Coherent Elastic Neutrino-Nucleus Scattering

NOW 2026 ; Aug. 31-Sep. 6, 2026

Manfred Lindner

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Erice: INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, 47th COURSE Sep 16 – 22, 2026

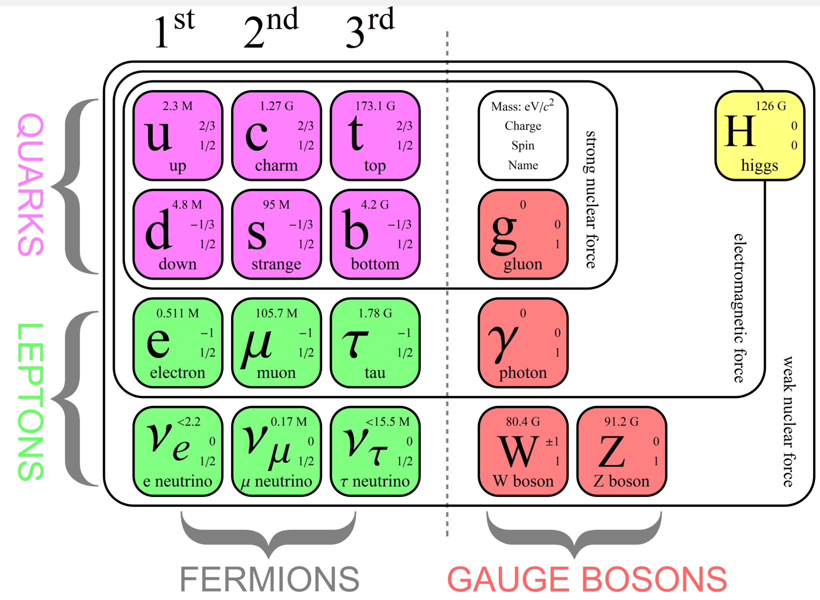
Fundamental Physics: Which Direction?

The Standard Model of Particle Physics works perfectly

- endpoint of a very successful development:
  role model: Quantum Electro Dynamics (QED)
  d=4 renormalizable gauge theory, symmetry

QED ⇒	QCD ⇒	SM
$U(1)_{em} \Rightarrow$	$SU(3)_c \Rightarrow$	$SU(3)_c \times SU(2)_L \times U(1)_Y$

- describes essentially all known (particle) physics
- many questions: group, generations, gravity, 4d, ...



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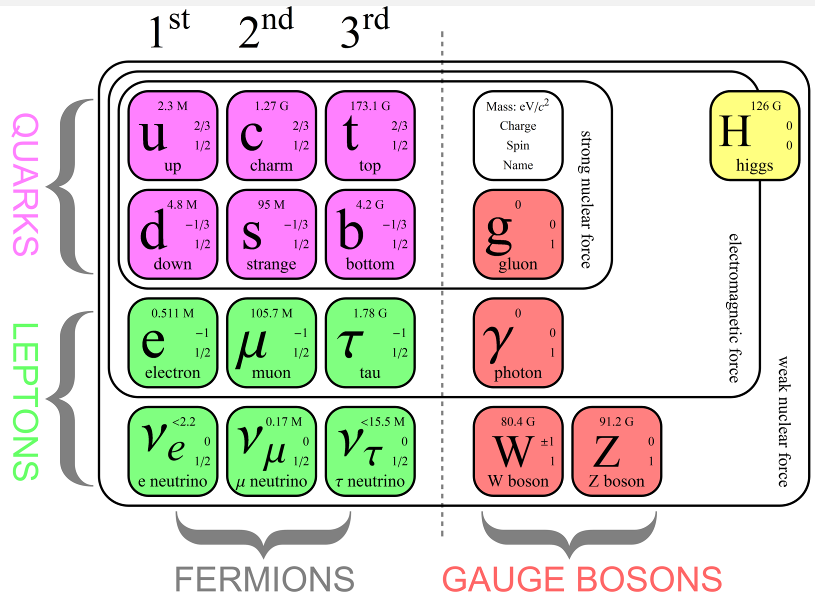

Experimental facts, hints, problems:

- Electro-weak scale ≪ Planck scale
- Gauge couplings almost unify
- **Neutrino masses & large mixings**
- Flavour: Patterns of masses & mixings
- Baryon asymmetry of the Universe
- Dark Matter
- Dark Energy

Theoretical problems:

SM does not exist without cutoff
(triviality, vacuum stability)
Gauge hierarchy problem – became worse
Gauge unification &charge quantization
Strong CP problem
Unification with gravity
3 generations, reps., d=4, many parameters

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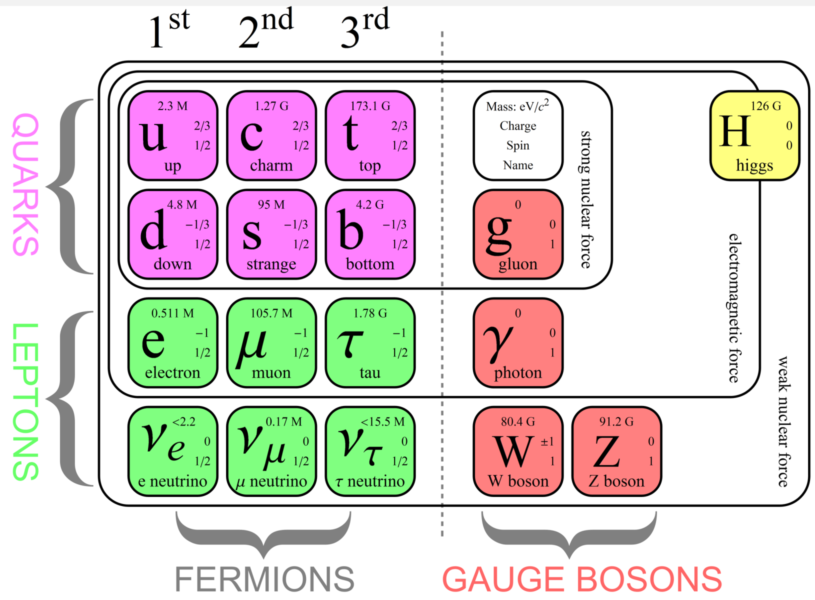

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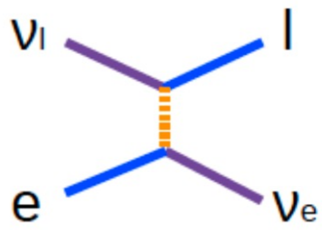
neutrinos: oscillations + look for new physics in neutrino interactions

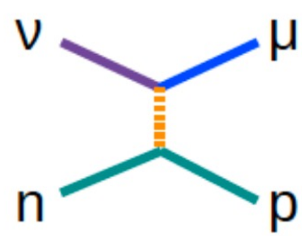
Neutrino Interactions in the Standard Model

Exchange of W and Z bosons
→ NC and CC interactions with:
- **leptons**
- **quarks & protons/neutrons**



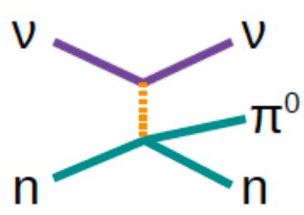
Inverese beta decay

Elastic neutrino electron scattering

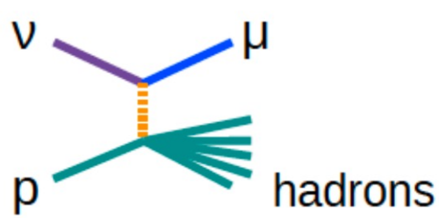


(Quasi-) elastic neutrino nucleon scattering

→ inelastic processes: **hadrons**

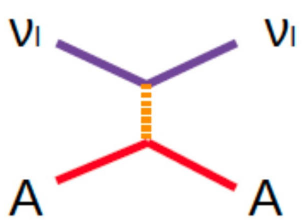


Nucleon excitation + resonance production



Deep inelastic scattering + jet production

Freedman 1974:
→ coherent scattering of neutrinos on the whole nucleus (CEνNS)
→ only via Z-exchange



Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

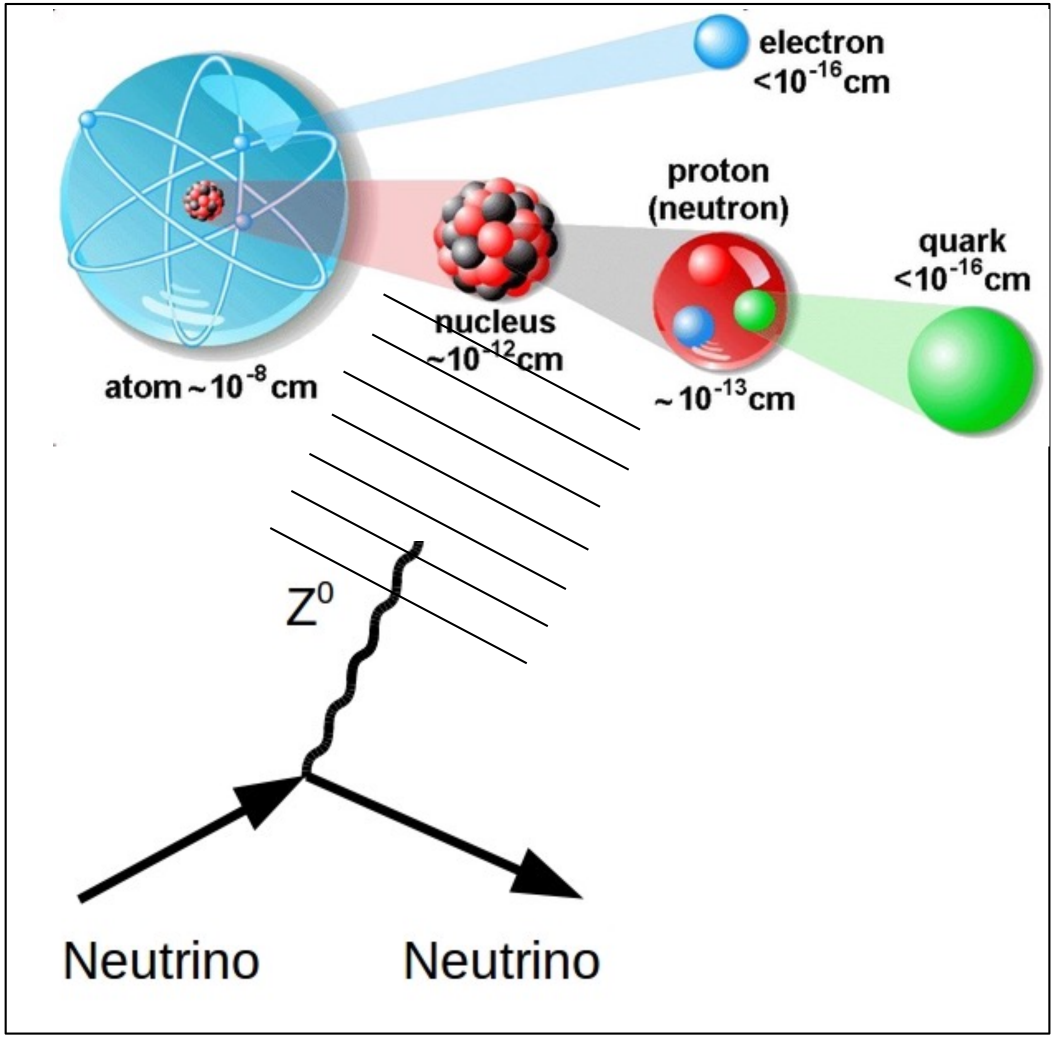
➔ unique & powerful channel
- test the Standard Model
- search for new physics
- learn uniquely about sources

CEνNS: The simple Picture

coherent scattering:

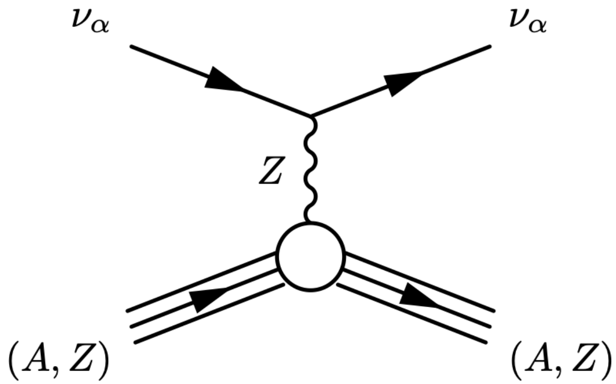
1. ν-wavelength big enough
   → Z scattering @whole nucleus
2. small momentum transfer
   → low detection threshold

- **coherence length ~ 1/E ←→ size**
  - E_ν below O(50) MeV
    ➔ include nuclear form factor $F(q^2)$
  - reactor ν's: <10 MeV
    ➔ fully coherent: $F(q^2) = 1$
- **cross section ~ $(E_\nu)^2$**
  → compensate:
  - very high ν flux close to reactor
  - coherence ~ N^2
    → much reduced detector size

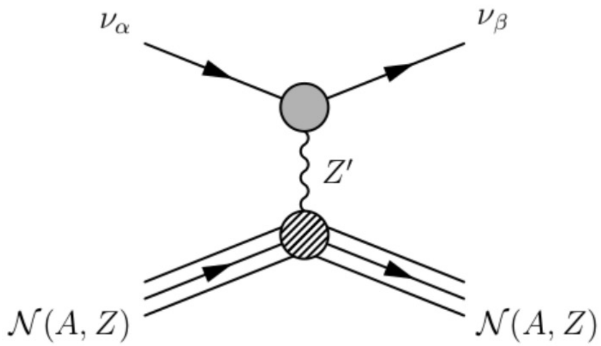


BSM Physics with CEνNS

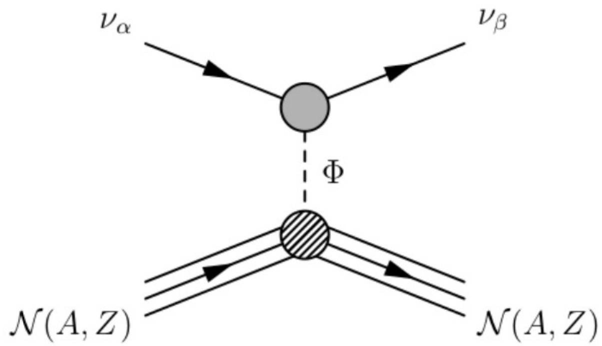
reference: SM neutral current



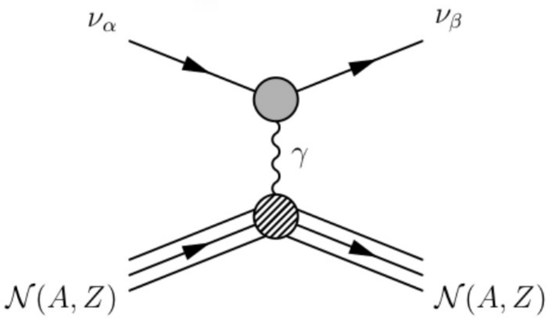
BSM Vector Mediator



BSM Scalar Mediator



Electromagnetic Interactions



millicharges
neutrino magnetic moments

modified low E running of $\sin^2\theta_W$

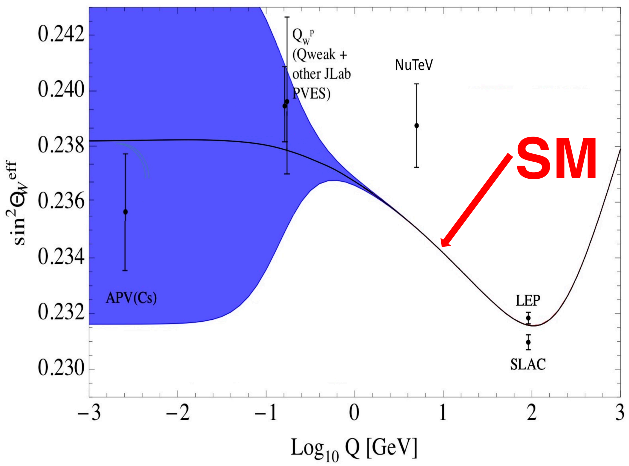
$\sigma \sim N - [(1 - 4{*}\sin^2\theta_W)\ Z\ ]^2$

←→ light dark sectors

dark matter candidates

g-2

...



What can be learned from CEνNS

aim at the most precise measurement

nuclear uncertainties
➔ go to low q^2 where $F(q^2) = 1$

Nuclear form factor

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi}\left(N - (1 - 4\sin^2\theta_w)Z\right)^2 F^2(q^2)\, m_A \left(1 - \frac{m_A T}{2E_\nu^2}\right)$$

+ new neutrino interactions⋯

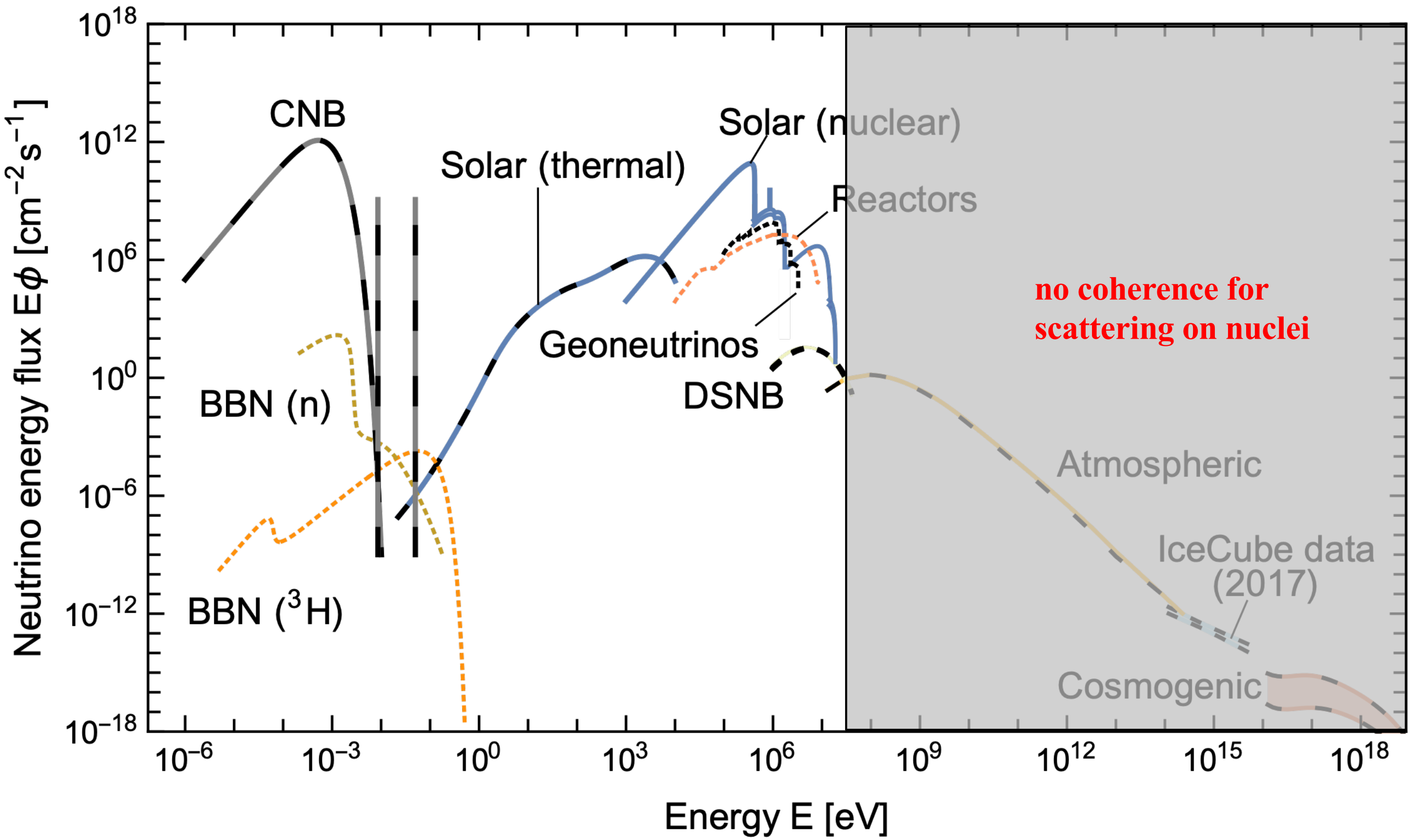
Weinberg angle

tests any new physics which modifies this relation

Inverted logic: If only SM ➔ CEνNS can be used to:

- test sources: the Sun, reactors, π@rest beams, ...
- unique tests of nuclear physics
- technological applications: reactor monitoring, safe-guarding,...

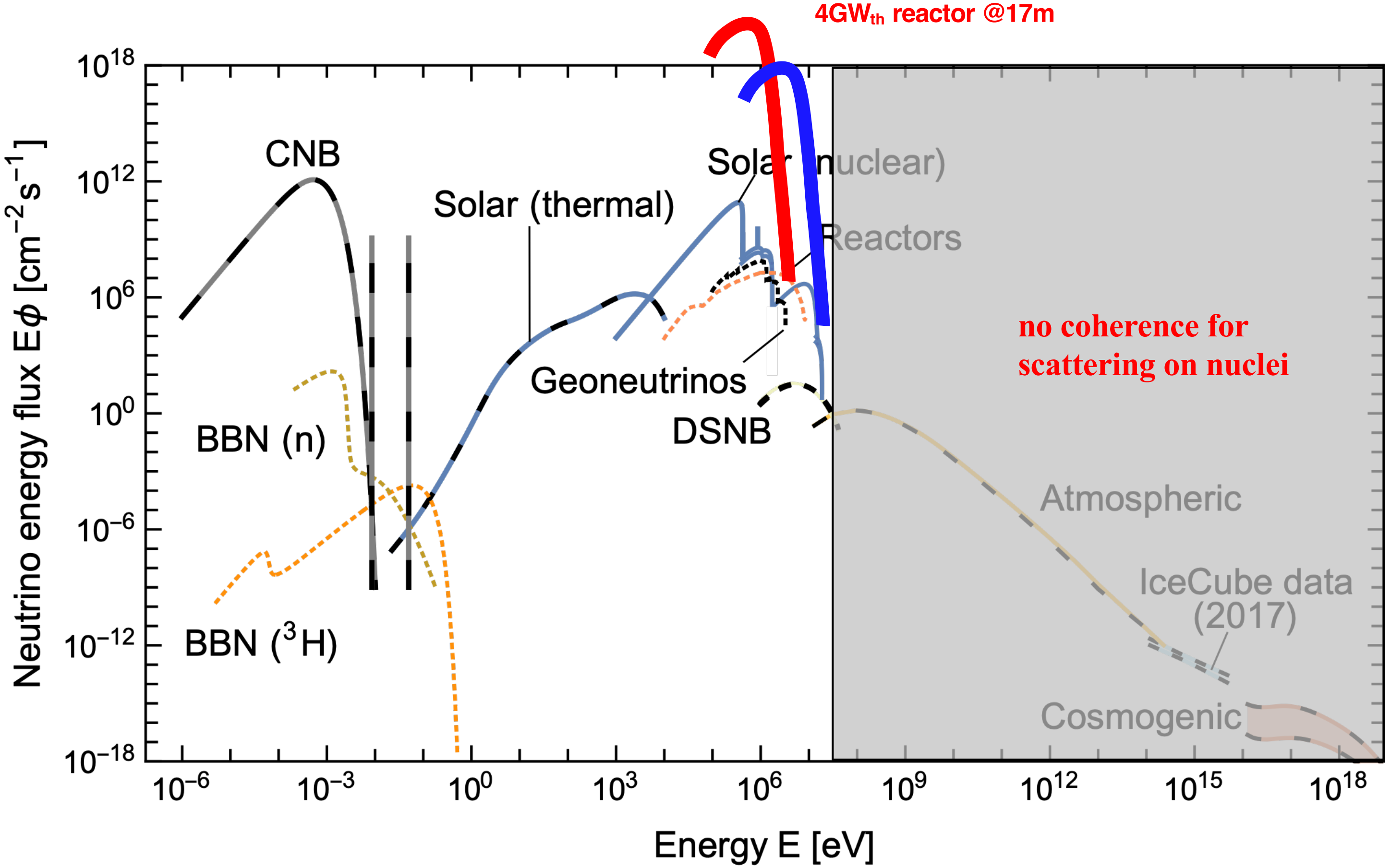
Neutrino Sources: Flux ⊗ Energy



Vitagliano, Tamborra, Raffelt
Rev.Mod.Phys. 92 (2020) 45006
arXiv:1910.11878

Neutrino Sources: Flux ⊗ Energy

➔ very different close to a nuclear power reactor and in a stopped π-beam or a supernova



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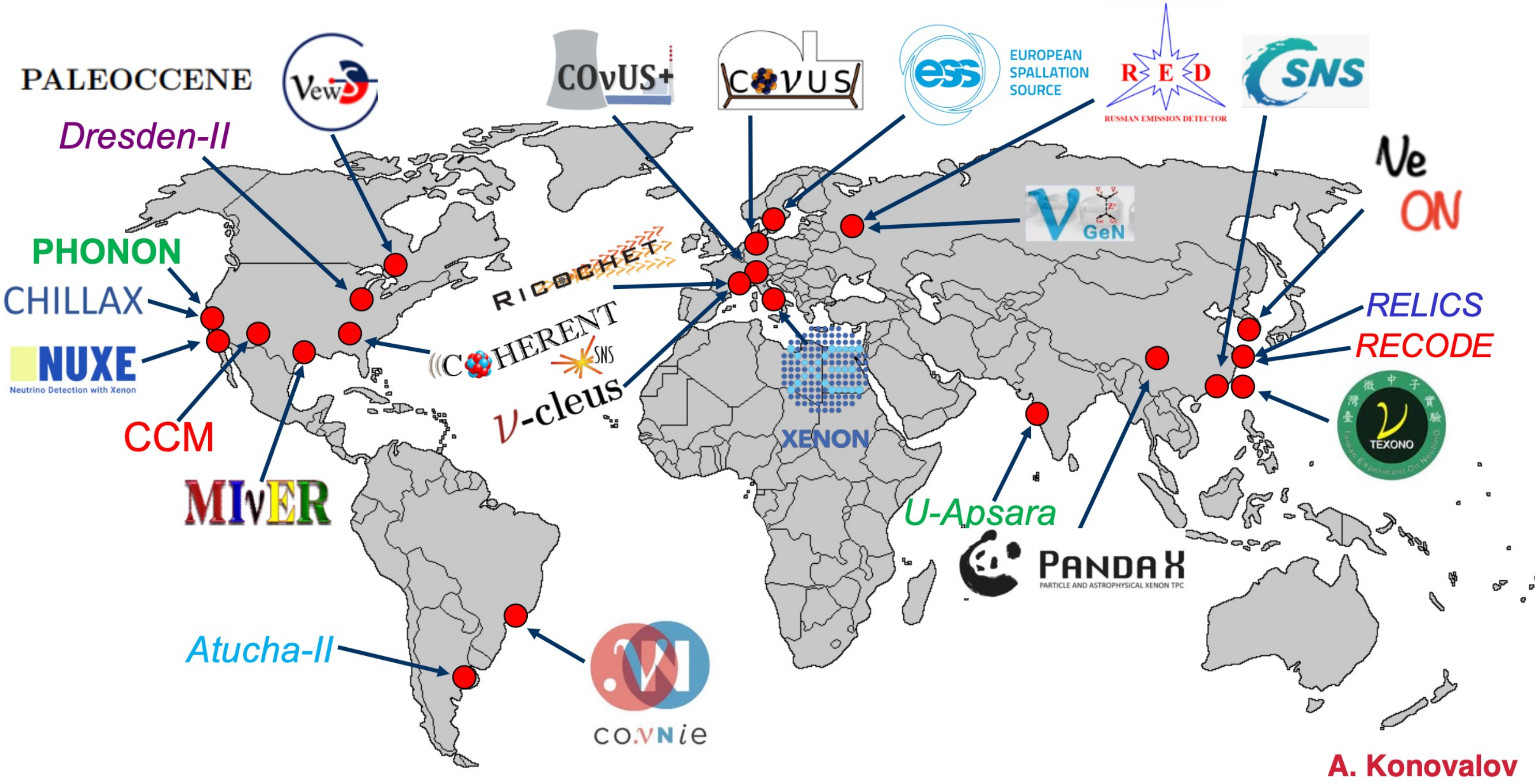
➔ event rates: neutrino flux ⊗ detector size ⇐⇒ backgrounds

The CEνNS World



1974 – prediction by D. Freedman

...

2017 – 1st observation by COHERENT in stopped π-beams ←→ $F(q^2)$ - not fully coherent

2024 – 1st with solar neutrinos by XENONnT and PandaX, later also LZ

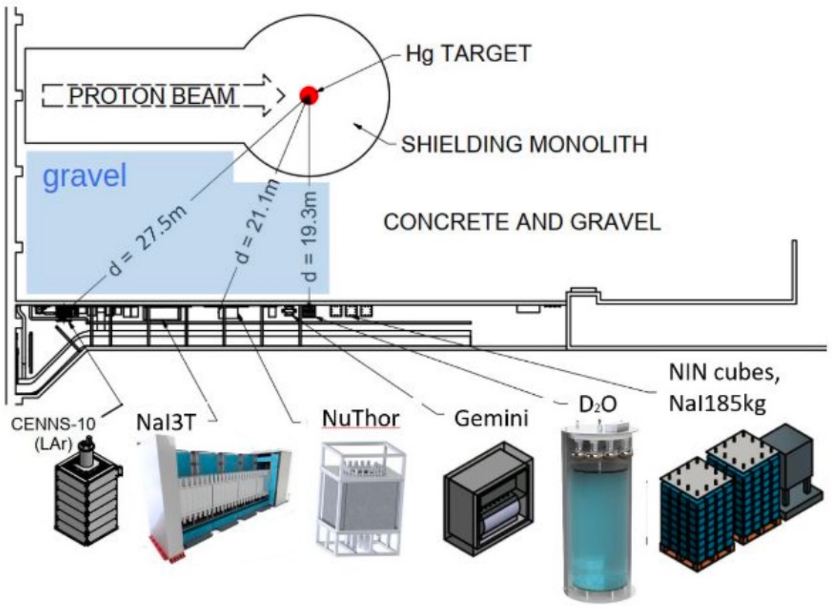
2025 – 1st with reactor neutrinos by CONUS+

COHERENT: π-DAR Neutrino Beam

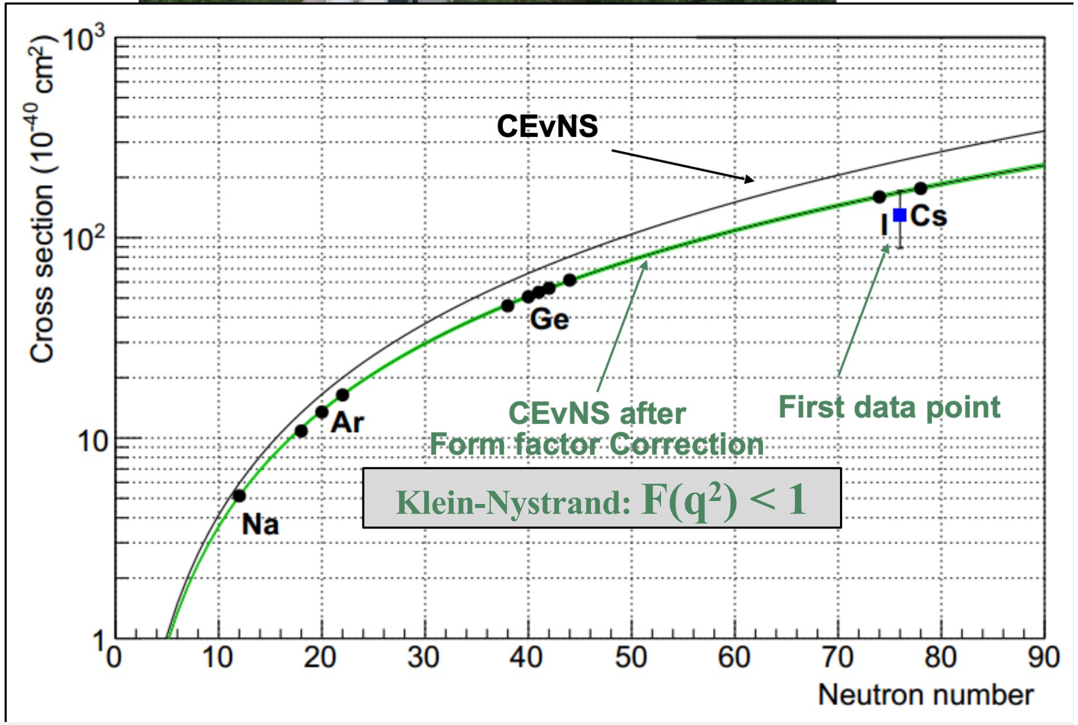
Located in Spallation Neutron Source, Oak Rigde National Laboratoy (USA).

Several detectors with different targets.

<u>First detection of CEνNS with CsI[Na] in 2017.</u>
<u>Detection with Ar in 2020 and with Ge in 2024.</u>

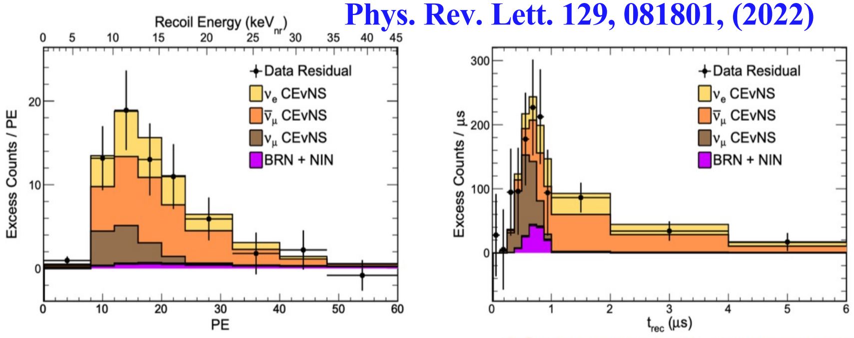


COHERENT collaboration 2021 JINST 16 P08048



COHERENT

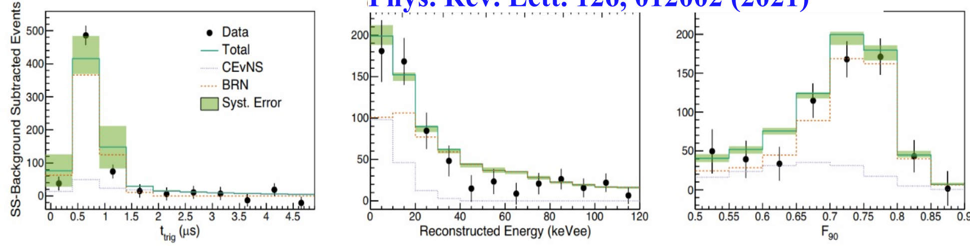
Phys. Rev. Lett. 129, 081801, (2022)



← CsI

→ Ar

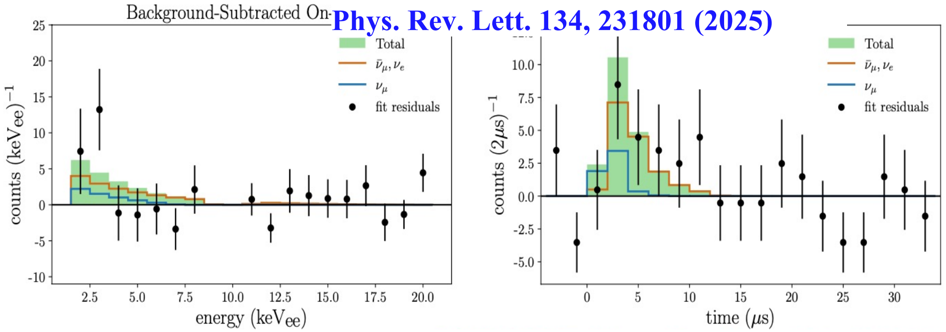
Phys. Rev. Lett. 126, 012002 (2021)

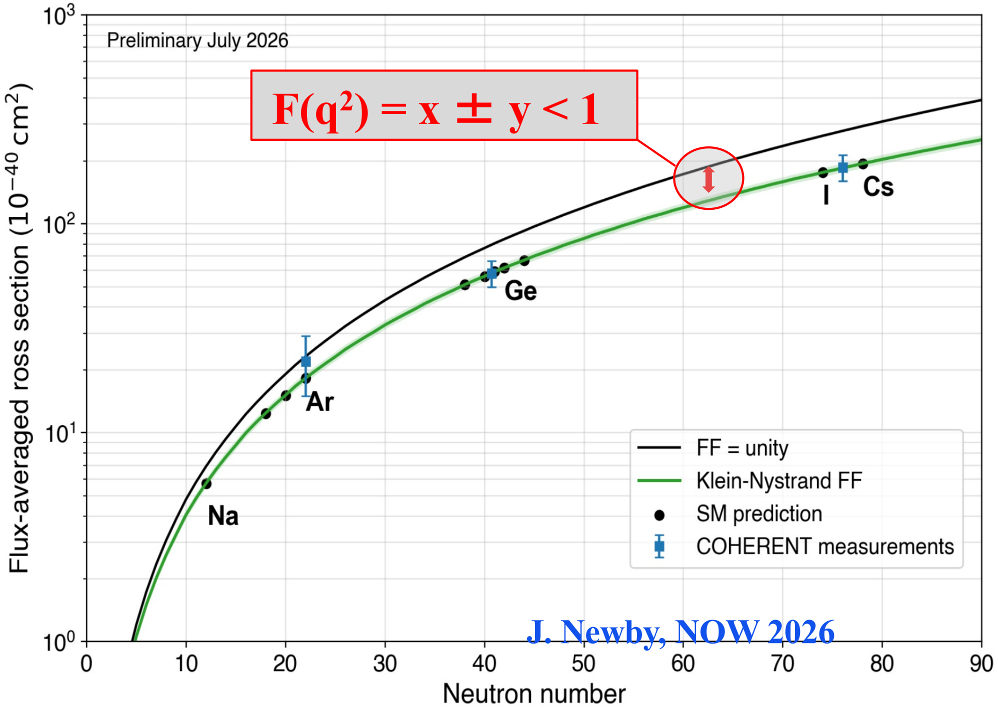


COHERENT, PRL 126 012002 (2021)

Ge →

Phys. Rev. Lett. 134, 231801 (2025)





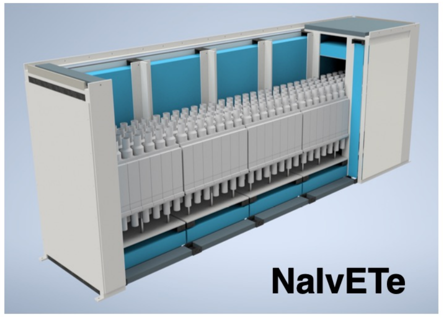
J. Newby, NOW 2026

see CEνNS for three targets
+ searches for BSM:

- **accelerator produced light DM**
- **$\sin^2\theta_W$**
- **charge radii**
- **...**

Future of COHERENT and others

- **COHERENT: continue data taking + on-going upgrades**



- SNS Proton Power Upgrade complete
- D_20 addressing leading syst. uncertainty
- 750-kg LAr target assembly ongoing @ORNL; expect ~5000 events/year
- 2.4 t NaIvETe (NaI): 5 modules, 315 crystals 7.7 kg each; total mass is 2.4t, partially deployed
- Cryo-CsI R&D, undoped CsI, 6.6 kg @T=77K, PMT readout, deployment: 2027
- NuThor observed ν-induced fission
- Liquid Neon...

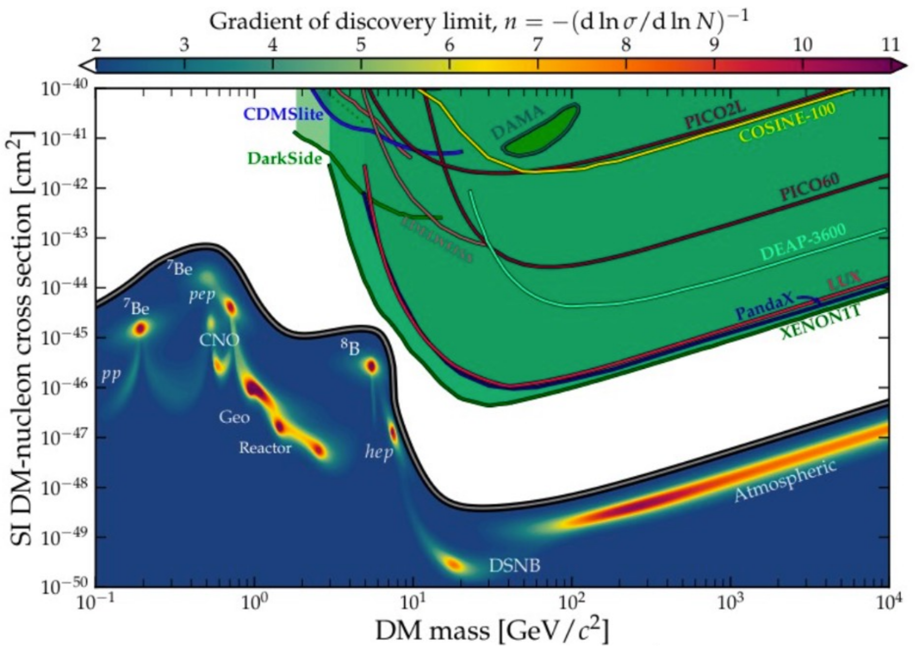
- **SNS @LUND (under construction) + planned CEνNS project(s)**
- **SNS @Dongguan, CICENNS project; 300 kg CsI, commissioning**

➔ towards precision CEνNS

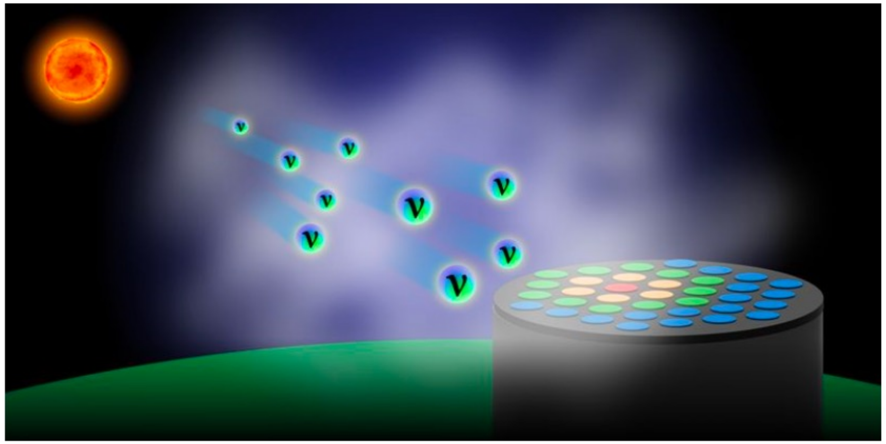
Direct Detection Dark Matter Experiments

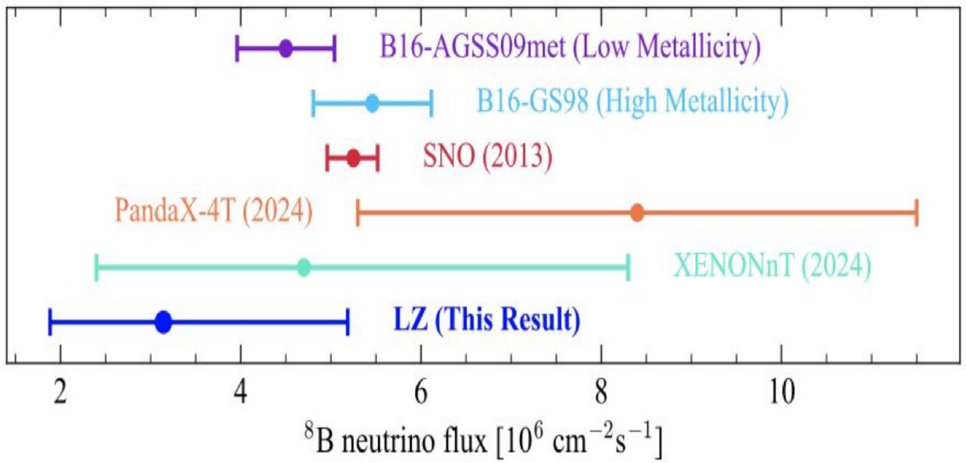
backgrounds include:
- atmospheric neutrinos
- neutrinos from the Sun

➔ "neutrino fog"
in dark matter experiments
➔ observe dark matter like signature
from 8B solar neutrinos



C.A.J. O'Hare , PRL 127, 251802 –(2021)


APS/Alan Stonebraker

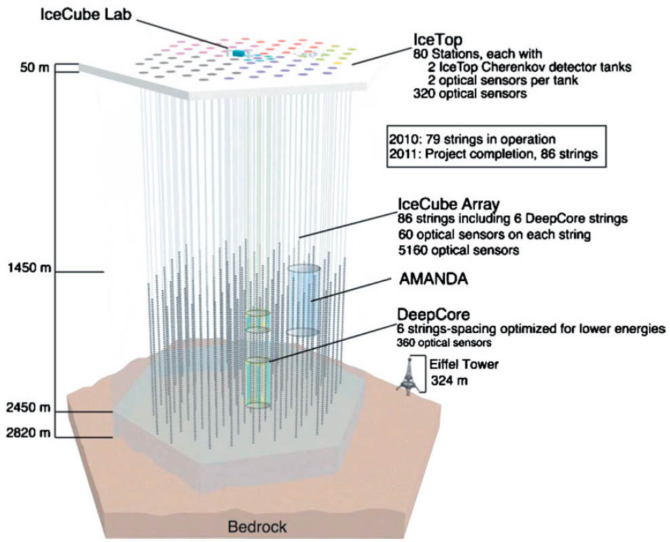


XENONnT (2.73σ) PRL 133, 191002 (2024)
PandaX-4T (2.64σ) PRL 133, 191001 (2024)
LZ (4.5σ) PRL 137, 091806 (2026)

Future: XLZD, Panda-xxT

Advantage of Reactor Neutrino Experiments

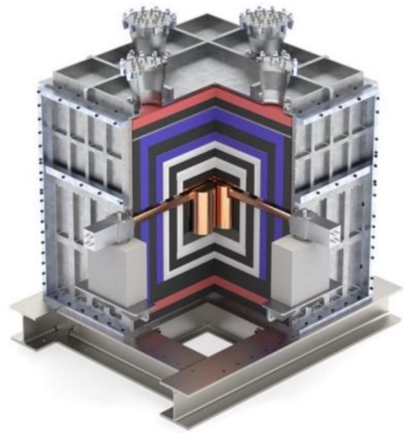
IceCube experiment: km^3



SuperKamiokande:
50.000 tons of water

CONUS+

- $\sigma \sim N^2$ + huge flux
- size ~2m^3
- active mass: few kg



neutrinos interact very weakly
➔ huge experiments

CEνNS
+ high flux @commercial reactors
➔ small experiments

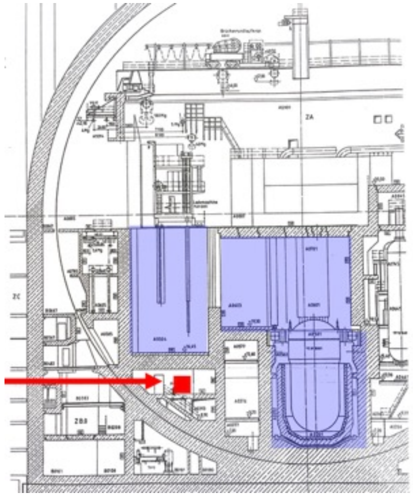
- cost
- time
- potential
- ...

Experimental Sites: CONUS → CONUS+

2018 – 2022 @Brokdorf (KBR)

3.9 GW_{th} reactor
CONUS @17m → **$2*10^{13}$ ν/cm^2/s**
→ Eur.Phys.J.C 79 (2019) 8, 699
→ Eur.Phys.J.C 83 (2023) 3

KBR shutdown in 2021 → more off data
final result: factor 1.6 (90%CL) away from SM
→ Phys.Rev.Lett. 133 (2024) 25, 251802

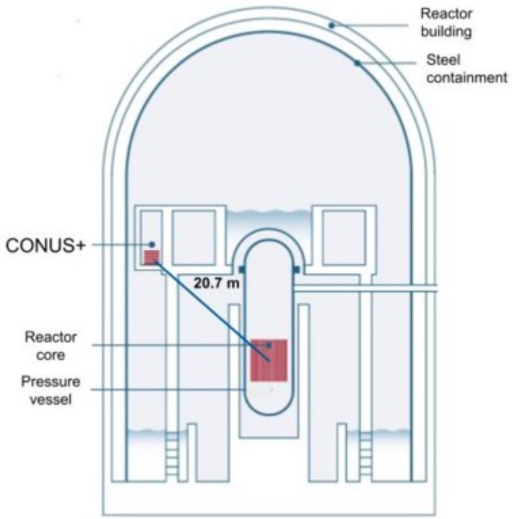


Since Dec. 2022 @Leibstadt (KKL)

3.6 GW_{th} reactor
CONUS+ @20.7m → **$1.45*10^{13}$ ν/cm^2/s**
different overburden: 7.4 mwe → better veto
outage: drywell above detector +3.8cm steel

different site + significant improvements:

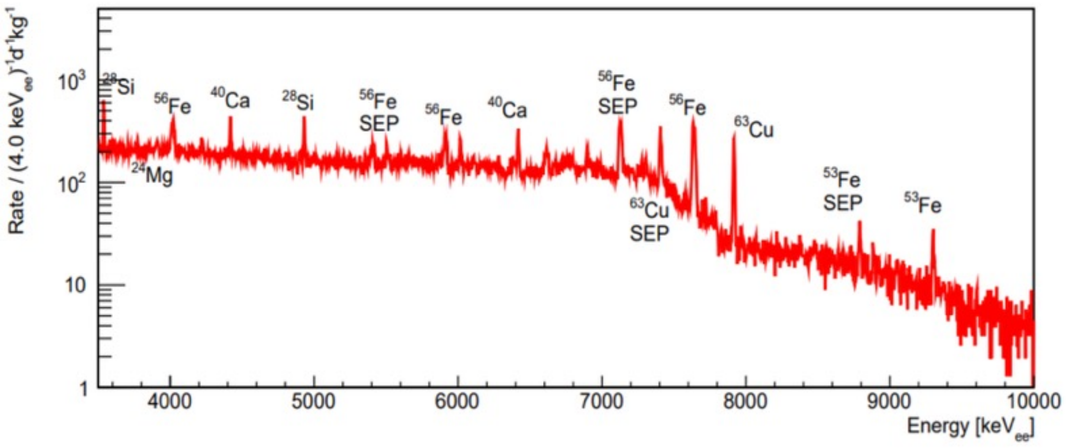
CONUS → CONUS+



typical: 11 months per year ON
1 month OFF for maintenance

Backgrounds @KKL Environment

Gamma rays

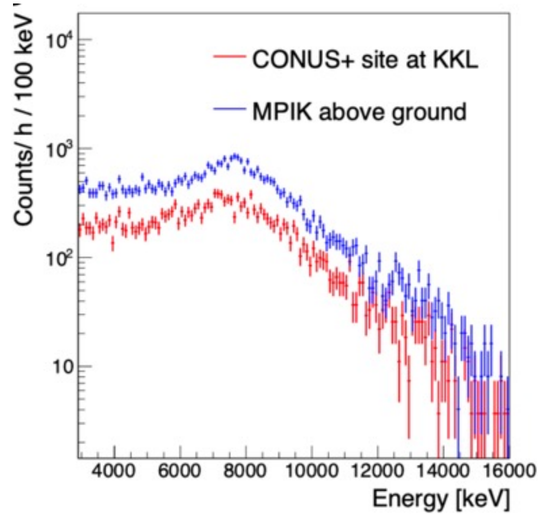


Muons

Muon rate in CONUS+ room:
(107 +- 3) counts/s/m^2

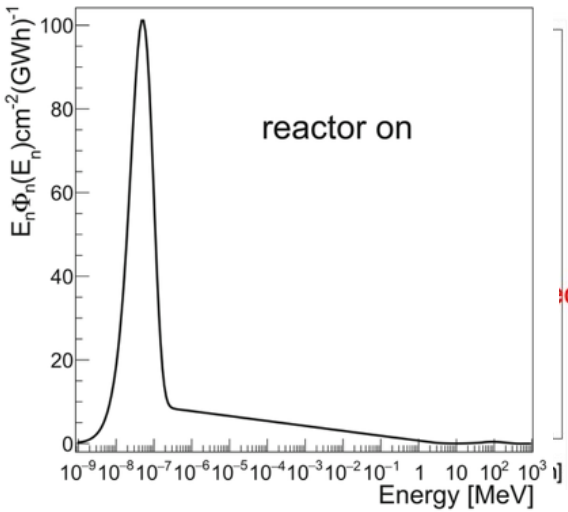
→ factor 1.9 reduction compared to outside

→ 7.4 m w.e. overburden

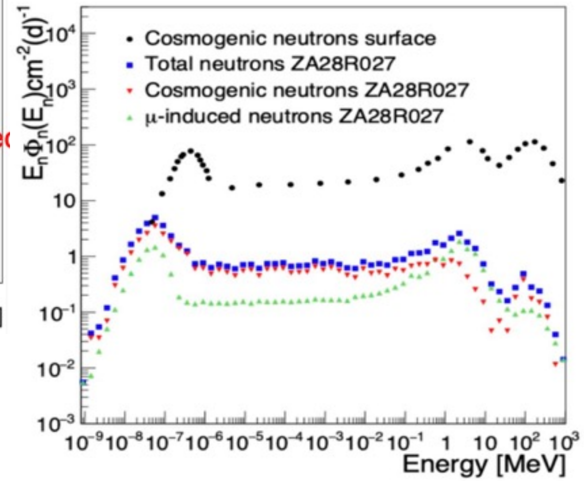


Neutrons

Energy region	$\phi\ (cm^{-2}\ (GW\ h)^{-1})$
Thermal	172.1 +- 16.3
intermediate	91.6 +- 6.3
Fast + cascade	1.0 +- 0.8
Total	264.7 +- 13.2



Cosmic Neutrons



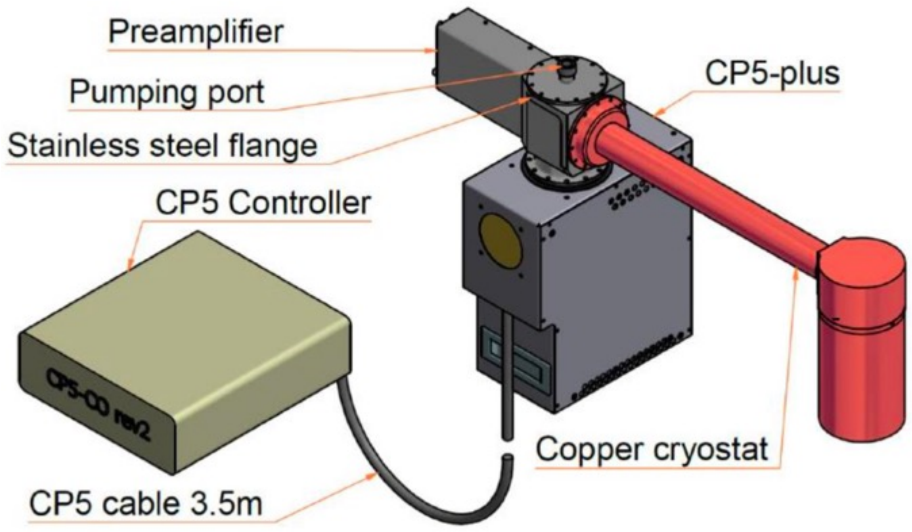
Radon: commercial device ~150 Bq/m^3

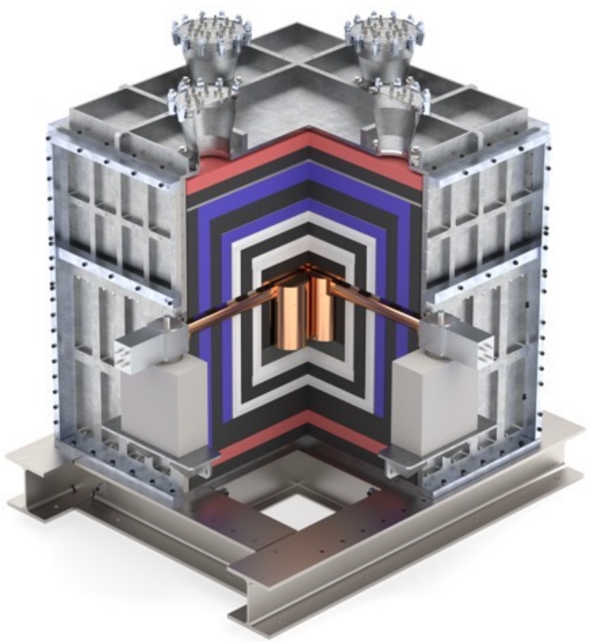
backgrounds well understood
→ **EPJC 85 (2025) 465**

The CONUS+ Detector (Eur.Phys.J.C 84 (2024) 1265)

4 point-contact HPGe detectors

- increased active mass, electrically cryo-cooled
- reduced pulser resolution (FWHM) ~ 50eV
- ASICs + reduced contact size & bonding
  → improved low E trigger efficiency
- pulse shape
- all components with very low background





Active + passive shield for background suppression

- stainless steel cage → safety (earthquakes)
- outer and inner μ-veto layers → higher muon flux @KKL
- lead for gamma suppression
- borated and pure PE layers ←→ neutrons
- all materials carefully selected and screened
- flushing with radon-free air → remove ^{222}Rn

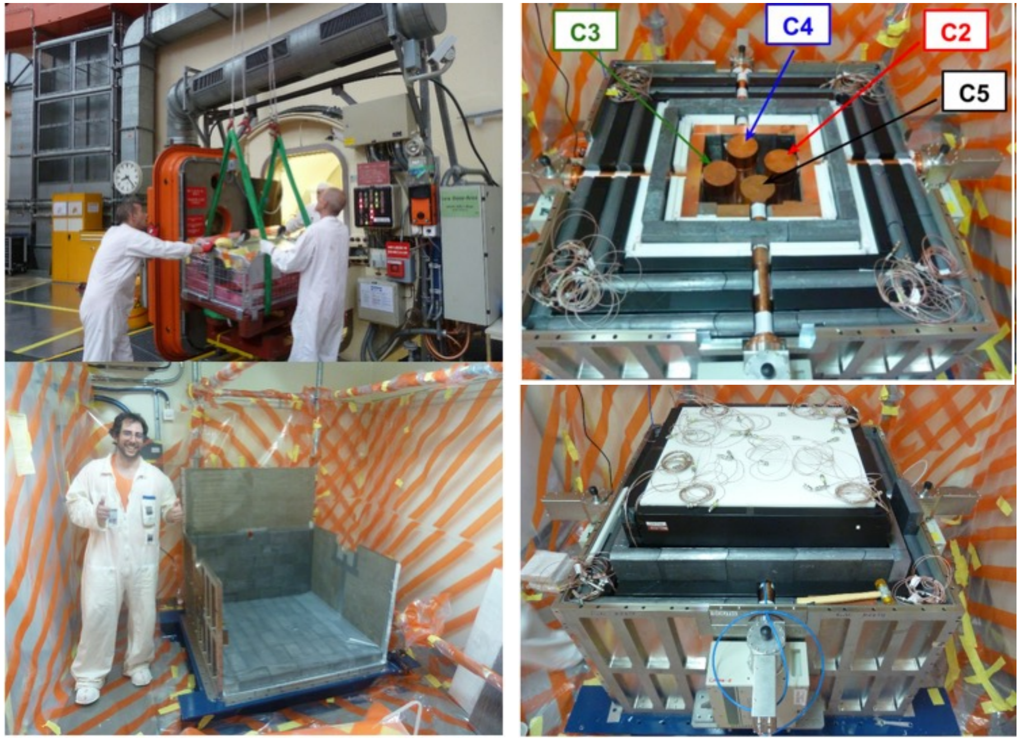
→ **background reduction by 4 orders of magnitude**

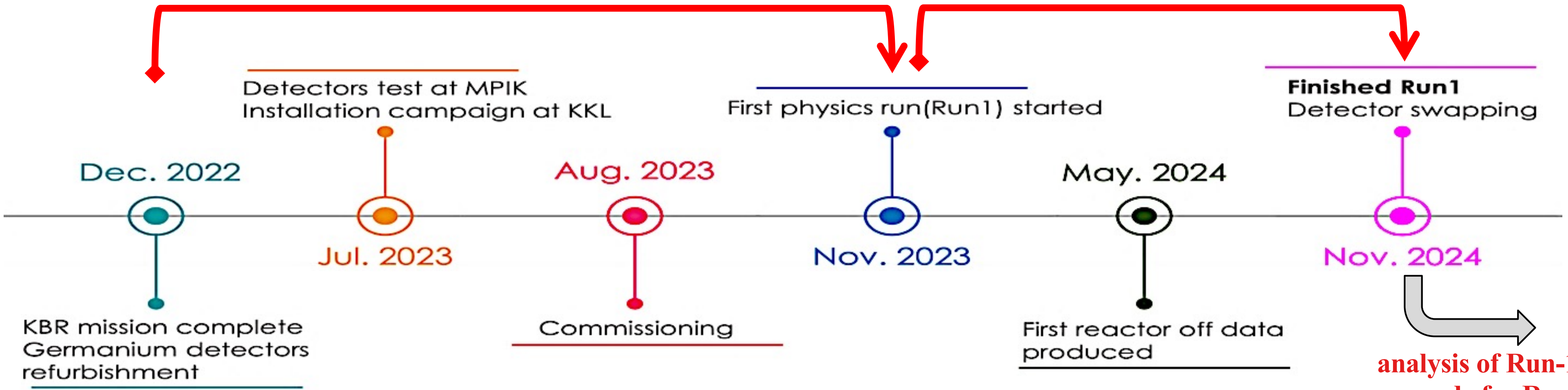
→ **like in an underground lab → ``virtual depth"**

Timeline of CONUS+

From KBR to KKL:

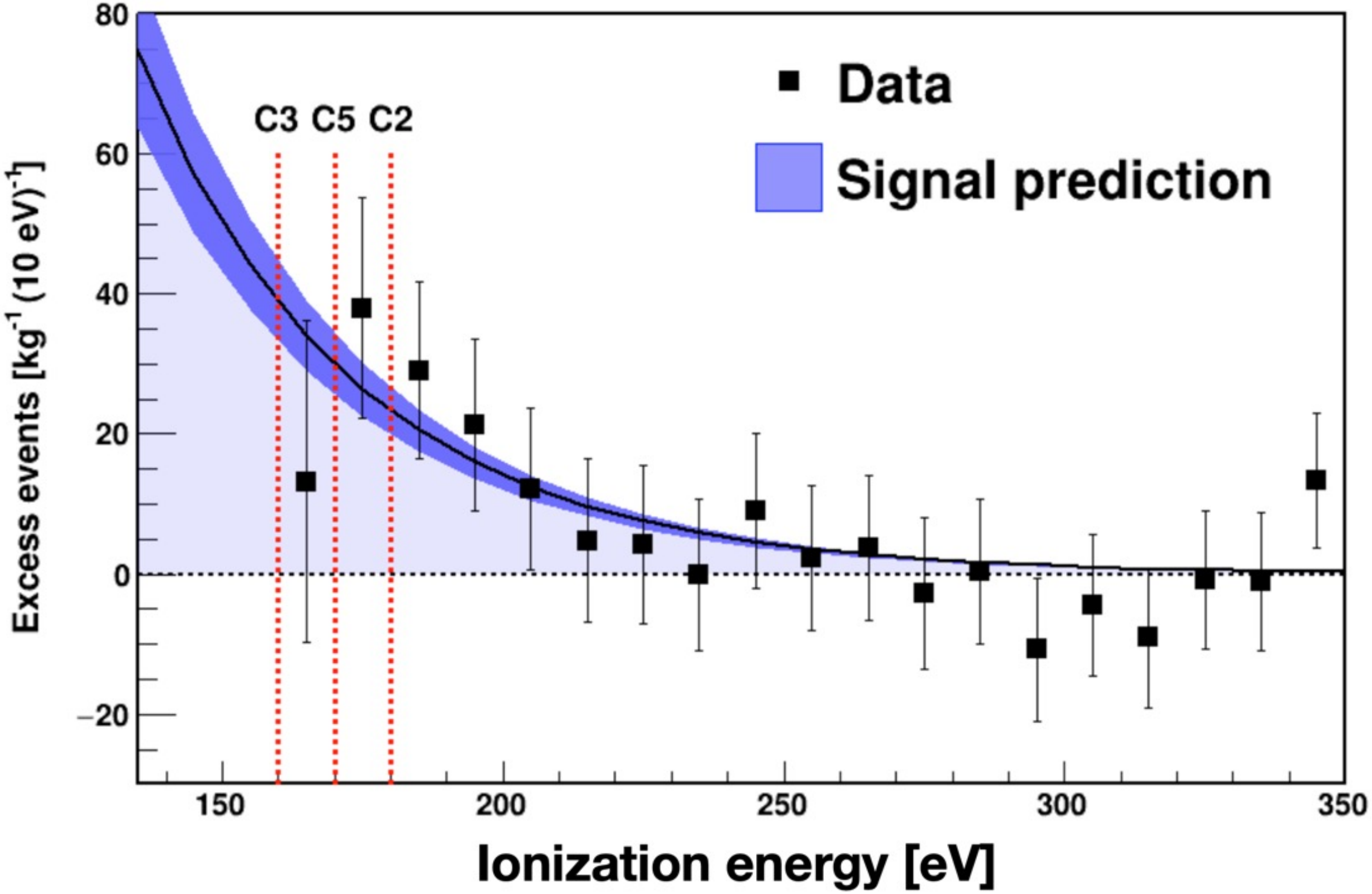
- dismantling
- transport
- improvements
- installation ➔
- data taking: Run-1
- analysis + upgarde
- **Run-2**





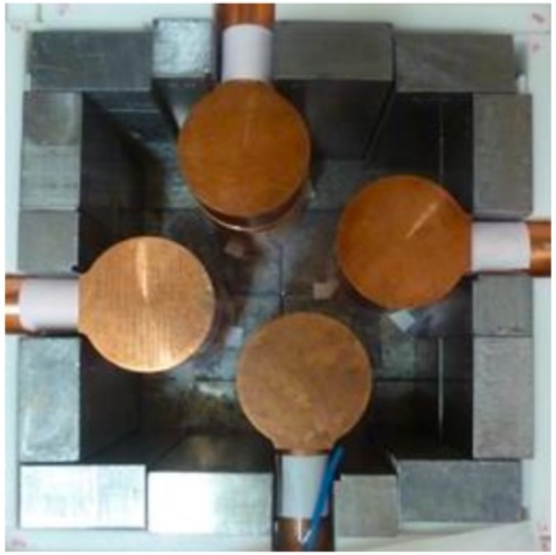
analysis of Run-1
upgrade for Run-2

CONUS+, Run-1: CEvNS Signal @Reactor

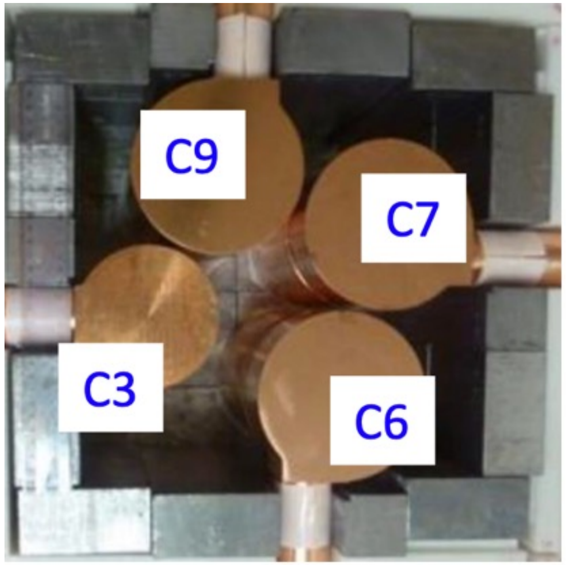


- **Excess Events (below 350 eV$_{ee}$) in Run-1; null hypothesis rejected at 3.7σ**
- Nature 643, 1229–1233 (2025)
- difference between 119 days of reactor on to the background model scaled to the total detector mass
- vertical lines indicate the energy thresholds of the three detectors used in the analysis

Run-2 Detector Upgrade

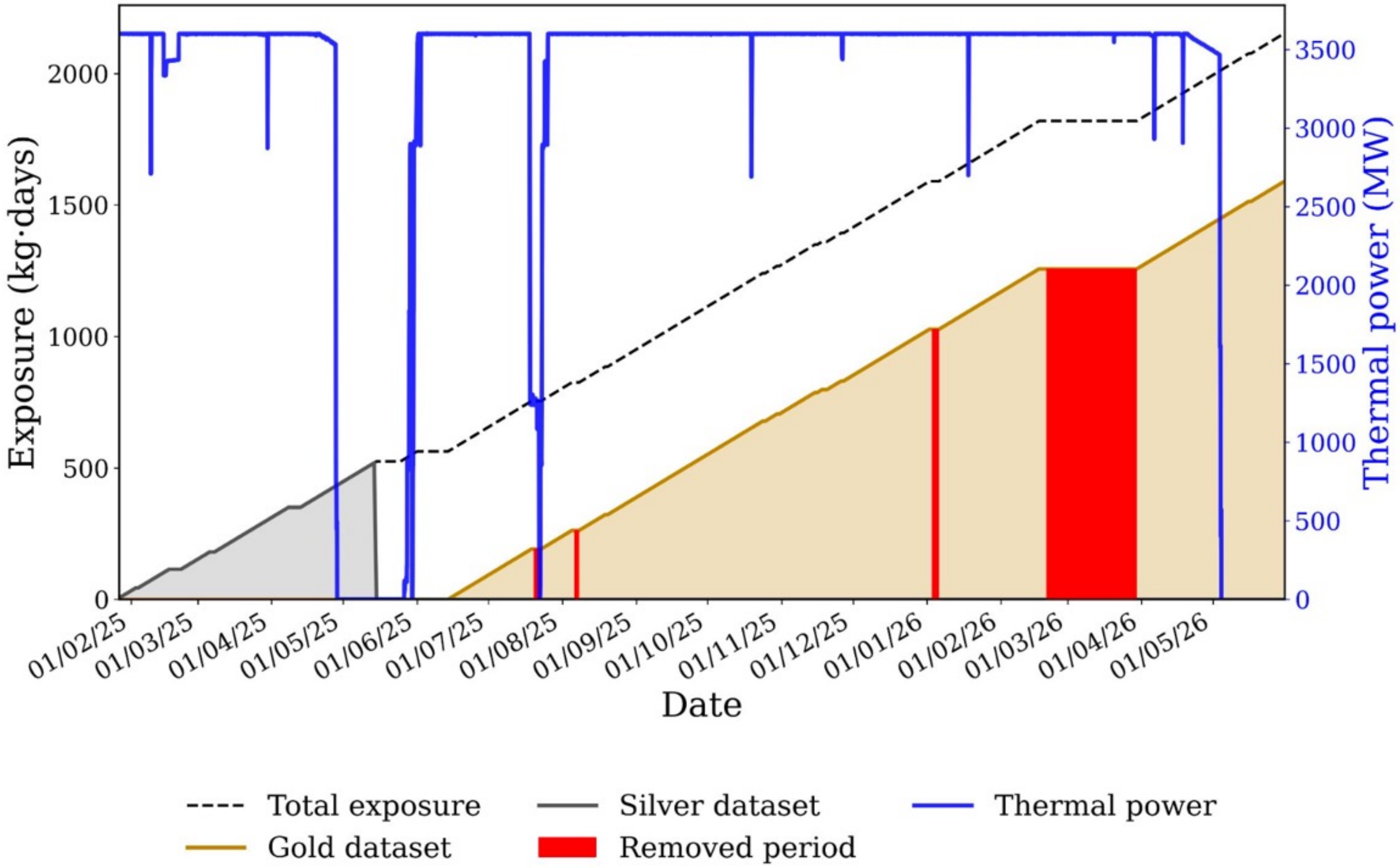


Nov. 2024 →



- 3 new 2.4 kg PPC Ge detectors:C9, C7 and C6
- one detector not operational
- one “old” 1kg detector (C3) for reference
  → total/active mass 5.9 / 5.6 kg
- better cryocooler stability with new coolant
- slight background improvement in new detectors
- thresholds at least as low as in previous detectors
- no hint of any new background induced

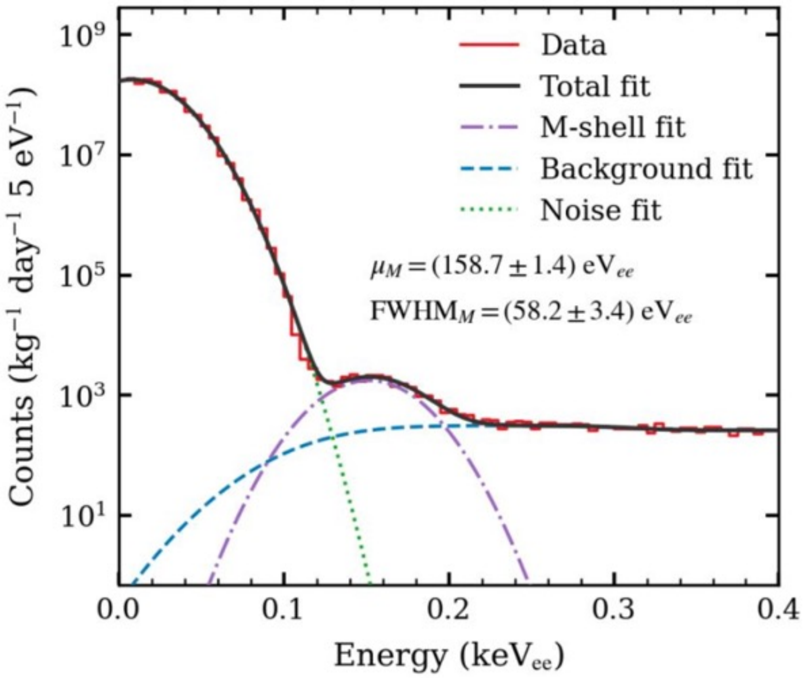
Run-2 Exposure of CONUS+

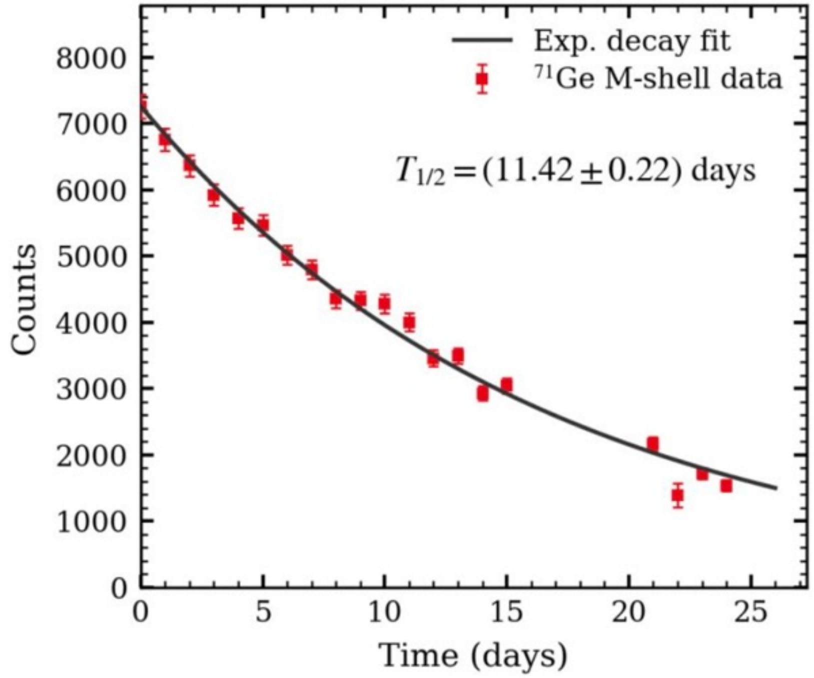


CONUS+ exposure of Run-2 for CEvNS analysis:

- **reactor ON 1296 kg*day**
- **reactor OFF 86 kg*day**

Sub-keV Energy Calibration with ^{71}Ge





Production of 71Ge by neutron irradiation: **arXiv:2604.25748**

- reconstructed value of the ^{71}Ge M-shell X-ray line: **158.7±1.4 eV$_{ee}$**
- consistent with literature

➔ validation of the energy reconstruction down to the energy threshold!

Detector Performance

Trigger efficiency > 80% down to 140 eV_{ee}.

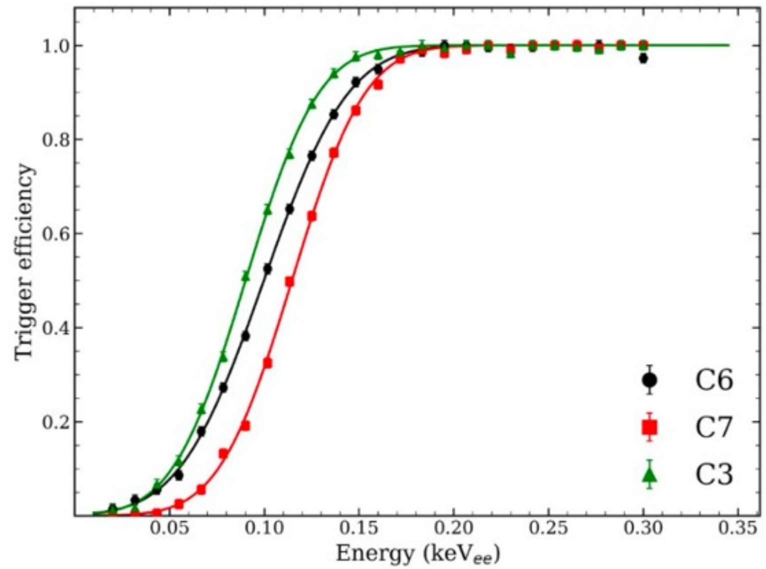
Pulser resolution <55 eV_{ee} for all detectors.

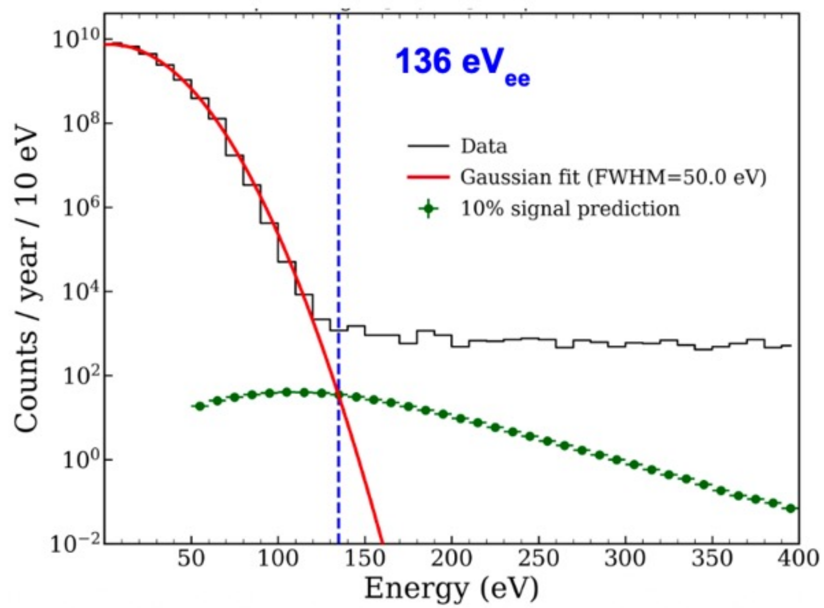
Energy scale uncertainty at the threshold level < 3 eV_{ee} for all detectors.

Maximum non-linearity reduced below 4 eV_{ew}.

Energy threshold defined based on noise contribution to signal region.

Detector	Threshold [eV_{ee}]
C6	160
C3	170
C7	140





Selection Cuts

- Muon veto background rejection > 99% with anticoincidence window of 450 µs

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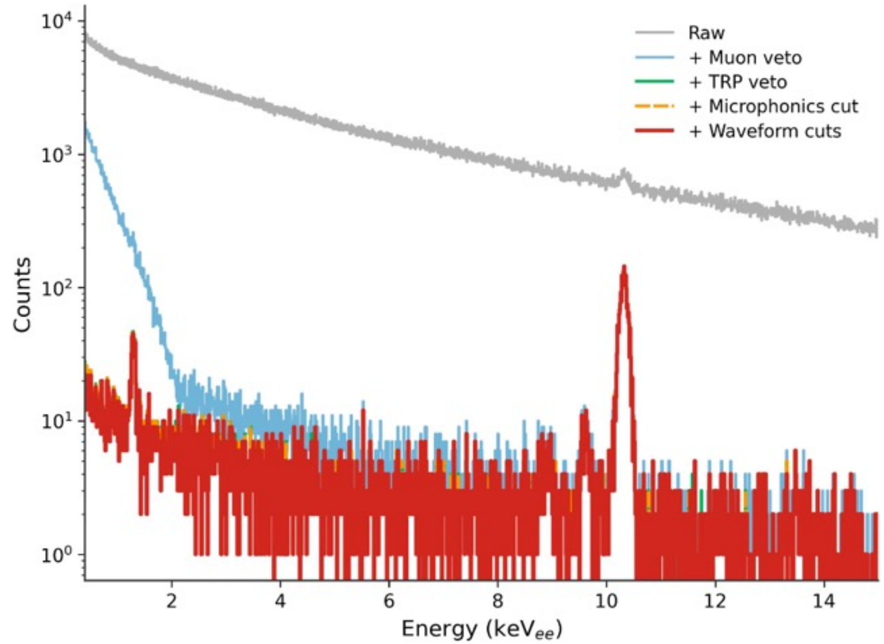
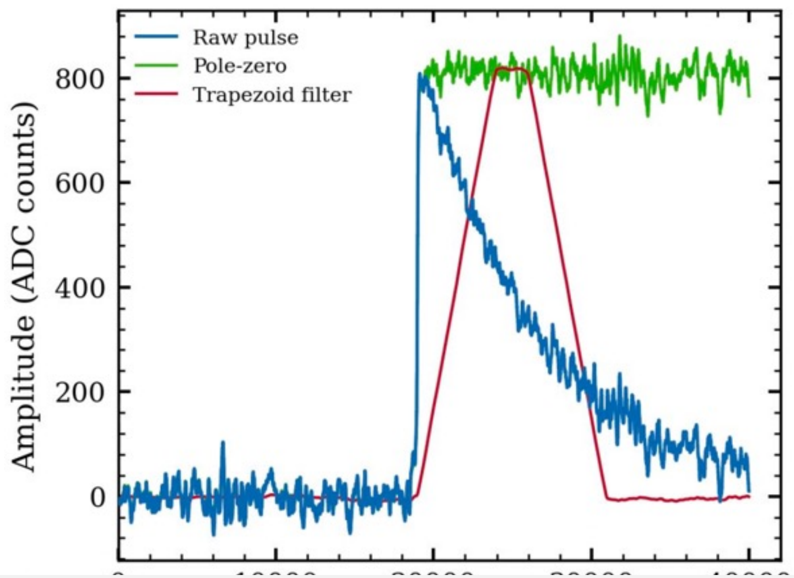
- Microphonics

- Waveform quality cuts to ensure proper energy reconstruction:

  - Energy correction delay events
  - Flat baseline in pre-trigger region
  - Pulse rise around trigger position

- Visual inspection of removed and remaining waveforms





Detector Stability: C6

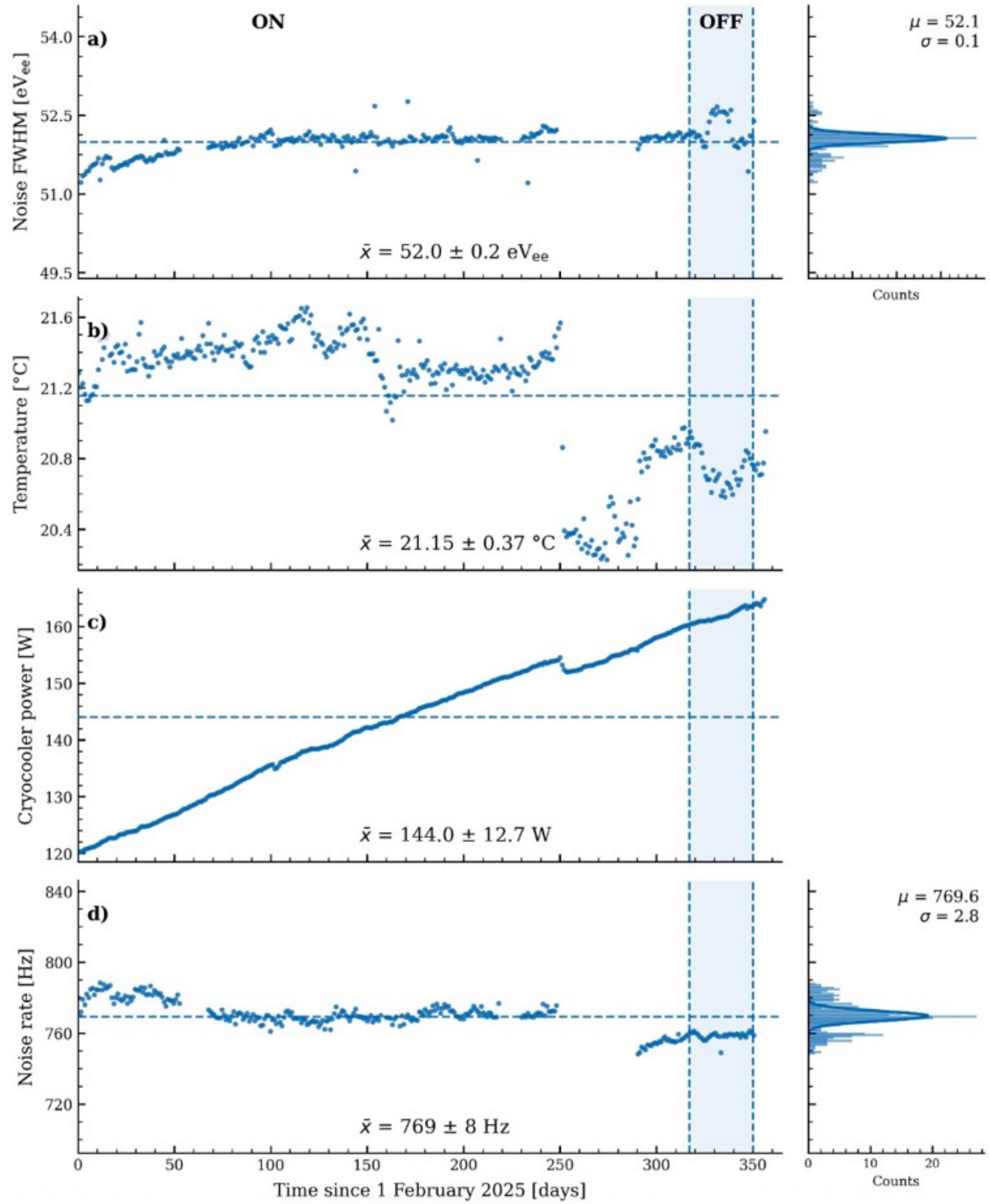
Noise level stable within 3% for all detectors.

Noise FWHM within 2 eV_{ee}

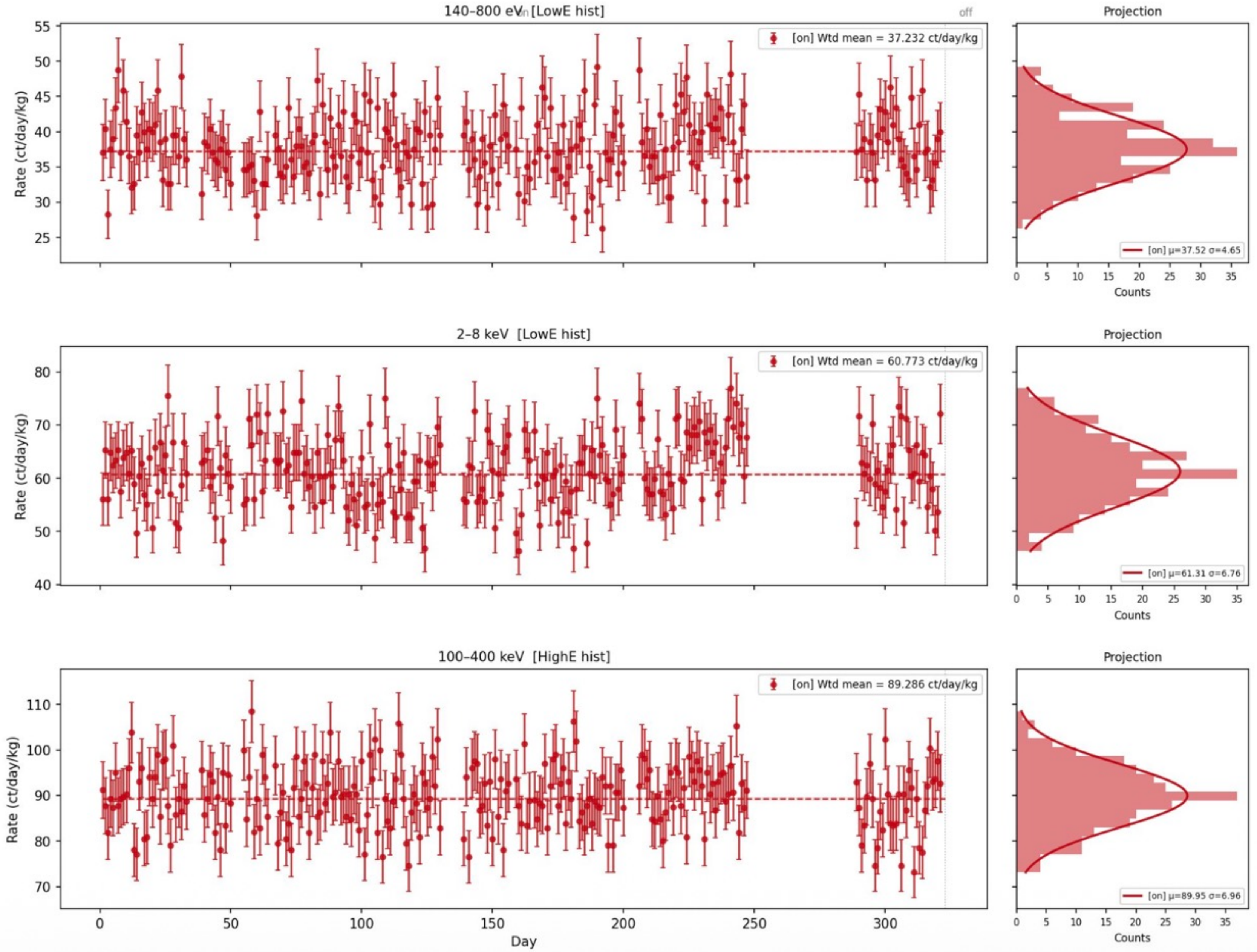
Increase in cryocooler power due to vacuum problem.

No correlation between rate at above 150 eV_{ee} and power.

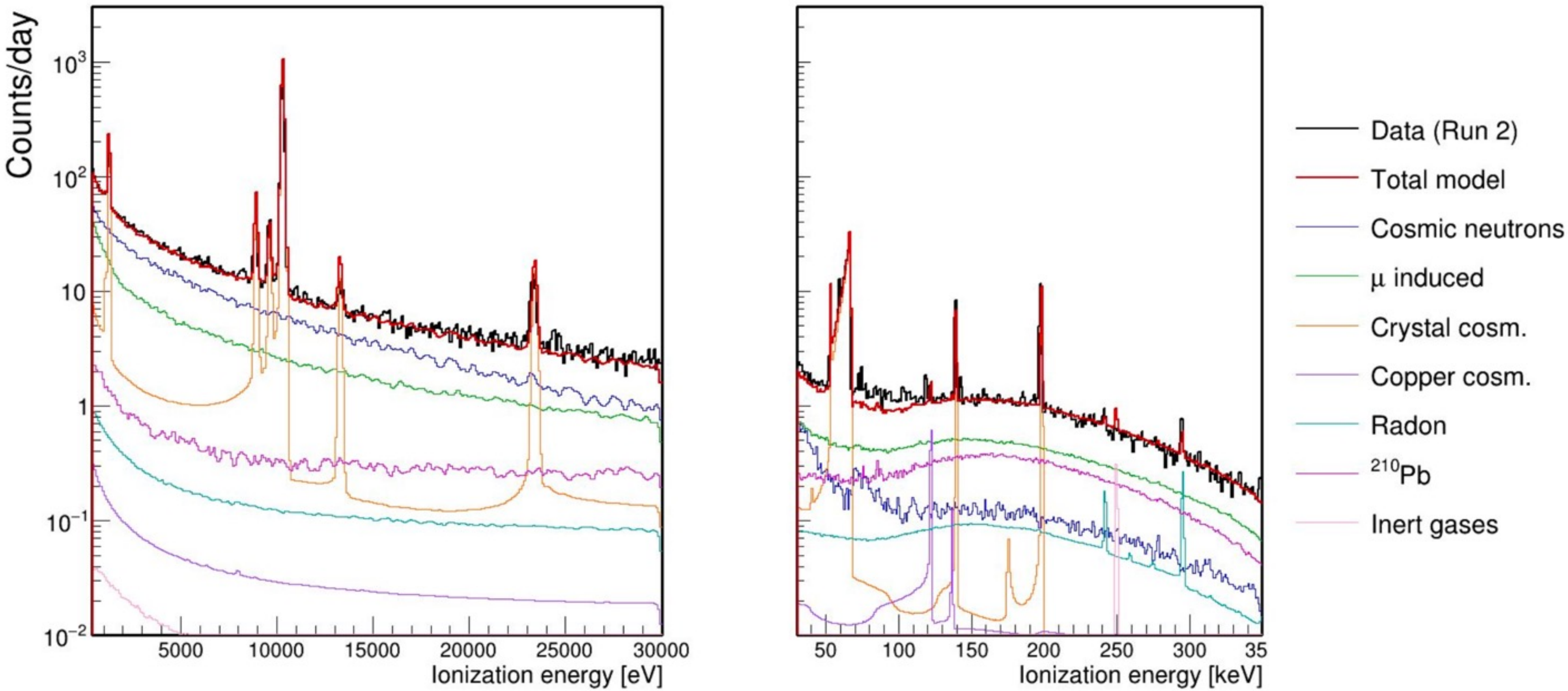
Very good stability!



Background Stability: C7

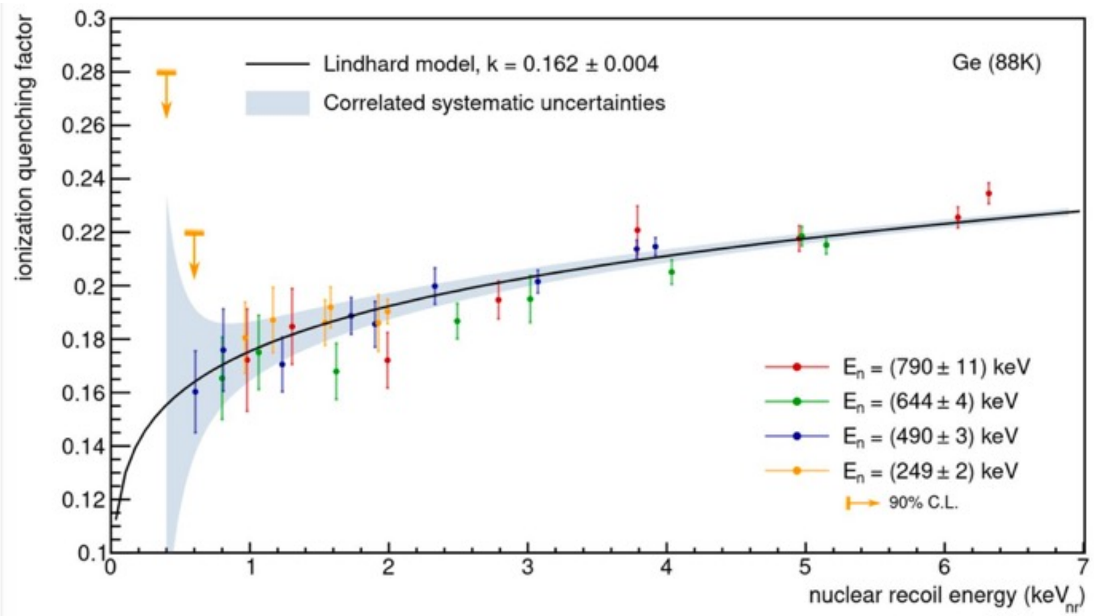


Background Model

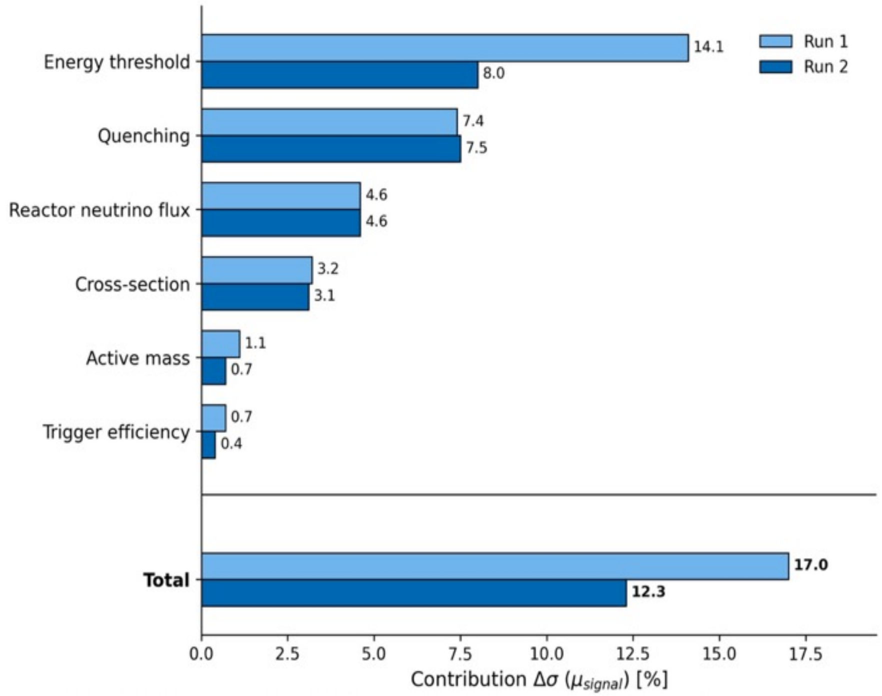


Signal Prediction

- Signal prediction based on DayaBay spectra including neutrinos over 8 MeV
- Lindhard quenching factor with **k=0.162±0.004**
  ➔ CEνNS signal prediction (SM) for Run-2: **1701±198**



EPJC 82 (2022) 815



error contributions

Unblinding of Run-2 Dataset

- Energy spectra of the are hidden for the signal region of interest below 400 eV_{ee}
- Staged approach for unblinding:
  - require good agreement between two likelihoods ✅
  - implementation of likelihood modifications over run-1 dataset ✅
  - Asimov data for run-2 with arbitrary signals ✅

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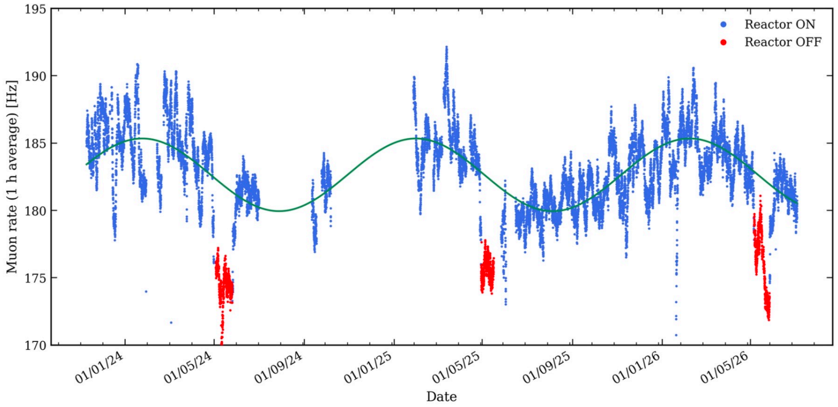
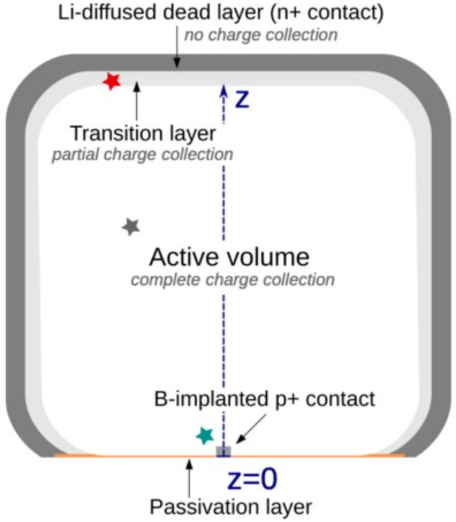
  - implementation of likelihood modifications over run-1 dataset ✅
  - Asimov data for run-2 with arbitrary signals ✅
  - various on-going final consistency checks (precision measurement); examples:



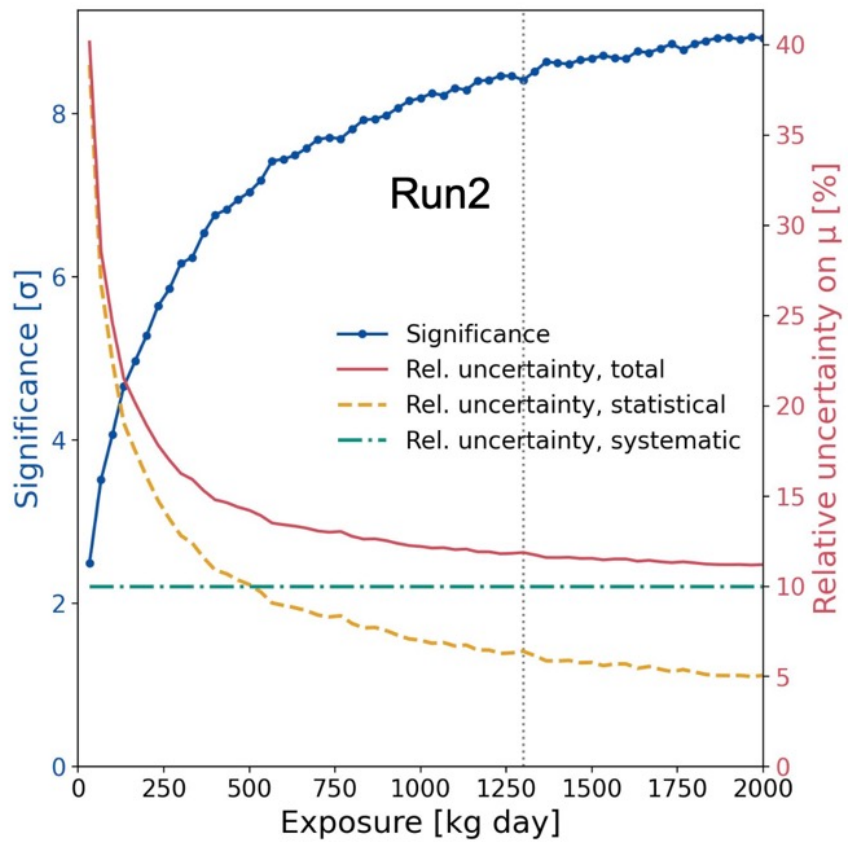
Muon rate for reactor-on (blue) and reactor-off (red)
ON higher than OFF ←→ fully consistent: 3.8cm steel (dry well)

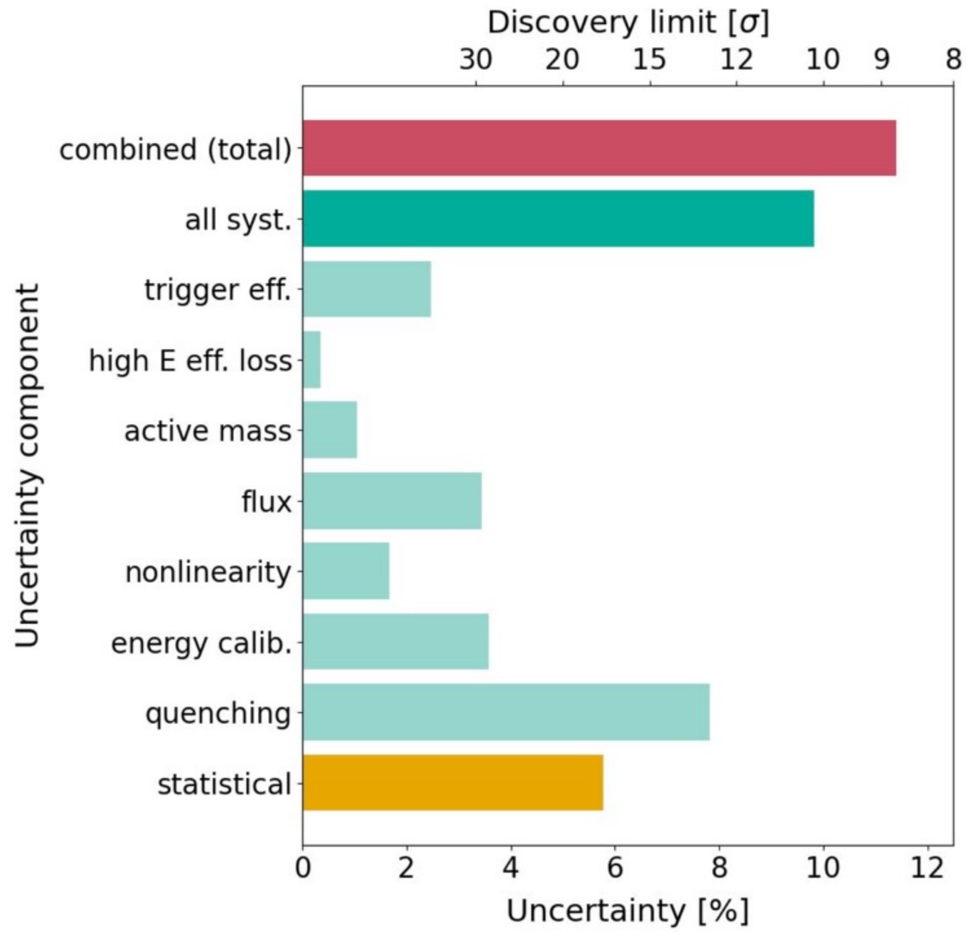


Slow pulses ←→ thickness of the transition layer

- **New results very soon!**

Run-2 Sensitivity Estimate





- Expectation for Run-2: **>8 σ , very soon, stay tuned...**
- Central value ←→ SM?
  ➔ updated analyses for all sort of BSM physics

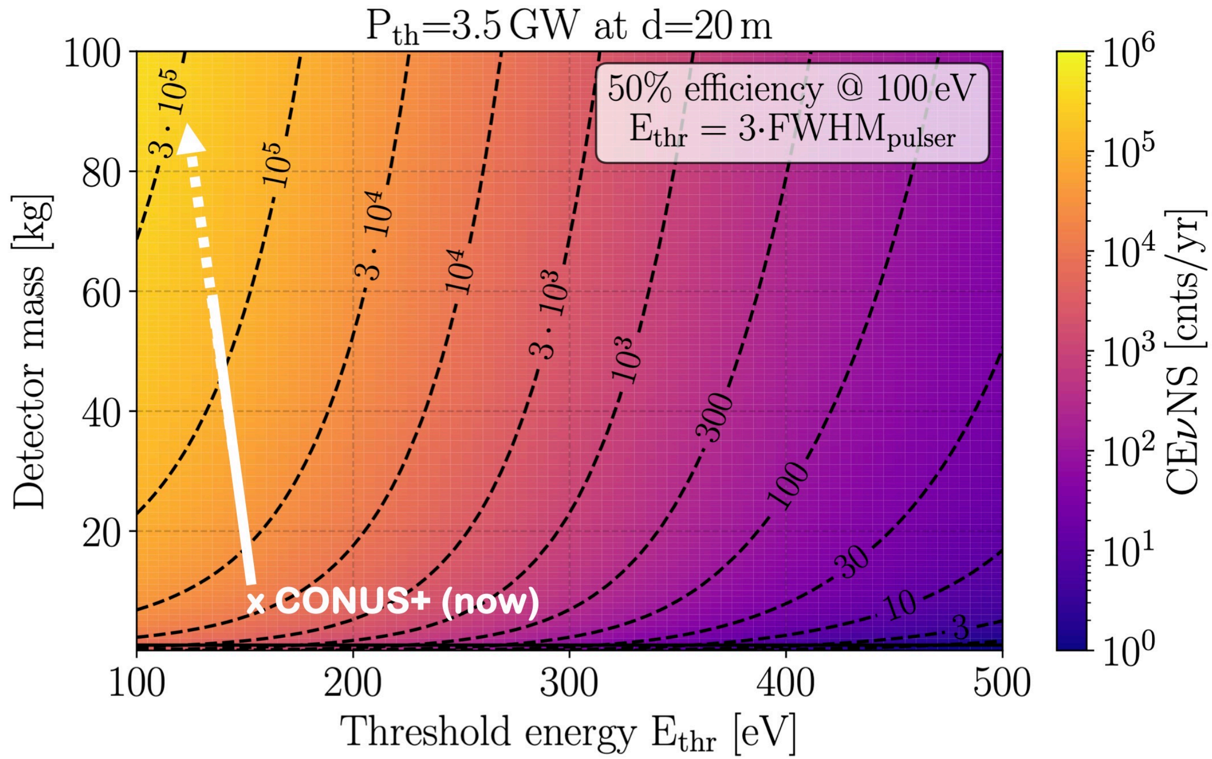
Future Prospects

technology for moderate size high statistics experiments established:

- O(100kg) Ge possible
- 100 eV threshold feasible

➔ 500.000 events in 5y
➔ plans for CONUS100
with enlarged collaboration

- other technolgies @reactors



ML, T. Rink, M. Sen, JHEP 08 (2024) 171

in addition:

- upgrades of COHERENT
- next generation LXe dark matter (XLZD, ...)

➔ precision CEνNS physics with excellent potential within a few years...

Reasons for Precision CEνNS

CEνNS relates to many interesting topics:

- Rather clean SM predictions for cross sections → BSM sensitivity
- Sensitivity to neutrino magnetic moment, $\langle r_\nu^2 \rangle$, millicharges, ...→ BSM sensitivity
- Possibility to measure $\sin^2\theta_W$ at low energies → BSM sensitivity
- Sterile neutrino searches → BSM
- Tests of lepton universality → BSM
- Connections to dark matter physics → BSM
- Measurements of neutron formfactors (nuclear structure) → unique
- Nuclear reactor monitoring (non-proliferation) → applications
- Flux and spectral measurements → synergy with other experiments (oscillation,...)
- CEνNS & energy transport in supernovae → important for next SN
- SN neutrino detection → SNEWS, pointing, ...
- Input for dark matter direct detection (neutrino floor) → solar neutrinos

→ some examples

New Bosons

Heavy: ➔ partially covered by NSI's (being integrated out...)
➔ interactions of new heavy bosons with SM bosons

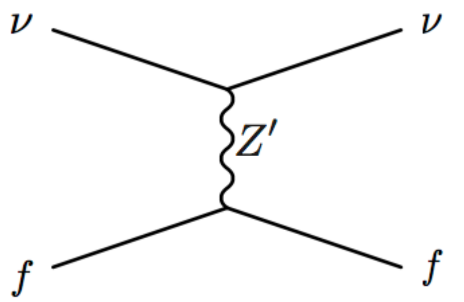
Light: ➔ simplified models

- new light scalar/vector mediators
- universal couplings
- light scalar boson ϕ : $\frac{d\sigma_\phi}{dT} = \frac{g_\phi^4 (14N + 15.1Z)^2 M^2 T}{4\pi E_\nu^2 (2MT + m_\phi^2)^2}$
- light vector boson Z': $\frac{d\sigma_Z{}'}{dT} = \left(1 - \frac{3 g_Z^\nu{}' g_Z^q{}' (Z+N)}{\sqrt{2} G_F Q_{SM} (2MT + m_Z^2{}')}\right)^2 \frac{d\sigma_{SM}}{dT}$

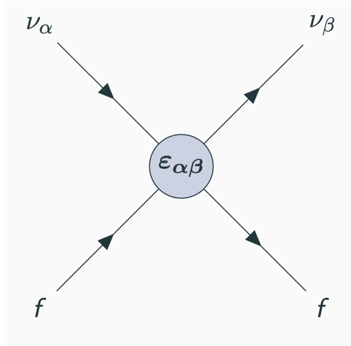
➔ **often connected to dark sector = DM**

BSM Physics as NSI's

NSI's ←→ BSM at high scales
... which is integrated out
Z', new scalars, … → ε_{ij}



→



$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^\rho\, \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \left\{ \left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) \right]^2 + \sum_{\alpha=\mu,\tau} \left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}) \right]^2 \right\}$$

Barranco et al. 2005

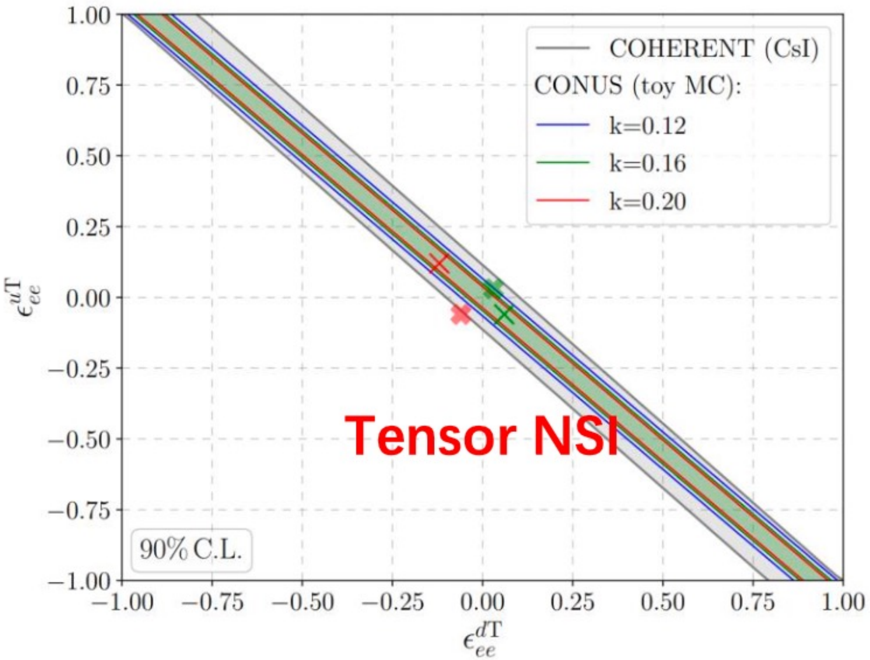
$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

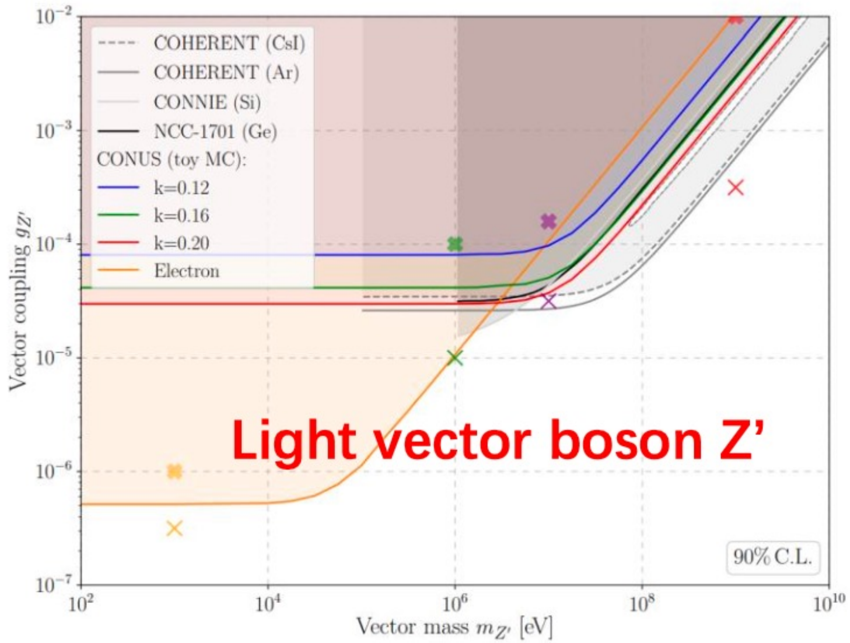
→ **a powerful method to test new physics**
$\varepsilon = 0.001$ ←→ test multi TeV scales

CONUS BSM Results: Run 1-4 @KBR

Fully coherent regime ➔ any deviation form SM = new physics:

Tensor/Vector NSI (non-standard interactions): limits the coupling parameter space
Light vector boson: limits the mass-coupling parameter space
Neutrino millicharged: $|q_\nu| < 3.3 \times 10^{-12}\ e_0$
Neutrino magnetic moment: $\mu_\nu < 7.5 \times 10^{-11}\ \mu_B$



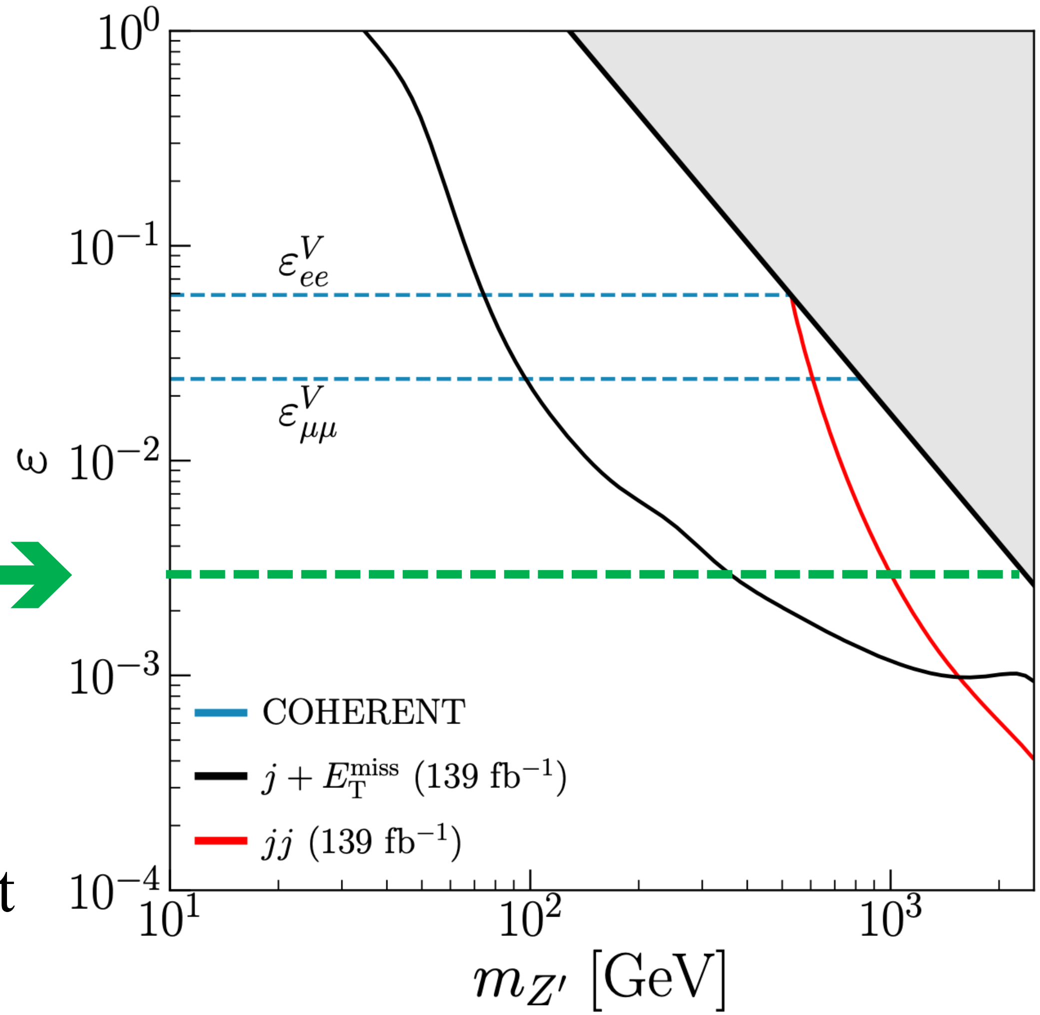


JHEP 05 (2022) 085

100kg Projection for a Z'

sensitivity to a new Z' gauge boson assuming weak coupling:

500k events →

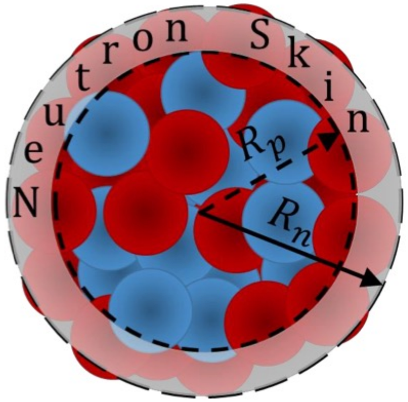


"scoping" → early evidence for BSM (or nothing) at a next huge collider...

Nuclear Models and NSI's

Klein-Nystrand form factor

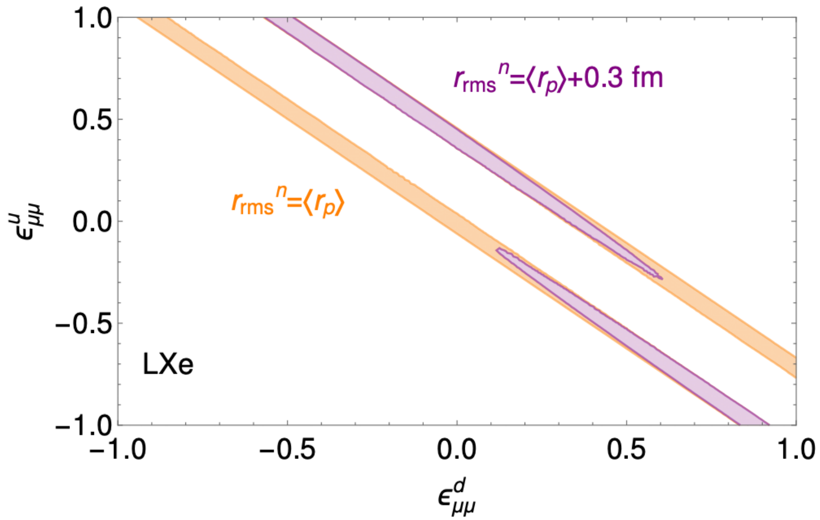
$$F_W(|\vec{q}|^2) = 3\frac{j_1(|\vec{q}|R_A)}{|\vec{q}|R_A}\left(\frac{1}{1+|\vec{q}|^2 a_k^2}\right)$$

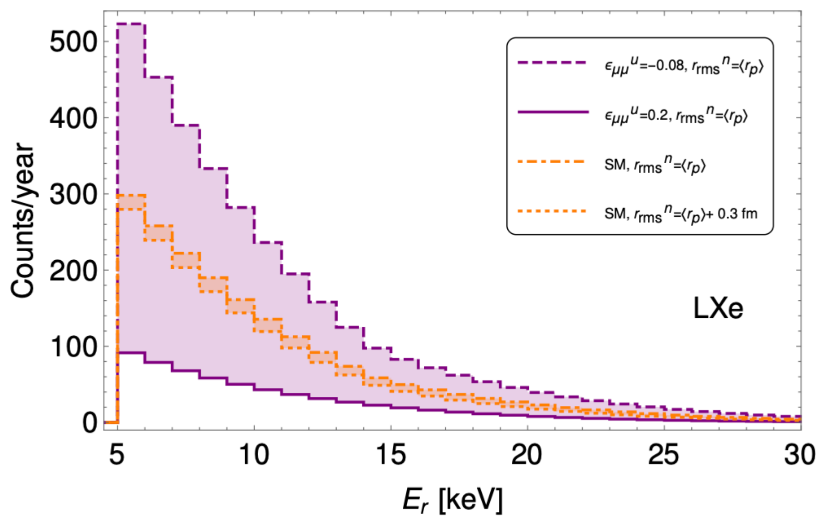


➔ **relies on a surface-diffuse distribution**
folding a short-range Yukawa potential with range a_k
over a hard sphere distribution with radius R_A

$$\langle r^2 \rangle_{KN} = \frac{3}{5}R_A^2 + 6a_k^2$$

Aristizabal Sierra, Liao, Marfatia, JHEP 06 (2019) 141
allowed regions in the NSI case and for two choices of the rms neutron radius





Nuclear Structure with coherent Scattering

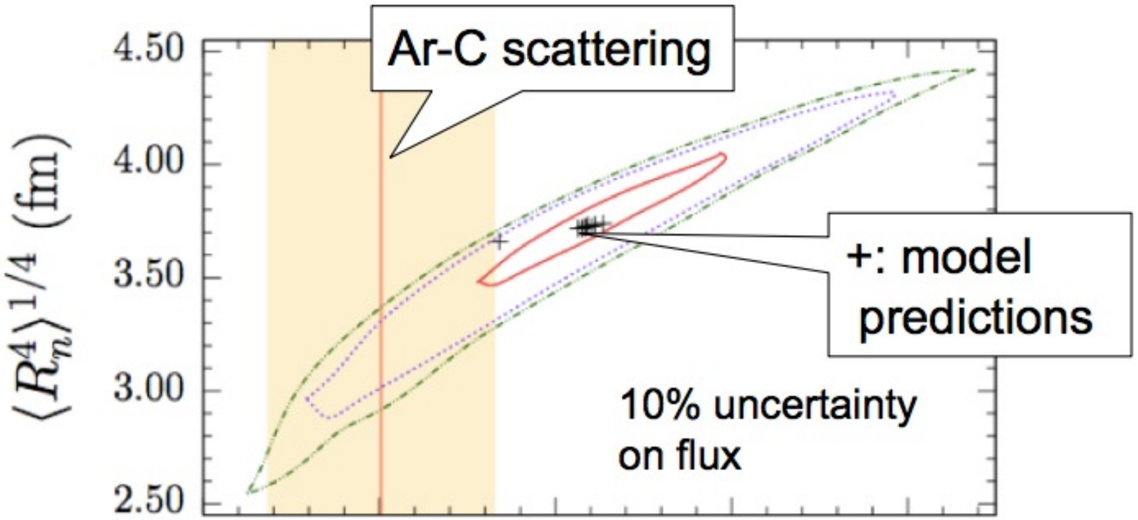
Remember: DAR sources close to de-coherence ←→ combine with reactor measurements

$$\frac{d\sigma}{dT} \approx \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E^2}\right)\left[N F_N(q^2) - Q_W Z F_Z(q^2)\right]^2$$

Nuclear form factors $F_{N,Z}(q)$ ~Fourier transforms of N & P densities
→ resolve nuclei (≃ neutrons) in neutrino light

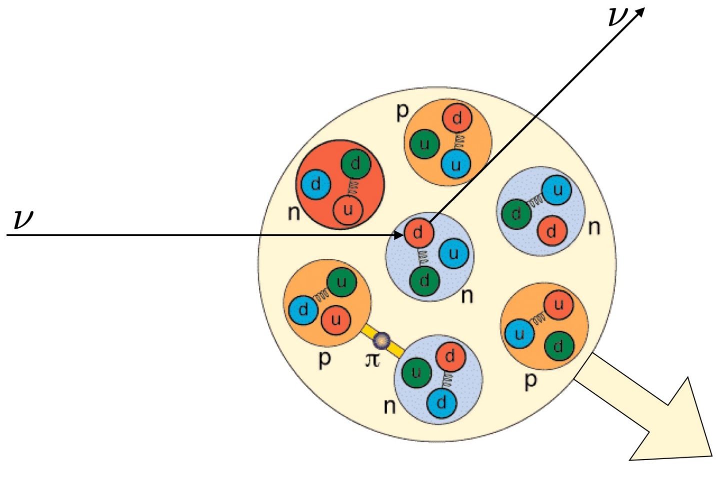
Fit recoil ***spectral shape*** to determine the $F(Q^2)$ moments
(requires very good energy resolution,good systematics control)

Example:
tonne-scale
experiment
at πDAR source



Neutrinos interact with quarks...

sub-structure of neutrons and protons?



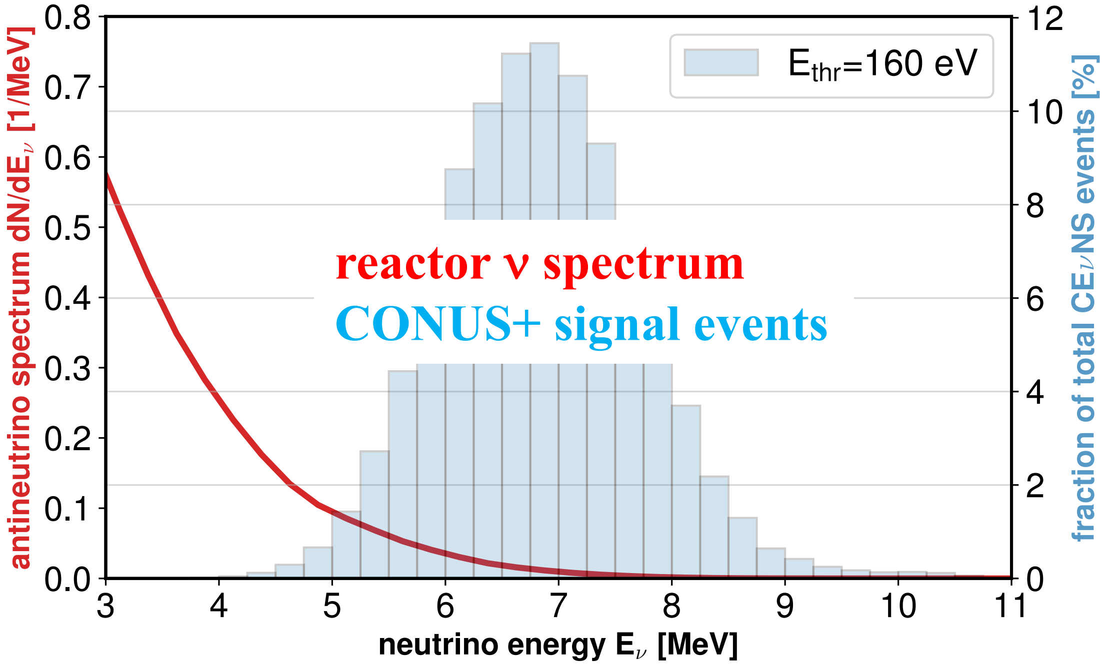
requirements: absence of individual recoil
←→ nuclear structure, binding
scattering in phase
←→ is the form factor picture sufficient
limitations of factorization $\sigma \otimes F(q^2)$

- **CEνNS in QFT ➔ conceptually very interesting questions**
  see e.g. **Akhmedov, Arcadi, ML, Vogl, JHEP 1810 (2018) 045, arXiv:1806.10962**
  - role of the recoil of constituents in quantized picture
  - semi-classical factorization of QFT process into (cross-section) * $F(q^2)$?

- **coherence length in QFT approach**
  Egorov, Volobuev: 1902.03602

➔ probably sub-leading for next generation, but very interesting

Learning about Sources: Reactors



Detector	Threshold [eV$_{ee}$]	Predictetd CEvNS counts
C5	170	116 (+20/-18)
C2	180	96 (+16/-14)
C3	160	135 (+23/-20)
COMBINED	-	345 (+34/-30)

CONUS+ signal comes from high energy tail of reactor spectrum

➔ importance of lowest possible threshold

➔especially sensitive to the least known HE end of the spectrum

←→ short lived isotopes

→ time slices of operation after re-fueling

→ burn up → improved understanding of ν-spectrum

useful for CEvNS @reactors and for many other experiments

Conclusions

- **CEνNS is already a hot topic**
  - observation in πDAR, ^{8}B solar n‘s and reactor anti-neutrinos
  - very soon significant increase of precision in CONUS+
  - various very interesting BSM implications
- **One can expect**
  - increasing precision of CEνNS measurements within a few years → interesting potential
  - growing number of studies discussing BSM, SM details, sources
  - interesting interplay of CEνNS, nuclear physics, HEP, astroparticle physics, source physics

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    → interesting potential
  - growing number of studies discussing BSM, SM details, sources
  - interesting interplay of CEνNS, nuclear physics, HEP, astroparticle physics, source physics
- **A predictions:**
  - a hot subject in next years

BACKUP

Quenching

Recoil energy deposition in Ge detector:

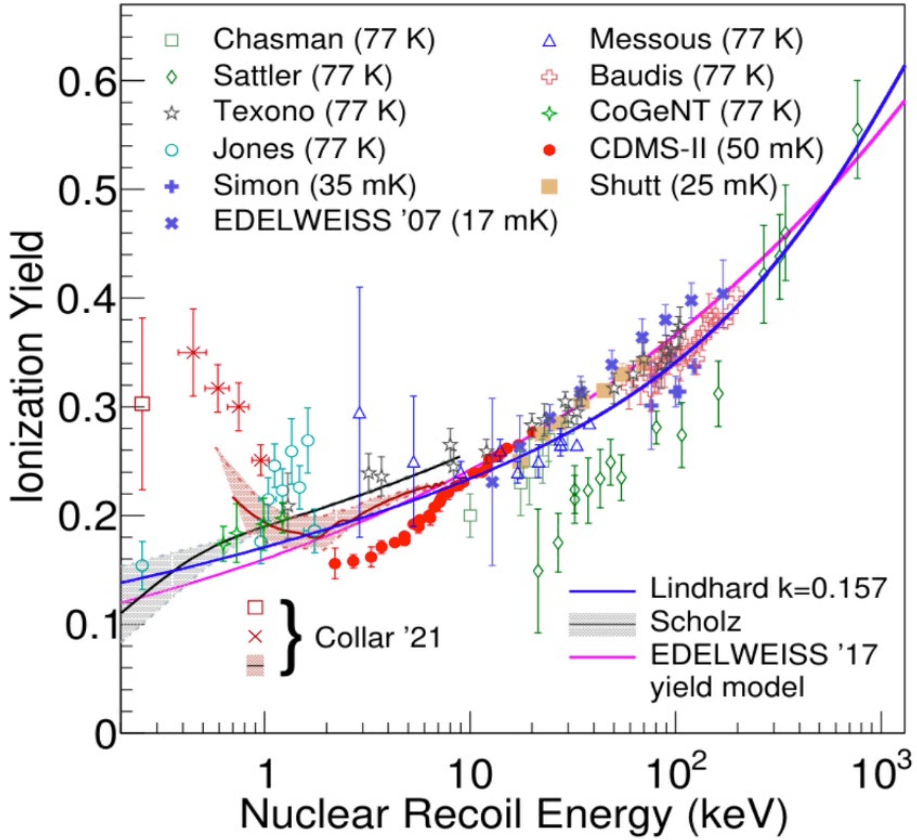
- partially converted into ionization
- drift to point contact, amplification, ...

quenching factor:
(energy dependent)

$$q = \frac{E_{ion}}{E_{rec}} = \frac{k\, g(\varepsilon)}{1 + k\, g(\varepsilon)}$$

$g(\varepsilon) = 3*\varepsilon^{0.15} + 0.7*\varepsilon^{0.6} + \varepsilon$; $\varepsilon = 11.5*Z^{-7/3} E_{rec}$

➔ large uncertainties for E_{rec} < few keV

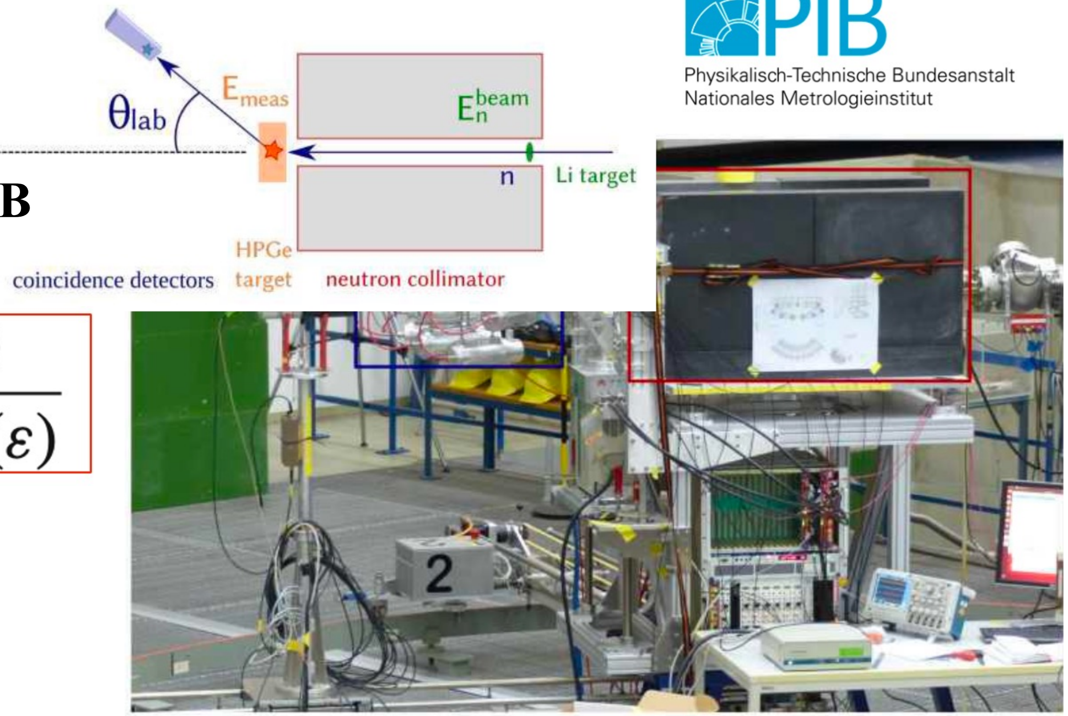


arXiv: 2202.07043

Theoretical / phenomenological description:
Lindhard theory
works well –tested in many limiting cases
should work well down to very low energies
←→ atomic physics

The CONUS Quenching Measurement

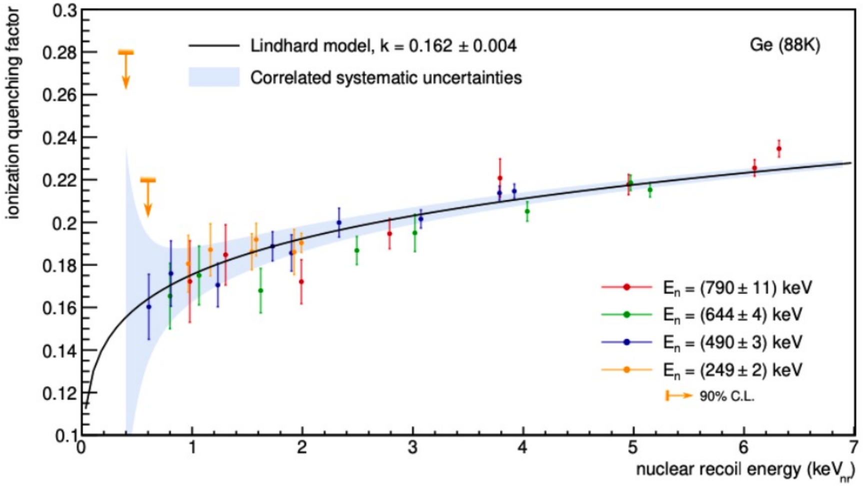
goal:
reduce large uncertainties for E_{rec} < few keV
➔ **dedicated measurement: CONUS + PTB**



quenching factor: $$q = \frac{E_{ion}}{E_{rec}} = \frac{k\, g(\varepsilon)}{1 + k\, g(\varepsilon)}$$

use monoenergetic neutron beam:

- recoil angle ➔ energy transfer E_{rec}
- signal in Ge detector: E_{ion}



➔ significantly improved measurement
➔ consistent with Lindard theory (as it should)
➔ **k =0.162 ± 0.004**

Eur.Phys.J.C 82 (2022) 9, 815

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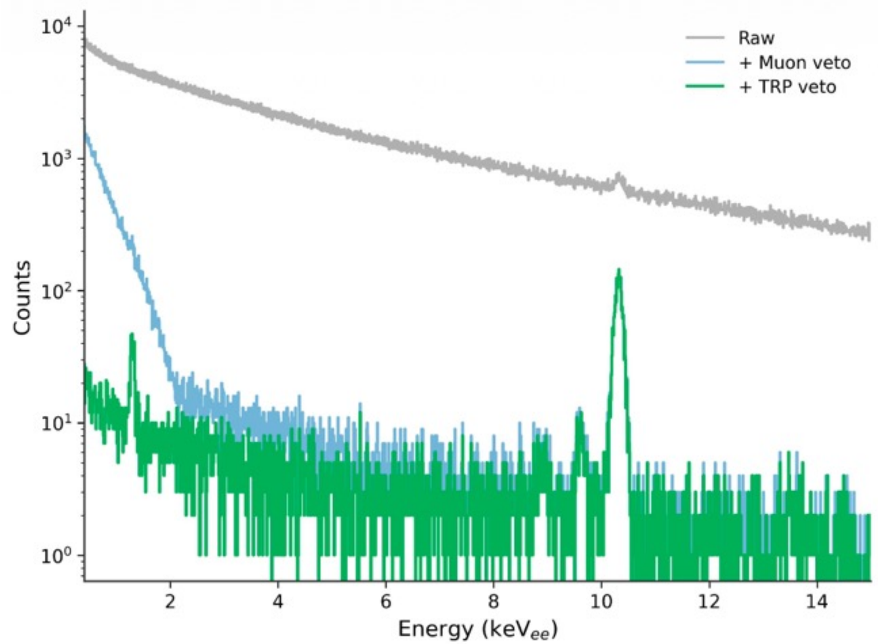

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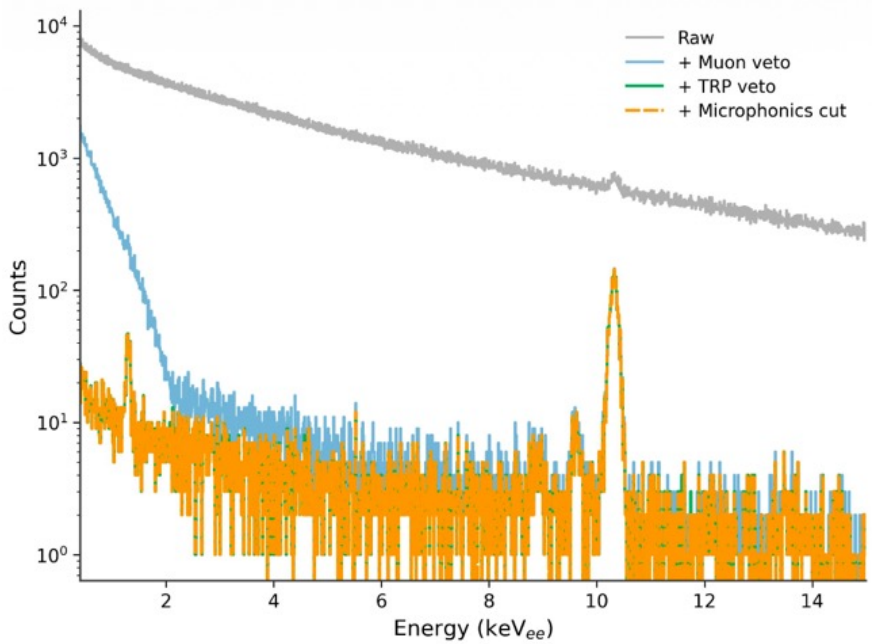

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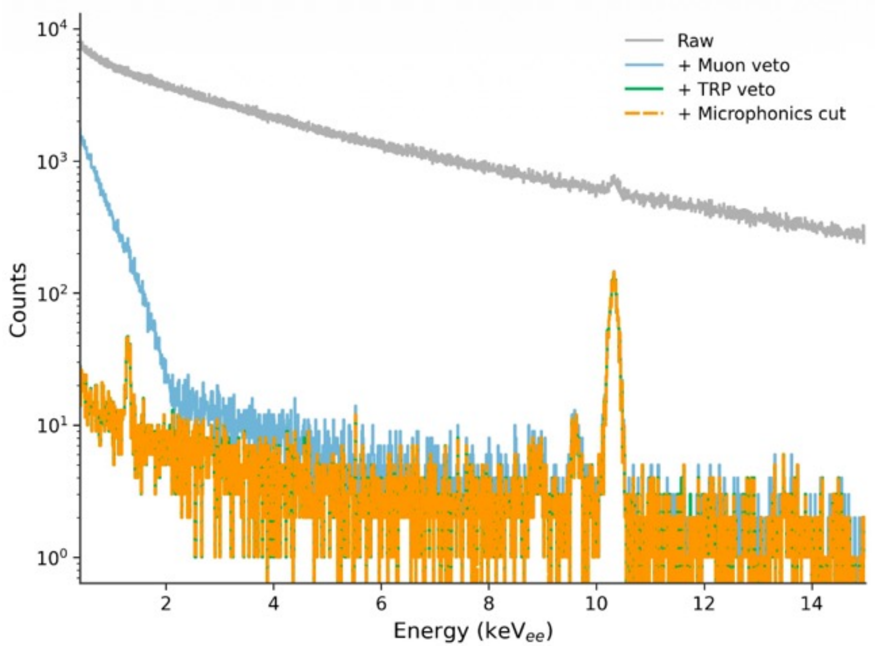

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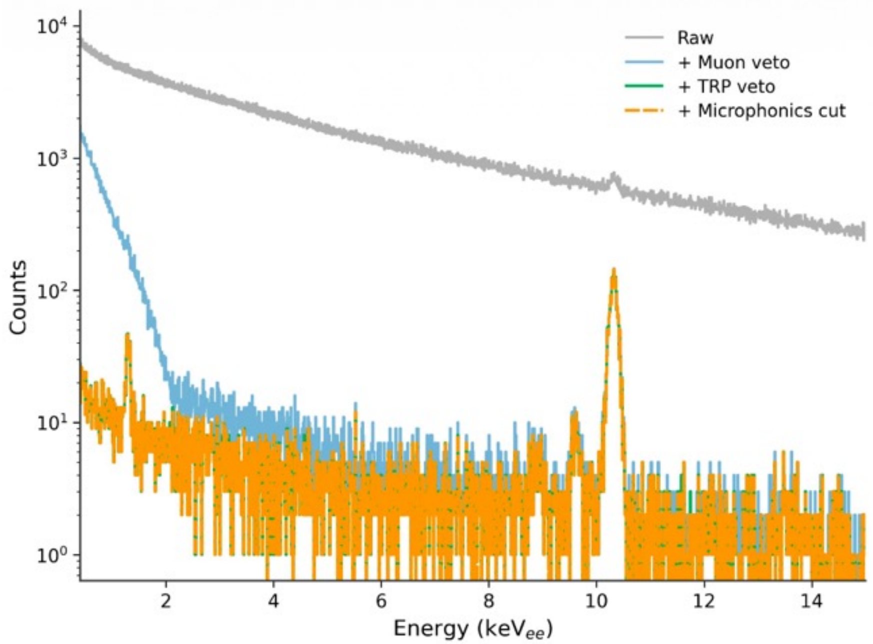

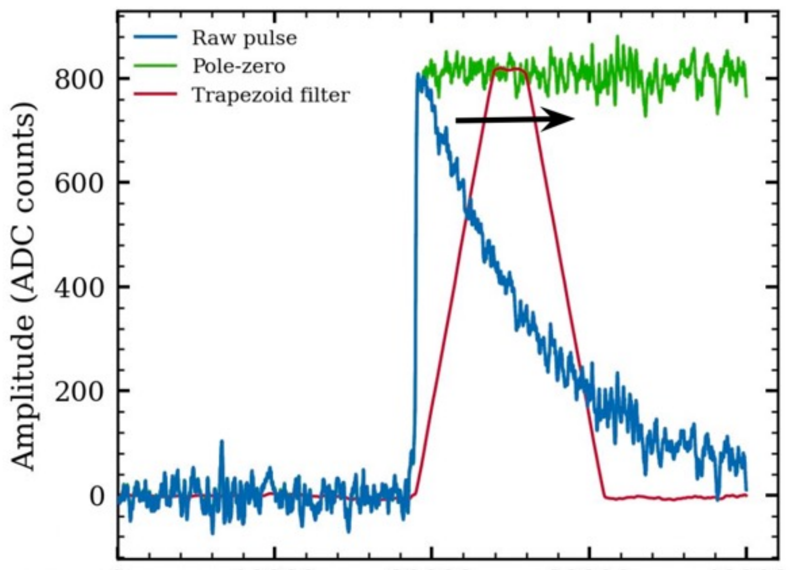

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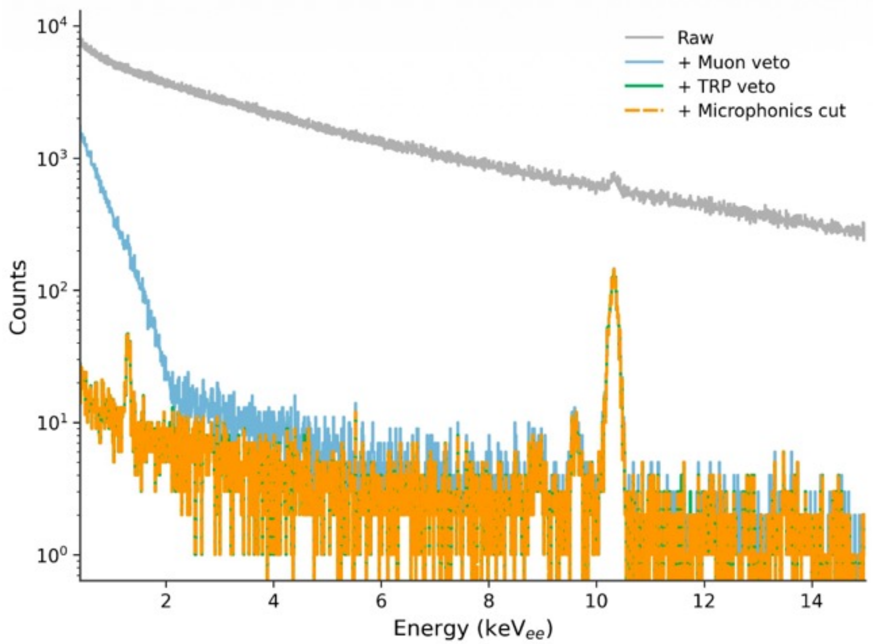

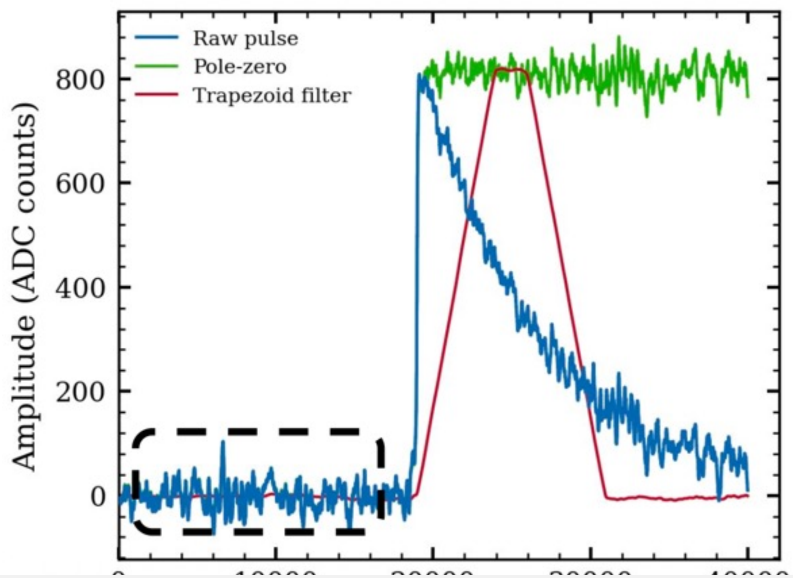

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