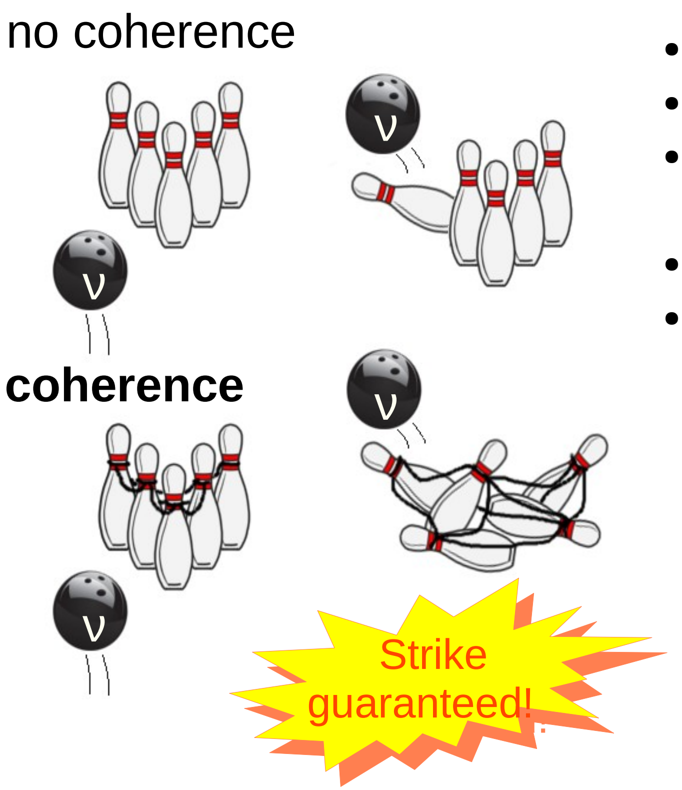
First detection of CEvNS on germanium by COHERENT

Janina Hakenmüller for the COHERENT collaboration

Duke University

JEPT (Wine and Cheese) Seminar, Fermilab, 1st of March, 2024

Coherent elastic neutrino nucleus scattering (CEvNS)



- standard model interaction, flavor blind, no energy threshold
- predicted in 1974: D.Z. Freedmann, Phys. Rev. 9 (1974) 5
- first detected in 2017: COHERENT experiment
  → CsI detector at pion decay-at-rest source
- detection at nuclear reactor (lower ν energies) still pending
- cross section **large** compared to other neutrino interactions (e.g inverse beta decay)

$$\frac{d\sigma}{d\Omega} = \frac{G_f^2}{16\pi^2}(N - (1 - 4\sin^2\theta_W)Z)^2 E_\nu^2 (1 + \cos\theta) F(Q^2)$$

neutrino energy

nucleus

nuclear form factor

$F(Q^2) \rightarrow 1$ for $Q^2 \rightarrow 0$

coherence condition:

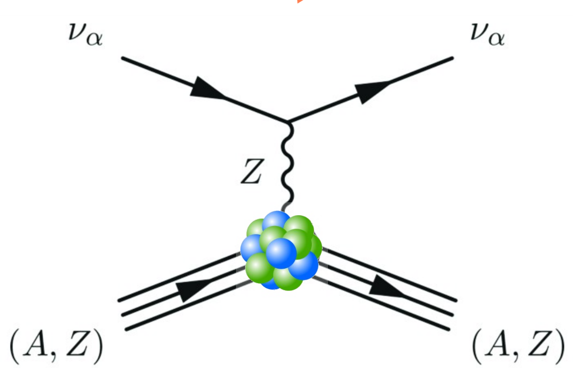
λ(mom. transfer Q) > size of atom => σ ~ (#scatter targets)^2

→ upper limit on neutrino energy:

$$E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}} \quad (\mathrm{MeV})$$

R_A=radius, A= mass number

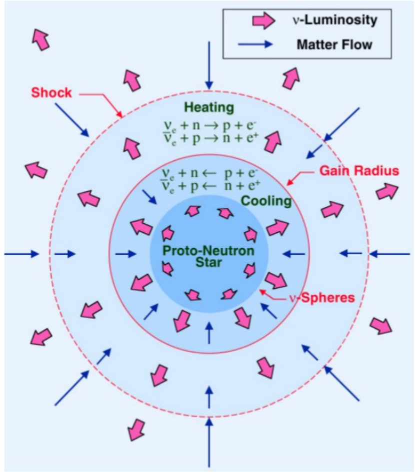
E_{max}≤50 MeV (for medium A)



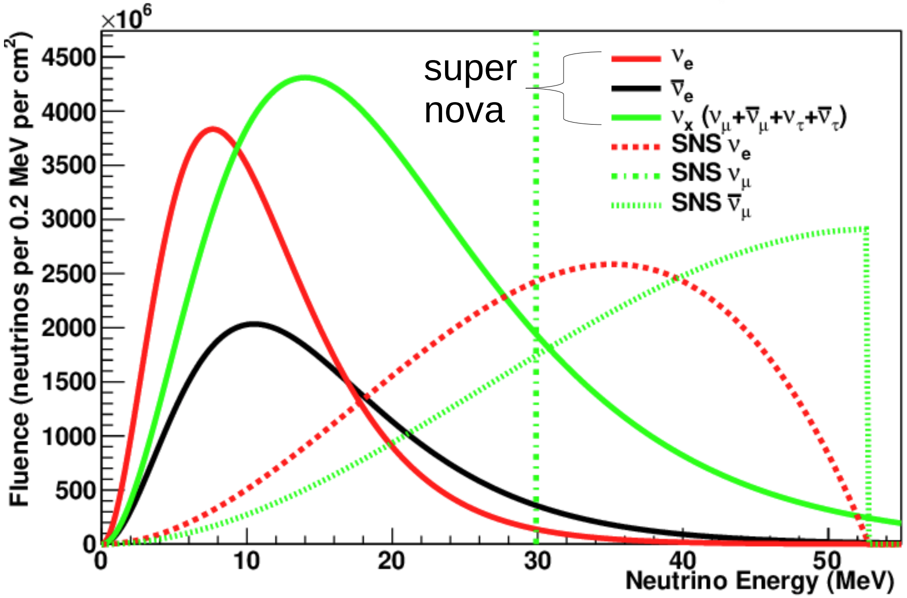
neutrino sources:
spallation source
supernovea
nuclear reactor
radioactive decay

Motivation

- stellar collapse: 99% energy released in neutrinos
  → burst modeling
  → detect on Earth

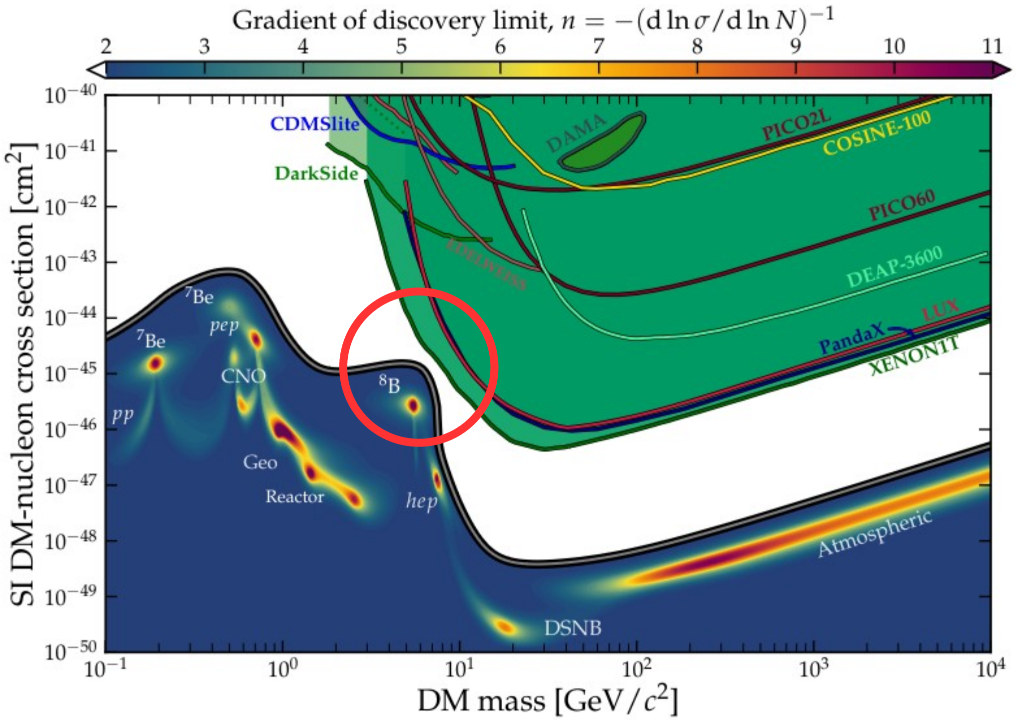


Credit: TeraScale Supernova Initiative



Efremenko, Yu, and William Raphael Hix. JPCS, Vol. 173. No. 1. IOP Publishing, 2009.

arXiv:2203.05914 [physics.ins-det]



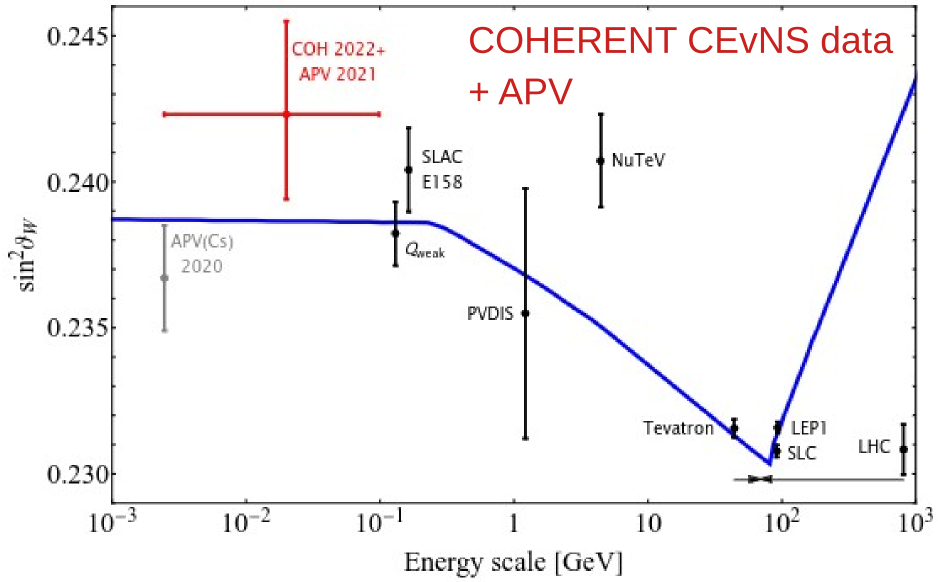
- “neutrino floor/fog” in dark matter experiments: signature like dark matter
  → same detector response

Motivation

- Weinberg angle at low energies

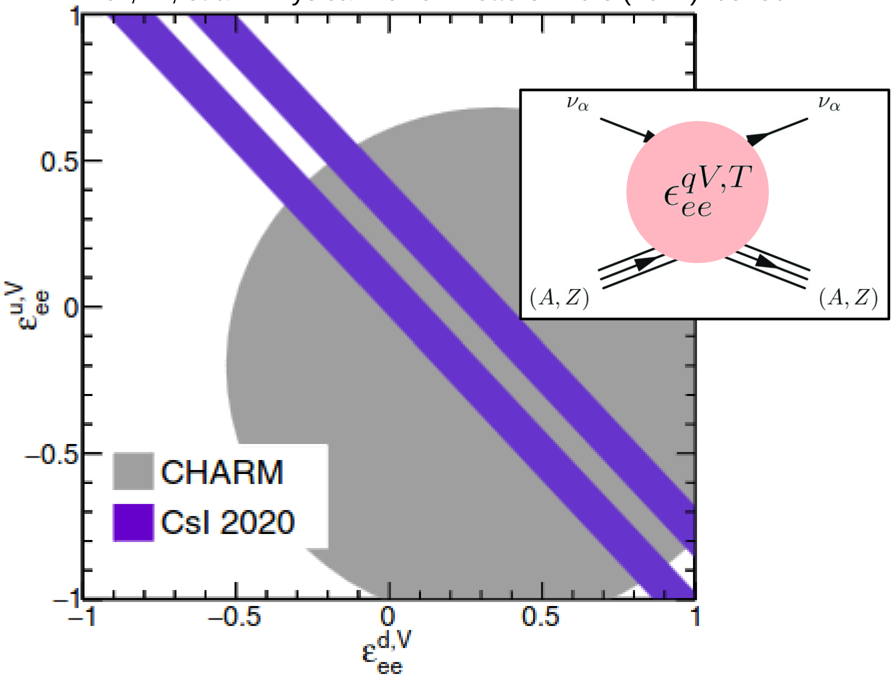
$$\frac{d\sigma}{d\Omega} \propto (N - (1 - 4\sin^2\theta_W)Z)^2$$

Cadeddu, M., F. Dordei, and C. Giunti. Europhysics Letters 143.3 (2023): 34001.

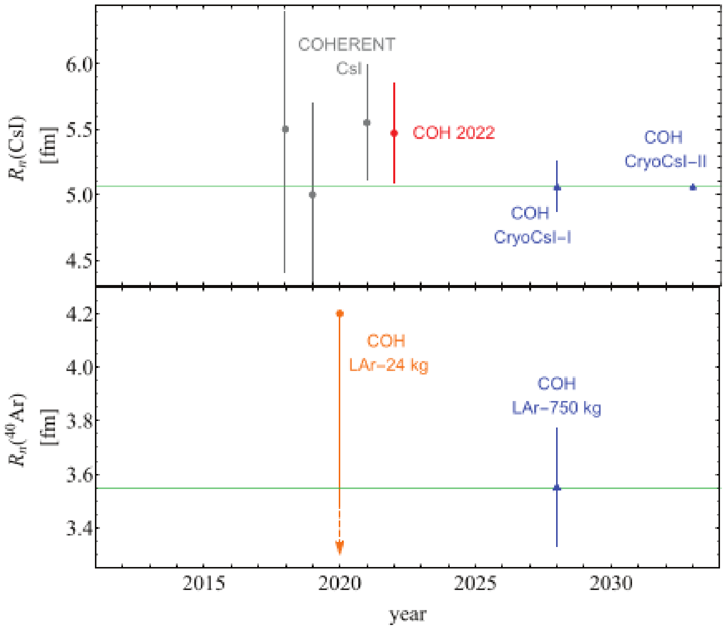


- neutron form factor $F(Q^2)$
- nuclear safeguarding (non-proliferation)

Akimov, D., et al. "Physical Review Letters 129.8 (2022): 081801.



- non-standard neutrino interactions (NSI),...

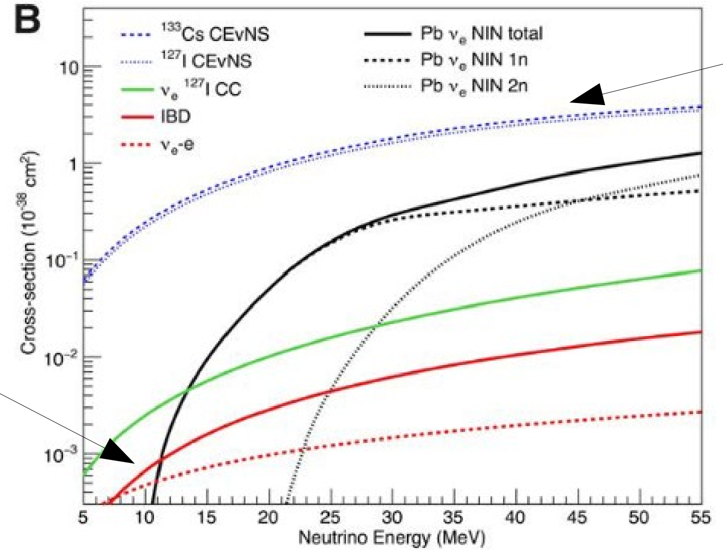


Cadeddu, M., F. Dordei, and C. Giunti. Europhysics Letters 143.3 (2023): 34001.

Detecting CEνNS

BOREXINO

D. Akimov et al., Science 10.1126/science.aao0990, 2017



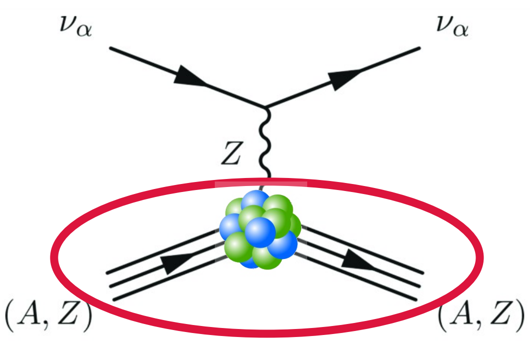
Coherence condition:

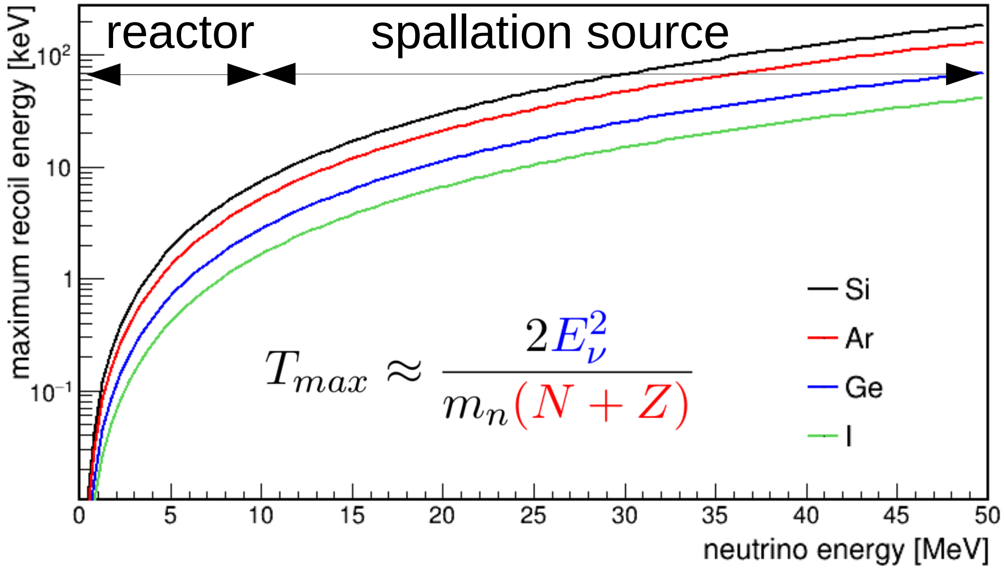
$$\sigma \propto N^2 E_\nu^2$$

COHERENT
CsI

large cross section
=> small detector (kg sized!)

Detection parameter:
recoil of target nucleus



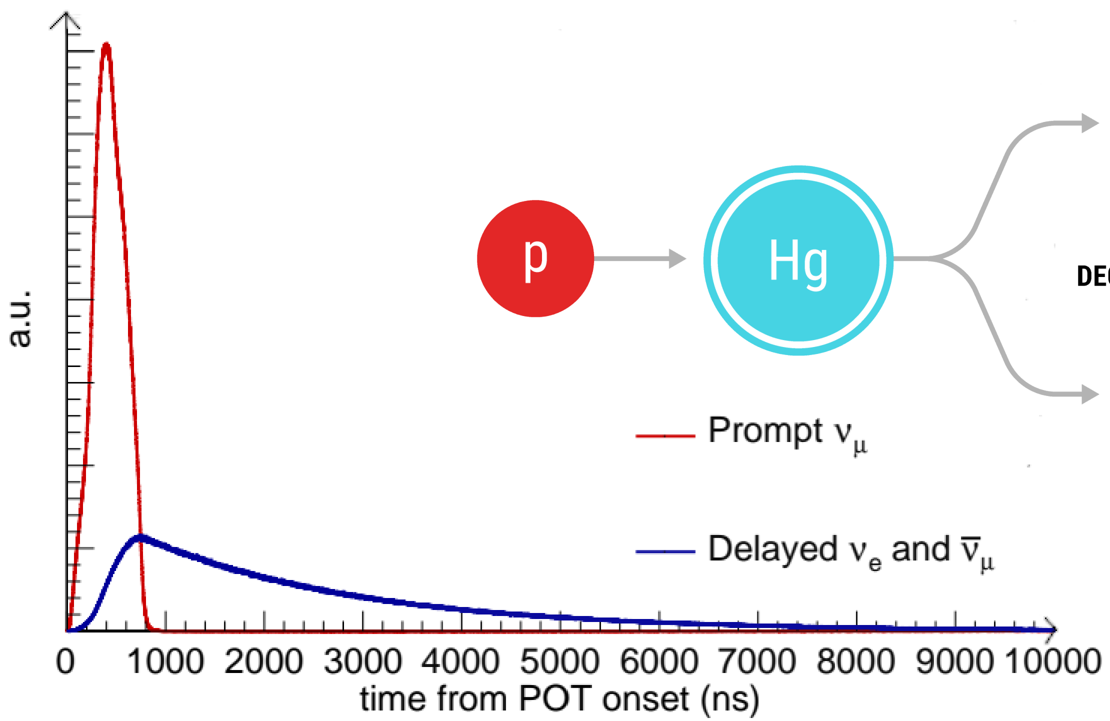


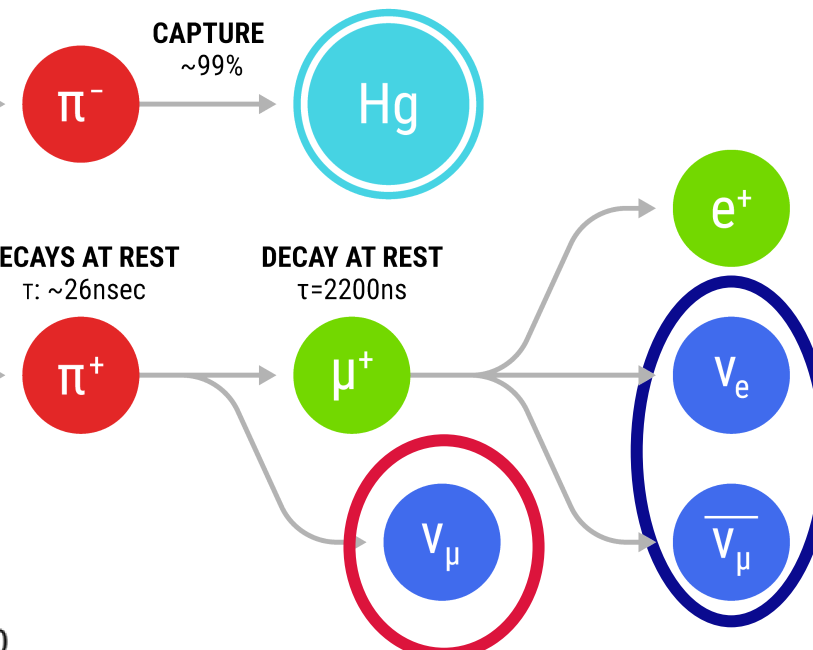
COHERENT experiment

Neutrino Alley at Spallation Neutron Source (SNS)
at Oak Ridge National Laboratory, USA

Pion decay-at-rest source:

- **pulsed** proton beam with 60 Hz
- ~10^{20} protons on target/d (POT)
  up to 1.7 MW power since this summer
  → about 0.29 ν per POT
- background rejection factor
  by beam time structure





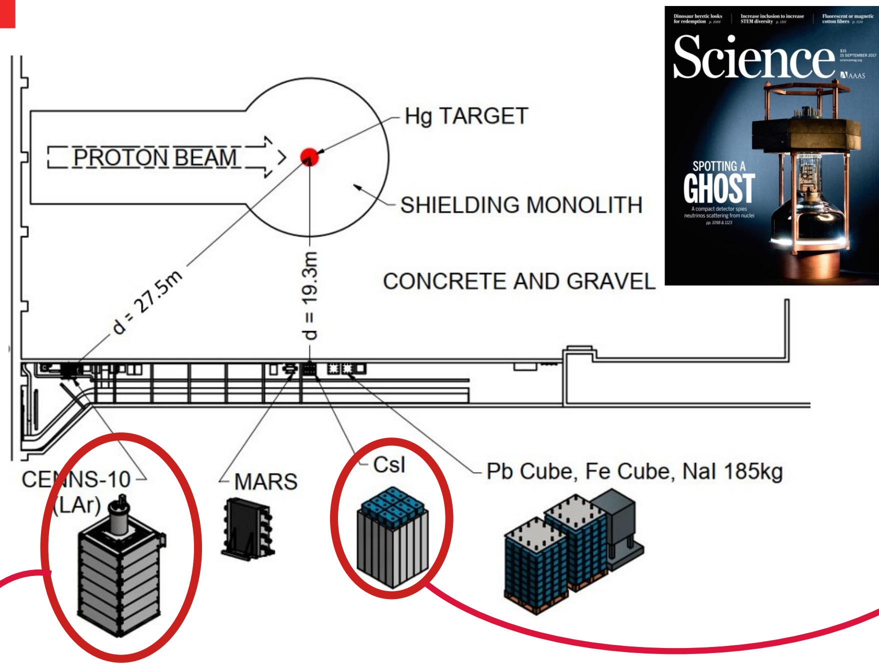
The COHERENT collaboration

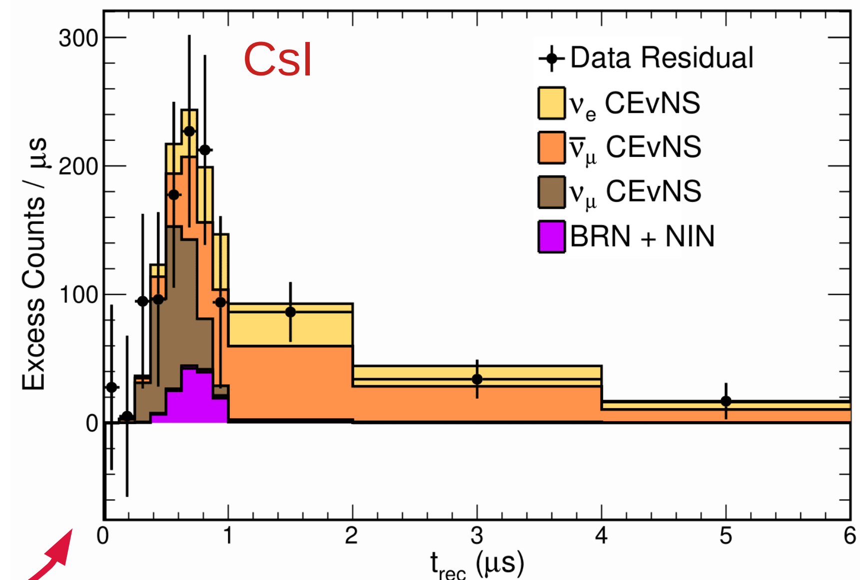
Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens
Carnegie Mellon University
CONCORD U
Duke University
UF University of Florida
Indiana University
Laurentian University / Université Laurentienne
Los Alamos National Laboratory EST. 1943
MEPhI
NC Central University
NC State University
Oak Ridge National Laboratory
Sandia National Laboratories
서울대학교 Seoul National University
SLAC National Accelerator Laboratory
University of South Dakota
The University of Tennessee Knoxville
Tufts University
TUNL
Virginia Tech
University of Washington
Washington & Jefferson College

NSF
NRF 한국연구재단 National Research Foundation of Korea
NNSA National Nuclear Security Administration
U.S. Department of Energy
Office of Science

We are grateful for logistical support and advice from SNS!

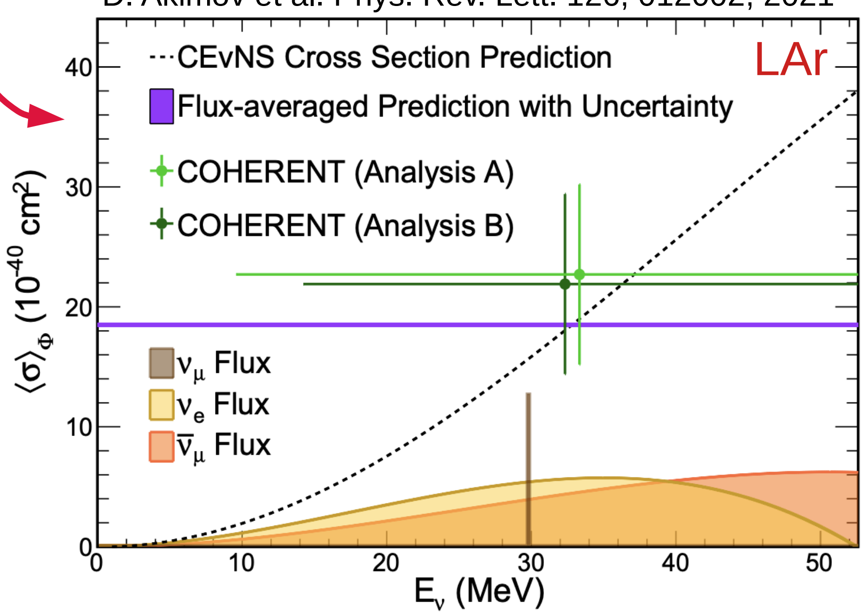
COHERENT CsI and LAr CEvNS results





D. Akimov et al. (COHERENT Collaboration) Phys. Rev. Lett. 129, 081801,2022

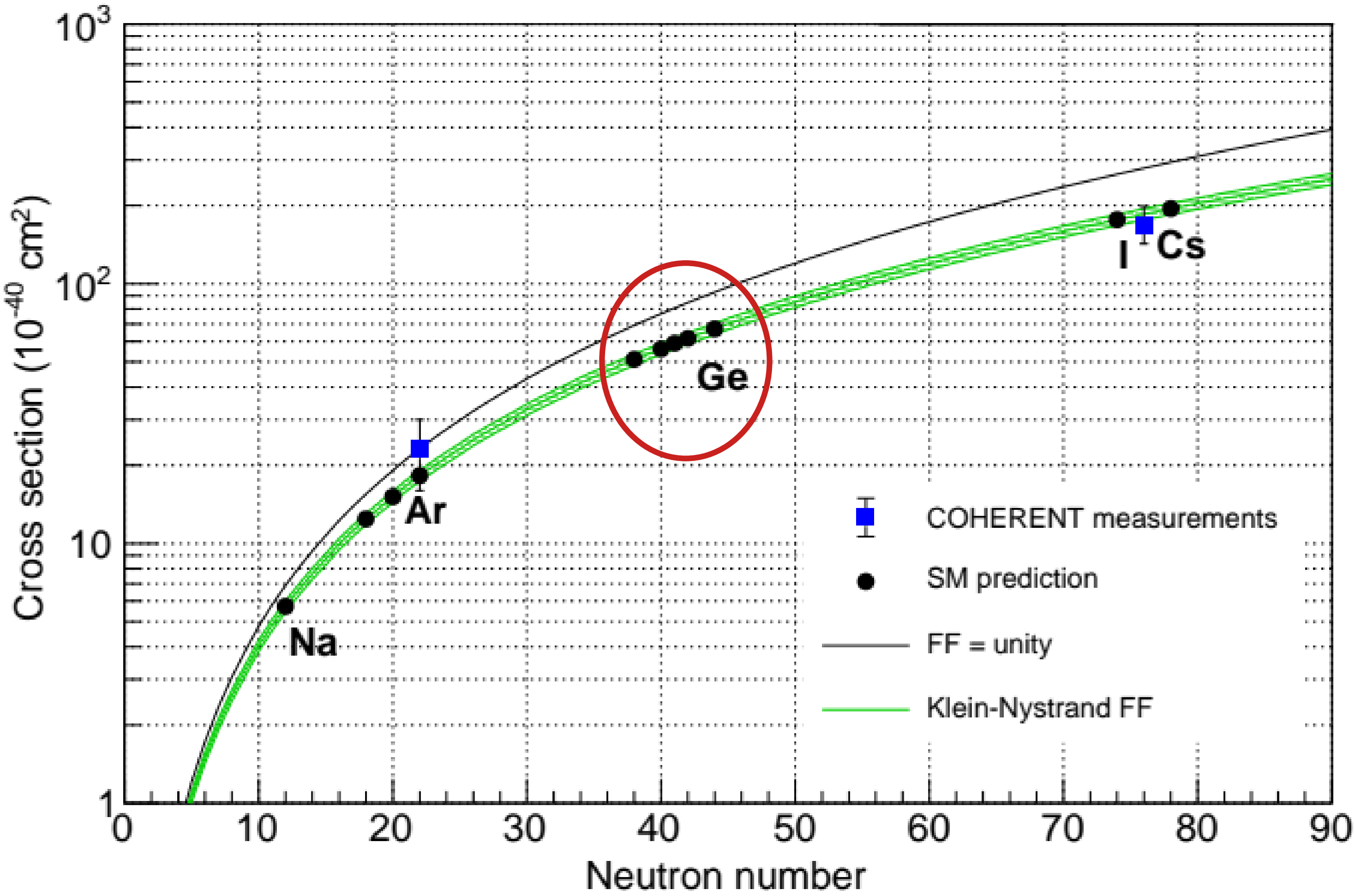
D. Akimov et al. Phys. Rev. Lett. 126, 012002, 2021



CEvNS	CsI 2017 2022	LAr 2021
mass/kg	14.6	24
exposure/GWh	7.48 13.99	6.12
nuclear recoil threshold/keV_{nr}	5	20
Significance (sigma)	6.7 11.6	3.5

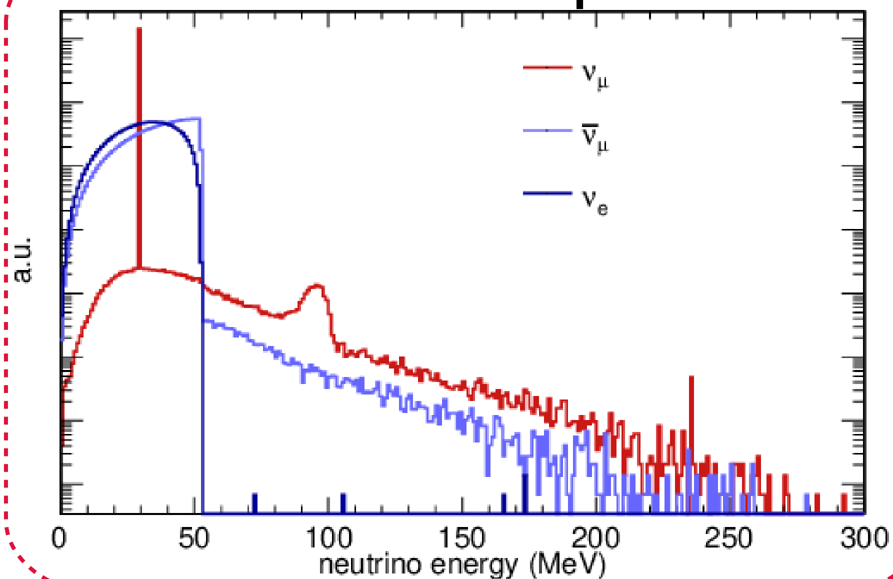
COHERENT experiment

several types of detectors → N^2 dependence



CEvNS on Germanium at SNS

SNS neutrino spectrum



Quenching Ge: *detectable with HPGe*

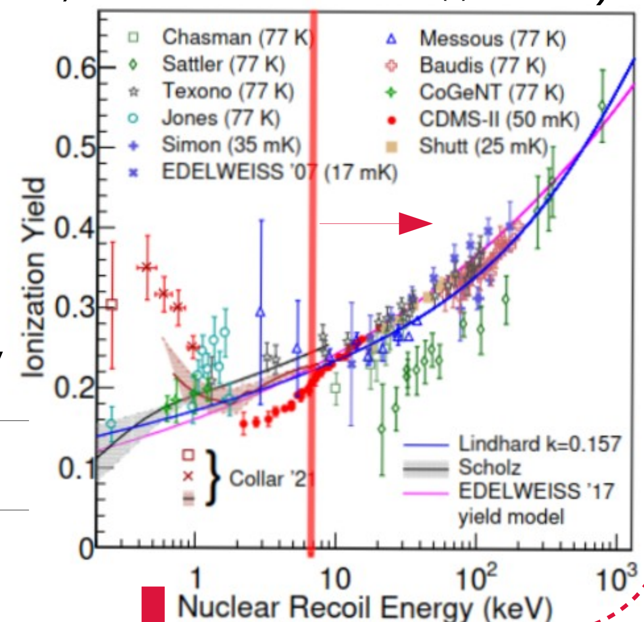
recoil → ionization energy + phonons

=> Lindhard theory with
parameter k=0.157, uncertainty 0.004
(CONUS meas., A. Bonhomme et al, EPJC, 82(9):815, 2022)

Quenching
k-factor

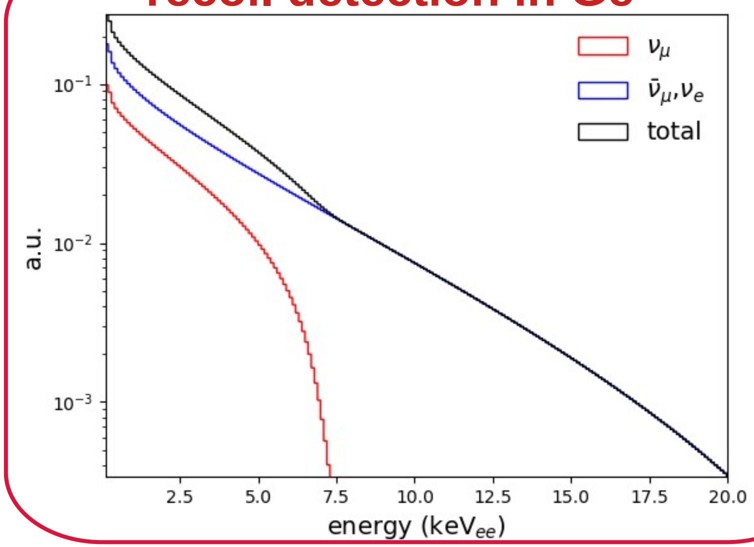
MF Albakry et al,
Physical Review D,
105(12):122002, 2022

E_ν	30 MeV
T_{max}	25 keV
E_{ion}	6.3 keV



Form factor Ge: ~shape of nucleus
small recoil energy → low mom. transfer
→ small impact ~5%

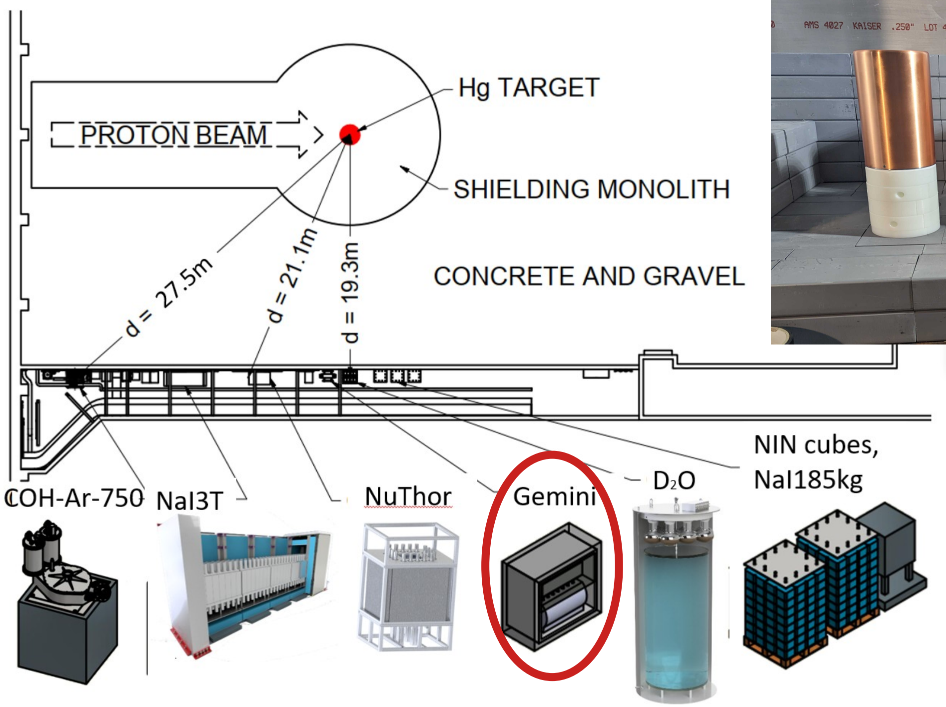
recoil detection in Ge



Ge-Mini

PHY-1920001

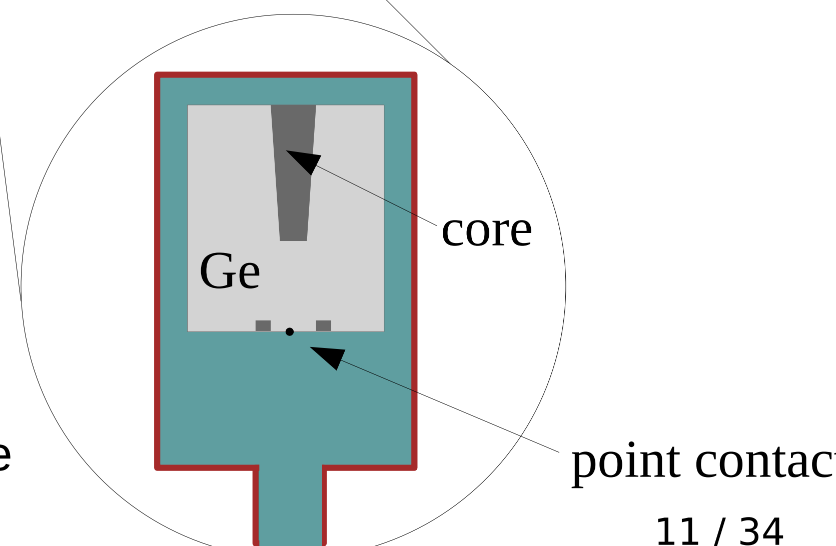
distance to target: (19.1+-0.1)m
former CsI location



In total eight high-purity Germanium diodes:

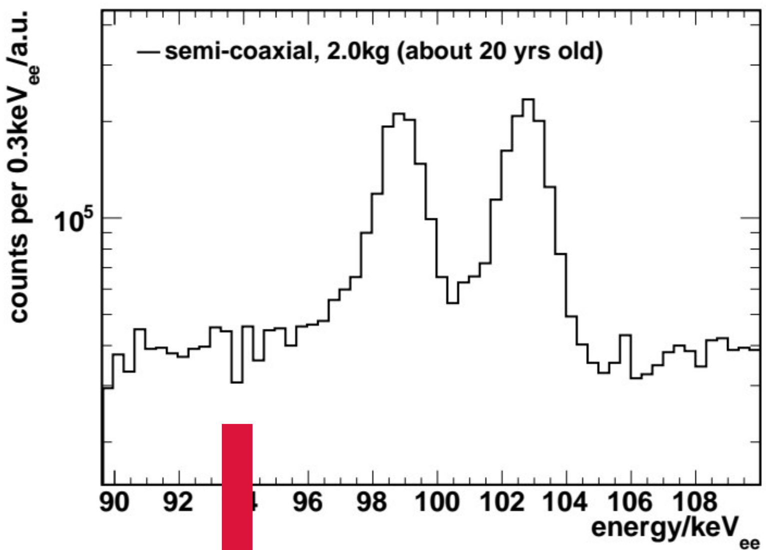
- mass per detector: ~2.2 kg (~96% active)
- inverted (semi) coaxial (ICPC)
- transistor reset preamplifier (TRP)

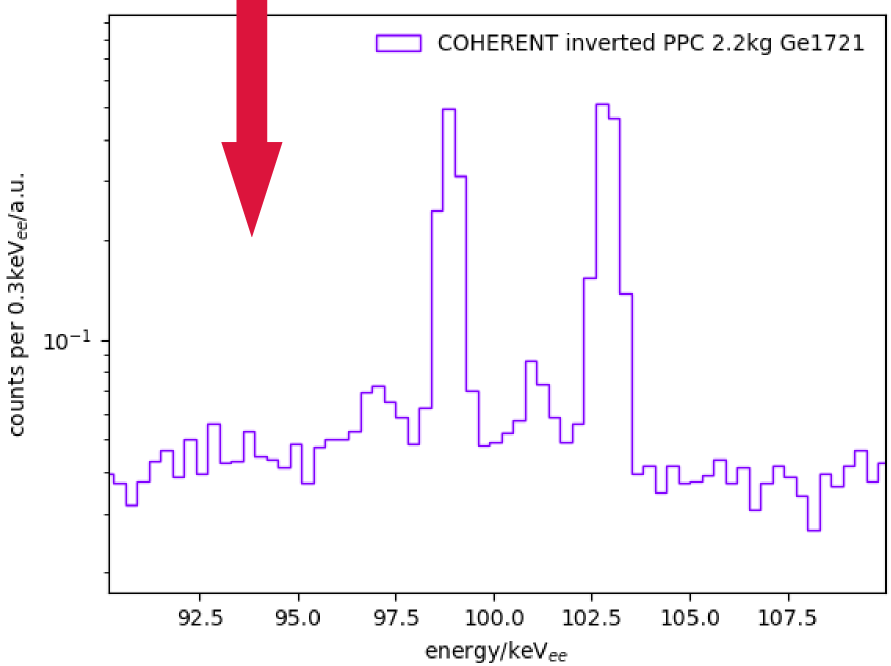
excellent energy resolution: **~110-150 eV** FWHM pulser resolution/noise

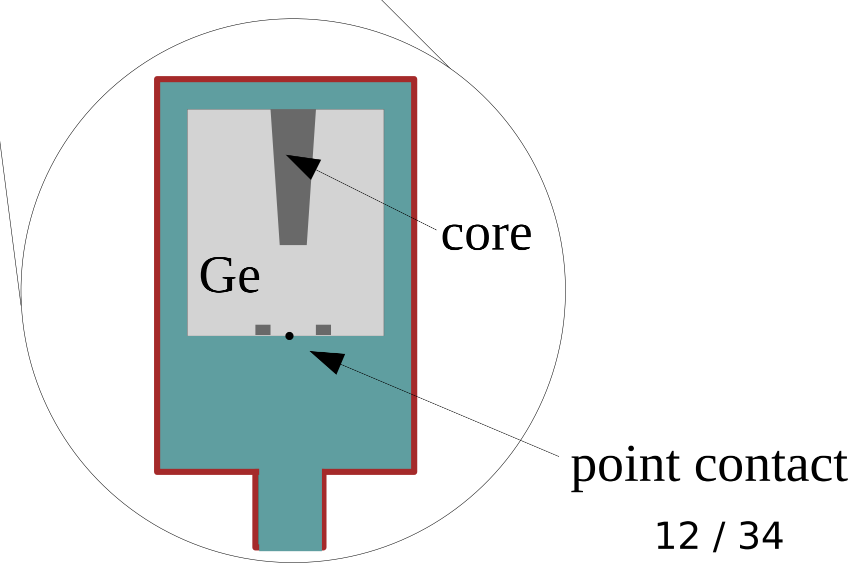


Ge-Mini

PHY-1920001

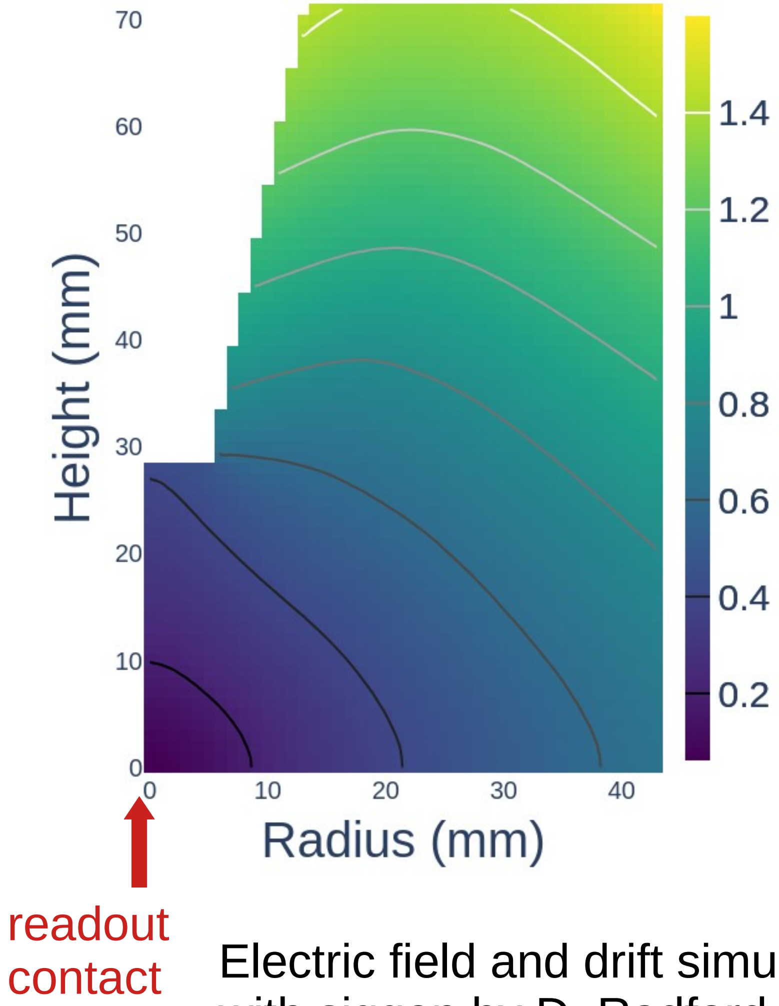


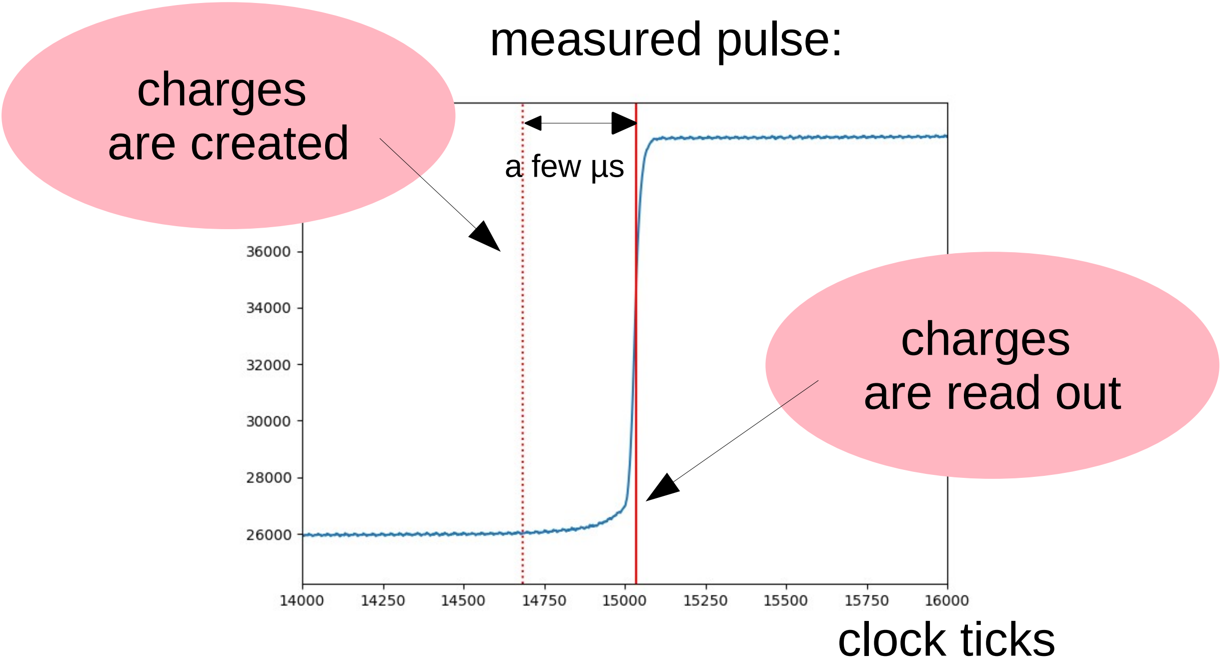




Drift time evalution

Simulated driftime map (μs)

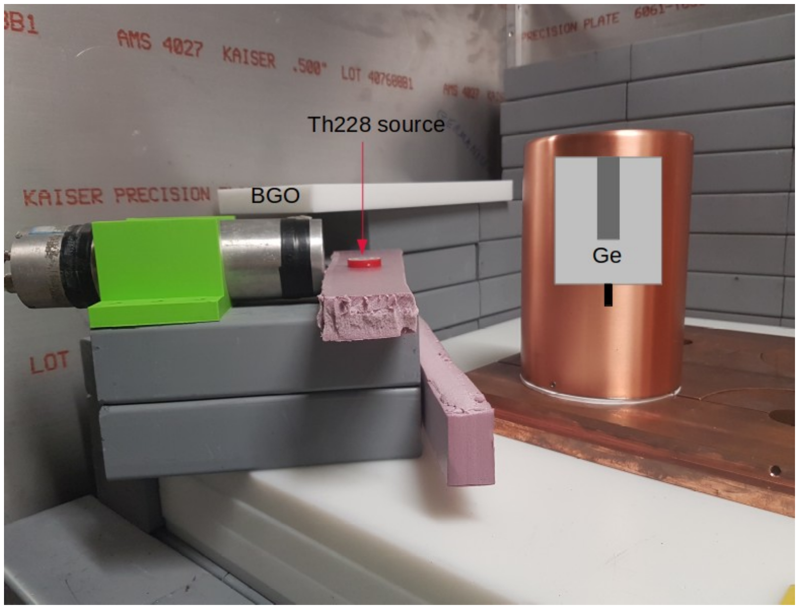


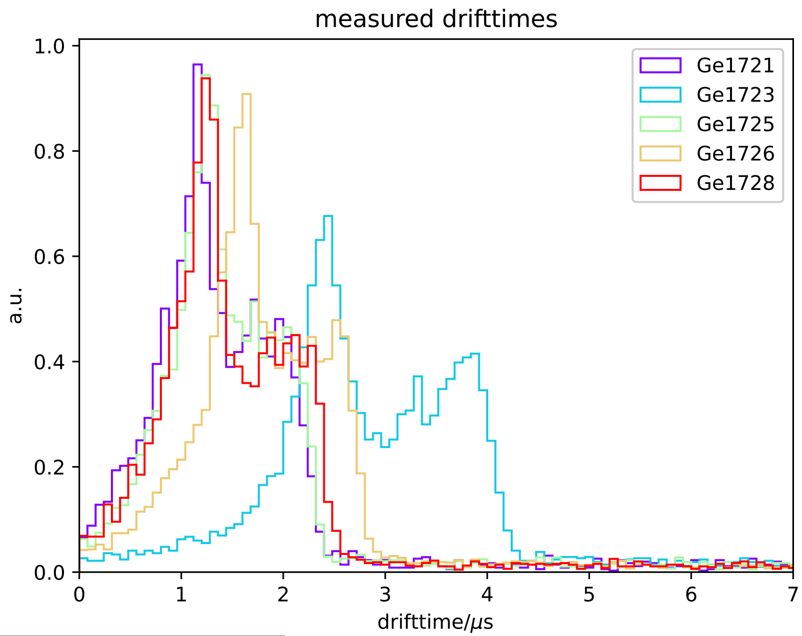


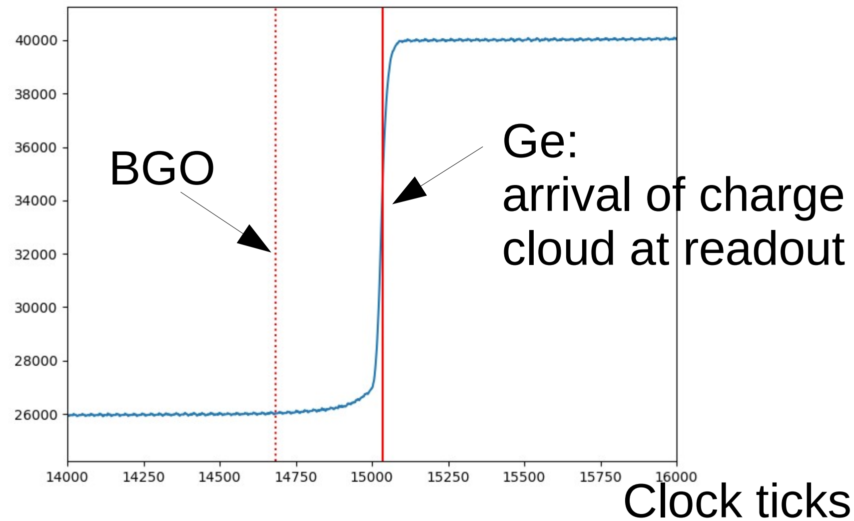
Electric field and drift simulation
with siggen by D. Radford
(simulation made by NCSU undergrad Hana Jones)

Drift time evalution

Driftime measurement with ^{228}Th source and a BGO detector:





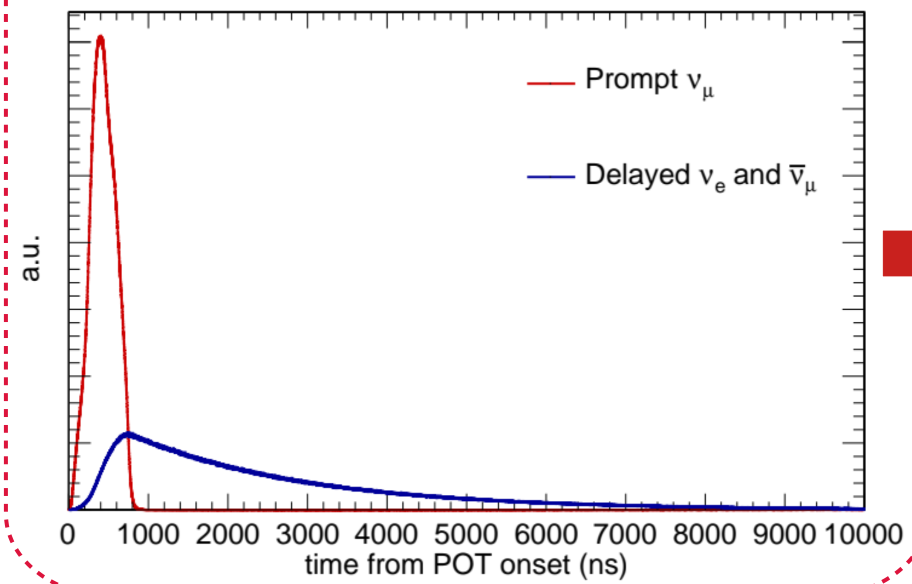


Ge-Mini: Timing spectrum

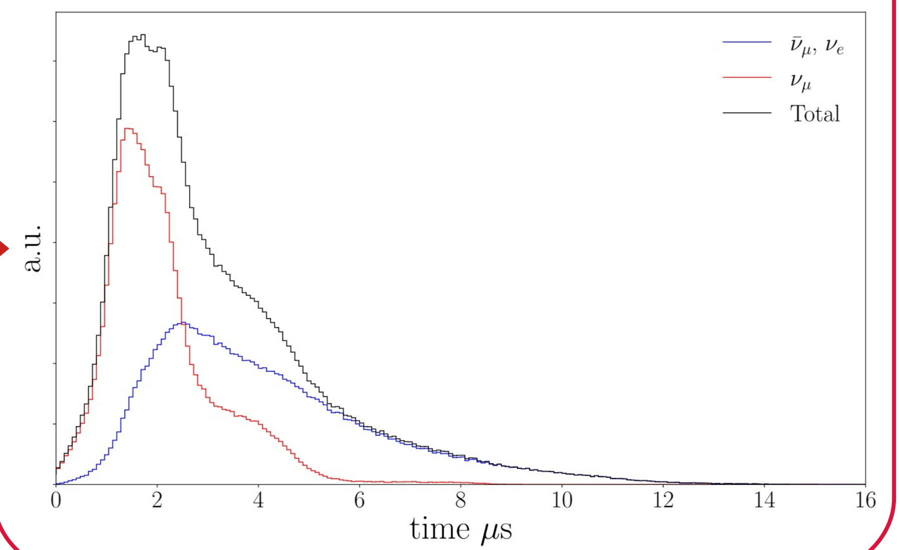
Simulation: homogeneous distributions of interaction vertices
Measurement: includes electronics response

combined for timing pdf

SNS neutrino spectrum



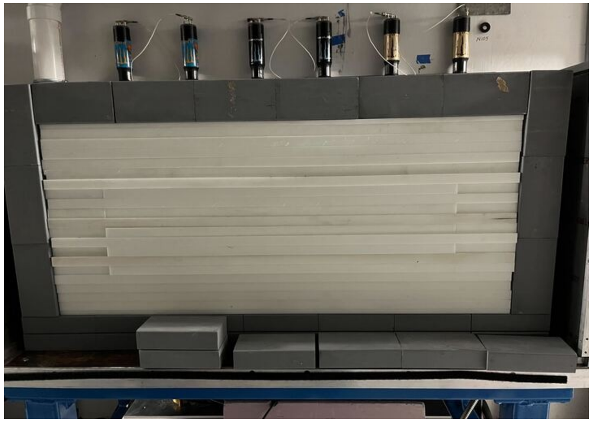
Ge-Mini timing signal expectation

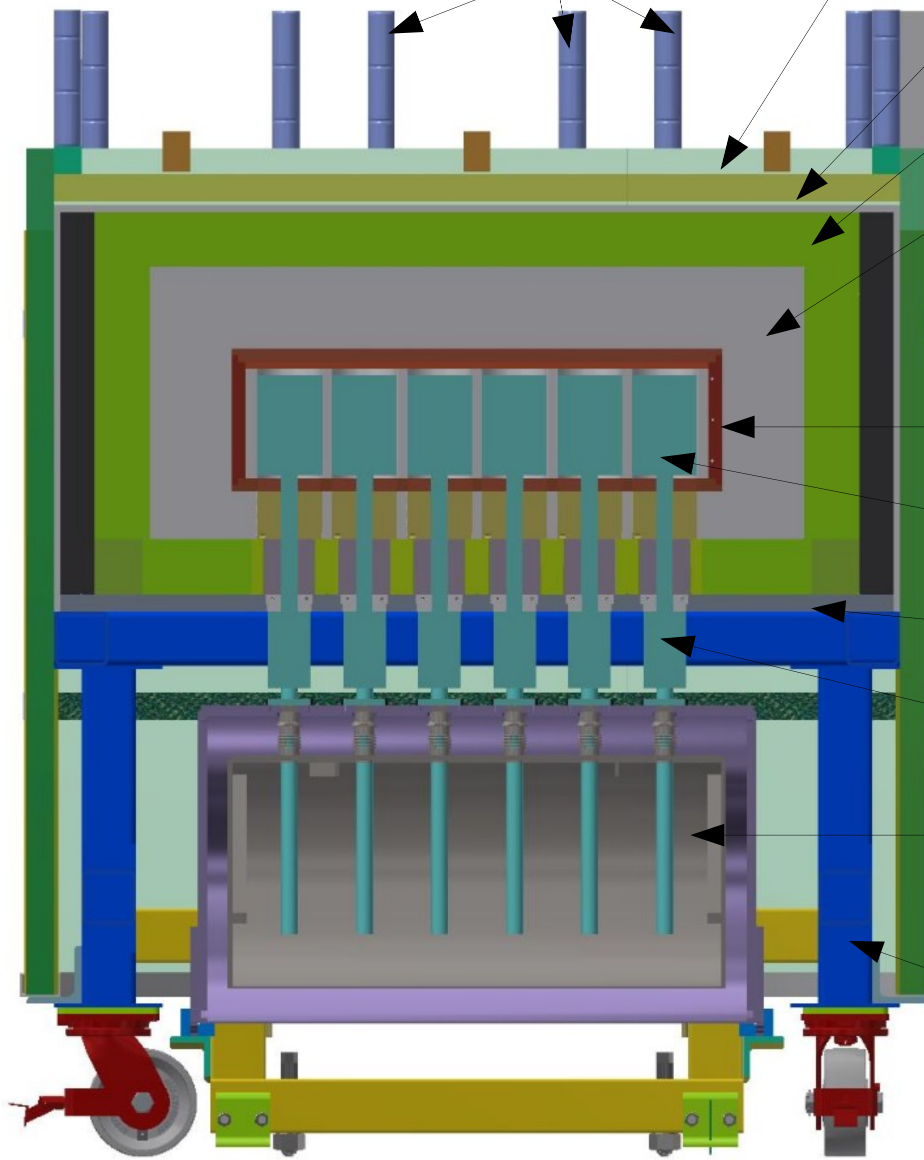


=> background suppression by beam correlation of **$7*10^{-4}$**

All neutrinos arrive within 12 µs!

Ge-Mini shield

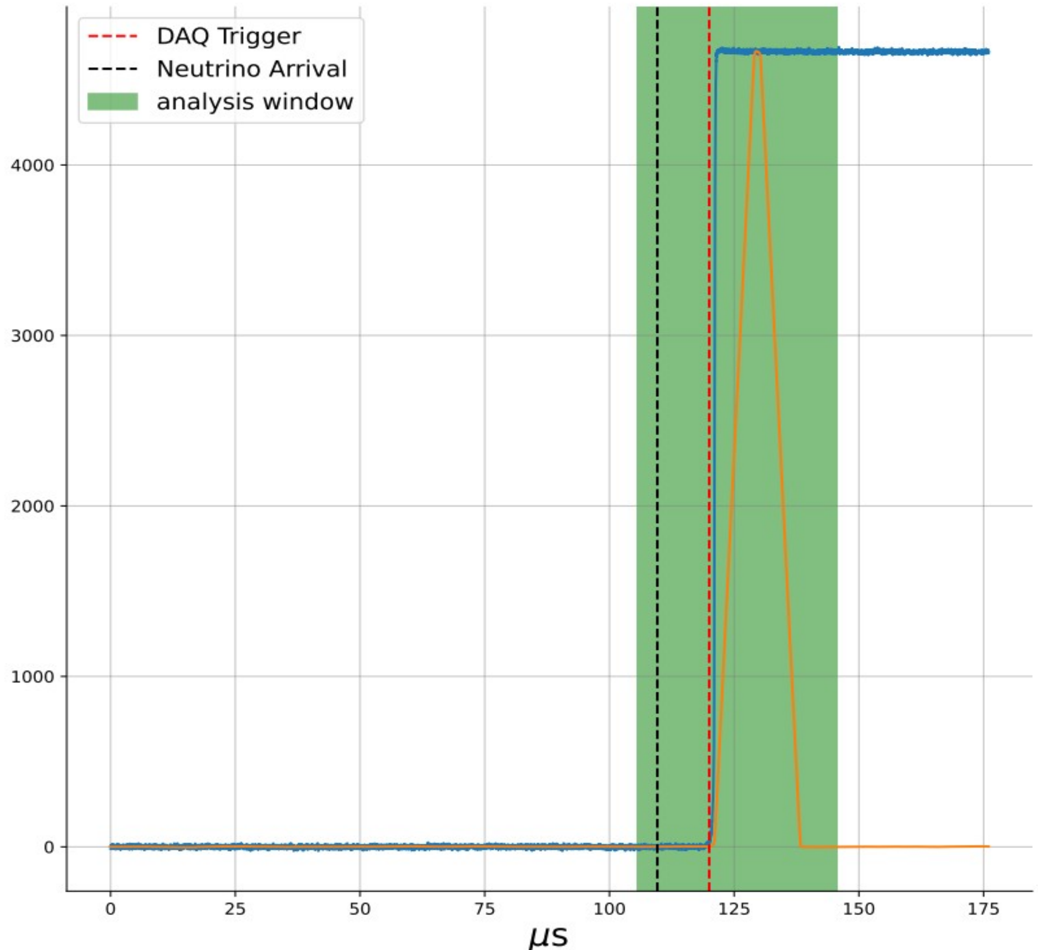




Commissioning: 5/2022-5/2023

Data collection Campaign-2

collected waveform after baseline correction:



176 μs, 125 MHz sampling

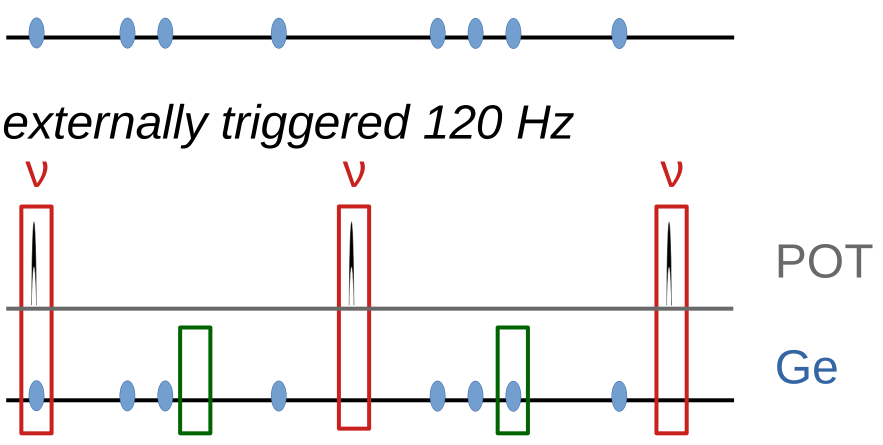
(Campaign-1: winter 2022)

Campaign-2 physics run:
6/21/23 - 8/15/23

Data acquisition:
Rdigdaq: HPGe and muon veto readout
ORCA: slow controls

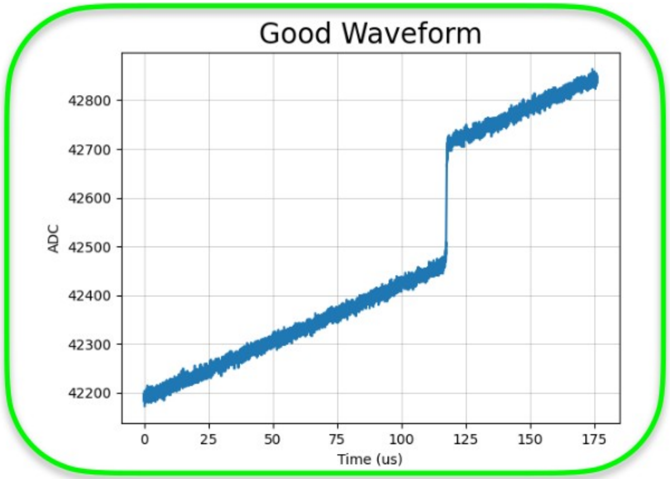
internally triggered: calibration

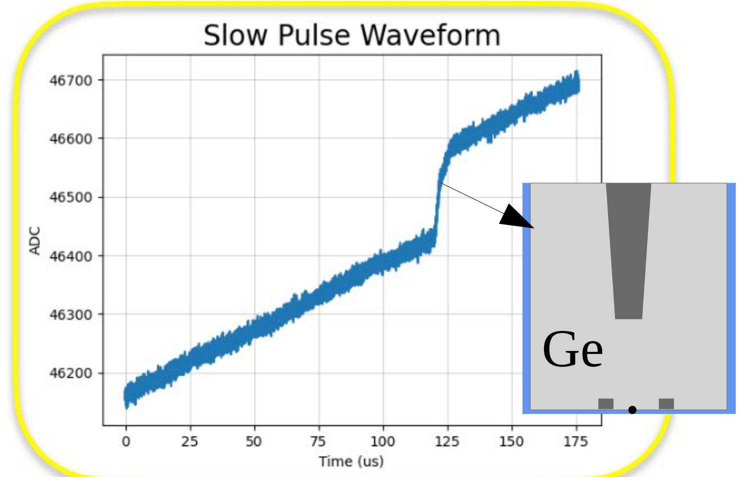
externally triggered 120 Hz

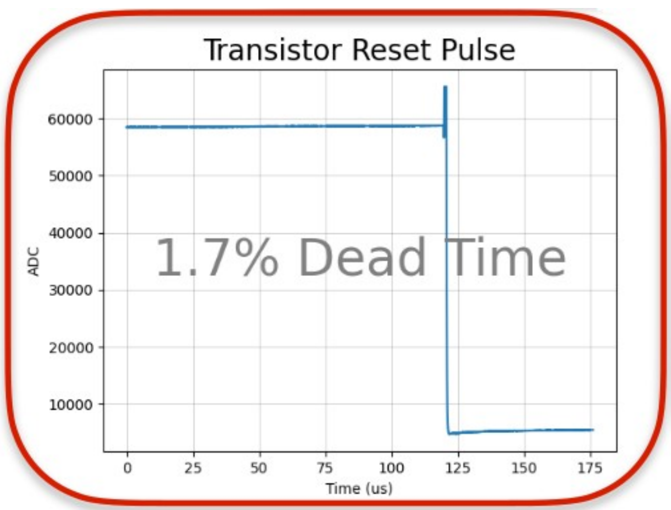


blinded beam windows
background windows

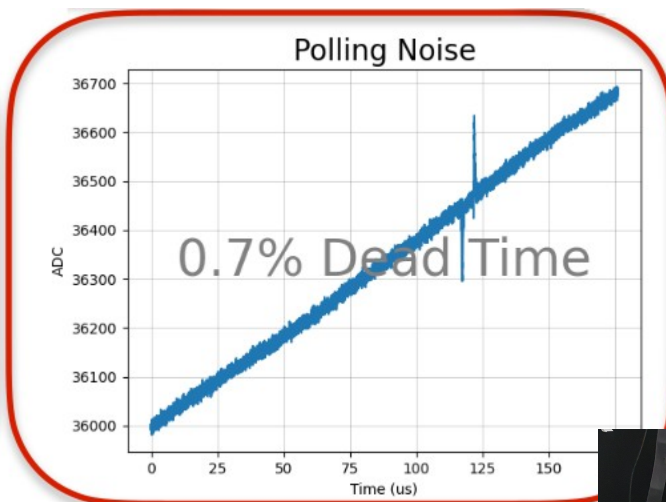
Ge-Mini: Data cuts



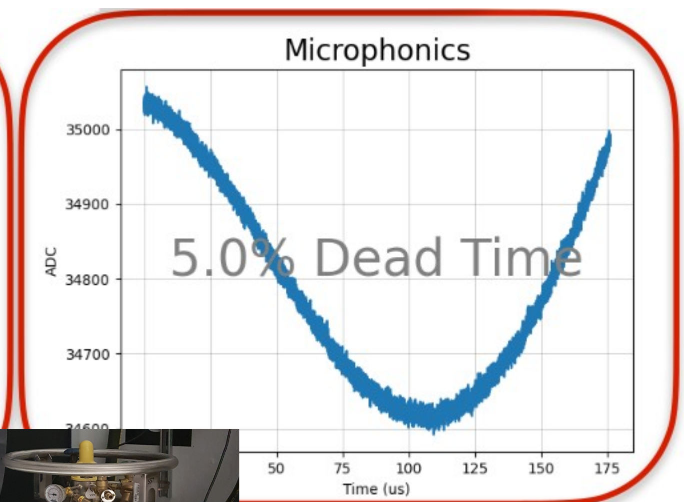


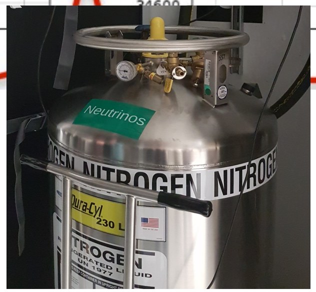


preamplifier



electronics



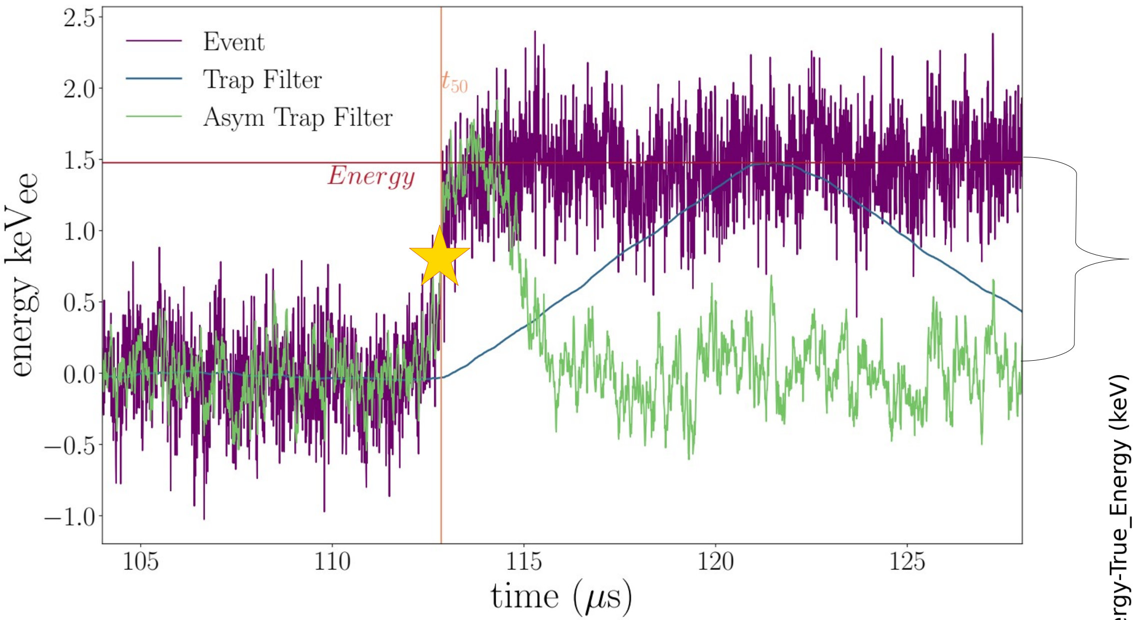


e.g. LN fills

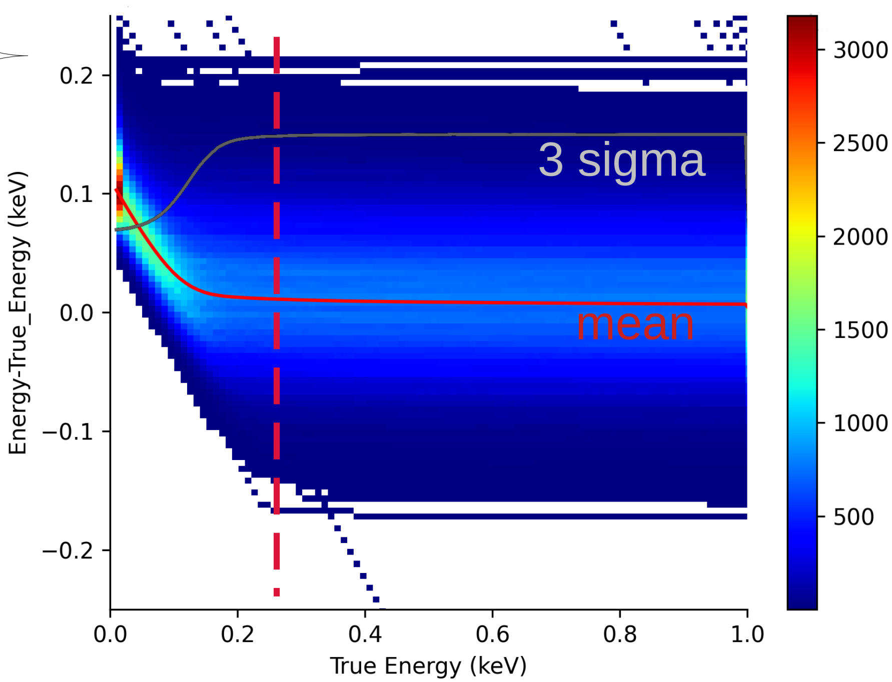
Ge-Mini processing

ENERGY

collected waveform after baseline correction:



Pulse height ↔ energy:
trapezoidal filter with weekly optimized parameters

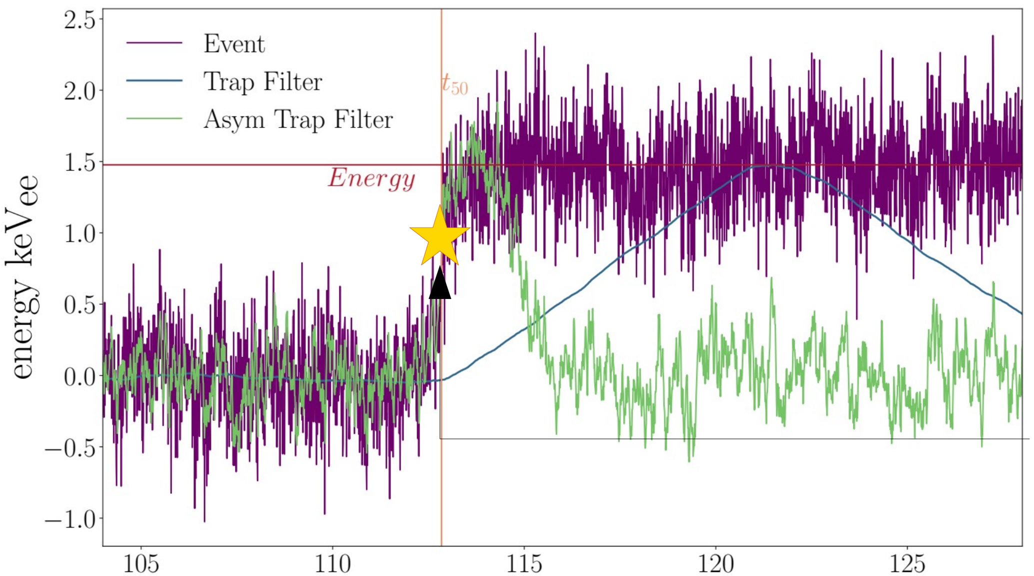


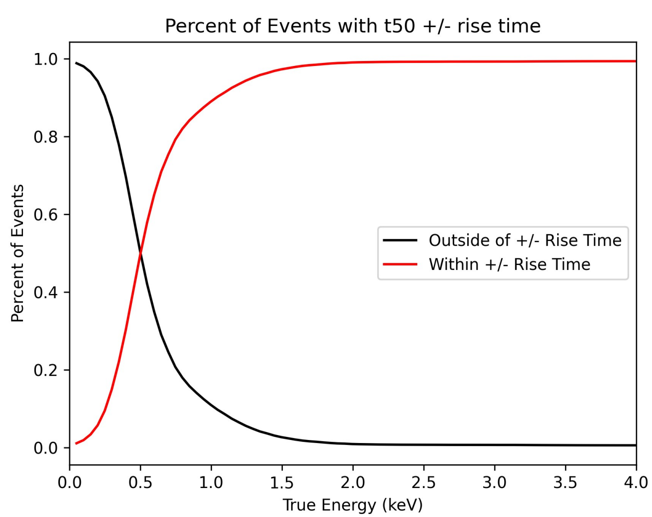
threshold **externally** triggered

Ge-Mini processing

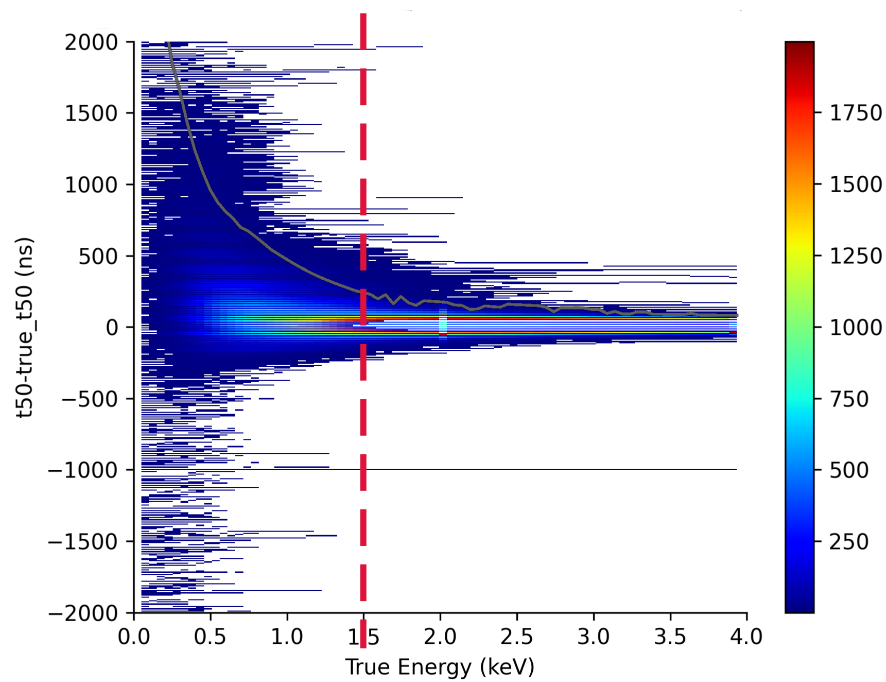
TIME

collected waveform after baseline correction:





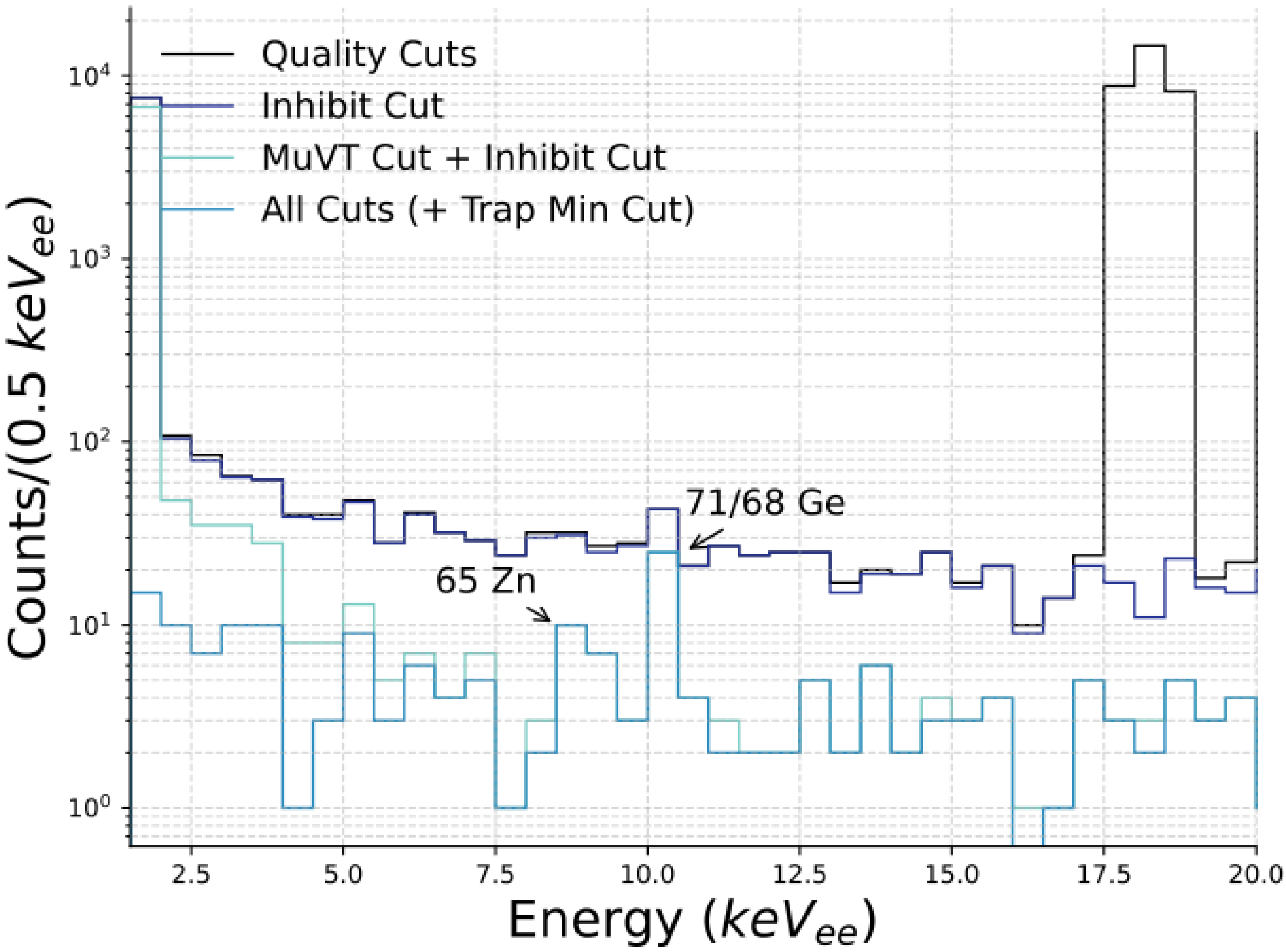
Arrival of charge cloud: t50
modified trapezoidal filter



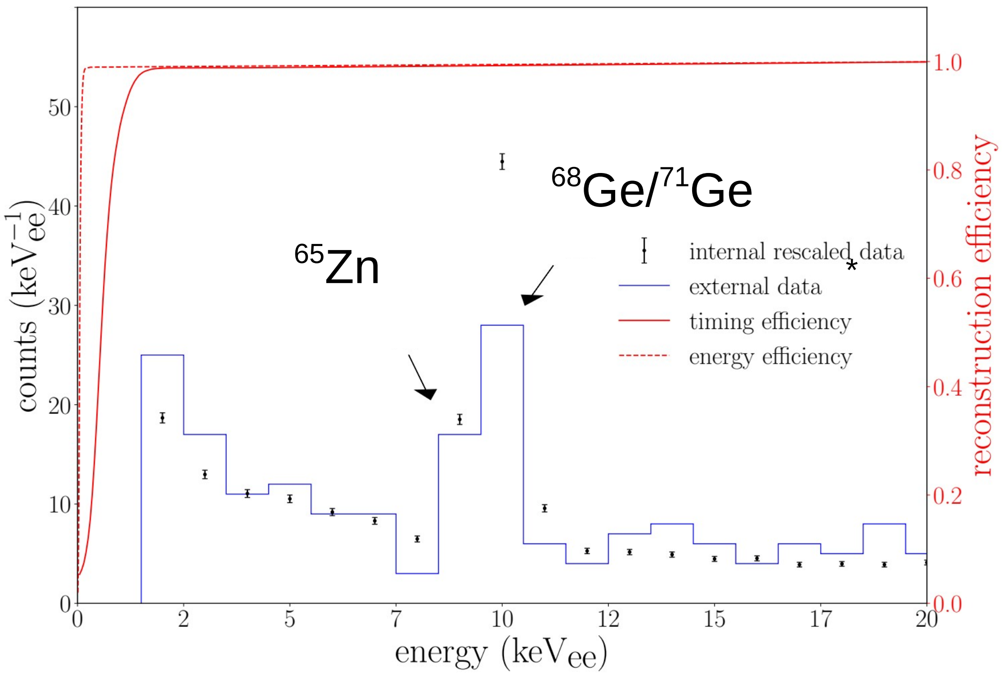
threshold **externally** triggered
→ limiting factor

Ge-Mini: Data cuts

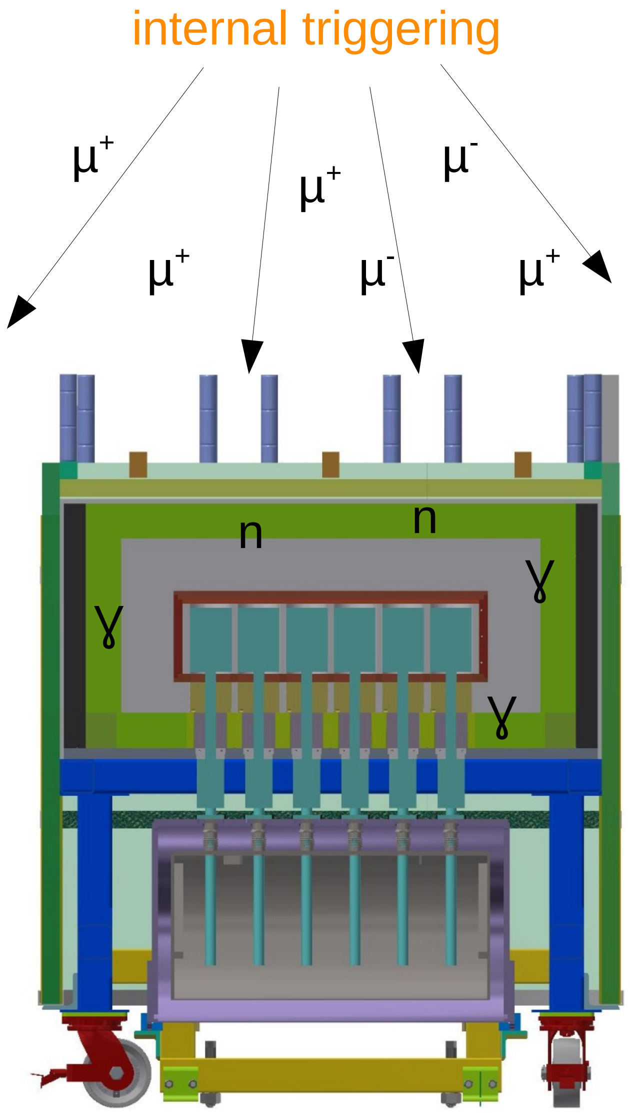
analysis energy threshold: 1.5 keV_{ee}



Ge-Mini: Background spectrum



* internally triggered spectra of the three detectors without efficiency loss above 1.5 keV$_{ee}$



Passive shield: survival fraction: 10^{-2}-10^{-3}

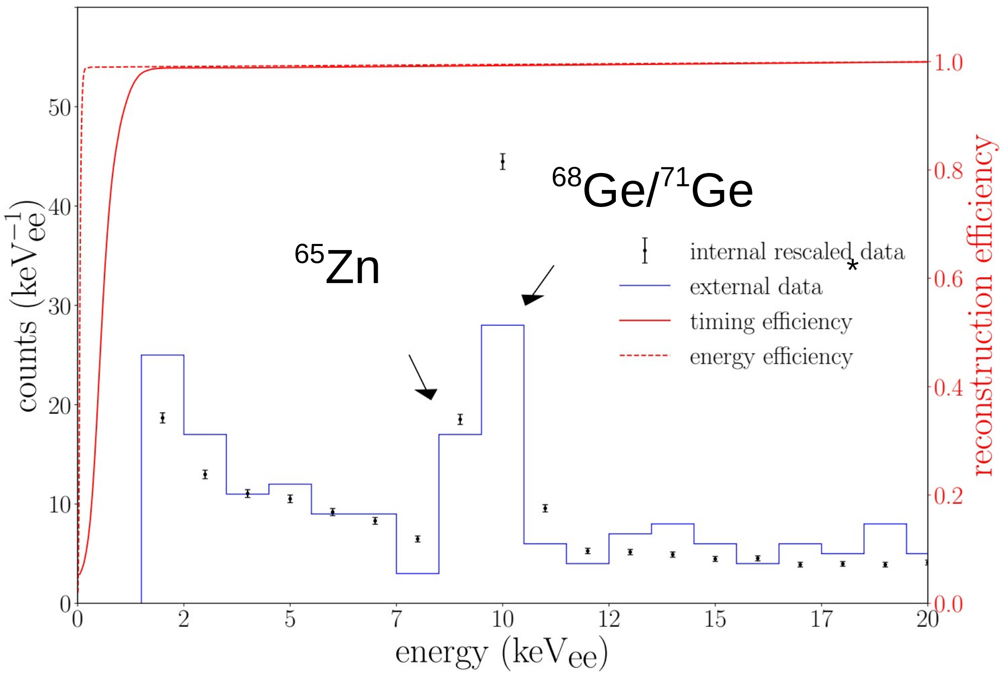
Pb, Cu → ext. electro-magnetic radiation (nat. radioactivity, muon-induced, contaminations)

HDPE → neutrons (muon-induced, beam)

Active muon veto: survival fraction: ~10^{-1}

=> ~350 cts/d in [1,20] keV$_{ee}$

Ge-Mini: Background spectrum



* internally triggered spectra of the three detectors without efficiency loss above 1.5 keV$_{ee}$

External triggering:

- **Beam correlation:**
  10 µs window: $6 \cdot 10^{-4}$ (counting analysis)
  40 µs window: $2.4 \cdot 10^{-3}$ (fit)
  => background comparable to ~1000 rock overburden!
- **Beam-correlated background:**
  - beam-related neutrons: (0.55±0.18) counts (MCNP sim.)
  - neutrino-induced neutrons: <0.01 (extrapolated from CsI result)

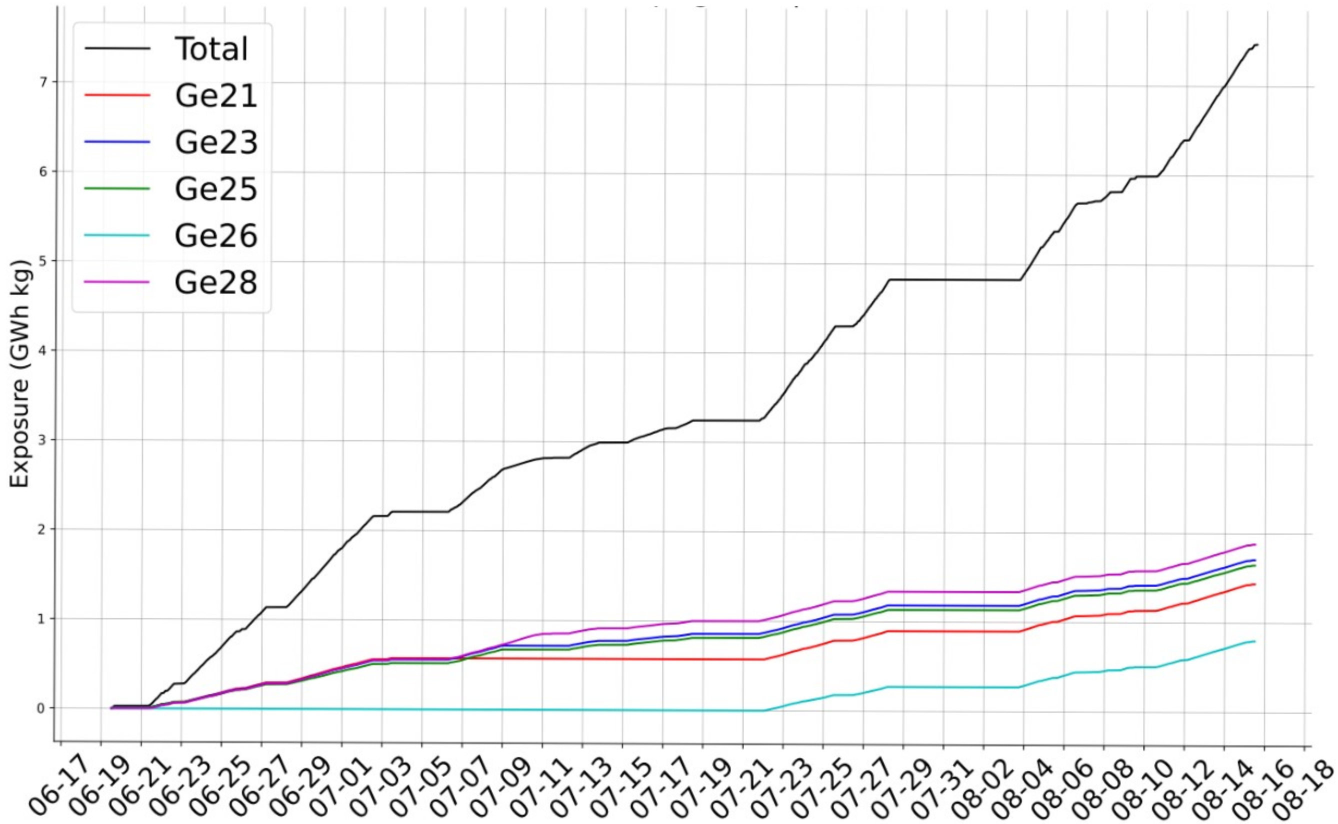
=> less than 5% of CEvNS signal

Background description for fit:
Energy pdf: internally triggered data
→ no efficiency loss at lower energies above 1.5 keV$_{ee}$
Timing pdf: uniform distribution as confirmed from data

Ge-Mini: Campaign-2

Five stable detectors: total mass 11.07kg

Ge-Mini campaign-2 exposure

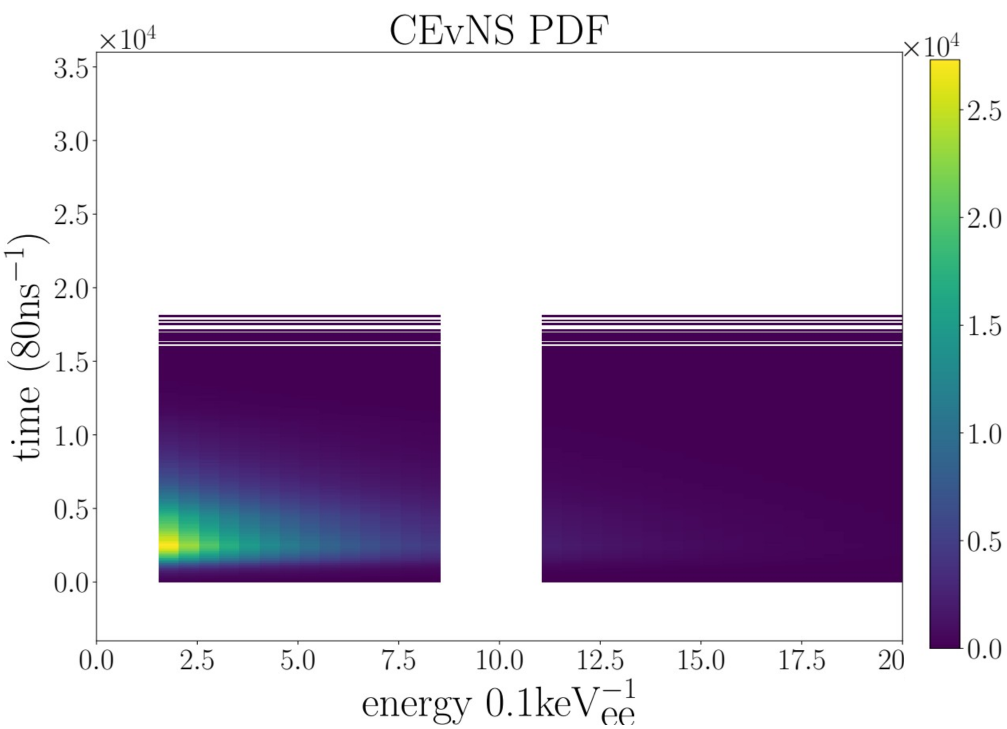


Total exposure: **7.47 GWh*kg**
(after all cuts including beam stability)
Mean total number of produced neutrinos: $3.8*10^{21}$

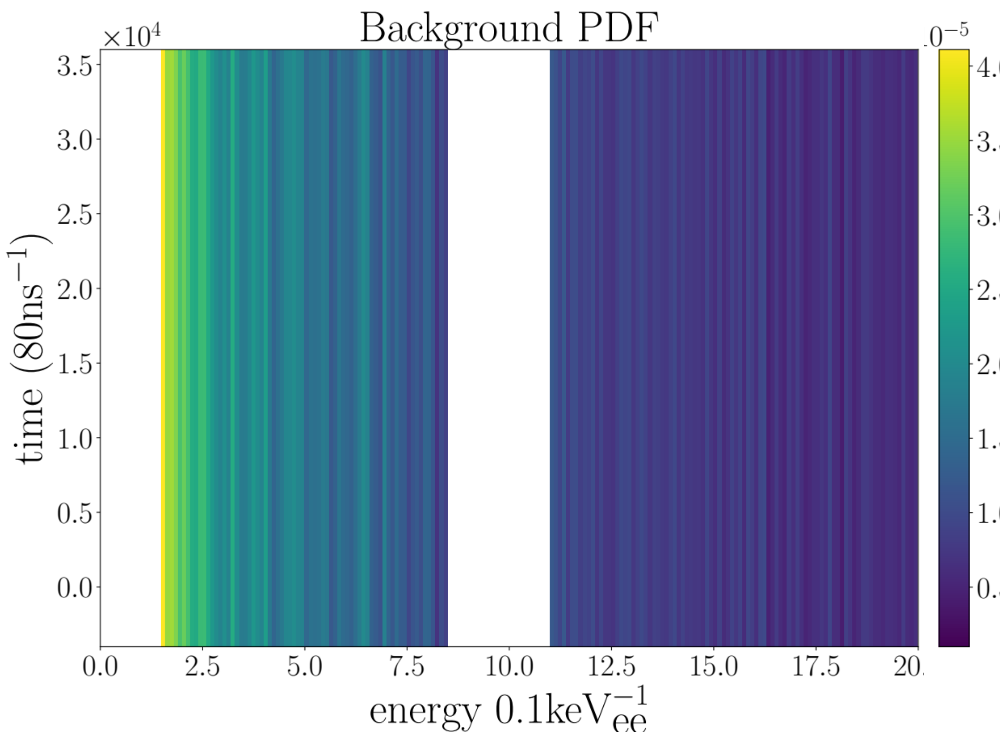
2d PDFs for likelihood fit

unbinned 2d likelihood fit in time and energy simultaneous for background and beam data

Signal



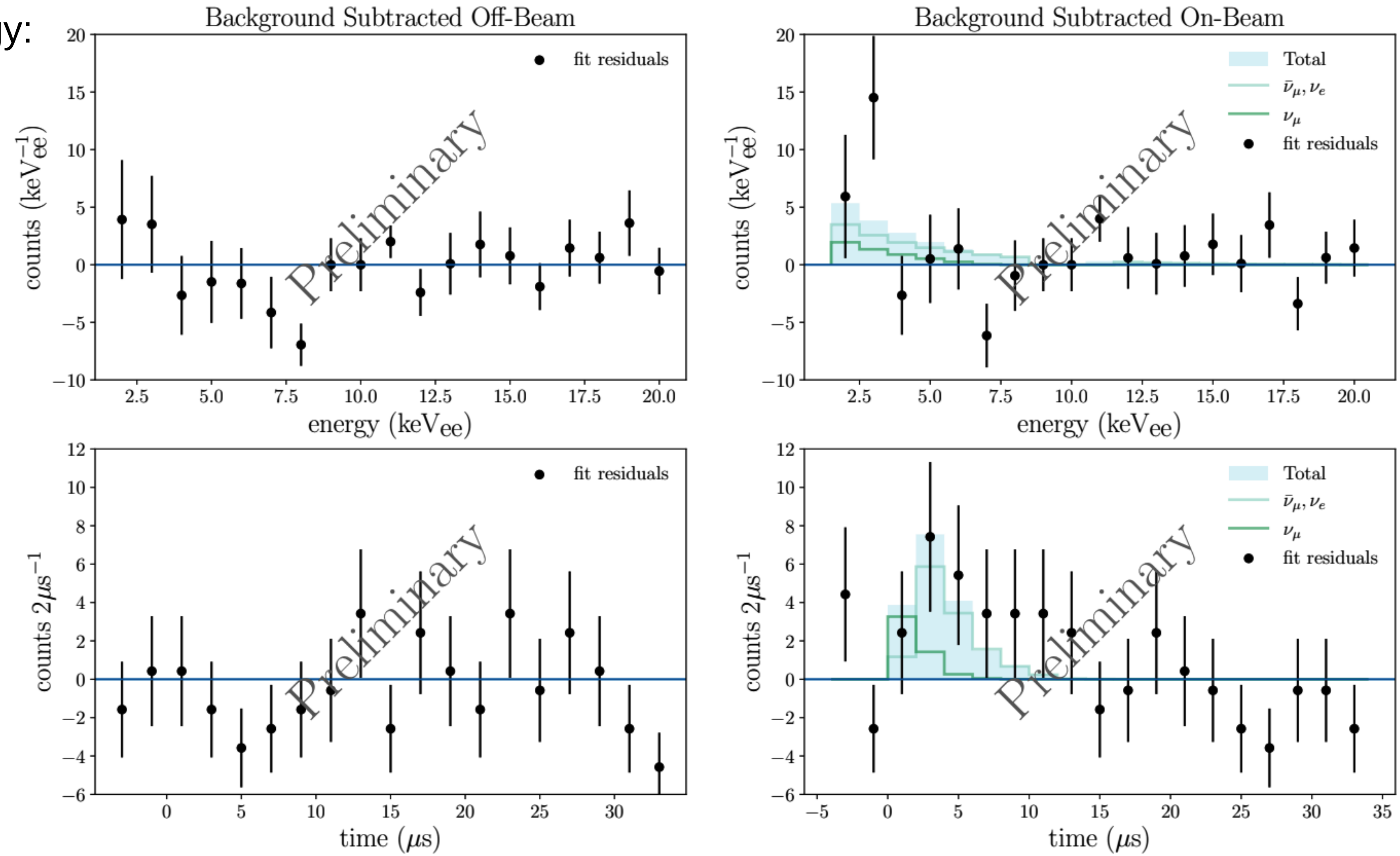
Background



Ge-Mini: CEvNS result

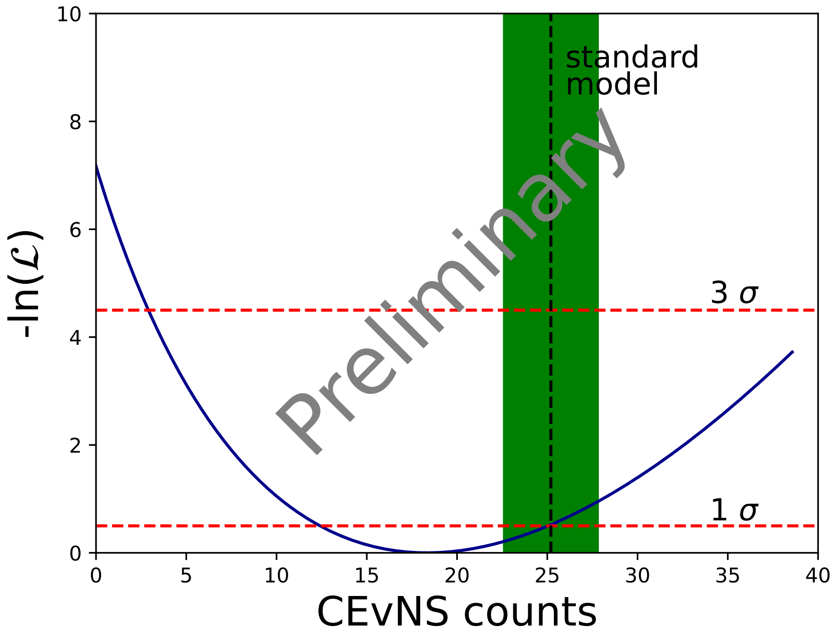
Energy:

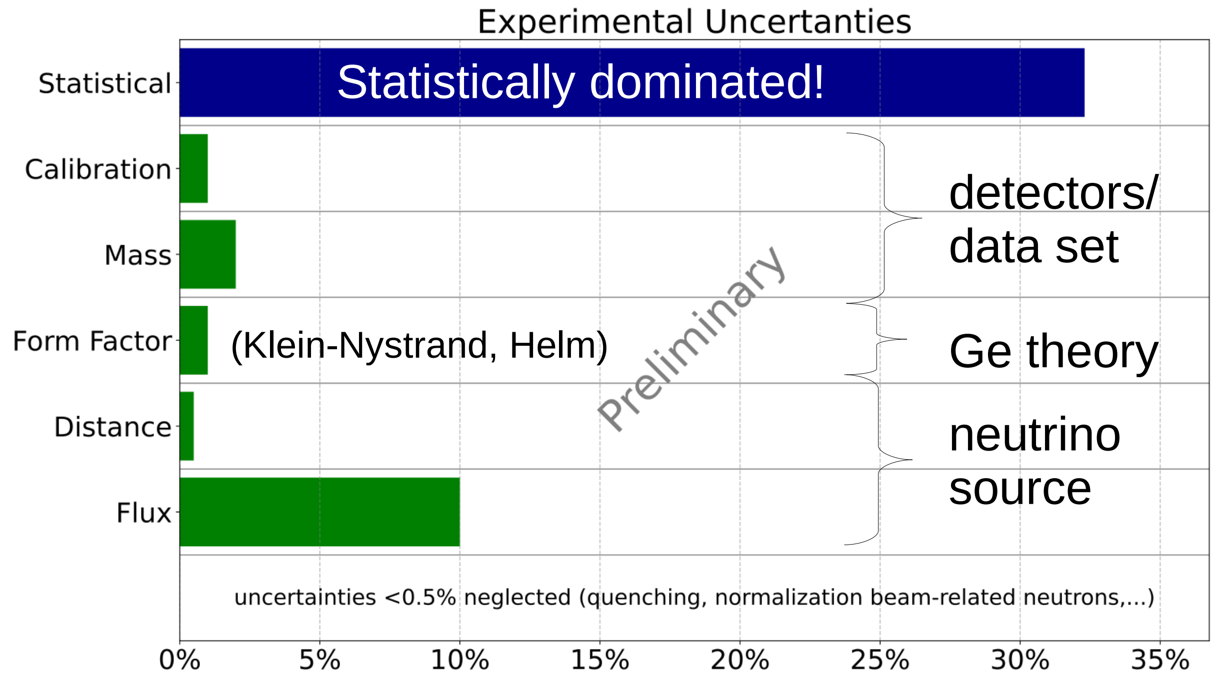
Time:



First CEvNS detection on germanium!

Ge-Mini: CEvNS result





Fit result: Null hypothesis rejected by **3.9 sigma**!

CEvNS signal:	18.4	- 5.9 + 6.7	(stat)
beam-related neutrons:	0.55	± 0.18	(input)
steady-state background: (40 μs window)	143.8	- 8.6 + 9.0	(stat)

Counting analysis:
S/B ~ 1
18.0 ± 7.7

Standard model prediction: 25.2 ± 2.6 (ratio to data: 0.73 ± 0.26)

agreement within 1 sigma!

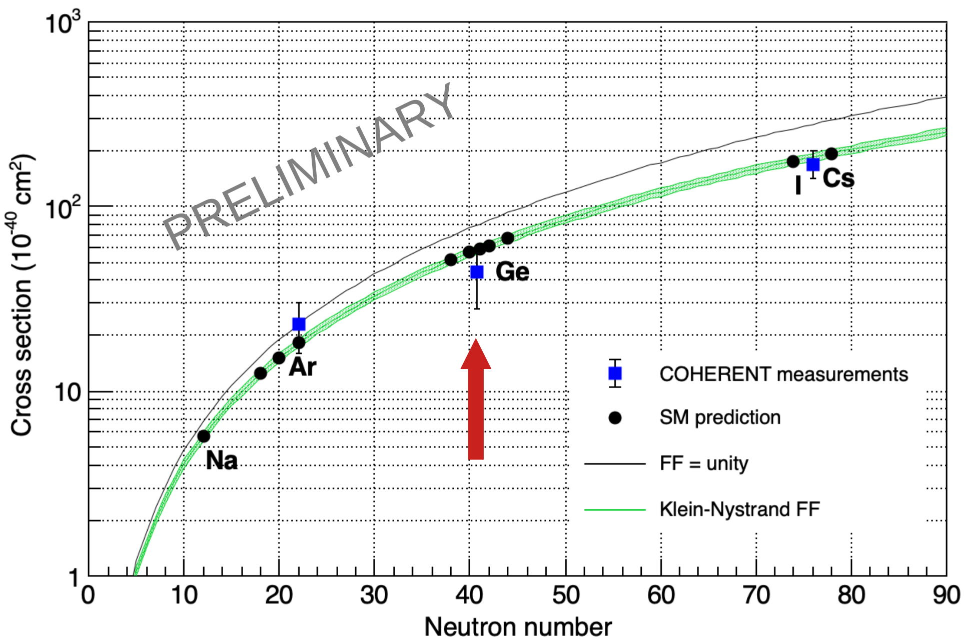
First CEvNS detection on germanium!

COHERENT: ongoing and future

Towards precision CEvNS detection!

Ge-Mini outlook:

- analysis: lower analysis threshold, remove more background by rise time cut
- data taking: stabilize all detectors



higher precision!
more isotopes!

[1] D. Akimov et al. Science 357 (2017) 6356, 1123-1126
[2] D. Akimov et al. Phys. Rev. Lett. 126, 012002, 2021
[3] D. Akimov et al. Phys. Rev. Lett. 129, 081801, 2022

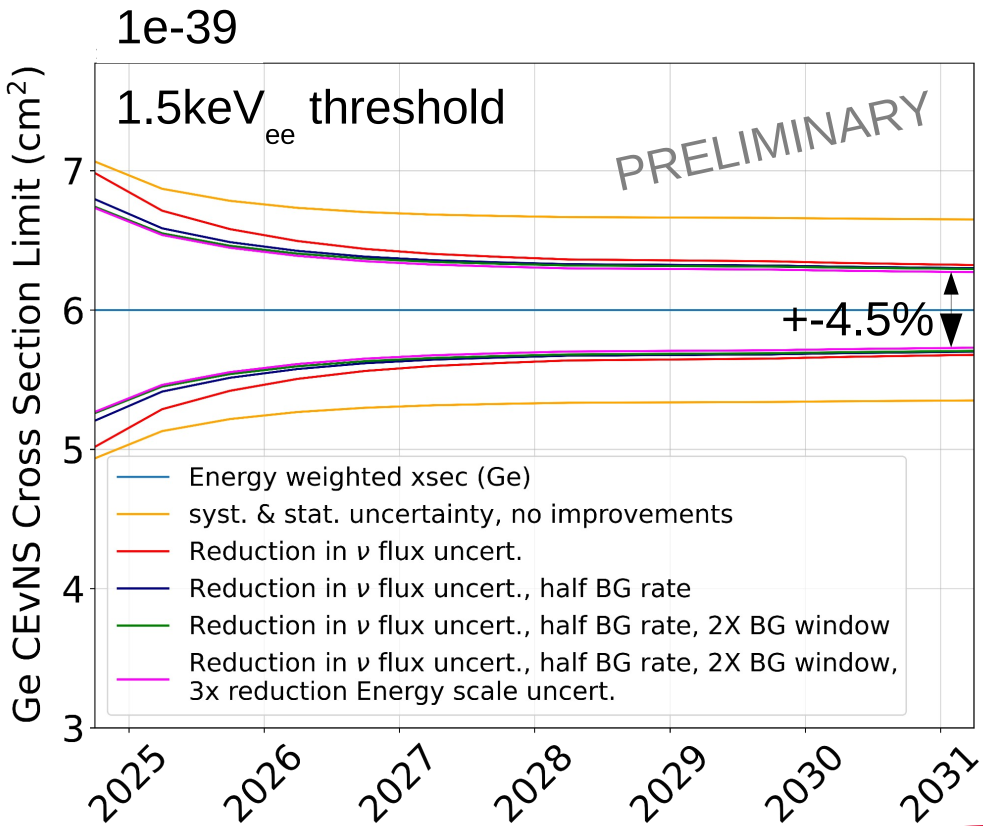
CEvNS	CsI 2017 [1] 2022 [3]	LAr 2021 [2]	Ge 2023
mass/kg	14.6	24	11.1
exposure/GWh	7.48 13.99	6.12	3.37
nuclear recoil threshold/keV_{nr}	5	20	7.5
Significance (sigma)	6.7 11.6	3.5	3.9

+ limits on NSI parameters
+ accelerator-based dark matter searches
  D. Akimov et al .Phys. Rev. D 106 (2022), 052004 202
  D. Akimov et al. Phys.Rev.Lett. 130 (2023) 5, 051803
+ charged-current neutrino interactions
  P. An et al., Phys. Rev. D 108, 072001
  P. An, et al., arXiv:2305.19594 (2023) (accepted at PRL)

reduce systematics, higher mass, more neutrinos!

more interactions beyond CEvNS!

Towards precision CEvNS



D_2O at neutrino alley: COHERENT collaboration 2021 JINST 16 P08048

- Cherenkov heavy water: charged-current deuteron scattering → well known cross section
- neutrino flux uncertainty reduction: ~10% → 2-3% (5 SNS years)

one module operating, second under construction

<u>Improvements:</u>

exposure, +neutrino flux uncertainty, +background (slow pulse cut,...), + energy scale

Predicted development based on:
SNS planned schedule: https://neutrons.ornl.gov/hfir/hfir-sns-5-year-working-schedule
D_2O: planned operations

=> exploration of the CEvNS shape: neutron form factor, Weinberg angle,….

COHERENT:
charged current (CC) results

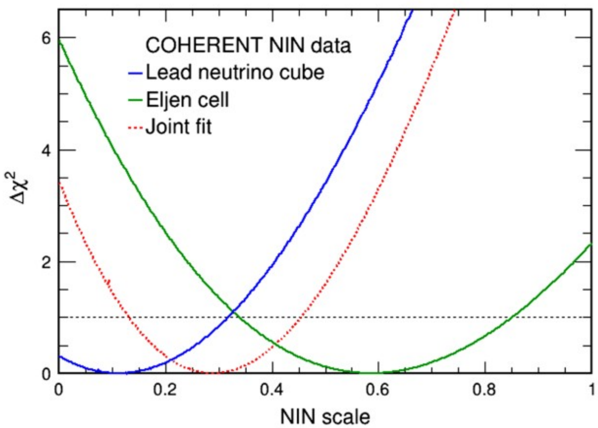
Higher energies!

Neutrino Cubes (Pb, Fe):

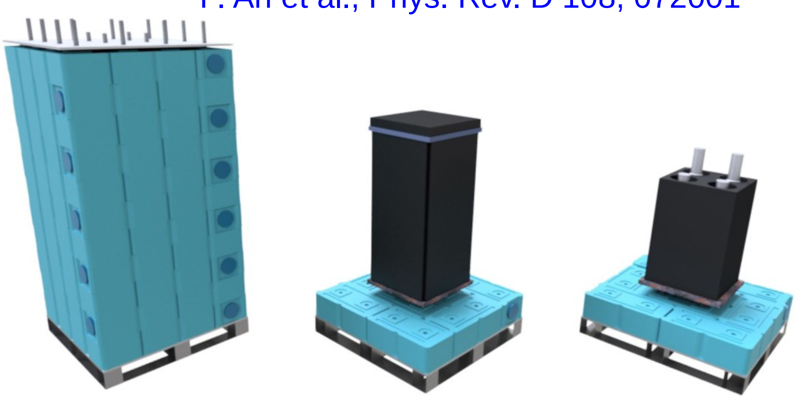
- neutrino-induced neutrons on Pb

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}^*$$

$$^{208}\mathrm{Bi}^* \rightarrow {}^{208-X}\mathrm{Bi} + Xn + Y\gamma$$



P. An et al., Phys. Rev. D 108, 072001

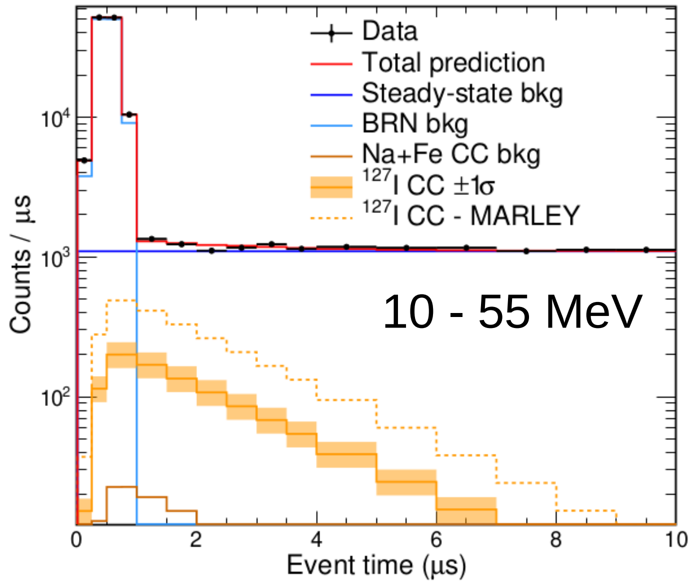


Sam Hedges, JEPT (Wine and Cheese), 12/2024

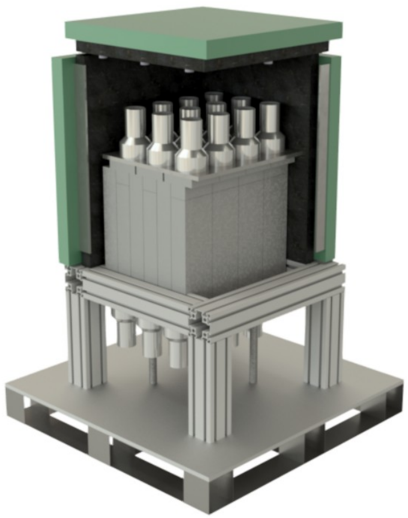
NaIvE

- 185 kg NaI(Tl) scint. Crystals
- deployed in 2016
- charged current on I: $^{127}\mathrm{I}(\nu_e, e^-)^{127}\mathrm{Xe}$

→ 5.8 σ evidence of CC events
~41% of nominal Marley prediction
(with supplied GT strength)



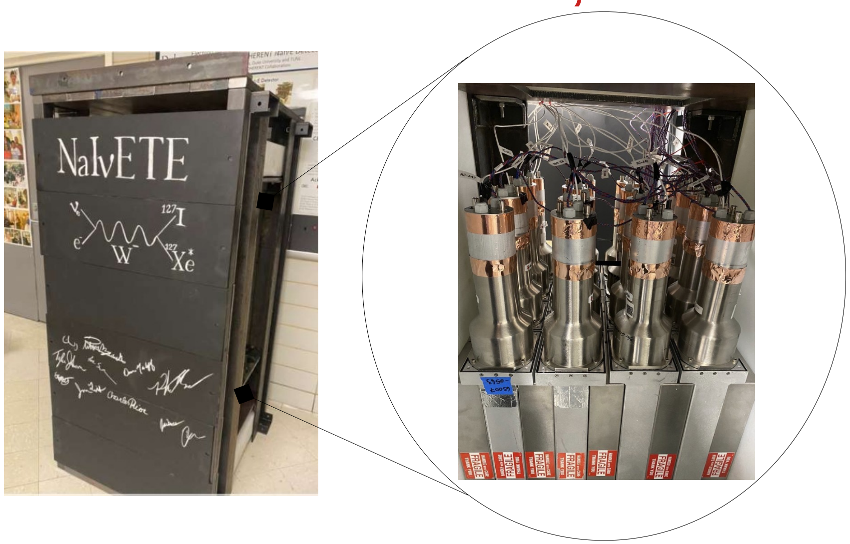
P. An, et al., arXiv:2305.19594 (2023) (accepted at PRL)



COHERENT ongoing and future

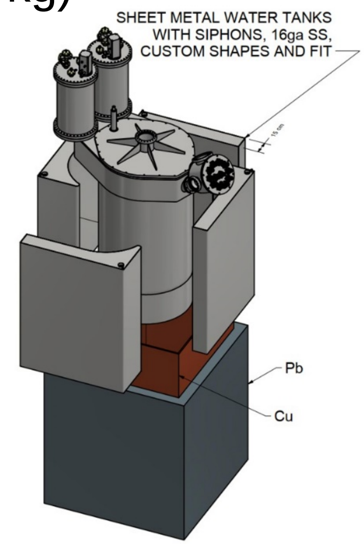
Lighter nuclei!

NaI scintillating crystals (Tl dopes):
since 2016: NaIve 185 kg
→ increase to 3.4t
NaIvETe → CEvNS on Na, I



More mass!

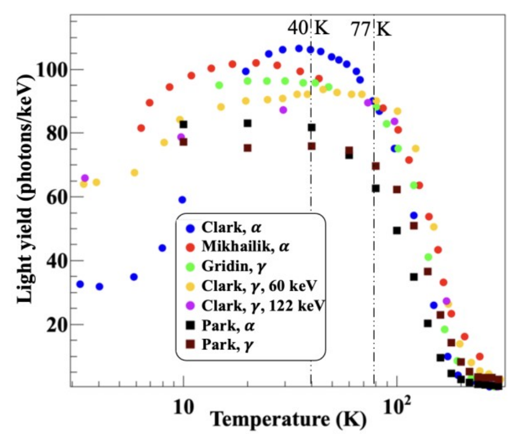
COH-Ar-10 (24kg, 20keV$_{nr}$):
~3 times more statistics to first result
charge current analysis
COH-Ar-750: ton-scale (~750/600 kg)



Lower energy threshold!

COH-CryoCsI

doped CsI → undoped CsI
cryo at 40K, ~1.4keV$_{nr}$ threshold



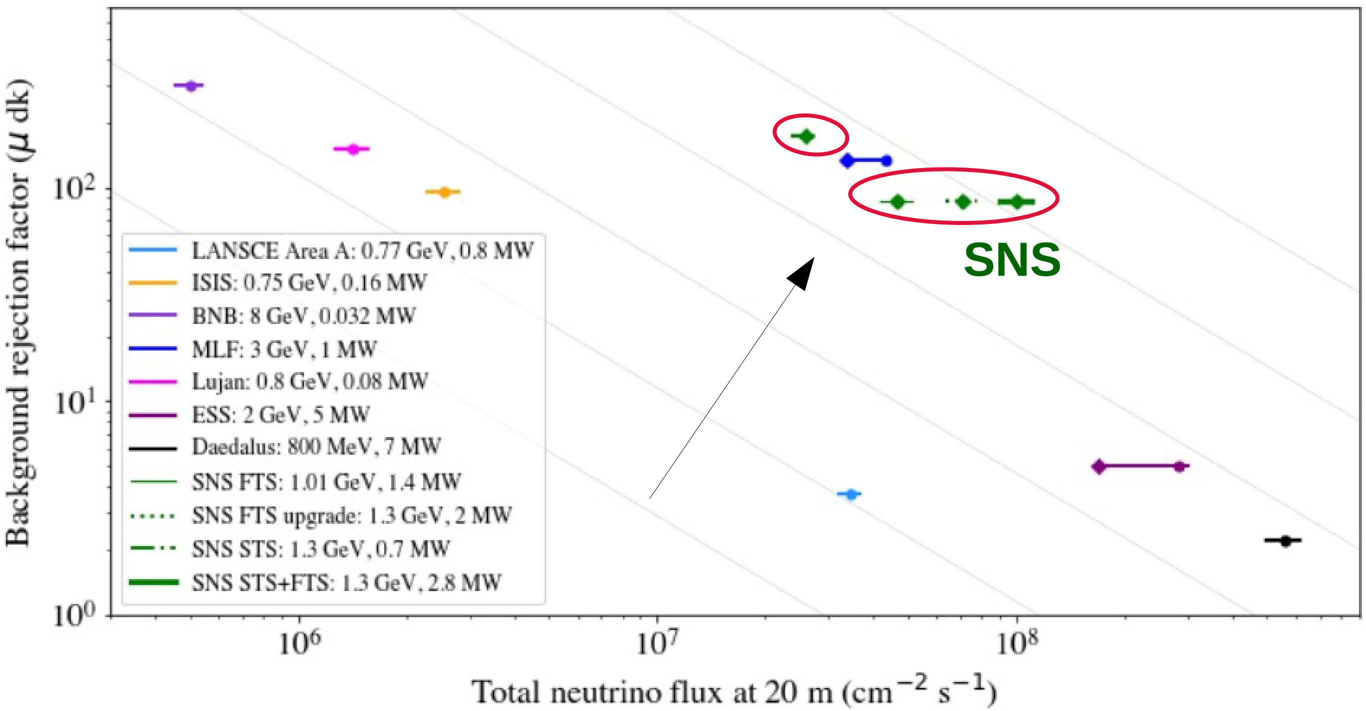
https://arxiv.org/abs/2311.13032

Also: MARS, NuThor, LArTPC...

SNS future

More neutrinos!

Snowmass contribution: arXiv:2204.04575v1 [hep-ex] 10 Apr 2022



- **exploration of new locations**
- **Proton Power Upgrade (PPU, 2024)**
  beam energy: 1.0 GeV → 1.3 GeV, beam power: 1.4 MW → 2.0 MW
- **Second Target Station (STS)** (expected completion: **early 2030s**)

Summary and outlook

Coherent elastic neutrino-nucleus scattering (CEvNS):
→ coherency condition fullfilled (<50MeV) (spallation source, nuclear reactor,...)
→ neutrino interacts with all nucleons in nucleus, enhancement of cross section (~N^2)
motivation: neutrino floor, supernova burst, Weinberg angle, NSI,...
=> detecting CEνNS = detecting a tiny recoil

Publication in preparation!

COHERENT at SNS: nuclear recoil in Ge <~20keV$_{ee}$
detection 2017 with CsI (first ever)
detection 2021 with LAr
2023 (Ge-Mini): First detection of CEvNS on germanium!

- signal/background ~ 1/1
- number of CEvNS counts: 18.4 – 5.9 + 6.7
- rejection of null hypothesis at 3.9 sigma, 1 sigma agreement to standard model

upcoming: NaIvETe, COH-Ar-750, power upgrade of SNS, Second Target Station,…
inelastics campaign: argon, D_2O,...

Thank you for your attention!