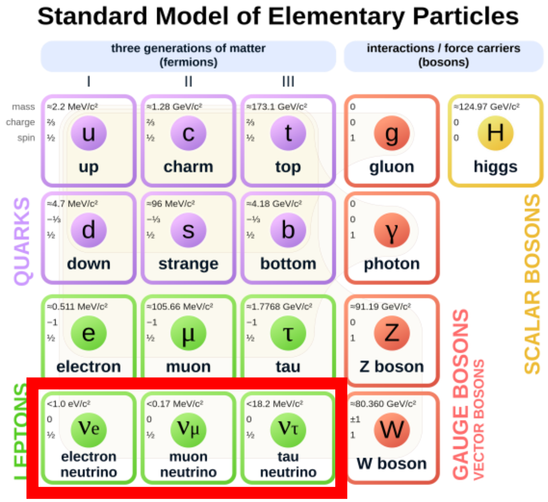
Latest Results from the BeEST Experiment

Inwook Kim
on behalf of BeEST Collaboration

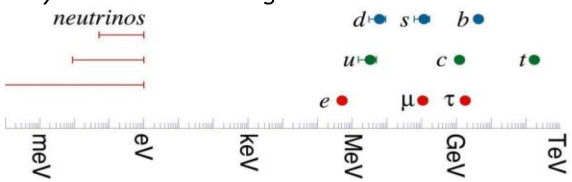
Prepared by LLNL under Contract DE-AC52-07NA27344.

Neutrino in the Standard Model



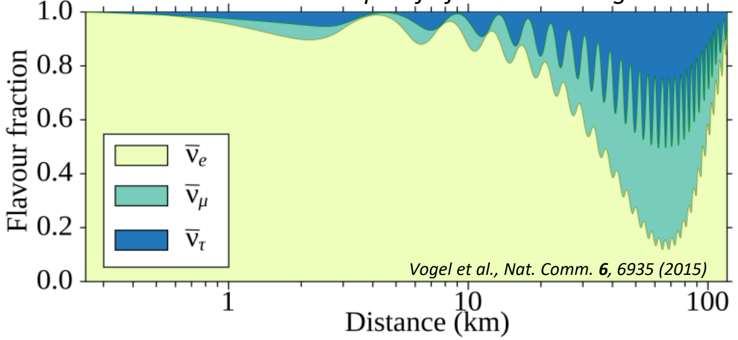
By MissMJ, Cush - Own work using:PBS NOVA

Why are neutrinos so light?



By HITOSHI MURAYAMA

Neutrino oscillation – a proof of neutrino being massive



The neutrino questions

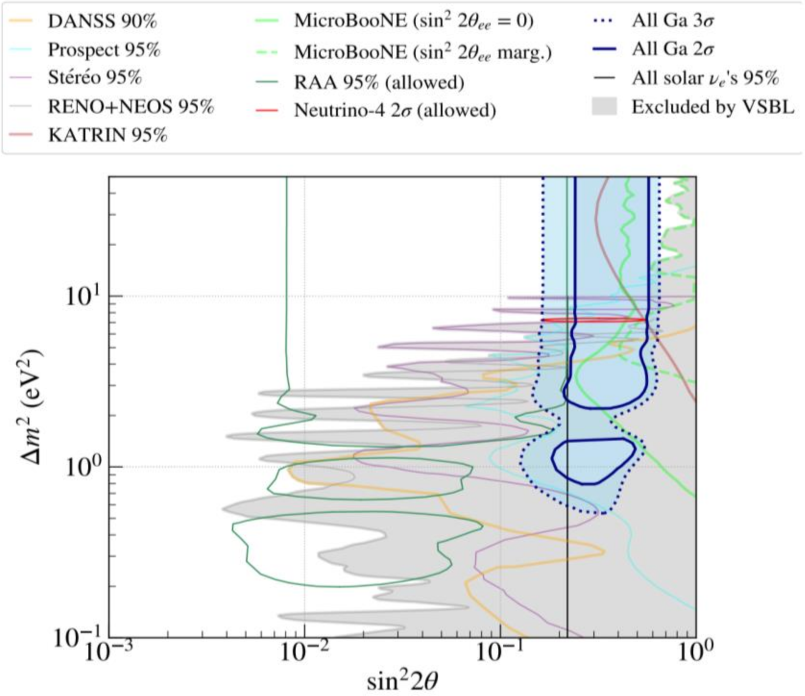
- What is the origin of neutrino mass?
- Why are neutrinos so light?
- Do right-handed neutrinos exist?

AIP Emilio Segre Visual Archives, Physics Today Collection

"Wu experiment"

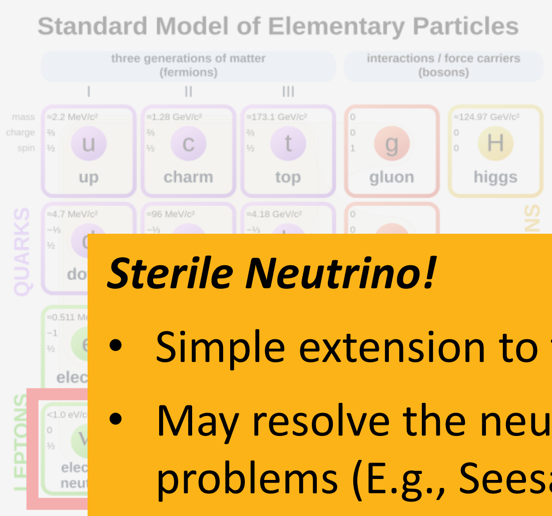
- Neutrinos are all left-handed!

Experimental evidences that there are 'something else'

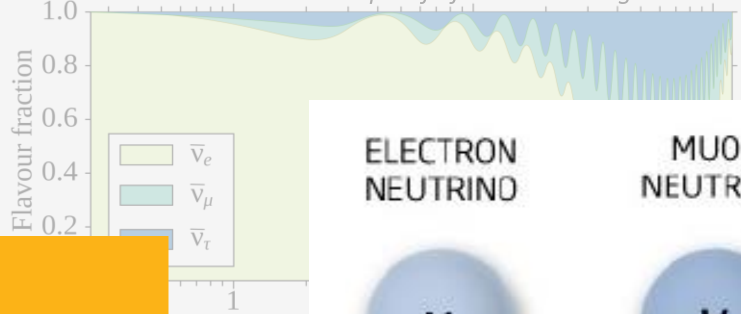


Phys. Rev. Lett. **128**, 232501

Neutrino in the Standard Model



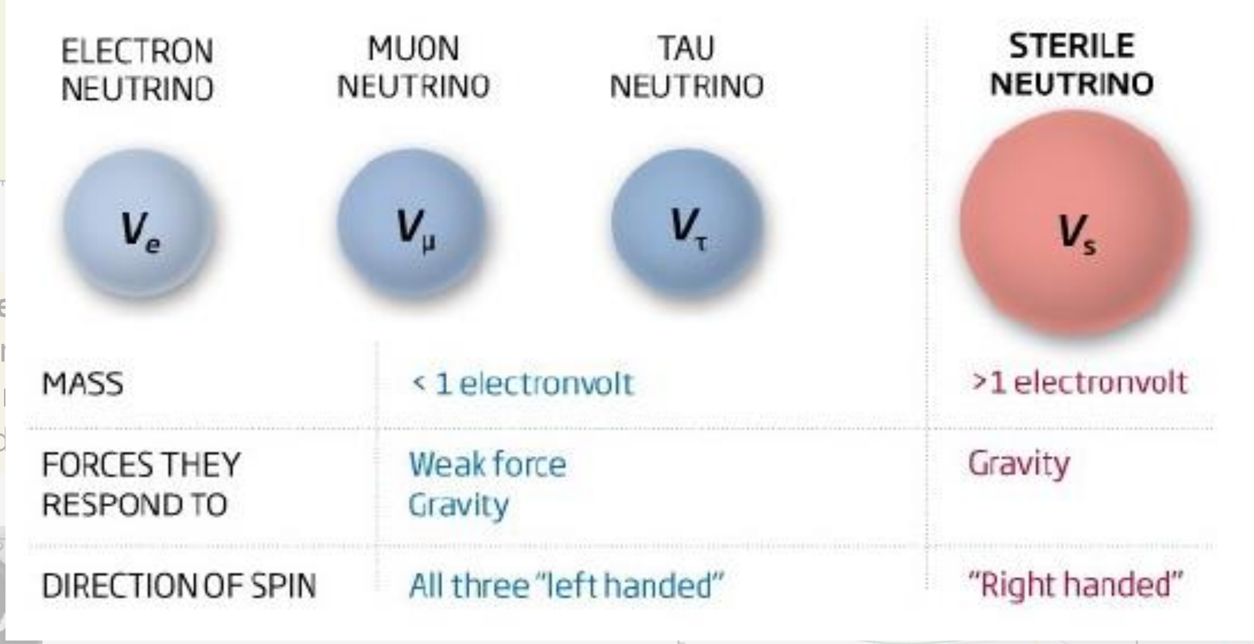
Neutrino oscillation – a proof of neutrino being massive



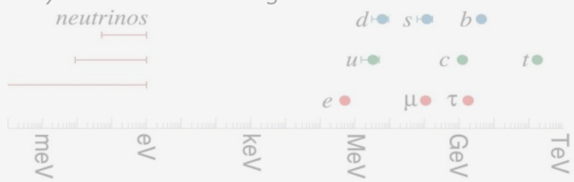
Experimental evidences that there are

Sterile Neutrino!

- Simple extension to the SM
- May resolve the neutrino mass problems (E.g., Seesaw mechanism)



Why are neutrinos so light?



By HITOSHI MURAYAMA

AIP Emilio Segre Visual Archives, Physics Today Collection

"Wu experiment"

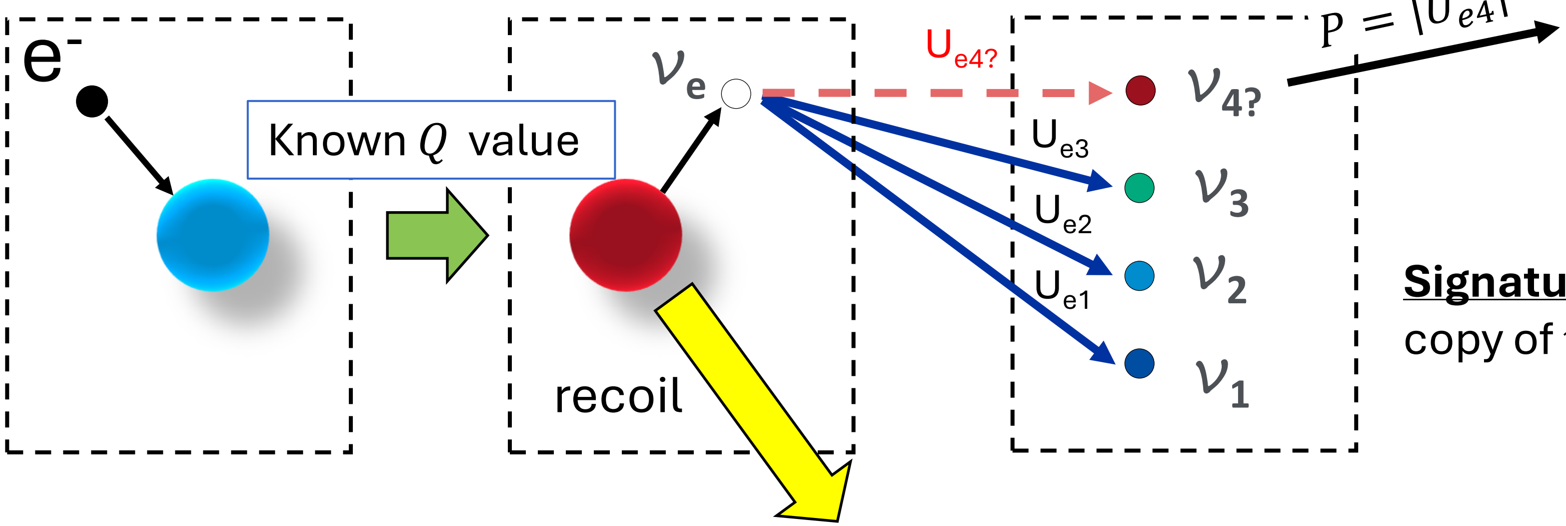
- Neutrinos are all left-handed!

Phys. Rev. Lett. **128**, 232501

Electron Capture and Neutrinos

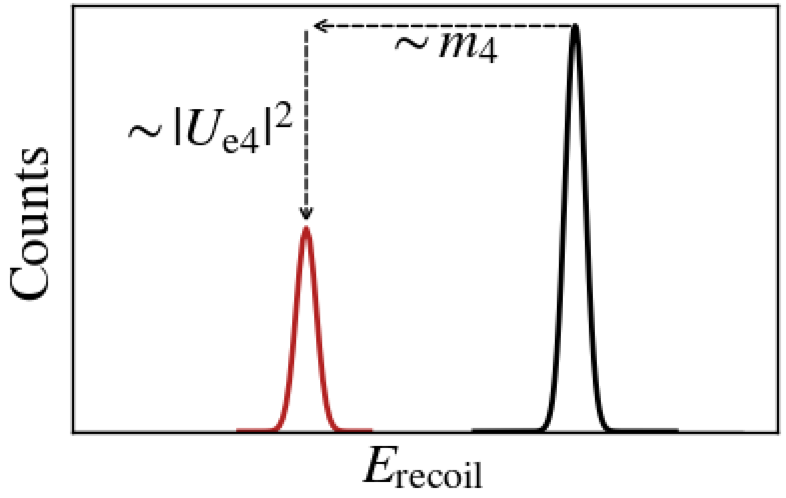
EC decay

Two-body process



$$E_{\text{recoil}} = \frac{\overbrace{Q^2}^{\text{known}} - \overbrace{m_4^2}^{\neq 0\,!}}{\underbrace{2(Q + M_{\text{nucl.}})}_{\text{known}}}$$

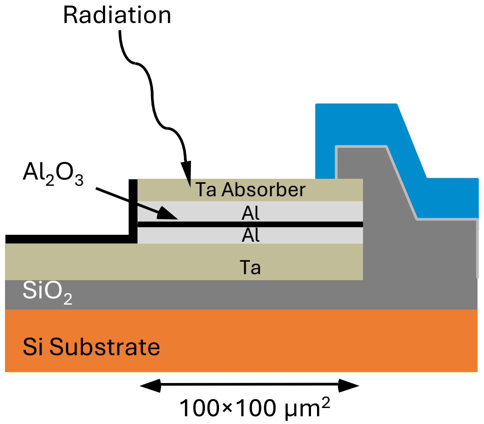
Signature: shifted (~m_4), scaled down (~ $|U_{e4}|^2$) copy of ν_{active} recoil spectrum.

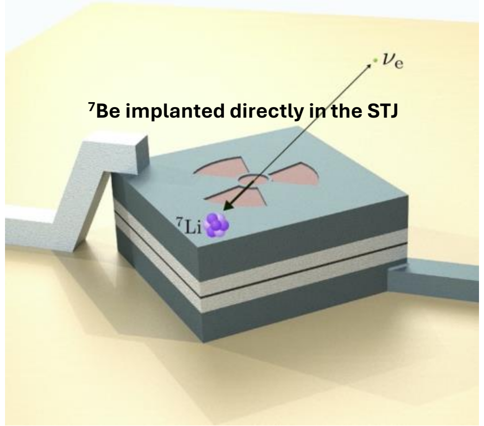


[7]Be is ideal because:

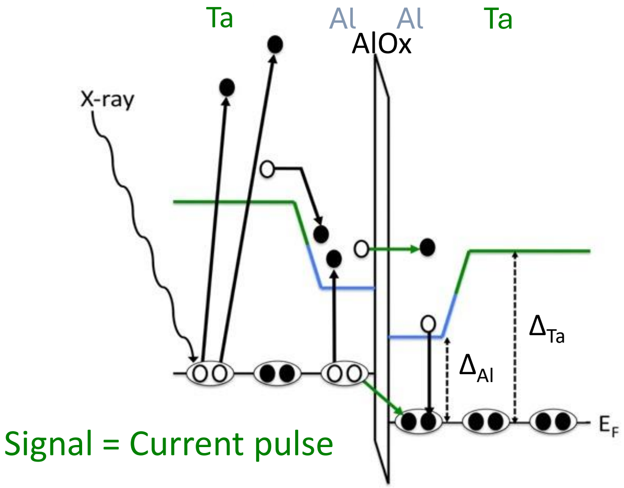
- Large decay energy (862 keV)
- Highest NR energy (**57 eV**)
- Simple atomic and nuclear structure

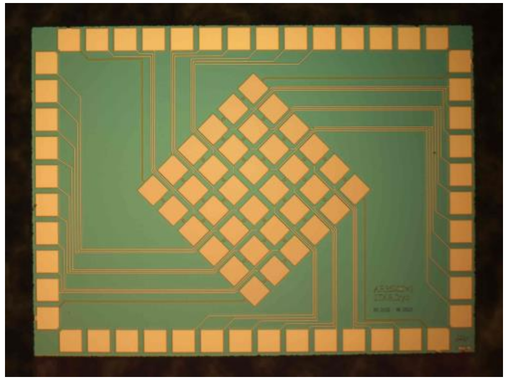
Superconducting Tunnel Junction (STJ)





- Two electrodes separated by a thin insulating tunnel barrier (S-I-S junction)
- Superconducting energy gap is of order of ~ meV
  → High intrinsic energy resolution (~ 1 eV)
- Timing resolution on the order of μs, making it one of the fastest high-resolution cryogenic sensors available
  →"High" rate: 10^4 s^{-1} per pixel





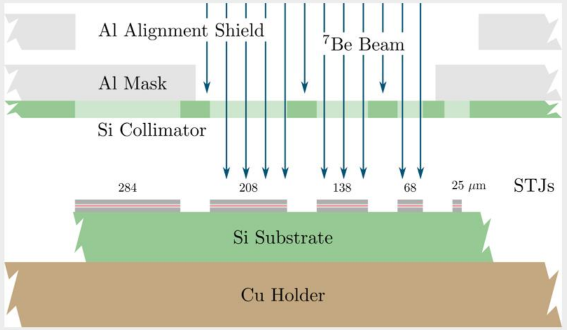
36-pixel array

128-pixel array

Two-body process
+
Advanced detector
=
THE BeEST

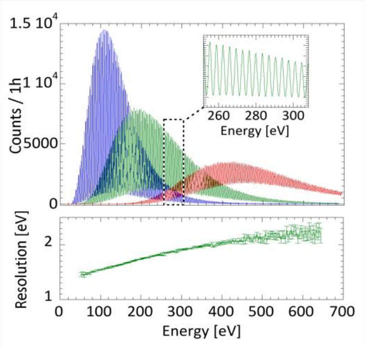
The BeEST Experiment

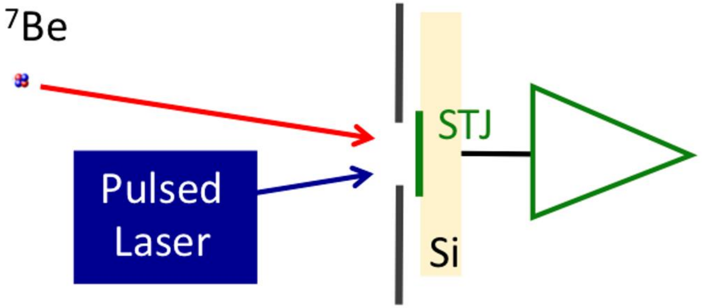
Implanted ^{7}Be Sample

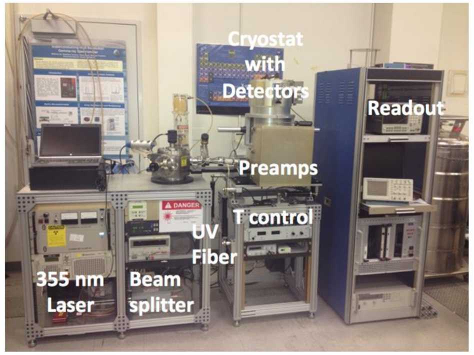


Simultaneous Laser Calibration

Provides energy calibration to <0.01 eV



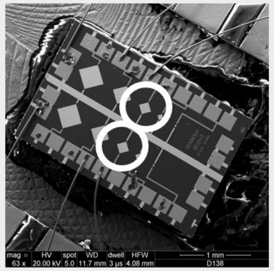




Ta-Based STJ Detectors

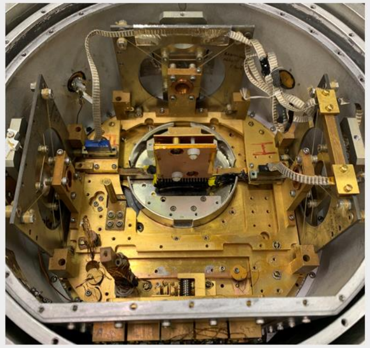
"Test" chips with 10 pixels of 5 sizes

Phase-I



Phase-II

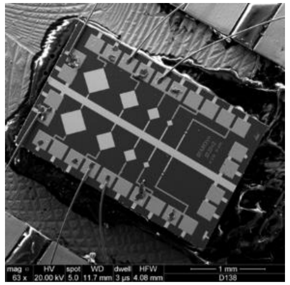
Cooled to 100 mK in an adiabatic demagnetization refrigerator (ADR)



Phases of the BeEST Experiment

Phase-I

Proof of Concept

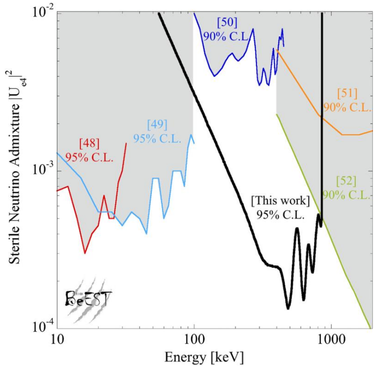


[PRL 125, 032701 (2020)]

- ^{7}Be was successfully implanted
- Beryllium L/K ratio was measured

Phase-II

Initial Release

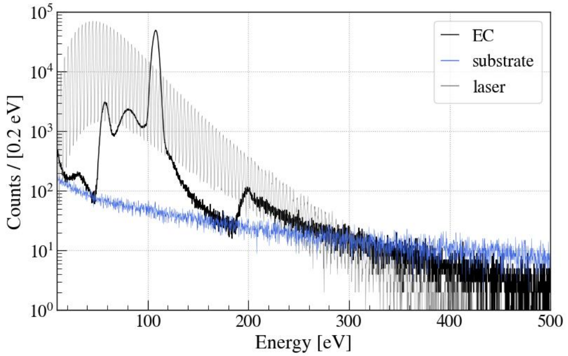


[PRL 126, 021803 (2021)]

- First results on heavy neutrino search
- The published limits improve over the previous limit by up to an order of magnitude

Phase-III

Scaling to multi-pixel



In progress

- 36-pixel array realized
- Improvements on implantation, detector performance, statistics, systematic understanding and analysis techniques

Phase-IV

128 pixels, improved setup

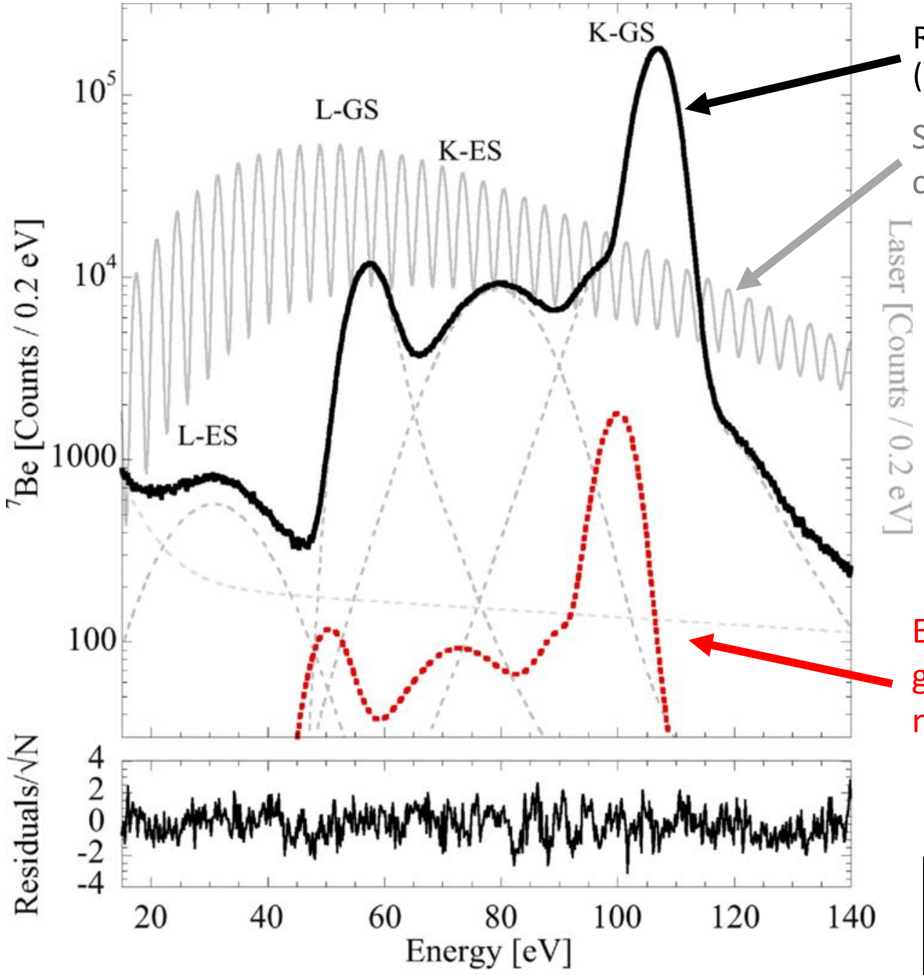
In future

- 128-pixel array STJ operated in more stable dilution refrigerator
- Use of Al-STJs may improve energy resolution

2018 **2020** **2022** **2024** **2026**

First Limits from BeEST Phase-II [Phys. Rev. Lett. 126, 021803 (2021)]

S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)

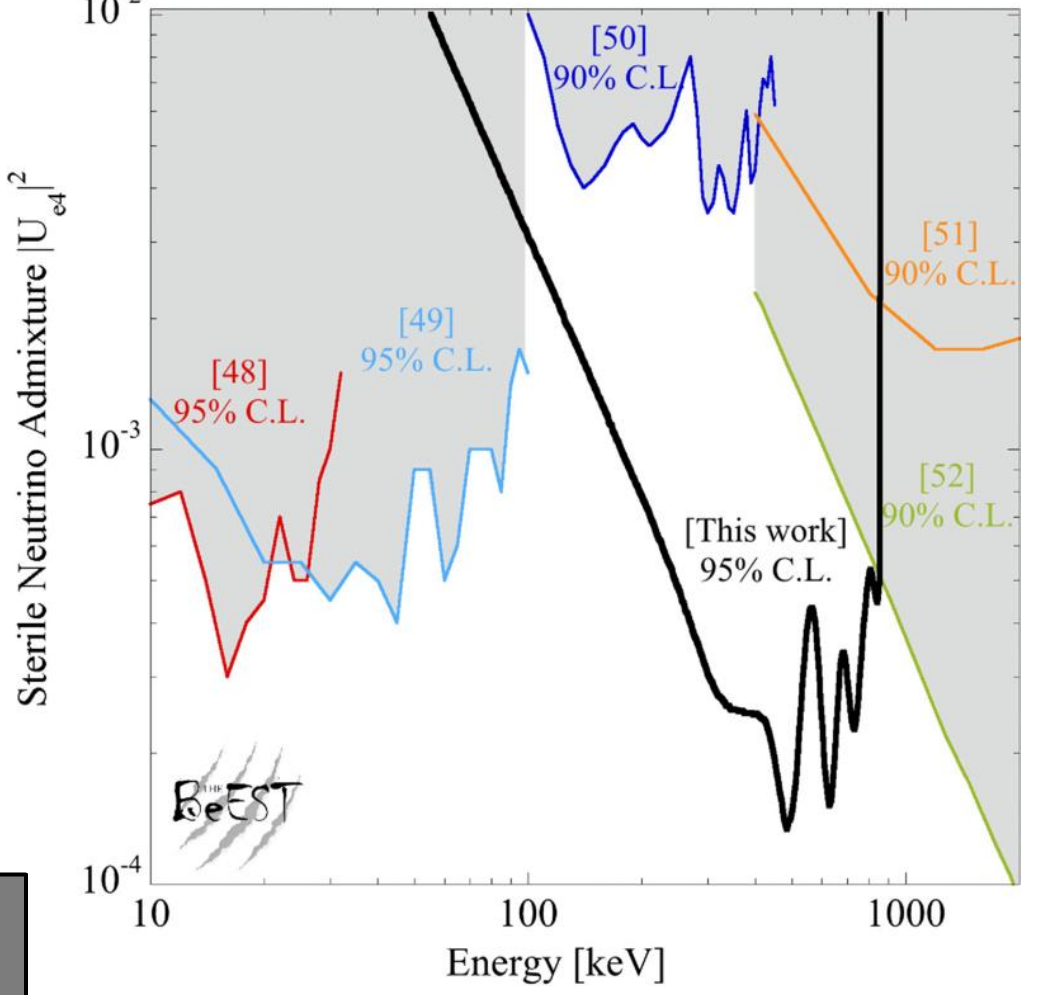


Recoil spectrum from electron capture (~28 days of counting)

Simultaneously acquired laser calibration spectrum

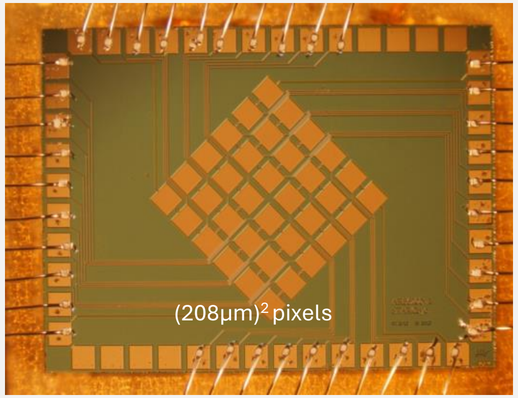
Example of signal that would be generated by 300 keV sterile neutrino with 1% mixing

S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)



Up to an order of magnitude improvement over the previous limits!

Development in Phase-III



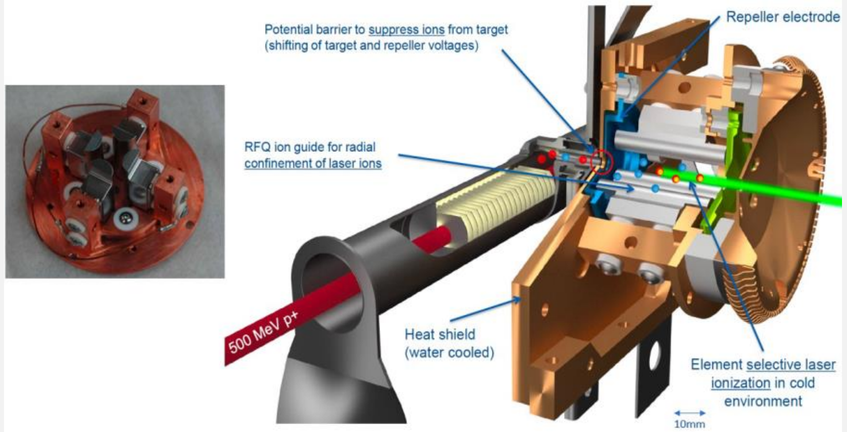
36-pixel array STJ operation

- Increased statistics
- Allows high-multiplicity events analysis

Data taking

- Data collection period:

  10.24.2022—12.26.2022 (incl. test runs)
- Data taking with 3 different DAQ
- In-situ laser calibration

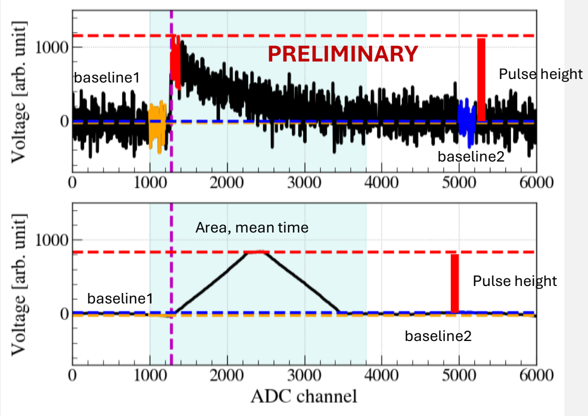


Improved Be-7 implantation

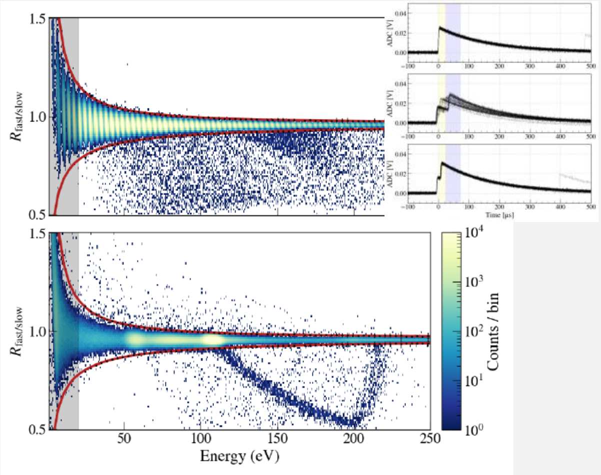
- The Ion guide laser ion source (IG-LIS): Highly selective ion beam to only select ^{7}Be

  → ^{7}Li suppression of x4,000 achieved
- ^{7}Be rate achieved: 20–50 Bq per pixel

TRIUMF

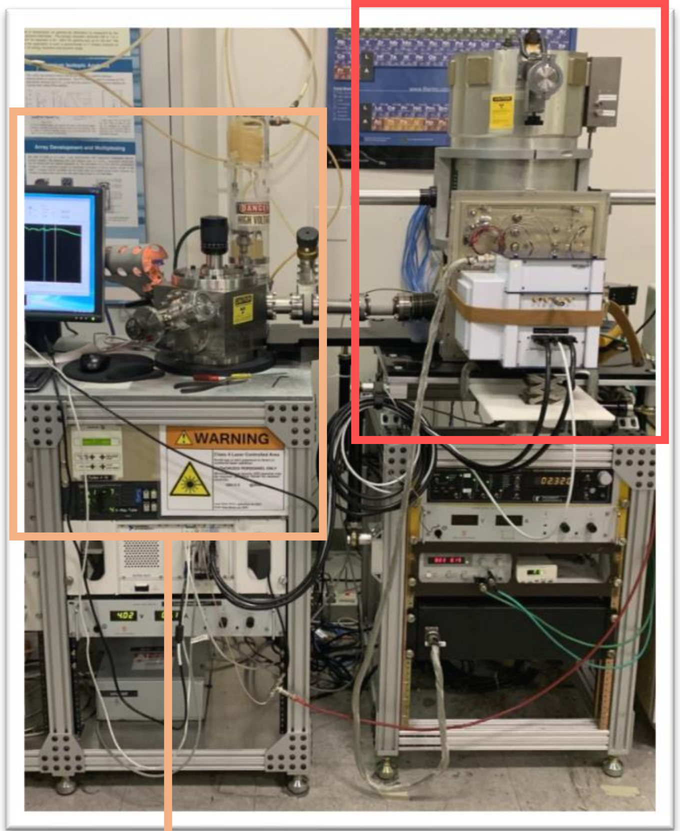


Continuous data taking for pulse shape analysis



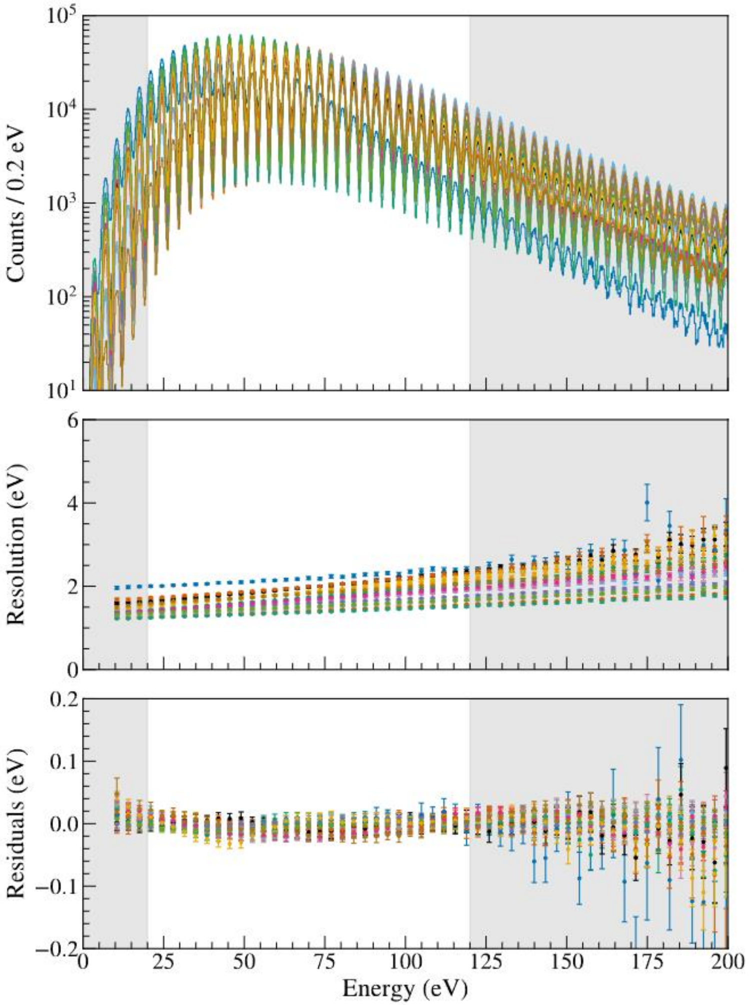
Phase-III data taking [Phys. Rev. D **111**, 052010 (2025)]

Adiabatic Demagnetization Refrigerator
(Base Temperature ~70 mK)



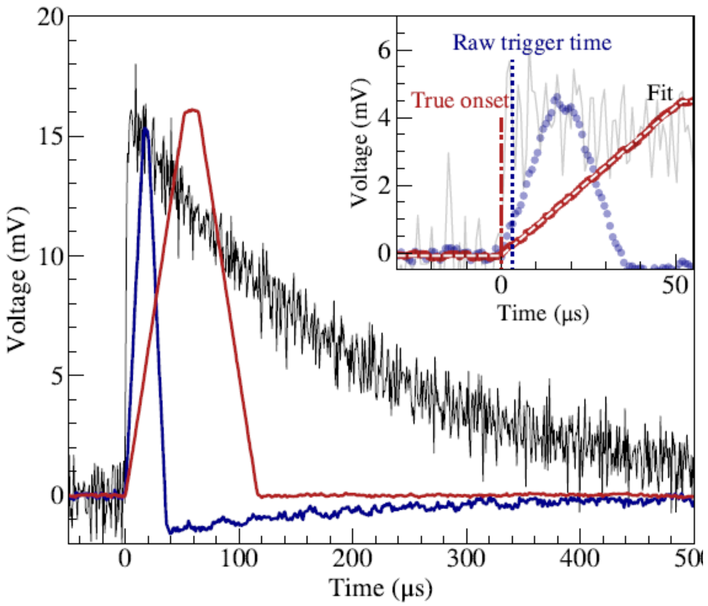
In-situ Laser Calibration

- Pulsed laser (3.5 eV) fed through optical fiber to 0.1 K stage of the ADR
- Illumination of STJs provides a comb of peaks at *integer multiples* of 3.5 eV
  → in-situ calibration source
- Intrinsic resolution of our Ta-based devices:
  1–2.2 eV FWHM @ 20–120 eV
- Stable response and small quadratic non-linearity

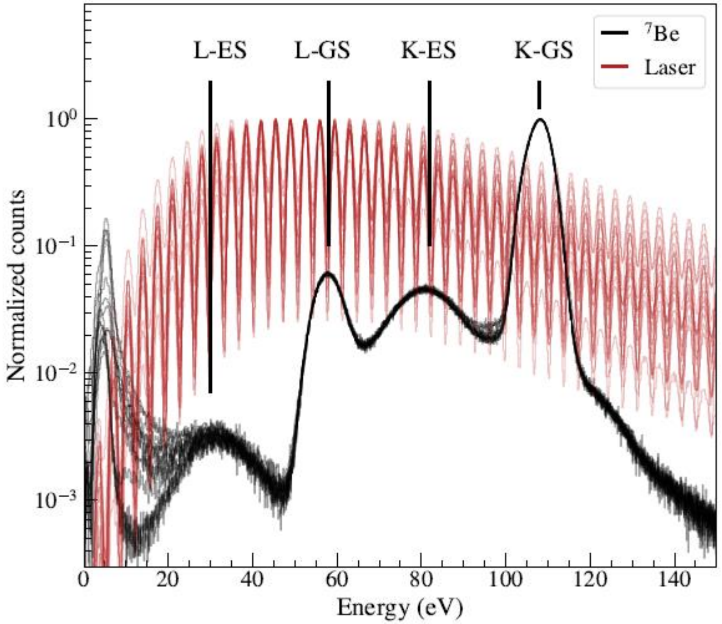


Automated signal processing & spectrum building
[Phys. Rev. D **111**, 052010 (2025)]

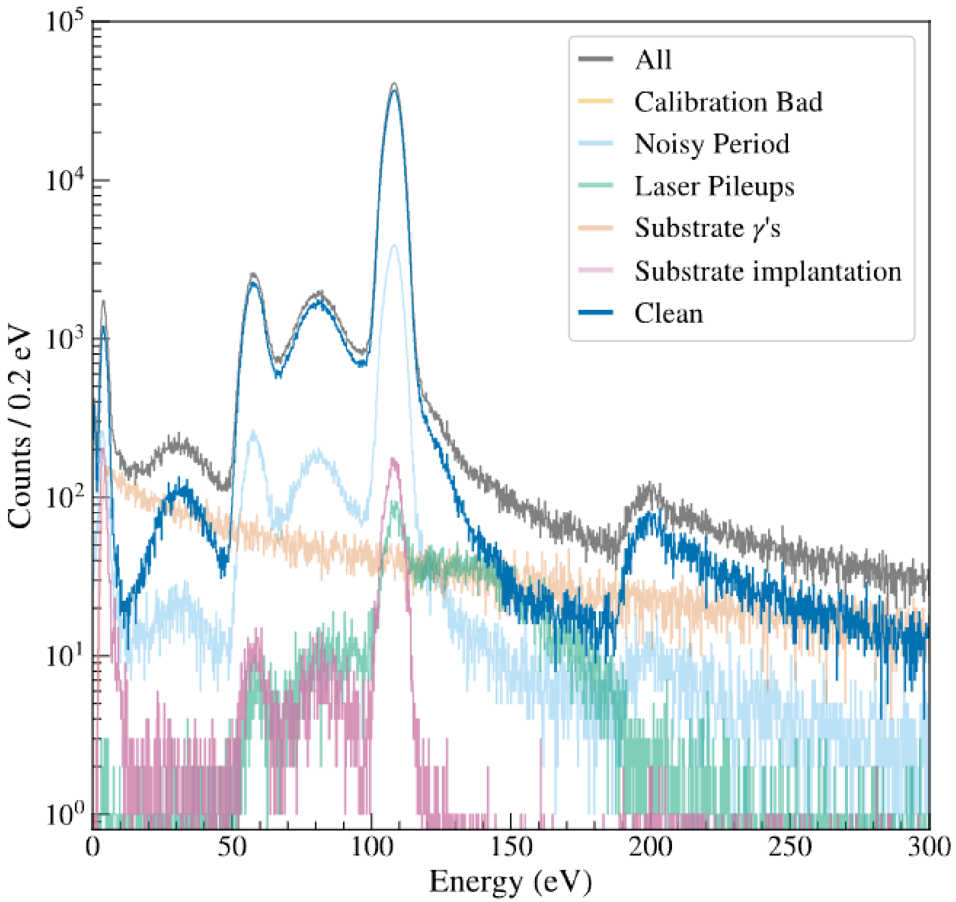
Pulse shape analysis



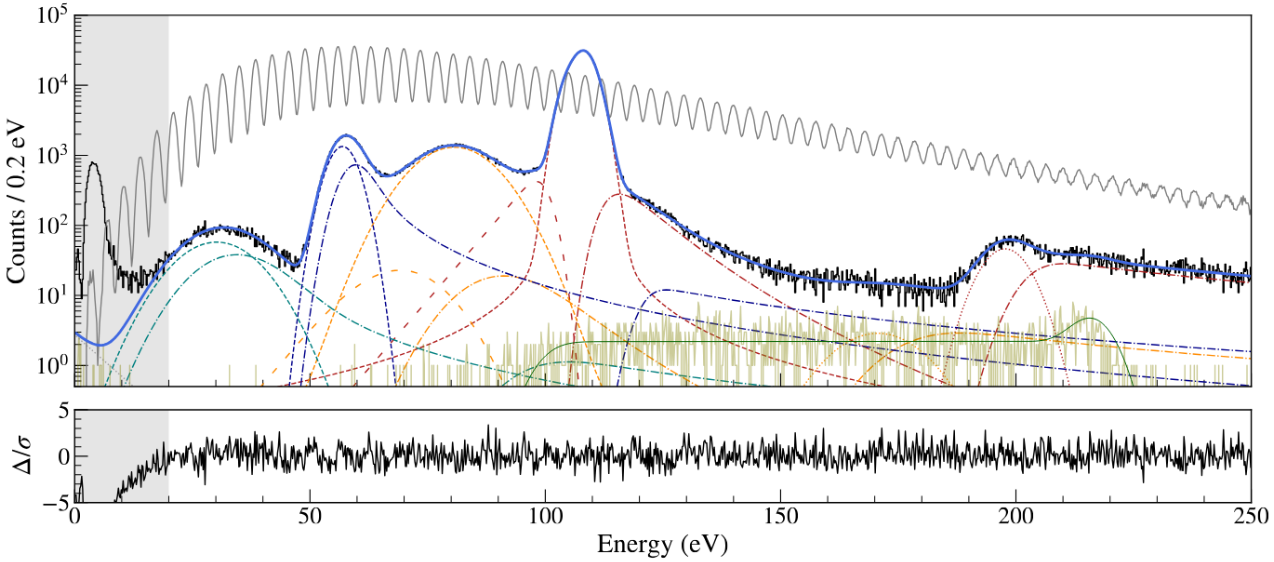
Precise energy calibration

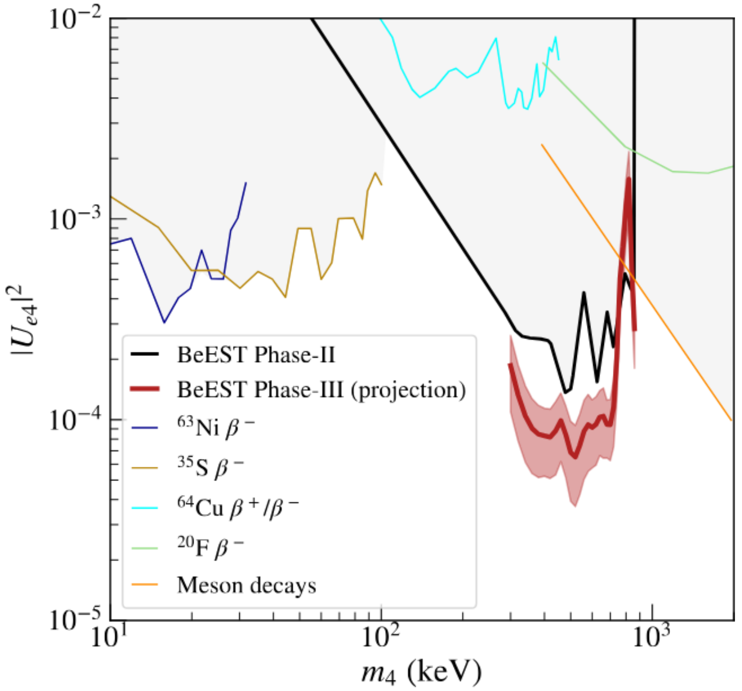


Data Cleaning



Sensitivity [arXiv:2409.19085, accepted in Phys. Rev. D]





Background modeling

- Precise background model is being studied

Phase-III sensitivity

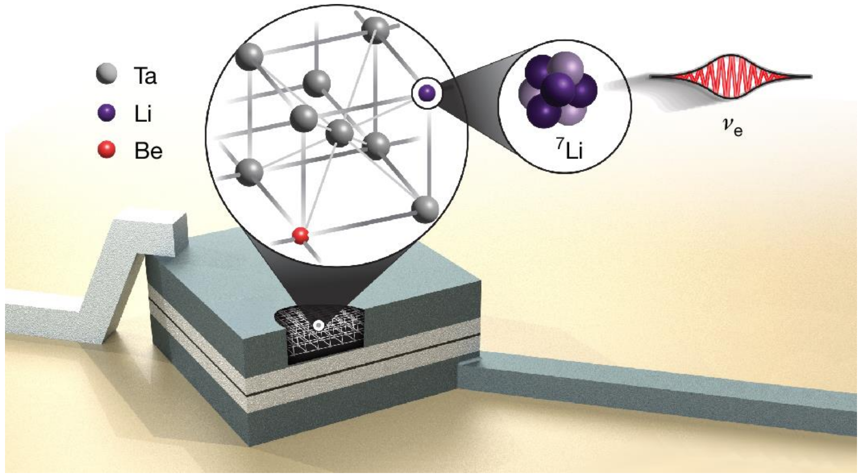
- Sensitivity is obtained by profiling the likelihood over the $(m_4, |U_{e4}|^2)$ parameter space.

Unblinding the full data in progress!

Limits on the Size of a Neutrino Wavepacket

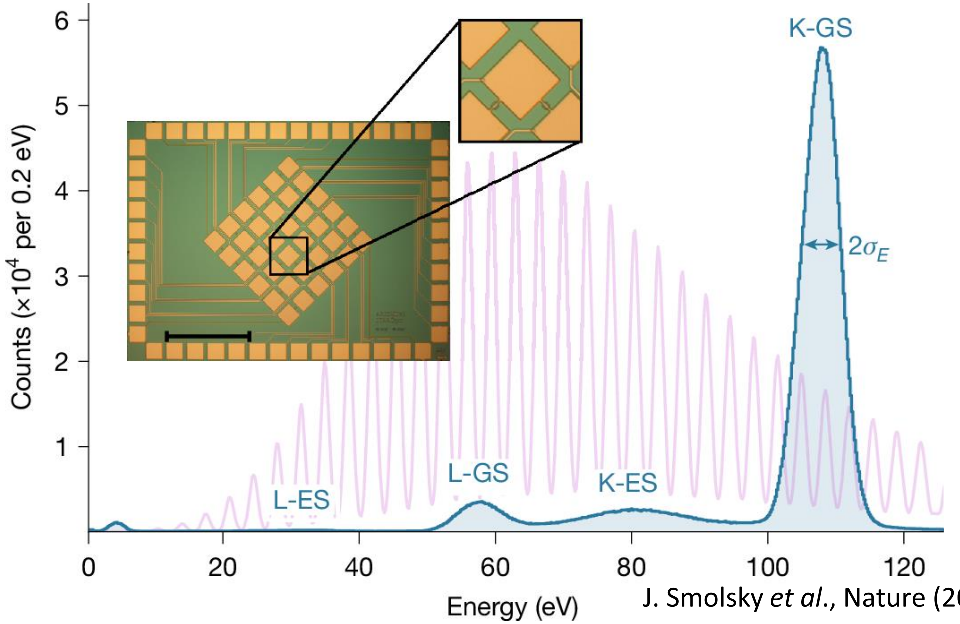
[Nature **638**, 640–644 (2025)]

Emitted as ν_e, travels in mass eigenstate



Uncertainty in spatial wavepacket extent may translate into energy uncertainty, i.e., peak broadening

Observation



J. Smolsky *et al.*, Nature (2025)

From energy viewpoint,

1. $\sigma_{\nu,E} = \sigma_{\mathrm{Li},E}$
2. $\sigma_{\nu,p} = \sigma_{\nu,E}$
3. $\sigma_{\nu,x} = \sigma_{\nu,p}/2\hbar$

From momentum viewpoint,

1. $\sigma_{\mathrm{Li},p} = \sqrt{m/2E}\,\sigma_{\mathrm{Li},E}$
2. $\sigma_{\nu,p} = \sigma_{\mathrm{Li},p}$
3. $\sigma_{\nu,x} = \sigma_{\nu,p}/2\hbar$

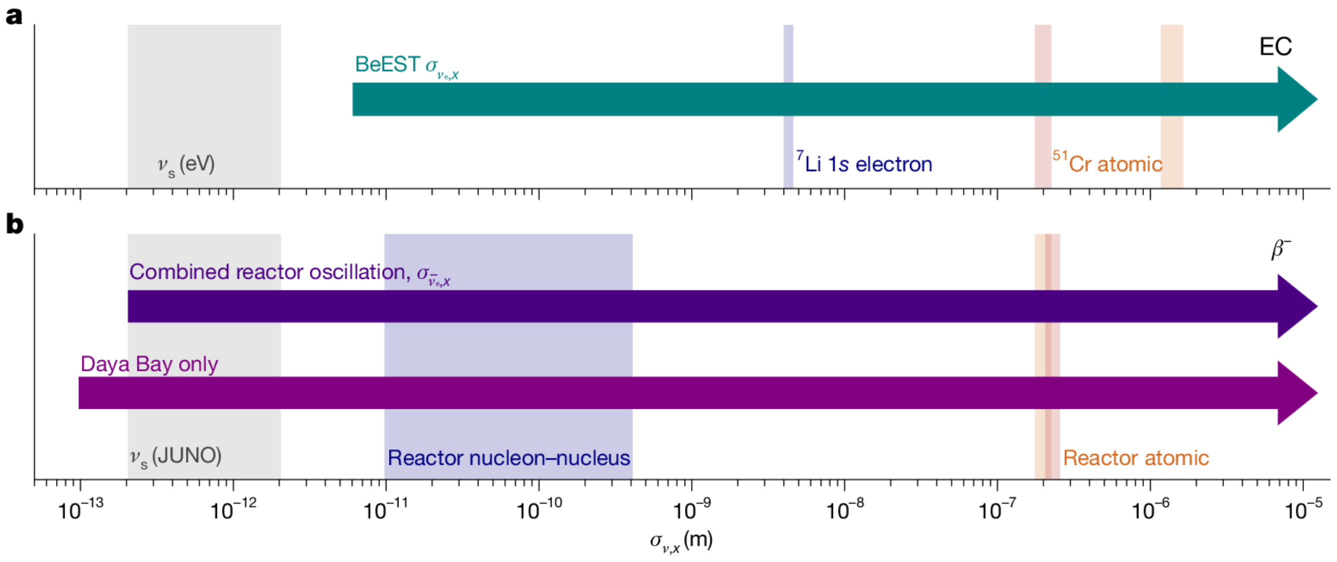
Nuclear recoil peak widths are broader than laser peaks

- No concrete explanation is found
- The broadening could be due to decoherence due to finite size of the electron neutrino wave packet

Limits on the Size of a Neutrino Wavepacket

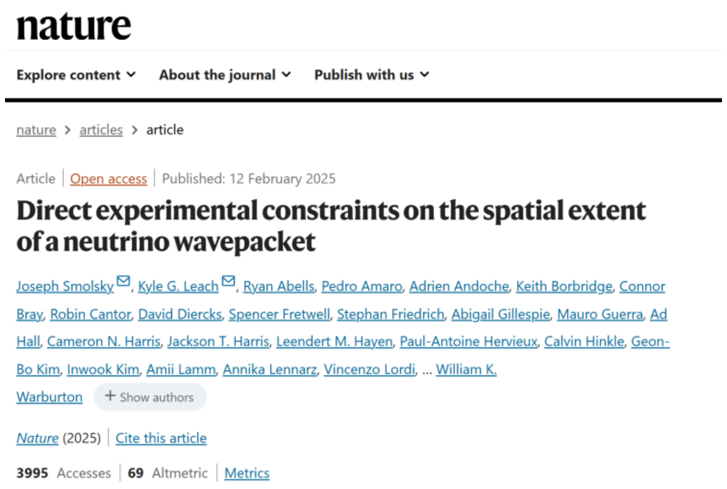
[Nature **638**, 640–644 (2025)]

J. Smolsky *et al.*, Nature (2025)



- Energy conservation yields $\sigma_{\nu,x} \geq$35nm
- Momentum conservation yields $\sigma_{\nu,x} \geq$6.2pm

→ BeEST conservative limit: 6.2pm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Article | Open access | Published: 12 February 2025

Direct experimental constraints on the spatial extent of a neutrino wavepacket

Joseph Smolsky, Kyle G. Leach, Ryan Abells, Pedro Amaro, Adrien Andoche, Keith Borbridge, Connor Bray, Robin Cantor, David Diercks, Spencer Fretwell, Stephan Friedrich, Abigail Gillespie, Mauro Guerra, Ad Hall, Cameron N. Harris, Jackson T. Harris, Leendert M. Hayen, Paul-Antoine Hervieux, Calvin Hinkle, Geon-Bo Kim, Inwook Kim, Amii Lamm, Annika Lennarz, Vincenzo Lordi, ... William K. Warburton + Show authors

Nature (2025) Cite this article

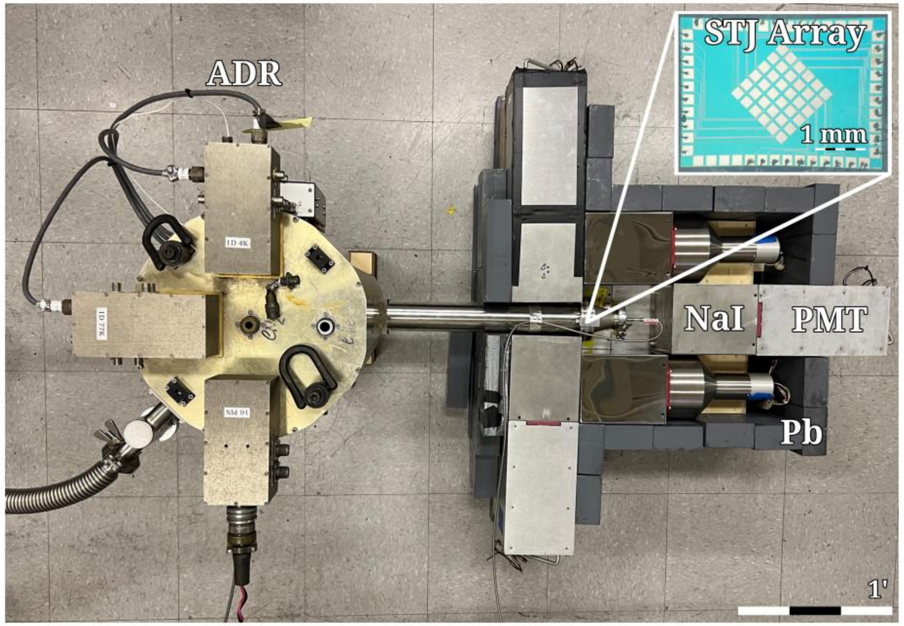
3995 Accesses | 69 Altmetric | Metrics

First direct experimental constraint on the size of a neutrino wavepacket

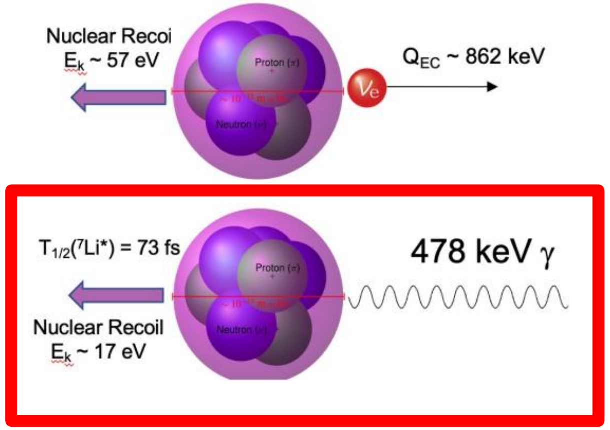
- Only limit on neutrino wavepackets from EC decays
- Only direct limit on nuclear decay product wavepackets

γ-Coincidence measurement

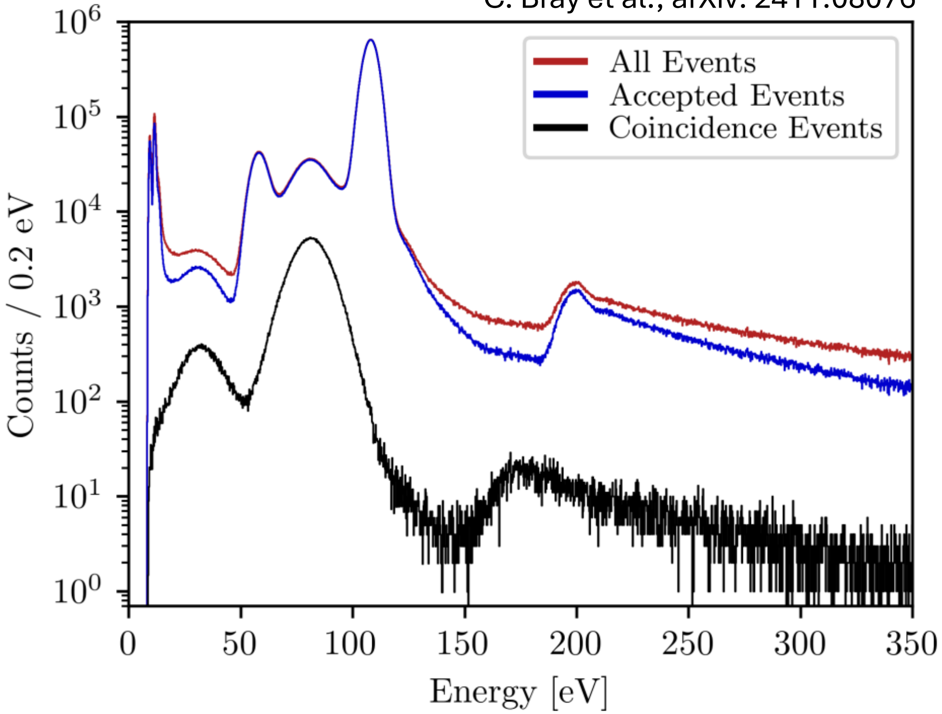
[arXiv: 2411.08076, submitted to Phys. Rev. Lett.]



C. Bray et al., arXiv: 2411.08076



C. Bray et al., arXiv: 2411.08076



γ-coincidence measurement of the EC decay allows for **selective measurement of nuclear recoil spectrum to a certain state**

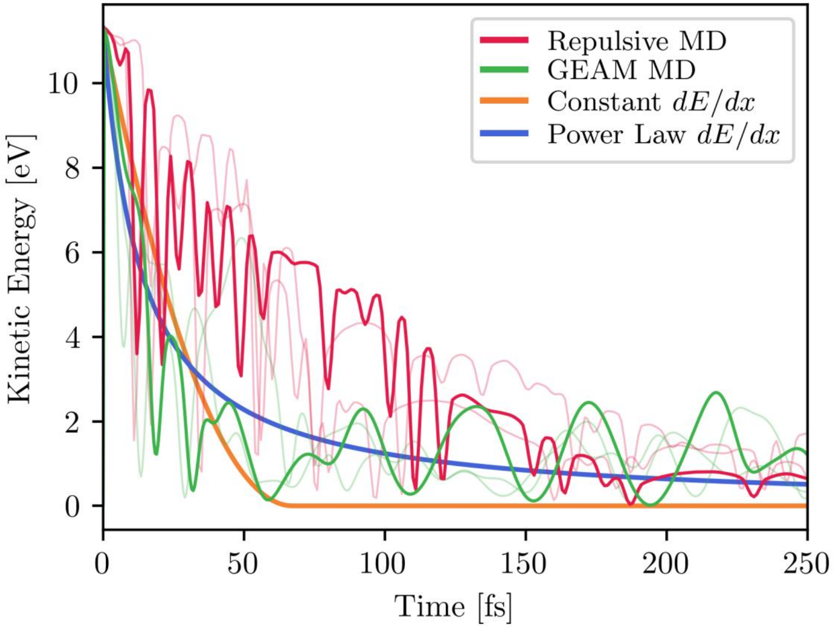
γ-Coincidence measurement

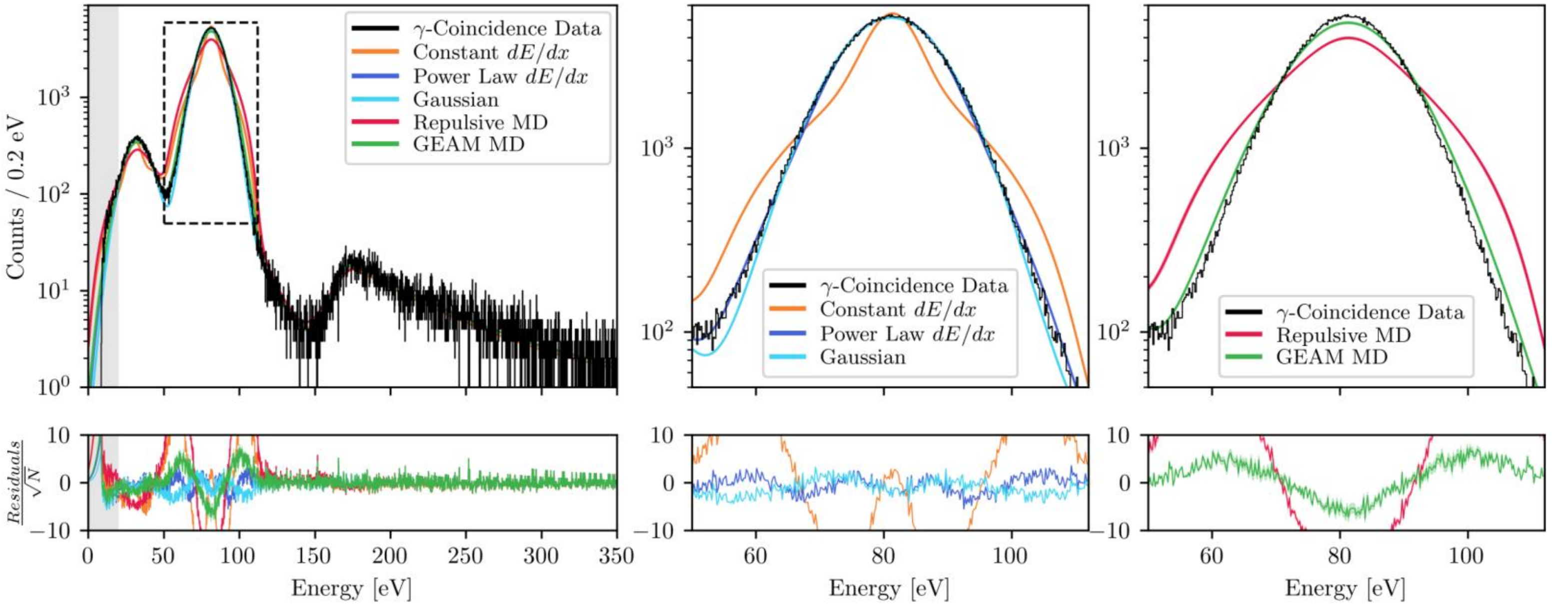
[arXiv: 2411.08076, submitted to Phys. Rev. Lett.]

Implication: one can precisely test models of nuclear recoil interactions in materials

Example: ion slowing down model comparison

C. Bray et al., arXiv: 2411.08076





BeEST Publications

Title	Journal	Author
Signal processing and spectral modeling for the BeEST experiment	*Phys. Rev. D* **111**, 052010 (2025)	I. Kim et al. (BeEST Collaboration)
Direct Experimental Constraints on the Spatial Extent of a Neutrino Wavepacket	*Nature* **638**, 640–644 (2025)	J. Smolsky et al. (BeEST Collaboration)
High-Precision Excited-State Nuclear Recoil Spectroscopy with Superconducting Sensors	Submitted to *PRL* (arXiv:2411.08076)	C. Bray, S. Fretwell, L. A. Zepeda-Ruiz, I. Kim et al (BeEST Collaboration)
Shake-up and Shake-off effects in the electron capture decay of ^{7}Be	To be submitted to *PRD*	M. Guerra et al. (BeEST Collaboration)
Final Results from BeEST Heavy Neutrino Search	To be submitted to *PRL*	I. Kim et al. (BeEST Collaboration)

...and more!

Conclusion

- BeEST experiment searches for the heavy neutrino mass eigenstate by examining the EC decay of ^{7}Be
- The Phase-III involves significant improvements in hardware, analysis tools, and the underlying theories that determine the electron capture spectra
- BeEST collaboration is actively publishing high-profile papers
- We plan to unblind the full data to set leading limits on mixing to heavy state

The BeEST Collaboration

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THE BeEST

GORDON AND BETTY MOORE FOUNDATION

U.S. DEPARTMENT OF ENERGY | Office of Science

EMPIR EURAMET

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NNSA National Nuclear Security Administration

2023 Collaboration Meeting
Livermore, CA