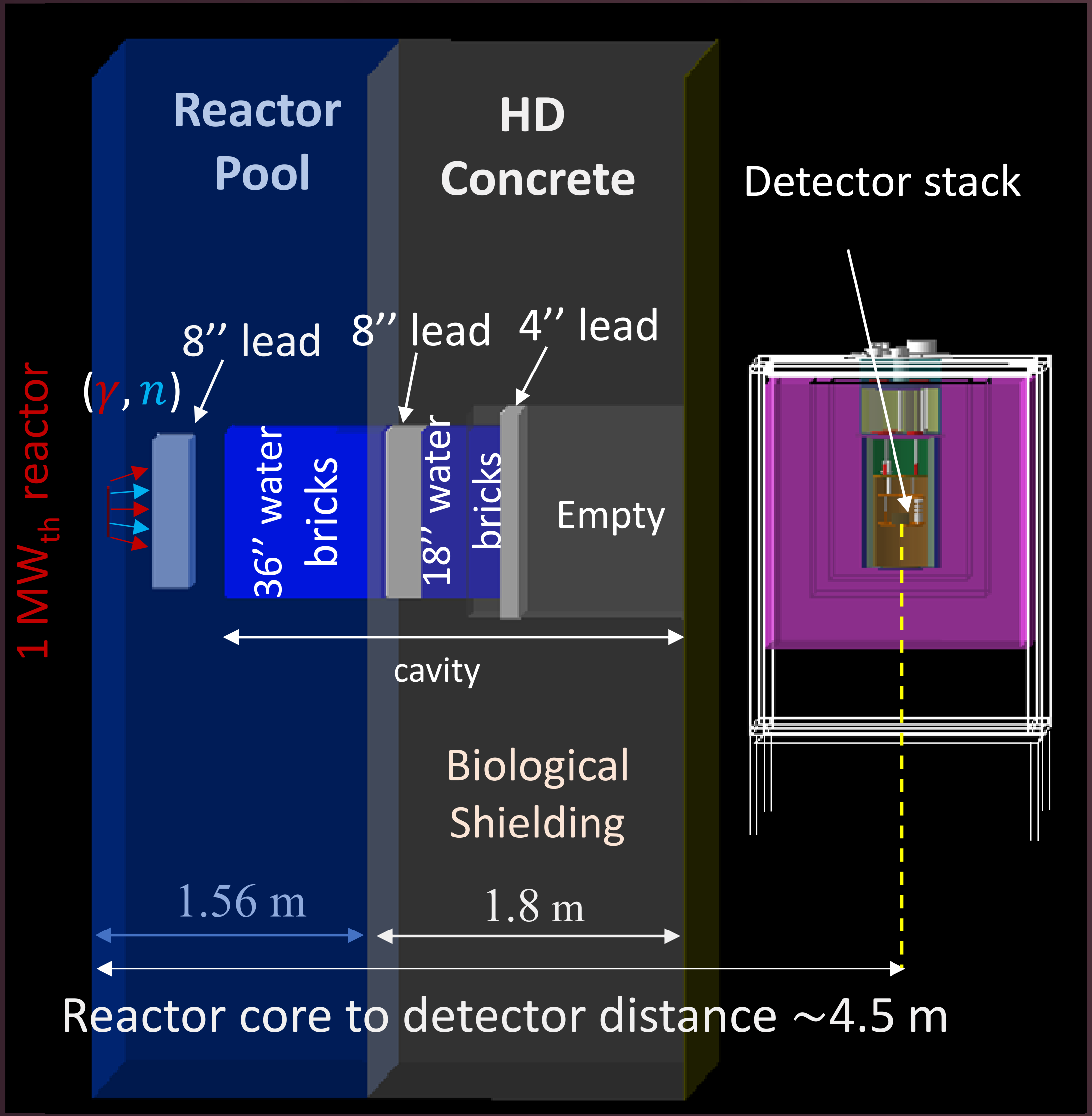


Mitchell Institute Neutrino Experiment at Reactor
Texas A&M University, USA

Adapted from C. Bonifazi, Neutrino 2022

MINER SETUP

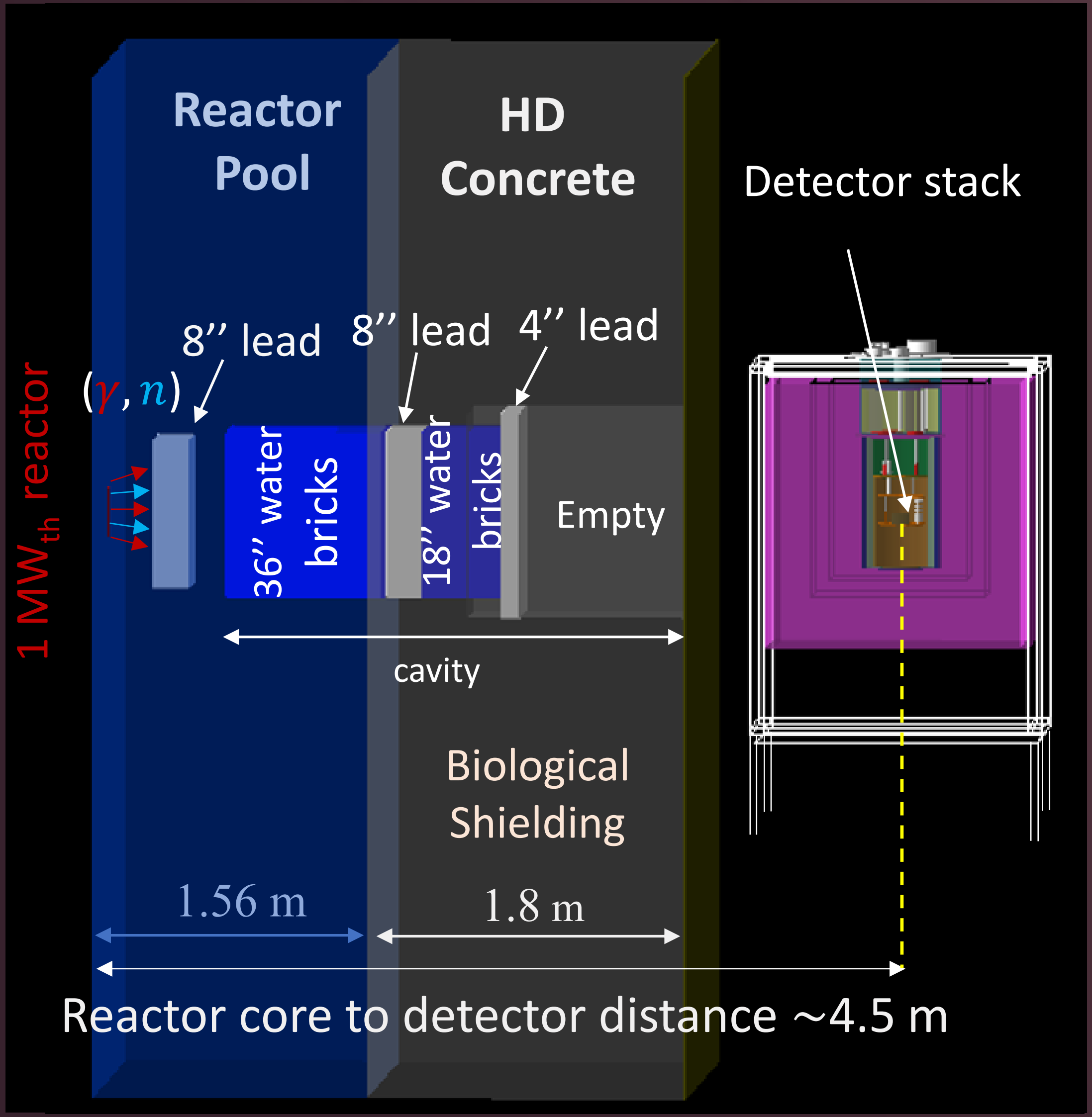
Experimental setup



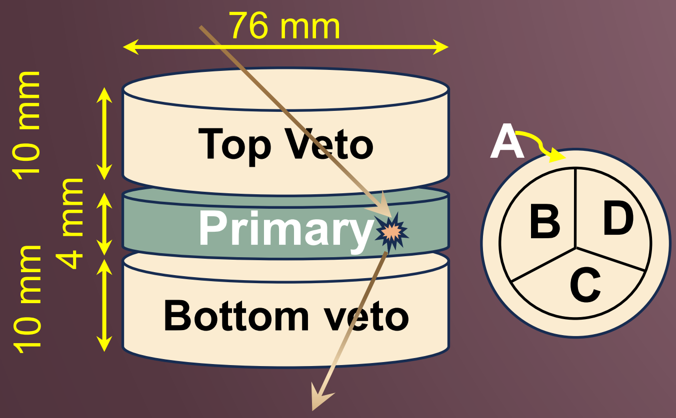
- Reactor power: 1 MW$_{th}$
- Baseline distance: 4.5 meters

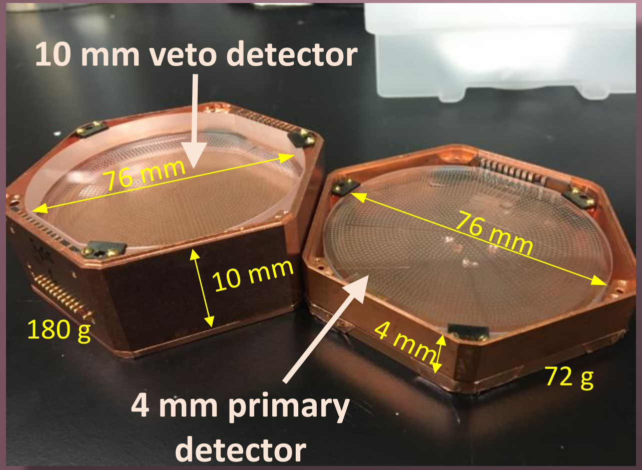
MINER SETUP

Experimental setup



Reactor core to detector distance ~4.5 m





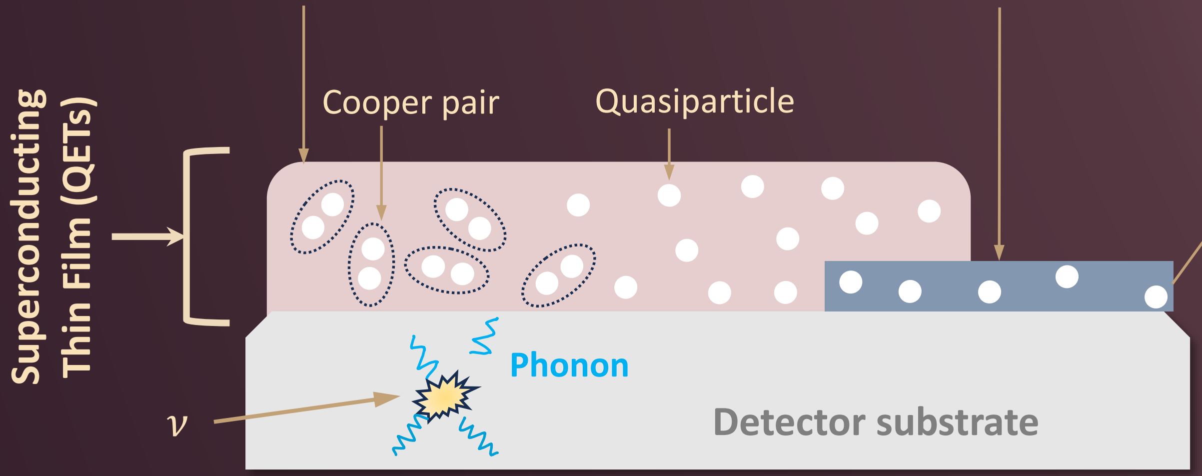
Detector	Baseline resolution [eV]
Primary	40
Veto	120

- Reactor power: 1 $\mathrm{MW_{th}}$
- Baseline distance: 4.5 meters
- Region of interest: 250 eV – 3 keV

CRYOGENIC DETECTION TECHNOLOGY

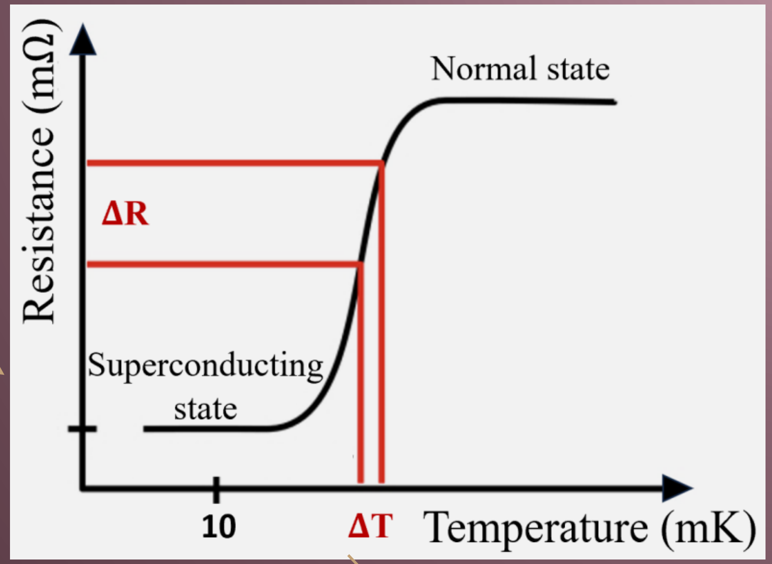
First superconductor (Al fin):
- Large volume
- Large bandgap energy (~340 μeV)
- Collect the phonons

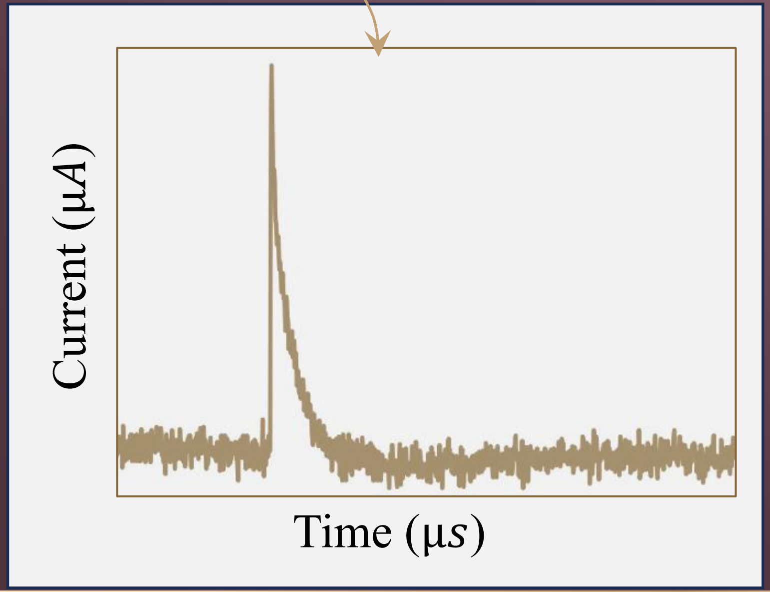
Second superconductor (Tungsten TES):
- Transition Edge Sensor
- Small bandgap energy (~20 μeV)
- Kept at its transition temperature (mK)



- Suitable for low recoil energy detection
- Provides excellent baseline resolution

Transition Edge Sensor graph

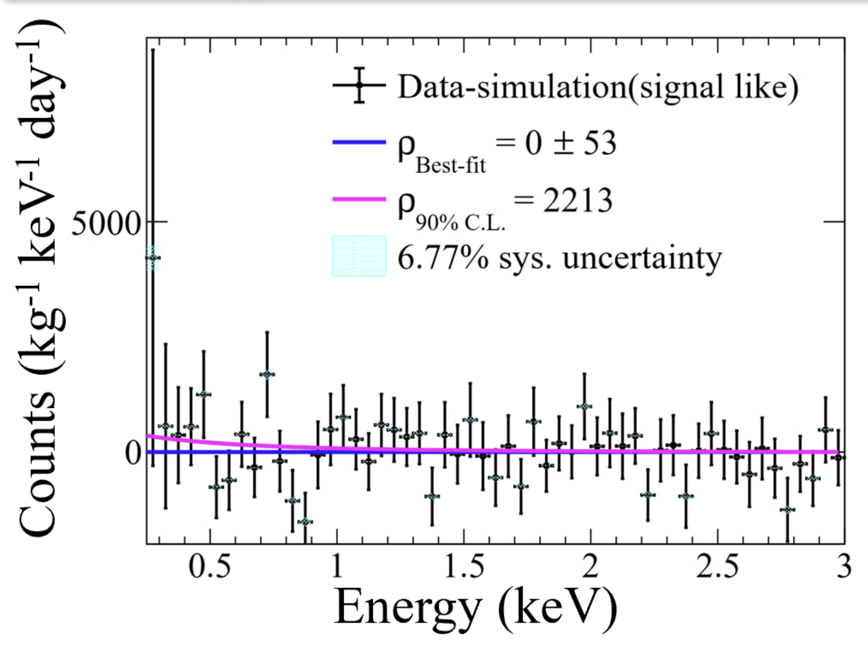




DATA AND SIMULATION RESULTS

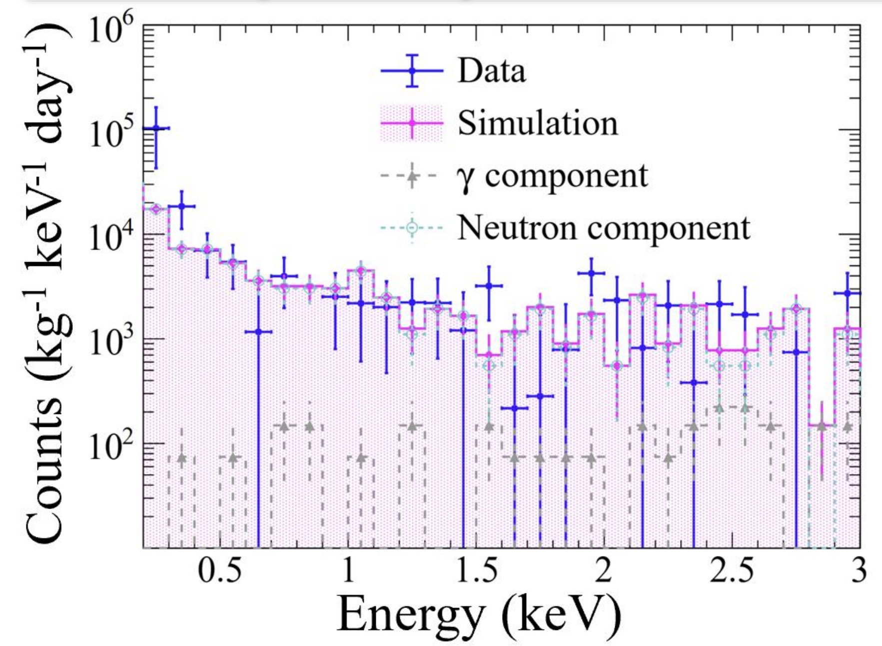
Phys. Rev. D ***114****, 032009*

χ^2- minimization



- ρ → ratio between data to SM cross section
- Upper limit set on ρ
- Theory prediction ~0.14 events/day/kg
- No hint of CEνNS event observed

Data (ON-OFF) vs simulation



- Reactor ON-OFF spectra agrees with simulation
- Data is dominated by reactor-related background
- Neutron background dominates over γ background
- Mismatch between data & simulation in 200-400 eV

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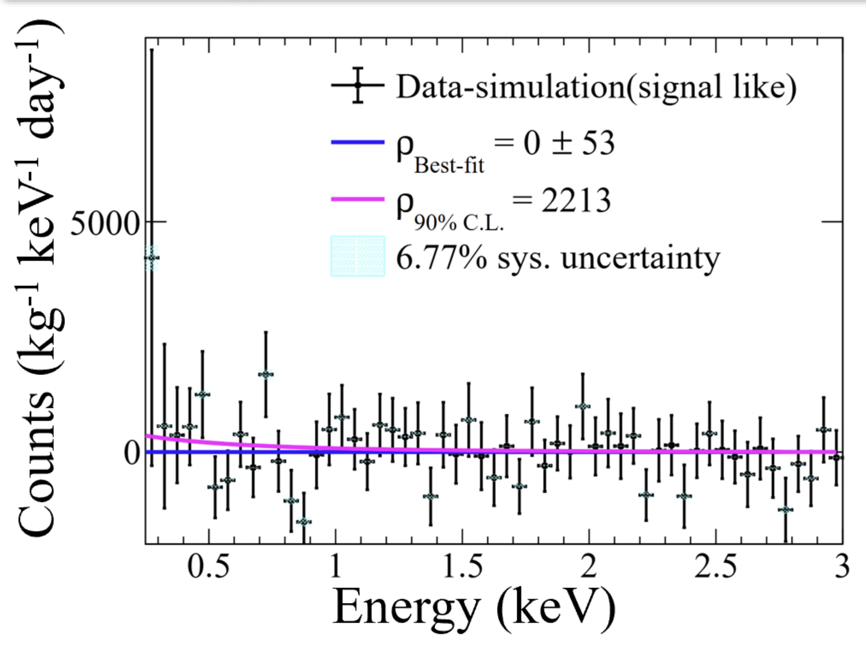

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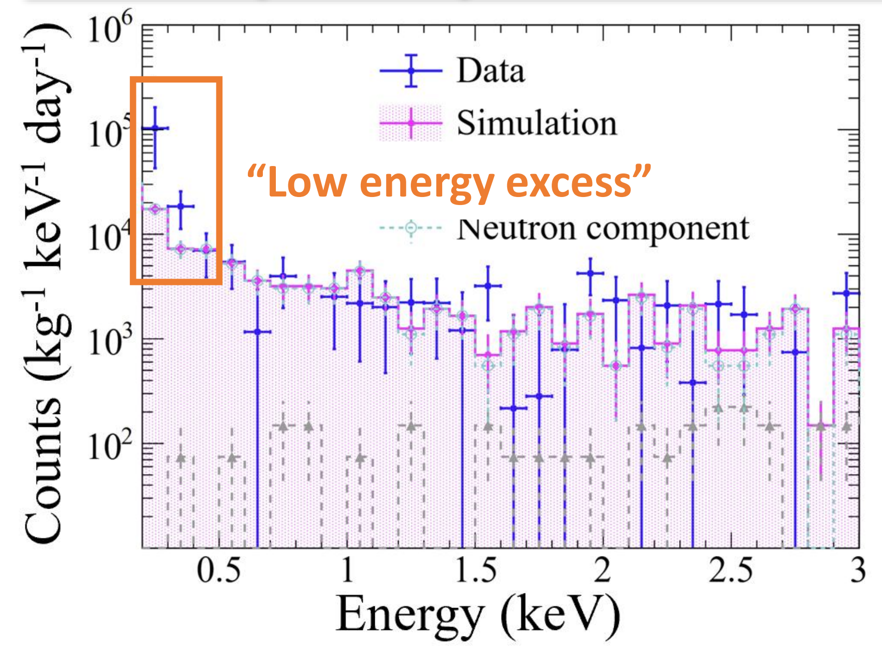

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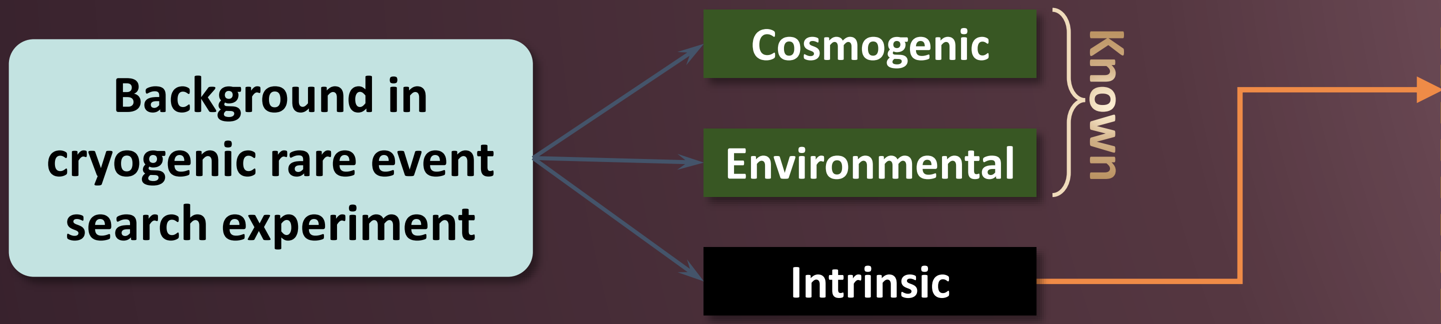
LOW ENERGY EXCESS



Background in cryogenic rare event search experiment

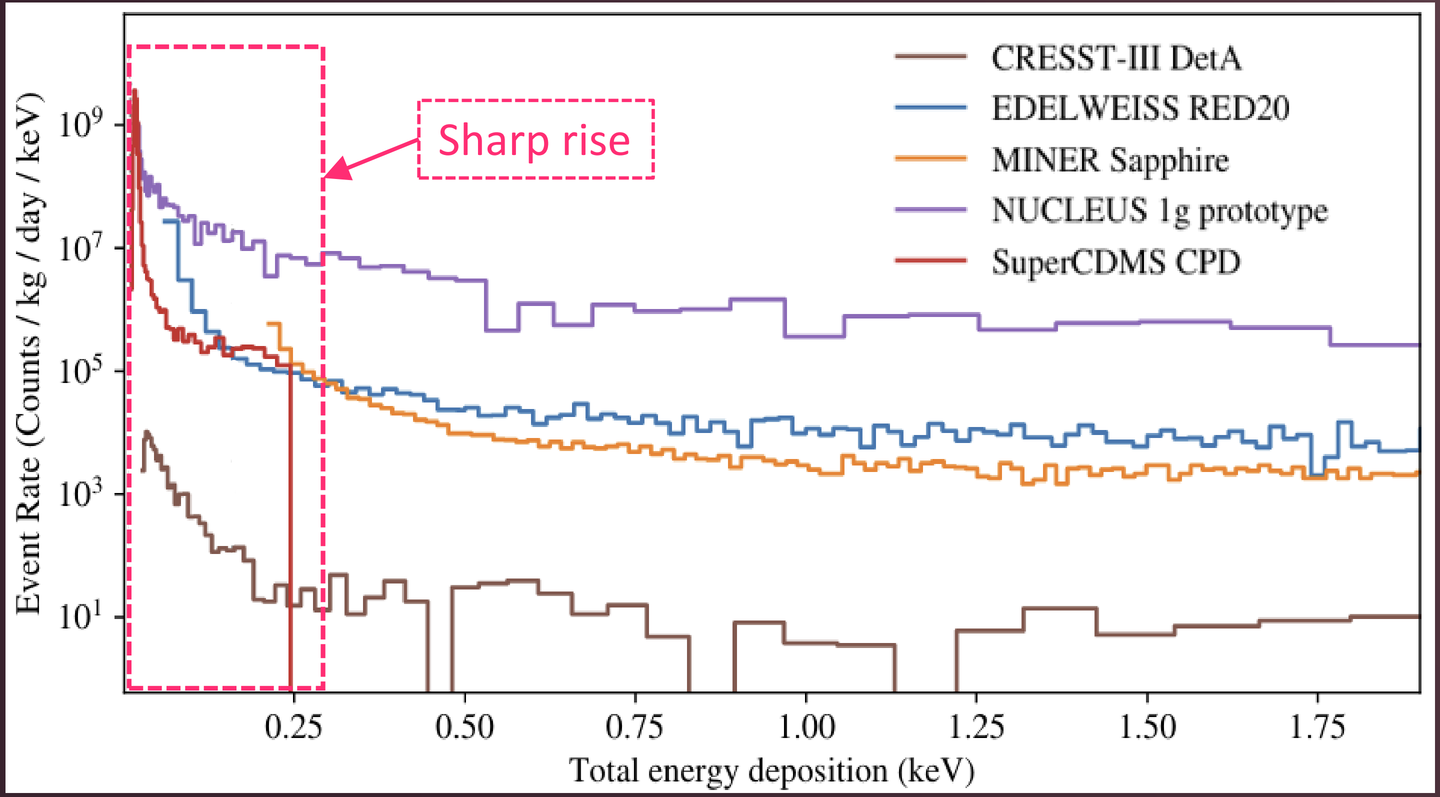
Cosmogenic

Environmental

Intrinsic

Known

SciPost Phys. Proc. 9, 001 (2022)

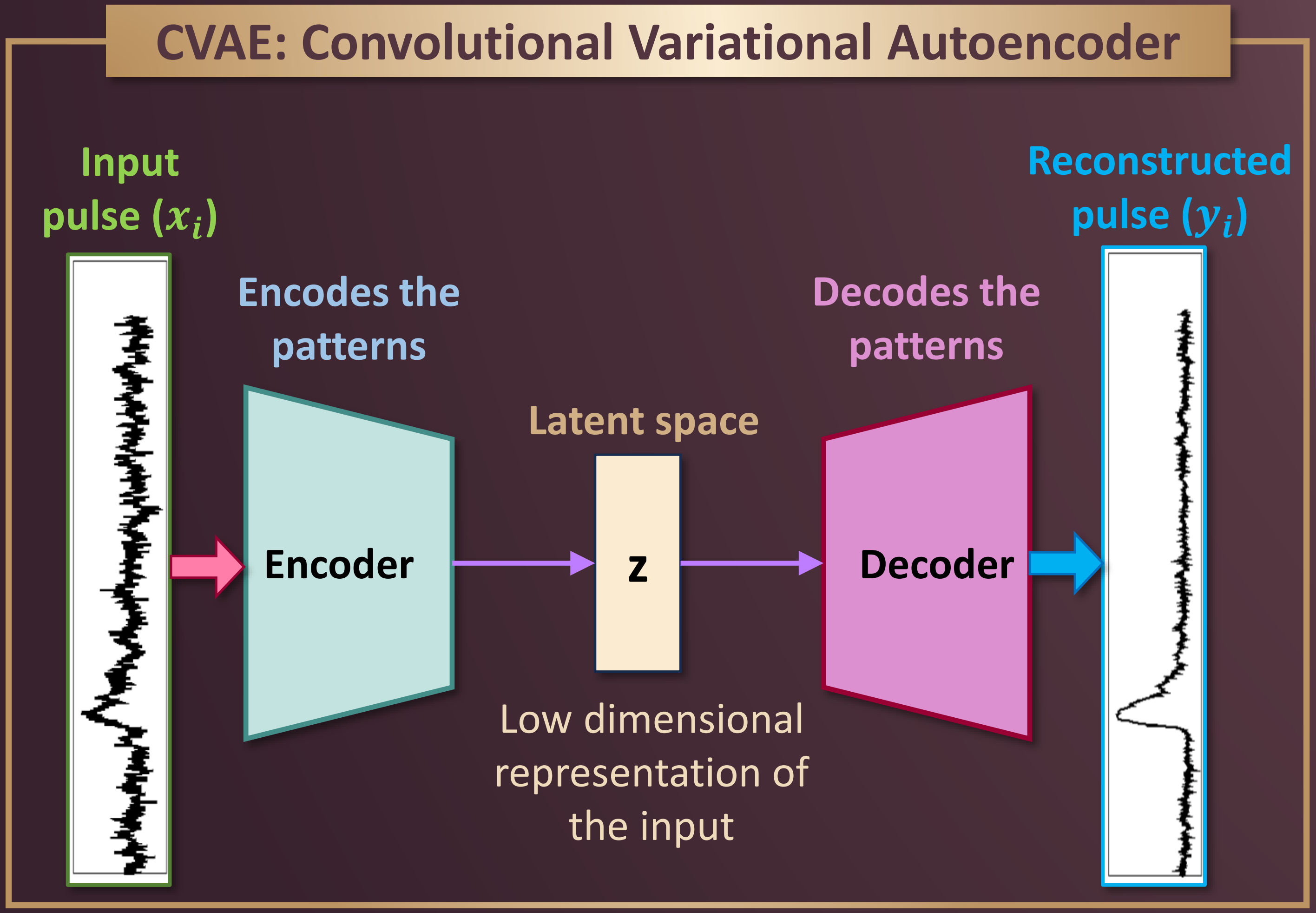


Sharp rise

LEE: Low-Energy Excess

- Event rate rises sharply toward the detector threshold
- Unexplained by known background sources
- Rate decreases with time
- Reappears following a warm-up and recooling cycle
- Limits sensitivity to rare low-energy signals such as CEνNS and Dark Matter searches

CVAE NETWORK



CVAE: Convolutional Variational Autoencoder

Input pulse (x_i)

Encodes the patterns

Encoder

Latent space

z

Low dimensional representation of the input

Decodes the patterns

Decoder

Reconstructed pulse (y_i)

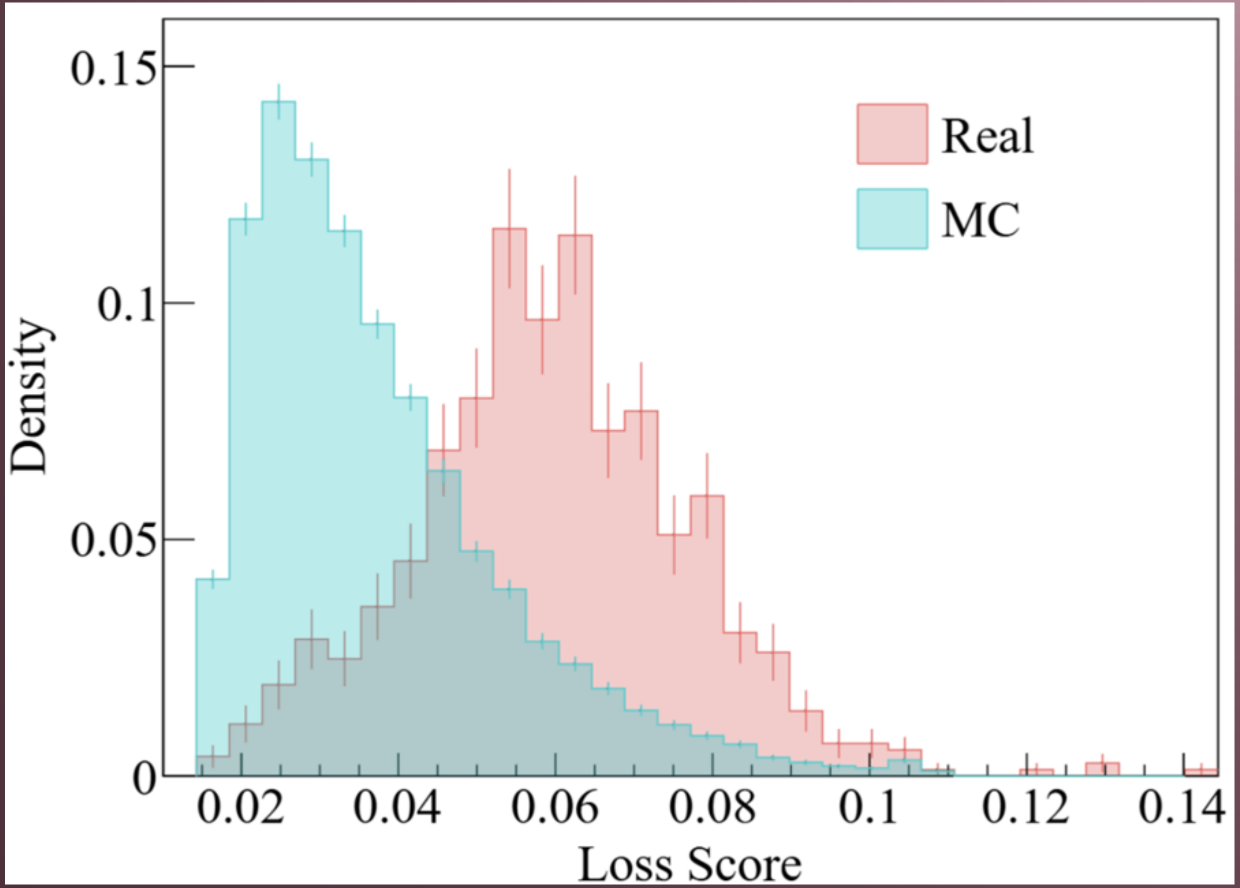
Reconstruction loss

$$\left(\frac{1}{N}\sum_{i=0}^{N}(x_i - y_i)^2 + \beta D_{KL}\right)$$

- x_i → input (pulse)
- y_i → CVAE output (recounstructed)
- N → No. of sample points (1024)
- β → constant weightfactor
- D_{KL} → Regularization term

RECONSTRUCTION LOSS: REAL VS MC

- Most MC events populate the low-loss region.
- Real data exhibits a significant population at higher loss values.
- An overlap region remains where signal-like and LEE events are not fully separated.

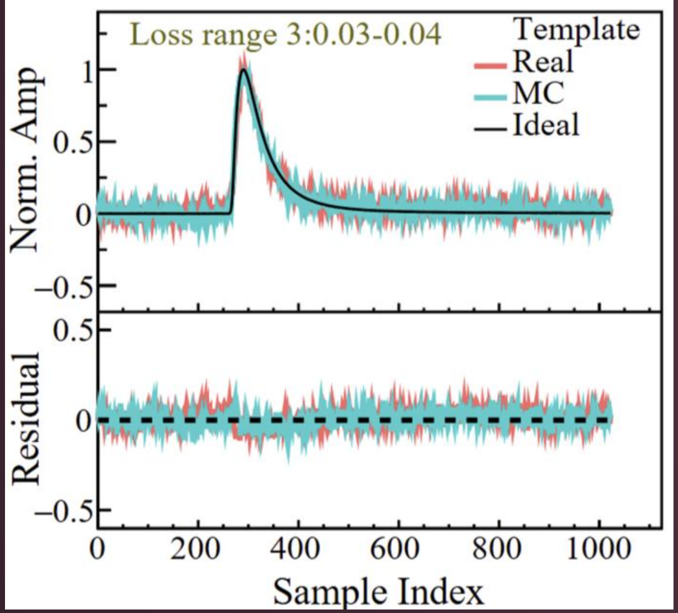


Pulse-shape evolution across loss-score intervals

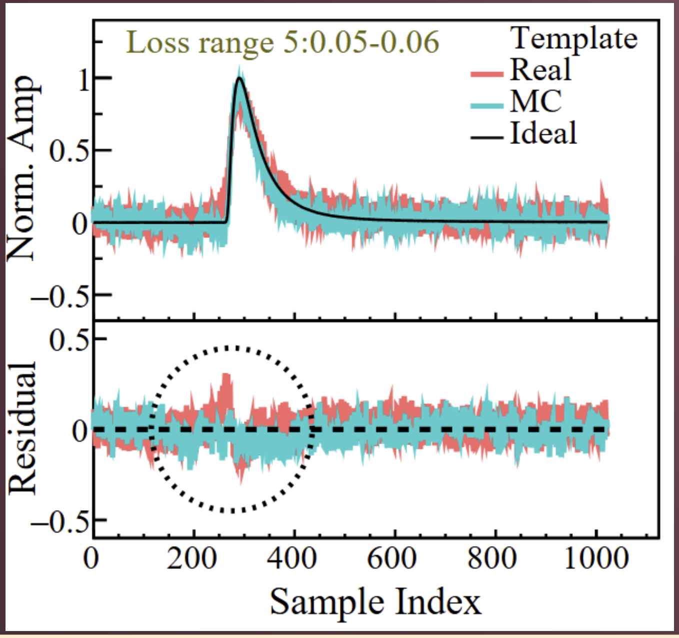
arXiv:2605.31190

ANOMALY IDENTIFICATION

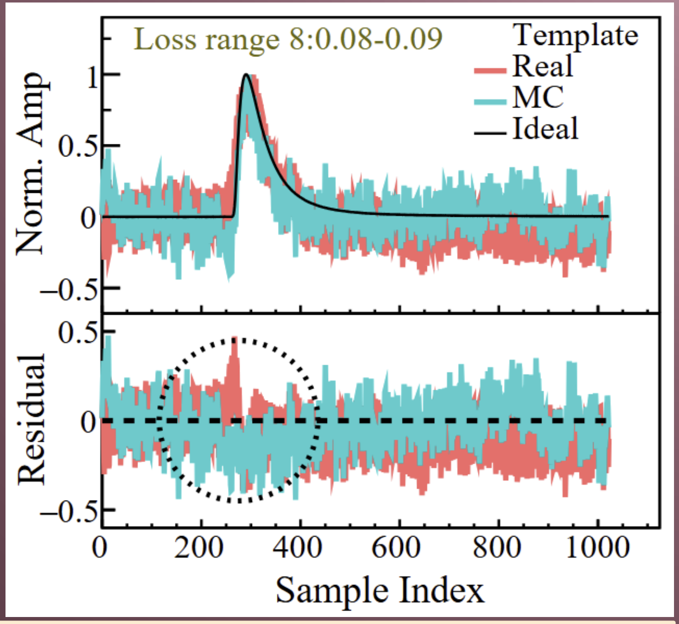
Low loss score



Mid loss score



High loss score

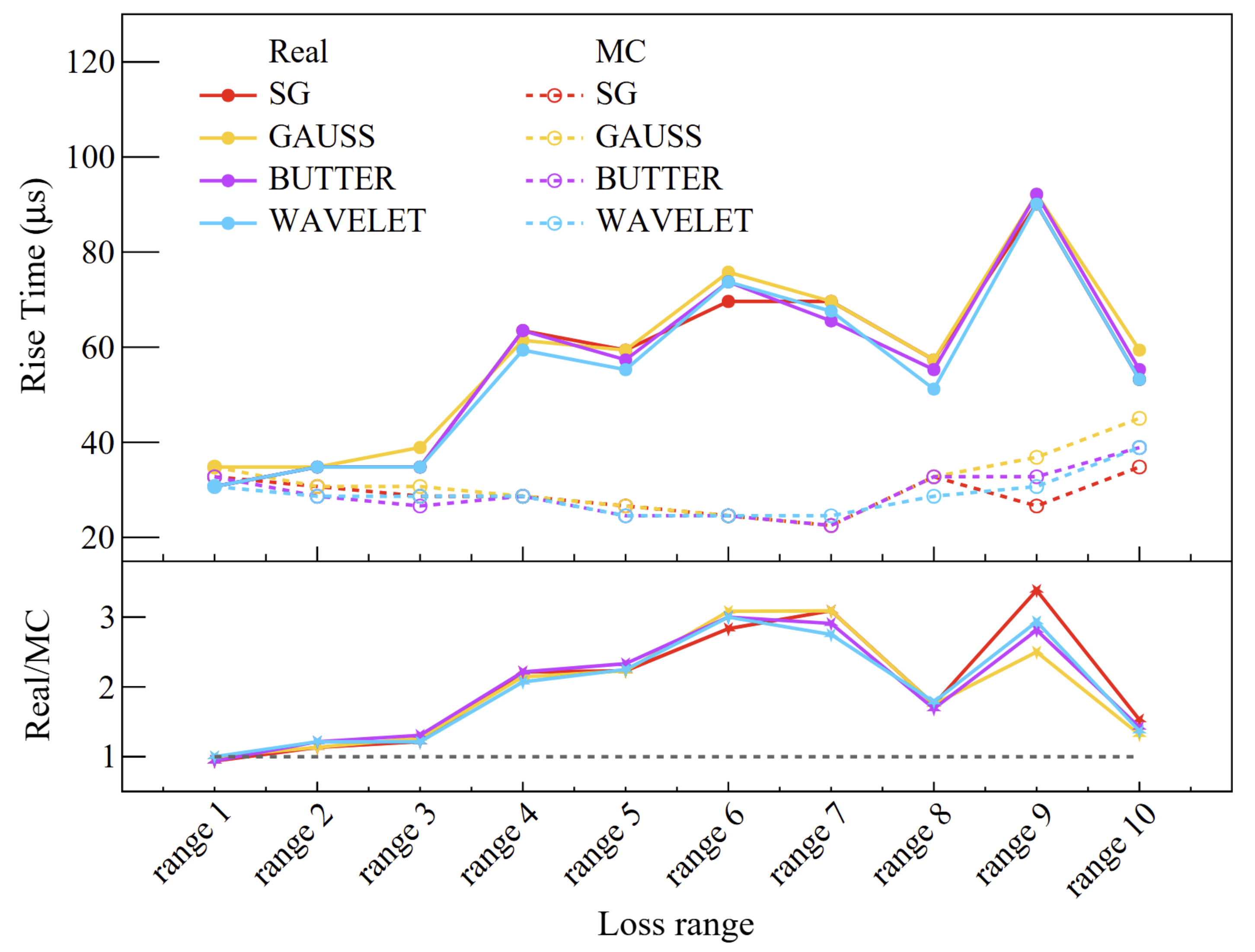


- Loss scores divided into 10 intervals (0–0.11).
- Residual mismatch appears for loss > 0.04.
- A slow-rise component emerges in real-data templates at higher loss scores.

Real-template show slower rise times compared to MC templates.

arXiv:2605.31190

TEMPLATE LEVEL RISE-TIME ESTIMATION



Multiple filtering algorithms tested to avoid bias.

- MC templates' rise time: 20 – 40 μs
- Rise time for real data templates reaches 3 times of the MC between 0.06 – 0.08.

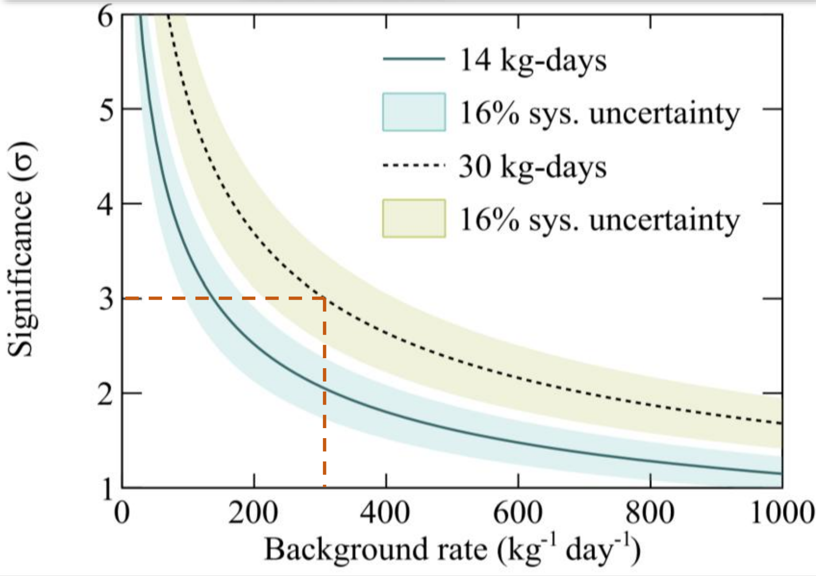
Developed a rise-time threshold to estimated the improvement in detection sensitivity.

arXiv:2605.31190

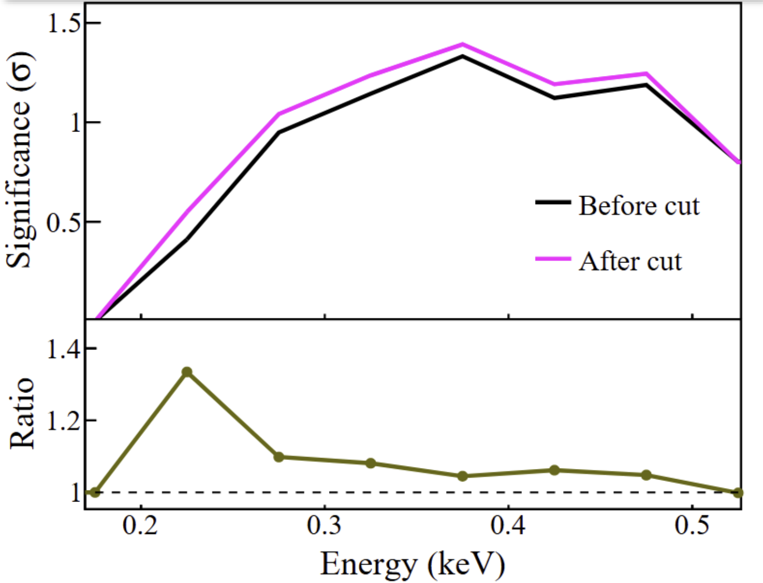
PROSPECTS: MINER@HFIR

Experiment	Power $[\mathrm{MW}_{th}]$	Baseline [m]	flux $[\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	Event rate $[\mathrm{kg}^{-1}\mathrm{day}^{-1}]$
MINER	1	4.5	$\sim 7 \times 10^{10}$	~ 0.14
MINER@HFIR	85	5	$\sim 5 \times 10^{12}$	~ 10

MINER@HFIR



Sensitivity improvement



- 3σ can be achieved in 30 kg. day of data taking with ~ 300/kg/day background level
- $Z = \frac{s}{\sqrt{s+b}}$
- 40% improvement in the lowest-energy bin
- Overall significance: 2.8σ to 3.1σ (~10% improvement)

arXiv:2605.31190

SUMMARY

- MINER demonstrates ultra-low-threshold CEνNS detection capability using cryogenic sapphire detectors, achieving a baseline energy resolution of 40 eV.
- No statistically significant CEνNS excess was observed in MINER at TRIGA
- Pulse-shape analysis identifies an anomalous slow-rise pulse population associated with the low-energy excess and enables rejection of a substantial fraction of these events.
- The move to HFIR, combined with improved background rejection, provides significantly enhanced prospects for a first CEνNS measurement with MINER.

Stay tuned !


CENTRO ETTORE MAJORANA
Blackett-San Domenico
APERTURA SERALE
LUGLIO - SETTEMBRE
19.00 - 22.30
EVENING OPENING
JULY - SEPTEMBER
7.00-10.30 P.M.
tutti i giorni / everyday 10.00-19.00
VISITA ERICE
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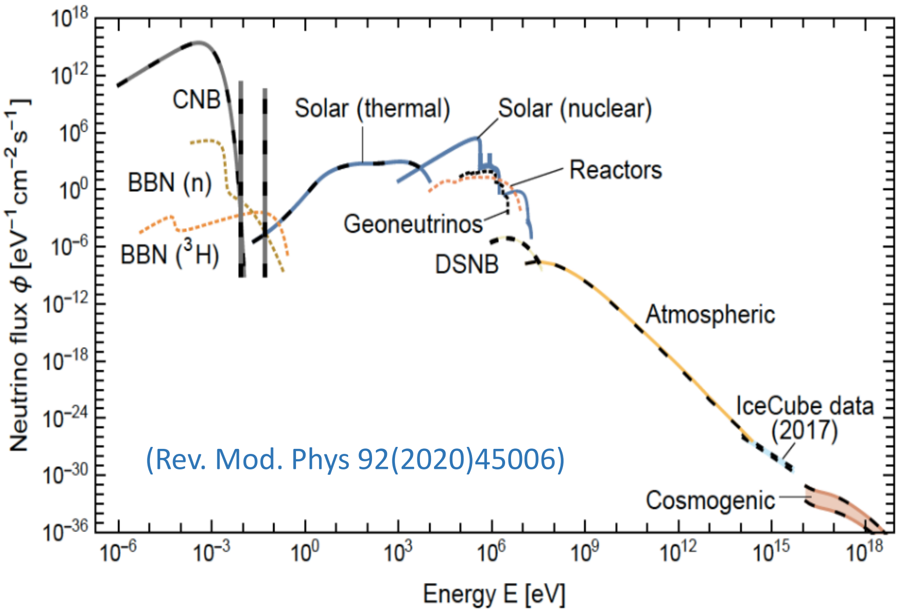
Thank you!!

BACKUPS

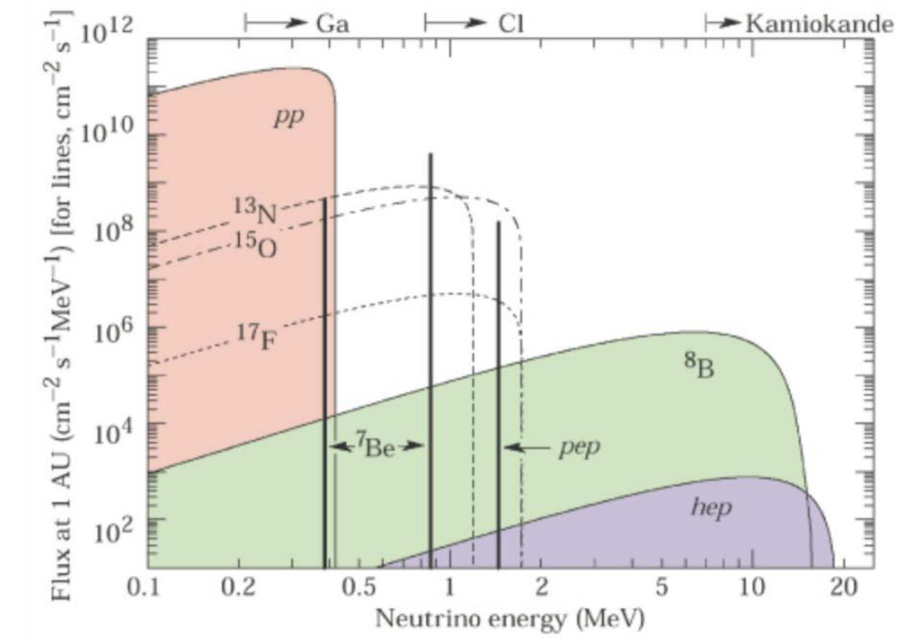
NEUTRINO SOURCES

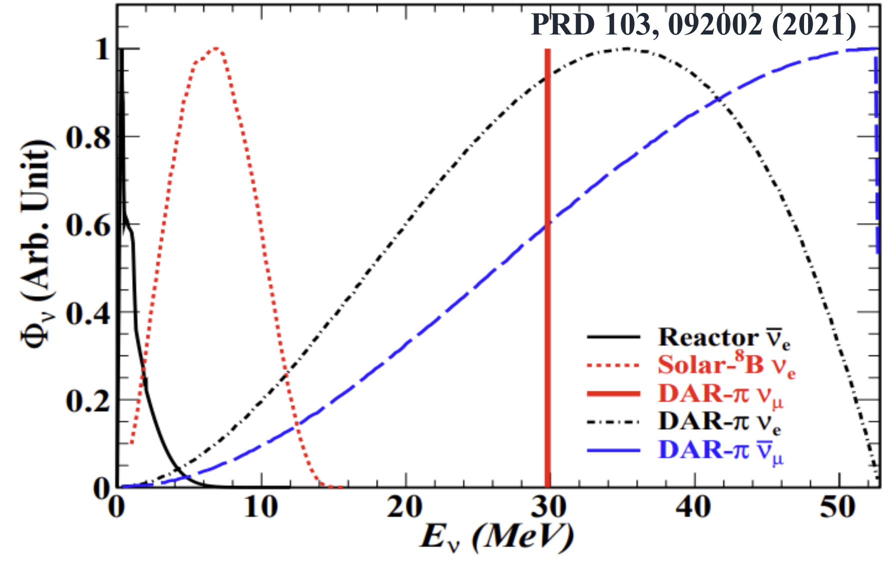
Grand unified neutrino spectrum at earth



(Rev. Mod. Phys 92(2020)45006)

Neutrino source type	Energy range
Solar	0.1 MeV – 20 MeV
Atmospheric	0.1 GeV – 100 TeV
Supernova	10 – 50 MeV
Spallation	1- 100 MeV
Accelerator	10 MeV - GeV
Reactor	0.1 – 10 MeV





PRD 103, 092002 (2021)

CEνNS CROSS - SECTION

- Differential cross- section for CEνNS

$$\frac{d\sigma(E_\nu,T)}{dT}=\frac{G_F{}^2M}{\pi}\left(1-\frac{MT}{2E_\nu^2}\right)\times\left[\mathcal{Q}_W^{\mathcal{N}}(|\vec{q}|)\right]^2$$

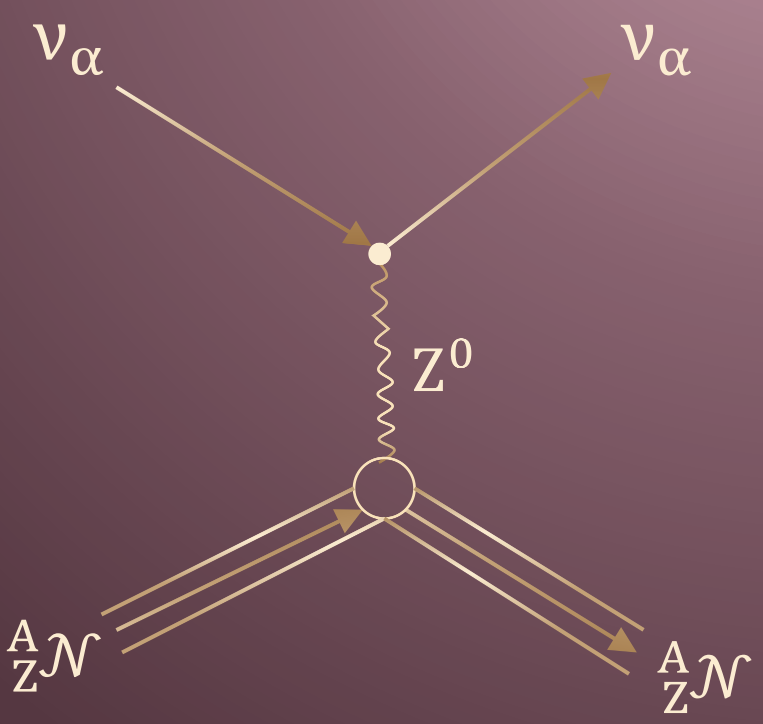
$$\mathcal{Q}_W^{\mathcal{N}}(|\vec{q}|)=g_V^{n}\,N\,F_N^{\mathcal{N}}(|\vec{q}|)+g_V^{p}\,Z\,F_Z^{\mathcal{N}}(|\vec{q}|)$$

$$\boxed{g_V^{n}\approx-\frac{1}{2}}$$

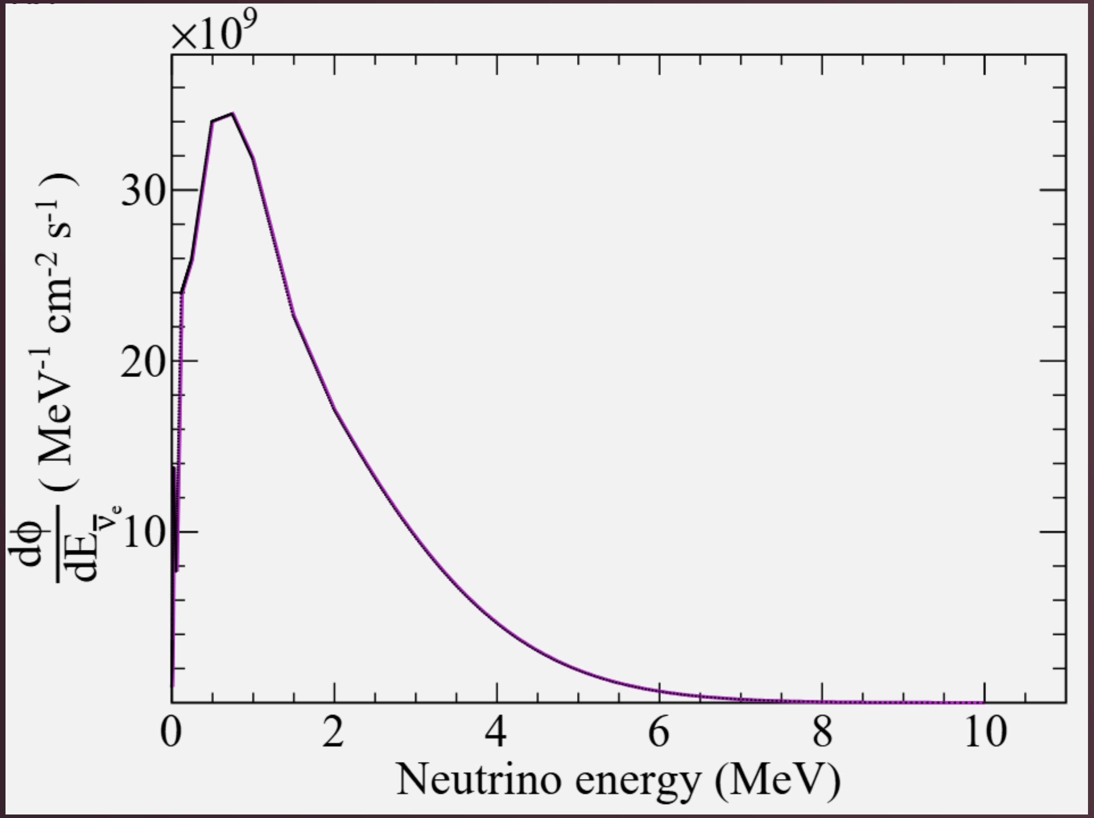
$$\boxed{g_V^{n}\approx\frac{1}{2}-2\times\sin^2\vartheta_W\approx 0.022}$$

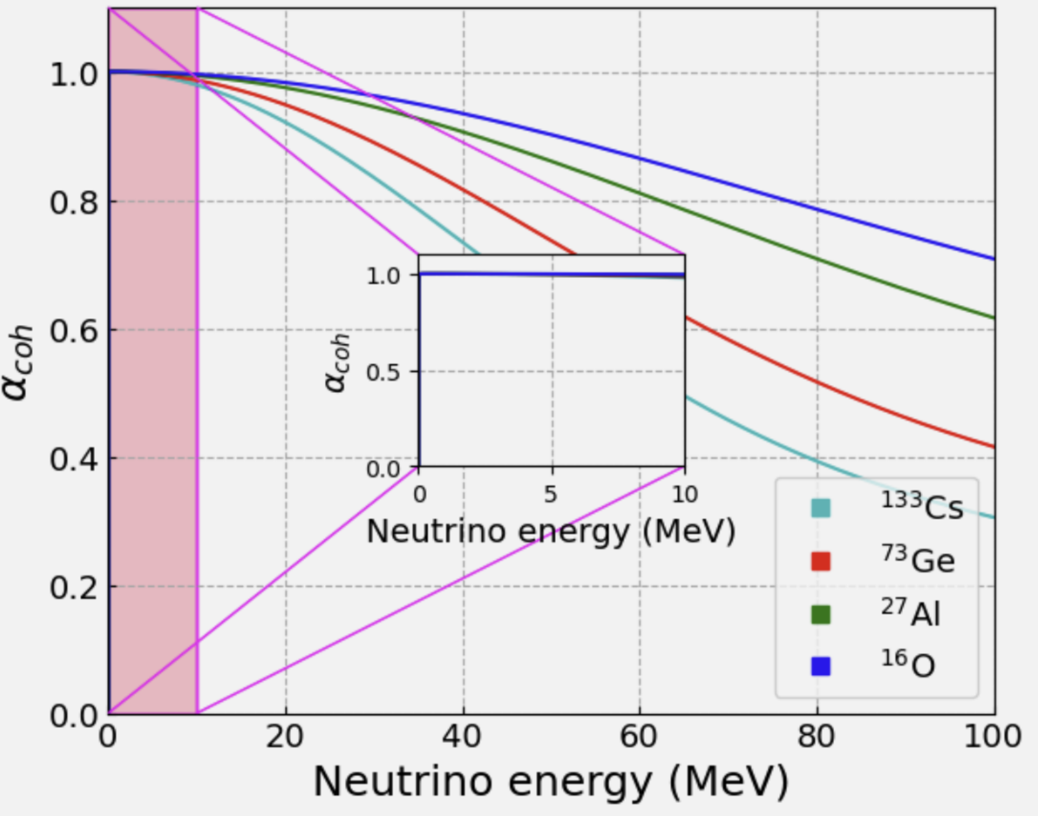
$$\Downarrow$$

$$\sin^2\vartheta_W\approx 0.239$$



COHERENCY FOR REACTOR AS A SOURCE

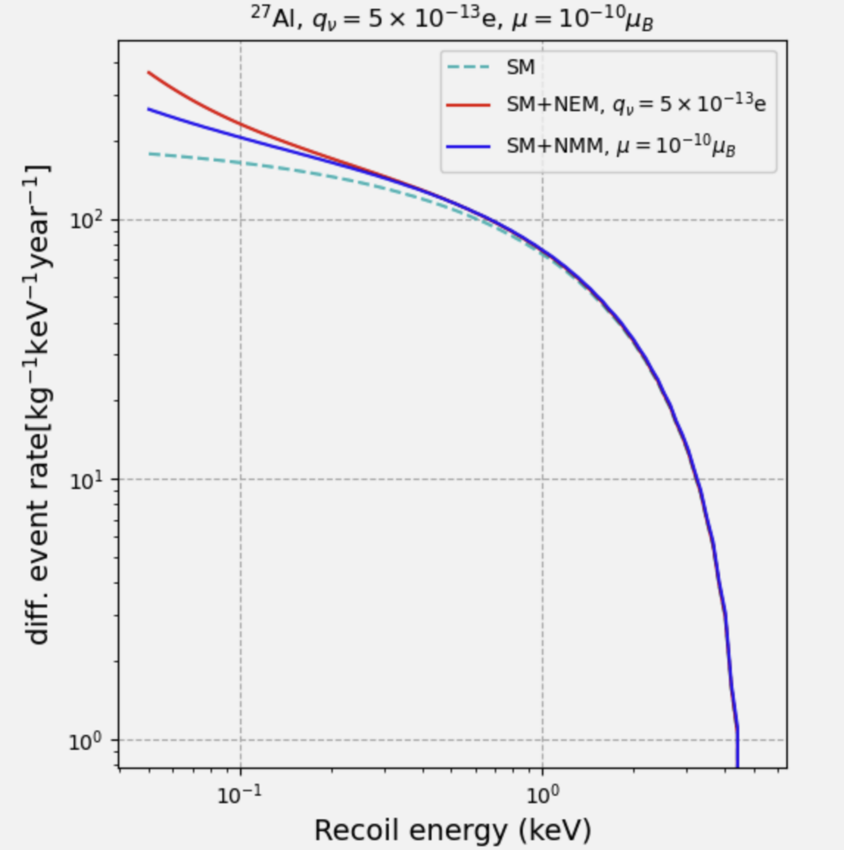


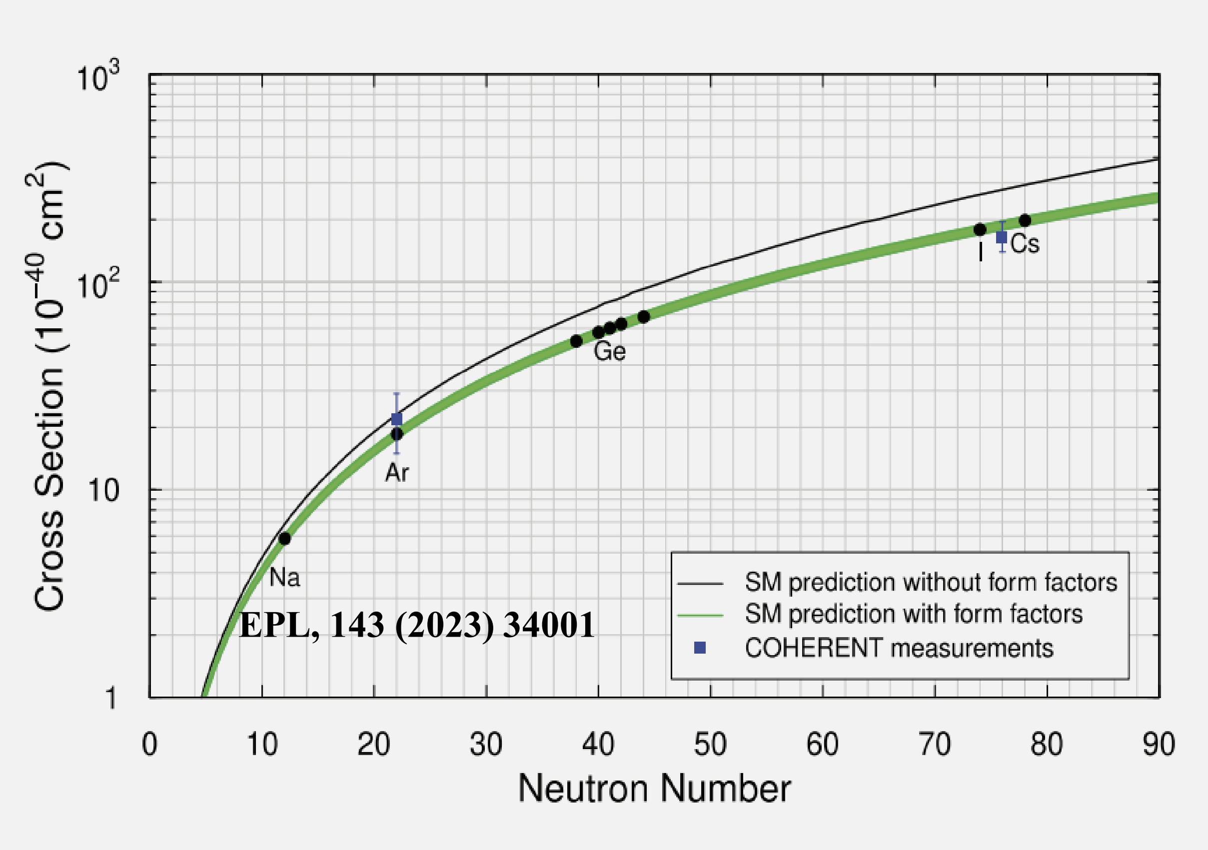


- Reactor power: 1 MW_{th}
- Fuel fraction: U235 (20%) , Pu239 (2%) , U238 (77 %) , Pu241(1%)
- Duty cycle: 100%
- Baseline distance: 4.5 m
- Detector efficiency: 100% (above threshold)

✓ Coherency almost 100% up to 10 MeV

CEνNS AS A PROBE FOR DIFFERENT PHYSICS





EPL, 143 (2023) 34001

- ✓ Excess can be observed in the lower recoil energy region

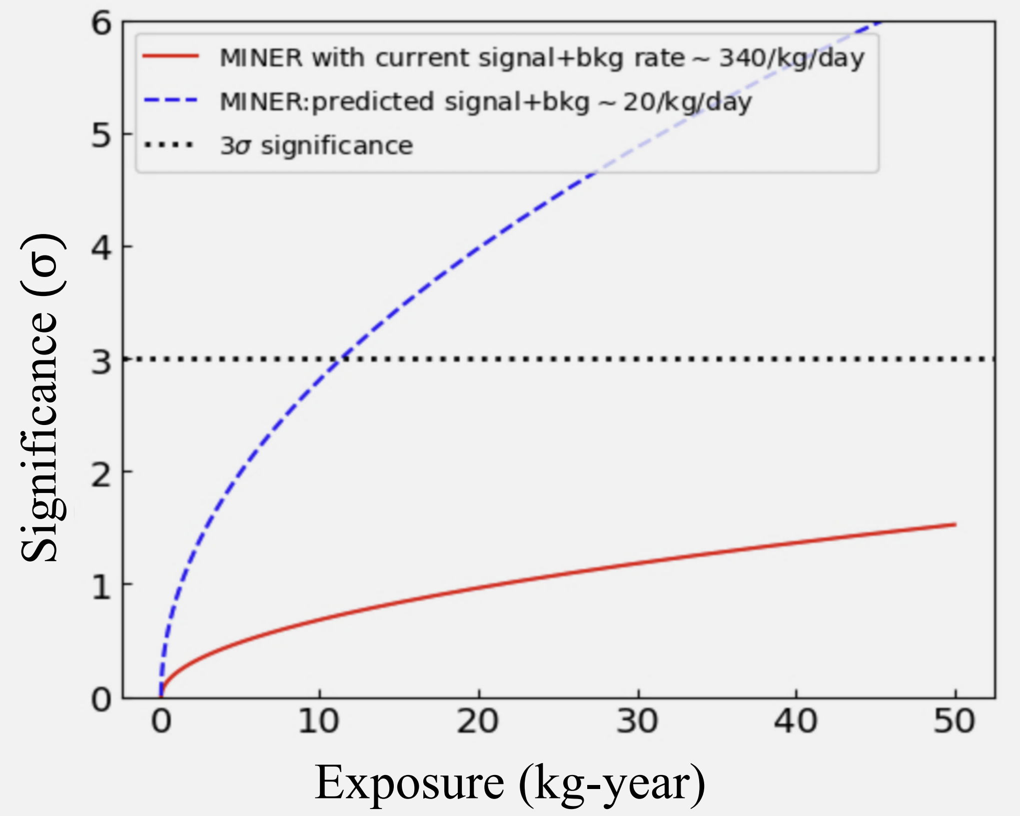
- ✓ Internal structure of the nucleus
  - ○ Neutron distribution is unknown

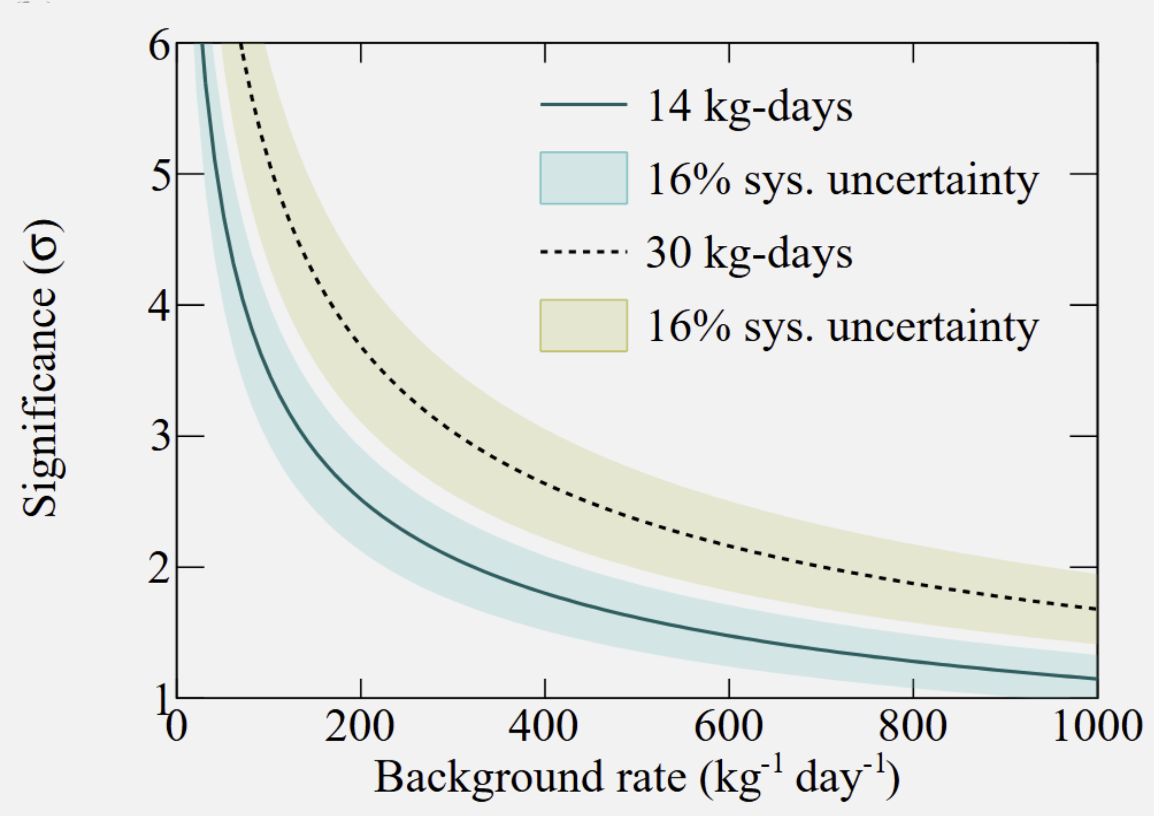
DEFINITION OF χ^2

$$\boxed{\chi^2(\delta,\beta,\zeta;\ \rho) = \sum_i \frac{[R_i^{ON} - \rho(1+\delta)R_i^{SM} - (1+\beta)R_i^{sim} - (1+\zeta)R_i^{OFF}]^2}{\sigma_{i,ON}^2 + (1+\zeta)\sigma_{i,OFF}^2} + \sum_{\mathrm{k}=\delta,\beta,\zeta}\left(\frac{\mathrm{k}}{\sigma_{\mathrm{k}}}\right)^2}$$

- Pull terms & corresponding systematic uncertainties → $\delta(\sigma_\delta = 16\%)$, $\beta(\sigma_\beta = 10\%)$ and $\zeta(\sigma_\zeta = 6.77\%)$
- R_i^{ON} → reactor ON event rate
- R_i^{SM} → theoretical CEνNS rate from SM
- R_i^{sim} → simulated background model
- R_i^{OFF} → reactor OFF event rate (background)
- $\sigma_{\mathrm{i,ON}}$ → statistical uncertainty for reactor ON spectrum
- $\sigma_{\mathrm{i,OFF}}$ → statistical uncertainty for reactor ON spectrum

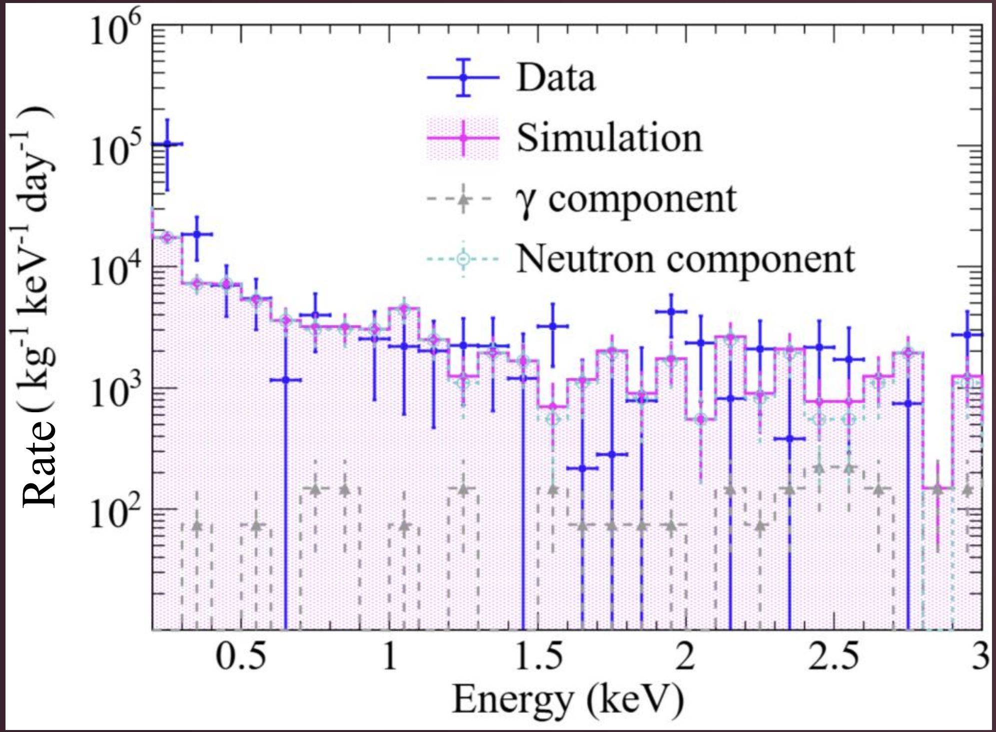
MINER SIGNIFICANCE & HFIR BACKGROUND

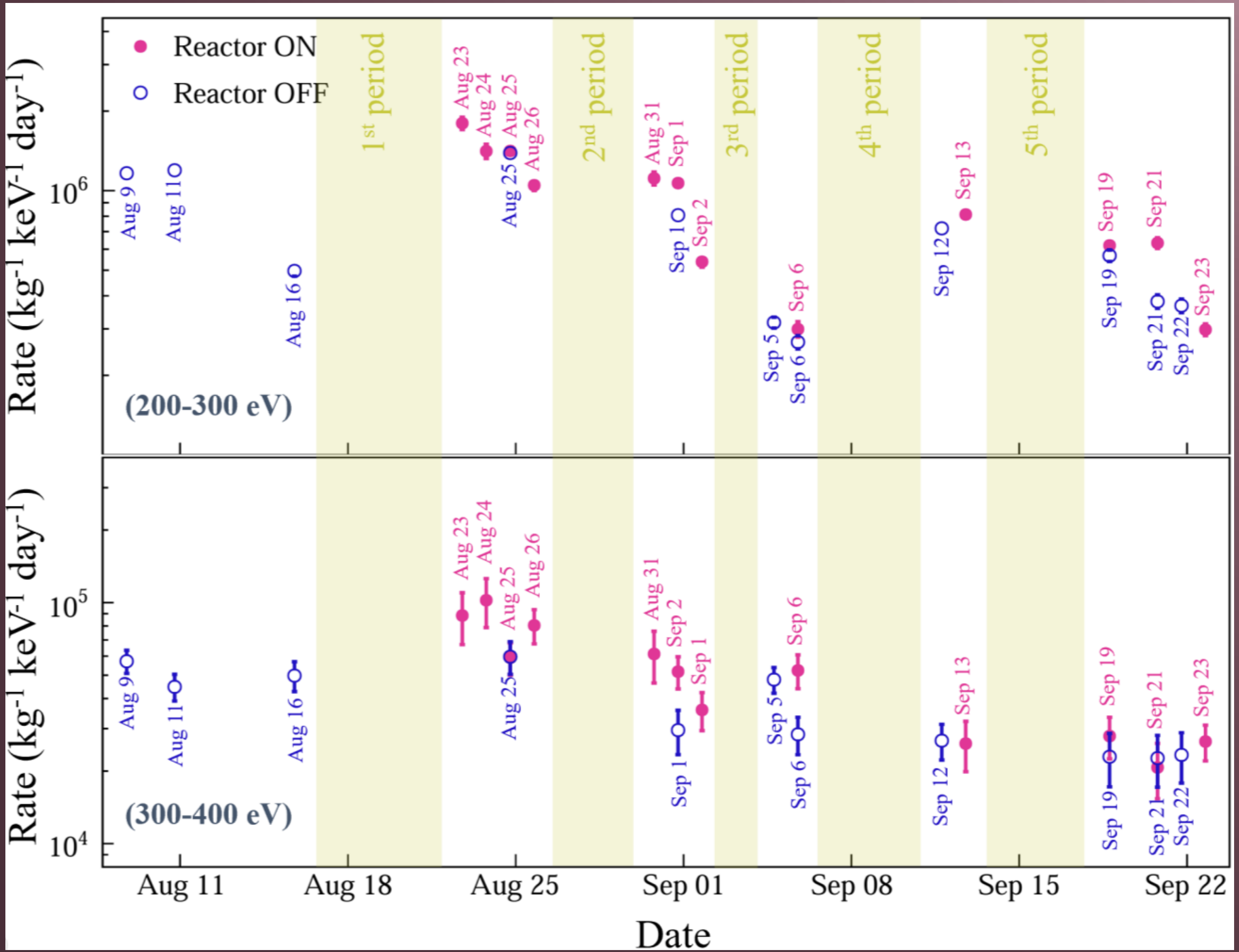




EVIDENCE OF LEE AT MINER

- **MINER (Mitchell institute of neutrino experiment at reactor) → searches for CEνNS at 1 MW$_{th}$ reactor using cryogenic sapphire detector**





- Data–simulation mismatch below 400 eV
- Strong time dependence after warm-up
- Present in both ON and OFF datasets

LEE : CRESST STUDY

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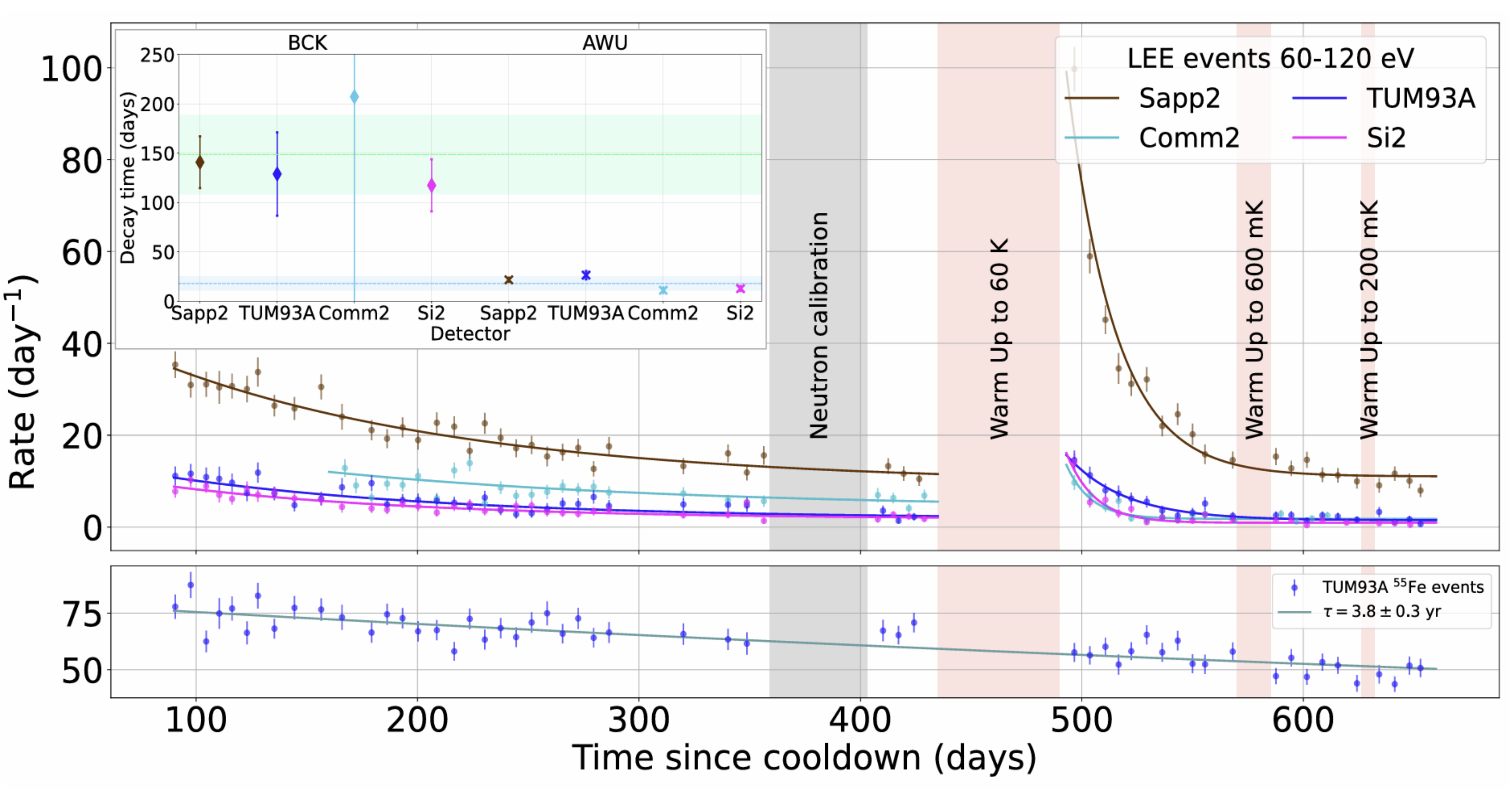

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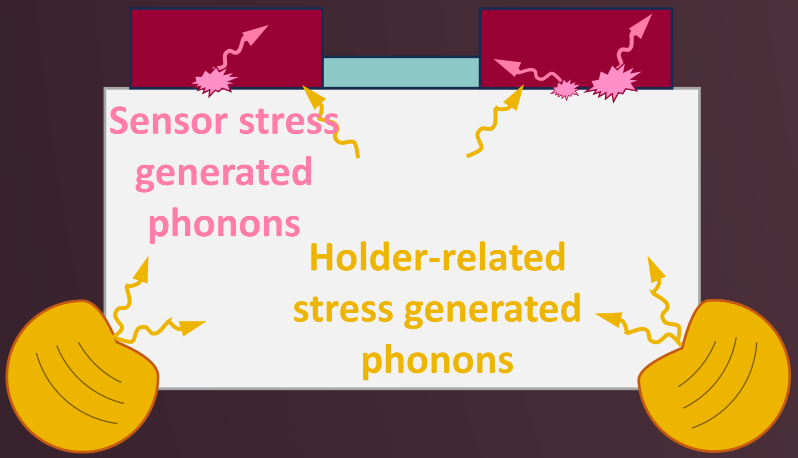
HYPOTHESES: ORIGIN OF LEE

(a) Stress generated



Sensor stress generated phonons

Holder-related stress generated phonons

(b) Bulk related

~1x LEE events

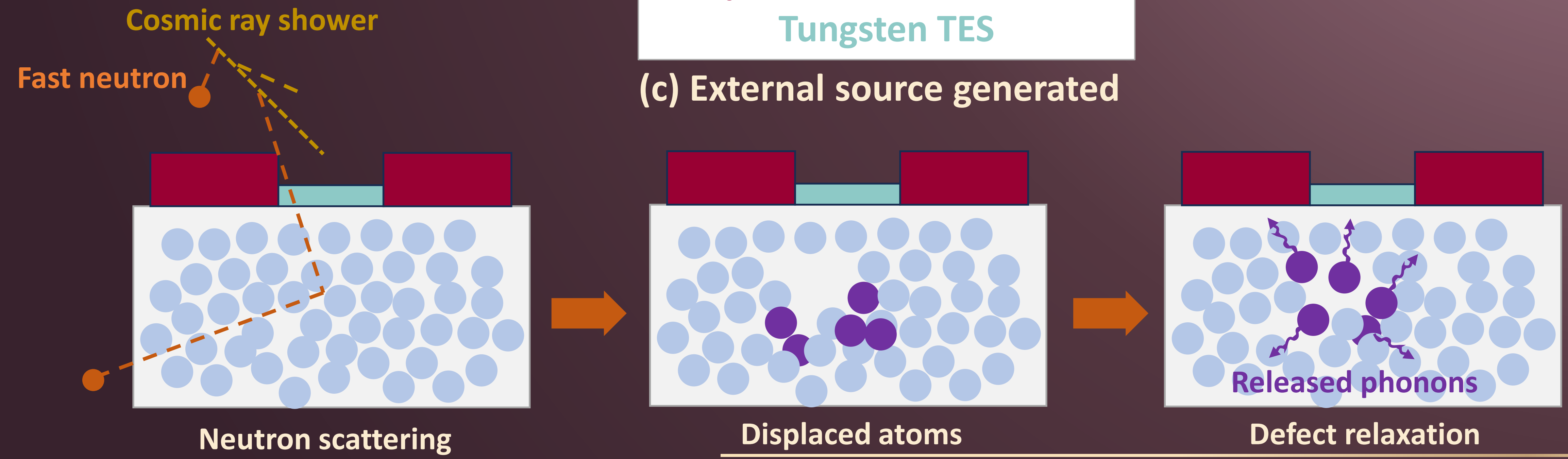
~4x LEE events

Detector substrate

Al phonon collection fins

Tungsten TES

(c) External source generated



Cosmic ray shower

Fast neutron

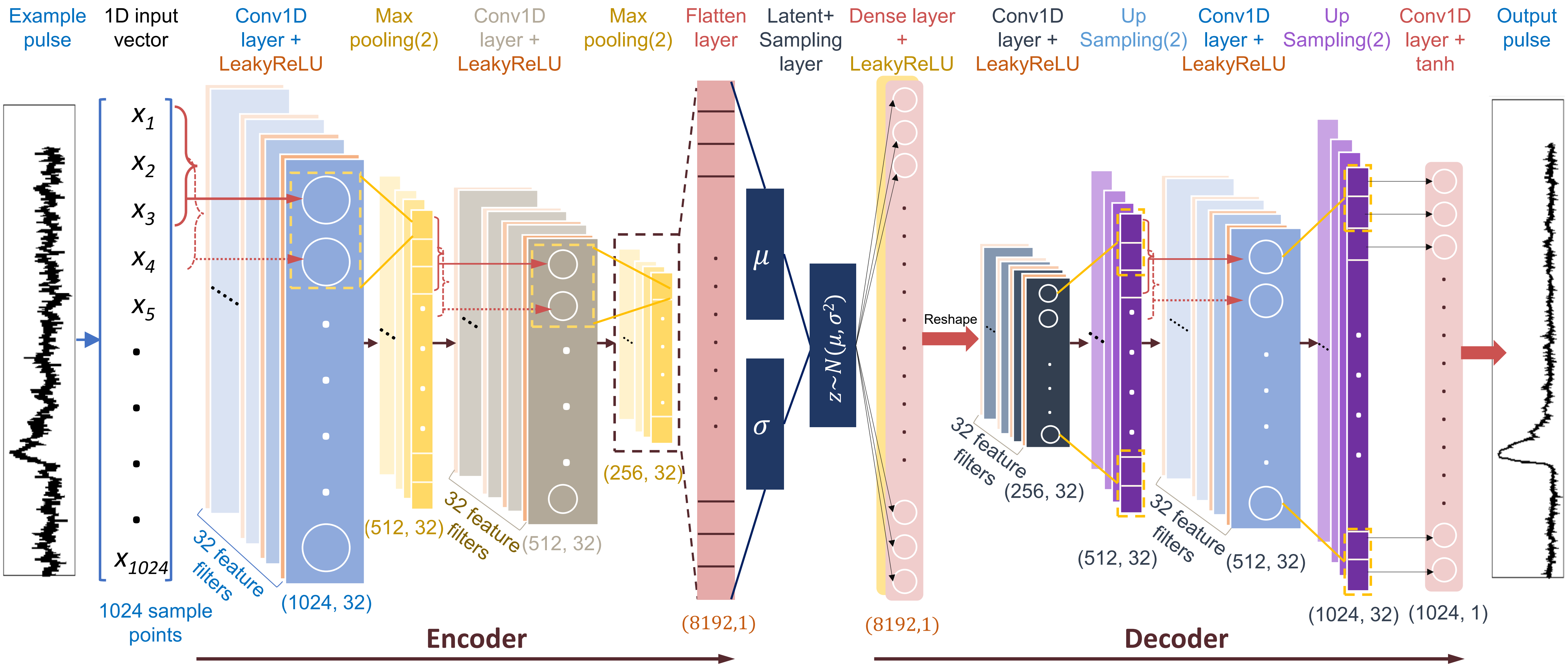
Neutron scattering

Released phonons

Displaced atoms

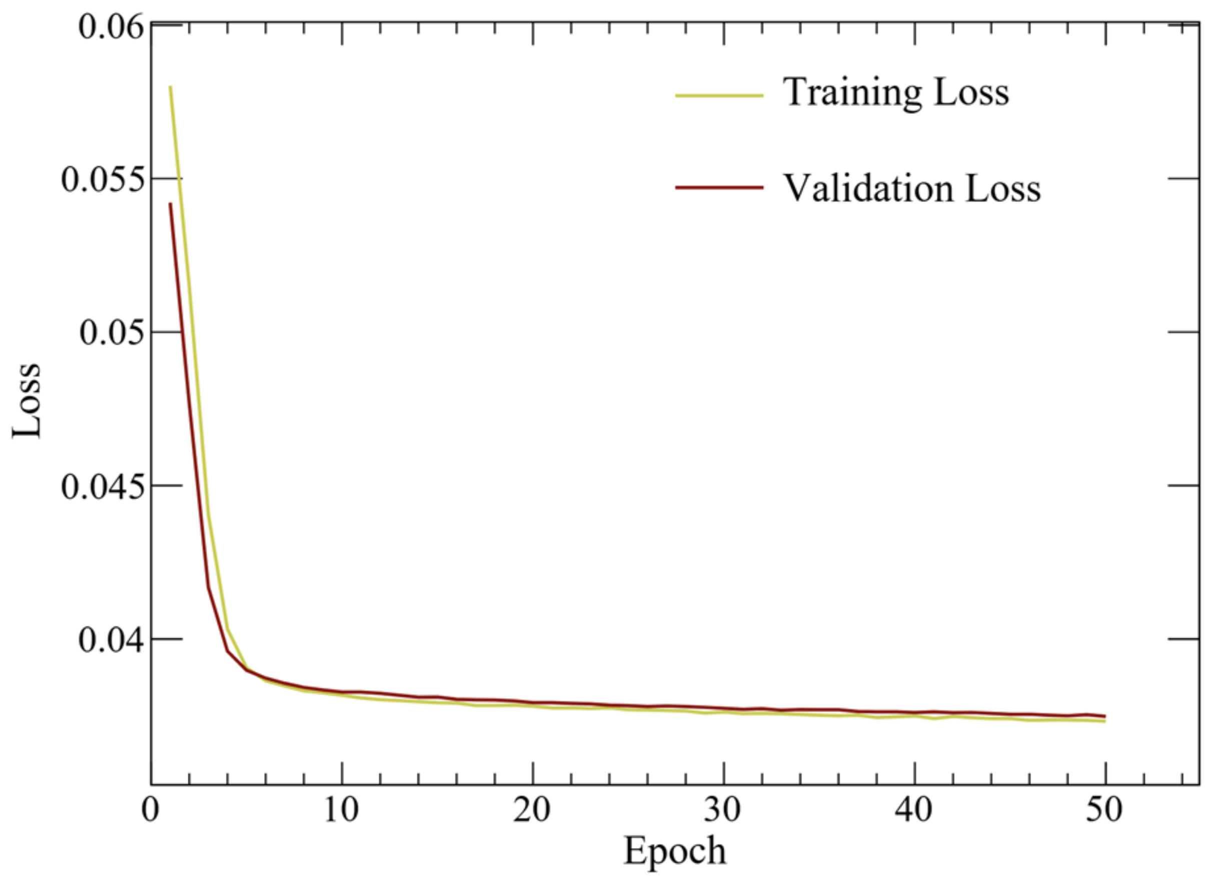
Defect relaxation

CVAE ARCHITECTURE



TRAINING OF THE NETWORK

Reconstruction loss



- *MC data split: 80% (training) - 20% (validation)*
- *One epoch → one complete pass of the training (or validation) dataset through the ML network*

➢ Loss quantifies the difference between the input and reconstructed pulse

➢ Training and validation losses converge

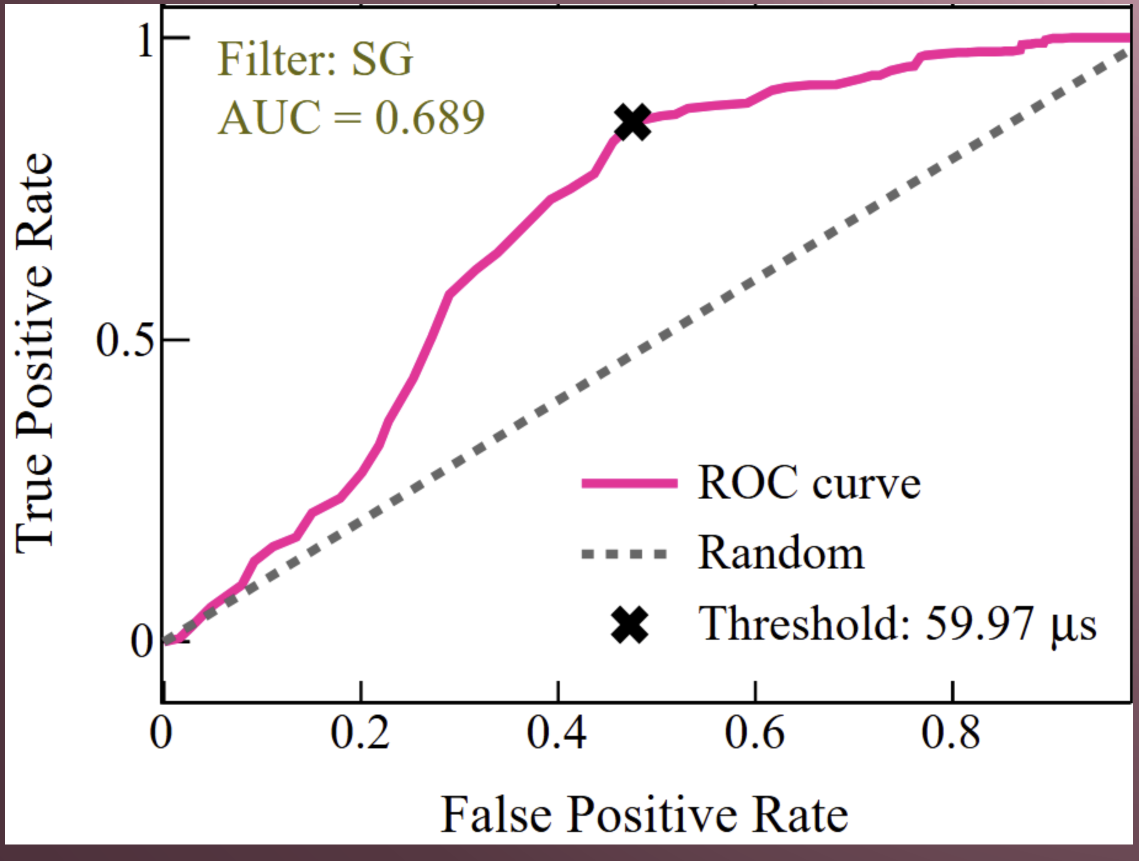
➢ Model generalizes well to unseen events

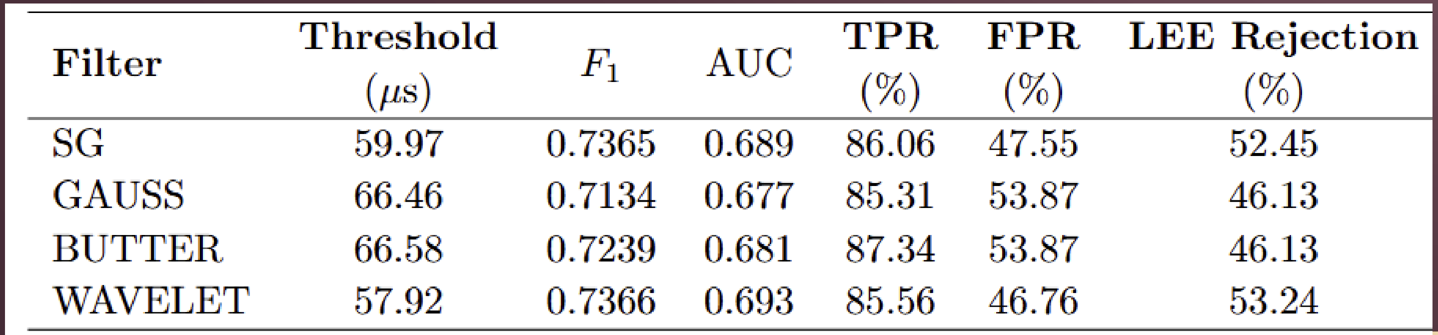
THRESHOLD DETERMINATION

- **Dataset prepared with:**
  - MC events (all 10,000 events)
  - High anomaly event > 0.04 loss score (633 events)

- **Three standard metrics**
  - $\text{Recall} = \dfrac{\text{TPR}}{\text{TPR}+\text{FNR}}$
  - $\text{Precision} = \dfrac{\text{TPR}}{\text{TPR}+\text{FPR}}$
  - $F_1 = \dfrac{2\times(\text{Recall}\times\text{Precision})}{\text{Recall}+\text{Precision}}$

True positive rate (TPR)
False negative rate (FNR)
False positive rate (FPR)





Filter	**Threshold** (μs)	F_1	**AUC**	**TPR** (%)	**FPR** (%)	**LEE Rejection** (%)
SG	59.97	0.7365	0.689	86.06	47.55	52.45
GAUSS	66.46	0.7134	0.677	85.31	53.87	46.13
BUTTER	66.58	0.7239	0.681	87.34	53.87	46.13
WAVELET	57.92	0.7366	0.693	85.56	46.76	53.24

ENERGY SPECTRA- LEE REJECTION

- **Best performance achieved with wavelet filter**
  - LEE rejection efficiency 53%

- **Steep component remains after applying selection criterion**
  - LEE has multiple origins
  - Incomplete separation of overlapping pulse populations.