Experimental efforts and physics capabilities of Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

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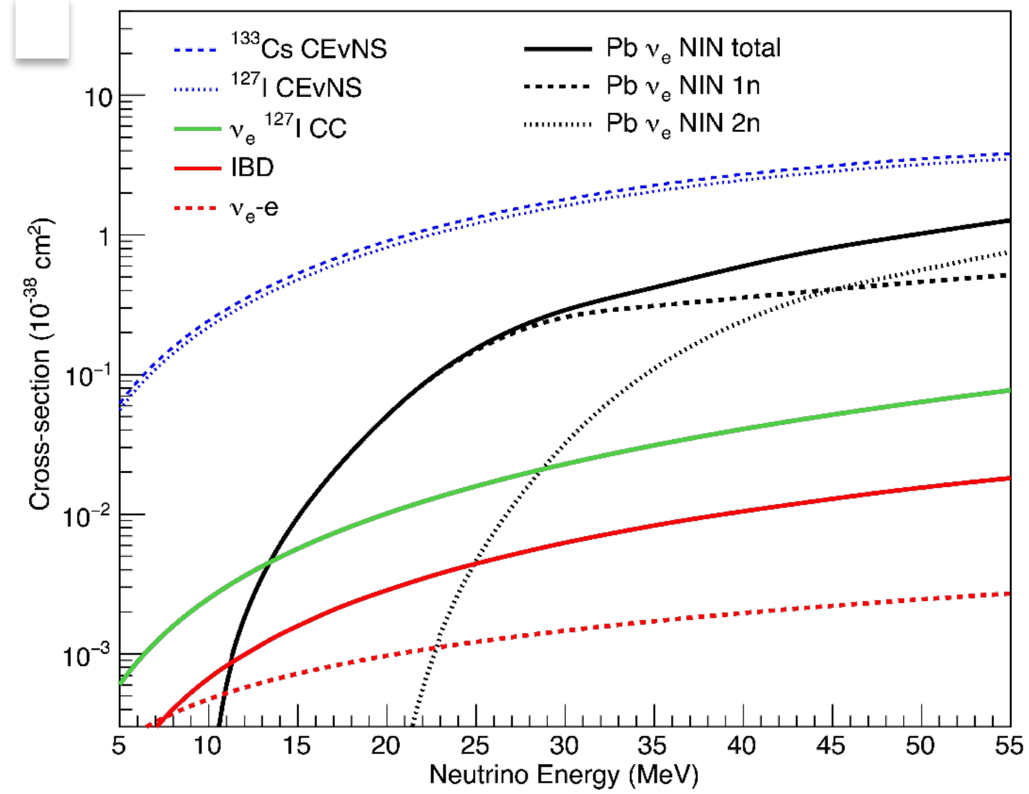
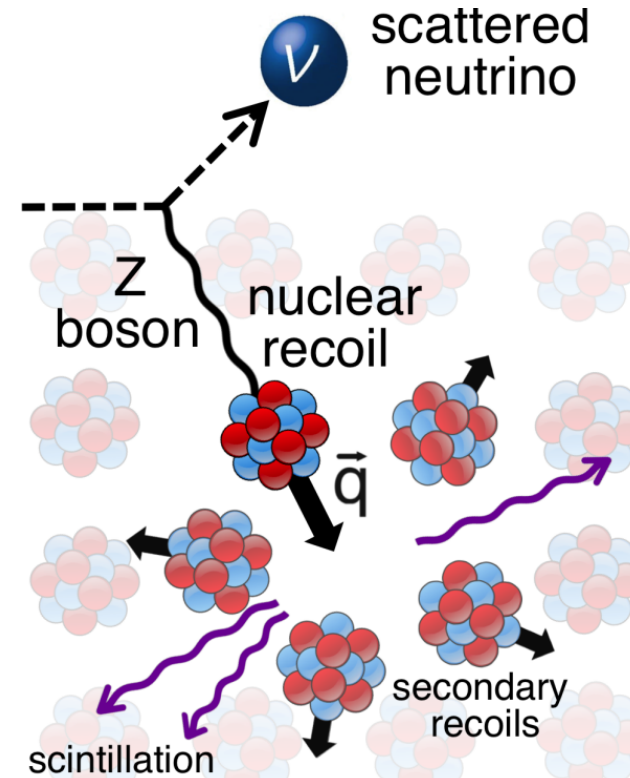
Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)

- Standard Model interaction
- First predicted by Freedman in 1974
- Neutrino interacts coherently with nucleons in target nucleus
  - Neutrino flavor blind, with no energy threshold!
- Signature is low-energy nuclear recoil
- Largest low-energy neutrino cross section on heavy nuclei
- Distinct N² dependence of cross section

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

- Searches ongoing using both stopped-pion and reactor neutrino sources



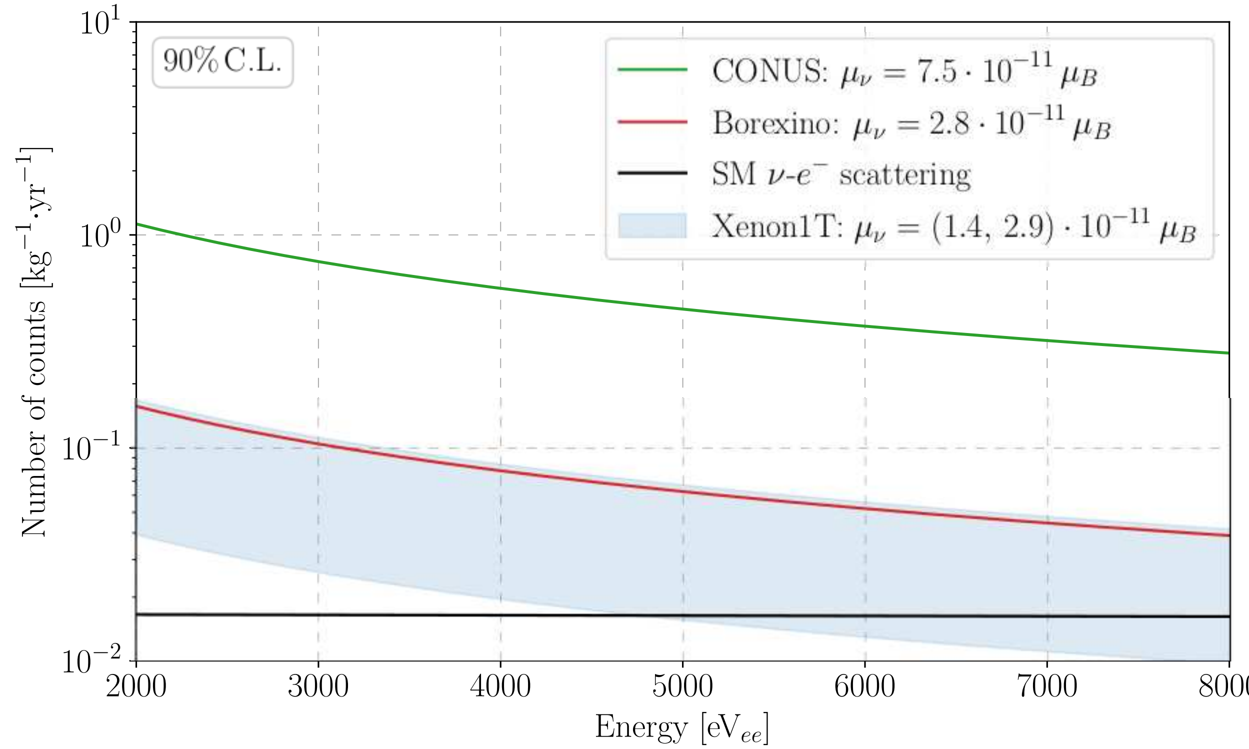


D. Akimov et al. (COHERENT). Science 357, 1123-1126 (2017)

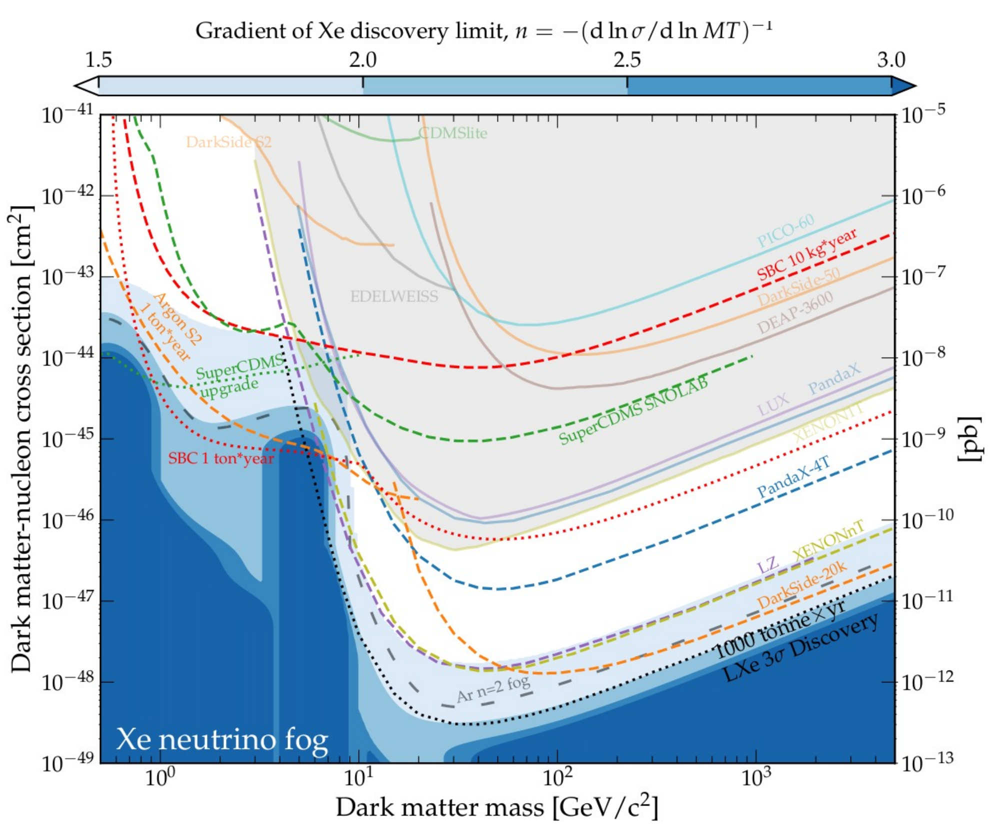
Physics Motivation for CEvNS Searches

Physics Motivation for CEvNS

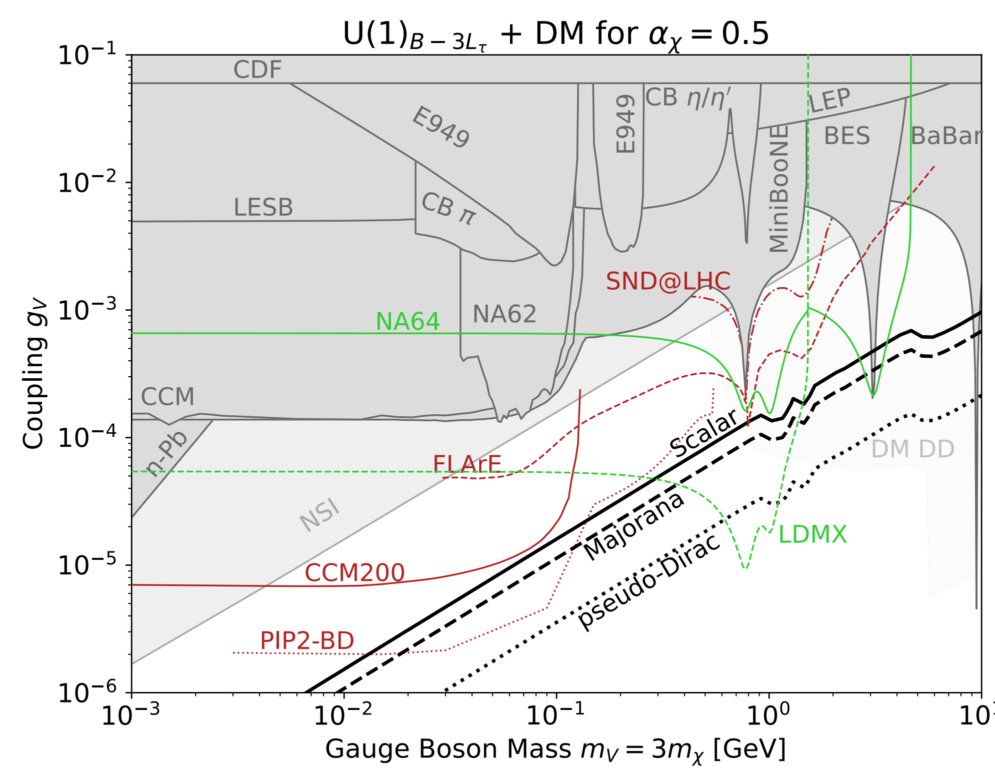
- CEvNS is Standard Model process, opens doors for new physics searches
  - Neutrino magnetic moment, non-standard interactions, etc.
- Dark matter and dark sectors
  - “Neutrino fog” for dark matter direct detection experiments



H. Bonet et al. (CONUS), arXiv:2201.12257[nucl-ex]



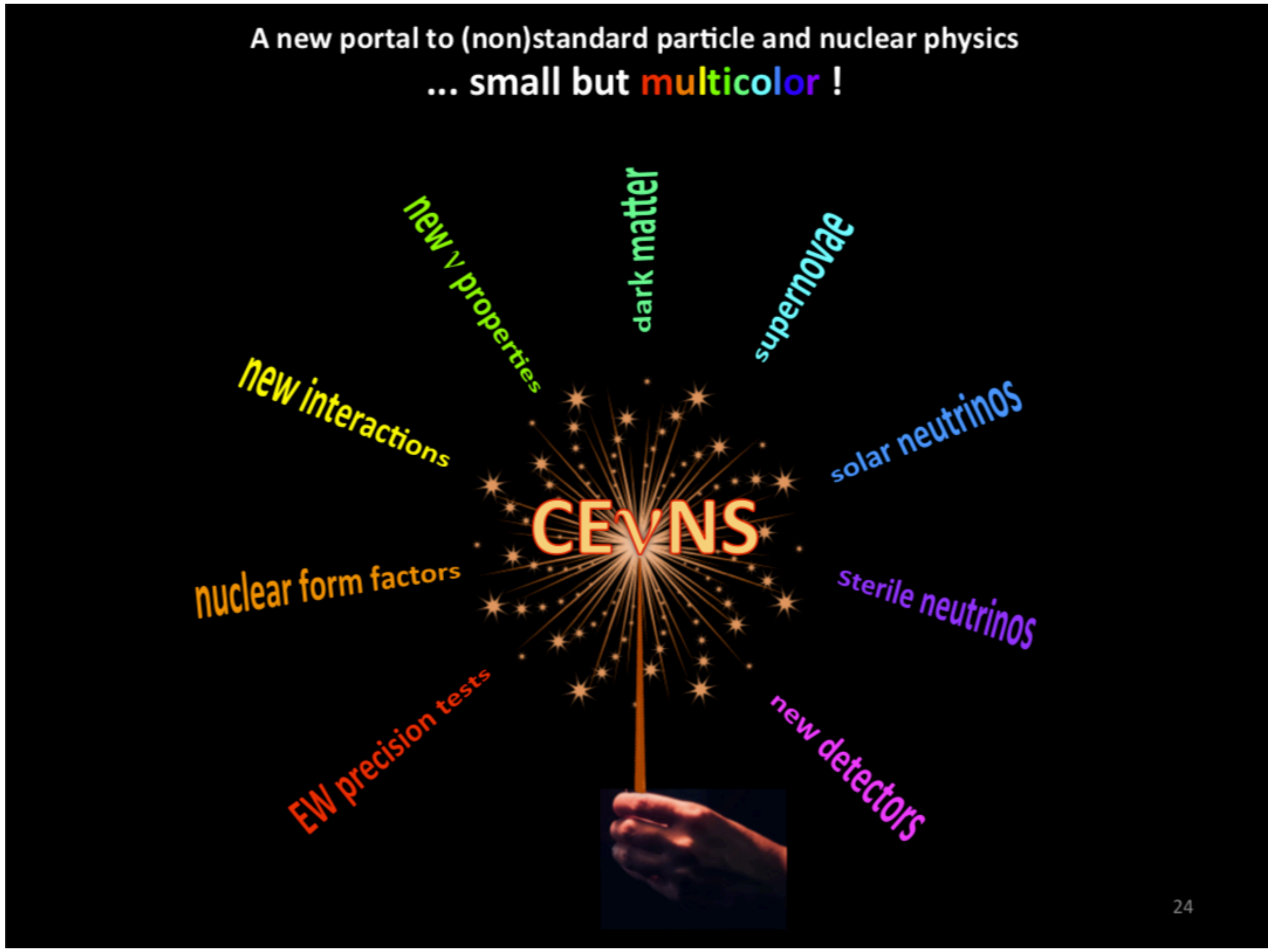
D. S. Akerib et al.,arXiv:2203.08084



G. Krnjaic et al, arXiv:2207.00597[hep-ph]

Physics Motivation for CEvNS

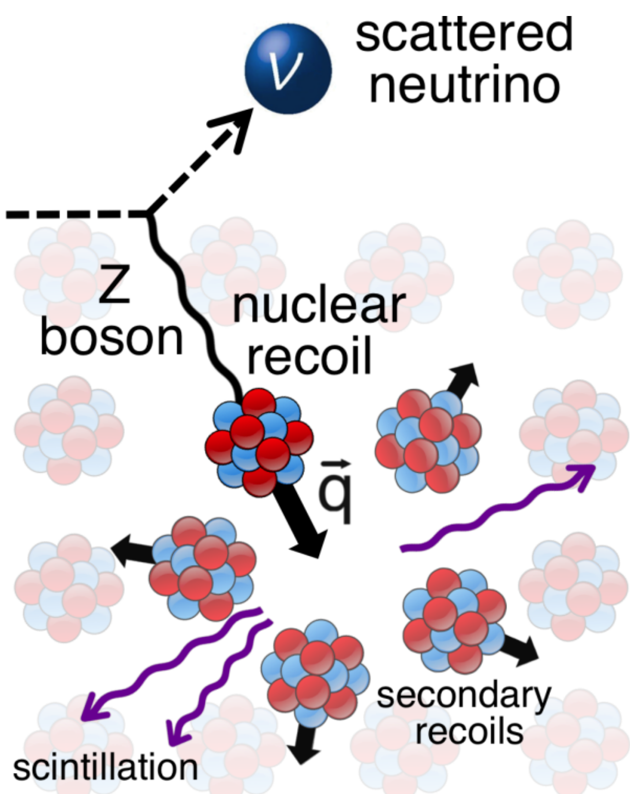
- Supernova neutrino detection
- Reactor antineutrino detection and nuclear nonproliferation
- Light sterile neutrinos
- Nuclear form factors
- Nuclear physics measurements

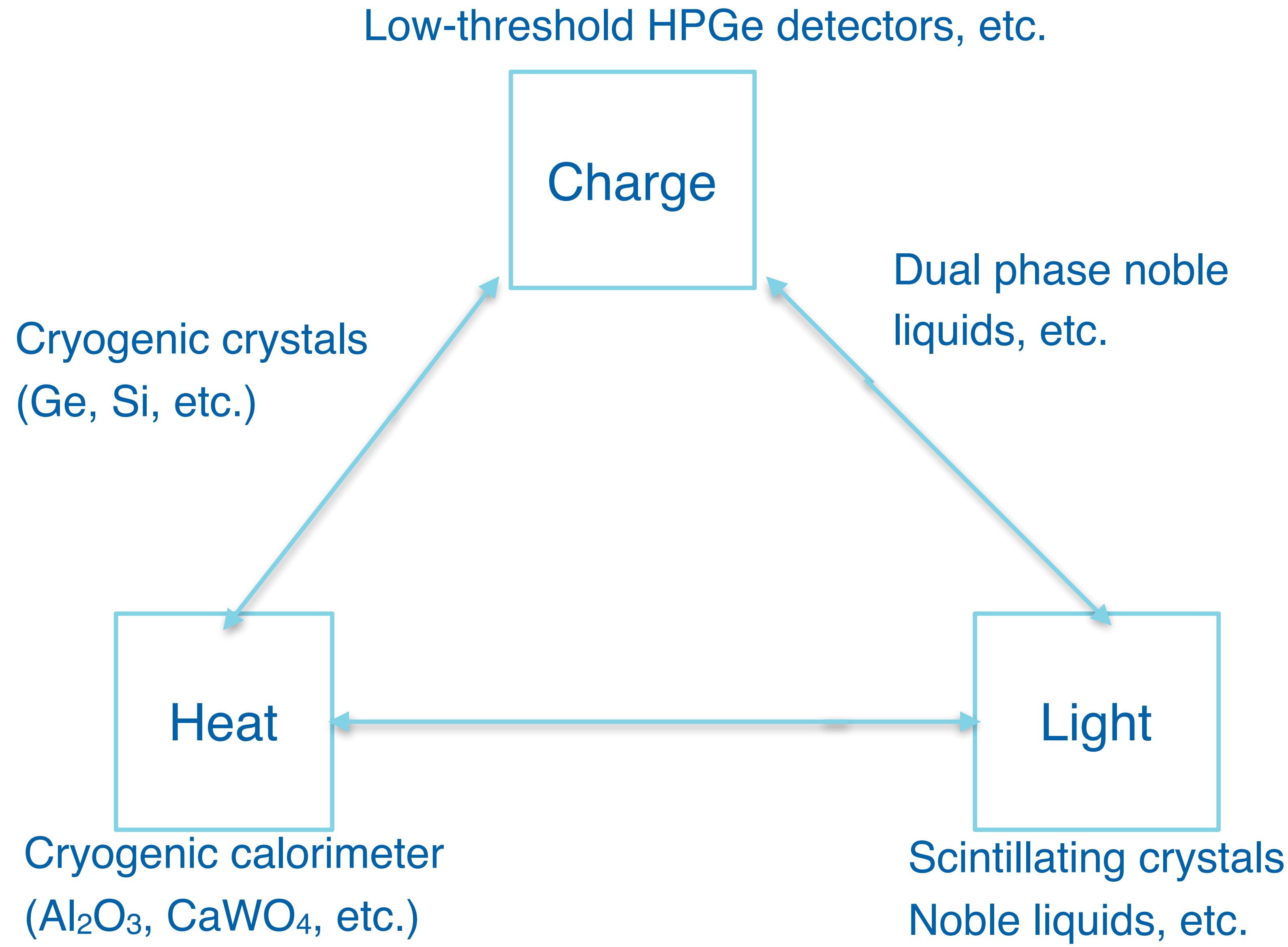


E. Lisi, NuINT 2018

Detecting CEvNS

Detecting CEvNS

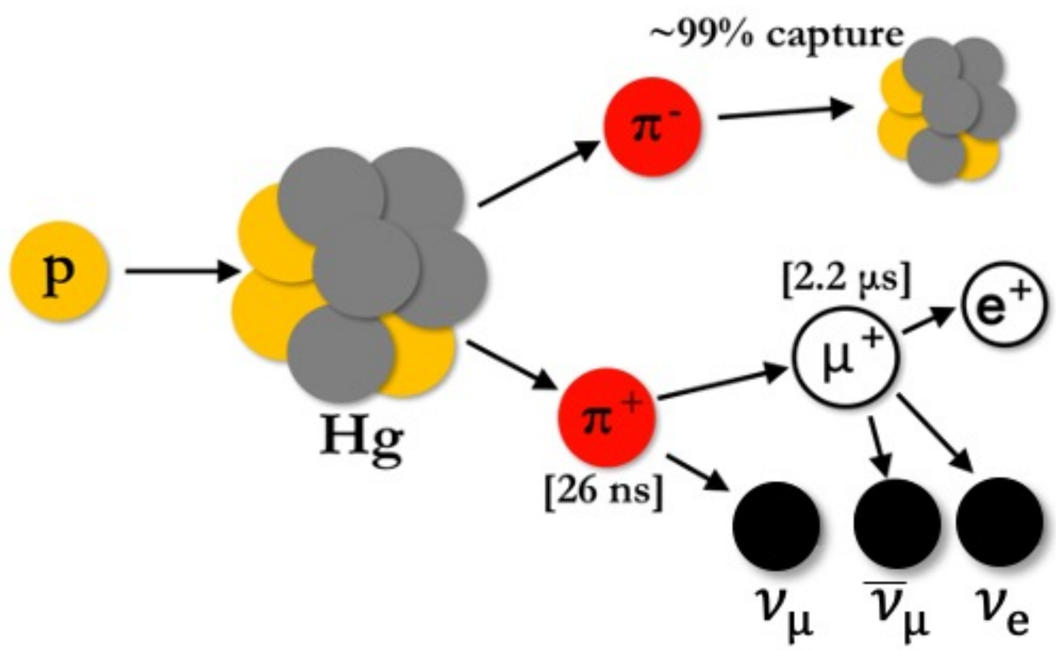




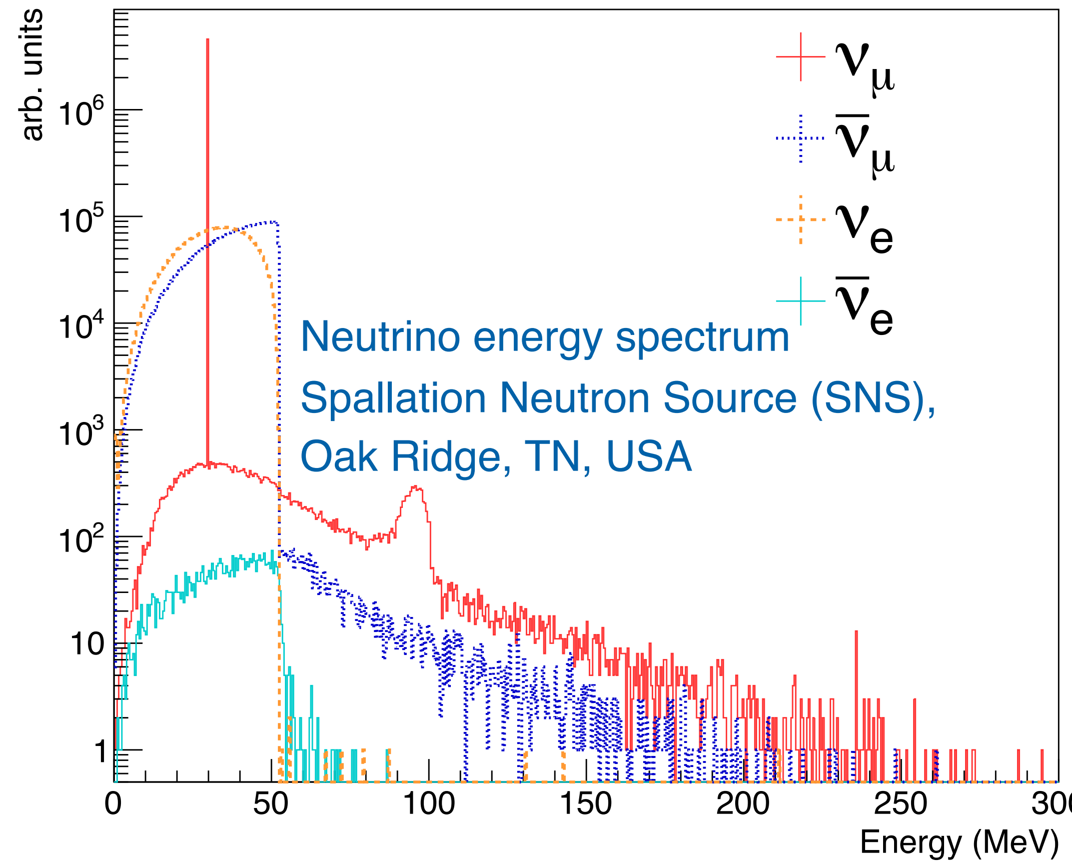
- Large CEvNS cross section allows for small detectors to measure neutrinos
  - Improvements come in larger mass (i.e. for noble liquid detectors) or lower energy thresholds (i.e. for cryogenic bolometers)
- Maximum nuclear recoil energy $T_{max} \sim E^2_{nu}/M$
- Understanding quenching factor = E_{meas}/E_{nr} is important

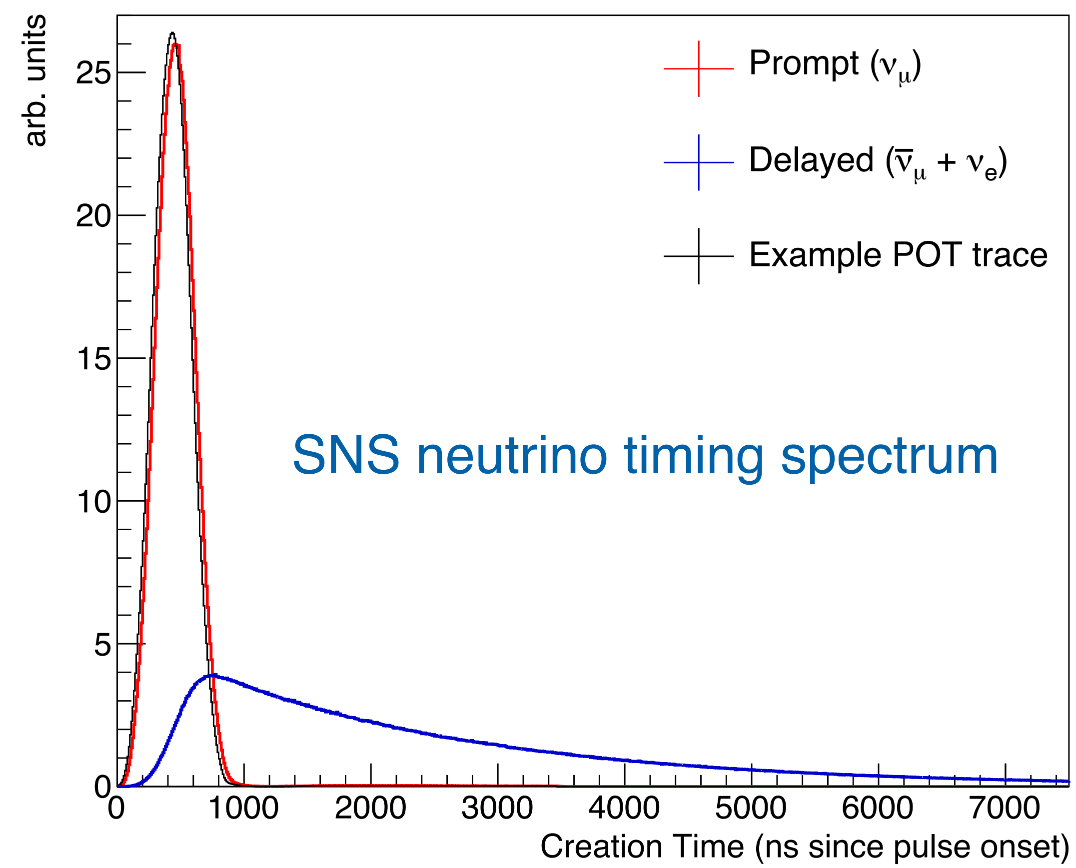
Searches for CEvNS at Stopped-pion Sources

Stopped-Pion Neutrino Sources



- Neutrinos produced from pion decay-at-rest via proton collisions with target
- Neutrino flux O(10^7)/cm^2/s at ~1 MW and 20 m from source
- Neutrino energy < 53 MeV relevant for CEvNS interaction
- Steady-state background suppression via pulsed beam

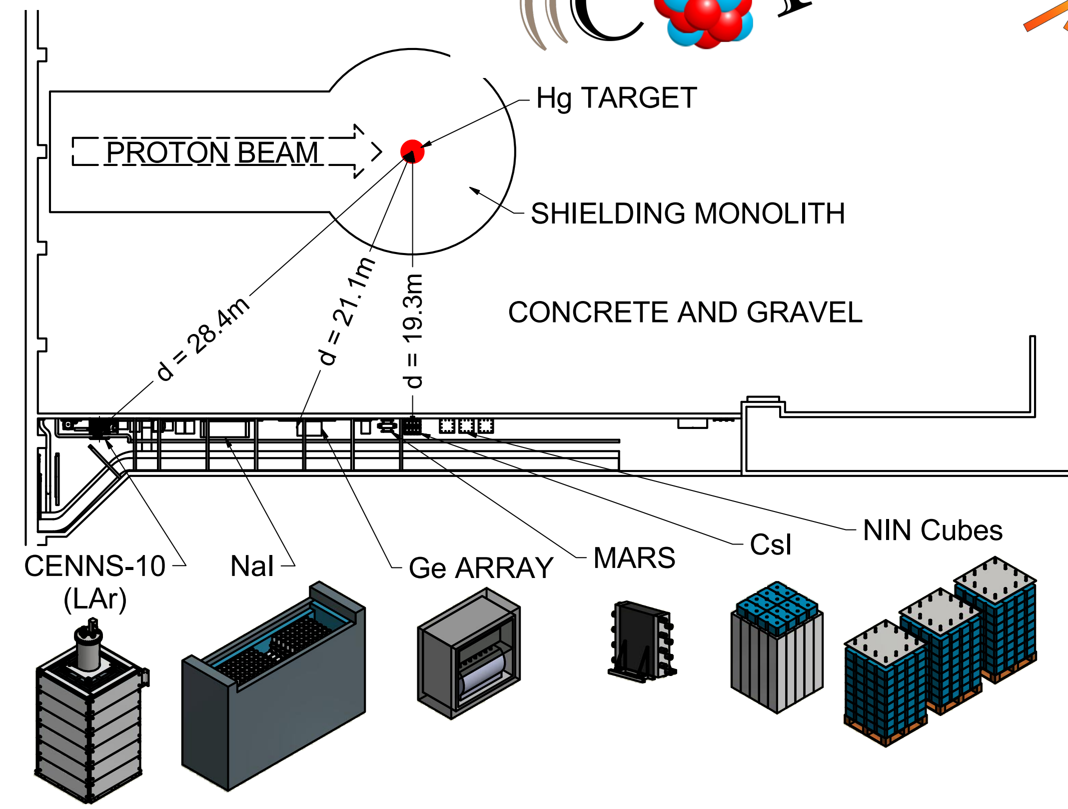




D. Akimov et al. (COHERENT) Phys. Rev. D (2022) 3, 032003

The COHERENT Experiment

- Using pulsed beam at the SNS
- 1.4 MW beam power
- Detectors located in Neutrino Alley at the SNS
- First phase goal to measure CEvNS with multiple detector technologies to test N^2 dependence

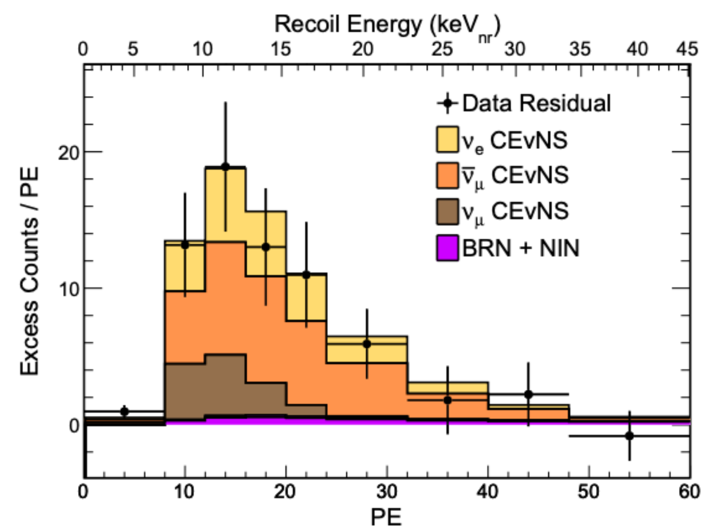


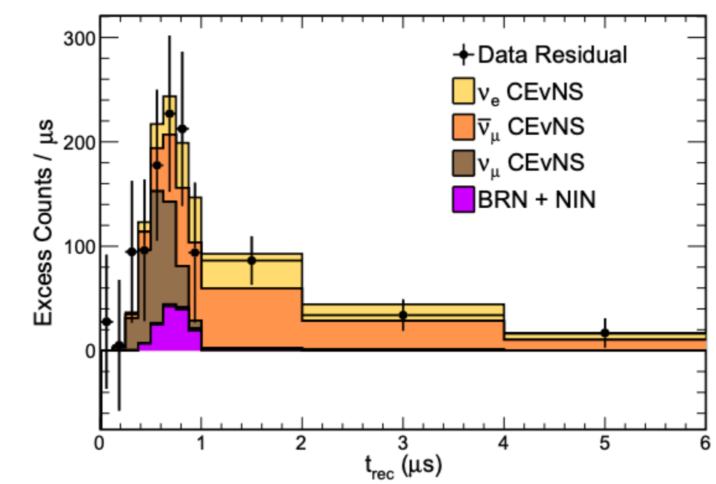
Target Nucleus	Det. Technology	mass (kg)	nuc. recoil threshold (keV)	Deployment
CsI	Scintillating Crystal	14	5	2015-2019
Ar	Single-phase Noble Liquid	24	20	2017-2021
NaI[Tl]	Scintillating Crystal	2500	13	2022
Ge	HPGe PPC	18	<5	2022
Ar	Single-phase Noble Liquid	750	20	2025
Ge	HPGe PPC	50	<5	2025
CsI	Cryogenic CsI	~ 10	1.4	2025

- Additional measurements planned for neutrino flux (D_2O), neutrino induced neutrons (Pb, Fe cubes), neutrino-induced fission (NuThor), and inelastic interactions on Ar

The COHERENT Experiment - First Light

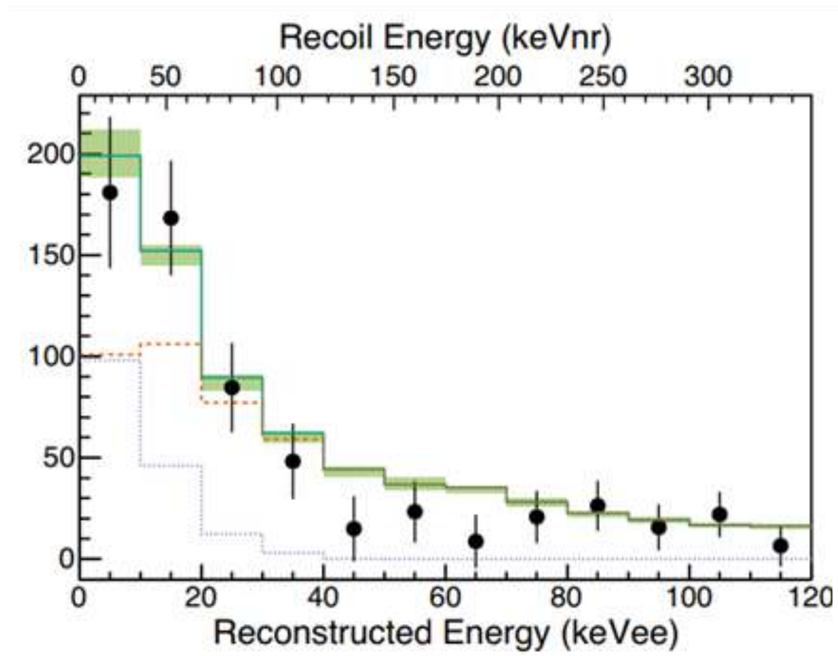
- 2017: Discovery of CEvNS using scintillating CsI[Na] crystal
  - 1.5 years of data, 5 keVnr threshold
  - 6.7σ measurement of CEvNS over null hypothesis
    - Result consistent with Standard Model
  - Updated results in 2022

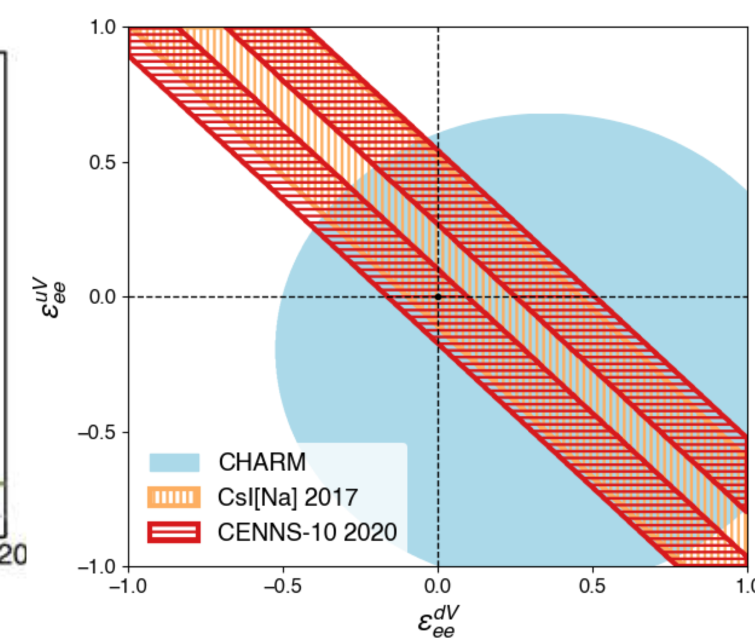




D. Akimov et al. (COHERENT) Science 357 (2017)
D. Akimov et al. (COHERENT) Phys. Rev. Lett 129, 080101(2022)

- 2021: First detection of CEvNS using single-phase LAr detector
  - 1.5 years of data, 20 keVnr threshold
  - 3.5σ observation of CEvNS over null hypothesis
    - Consistent with Standard Model
  - Additional ~2 years of data available, analysis in progress





D. Akimov et al. (COHERENT) Phys. Rev. Lett 126, 012002 (2021)
JCZ, Ph.D. thesis, Indiana University, Bloomington (2020)

Future CEvNS Searches at Stopped-pion Sources

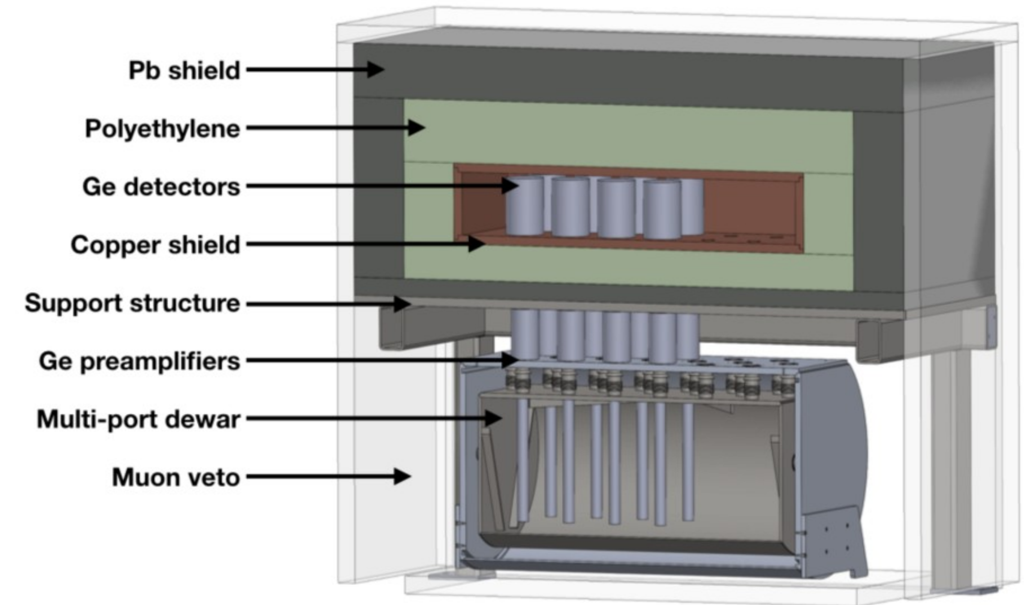
COHERENT Experiment - Near Future

- D_2O: Precise Measurement of the Neutrino Flux
  - Reduction of flux uncertainty from 10% to 2% in 5 years of running
  - First stage filled with light water installed and commissioning

D. Akimov et al. (COHERENT) JINST 16 (2021) 08, 08

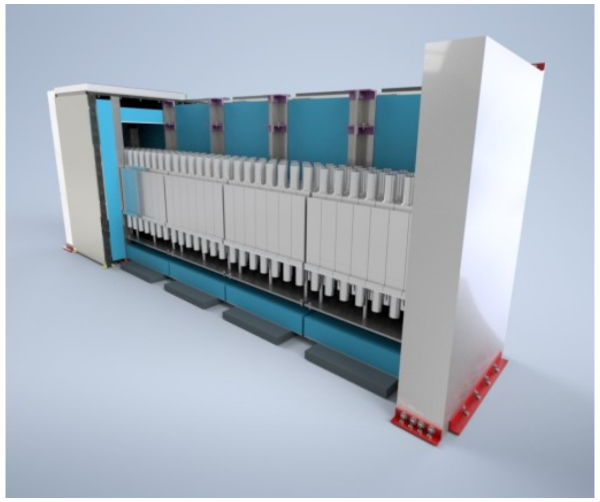
D_2O concept

- NaI[Tl] detectors
  - 185 kg of detectors installed in Neutrino Alley since 2016
  - Charged current interaction on I: $^{127}I(\nu_e,e^-)^{127}Xe$
  - Planned upgrade to 3.5 tons of detectors with CEvNS sensitivity
    - Installation ongoing



Ge-Mini detector concept

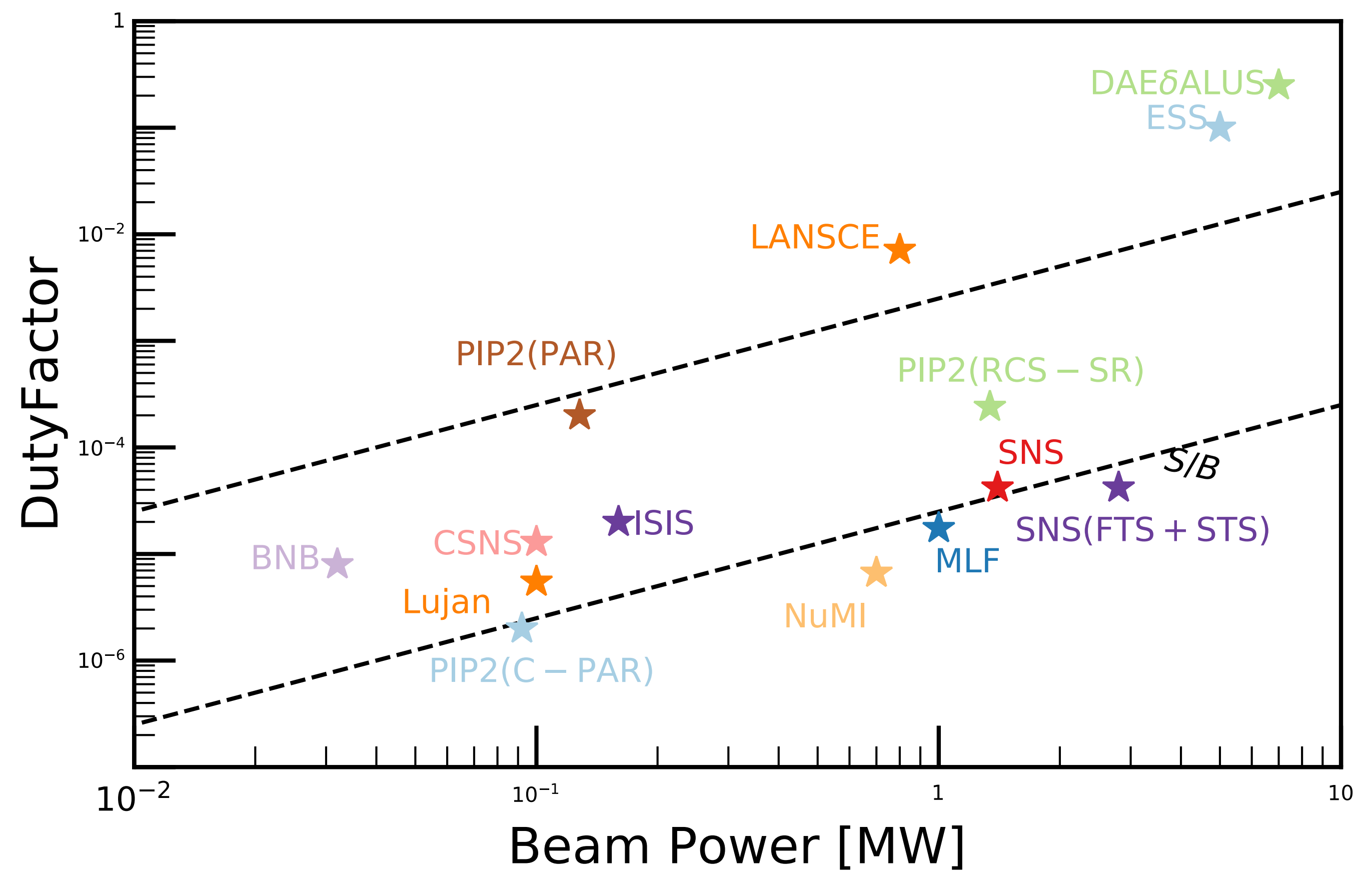
- HPGe detectors
  - 8 kg-scale Ge detectors, 18 kg total mass
  - Low energy threshold expected of <5 keV nuclear recoil energy
  - Installation ongoing



NaIvETE detector concept

Future Stopped-pion Sources for CEvNS Experiments

- Near-future Proton Power Upgrade at the SNS allow for more powerful source
  - Increase beam energy to 1.3 GeV and beam power to 2 MW
- SNS second target station (STS) ~2030, total beam power of 2.8 MW
- European Spallation Source, 2 MW by 2027
- Exploring possibility to couple upcoming PIP-II accelerator at Fermilab to accumulator ring to enable CEvNS detector program by the end of the decade

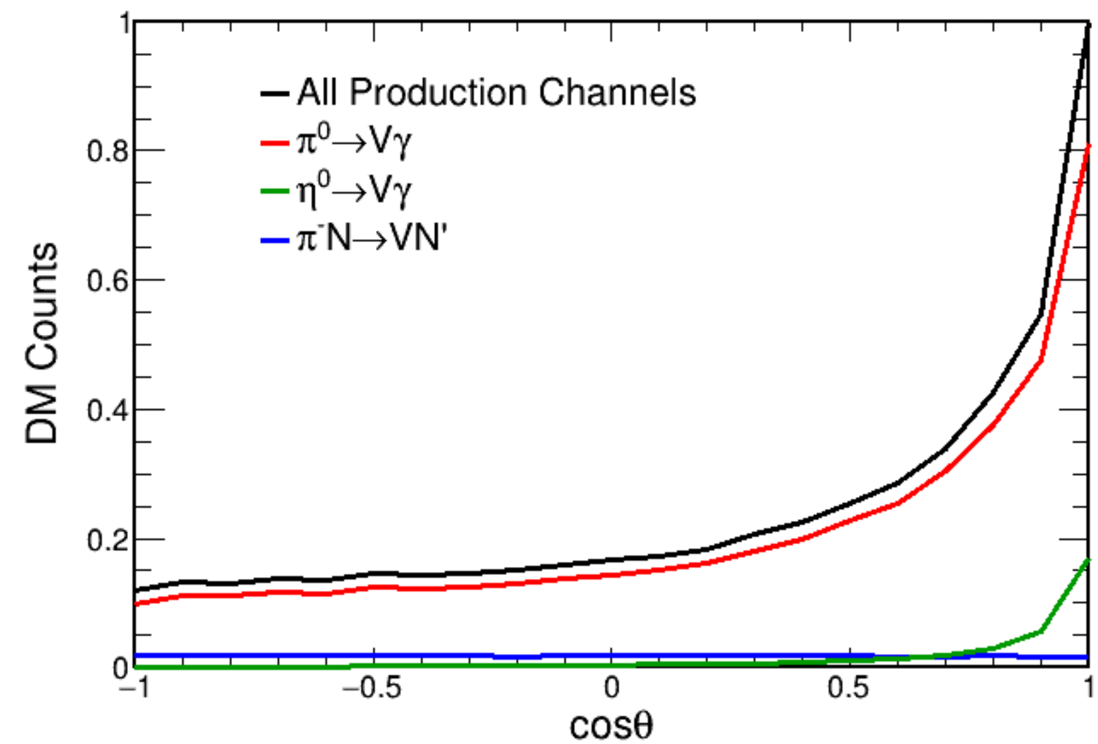


Adapted from JHEP 08 (2021) 087

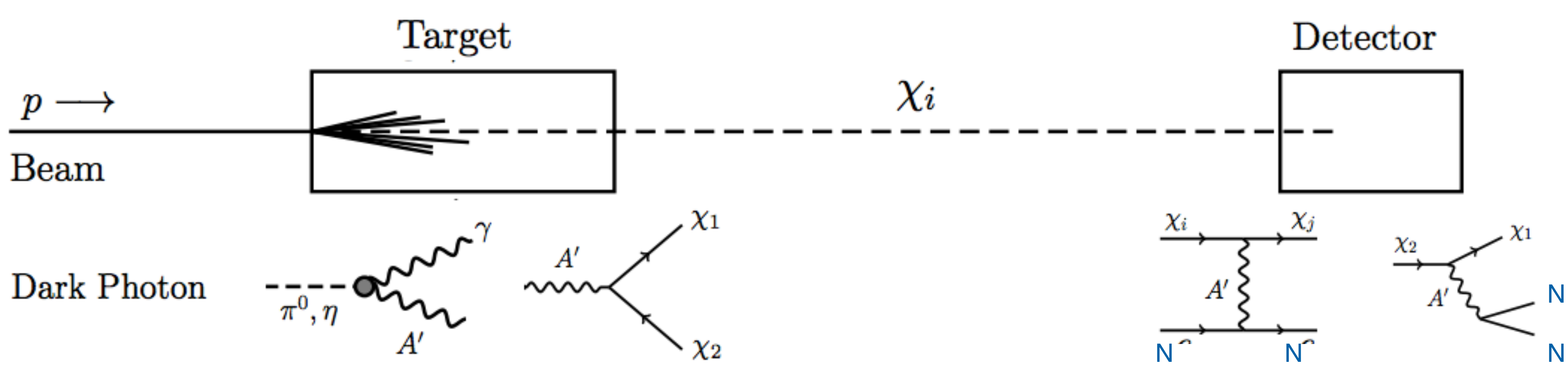
Connections to Accelerator-Produced Dark Sector Searches

Connections to Accelerator-based Dark Sector Searches

- Proton-target collisions produce dark sector mediators (V/A') between SM and dark sector (χ)
- Produced dark matter particles boosted towards forward direction
- Signature in detector is low-energy nuclear recoil



Phys. Rev. D 102 (2020) 5, 052007

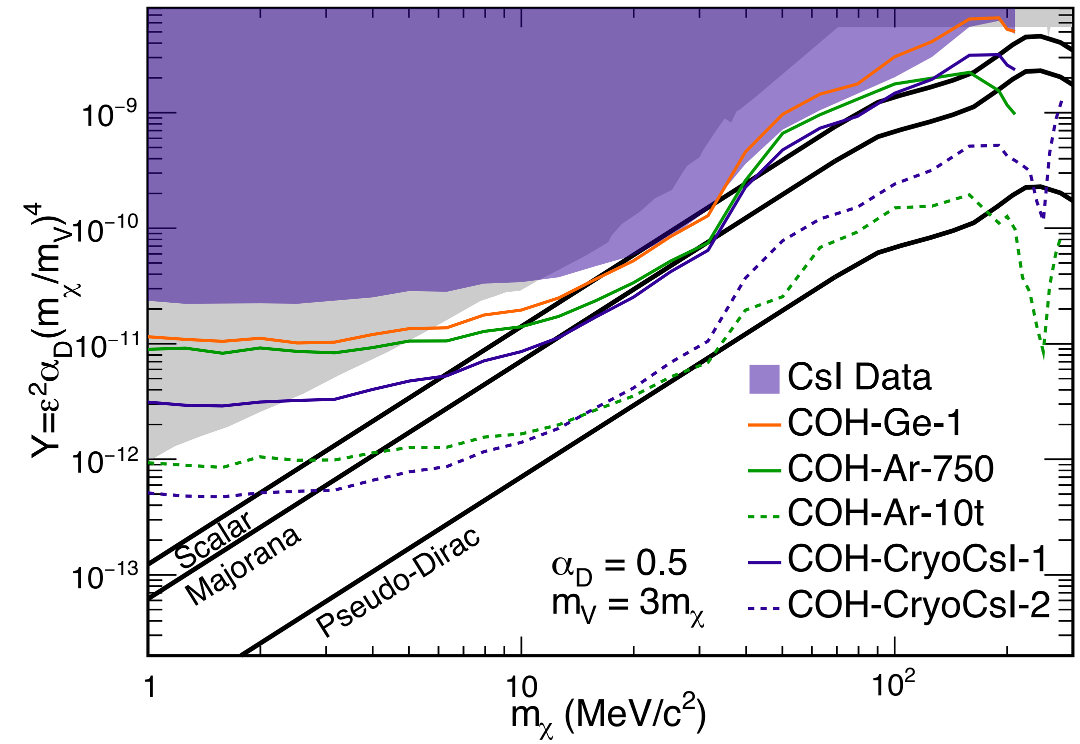


P. deNiverville et al., Phys. Rev. D 92 (2015) 095005

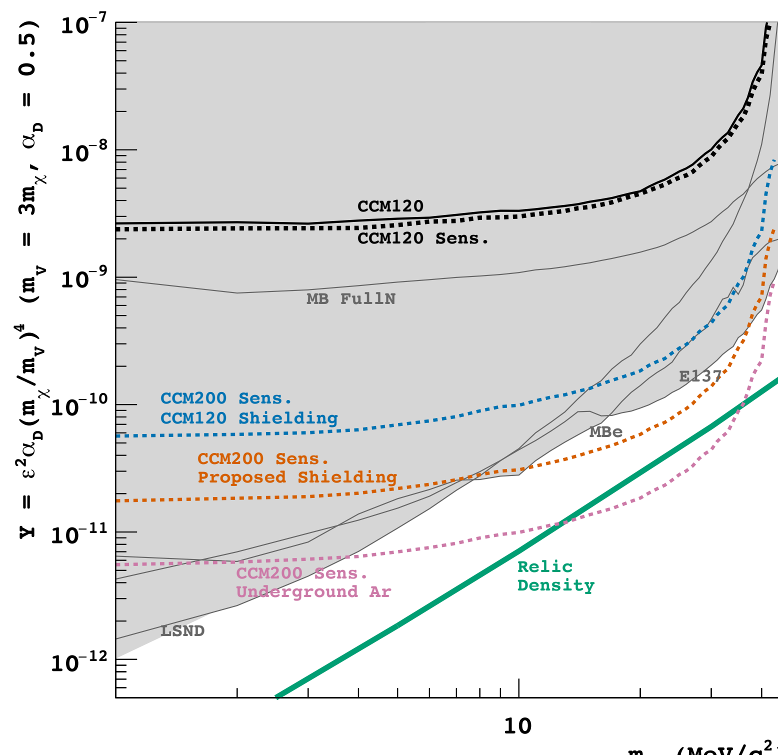
B. Dutta et al., Phys. Rev. Lett 124 (2020) 121802

Capabilities of CEvNS Detectors

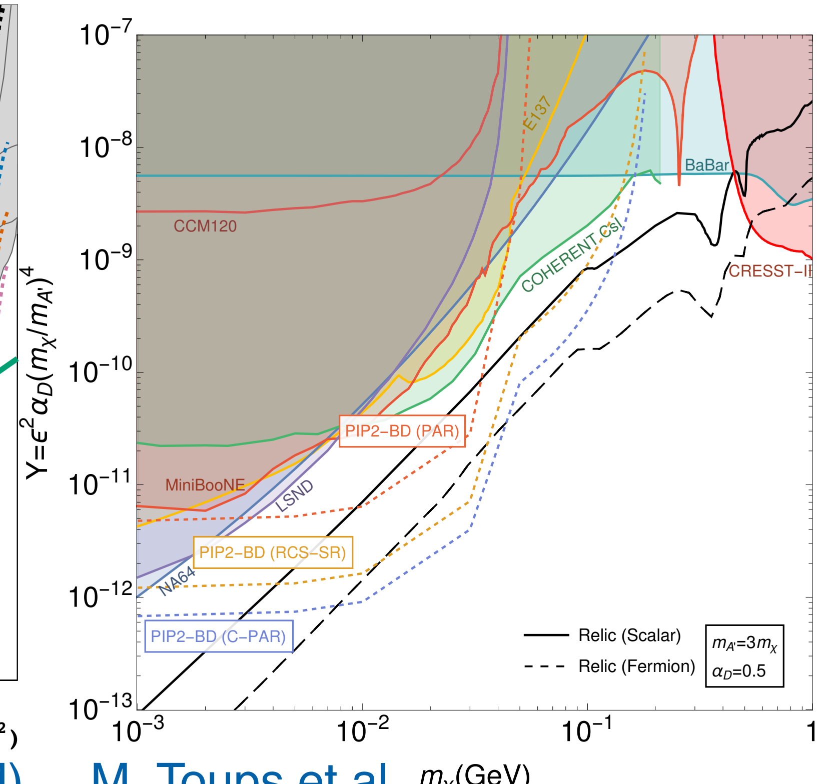
- CEvNS detectors place strong limits on a variety of accelerator-produced sub-GeV dark matter models
  - Including leptophobic, inelastic DM, and axion-like particle (ALP) models
- COHERENT recently set limits on vector-portal dark matter using latest CsI[Na] data
- Coherent Captain-Mills (CCM) set limits with ton-scale single-phase liquid argon detector at Lujan beam at Los Alamos National Laboratory
- Placing a 100-ton scale liquid argon detector at PIP-II at FNAL plus accumulator ring, PIP2-BD, sets very strong limits on accelerator-produced dark sector models



D. Akimov et al, (COHERENT) arXiv:2110.11453[hep-ex]



A. Aguilar-Arevalo et al. (CCM), arXiv:2105.14020

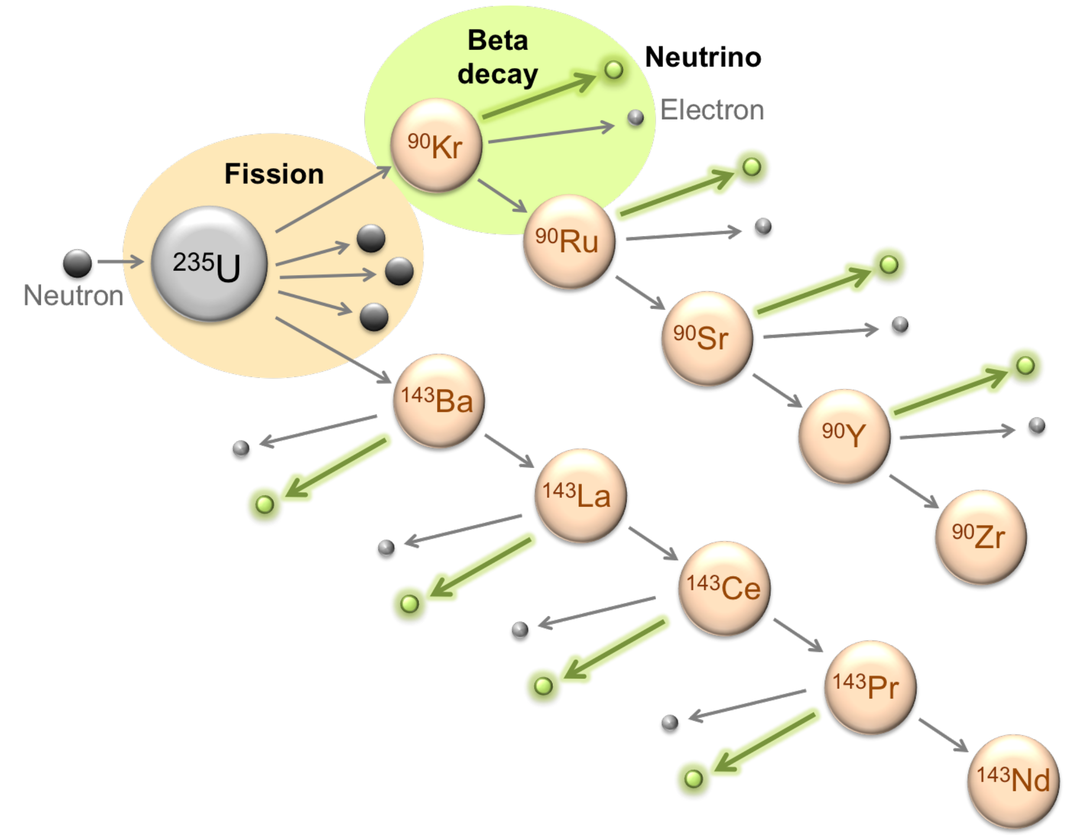


M. Toups et al., arXiv:2203.08079

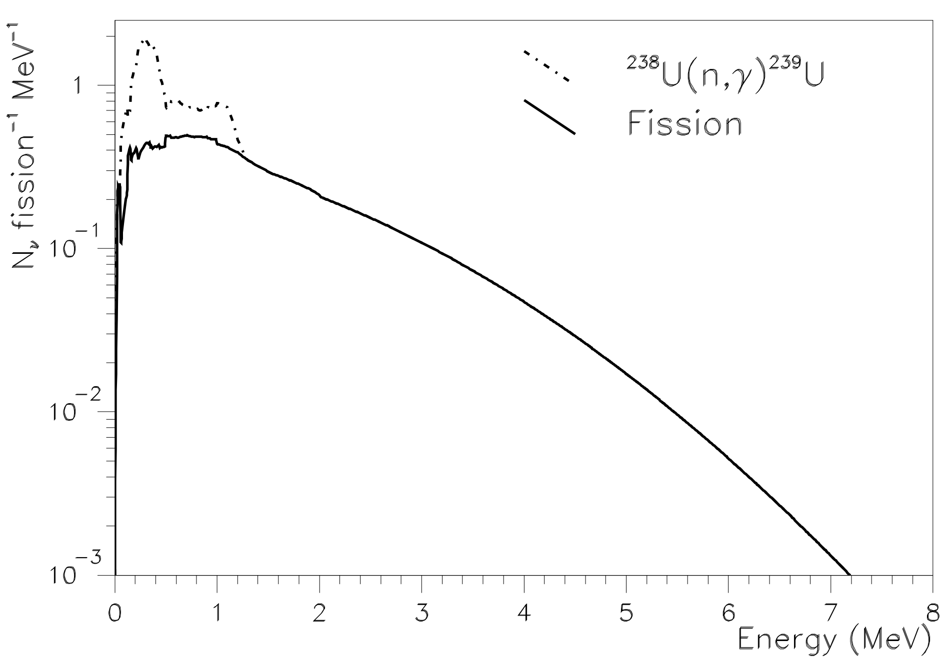
Searches for CEvNS at Reactor Neutrino Sources

Reactor Neutrino Sources

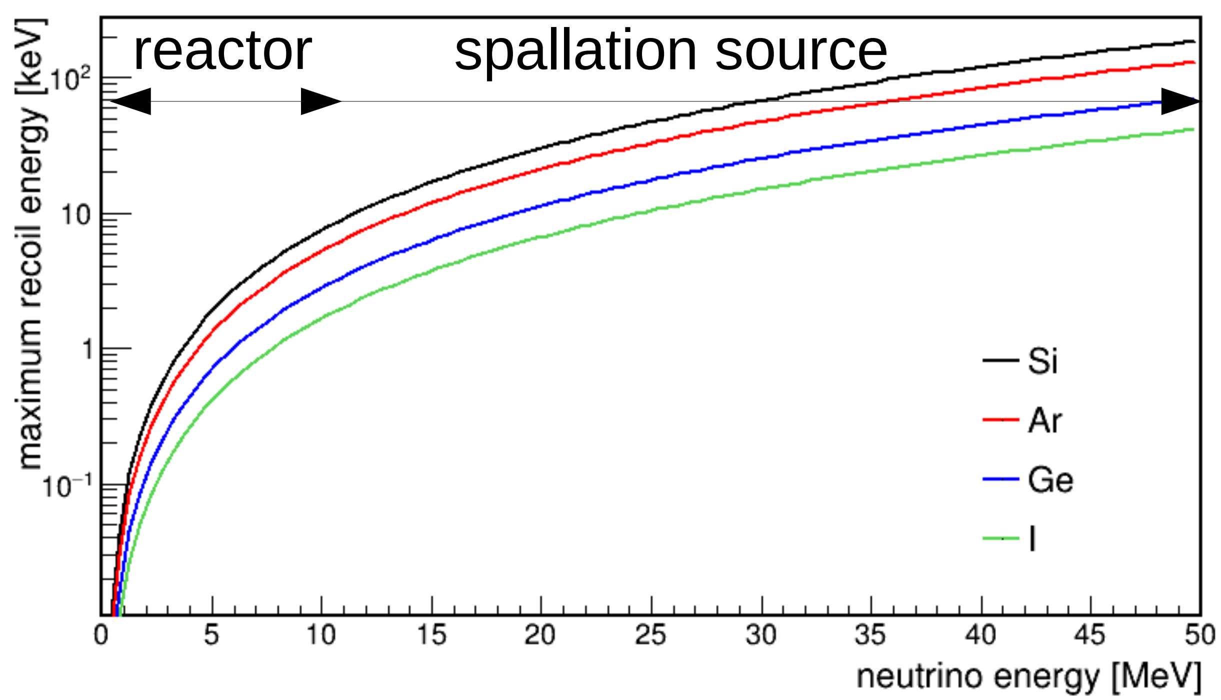
- Neutrinos produced from beta decay of fission isotopes
- Power values range from tens of MW at research reactors to several GW at commercial reactors
  - Antineutrino flux: 10^{12} - 5×10^{13}/cm^2/s at tens of meters from the reactor core
- CEvNS detection at reactors requires thresholds of O(100 eVnr)



Rev. Mod. Phys. 92 (2020) no.1, 011003



H.Y. Liao, et al. (TEXONO), J.Phys.G35:077001 (2008)



J. Hakenmuller, NDM 2022

Current Landscape of Reactor CEvNS Searches

Landscape of Reactor CEvNS Experiments

HPGe detectors

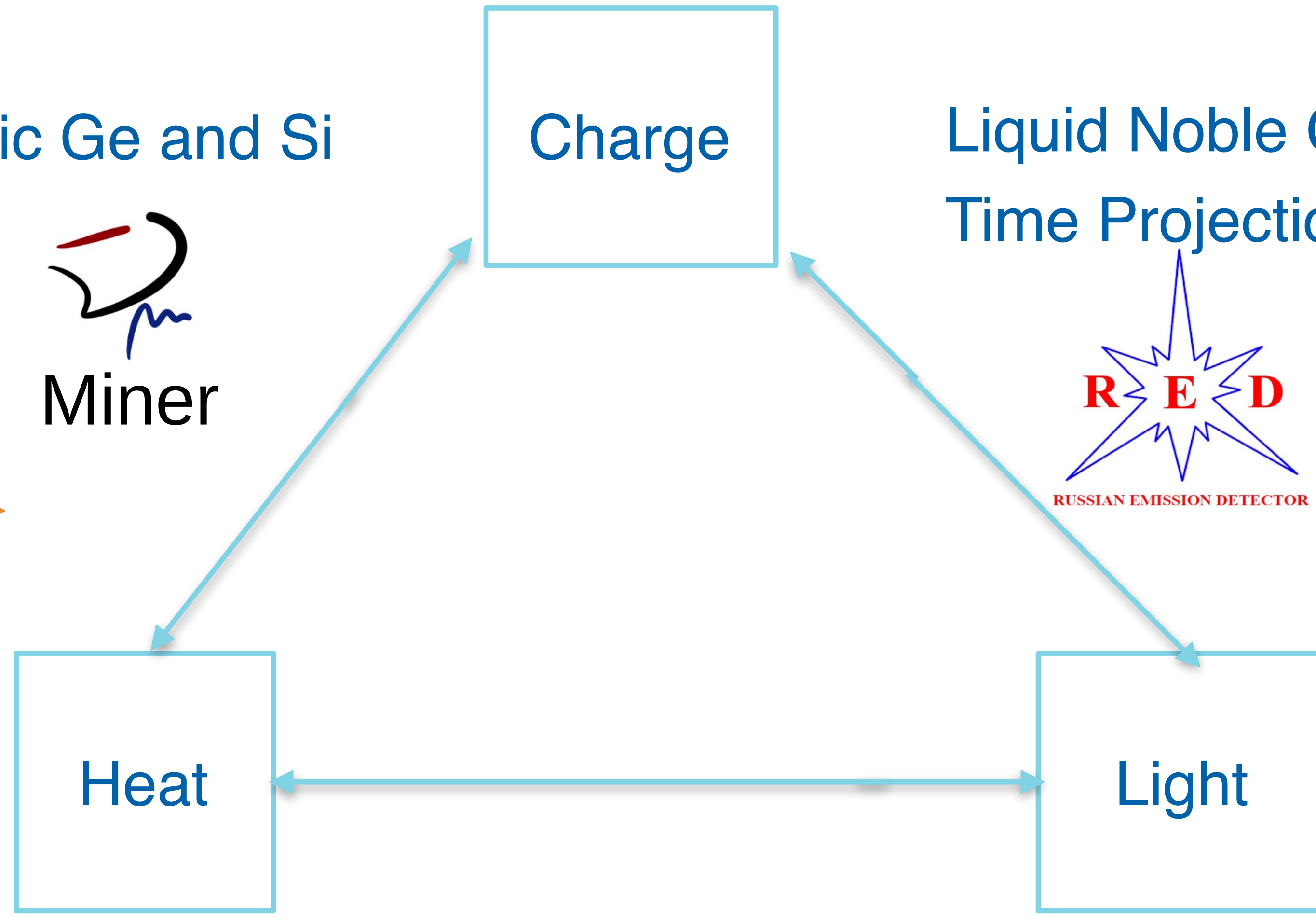
NCC-1701

Cryogenic Ge and Si

Miner

Cryogenic Si, Zn

RICOCHET



Liquid Noble Gas

Time Projection Chambers

RED

RUSSIAN EMISSION DETECTOR

NUXE, CHILLAX

CCD, Skipper CCD

Cryogenic Calorimeters

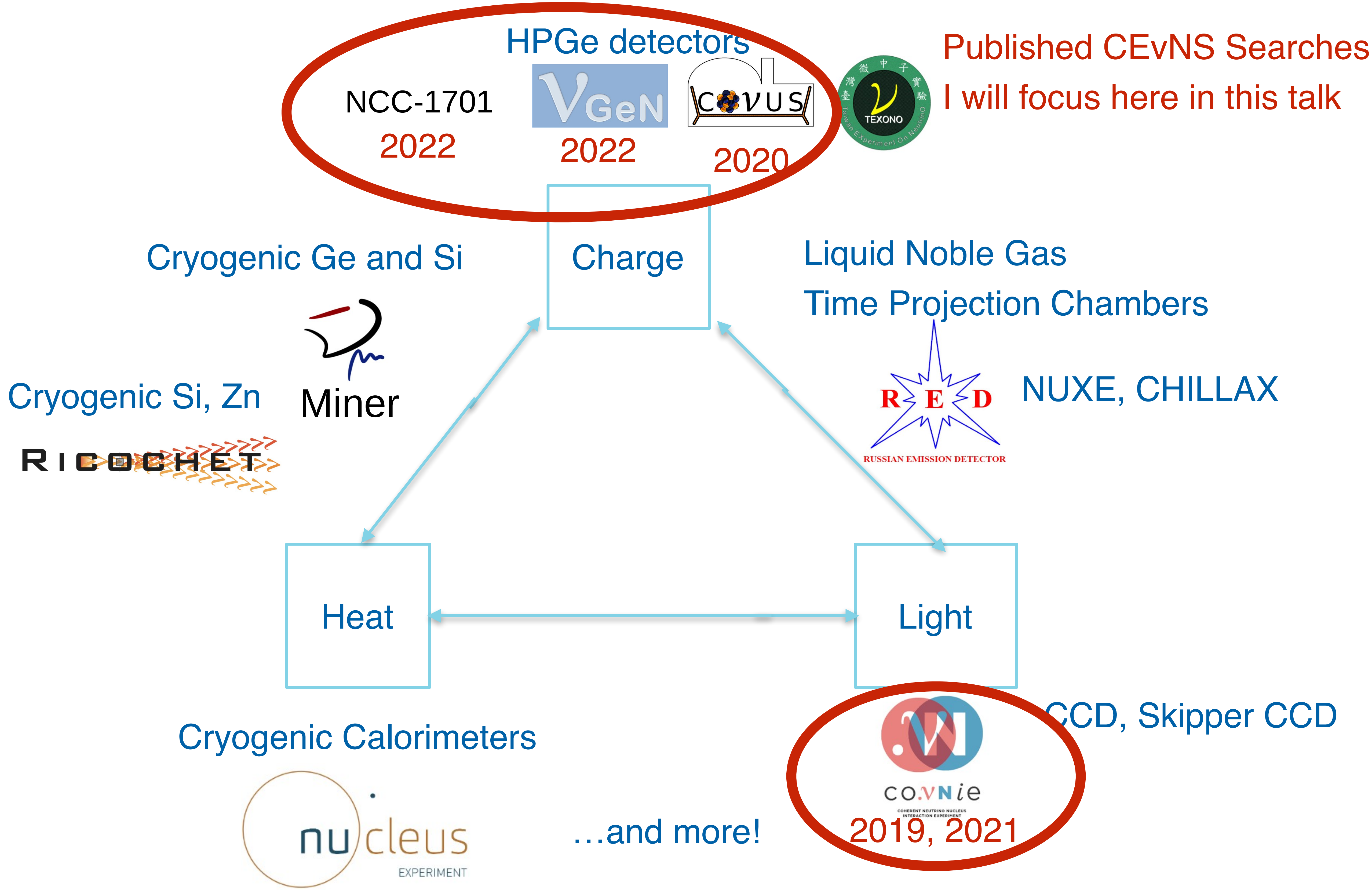
nucleus EXPERIMENT

…and more!

CONNIE

COHERENT NEUTRINO NUCLEUS INTERACTION EXPERIMENT

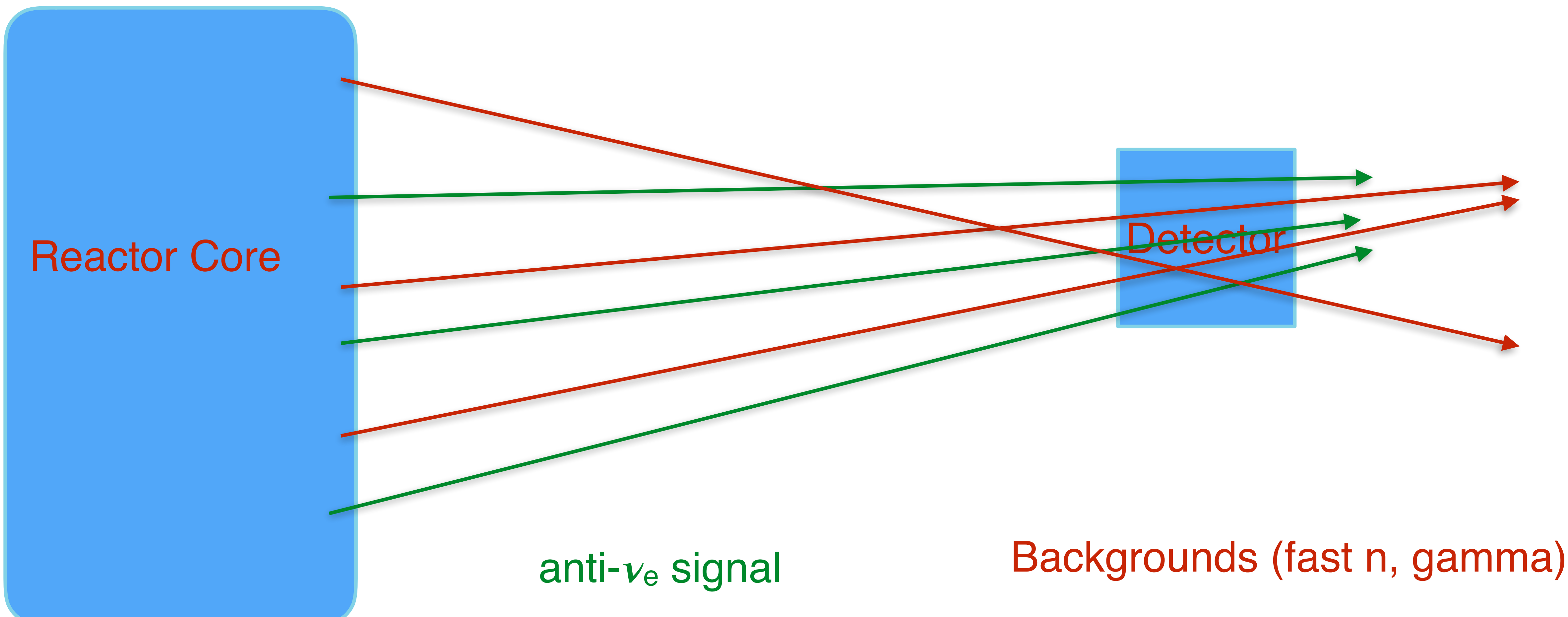
Landscape of Reactor CEvNS Experiments



No definitive CEvNS detection yet!

Challenges of Reactor CEvNS Detection

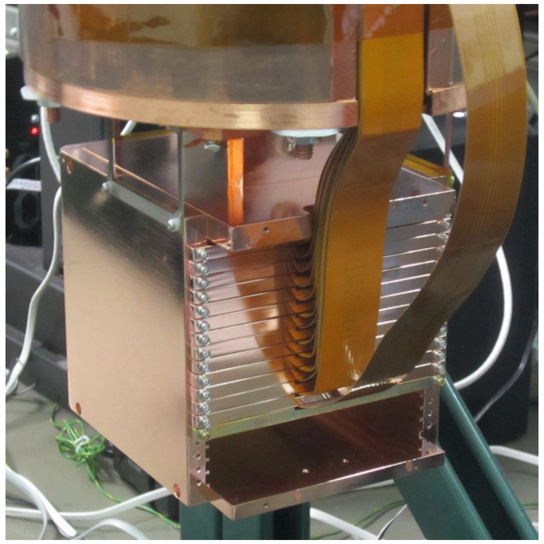
- Reactor neutrino energies require very low detector thresholds for sensitive CEvNS searches
- Reactor CEvNS recoil energy spectrum much closer to detector thresholds, modeling quenching very important
- Backgrounds from fast neutrons and gammas not easy to measure
  - Steady-state backgrounds only measurable when reactor is shutdown

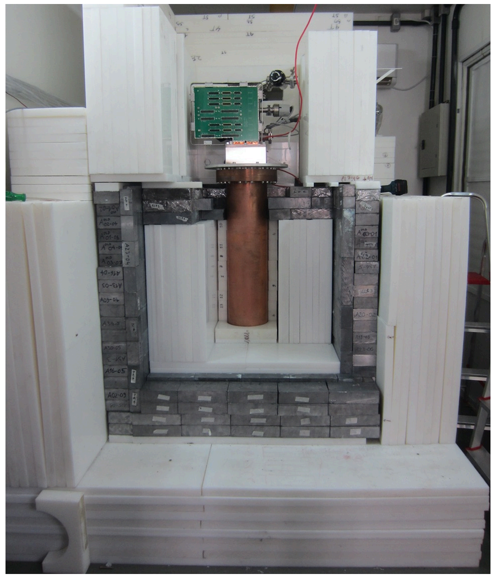


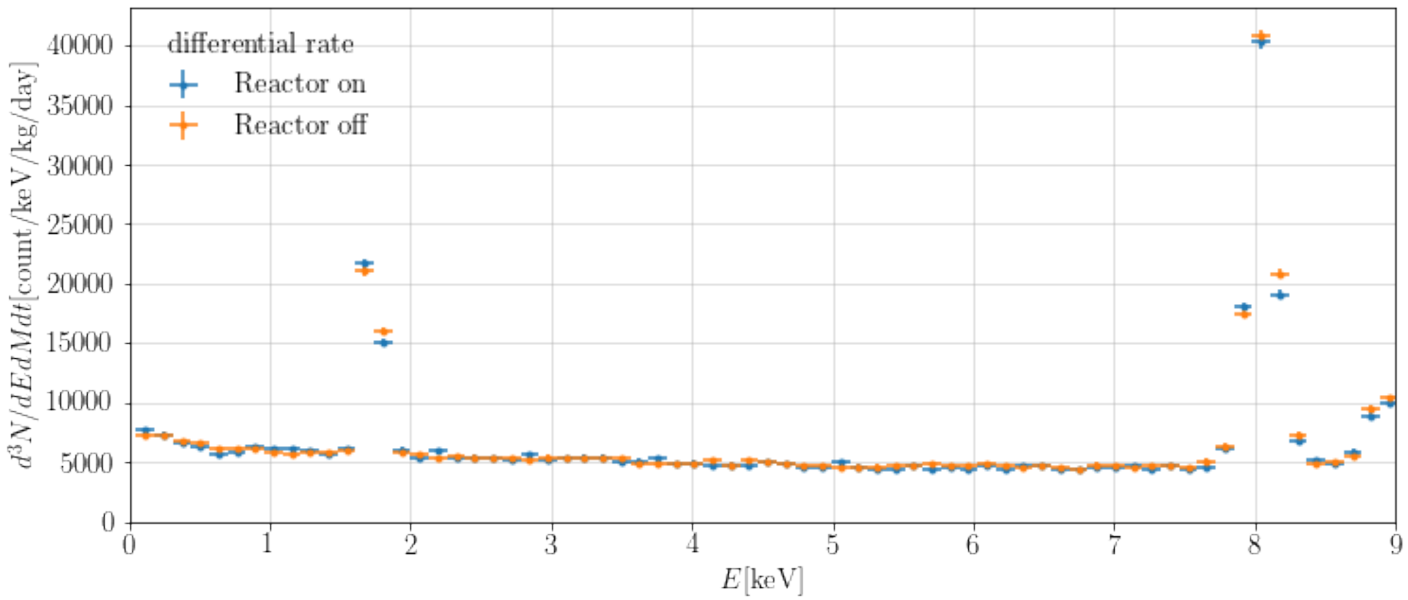
Current Reactor CEvNS Searches

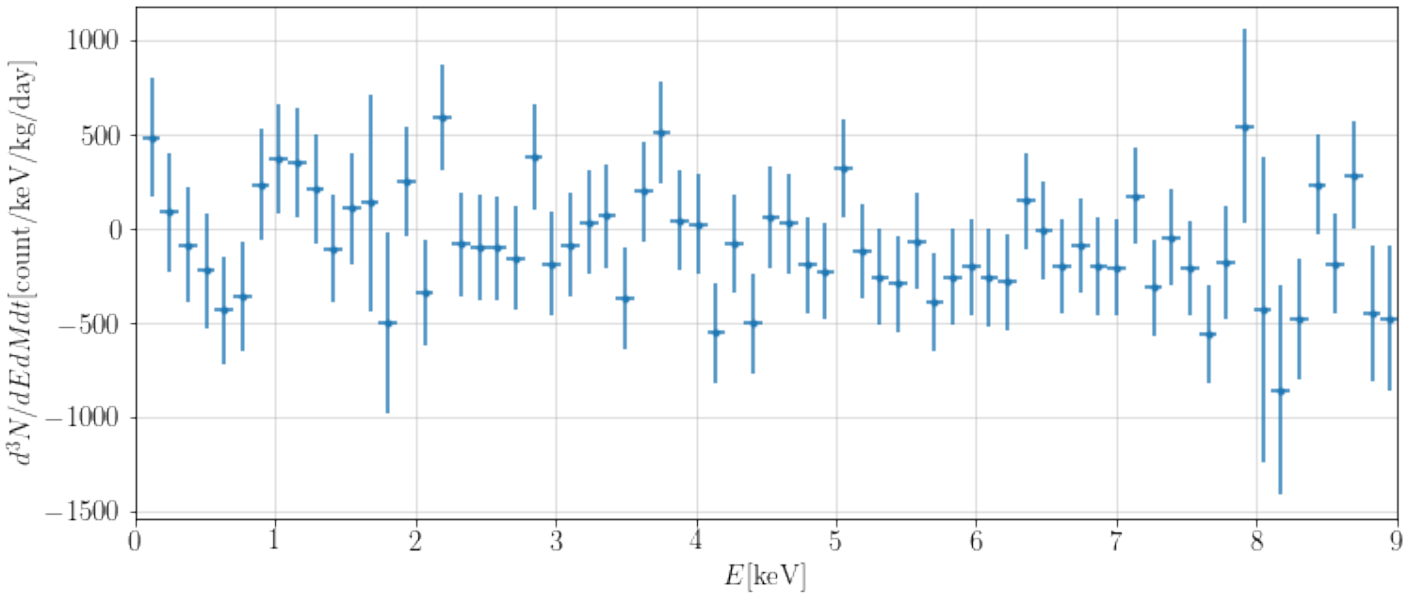
Current Reactor CEvNS Searches

- O(10) gram-scale Si CCD array at commercial reactor, CONNIE experiment
- Current results show no excess from CEvNS
- Installing gram-scale skipper CCD detectors
  - Expected to lower energy threshold to 10 eV





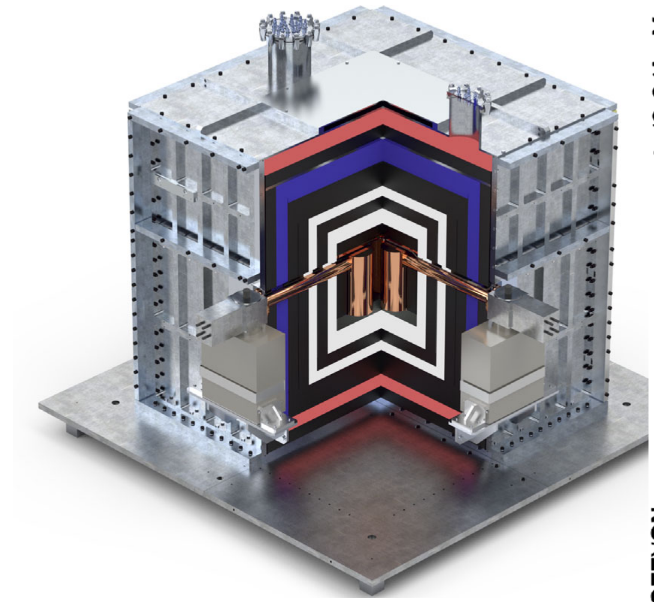


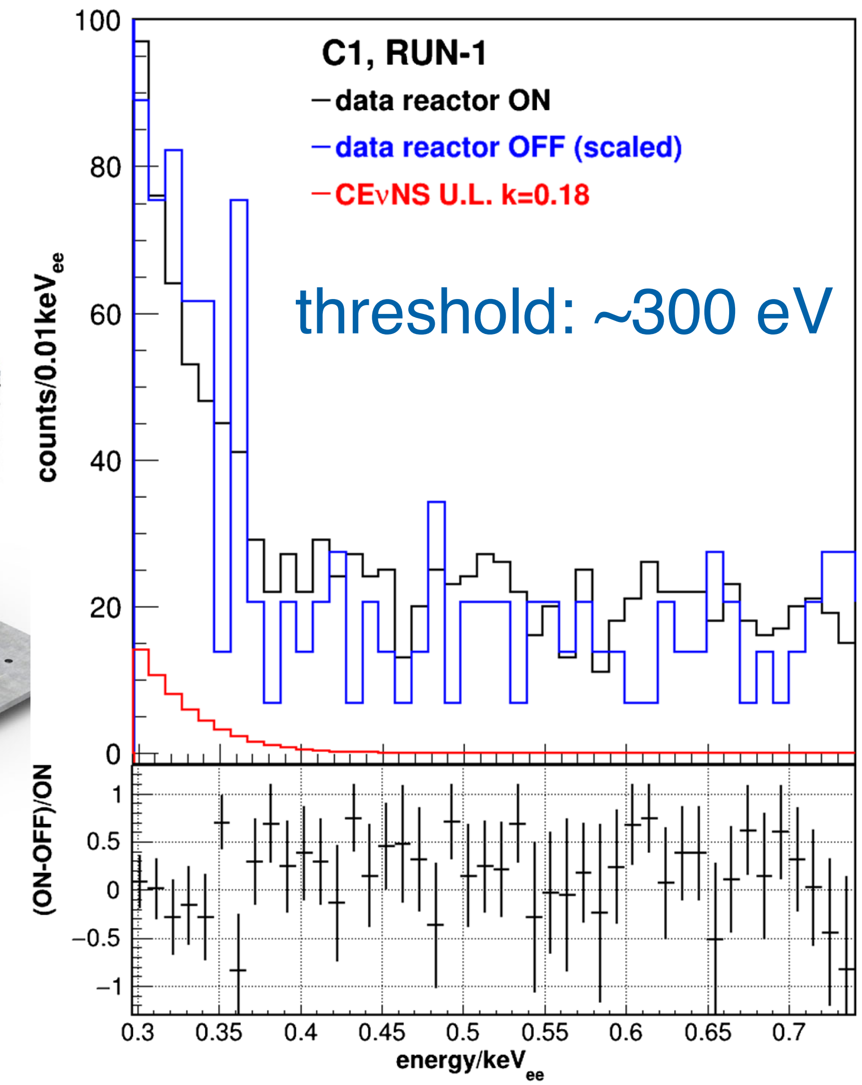


A. Aguilar-Arevalo et al. (CONNIE), Phys. Rev. D 100, 092005 (2019)
A. Aguilar-Arevalo et al. (CONNIE), J. High Energ. Phys. 2022, 17 (2022)

Current CEvNS Searches

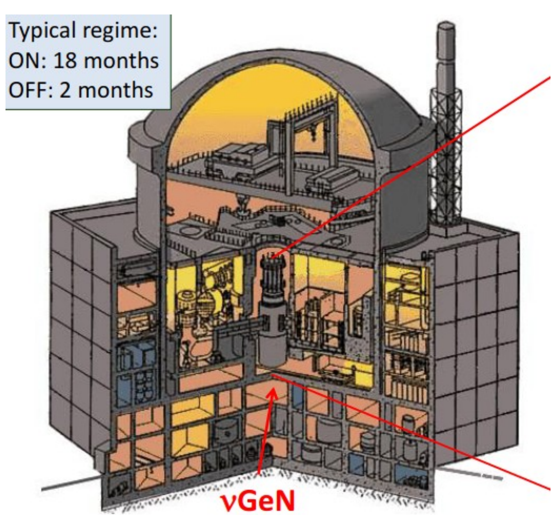
- HPGe detectors
  - CONUS and νGEN, kg-scale HPGe detectors located at research reactors
  - Latest results from both experiments show no evidence of CEvNS-related excess
  - Both experiments looking to upgrade electronics and improve background rejection strategies





H. Bonet et al. (CONUS), Phys. Rev. Lett 126, 041804 (2021)

H. Bonet et al. (CONUS),arXiv:2201.12257



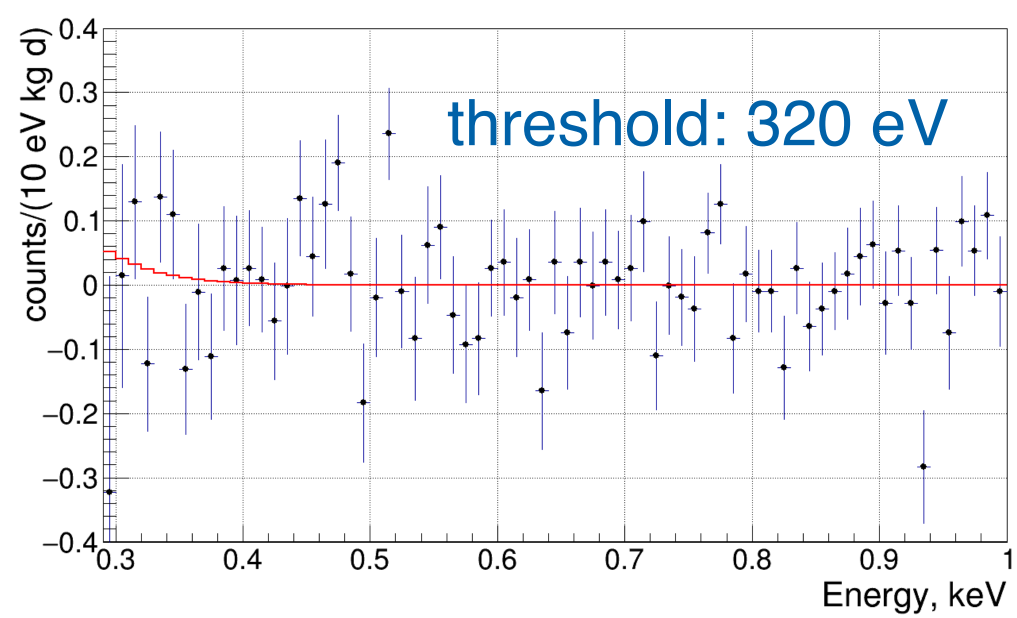


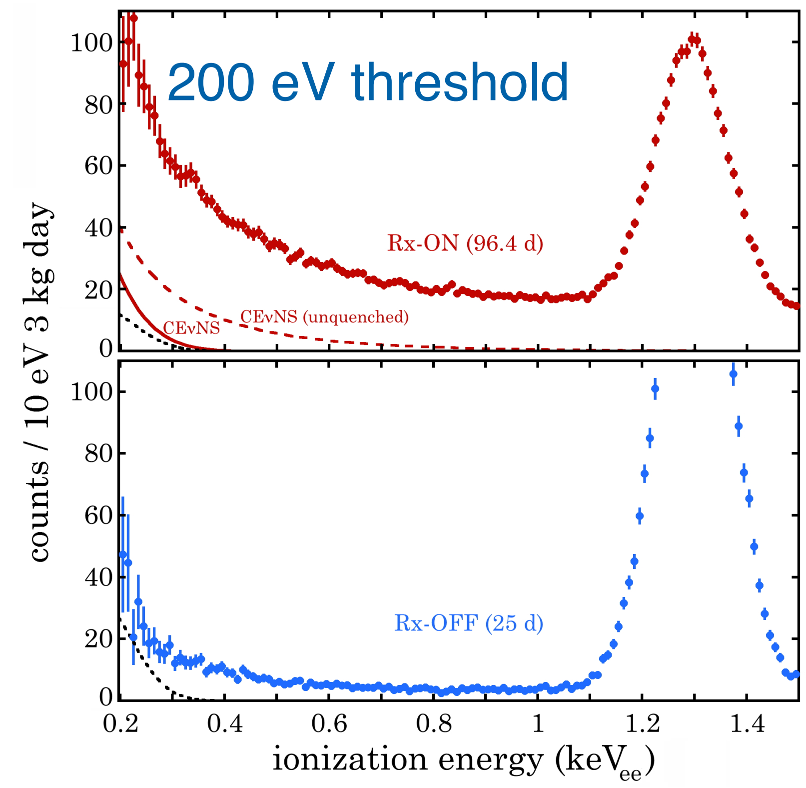
FIG. 9. Residual spectrum (ON-OFF). Red line demonstrates a prediction from CEνNS with k = 0.179

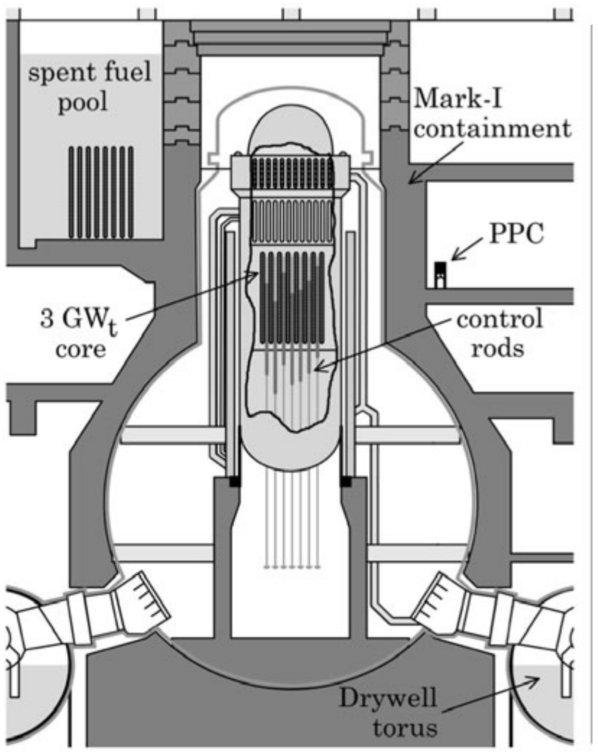
arXiv: 2205.04305 [nucl-ex]

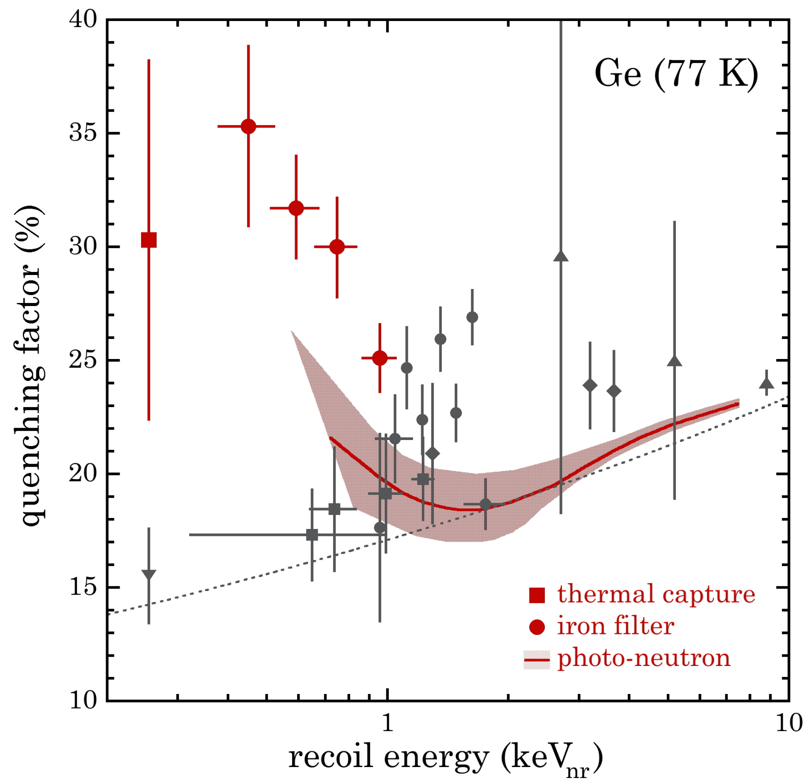
A. Lubashevskiy, TAUP 2021 Slides

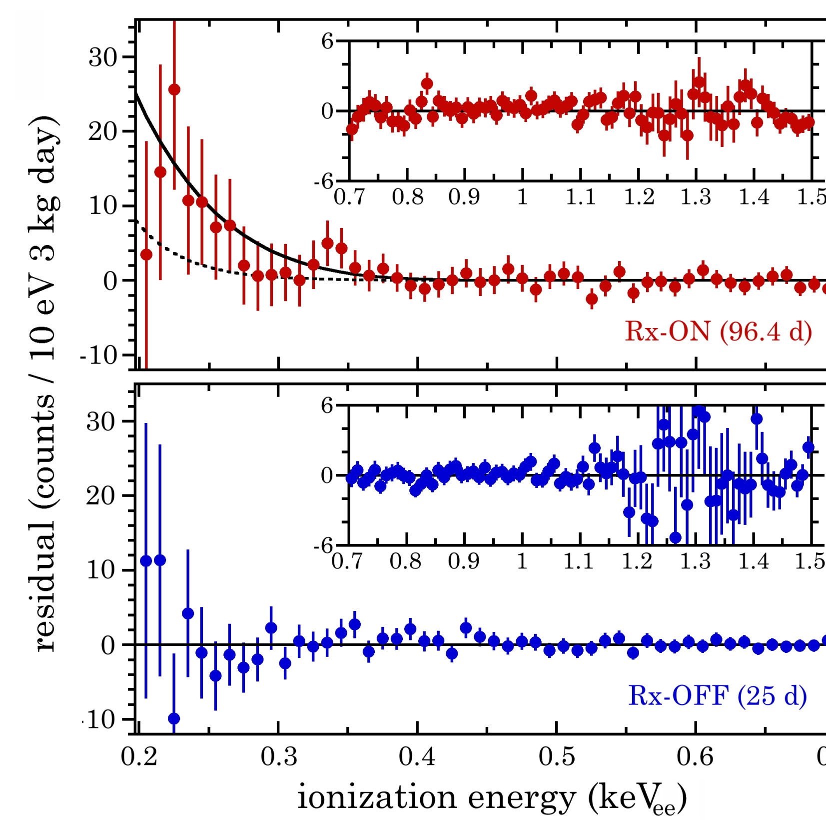
The Dresden-II (NCC-1701) Experiment

- Single 2.92 kg HPGe detector at Dresden-II reactor in IL, USA
- Latest data shows suggestive evidence of excess above background
  - Consistent with CEvNS only for specific quenching measurement detailed in Phys. Rev. D 103, 122003 (2021)
- Planned upgrades are upgraded shielding and relocation of the detector to reduce the background correlated with reactor operations









J. I. Collar et al., Phys. Rev. D 103, 122003 (2021)

J. Colaresi et al., Phys. Rev. D 104, 072003 (2021)

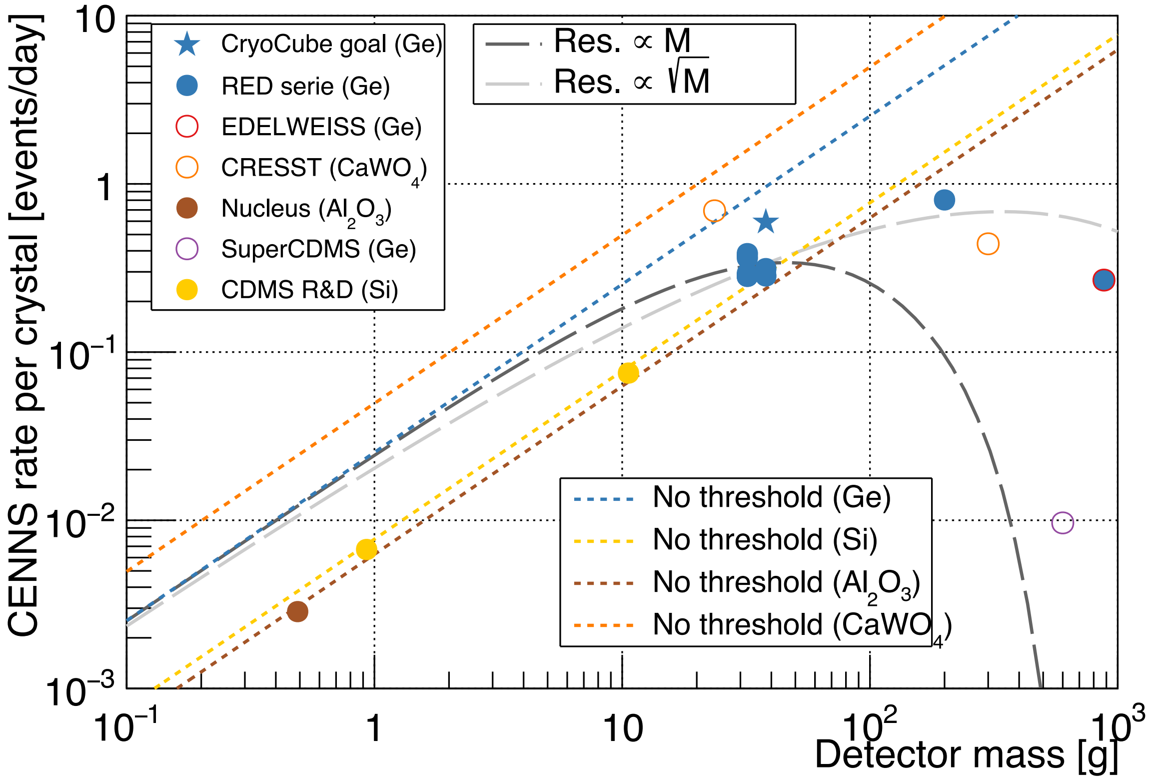
J. Colaresi et al., arXiv:2202.09672 [nucl-ex]

Other Reactor-based CEvNS Searches

Other Reactor CEvNS-based experiments

- Liquid noble detectors
  - RED-100 experiment: 100-kg scale LXe experiment at Kalinin Nuclear power plant, run in Winter 2022 with reactor on/off periods
    - LXe data analysis ongoing with detector decommissioned and undergoing upgrade for LAr operations
  - NUXE concept: Sensitivity studies ongoing with 100-kg scale LXe/LAr detector at reactor neutrino energies
- A lot of R&D towards <kg-scale detectors with very-low thresholds
  - Ricochet experiment: Ge+Zinc detectors with sub-100 eV threshold planned at ILL reactor site in France, neutron background measurements ongoing
  - Nucleus experiment: 6 g $CaWO_4$ (Bkg+CEvNS) and 4 g Al_2O_3 (Bkg) detectors to be deployed at Chooz nuclear reactor complex, 100 m from core, simulations and crystal R&D ongoing
  - …and more!

D.G. Rudik (RED-100), Neutrino 2022 Poster:
https://indico.kps.or.kr/event/30/contributions/358/
K. Ni et al. (NUXE), Universe 2021, 7, 54
C. Augier et al. (Ricochet), arXiv:2208.01760
V. Wagner et al. (NUCLEUS), J. Phys. Conf. Ser. 2156 012118



Summary

- CEvNS was first predicted in 1974 as a consequence of the discovery of the weak interaction
- CEvNS detection requires low recoil detection thresholds and the detectors are capable of probing many interesting physics questions
- CEvNS was first discovered in 2017 by the COHERENT collaboration using a stopped-pion source in Oak Ridge, TN, USA
- CEvNS detectors at accelerator-based facilities capable of strong dark sector searches now and in the future
- Rich reactor-based CEvNS detection program using many different detector technologies
  - No definitive detection observed yet! Stay tuned!
  - Detectors with very-low threshold have distinct physics capabilities
- CEvNS is an exciting new tool for neutrino physics searches with a rich experimental program!

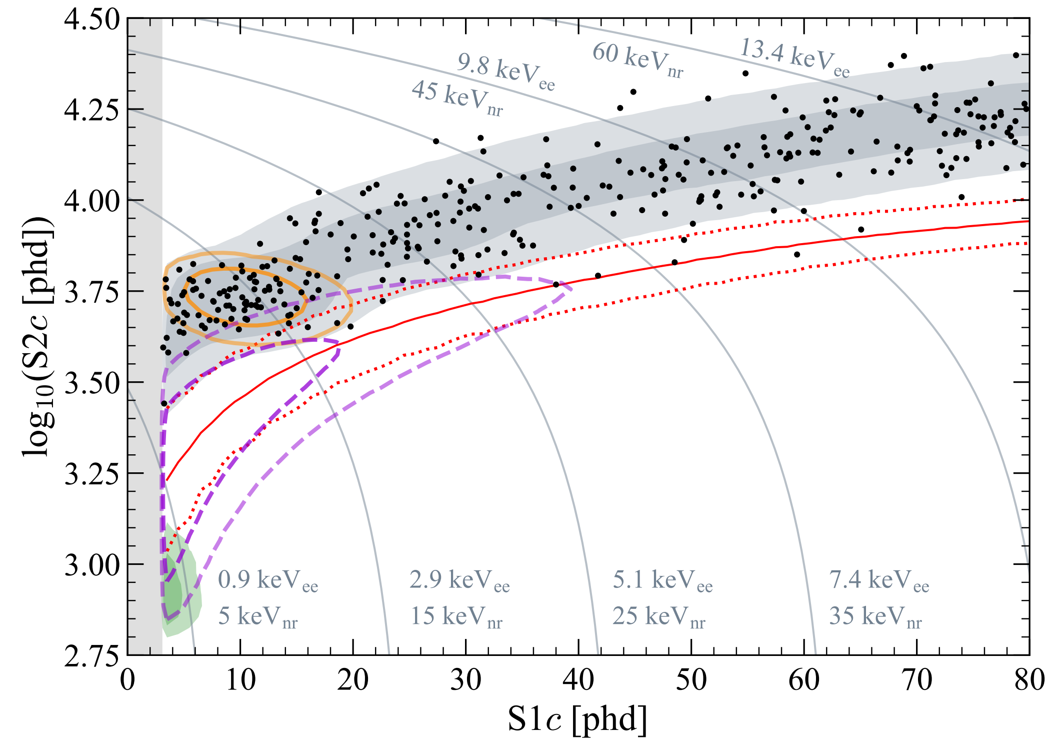
Backup

Modeling Quenching

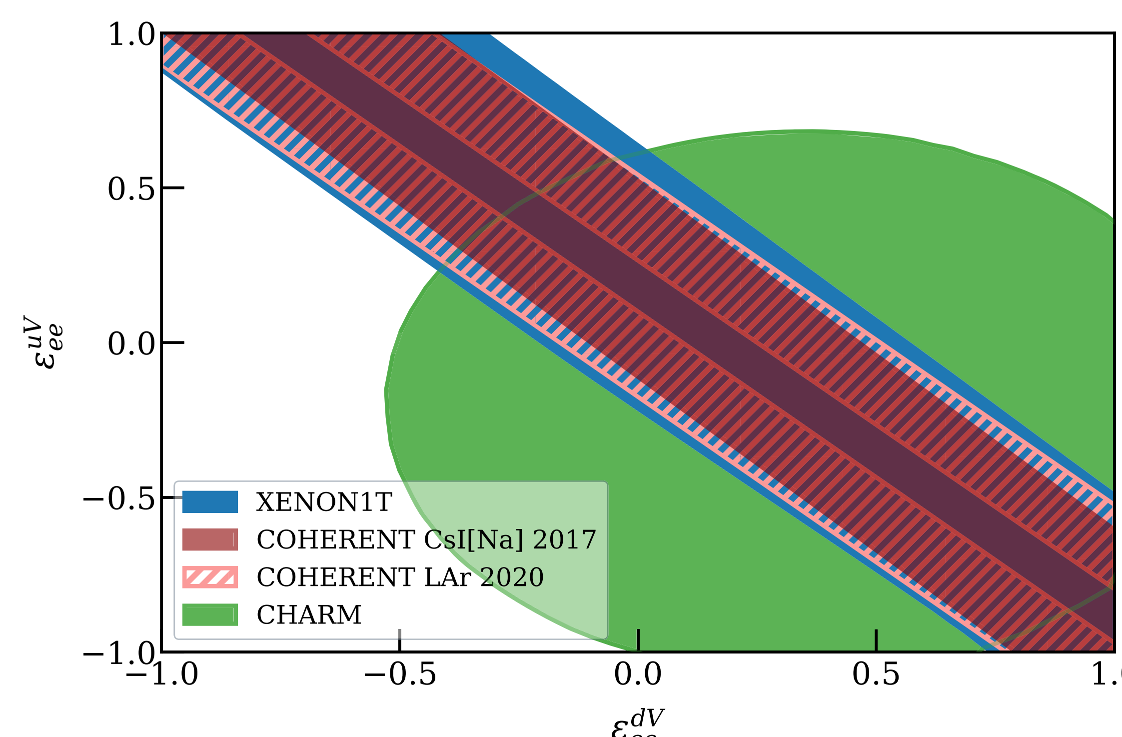
- Reactor CEvNS experiments very sensitive to quenching
- HPGe detectors look at “modified Lindhard theory”
  - Model of free electron screening
- Material dependent

CEvNS from Solar and Atmospheric Neutrinos

- Direct detection DM experiments sensitive to ^{8}B CEvNS
- Current generation ton-scale experiments such as LZ, XENON-1T and XENON-nT can search for this signature
- Irreducible background to dark matter searches
- These searches can also constrain models such as non-standard neutrino interactions



J. Aalbers, et al. (LZ), arXiv:2207.03764



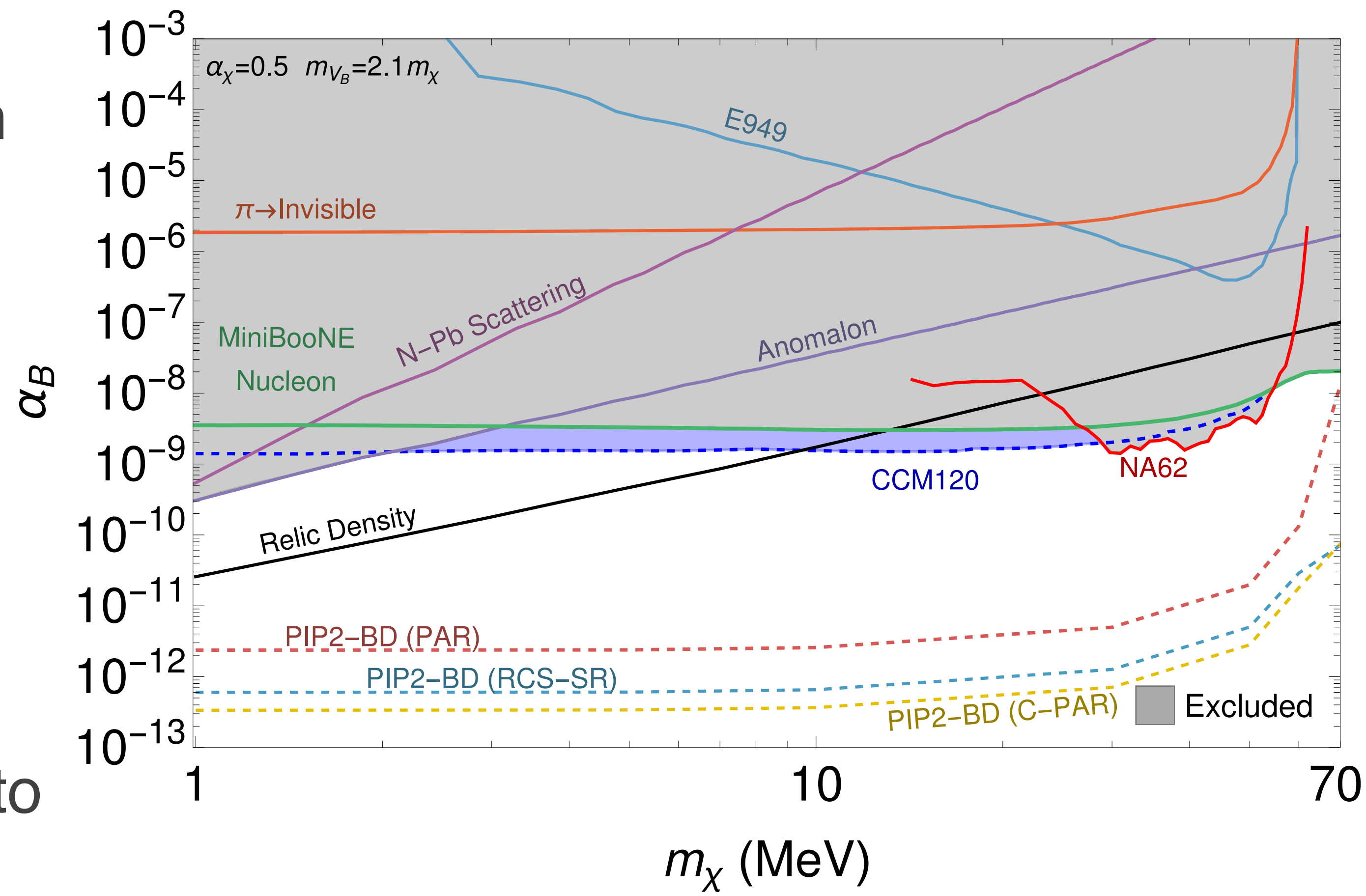
E. Aprile et al. (XENON), Phys. Rev. Lett 126, 091301 (2021)

Leptophobic DM Search with CEvNS Detectors

- Kinetic mixing dark sector model couples to quarks rather than leptons
  - Example dark matter scenario for which proton beam searches provide robust sensitivity

$$\mathcal{L}_B \supset -A^\mu_B (g_B J^B_\mu + g_\chi J^\chi_\mu + \varepsilon_B e J^{\mathrm{EM}}_\mu)$$

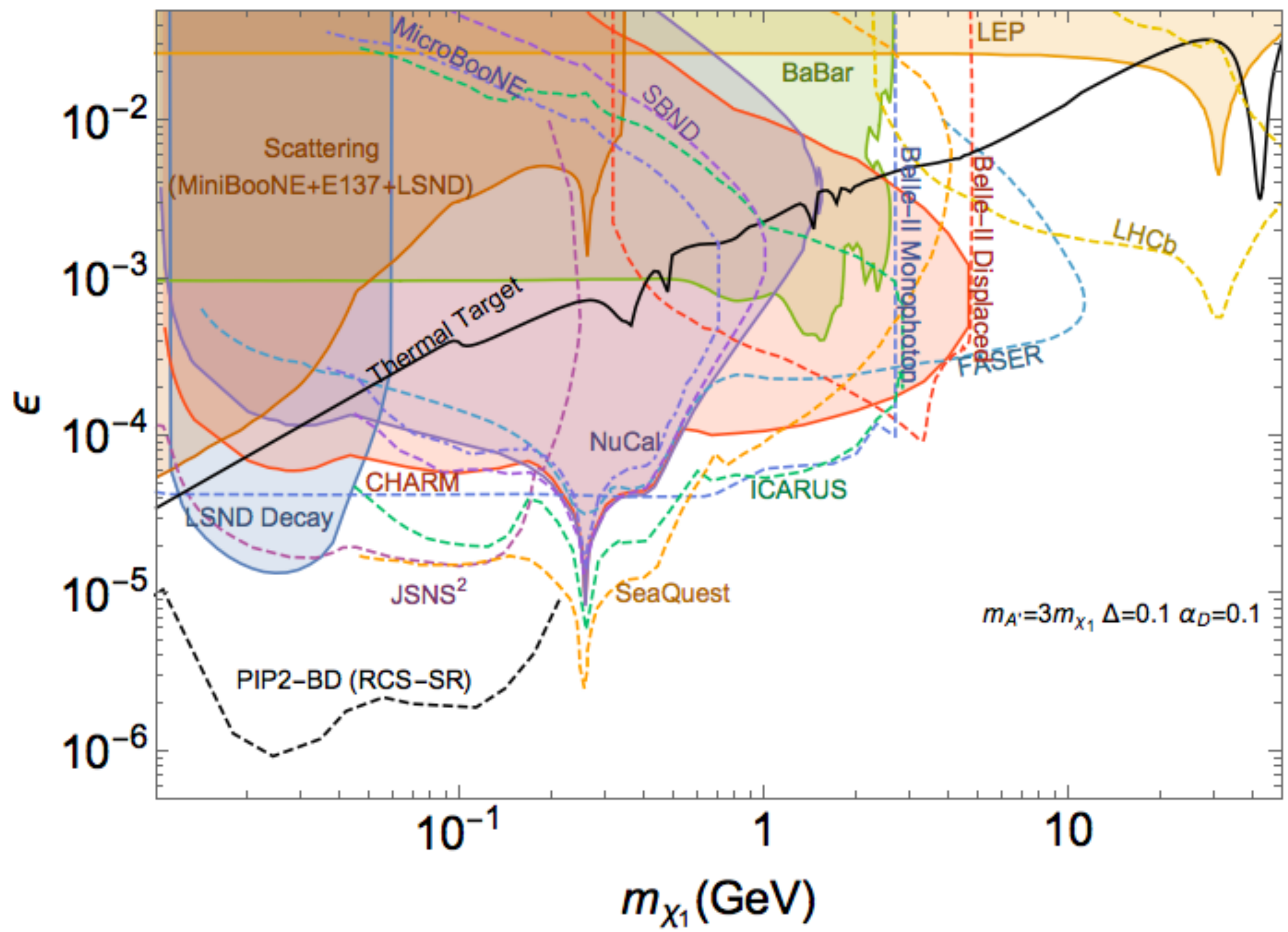
- Model predicts the same DM nuclear recoil energy distributions as the vector-portal model
  - Rate scales with as $\alpha_\chi \, \alpha^2_{\mathrm{B}}$ as opposed to ε^4
- Large CEvNS detectors at stopped-pion sources have the opportunity to set strong new limits on these models



M. Toups et al., arXiv:2203.08079

Inelastic dark matter search with CEvNS detectors

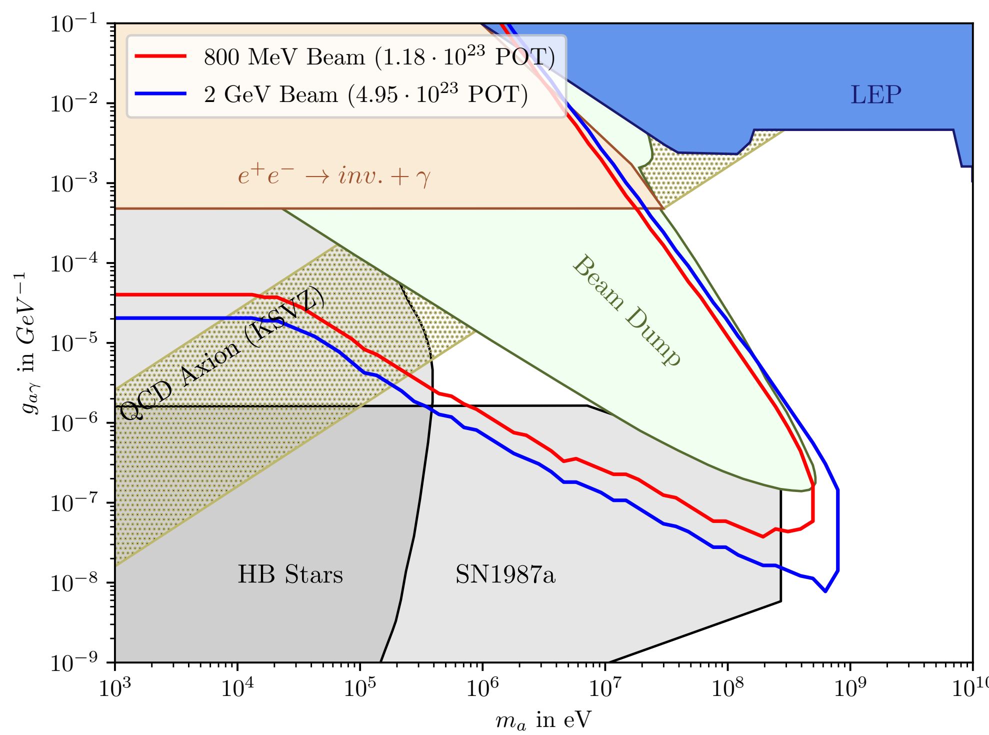
- Extend minimal vector portal scenario to include two DM particles χ_1 and χ_2
- Require $\Delta = (m_{\chi_2} - m_{\chi_1})/m_{\chi_1} > 0$
- Possibility of χ_2 decay into e+e-
- If decay not kinematically allowed, DM observation also possible through its up- or down-scattering off of electrons in the detector
- Large-scale liquid noble gas CEvNS detectors set strong new limits on this model

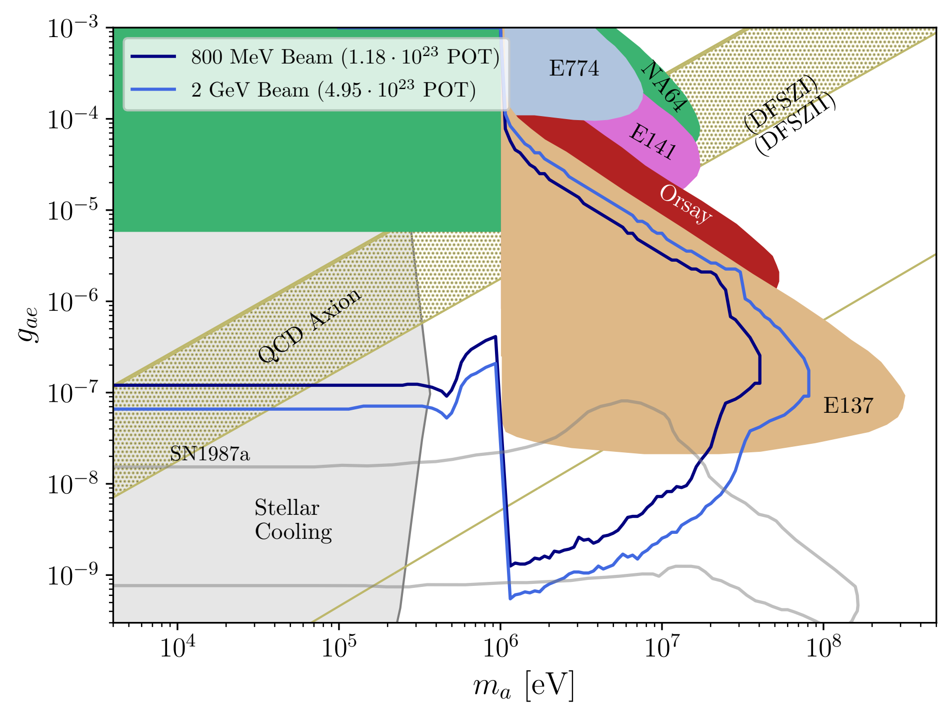


M. Toups et al., arXiv:2203.08079

Axion-like particles (ALP) search with CEvNS detectors

- ALPs that couple to photons can be produced in the beam dump via Primakoff process, detectable via inverse Primakoff process or decay into two photons
- ALPs coupling to electrons detectable via inverse Compton, e+e- conversion, or decay to e+e-
- Interested in "cosmological triangle" region for photon-couple ALPs
- Large-scale CEvNS detectors able to probe QCD axion space for photon and electron-couple ALP models





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