Neutrino nucleus coherent scattering - Prospects of future reactor experiments with germanium detectors

Marco Salathe[1], Thomas Rink[2]

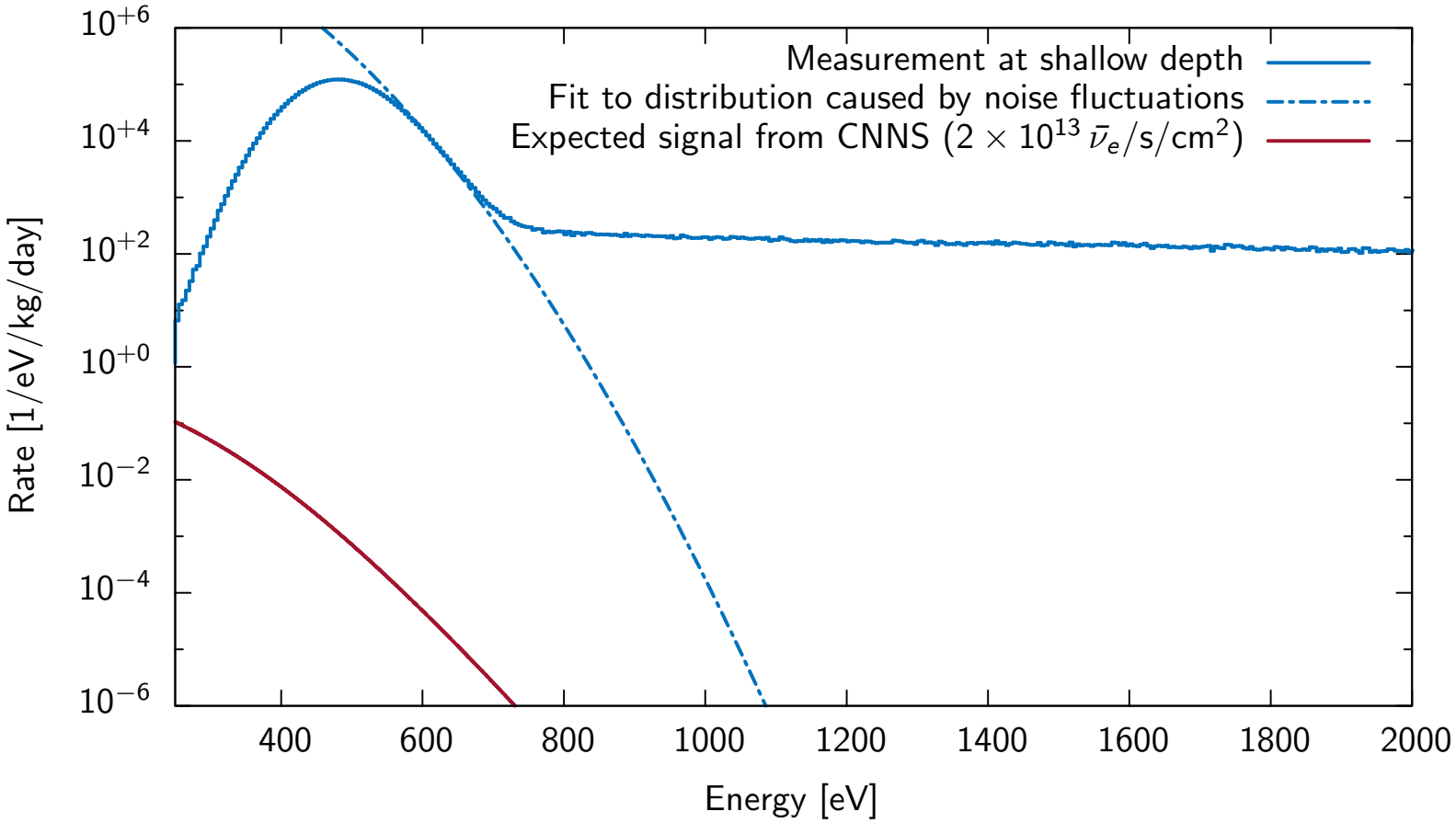
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

8 December 2015
Applied Antineutrino Physics - Virginia Tech

[1]marco.salathe@mpi-hd.mpg.de, [2]thomas.rink@mpi-hd.mpg.de

Coherent neutrino-nucleus scattering at a nuclear reactor with germanium detectors

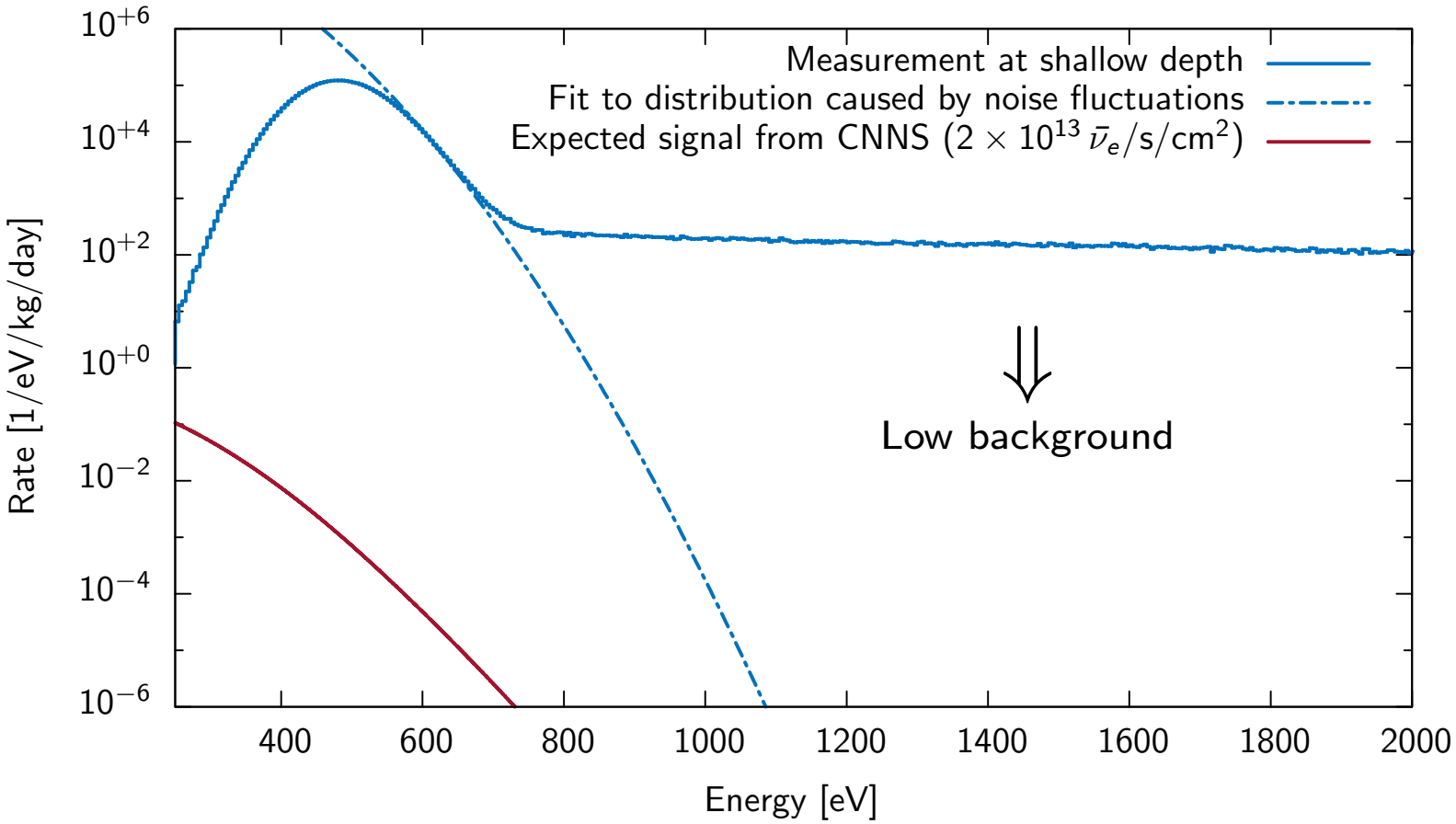
What does it require?



- Measurement with point contact germanium detector (noise resolution of 300 eV, measured with a pulser measurement) at shallow depth with little shielding
- Earlier efforts: CoGeNT, TEXONO, GEMMA

Coherent neutrino-nucleus scattering at a nuclear reactor with germanium detectors

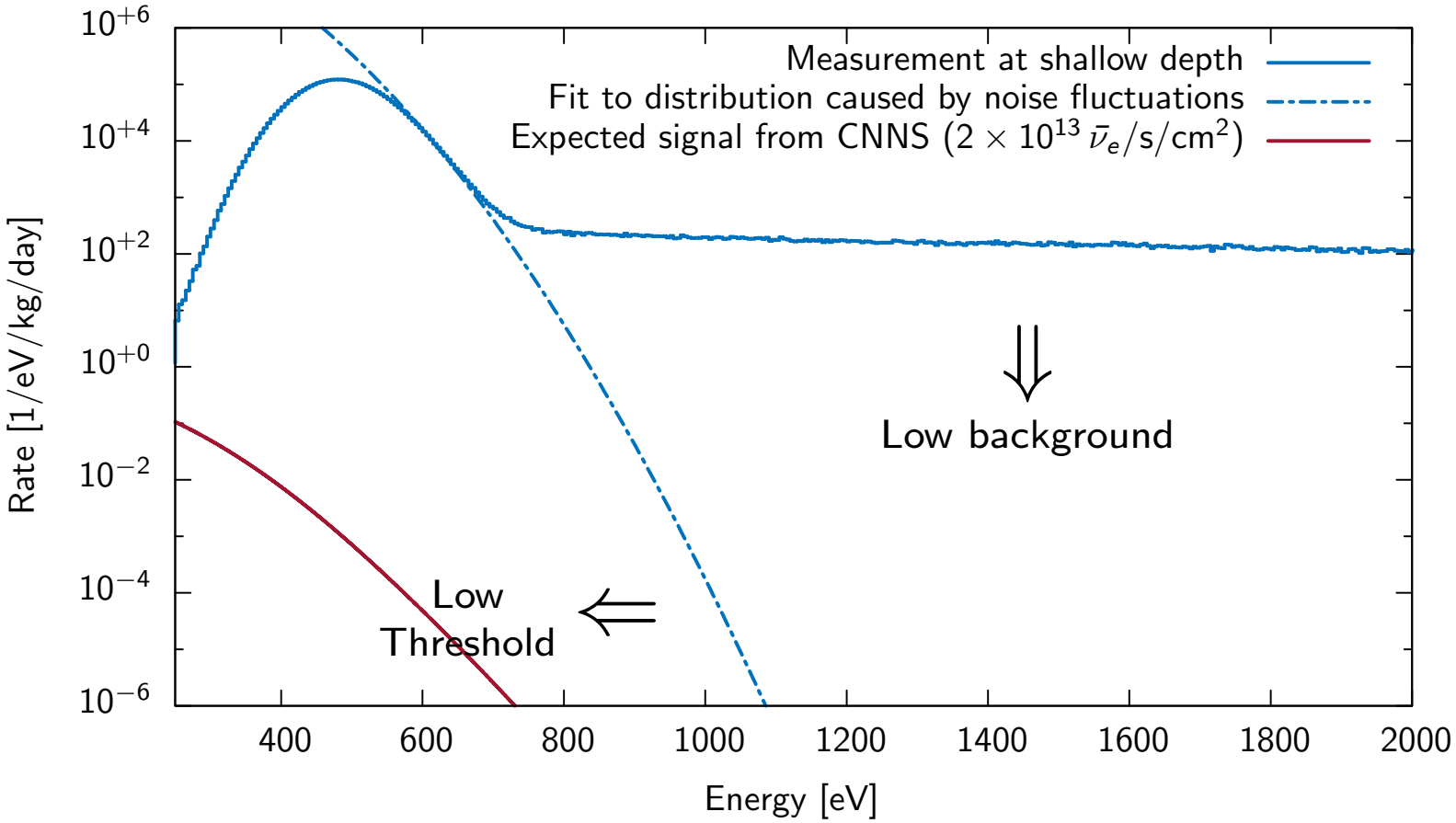
What does it require?



- Measurement with point contact germanium detector (noise resolution of 300 eV, measured with a pulser measurement) at shallow depth with little shielding
- Earlier efforts: CoGeNT, TEXONO, GEMMA

Coherent neutrino-nucleus scattering at a nuclear reactor with germanium detectors

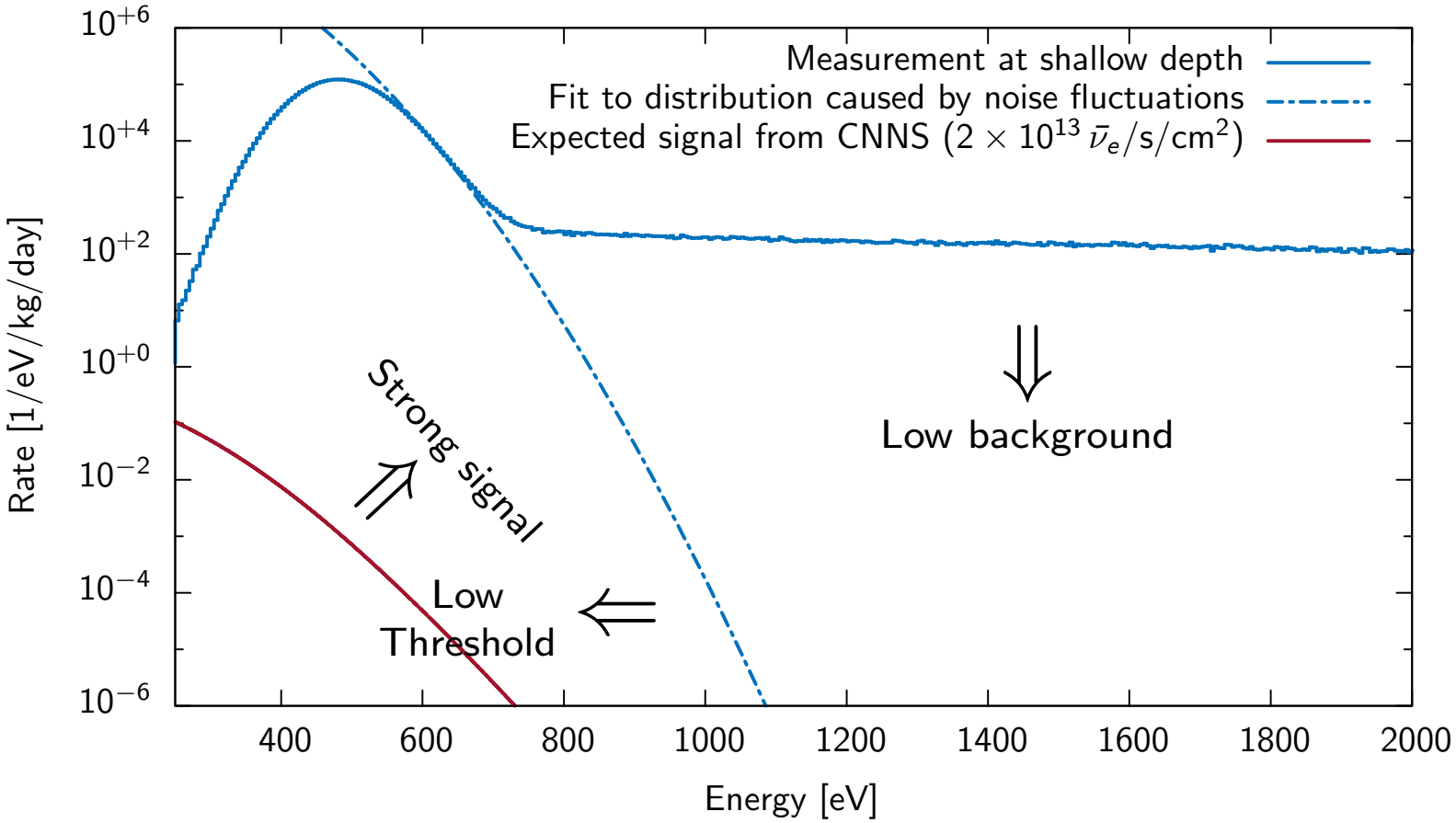
What does it require?



- Measurement with point contact germanium detector (noise resolution of 300 eV, measured with a pulser measurement) at shallow depth with little shielding
- Earlier efforts: CoGeNT, TEXONO, GEMMA

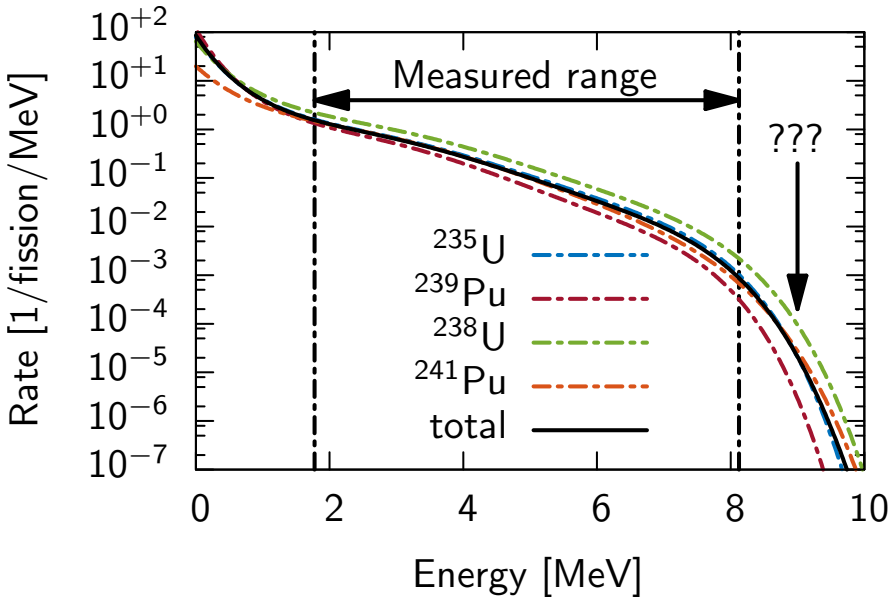
Coherent neutrino-nucleus scattering at a nuclear reactor with germanium detectors

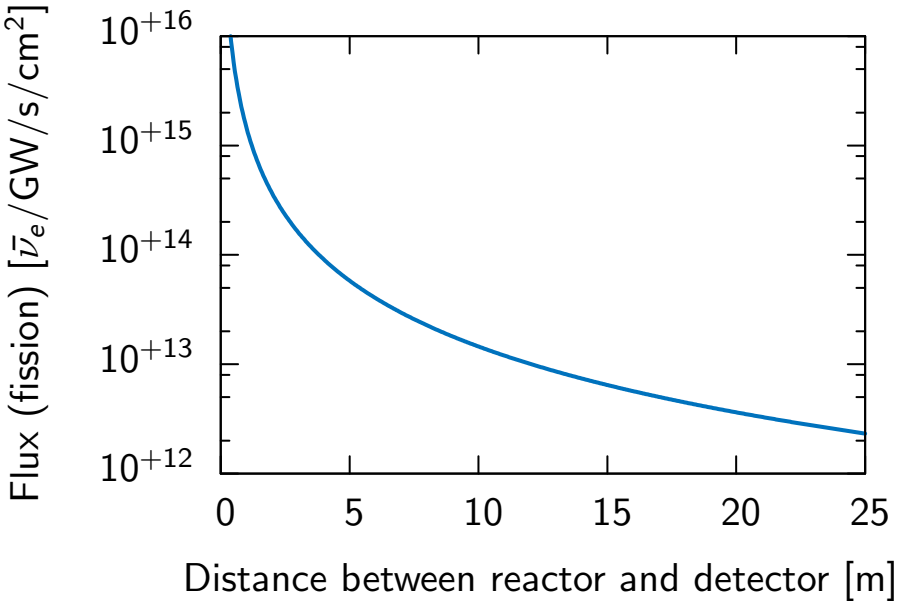
What does it require?



- Measurement with point contact germanium detector (noise resolution of 300 eV, measured with a pulser measurement) at shallow depth with little shielding
- Earlier efforts: CoGeNT, TEXONO, GEMMA

Reactor anti-neutrino spectrum





- Typical reactor composition[1]: 50% ^{235}U, 30% ^{239}Pu, 7% ^{238}U, 5% ^{241}Pu
- Average energy release: 205.2 MeV/fission
- Approximately 6 $\bar{\nu}_e$/fission are released
- Spectral distribution has been extracted from measured β-spectra (2-8 MeV)[2,3]

- Parametrization available for this range[2,3]
- Neutrinos beyond this range are below the typical threshold or below the typical background

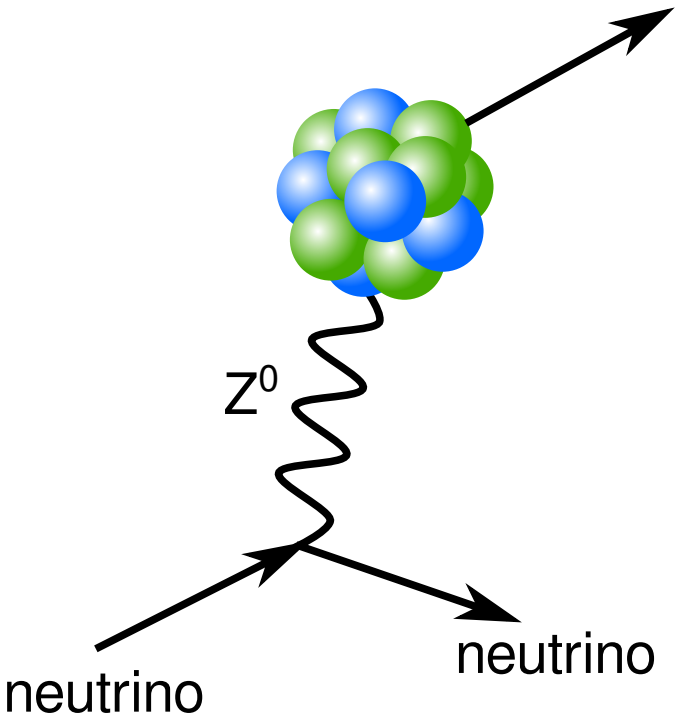
Assumption: 3 GW reactor, 15 m distance
$\Rightarrow$ flux: $\sim 2 \times 10^{13}\,\bar{\nu}_e$/s/cm^2

[1] Beda, A. G. et al. First result for the neutrino magnetic moment from measurements with the GEMMA spectrometer. English. Phys. At. Nucl. 70, 1873–1884 (2007).

[2] Huber, P. Determination of antineutrino spectra from nuclear reactors. Phys. Rev. C 84, 24617 (Aug. 2011).

[3] Haag, N. et al. Experimental Determination of the Antineutrino Spectrum of the Fission Products of 238 U. Phys. Rev. Lett. 112, 122501 (2014).

Coherent neutrino-nucleus scattering (CNNS)



- Neutrinos (of all flavor) interact simultaneously with all nuclei in the atom:

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{16\pi^2} Q_W^2 E_\nu^2 (1+\cos\theta) F^2(Q^2)$$
$$Q_W = \left[N - (1 - 4\sin^2\theta_W) Z\right]$$

- The coherence condition (the de Broglie wavelength of the momentum transfer is large compared to the size of the atom) is satisfied for neutrinos of $E_\nu < 50\,\mathrm{MeV}$
- $4\sin^2\theta_W \approx 0.944 \Rightarrow$ number of neutrons in atom is important (N=40.6 for germanium)
- Semi-classical treatment (Recoil energy $T \ll$ mass of nucleus m_N):

$$T = Q^2/2m_N = E_\nu^2(1-\cos\theta)/m_N$$

$\Rightarrow$ Maximal recoil energy $T_{\max} = 2E_\nu^2/m_N$
$\Rightarrow$ Differential cross section:

$$\frac{d\sigma}{dT} = \frac{G_f^2}{4\pi} Q_W^2 m_N \left(1 - \frac{m_N T}{2E_\nu^2}\right)$$

Drukier, A. & Stodolsky, L. Principles and applications of a neutral-current detector for neutrino physics and astronomy. Phys. Rev. D 30, 2295–2309 (1984).

Recoil spectrum of reactor-antineutrino in germanium and quenching

- Flux of $\Rightarrow 2 \times 10^{13}\,\bar{\nu}_e/\mathrm{s/cm^2}$ at 15 m distance
- Germanium atom has large mass ($m_N = 68.2\,\mathrm{GeV/c^2}$), thus the recoil energy T will be low ($T_{\max} = 2E_\nu^2/m_N$)
- Only fraction of energy is converted into ionization signal (Quenching factor $\varepsilon = E_{ion}/T$)
- Lindhard model:

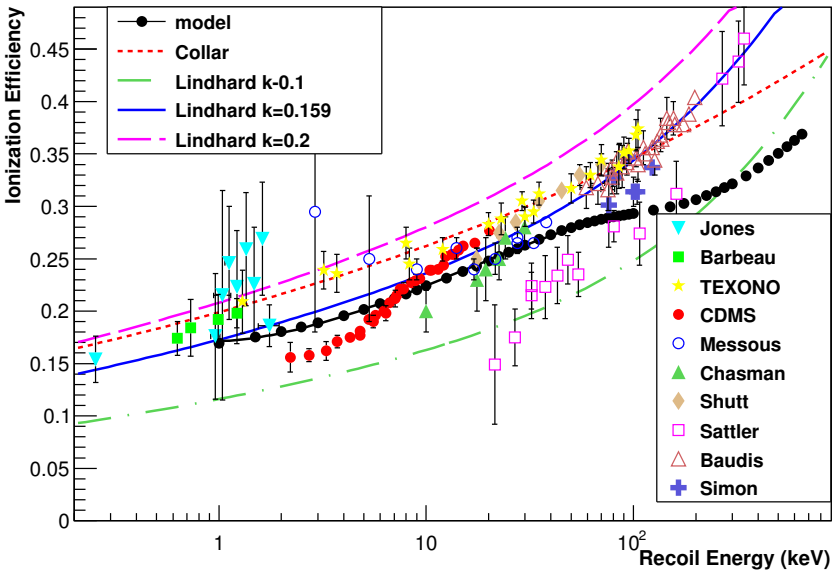
$$\varepsilon = \frac{k \cdot g(\epsilon)}{1 + k \cdot g(\epsilon)}$$

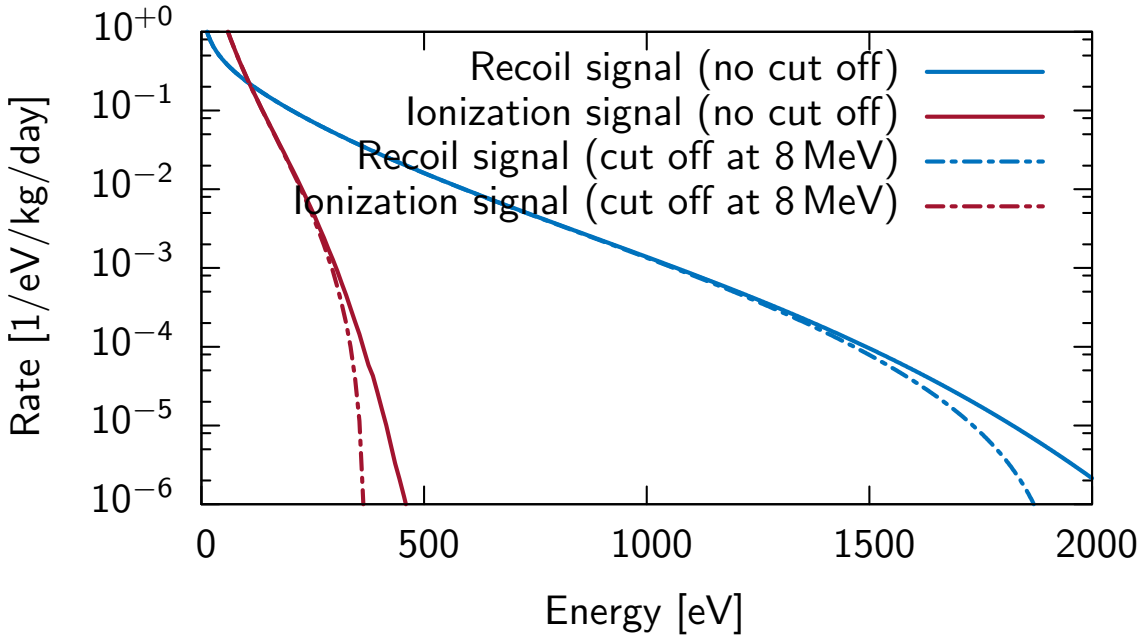
$$k = 0.133 Z^{2/3} A^{-1/2}$$

$$g(\epsilon) = 3\epsilon^{0.15} + 0.7\epsilon^{0.6} + \epsilon$$

$$\epsilon = 11.5\,T Z^{-7/3}$$

- Germanium: Z=32, A=72.6 $\Rightarrow$ k=0.157 $\Rightarrow \varepsilon \sim 15 - 20\%$
- At ~ 0.1 cts/kg/keV/day level endpoint of neutrino spectrum only marginally of importance



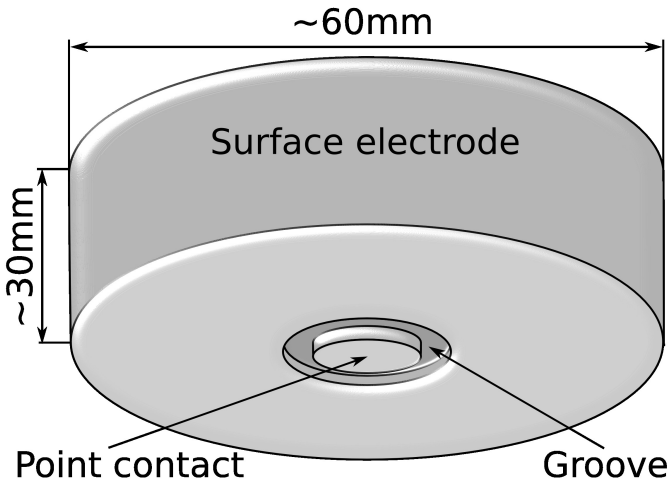


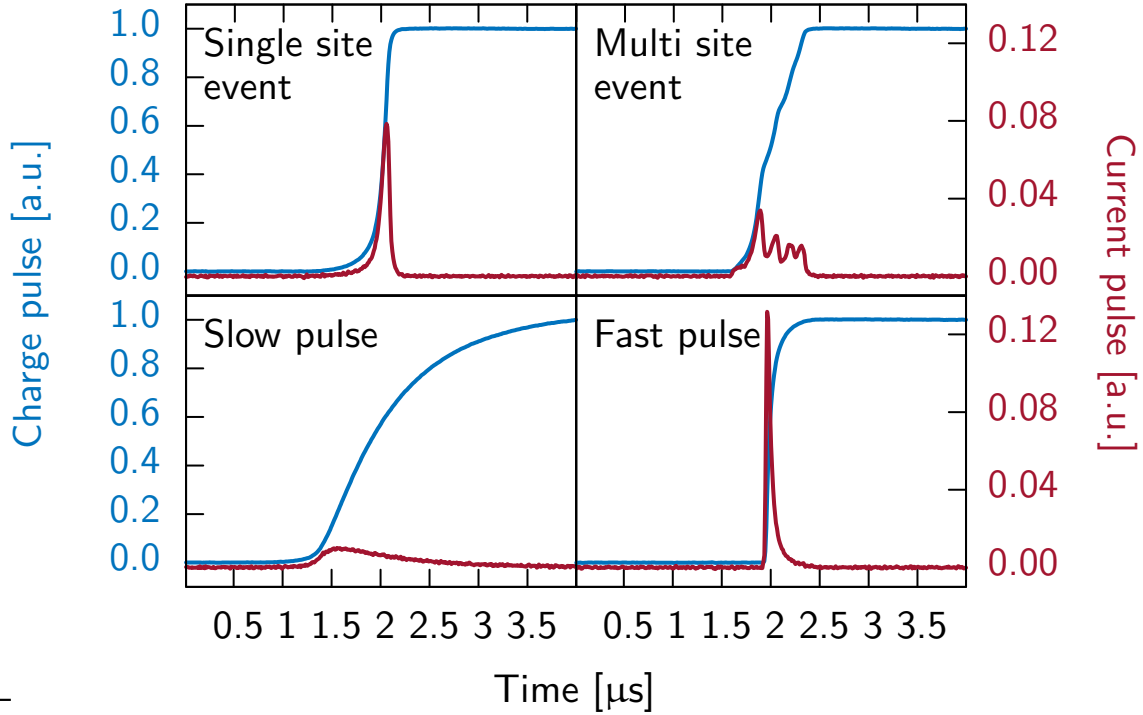
Top figure and model description from: Barker, D. & Mei, D.-M. Germanium detector response to nuclear recoils in searching for dark matter. Astropart. Phys. 38, 1–6 (Oct. 2012).

Point contact germanium detectors

- First proposed by Luke et al.[1] from Lawrence Berkeley National Laboratory in 1989 as a 'low capacitance large volume shaped-field germanium detector'
- Geometry:
  - A cylindrical shape
  - A small read out electrode embedded in a base of the cylinder (point contact)
  - A large high voltage electrode covering most of the remaining surface
- Features:
  - Small capacitance (a few pF) $\Rightarrow$ Low noise properties
  - Unique time profile of signals that allows to distinguish certain types of events

- Example: Broad Energy Germanium (BEGe) detector, produced by Canberra





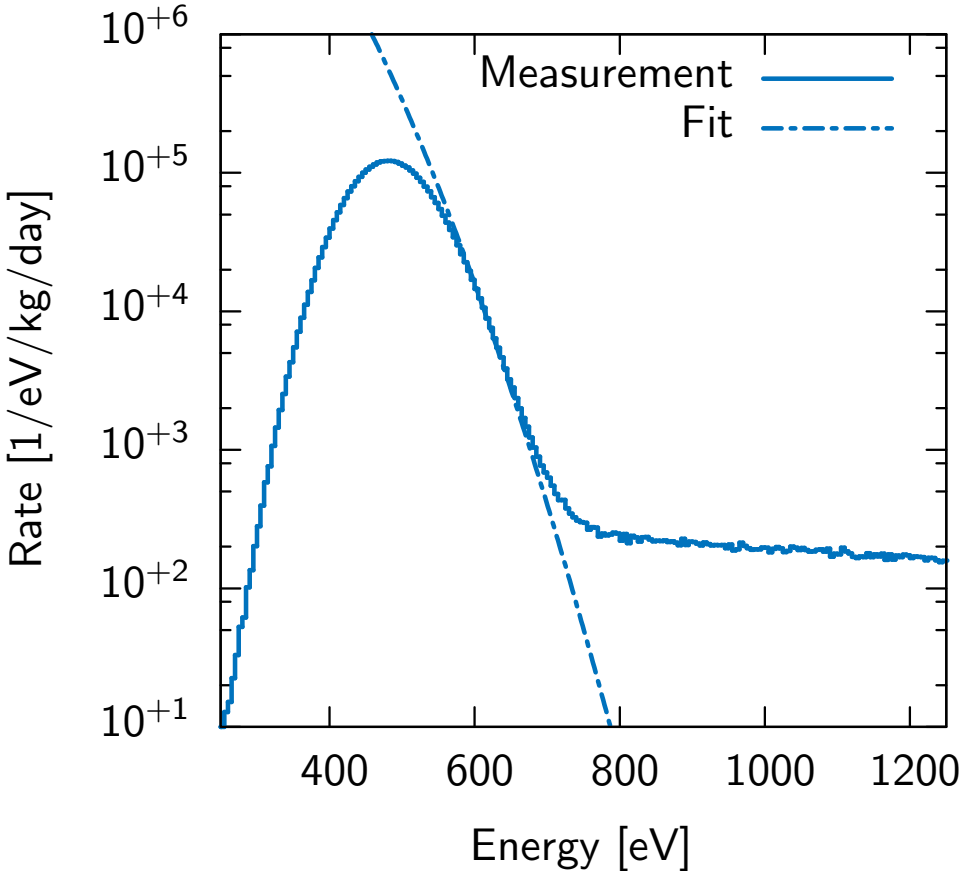
[1] Luke, P. N. et al. Low capacitance large volume shaped-field germanium detector. Nucl. Sci. IEEE Trans. 36, 926–930 (Feb. 1989).

Energy threshold - simple model

- The number of accidentally triggered events above a discrimination level d is described by [1,2]:

$$N(d) = N_0 \exp\left(\frac{-d^2}{2\sigma_N^2}\right), \qquad \frac{dn}{dE}(E) = \frac{N_0}{\sigma_N^2} E \exp\left(\frac{-E^2}{2\sigma_N^2}\right)$$

- σ_N is the electronics noise. N_0 is the trigger rate if the threshold level is set to zero. For a RC-CR shaper $N_0 = 1/(2\pi T_s)$, with T_s being the shaping time of the shaping filter[3]
- Assumption: Gaussian noise distribution + Gaussian temporal correlation
- Fit to data (cusp filter, with 2.4 µs shaping time): $N_0 \sim 1.3 \times 10^{10}$ cts/day
- Simple formula (RC-CR shaper): $N_0 \sim 0.6 \times 10^{10}$ cts/day

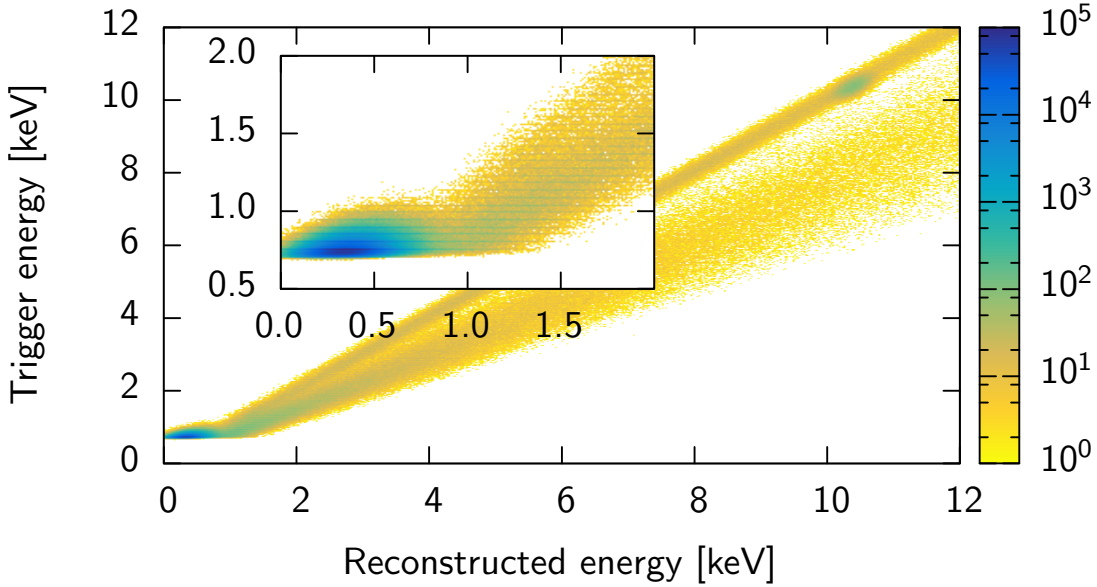


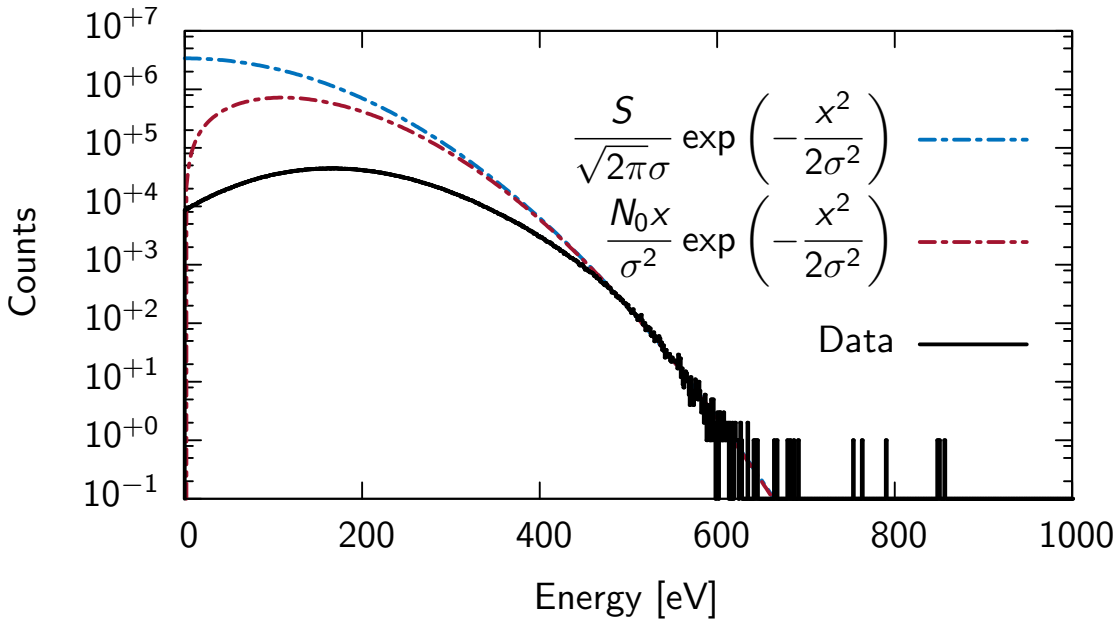
[1] Rice, S. O. Mathematical Analysis of Random Noise. Bell Syst. Tech. J. 23, 46–156 (1944).
[2] Rice, S. O. Mathematical Analysis of Random Noise. Bell Syst. Tech. J. 24, 46–156 (1945).
[3] Spieler, H. Semiconductor Detector Systems. Oxford University Press (2005).

Energy threshold - reality

- Different filter used for triggering data acquisition and final data analysis
  ⇒ Additional lower cut off
- Non-Gaussian noise distribution, non-Gaussian time correlation (shaping filter)
  ⇒ Real noise distribution needs to be evaluated for each situation individually
- The actual distribution can be easily extracted from signals only consisting of noise fluctuations

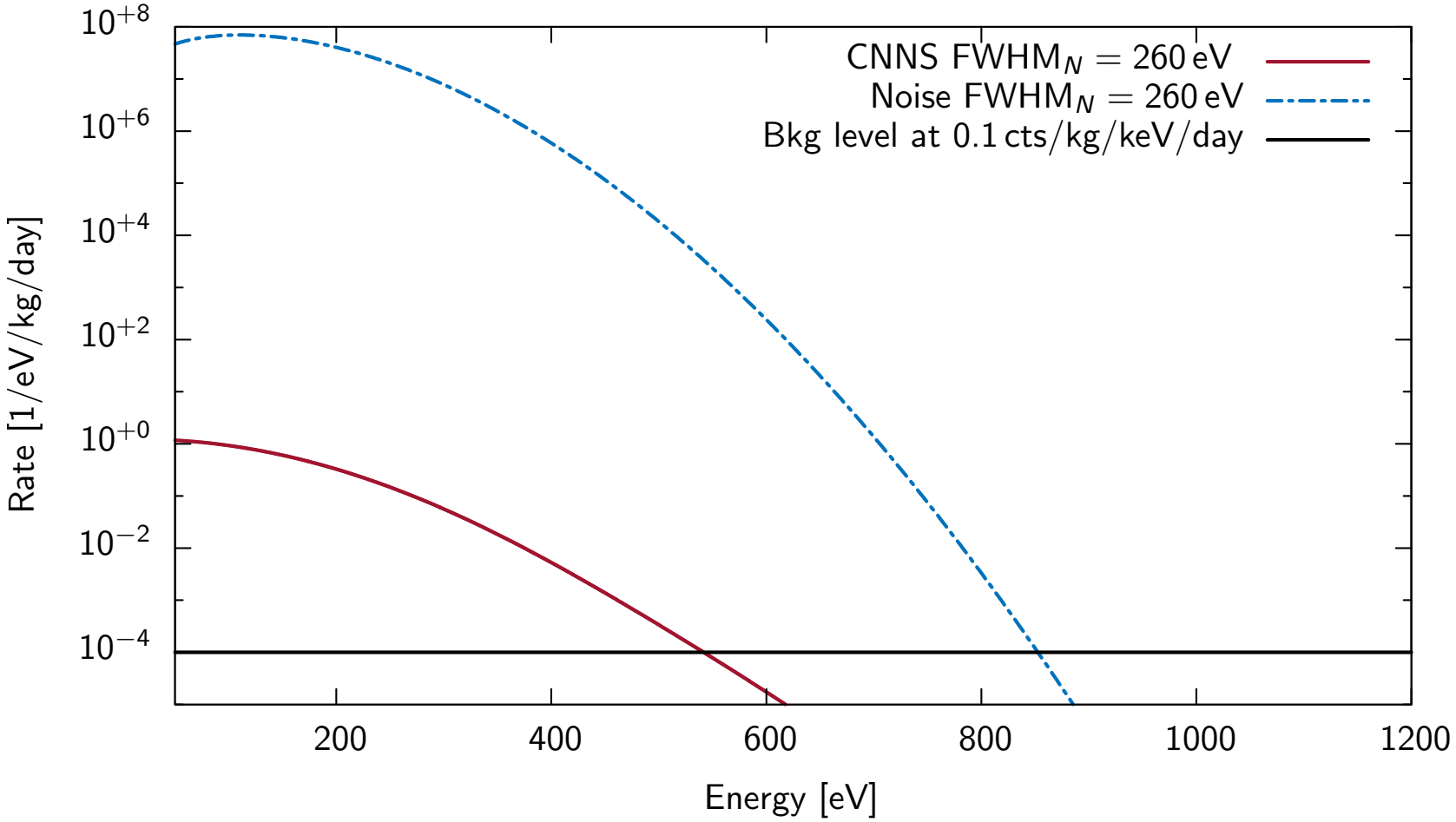
- The simple model works close to the onset of the peak created by accidentally triggered events
- The energy threshold is defined through the electronics noise contribution (pulser resolution).





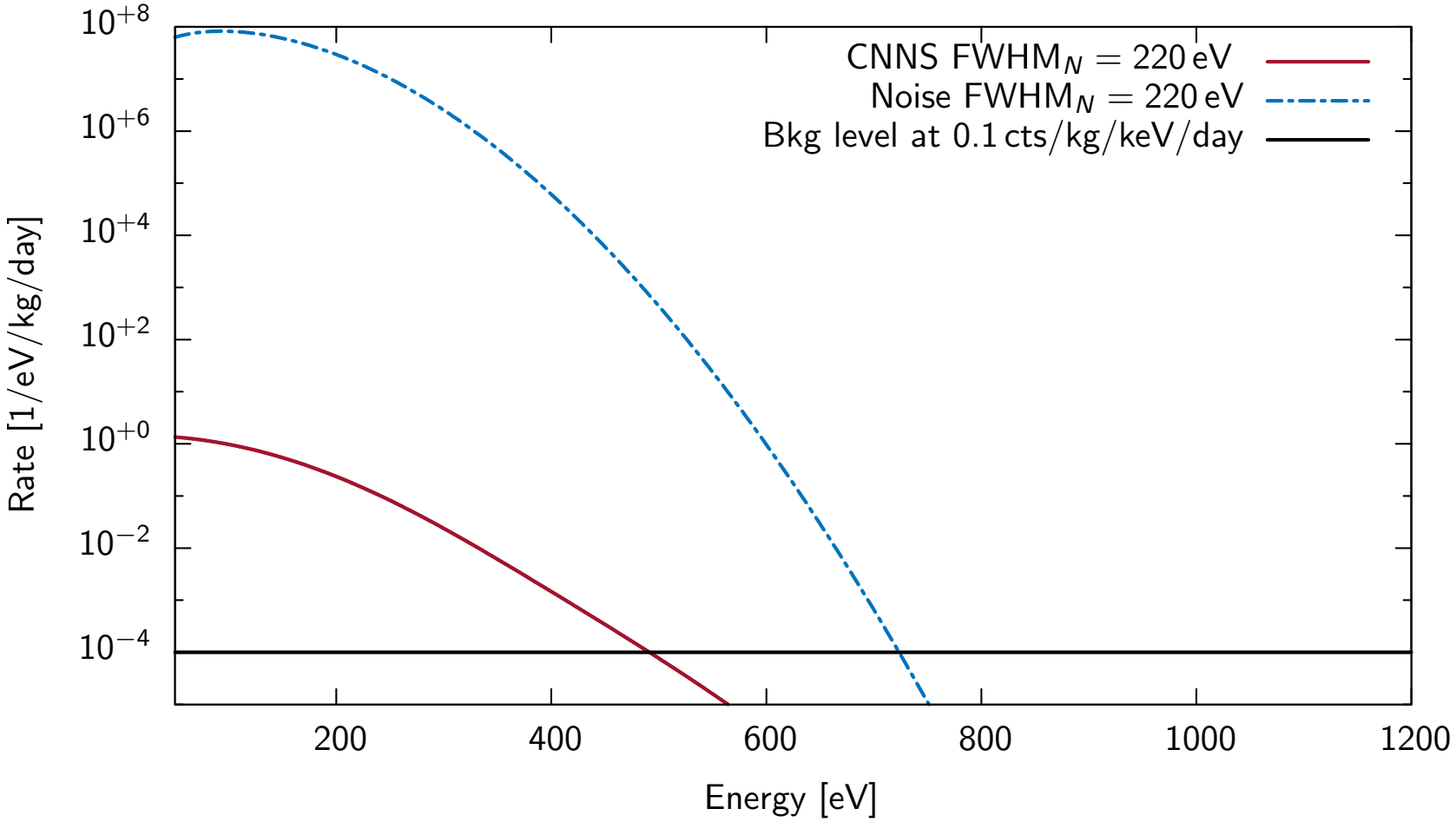
Sensitivity study

- Antineutrino flux: $2 \times 10^{13}\,\bar{\nu}_e/\mathrm{s/cm^2}$ (15 m distance from core)
- The ionization spectrum is smeared by the electronics noise
- At a fixed background level the electronic noise entirely defines the sensitivity
- The region of interest is limited by the distribution of accidentally triggered events and the background level



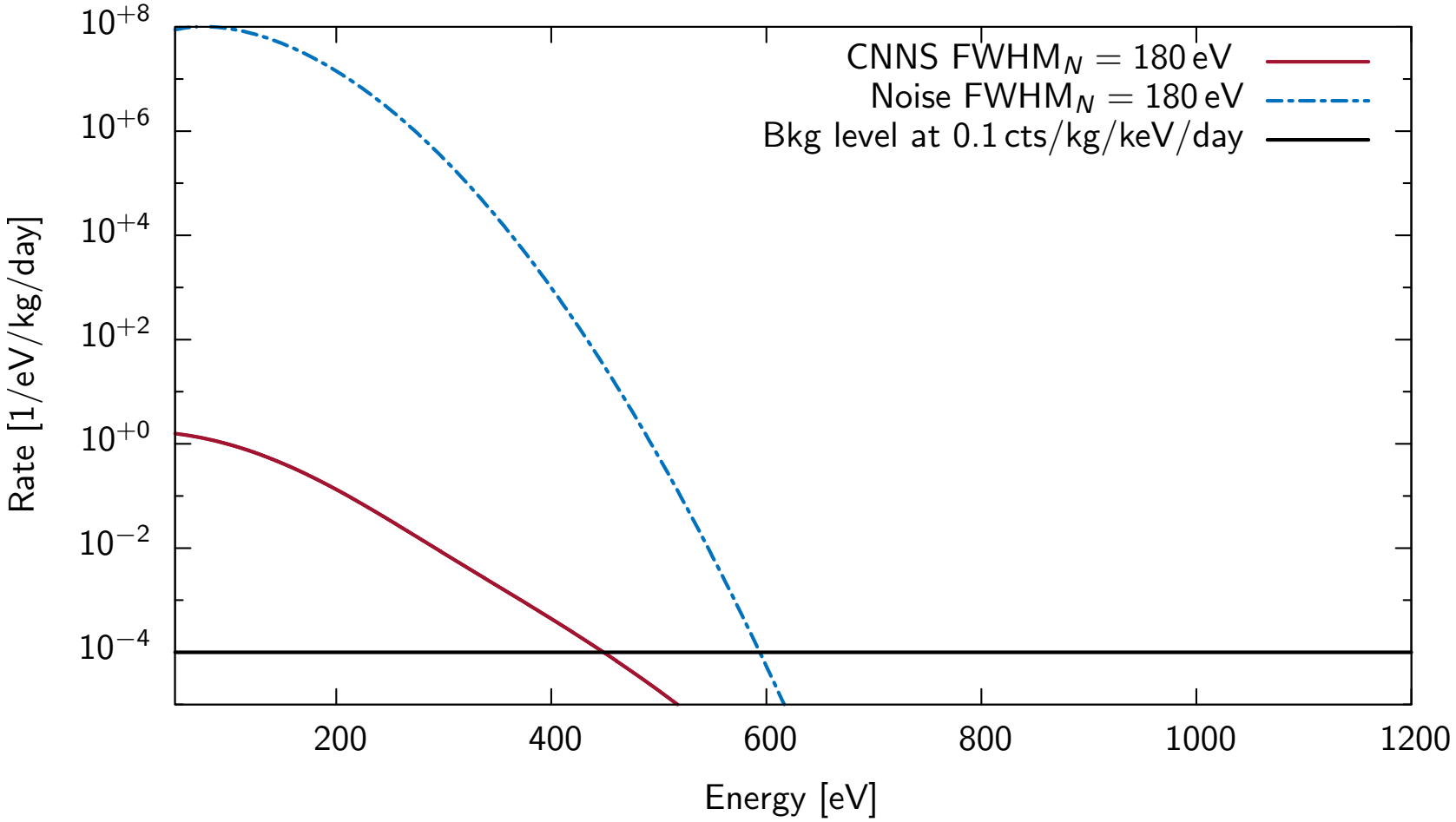
Sensitivity study

- Antineutrino flux: $2 \times 10^{13}\,\bar{\nu}_e/\mathrm{s}/\mathrm{cm}^2$ (15 m distance from core)
- The ionization spectrum is smeared by the electronics noise
- At a fixed background level the electronic noise entirely defines the sensitivity
- The region of interest is limited by the distribution of accidentally triggered events and the background level



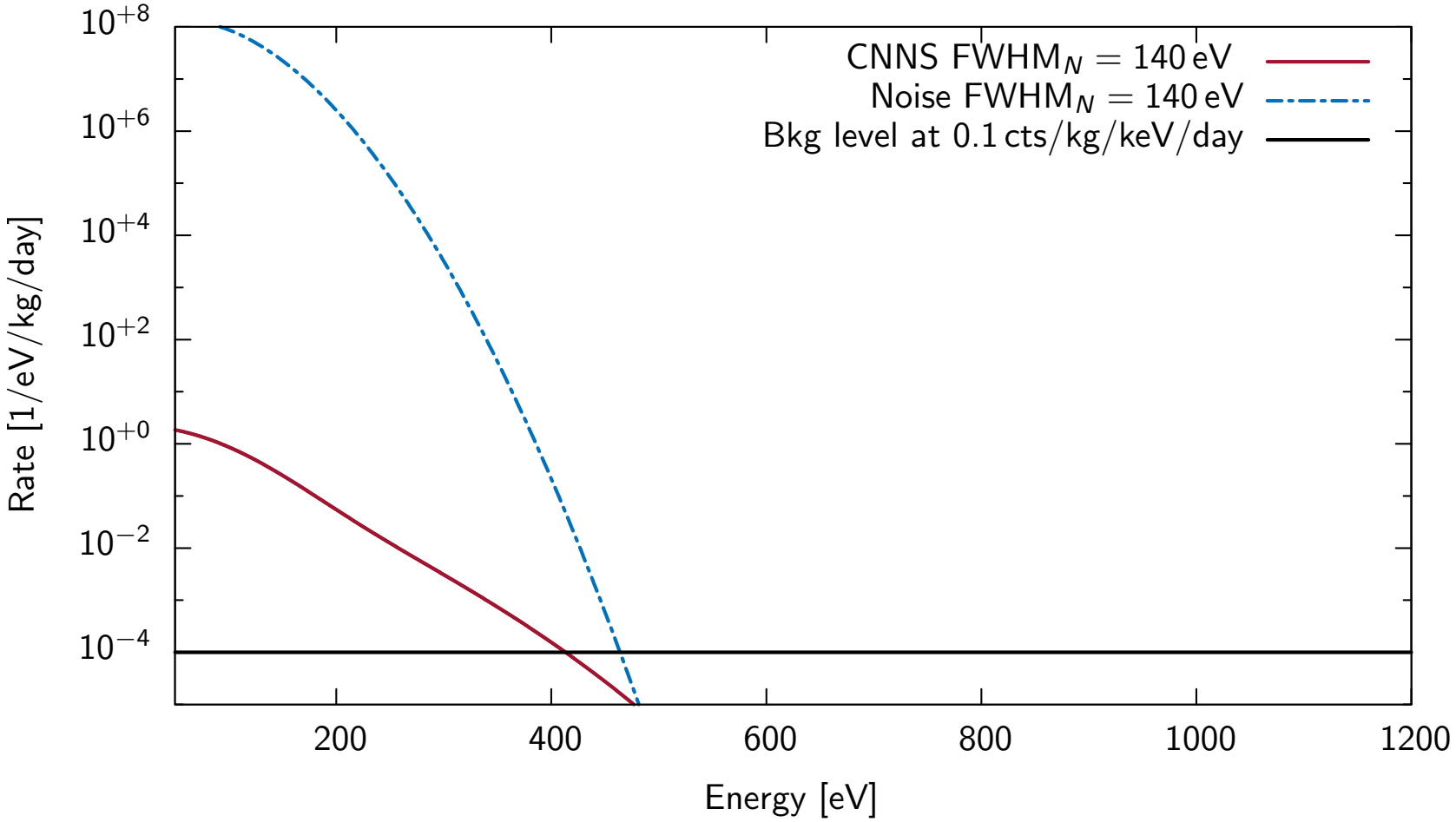
Sensitivity study

- Antineutrino flux: $2 \times 10^{13}\,\bar{\nu}_e/\mathrm{s}/\mathrm{cm}^2$ (15 m distance from core)
- The ionization spectrum is smeared by the electronics noise
- At a fixed background level the electronic noise entirely defines the sensitivity
- The region of interest is limited by the distribution of accidentally triggered events and the background level



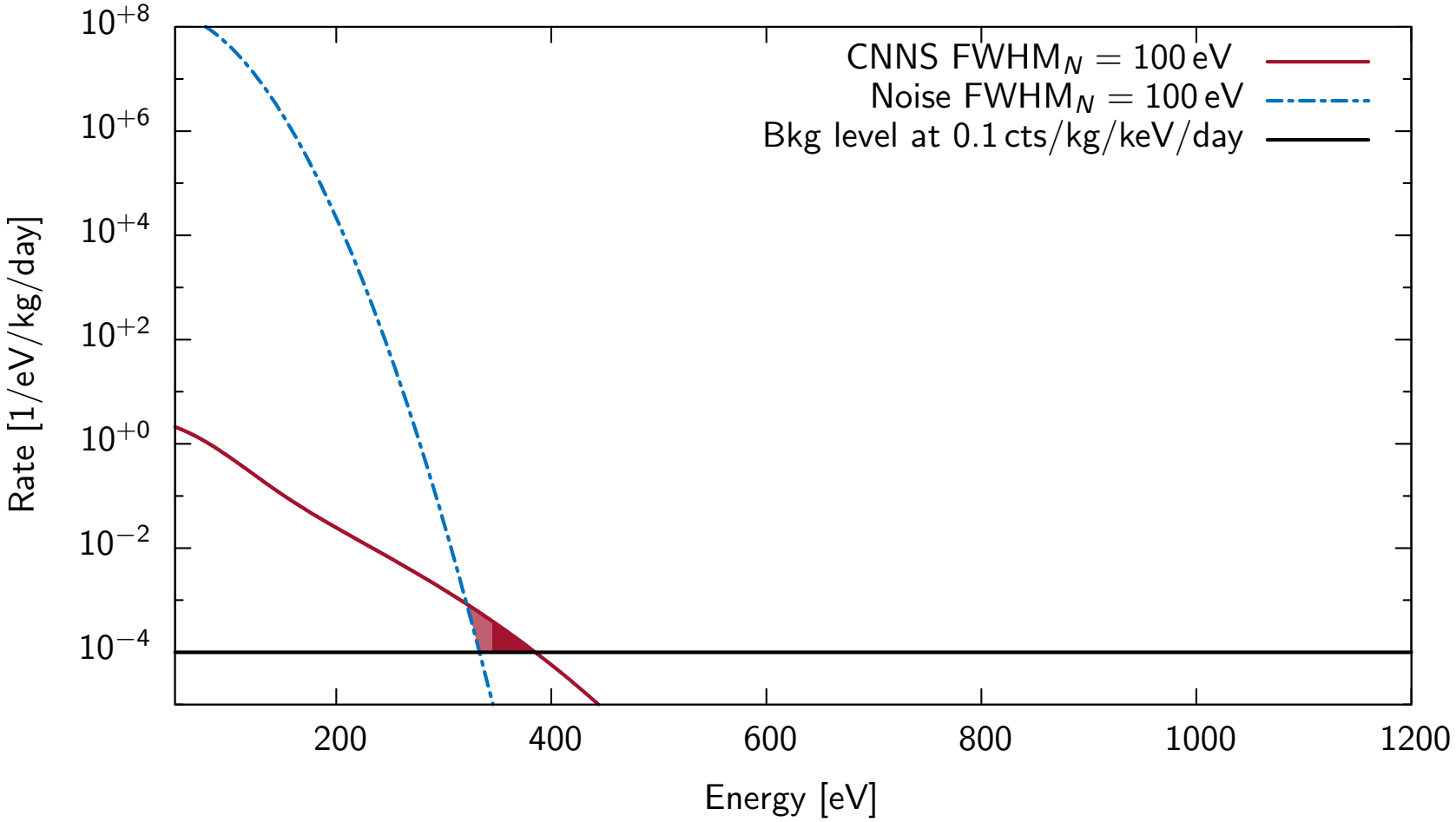
Sensitivity study

- Antineutrino flux: $2 \times 10^{13}\,\bar{\nu}_e/\mathrm{s}/\mathrm{cm}^2$ (15 m distance from core)
- The ionization spectrum is smeared by the electronics noise
- At a fixed background level the electronic noise entirely defines the sensitivity
- The region of interest is limited by the distribution of accidentally triggered events and the background level



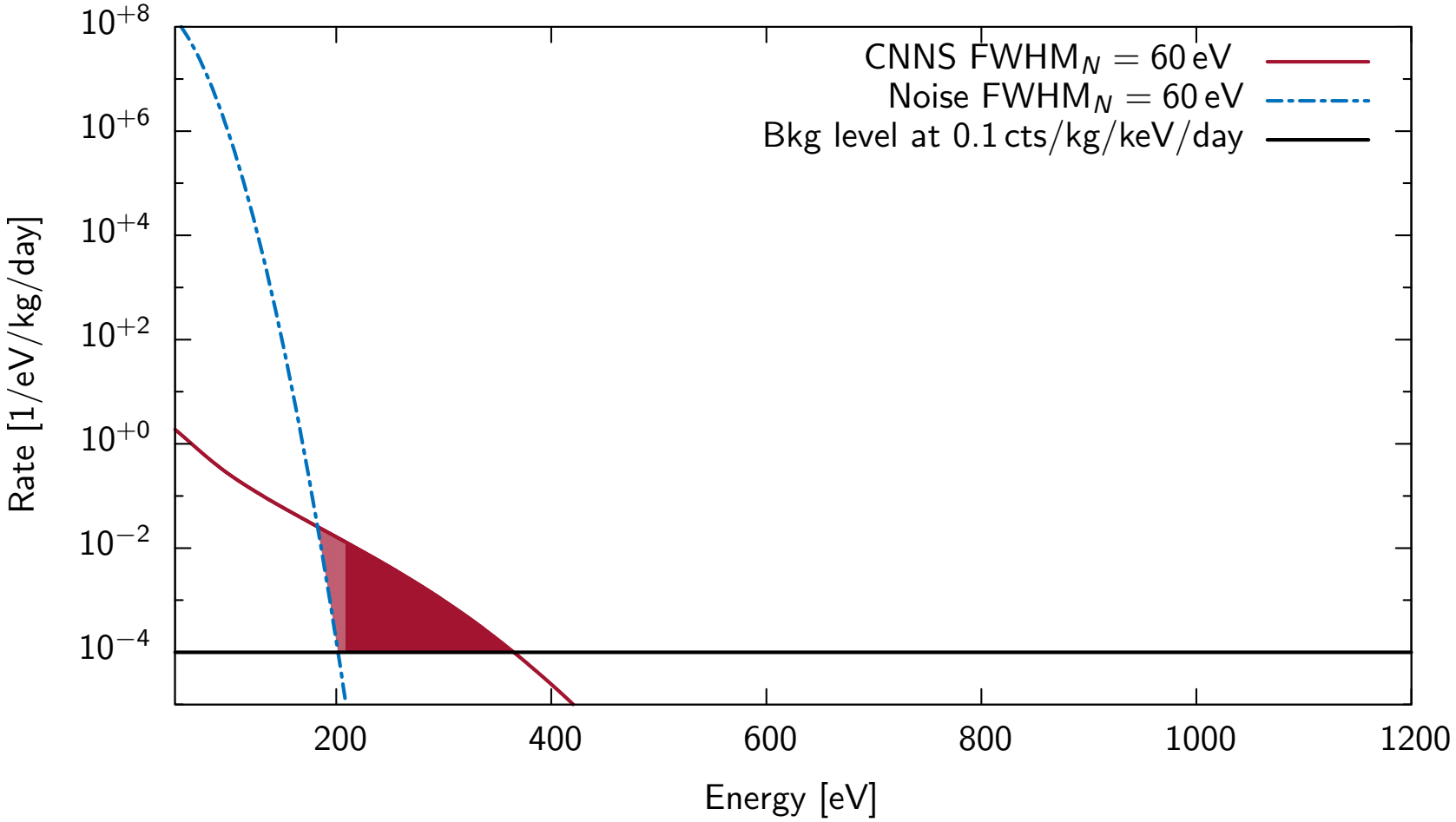
Sensitivity study

- Antineutrino flux: $2 \times 10^{13}\,\bar{\nu}_e/\mathrm{s}/\mathrm{cm}^2$ (15 m distance from core)
- The ionization spectrum is smeared by the electronics noise
- At a fixed background level the electronic noise entirely defines the sensitivity
- The region of interest is limited by the distribution of accidentally triggered events and the background level

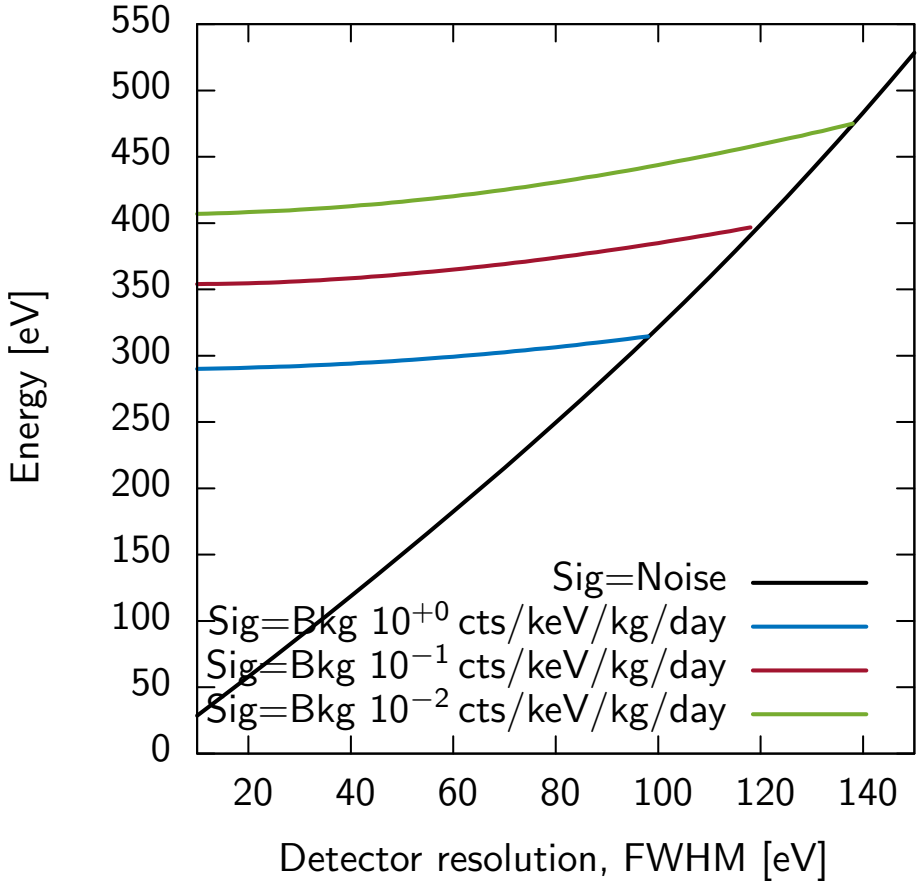


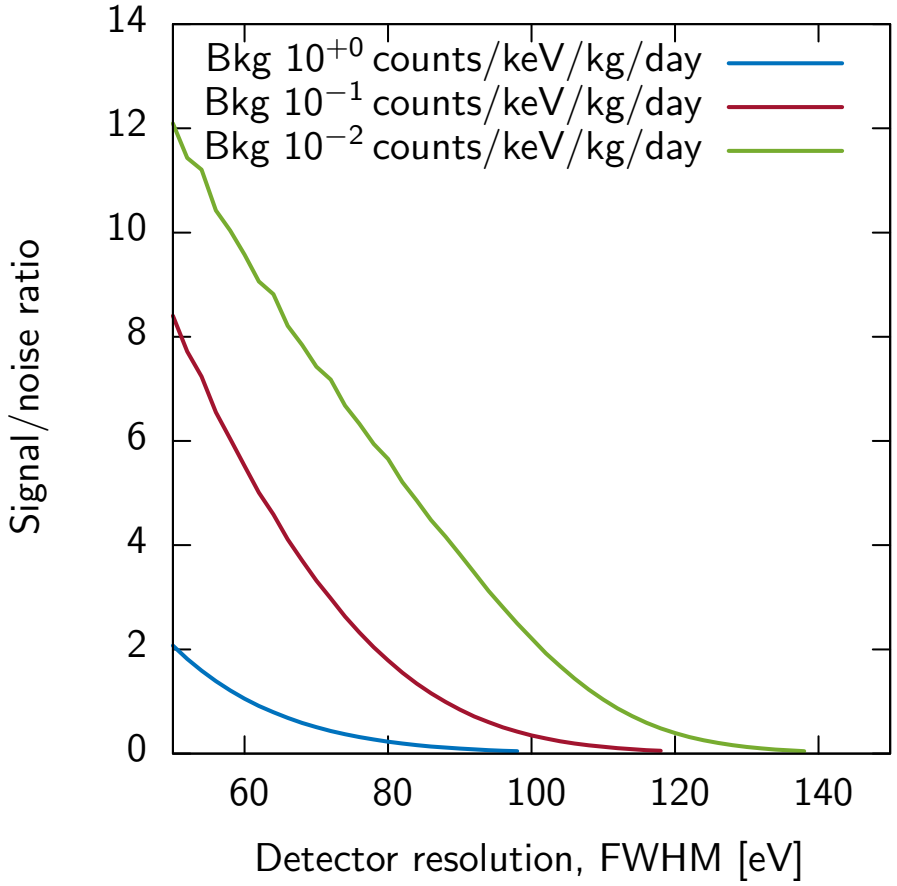
Sensitivity study

- Antineutrino flux: $2 \times 10^{13}\,\bar{\nu}_e/\mathrm{s}/\mathrm{cm}^2$ (15 m distance from core)
- The ionization spectrum is smeared by the electronics noise
- At a fixed background level the electronic noise entirely defines the sensitivity
- The region of interest is limited by the distribution of accidentally triggered events and the background level



Sensitivity study

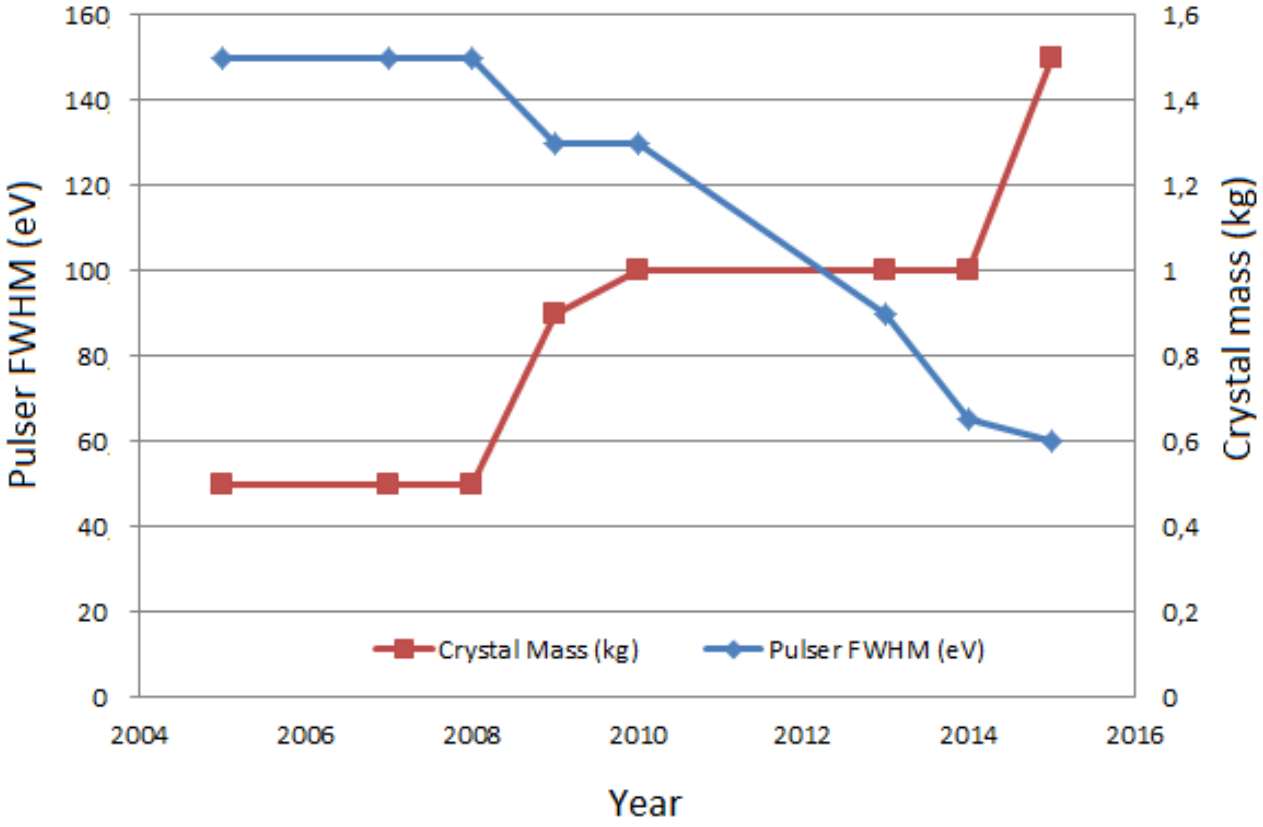




- Antineutrino flux: $2 \times 10^{13}\,\bar{\nu}_e/\mathrm{s/cm^2}$ (15 m distance from core)
- Small region of interest for high electronic noise
- Little improvement by reduction of background level

- Background levels of the order of 0.1-1 count/kg/keV/day required
- A pulser resolution of less than ~ 100 eV required for being sensitive to the CNNS
- A significance of more than 5σ can be reached with roughly 2 years·kg exposure

Feasibility: Electronics noise

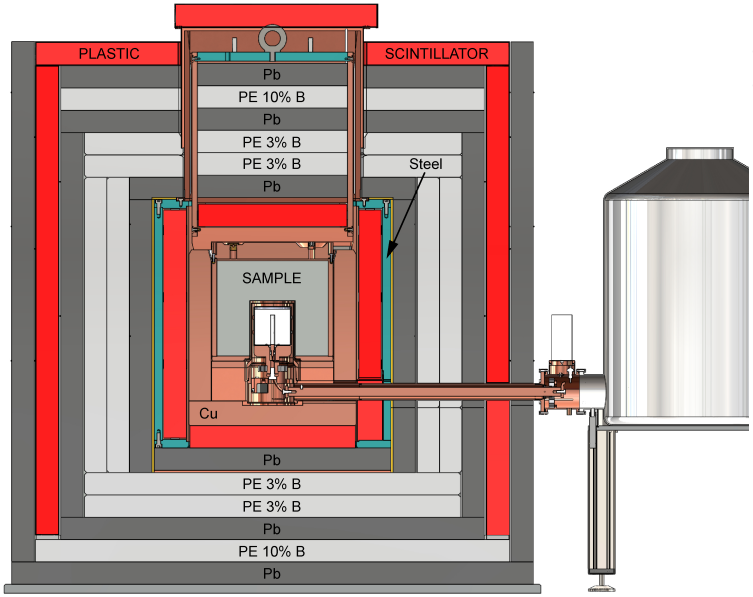


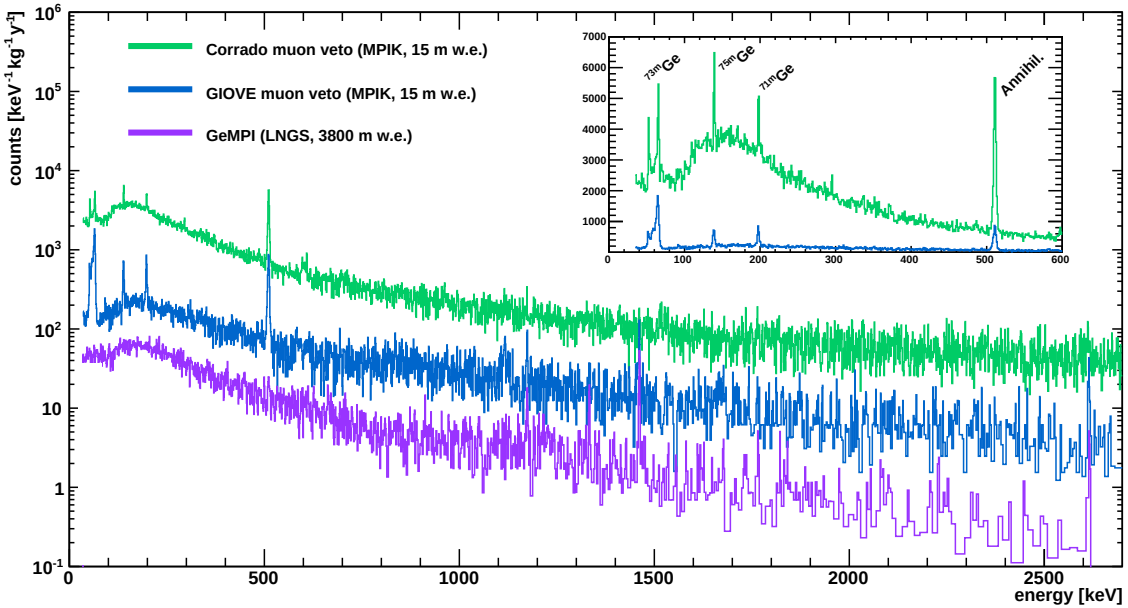
Example: Canberra Lingolsheim

- Large volume (~ 1 kg) with low noise characteristics (< 100 eV FWHM noise resolution) available

Figure from: V. Marian, HPGe detector fabrication at CANBERRA, CANBERRA Specialty Detectors (Lingolsheim), Final Symposium of the Sino-German GDT Cooperation, Ringberg Castle, October 2015, https://indico.mpp.mpg.de/getFile.py/access?contribId=18sessionId=3resId=0materialId=slidesconfId=3121

Feasibility: Background level





- New shallow depth (15 m w.e.) material screening facility at Max-Planck-Insitut für Kernphysik, Heidelberg
- High muon veto efficiency ($> 99\%$), good neutron moderation, low radioactivity of components
- Background levels below the required 1 count/kg/keV/day are observed
- A similar setup at a similar depth near a nuclear reactor is realistic and can produce similar background suppression.

Heusser, G. et al. GIOVE - A New Detector Setup for High Sensitivity Germanium Spectroscopy At Shallow Depth, 17 (July 2015).

Conclusion

- Close to a reactor core high antineutrino fluxes can be observed ($\sim 2 \times 10^{13}\,\bar{\nu}_e/\mathrm{s}/\mathrm{cm}^2$ at 15 m distance of a 3 GW reactor)
- Background levels of the order of 0.1-1 count/s/keV/kg/day are necessary, but can be achieved
- The energy threshold is entirely defined by the noise resolution of the detector (can be measured with a pulser measurement)
- Large volume detectors (~ 1 kg) are required as the rate of accidentally triggered signals is independent of the detectors mass.
- A sufficiently low energy threshold can be achieved with a point contact germanium detector of a noise resolution below 100 eV. Some manufactures claim that they can reach such a low noise level
- A significance of more than 5σ can be reached with roughly 2 years·kg exposure

CNNS can be measured at a reactor site with modern point contact germanium detector systems and state-of-the-art background suppression/shielding methods

Important notes:

- The spectrum < 1 keV most likely is not flat: Lines from neutron activation (cosmic and reactor) of the germanium are to be expected, but also lines from external backgrounds (Uranium, Thorium)
- Reactor neutron flux must be controlled and sufficiently suppressed
- Reactor on/off measurements are crucial to understand these effects