Reactor Monitoring using Coherent Elastic Neutrino-Nucleus Scattering

MTV Kickoff Meeting

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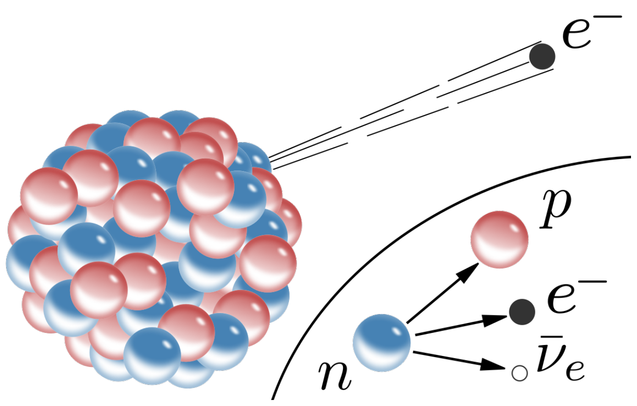
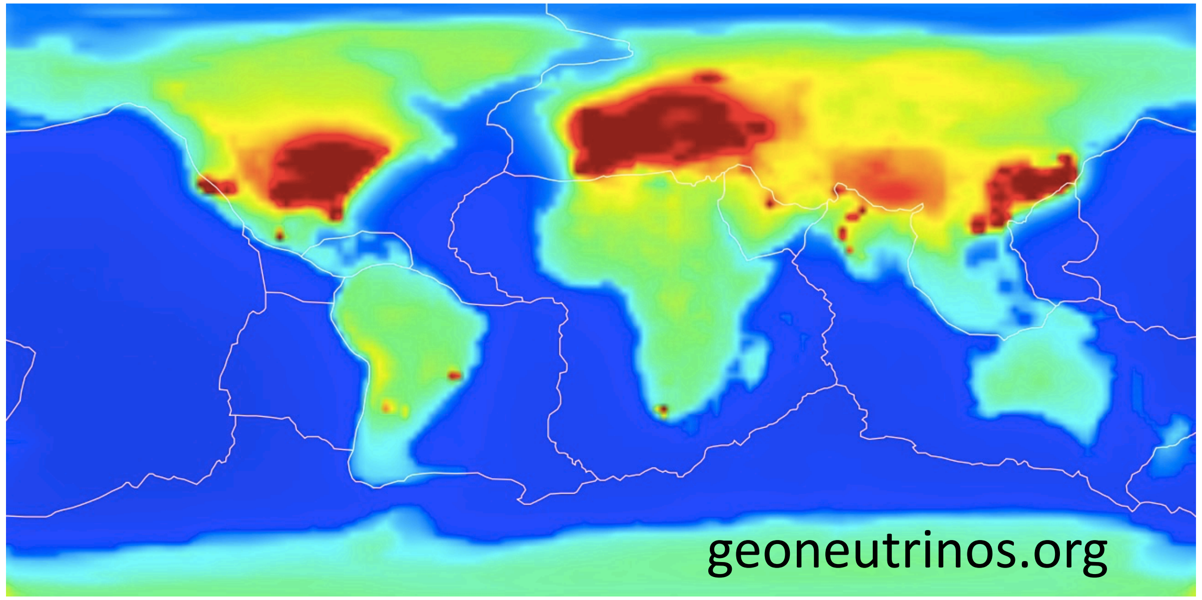
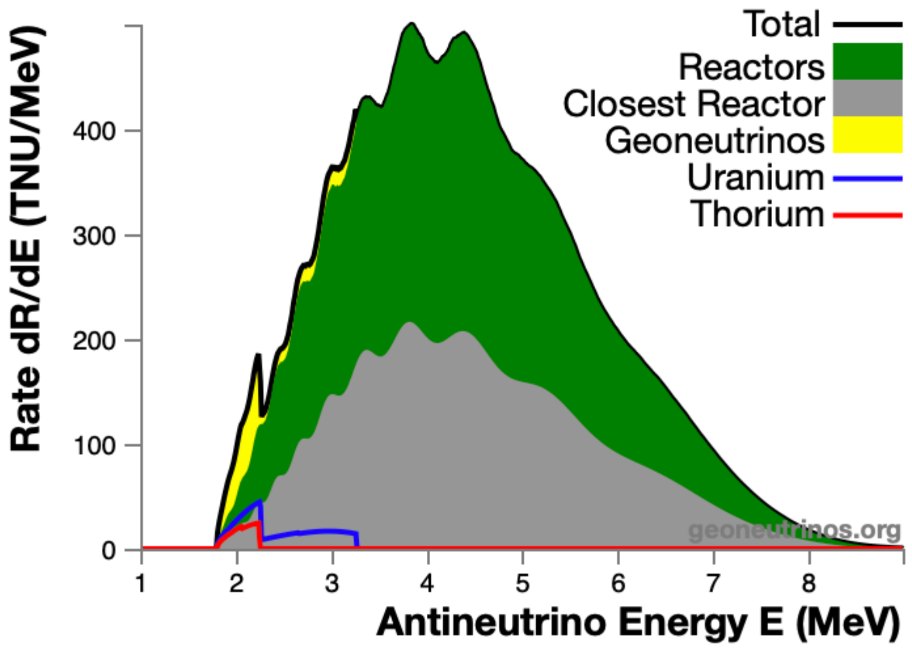
Introduction and Motivation

- There is an ongoing need to monitor the operation of existing nuclear reactors and detect undeclared reactors, safeguard nuclear material including spent fuel, and detect nuclear tests.
- Technologies are sought that can complement the existing methods: increase sensitivity, improve confidence, resolve ambiguities.
- Antineutrino detection has been identified as a promising method for proliferation measurements.



~10^{20} cm^2 / GWth

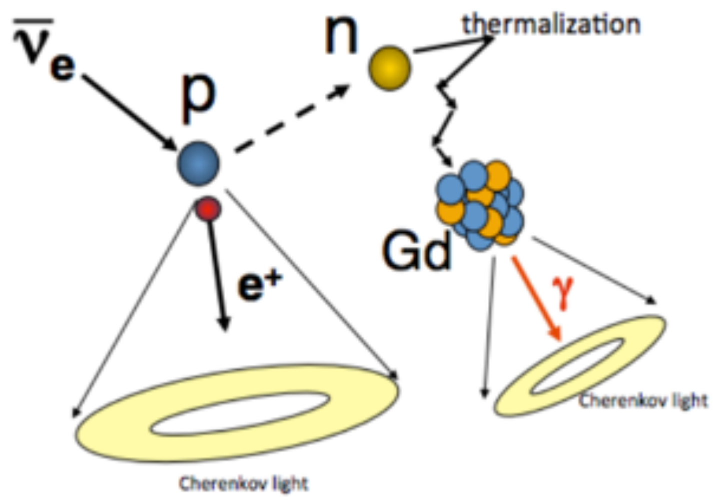




Methods for antineutrino detection

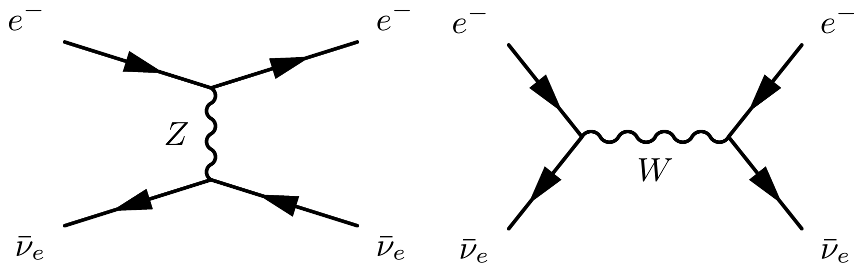
Inverse beta decay

$$\bar{\nu} + p \rightarrow e^{+} + n$$



- 1.8-MeV energy threshold
- Technologically mature
- Flavor sensitive

Electron elastic scattering



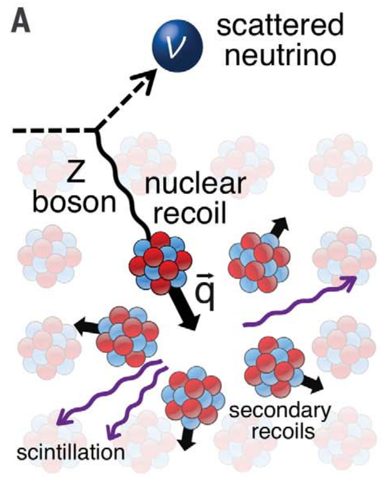
$$\bar{\nu}_e e^- \rightarrow \bar{\nu}_e e^-$$

$$\sigma(\nu_e e^-) \approx 10^{-41} E \text{ cm}^2$$

$$E \text{ in GeV}$$

- No energy threshold
- Highly directional
- Low cross section
- Susceptible to backgrounds

Coherent elastic neutrino-nucleus scatting (CEvNS)



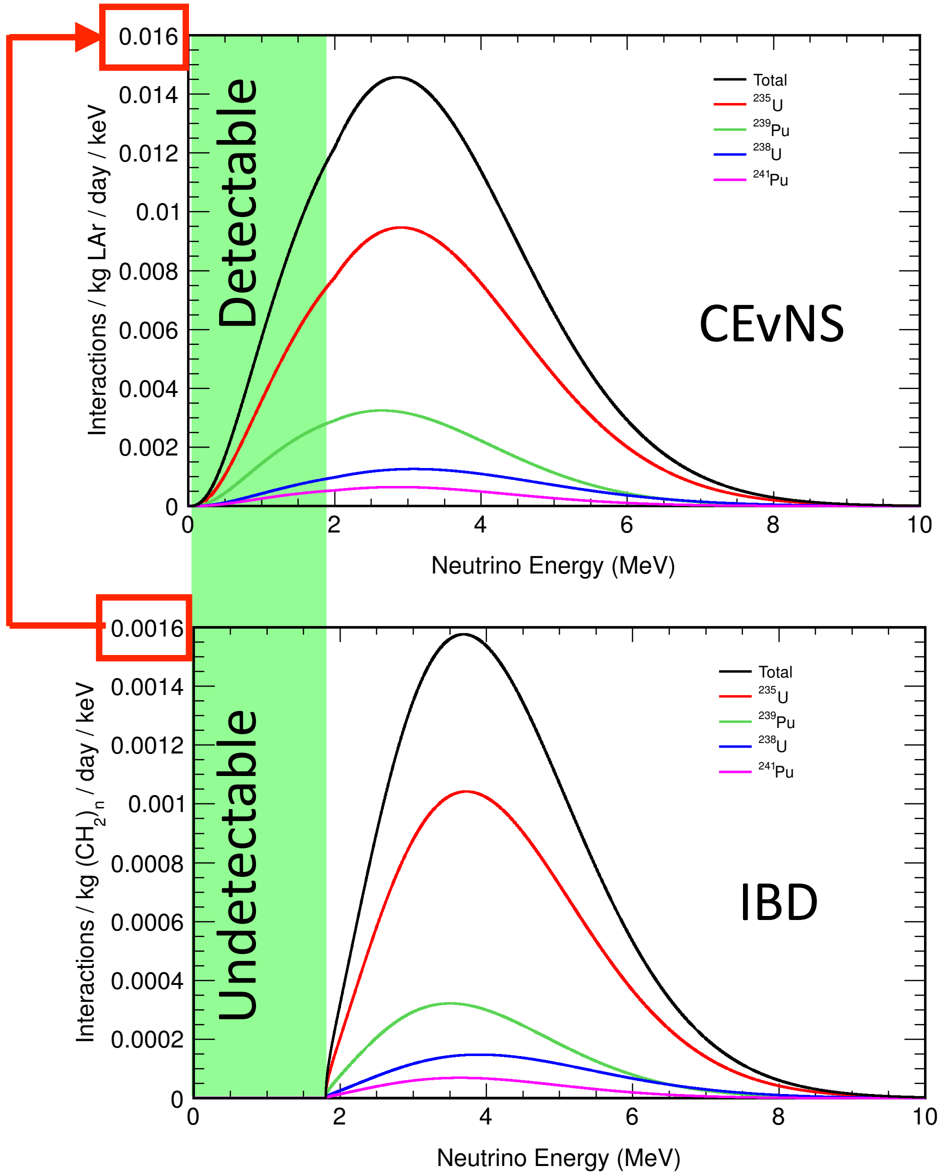
Akimov et al., Science 357, 1123–1126 (2017)

- No energy threshold
- **The greatest cross section of all neutrino-matter couplings**
- Flavor blind

Mission Relevance

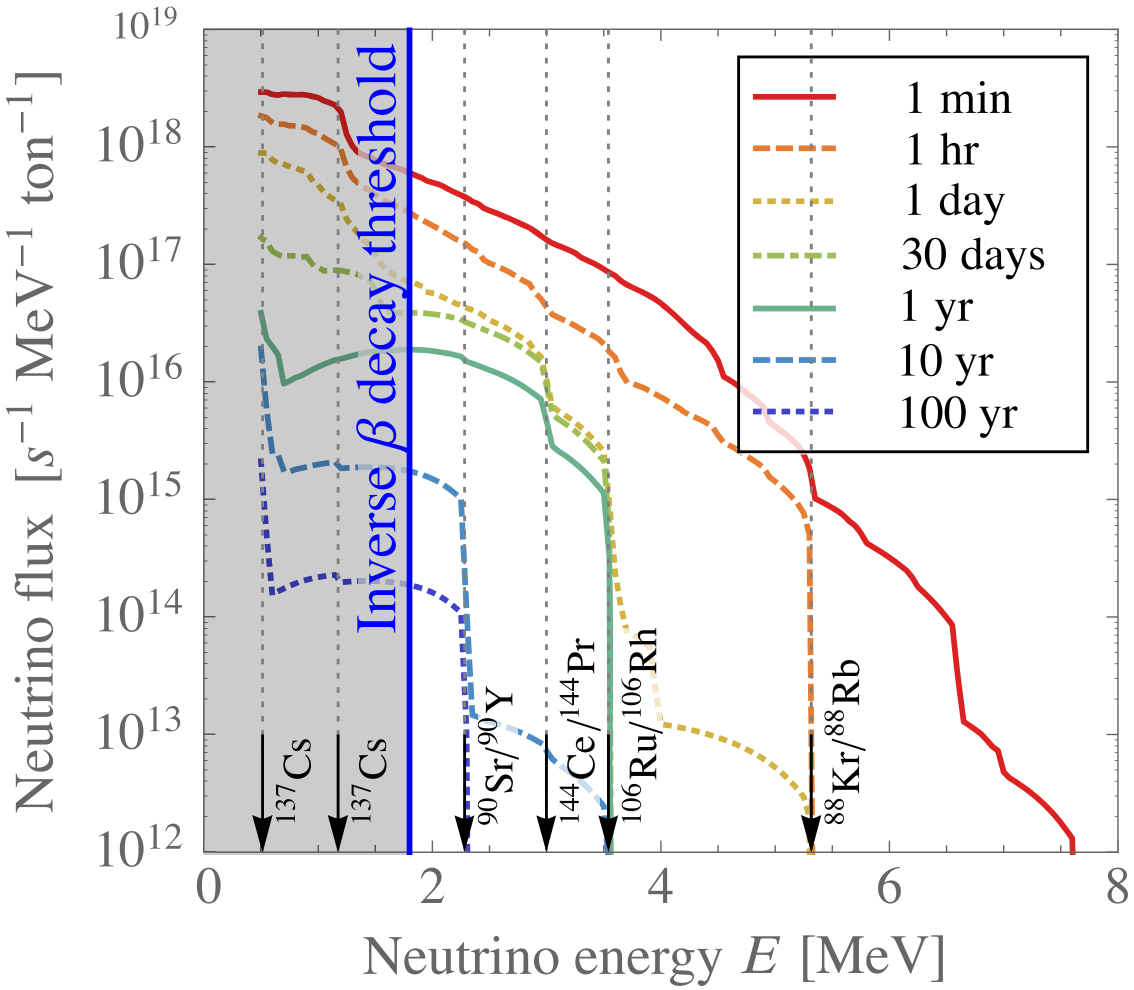
Detection and monitoring of plutonium production

Large increase in cross section



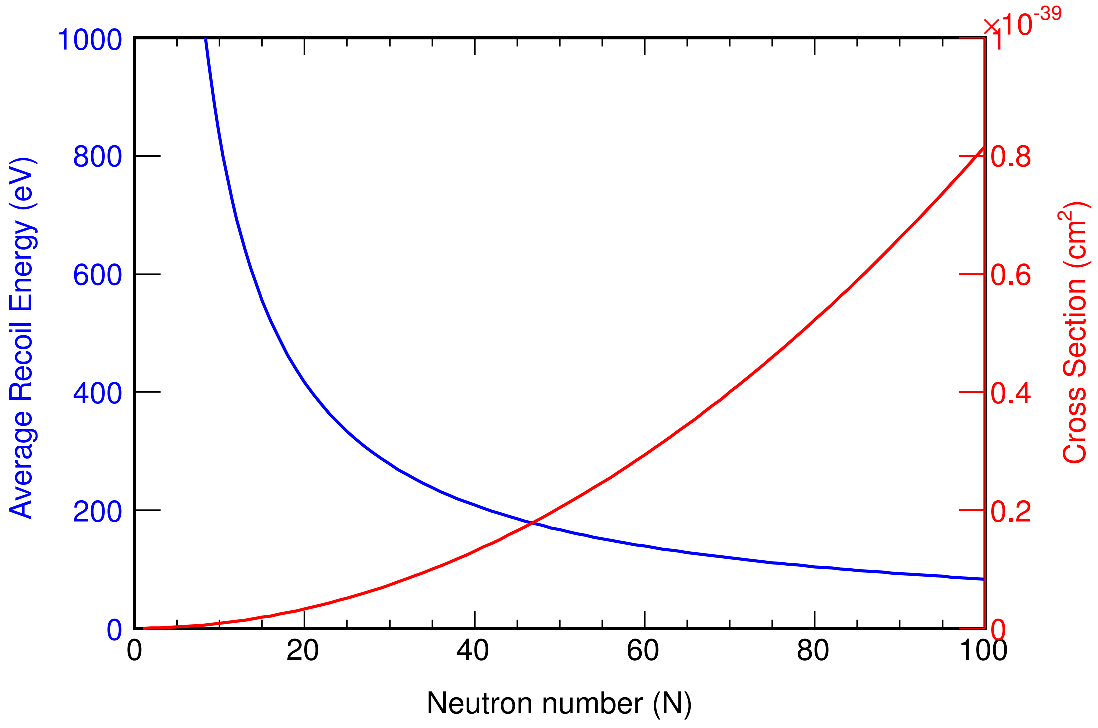
M. Foxe, dissertation (2013)

Monitoring of spent fuel



V. Brdar et al., Phys. Rev. Applied 8, 054050 (2017)

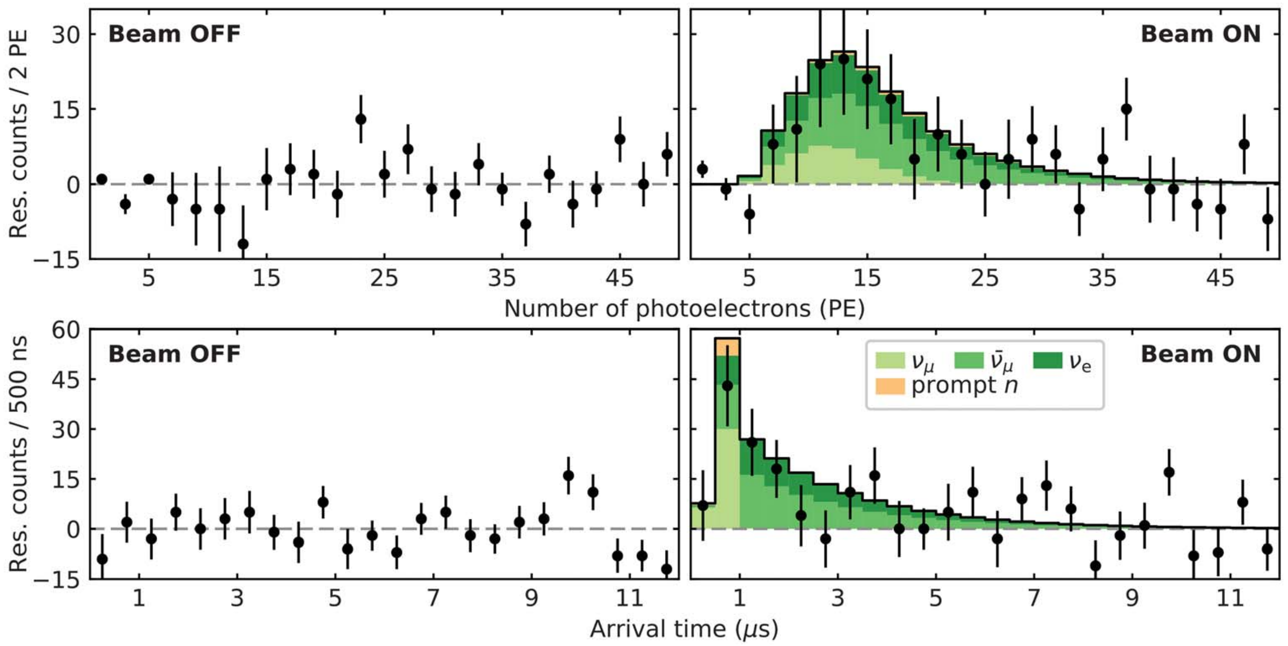
CEvNS detection



$$\sigma \sim 0.4 \times 10^{-44} N^2 \left(\frac{E_\nu}{\text{MeV}}\right)^2 \text{ cm}^2$$

$$\langle E_r \rangle = \frac{2}{3}\left[\frac{\left(\frac{E}{MeV}\right)^2}{A}\right]$$

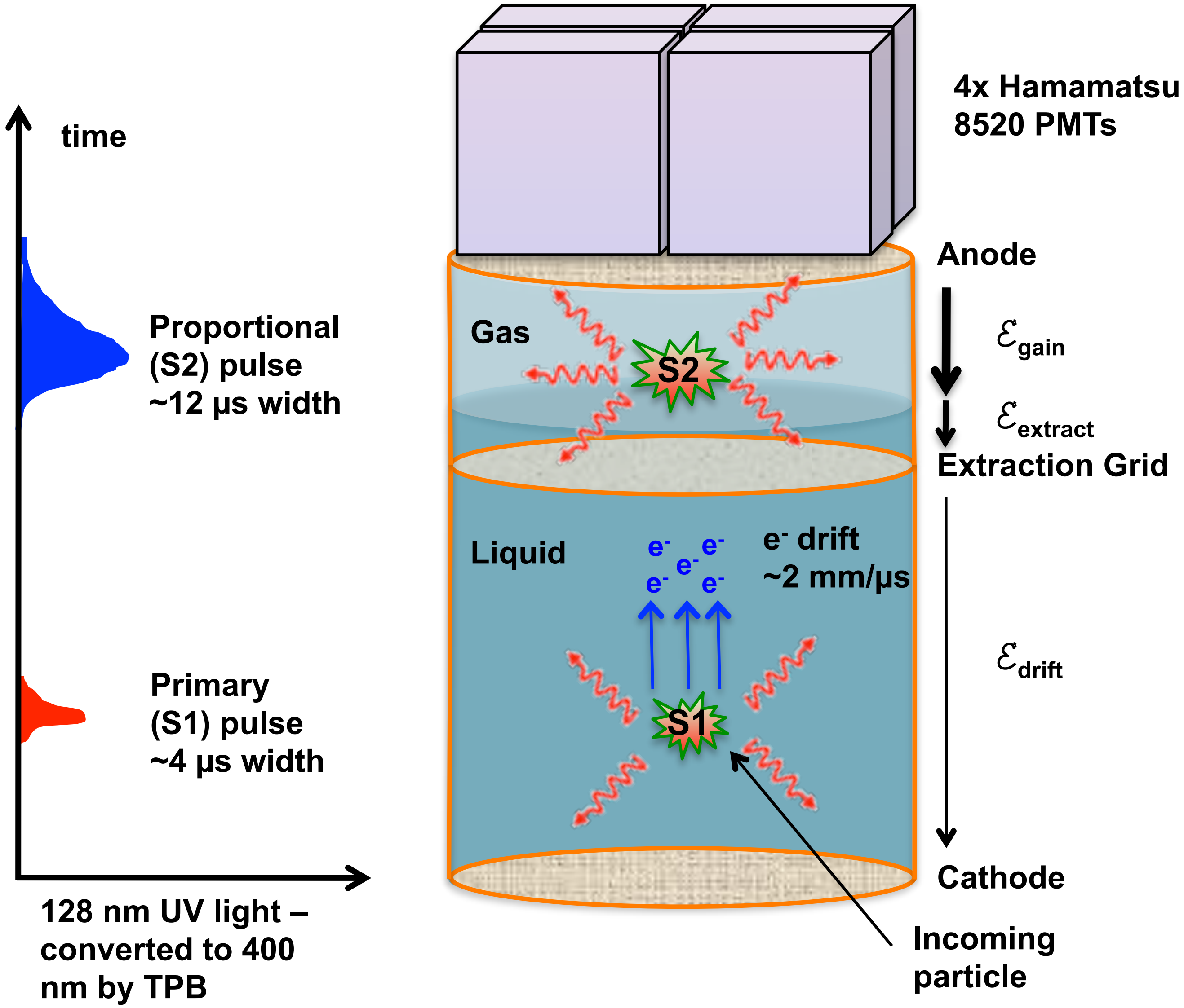
The key challenge is detecting low-energy nuclear recoils!



Akimov et al., Science 357, 1123 (2017)

- CEvNS was detected for the first time in 2017 in an accelerator experiment at the ORNL Spallation Neutron Source
- Detection medium: ~15 kg of CsI(Na)
- Powerful background determination due to time structure of accelerator signal
- Such time structure is not available for relevant nonproliferation use cases

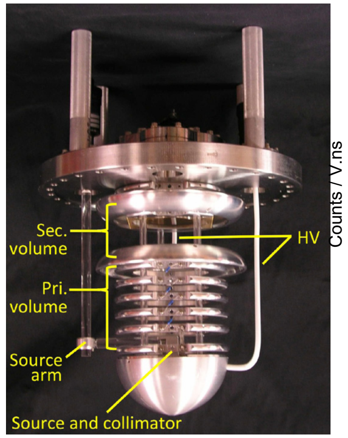
Noble element detection

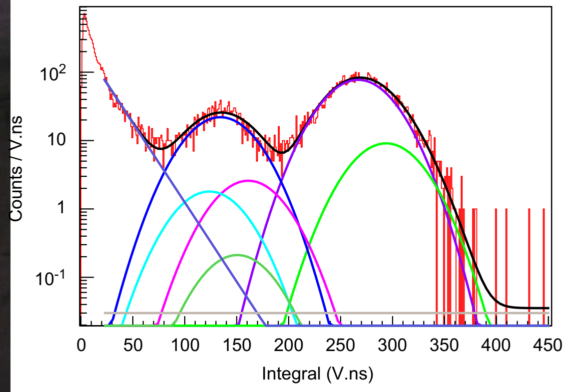


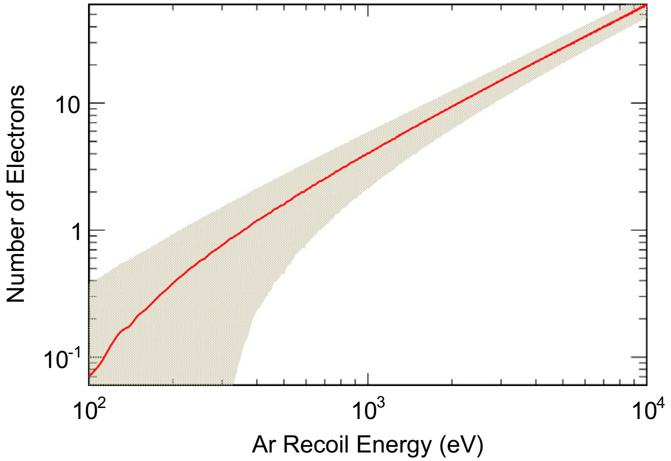
- Scalable target mass in liquid phase
- Wavelength shifting from 128 nm primary Ar scintillation
- Primary scintillation (S1) not detectable for low-energy nuclear recoils
- High efficiency for electron transport; position sensitivity in time projection chamber
- High electron extraction efficiency into gas phase
- Secondary scintillation (S2) proportional to electron yield
- Low-energy nuclear recoil yield (quenching) has been unknown

Past results

Detector construction, operation, and simulation

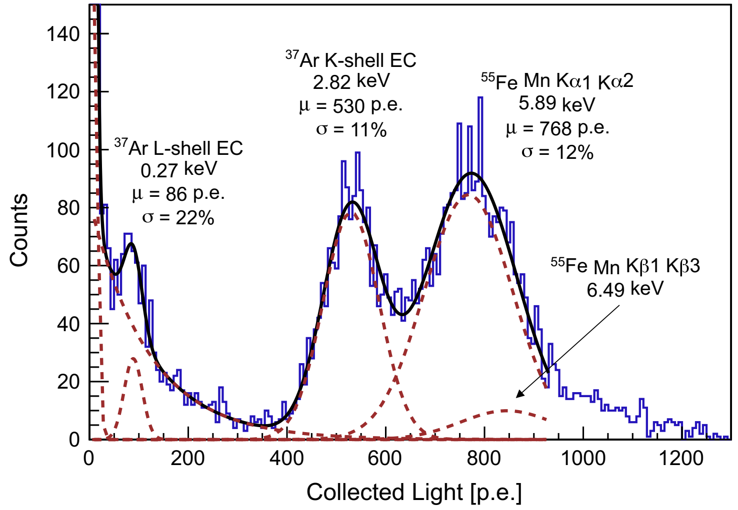


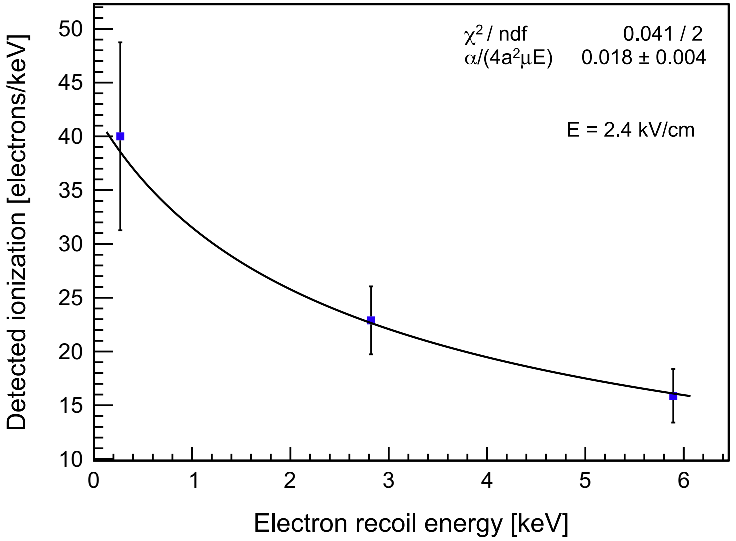




K. Kazkaz et al., NIM A 621, 267 (2010)
M. Foxe et al., Astropart. Phys. 69, 24 (2015)

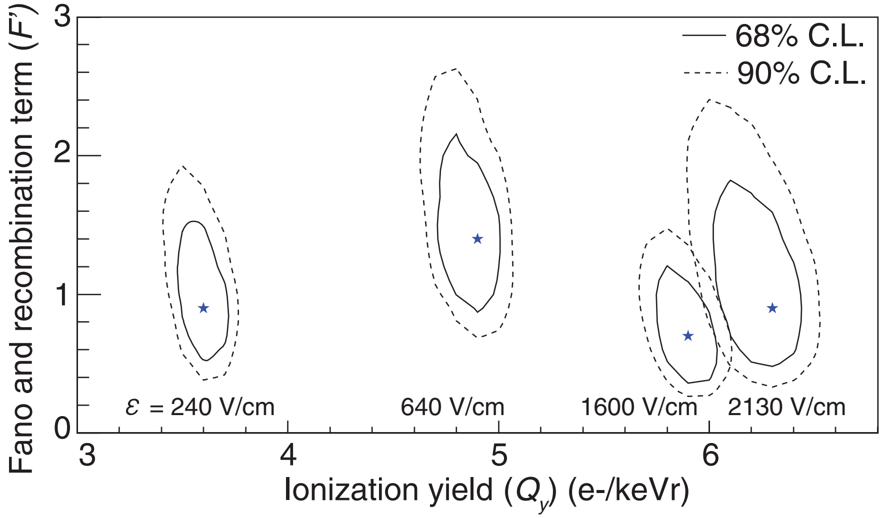
Electron ionization yield in LAr <1 keV

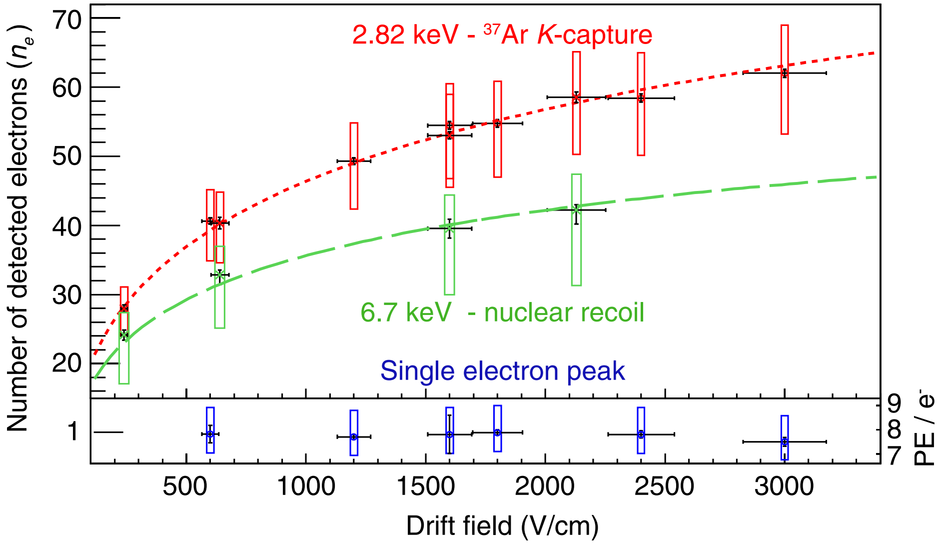




S. Sangiorgio et al., NIM A 728, 69 (2013)

Nuclear ionization yield in LAr at 6.7 keV

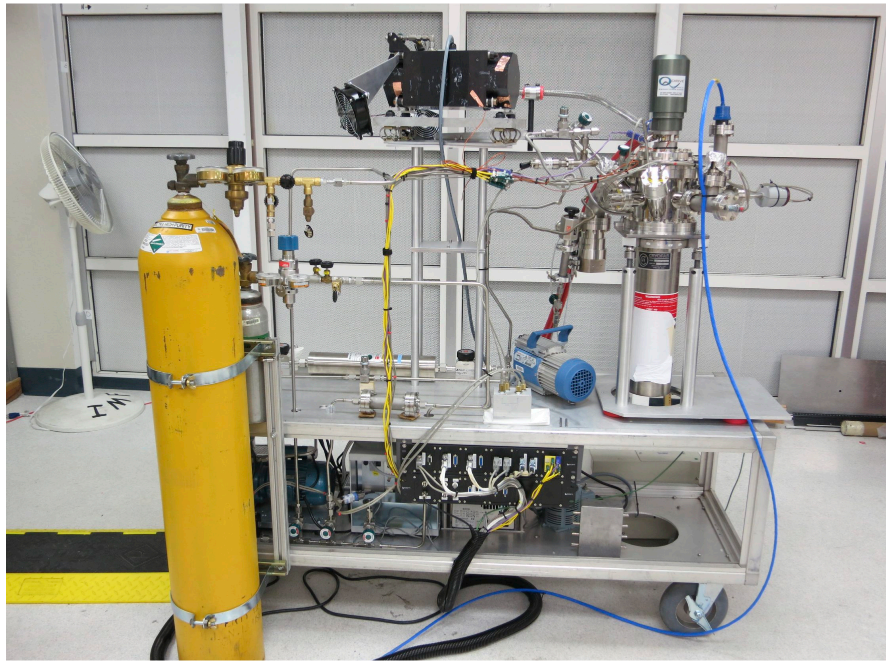




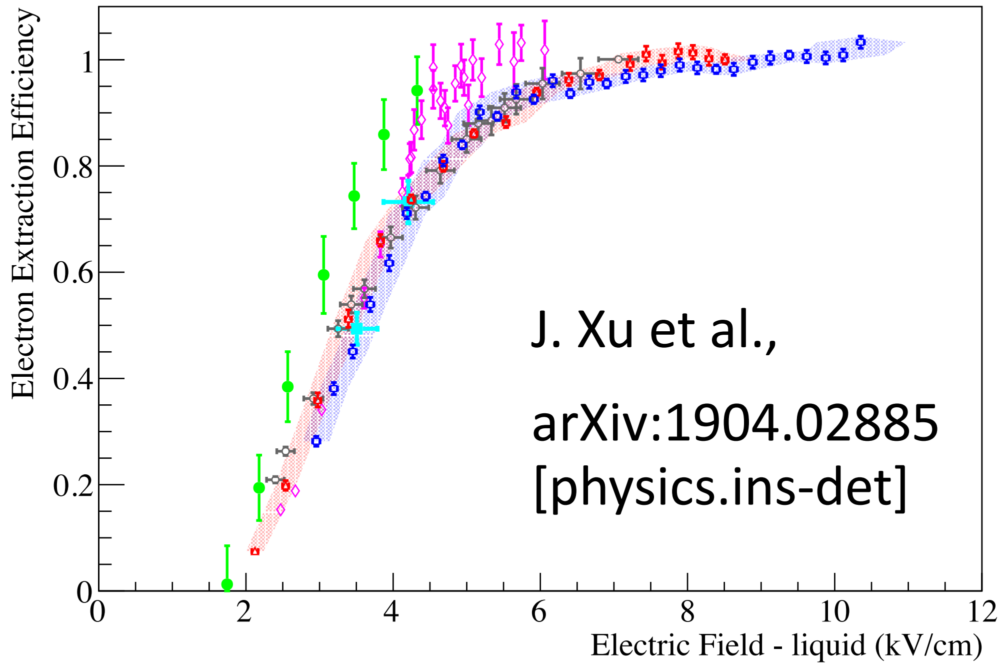
T. H. Joshi et al., PRL 112, 171303 (2014)

Technical Work Plan

- Over the 5-year period, this project will help to advance the noble element detector technology towards CEvNS demonstration at a nuclear reactor
- Major tasks:
  - Explore the reduction of background by complete electron extraction from LXe
  - Measure and maximize the electron extraction efficiency from LAr
  - Measure the LAr and LXe ionization yield at low energies consistent with reactor antineutrino CEvNS
  - Explore an opportunity to deploy a demonstration experiment within the Advanced Instrumentation Testbed



Existing LAr detector testbed at LLNL

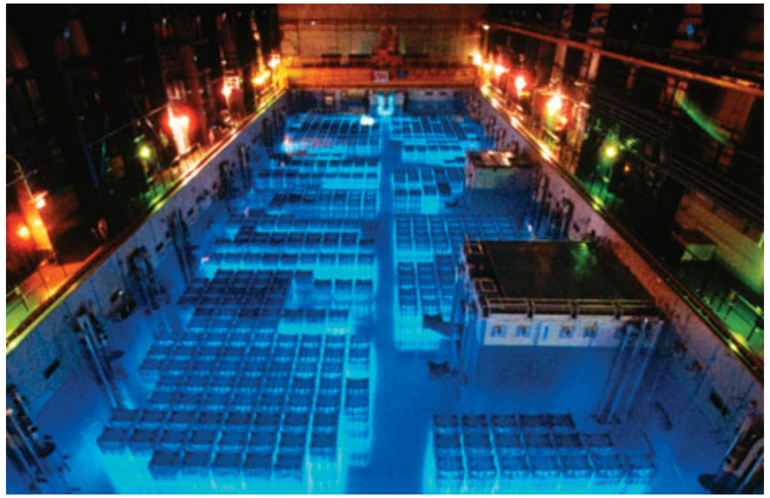


Expected Impact

Reduction of detector mass for reactor monitoring applications

- Reduction of detector mass/ volume by 2-3 orders of magnitude
- Compact deployment within the plant perimeter

Monitoring of spent fuel using antineutrinos



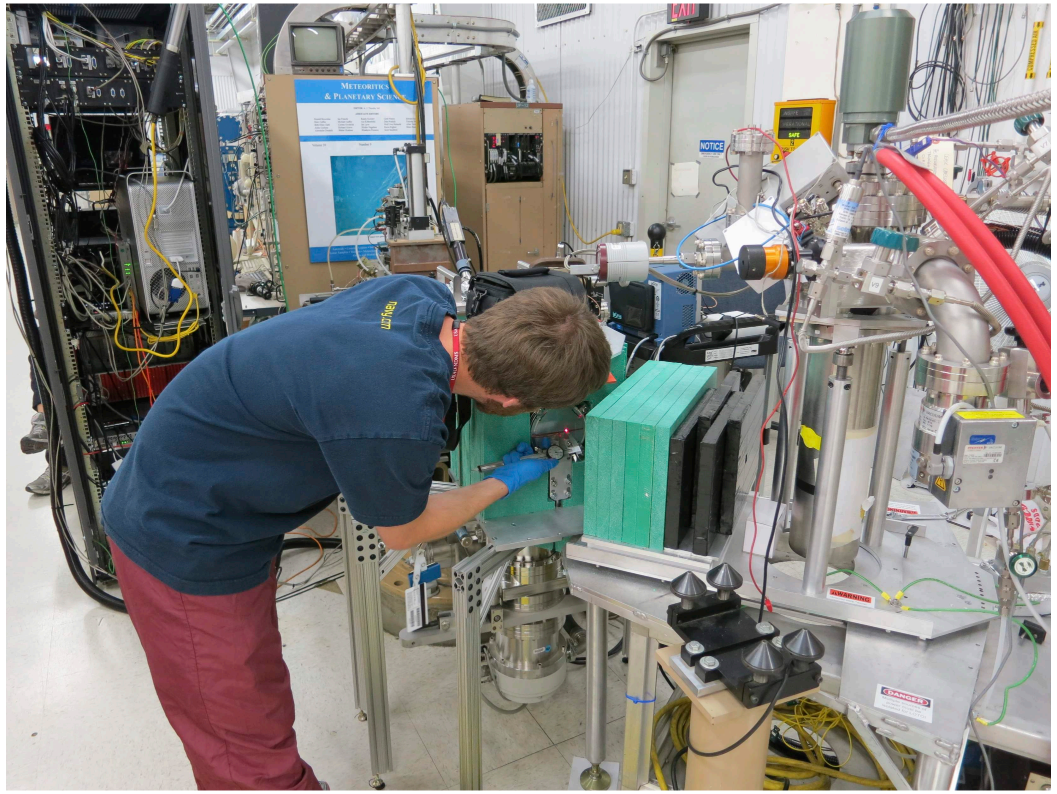
- Ability to monitor spent nuclear fuel over a longer period as the antineutrino spectrum softens

Fundamental science

- Neutrino transport in neutron stars and in stellar collapse
- Determination of background for WIMP searches

MTV Impact

- MTV provides a framework and support for collaboration with the Rare Event Detection Group at Lawrence Livermore National Laboratory
- Acceleration of advanced noble element R&D at national laboratories
- Support for participation in key technical meetings (Applied Antineutrino Workshop, IEEE Nuclear Science Symposium, SORMA)
- Student transition into national laboratory careers



Example of recent personnel impact:

Michael Foxe
Past PhD working on CEvNS using LAr
Current position: staff scientist at PNNL

National Nuclear Security Administration

UNIVERSITY OF MICHIGAN

Conclusion

- CEvNS is a method for neutrino detection that could contribute to nuclear safeguards, including reactor and spent fuel monitoring
- CEvNS has yet to be demonstrated using reactor antineutrinos
- CEvNS has the largest cross section, but significant R&D is needed to evaluate its performance when compared to inverse beta decay
- This research will leverage synergistic LLNL initiatives and prior collaborations on argon-based dual-phase detection
- There is a path to integrate future demonstrations with the Advanced Instrumentation Testbed

Acknowledgements

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