Background simulations and shielding calculations

Vitaly A. Kudryavtsev

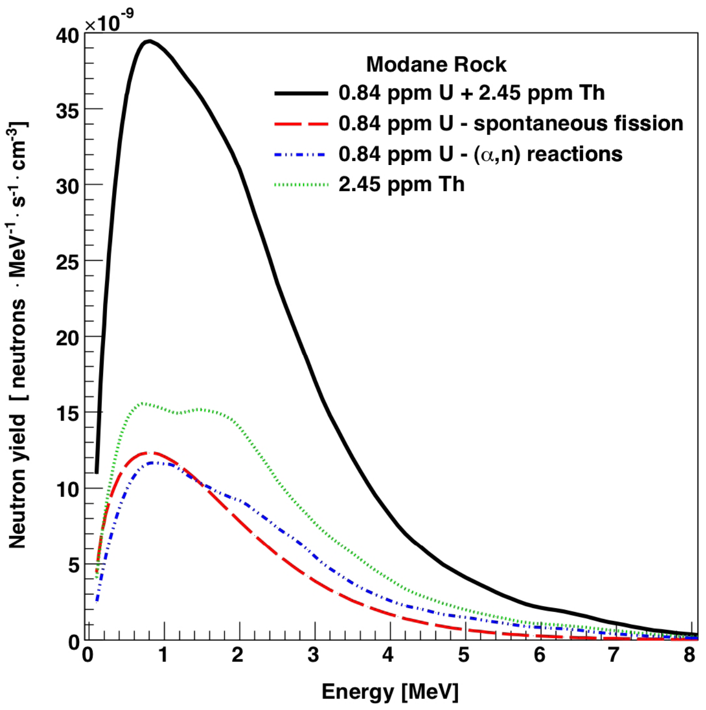
University of Sheffield

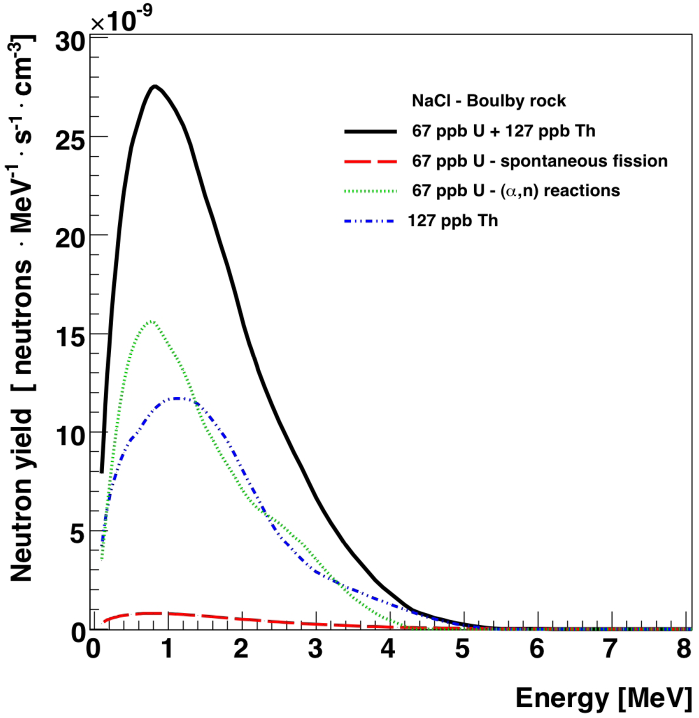
Contributions from many others

Outline

- Note 1: results are relevant to many experiments and techniques (mainly dark matter).
- Note 2: here I present mainly our work + some graphs from other groups and experiments.
- Note 3: see next talk by Henrique Araújo and talk to Henrique and Luciano Pandola if you want to learn more about GEANT4.
- Note 4: see the extended version of my talk at SNOLAB2010.
- Neutrons and gamma-rays from radioactivity.
  - Spectra of neutrons.
  - Gamma-ray and neutron transport through the shielding.
  - Different shielding configurations.
  - Background from detector components and intrinsic radio-purity.
- Muon-induced neutrons.
  - Neutron production rate by muons in different materials.
  - MC for specific detectors: common features and specific predictions.
  - Water Cherenkov veto.

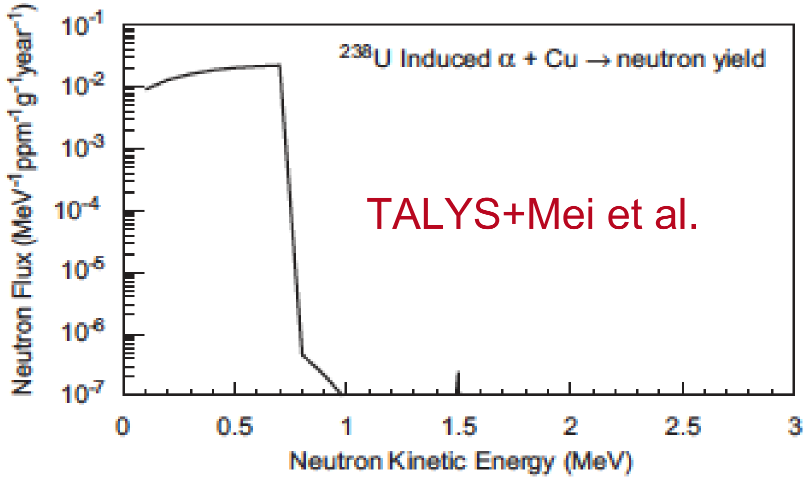
Neutron spectra in different rocks



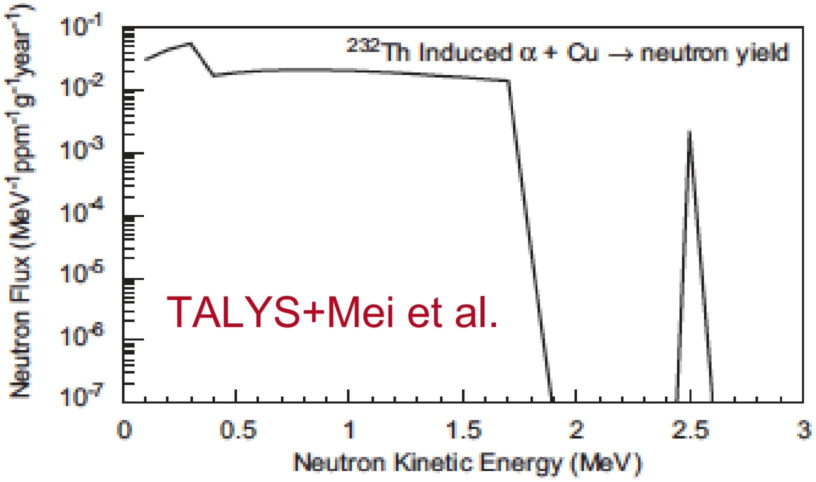


- Neutron spectra from modified SOURCES4A (Wilson et al. Sources4A. Technical Report, LA-13639-MS (1999); Carson et al. Astropart. Phys. 21 (2004) 667). Spectra and rates strongly depend on the material (composition).
- Plots taken from Tomasello et al. NIMA 595 (2008) 431; Astropart. Phys. 34 (2010) 70; V. Tomasello, PhD Thesis, Univ. of Sheffield (2009).
- 1% of hydrogen reduces neutron flux on the rock face (after transport) by a factor 4.7 (1.8) above 100 keV (1 MeV).

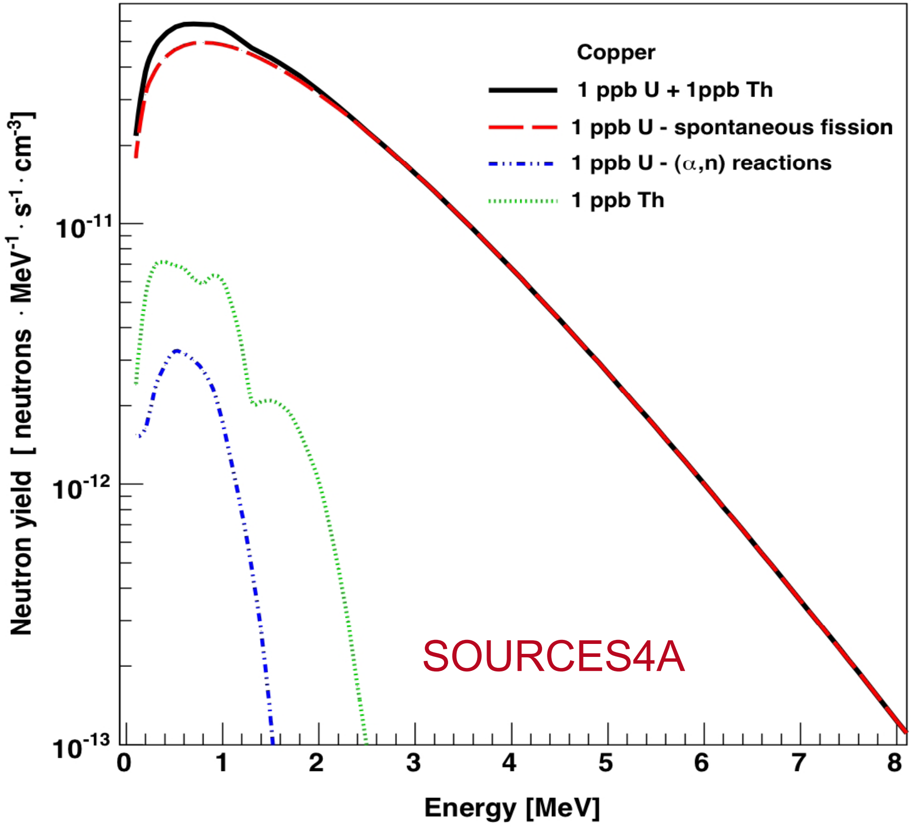
Different calculation techniques



TALYS+Mei et al.



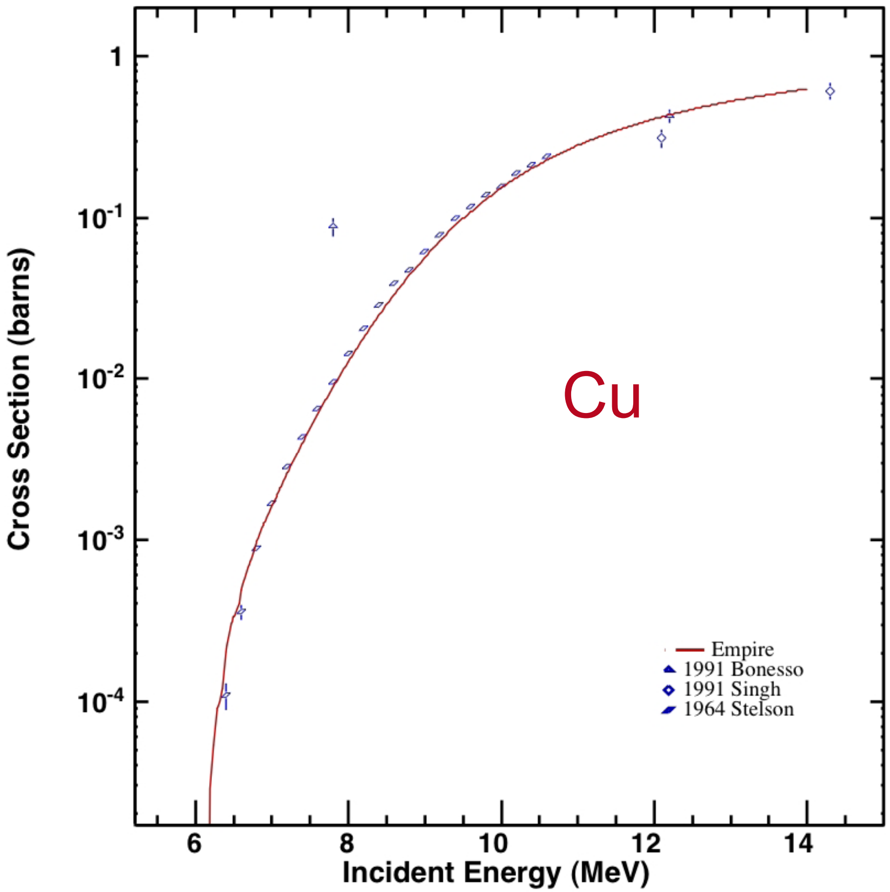
TALYS+Mei et al.

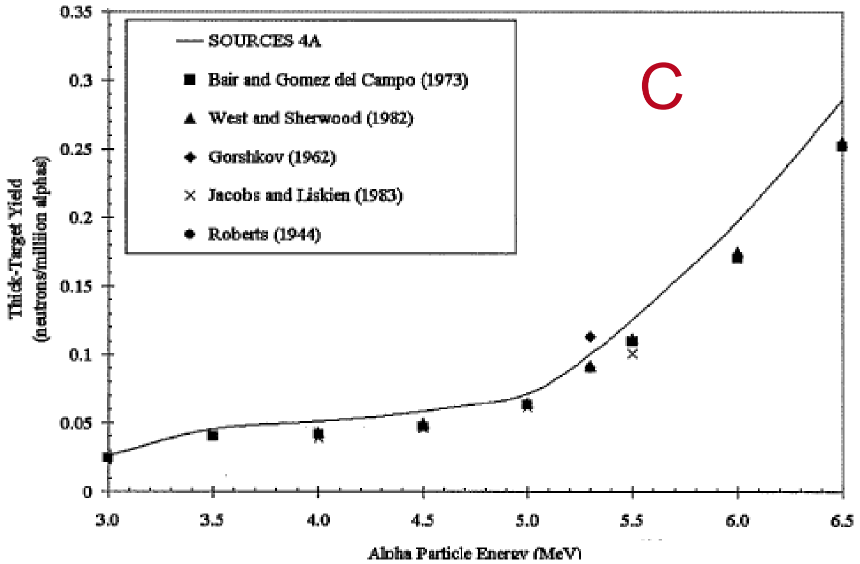


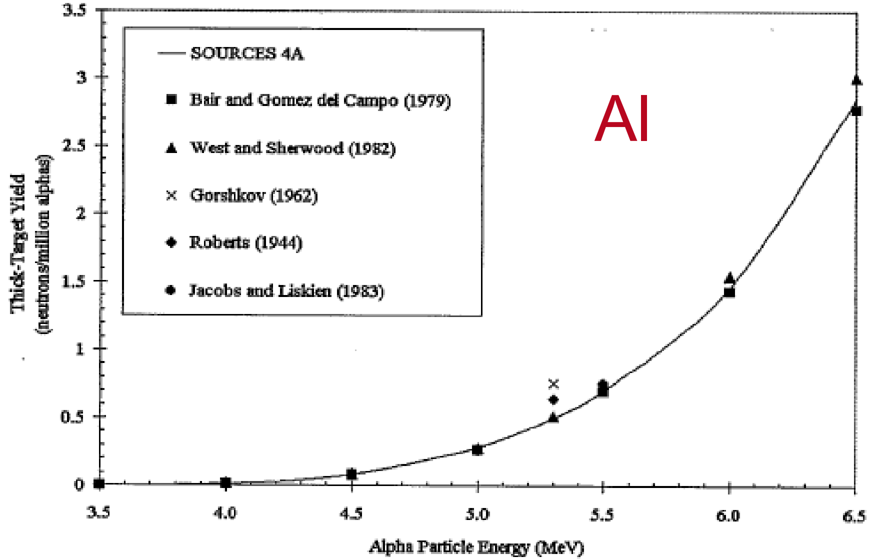
SOURCES4A

- **TALYS + Mei et al. NIMA 606 (2009), 651: 3.4×10^{-12} (U), 10.8×10^{-12} (Th) cm^{-3} s^{-1} ppb^{-1}.**
- **EMPIRE-2.19 + modified SOURCES4A: 2.8×10^{-12} (U), 8.4×10^{-12} (Th) cm^{-3} s^{-1} ppb^{-1}.**

Validation of EMPIRE and SOURCES







(α,n) cross-section on Cu and thick-target neutron yields in C and Al.

Validation of SOURCES4A

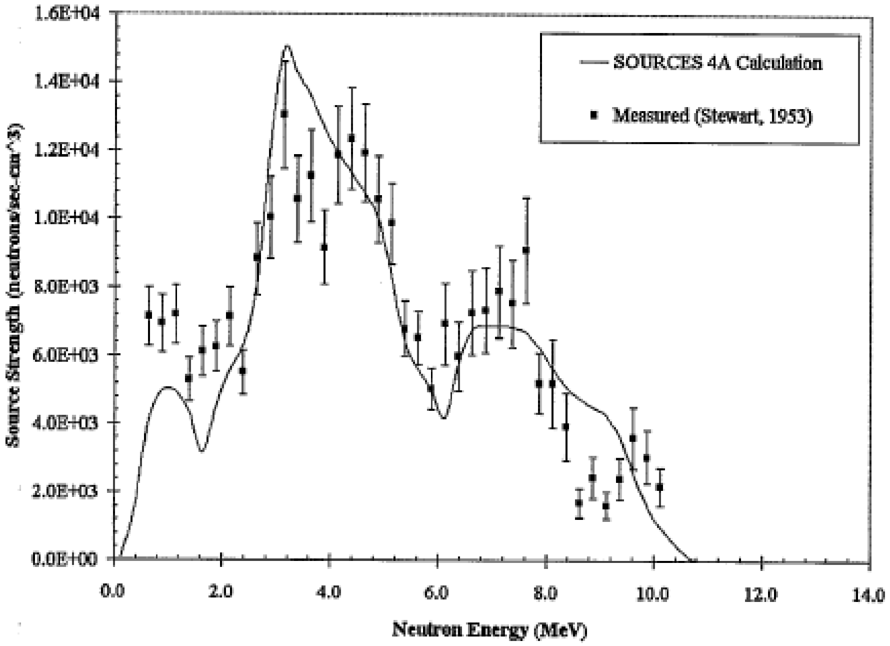


Fig. 9. Energy-Dependent Neutron Source Strength in PuBe$_{13}$ Homogeneous Problem as Calculated by SOURCES 4A and Compared with Measured Data.

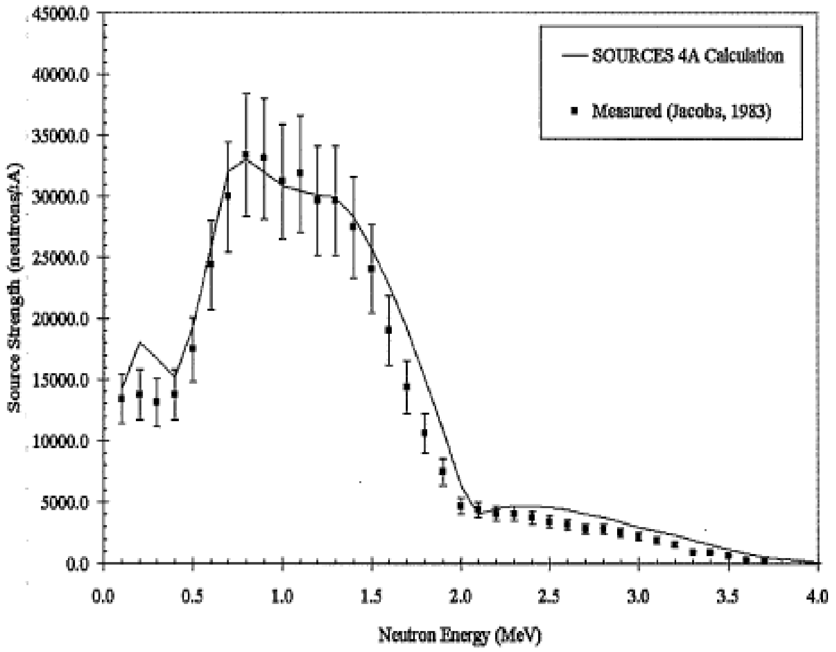
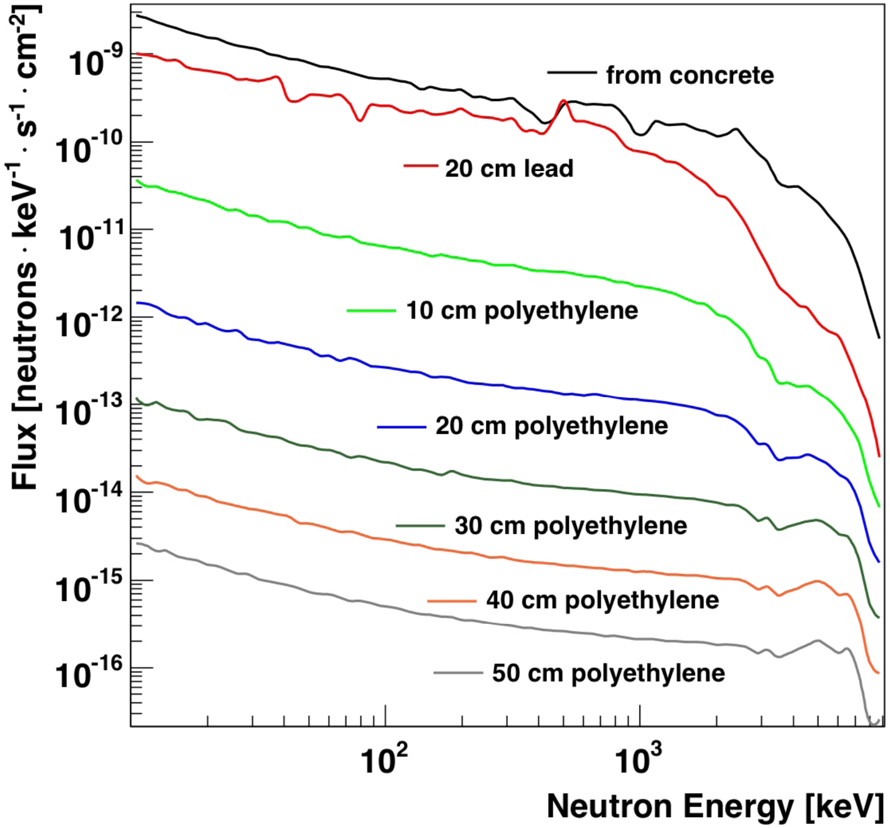
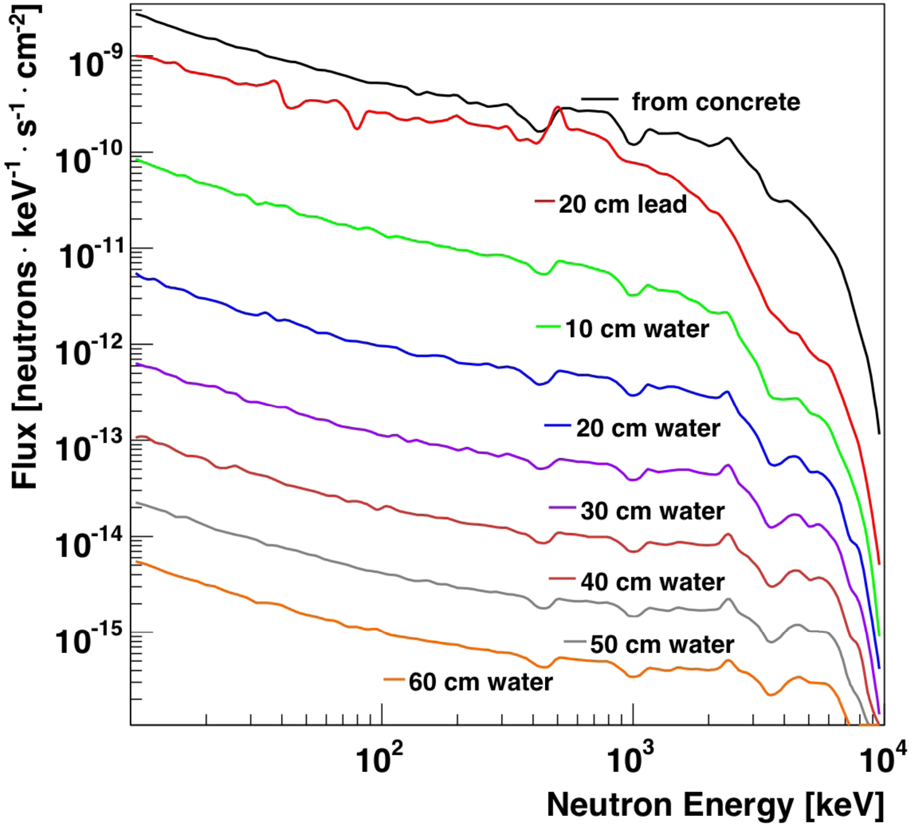


Fig. 19. Energy-Dependent Neutron Source Strength from 5.0 MeV α-Particles Incident on Aluminum Oxide Slab as Calculated by SOURCES 4A and Compared to Measured Data.

Neutron spectra from Pu-Be homogeneous source (thick target, left) and from 5.0 MeV alphas incident on aluminum oxide slab (right); from SOURCES4A manual.

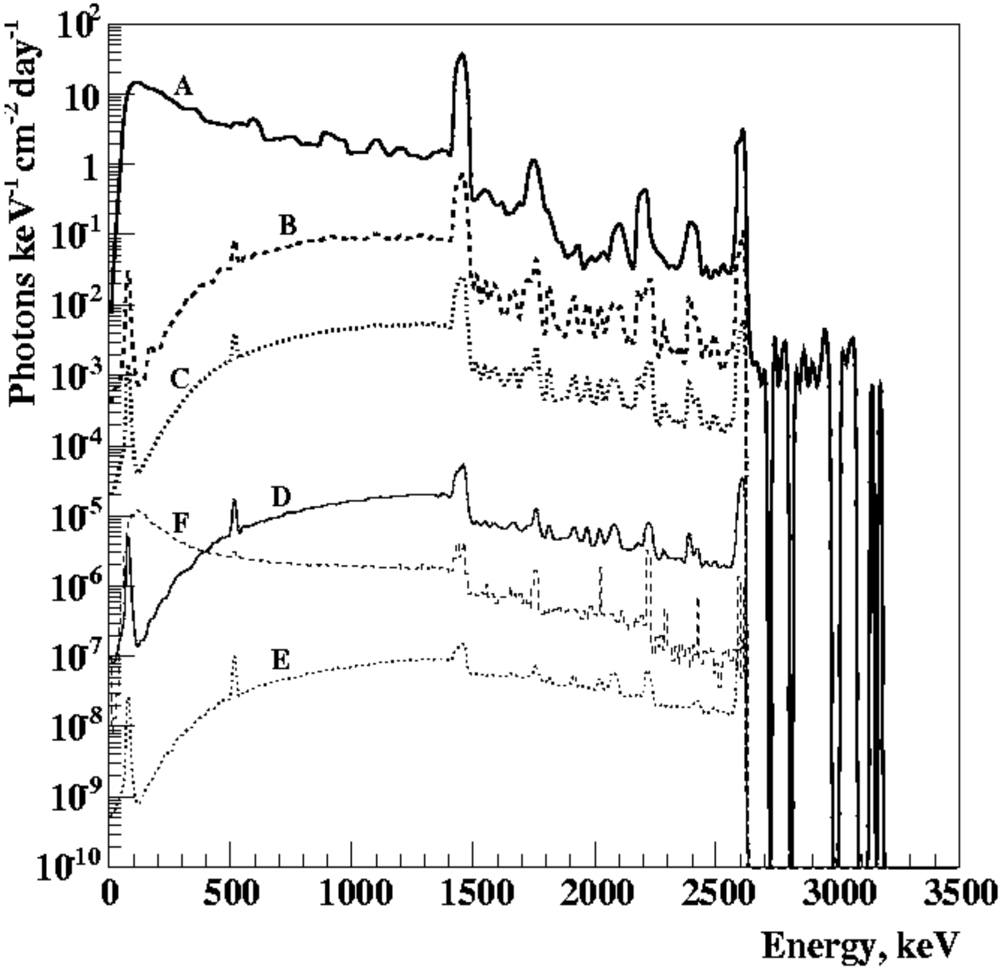
Neutrons in water and CH_2





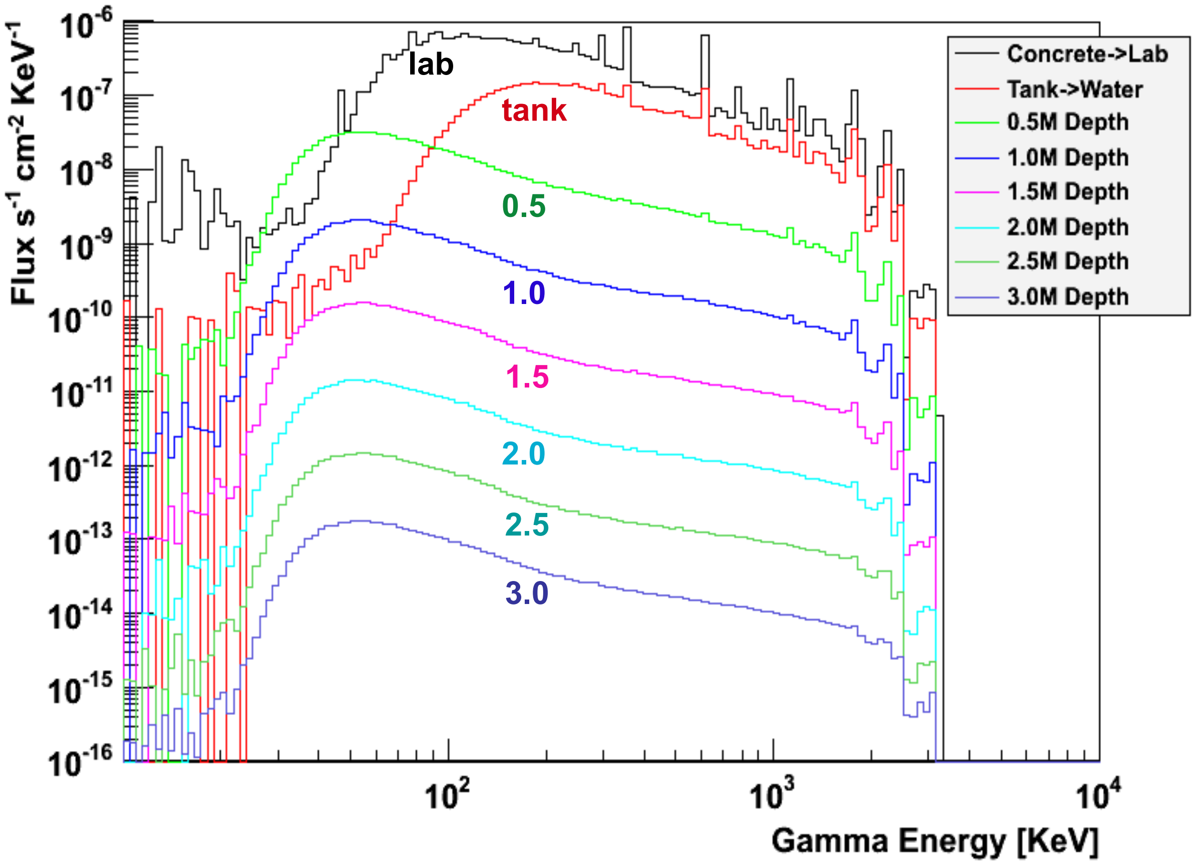
- Neutron attenuation in water and CH_2 - V. Tomasello, PhD Thesis, Univ. of Sheffield (2009); Tomasello et al. Astropart. Phys. 34 (2010), 70.
- Inelastic scattering in lead helps with neutron attenuation at E > 1 MeV.
- ~25 cm Pb + 50 cm of CH_2 is ok for DM experiments.

Gamma-ray attenuation in lead



- A - spectrum from rock;
- B - behind 5 cm of lead;
- C - 10 cm of lead;
- D - 20 cm of lead;
- E - 30 cm of lead;
- F - 20 cm of lead and 40 g/cm^2 of CH_2.
- From M. J. Carson et al., Nucl. Instrum. and Meth. A 548 (2005) 418.
- Or several layers (XENON100): polyethylene, lead, polyethylene, copper (or archeological lead but be careful: there may be U).

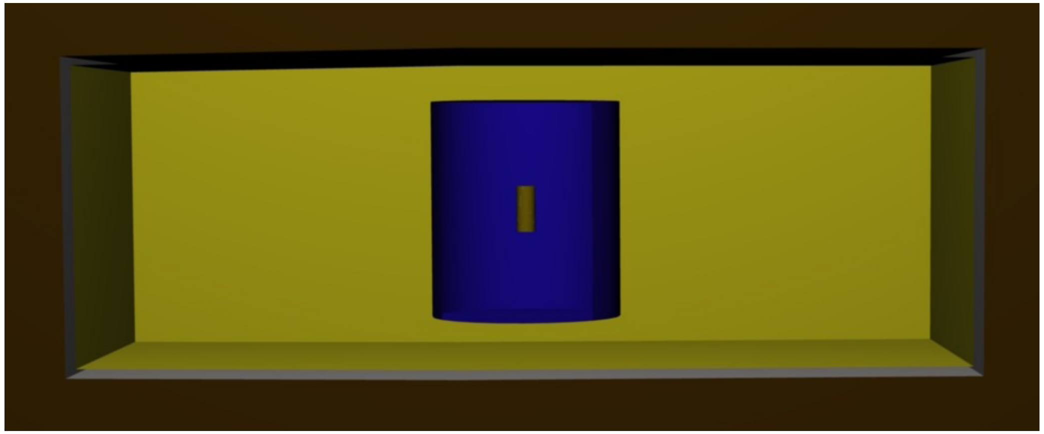
Attenuation in water



Spectra of gamma-rays from U in concrete. On average ×10 suppression per 0.5 m of H_2O.
See also talk by P.Cushman.

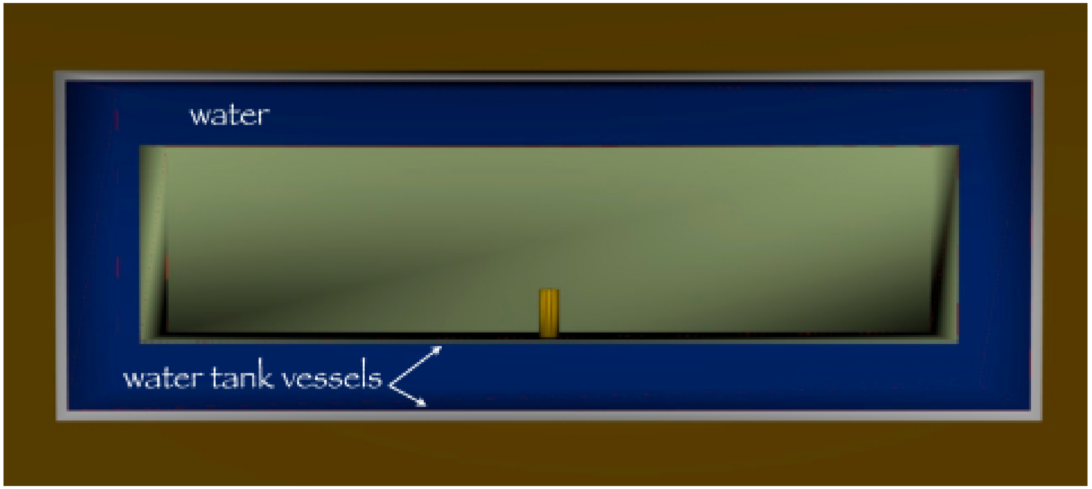
- **The background from concrete may dominate over that from rock.**
- **If d = 30 cm (concrete) only <5% of radiation comes from rock.**
- **Required suppression of gamma-rays for a 1 t experiment is achieved with 3 m of water (discrimination $<10^{-4}$).**
- **Holes (pipes, readout) may be important.**
- **Similar attenuation calculated for XENON1T (worse discrimination): Selvi, Talk ay IDM2010.**

Submarine vs swimming pool



Swimming pool

Submarine

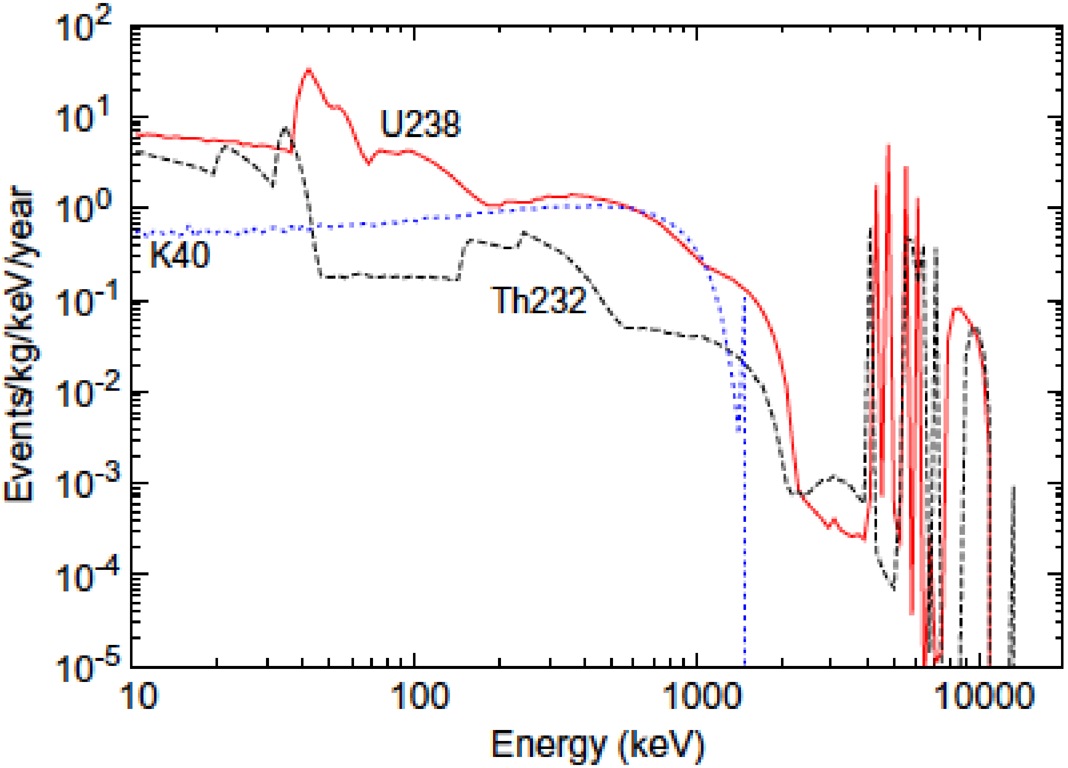


- Assume 1 ppb U/Th in steel in equilibrium.
- About 17 nuclear recoils per year at 10-50 keV in 100 kg of Ge from the water tank stainless steel vessel (2 cm thick) along the walls.
- About 10^6 electron recoils per year at 10-50 keV in 100 kg of Ge from the water tank stainless steel vessel (2 cm thick) along the walls.

Detector components

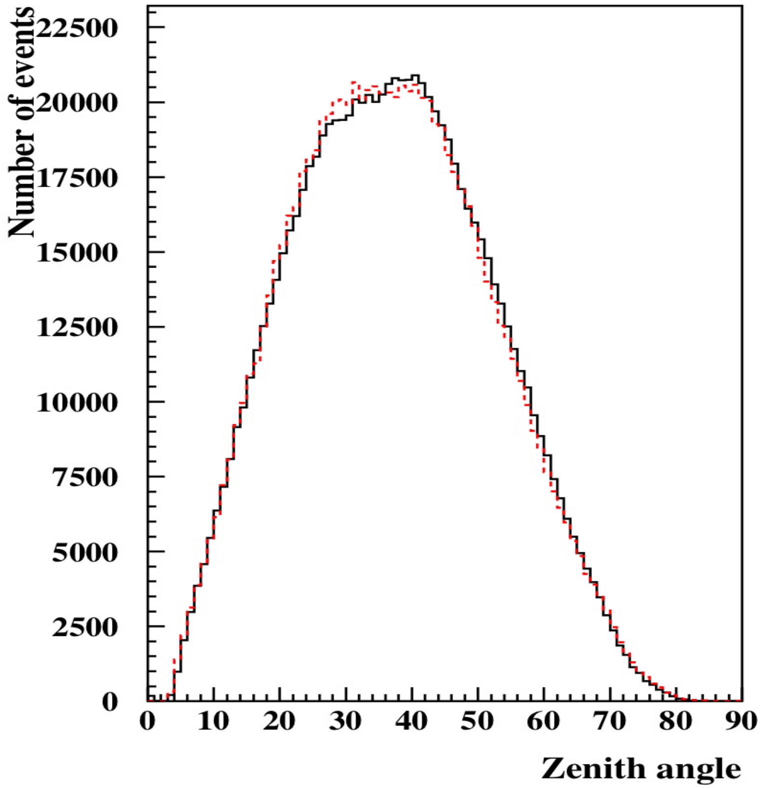
- Consider dark matter detector with Ge target.
- Source: 1.6 ppt U, 5.7 ppt Th, 0.01 mBq/kg ^{60}Co in ~3 tonnes of Cu (upper limits from G. Heusser, Talk at LRT 2004; M. Laubenstein et al., Appl. Radiat. Isot. 53 (2004) 167). Event rate per tonne of target (EURECA: Ge/$CaWO_4$) per year at 10-50 keV: < 10^5 electron recoils, < 1 nuclear recoil.
- Source: 1 ppb U/Th in 100 kg of stainless steel close to the target. Event rate per tonne of target per year at 10-50 keV: ~4×10^5 electron recoils, ~3 nuclear recoils.
- No more than 20-30 kg of materials with ~1 ppb concentrations of U/Th.
- Liquid Xe target: fiducialisation should help with discrimination against background gammas and neutrons.

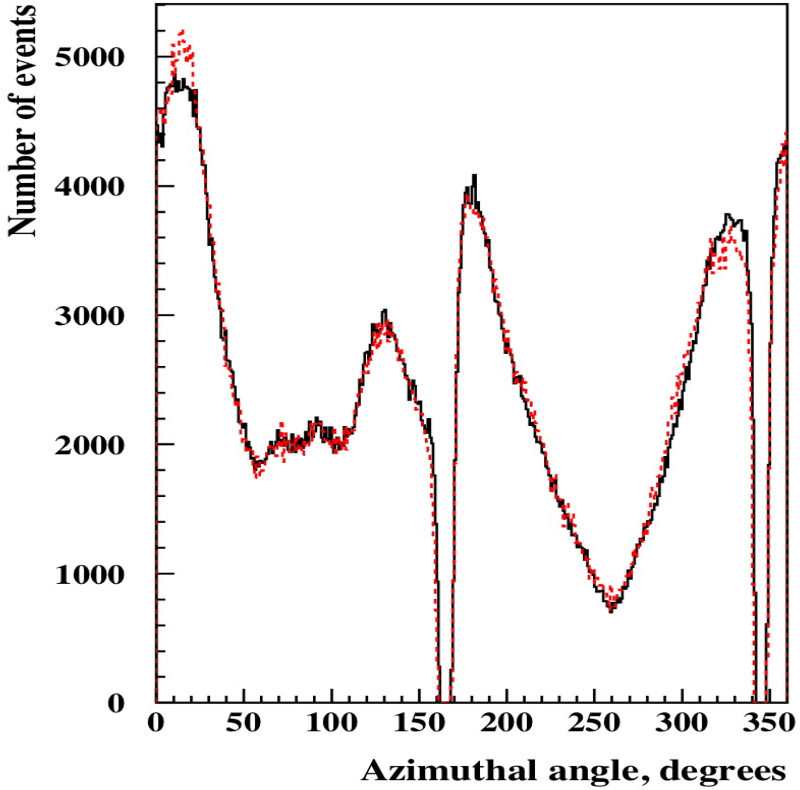
Intrinsic contamination (Ge)



- **1 ppt U/Th in equilibrium, 1 ppb K; single hits.**
- **With 1 tonne target and 10^{-5} discrimination factor, the concentrations of <0.5 ppt U/Th and < 1 ppb K are required - almost there with EDELWEISS-II.**

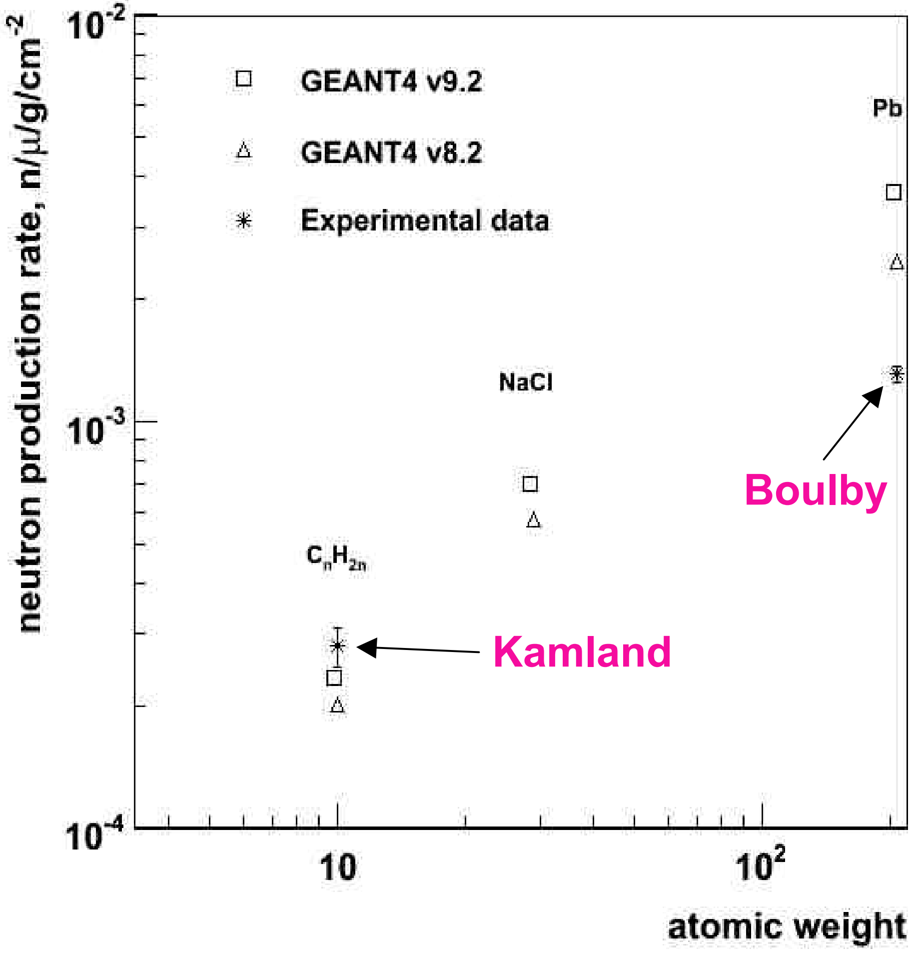
Muon generator - MUSUN





- **Zenith and azimuth angular distributions of muons from MUSUN (black) at LSM compared with data from the Frejus proton decay experiment (red).**
- **MUSIC and MUSUN, V. Kudryavtsev, Comp. Phys. Comm. 180 (2009) 339.**
- **The MUSUN code exists for LNGS, LSM, Soudan, SNOLab, Boulby, and for flat surface in standard rock and water.**

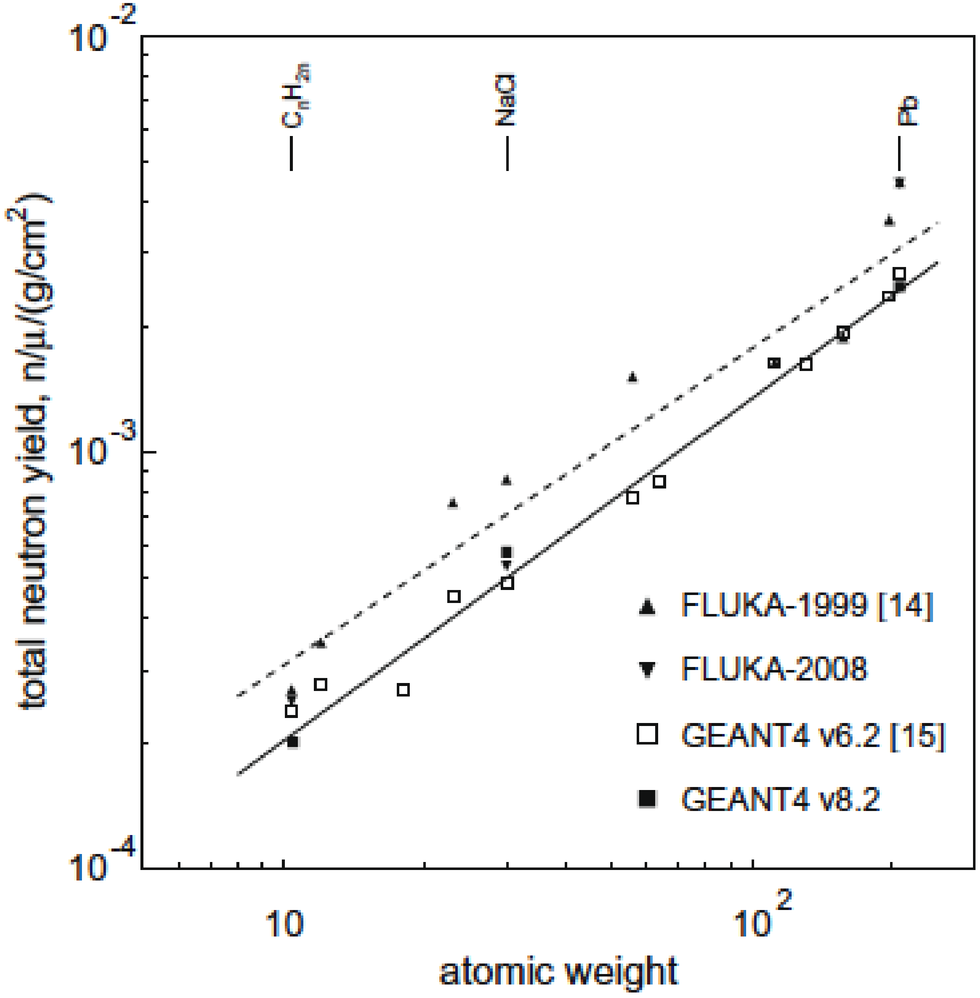
Neutron yield in different materials



Tomasello, PhD Thesis, Univ. of Sheffield (2009).

- Only two recent measurements with fully modelled setups are shown (~280 GeV muons). Slightly higher rate in CH_2 and lower rate in Pb were observed compared to simulations.
- Neutron capture rate is converted into the neutron yield - requires certain assumptions about neutron spectra, transport etc, taken from MC. Direct comparison between data and MC is crucial.
- Different versions and different models give different results. Various models were checked by M. Bauer (talk at IDM04) and others: <30% difference.

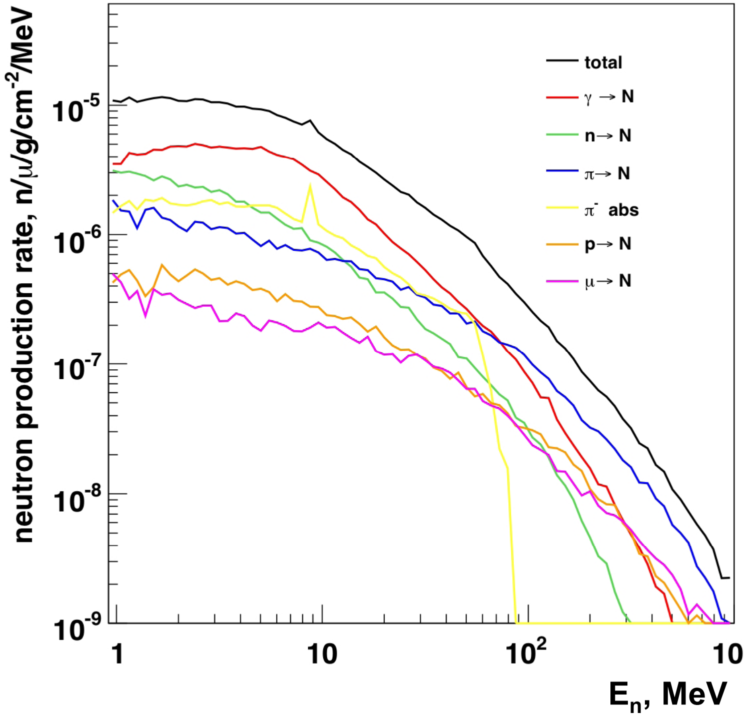
Neutron yield in different materials

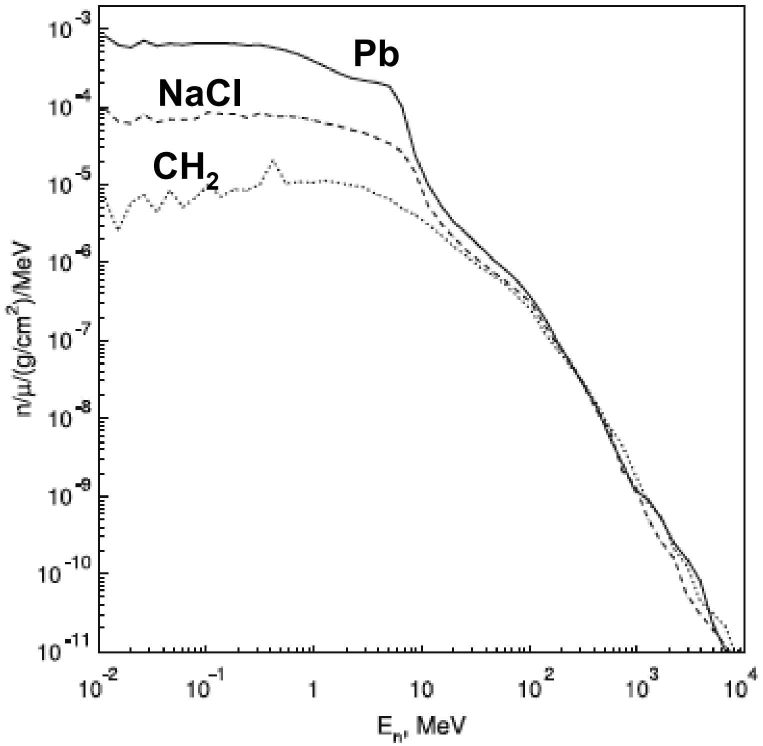


A. Lindote et al. Astropart. Phys., 31 (2009) 366.

- 280 GeV muons.
- The trend is shown by the dashed (FLUKA-1999) and solid (GEANT4 6.2) lines.
- Simulation results for different materials deviate significantly from the lines.
- It is not excluded that the model is more or less correct for some materials but does not give accurate predictions for another one.
- More measurements in different materials are needed supported by full MC.

Neutron spectra at production





- **Left: CH_2, 280 GeV muons, GEANT4 9.2 (V. Tomasello, 2009); also M. Horn, H. Araújo, M. Bauer, A. Lindote, R. Persiani and others with various versions of GEANT4.**
- **Right: spectra in CH_2, NaCl and lead; <E> = 65.3 MeV, 23.4 MeV and 8.8 MeV (A. Lindote et al. Astropart. Phys., 31 (2009) 366). Neutron spectrum strongly depends on the material.**

Angular dependence

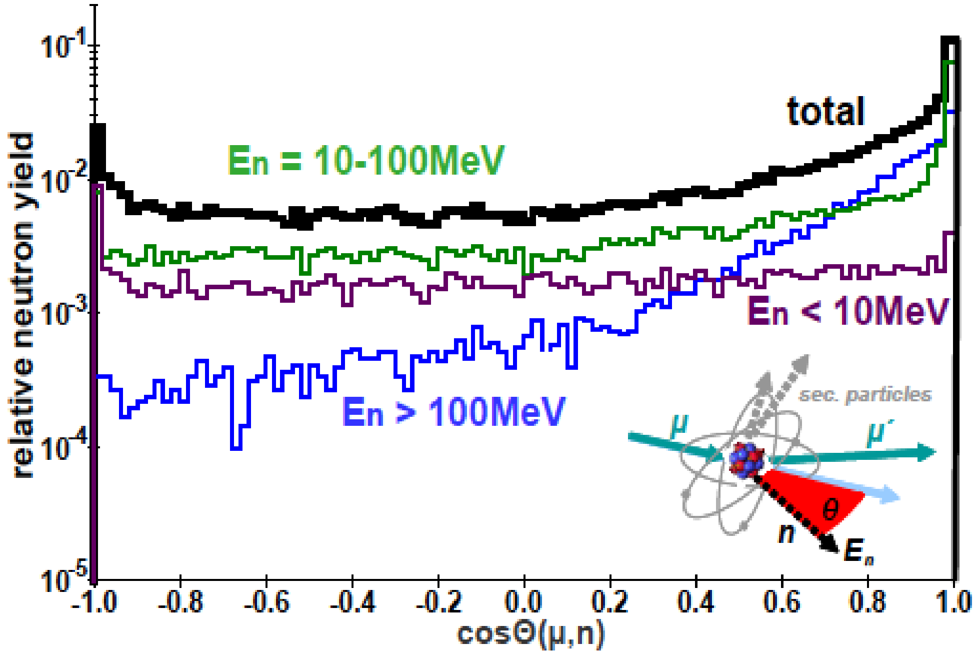


Figure 3.9: Angular distribution relative to the total neutron yield of neutrons produced in muon nuclear reactions with *Geant4* `8.2.p01`. For all neutron kinetic energies (black) or the respective kinetic energy ranges, $E_n > 100\ MeV$ (blue), $10\ MeV < E_n < 100\ MeV$ (green) and $E_n < 10\ MeV$ (purple). The inlet shows the definition of the angle θ with respect to the incident muon. See text for details.

M. Horn. PhD thesis. Univ. of Karlsruhe (2007).

- **Angular distribution of emitted neutrons.**
- **High-energy neutron emission is not isotropic but is correlated with the muon direction.**
- **Hence the signal from high-energy neutrons travelling long distance to the detector (from rock) may be accompanied by the energy deposition from a muon or muon-induced cascade.**
- **Production and transport of all particles in a cascade is important for correct evaluation of neutron-induced signal.**

Spectra in detectors: LXe (2005)

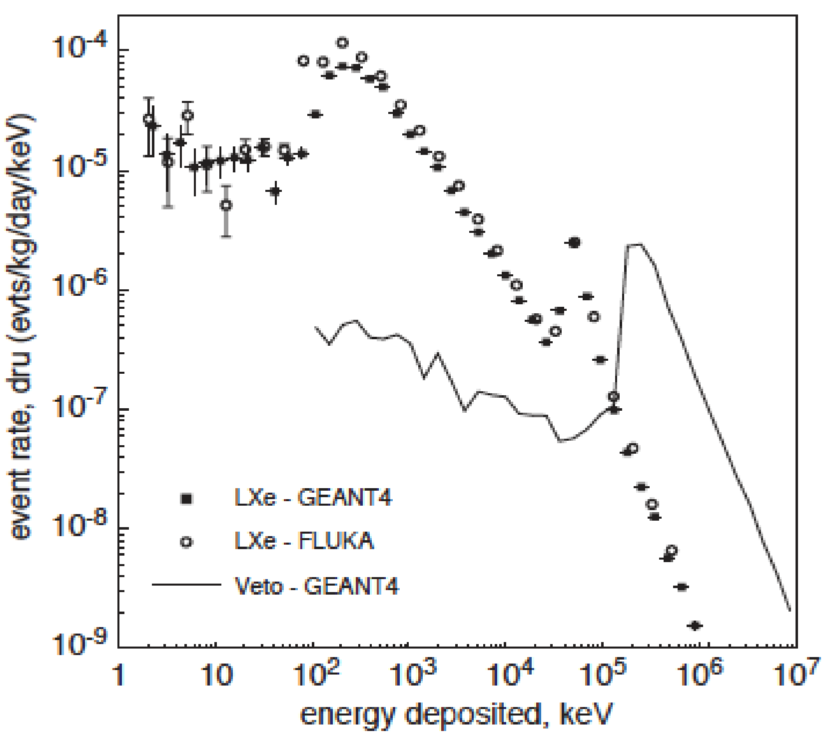


Fig. 11. Differential spectra of the total energy deposited in the liquid xenon (LXe) target as predicted by GEANT4 and FLUKA and in the veto scintillator according to GEANT4 (the latter is scaled down by a factor of 5×10^4).

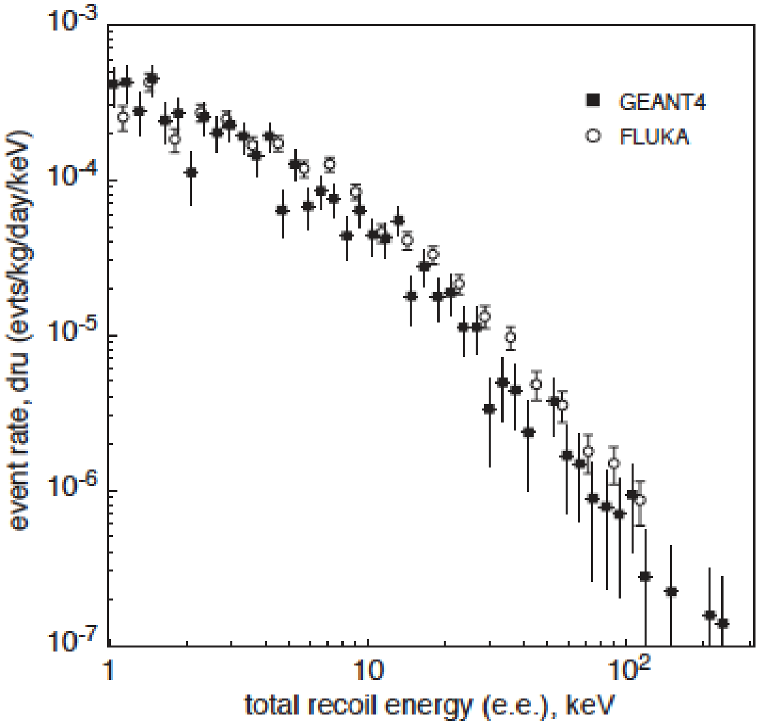
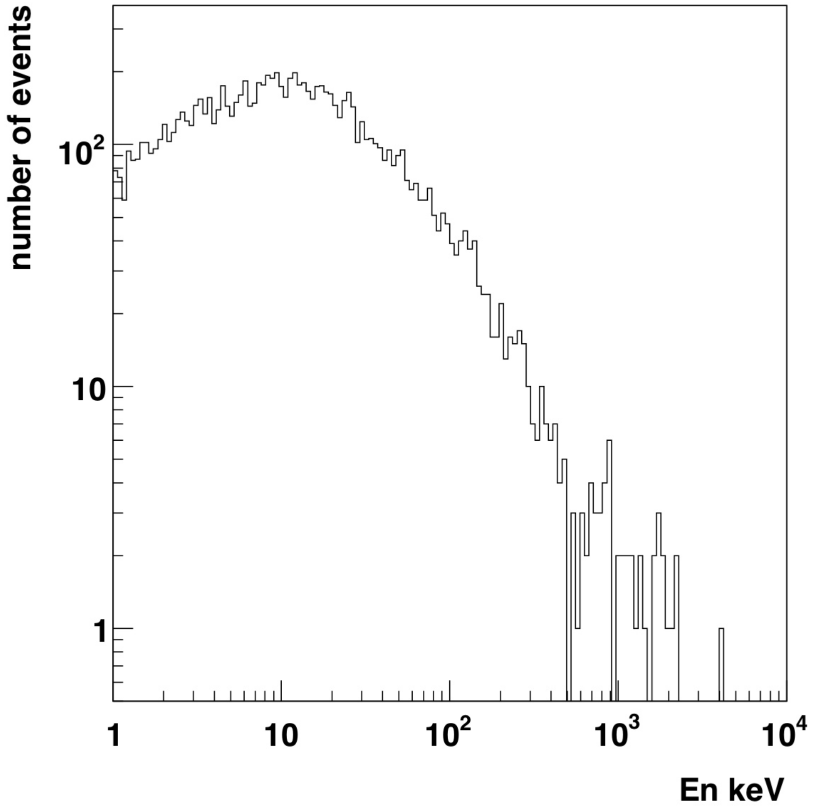
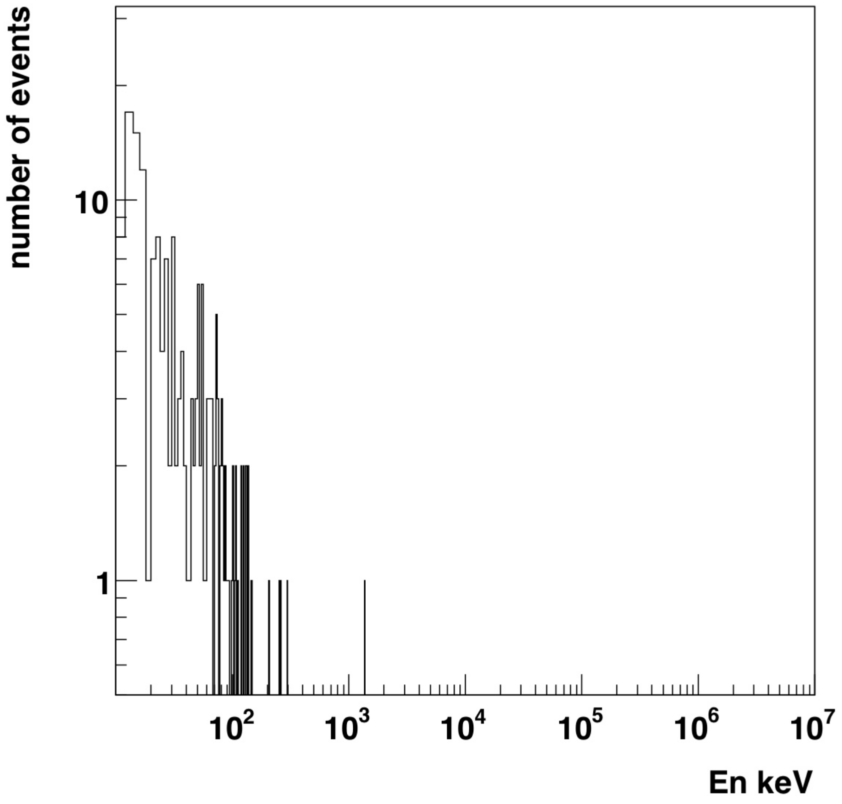


Fig. 12. NR energy spectrum in the liquid xenon detector as a function of the visible energy deposited by all nuclear recoils in each event. The spectra include 'mixed' events involving electromagnetic energy deposits, not just 'pure' nuclear recoils, but only the energy left by NRs was counted.

Araújo et al. NIMA 545 (2005) 398. Boulby lab, 250 kg of xenon, shielding - 30 cm Pb (ext), 40 g/cm² CH_2 (int); only 2-3 single recoils per year at 10-50 keVnr (w/o veto); < 1 per year with veto. (Nuclear recoil quenching = 0.2.)

Muon-induced neutrons: Ge target



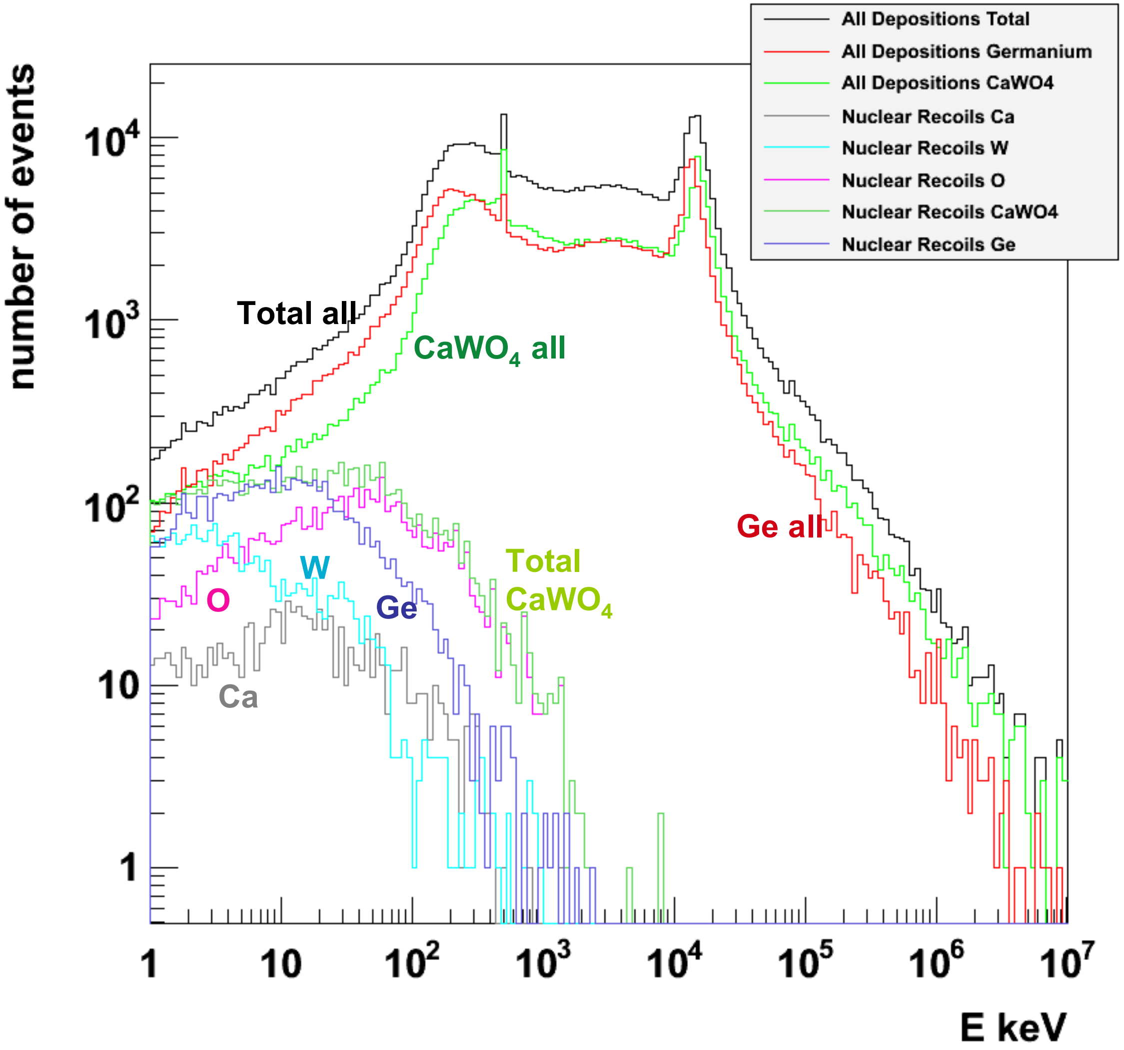


Spectrum of nuclear recoils in a Ge crystal (300 g each, 1 t total) - all multiplicities. Other energy depositions are ignored. 3.7 years' statistics.

Spectrum of single nuclear recoils. Other energy depositions are ignored. The energy threshold - 10 keV.

Muon-induced neutrons in EURECA

- LSM - 3 m water shielding around the cryostats.
- Only single nuclear recoils (without any other energy deposition): 1.6±0.5 events/year at E > 10 keV keV in 1 t (independently of the signal in veto - veto is not switched on).
- No events in anticoincidence with veto.
- One event with energy deposition in veto of only 0.278 GeV. Others - with E_{dep} > 1 GeV.
- In $CaWO_2$ most events are O recoils at high energies.



Conclusions (mainly for DM)

- **Shielding for one-tonne scale experiment (10^{-10} pb, discrimination ~10^{-5}):**
  - **20-25 cm of lead + 40-50 g/cm^2 of CH_2 or**
  - **3 m of water.**
- **Water shielding along the walls is not efficient: many background events from the water tank walls if no additional shielding in the lab is in place.**
- **Ultra-pure copper (< 10 ppt U/Th) is OK as a material for detector vessels/cryostats. Materials with concentrations ~ 1 ppb should not be present in large quantities (<20-30 kg).**
- **Still an uncertainty of ×2 in measured and simulated neutron production rate by muons, especially in high-Z targets. We need to simulate and compare with the measurements exactly what is measured - in most cases this is neutron capture rate, not the neutron production rate.**
- **Optimistic results for muon-induced neutrons (with uncertainty about ×2).**
  - **1.6 ± 0.5 events/year/tonne - single recoils above 10 keV in EURECA at LSM. No event survives a veto cut (*E* > 0.2 GeV) in 11.1 years of simulated statistics.**
  - **Shielding configuration is important.**