Coherent Elastic Neutrino-Nucleus Scattering

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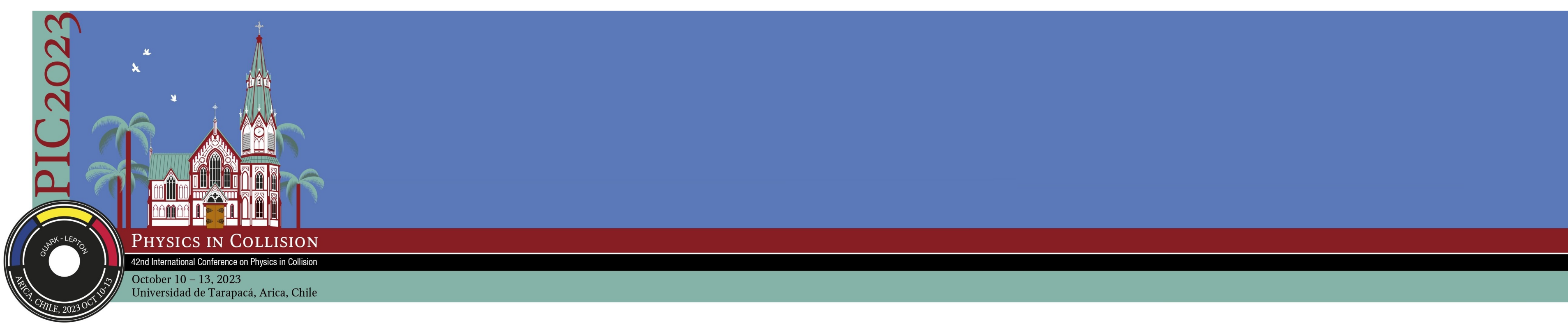
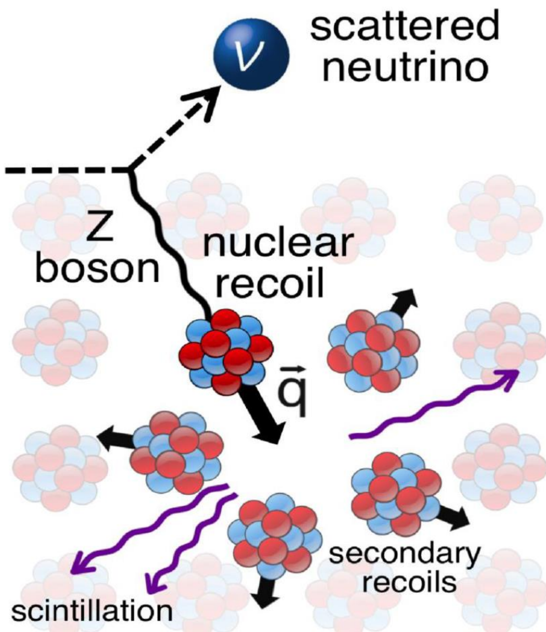
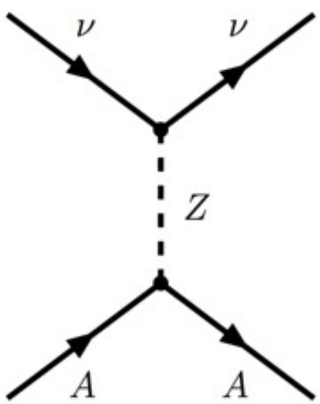


Coherent elastic νN scattering

- In the Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) interaction, the neutrino scatters off the nucleus as a whole.
- Neutral-current interaction, all neutrino flavours.
- Experimentally the aim is to measure the small nuclear recoil.





Coherent elastic νN scattering

- In the Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) interaction, the neutrino scatters off the nucleus as a whole.
- Predicted by Daniel Z. Freedman in 1974.

D. Freedman, Phys.Rev. D 9 1389 (1974)

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
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and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

There is recent experimental evidence[1] from CERN and NAL which suggests the presence of a neutral current in neutrino-induced interactions.

important to interpret experimental results in a very broad theoretical framework.[4] We assume a general current-current effective Lagrangian

Coherent elastic νN scattering

- In the Coherent Elastic Neutrino-Nucleus Scattering (CEνNS) interaction, the neutrino scatters off the nucleus as a whole.
- Discovered by COHERENT in 2017.

Science 357, 1123, 2017

Science REPORTS

Cite as: D. Akimov *et al.*, *Science* 10.1126/science.aao0990 (2017).

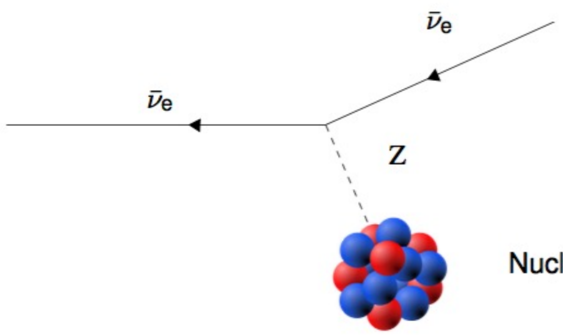
Observation of coherent elastic neutrino-nucleus scattering

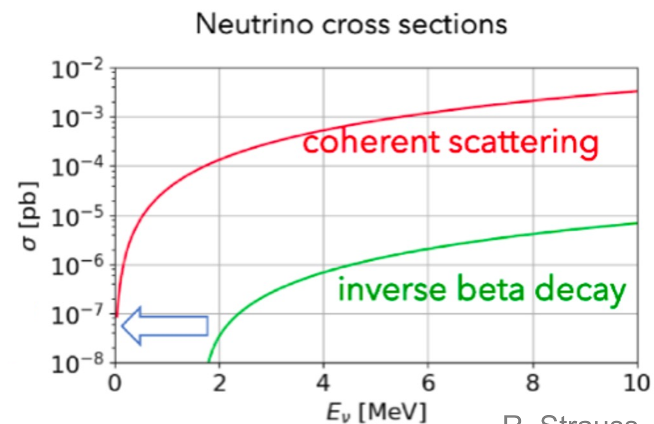
D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9]* R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13]† D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9]‡ W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9]§ M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3]|| S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13]¶ S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

The coherent elastic scattering of neutrinos off nuclei has eluded detection for four decades, even though its predicted cross-section is the largest by far of all low-energy neutrino couplings. This mode of interaction provides new opportunities to study neutrino properties, and leads to a miniaturization of detector size, with potential technological applications. We observe this process at a 6.7-sigma confidence level, using a low-background, 14.6-kg CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. Characteristic signatures in energy and time, predicted by the Standard Model for this process, are observed in high signal-to-background conditions. Improved constraints on non-standard neutrino interactions with quarks are derived from this initial dataset.

Coherent elastic νN scattering

- Coherent enhancement of the scattering cross-section at low energies: E_ν < 50 MeV.





R. Strauss,
Magnificent CEvNS 2021

$$\frac{d\sigma}{dE_{rec}} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{M E_{rec}}{2E_\nu^2}\right)[Z(1-4\sin^2\theta_w) - N]^2 (f(q^2))^2$$

with $[Q_w = Z(1-4\sin^2\theta_w) - N]$ the weak charge,

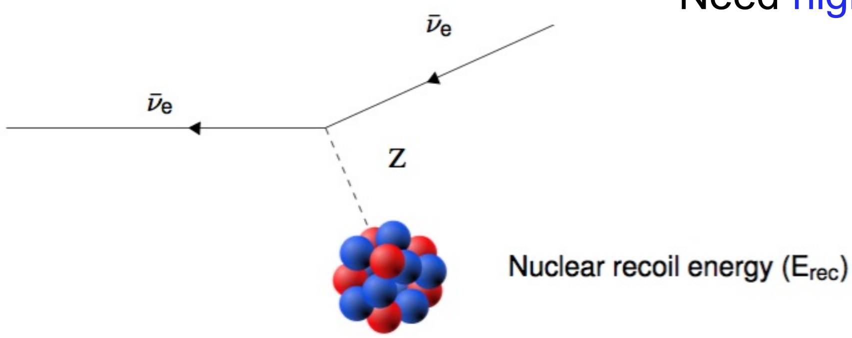
θ_w= weak mixing angle, M= nucleus mass, Z = atomic number, N = number of neutrons

- The total cross-section is proportional to N^2.
- Nuclear form-factor is $f(q^2) \approx$ 1 in the coherence limit $(q^2 \to 0)$.
- CEνNS is the dominant interaction at low energies.

Coherent elastic νN scattering

- Coherent enhancement of the scattering cross-section at low energies: E_ν < 50 MeV.

Need high-flux neutrino sources at these energies.



$$E_{rec} = \frac{q^2}{2M} = E_\nu - E_{\nu'}$$

Recoils can vary between 0 and $\dfrac{2E_\nu^2}{M + 2E_\nu}$

$$\frac{d\sigma}{dE_{rec}} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{M E_{rec}}{2E_\nu^2}\right)[Z(1 - 4\sin^2\theta_w) - N]^2 (f(q^2))^2$$

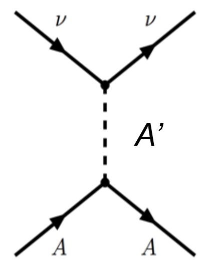
with $[Q_w = Z(1 - 4\sin^2\theta_w) - N]$ the weak charge,

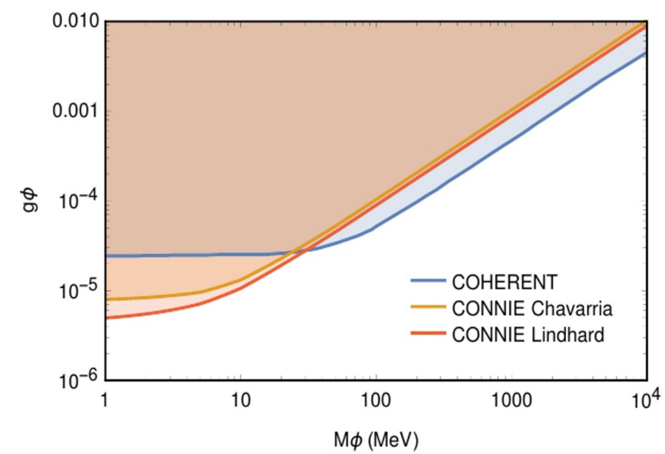
θ_w= weak mixing angle, M= nucleus mass, Z = atomic number, N = number of neutrons

- Despite the large cross-section, the nuclear recoils are tiny, $\lesssim$ keV.
- Low-threshold detection is the biggest experimental challenge.

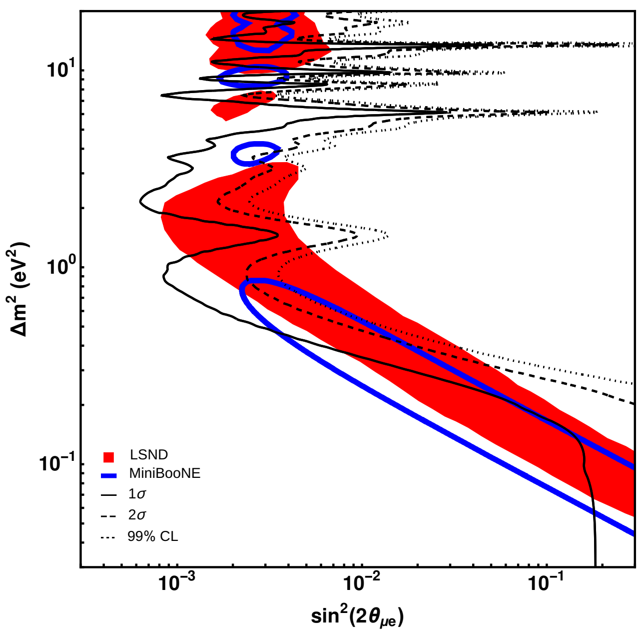
New Physics with neutrinos

- The coherent scattering rates are calculated with precision in the SM.
- Any discrepancy can be a sign of contributions from New Physics:
  - Non-Standard Interactions of neutrinos.
  - Light sterile neutrinos.
  - Neutrino magnetic moment.
  - Neutrino millicharge.
  - Weak angle measurement.

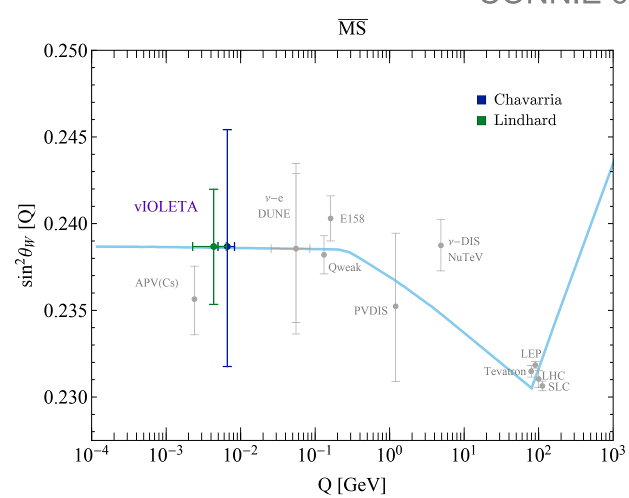




CONNIE collab., JHEP 04 (2020) 054



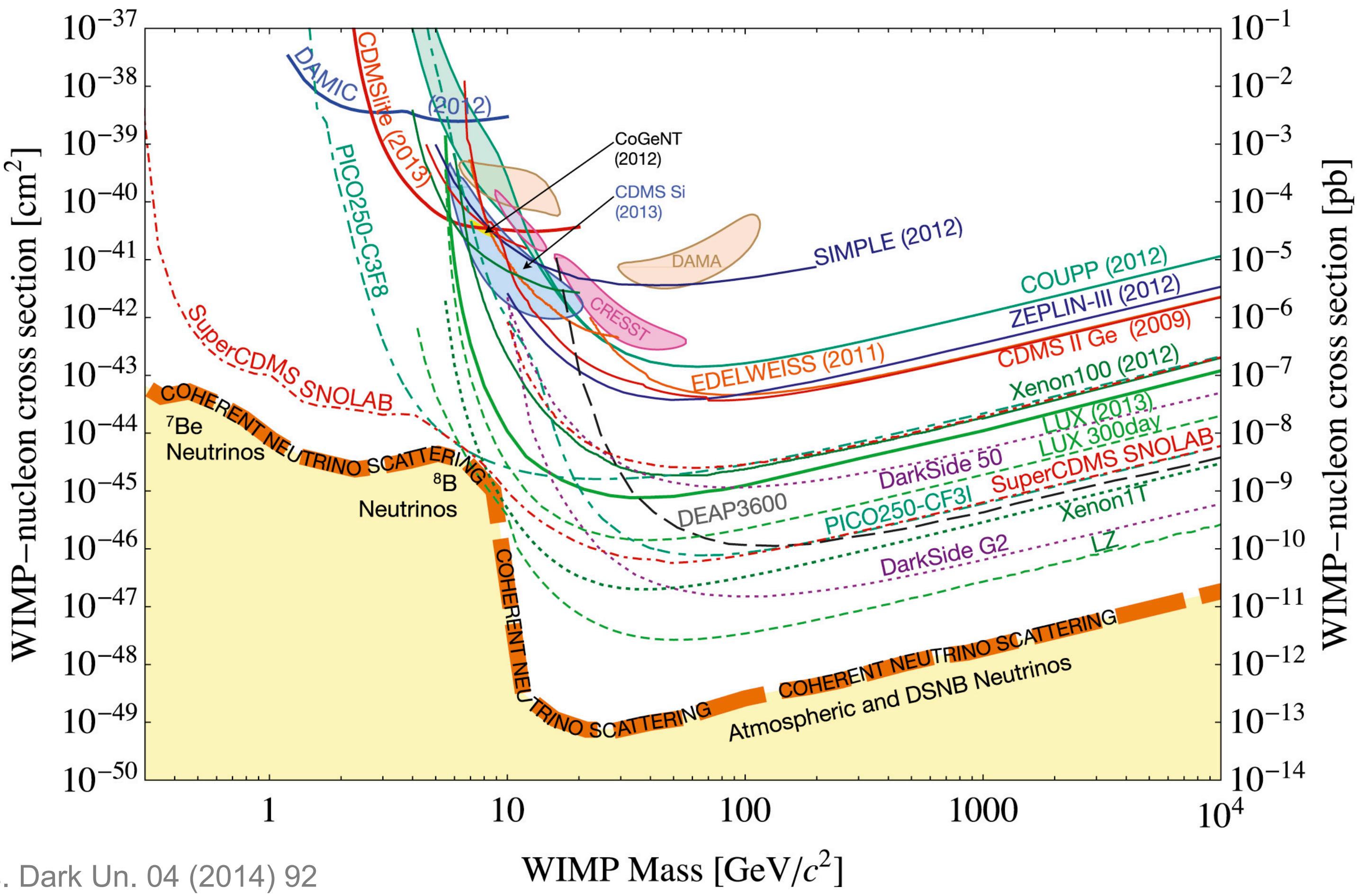
C.Blanco et al, Phys.Rev. D101, 075051 (2020)



G. Fernandez-Moroni et al, JHEP 03 (2021) 186

Dark Matter searches

- CEνNS from solar, atmospheric and diffuse supernova neutrinos forms an irreducible background to direct Dark Matter search experiments.

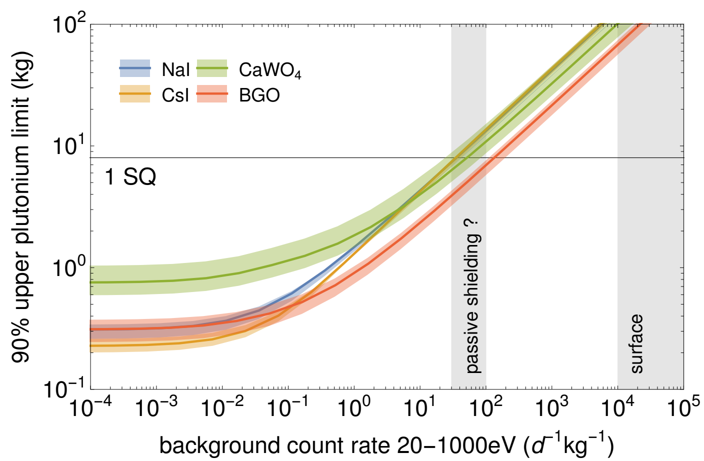


J. Cooley, Phys. Dark Un. 04 (2014) 92

More CEνNS physics

- Supernova physics:
  - Important for models of energy transport in supernovae.
  - The large CEνNS experiments can detect supernova neutrinos.
- Nuclear physics:
  - Nuclear form factors.
  - Neutron distribution radius.
- Reactor applications:
  - Possibility to create compact detectors for measuring reactor flux.
  - Nuclear non-proliferation monitoring.

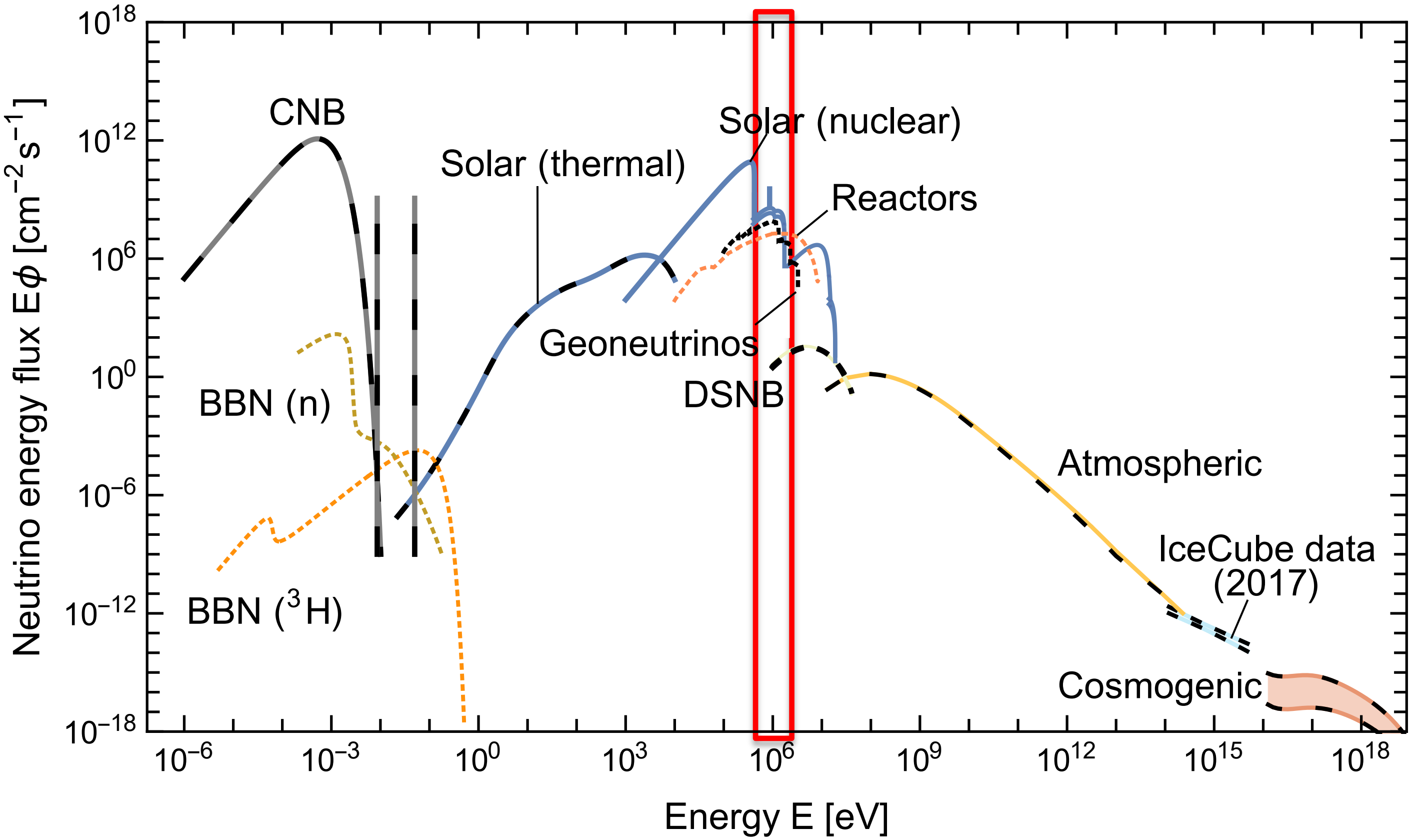
$$\frac{d\sigma}{dE_{rec}} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{M E_{rec}}{2E_\nu^2}\right) Q_w^2 (f(q^2))^2$$



B. Cogswell et al, Phys.Rev. Applied 16 (2021) 6, 064060

Neutrino sources

- Required: sources of low-energy neutrinos (E_ν < 50 MeV) with a high flux.
- Required: detectors with low-energy thresholds and low background contamination.

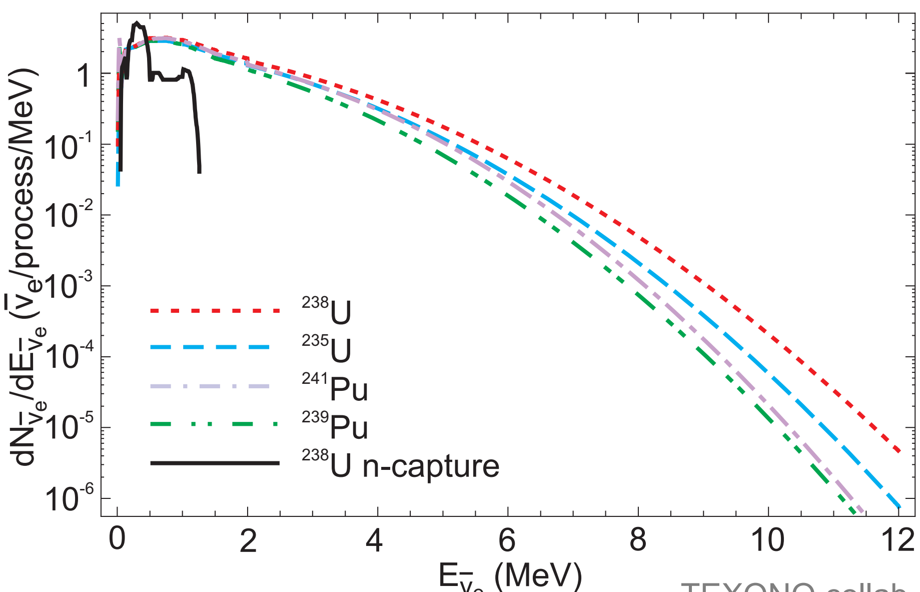


E. Vitagliano et al, Rev. Mod. Phys. 92, 45006 (2020)

Neutrino sources

- Required: sources of low-energy neutrinos (E_ν < 50 MeV) with a high flux.
- Required: detectors with low-energy thresholds and low background contamination.

- Reactors.
  - Around 6 electron antineutrinos per fission via beta decay.
  - High fluxes of $2*10^{20}$ s^{-1} per GW reactor power.
  - Reactor-off periods crucial for background measurement.
  - Energy range (0–10) MeV means full coherence.

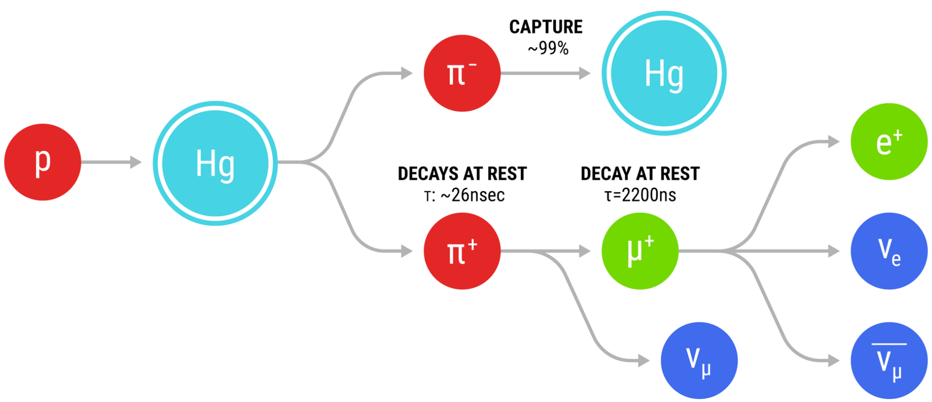


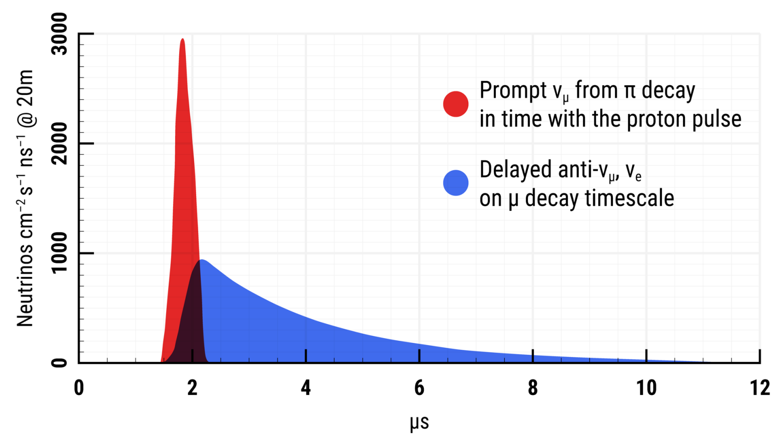
TEXONO collab., Phys.Rev. D75, 012001 (2007)

Neutrino sources

- Required: sources of low-energy neutrinos (E_ν < 50 MeV) with a high flux.
- Required: detectors with low-energy thresholds and low background contamination.

- Pion decay at rest (π-DAR).
  - Pulsed source of electron neutrinos and muon (anti)neutrinos.
  - Timing information crucial for background suppression.
  - Higher energy (10–50) MeV means partial coherence, but higher recoils.
- Spallation Neutron Source (SNS) at Oak Ridge National Laboratory (USA).
- European Spallation Source (ESS) under construction (Sweden).





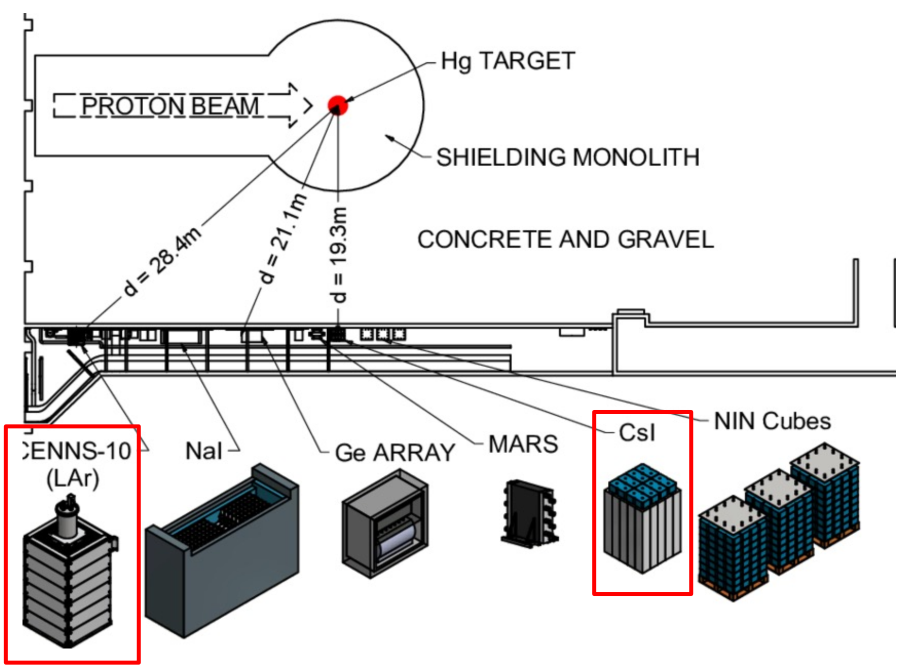
COHERENT collab

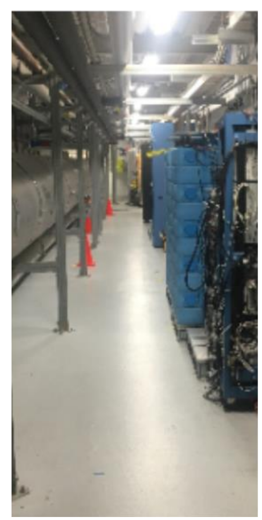
CEνNS experiments

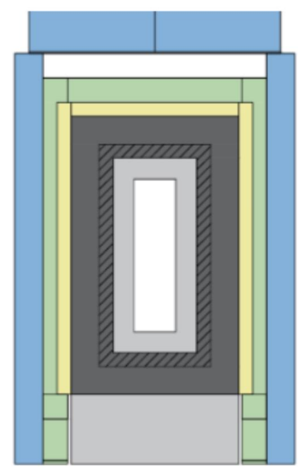
C. Bonifazi, Neutrino 2022

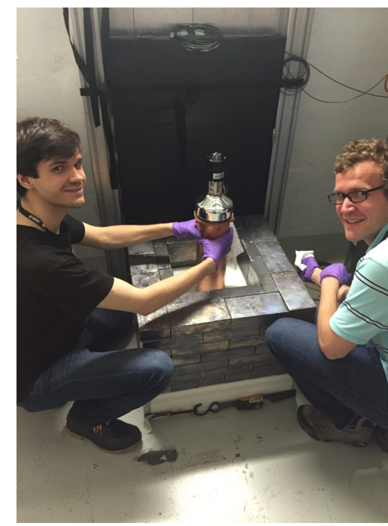
The COHERENT experiment

- Pulsed neutrino beam from pion decay at rest at Spallation Neutron Source (SNS).
- CsI[Na] detector was the world's smallest working neutrino detector.
  - 14.6 kg mass, 6.5 keV_{nr} threshold.
  - 19.3 m from the source.
  - Good shielding from beam backgrounds.
  - Muon vetoes and lead, water and plastic passive shielding.
  - Different neutrino flavours resolved using timing.



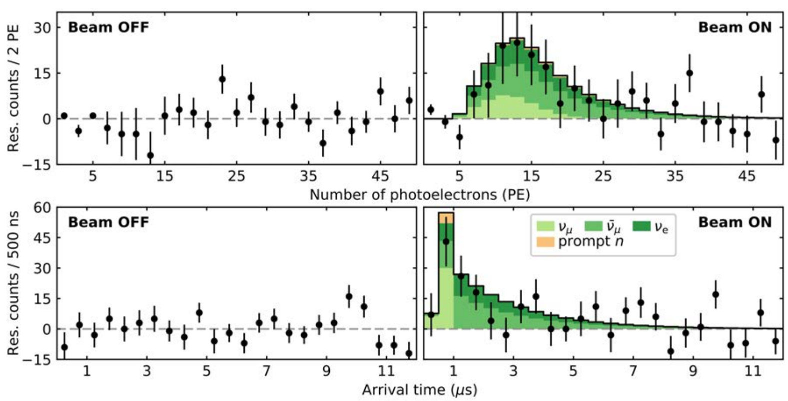






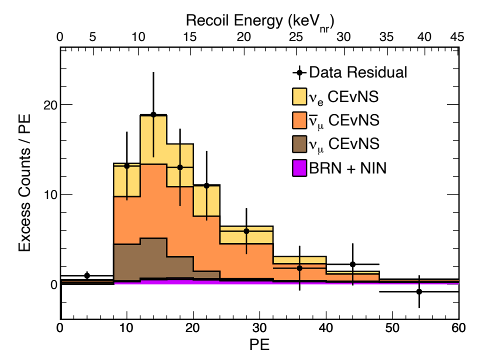
COHERENT CsI measurement

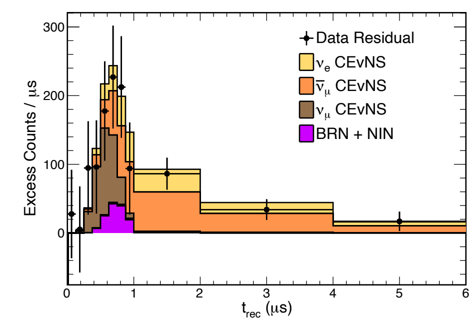
- First observation of CEνNS with the CsI[Na] detector in 2017.
- Full CsI[Na] dataset 2.2 times bigger, before decommissioning in 2019.
  - Updated scintillator response model, improved systematic uncertainties.
- Measurement of the CEνNS cross-section.
  - Compatible with the Standard Model prediction and most precise to date.
  - Limits on nonstandard neutrino interactions, weak mixing angle measurement.



134 ± 22 events observed
173 ± 48 events predicted
6.7σ significance

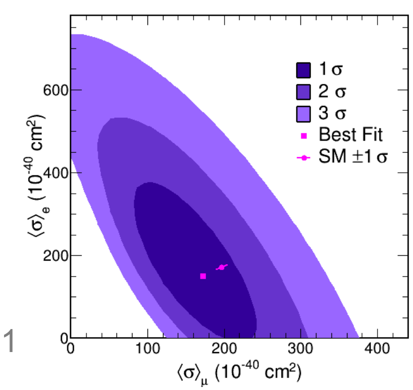
COHERENT collab., Science 357, 1123, 2017





$$\langle\sigma\rangle_\phi = (165^{+30}_{-25})\times 10^{-40}\ cm^2$$

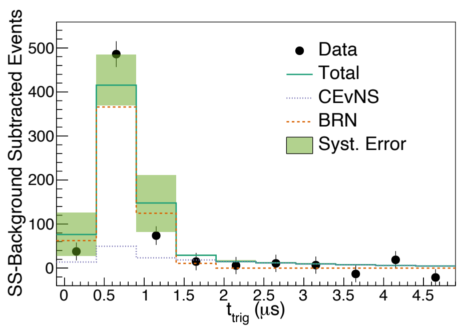
$$\sin^2\theta_W = 0.220^{+0.028}_{-0.026}$$
at $Q^2 \approx (50 MeV)^2$

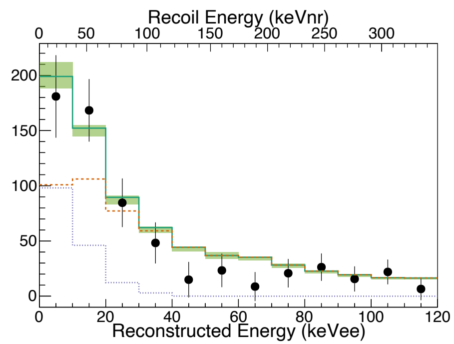


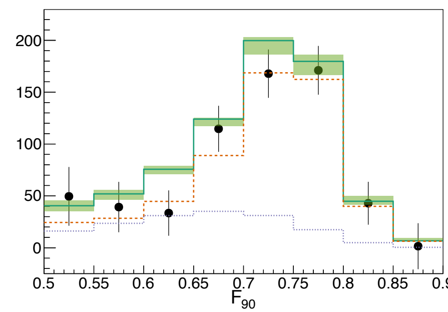
COHERENT collab., PRL 129 (2022) 8, 081801

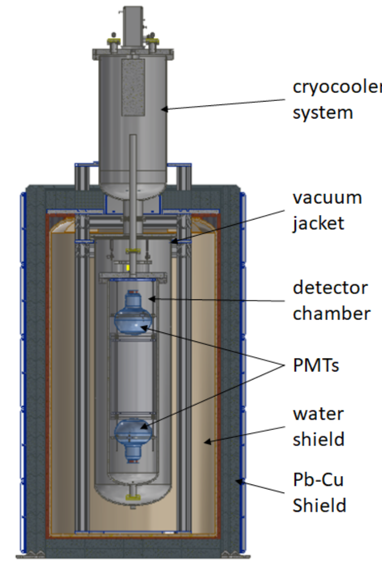
COHERENT Ar measurement

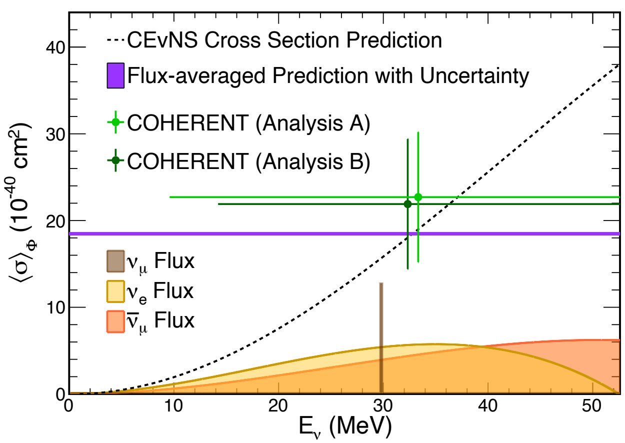
- CENNS-10 Liquid Argon single-phase (scintillation) detector.
  - 24.4 kg mass, 20 keV_{nr} threshold.
  - CEνNS excess with 3.5σ significance.
- Measurement of the CEνNS cross-section on argon.
  - First confirmation of its N^2 dependence.

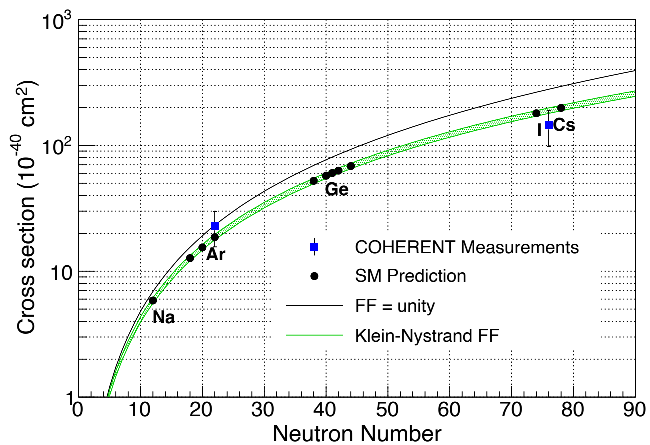








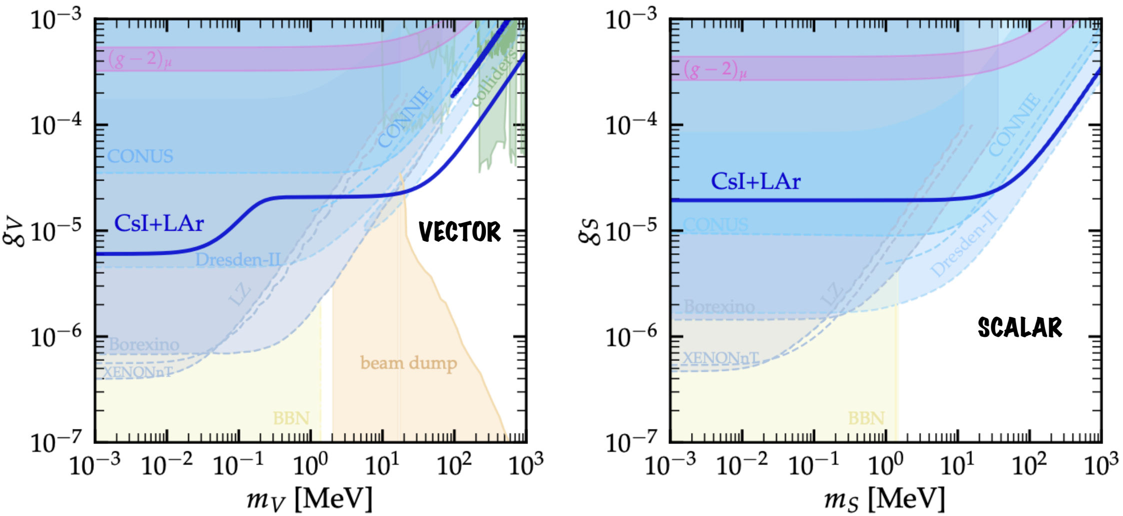




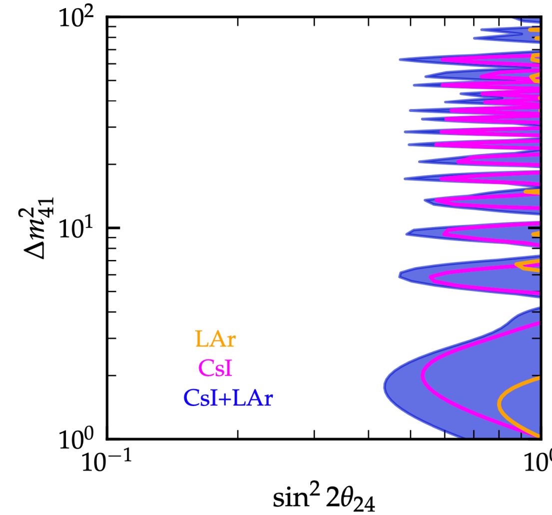
COHERENT collab.,
PRL 126 (2021) 1, 012002

COHERENT results impact

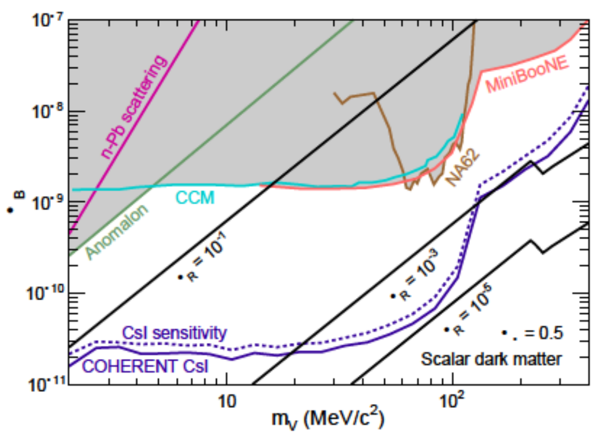
Limits on NSI with light vector and scalar mediators.



Limits on sterile neutrino oscillations.

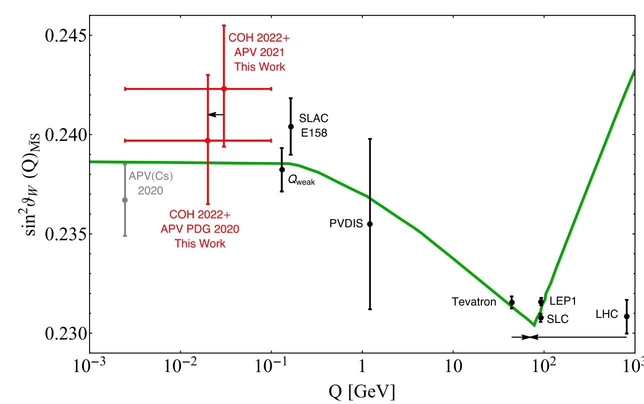


V. de Romeri et al, JHEP 04 (2023) 035



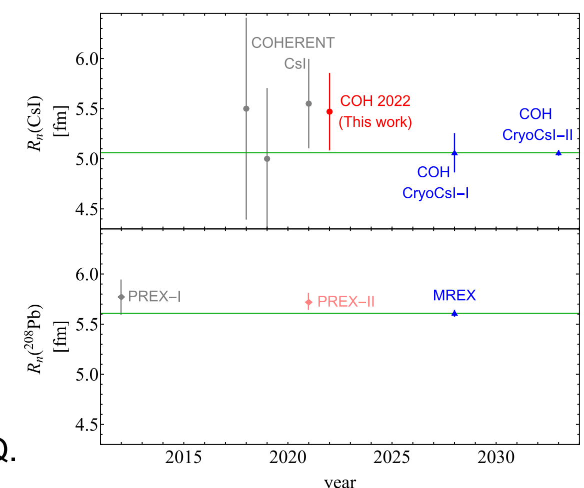
Limits on sub-GeV leptophobic dark matter.

COHERENT collab., PRD106 (2022) 5, 052004



Weak mixing angle measurement at low Q.

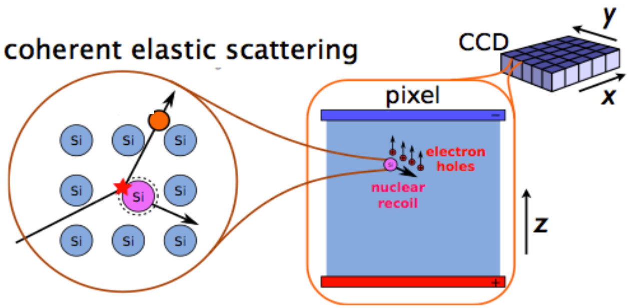
M. Corona et al, Eur. Phys. J. C (2023) 83:683

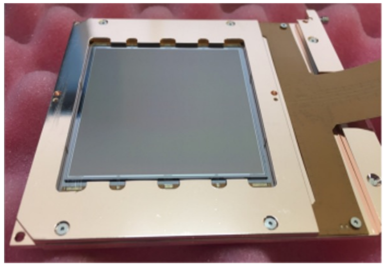


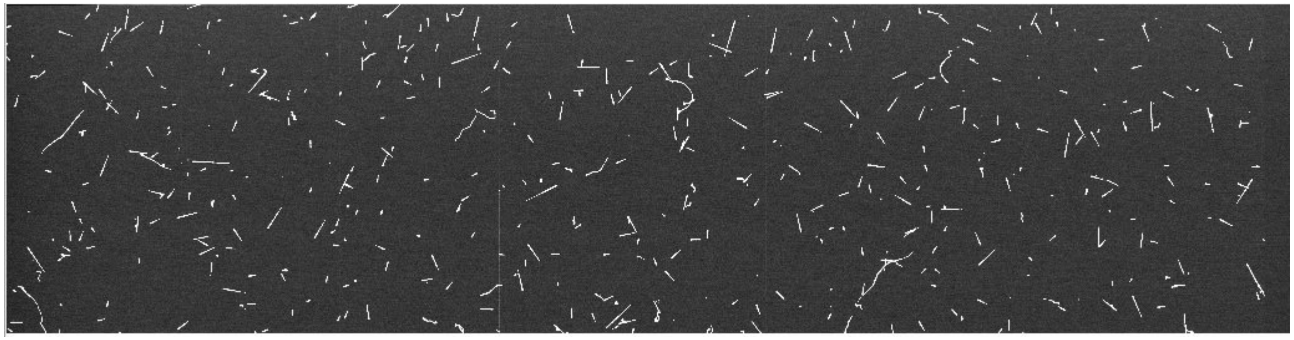
Neutron distribution radius.

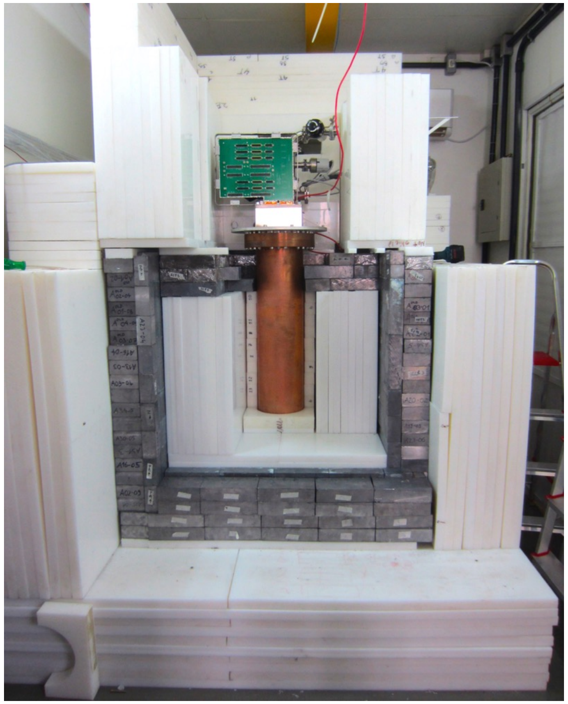
The CONNIE experiment

- Reactor neutrino experiment at 30 m from 3.95 GW_{th} the Angra 2 reactor in Brazil.
  - Low-energy (1-2 MeV) antineutrinos, flux 7.8 x 10^{12} $\bar{\nu} s^{-1} cm^{-2}$.
- Thick scientific silicon CCD detectors.
  - 8 CCDs of 6 g mass each, 16M pixels.
  - Passive polyethylene and lead shielding.
  - Particle identification based on event topology.







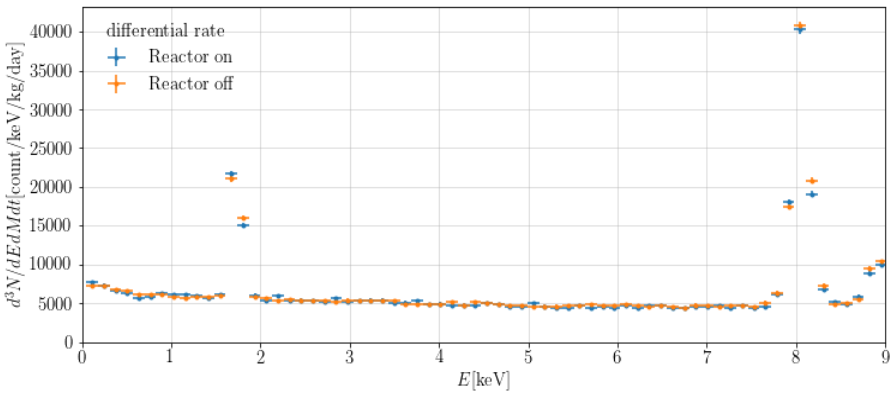


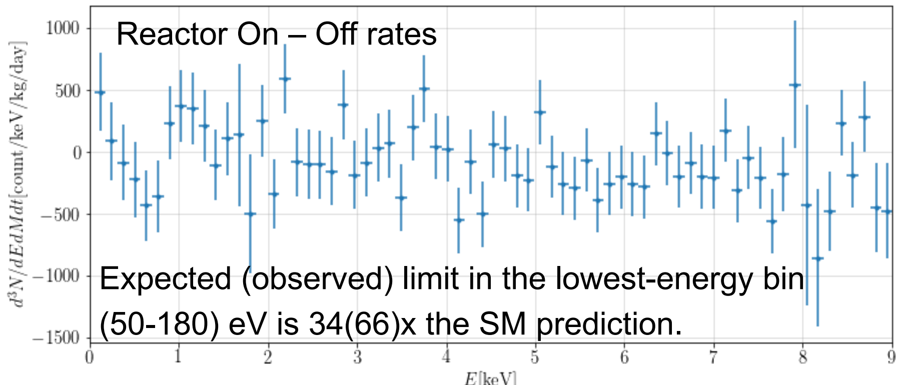
CONNIE collab., Phys. Rev. D100 (2019) 092005

CONNIE measurements

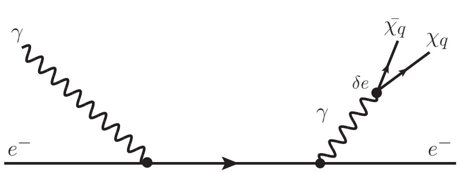
- Analysis compares the energy spectra with the reactor on and off in 2019 data.
  - Total exposure of 2.2 kg-days.
  - Low noise (~2 e-) and low dark current (~3 e-/pix/day).
  - Energy threshold 50 eV_{ee}.
- Upper limits on the measured neutrino rate at 90% CL.

CONNIE collab., JHEP 05:017, 2022

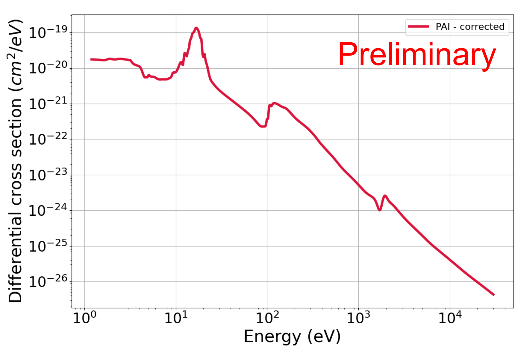


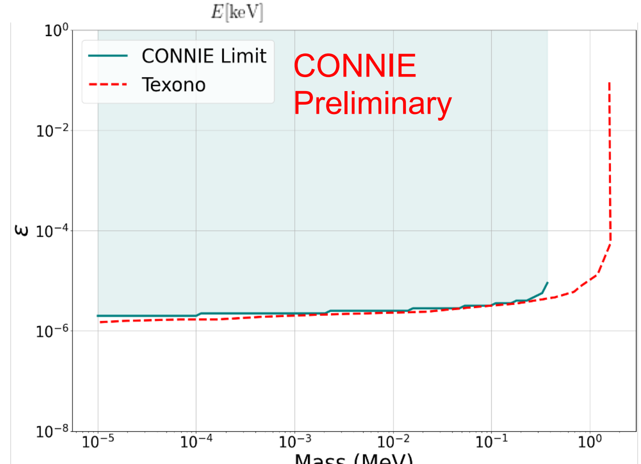


- Search for relativistic millicharged particle production.



Using first bin, (100-150) eV. Competitive limit, to update with full dataset.

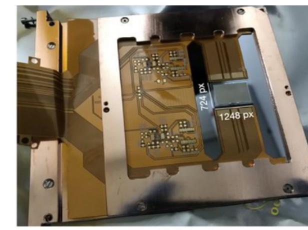


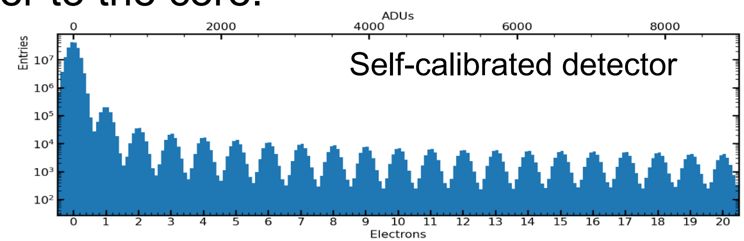


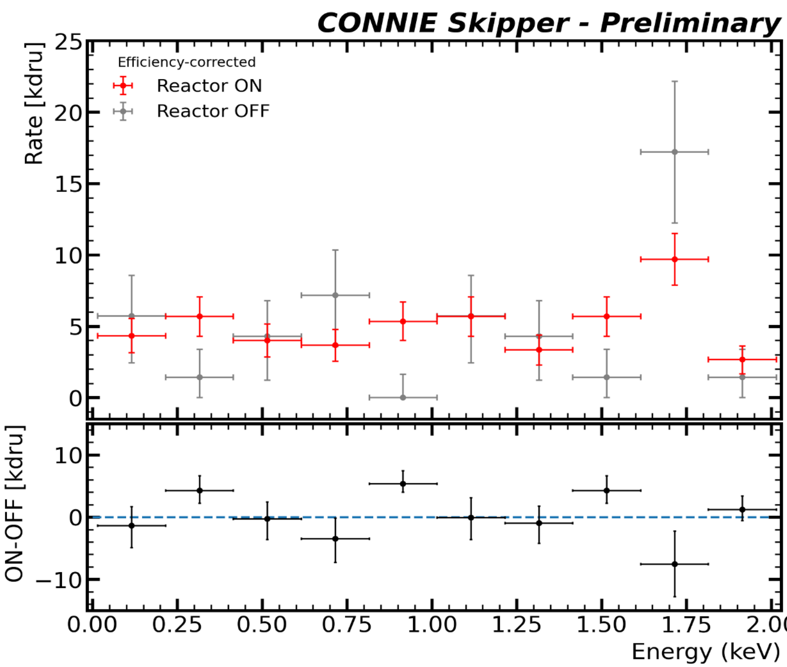
CONNIE with Skipper-CCDs

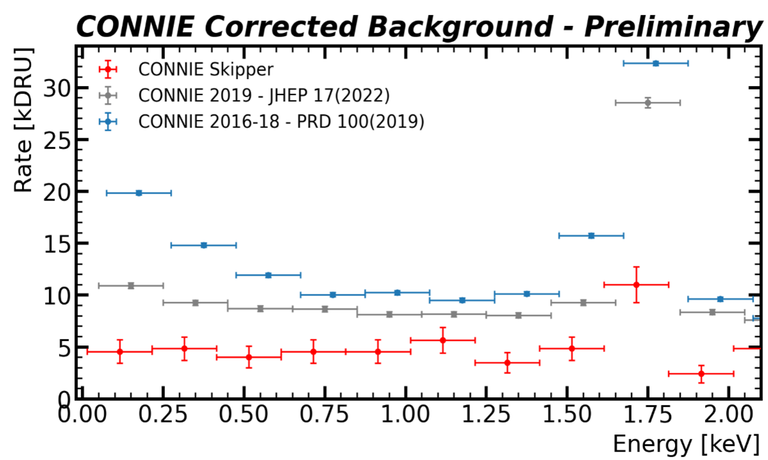
- 2 Skipper-CCDs (0.4 g mass) and new electronics installed in 2021.
  - Multiple non-destructive charge measurements.
  - Readout noise reduces as $1/\sqrt{N}$ samples.
- Stable performance and promising preliminary results.
  - Readout noise = 0.15 e-, single-electron rate = 0.04 e-/pix/day.
  - Energy threshold 15 eV_{ee}, lowest of any CEνNS experiment.
- Prospects to increase mass and move closer to the core.

J. Tiffenberg et al, PRL 119 (2017)



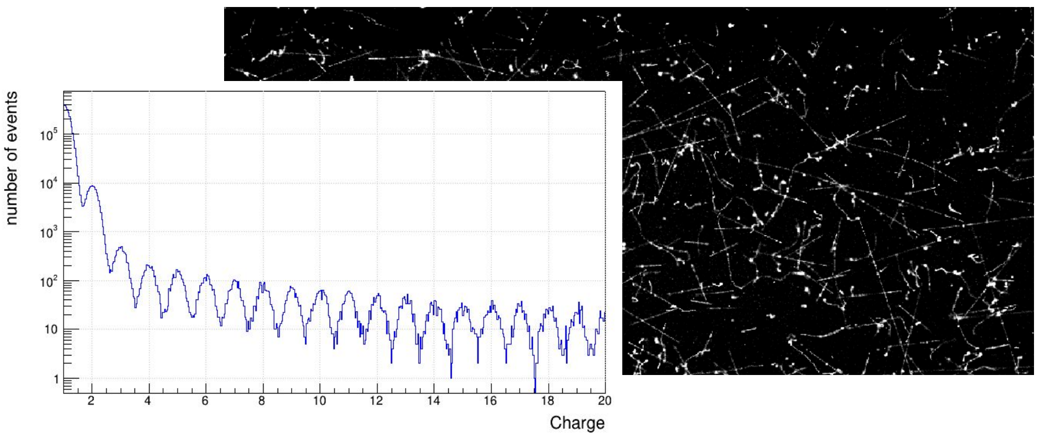


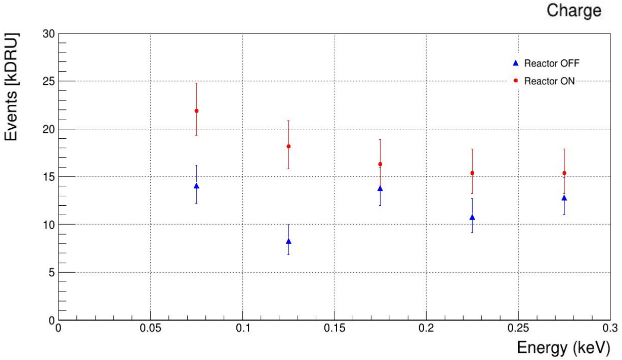


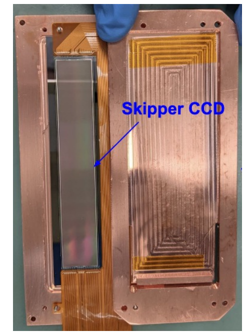


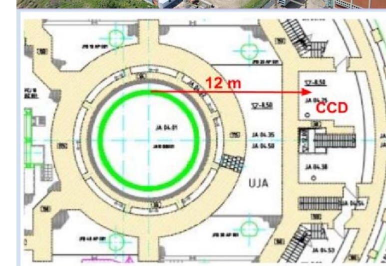
Skipper-CCDs at Atucha

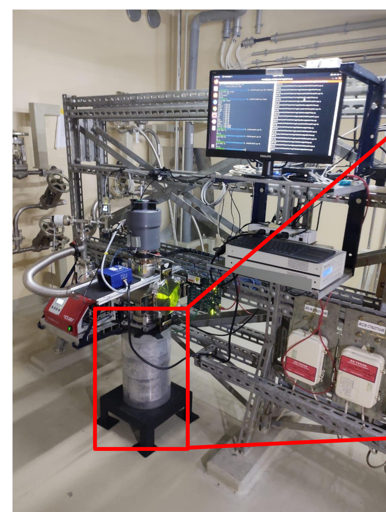
- Reactor neutrino experiment at 12 m from 2 GW_{th} the Atucha 2 reactor in Argentina.
  - Flux 2 x 10^{13} $\bar{\nu}s^{-1}cm^{-2}$.
- Taking data with Skipper-CCDs of 2.5 g.
  - Readout noise = 0.17e-.
  - Studying performance, background and reach.
  - New neutron shielding installed.









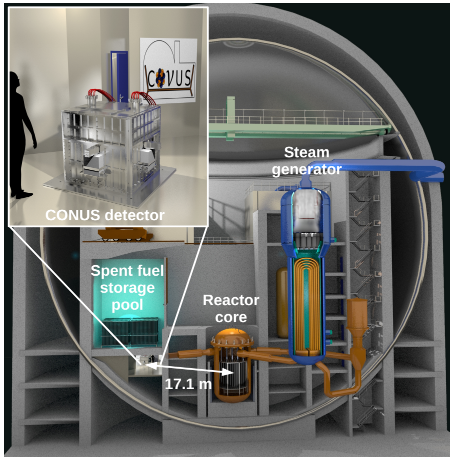


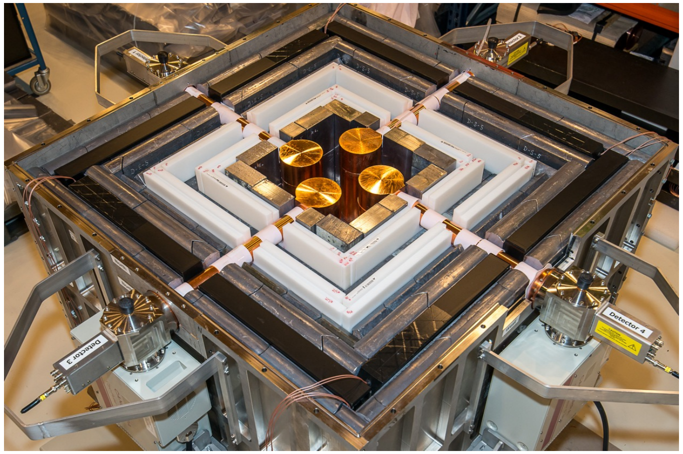
After

M. Cababie, TAUP2023

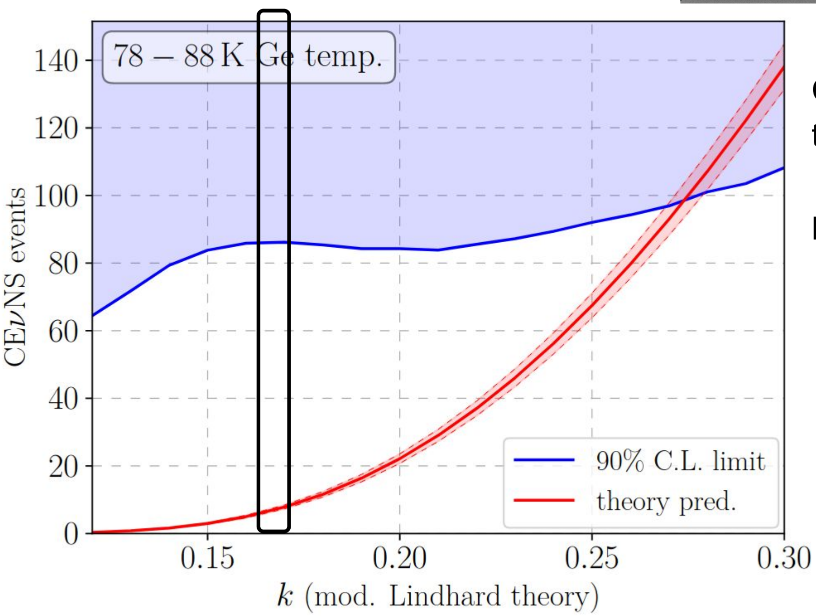
The CONUS experiment

- Reactor neutrino experiment at 17 m from 3.95 GW_{th} the Brokdorf reactor in Germany.
  - Flux 2.3 x 10^{13} $\bar{\nu}s^{-1}cm^{-2}$.
- Four 1-kg p-type point contact High-Purity Germanium detectors.
  - 24 m.w.e overburden, muon veto and passive shielding.
  - Run 1 & 2 data with threshold 300 eV_{ee}.
- Best limit on CEνNS in the fully coherent regime as a function of the quenching factor parameter k.





CONUS collab., PRL 126, 041804 (2021)



Confirms Lindhard theory QF = 0.162

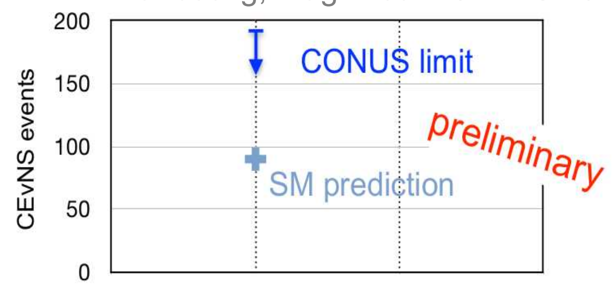
Limit 17x SM rate

CONUS results

- Improvements in run 5 before decommissioning the reactor in 2022:
  - Improved efficiency and temperature stability.
  - New pulse-shape discrimination.
  - Energy threshold down to 210 eV_{ee}.
- Limit on CEνNS using full dataset at 2x the SM prediction.
- Limits on electromagnetic properties from ν–e scattering:
  - Neutrino magnetic moment $\mu_\nu < 7.5 \cdot 10^{-11} \mu_B$
  - Neutrino millicharge $|q_\nu| < 3.3 \cdot 10^{-12} e_0$
- Limits on Non-Standard Interactions of neutrinos:
  - World best limits on tensor interactions.

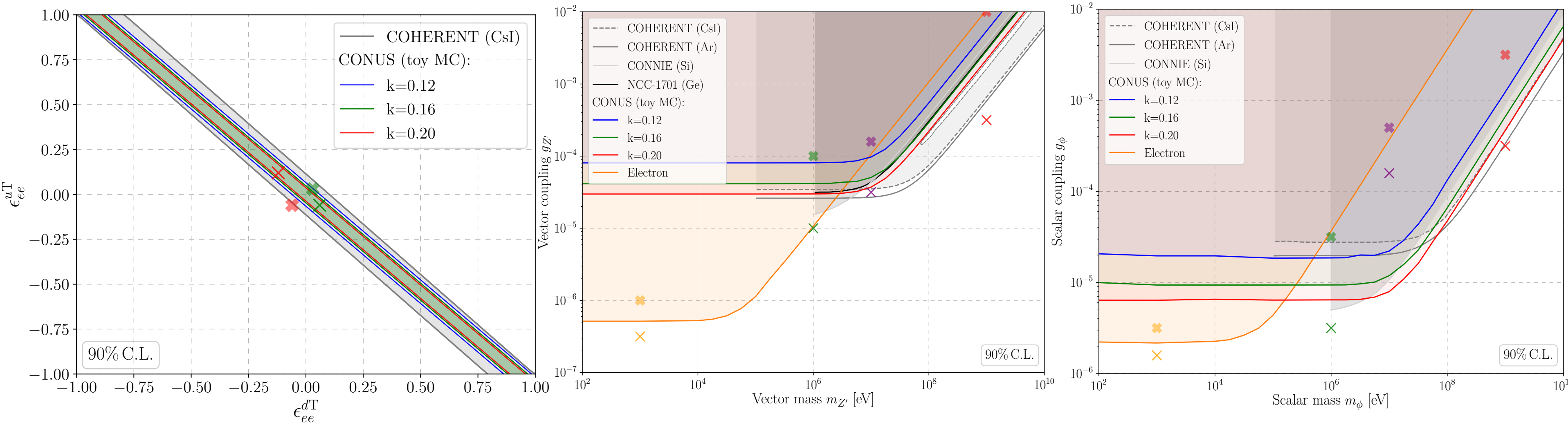
arXiv:2308.12105

W. Maneschg, Magnificent CEνNS 2023



EPJ C (2022) 82:813

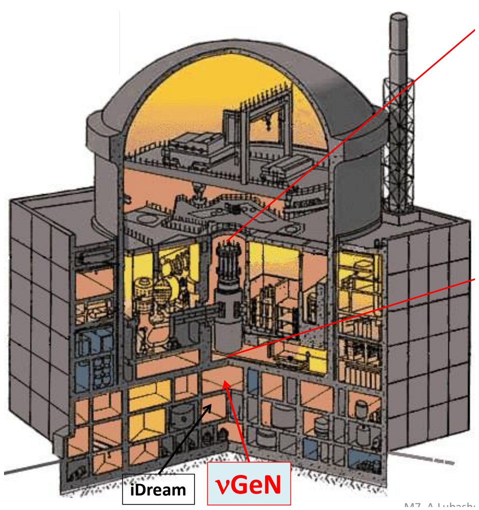
JHEP 05 (2022) 085

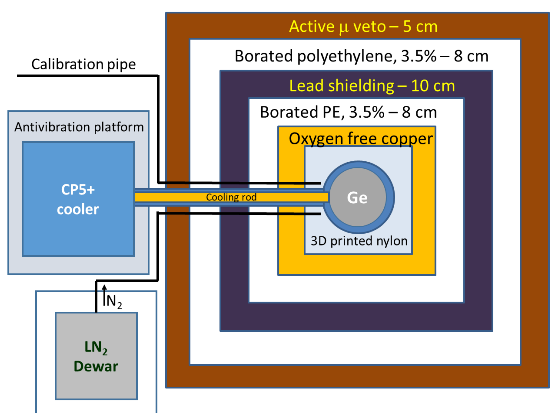


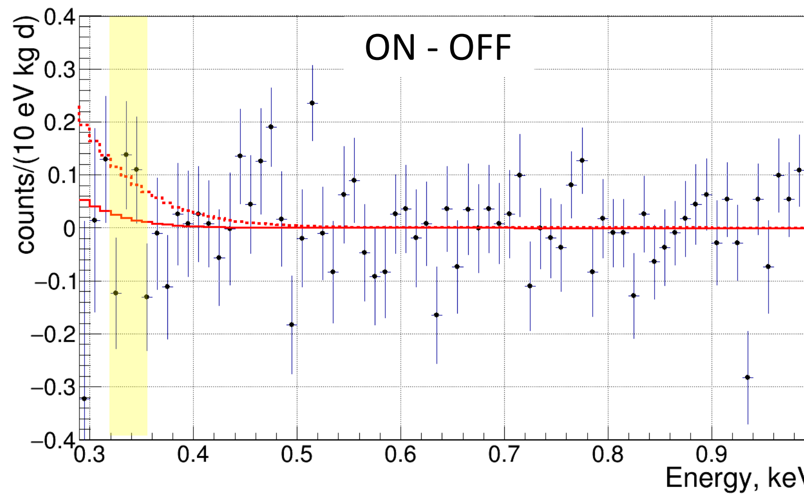
The nuGeN experiment

- Reactor neutrino experiment at 11 m from 3.1 GW_{th} the Kalinin reactor in Russia.
  - Flux 5 x 10^{13} $\bar{\nu}s^{-1}cm^{-2}$.
  - Distance to reactor can be varied 11-12 m.
- 1.5-kg p-type point contact High-Purity Germanium detector.
  - 50 m.w.e. overburden.
- Limits on CEνNS with 2021 and 2022 data.
  - Taking data with improved conditions since 2022.
  - Reduced background at low energy.

nuGEN collab., PRD 106 (2022) 5, L051101



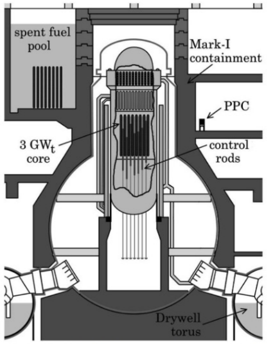


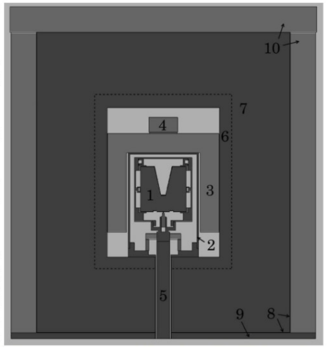


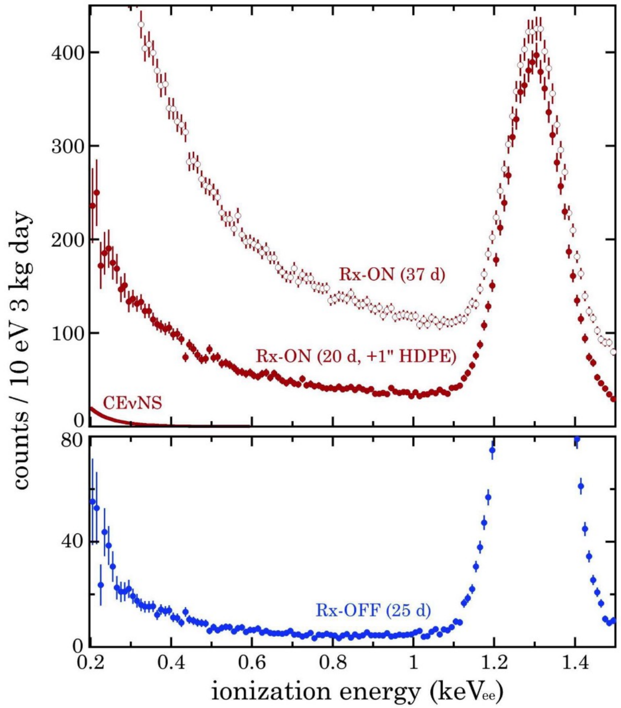
A. Lubashevskiy, Magnificent CEνNS 2023

NCC-1701 at Dresden II

- Reactor neutrino experiment at 8 m from 2.96 GW_{th} the Dresden-II reactor in USA.
  - Flux $8.1 \times 10^{13}\ \bar{\nu} s^{-1} cm^{-2}$.
- 3-kg p-type point contact High-Purity Germanium detectors.
  - Energy threshold 200 eV_{ee}.
- Excess in reactor-on data consistent with CEνNS.
  - Highly dependent on the quenching factor.
  - High backgrounds need better understanding.

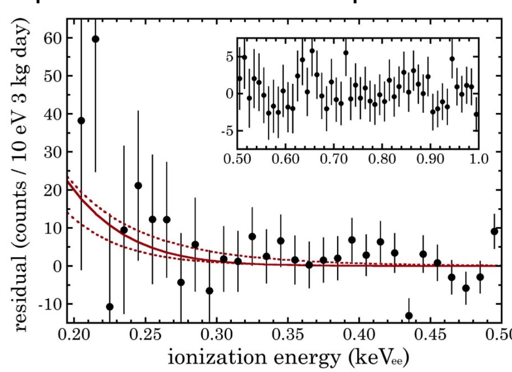




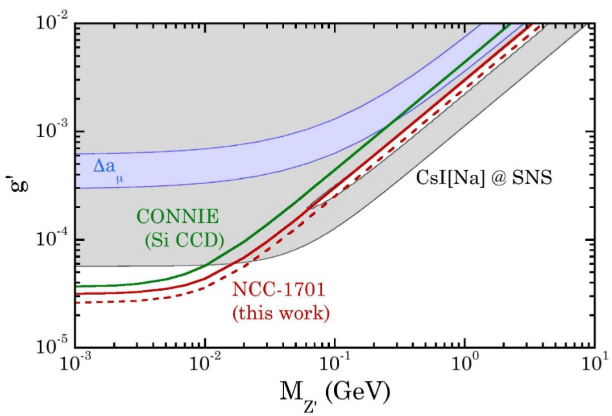


Epithermal neutrons dominate low energies.

Spectrum after subtraction of modeled epithermal neutron component



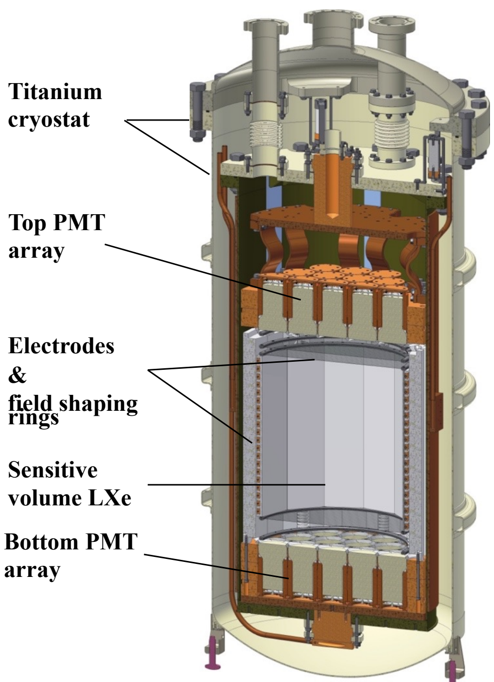
Limit for low-mass vector mediators

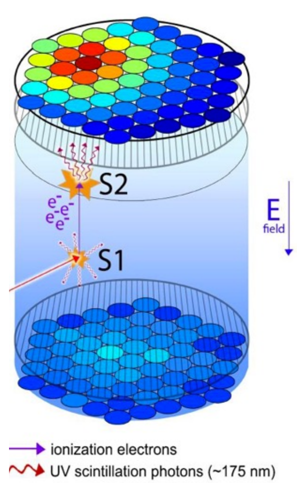


J. Colaresi et al, PRD 104 (2021) 7, 072003

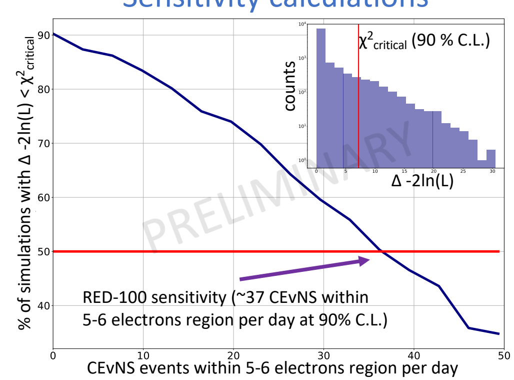
The RED-100 experiment

- Reactor neutrino experiment at 19 m from 3.1 GW_{th} the Kalinin reactor in Russia.
  - Flux $1.35 \times 10^{13}\ \bar{\nu} s^{-1} cm^{-2}$.
- 100-kg two-phase liquid Xenon emission detector.
  - 50 m.w.e. overburden.
  - Sensitive to single ionisation electrons.
  - Multivariate selection and blind analysis.
- Plans to substitute LXe for LAr, higher recoil energies.

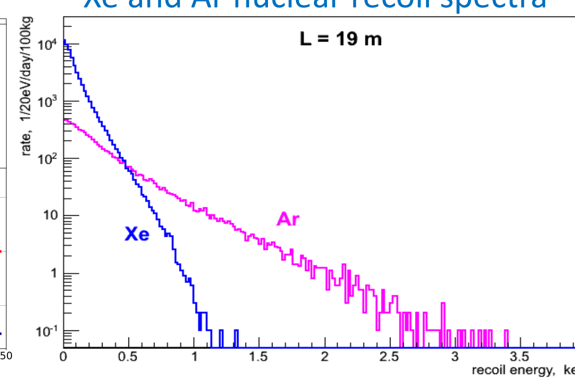




Sensitivity calculations



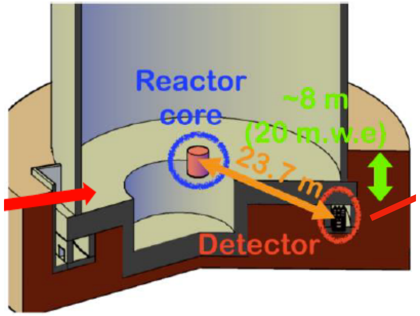
Xe and Ar nuclear recoil spectra

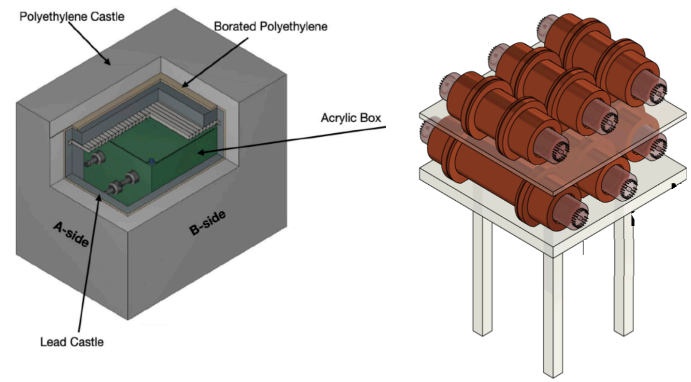


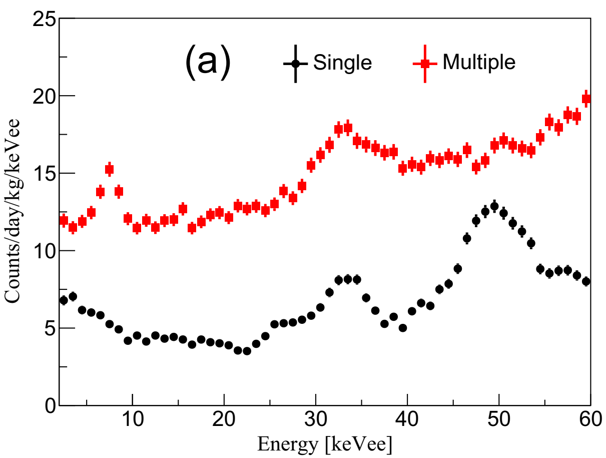
D. Rudnik, Magnificent CEνNS 2023

The NEON experiment

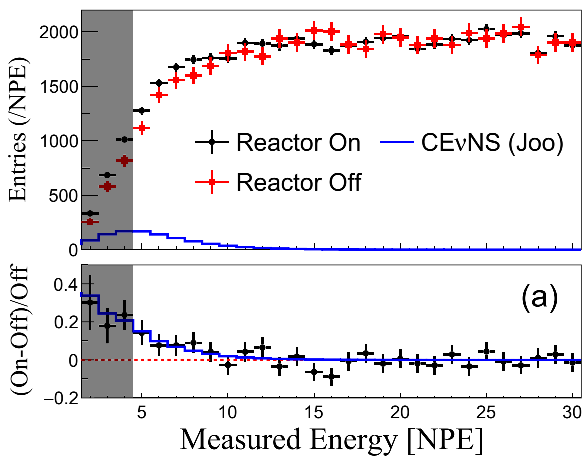
- Reactor neutrino experiment at 23.7 m from 2.8 GW_{th} the Hanbit 6 reactor in Korea.
  - Flux 7.1 x 10^{12} $\bar{\nu}s^{-1}cm^{-2}$.
- 16.7-kg scintillator NaI[Tl] detectors.
  - Lower cross-section but higher recoils in Na, 22 PE/keV yield.
  - Energy threshold 200 eV_{ee}.
- Taking data and studying expected sensitivity to CEνNS.
  - Background 7 dru at low energy.
  - Expect 3σ with 1 year on and 100 days off.







(a) 2–60 keVee

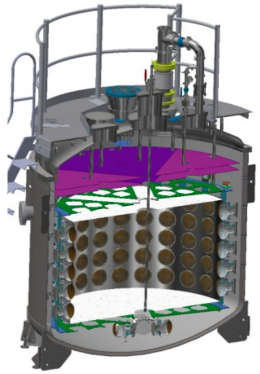


NEON collab., Eur.Phys.J.C 83 (2023) 3, 226

Future experiments

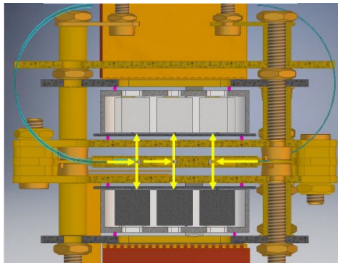
Coherent Captain Mills (CCM)

- 7t LAr instrumented cryostat.
- Lujan Center @ LANSCE.
- Engineering run ongoing.



NUCLEUS

- g-scale $CaWO_4$ and Al_2O_3 bolometer crystals @mK.
- Threshold 20 eV.
- At the CHOOZ reactors.



Gaseous detector for Neutrino physics at the ESS (GaNESS)

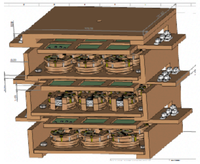
- Plans for 20-kg Xe high pressure TPC.
- At the European Spallation Source.

RICOCHET

A Coherent Neutrino Scattering Program

- Cryogenic phonon detectors.
- Threshold 100 eV.
- At the ILL reactor.

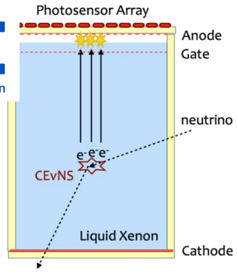
CRYOCUBE
Ge (& Si?)



Neutrino Detection with Xenon

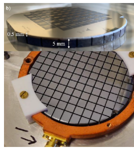
NUXE – Neutrino Detection with Xenon

- Single-electron sensitive LXe detector.
- R&D for 10-kg detector for reactor.



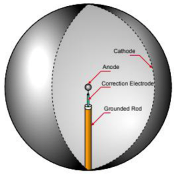
BULLKID

- Si/Ge w/ kinetic inductance detectors.



NEWS-G3

- Spherical Proportional Counter.
- Working on final design



Scintillating Bubble Chamber (SBC)

- Quasi-bkg-free detection in Ar/Xe.

PALEOCCENE

- Colour centre passive detectors.

Summary

- The recent first observation of coherent elastic neutrino-nucleus scattering by COHERENT has led to a prolific physics programme.
  - Novel experimental techniques for low-threshold, low-background detection.
  - Theory interpretations and predictions.

- Many ongoing efforts and next-generation experiments.
  - Complementary approaches.
  - Expect more exciting results soon.

- Rich physics potential for neutrino discoveries and applications to areas beyond.