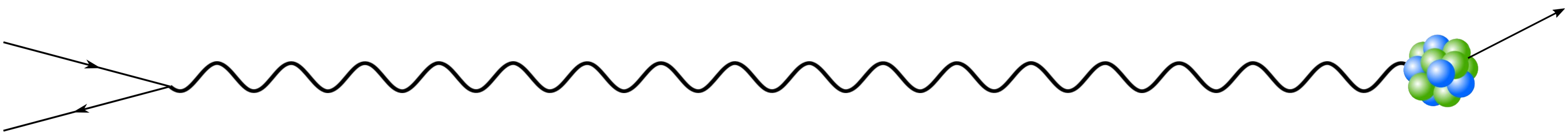
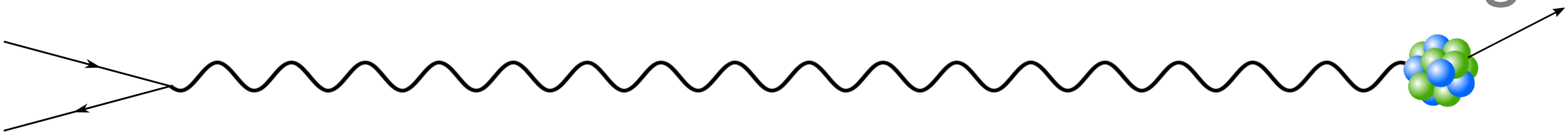
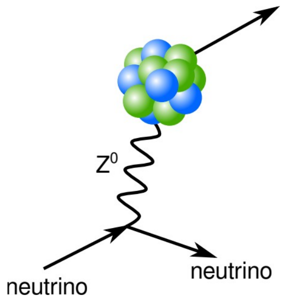
CONUS experiment: New results and the upgrade campaign to CONUS+



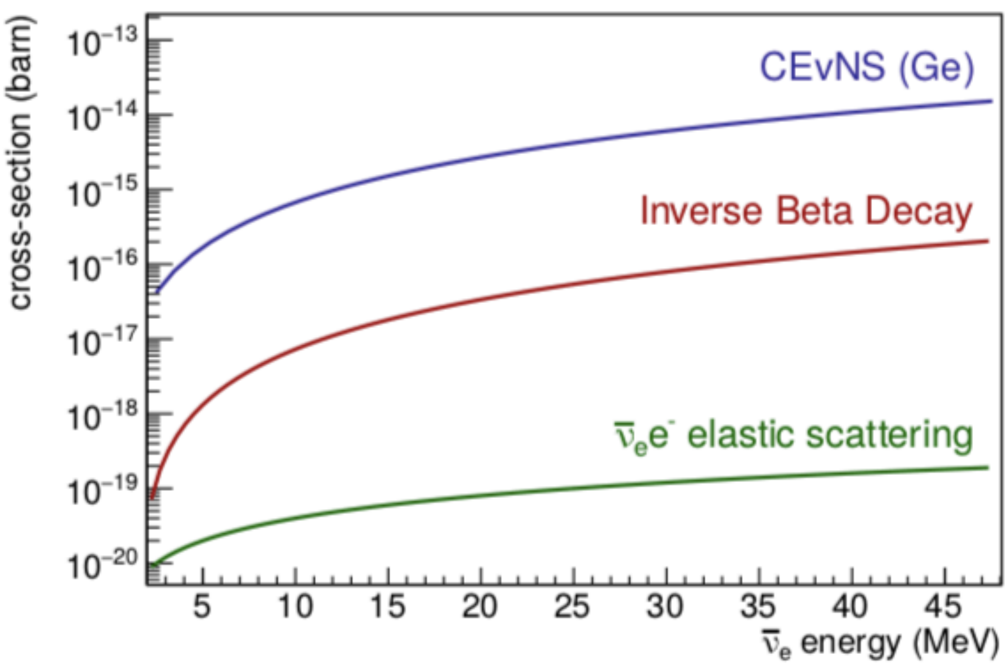
Christian Buck (on behalf of the CONUS collaboration)
Max-Planck-Institut für Kernphysik, Heidelberg
Neutrino Telescopes, Venice, October, 25th (2023)

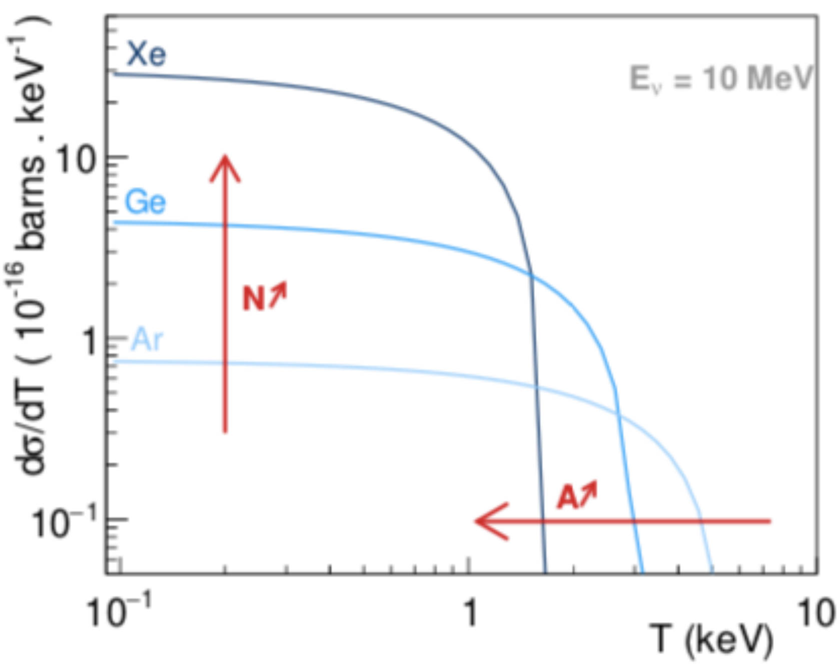
Coherent elastic neutrino nucleus scattering





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

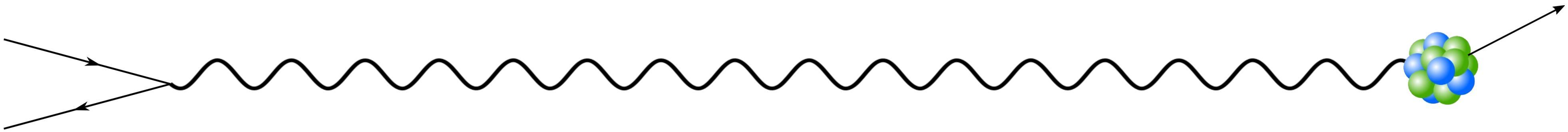


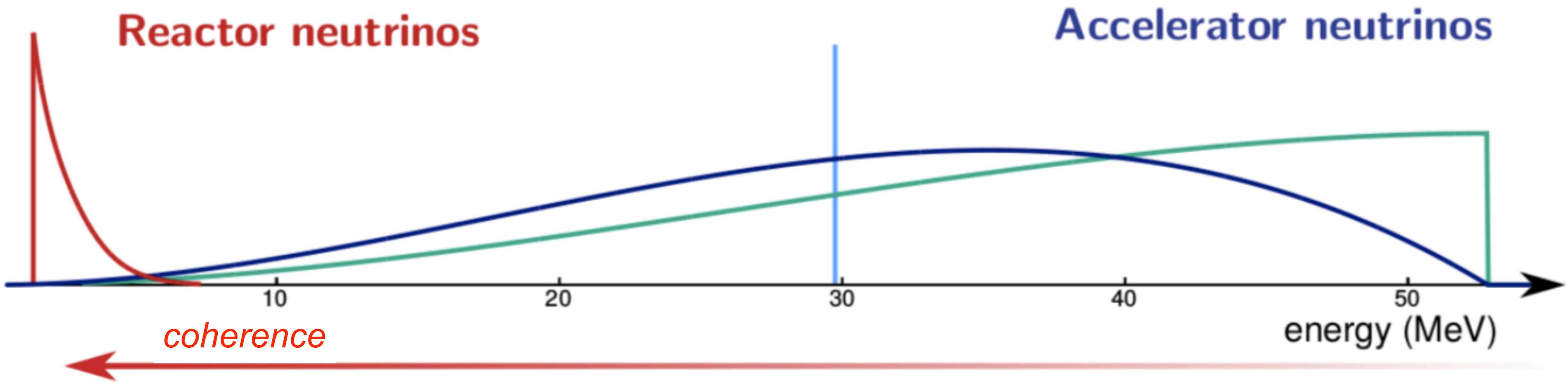


- Higher cross-section
- Chance for compact neutrino detector

- Interaction rate vs recoil energy
- Ge good compromise

Neutrino sources for CEvNS studies



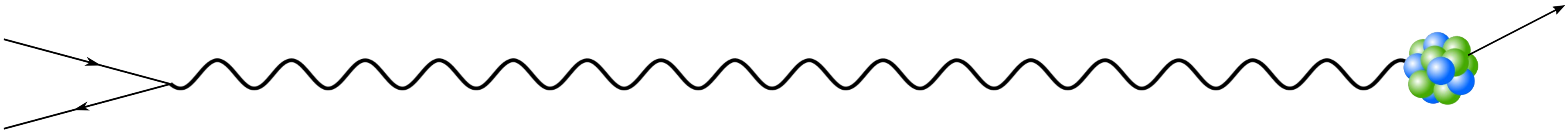


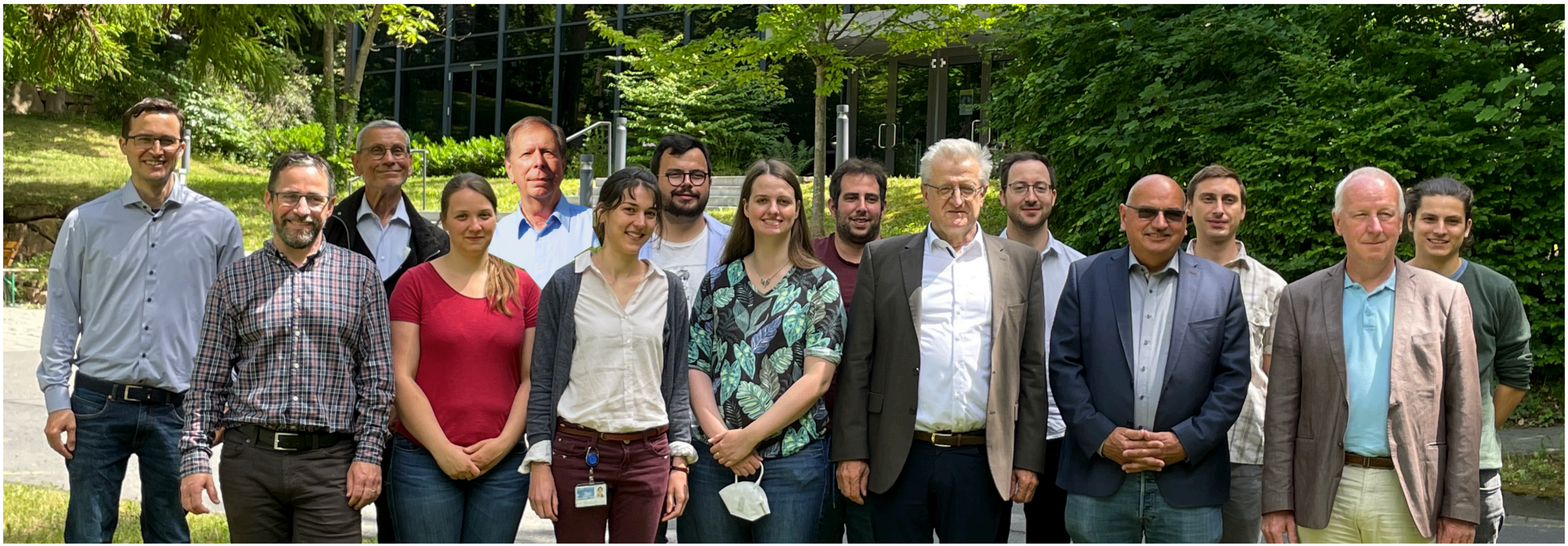
- Pure flux of electron antineutrinos
- E < 10 MeV ==> form factor ~1
- High sensitivity for BSM physics
- CONUS, νGeN, CONNIE, Dresden-II, Nucleus, Ricochet,…

- Different neutrino flavors
- E ~ 20 - 50 MeV ==> form factor < 1
- COHERENT: first observation in 2017

Other sources: solar or Supernova neutrinos

CONUS Collaboration





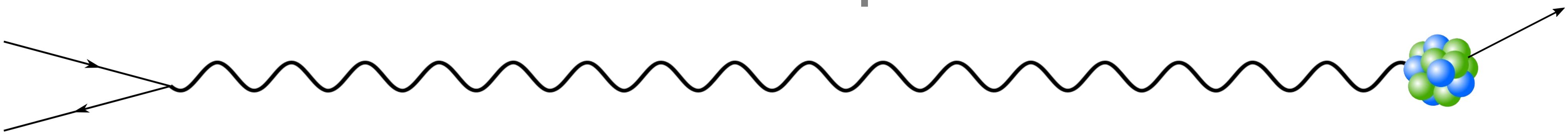
N. Ackermann, S. Armbruster, H. Bonet, A. Bonhomme, C. Buck, J. Hakenmüller, J. Hempfling, J. Henrichs, G. Heusser, T. Hugle, M. Lindner, W. Maneschg, K. Ni, T. Rink, E. Sanchez Garcia, J. Stauber, H. Strecker
Max-Planck-Institut für Kernphysik (MPIK), Heidelberg

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

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

Preussen Elektra

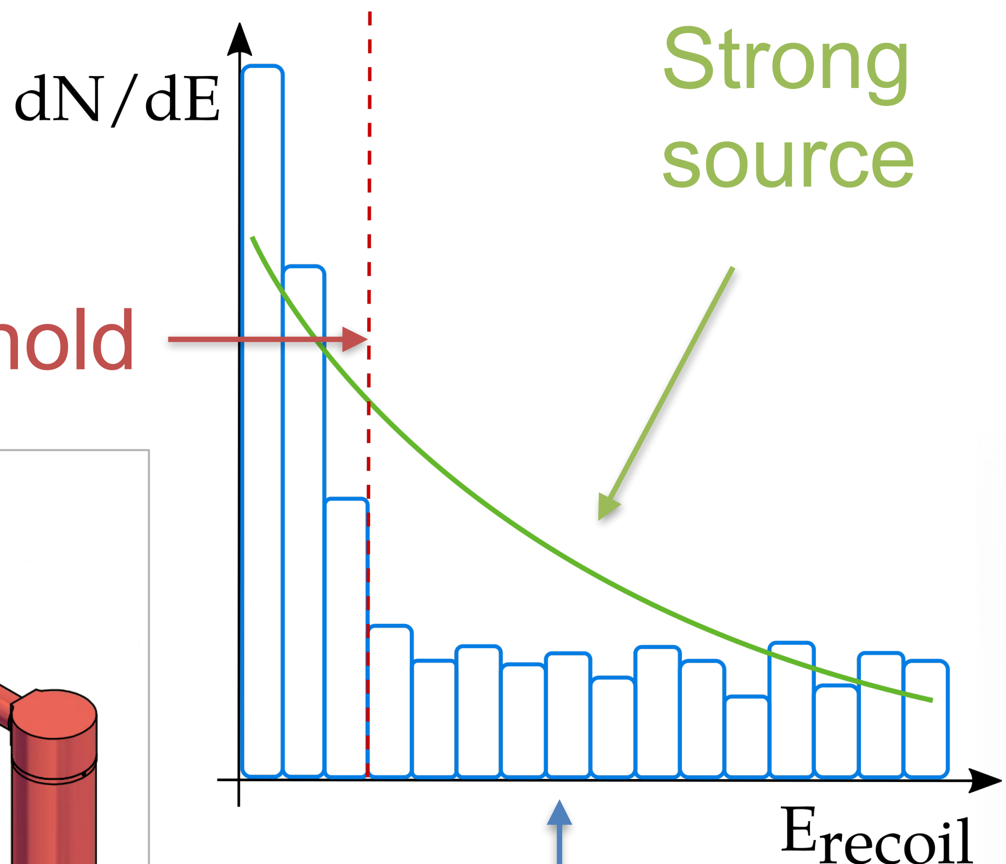
Concept



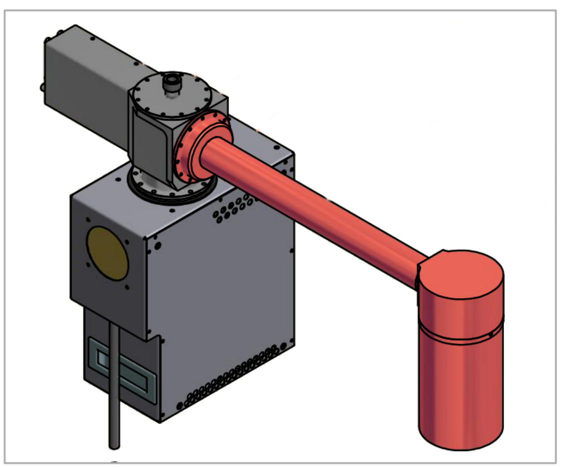
Strong source

Nuclear power plant (Brokdorf, KBR)

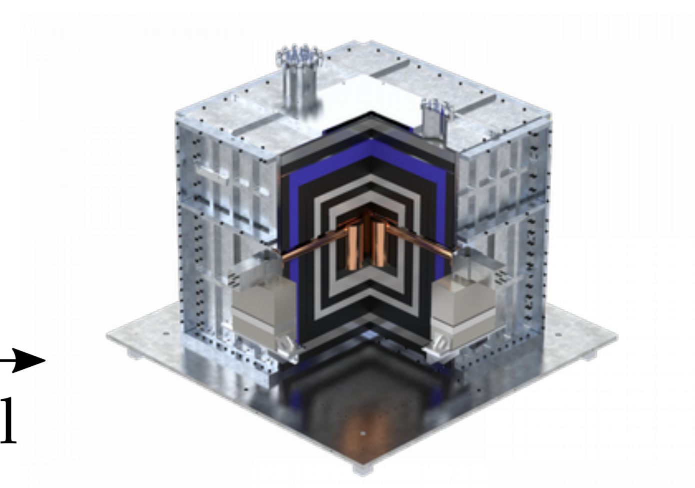
Low threshold



Low background

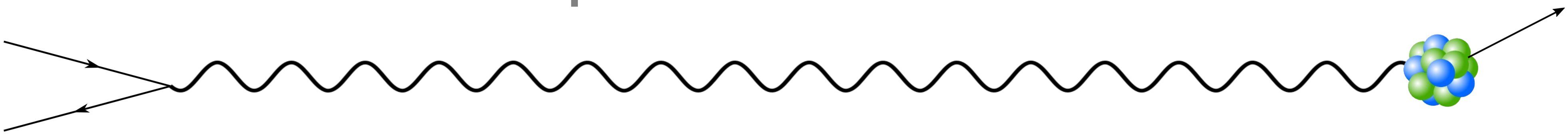


4 x 1 kg point contact HPGe spectrometer



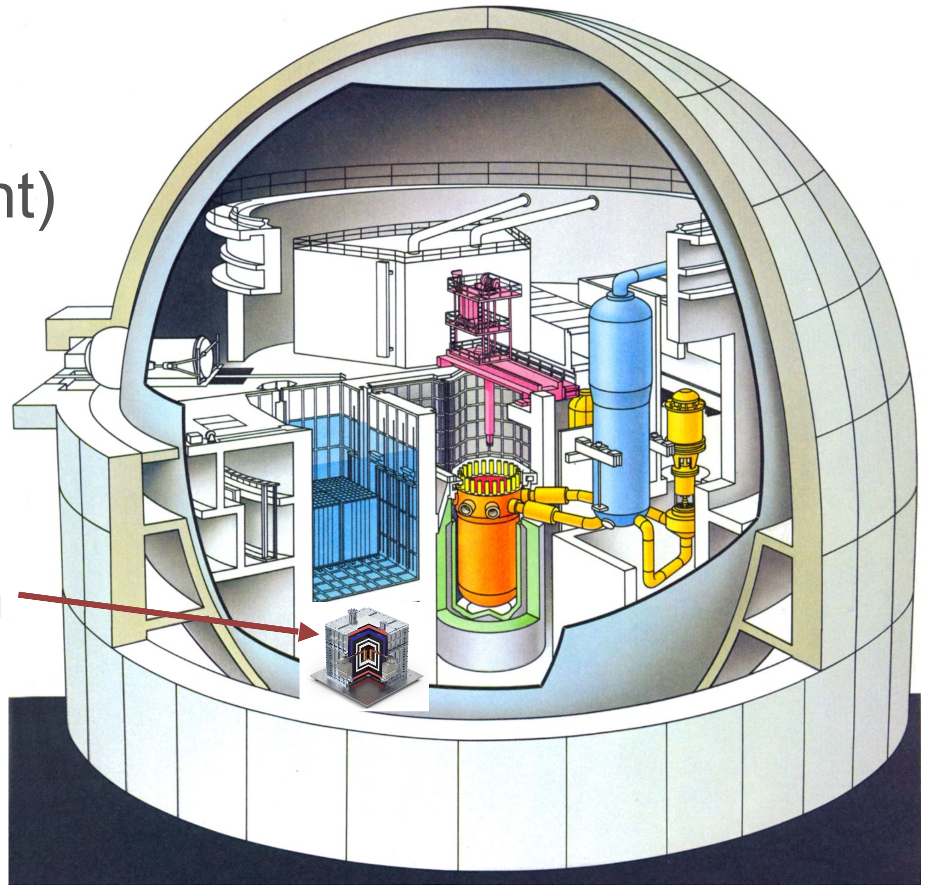
Shield (11 t, 1.6 m^3)

Experimental Site



Overburden:
10 - 45 m w.e.
(angle-dependent)

CONUS location

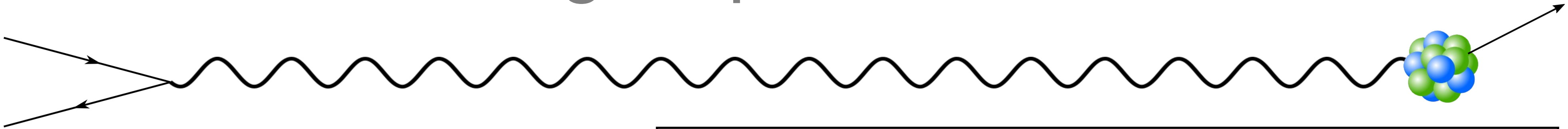


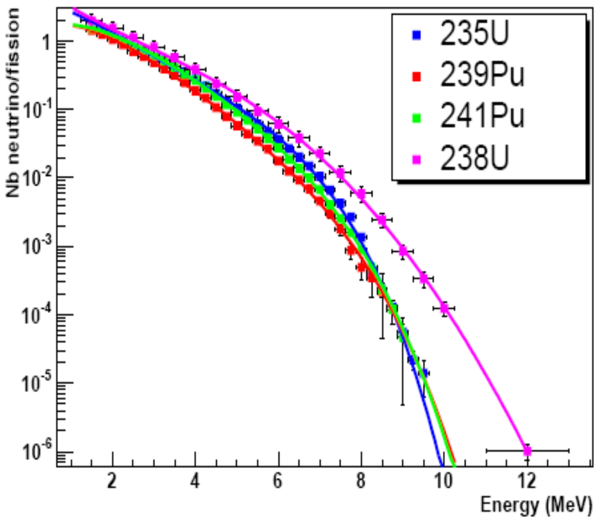
KBR Brokdorf:

- 3.9 GWth
- Distance 17.1 m
- Data taking 5 years
- Stopped end 2021
- Long reactor OFF measurement in 2022

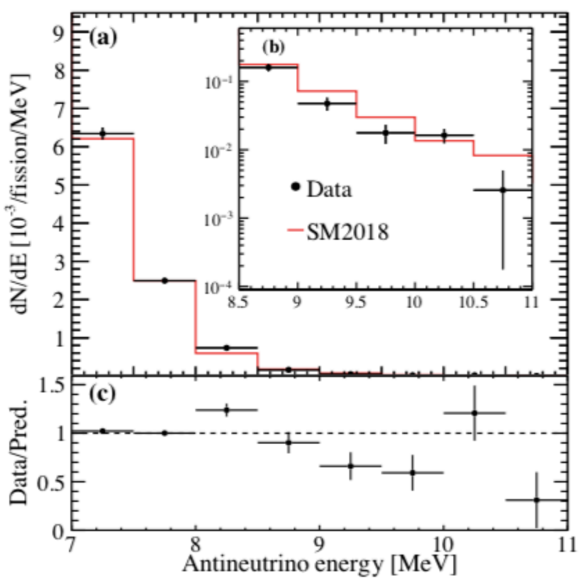
Challenging environment: no remote control, restricted materials, earthquake safety, access, different ON and OFF conditions,…

Signal prediction

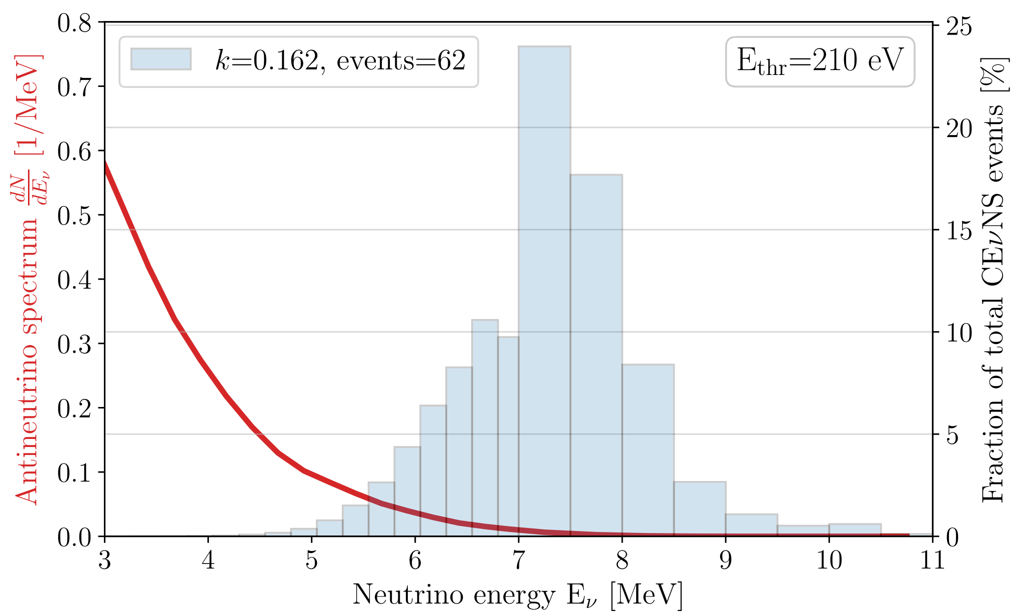




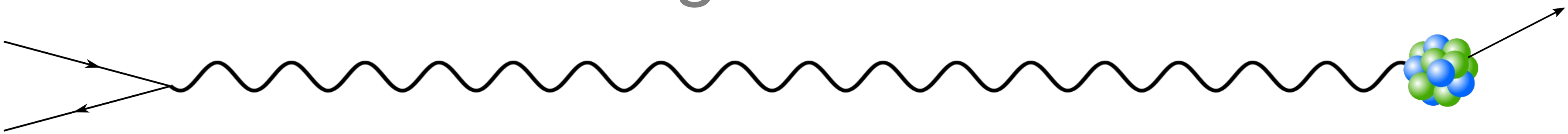
- Thermal power and energy per fission
- Flux at CONUS site: 2.3x10[13] /(cm[2] s)
- Consider evolution of fission fractions
- Spectrum: data-based method and high E spectrum from Daya Bay
- High quenching factor (f) dependence! (Ionization signal E_{det}= f * T_{nr})



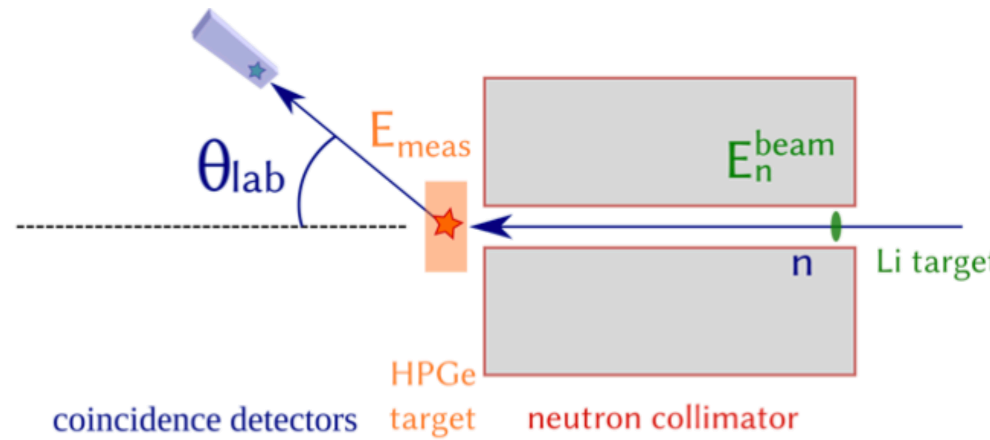
Daya Bay, PRL 129 (2022) 041801

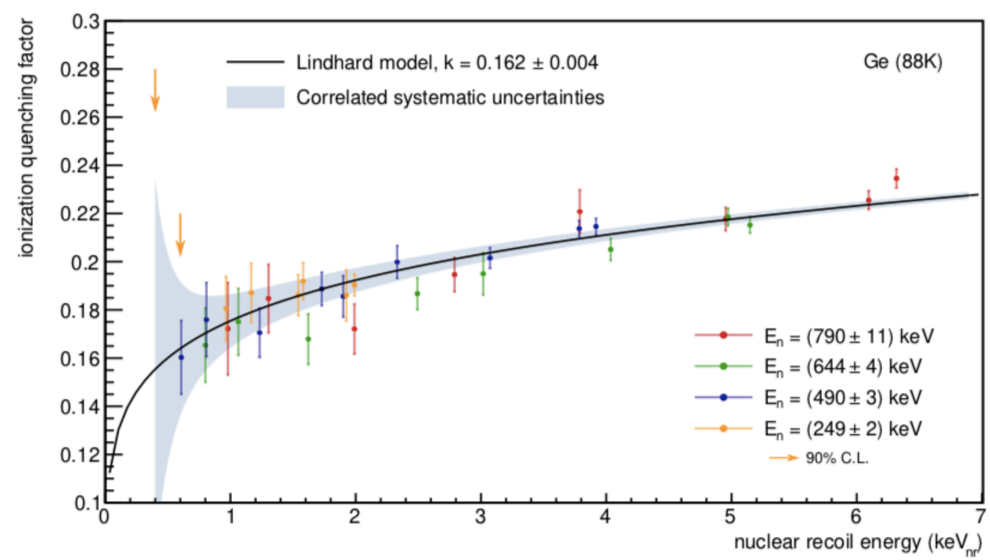


Quenching measurement



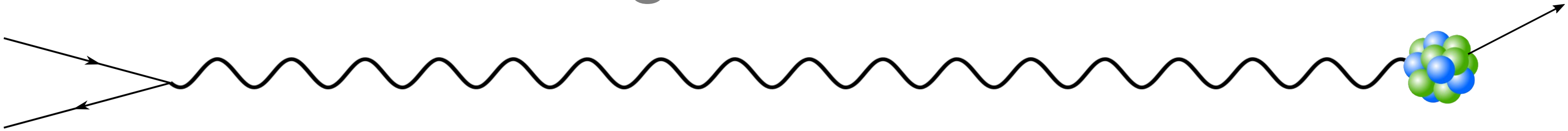
- Experimental setup (beam facility a PTB Braunschweig)
  - Model-independent method
  - Triple coincidence
  - Beam energy 250 - 800 keV
  - Angles 18-45° (1° precision)
  - Nuclear recoils 0.4 - 6 keV
- Results
  - Compatible with Lindhard theory!
  - **k = 0.162 ± 0.004** (stat.+syst.)
  - Challenge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



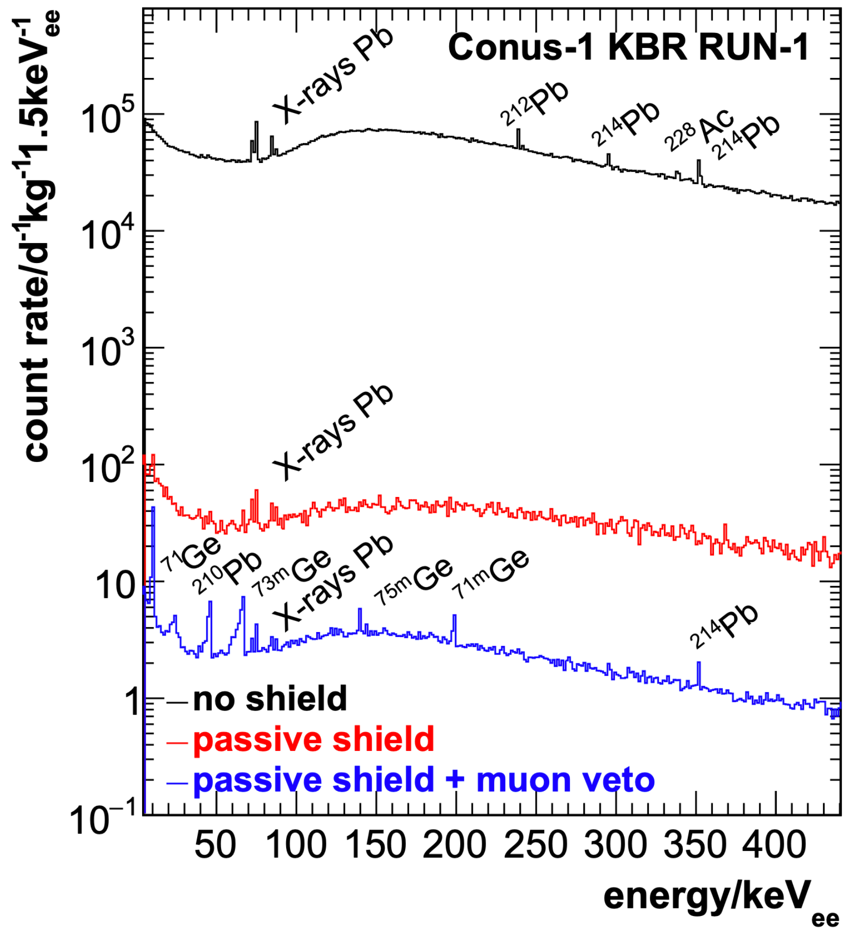


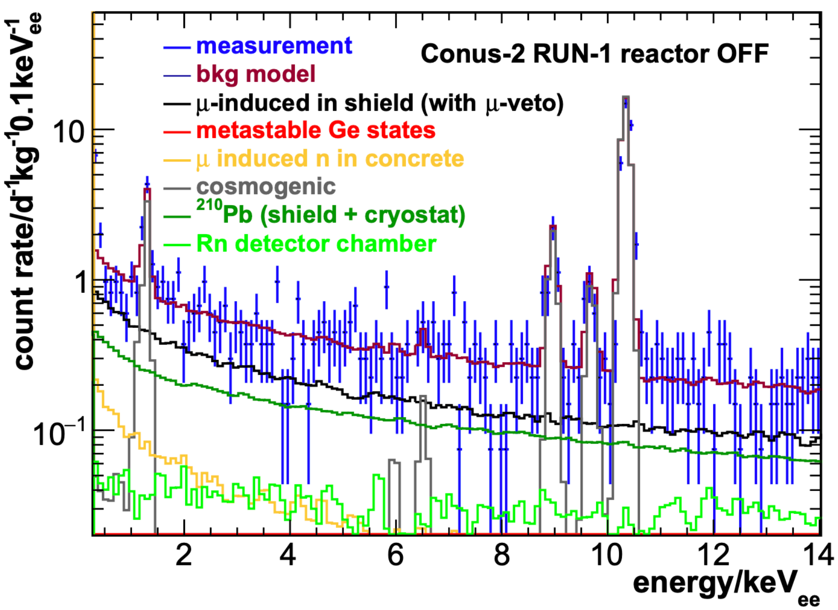
Bonhomme et al., EPJ C 82:815 (2022)

Background model



- Passive + active shield: Background suppression ~10^4
- Rate 0.5-1 keV: ~10 /(keV d kg)
- “Virtual depth”
- Reactor neutrons under control

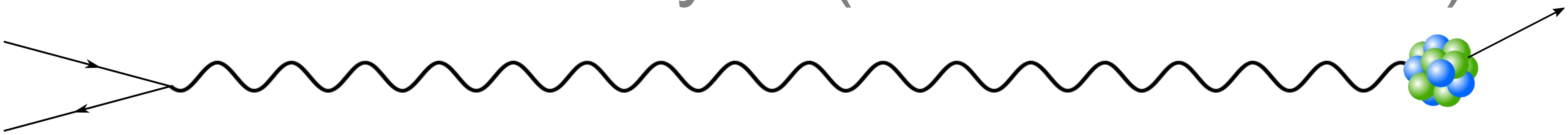




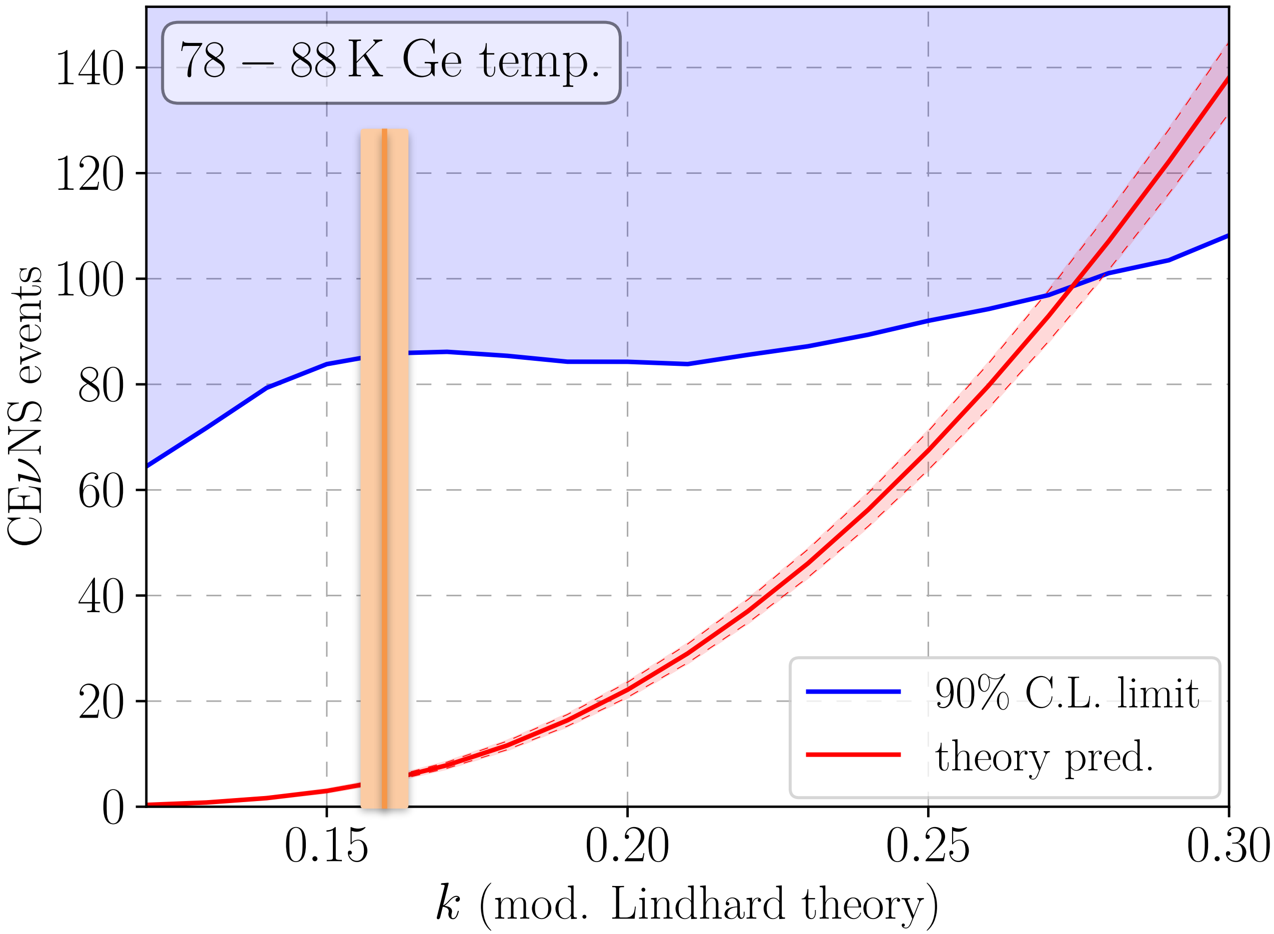
CONUS, EPJ C 83:195 (2023)

CONUS, EPJ C 79:699 (2019)

CEvNS data analysis (Run-1 and Run-2)



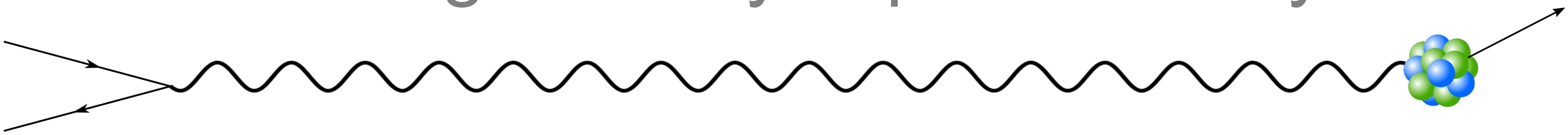
CONUS, PRL 126 (2021) 041804



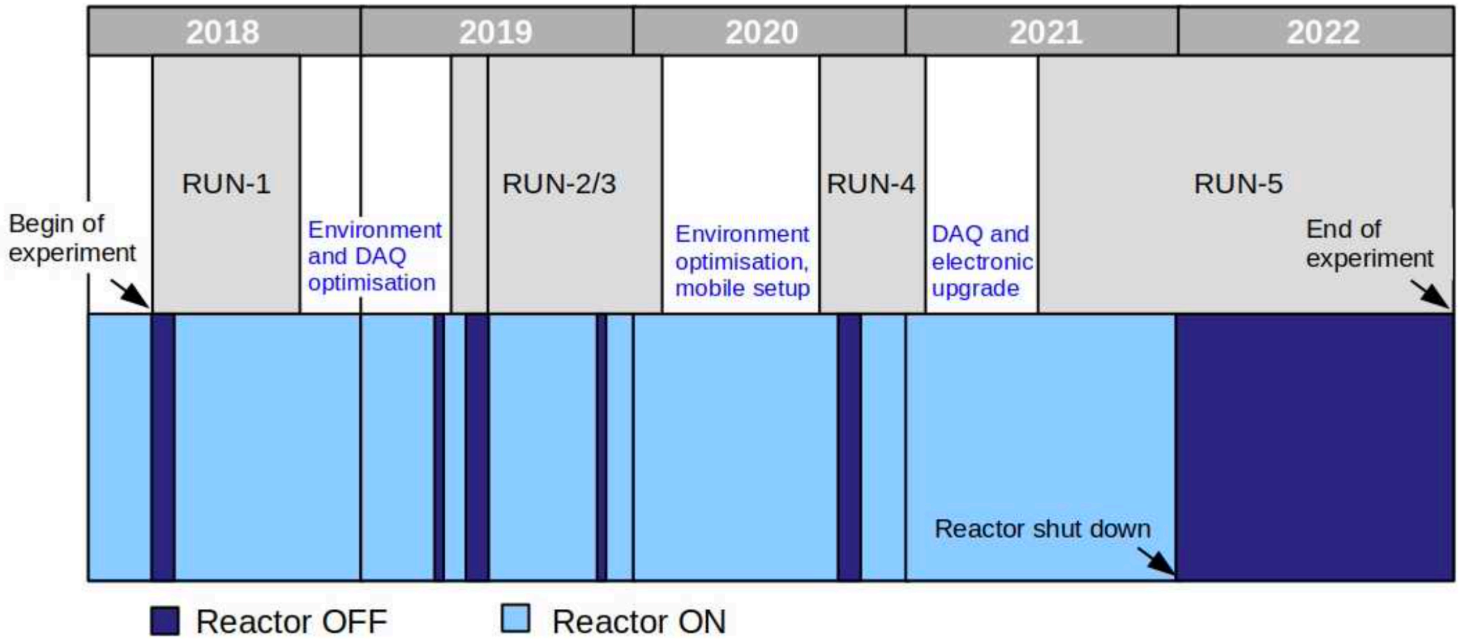
- 249 kg d ON
- 59 kg d OFF
- CEvNS limit: < 0.4 /(d kg)

Run 1+2 limit is 17 times higher than SM signal prediction

Run-5: significantly improved analysis

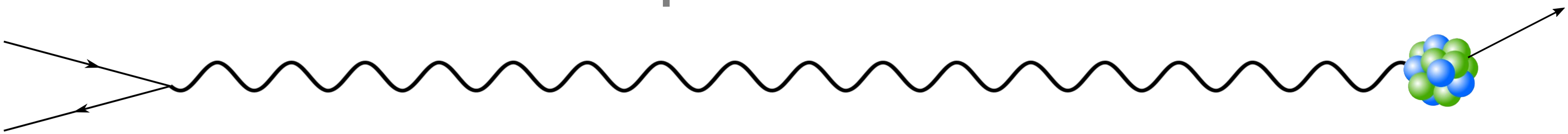


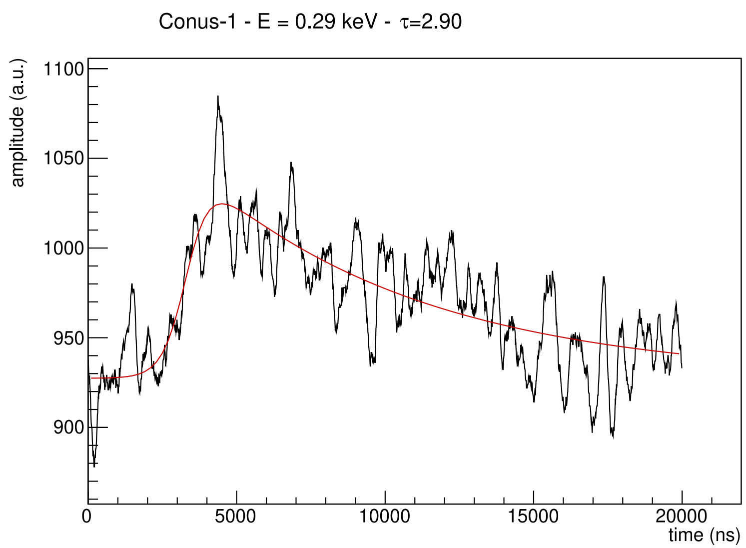
Detectors	ON [kg d]	OFF [kg d]	E threshold [eV]
C1, C2, C4	~450	~300	210

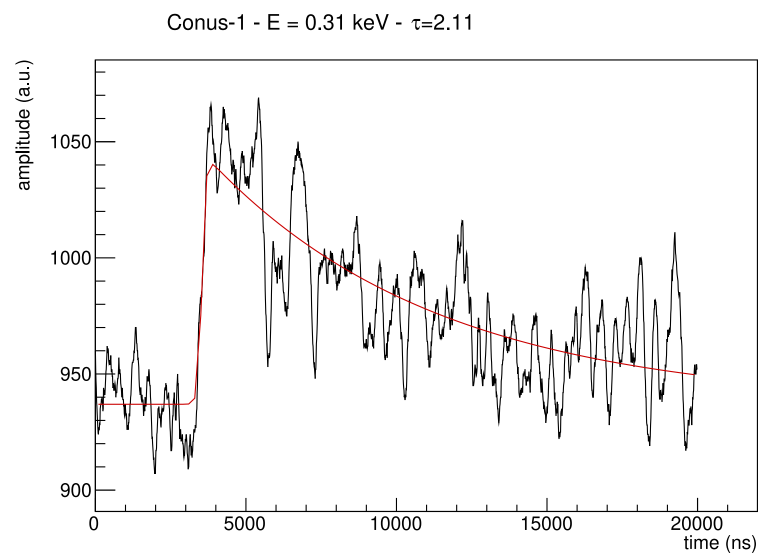


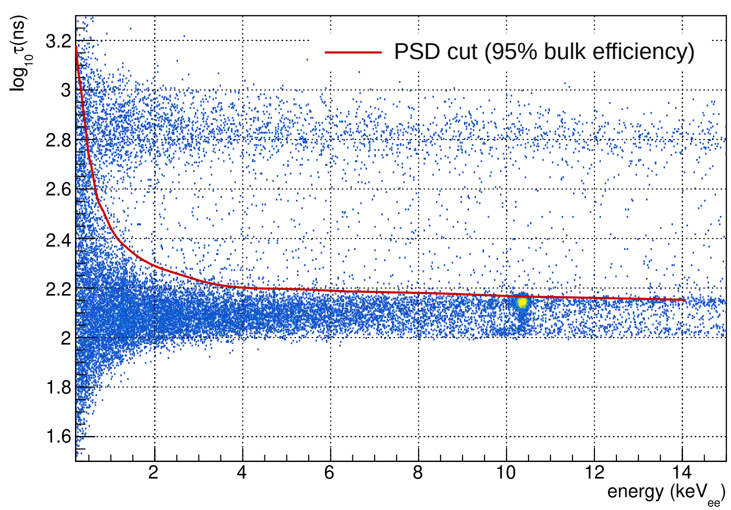
- Improvements: stability, DAQ, E threshold, PSD, OFF statistics…
- Data with high noise variations excluded

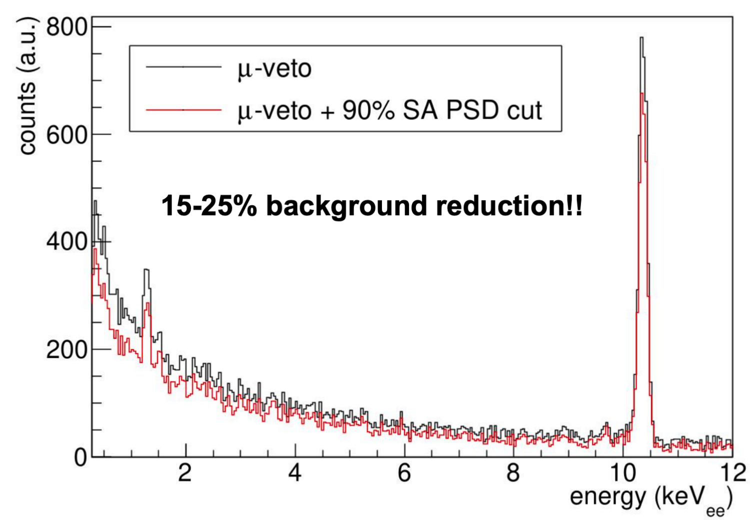
Pulse shape discrimination







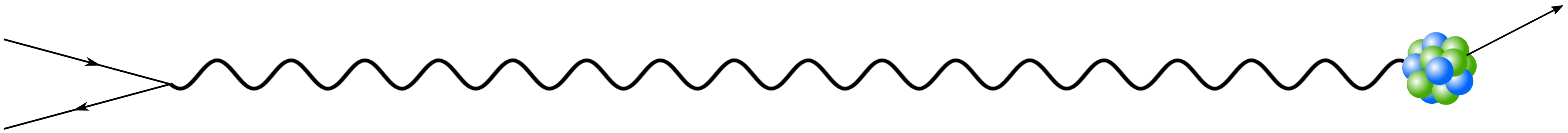


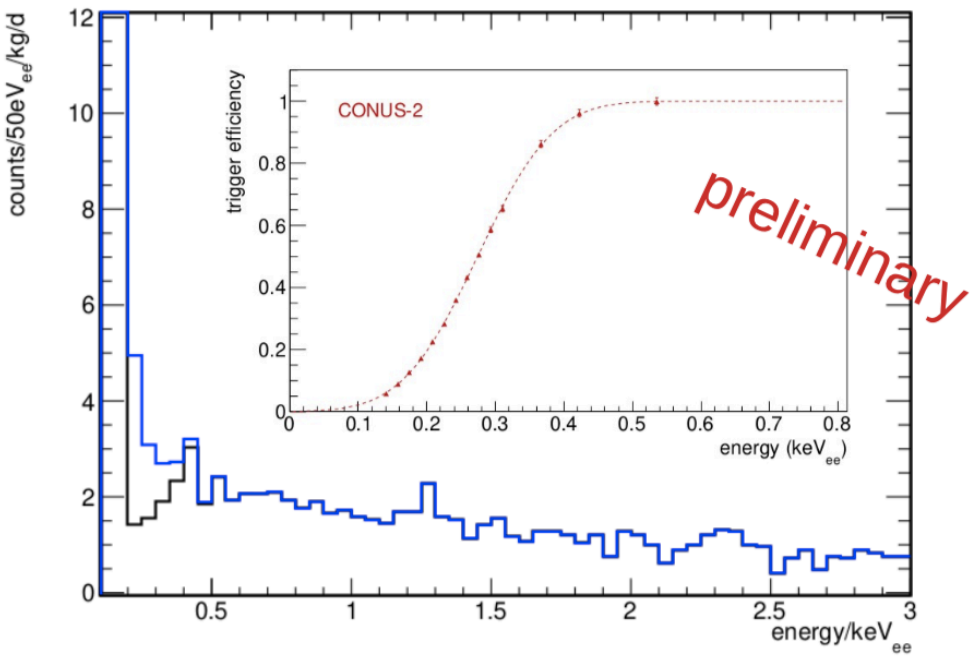


CONUS, arXiv2308.12105 (2023)

Signal acceptance in Run-5: 97%

Run-5 result

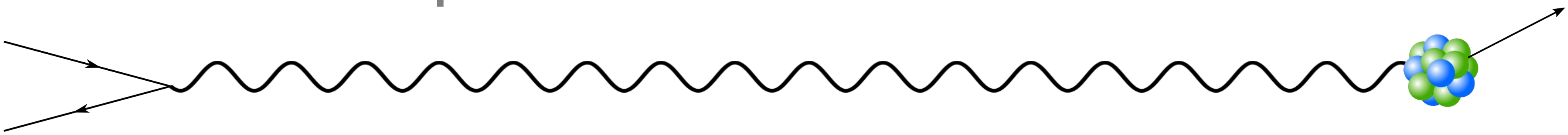




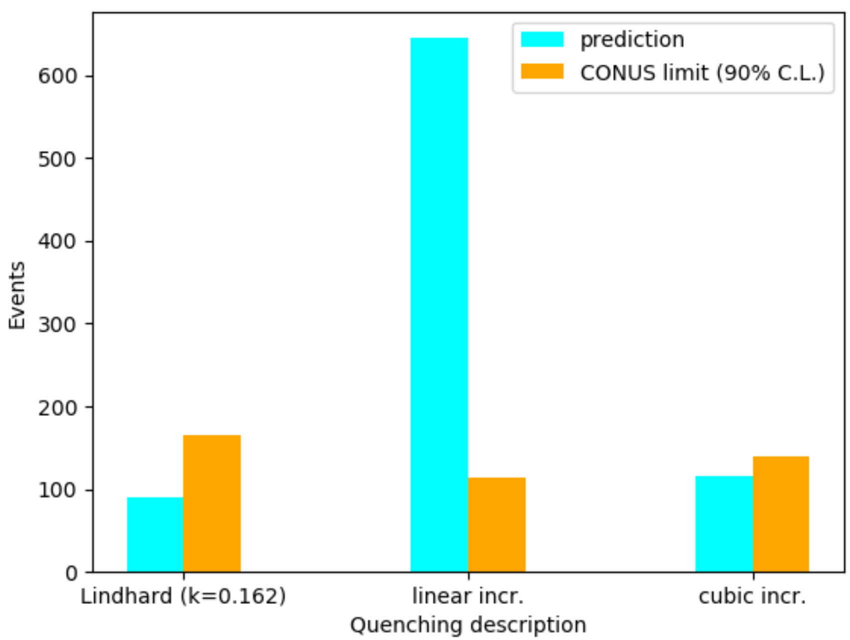
Detector	Signal prediction	Fit constraint (90% C.L.)
C1	42±8	< 59
C2	26±5	< 75
C4	24±4	< 90
All	92±10	< 163

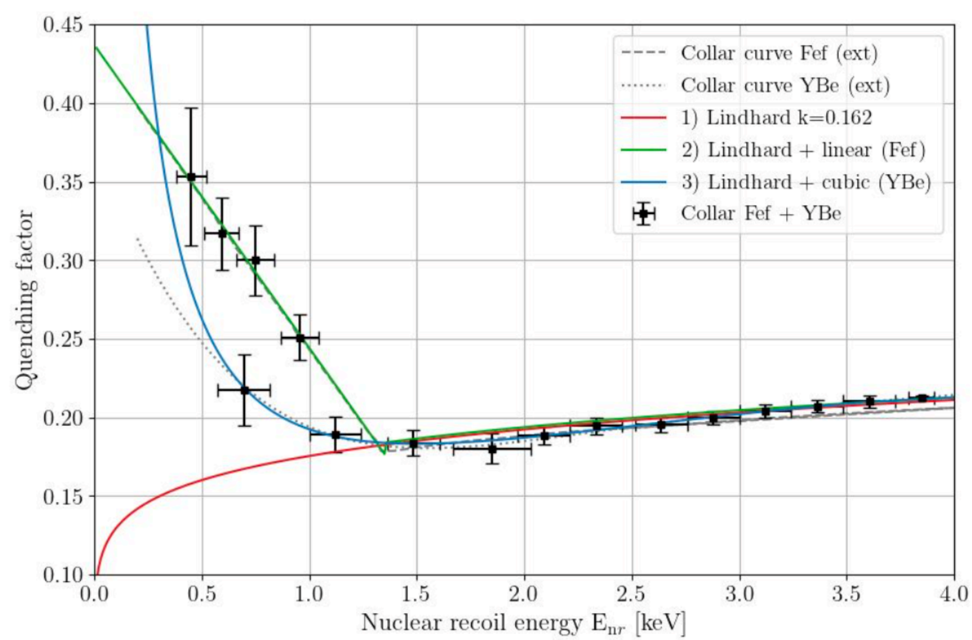
- Limit factor ~2 above predicted SM value (strongest limit at reactor)
- ~ 1 order of magnitude improvement as compared to Run-1+2!

Comparison with other results

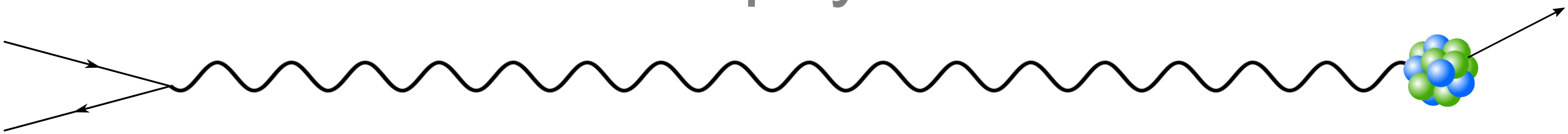


- Constraints from vGen, CONNIE, TEXONO
- Colaresi et al., PRL 129, 211802 (2022)
  - "…very strong preference…for the presence of… CEvNS…"
  - Signal prefers low energy excess of quenching factor as compared to Lindhard quenching to be consistent with SM predictions

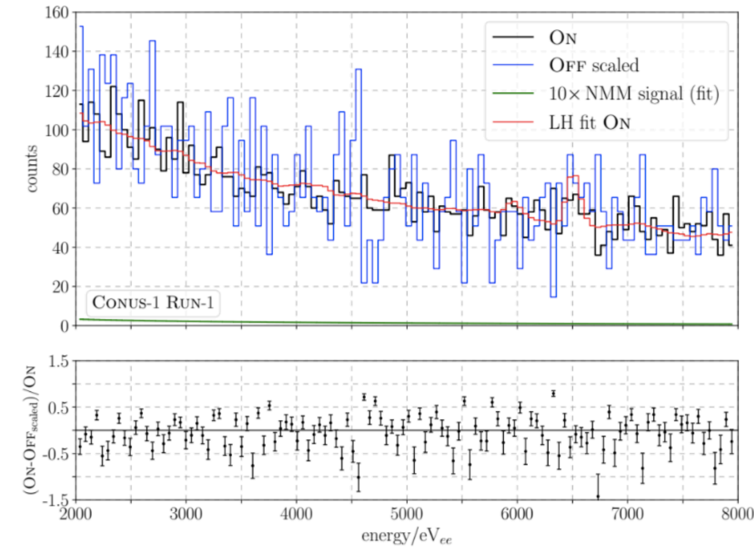


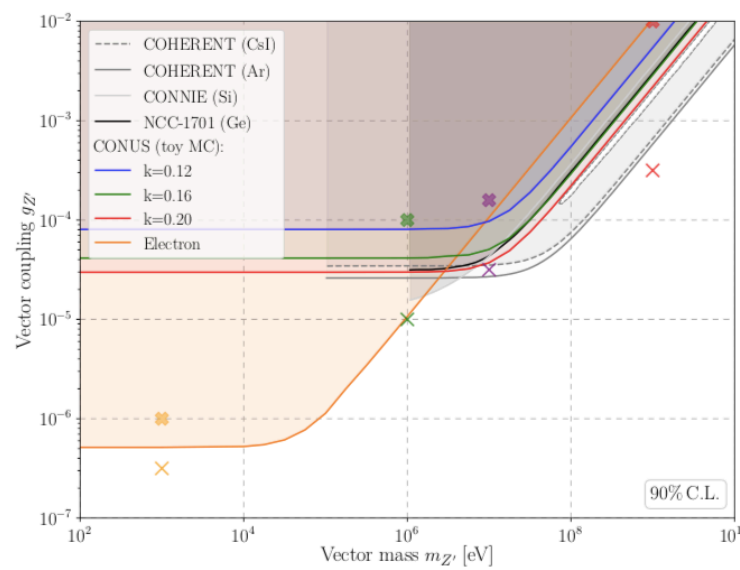


BSM physics

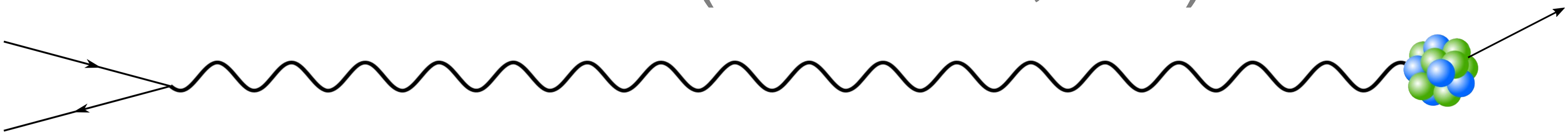


- Magnetic moment / electric millicharge
  - $\mu_\nu < 7.5 \times 10^{-11}\ \mu_B$
  - $q_\nu < 3.3 \times 10^{-12}\ e_0$
- Non standard interactions
  - Tensor type
  - Vector type
- Simplified models
  - Light scalar mediators
  - Light vector mediators

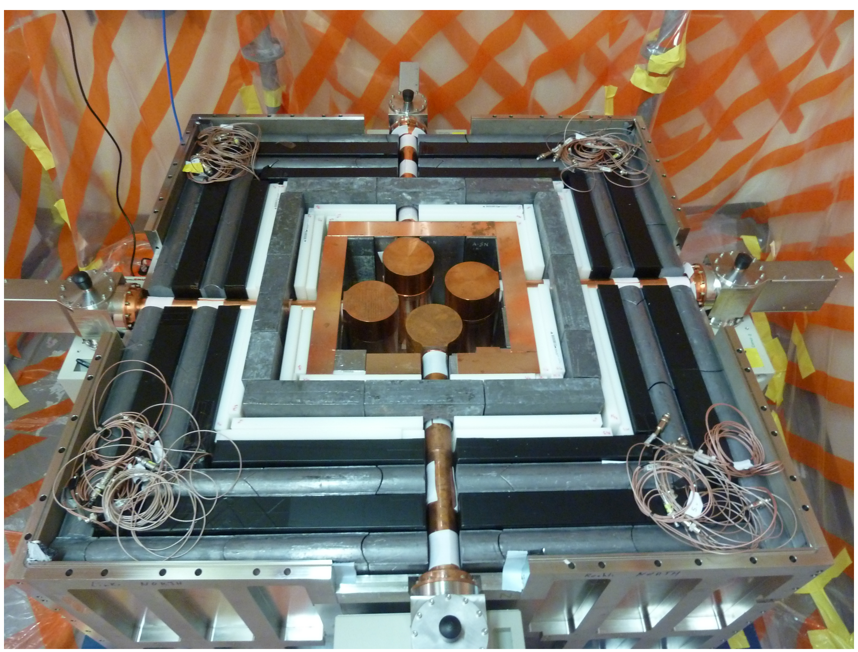


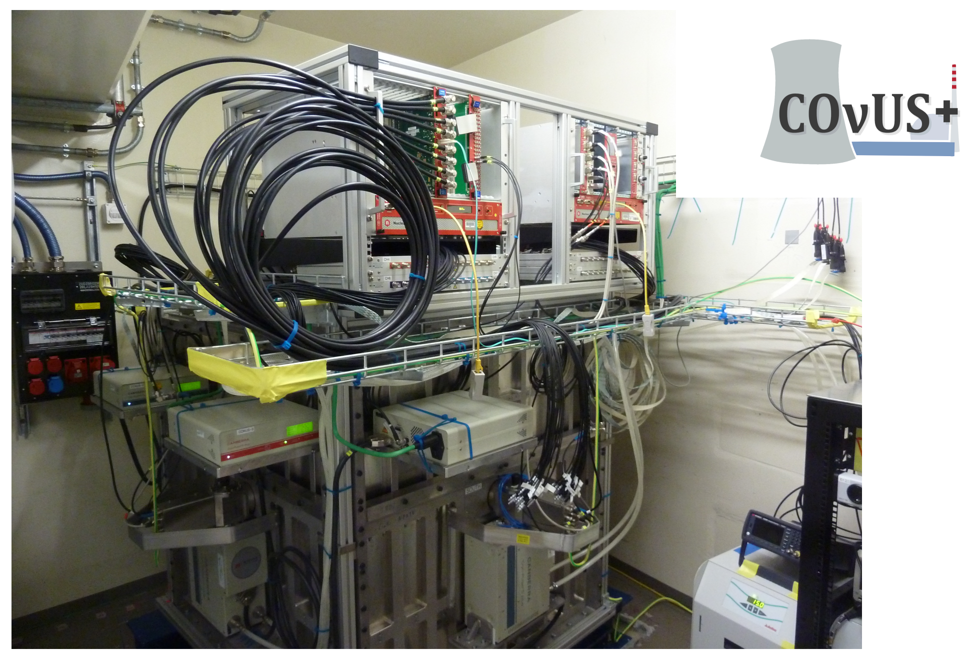


CONUS+ (Leibstadt, CH)

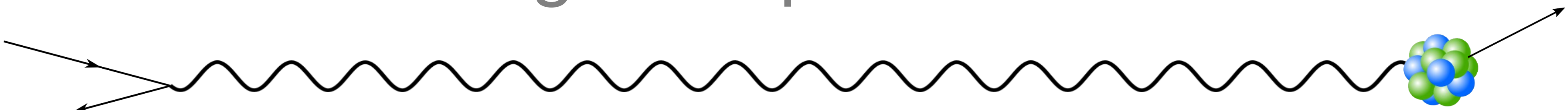


- Site characterisation (d=20.7 m): high E gamma (> 3 MeV) flux lower, neutron flux higher and less overburden (7-8 m w.e.) as KBR site
- Further improve energy resolution, detector thresholds, trigger efficiency and muon veto performance (added additional layer)
- Improved CONUS setup installed this Summer!

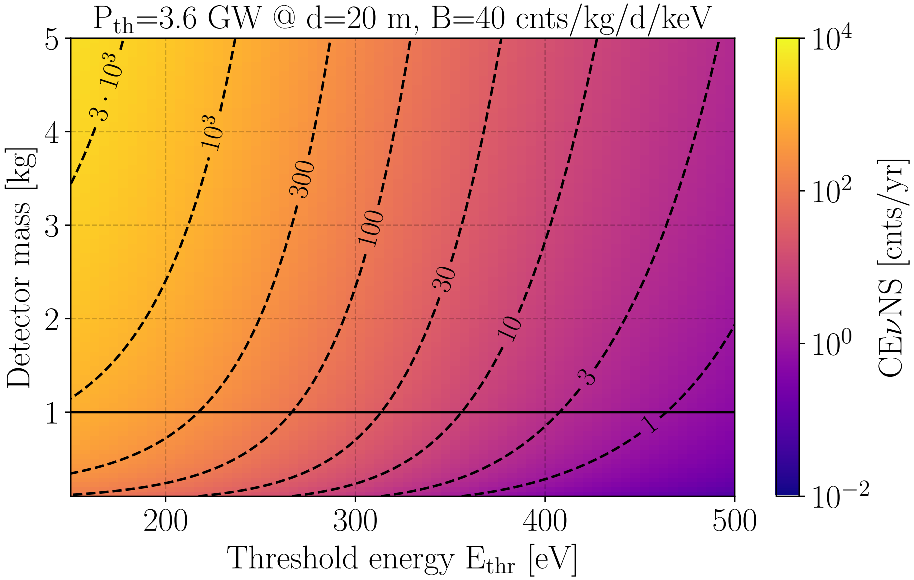




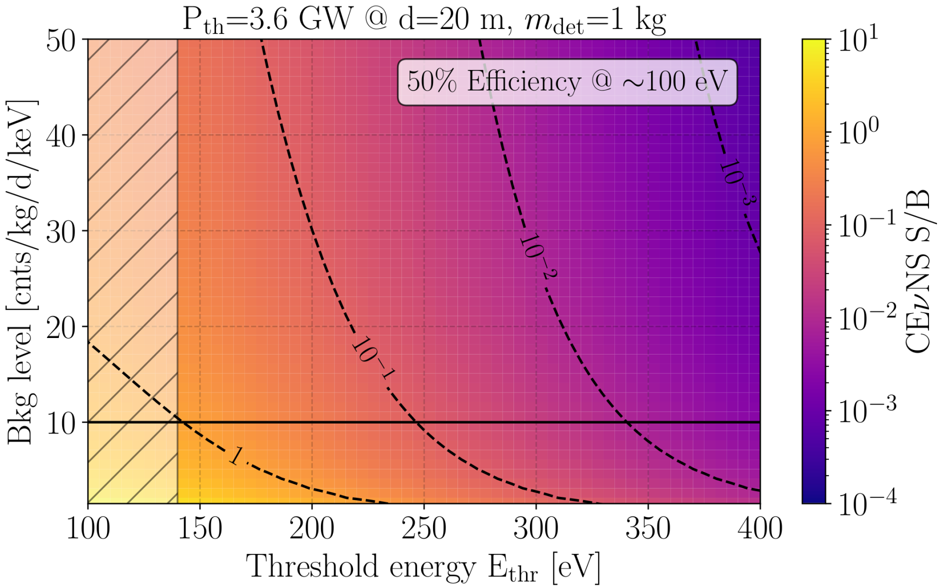
Signal expectation



Event rate per year

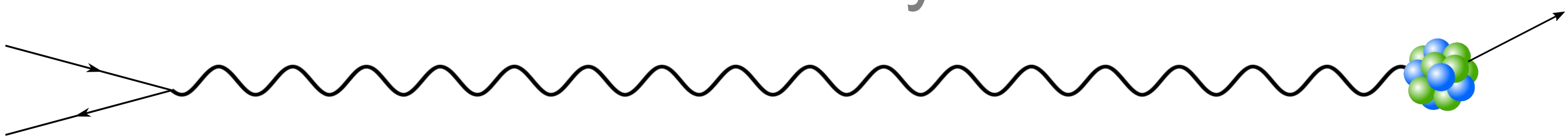


Signal to background ratio

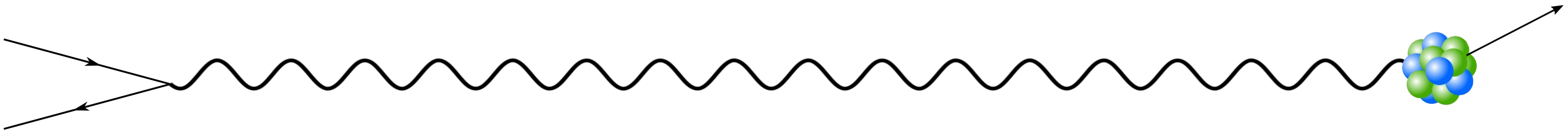


CEvNS signal might be around the corner!

Summary

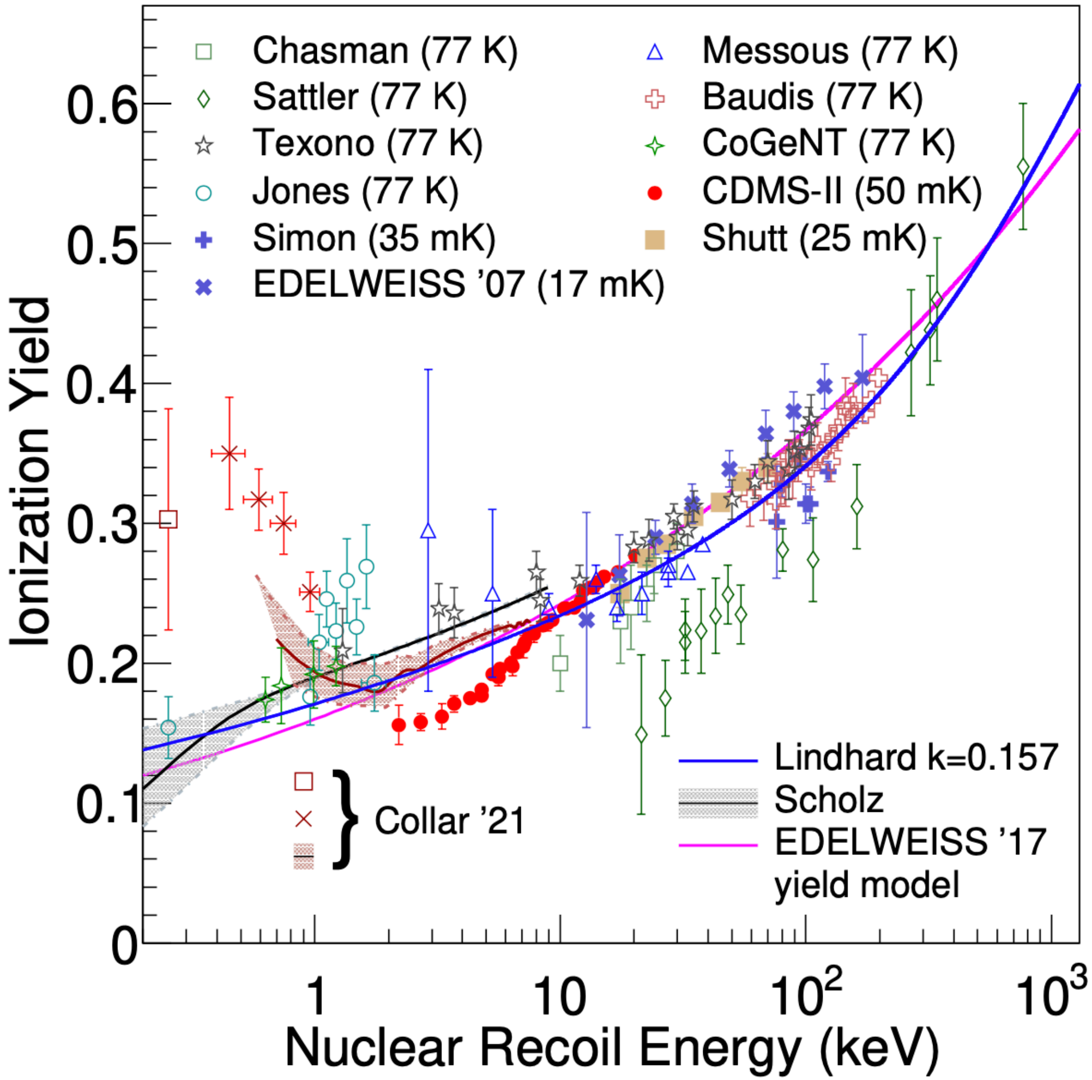


- High cross-section of CEvNS ==> compact neutrino detectors
- CONUS: Low energy threshold HPGe 17.1 m from reactor core
- Ge quenching: data consistent with predictions from Lindhard theory
- Strong constraints on CEvNS: factor < 2 above SM prediction
- CONUS+: Continue in Leibstadt (CH) with improved setup (commissioning phase)



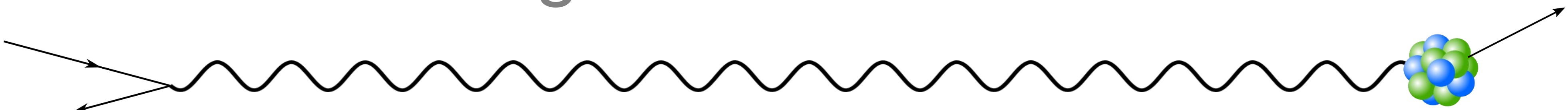
Backup

Other QF results



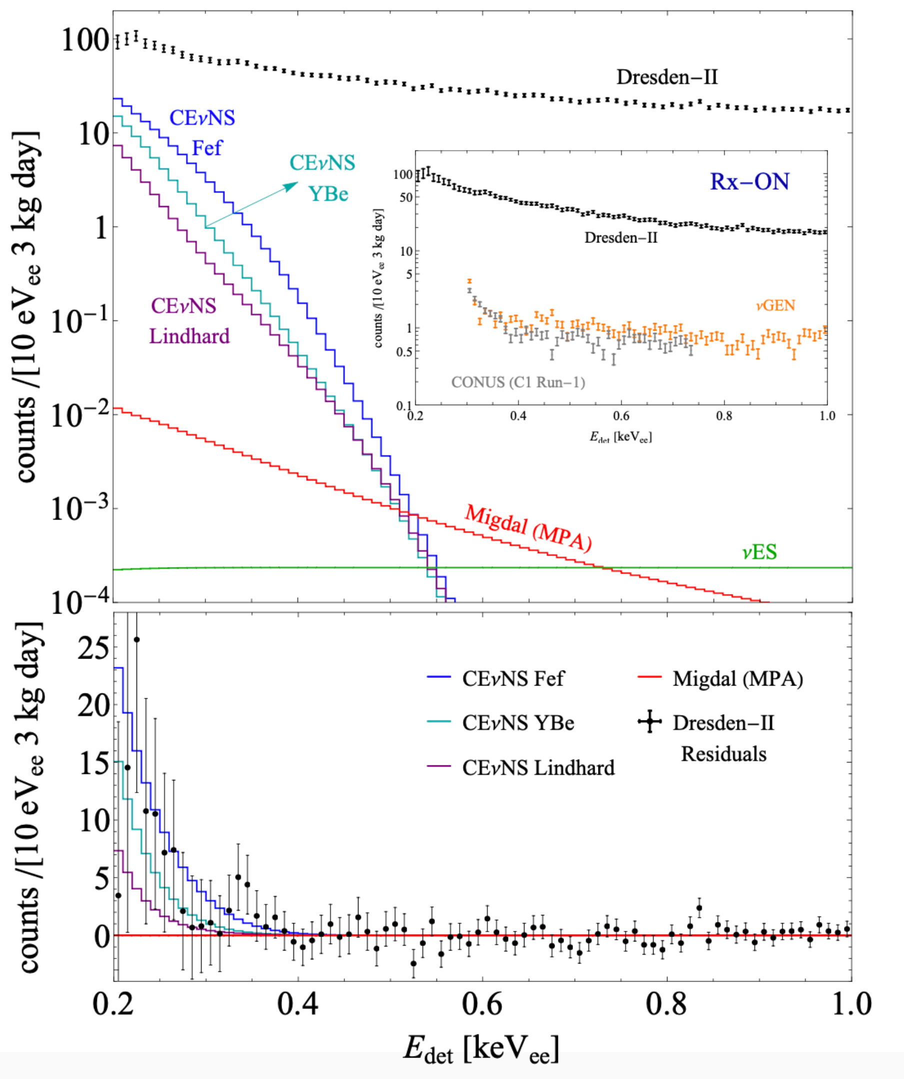
SuperCDMS, PRD 105 (2022) 12, 122002

Migdal contribution



CEvNS expectation and Migdal contribution vs reactor ON data

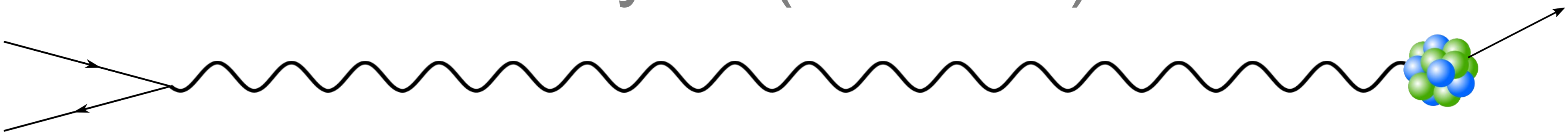
Dresden-II background subtracted



- Blue: quenching from monochromatic filtered n beam
- Cyan: prediction from photoneutron source data (YBe)
- Purple: Lindhard

M. Atzori Corona, M. Cadeddu, N. Cargioli, F. Dordei, C. Giunti, arXiv2307.12911 (2023)

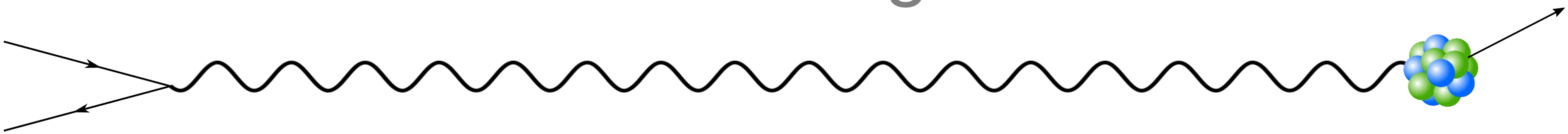
Analysis (Run-1/2)



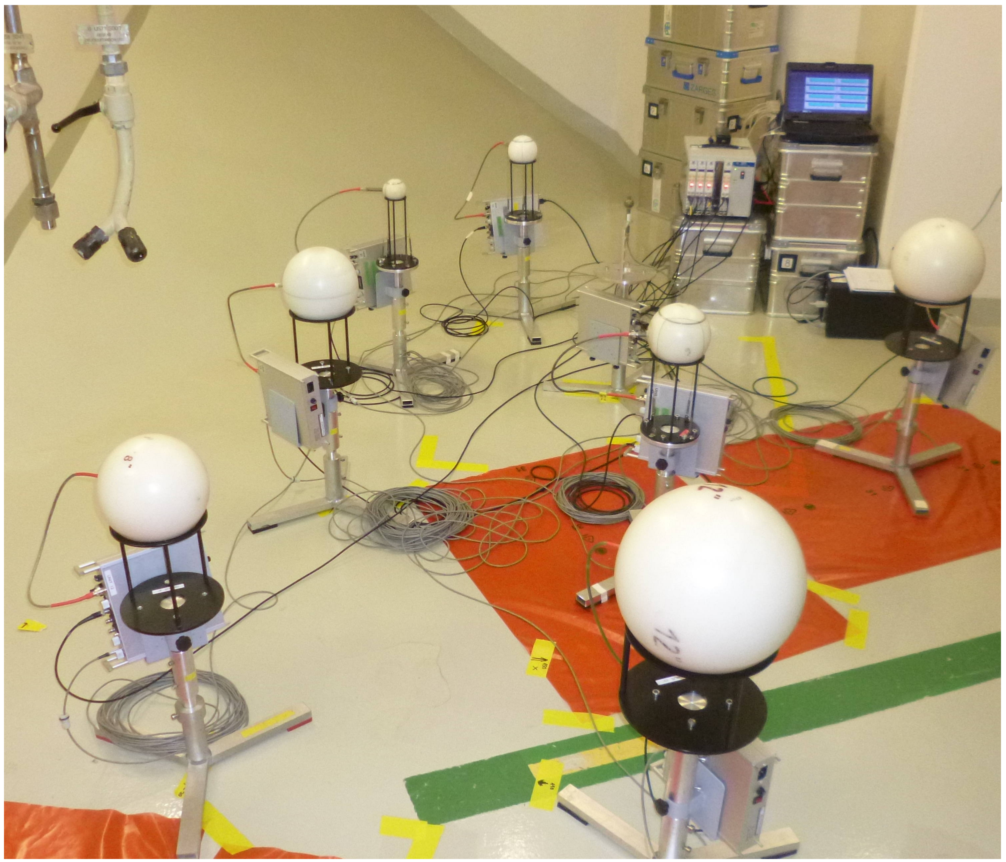
- Binned likelihood ratio test
- Background: MC modelling, free normalization parameter in fit (exponential fit for electronic noise in Run-1/2)
- Simultaneous fit ON/OFF (all detectors and runs)
- Scan over signal parameter
- Systematics via gaussian pull terms

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

Neutron background

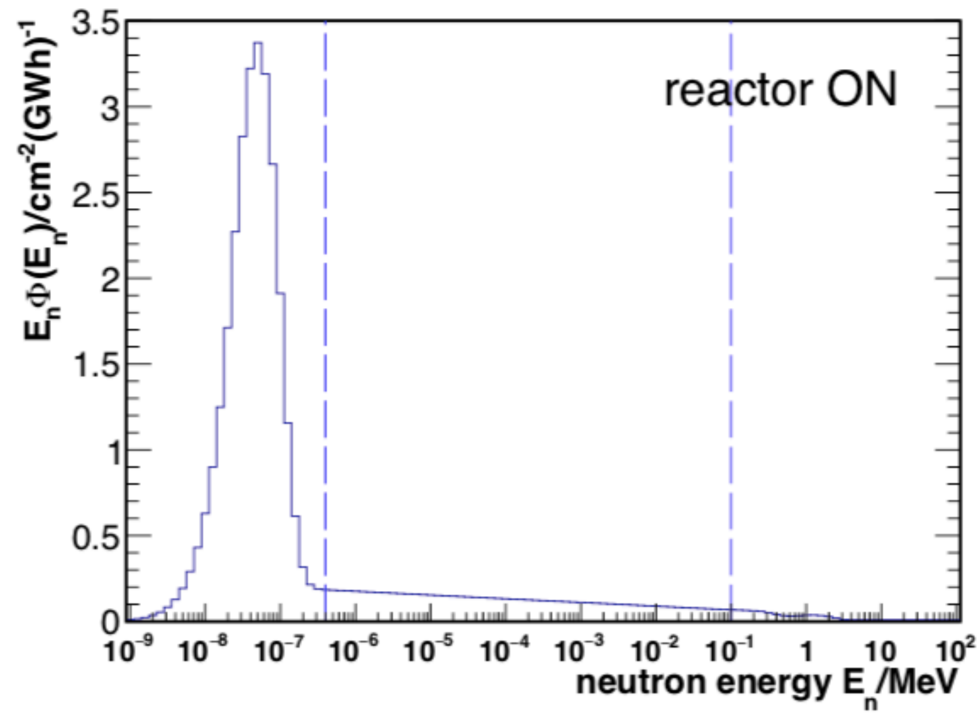


Reactor-correlated!



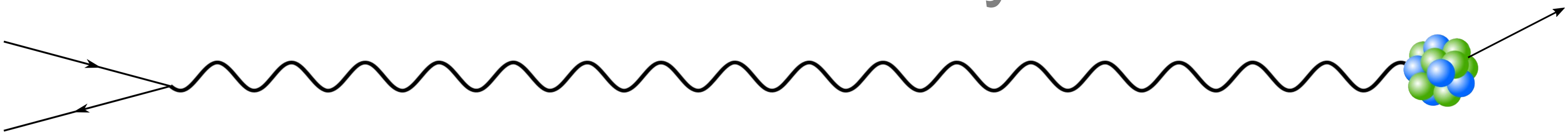
Campaign with Bonner spheres
(in cooperation with PTB)

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

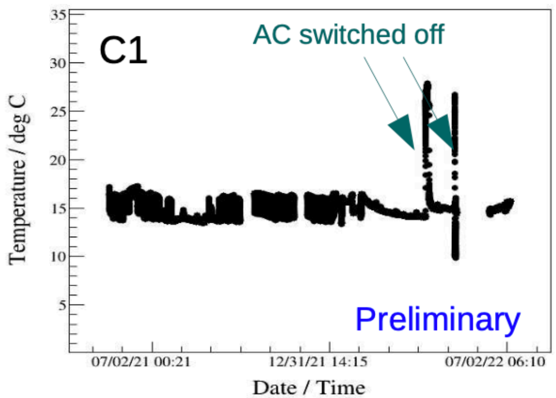


CONUS, Eur. Phys. J. C (2019) 79:699

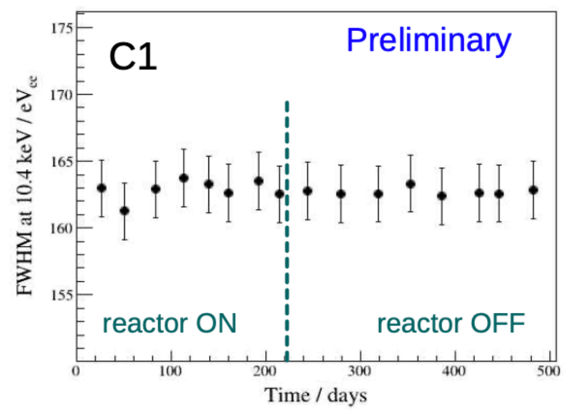
Run-5 stability



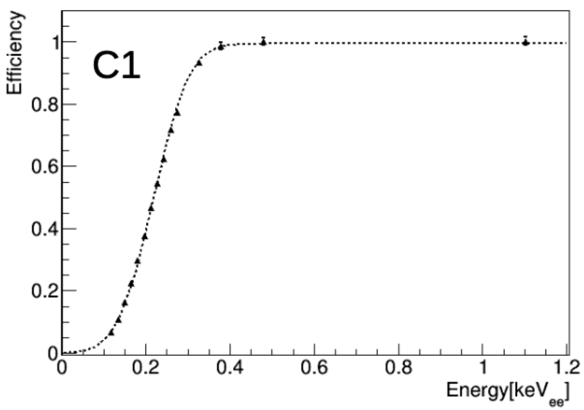
Room temperature



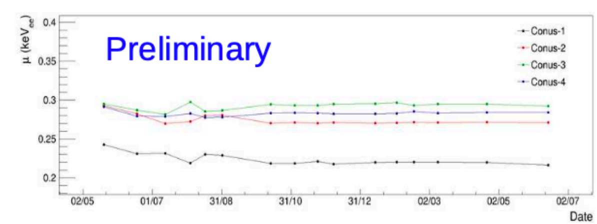
Peak pos. of 10.4 keV line

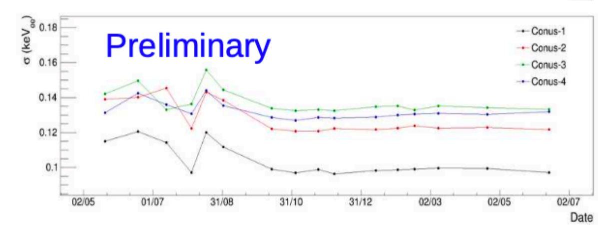


Trigger efficiency curve

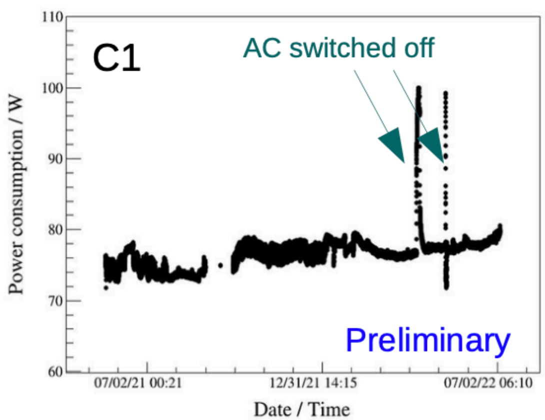


Analytical description: 0.5*[1+erf((x-μ)/σ))]

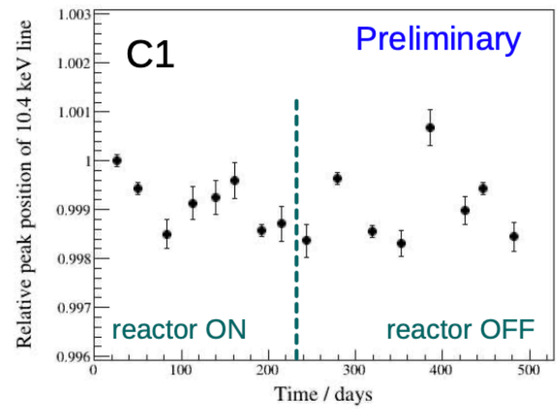




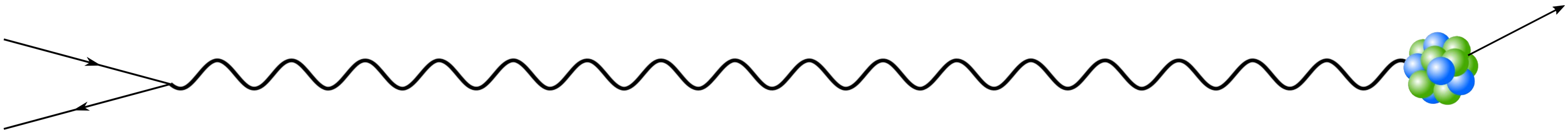
Power consumption



FWHM of 10.4 keV line

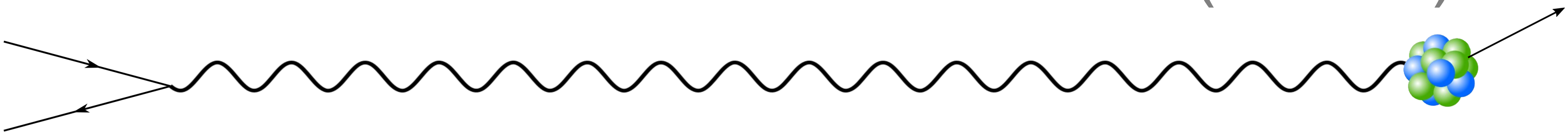


BSM dataset

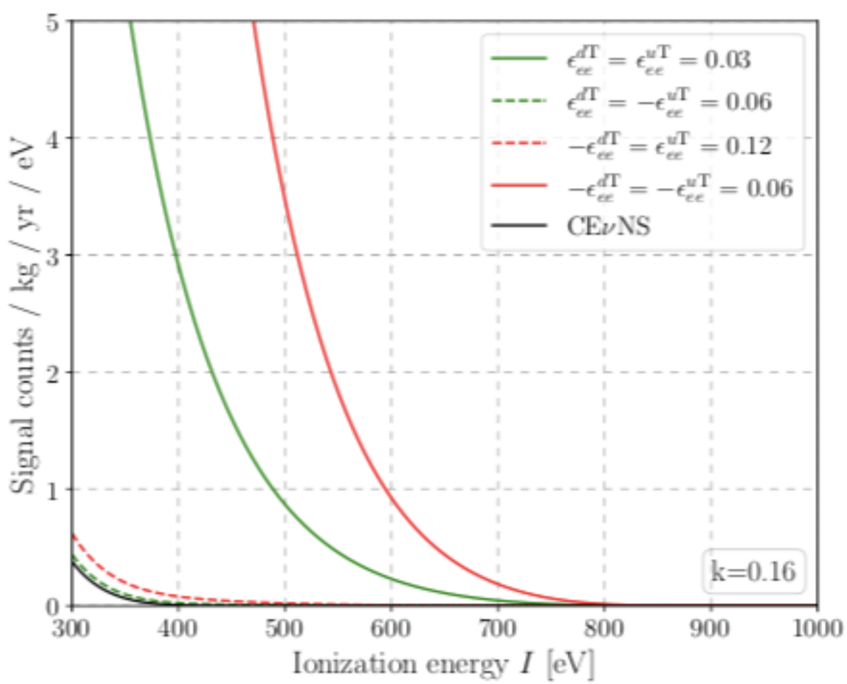


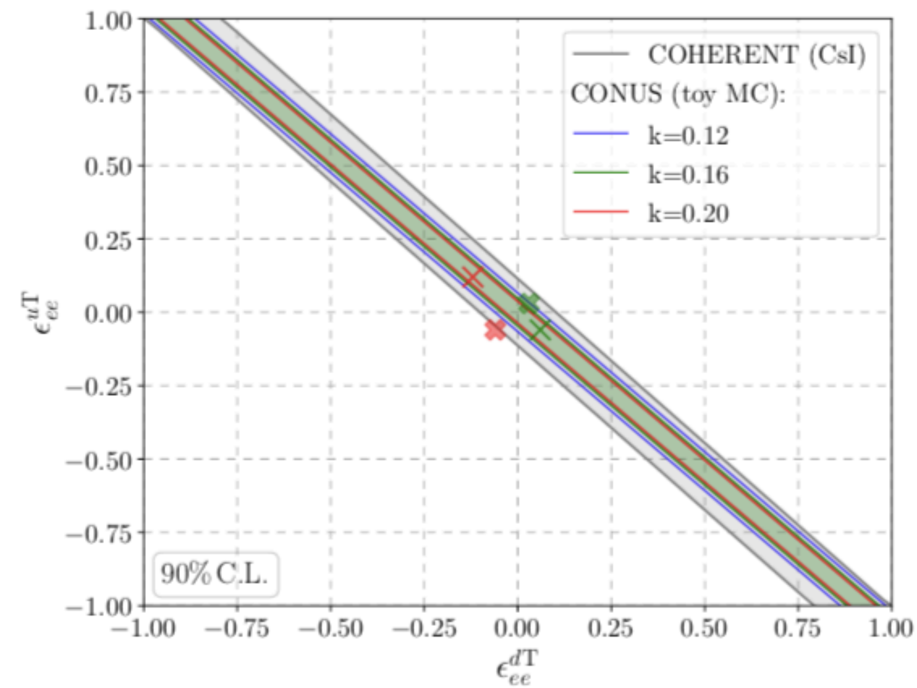
Scattering channel	Detector	On [kg d]	Off [kg d]	ROI [eV_{ee}]
$\bar{\nu}_e + A(Z,N)$	C1	96.7	13.8	276–741
	C2	14.6	13.4	281–999
	C3	97.5	10.4	333–991
	all	208.8	37.6	
$\bar{\nu}_e + e$	C1	215.4	29.6	2013–7968
	C2	184.6	32.2	2006–7990
	C3	248.5	31.7	2035–7989
	all	648.5	93.5	

BSM: non standard interactions (tensor)



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

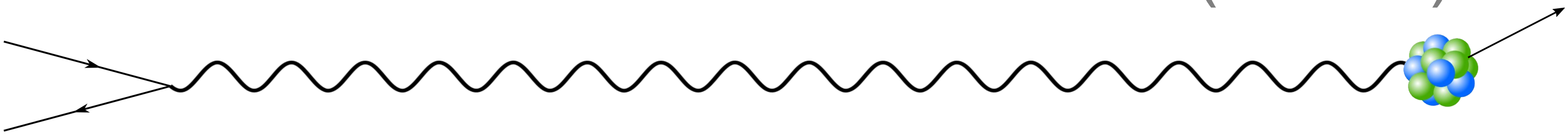




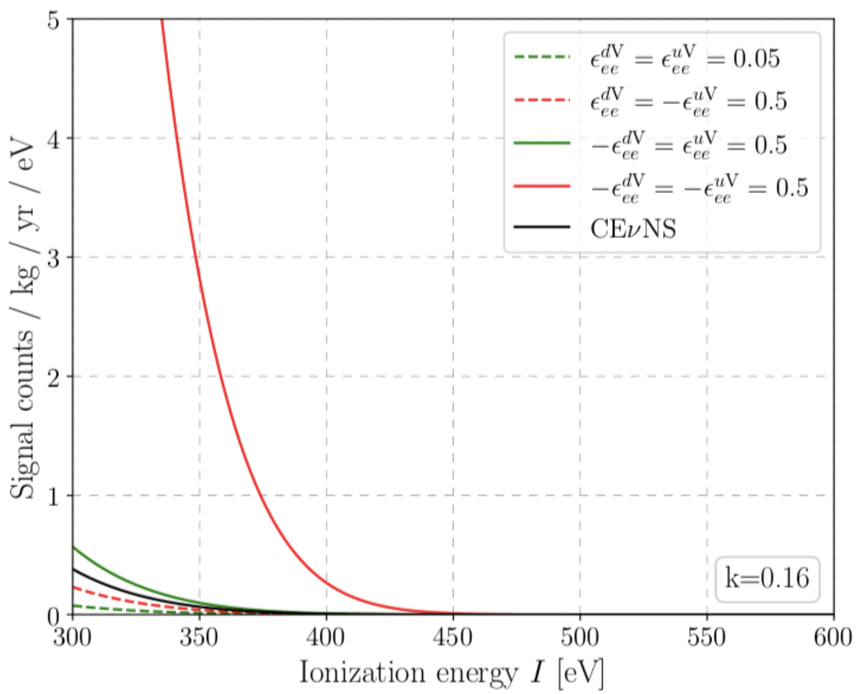
Very competitive results!

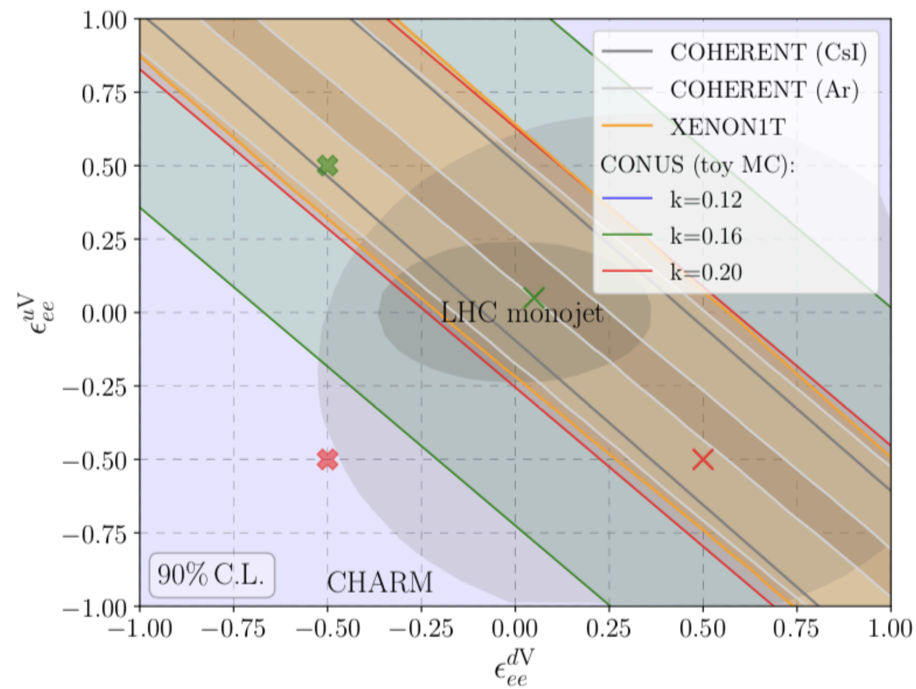
CONUS, JHEP 05 (2022) 085

BSM: non standard interactions (vector)



New interaction similar to CEvNS: modified weak charge

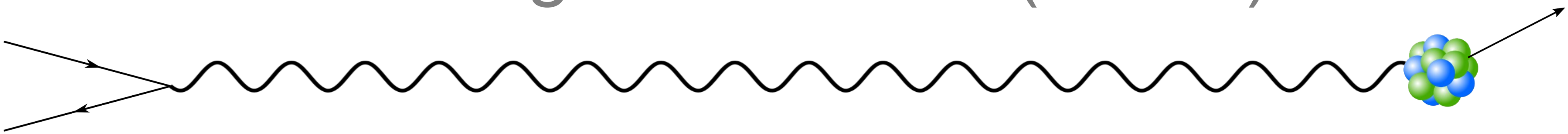




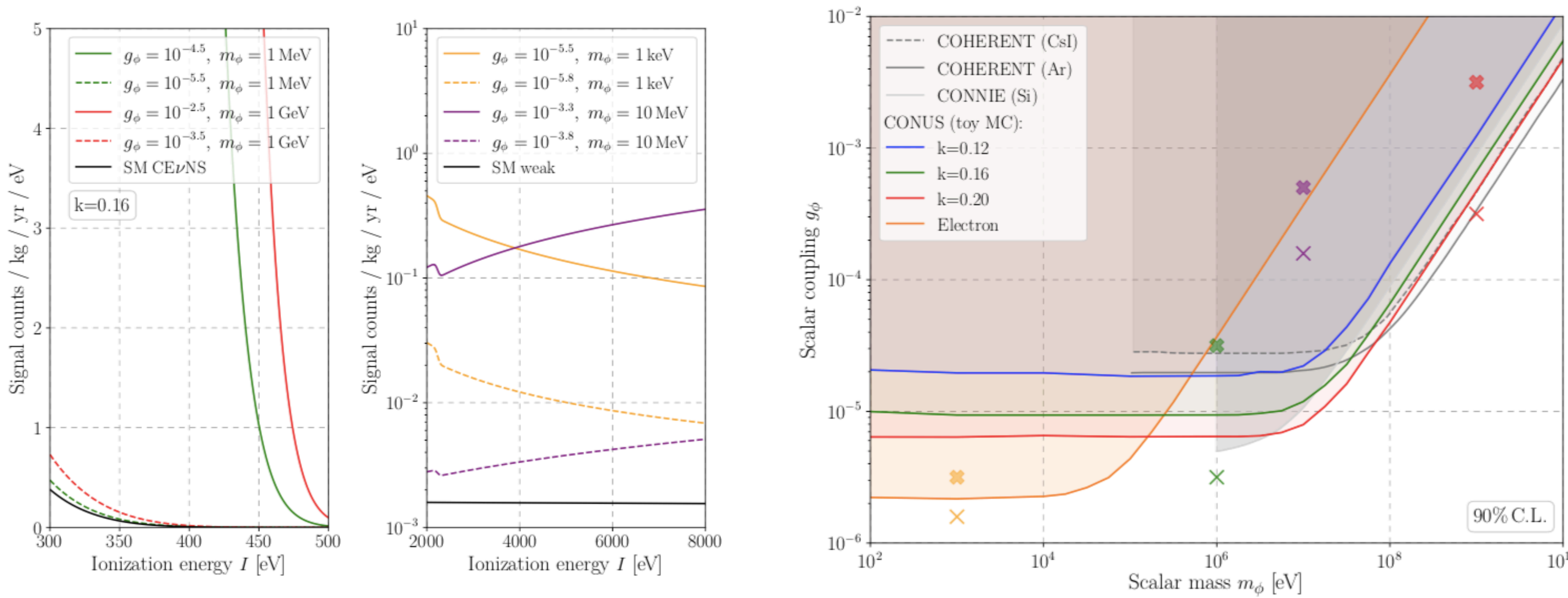
Destructive interference possible

CONUS, JHEP 05 (2022) 085

BSM: light mediators (scalar)

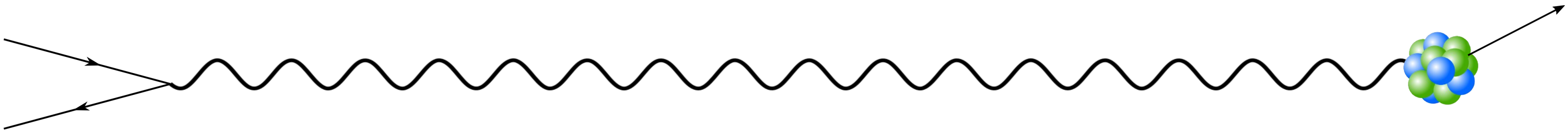


- Testing simplified models assuming universal couplings
- Nucleus and electron (2-8 keV) channels included



CONUS, JHEP 05 (2022) 085

Neutrino electromagnetic properties (Run-1+2)

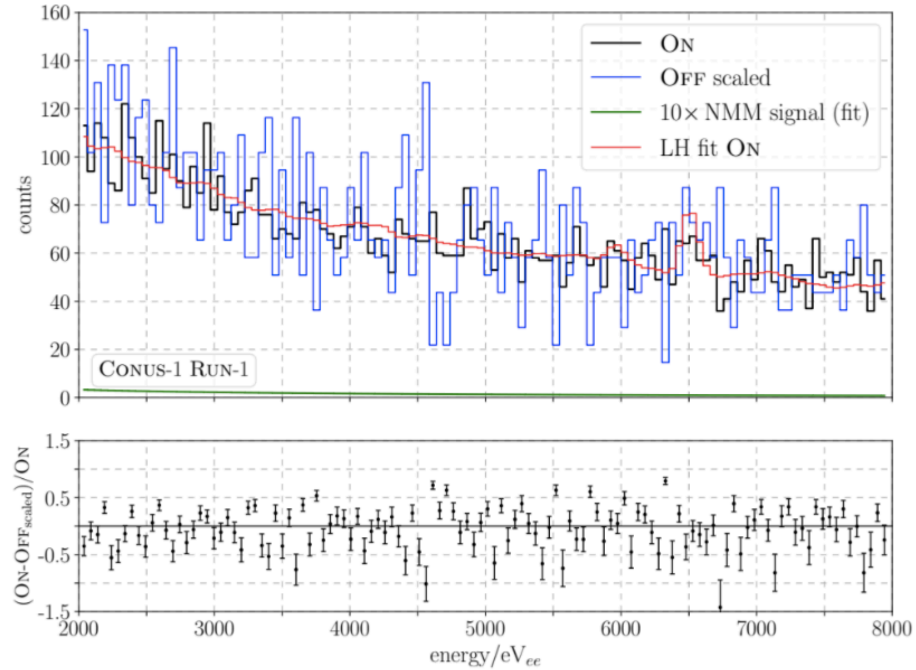


Magnetic moment:

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

CONUS bound (90% CL) from ν-e scattering in 2-8 keV window:

$\mu_\nu < 7.5\times10^{-11}\ \mu_B$

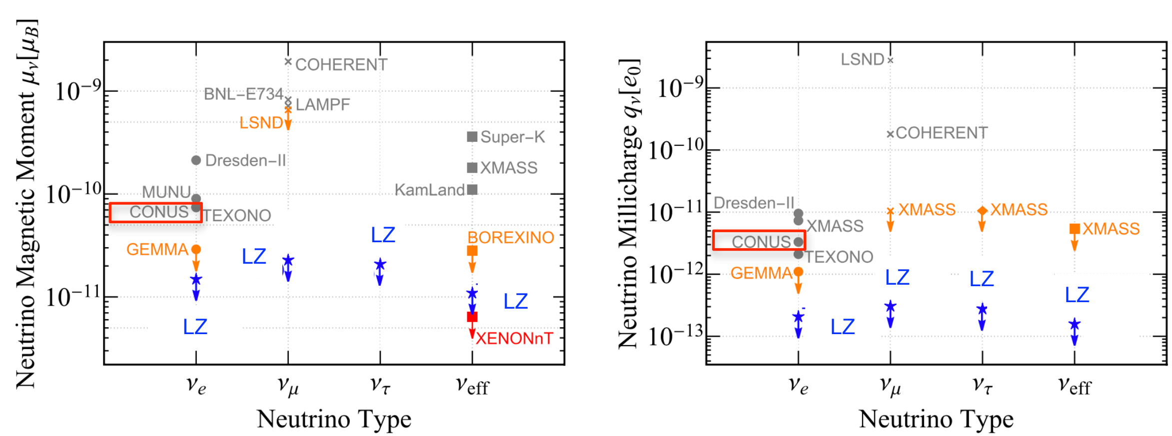


Conversion to millicharge limit:

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

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)