CONUS
Detecting elastic neutrino nucleus scattering in the fully coherent regime with reactor neutrinos

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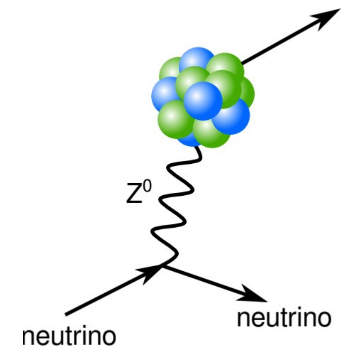
Coherent elastic neutrino nucleus scattering (CEνNS)

- **Freedman (1974): weak neutral current, flavor-blind!**

  → Promising new neutrino channel, but …
- **COHERENT (2017): first detection with π-DAR source**

  → So far consistent with SM!
- **CONUS (2018): start of operation and first indication**



The channel:

- Observable = nuclear recoil energy T_N

$$\frac{d\sigma_{\nu A}}{dT_N} \simeq \frac{G_F^2}{8\pi}\left[Z\left(1-4\sin^2(\theta_W)\right)-N\right]^2\left[1-\frac{T_N}{4E_\nu^2}\right]\cdot F^2(T_N)$$

- Coherence = enhancement $\sim N^2$

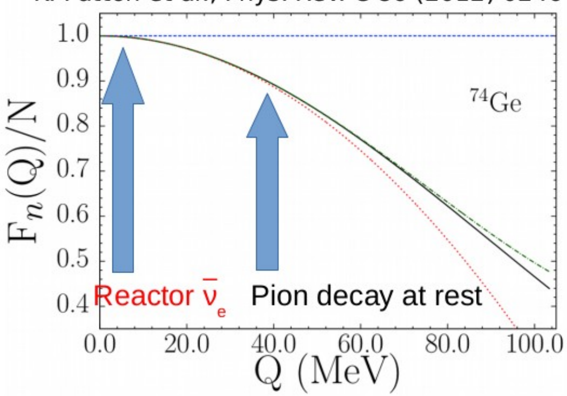
$$E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}}[\mathrm{MeV}]$$

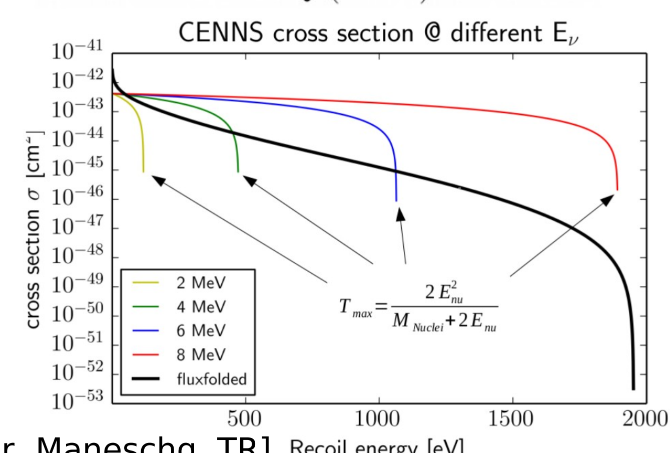
- Hard to detect:
  - $T_N \sim N^{-1}$
  - quenching

For Germanium:
E_{max} <50 MeV
Full coherence regime< 30MeV

Cross section σ vs. nuclear recoil T_N

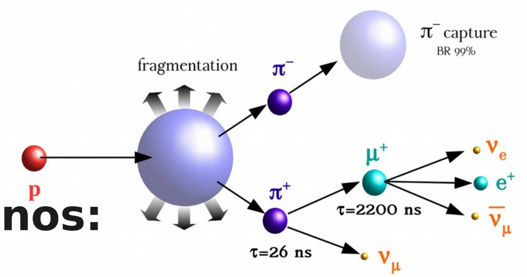
K. Patton et al., Phys. Rev. C 86 (2012) 0246





[Lindner, Maneschg, TR]

Two complementary paths



Π-decay at rest neutrinos:

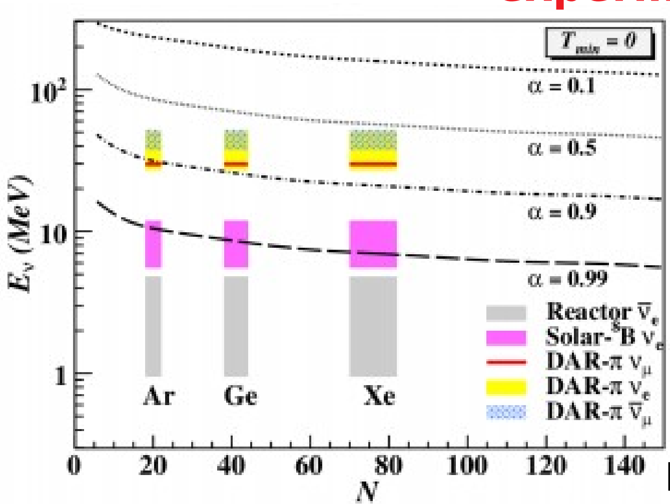
- Pulsed GeV-proton beam hitting heavy target → multiple ν-flavors
- Time correlation between prompt and delayed events → strong background suppression 10^3 to 10^4
- Higher ν-energies → larger x-section, but lack of coherence & neutrino-induced neutrons (NINs)

→ COHERENT experiment

Reactor antineutrinos:

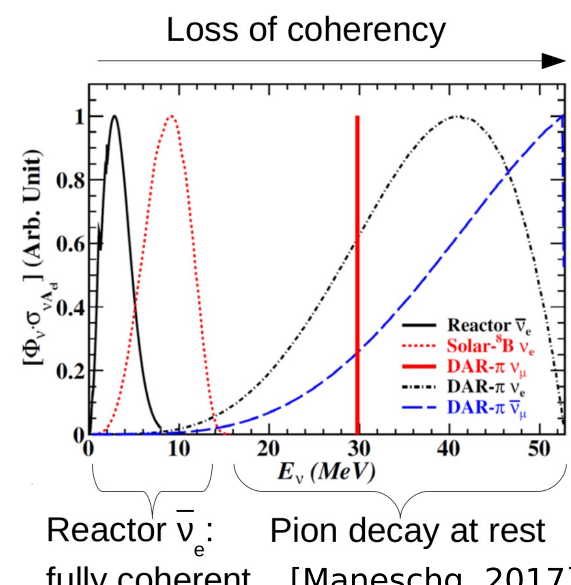
- β-decays in nuclear reaction chains
  → only electron antineutrinos $\bar{\nu}_e$
- Strongest neutrino source on earth: ~10^{20} $\bar{\nu}_e$'s/GW/s
- ν-energies up to 10 MeV
  → fully coherent regime!
- Safety restrictions close to core
  → no cryogenic liquids

→ CONUS



[Kerman et al., 2016]

CEvNS at reactor site as high statistic baseline for multi-target and multi-flavored beam investigations!



[Maneschg, 2017]

Experimental requirements at reactor site

Goal: Detecting CEνNS with high accuracy!

Several obstacles to overcome:

1) Beat $1/R^2$ factor

→ strong (= commercial) power plant but safety restrictions inside building

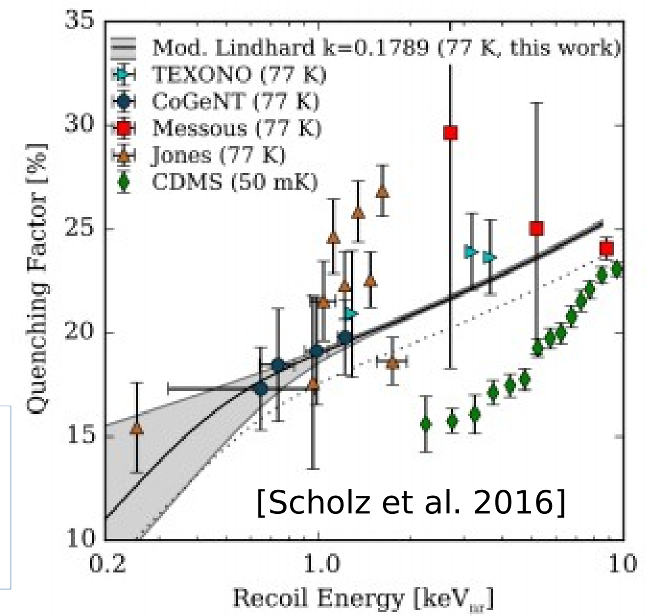
2) Compensate quenching ($E_{recoil} \rightarrow E_{ion}$)

→ lowest possible detection threshold

3) Low background outside lab conditions

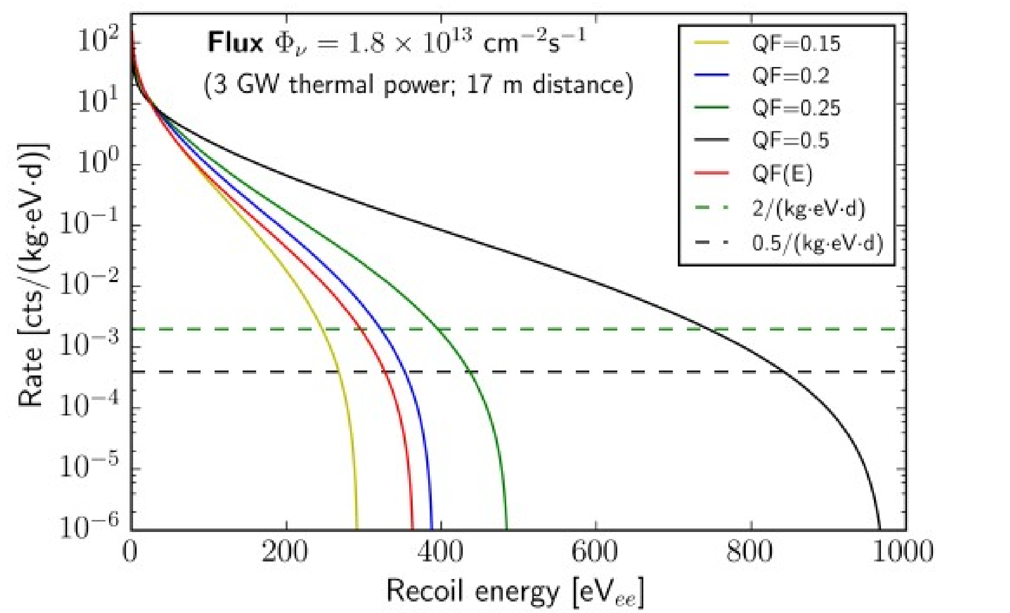
→ moderate overburden & limited shielding capacities

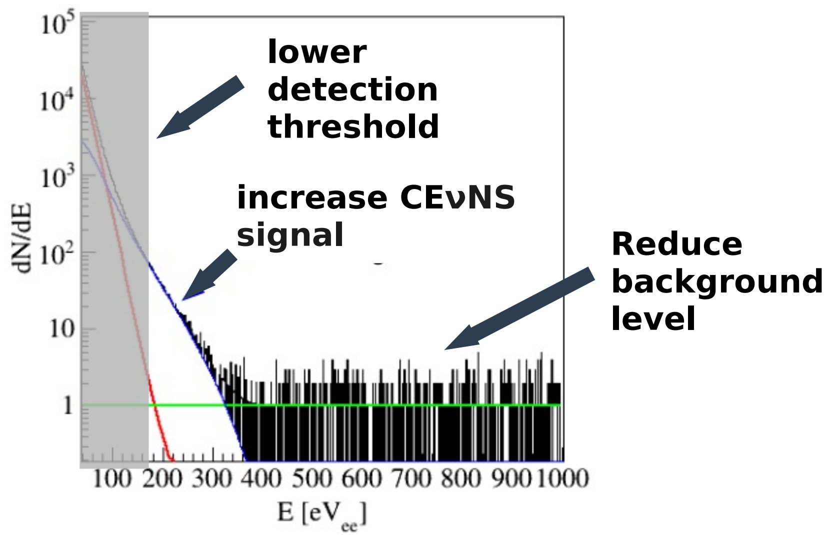
E_ν: 10MeV
max E_{Recoil}: 3keV
maxE_{ion}: ~600eV



[Scholz et al. 2016]

[Lindner, Maneschg, TR]





The CONUS collaboration

Collaboration:

A. Bonhomme, C. Buck, J. Hakenmüller, G. Heusser, T. Hugle, M. Lindner, W. Maneschg, T. Rink, T. Schierhuber, H. Strecker **- Max Planck Institut für Kernphysik (MPIK), Heidelberg**

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

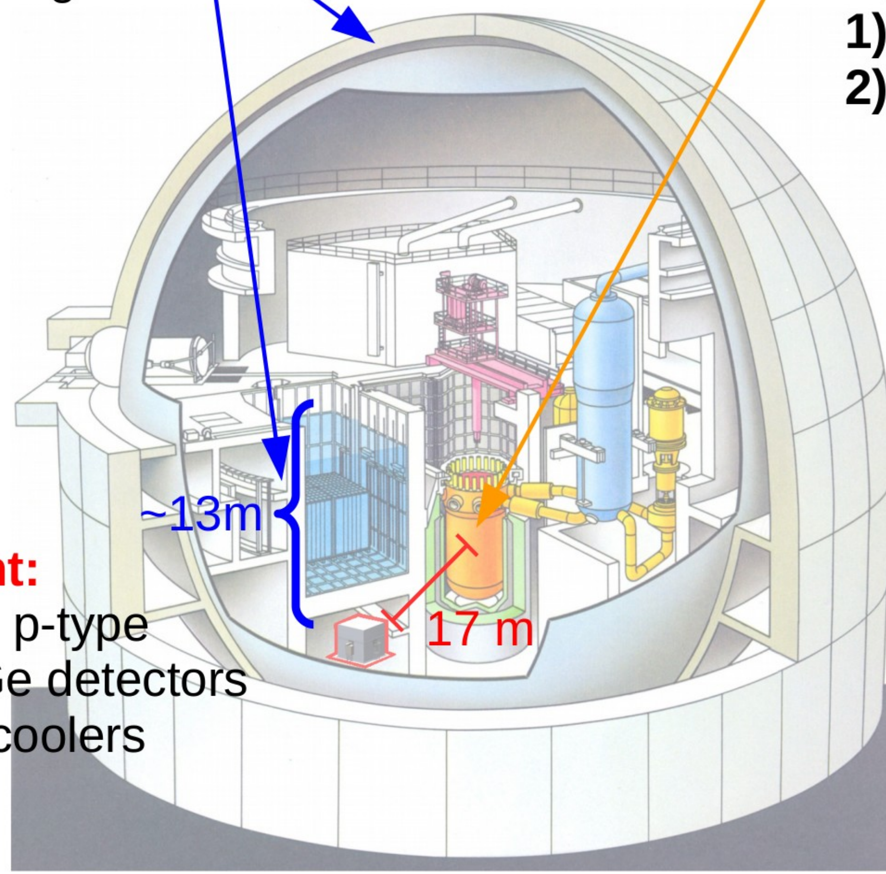
Scientific cooperation:

M. Reginatto, M. Zboril, A. Zimbal **- Physikalisch-Technische Bundesanstalt (PTB), Braunschweig**

Nuclear power plant in Brokdorf

Overburden at <u>shallow</u> depth:
10-45 m w.e. (angular dep.)
=> muon-induced background

Reactor core:
thermal power 3.9 GW
high duty cycle (1 month/yr off)
1) Signal: Anti neutrinos @17m
2) Potential background: Neutrons



CONUS Experiment:
- **4kg** low threshold p-type point contact HPGe detectors
- electrical PT cryocoolers

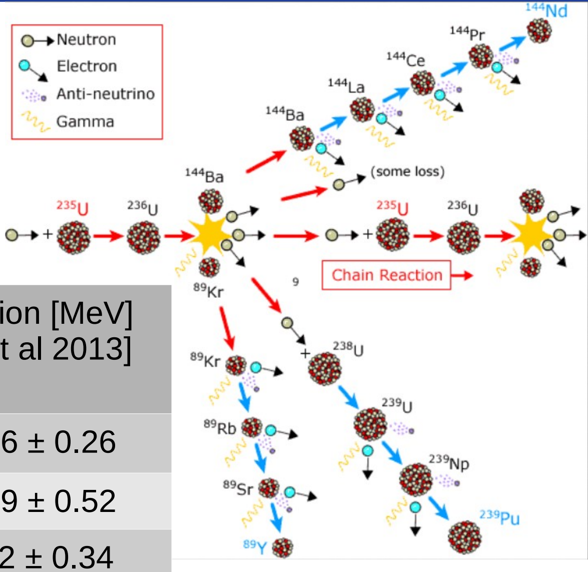
Fast neutron classes	Corr. with therm. power
μ-ind. in Pb inside shield	No
μ-ind. above ceiling	No
$(\alpha$,n)-reactions from walls	No
fission n from spent fuel rods	No
fission n from reactor core	Yes

Antineutrinos from nuclear reactions

Antineutrino emission in β-decays of fuel reaction chain

- Mainly from ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu **→ >99%**
- ~ 6-7 ν's/fission up to 10MeV
- Spectral distribution

$$S(E_\nu) = \frac{1}{4\pi R^2}\frac{W_{th}}{\sum_i \alpha_i E_i}\sum_i \alpha_i \left(\frac{dN_i}{dE_\nu}\right)$$



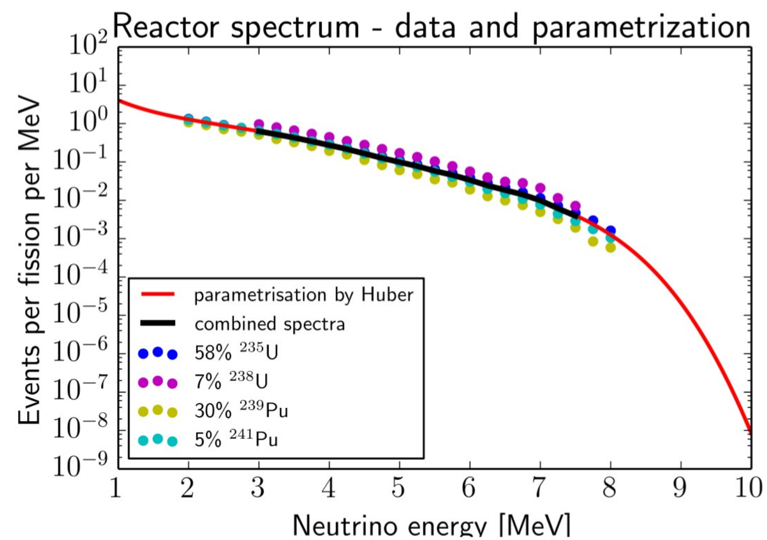
isotope	Fission fraction α (PWR)	E/fission [MeV] [Ma et al 2013]
235U	57%	202.36 ± 0.26
238U	8%	205.99 ± 0.52
239Pu	30%	211.12 ± 0.34
241Pu	5%	214.26 ± 0.33

Knowledge about a reactors emission spectra

- Summation methods [e.g. Kopeikin, Mikaelyan, Sinev, 2004]
  → summing β-branches of all fission fragments
- Conversion methods [Haag et al., 2013 P. Huber, 2011; Mueller et al., 2011]
  → measure β-decay electron spectrum and convert into ν spectrum
- Direct measurements (IBD) [An et al., 2017]

Reality much more complicated…
- Varying reactor power → **P(t)**
- Changing fuel composition → **α(t)**

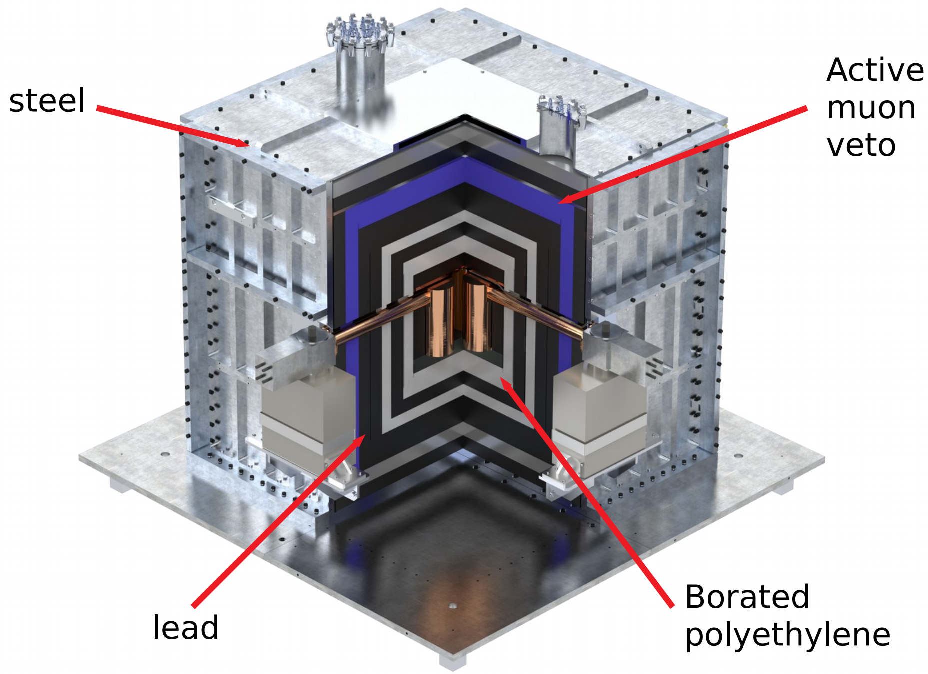
Virtue out of necessity:
CEνNS as flux measuring tool

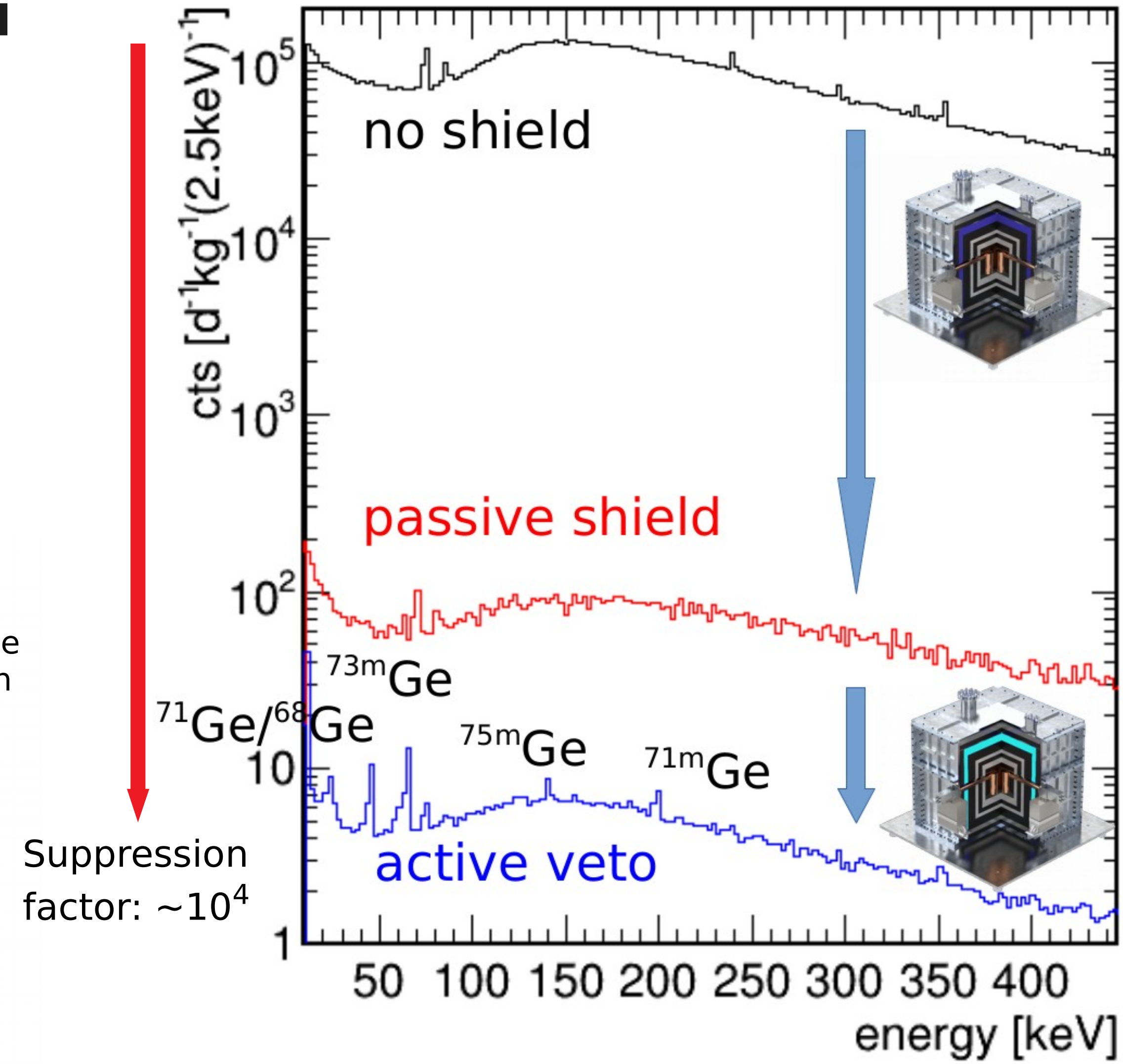


Parametr./Data: from P.Huber and N.Haag

CONUS shield design

- **Onion-like structure with active and passive components**
  - Pb + borated polyethylene
    - → γ and n-capture
  - Active muon-veto systeme
    - → ~99% efficiency
- **Very compact design**
  - → V=1.65 m³ & m=11 t





Background level [0.5, 1.0] keV:
~10 counts/kg/day/keV

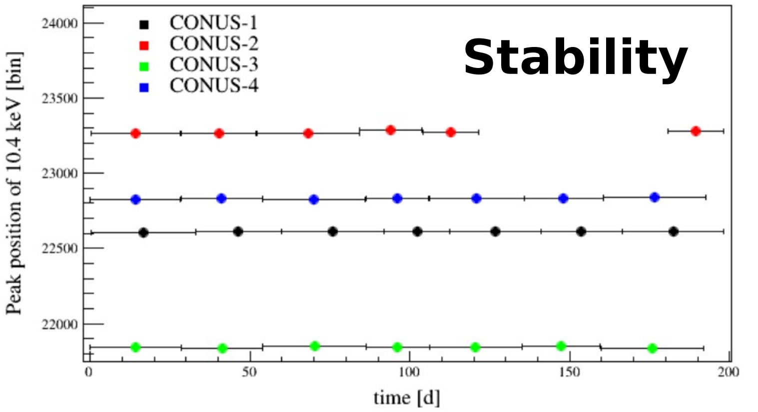
CONUS detectors

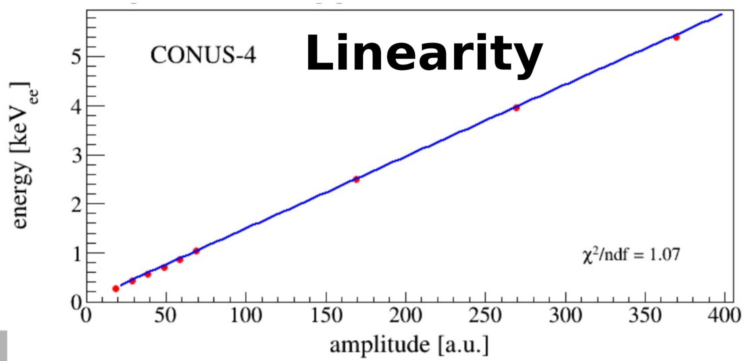
CONUS 1-4:

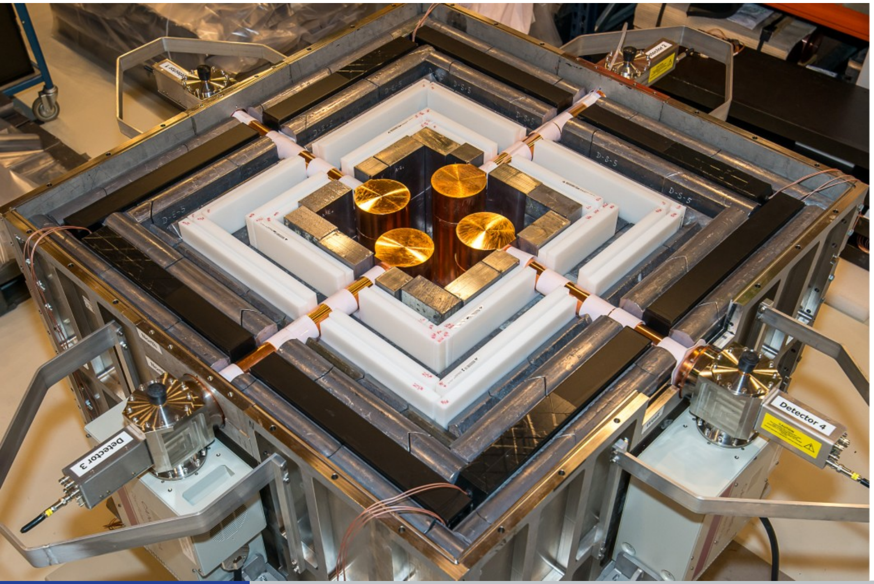
- Detectors designed for shield dimensions
- P-type point contact HPGe
- crystal/active mass: 4.0/3.74 kg
- Pulser resolution ≤85eV

  ➡ ≤300eV noise threshold
- Electrical PT cryocoolers
- Very low background design

novel development!

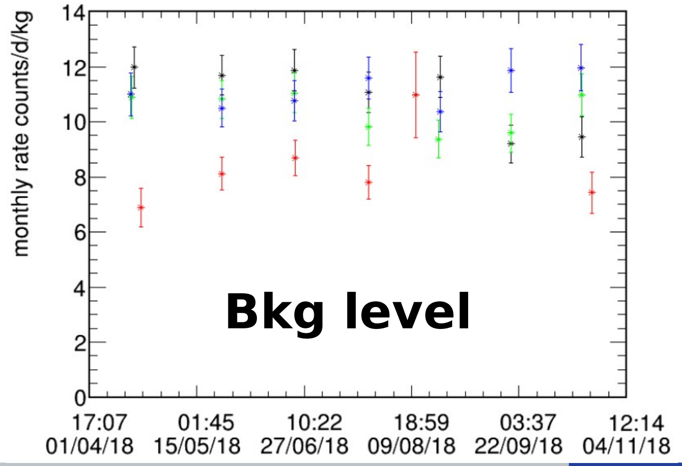






Detector performance under lab conditions

detector	Pulser FWHM [eV_{ee}]
C1	74 ± 1
C2	75 ± 1
C3	59 ± 1
C4	74 ± 1

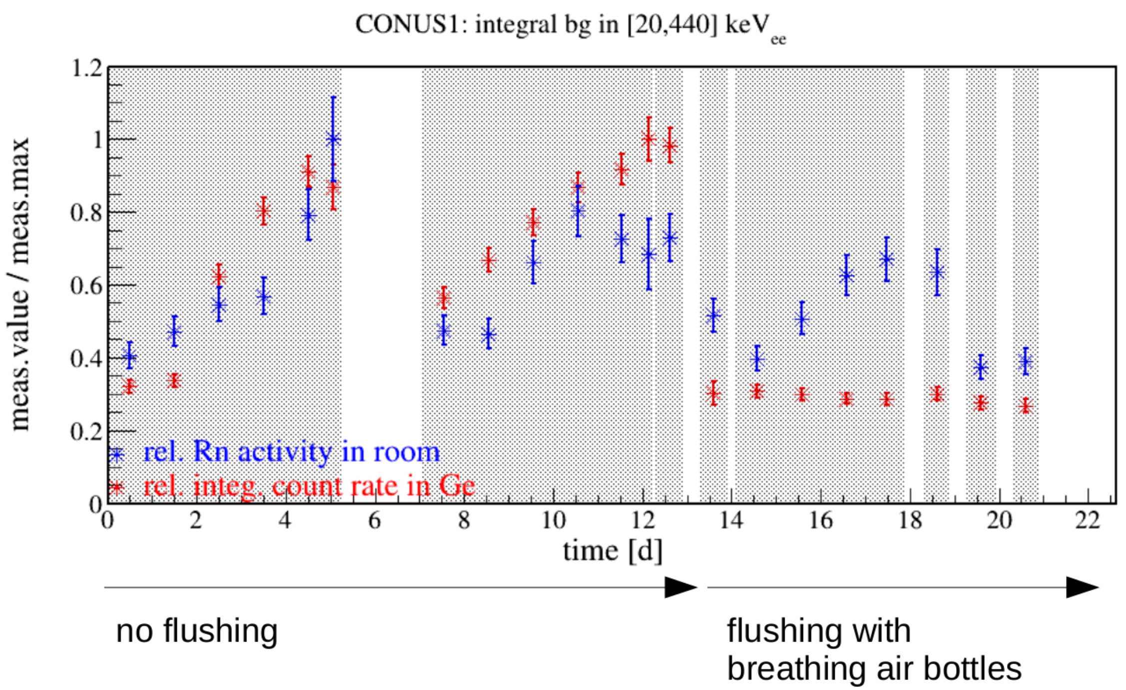


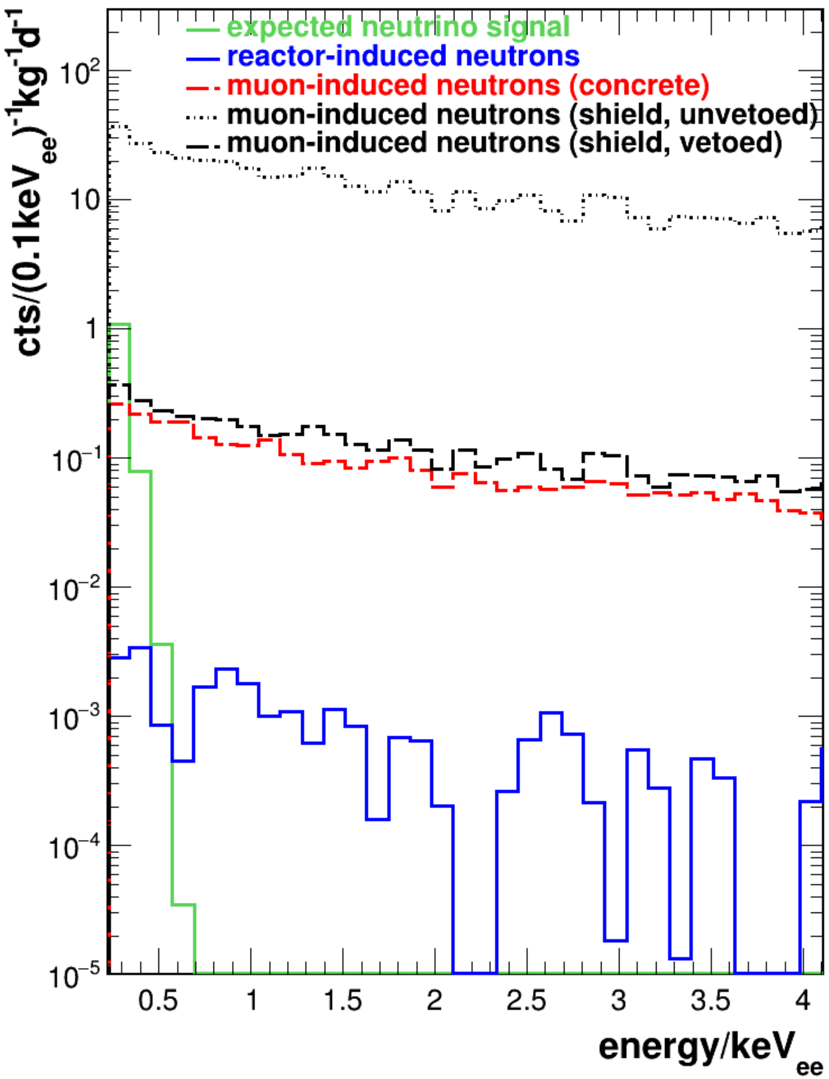
Operating in an “unusual” environment

Understanding the experimental site:

- Close to a huge gamma and neutron source
  → correlation with reactor power ➡ **like CEνNS!**
- Low bkg experiment encapsulated by large amounts of usual concrete → radon emanation from walls
- Usual environmental radioactivity → wipe tests

Signal expectation

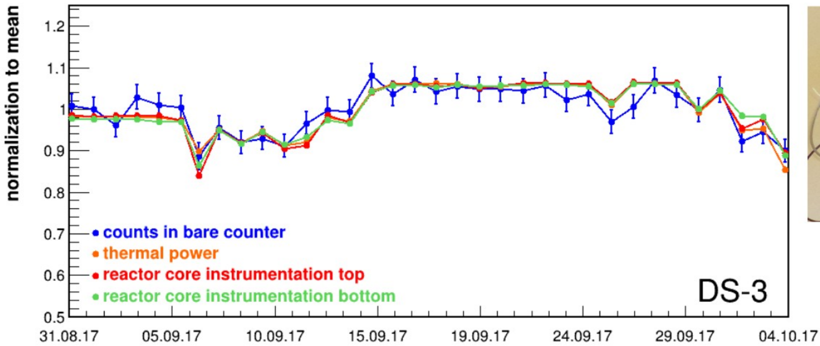


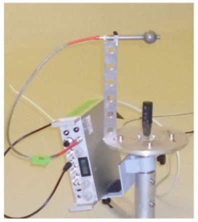


Power-correlated reactor radiation

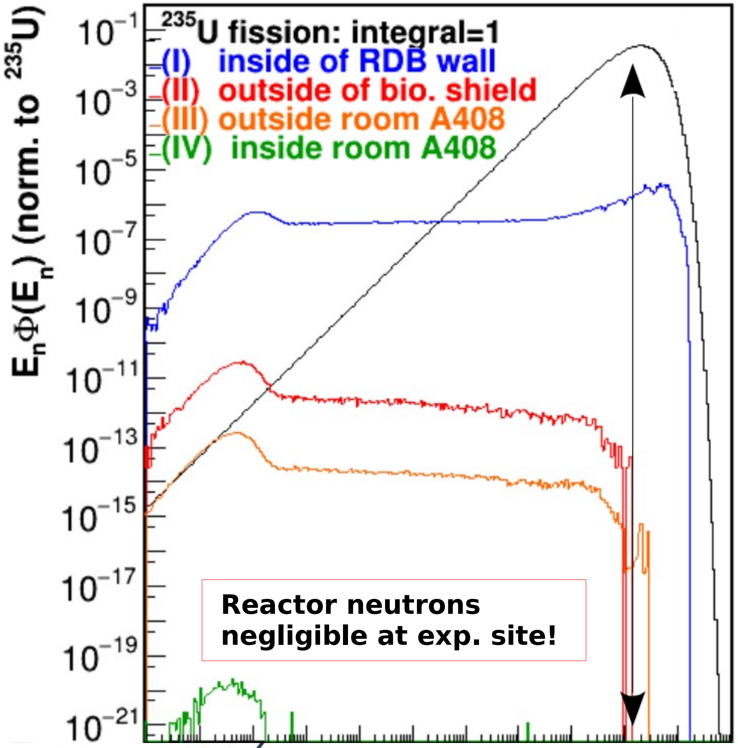
→ **Dedicated investigation of reactor-correlated background contributions: arXiv:1903.09269**

- Simulation and validation of neutrons emitted from reactor core (at CONUS site) → thermal neutron counter

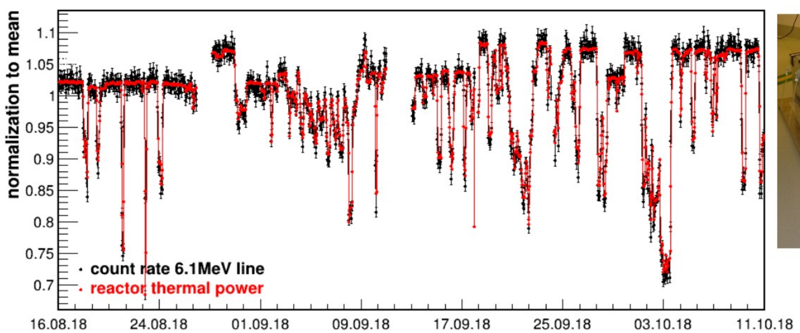




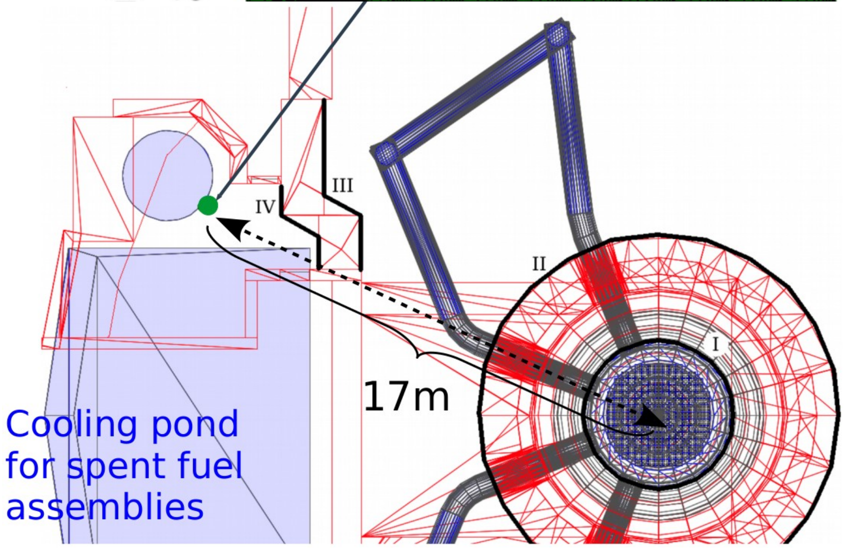
Correlation to incore and excore instrumentation



- γ-radiation (6.1MeV from ^{16}N)



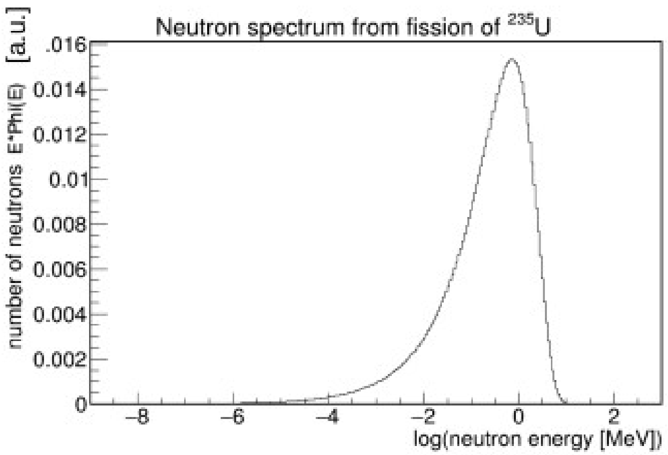
Unshielded HPGe detector



Reactor-correlated neutrons at site

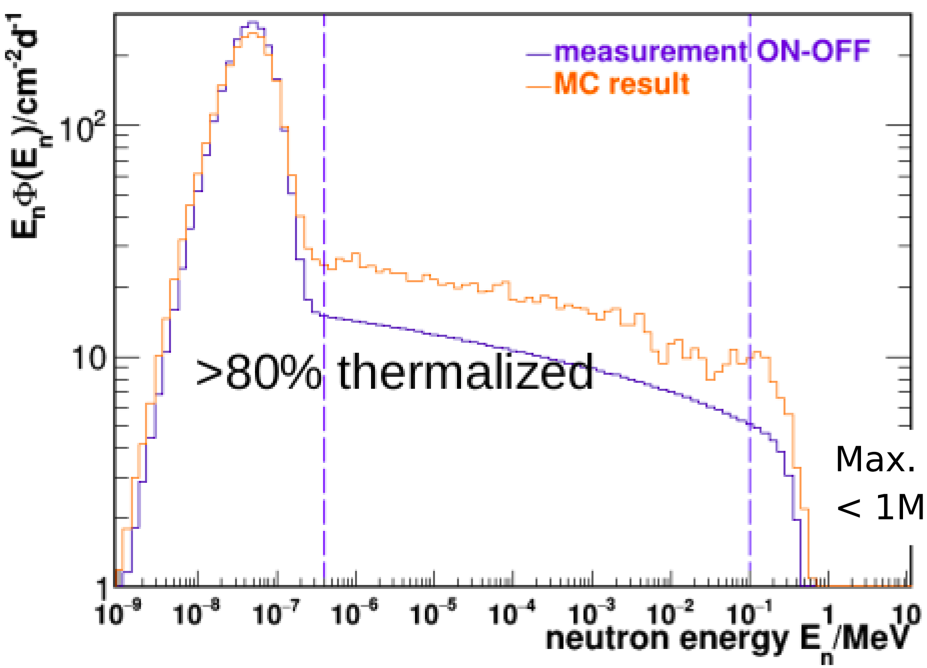
ON - OFF = reactor correlated

at reactor core



propagation

water
steel
concrete
...



Max. E_n < 1MeV

Main fission isotopes: ^{235}U (>50%), ^{239}Pu, ^{241}Pu

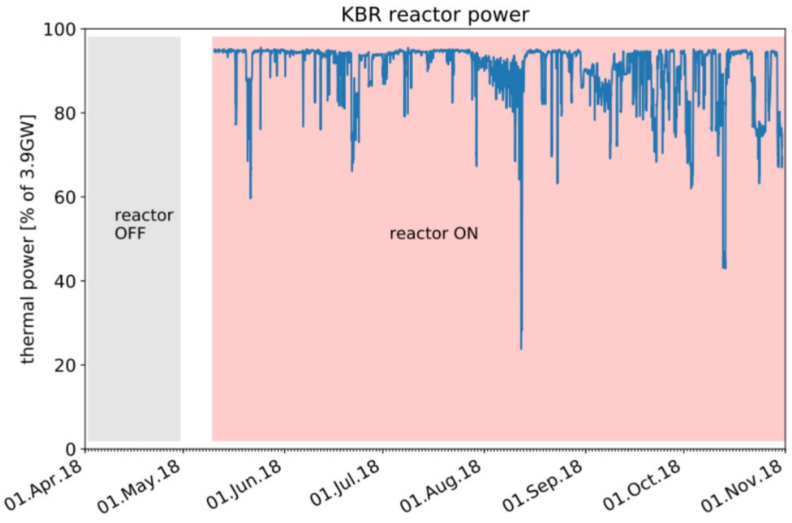
Results of neutron investigation:

1) Neutron fluence ~factor 2 lower than on earth surface
2) Highly thermalized neutron field
3) Inhomogeneity in thermal neutron fluence ~20%
4) MC simulations in front of room similar to data, same peak energy

Latest result of CONUS analysis

First data set: 1 month OFF, 6 months ON

- So far **rate-only** analysis
- Statistically limited by reactor OFF time
- With realistic quenching same order of magnitude as prediction



Preliminary result (only 3 detectors)

Analysis [300; 550] eV_{ee}	**counts**
Reactor OFF (65 kg*d)	354 ± 19
Reactor ON (417 kg*d)	2405 ± 49
Residual ON-OFF	133 ± 130

Prediction:

quenching	0.15	0.175	0.2	0.225	0.25
events	7	19	41	74	117

Shape analysis: ongoing

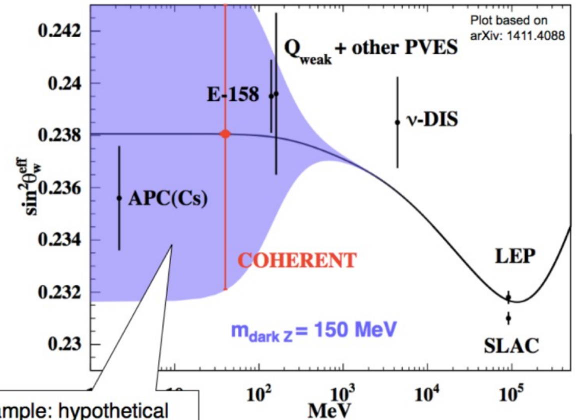
- Data selection for clean detection thresholds
- Strong dependence on quenching!
- Systematics:
  - Energy scale stability
  - Detection efficiencies
  - Background stability
  - Neutrino emission and flux prediction

New physics reach

Weinberg angle at low Q:

Clean SM prediction for the rate ➔ measure $\sin^2\theta_W$eff ;
deviation probes new physics

$$\sigma \sim \frac{G_f^2 E^2}{4\pi}(N - (1 - 4\sin^2\theta_W)Z)^2$$

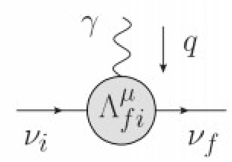


K. Scholberg

Example: hypothetical dark Z mediator (explanation for g-2 anomaly)

CEvNS sensitivity is @ low Q; need sub-percent precision to compete w/ electron scattering & APV, but **new channel**

Neutrino magnetic moment:



- Loop induced effect → small!
- Model-dependent expectations
  - → Dirac vs. Majorana $\mu^D_{kk} \simeq 3.2 \cdot 10^{-19}\left(\frac{m_k}{\mathrm{eV}}\right)\mu_B$

$$\mu^M_{kk'} \lesssim 4 \cdot 10^{-19}\left(\frac{m^M_{kk'}}{\mathrm{eV}}\right)\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \mu_B$$

- Low-threshold detectors needed!

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

$$\mathrm{sensitivity}(\mu_\nu) \propto N^{-\frac{1}{2}}\left[\frac{B}{M \cdot t}\right]^{\frac{1}{4}}$$

Light mediator searches: $y_\nu = C_\nu - iD_\nu$

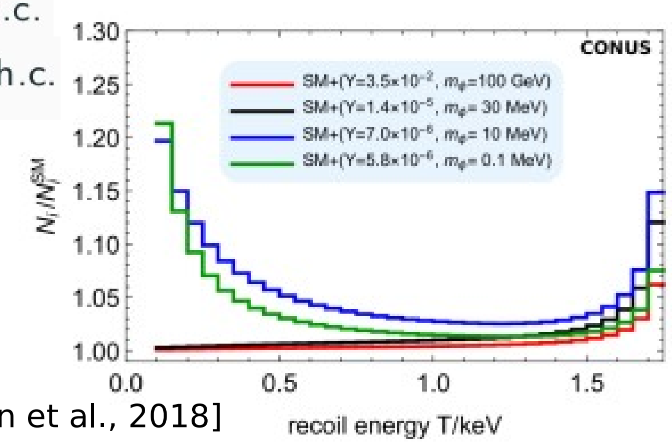
$$\mathcal{L}_{\mathrm{LNC}} = y_\nu \phi \bar{\nu}_R \nu_L + \mathrm{h.c.}$$
$$\mathcal{L}_{\mathrm{LNV}} = \frac{y_\nu}{2}\phi \bar{\nu}^c_L \nu_L + \mathrm{h.c.}$$

- Light scalar coupling to neutrinos
- New chirality-flipping channel:

$$\frac{d\sigma}{dT} = \frac{d\sigma_{\mathrm{SM}}}{dT} + \frac{d\sigma_\phi}{dT} \qquad Y^4 \equiv \frac{C_N^2}{A^2}|y_\nu|^2$$

$$= \ldots + \frac{MY^4A^2}{4\pi(2MT + m_\phi^2)^2}\left[\frac{MT}{E_\nu^2} + \mathcal{O}\left(\frac{T^2}{E_\nu^2}\right)\right]$$

Spectral distortion for **small recoil energies!**



[Farzan et al., 2018]

Further New Physics prospects

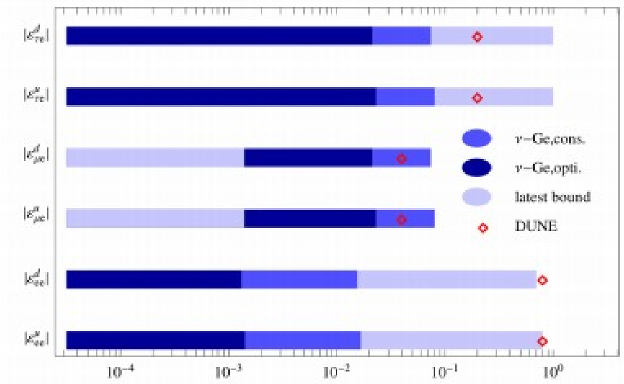
Non-standard neutrino interactions [Barranco et al., 2005]

$$\frac{d\sigma_{\nu A}}{dT_N} \propto \left\{\left[Z(g_V^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV}) + N(g_V^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})\right]^2 + \sum_{\alpha=\mu,\tau}\left[Z(2\epsilon_{\alpha e}^{uV} + \epsilon_{\alpha e}^{dV}) + N(\epsilon_{\alpha e}^{uV} + 2\epsilon_{\alpha e}^{dV})\right]^2\right\}$$

- ε partially degenerate → different isotopes
- If sub-percent sensitivity $\epsilon_{\alpha\beta}^{q} \approx \frac{m_W^2}{\Lambda_{NSI}^2}$

  → probing **TeV-scale** physics!

→ further: scalar-/tensor-NSI, GNI [Bischer, Rodejohann, 2019]

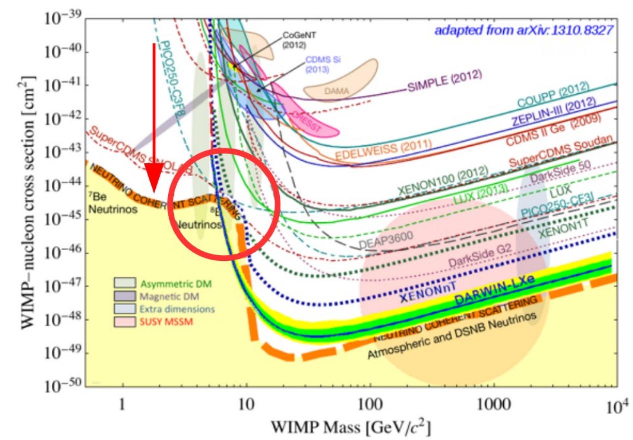


[Lindner, Rodejohann, Xu, 2017]

Dark matter and supernova physics

- Neutrino floor = CEνNS of solar neutrinos
- Same detector response

  → today's signal, tomorrow's background
- CEνNS plays important role in SN evolution



https://agenda.infn.it/getFile.py/access?contribId=11&sessionId=3&resId=1&materialId=slides&confId=9608

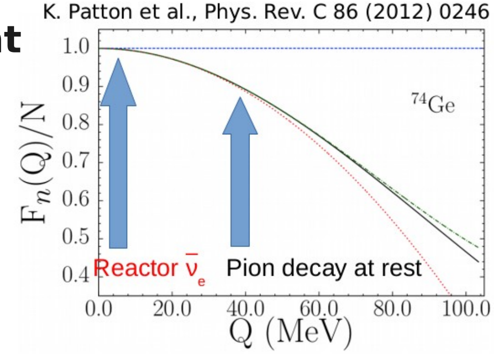
eV-sterile neutrino & precision flux measurement

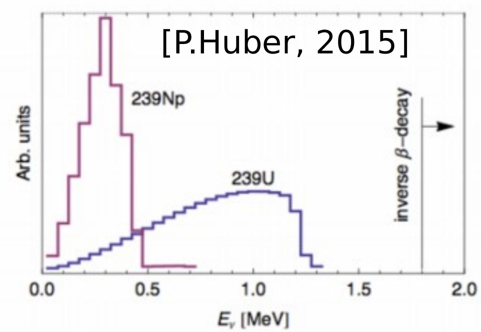
- A new data point at 17m from PWR
- Neutrino monitoring of fuel evolution

Neutron form factor

Nuclear safeguarding

K. Patton et al., Phys. Rev. C 86 (2012) 0246





Conclusion

- **CEvNS opens era of high statistics neutrino physics**

  → beams and reactors go hand in hand!

- **CONUS = low-E HPGe detectors in sophisticated shield close to 3.9 GW$_{th}$ reactor core of NPP Brokdorf (Germany)**

  → more background data this June!

- **Extensive work to understand experimental environment**

  → Reactor-correlated neutrons negligible inside shield!

- **CONUS is operating stable so far: preliminary rate analysis, limited by statistics**

  → 1σ excess in ROI, ongoing shape analysis

- **Planned CONUS upgrades: systematics, shape information, PSD, …**
- **Various possibilities for BSM investigations as well as practical application!**

Backup

Neutrino sources in comparison

parameter	π-DAR ν's (DAR=decay-at-rest)	reactor ν's	radioactive ν's	natural ν's (sol.,atm.,DSNB,SN)
ν flux, Φ_ν	1×10^{15}/s $\rightarrow$ $2\times10^{7}/(\text{s}\cdot\text{cm}^2)$ in 20 m dist.	$2\times10^{20}/(\text{s}\cdot\text{GW})$ $\rightarrow$ **$1\times10^{13}/(\text{s}\cdot\text{cm}^2)$** in 15 m dist.	^{144}Ce:4×10^{15}/s	^{8}B:$5\times10^{6}/(\text{s}\cdot\text{cm}^2)$ DSNB:ν_e $<1.2/(\text{s}\cdot\text{cm}^2)$ DSNB:$\bar{\nu}_e$ $<70/(\text{s}\cdot\text{cm}^2)$ SN(10kpc): 10^{12} cm^{-2}
ν variability	high, **pulsed-beam**	mediocre	steady-state	s.-s./1 pulse (SN)
ν extension	small 1/R dep; ster. ν	small 1/R dep; ster. ν	pointlike 1/R dep; ster. ν	diffuse no 1/R dep
ν flavor	ν_μ,ν_e,$\bar{\nu}_\mu$	$\bar{\nu}_e$	ν_e or $\bar{\nu}_e$	$\bar{\nu}_e$,ν_α,$\bar{\nu}_\mu$
ν ener., E_ν	$<$50 MeV coh.-decoh. reg.	$<$8 MeV coh. reg.	1-10 MeV ^{144}Ce:$<$3.0 MeV ^{8}Li:$<$12.9 MeV coh. reg.	^{8}B: $<$16 MeV DSNB: $<$100 MeV atm: $<$1 GeV SN:$\langle E\rangle$ $\leq$25 MeV coh.-decoh. reg.
location	access restr.	high access restr.	access restr.	no restriction
background	shallow depth neutrons, NIN	shallow depth neutrons	deep undergr. gamma's	deep undergr. few high-energy n

[W.Manscheg, 2017]

$\rightarrow$ **most promising:** π-DAR vs. reactor

- background discrimination (pulsed beam)
- high recoil energies
- high $\bar{\nu}$-flux
- full coherency regime

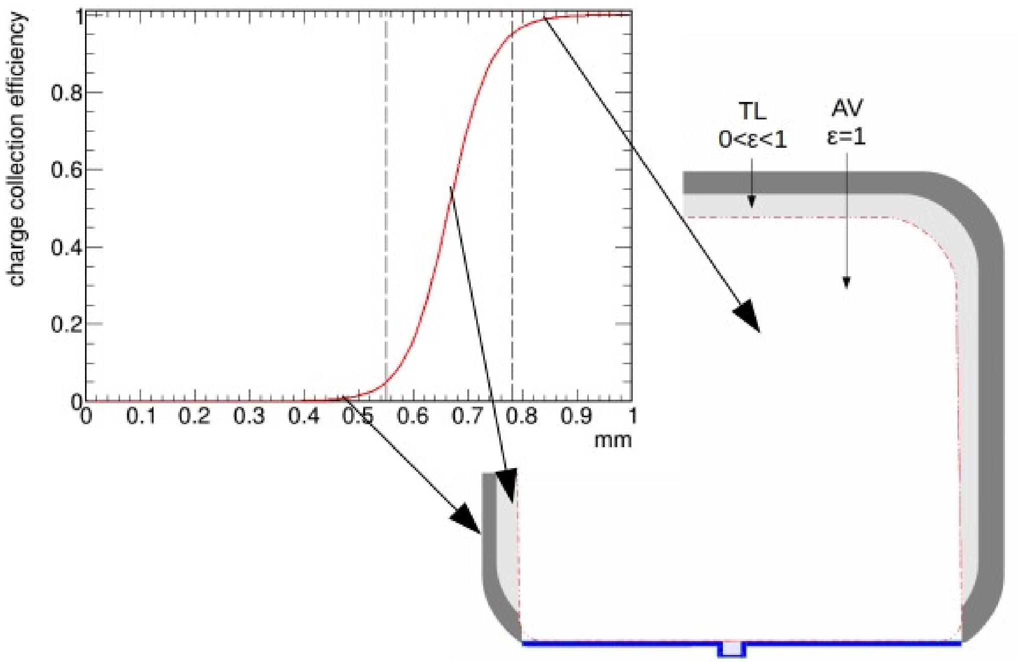
Boon and bane of cosmogenic activated lines

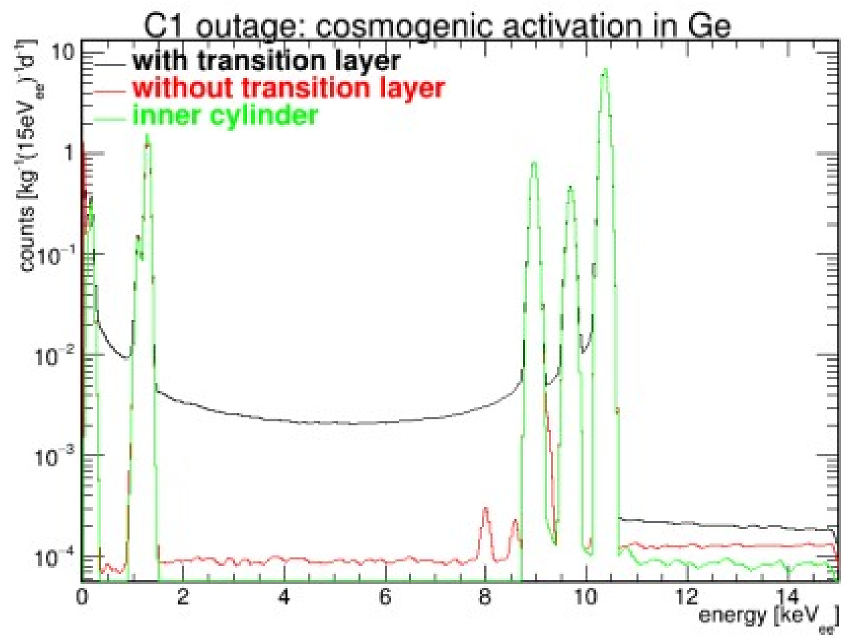
Cosmogenic activated lines used for energy calibration!

- Originating from above-ground storage during manufacturing
- Well known literature for K-/L-shell peaks as well as their ratio
- Pulse generator scans guarantee linearity of energy calibration

Main isotope	$T_{1/2}$ [d]	E_n [MeV]
Ge-71	11.4	10^{-6}-1
Ge-68	271.0	>20
Ga-68	0.046	$\leftarrow$Ge-68
Zn-65	244.0	>60

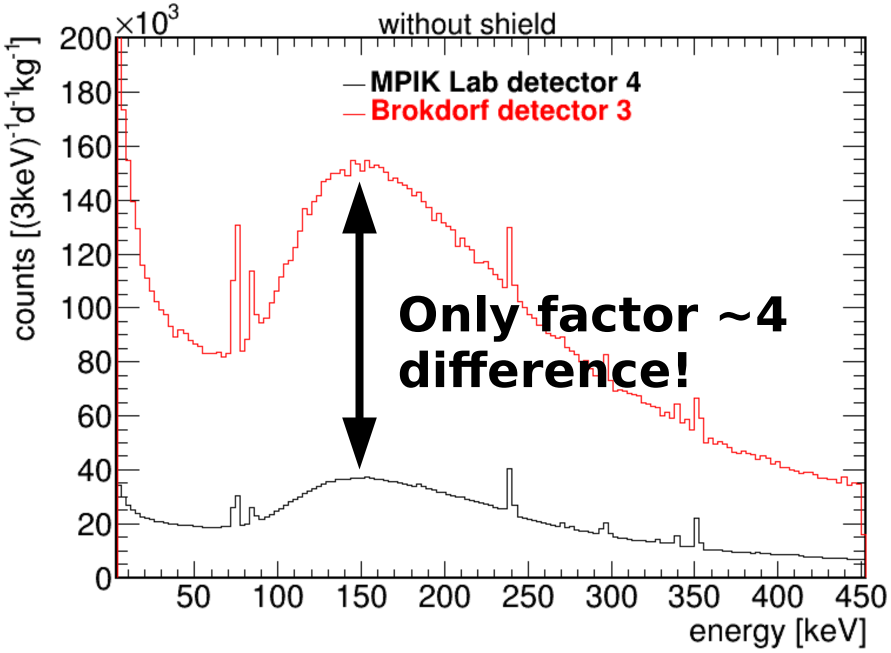
BUT: decaying background contribution!

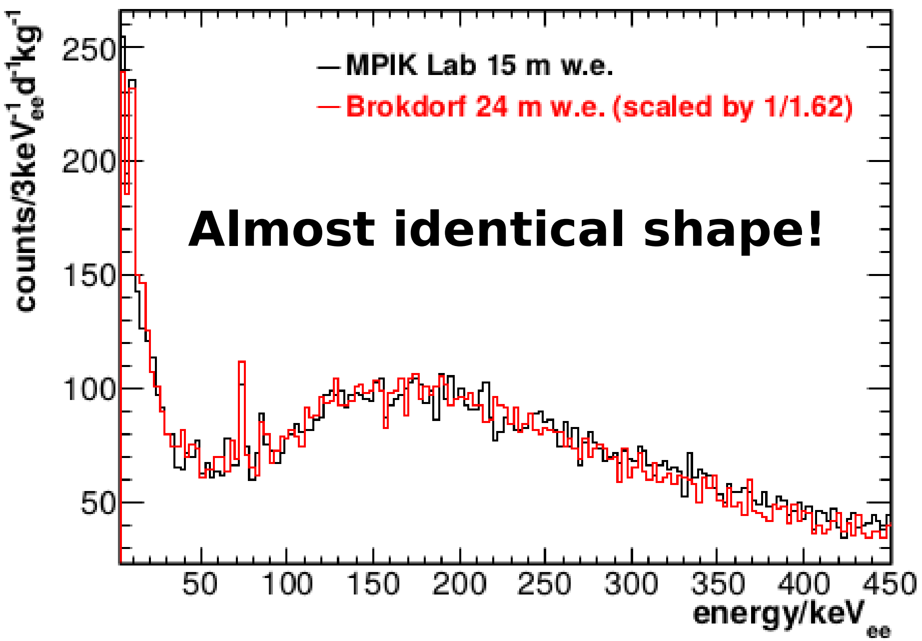




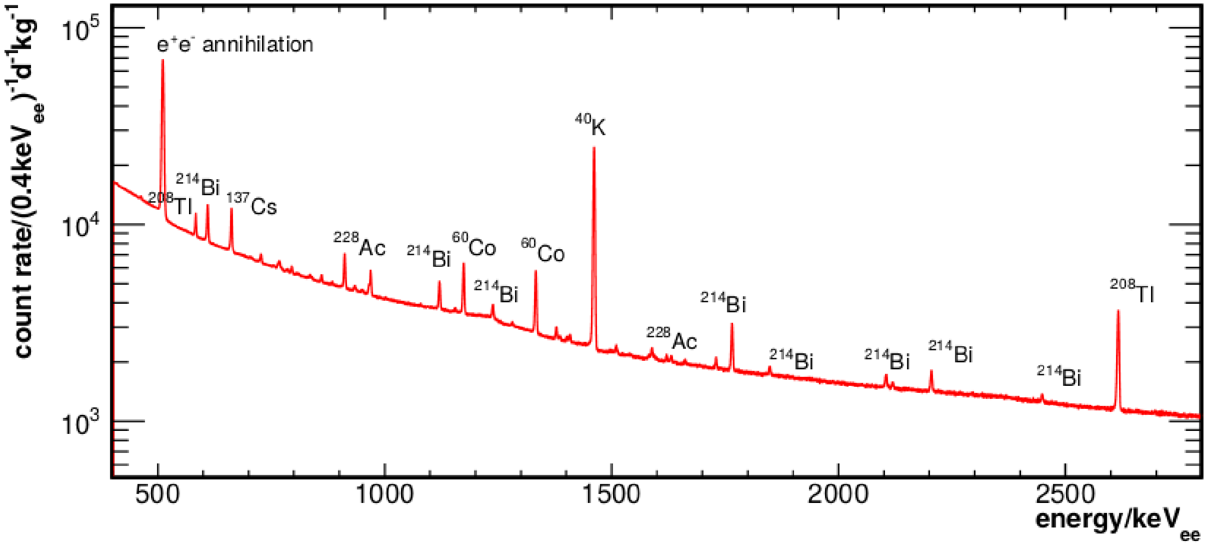
Background comparison

Spectrum of CONUS detector at site



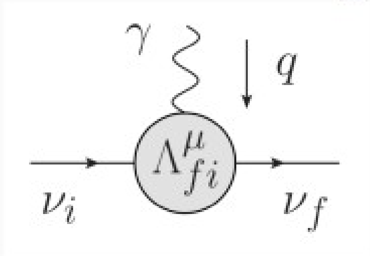


Spectrum of unshielded CONRAD detector at site → dominated by natural radioactivity



Neutrino magnetic moment & millicharge

Loop-induced electromagnetic quantities:



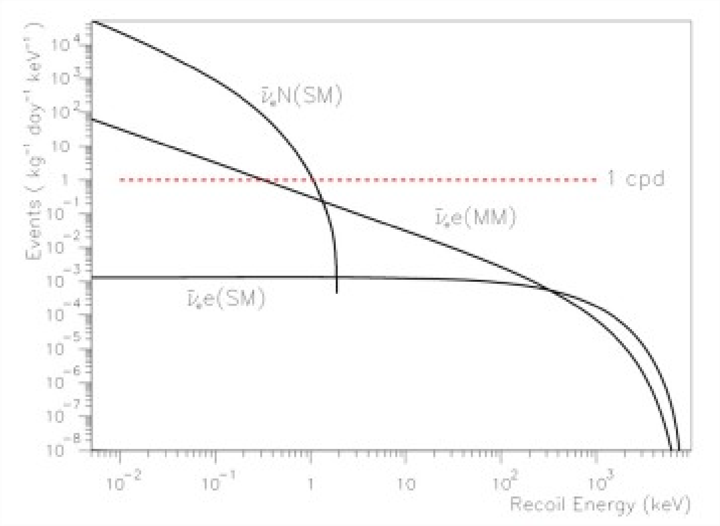
$$\longrightarrow \left(\frac{d\sigma}{dT}\right) = \ldots + \left[\left(\frac{d\sigma}{dT}\right)_{\mu_\nu} + \left(\frac{d\sigma}{dT}\right)_{q_\nu}\right]_{EM}$$

- Neutrino magnetic moment:

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

- Neutrino millicharge:

$$\left(\frac{d\sigma}{dT}\right)_{q_\nu} = \frac{2\pi\alpha^2}{m_e^2}\frac{q_\nu}{m_e T^2} \propto \frac{1}{T^2}$$



[Wong et al., 2006]

T: nuclear recoil energy

- model-dependent expectation, difference between Dirac and Majorana neutrinos

$\mu^D_{kk} \simeq 3.2 \cdot 10^{-19} \left(\frac{m_k}{\mathrm{eV}}\right) \mu_B$ vs. $\mu^M_{kk'} \lesssim 4 \cdot 10^{-19} \left(\frac{m^M_{kk'}}{\mathrm{eV}}\right)\left(\frac{\mathrm{TeV}}{\Lambda}\right)^2 \mu_B$

$\rightarrow$ enhancement through heavy particles or breaking of $\mu_\nu - m_\nu$-relation

- light scalar coupling to neutrinos

$$\mathcal{L}_{\mathrm{LNC}} = y_\nu \phi \bar{\nu}_R \nu_L + \mathrm{h.c.} \qquad \text{or} \qquad \mathcal{L}_{\mathrm{LNV}} = \frac{y_\nu}{2} \phi \bar{\nu}_L^c \nu_L + \mathrm{h.c.}, \qquad y_\nu = C_\nu - i D_\nu$$

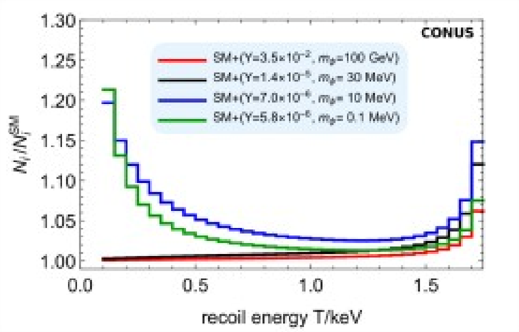
- scalar-nucleus interaction:

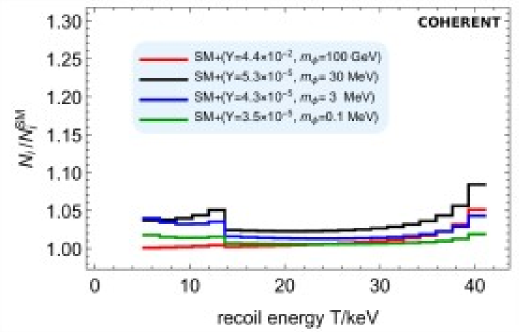
$$\mathcal{L}_{q\phi} \to \mathcal{L}_{N\phi} = \overline{\psi}_N \Gamma_{N\phi} \psi_N \phi, \qquad \Gamma_{N\phi} = C_N + i\gamma^5 D_N$$

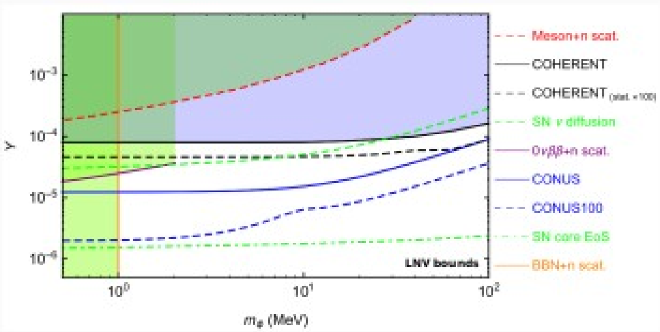
- new chirality-flipping channel:

$$\frac{d\sigma}{dT} = \frac{d\sigma_{\mathrm{SM}}}{dT} + \frac{d\sigma_\phi}{dT} = \ldots + \frac{M Y^4 A^2}{4\pi(2MT + m_\phi^2)^2}\left[\frac{MT}{E_\nu^2} + \mathcal{O}\left(\frac{T^2}{E_\nu^2}\right)\right], \; Y^4 \equiv \frac{C_N^2}{A^2}|y_\nu|^2$$

$\to$ spectral distortion for small recoil energies!







[Farzan et al., 2018]