CEvNS studies at nuclear reactors with the CONUS experiment

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Max-Planck-Institut für Kernphysik, Heidelberg
NOW 2022, September 10, 2022

MAX PLANCK GESELLSCHAFT

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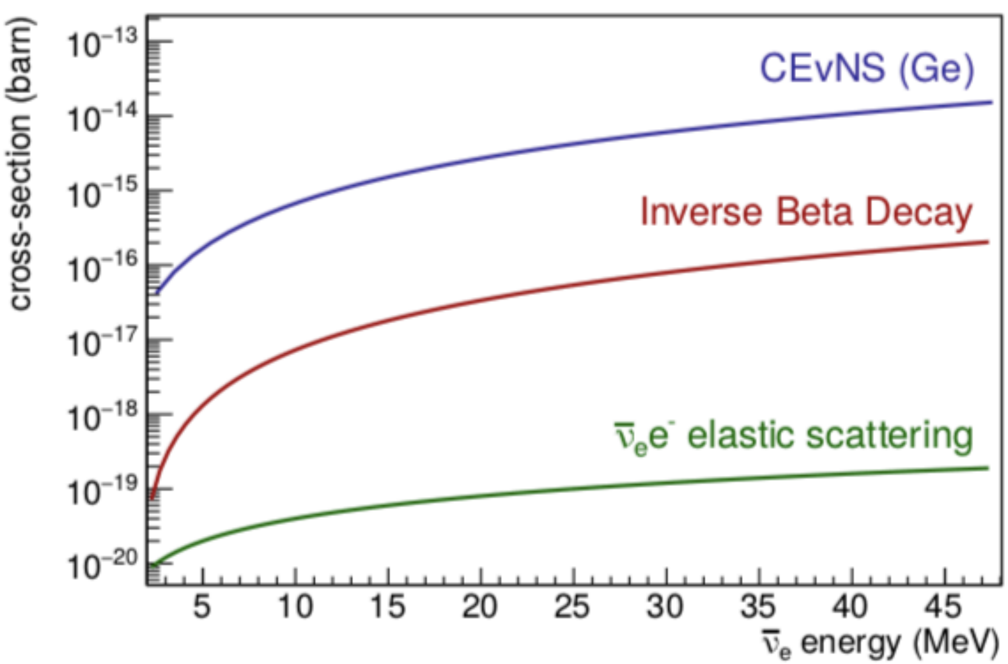
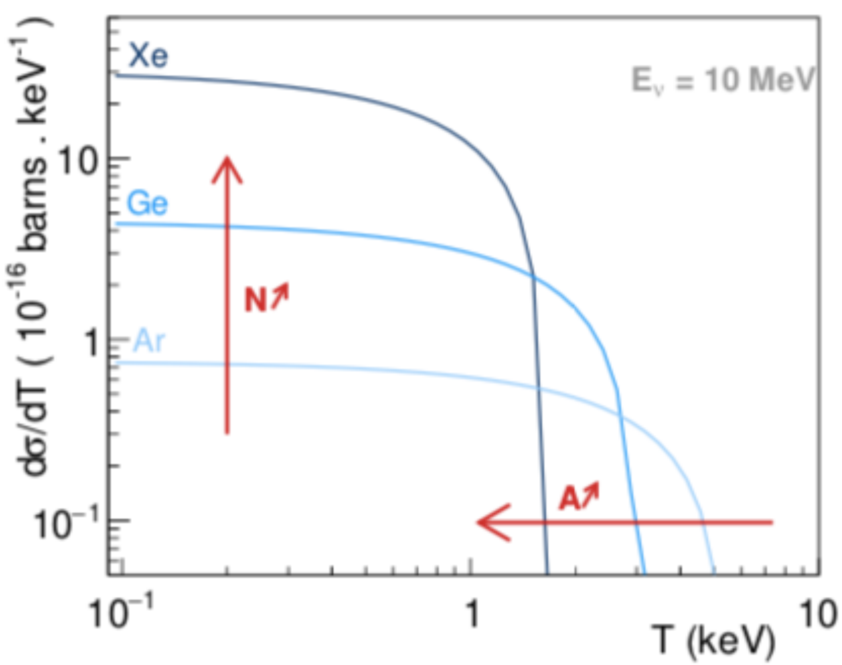
CONUS

Coherent elastic neutrino nucleus scattering

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

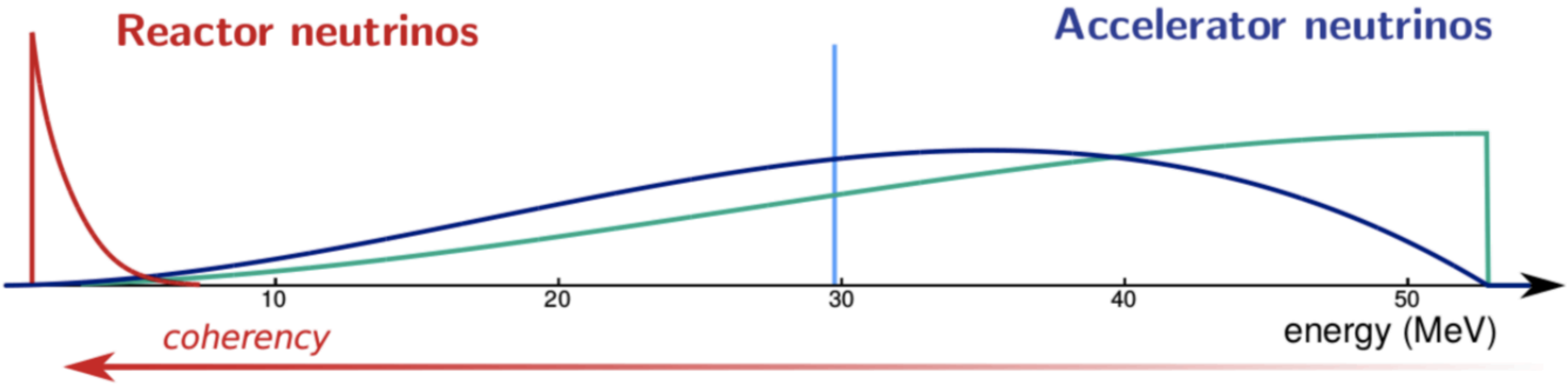




High cross-section ==> compact detectors!

Interaction rate vs recoil energy

Neutrino sources for CEvNS studies



- Pure flux of electron antineutrinos
- E ~ 0 - 10 MeV ==> form factor close to 1 (fully coherent regime)
- CONUS, nuGeN, CONNIE, NCC-1701, Nucleus, Ricochet,…

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

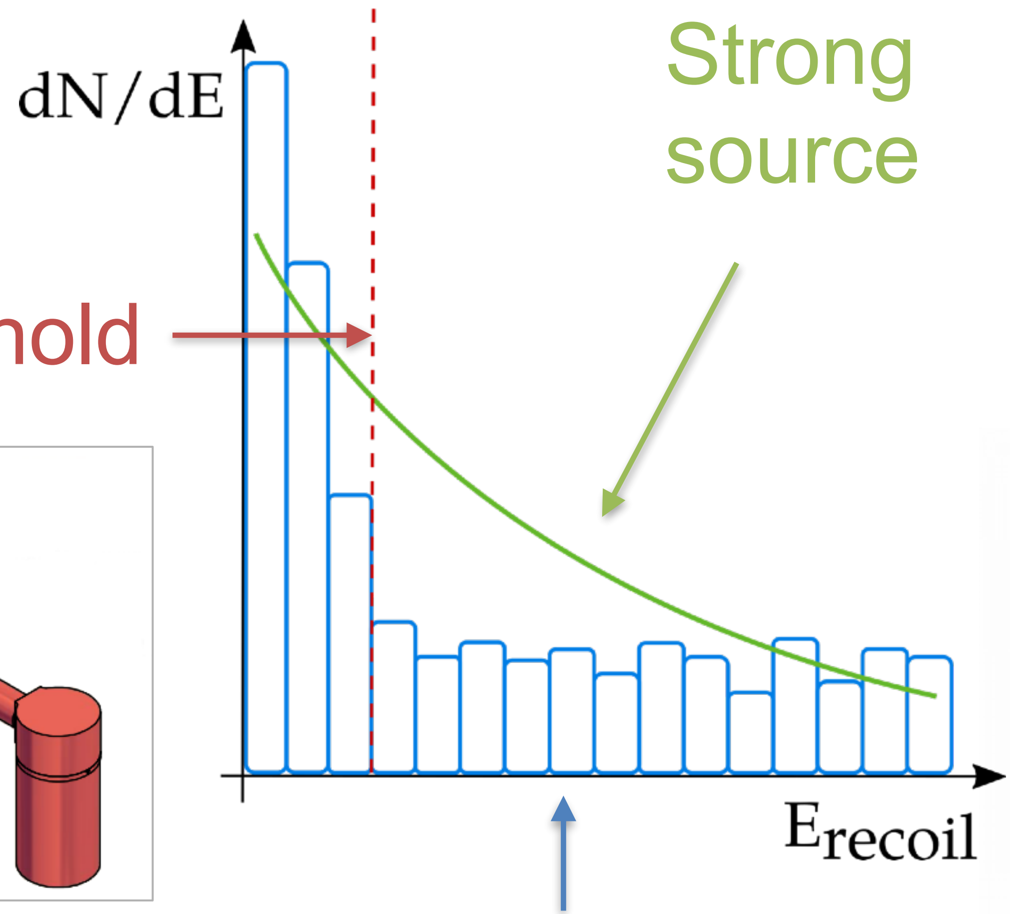
Complementarity !

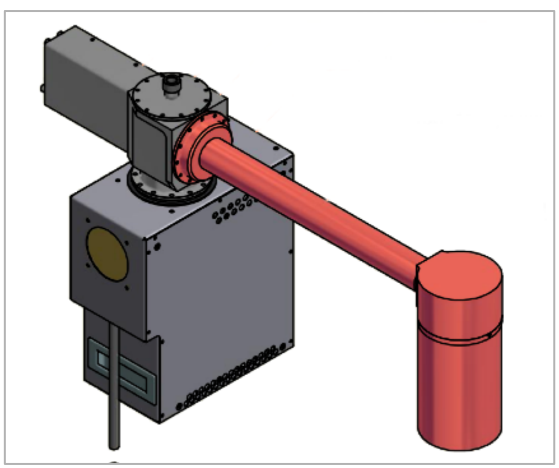
Requirements

Strong source

Nuclear power plant
(Brokdorf, KBR)

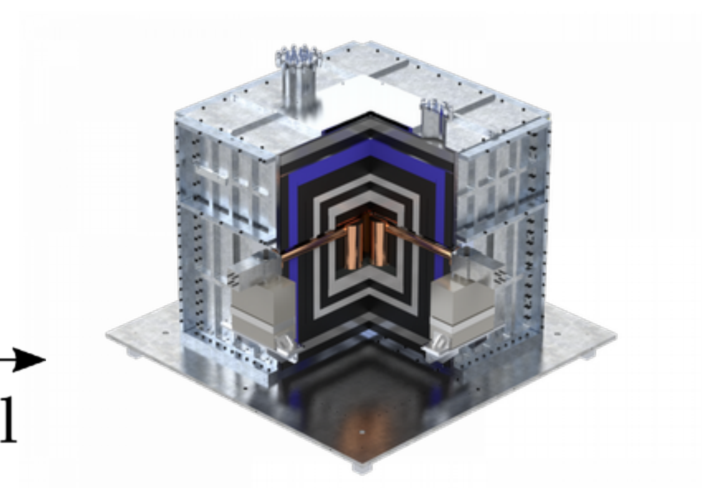
Low threshold





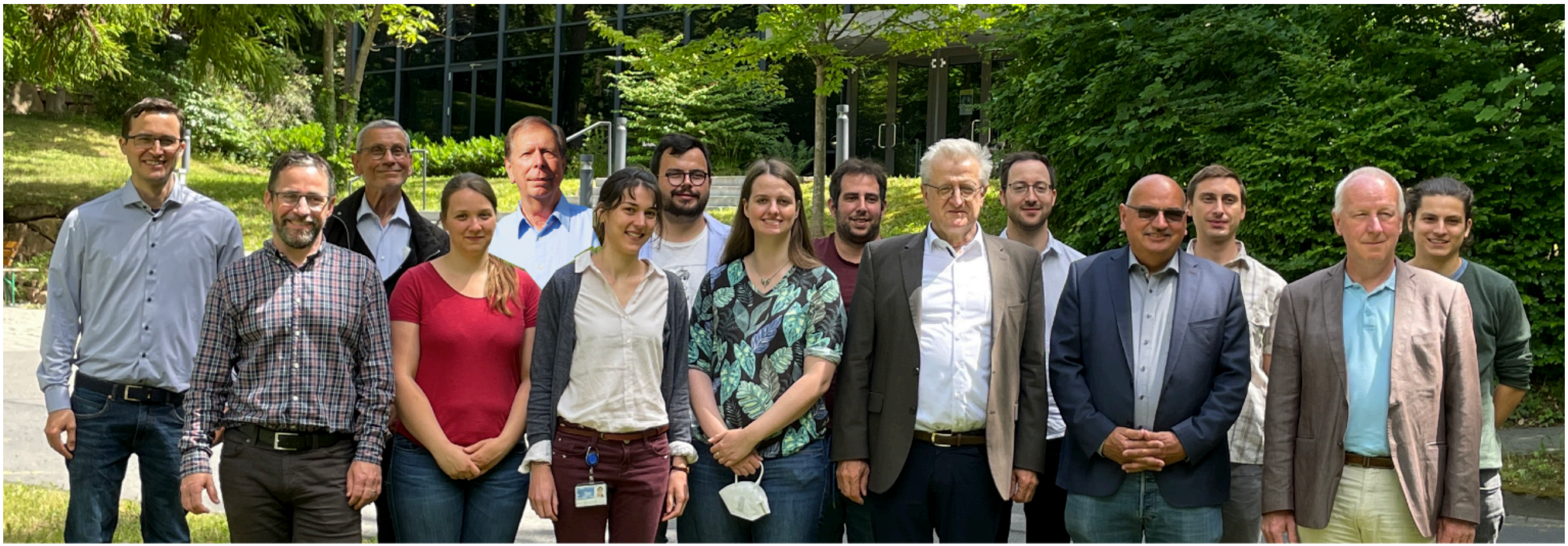
Point contact
HPGe spectrometer

Low background



Shield (shallow depth)

CONUS Collaboration



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

Max-Planck-Institut für Kernphysik Heidelberg

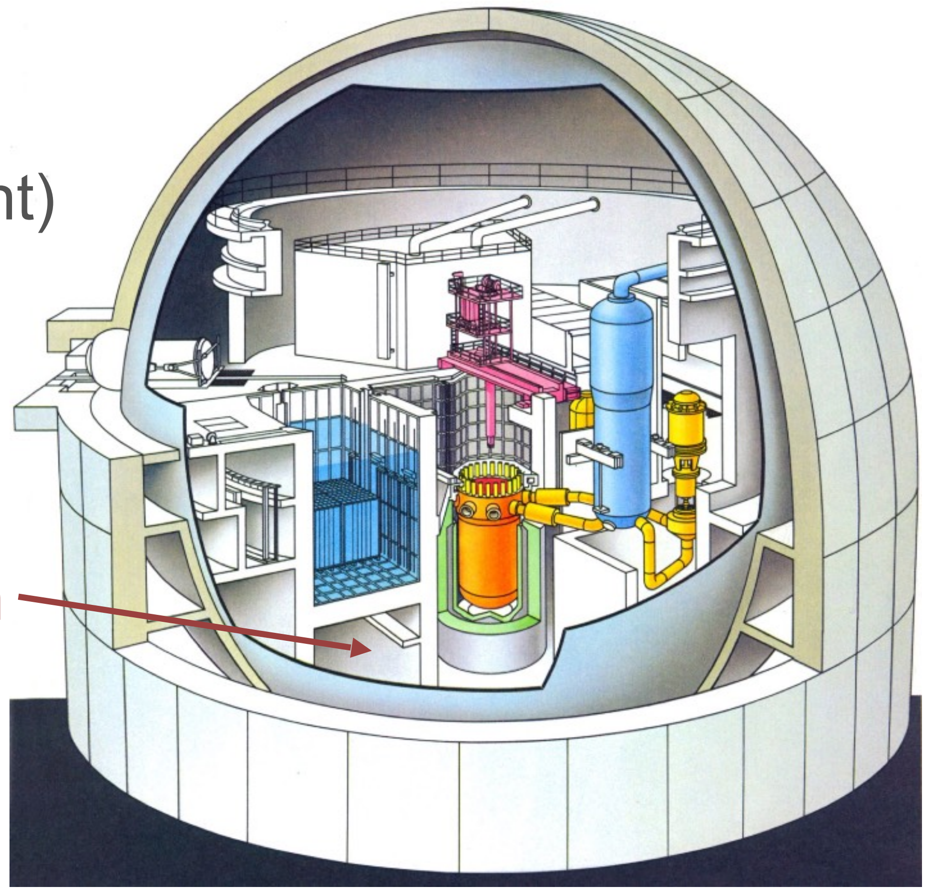
K. Fülber, R. Wink
Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR)

Preussen Elektra

Experimental Site

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

CONUS location

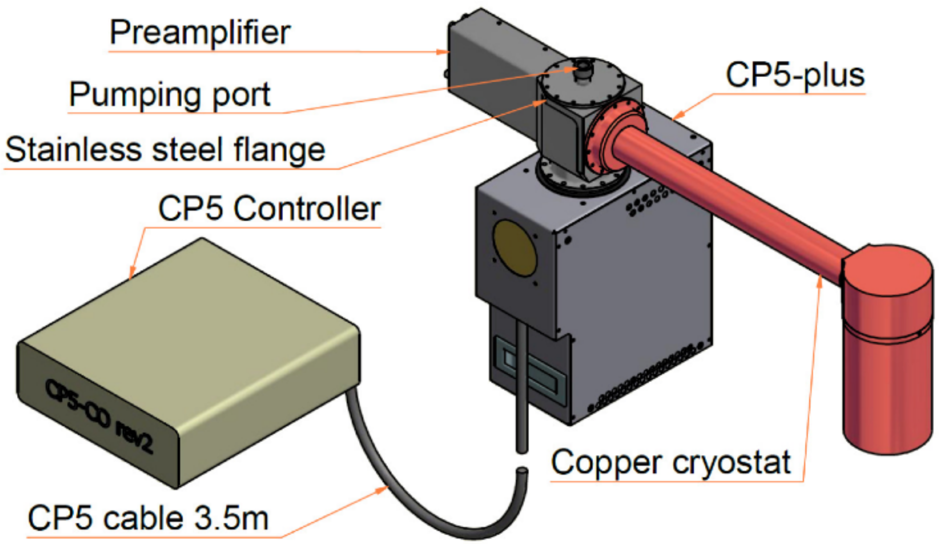


KBR Brokdorf:

- 3.9 GW thermal power
- Distance 17.1 m
- OFF time ~1 m/y
- Operational until end of 2021

Challenging environment: no remote control, restricted materials, earthquake engineering, access, temperature fluctuations,…

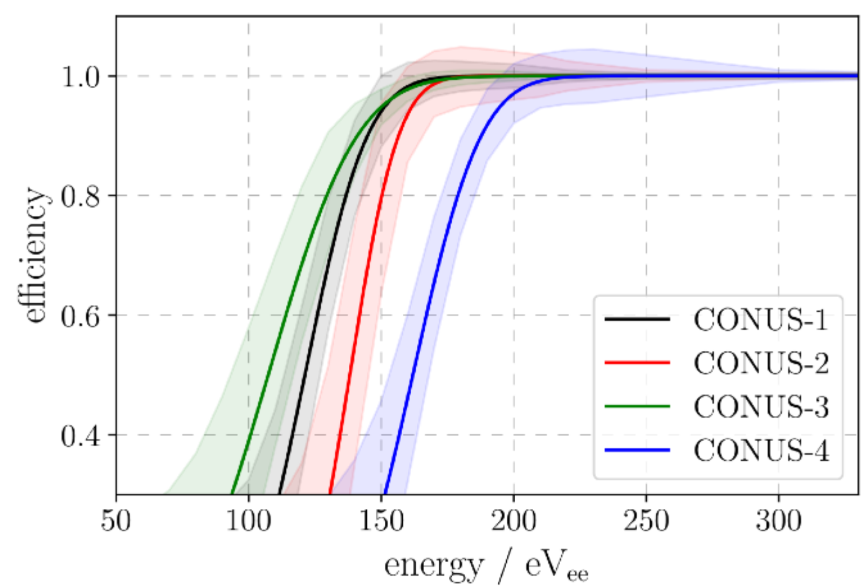
Detectors



4 p-type HPGe detectors:

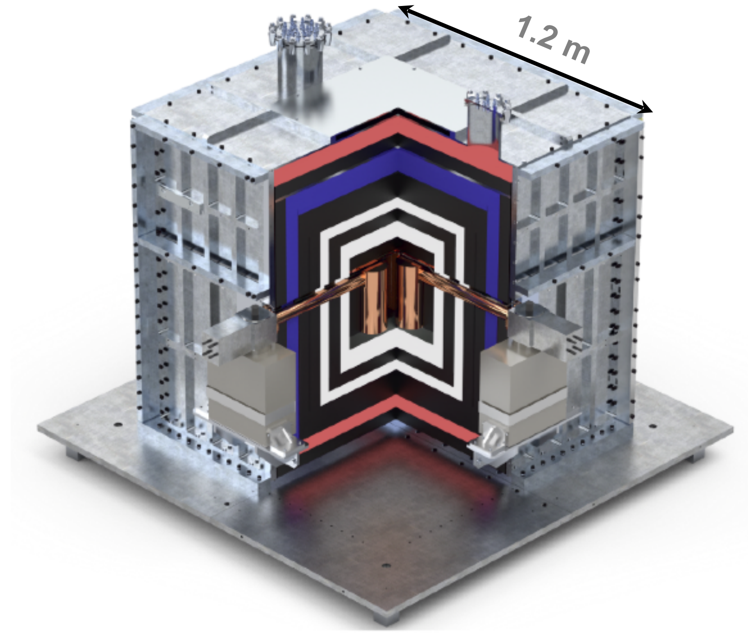
- Total mass: 4.0 kg
- Pulser resolution < 80 eV
- Efficiency ~1 in ROI
- Electrical cooling


Electro-polished copper cryostat parts



CONUS, EPJ C (2021) 81:267

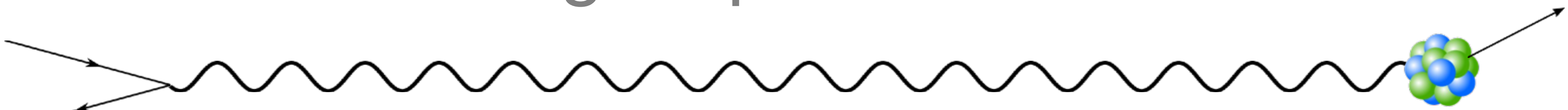
CONUS setup

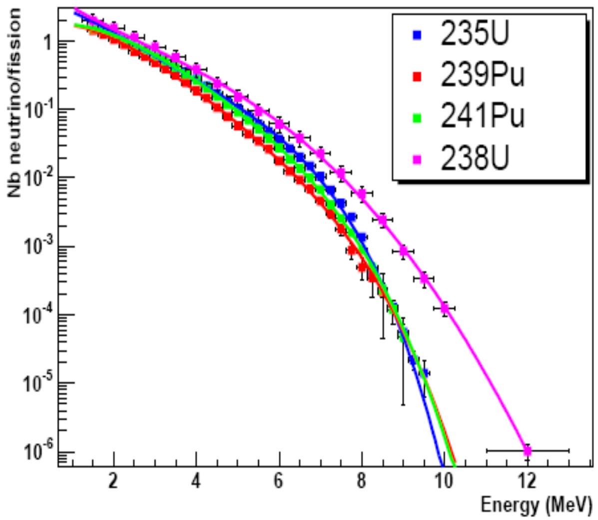


- Design basis: GIOVE (MPIK)
- V = 1.65 m^3, m = 11 tons
- Low radioactivity lead (Pb)
- Borated PE (n moderation + capture)
- Active muon veto (~97% rejection)
- Construction, commissioning and installation: ~2y
- Start: 04/2018

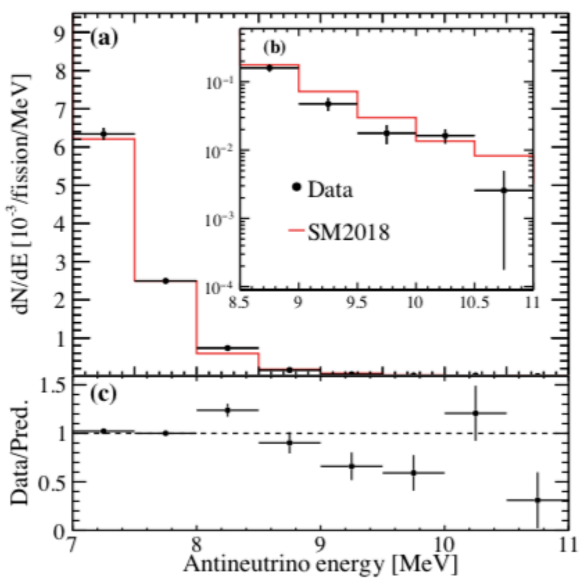
Radon removal:
Flush with air bottles

Signal prediction

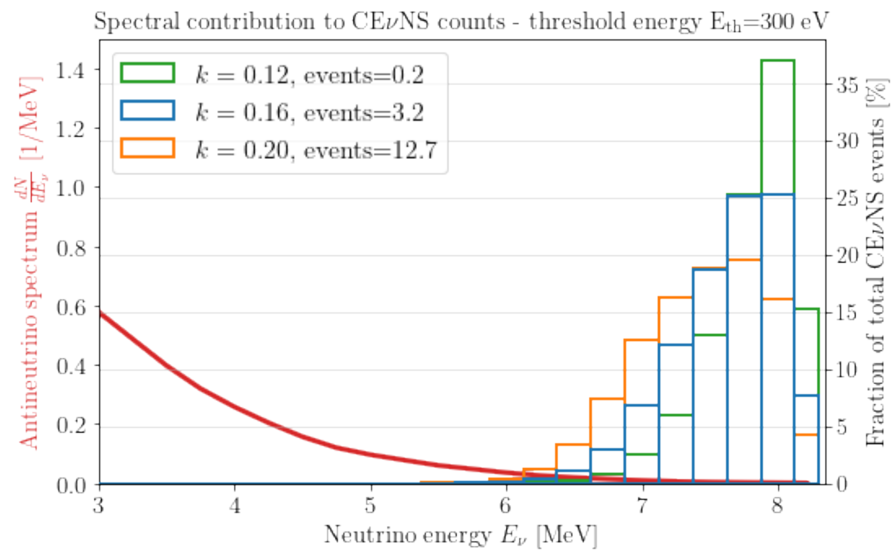




- Thermal power and energy/fission
- Flux at CONUS site: 2.3×10^{13} /(cm^2 s)
- From now use data-based method and high E spectrum from Daya Bay
- Consider fission fraction evolution
- High quenching factor dependence!



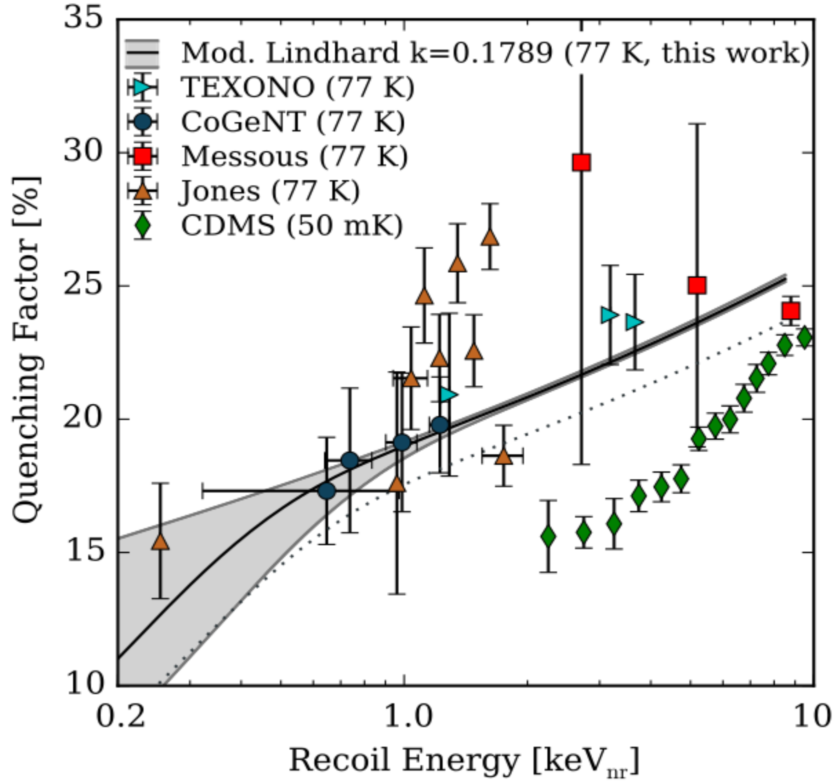
Daya Bay, PRL 129 (2022) 041801



Example for one detector in first phase of data taking

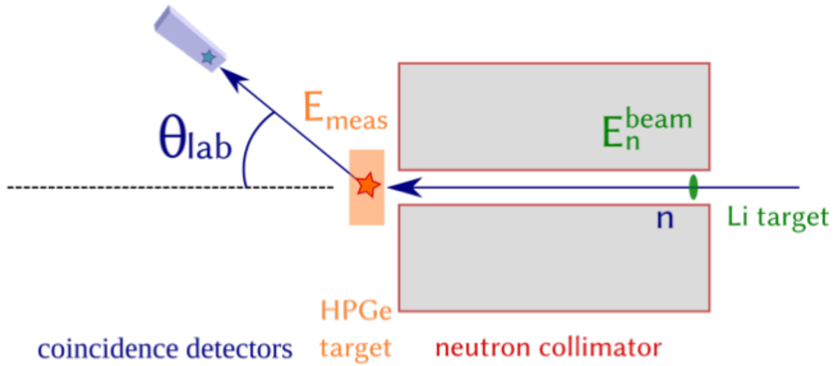
Quenching measurement

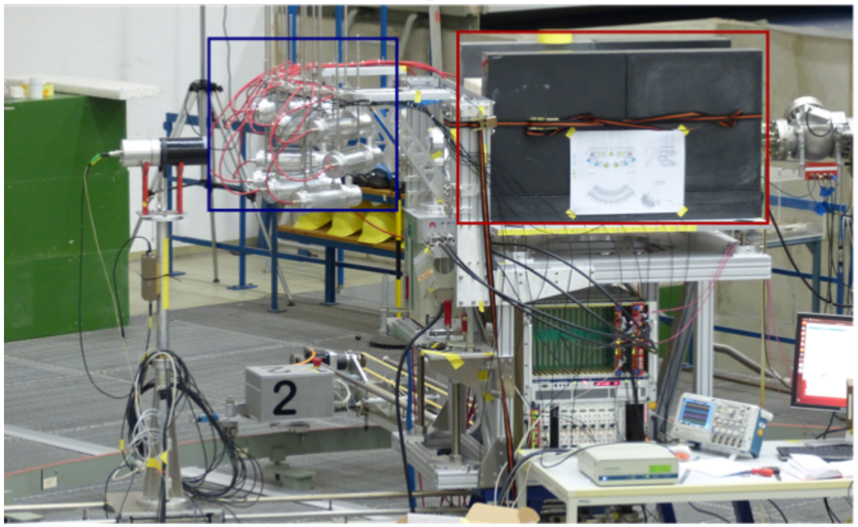
Situation at start of CONUS:



Scholz et al, PRD 94, 122003 (2016)

- Large variation of data points
- Lack of data at very low energies

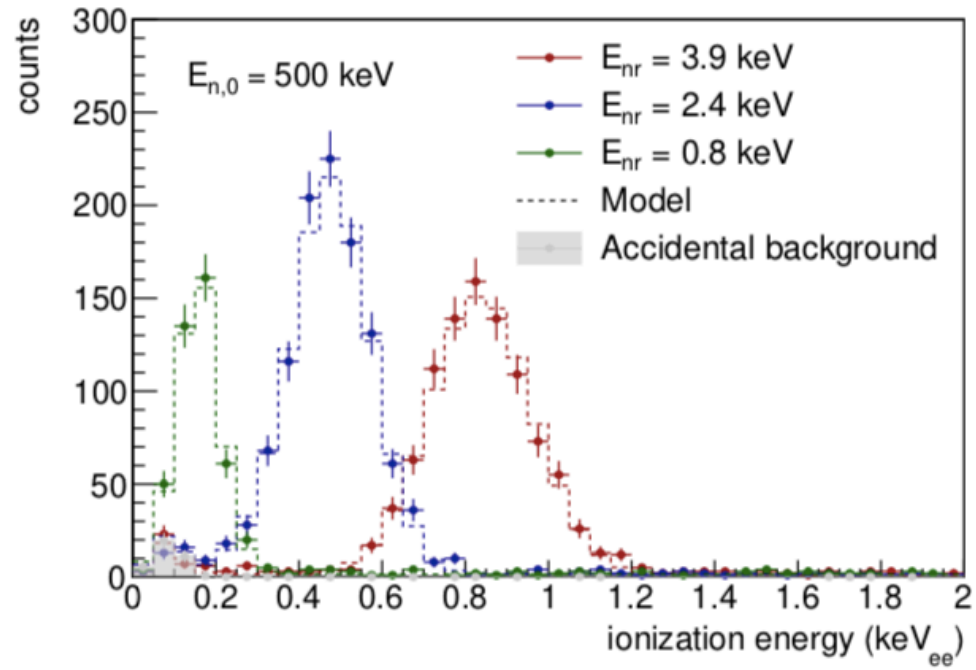




Cooperation with PTB Braunschweig

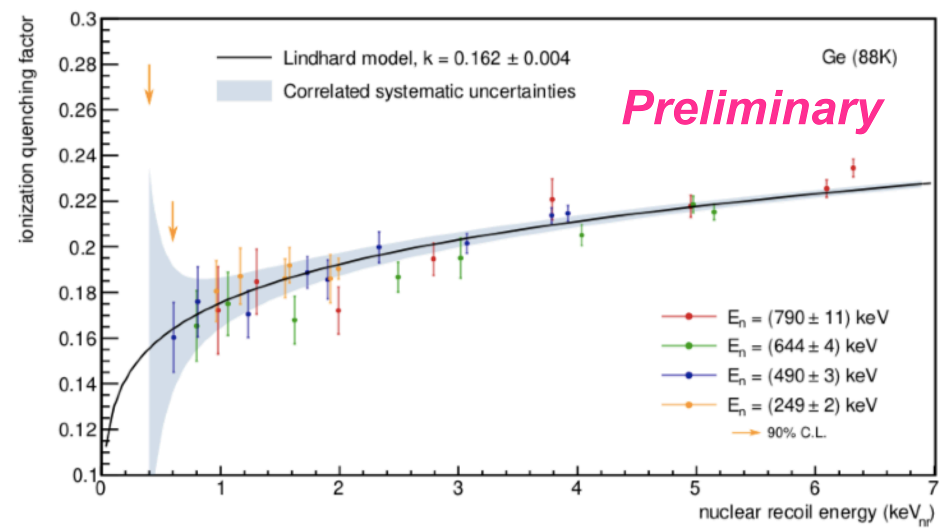
PTB Physikalisch Technische Bundesanstalt Braunschweig und Berlin

Quenching results



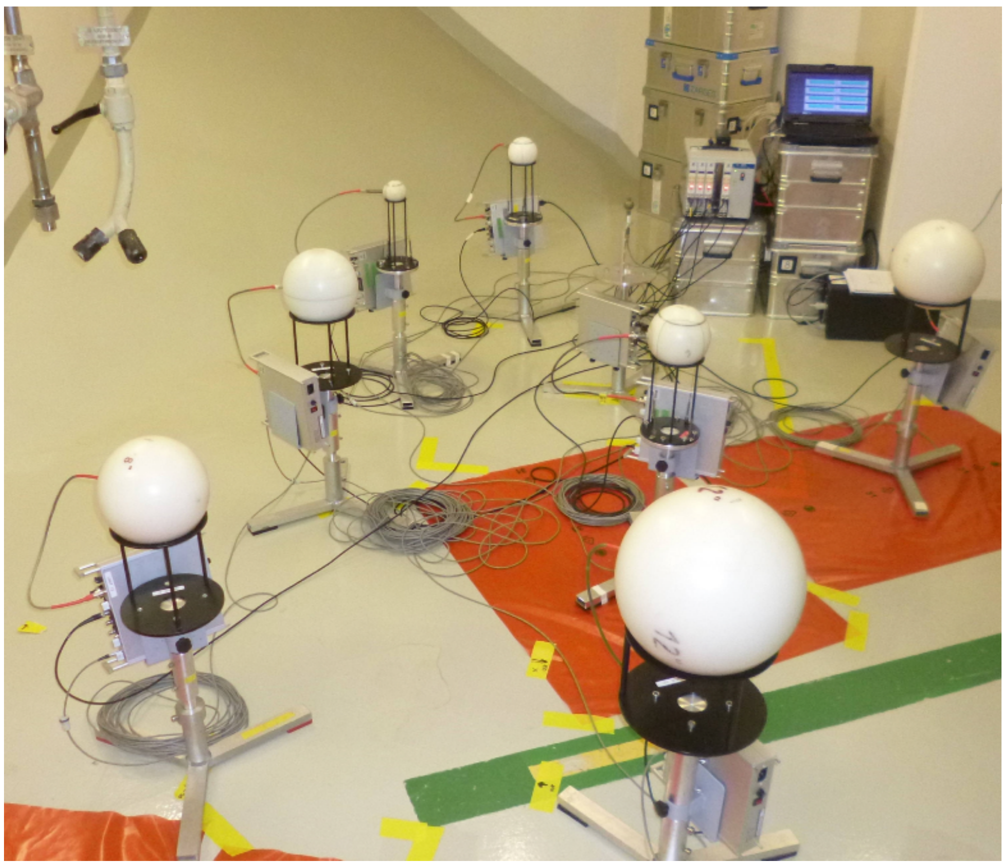
- Method
  - Model-independent
  - Triple coincidence
  - Beam energy 250 - 800 keV
  - Angles 18-45° (1° precision)
  - Nuclear recoils 0.4 - 6 keV
- Results
  - Good compatibility with Lindhard theory!
  - k = 0.162 ± 0.004 (stat.+syst.)
  - Challenge for CEvNS signal detection with Ge at reactor

Bonhomme et al., arXiv:2202.03754



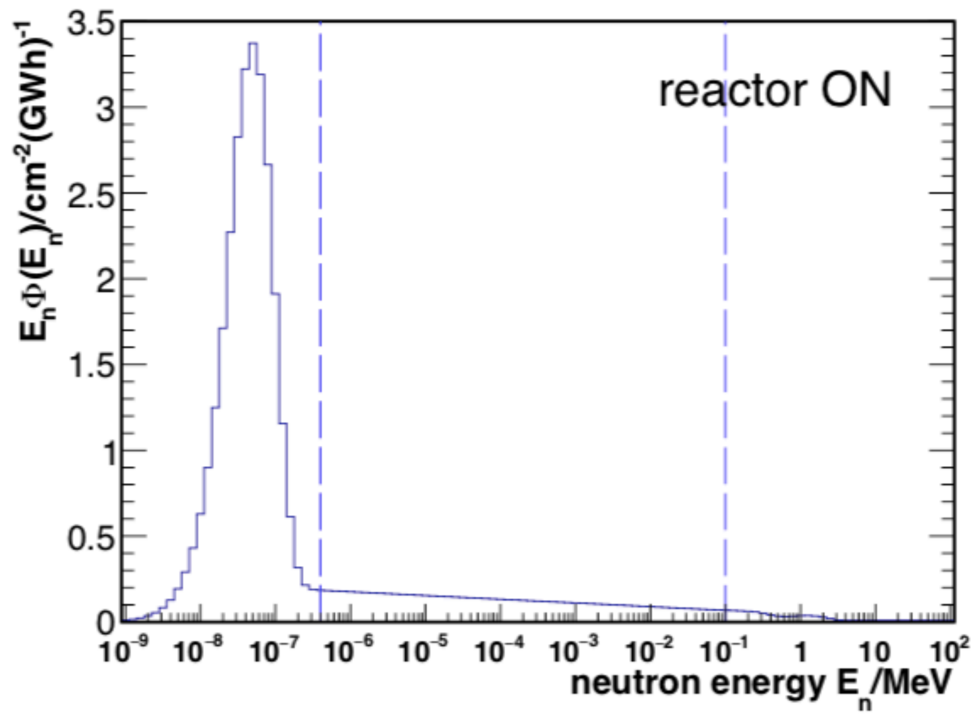
Neutron background

Reactor-correlated!



Campaign with Bonner spheres
(in cooperation with PTB)

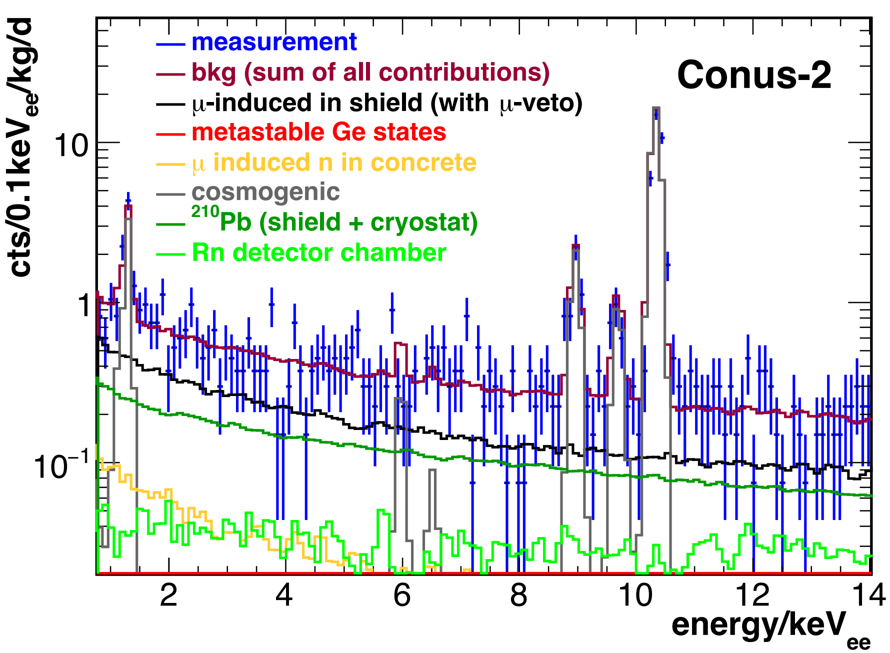
- Neutron flux in CONUS room suppressed by factor $>10^{20}$
- 80% of neutron flux is thermal

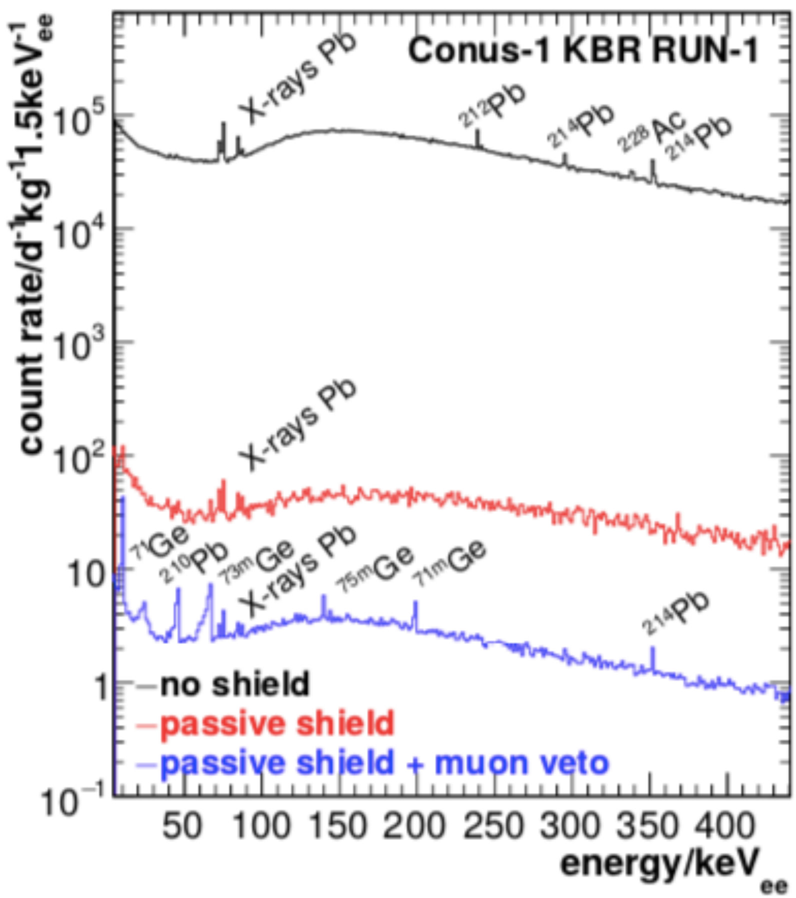


CONUS, Eur. Phys. J. C (2019) 79:699

Background model

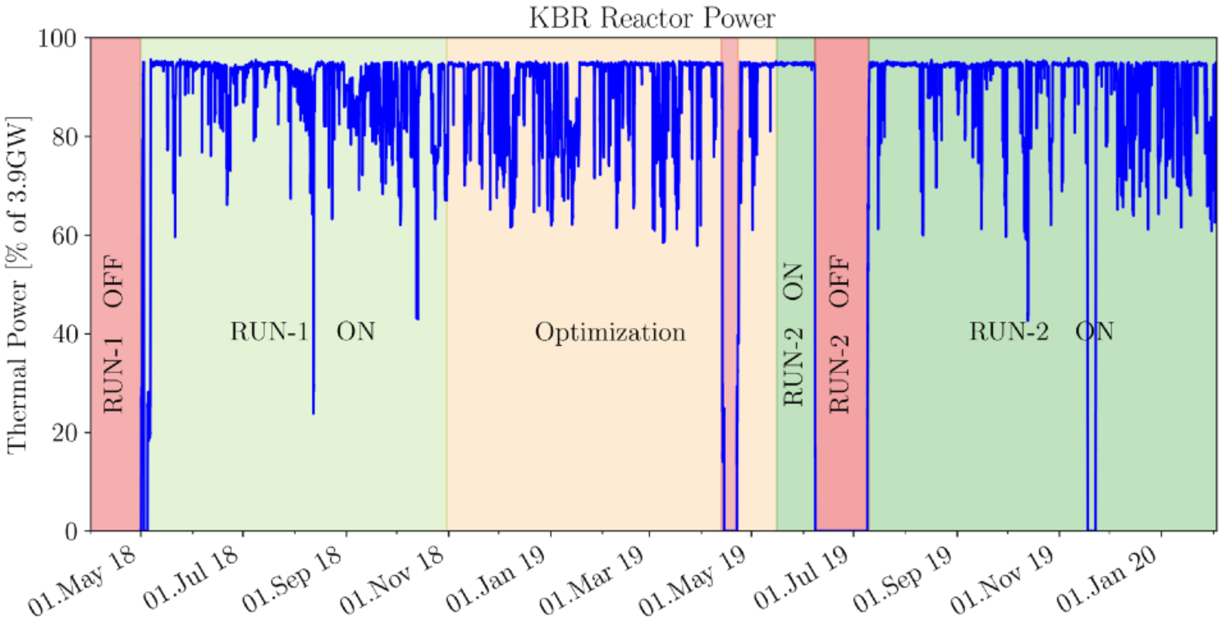
- Passive + active shield: Background suppression ~10^4
- Rate 0.5-1 keV: ~10 /(keV d kg)
- Bg spectrum well understood (MC + commissioning @ MPIK)



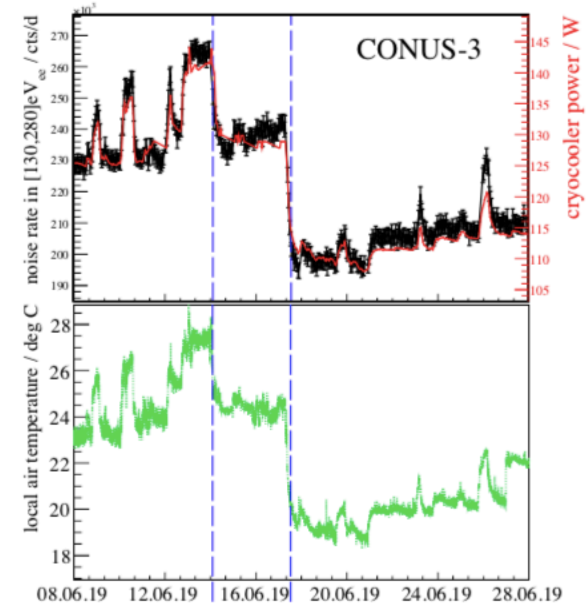


CONUS, arXiv:2112.09585

Data Selection

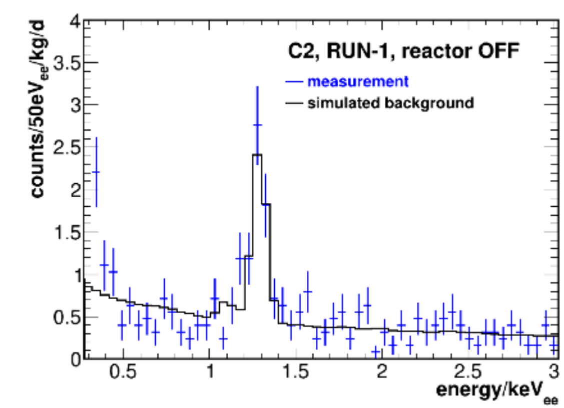


Temperature, cryocooler power and noise rate correlated



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 58.8 (kg*d)



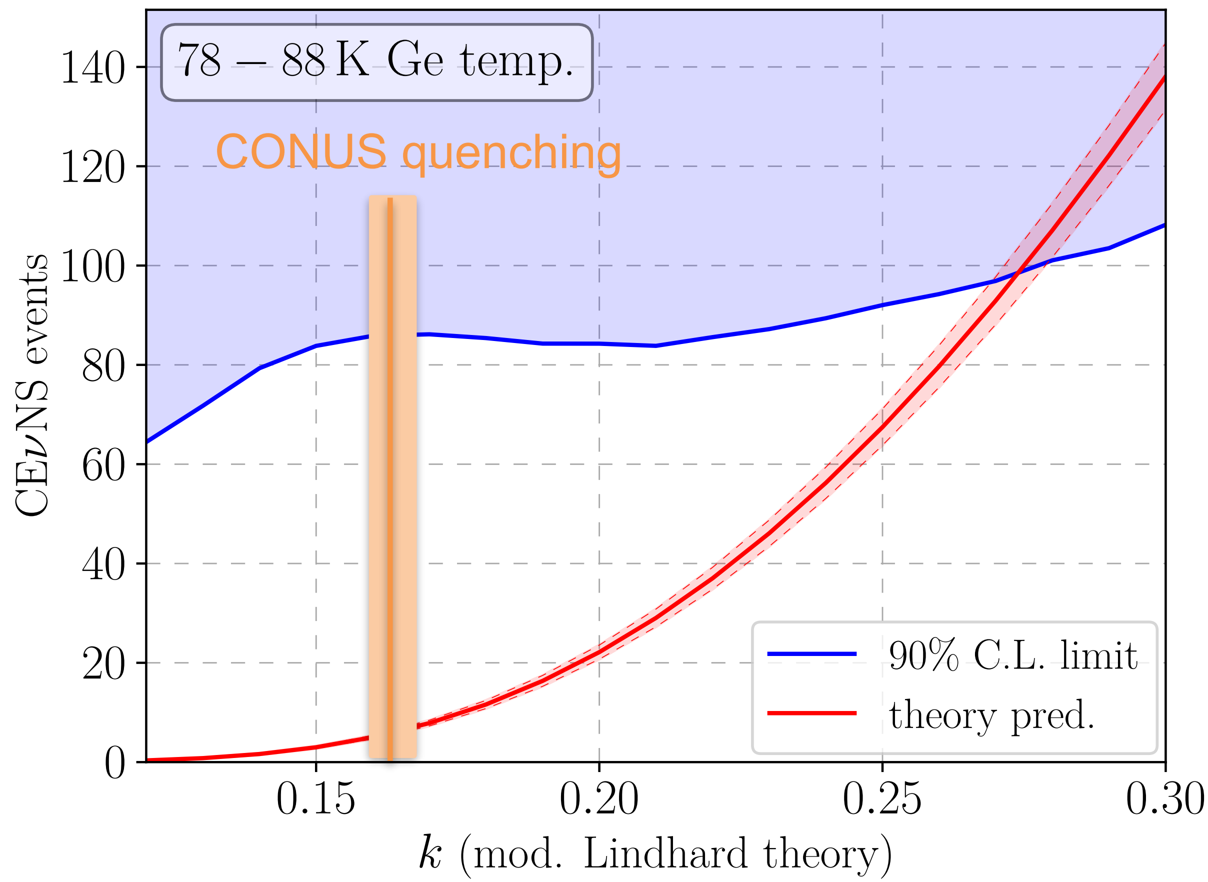
CEvNS data analysis

Background treatment

- MC modelling
- Free normalization parameter in fit
- Exponential fit for electronic noise

Likelihood

- Simultaneous fit ON/OFF (all detectors and runs)
- Scan over signal parameter
- Systematics via pull terms (energy scale, fiducial mass, efficiency, neutrino flux)



CONUS, PRL 126 (2021) 041804

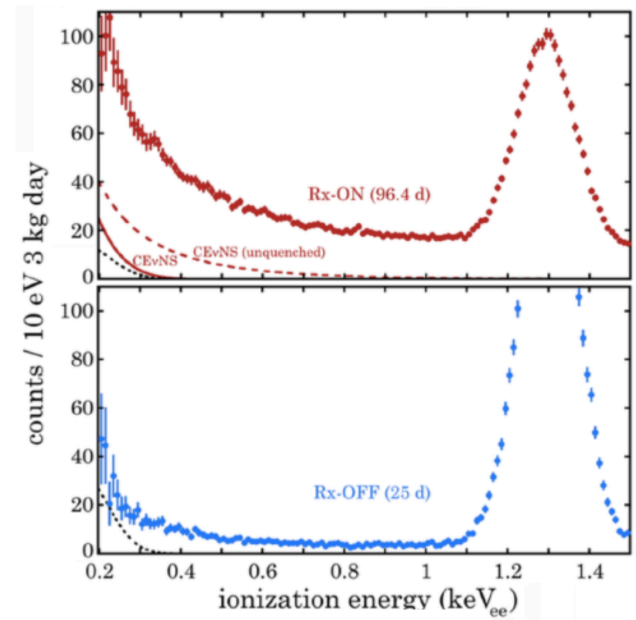
CEvNS already detected at reactor???

J.Colaresi et al., arXiv:2202.09672

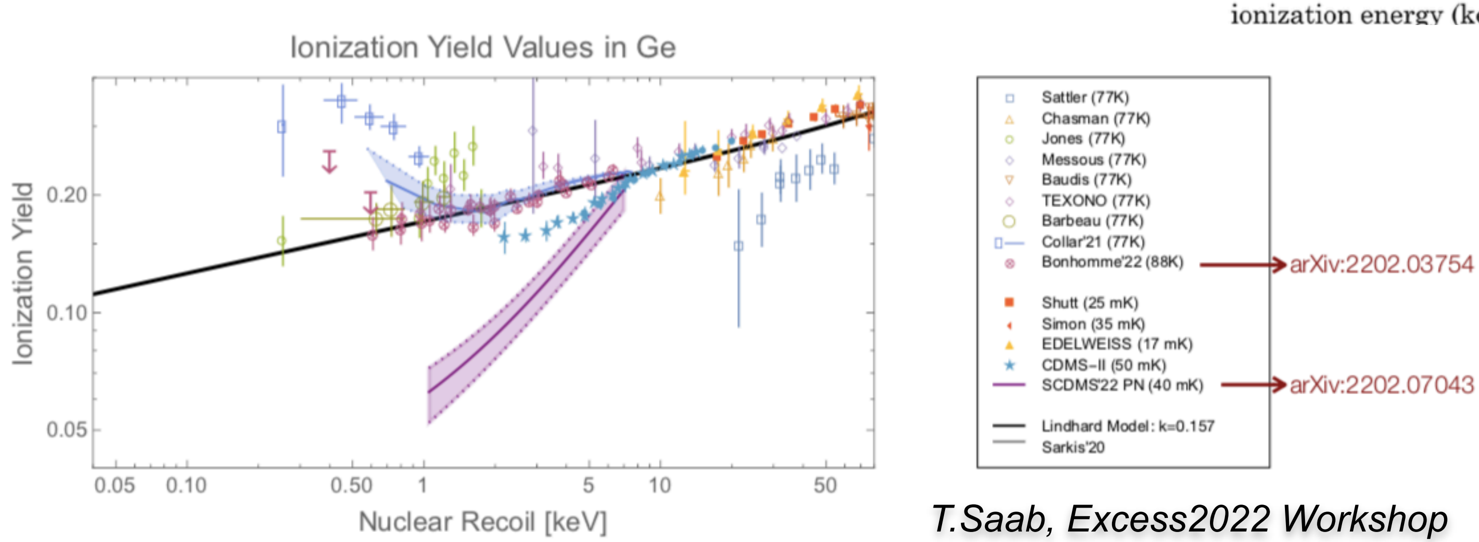
Suggestive evidence for coherent elastic neutrino-nucleus scattering from reactor antineutrinos

J. Colaresi[1], J.I. Collar[2,*] T.W. Hossbach[3], C.M. Lewis[2], and K.M. Yocum[1]
[1] *Mirion Technologies Canberra, 800 Research Parkway, Meriden, CT, 06450, USA*
[2] *Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA and*
[3] *Pacific Northwest National Laboratory, Richland, Washington 99354, USA*
(Dated: February 22, 2022)

The 96.4 day exposure of a 3 kg ultra-low noise germanium detector to the high flux of antineutrinos from a power nuclear reactor is described. A very strong preference for the presence of a coherent elastic neutrino-nucleus scattering (CEνNS) component in the data is found, when compared to a background-only model. No such effect is visible in 25 days of operation during reactor outages. The best-fit CEνNS signal is in good agreement with expectations based on a recent characterization of germanium response to sub-keV nuclear recoils. Deviations of order 60% from the Standard Model CEνNS prediction can be excluded using present data. Standing uncertainties in models of germanium quenching factor, neutrino energy spectrum, and background are examined.



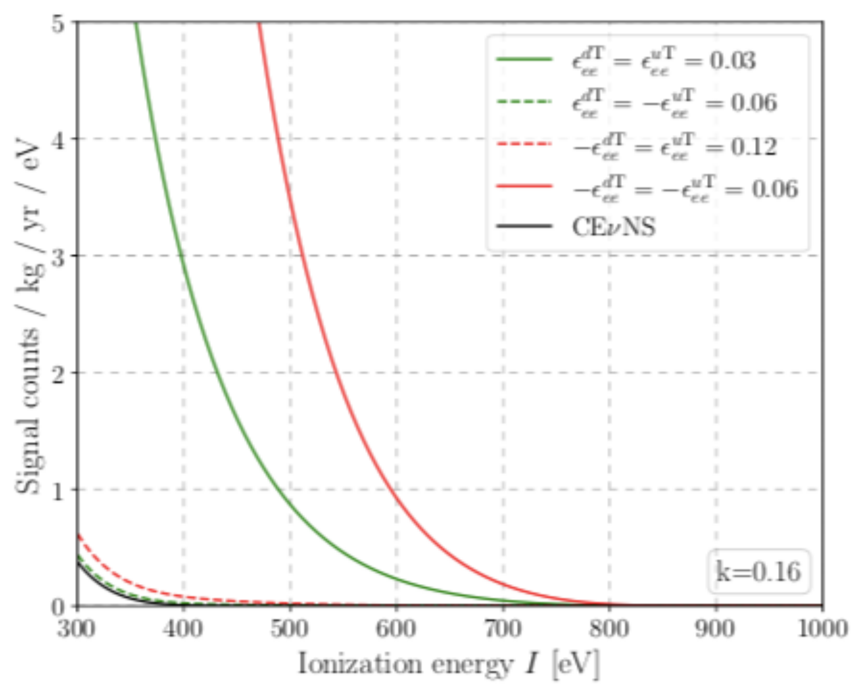
Result compatible with SM with enhanced quenching at low E: conflict with other quenching measurements

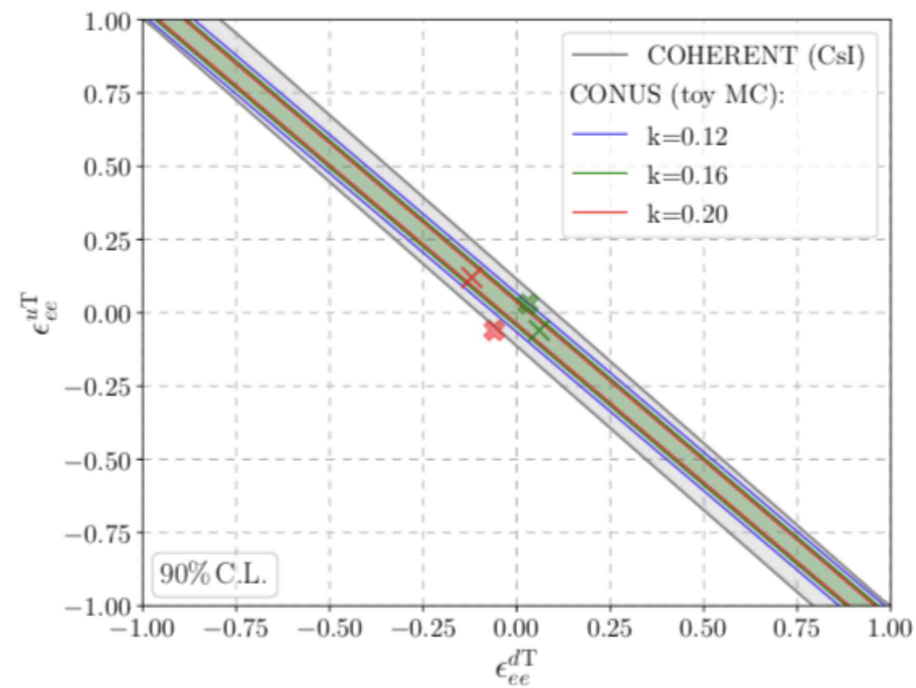


T.Saab, Excess2022 Workshop

BSM: non standard interactions (tensor)

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



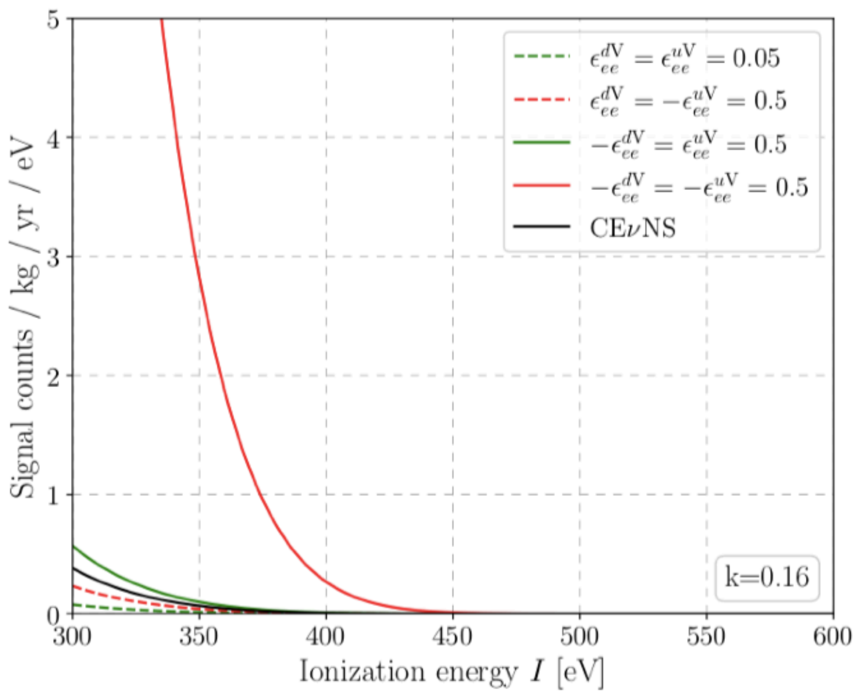


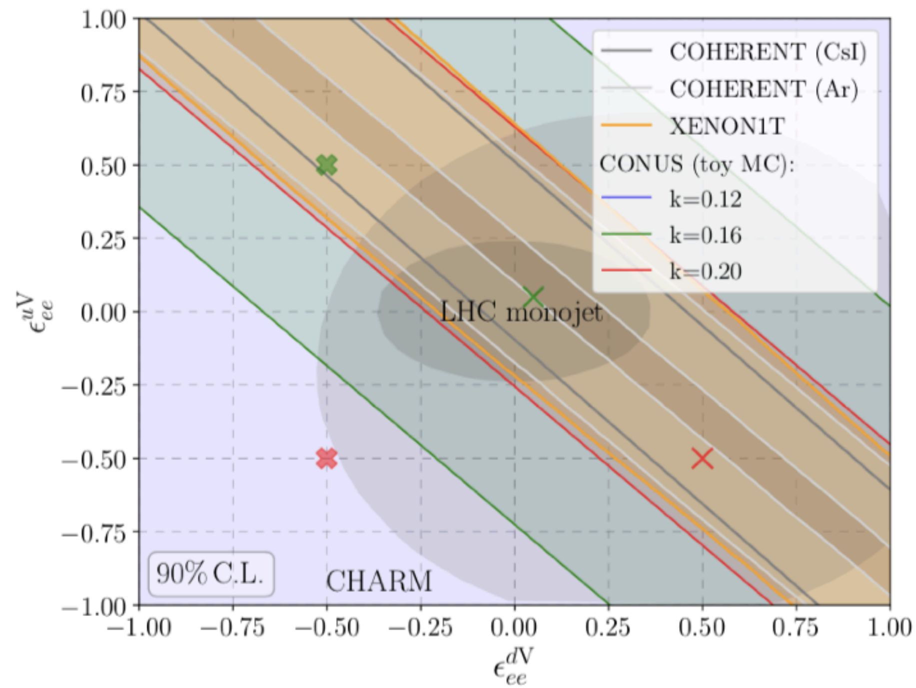
Very competitive results!

CONUS, JHEP 05 (2022) 085

BSM: non standard interactions (vector)

New interaction similar to CEvNS: modified weak charge



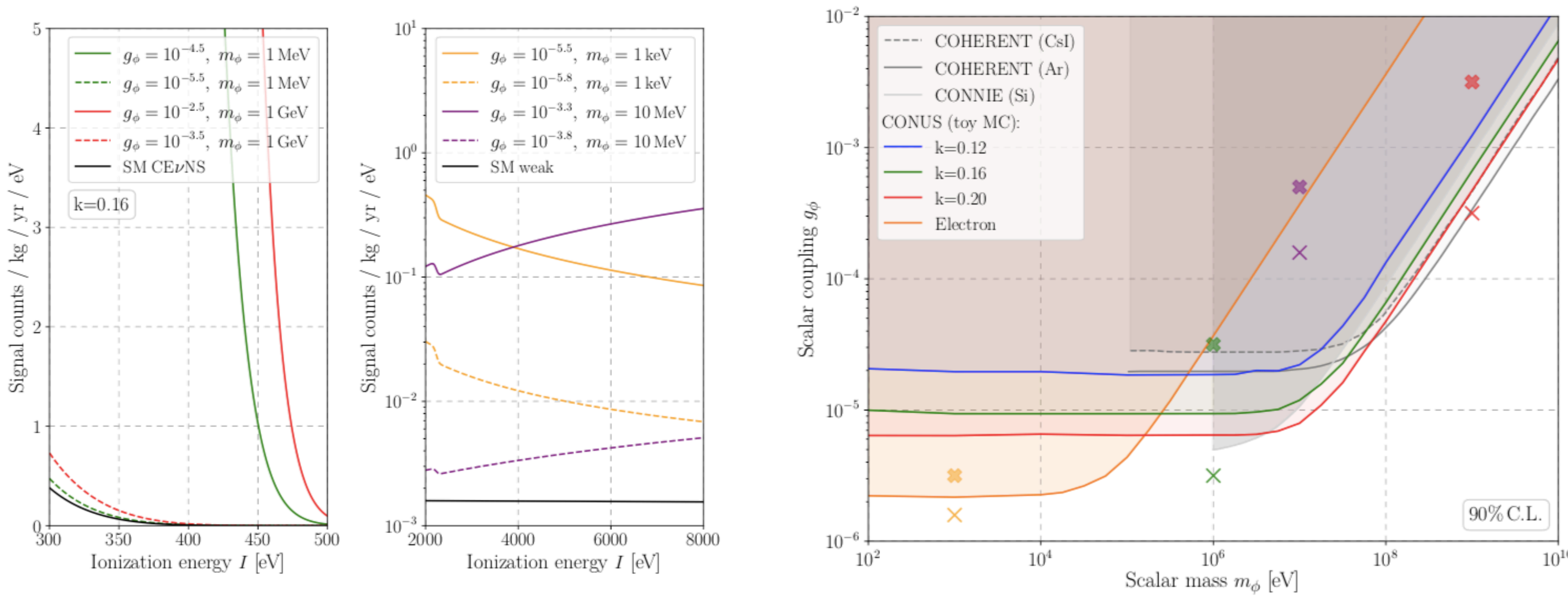


Destructive interference possible

CONUS, JHEP 05 (2022) 085

BSM: light mediators (scalar)

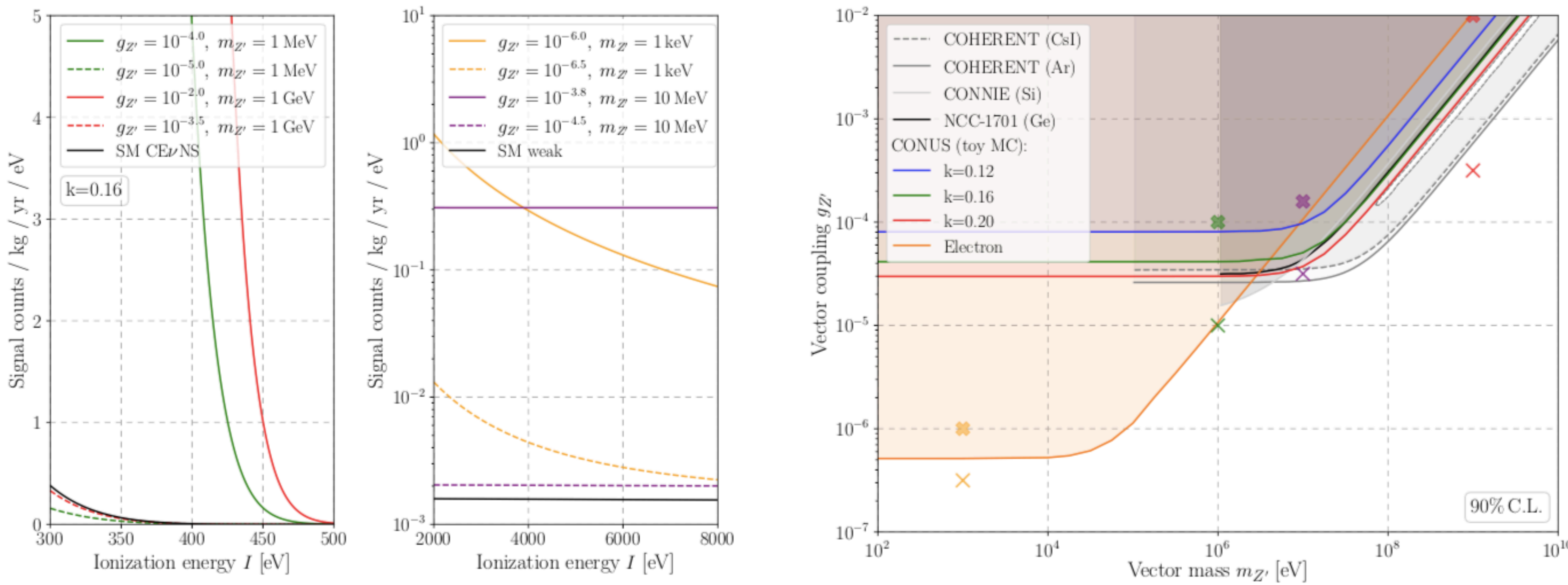
- Testing simplified models assuming universal couplings
- Nucleus and electron (2-8 keV) channels included



CONUS, JHEP 05 (2022) 085

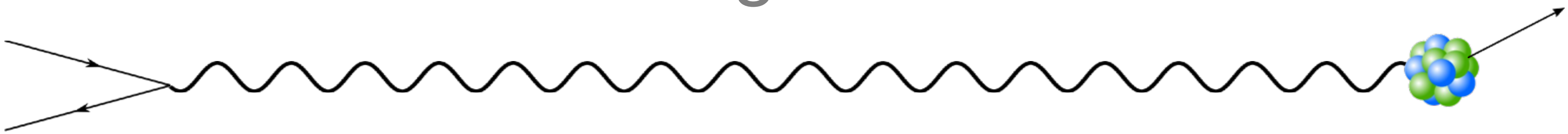
BSM: light mediators (vector)

Reactor as source: high sensitivity for mediator masses below the energy of the neutrino (< 10 MeV)



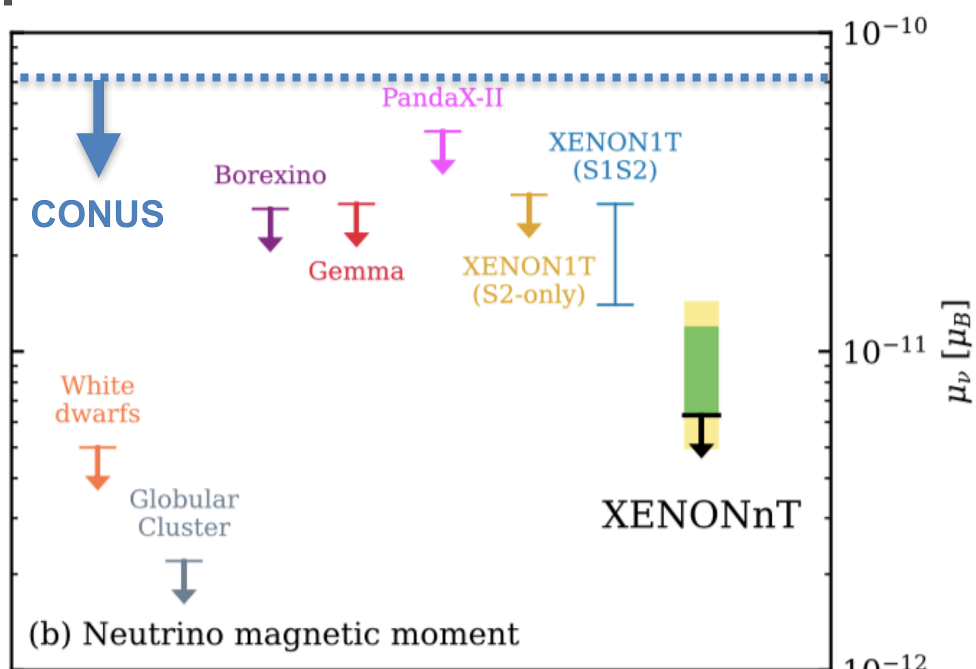
CONUS, JHEP 05 (2022) 085

Neutrino magnetic moment

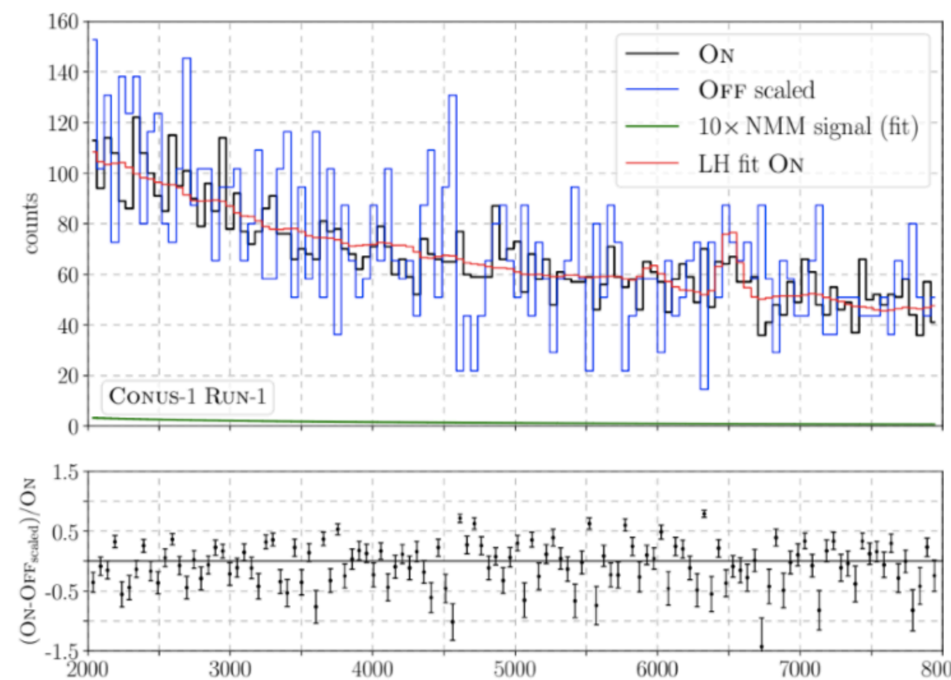


$$\left(\frac{d\sigma}{dT}\right)^{e^-}_{\mu_\nu} = \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)\left(\frac{\mu_{\nu_e}}{\mu_B}\right)^2$$

CONUS bound (90% CL) from ν-e scattering in 2-8 keV window:
$\mu_\nu < 7.5\text{x}10^{-11}$



Xenon Coll., arXiv:2207.11330



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

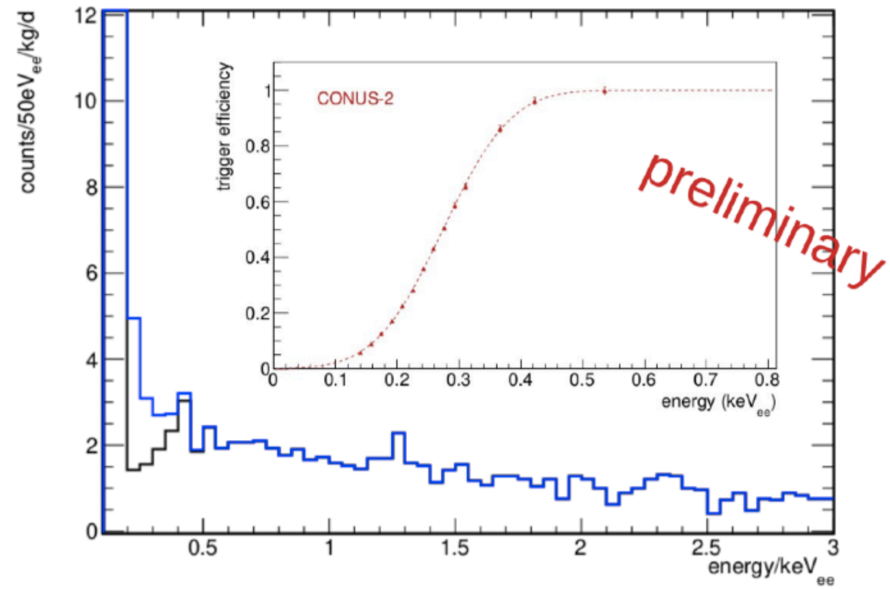
A. Studenikin, EPL 107(2), 21001 (2014)

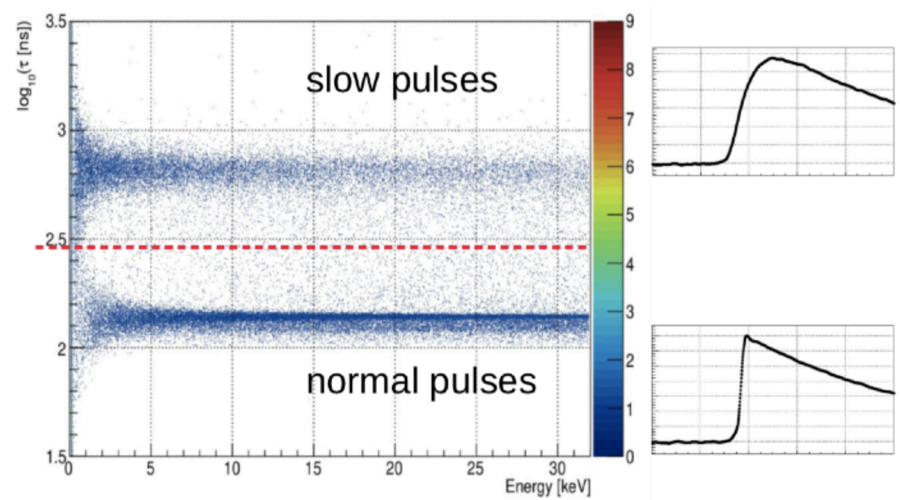
Conversion to millicharge limit:
$q_\nu < 3.3\text{x}10^{-12}\ e_0$

CONUS, arXiv:2201.12257

Outlook

- More statistics: additional ON and OFF (since 01/2022)
- Lower threshold: DAQ/electronics upgrade (< 250 eV)
- Pulse shape discrimination (~20% reduction in ROI)
- Better stability (Temp./noise control)
- Improved background knowledge from simulation studies
- Exploring new reactor site





Summary

- Nuclear reactors: intense source of low energy (< 10 MeV) electron antineutrinos ==> CEvNS in fully coherent regime
- CONUS: Low energy threshold HPGe-detectors 17.1 m from reactor core (Brokdorf)

Eur. Phys. J. C (2021) 81:267

- Extensive background studies/modeling

Eur. Phys. J. C (2019) 79:699
arXiv:2112.09585

- Constraints on CEvNS at reactor

PRL 126 (2021) 041804

- BSM constraints (NSI and light mediators)

JHEP 05 (2022) 085

- Constraints on electromagnetic neutrino properties

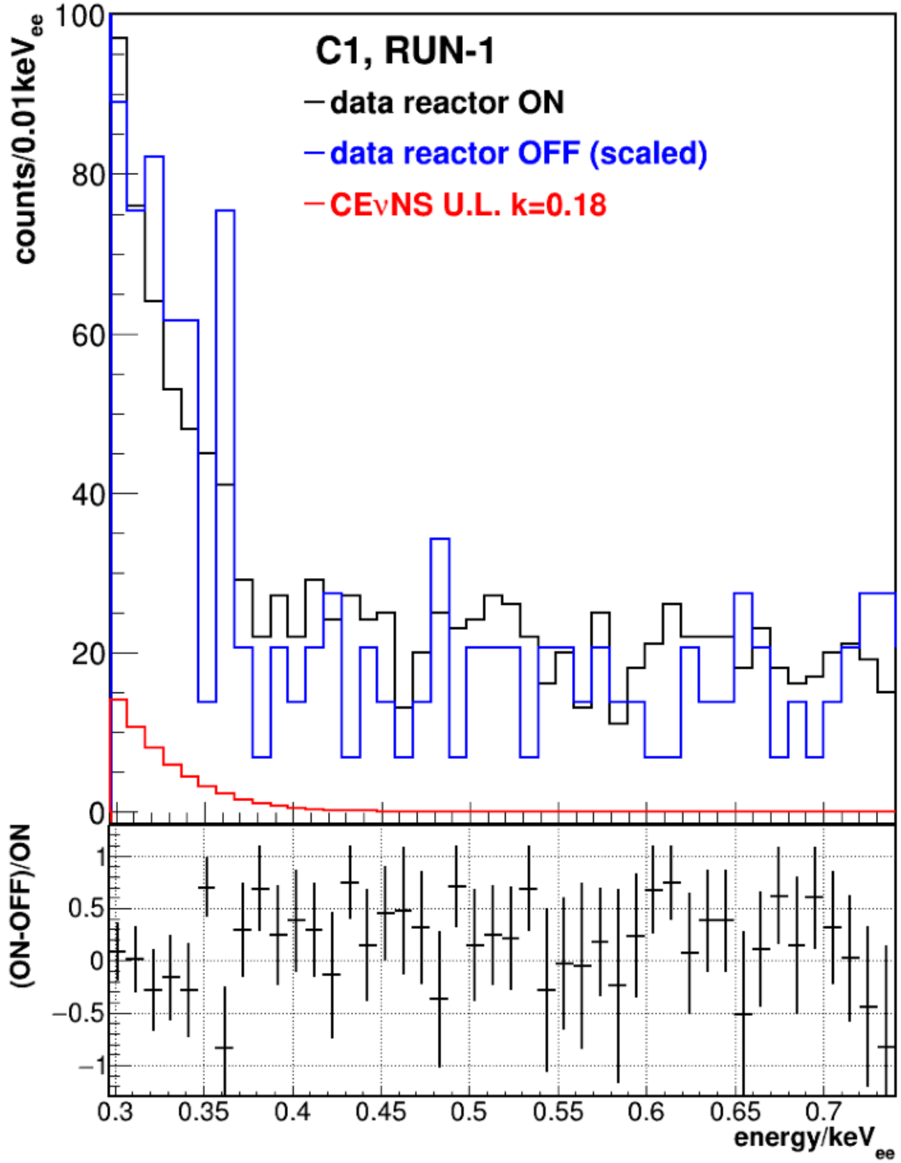
arXiv:2201.12257, accepted for publication

- Ge-quenching study at PTB: consistent with Lindhard theory

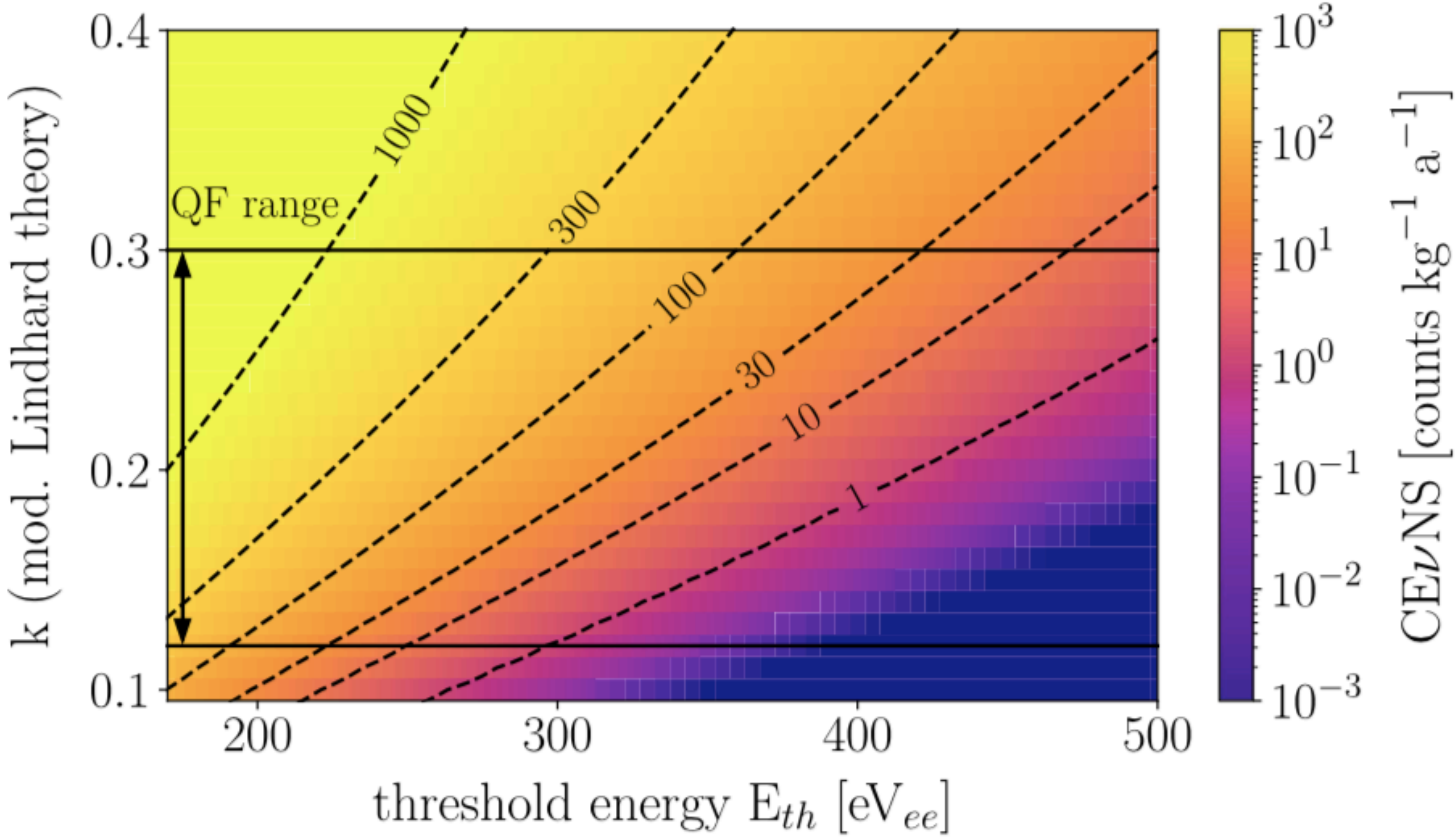
arXiv:2202.03754, accepted for publication

Backup

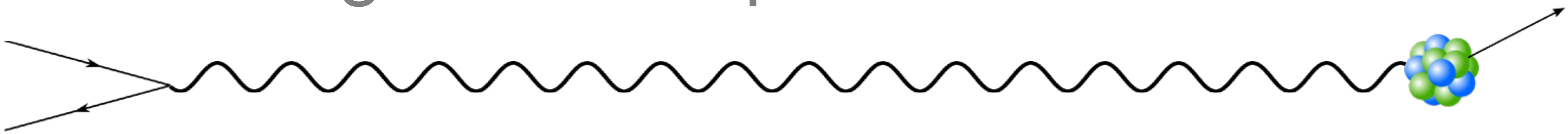
Measured spectra (ON vs OFF)

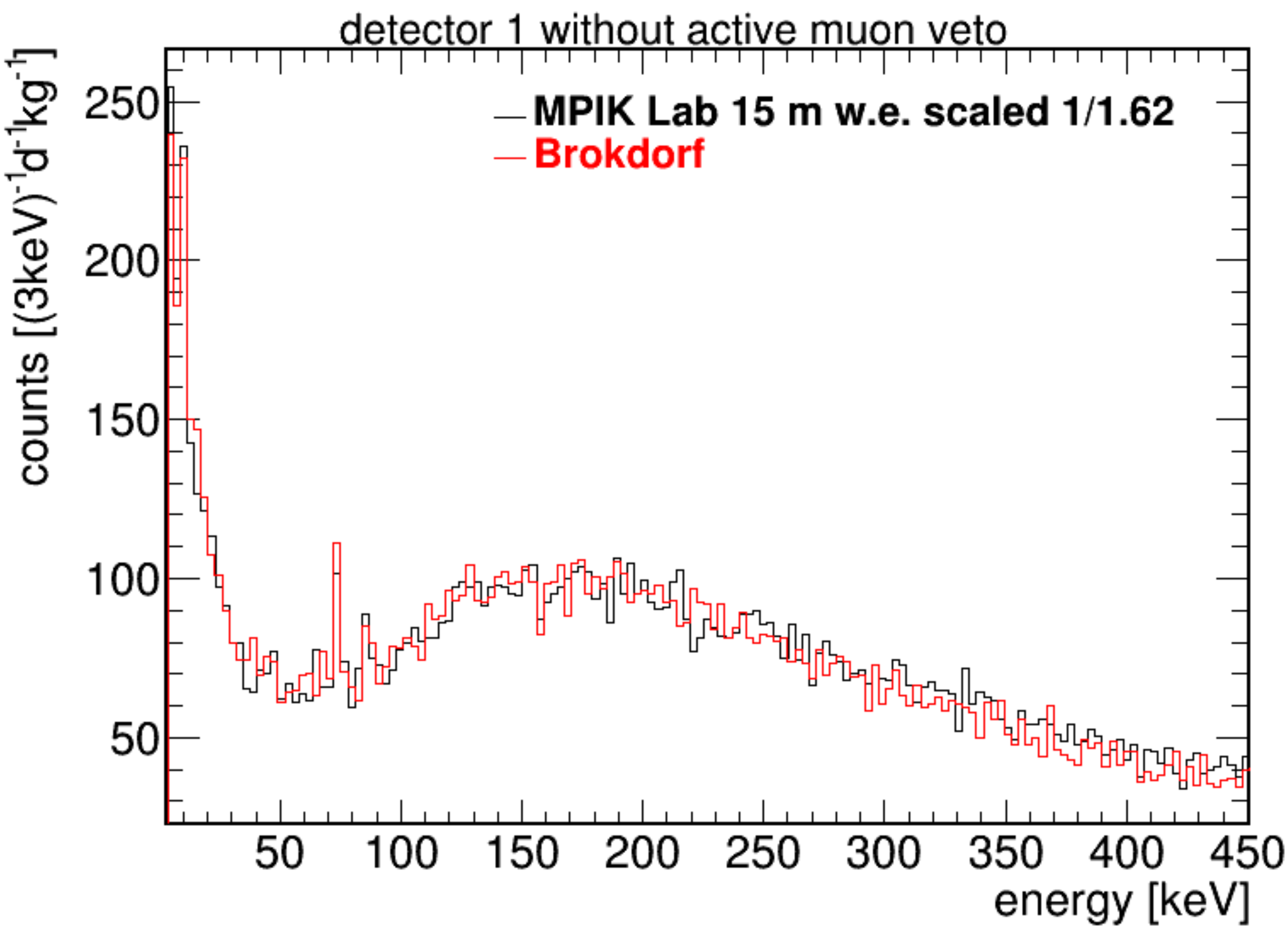


CONUS signal



Background comparison KBR/MPIK





Systematic uncertainties

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

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	