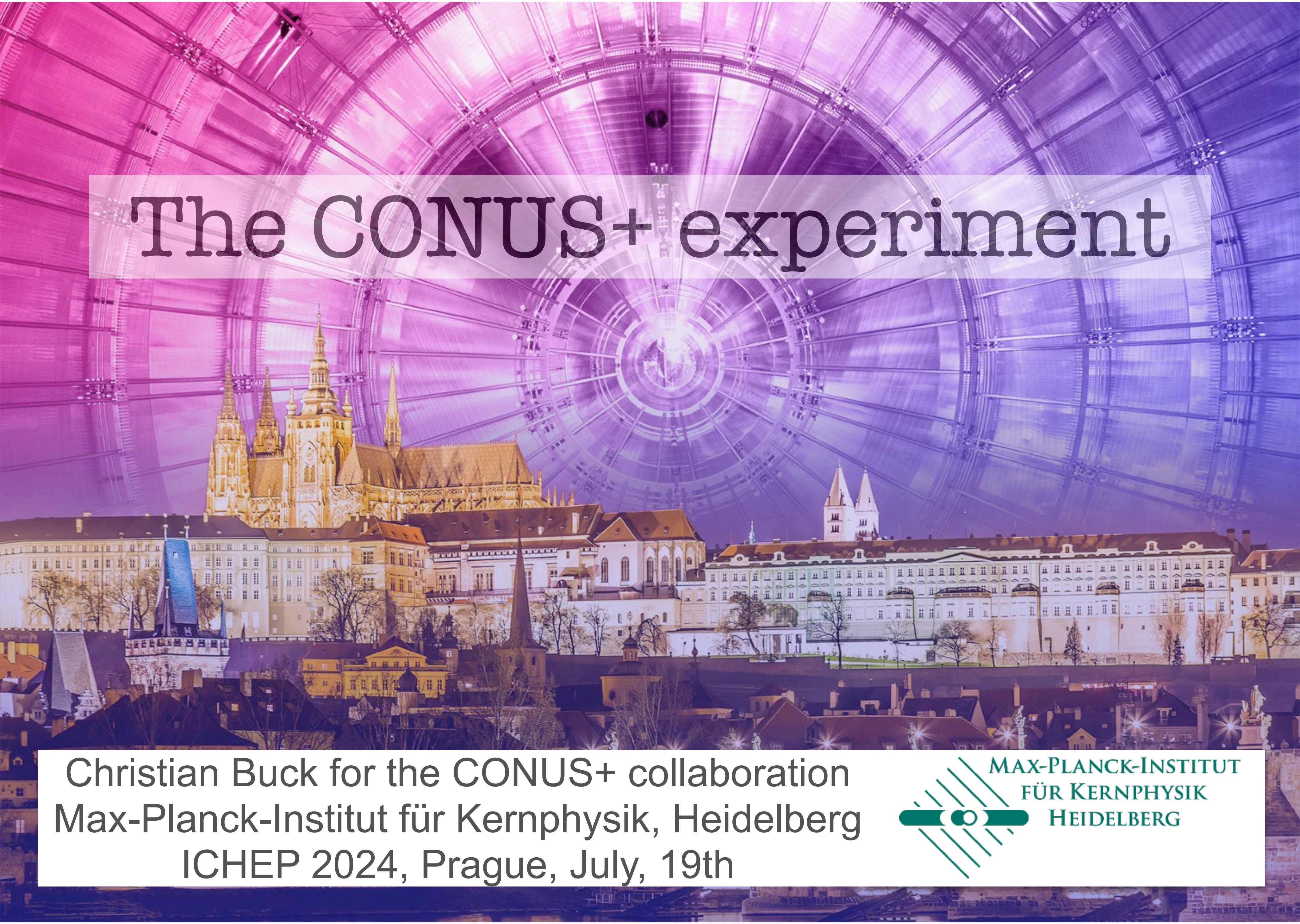
# The CONUS+ experiment



Christian Buck for the CONUS+ collaboration
Max-Planck-Institut für Kernphysik, Heidelberg
ICHEP 2024, Prague, July, 19th

MAX-PLANCK-INSTITUT
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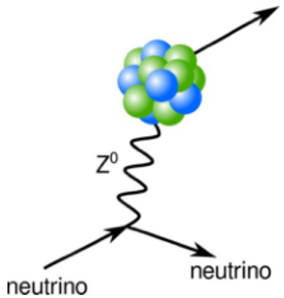
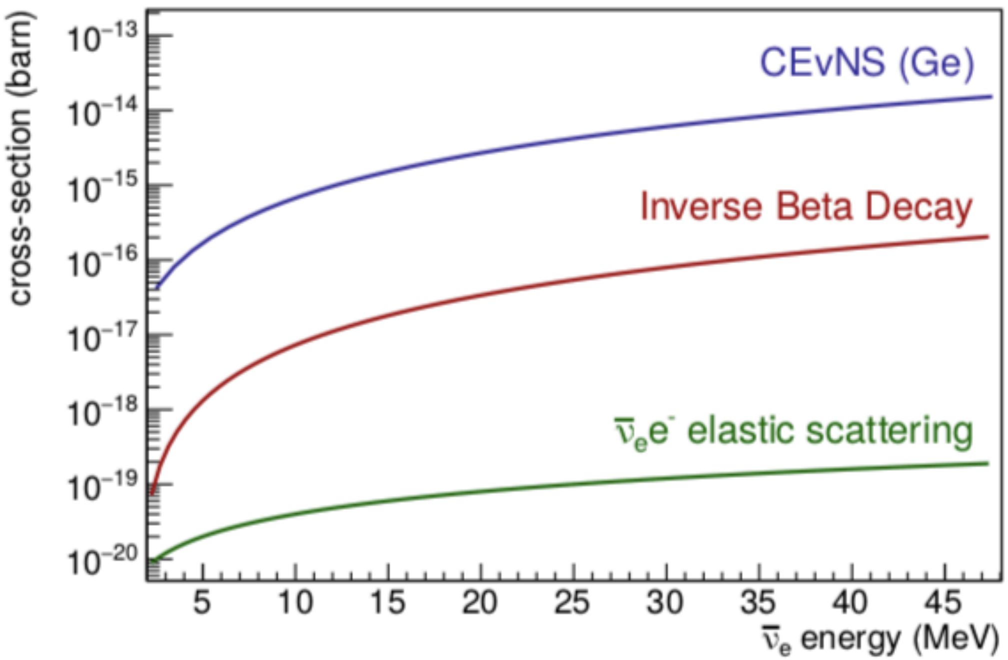
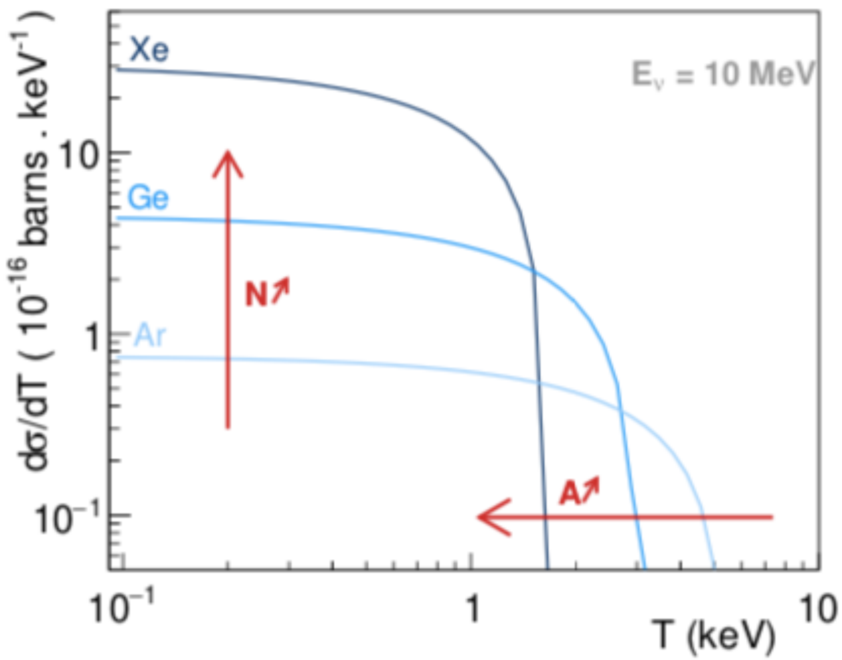
# Coherent elastic neutrino nucleus scattering




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

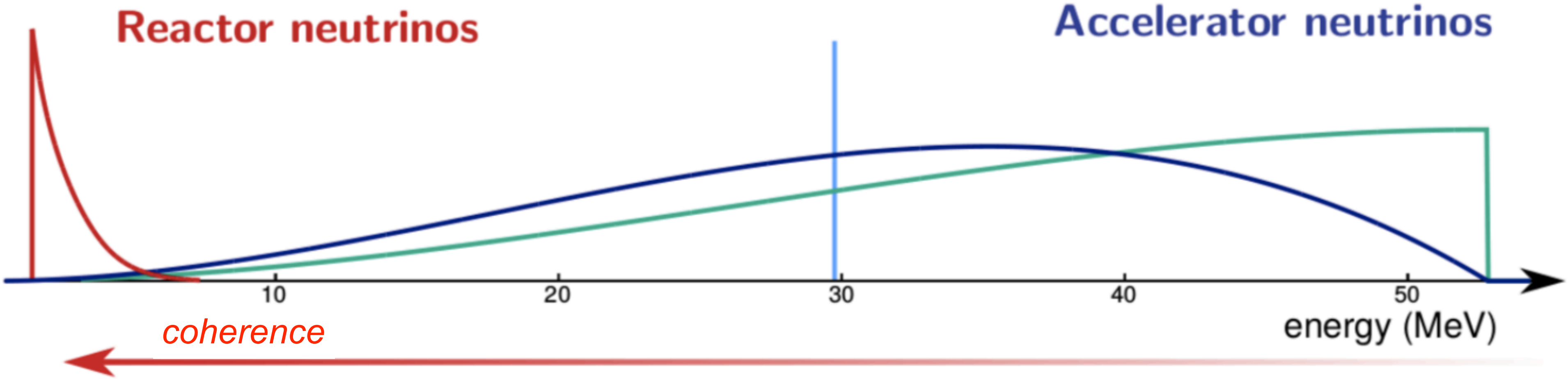



- Cross-section of CEvNS higher
- Allows much smaller neutrino detectors

- Interaction rate vs recoil energy
- Balance rate vs energy threshold

# Neutrino sources for CEvNS studies




- Pure flux of electron antineutrinos
- E < 10 MeV ==> form factor ~1
- High sensitivity for BSM physics
- TEXONO, CONNIE, νGeN, Dresden-II, Nucleus, Ricochet,…

- Different neutrino flavors
- E ~ 20 - 50 MeV ==> form factor < 1
- COHERENT: first observation (various target materials)

**Other sources: solar (XENONnT!) or Supernova neutrinos**

# CONUS+ Collaboration

Max-Planck-Institut für Kernphysik Heidelberg

Preussen Elektra

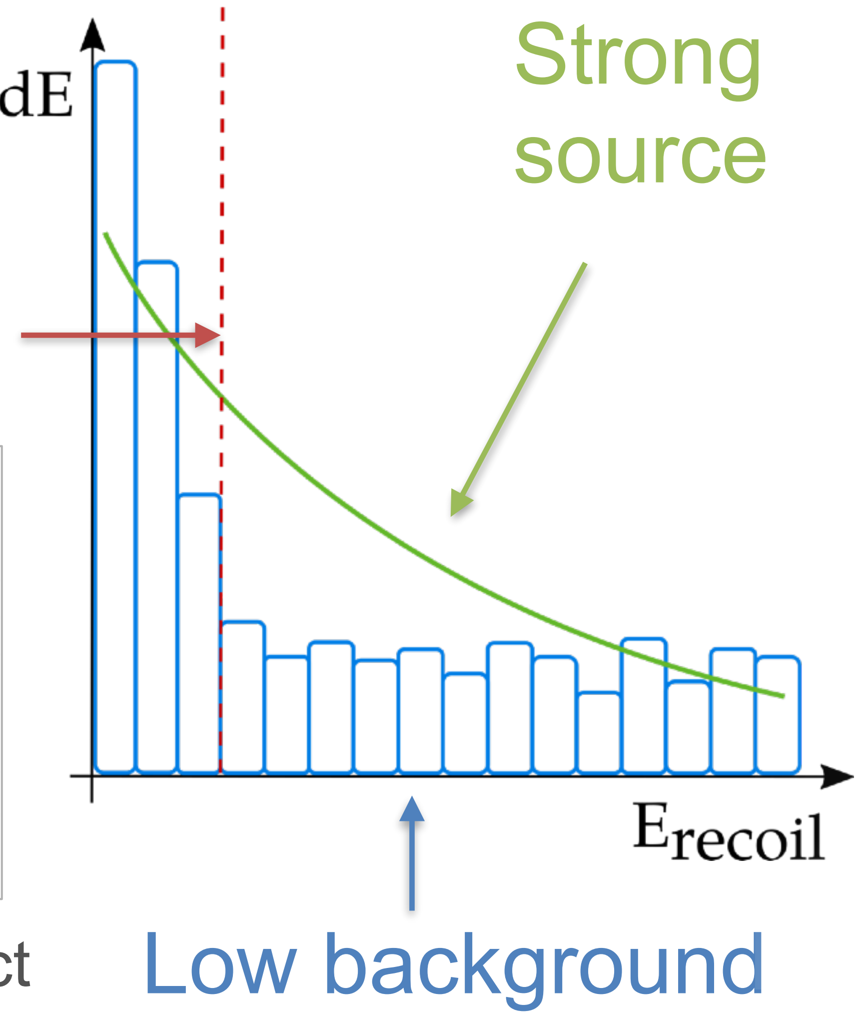
Kernkraftwerk Leibstadt

**N. Ackermann, S. Armbruster, H. Bonet, C. Buck, J. Hakenmüller, J. Hempfling, G. Heusser, M. Lindner, W. Maneschg, K. Ni, T. Rink, E. Sanchez Garcia, H. Strecker**
*Max-Planck-Institut für Kernphysik (MPIK), Heidelberg, Germany*

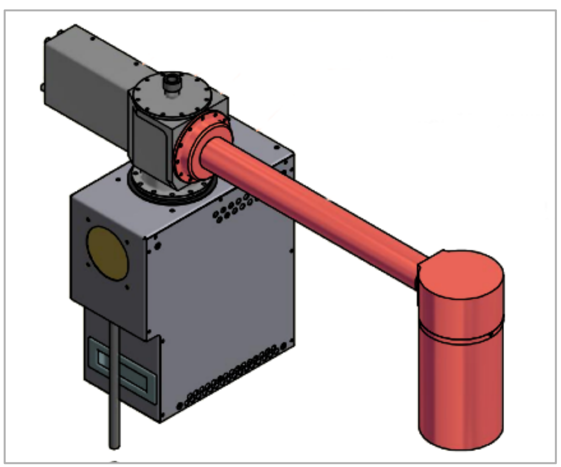
**K. Fülber, R. Wink**
*Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Germany*

**M. Rank, I. Stalder, J. Woenckhaus**
*Kernkraftwerk Leibstadt AG (KKL), Switzerland*

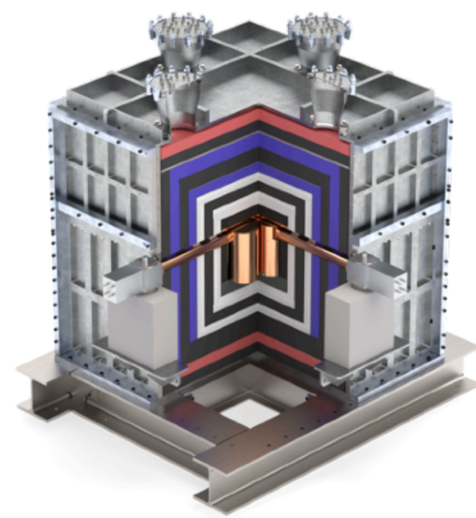
# Concept




Nuclear power plant
(Leibstadt, CH, KKL)

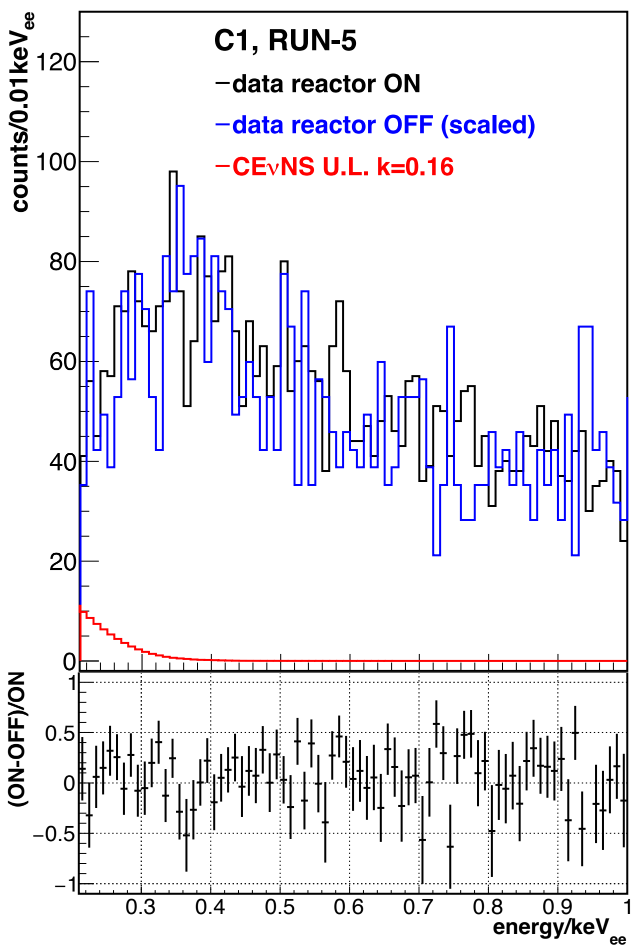


4 x 1 kg point contact
HPGe spectrometer



Shield

# CONUS final result (at Brokdorf)



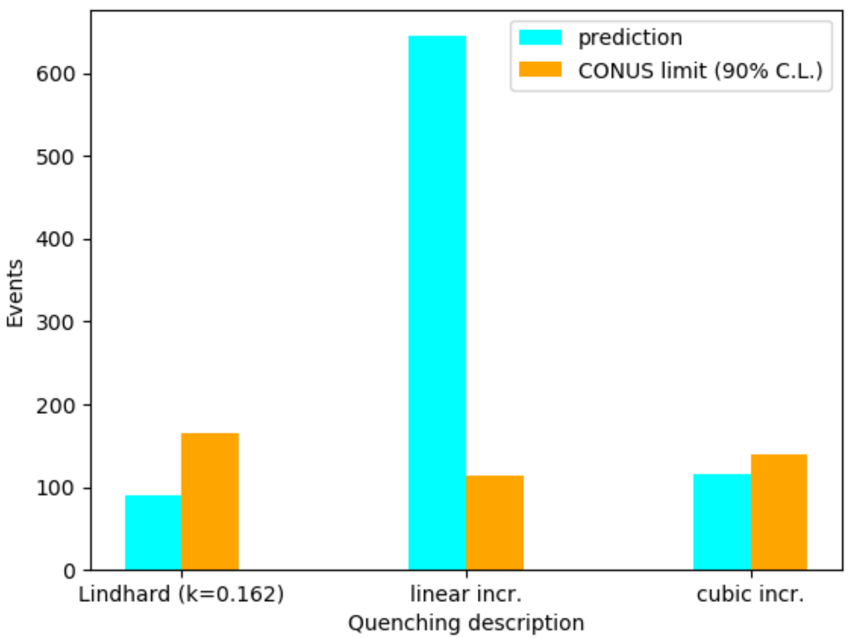

*Data taking: 2018 - 2022*

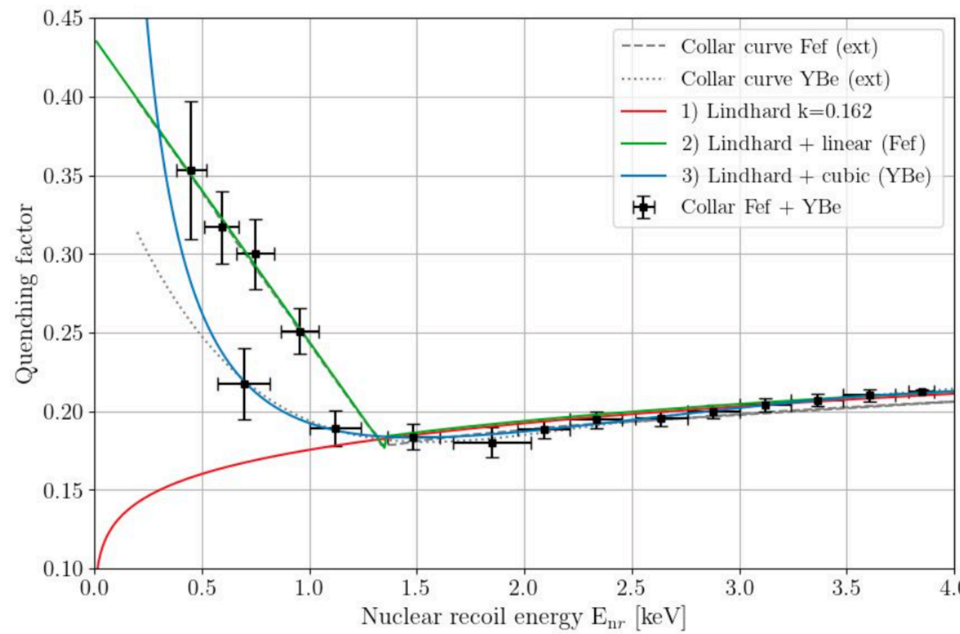
| Detector | Signal prediction | Fit constraint (90% C.L.) |
|---|---|---|
| C1 | 41±8 | < 47 |
| C2 | 26±5 | < 67 |
| C4 | 23±5 | < 79 |
| All | 91±10 | < 143 |

- Limit factor ~2 above SM prediction (strongest limit at reactor)
- Order of magnitude improvement as compared to previous result!

# Comparison with other results

- Constraints from CONNIE, TEXONO, vGen
- Colaresi et al., PRL 129, 211802 (2022)
  - "…very strong preference…for the presence of… CEvNS…"
  - Signal prefers low energy excess of quenching factor as compared to Lindhard quenching to be consistent with SM predictions



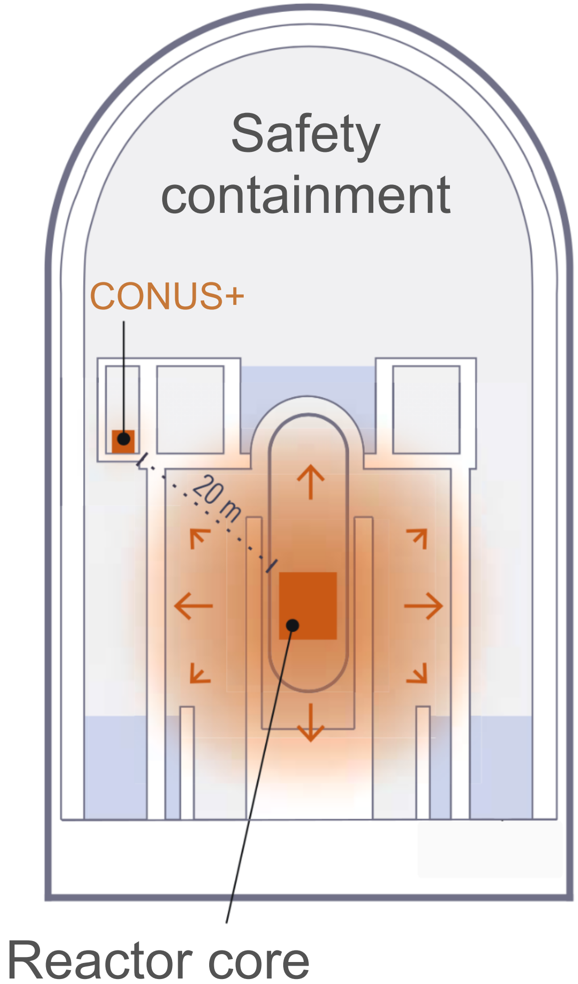




*Our quenching measurement at PTB agrees with Lindhard theory down to 0.6 $keV_{ee}$*

# KKL experimental site

KKL Leibstadt:

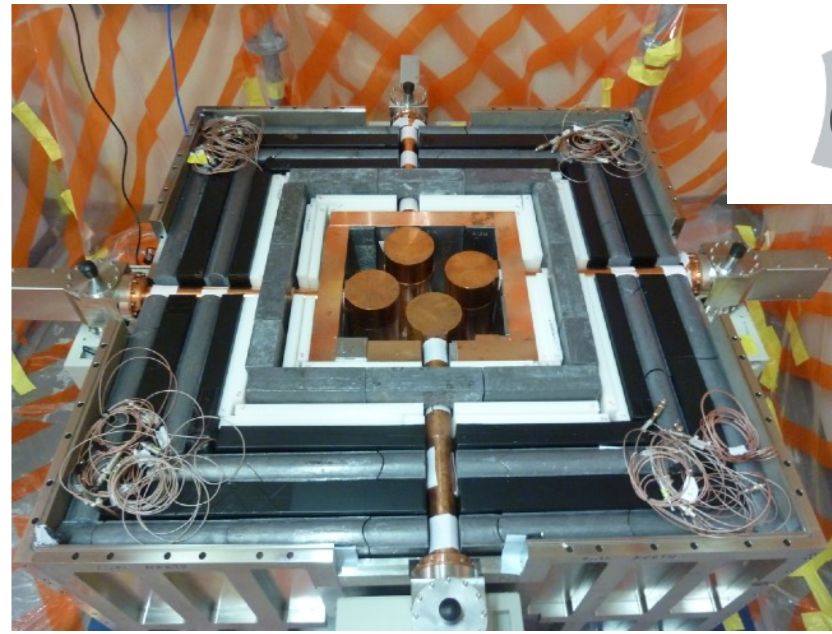
- 3.6 GWth
- Distance 20.7 m
- Flux: ~$1.5 \cdot 10^{13}$ /(s·cm$^2$)
- Data taking started 11/2023
- About 4 weeks of reactor OFF/year




Overburden: ~7 m w.e. (Muon-induced background!)

Challenging environment: Restricted materials, earthquake safety, access, ON vs OFF stability,…

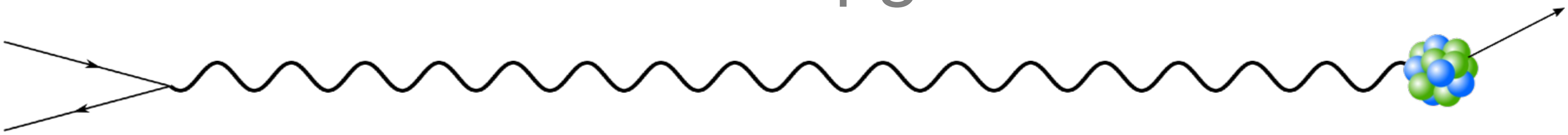
# Installation



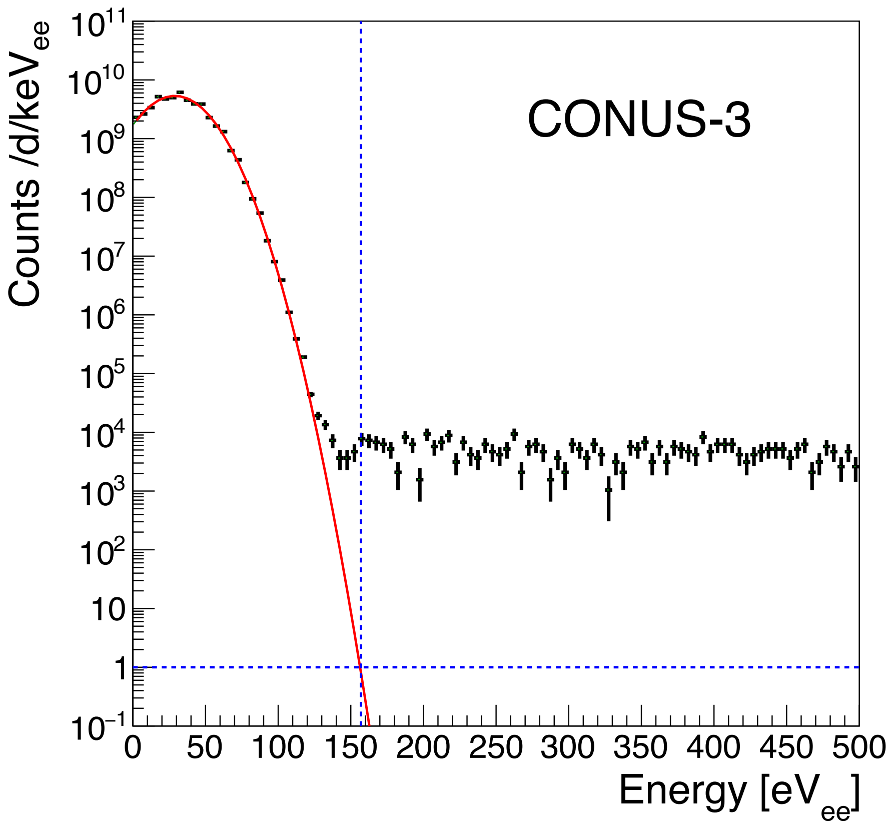
CONUS+

- **Dec. 2022** — KBR mission complete. Germanium detectors refurbishment.
- **Apr. 2023** — KBR dismantling. KKL onsite preparation.
- **Jul. 2023** — Detectors test at MPIK. Final installation campaign.
- **Aug. 2023** — Commissioning
- **Nov. 2023** — First physics run(Run1) started
- **May. 2024** — **First reactor-off data produced!**

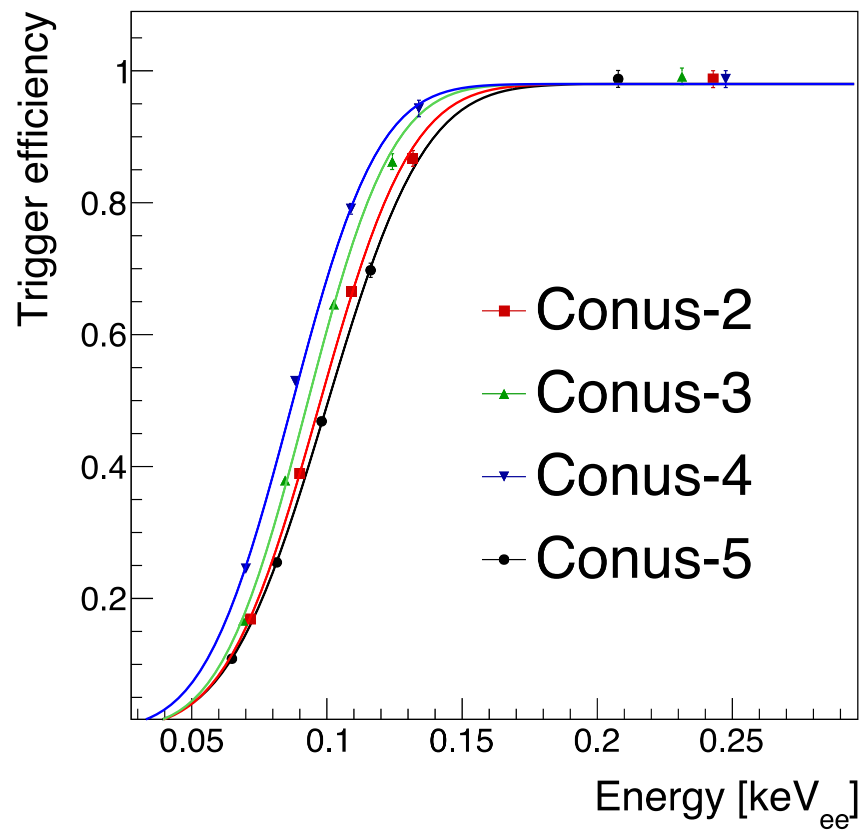
# Detector upgrade



## Noise spectrum




## Trigger efficiency

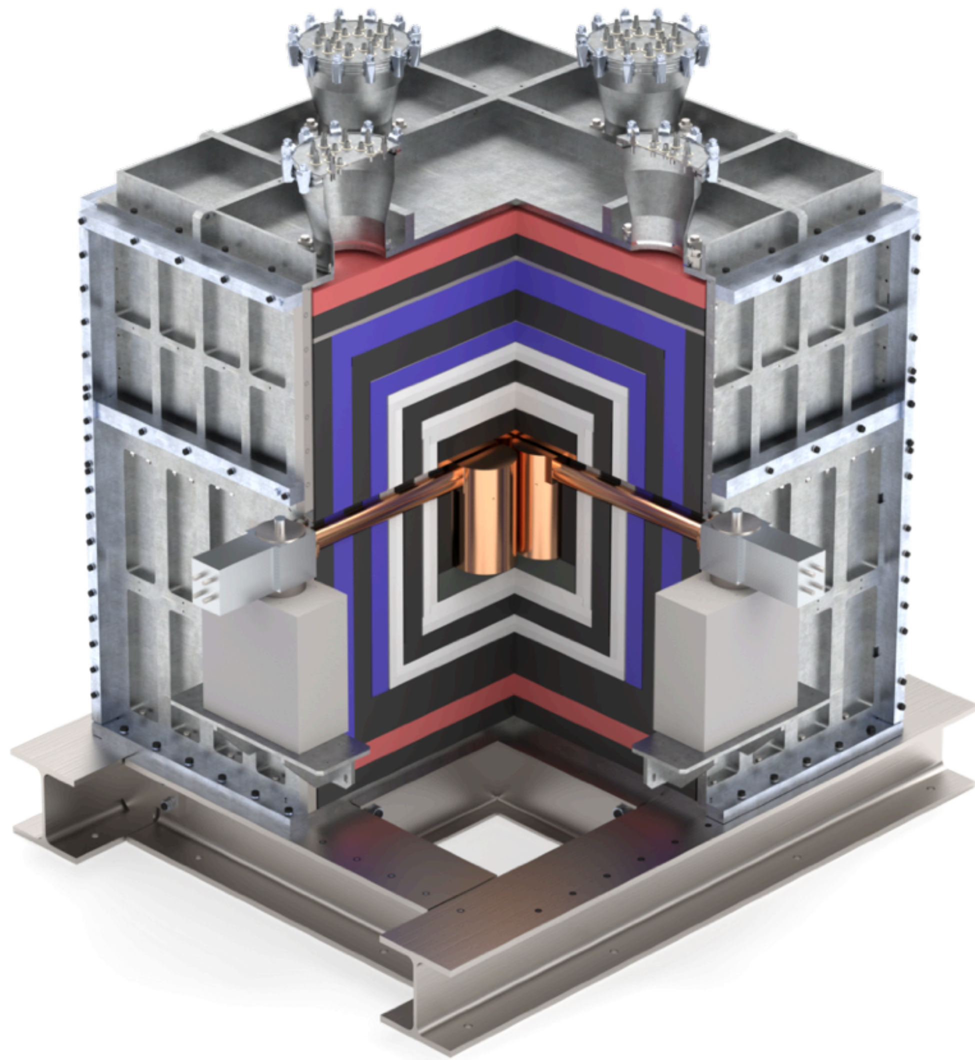



Energy threshold from 210 eV (KBR) to ~160 eV!

CONUS+ Collaboration, arXiv:2407.11912

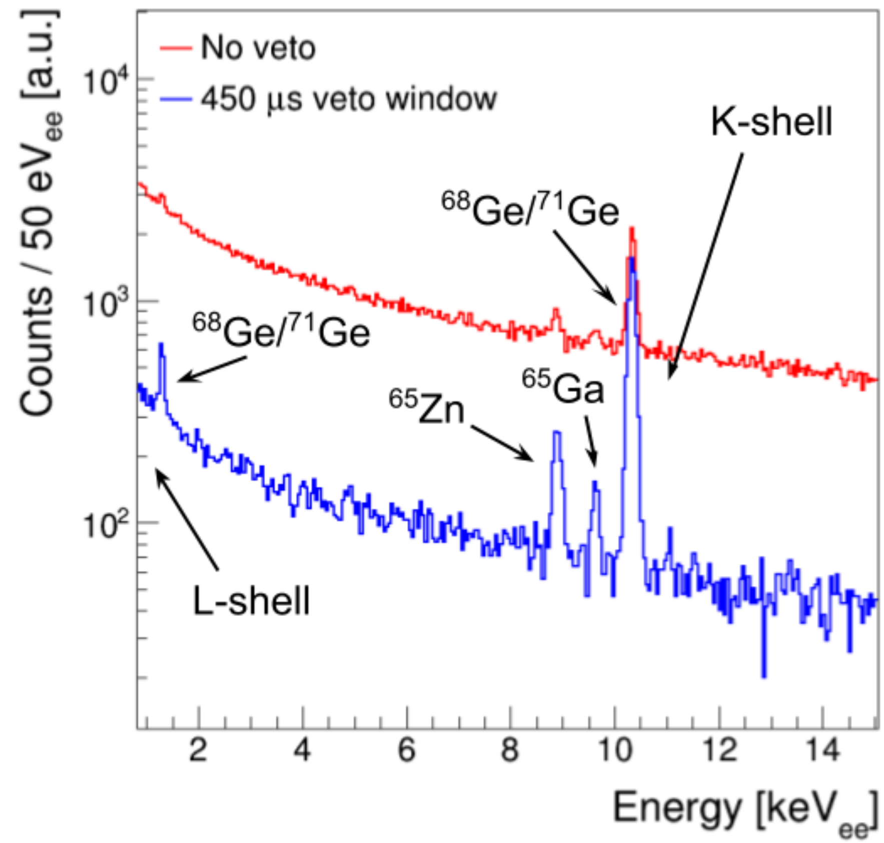
# Shield upgrade

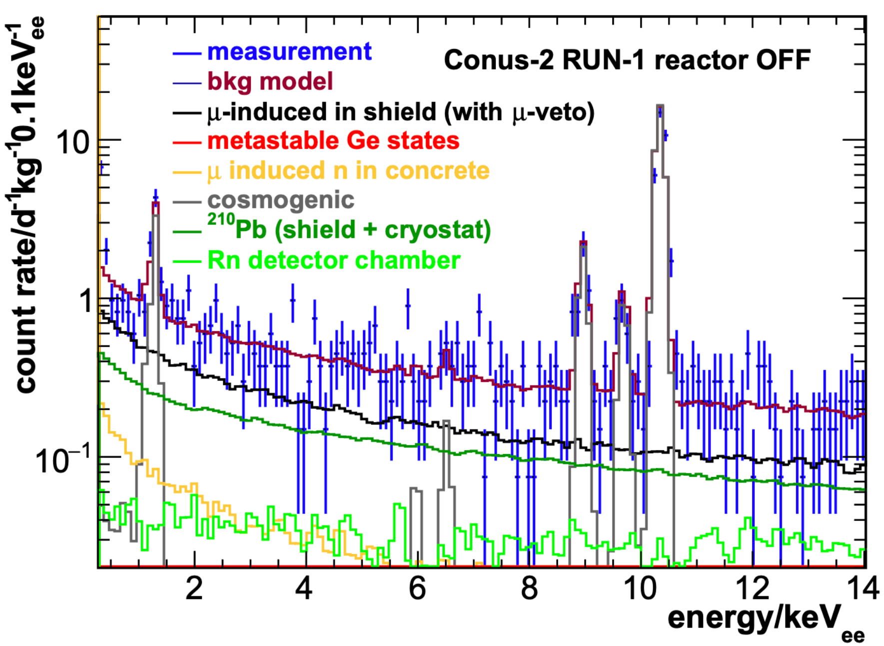
- ~ 10 tons, 1.6 m$^3$
- Replace one layer of Pb with plastic scintillator
- Reinforced steel structure
- Flushing with air bottles (Radon)
- ~ 4 orders of magnitude background reduction



# Background model

- Starting point: KBR simulation
- Rate 0.5-1 keV: ~10 /(keV d kg)
- Neutron measurements with PSI
- Ge and liquid scintillator detectors

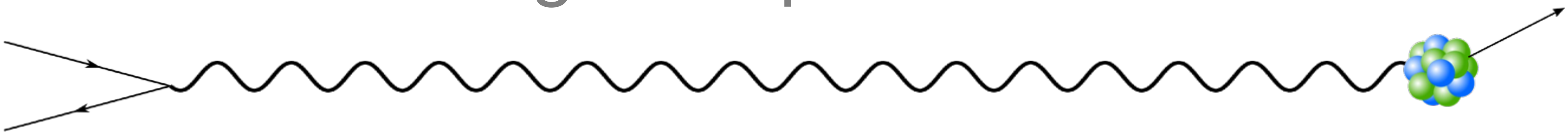


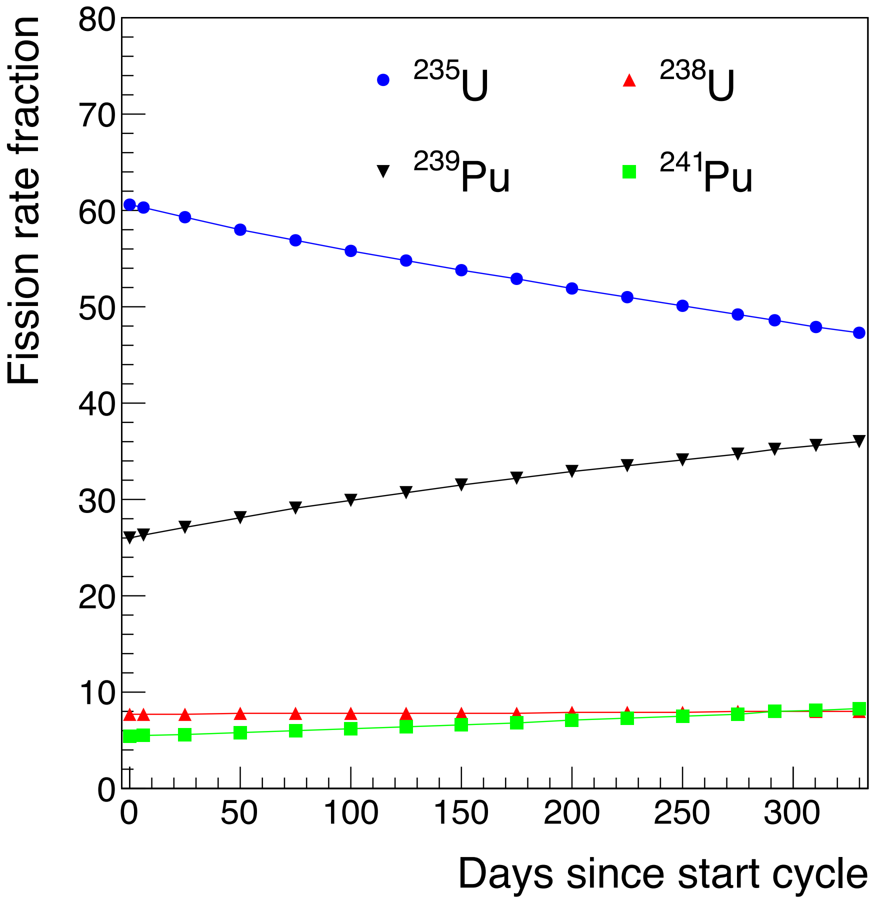

Comparison KKL vs KBR

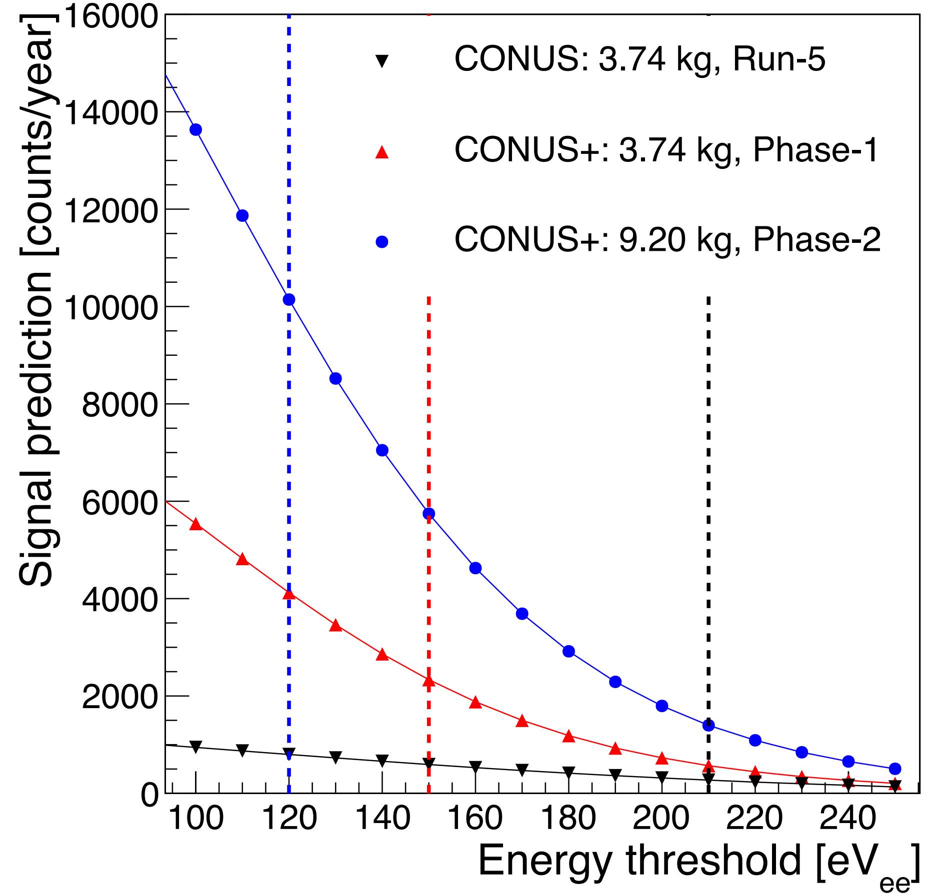
- Neutrons and muon flux higher
- High energy γ and $^{210}Pb$ lower

# Signal expectation



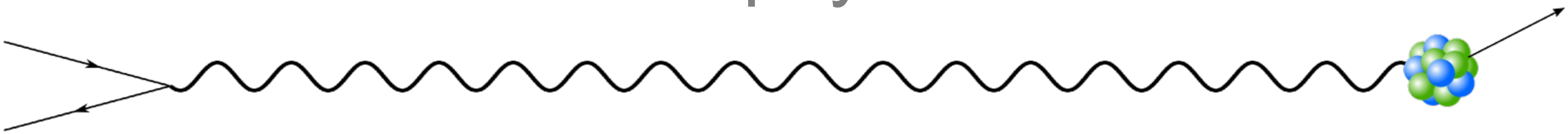
CONUS+ Collaboration, arXiv:2407.11912




Expect > 2000 neutrino events per detector and year
(almost factor 10 improvement compared to KBR)

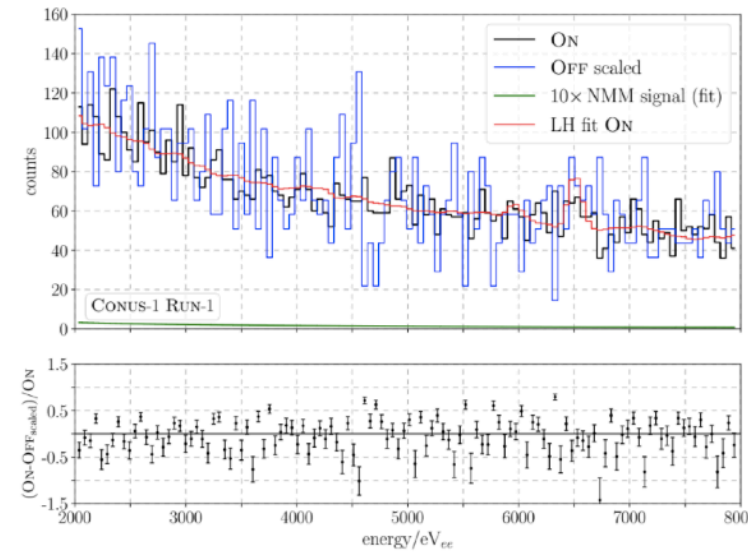
# BSM physics



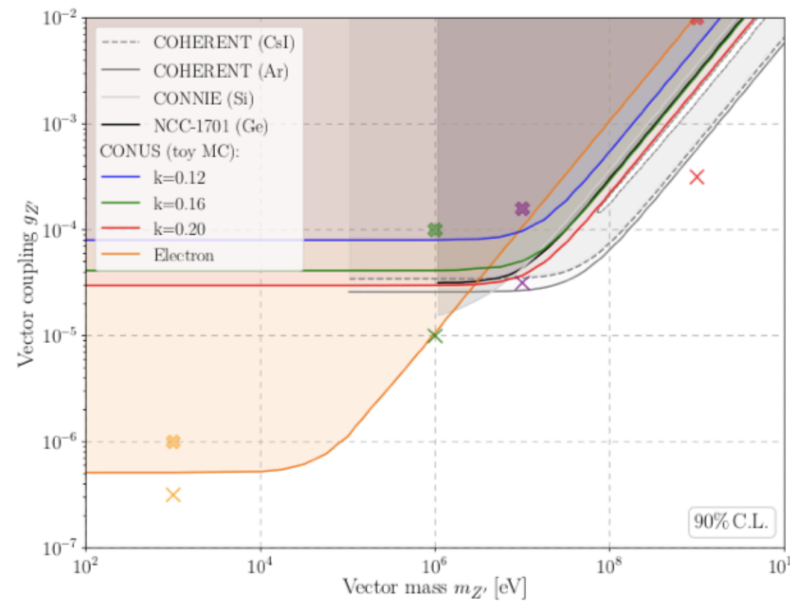
*Preliminary!*

- Magnetic moment / electric millicharge
  - **$\mu_\nu < 5.2\times10^{-11}\,\mu_B$**
  - **$q_\nu < 1.8\times10^{-12}\,e_0$**

PhD thesis, J.Hempfling, Heidelberg (2024)




- Non-standard interactions
  - Tensor type
  - Vector type
- Simplified models
  - Light scalar mediators
  - Light vector mediators



# Summary

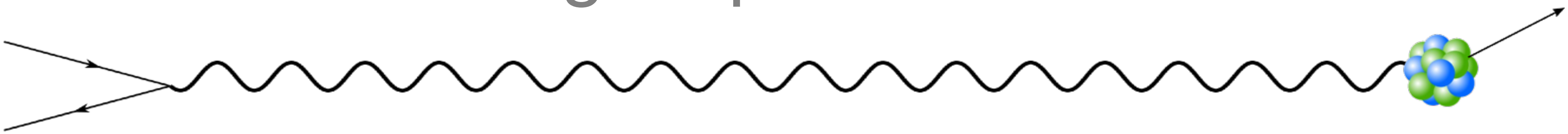
- High cross-section of CEvNS ==> compact neutrino detectors
- CONUS+: 4 x HPGe detectors at 20.7 m from reactor core
- CONUS is constraining CEvNS rate factor < 2 above SM prediction
- Continue in Leibstadt (CH) with improved setup (lower energy threshold, improved veto, remote control —> stability)
- Data taking since 11/2023 including reactor ON and OFF phases

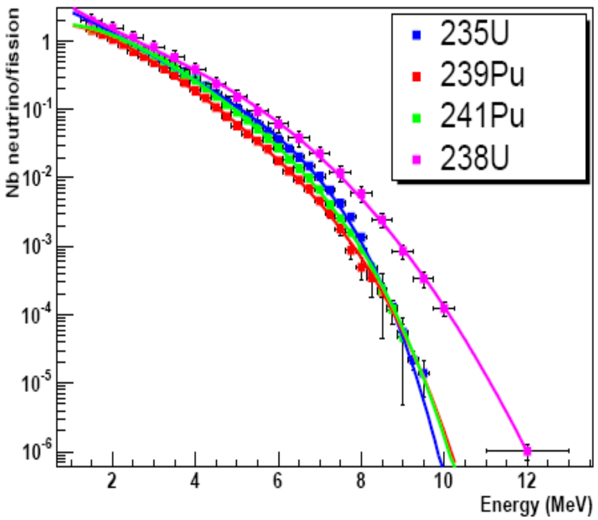
*References:*


- *CONUS first CEvNS result: CONUS, PRL 126 (2021) 041804*
- *Electromagnetic properties: CONUS, EPJ C 82:813 (2022)*
- *Other BSM studies: CONUS, JHEP 05 (2022) 085*
- *Quenching measurement: Bonhomme et al., EPJ C 82:815 (2022)*
- *Background model: CONUS, EPJ C 83:195 (2023); Hakenmüller et al., EPJ C 79:699 (2019)*
- *Pulse shape studies: CONUS, EPJ C 84:139 (2024)*
- *CONUS final results (KBR): arXiv2401.07684*
- ***CONUS+: arXiv2407.11912***

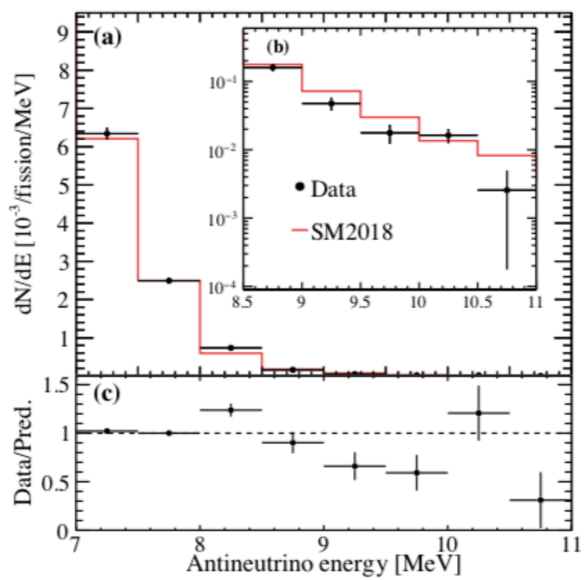
# Backup

# Signal prediction

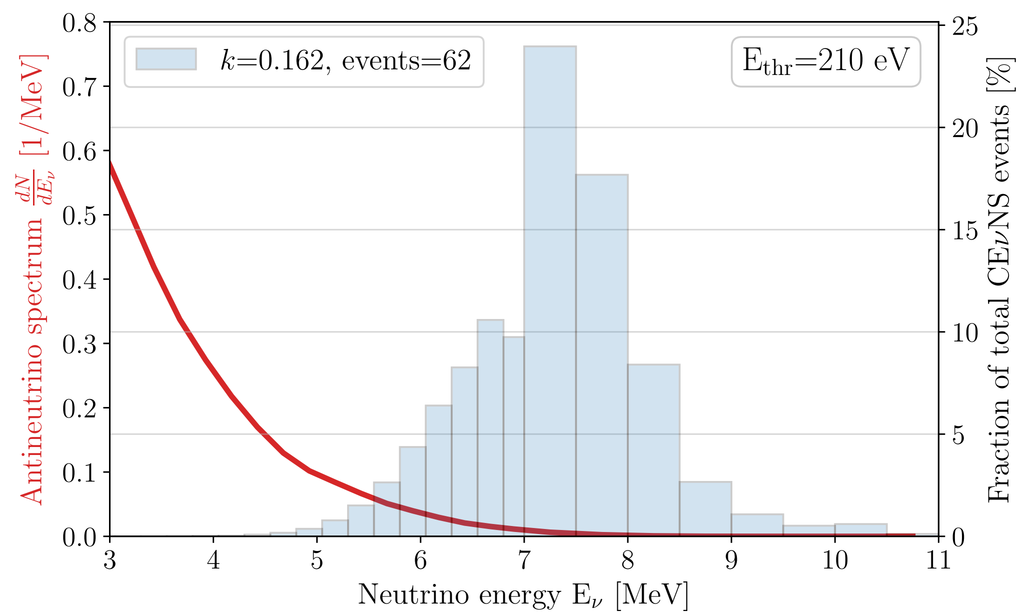





- Thermal power and energy per fission
- Consider evolution of fission fractions
- Spectrum: data-based method and high E spectrum from Daya Bay
- High quenching factor (f) dependence! (Ionization signal $E_{det}$= f * $T_{nr}$)

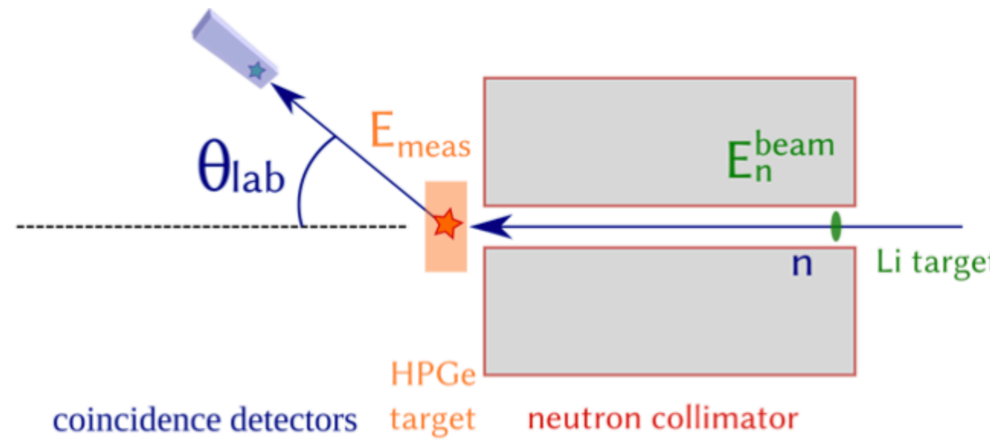


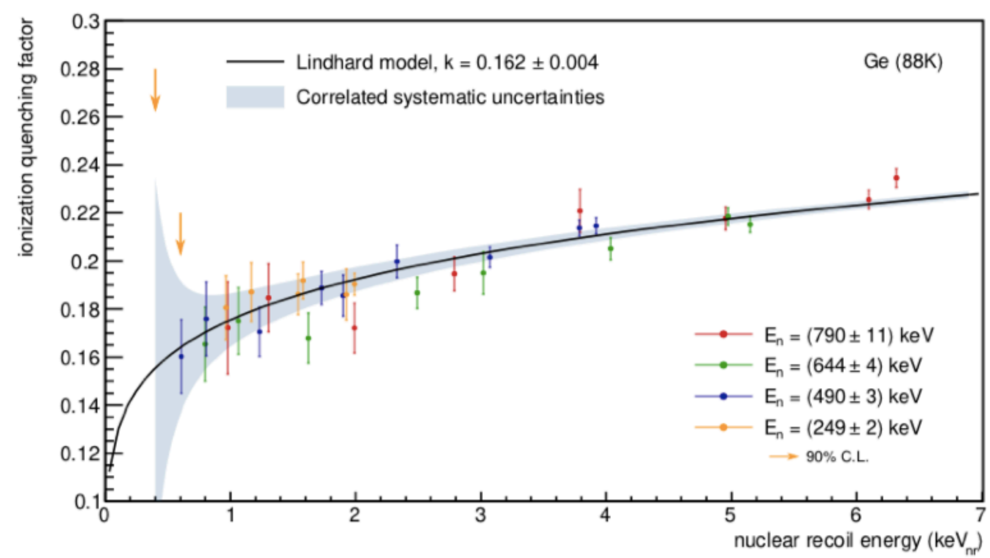

*Daya Bay, PRL 129 (2022) 041801*



# Quenching measurement

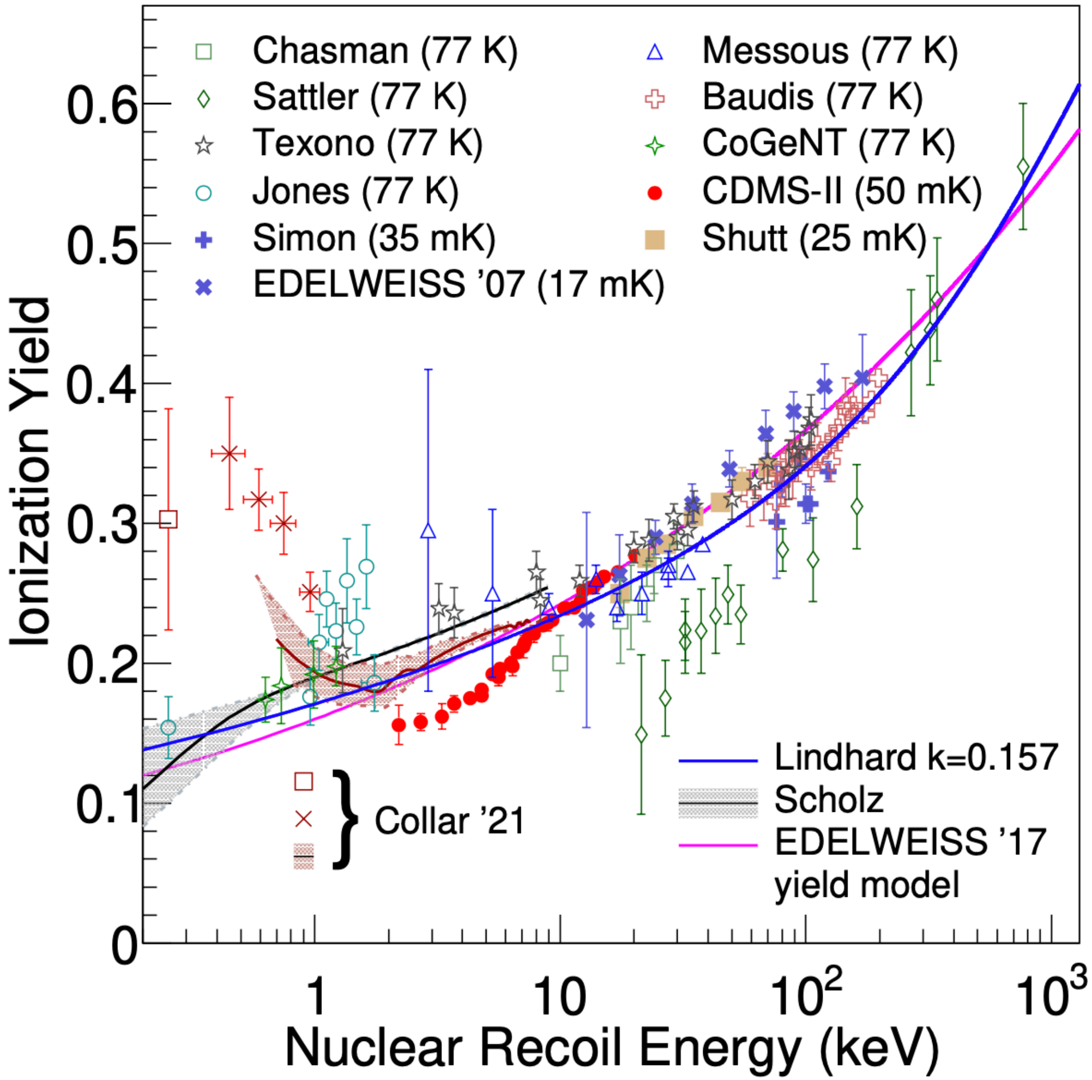
- Experimental setup (beam facility a PTB Braunschweig)
  - Model-independent method
  - Triple coincidence
  - Beam energy 250 - 800 keV
  - Angles 18-45° (1° precision)
  - Nuclear recoils 0.4 - 6 keV
- Results
  - Compatible with Lindhard theory!
  - **k = 0.162 ± 0.004** (stat.+syst.)
  - Challenge for CEvNS signal detection with Ge at reactor



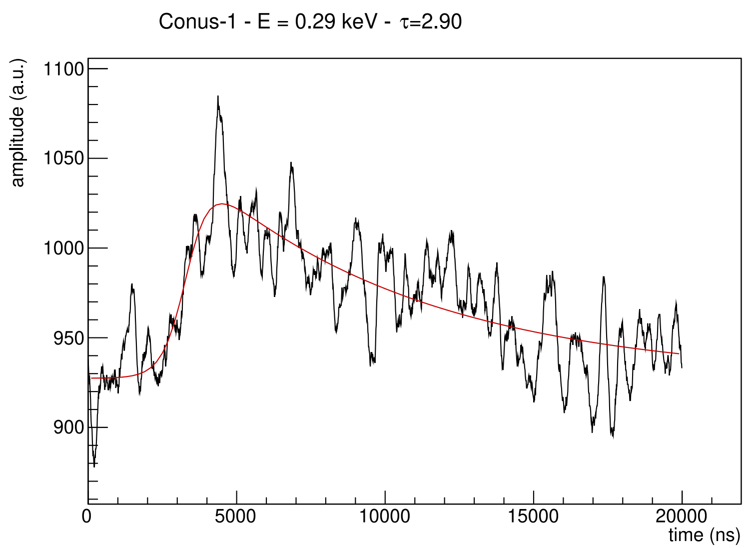

Bonhomme et al., EPJ C 82:815 (2022)

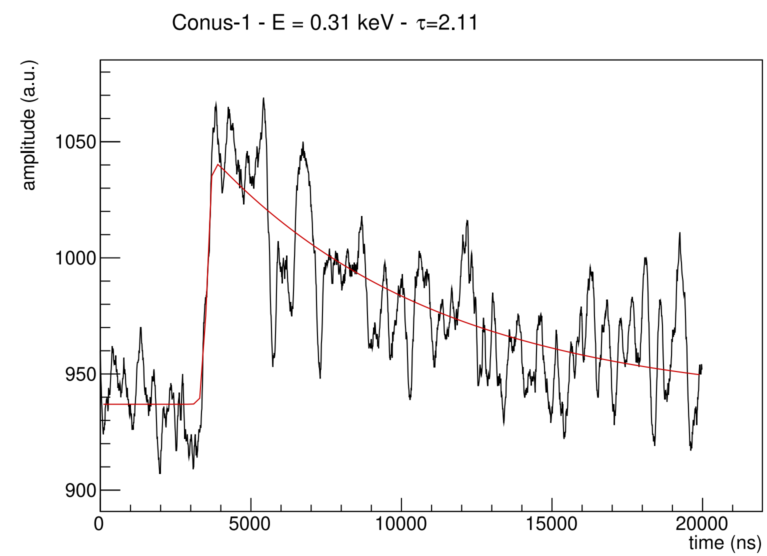
# Other QF results

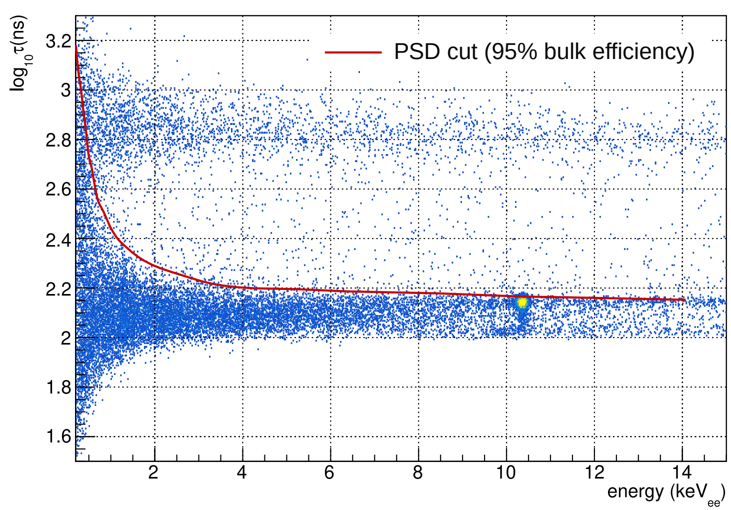


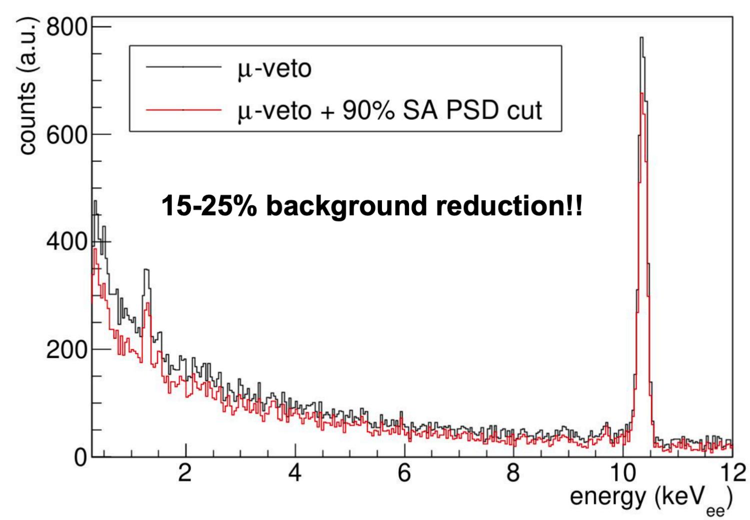

*SuperCDMS, PRD 105 (2022) 12, 122002*

# Pulse shape discrimination



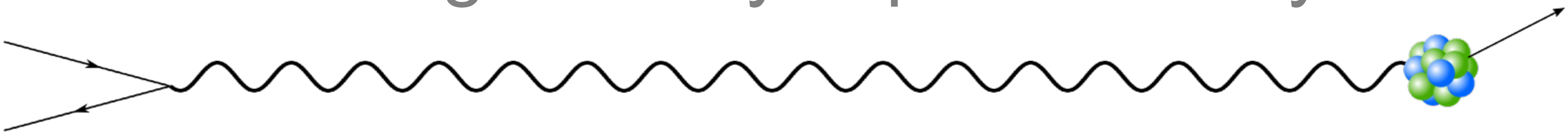



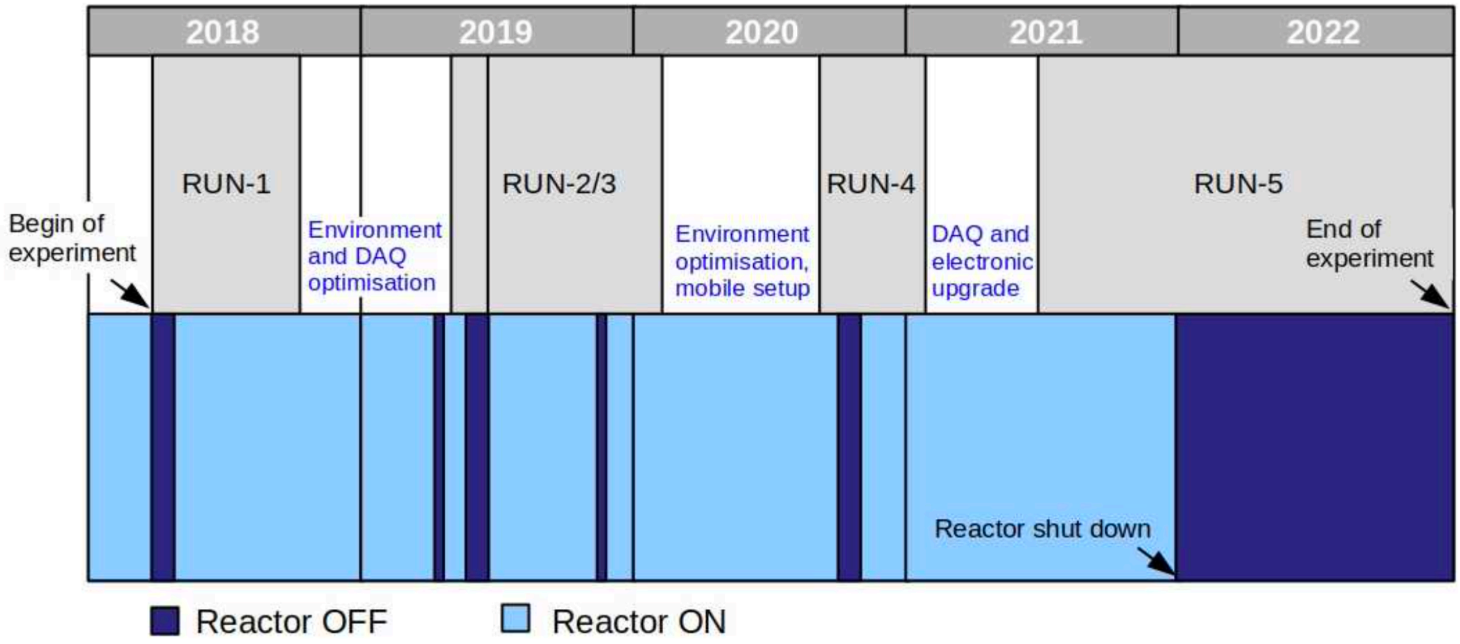

CONUS, arXiv2308.12105 (2023)

Signal acceptance in Run-5: 97%

# Run-5: significantly improved analysis

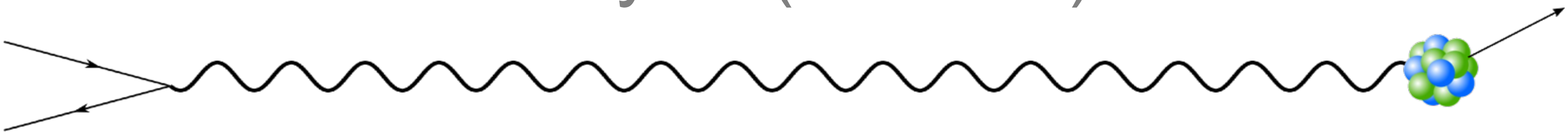


| Detectors | ON [kg d] | OFF [kg d] | E threshold [eV] |
|---|---|---|---|
| C1, C2, C4 | ~450 | ~300 | 210 |




- Improvements: stability, DAQ, E threshold, PSD, OFF statistics…
- Data with high noise variations excluded

# Analysis (Run-1/2)

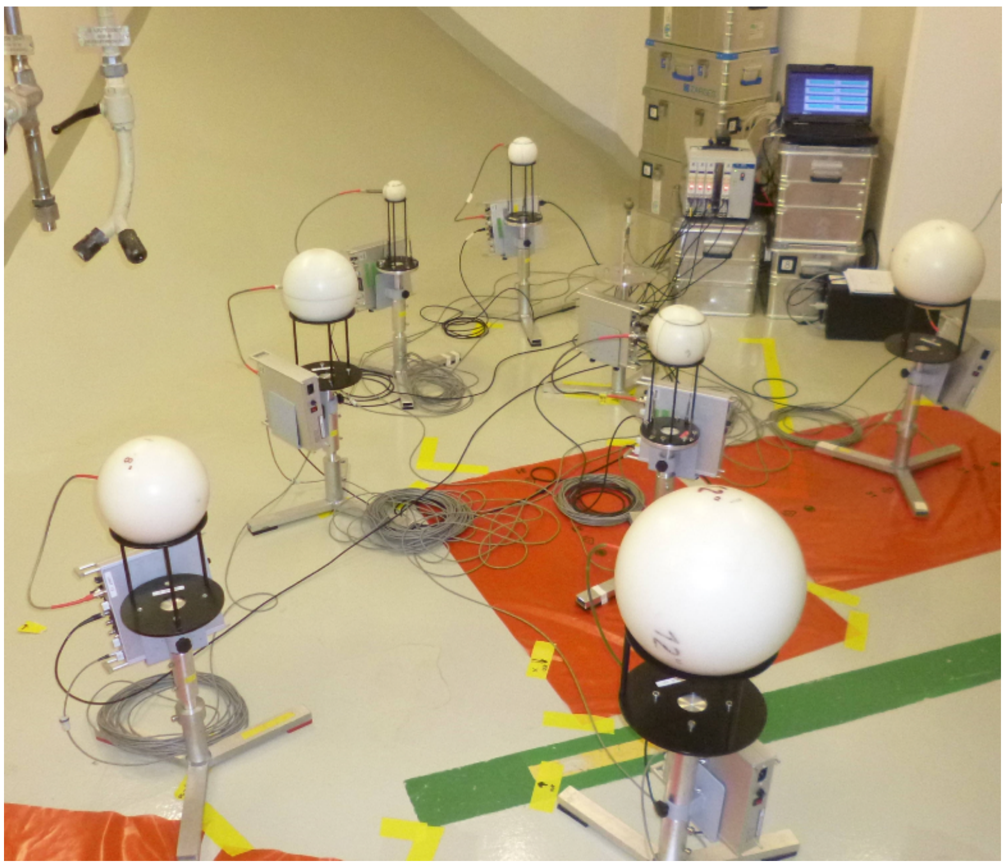


- Binned likelihood ratio test
- Background: MC modelling, free normalization parameter in fit (exponential fit for electronic noise in Run-1/2)
- Simultaneous fit ON/OFF (all detectors and runs)
- Scan over signal parameter
- Systematics via gaussian pull terms

| **Parameter** | **Uncertainty** |
|---|---|
| **s** signal | scanned over |
| b MC background normalization | free parameter |
| $\theta_{thr1}$, $\theta_{thr2}$ electronic noise | free parameters, exponential |
| $\theta_{rea}$ reactor neutrino spectrum | ~3% (thermal power, fission fractions) |
| $\theta_{det}$ detector and DAQ | 1-5% (indep. measurements) |
| $\Delta E$ energy scale calibration | 10-20eV, highly stable |

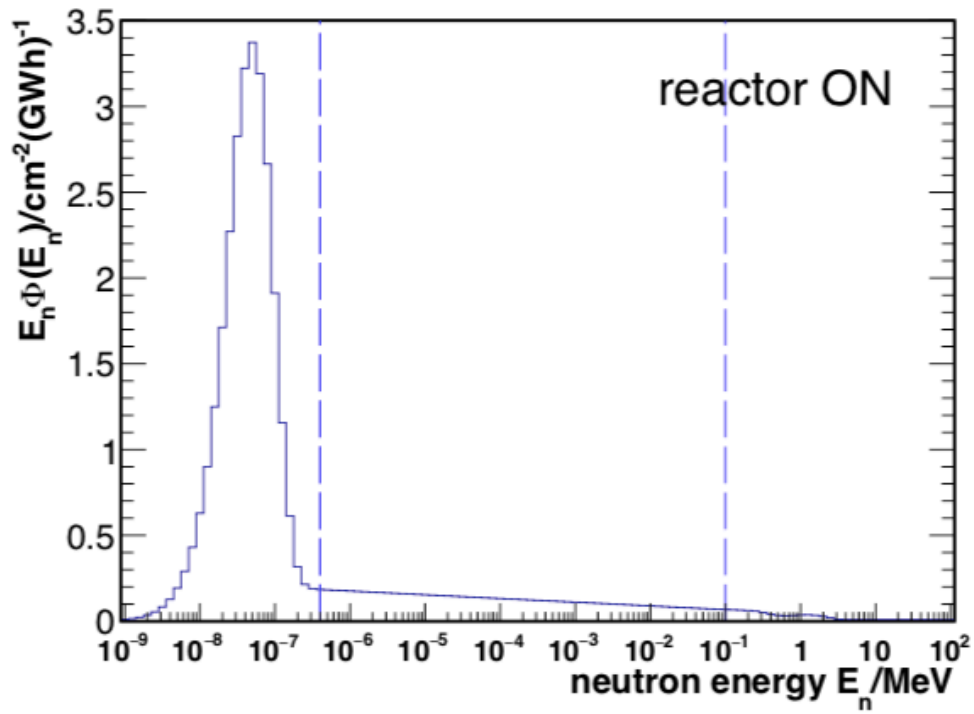
# Neutron background

Reactor-correlated!



Campaign with Bonner spheres
(in cooperation with PTB)

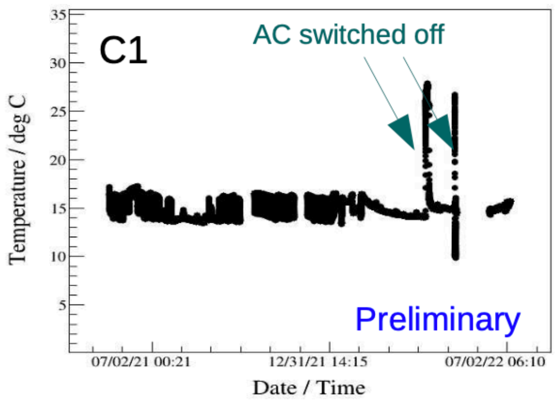
- Neutron flux in CONUS room suppressed by factor $>10^{20}$
- 80% of neutron flux is thermal



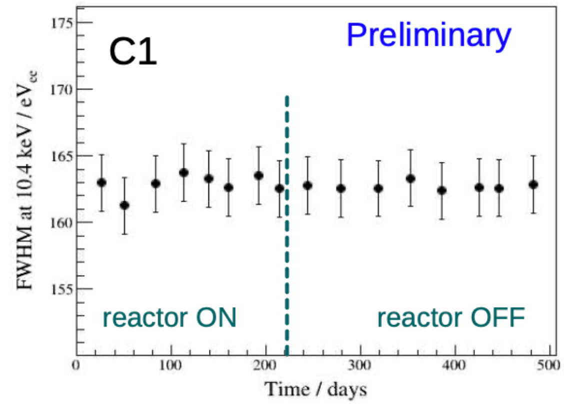

CONUS, Eur. Phys. J. C (2019) 79:699

# Run-5 stability

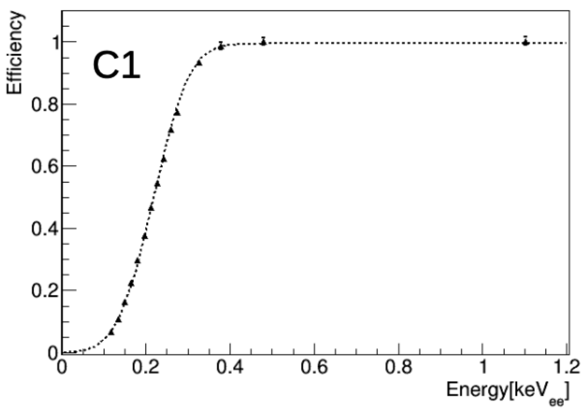
Room temperature




Peak pos. of 10.4 keV line

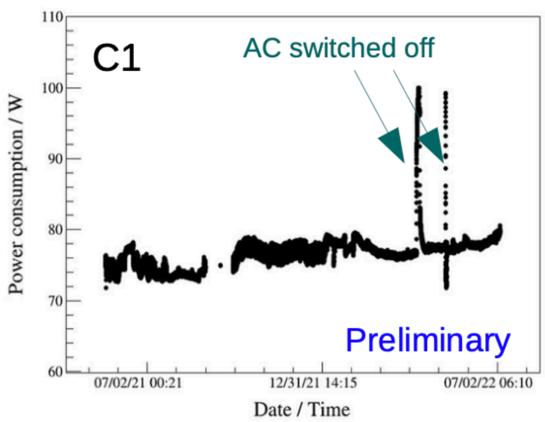



Trigger efficiency curve

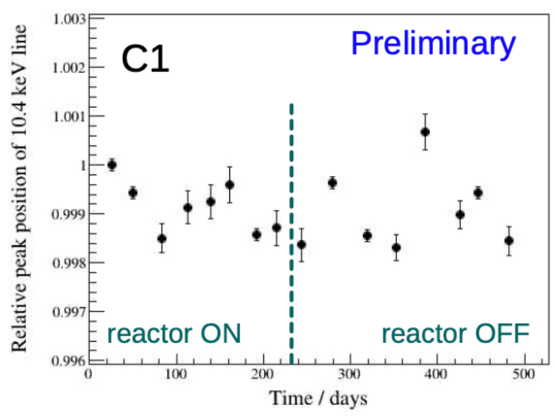


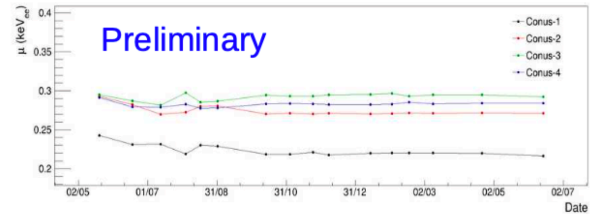

Analytical description: 0.5*[1+erf( (x-μ)/σ) )]

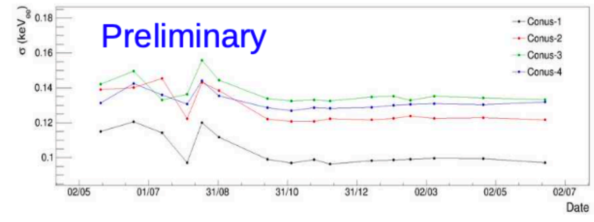
Power consumption




FWHM of 10.4 keV line

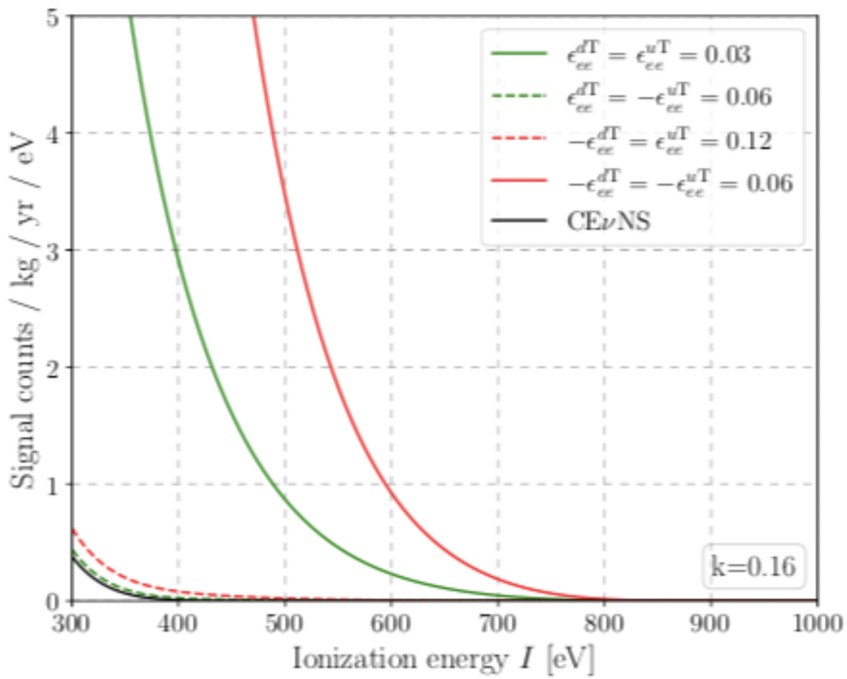


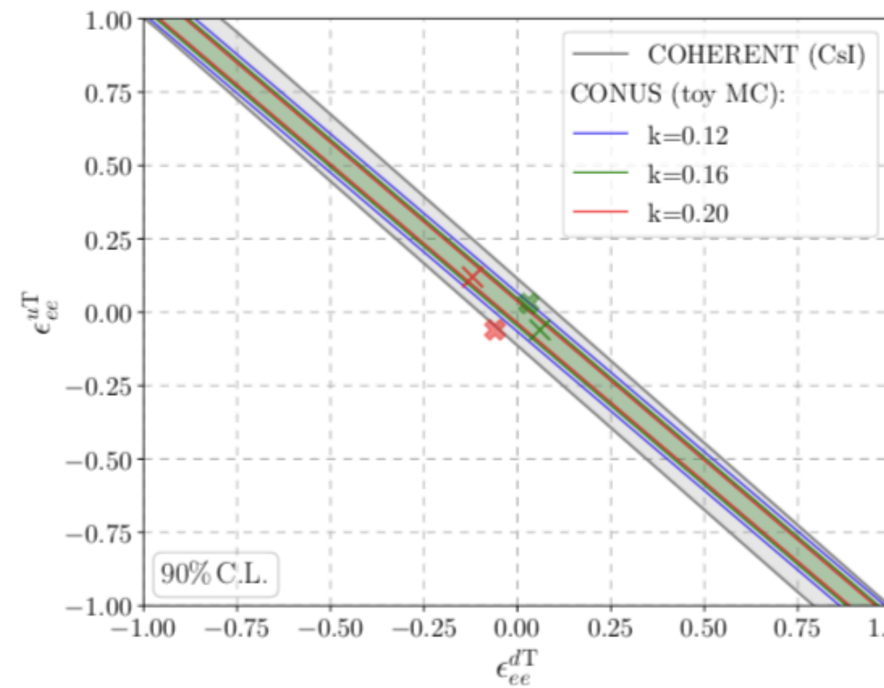



# BSM: non standard interactions (tensor)

New coupling with nuclear charge term adding to CEvNS cross-section
Higher kinematic cutoff ==> rather weak quenching dependence



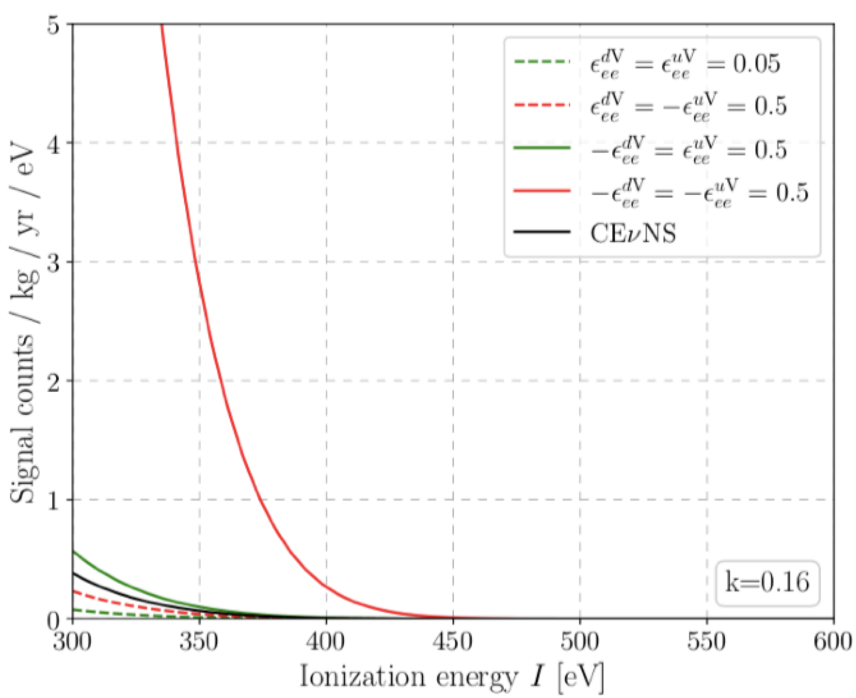



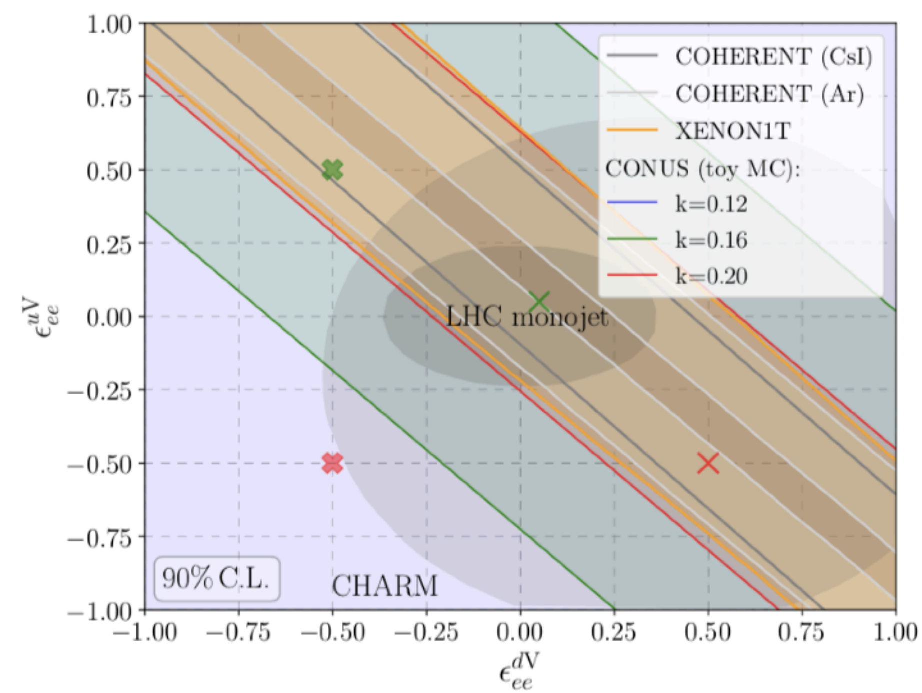

Very competitive results!

CONUS, JHEP 05 (2022) 085

# BSM: non standard interactions (vector)

New interaction similar to CEvNS: modified weak charge



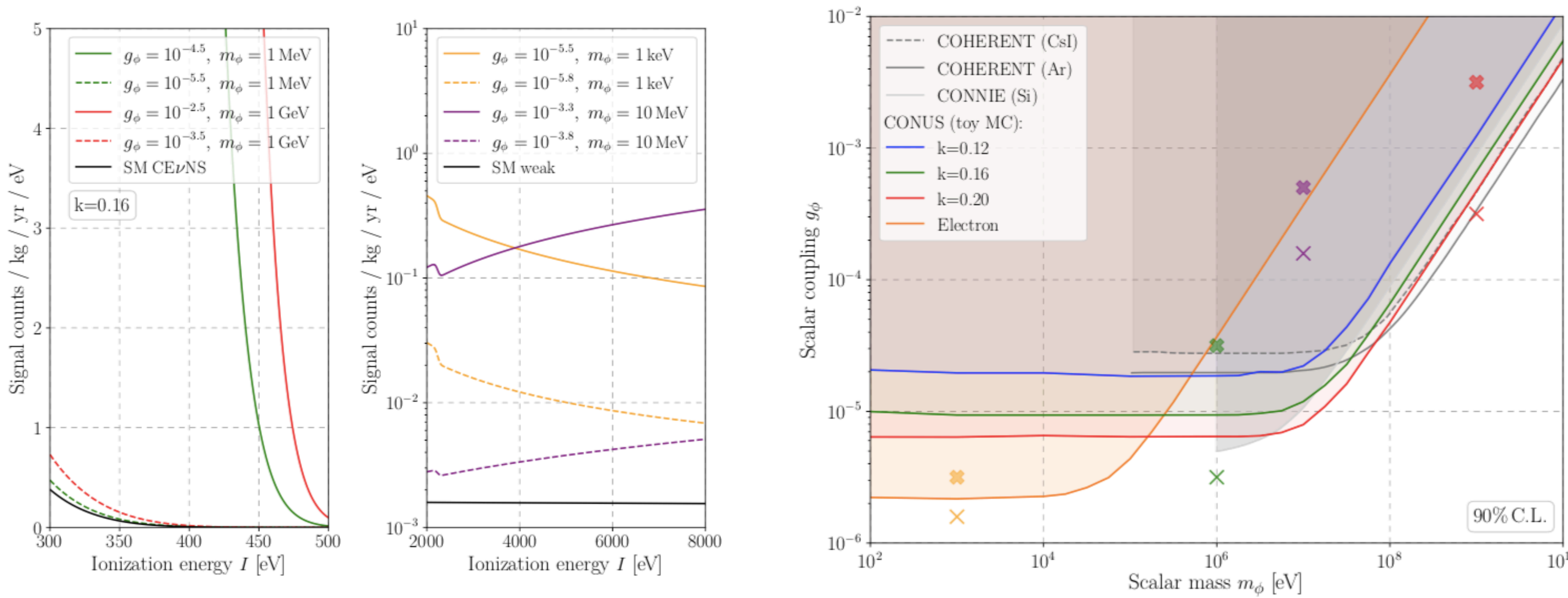




Destructive interference possible

CONUS, JHEP 05 (2022) 085

# BSM: light mediators (scalar)

- Testing simplified models assuming universal couplings
- Nucleus and electron (2-8 keV) channels included

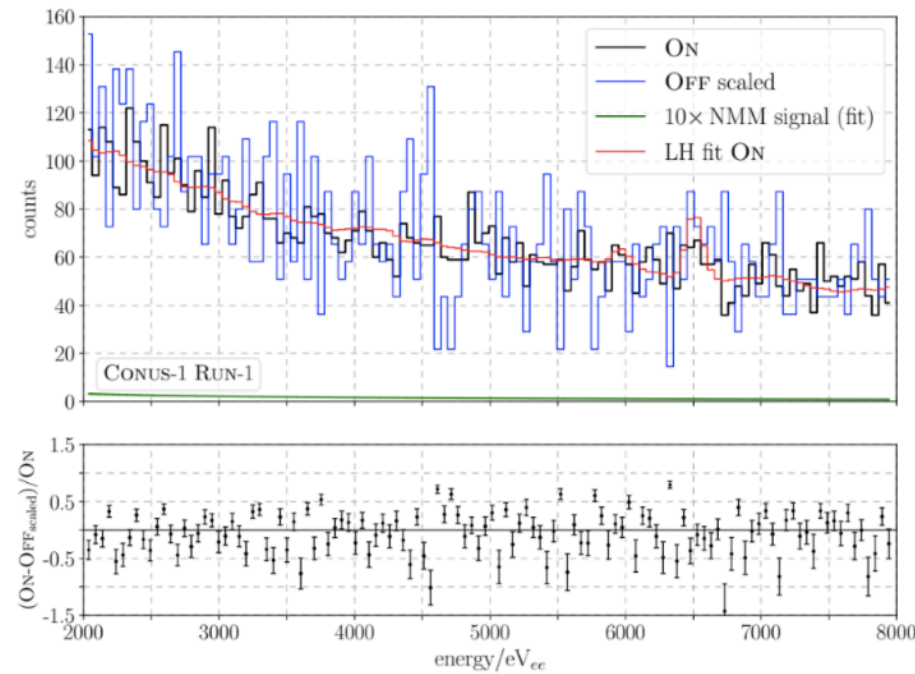



CONUS, JHEP 05 (2022) 085

# Neutrino electromagnetic properties (Run-1+2)

Magnetic moment:

$$\left(\frac{d\sigma}{dT}\right)^{e^-}_{\mu_\nu} = \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_e}}{\mu_B}\right)^2$$



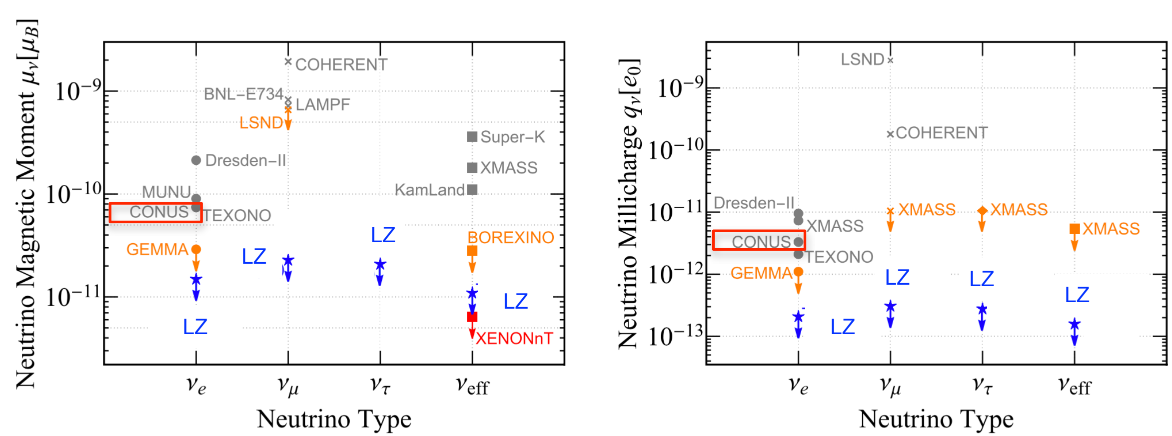

CONUS bound (90% CL) from ν-e scattering in 2-8 keV window:
**$\mu_\nu < 7.5\times10^{-11}\ \mu_B$**

Conversion to millicharge limit:

$$q_\nu^2 < \frac{T}{2m_e}\left(\frac{\mu_\nu}{\mu_B}\right)^2 e_0$$

*A. Studenikin, EPL 107(2), 21001 (2014)*

**$q_\nu < 3.3\times10^{-12}\ e_0$**




CONUS, EPJ C 82:813 (2022)

*M. Atzori Corona et al., PRD 107, 053001 (2023)*

# Network connections