What do we need to know about background to design high-sensitivity direct dark matter experiments?

V. A. Kudryavtsev

Department of Physics and Astronomy
University of Sheffield

On behalf of ILIAS

Outline

- Introduction.
- Gamma-ray background and its attenuation.
- Neutrons from radioactivity.
- Neutrons from cosmic-ray muons.
- Summary.

See also presentations and other documentation related to ILIAS activities on background studies: links available from www-ilias.cea.fr
Links to publications are also available.

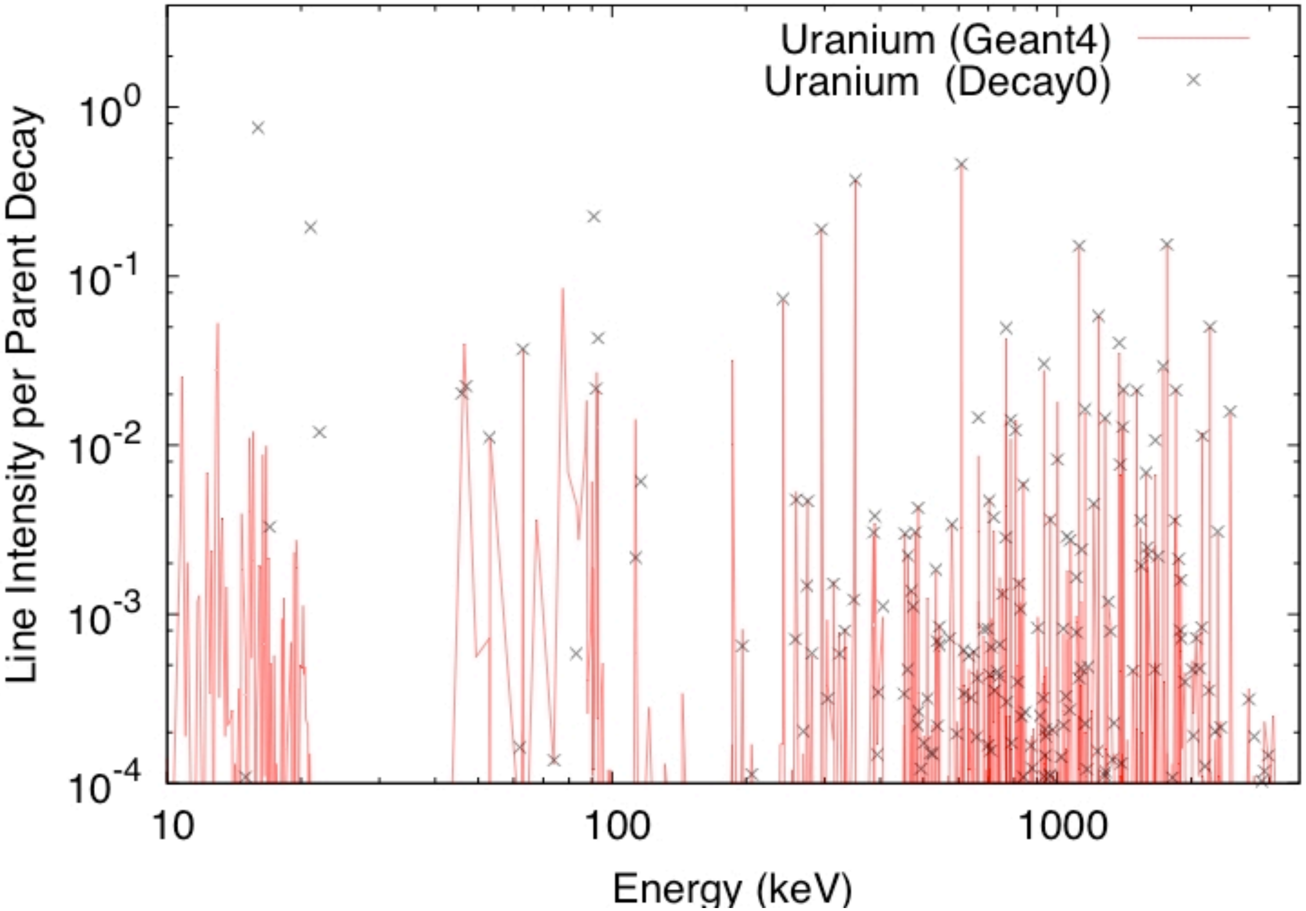
Background studies in ILIAS

- ILIAS - EU funded FP6 Programme: Integrated Large Infrastructures for Astroparticle Science.
- A working group on background studies within N3 (Direct Dark Matter Detection - DMD) and JRA1 (Low Background Techniques for Deep Underground Science - LBT-DUSL) activities.
- Active participants from: France - Saclay, LSM, Lyon, Grenoble; Germany - Tuebingen, Munich-Garching, Karlsruhe, Heidelberg; Spain - Zaragoza, Canfranc; Italy - Milan, LNGS, Bologna; Switzerland - Zurich; UK - Imperial College, RAL, Edinburgh, Oxford, Sheffield. Also: Poland, Czech Republic, Serbia, Russia, Ukraine.
- Main goals:
  - Measurements and simulations of background radiations in underground laboratories;
  - Calculation of background rates in dark matter experiments;
  - Investigation of background suppression and rejection.

Backgrounds for dark matter experiments

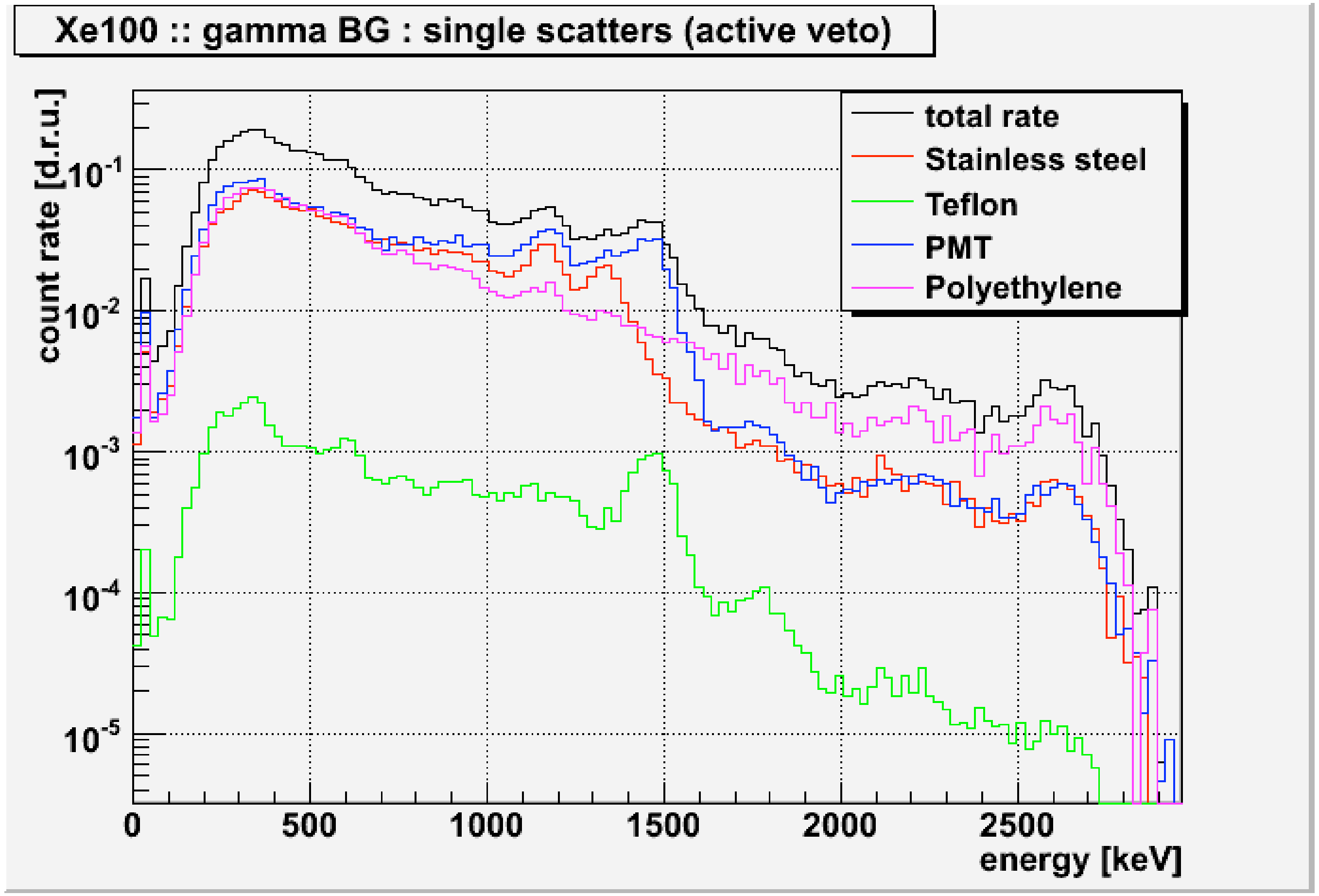
- **Several large-scale (≥ 1 tonne) experiments are discussed for WIMP dark matter searches down 10^{-10} pb.**
- **Tolerated, non-discriminated, rate - no more than a few events/tonne/year.**
- **Questions to answer:**
  - **Are there reliable Monte Carlo codes able to produce, transport and detect background radiations? Yes.**
  - **Are these codes tested against each other and/or experimental data? Yes.**
  - **What is the required composition / thickness /configuration of shielding to attenuate neutrons and gammas from rock / walls (suppression of $>10^6$ should be achieved for neutrons and gammas)? In progress.**
  - **What is the required purity of materials in the vicinity of the detectors (including shielding) given a certain neutron/gamma discrimination factor? In progress.**
  - **What is required efficiency and the best design for an active veto system (mainly against cosmic-ray muons)? In progress.**
  - **How to solve the radon problem? In progress.**
  - **How to get rid of cosmogenically produced isotopes? In progress.**

Gamma-ray production



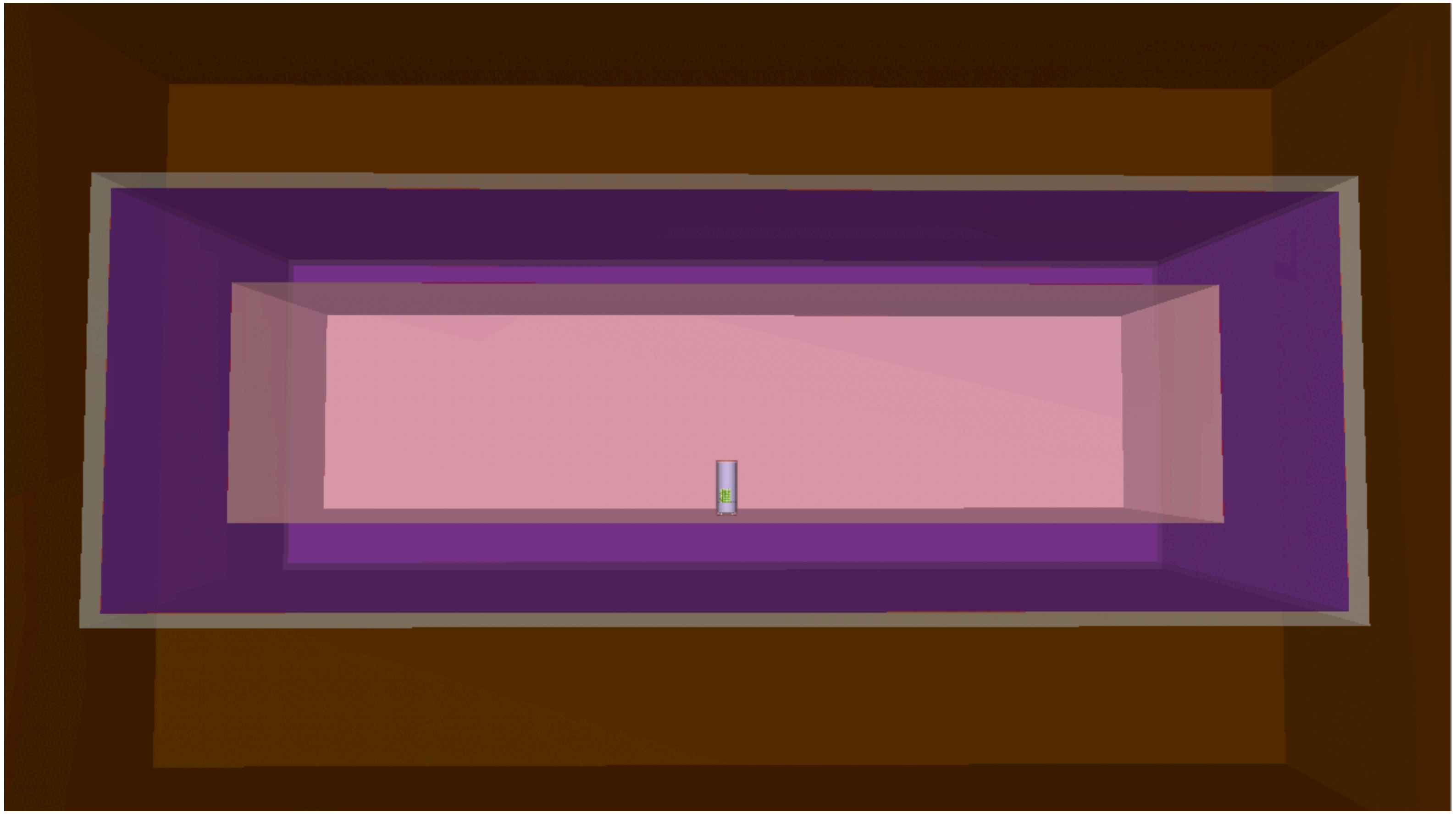
- **GEANT4 - D. Budjas and L. Pandola. Gerda Report GSTR-07-010 (2007).**
- **DECAY0 - Courtesy of V. Tretyak (INR, Kiev).**

Gamma-ray background in XENON100



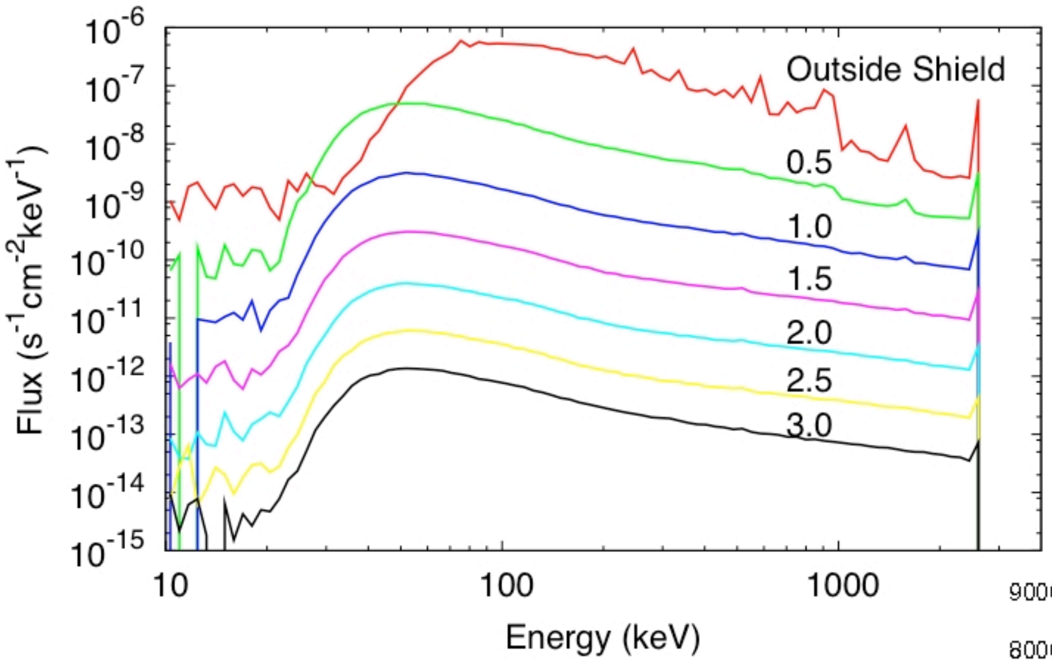
- E. Tziaferi. Talk at 4th Patras Workshop on Axions, WIMPs and WISPs (DESY, Hamburg, 18-22 June 2008); L. Baudis, this workshop.
- Similar simulations for ZEPLIN-III, LUX etc.

Water shielding



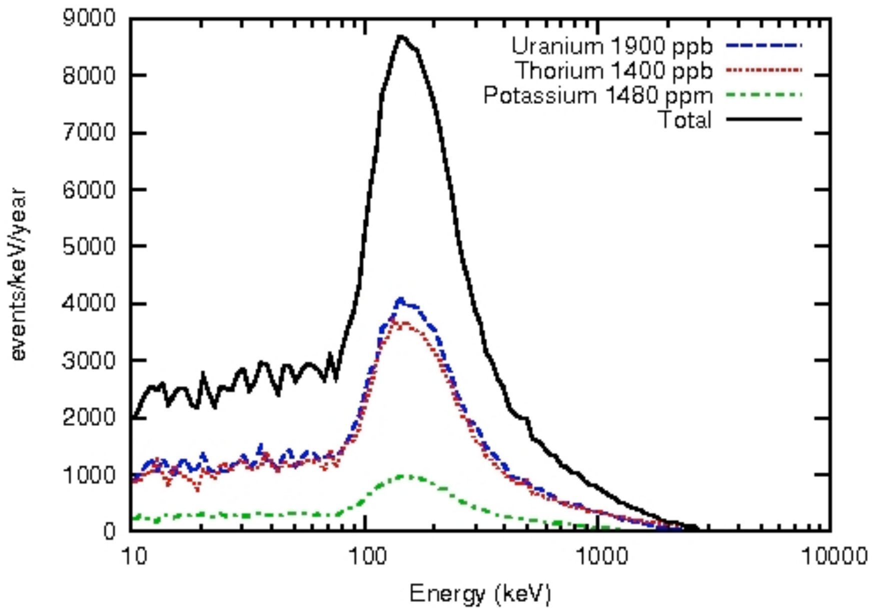
- ULISSE project for a new lab at Modane: water shielding along the walls (2 m thick).
- Another option at LSM: water shielding around a detector (EURECA, for instance). Also other experiments with planned water shielding, e.g. LUX.

Water shielding

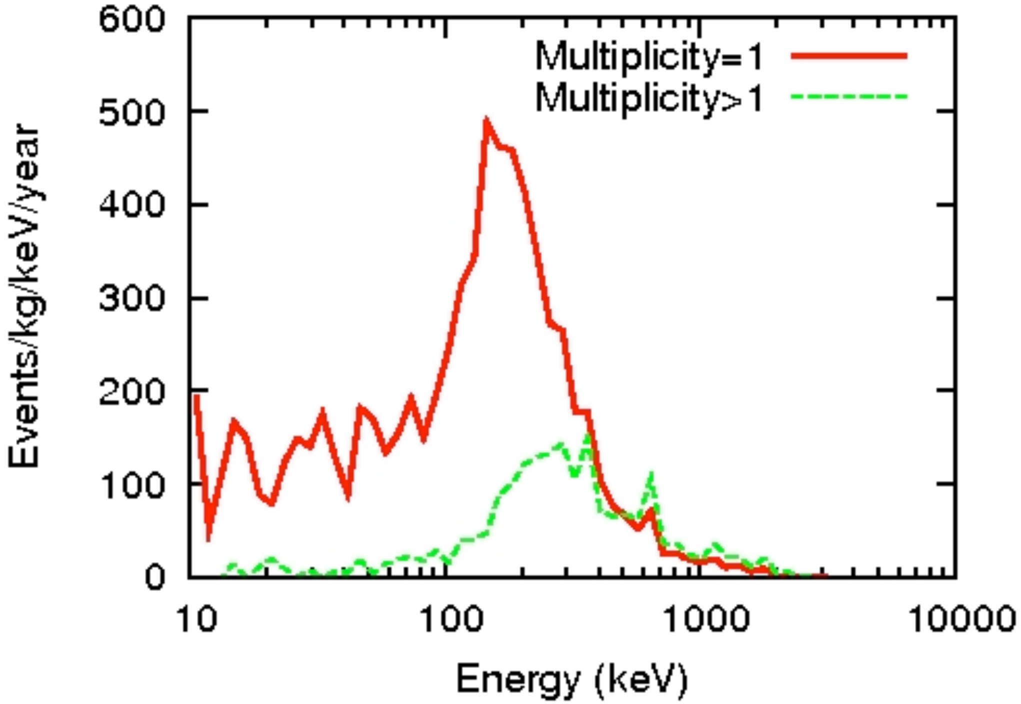


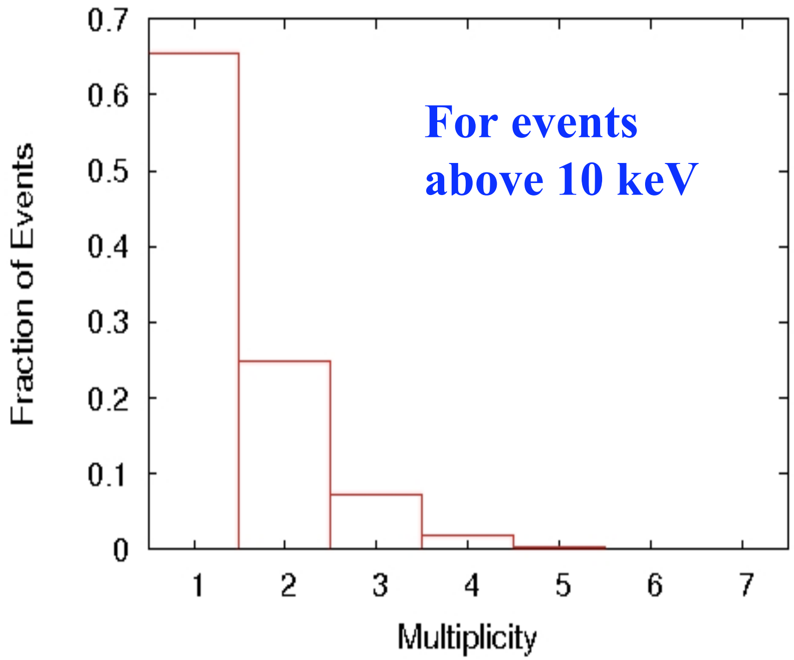
- Gamma-ray and electron fluxes from rock and concrete (Th): rock flux is less than 10% of that from concrete (30 cm of concrete).
- Simulations for Ge in EURECA.
- M. Robinson. Unpublished.

Rates in 100 kg of Ge (10-50 keV) beyond 2 m of water (single recoils):
1.9 ppm U - 4.6×10^4 ev/year;
1.4 ppm Th - 4.2×10^4 ev/year;
1480 ppm K - 1.1×10^4 ev/year;
Sum - $\sim1.0\times10^5$ ev/year.
Beyond 3 m: ~1200 ev/year.



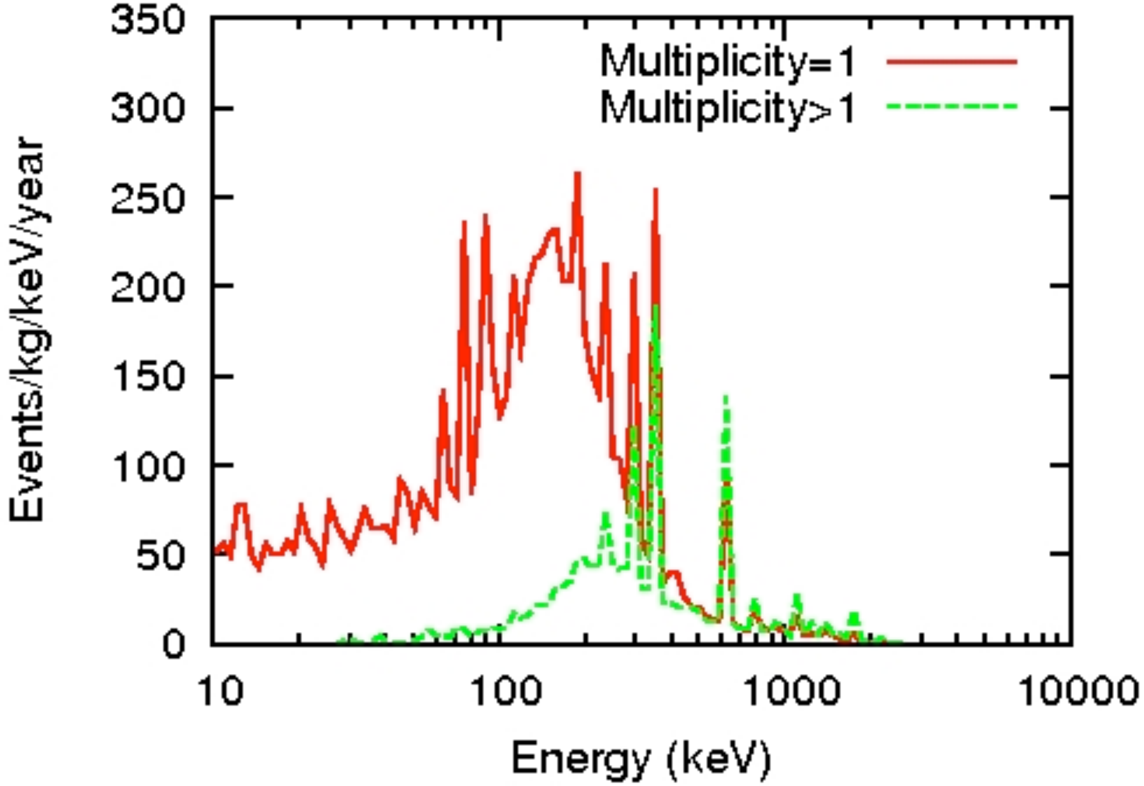
Stainless steel vessel of the water tank





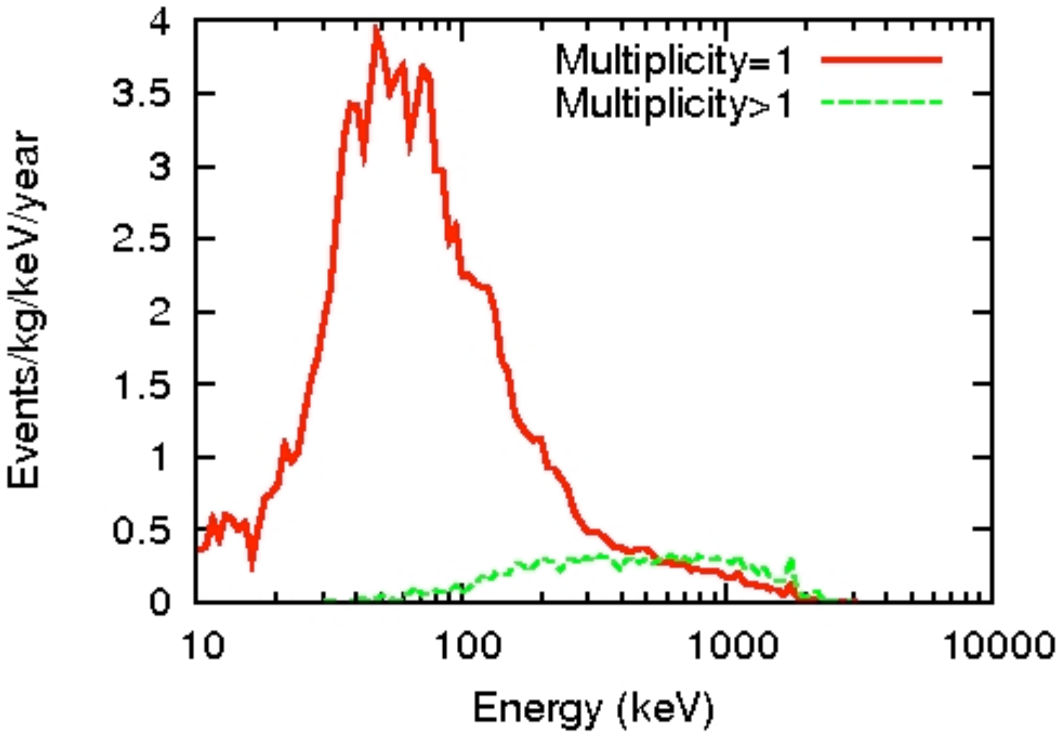
- **Typical concentrations: U - ~1 ppb, Th - ~1 ppb, K - ~ 1 ppm.**
- **Rate (10-50 keV, 100 kg Ge): ~8×10^5 ev/year (2 cm thick vessel).**
- **Can be reduced by a factor of 25 using inner shielding: 5 cm of Pb and 10 cm of CH_2 (need to be sure that Pb and CH_2 are less contaminated than steel).**

Detector vessels (cryostat)



- Energy spectrum shown is for U decay chain assuming 1 ppb, but typical concentrations in copper are 0.01 ppb U/Th, << 1 ppm K.
- Rate (10-50 keV, 100 kg Ge, ~300 kg copper): 6.4×10^{3} ev/year.
- If 10 kg of stainless steel is added (1 ppb U/Th), then the rate increases to 2×10^{4} y^{-1}.

Cryostat and inner shielding



Energy spectrum of single electron recoils from U in stainless steel vessel behind inner shielding: lead and polyethylene - more events at low energies due to the presence of polyethylene close to the crystals.

- **If the inner vessel is made out of steel (~400 kg, 1 ppb U/Th): 4.4×10^5 ev/year.**
- **Adding 5 cm of Pb and 10 cm of CH_2 inside the cryostat: 1.7×10^4 ev/year.**
- **But spectrum changes leading to more events at low energies.**
- **Polyethylene itself (0.1 ppb U/Th, 10 cm inside the cryostat) gives 10^5 ev/year.**
- **A few cm of copper should reduce the rate at 10-50 keV down to 10^4 ev/year; also removing surface events.**

Discrimination

- It looks like a gamma-ray suppression of at least 10^4 (most likely 10^5) is required. (Liquid argon needs better performance because of ^{39}Ar).
- Xenon-based detectors may require higher gamma-ray suppression because of the presence of the PMTs.
- Liquid noble gas detectors can use an active shield of outer volume of target reducing the fiducial mass (more expensive); this is more difficult for solid state detectors (active veto inside the cryostat?).
- Very promising measurements of U/Th/K concentrations in PMTs, stainless steel and copper by XENON100.

Neutron production in U/Th decay chains

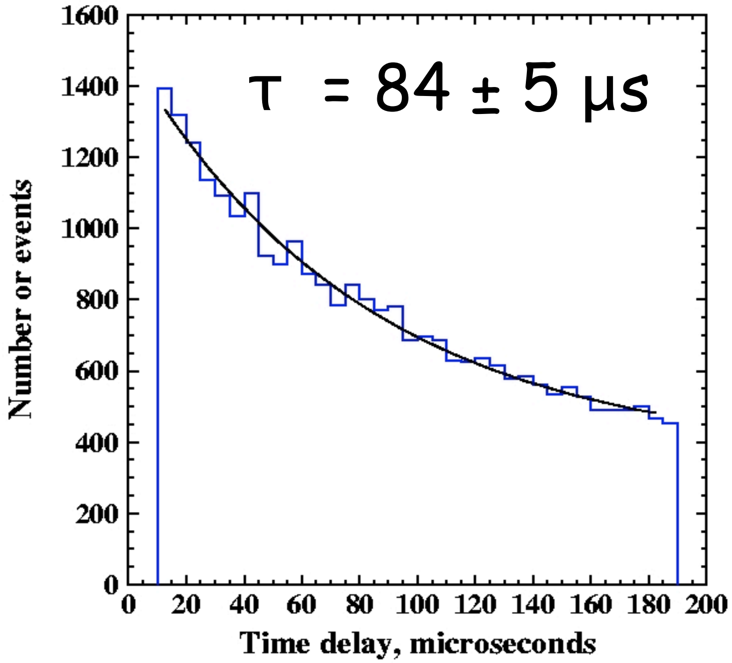
- Talk by Vito Tomasello (this session).
- SOURCES-4A (Wilson et al. SOURCES4A, Technical Report LA-13639-MS, Los Alamos, 1999) - code to calculate neutron flux and energy spectrum arising from U/Th contamination in various materials (new version - SOURCES-4C). Checked by the authors for various materials.
- Modifications to SOURCES: Carson et al. Astropart. Phys. 21 (2004) 667; Lemrani et al., NIMA 560 (2006) 454.
- Recent improvements (Tomasello et al. NIMA, 2008, hep-ph/0807.0851):
  - Calculation of cross-sections and excitation functions (probabilities of transitions to excited states) using EMPIRE-2.19 (http://www.nndc.bnl.gov/empire219). Checked by the authors (see also talk by Vito Tomasello).
- Transitions of the nucleus to excited states reduces neutron energies.
- Unlike gamma-ray spectra, neutron spectra depend on the material:
  - ^{238}U spontaneous fission dominates in high-Z materials; (α,n) reactions are important for low-Z elements ($Z<25$);
  - (α,n) cross-sections and neutron spectra are different for different isotopes.

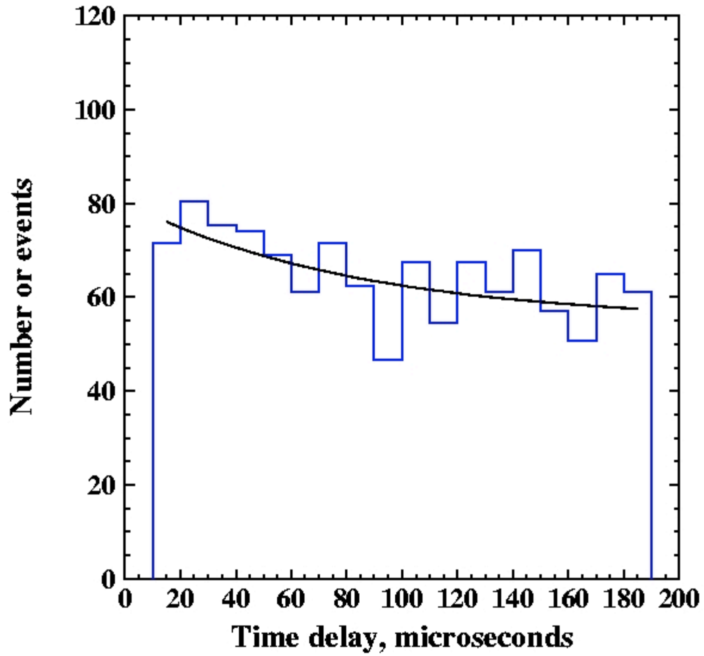
Comparing different rocks

- **Boulby - NaCl; Modane - O - 50% , Ca - 31%, C - 6%, Si - 7%, Mg - 1%, Al - 2%, H - 1%, Fe - 2% (Chazal et al. Astroparticle Physics (1998)).**
- **Higher U/Th concentrations in the Modane rock.**
- **Similar neutron yields due to lower thresholds of (α,n) reactions in Na and Cl - in Modane rock (α,n) reactions give 77% of neutron yield, in NaCl - 98%.**
- **Smaller neutron flux in the Modane lab - due to the presence of hydrogen: suppression by a factor of 1.8 above 1 MeV compared to the case without hydrogen.**
- **Details in Lemrani et al. NIMA 560 (2006) 454.**

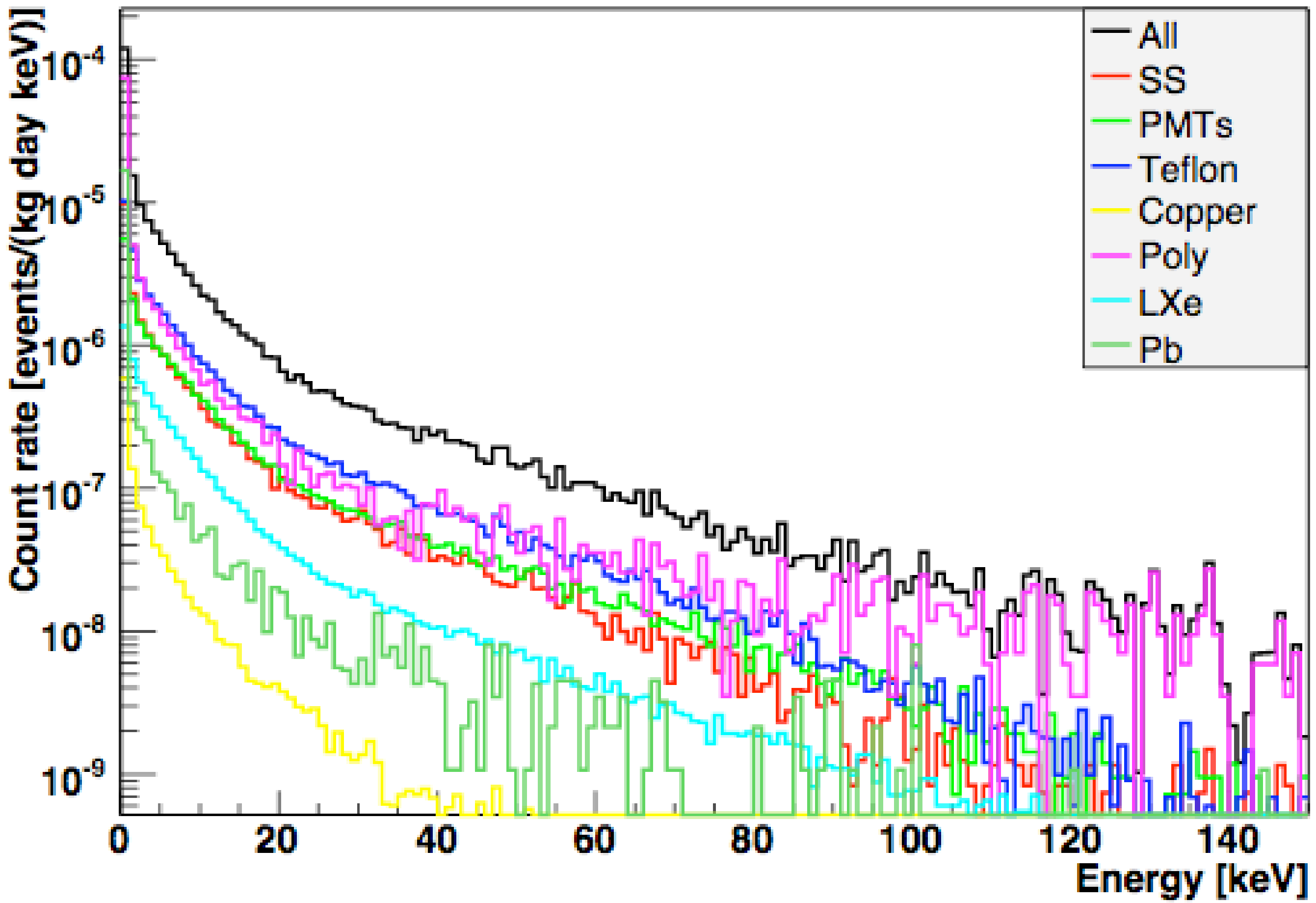
Checking MC

- Measurements of neutron flux in underground labs (Boulby, Modane etc.).
- Boulby: Gd-loaded liquid scintillator; signature: two pulses (proton recoils and gammas from neutron capture) in delayed coincidences (E. Tziaferi et al. Astroparticle Phys. 27 (2007) 326).
- Neutron flux at Boulby (>0.5 MeV): (1.72 ± 0.61 (stat) ± 0.38 (syst))×10^{-6} n/cm^{2}/s - in agreement with MC assuming measured concentrations of U/Th (1.20×10^{-6} n/cm^2/s).





Neutron background in XENON100

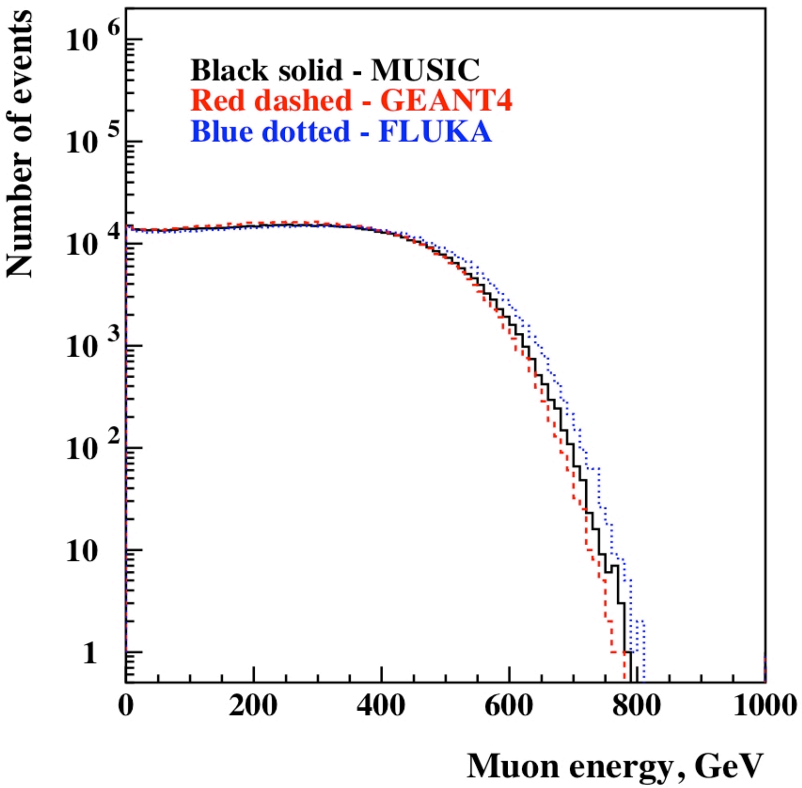


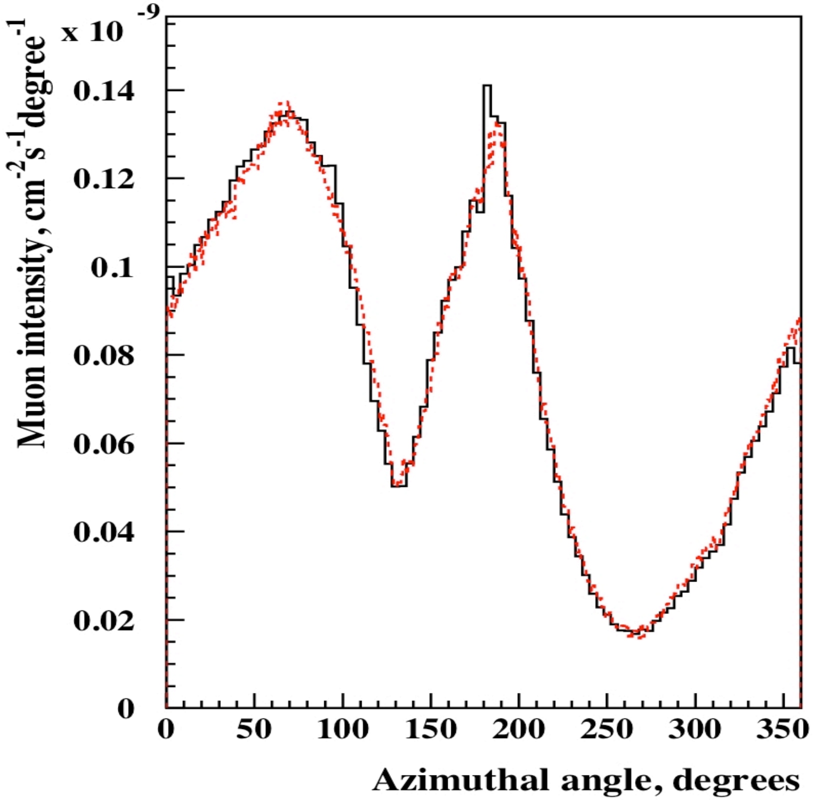
- E. Tziaferi. Talk at 4th Patras Workshop on Axions, WIMPs and WISPs DESY, Hamburg, 18-22 June 2008; L. Baudis, this Workshop.

Muon-induced neutrons

- **Inputs:**
  - **Muon rate - measurements at a particular underground site.**
  - **Muon spectrum and angular distribution (normalised to the total rate) - simulations or measurements (if available) - not a problem (for example, MUSIC code for muon propagation - Antonioli et al., Astrop. Phys. 7 (1997) 357, Kudryavtsev et al. Phys. Lett. B 471 (1999) 251 or MUSUN code for muon simulations underground - Kudryavtsev et al. NIMA, 505 (2003) 688).**
  - **Neutrons from muons - production, propagation, detection together with all other particles (muon-induced cascades): GEANT4 (GEANT4 Coll. NIMA, 506 (2003) 250) or FLUKA (Fasso et al. Proc. MC2000 Conf., Lisbon, 2000, p. 159; ibid. p. 995).**
- **Important: all particles should be produced, propagated and detected with one code to look for simultaneous detection of neutrons and other particles, such as photons, electrons, muons, hadrons.**
- **FLUKA calculates kerma factors as average energy depositions from nuclear recoils - not very accurate treatement on event-by-event basis.**

Muon flux and interactions



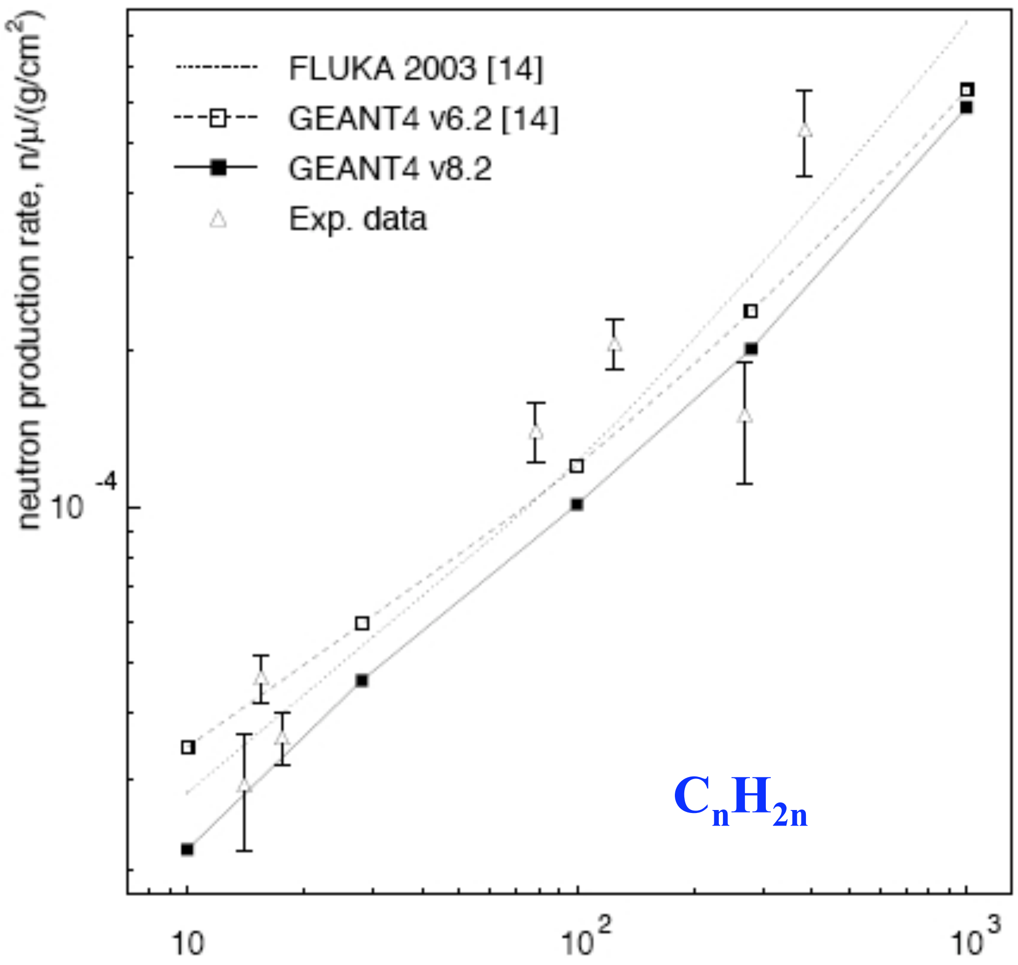


Muon transport through 3 km w.e. in standard rock (2 TeV muons):

A. Lindote et al. In preparation.

Angular distribution at LNGS (MUSUN):
V. Kudryavtsev et al. EPJA, 36 (2008) 171.
$<E_\mu>$: MUSUN - 273 GeV;
MACRO (meas.) - 270 ± 3 (stat) ± 18 (syst).
Versions exist for LNGS, LSM, Boulby, Soudan.

Dependence on muon energy



- Neutron production rate in $(CH_2)_n$ (liquid scintillator):

FLUKA - Kudryavtsev et al. NIMA, 505 (2003) 688;

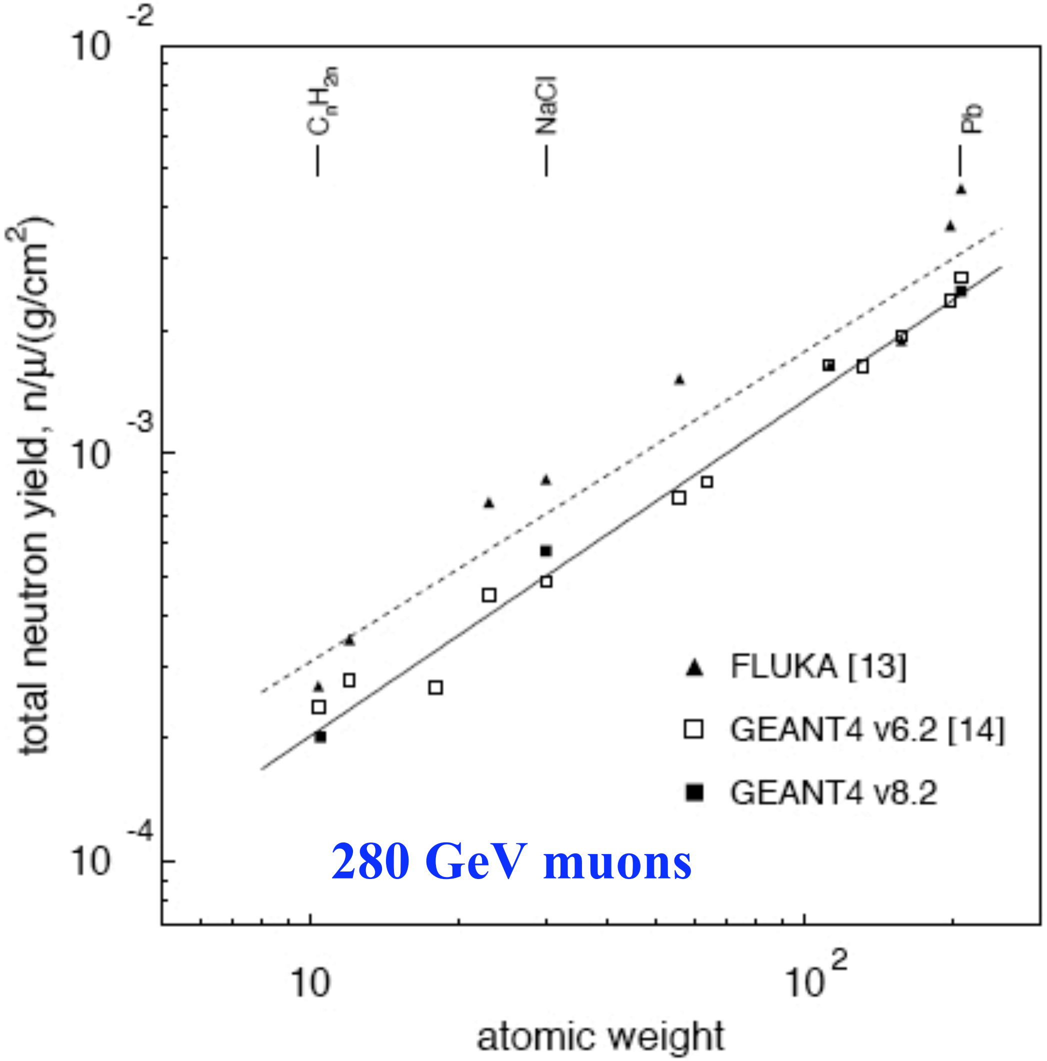
GEANT4 v6.2 - Araujo et al., NIMA 545 (2005), 398; hep-ex/0411026;

GEANT4 v8.2 - Lindote et al., in preparation.

Similar simulations by M. Horn, M. Bauer and others.

- No accurate simulations of the detector geometry and response for any of the experiments at large depths.
- Smaller neutron yield in GEANT4 v8.2 than in v6.2 and FLUKA.

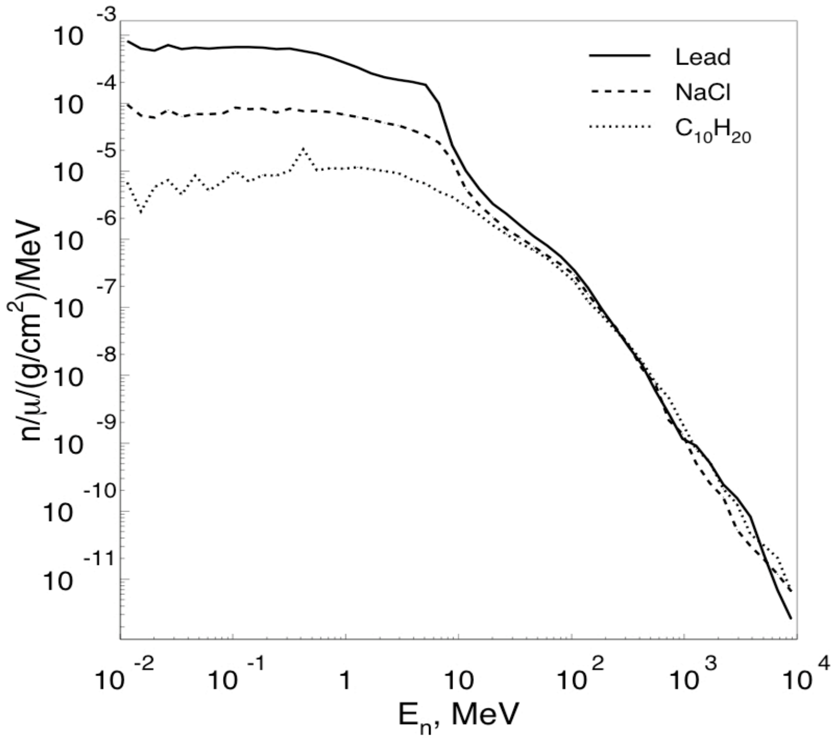
Muon-induced neutrons: A-dependence



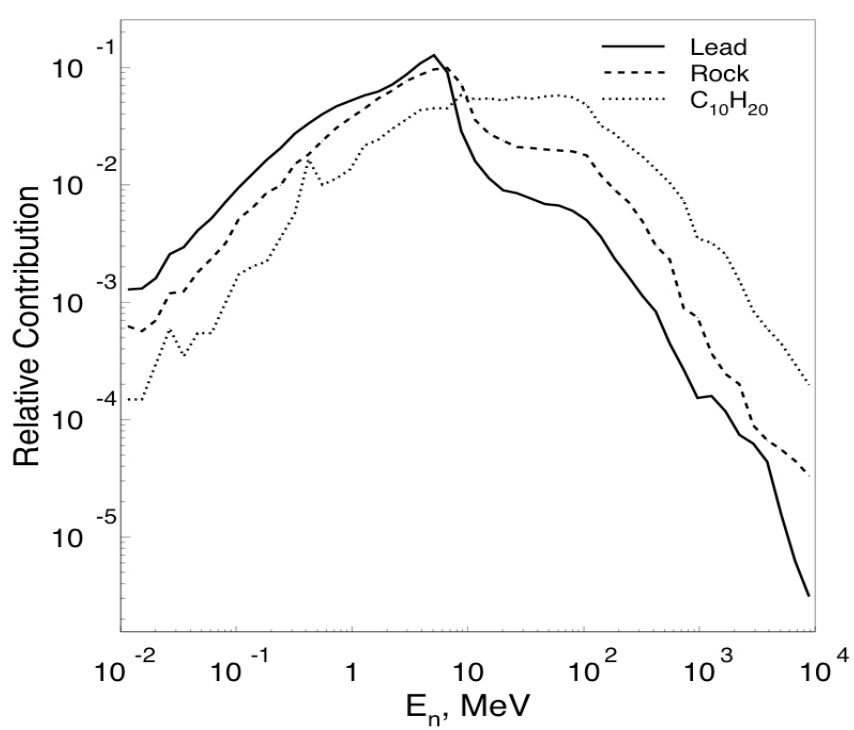
A-dependence of neutron production rate -
GEANT4 v6.2: Araujo et al. NIMA 545 (2005), 398;
GEANT4 v8.2: Lindote et al., in preparation;
FLUKA: Kudryavtsev et al.
FLUKA gives twice as many neutrons as GEANT4 in most materials tested.

Energy spectra in different materials

Differential spectrum

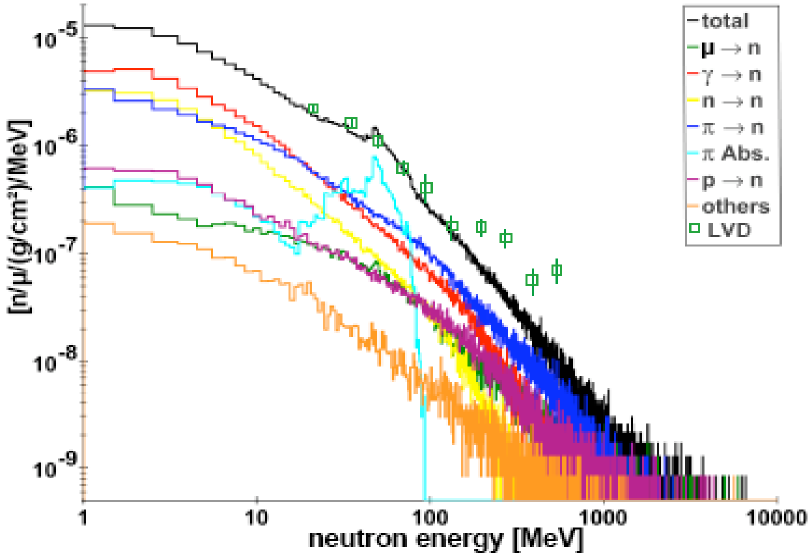


Integrated over each energy bin

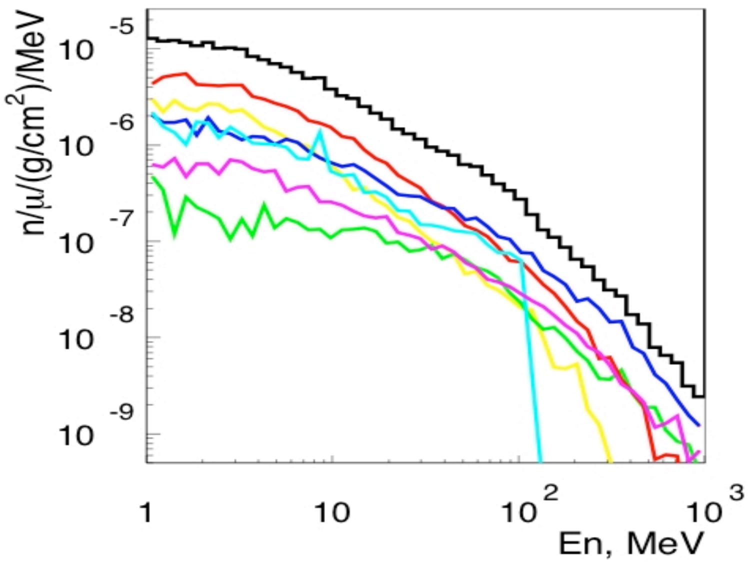


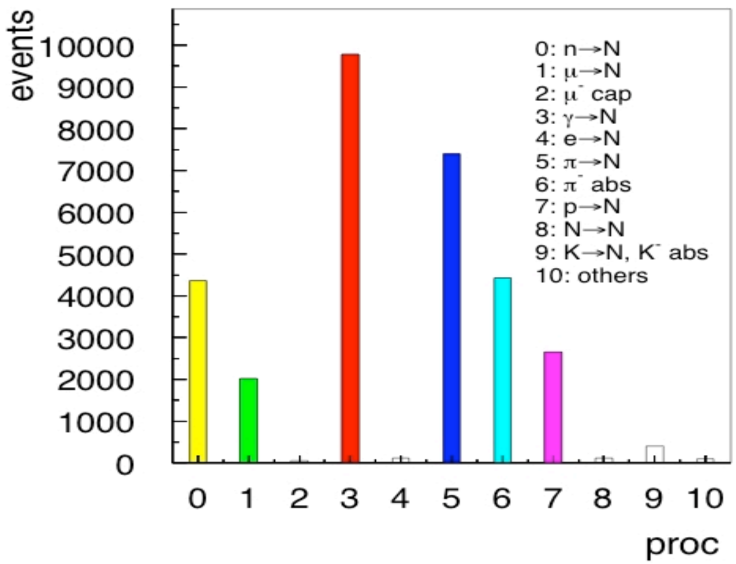
- **Energy spectrum depends on the material: large enhancement in neutron intensity for high-A targets is seen mainly below 20 MeV.**
- **Mean neutron energies at production: C_nH_{2n} - 65 MeV; NaCl - 23 MeV; Pb - 8.8 MeV (GEANT4 v8.2; Lindote et al., in preparation).**

Energy spectrum

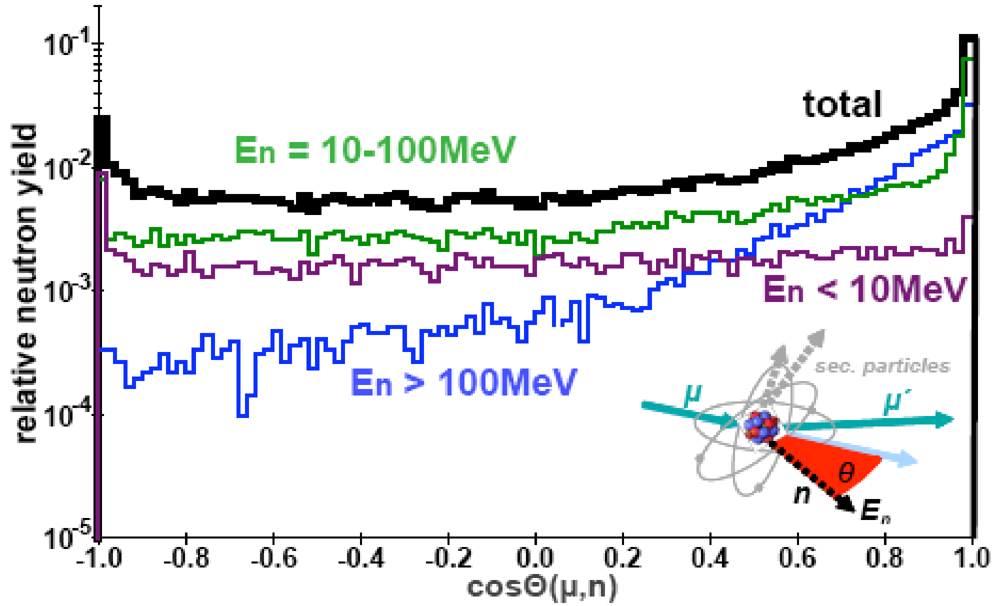


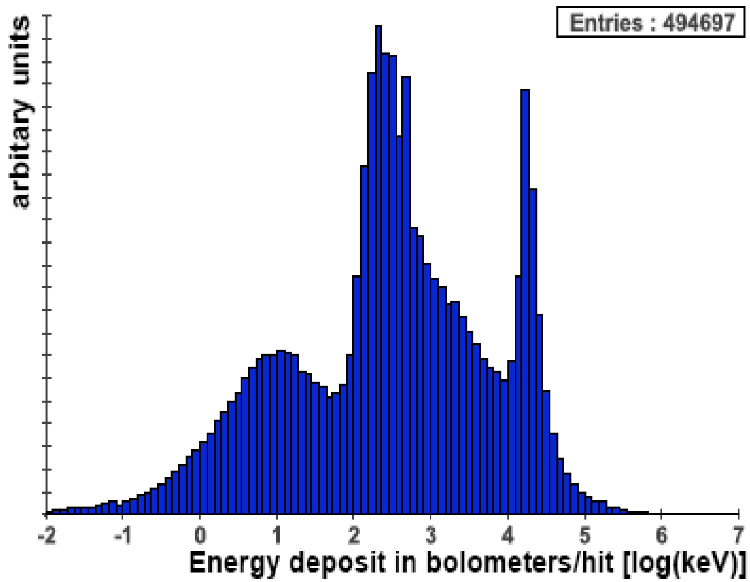
- **Contributions of different processes to the neutron spectrum in C_nH_{2n} (280 GeV muons);**
- **Left - GEANT4 v8.1, G4PiMinusAbsorptionAtRest; M. Horn. PhD Thesis, U. of Karlsruhe (2007).**
- **Below - GEANT4 v8.2, QcaptureAtRest (CHIPS); A. Lindote et al., in preparation.**





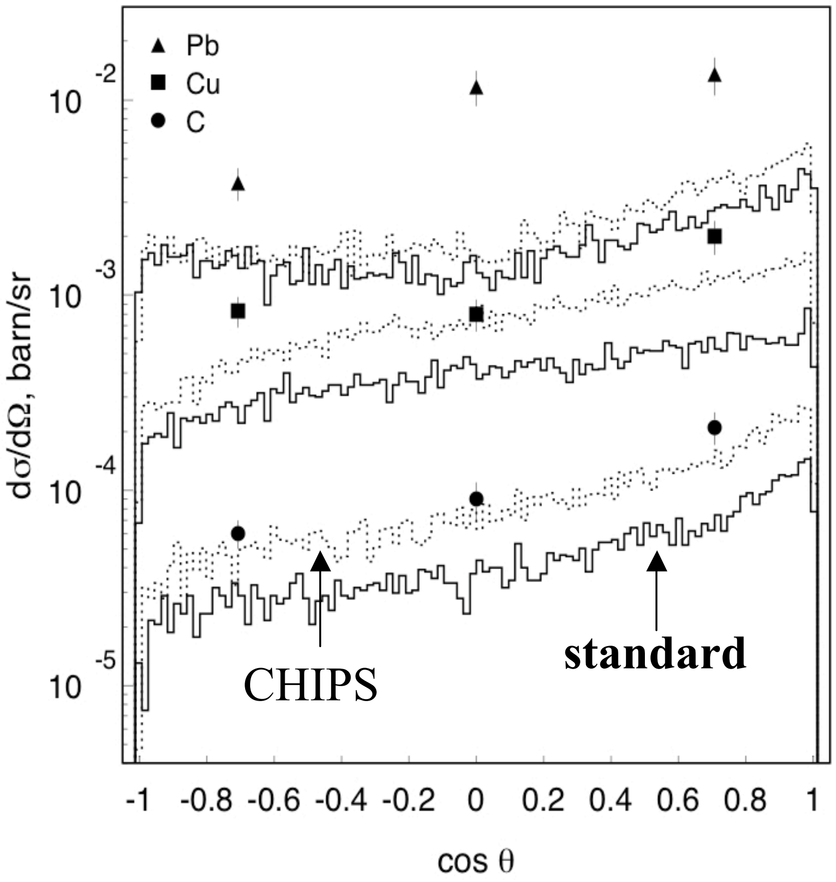
Neutron angular distribution





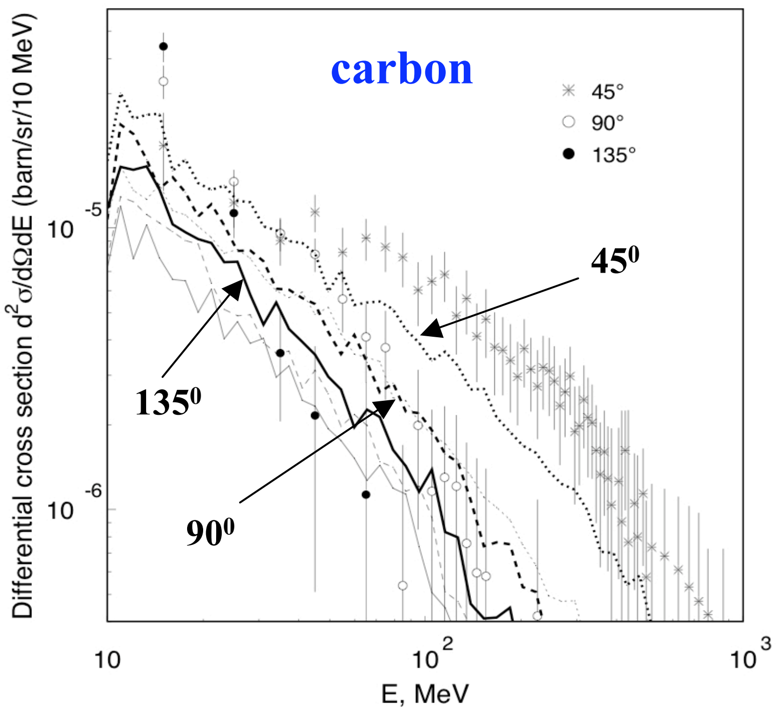
- M. Horn. PhD Thesis, University of Karlsruhe (2007).
- Correlation between muon and neutron direction - need for full 3D Monte Carlo and transport of all particles.
- Energy spectrum of events in EDELWEISS-II:
  - neutron-induced nuclear recoils mainly below 20 keV;
  - backscatter (~200 keV) and annihilation (511 keV) peaks from gamma-rays;
  - muon energy deposition above 10 MeV (~20 MeV peak from vertical muons).

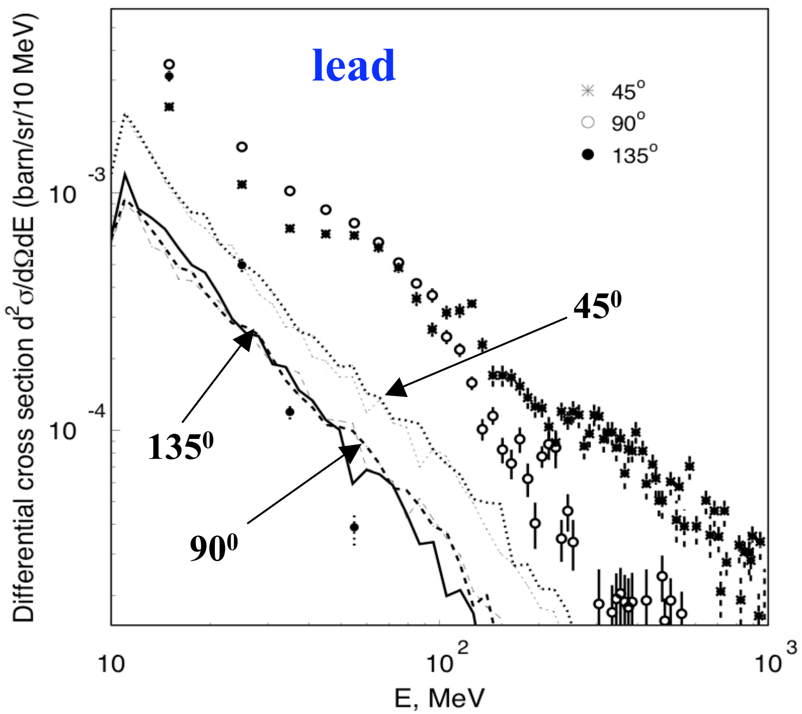
Muon-induced neutrons: problems



- **Cross-section of neutron production in thin targets for 190 GeV muons (E_n>10 MeV). Lower solid histograms - GEANT4 v8.2 'standard'; upper dashed histogram - GEANT4 CHIPS (CHiral Invariant Phase Space) (Lindote et al.); data - NA55 (Chazal et al. NIMA, 490 (2002) 334).**
- **Other data for lead (Bergamasco et al. Nuovo Cim. A, 13 (1973) 403; Gorshkov et al. Sov. J. Nucl. Phys., 18 (1974) 57) are old and controversial but also show significantly higher neutron production compared with simulations.**
- **Lead is important since it is used as a shield in DM experiments.**
- **New measurements using dark matter detectors or active veto systems.**

Muon-induced neutrons: problems





- **None of the models can explain the measured spectra (NA55 experiment) for any target.**
- **Is this a problem of the models or the measurements?**

Summary - I

- **Gamma-rays:**
  - GEANT4 and DECAY0 are in reasonable agreement for generating gamma-ray spectra above 100 keV.
  - Water as a shield against gamma-rays - at least 3 metres or 2 metres plus inner shielding.
  - If water is placed along the walls, then stainless steel of the tank will produce high background.
  - All materials close to the fiducial volume (in direct visibility) should have concentrations of U/Th less than 0.01 ppb. Only a few tens of kg of materials with much higher concentrations may produce a detectable background rate.
- **Low-energy neutrons:**
  - EMPIRE2.19 plus experimental data (if available) give (α,n) cross-sections and excitation functions quite reliably.
  - Modified SOURCES4A calculate accurately thick target neutron yield and spectra.
  - Accurate measurements of neutron fluxes from rock and from radioactive sources confirm the reliability of neutron transport and detection using GEANT4 and MCNPX.

Summary - II

- **Muon-induced neutrons:**
  - Models (codes, in particular, GEANT4) are still under development.
  - FLUKA and GEANT4 agree within a factor of 2 (even better for some materials and energies).
  - Most experimental data (although with large uncertainties) are also in agreement with simulations within a factor of 2; some data show significantly higher neutron yield in heavy materials. However, comparison is not straightforward since full Monte Carlo is absent for most of the data sets. More measurements and simulations are needed.
  - All particles should be transported down to the detectors in muon-induced cascades, not just neutrons.