The Progress Since Mei& Hime's Paper

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Worldwide Efforts

- Comparison between experiments and simulations
  - LANL/TUNL neutron beam experiments
  - DEAP/CLEAN, Majorana/GERDA, CUORE, KamLAND, LVD, BOREXINO, LUX, MAX, Xenon-100, CDMS, EXO, ZEPLIN-II, EDELWEISS, CRESST, Daya Bay, Double CHOOZ, and S4 groups, etc
  - Homestake, Gran Sasso, Boulby, SNO, LSM, Soudan, Canfranc, Kamioka, Daya Bay, CHOOZ, etc

Discrepancy, Discrepancy, Discrepancy

Important, Important, Important

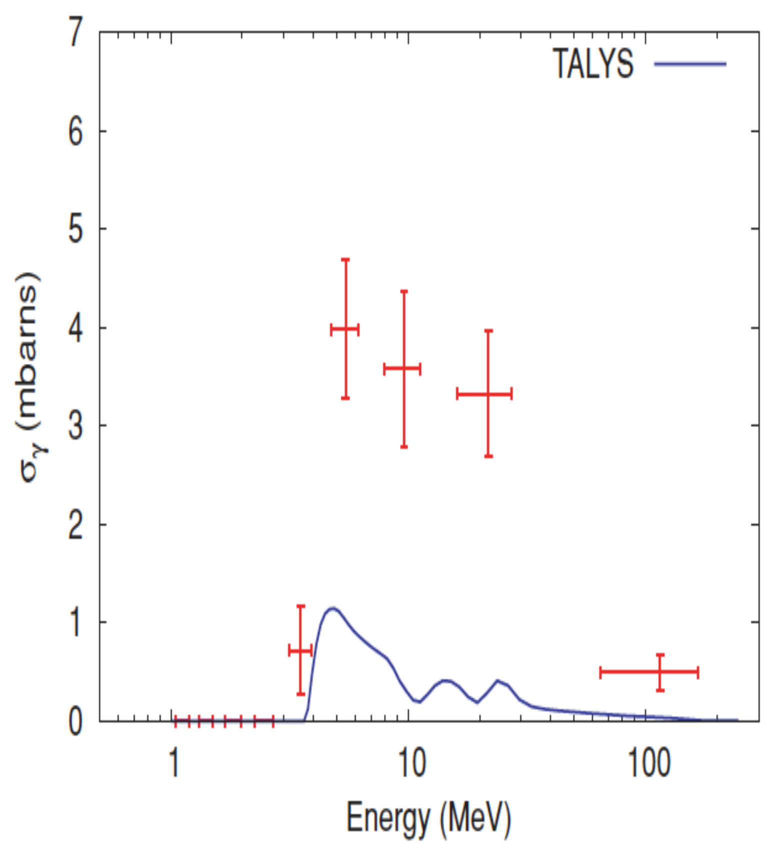
LANL Beam Experiments

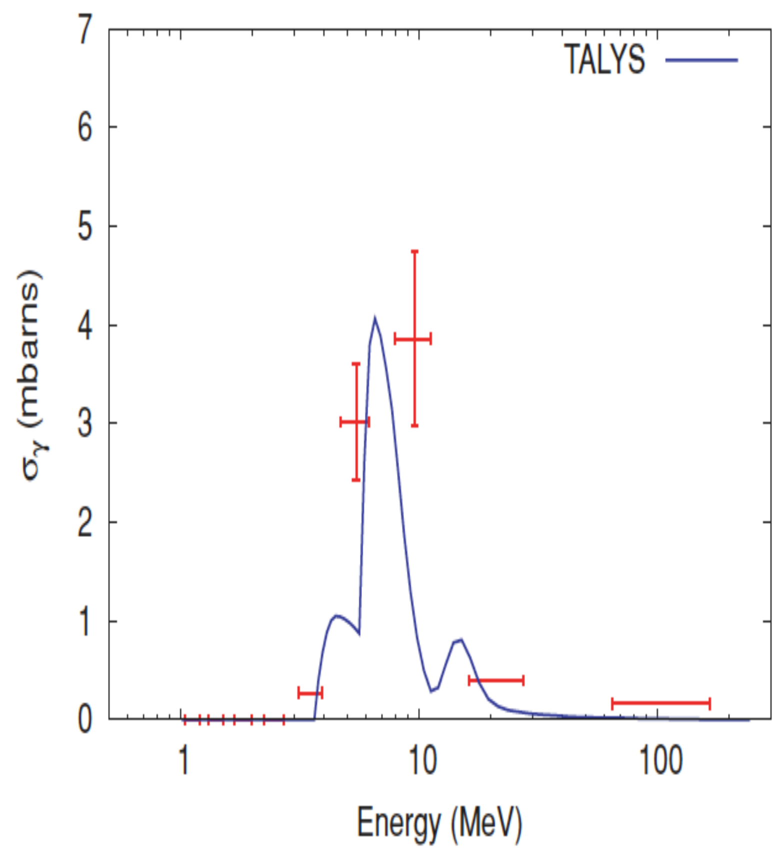
- Motivated by possible background in the ROI (2041 keV, and 3062 keV) induced by neutron inelastic scattering processes

$$^{206}Pb(n,n'\gamma),^{207}Pb(n,n'\gamma),^{208}Pb(n,2n'\gamma),...$$

- Two publications so far
  - PRC 77, 054614 (2008)
  - PRC 79, 054604 (2009

Some Results





Summary of muon-Induced Background I

1. Muon-induced neutrons in the surrounding rock
   - Cannot be vetoed
   - Can be attenuated by water
2. Muon-induced neutrons in the water
   - Neutron elastic scattering induced by through-going muons can be vetoed
   - Neutrons generated by stopping muons through negative muon capture cannot be vetoed

$$\mu^- + {}^{16}O \rightarrow {}^{15}N + n + \nu$$

$$\mu^- + {}^{16}O \rightarrow {}^{14}N + 2n + \nu$$

3. Muon-induced neutrons in the xenon as an example
   - Neutron elastic scattering induced by through-going muons can be vetoed
   - Neutrons generated by stopping muons through negative muon capture

$$\mu^- + Xe \rightarrow I + n + \nu$$

$$\mu^- + Xe \rightarrow I + \nu$$

May be vetoed

$$\mu^- + Xe(gas) \rightarrow I + \nu$$

$$\mu^- + Xe(gas) \rightarrow I + n + \nu$$

May not be vetoed

Summary of muon-Induced background II

1. Muon directly induced cosmogenic production

A. Negative muon capture $\mu^- + Xe \longrightarrow I + n + \nu$

B. Muon spallation

$$\mu \longrightarrow \widehat{\gamma}$$

$$\widehat{\gamma} + Xe \longrightarrow N^* + n(p, \pi, \mu, \gamma, etc)$$

2. Cosmogenic production by muon-induced processes

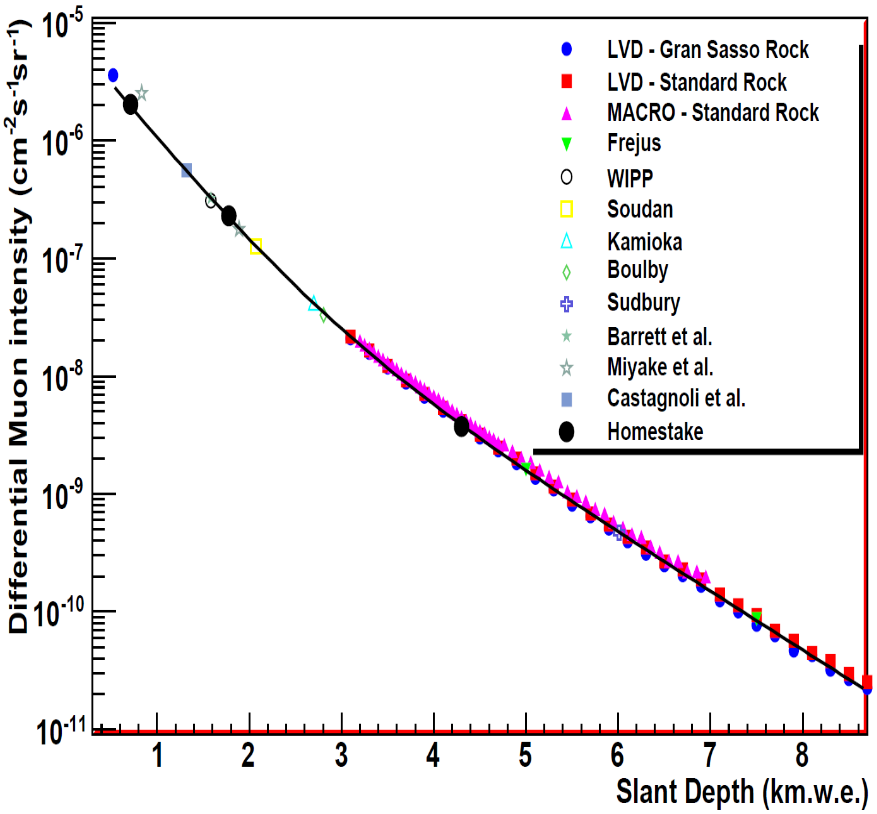
A. Neutrons produced by muon-induced processes (showers) in the target

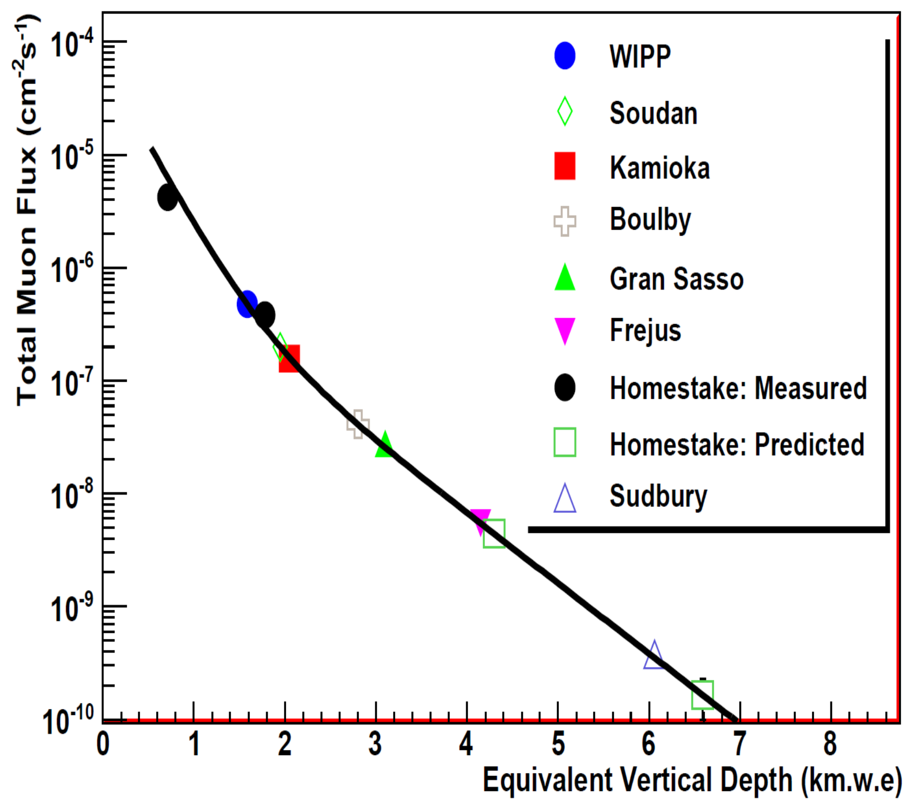
B. Neutrons emerging in the target when they were produced by muon-induced processes (showers) in the surrounding materials

Muons and Neutrons

Muon flux at the 4850-ft level

Through-going muons





Muon flux at Homestake: F. Gray et. al. , accepted by NIM for publication, Mei &Hime, PRD 73, 054003 (2006)

Muon energy spectrum

- We simulated muons with an energy spectrum locally generated in an effective rock layer
  - Uncertainty in the energy spectrum
  - Uncertainty in the mean muon energy
  - Uncertainty in low energy muons
- It would be good to simulate muons using the surface energy spectrum
  - It takes very long time to have meaningful results
  - Uncertainty in the surface muon energy spectrum above TeV
  - Uncertainty in the rock compositions for large overburden

Localized Muon Energy Spectrum

$$\frac{dN}{dE_\mu} = Ae^{-bh(\gamma_\mu - 1)} \bullet (E_\mu + \varepsilon_\mu (1 - e^{-bh}))^{-\gamma_\mu}$$

A: a normalization constant with respect to the differential muon intensity at a given depth

E_μ: muon energy after crossing the rock slant depth *h (km.w.e.)*

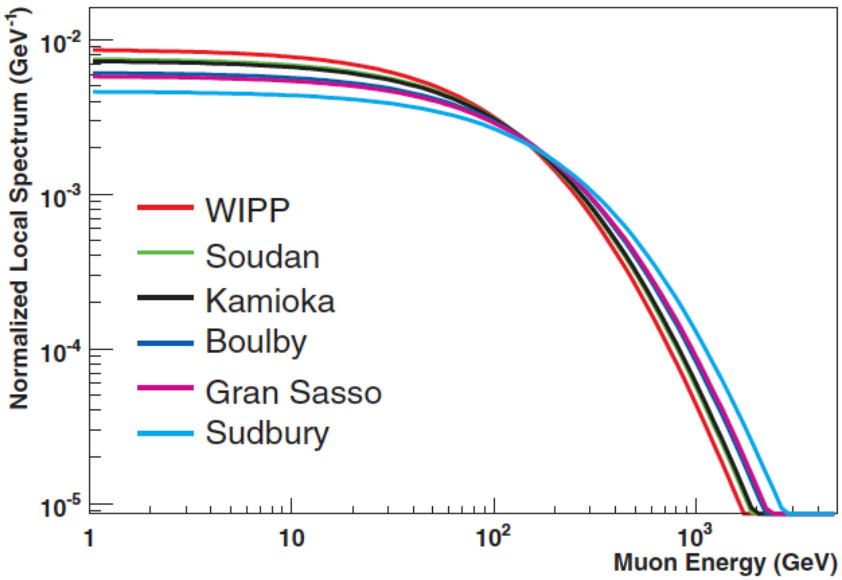
b: 0.4/km.w.e. (Groom's), 0.383/km.w.e. (Lipari et al.)

ε_μ: 693 GeV (Groom's), 618 GeV (Lipari et al.)

γ_μ: 3.77 (Groom's), 3.7 (Lipari et al.)

Comments: model dependent parameters, the sources of uncertainty.

Localized Energy Spectrum cont. (Mei &Hime, PRD 73, 053004, 2006)



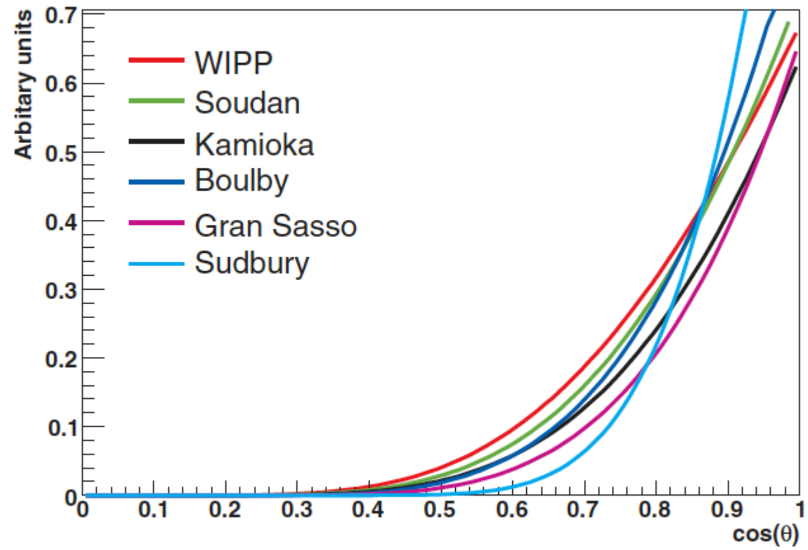


TABLE II. Single muon average energies for the various underground sites.

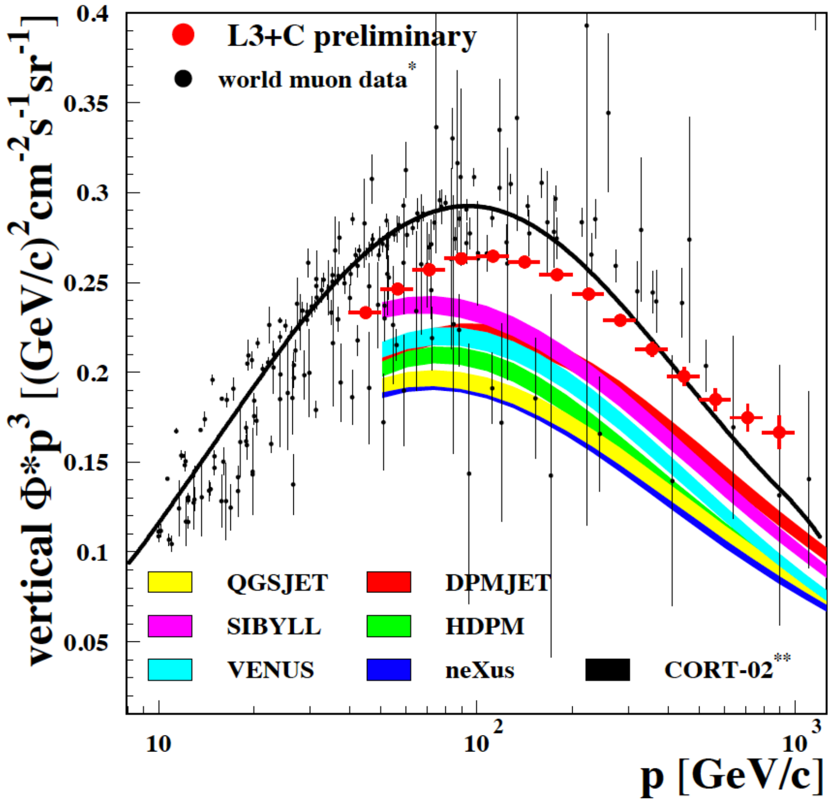
Site	Lipari *et al.*	Groom *et al.*	Measured value
WIPP	165 GeV	184 GeV	
Soudan	191 GeV	212 GeV	
Kamioka	198 GeV	219 GeV	
Boulby	239 GeV	264 GeV	
Gran Sasso	253 GeV	278 GeV	270 ± 18 GeV [21]
Sudbury	327 GeV	356 GeV	

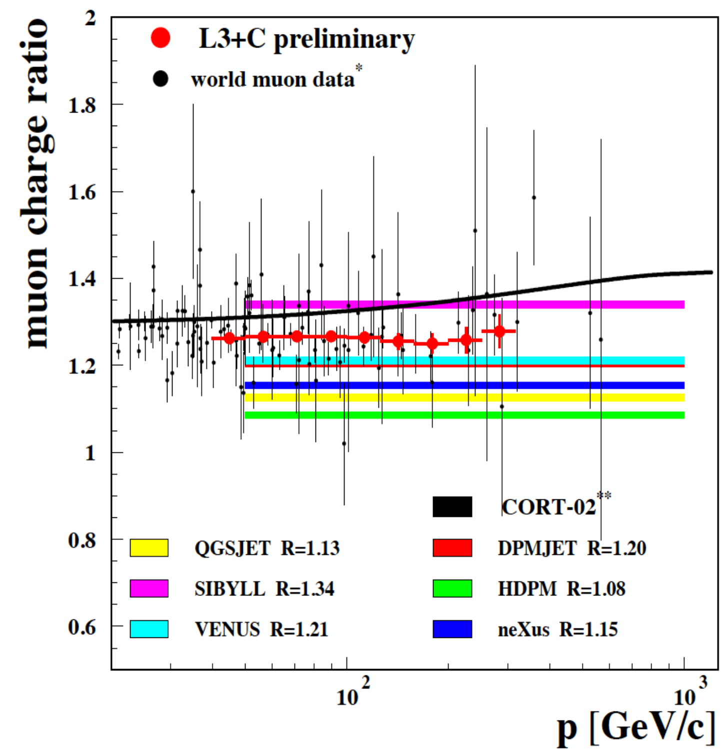
Comments:
Model dependent, the uncertainty can be as large as ~10% between the models

Muon Energy Spectrum on the Surface

- What energy is required for a muon to reach the depth of 4300 m.w.e. from the surface?
  - Standard rock: $E_T > 2.8$ TeV
  - Do we have a well measured muone energy spectrum on the surface above 2.8 TeV?
- What about boundary effects when high energy muons propagate through the rock?
  - CSDA is usually used in the energy loss in media for high energy muons. What about the different layers of the rock with different density?
  - Stopping power fluctuations and straggling
  - Multiple scattering and density effects
- How well do we know the rock chemical composition distribution?
- Hong long does it take to run a meaningful simulation?

Muon Energy Spectrum on the Surface Cont.





hep-ph/0102042
hep-ph/0201310

Muon energy spectrum on the surface Cont. (Yu.F Novoseltsev et al.)

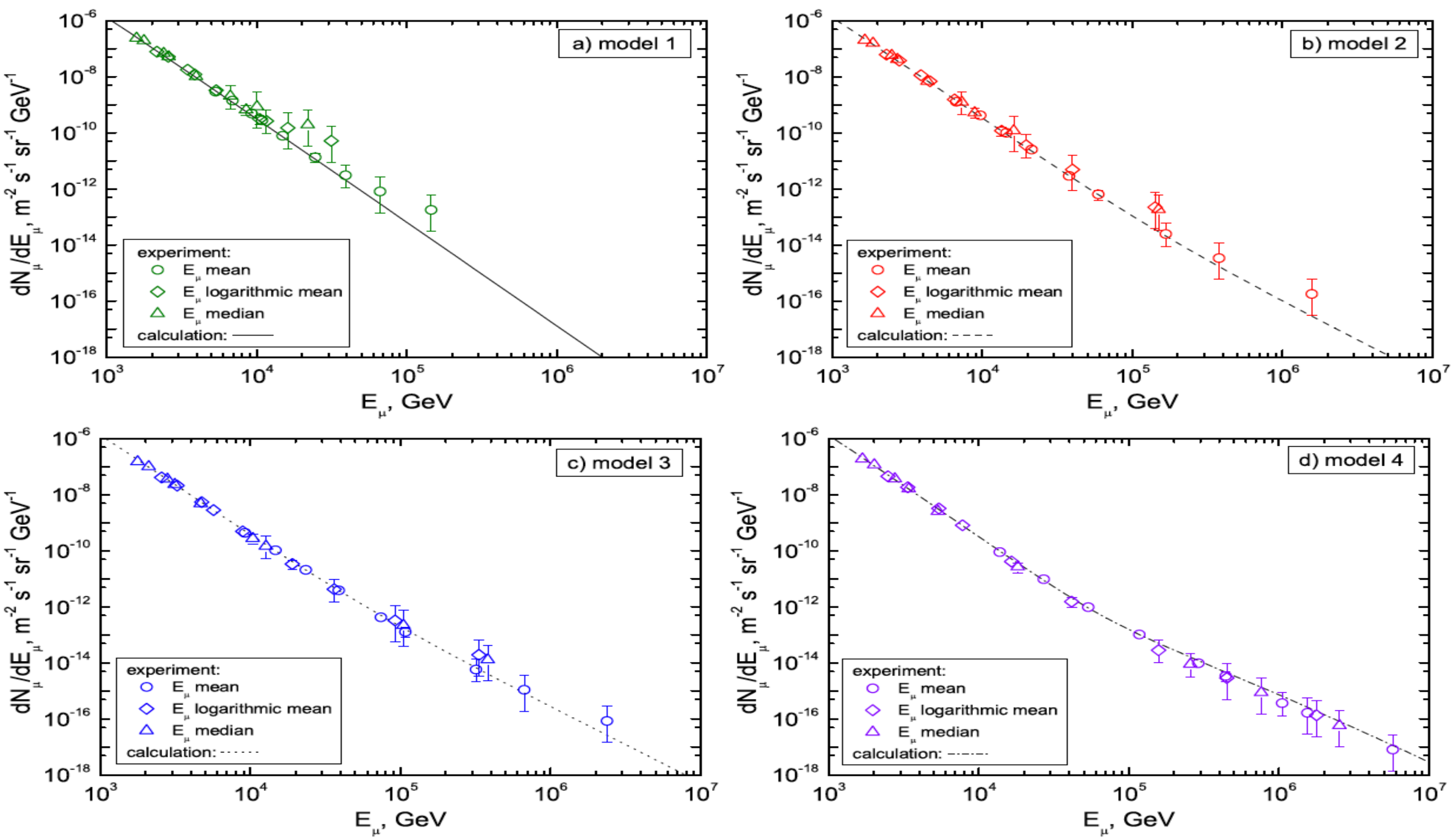


Figure 5: Differential muon energy spectra reconstructed from BUST data on multiple interactions at different assumptions on muon spectrum model (a,b,c,d) with different choice of effective muon energy: mean (circles), logarithmic mean (diamonds), and median (triangles).

Summary on the muon energy spectrum in the simulation

- Localized muon energy spectrum
  - Model dependent
  - Uncertainty can be large
- Muon energy spectrum on the surface
  - Again model dependent
  - Uncertainty is at least on the order of 30 – 50%

Muon charge ratio impact the secondary particles by stopping muons

Low energy muons generated backgrounds (a paper is in preparation)

- Negative muons
  - Muonic atoms (X-ray emission)
  - Capture on nuclei (gamma-ray, neutrons, protons, etc emission)
  - Atomic and Nuclear recoils induced by the above processes
- Positive muons
  - Muonium atoms (muon acts as nucleus, MuXe?)
  - Decay

Stopping muon flux

1. **At the 4850-ft level (4300 mwe), the stopping muons is 0.5% of through-going muons for a 100 g/cm^2 detector. How reliable is this estimation?**

2. **Scaling factor: M/A, M: mass of the target, A: the effective area with respect to the incident muon direction**

Reference: PRD 7, 2022 (1973)

Therefore the negative stopping muon flux varies with the shielding materials and target

Without a good measurements, it is hard to estimate the uncertainty

Negative Stopping muon Capture cross-section

$$\sigma = \frac{A}{N_0 t v \rho}$$

A: Atomic mass number of nucleus
N_0: Avogadro constant
t: Lifetime in the target
P: Density of the target

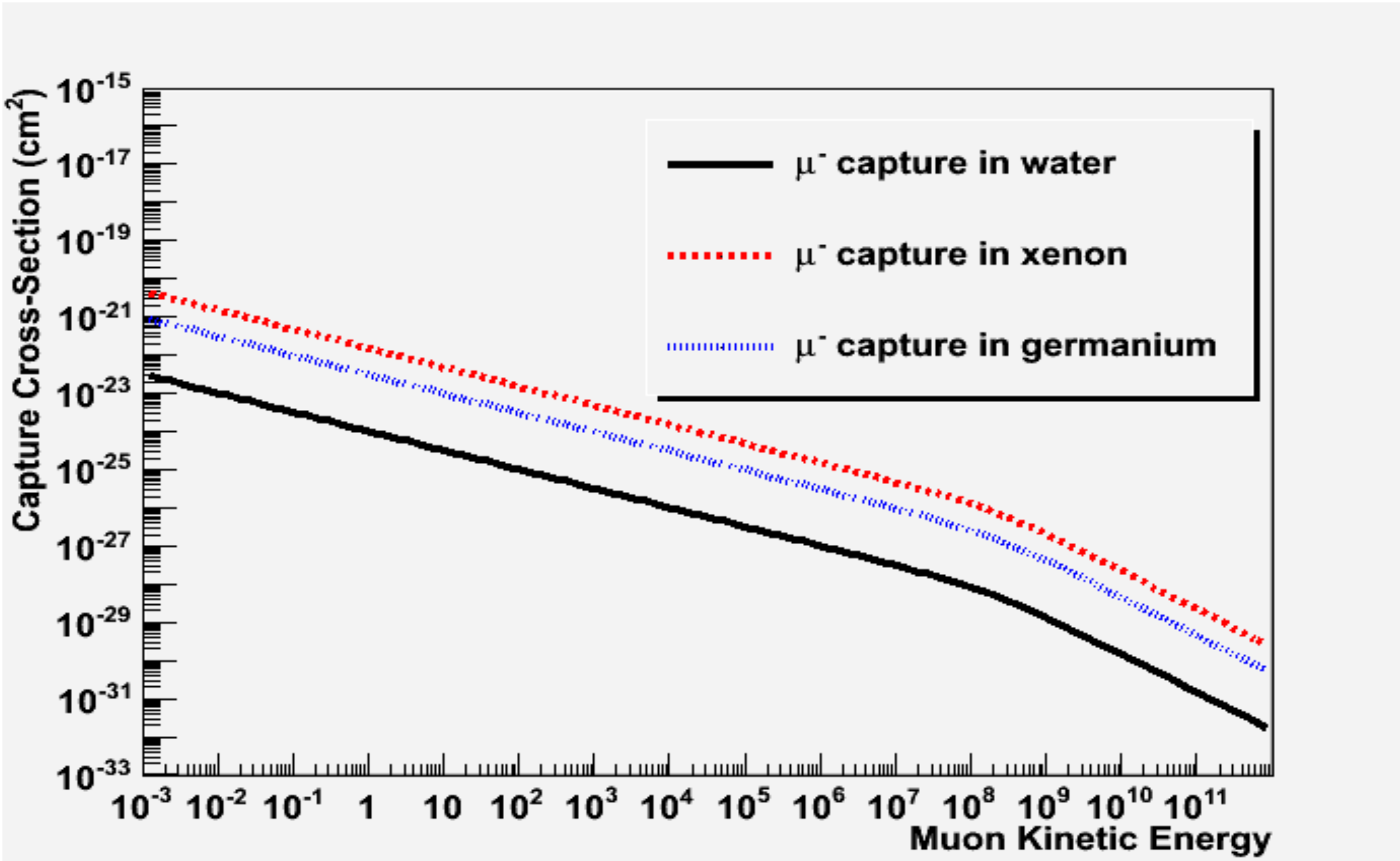
$$\frac{1}{t} = \frac{1}{t_0} + \frac{1}{t_c}$$

t: Lifetime in the target
t_0: lifetime in vacuum
t_c: capture time in the target (101.7 ns in xenon)

$\sigma = 1.1 \times 10^{-21} cm^2$

Reference: Mei ei al., PRC 81, 055802 (2010), Mamedov et al, JETP Letters, 69, (1999) 192-195

Negative Muon Capture Cross Section



$$\mu^- + (Z,A) \rightarrow (Z-1,A)^* + \nu$$

$$u^- + (Z,A) \rightarrow (Z-1,A-1) + n + \nu + \gamma$$

Summary of the uncertainty on low energy muons

1. Local low muons generate by high energy muons through different processes
2. There is no good measurements on the low energy muons in different target
3. Scaling method may not be reliable

Comments:

The total uncertainty could be as large as a factor of 10.

What could be done?

Measuring muons:

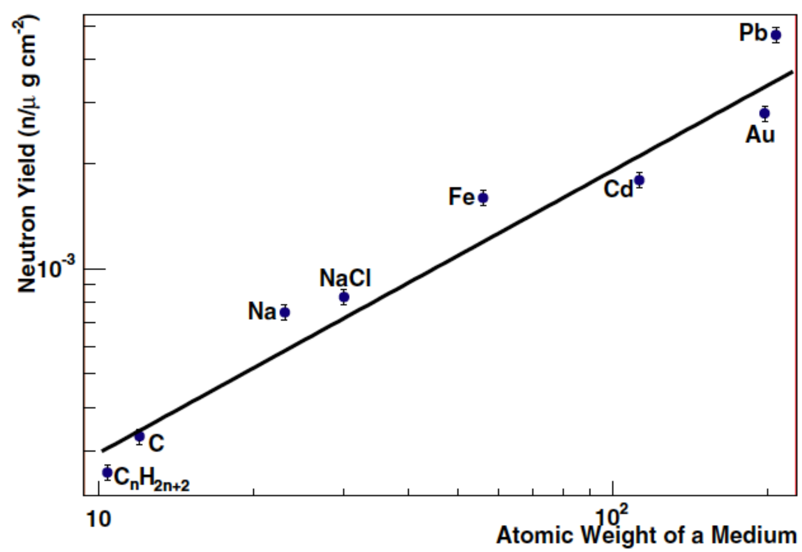
1) Bai at SDSMT proposed to measure muons with a surface array in coincidence with the underground detector. It needs to be further investigated.
2) Measuring muons on the site with water Cherenkov detectors
3) We also need to measure the energy spectrum and how? Liquid scintillation detector
4) Measuring low energy muons generated by through-going muons with Michel electrons? Other ways to measure negative muon capture?

Neutron yield uncertainty

1. Due to initial muon energy spectrum: ~30% or higher
2. Due to low energy muons production: ~a factor of 10 (not dominant at large depth in terms of neutron yield)
1. Due to high energy muon interaction with different nuclei: ~10%
2. Due to unknown cross section of high energy muons and secondary particles interacting with heavy nuclei: ~100% to 500% (a few papers)

Comments:

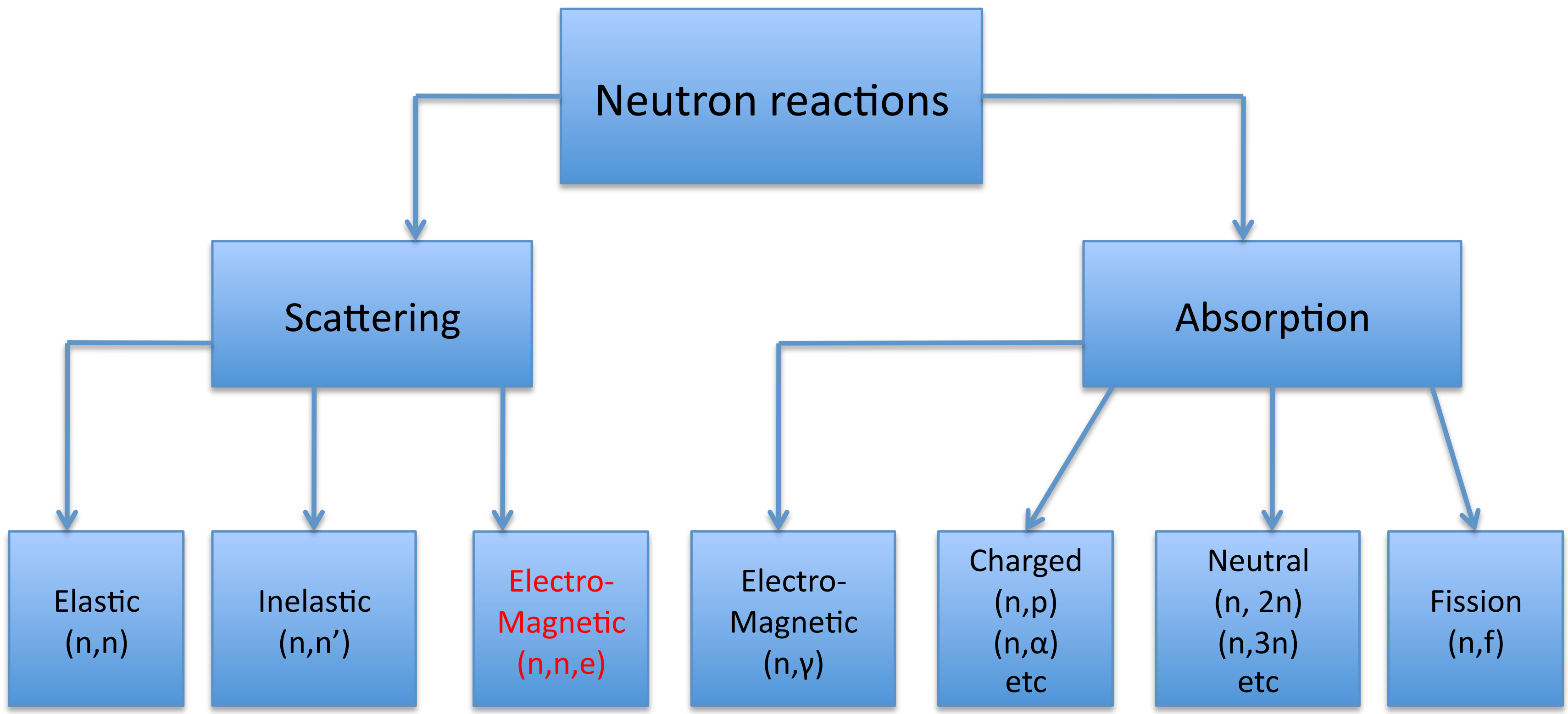
Neutron yield could have an uncertainty as high as factor of 1-5 depending on the target.



Neutron energy spectrum uncertainty

1. The uncertainty is large with respect to different target
2. Low neutron emission is model dependent
3. High energy neutron emission is constrained by physics such as high energy muon interaction with media

Neutrons Reactions



Neutrons are problematic

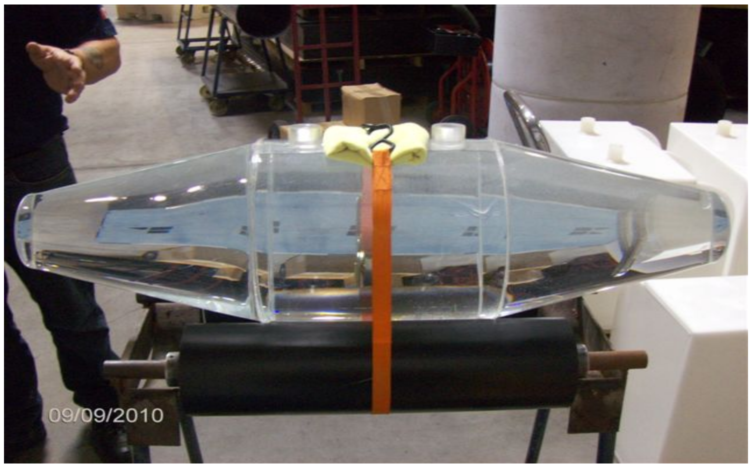
1. Neutrons from natural radioactivity
   a) Flux is on the order of 10^{-6} $cm^{-2}s^{-1}$, gamma-ray flux is a few × $cm^{-2}s^{-1}$
   c) Energy ranges from keV to MeV
   d) Flux annual modulates
   e) Must be measured continuously during the course of DUSEL
2. Neutrons from muon-induced processes
   a) Flux is on the order of 10^{-9} $cm^{-2}s^{-1}$ in the laboratory hall
   b) Energy ranges from keV to Gev
   c) Flux annual modulates
   d) Flux dependence on the targets
   e) Very complicated production process
   f) Very hard to veto
   g) Large uncertainty on the production processes
   h) Difficult to simulate correctly
   i) Must be measured continuously during the lifetime of DUSEL

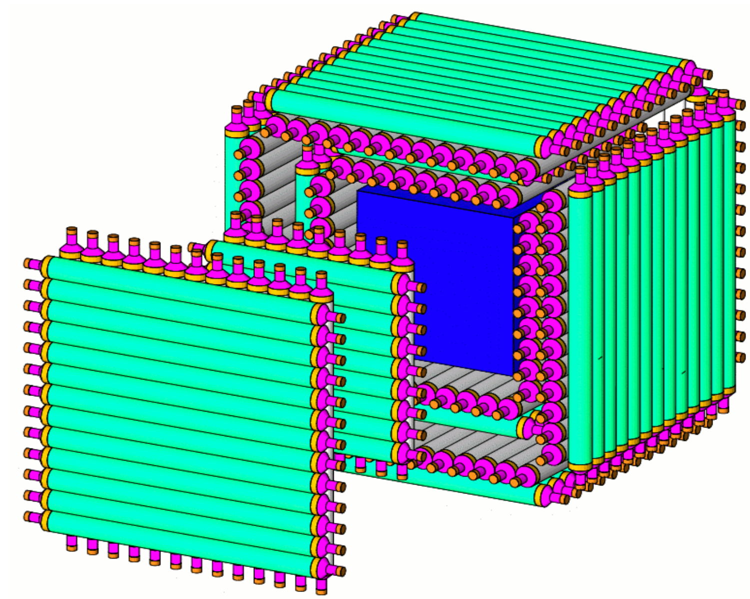
Measuring neutrons

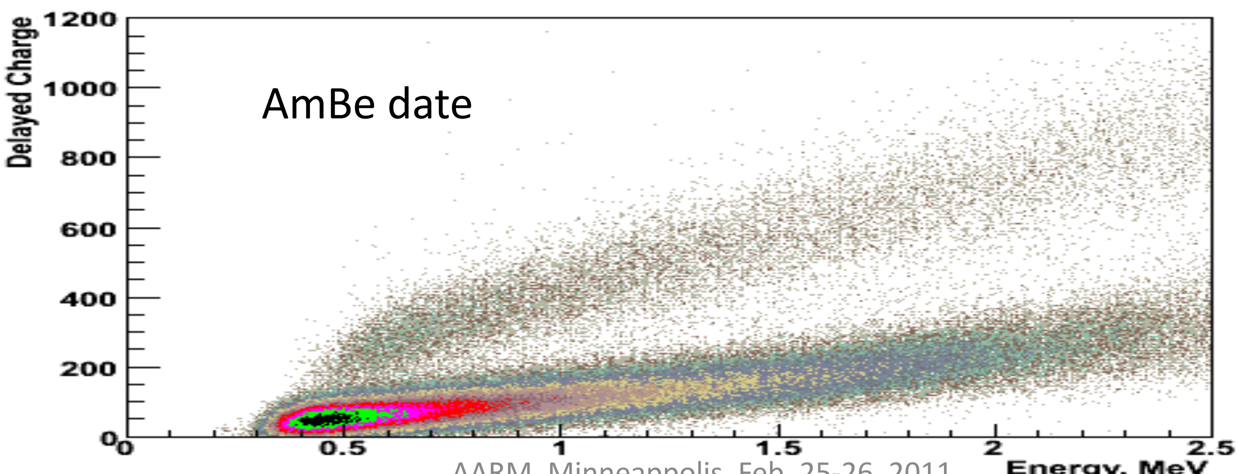
1. Must have n/g discrimination capability
   a) Scinillator, germanium detector, and TOF
2. Must be able to measure high energy neutrons
   a) Neutron attenuation in lighter elements and TOF
3. Must be large enough to measure neutrons
   a) Big detector or detector array
4. Must also measure muons and various showers
   a) Detector array
5. Must also measure the multiplicity
   a) Gd-doped water Cherenkov detector

A hybrid detector array that consists of liquid scintillators and Gd-doped water

Hybrid Detector Array

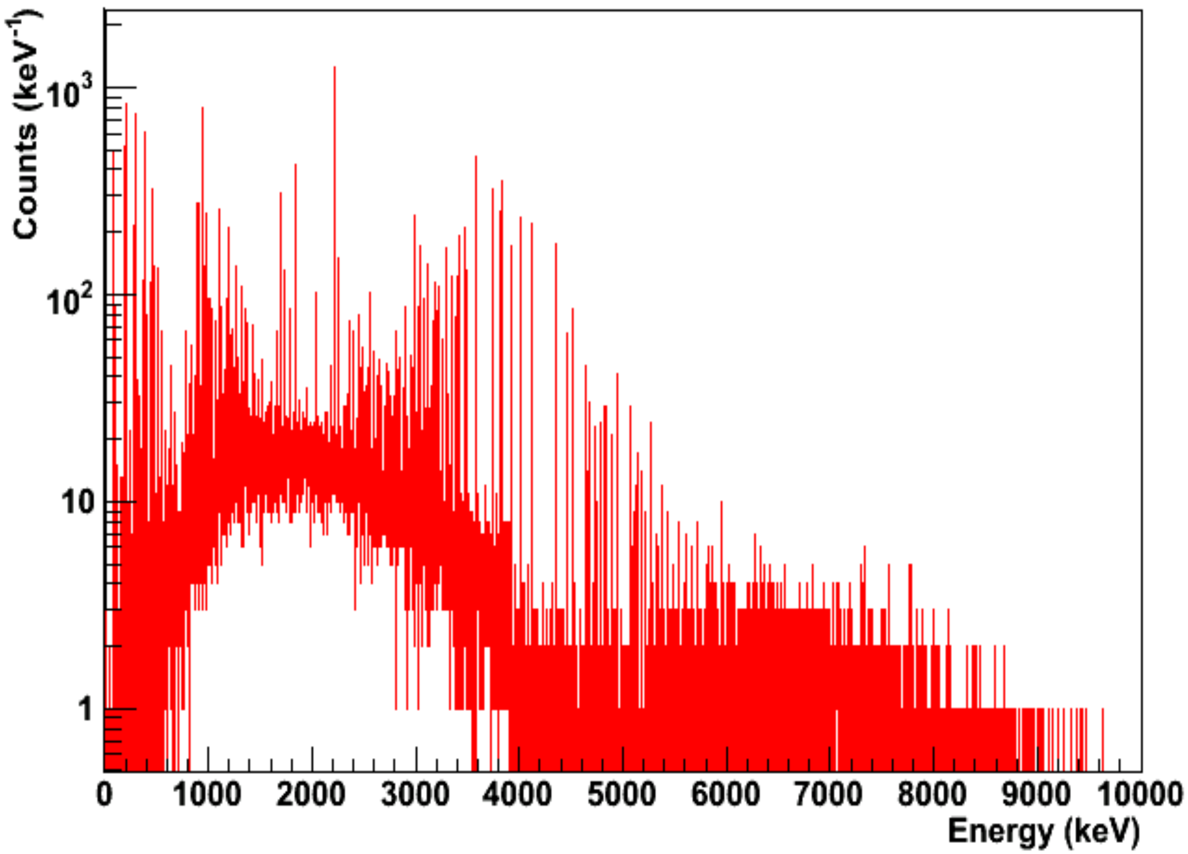






Gd-doped water Cherenkov detector

1. 0.2 % of Gd-doped concentration
2. 46 liters of total liquid volume
3. Acrylic tube



Status of the project

1. The current NSF funding is being implemented and one scintillator is built. One Gd-doped water Cherenkov detector is being built.
2. The renewal NSF funding has been submitted. This proposal will allow us to build 8 more detectors in next three years.
3. A major research instrument proposal is being planned to build 252 detectors in total.
4. The detector array will be in operation at DUSEL in 2016.