CEvNS and BSM physics with the reactor neutrino experiment CONUS

On behalf of the CONUS Collaboration

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

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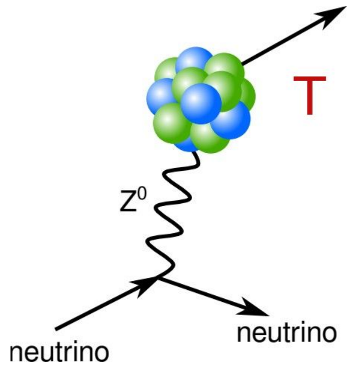
(MPIK)

ICHEP (Bologna), 8 July 2022

Coherent elastic neutrino nucleus scattering



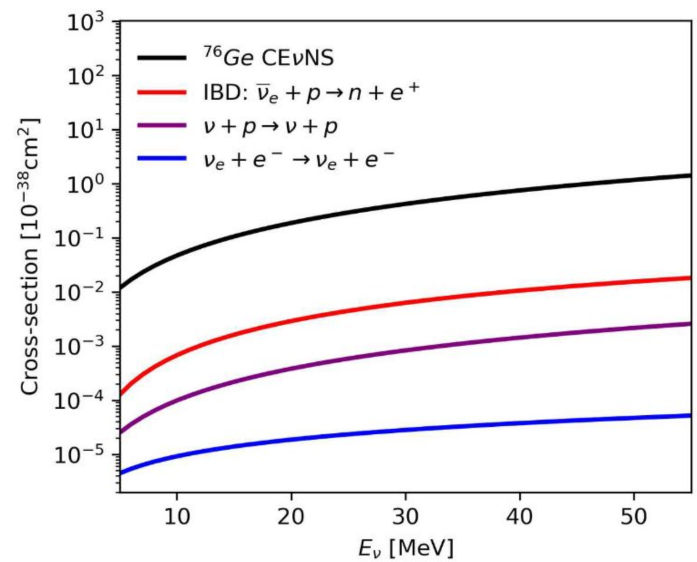
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi}\underbrace{\left[N - \left(1 - 4\sin^2\theta_W\right) Z\right]^2}_{\theta_W \sim 0.238 \;\to\; N^2} M\left(1 - \frac{MT}{2E_\nu^2}\right)\underbrace{F^2(q^2)}_{F^2 \to 1}$$

Low momentum transfer → full coherence (in Ge E_ν< 20 MeV).

CEvNS cross section is “large”. Small, potentially mobile neutrino detectors feasible.

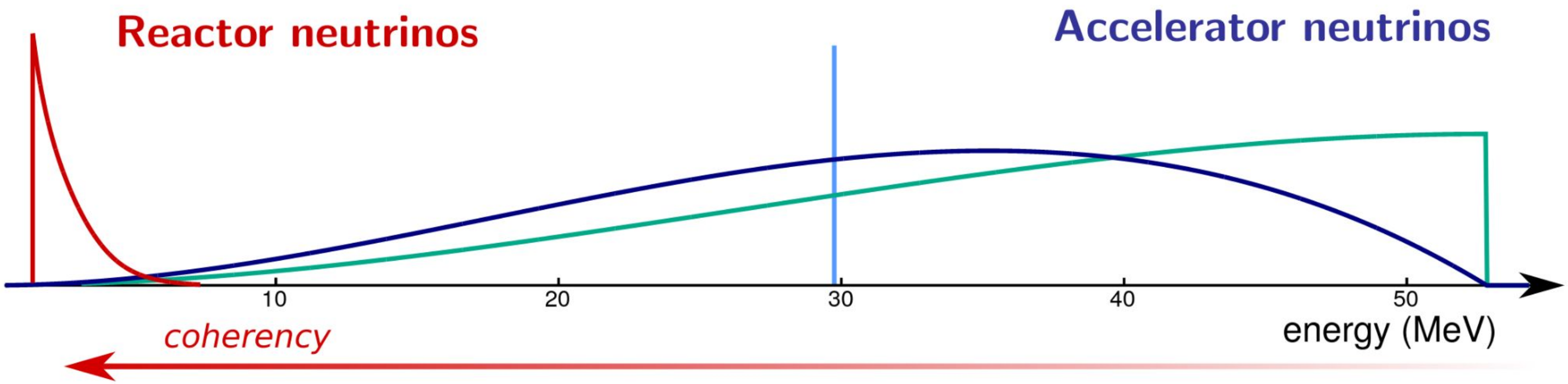
Experimental signature: low energy recoil of the nucleus:

$$T_{Max} \approx \frac{2\,E_\nu^2}{m_n A}$$



<u>The isotope selection is a push-pull situation.</u>

Experimental detection of CEvNS



$\bar{\nu}_e$ from β-decays of fissile isotopes.

Pure flux of $\bar{\nu}_e$.

E_ν ~ 0-10 MeV (fully coherent → F ~ 1).

Still no observation. Claim few months ago (arxiv:2202.09672). Many experiments ongoing.

ν from π-DAR.

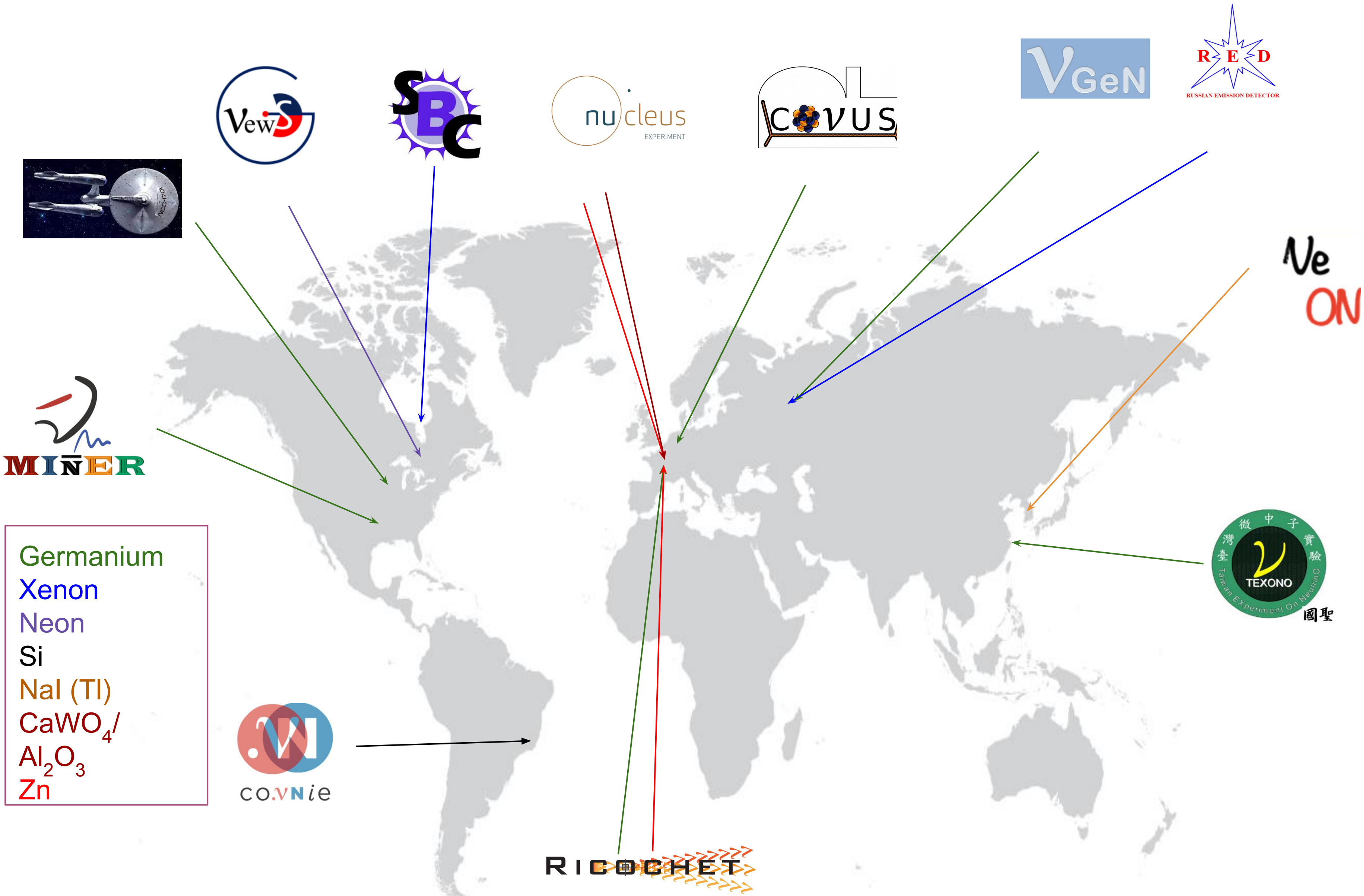
Different neutrino flavors.

E_ν ~ 20-50 MeV (F < 1).

Observation by COHERENT with CsI[Na] in 2017 and with Ar in 2020.

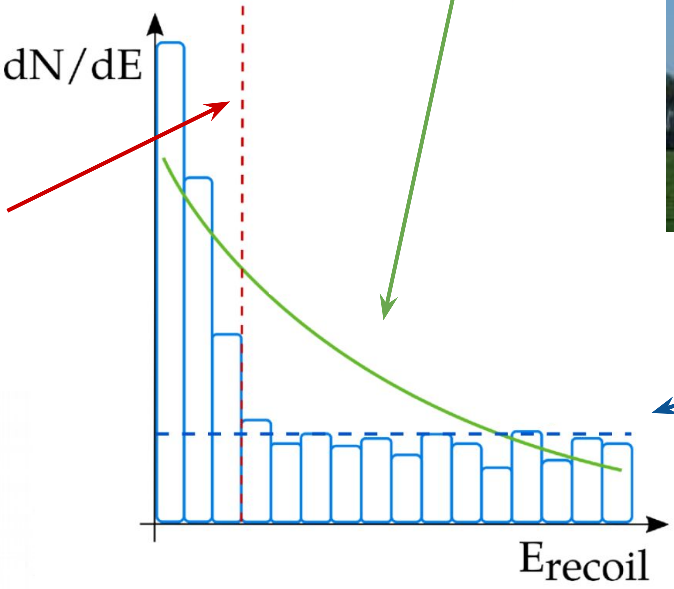
<u>Complementary experiments</u>

CEvNS detection at reactors



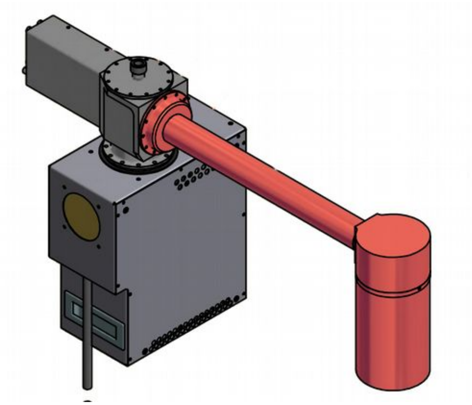
Experimental detection of CEvNS

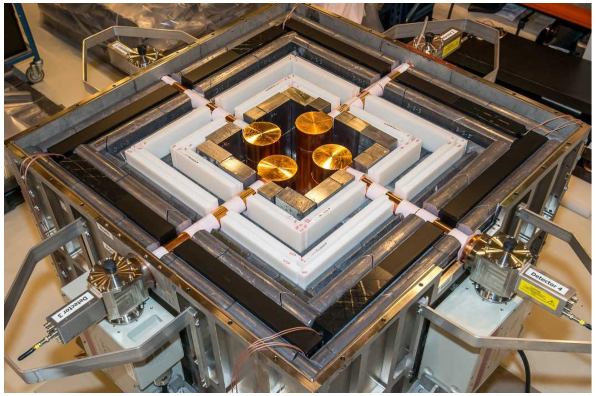
Strong neutrino source. Commercial reactors
and/or large active mass.



Low energy threshold.
Point-contact HPGe
detectors.

Low background: ultrapure
materials and shielding.





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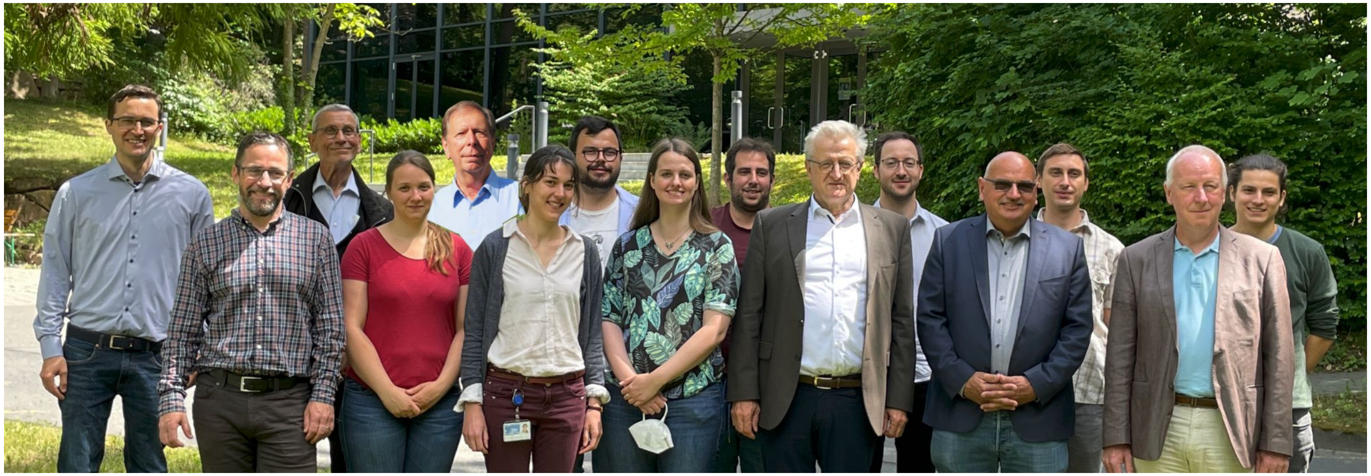


Max Planck Institut fur Kernphysik (MPIK)

N. Ackermann, H. Bonet, A. Bonhomme, C. Buck,
J . Hakenmüller, J. Hempfling, J. Henrichs, G. Heusser,
T. Hugle, M. Lindner, W. Maneschg,T. Rink,
E. Sanchez Garcia, J. Stauber and H. Strecker

Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR)

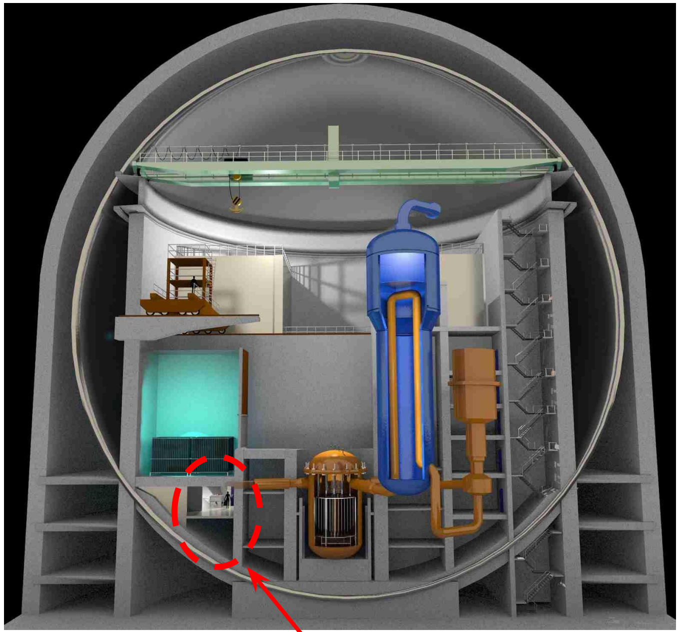
K. Fülber and R. Wink

Experimental site

CONUS is installed in the Brokdorf nuclear power plant (KBR) in Germany.

Experimental conditions:

- 17 m from 3.9 GWth reactor core → high antineutrino flux expected $2.3 \times 10^{13}\ \bar{\nu}_e\ s^{-1} cm^{-2}$.
- High duty-cycle: 1 month/year of reactor-off.
- Shallow-depth site (24 m w.e.).



CONUS

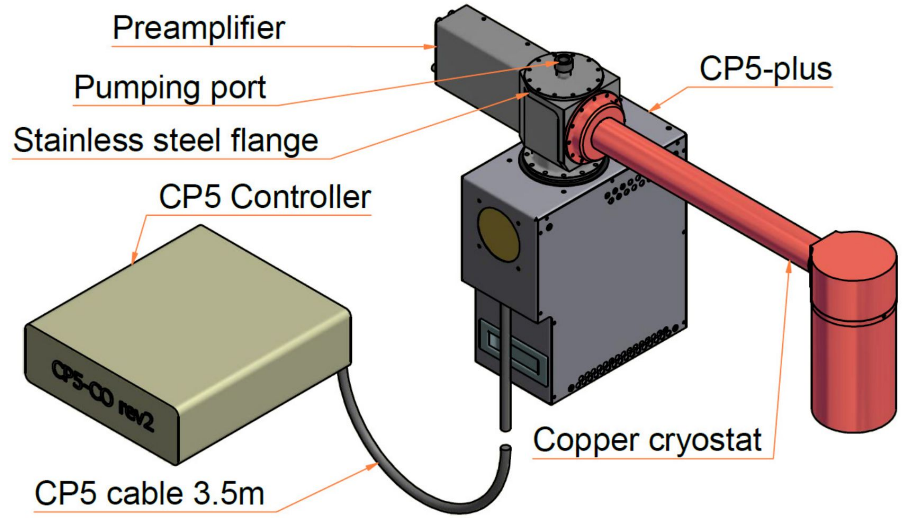
Working conditions:

- Strict access permission.
- Strict safety requirements.
- No cryogenic liquids

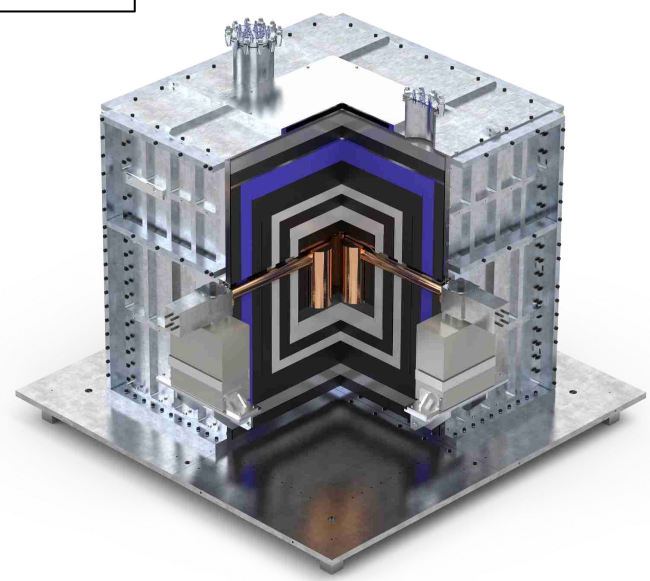
CONUS detector

4 p-type point contact HPGe:

- Total crystal/active mass: 4 kg /3.74kg.
- Pulser resolution (FWHM) < 80eVee.
- Energy threshold ≤ 300eVee.
- Radiopure components.



1.6 m^3
11 tons



Active + passive shielding:

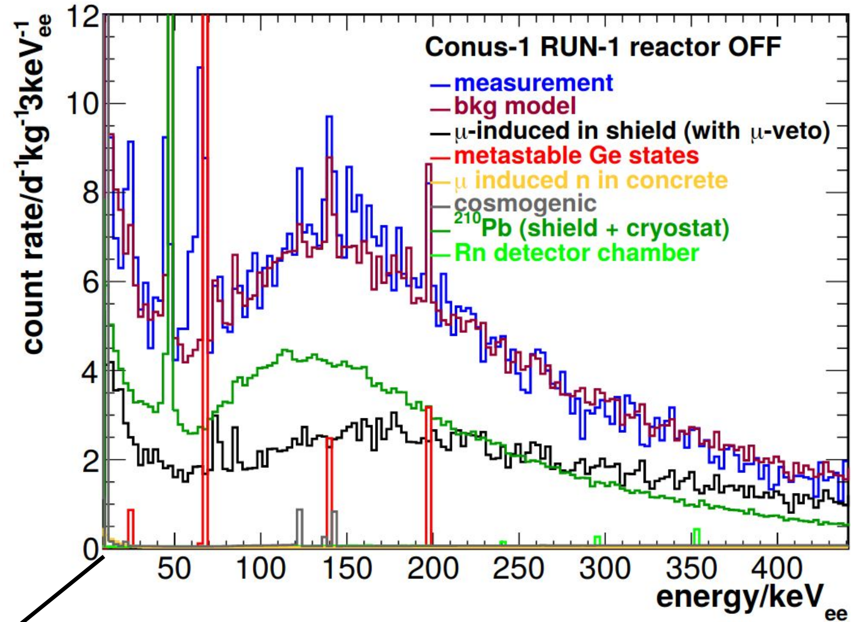
- Low ^{210}Pb lead.
- Borated and pure PE.
- Active μ-veto (plastic scintillator).

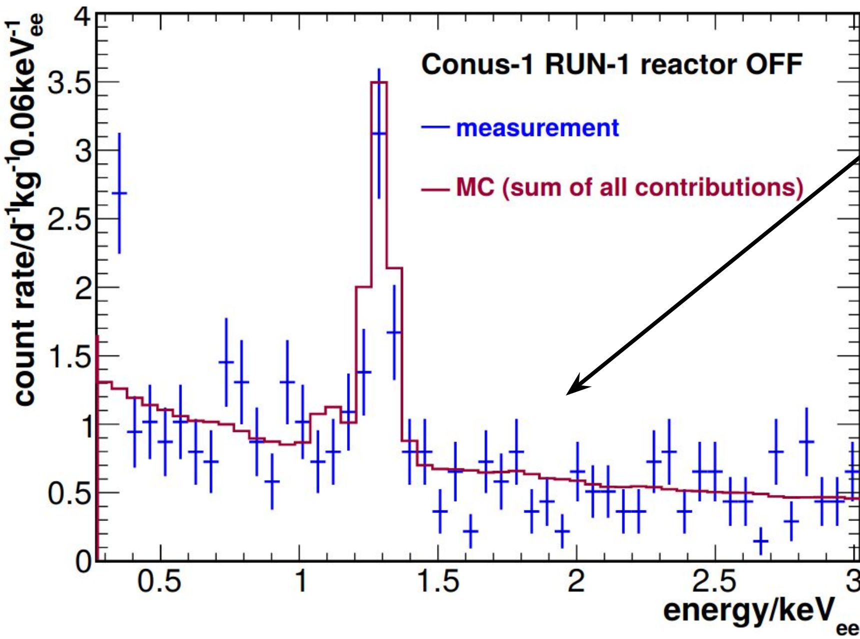
CONUS Collaboration, Eur. Phys. J. C (2021) 81, 267

Background in CONUS

Neutron spectrometry with NEMUS detectors with PTB and γ's measurements from non shielded HPGe detectors.

Reactor-correlated background inside shield negligible.





Background level in [0.5 − 1] keV_{ee} stable: ~10 counts/kg/d/keV_{ee} .

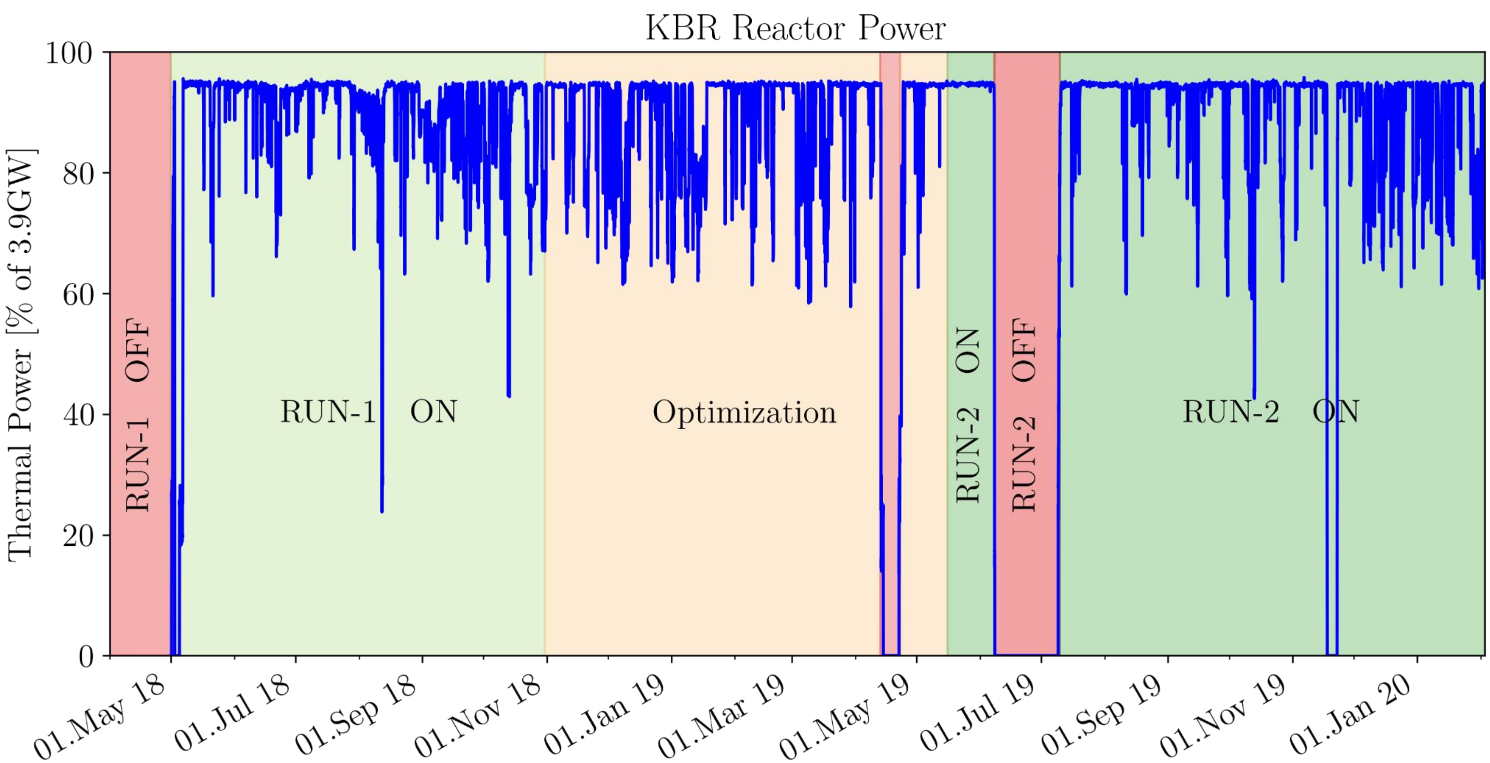
Residual background fully described by MC simulations.

J. Hakenmueller et al., Eur. Phys. J. C (2019) 79, 699
CONUS Collaboration, arXiv:2112.09585

Data period for analysis

Run-1+2 (2018-2019) exposure after all cuts:

Det.	RUN	ON [d]	OFF [d]	ROI [keV_{ee}]
C1	1	96.7	13.8	0.296 - 0.75
C2	1	14.6	13.4	0.311 - 1.00
C3	1	97.5	10.4	0.333 - 1.00
C1	2	19.6	12.1	0.348 - 0.75
C3	2	20.2	9.1	0.343 - 1.00
Total		248.7 kg*d	58.8 kg*d	



CEvNS analysis

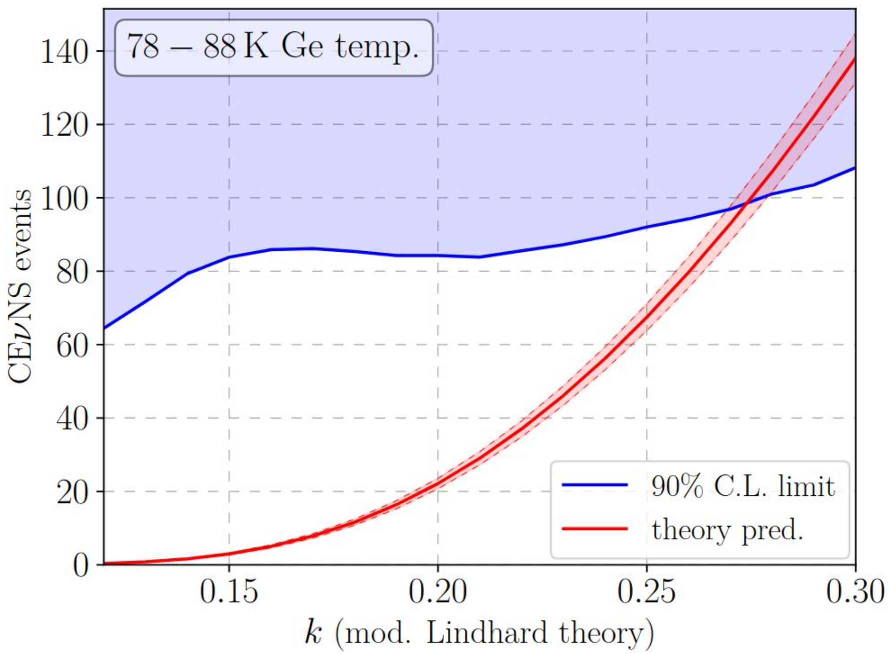
CONUS Collaboration, PRL 126 (2021) 041804

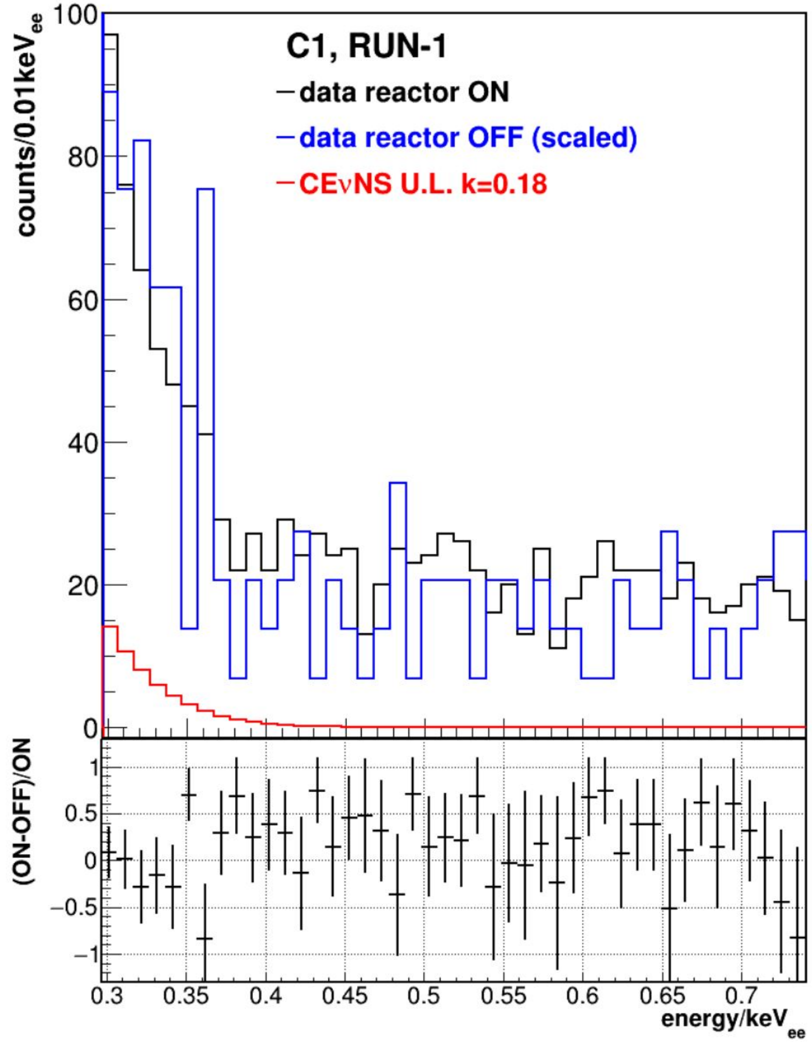
Simultaneous likelihood fit ON/OFF for all detectors and runs.

<u>CEvNS limit at reactor: < 0.4 d^{-1} kg^{-1} (90 % C.L.) at k=0.16. Factor 20 over prediction.</u>

Signal expectation depends on quenching factor described by Lindhard theory. k > 0.27 disfavored from CONUS reactor data alone.

Major systematics: quenching parameter





Quenching measurement

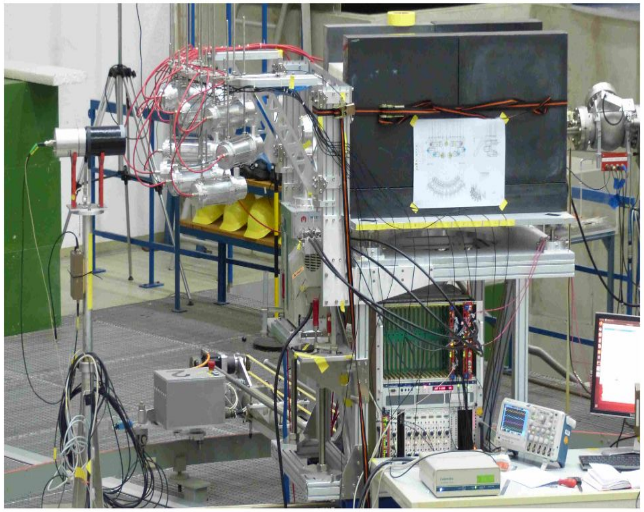
CONUS and PTB collaboration for a direct, model-independent (purely kinematics) measurement using neutrons (nuclear recoils).

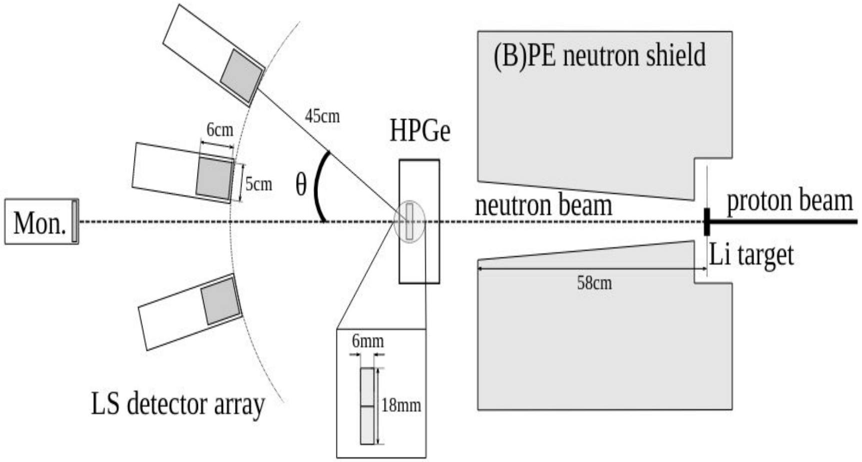
Scientific cooperation with PTB. PIAF pulsed proton beam to generate mono-energetic neutron beams via Li(p,n) reaction.

Dedicated thin HPGe as target (6 mm thick).

Triple time coincidence: beam stop – target HPGe – liquid scintillator detectors.

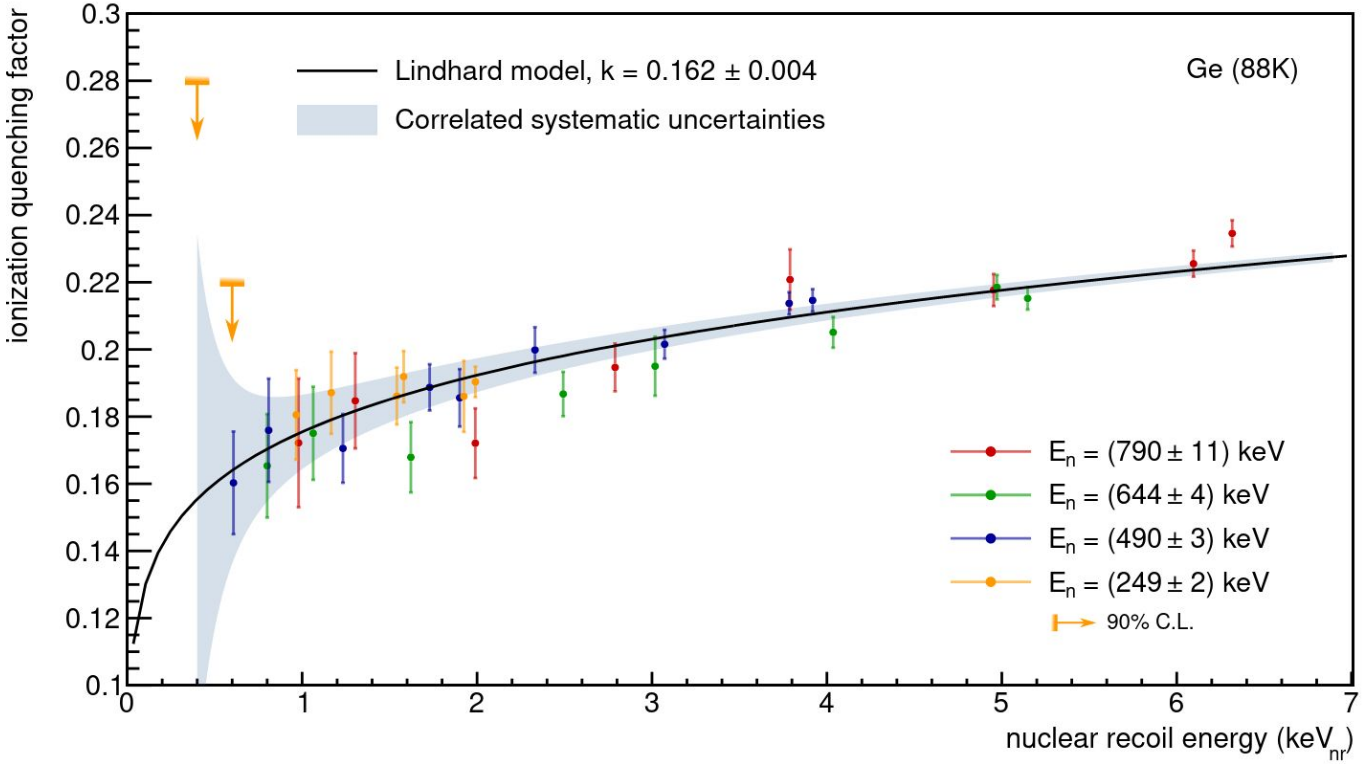
Angles varied between 18-45° (1° precision) and neutron beam from 250 to 800 keV
→ <u>nuclear recoils: 0.4 - 6 keV</u>





Quenching measurement

A. Bonhomme et al. , arXiv:2202.03754



All relevant systematic uncertainties included: setup geometry, beam energy, detector response including energy scale non-linearities.

Data compatible with Lindhard theory down to sub-keV: <u>k = 0.162 ± 0.004 (stat+syst).</u>

Non-standard interactions

CONUS Collaboration,
J. High Energ. Phys. 2022, 85 (2022)

CONUS is sensitive to physics beyond the standard model, as non-standard neutrino-quark interactions. New coupling with nuclear charge term adding to CEvNS cross-section:

$$\left(\frac{d\sigma}{dT_N}\right) = \left(\frac{d\sigma}{dT_N}\right)_{CE\nu NS} + \frac{4G_F^2 M}{\pi} Q_{NSI}{}^2 \left(1 - \frac{MT_N}{4E_\nu^2}\right).$$

ROI: 0.3-1 keV
Exposure: 208 kg*d ON 38 kg*d OFF

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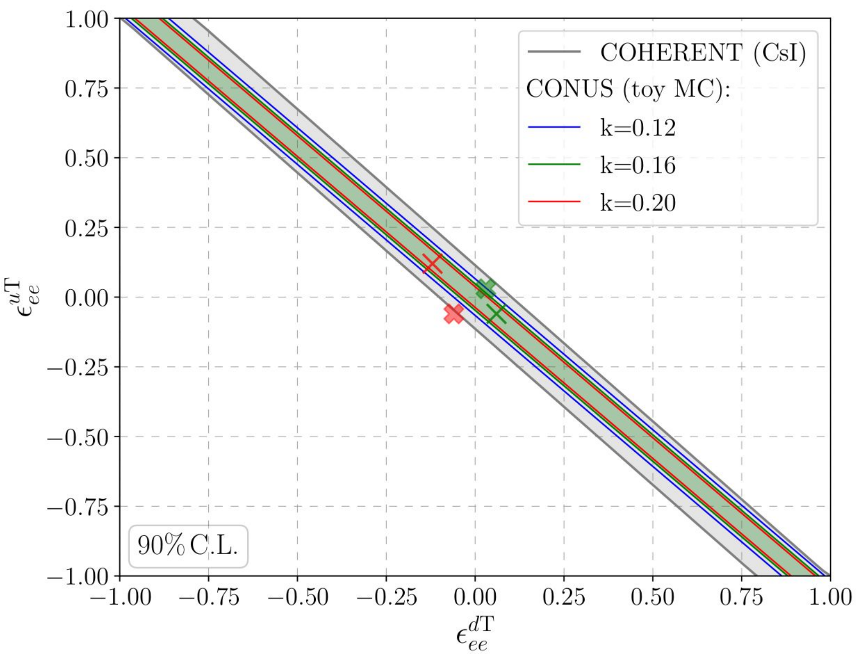
Tensor-type interaction



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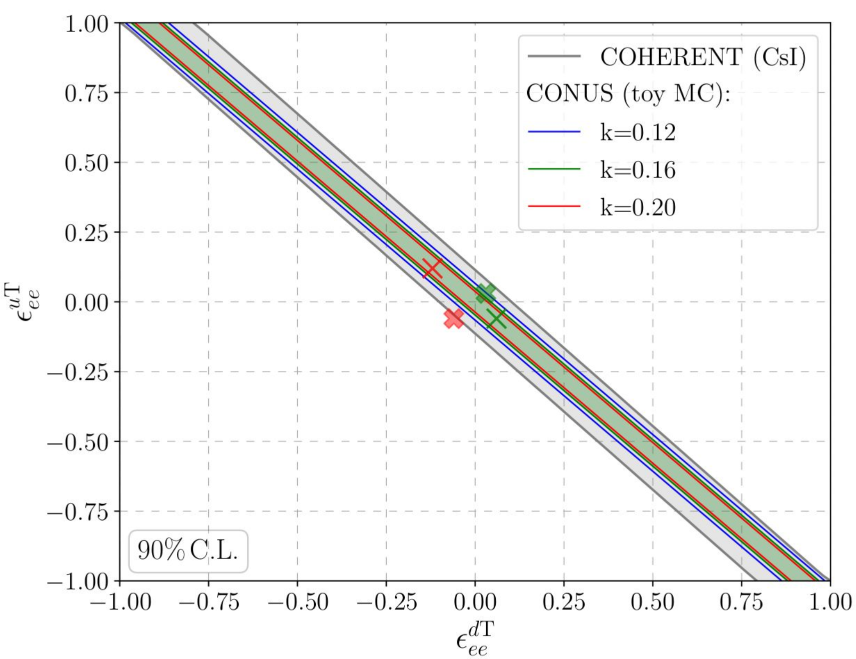
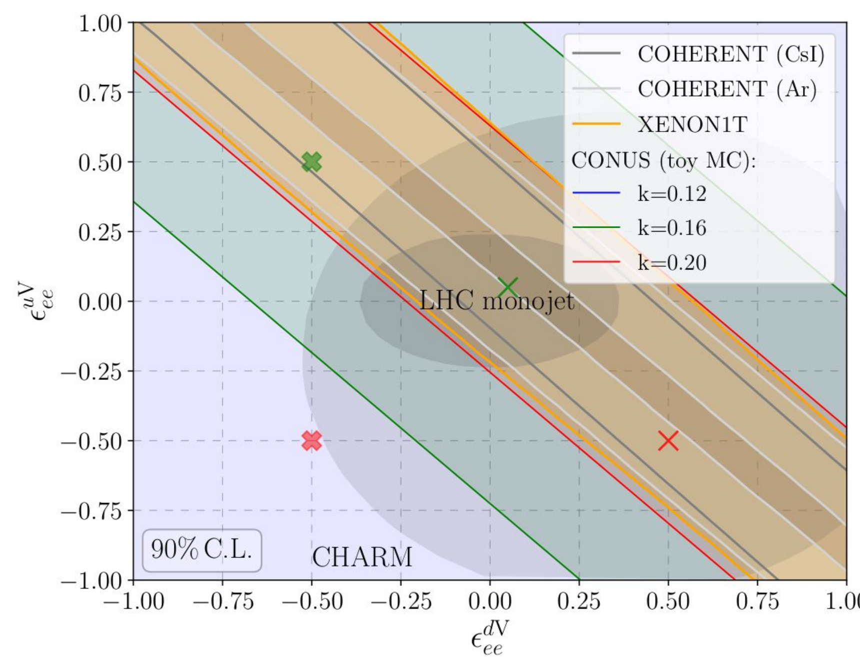


Vector-type interaction



Simplified models: Light mediators

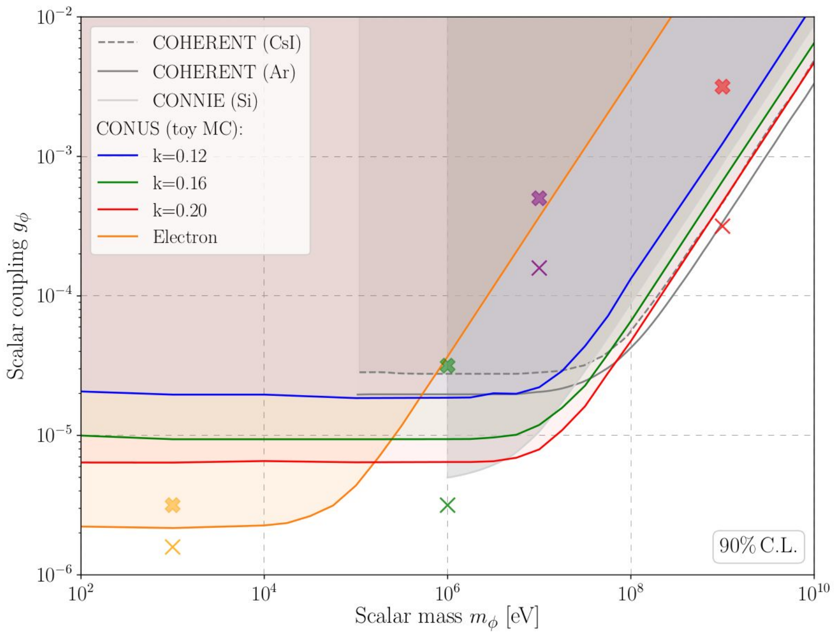
Test simplified mediator models that contribute to **CEvNS** / **EvES** assuming universal couplings to quarks / neutrinos.

Reactor neutrinos for low masses and π-DAR neutrinos for higher masses.

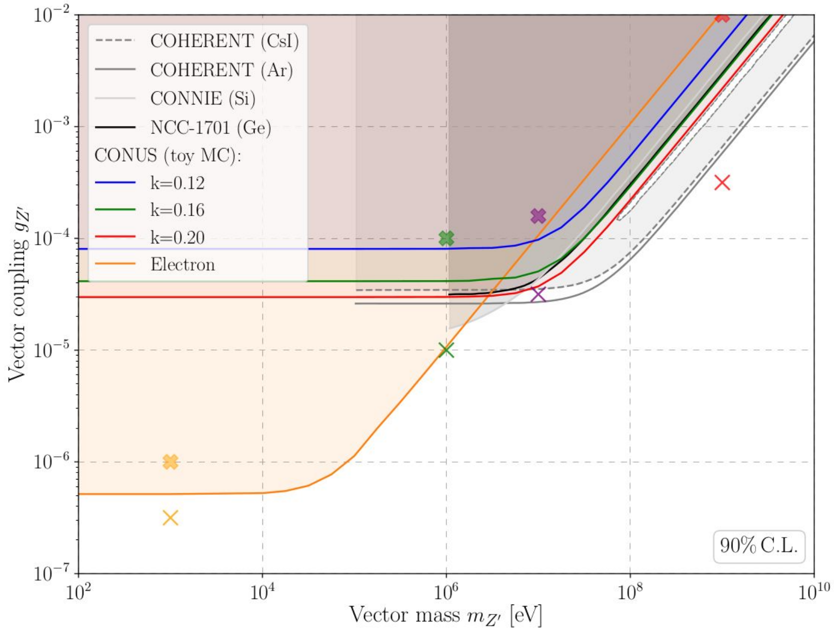
ROI: 0.3-1 keV
Exposure:
208 kg*d ON 38 kg*d OFF

ROI: 2-8 keV
Exposure:
649 kg*d ON 93 kg*d OFF

Scalar mediator



Vector mediator



CONUS Collaboration, J. High Energ. Phys. 2022, 85 (2022)

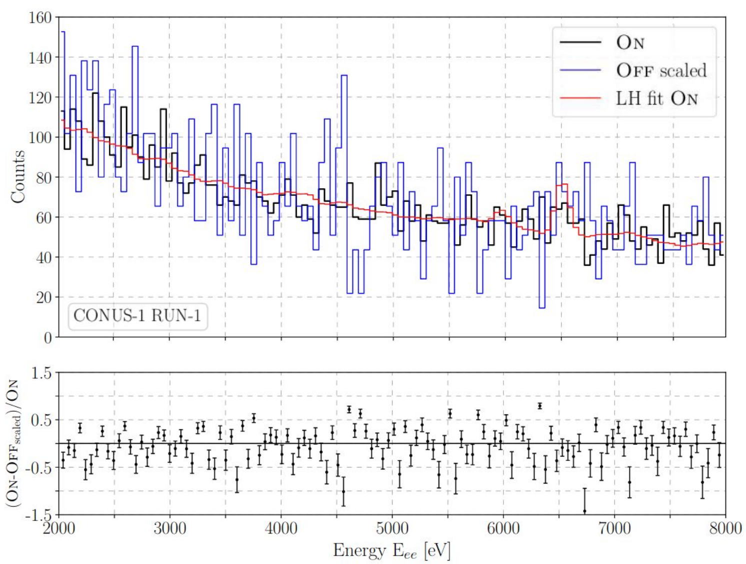
Neutrino electromagnetic properties

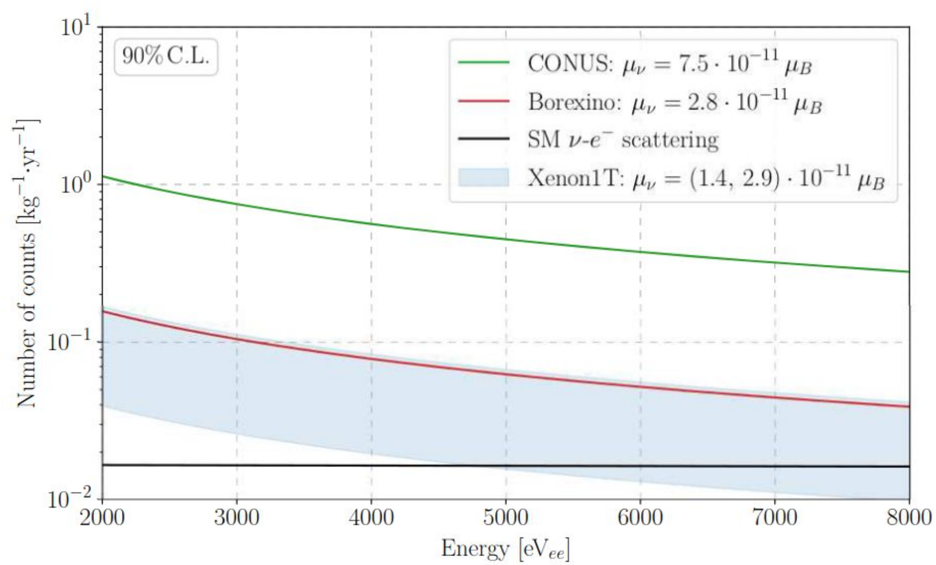
It is possible to study the neutrino magnetic moment from electron scattering at reactor site:

CONUS Collaboration, arXiv:2201.12257

$$\left(\frac{d\sigma}{dT_e}\right)_{\nu MM} = \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T_e}-\frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_e}}{\mu_B}\right)^2 \cdot$$

ROI: 2-8 keV
Exposure: 689 kg*d ON 131 kg*d OFF





$\mu_\nu < 7.5\ 10^{-11}\ \mu_B$ (90% C.L.)

$q_\nu < 3.3\ 10^{-12}\ e_0$ (90% C.L.)

Summary

- Nuclear reactors: intense source of low energy (< 10 MeV) electron antineutrinos → CEνNS in fully coherent regime.

- CONUS experiment, data taking in Brokdorf since April 2018. Very good control/modeling of background.

- CONUS experiment sets best limit on CEvNS with reactor neutrinos.

- Competitive limits for certain BSM models.

- New limits on neutrino electromagnetic properties.

- New precise Ge-quenching measurement at PTB consistent with Lindhard theory down to nuclear recoil energies of 0.4 keV.

Future

- CONUS data taking is still ongoing. Reactor off since end of 2021 →unique opportunity for a long background measurement.

- In ongoing run at KBR several improvements with respect to Run-1+2:

    - Lower energy threshold.

    - Improved control on the electronics and environmental stability.

    - Pulse shape studies for noise and background suppression.

- Analysis of new reactor data ongoing.

- New experimental site under discussion!

Thank you for your attention

Reactor-correlated background

MC propagation of residual fluence inside shield

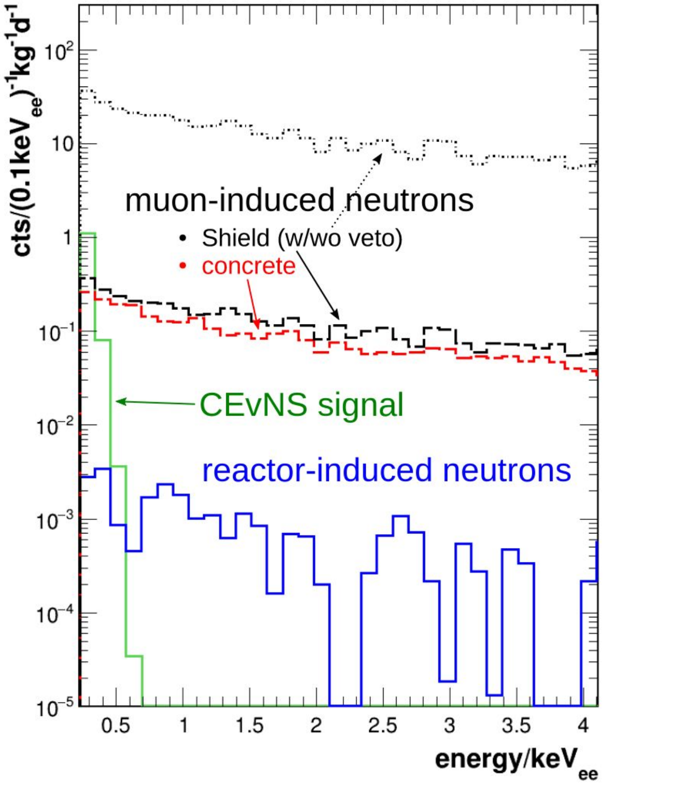
Reactor-correlated backgrounds are critical for CONUS since they can mimic a CEvNS signal.

Neutron spectrometry with NEMUS detectors by PTB and γ's measurements from non shielded HPGe.

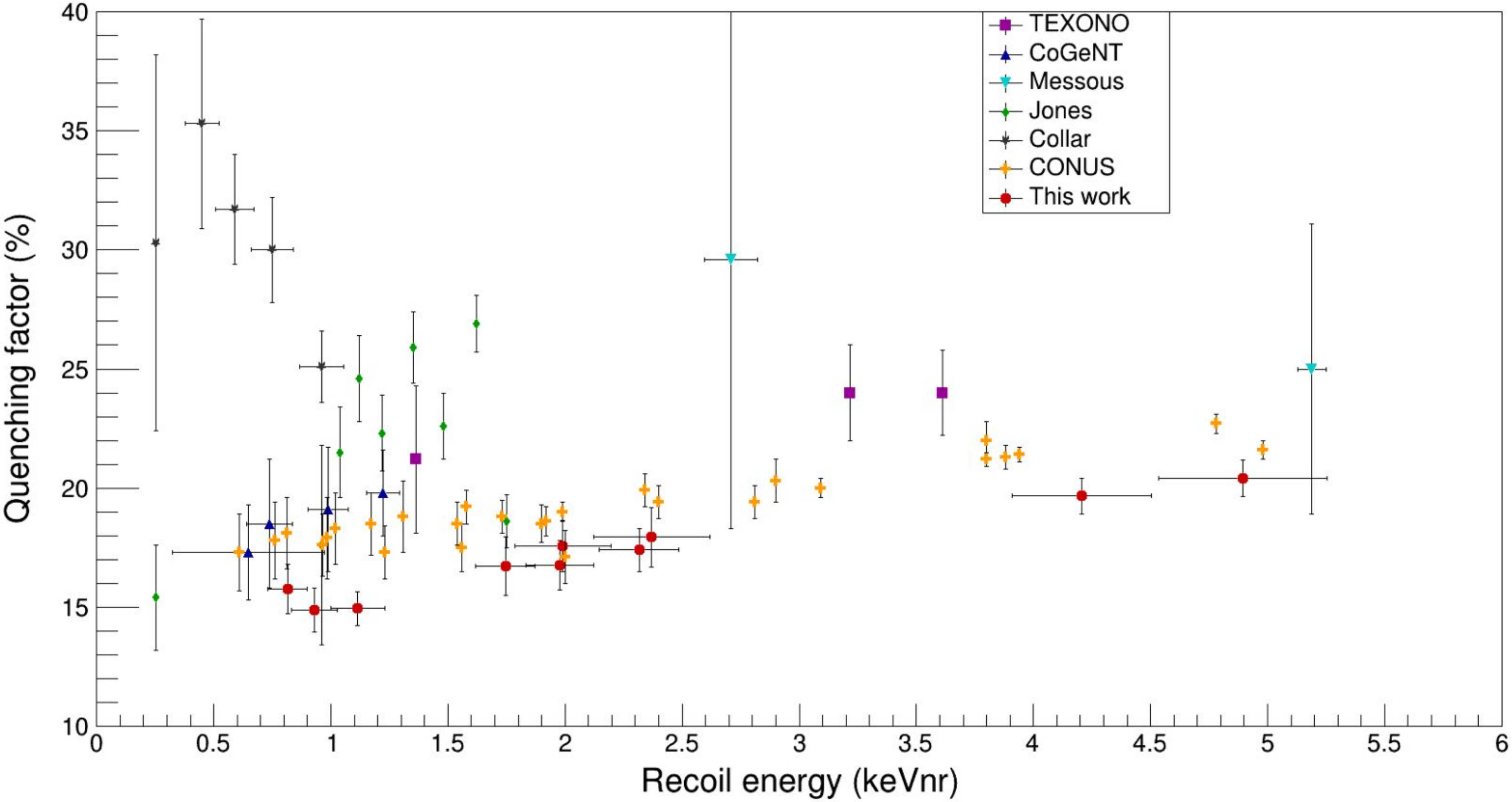
Neutron flux in CONUS room suppressed by factor $>10^{20}$.

Neutron field highly thermalized (>80%).

Correlated with thermal power.



<u>Negligible reactor-correlated contributions inside CONUS shield!</u>



Li, Long (2022). *A Measurement of The Response of A High Purity Germanium Detector to Low-Energy Nuclear Recoils.* Dissertation, Duke University.