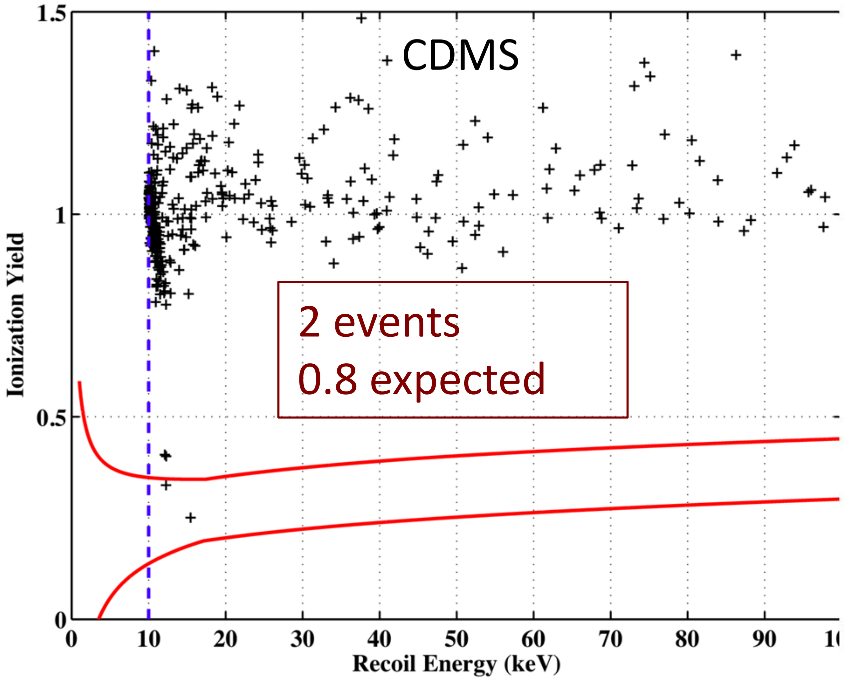
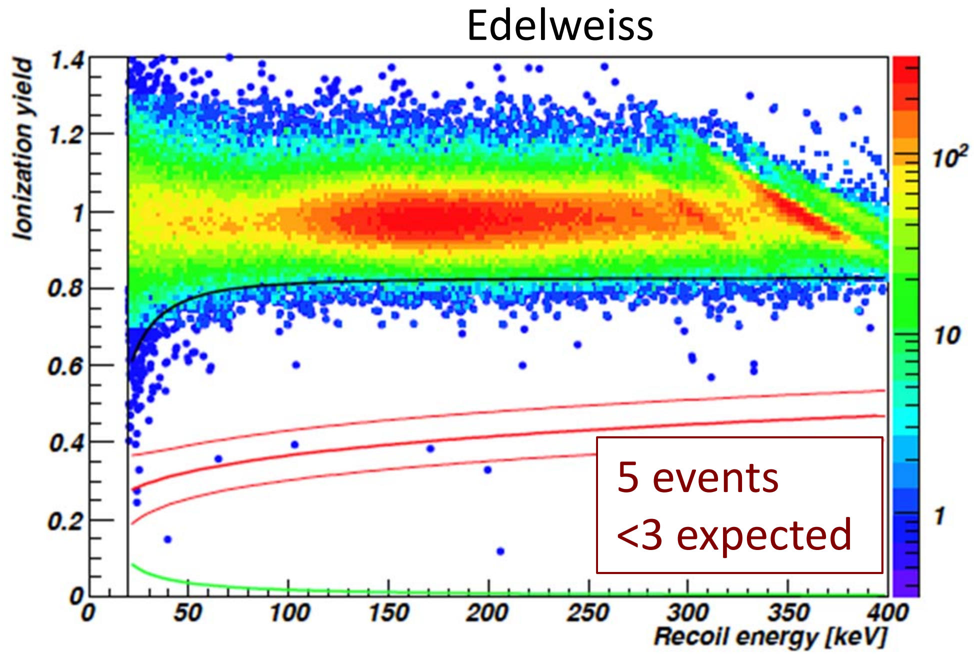
# Standardized tools for Underground Science: Radiogenic and Cosmogenic Backgrounds

Priscilla Cushman
University of Minnesota

Patras Workshop
Mykonos, June 27, 2011

# ***WIMP hints*** or just poorly understood background?



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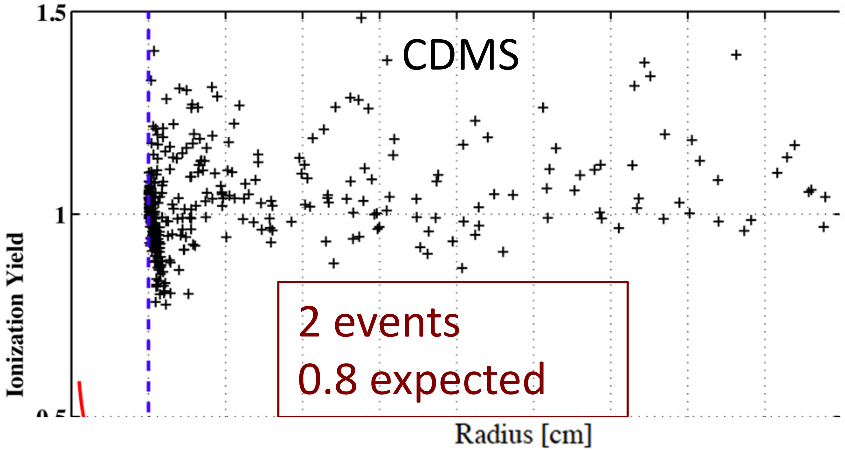


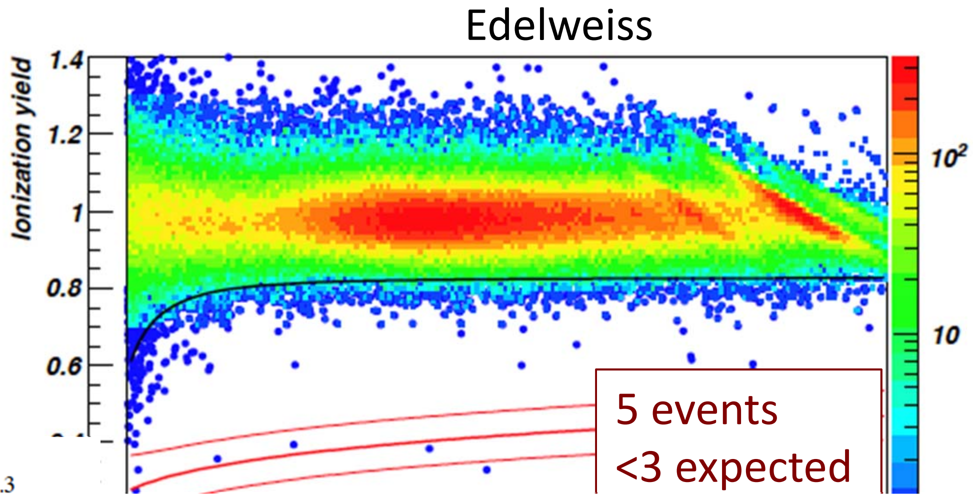


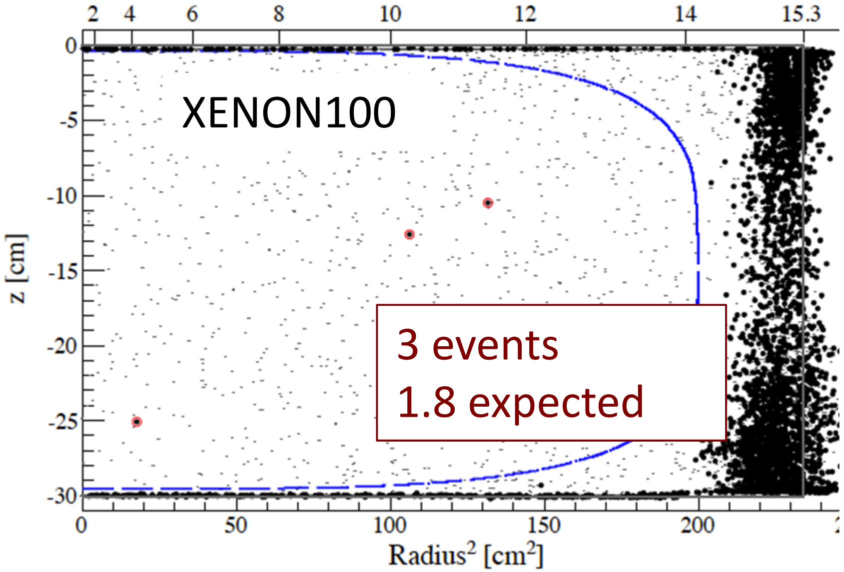


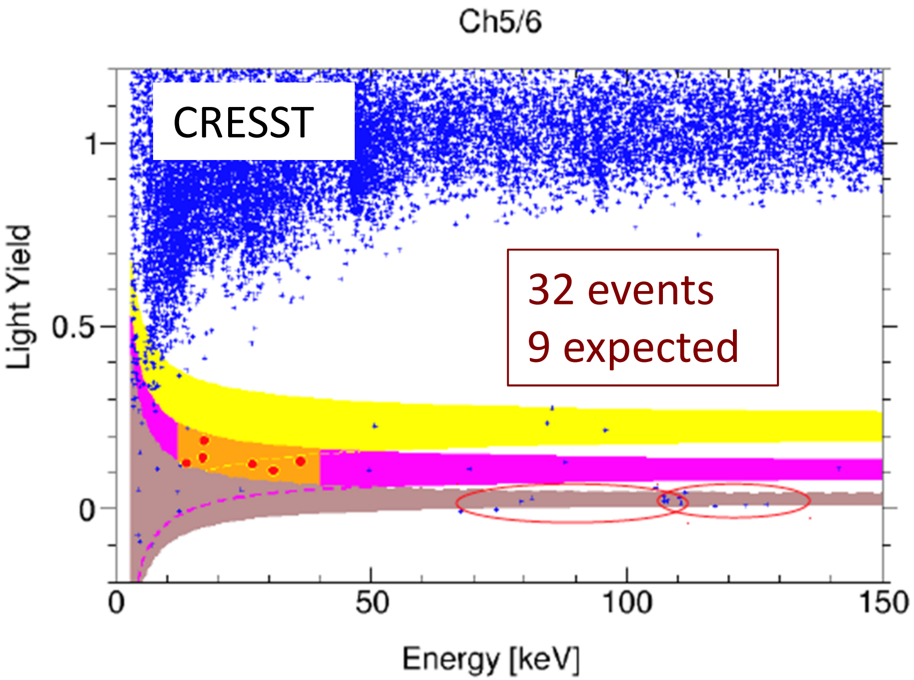

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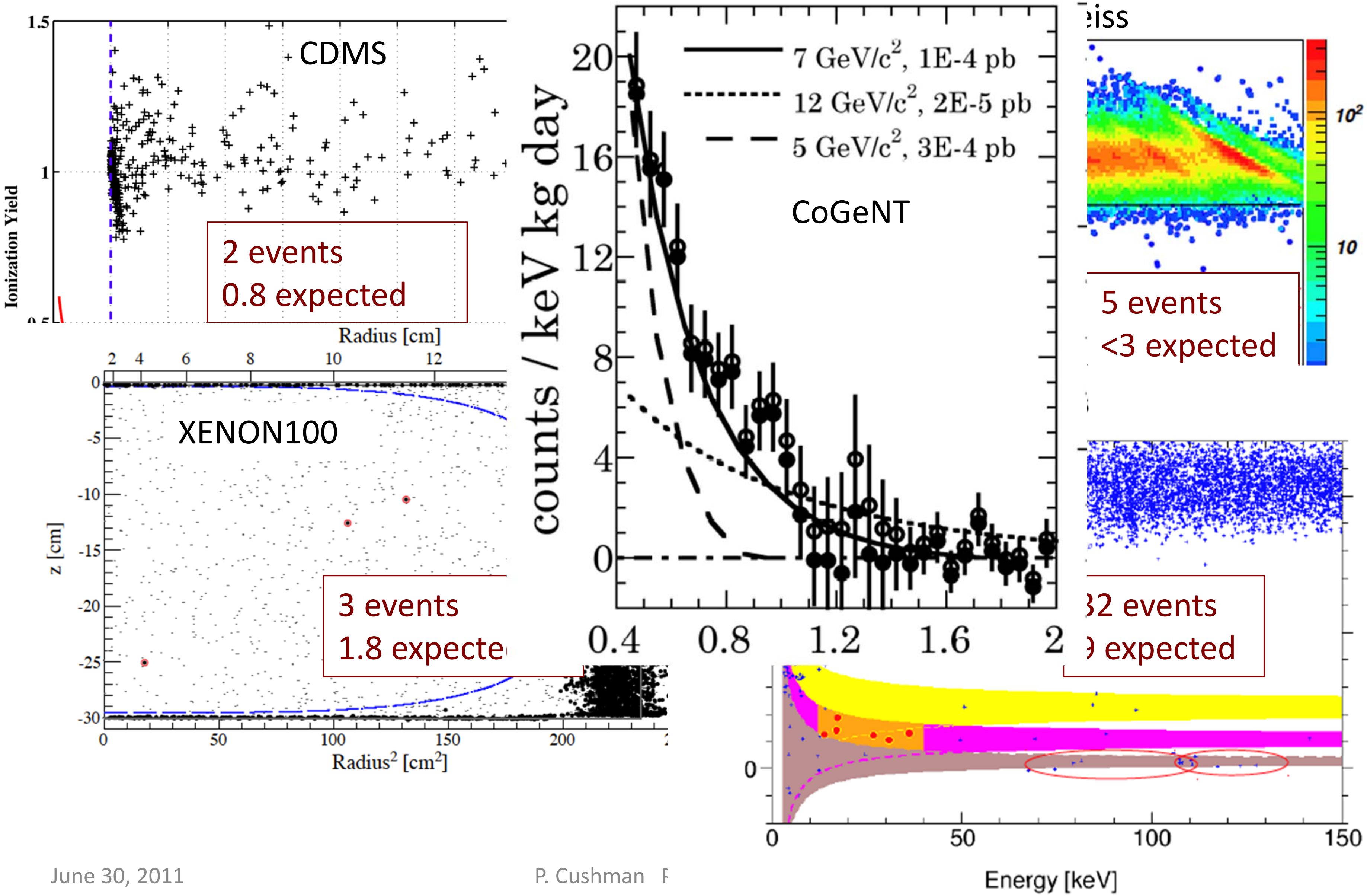
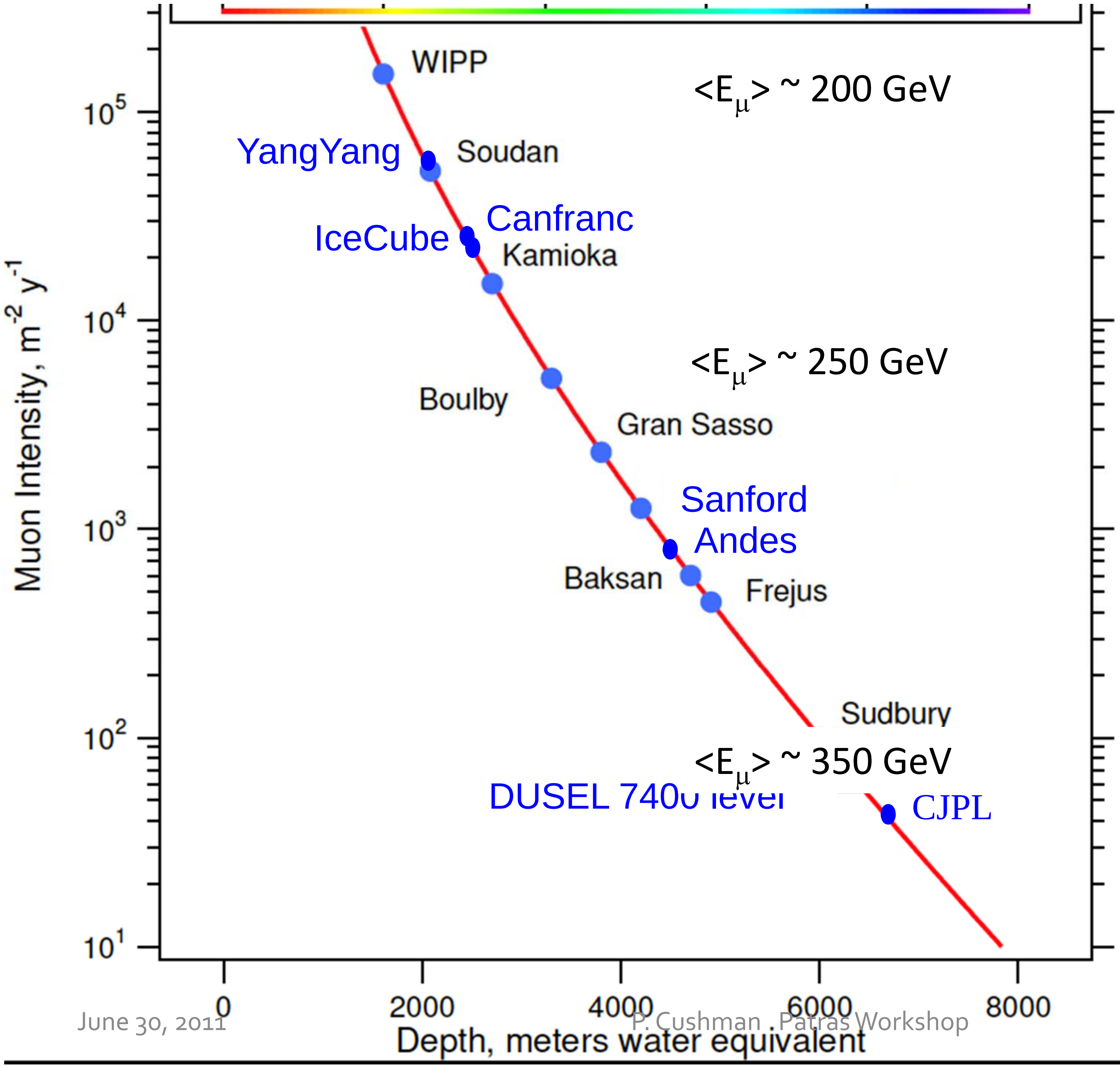


*If we do not understand our neutron background, we cannot make strong statements as we move to the ton scale.*




**$E_n$ > 10 MeV**

$6 \times 10^{-9}\ cm^{-2}s^{-1}$

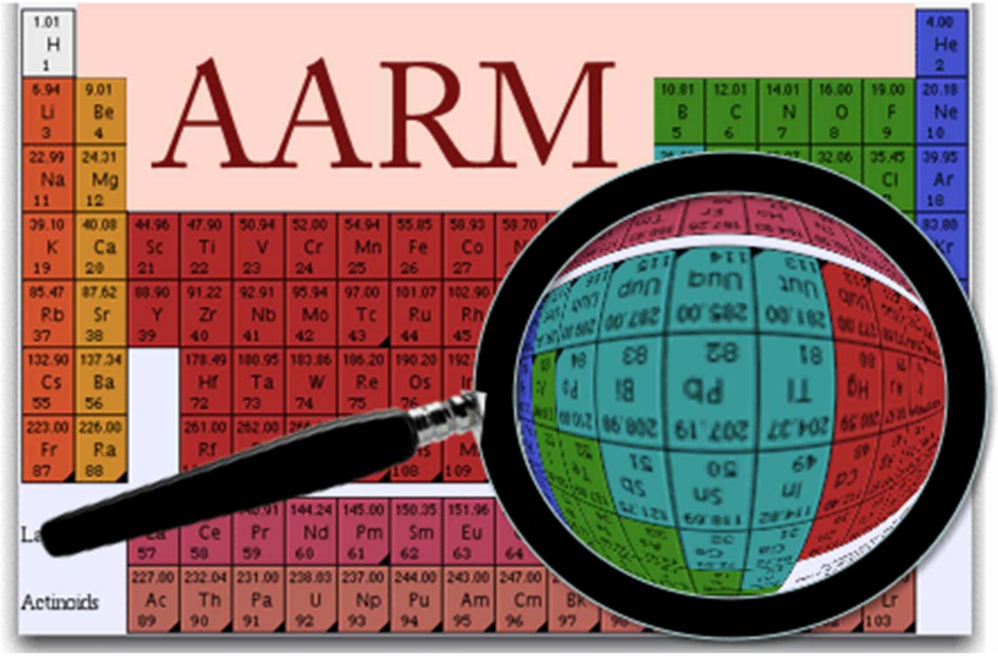
$1 \times 10^{-9}\ cm^{-2}s^{-1}$

water shields
muon veto

$1 \times 10^{-11}\ cm^{-2}s^{-1}$

relaxed shielding
but ?
penetrating n's
high multiplicity evts

# Assay and Acquisition of Radiopure Materials




## Principle Investigators

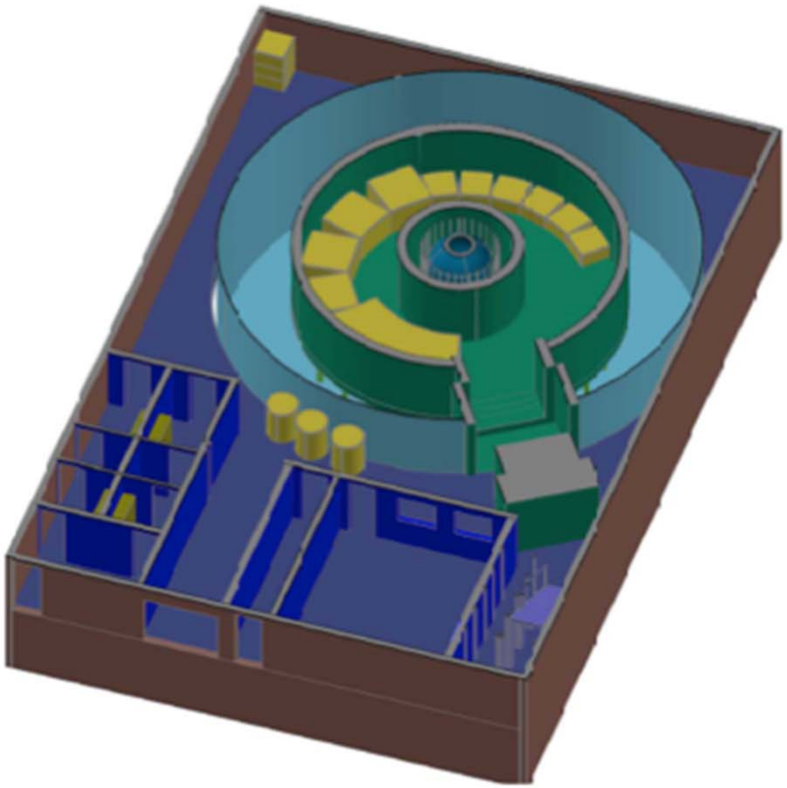
Priscilla Cushman (University of Minnesota)
Dongming Mei (University of South Dakota)
Kara Keeter (Black Hills State University)
Richard Schnee (Syracuse University)

## Engineering Consortium

CNA Consulting Engineers (Lee Petersen)
Dunham Associates
Miller Dunwiddie Architecture, Inc

An NSF S4 (~ $1M) was awarded for these specific tasks

- Characterize radon, neutron, gamma, and alpha/beta backgrounds at Homestake
- Develop a conceptual design (+ cost & schedule) for a common, dedicated facility (FAARM) for low background counting and other assay techniques
- Assist where appropriate in the creation of common infrastructure required to perform low background experiments.
- Perform targeted R&D for ultra-sensitive screening and water shielding

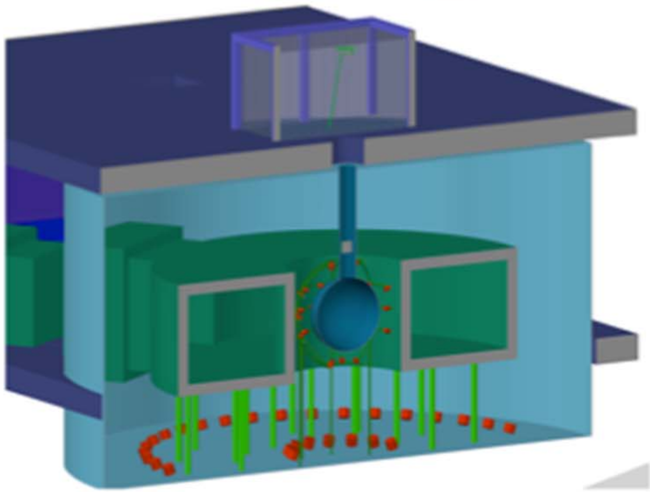


## Inner Tunnel Lab

γ-flux  $7.974\times10^{-5}$  $cm^{-2}\ s^{-1}$
n-flux  $4.817\times10^{-10}$  $cm^{-2}\ s^{-1}$

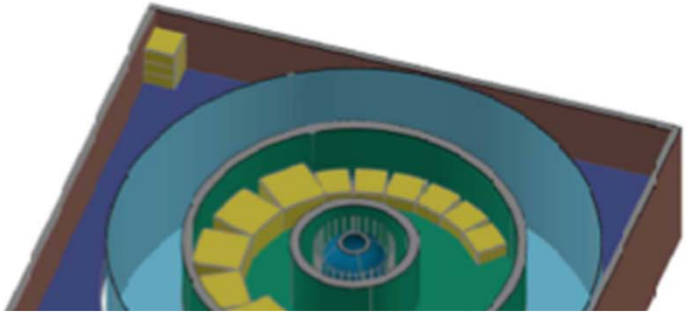
4 < ppt (GeMPI, arrays)
6 < ppb (well, clover, coax)
2 Beta Cages
Prototyping Space
(DM or $0\nu\beta\beta$ or novel assay)

Radon Mitigation
Common cryogen plumbing and
LN boil-off for screeners



## Central Pool

0.1 counts/day, E > 250 keV
sensitivity of $10^{-14}$ g/g U/Th  $10^{-12}$ g/g K
modeled on Borexino CTF
2m diam nylon vessel filled with LS
Observed by low rad QUPIDs
Top-loading from dedicated Clean Room



**Inner Tunnel Lab**

| | | |
|---|---|---|
| γ-flux | $7.974\times10^{-5}$ | $cm^{-2}\ s^{-1}$ |
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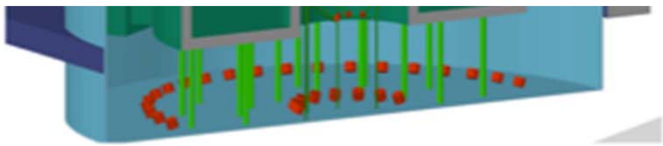
4 < ppt (GeMPI, arrays)

# With the Demise of DUSEL, the detailed engineering plans for the "FAARM" become irrelevant

***unless parts can be adopted elsewhere…***
***water-shielded central pool for ultra-sensitive screening?***
***see me after the talk !***



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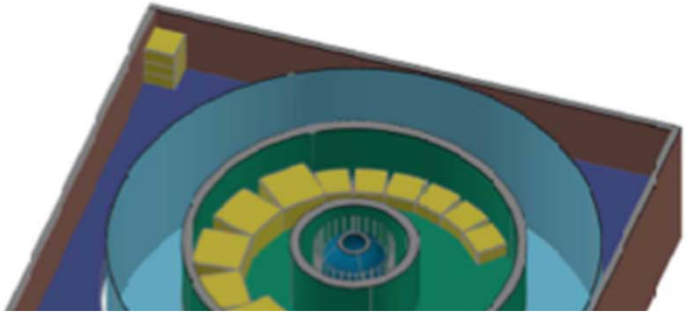

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*see me after the talk !*

# Redirect Funds to "Integration" Tasks

# Identified the following task as a priority

*Validate and improve the Physics in current Simulations*
*Create a Common Simulation Framework for underground experiments.*

**Begin work by comparing simulations**

across collaborations
across simulation packages (GEANT4 vs FLUKA)
across caverns (rock composition, overburden)
across muon distributions (site-specific MUSIC vs Groom parameterization)

**Detailed plans (working groups) were formulated in the areas of**

Cosmogenics
Radiogenics (alpha-n, fission, material screening)
and Universal Materials database
Modular Geant4 Framework for Underground Science

# We are drawing on expertise from a larger collaboration

## AARM Scientific Collaboration

Craig Aalseth
Henning Back
Tim Classen
Jodi Cooley
Darren Grant
Yuri Efremenko
Brian Fujikawa
Reyco Henning
Jeff Martoff
Robert McTaggart
Eric Hoppe
Andreas Piepke
Andrew Sonnenshein
John Wilkerson
Tullis Onstott

## AARM International Scientific Advisory Panel

Laura Baudis , Richard Ford, Gilles Gerbier, Gerd Heusser, Andrea Giuliani,
Mikael Hult, Vitaly Kudryavtsev, Pia Loaiza, Matthias Laubenstein, Neil Spooner

**Much of the recent planning was done in**

1. **AARM Collaboration Meeting (Feb 2011)**
   http://zzz.physics.umn.edu/lowrad/meeting3/talks
2. **Berkeley Comos Workshop (April 2011)**
   https://docs.sanfordlab.org/docushare/dsweb/View/Wiki-141

## COSMOGENICS GEANT4 Physics Improvements

*SLAC GEANT4 Collaboration (esp. Dennis Wright)*

### New Physics List called "*Shielding*" in Geant 4.9.4

designed for use in shielding applications, and also in high energy

similar to QGSP_BERT_HP, except

*uses a different string fragmentation model (FTF instead of QGS)*

*better handling of ions (Binary cascade for light, QMD for heavy)*

*improved neutron cross sections from JENDL database*

### use G4 builder classes to extend physics list

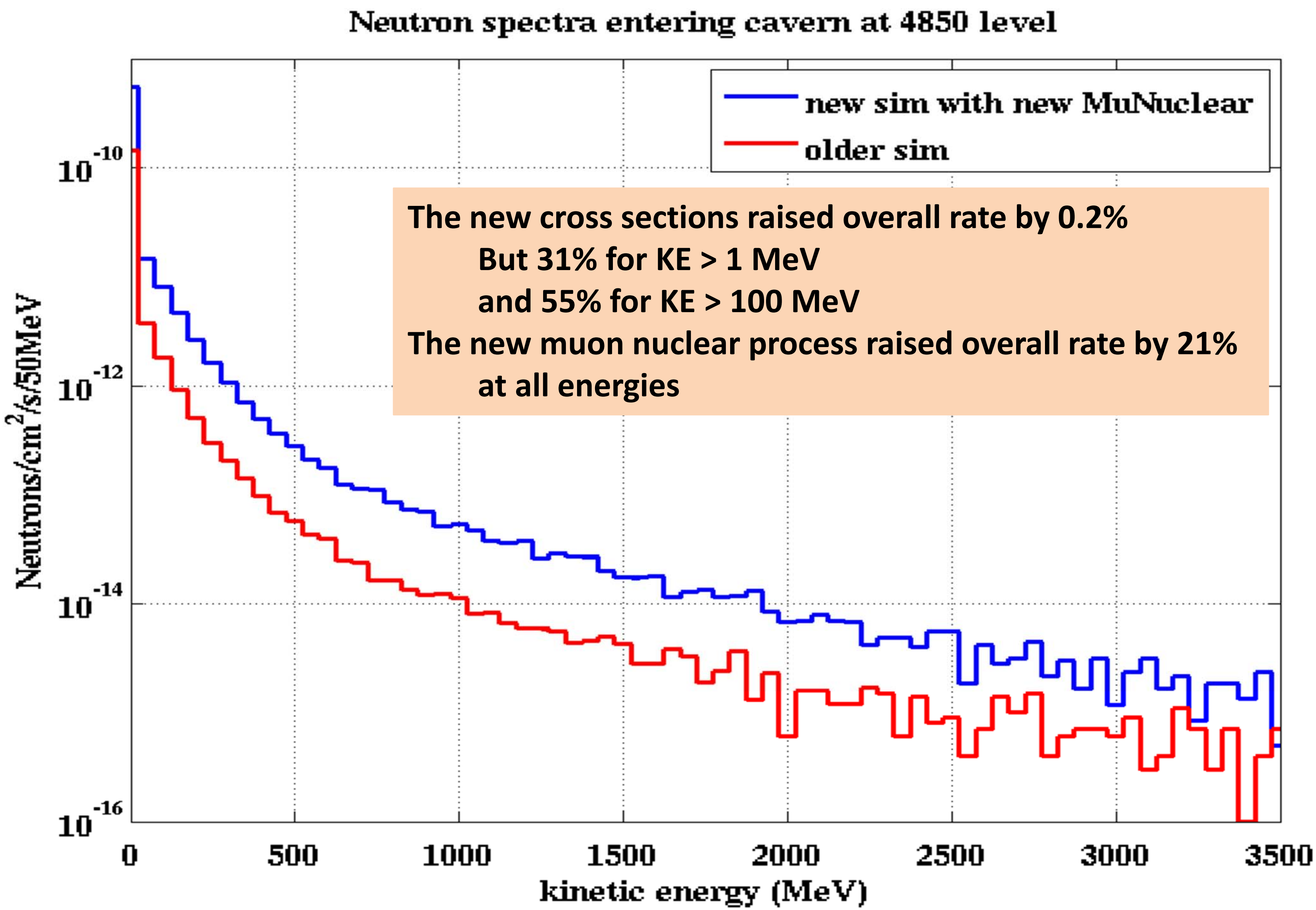
- add radioactivity model to all recoil ions with option to de-activate
- could also add optical photons

### improved light-ion-induced reactions

- Shielding already replaces old GHEISHA-style models with G4BinaryLightIon and QMD models

### new muon-nuclear process, model and cross section developed

- Muon exchanges virtual photon with nucleus
- Virtual photon treated as "0" to initiate cascade
- Bertini cascade (0–10 GeV), FTFP (> 10 GeV)



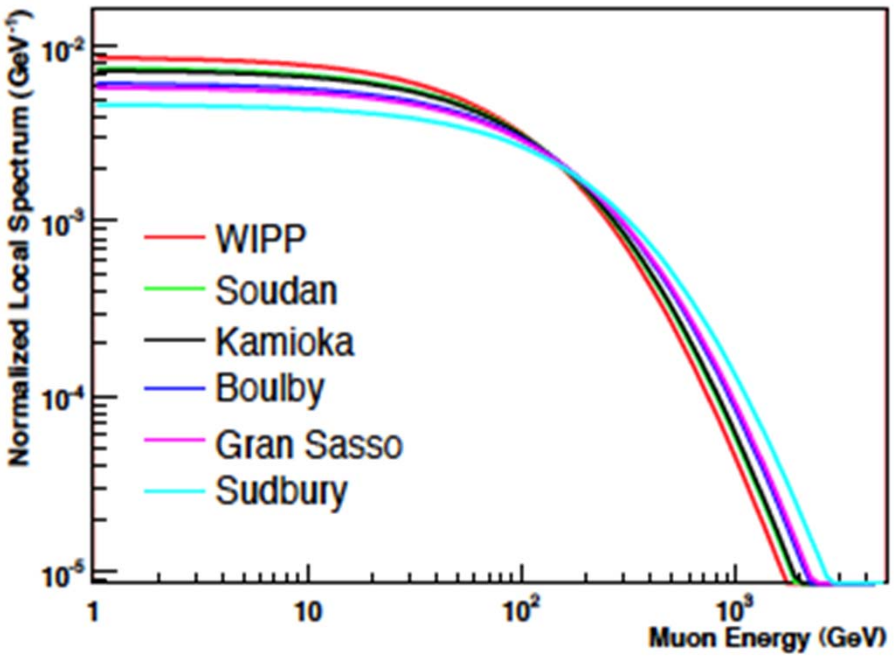

**study by A. Reisetter**

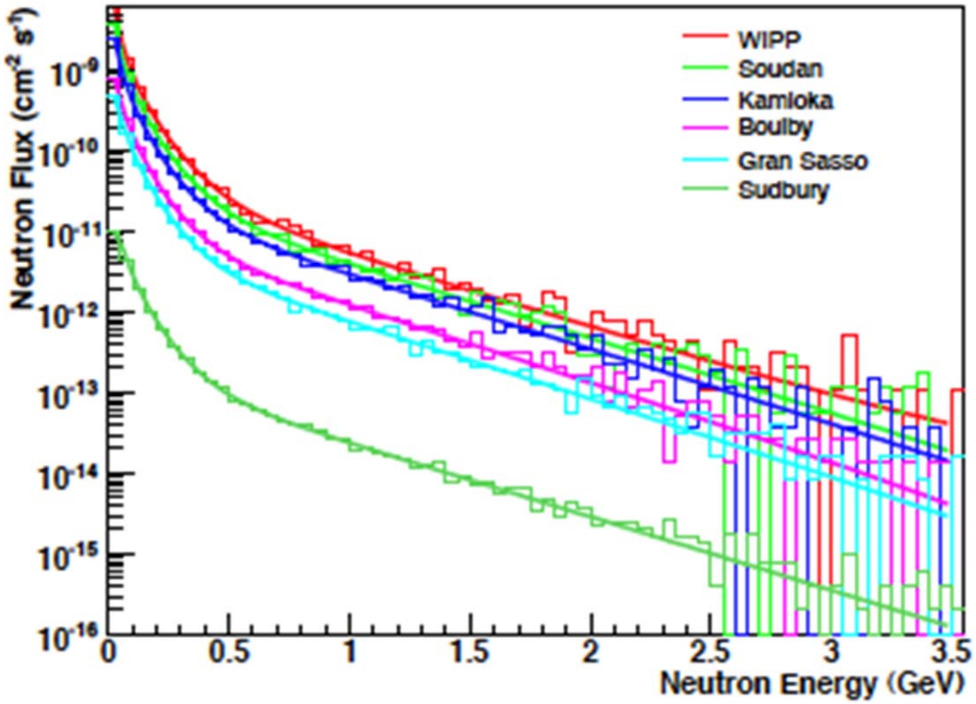
# Mei & Hime (arXiv:astro-ph/0512125)

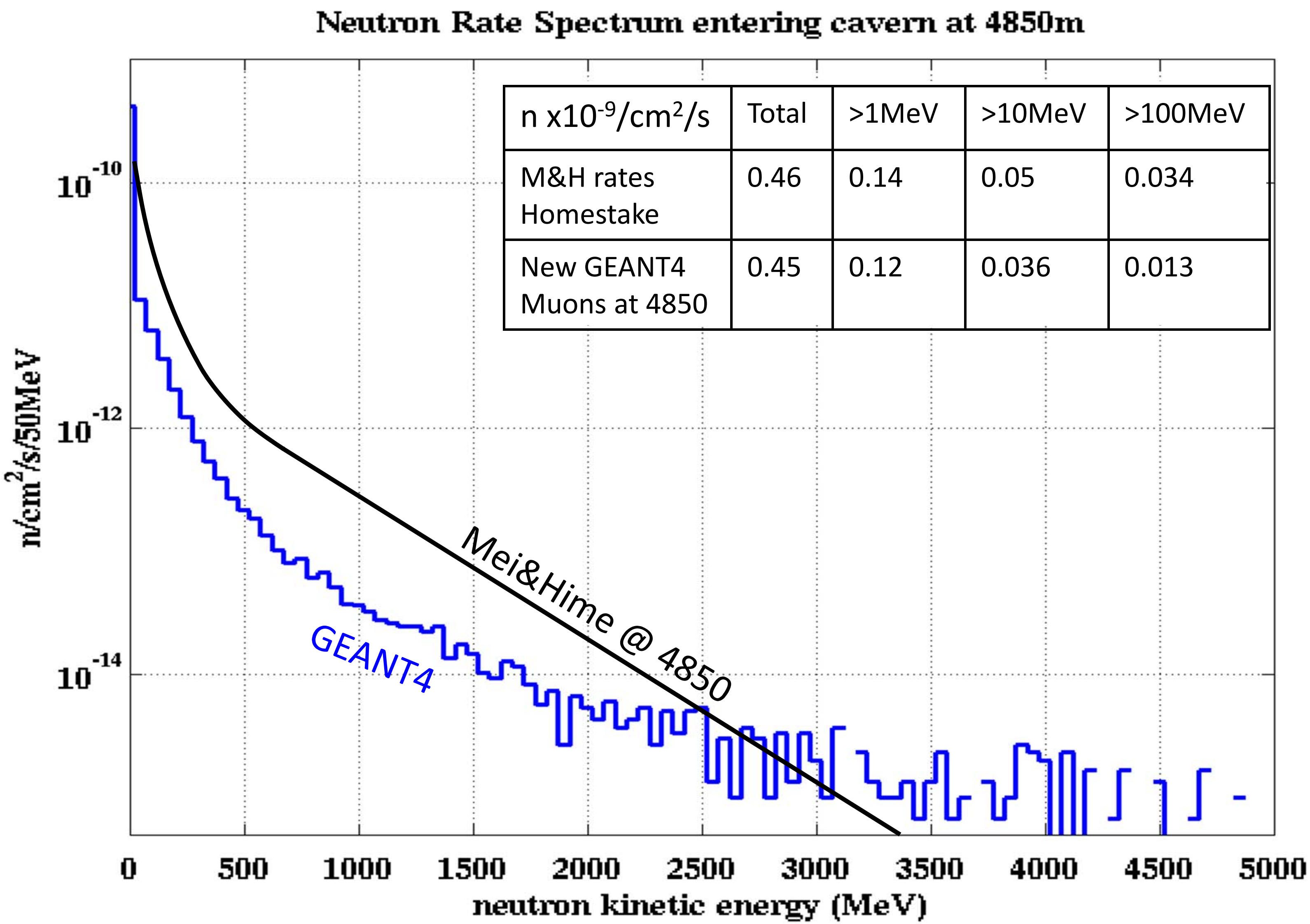
An early attempt to parameterize cosmogenic neutrons wrt depth

Input well-known muon spectra and flux wrt depth

Resulting neutron spectra: Parameterization of a FLUKA simulation, adjusted upward to match data

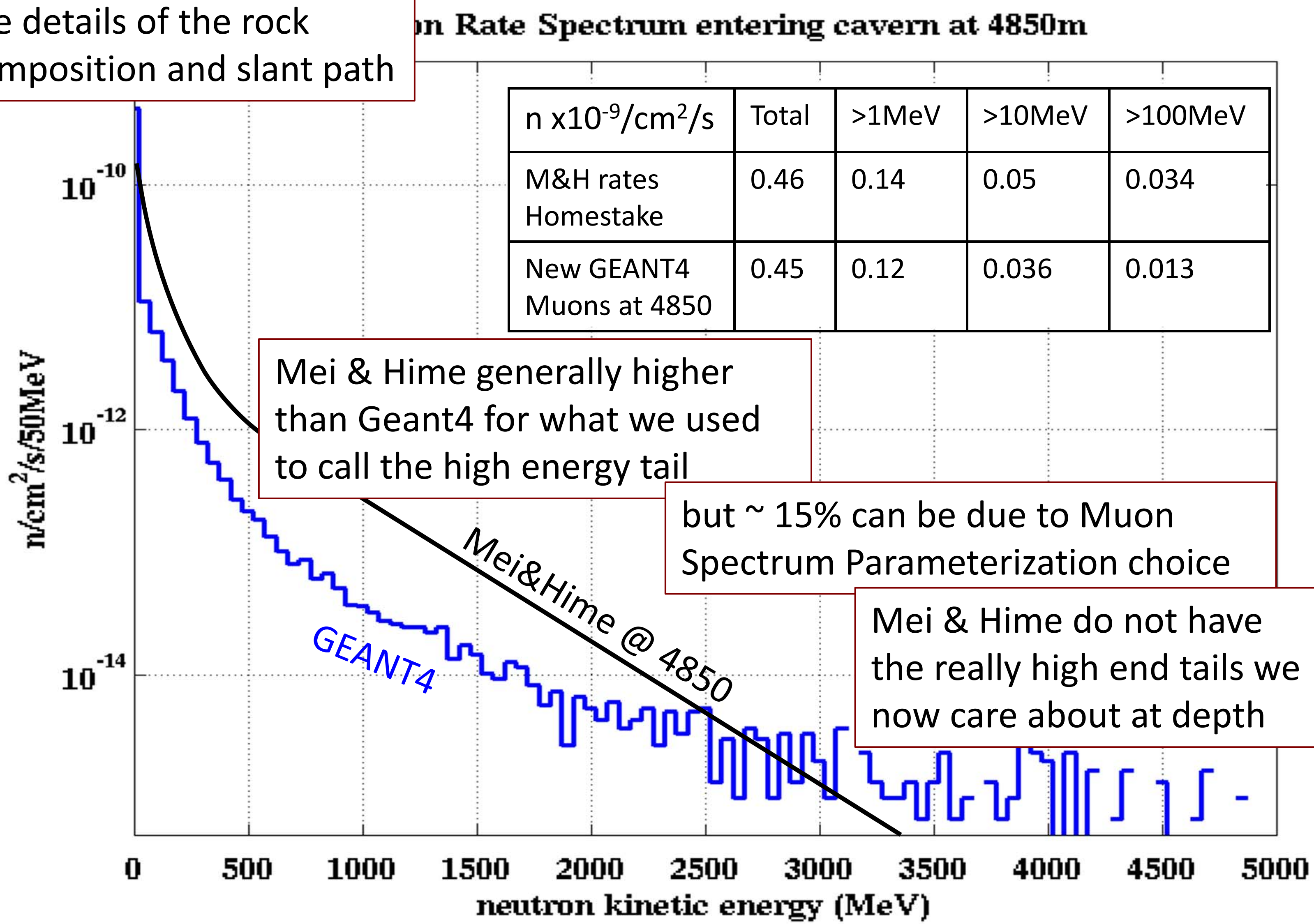





| n x10$^{-9}$/cm$^2$/s | Total | >1MeV | >10MeV | >100MeV |
|---|---|---|---|---|
| M&H rates Homestake | 0.46 | 0.14 | 0.05 | 0.034 |
| New GEANT4 Muons at 4850 | 0.45 | 0.12 | 0.036 | 0.013 |

Lower energy depends on the details of the rock composition and slant path

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Mei & Hime generally higher than Geant4 for what we used to call the high energy tail

but ~ 15% can be due to Muon Spectrum Parameterization choice

Mei & Hime do not have the really high end tails we now care about at depth

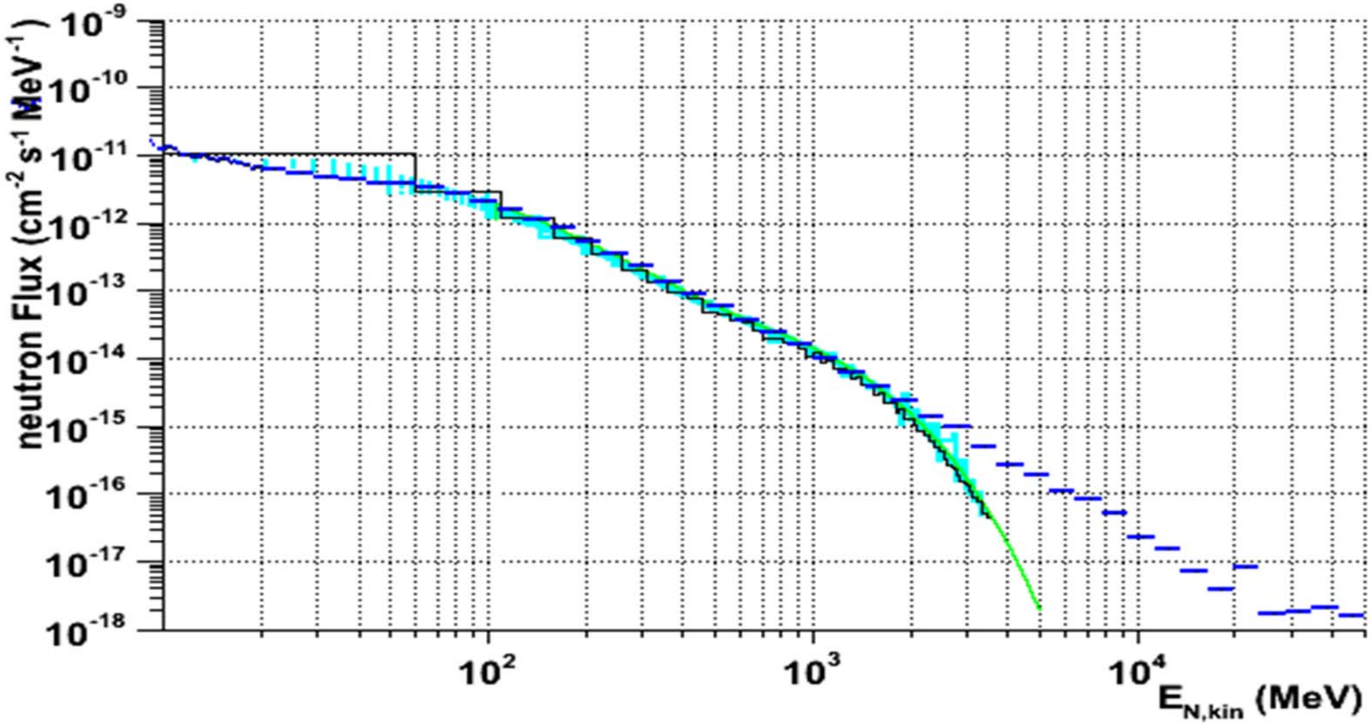
# Muon-induced Neutron Kinetic Energy Spectrum

*at the rock cavern boundary (geometry: 6m$^3$ centered in 20m$^3$)*

our current result

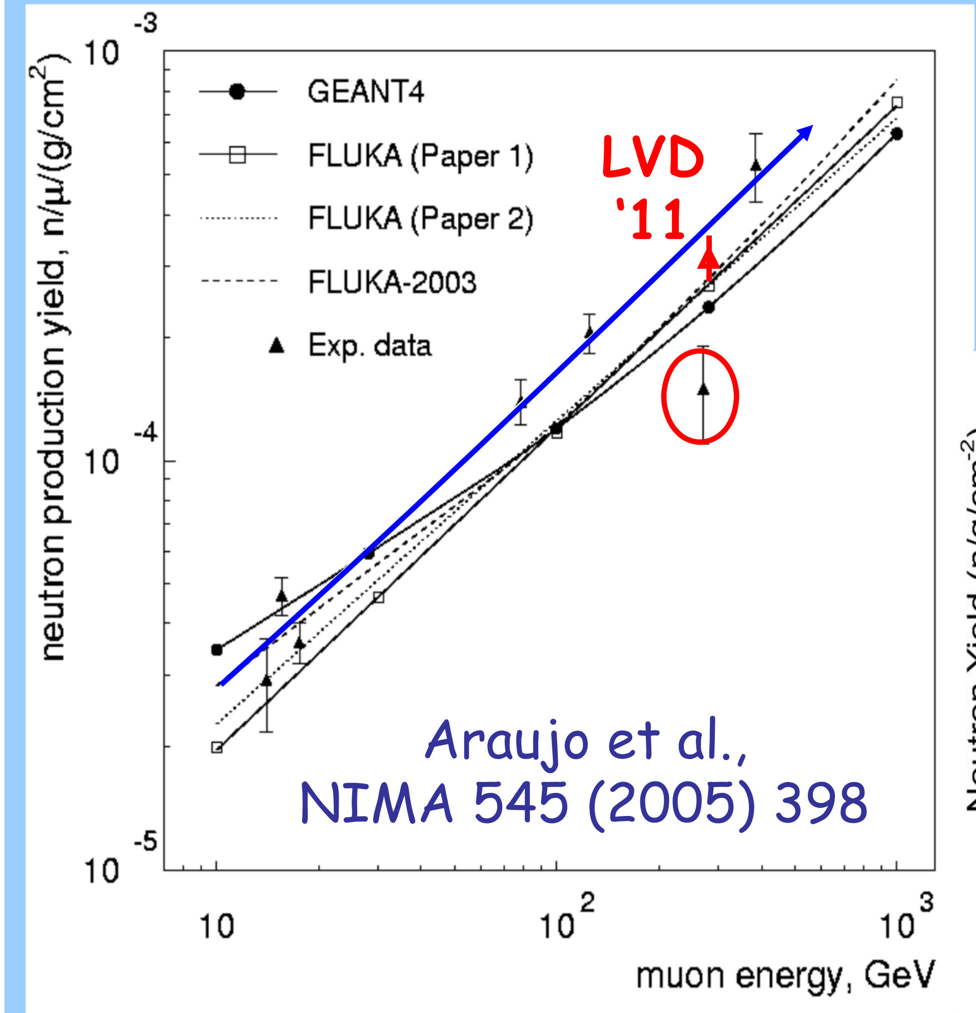
A. Dementyev etal Gran Sasso note: INFN/AE-97/50, 22 Sep 1997 - Bezrukov and Bugaev + SHIELD

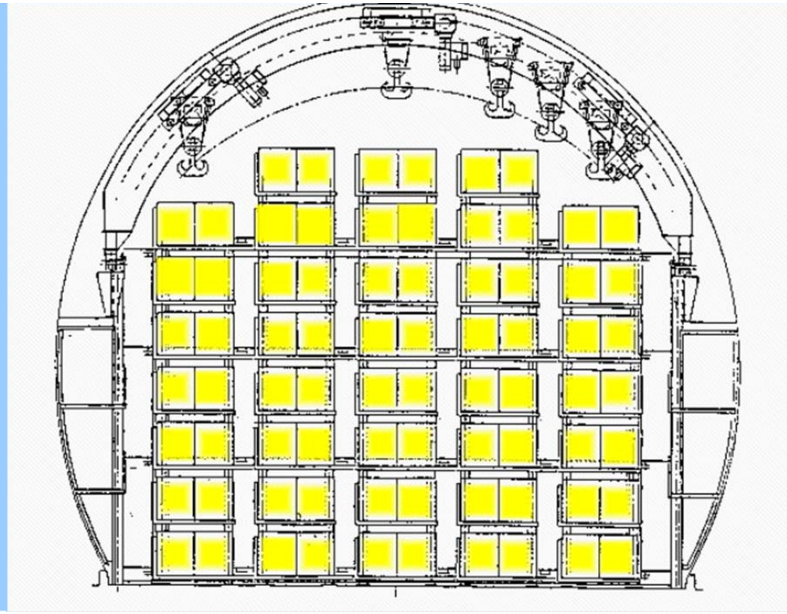
A. Hime and D.-M. Mei, parameterization arXiv:astro-ph/0512125 v2 6 Dec 2005 - FLUKA (coincident direct muons?, A?)

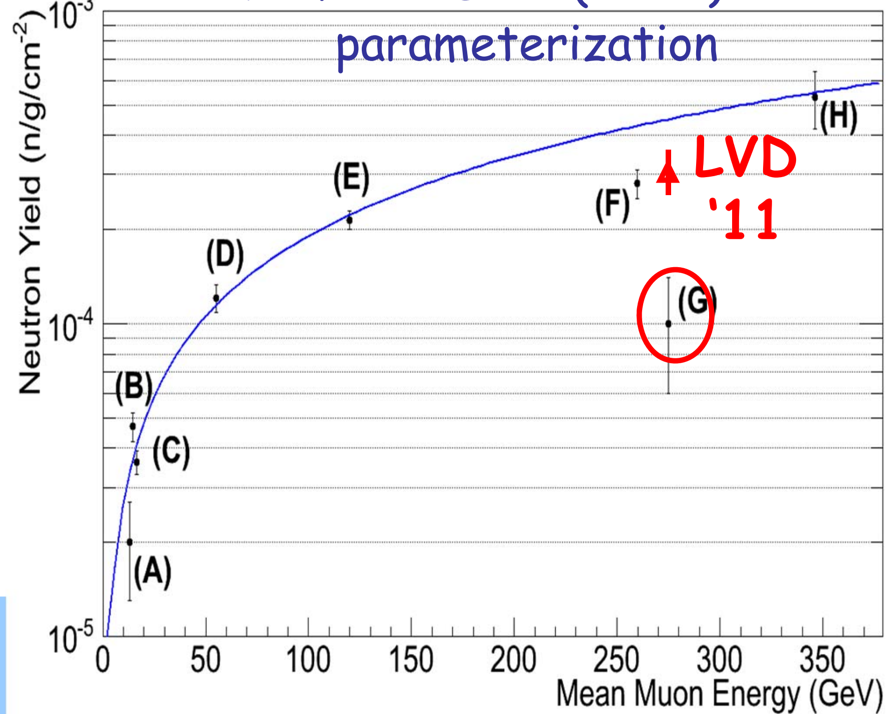



Note: the FLUKA versions used here differ - in particular FLUKA now features 260 low energy neutron groups rather than the 72 previously.

# Neutron yield in Liquid Scintillator





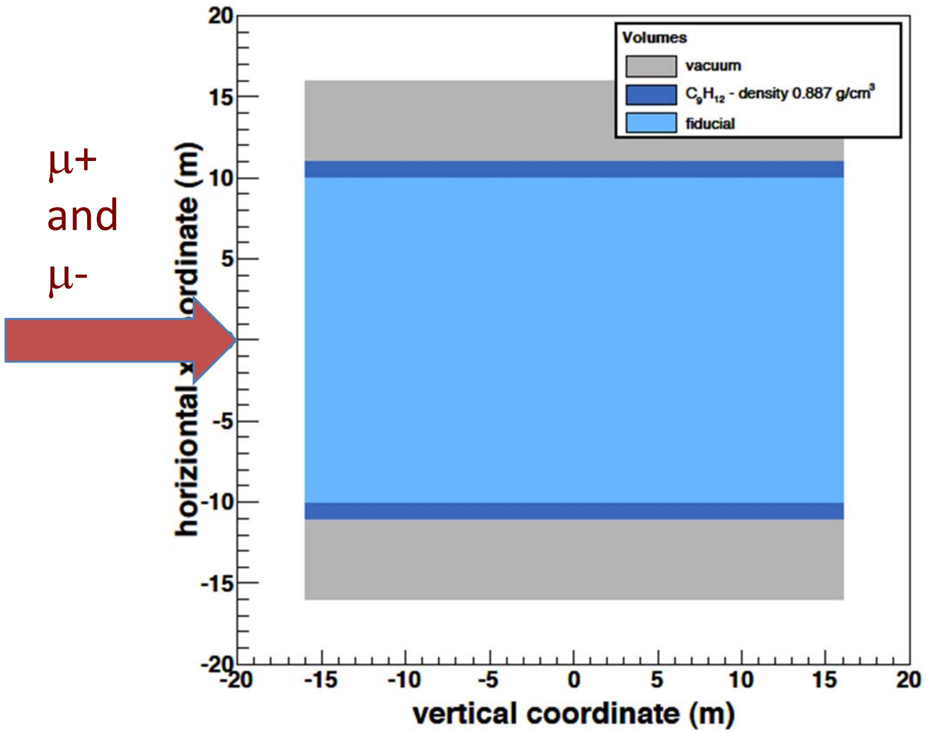
# COSMOGENICS Comparing GEANT4 vs FLUKA

*Neutron Yield is a key uncertainty. Mount a careful Study*

Muon energies: 10, 30, 100, 280, 1000 GeV.
Materials: C, $CH_2$, $H_2O$, $CaCO_3$, NaCl, Fe, Pb.

Tony Empl (FLUKA)
Anthony Villano (GEANT4)
Vitaly Kudryavtsev (Advisor)

Simple Fiducialized Geometry




Neutron production rate per muon per g/cm$^2$
All neutrons produced inside the material are counted, but only those produced in the middle are included in the final neutron yield.

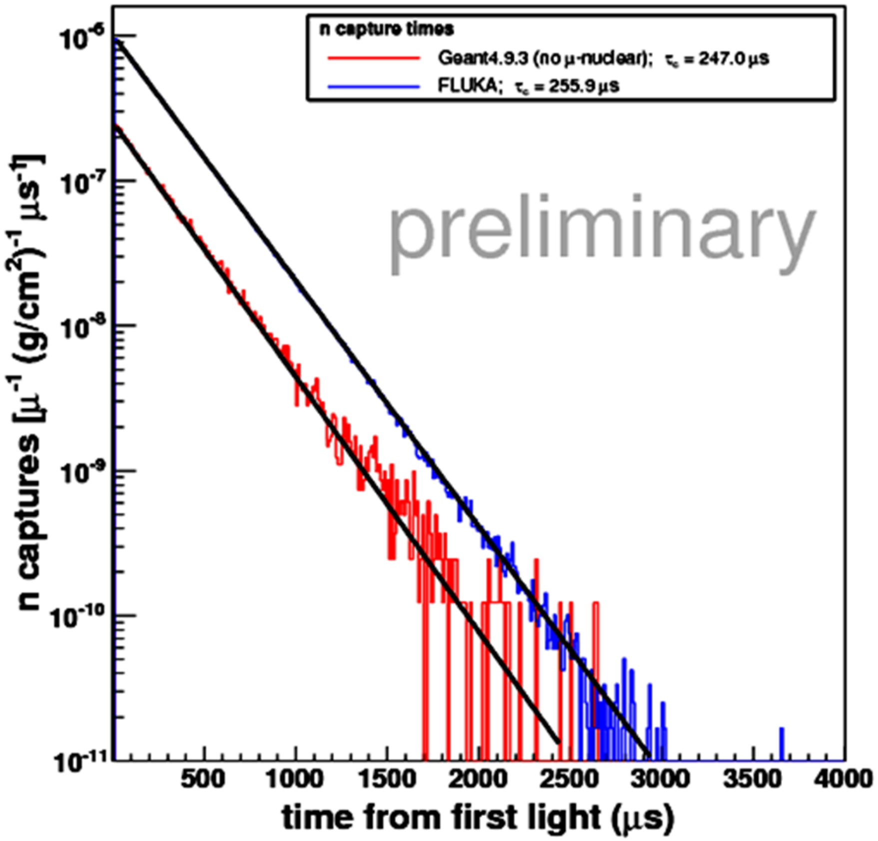
All vertices fully reconstructed
All physics processes recorded
Care taken to avoid double counting

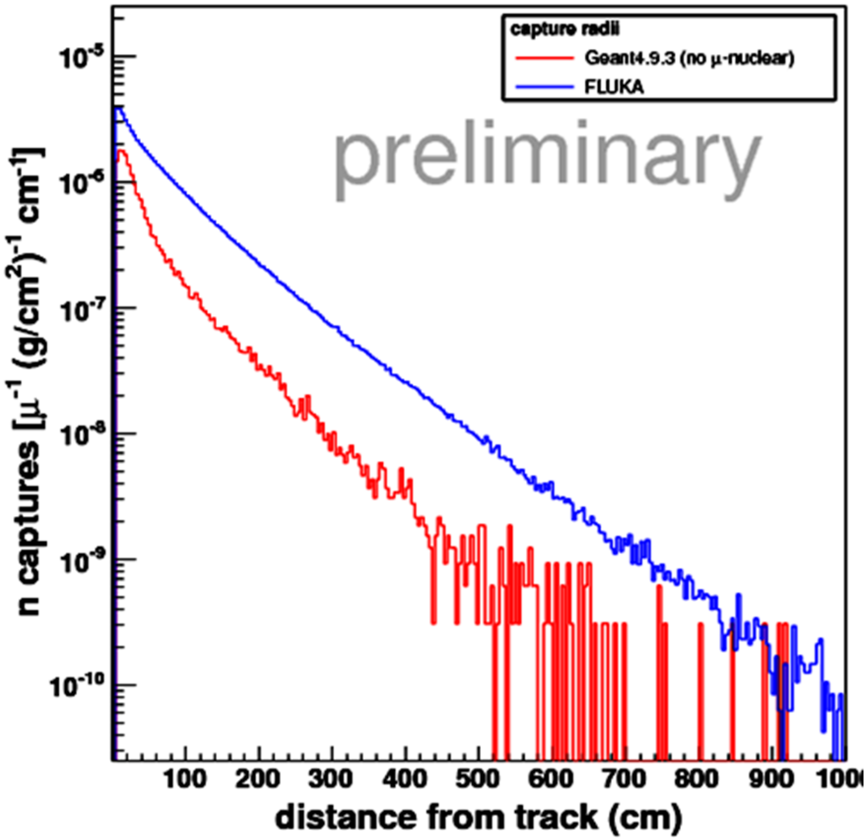
First try with Liquid scintillator chosen in order to be able to compare with Borexino and Kamland. *(and LVD)*
$C_9H_{12}$ at density $\rho = 0.887$ g/cm$^3$.

# COSMOGENICS Comparing GEANT4 vs FLUKA

Time from 1st interaction to n-capture.
$\tau$ = 247.0 $\mu$s (G4) 255.9 $\mu$s (FLUKA)
Borexino takes data only after around 200 $\mu$s
Kamland after about 1300 $\mu$s.

Position from primary track to n-capture.
Possible observable for delayed captures



# COSMOGENICS Standardizing Muon and Neutron Distributions

*An Object Lesson in the importance of Mutually Acceptable Input Parameters*.

Question from DUSEL planning "Can GEODM (7400 level) be redesigned to work at 4850?"

| The results of the GEODM 4850 Sim | were in | direct contradiction to LZ20 Sim |
|---|---|---|
| 3 m water shield reduced # evts with n (KE>200keV) by only .16 | | 3-4 orders of magnitude reduction<br>0.3 $nDRU_r$ $\mu$-induced bkgd evts *before* analysis cuts |

Turned out to hinge on details of the INPUT neutrons and accompanying shower particles (next few slides show why)

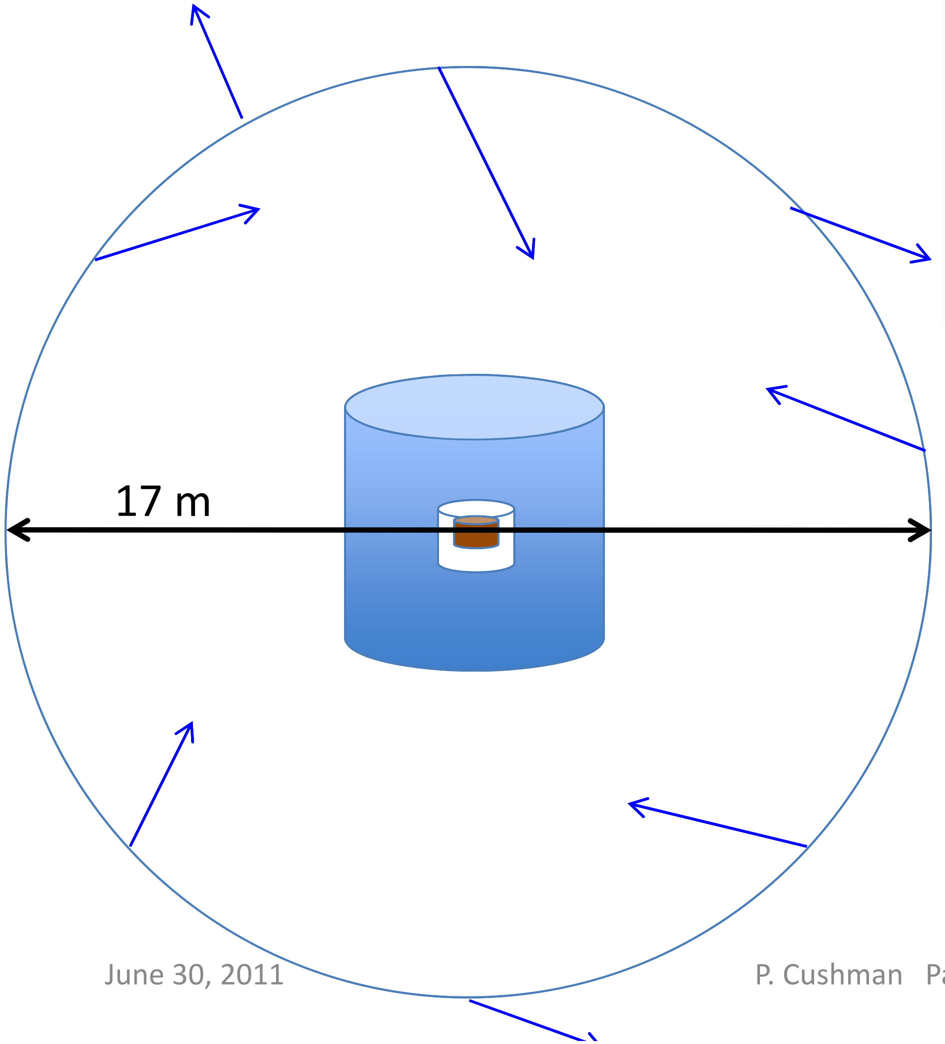
**Solution:**

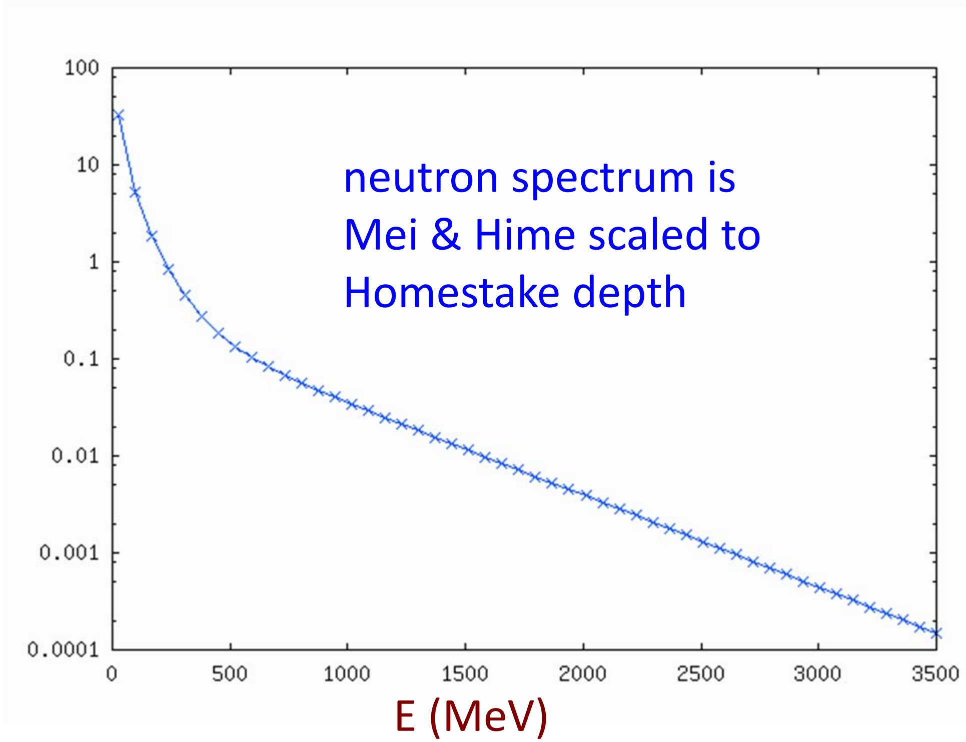
Everybody MUST AGREE on the same set of backgrounds for the same cavern.

Need to produce and validate and make available a background environment for each lab.

# Methodology of the LZ20 Simulation:

Single neutrons from a parameterized spectrum. Thrown isotropically from a sphere surrounding detector.
Whole thing is in a vacuum without walls



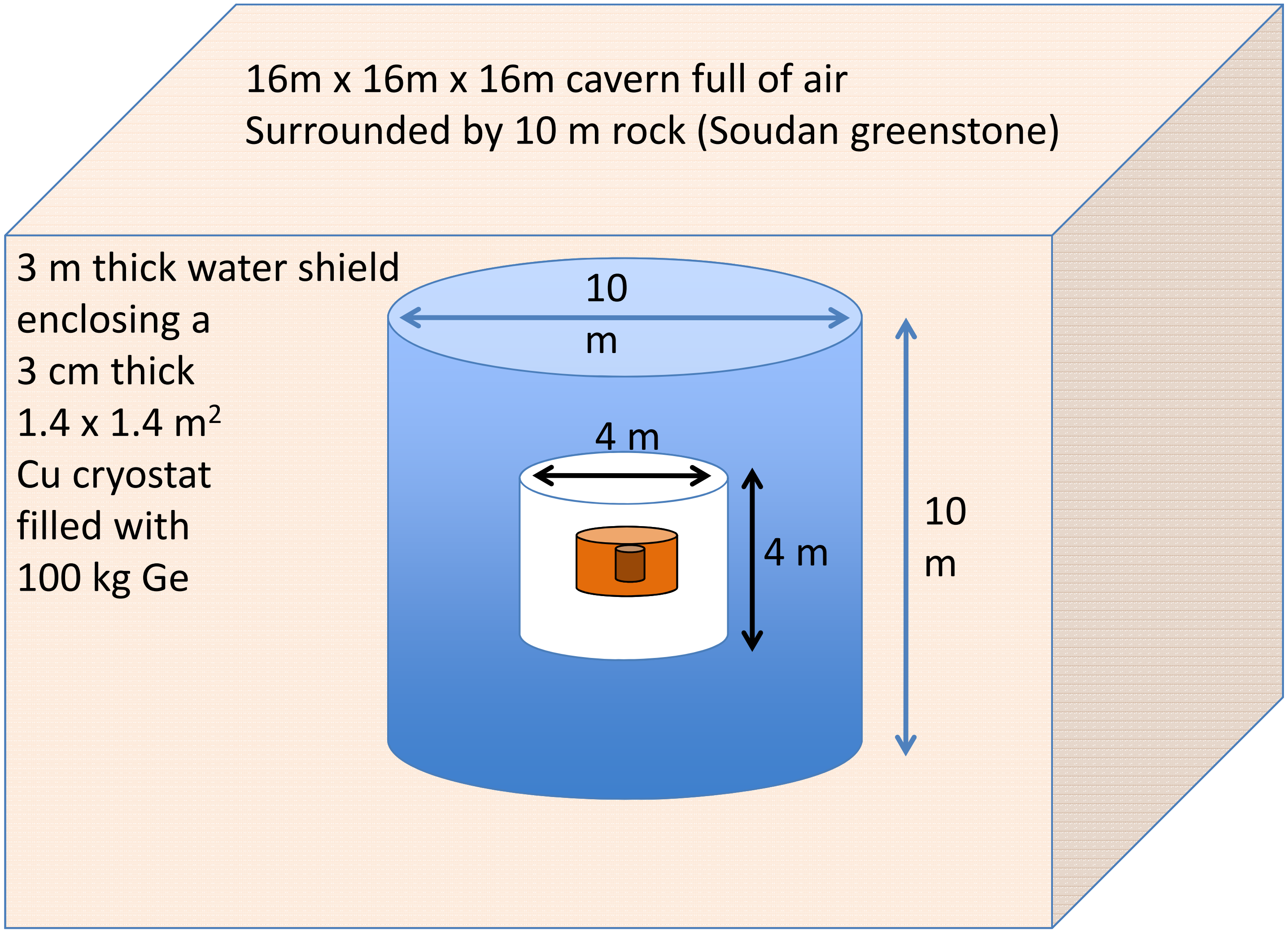




Advantage: Easy to get lots of stats

Disadvantages:

- No shower particles or $2^{ndry}$ n's
- No parent muons
- No correlations
- No multiplicity

# GEODM 4850 full G4 MC has extremely simple model of Detector, but a sophisticated generation of neutrons



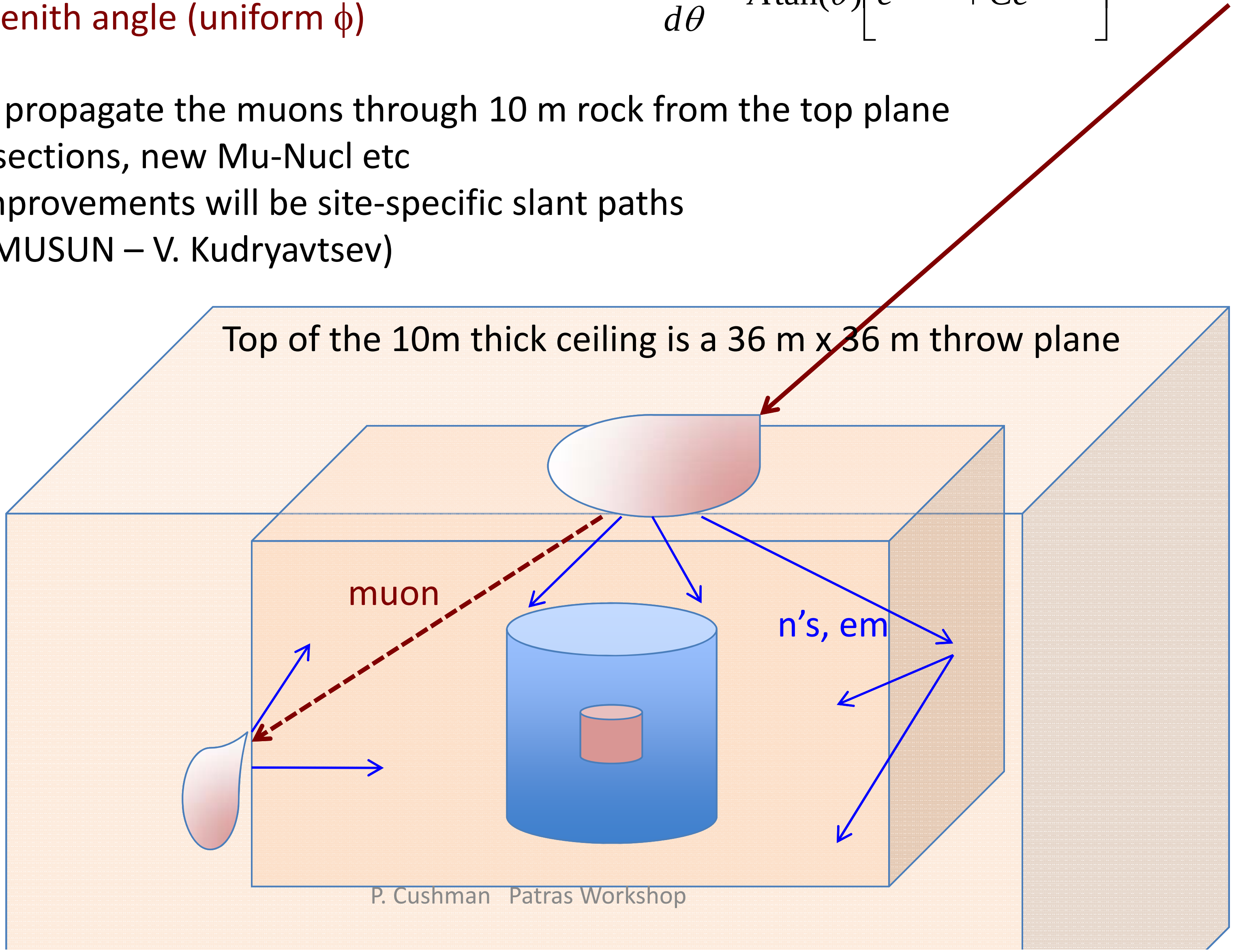
Muon Parameterization ( > 1000 mwe)
Phys.Rev.D7 p2022 (Cassiday et al.)

- g(E) is energy loss rate
- x(E) is muon stopping distance
- θ is zenith angle (uniform φ)

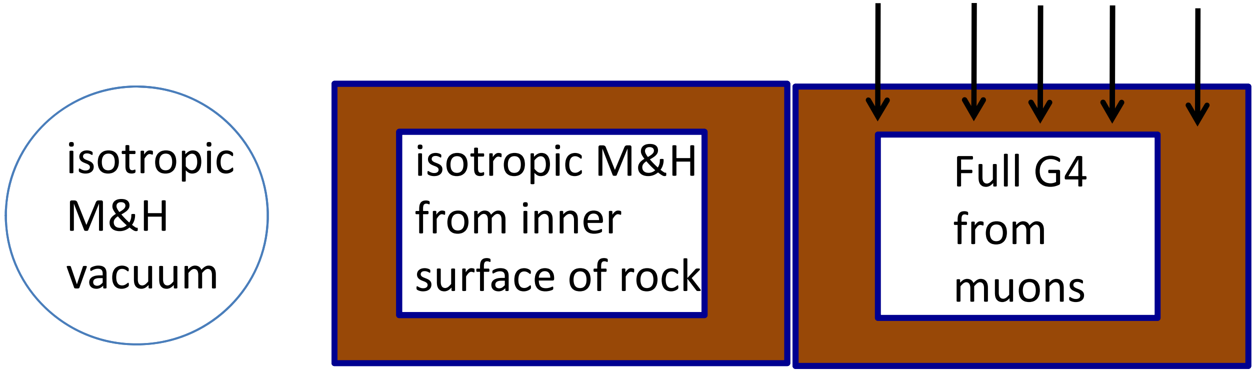
$$\frac{dN}{dE} = \frac{A}{g(E)}\left[e^{-Bx(E)} + Ce^{-Dx(E)}\right]$$

$$\frac{dN}{d\theta} = A\tan(\theta)\left[e^{\frac{-B}{\cos(\theta)}} + Ce^{\frac{-D}{\cos(\theta)}}\right]$$

Let Geant4 propagate the muons through 10 m rock from the top plane
New cross sections, new Mu-Nucl etc
Eventual improvements will be site-specific slant paths
(MUSUN – V. Kudryavtsev)



# Try different generators in the GEODM geometry




| GEODM geometry with Different n Generators | Isotropic Sphere (8.75 ton-y) scaled to 1 | Isotropic Cavern (0.895 ton-y) scaled to 1 | Full Rock Sim (1.25 ton-y) scaled to 1 |
|---|---|---|---|
| neutrons in Ge | 76 n = 11 evts | 106 n = 15.8 6.7 evts | 2,754 n = 12.3 224 evts |
| nuclear recoils in Ge (10 – 100 keV) (Veto not yet applied) | 14.5 NR = 3.3 4.46 evts (1.5 singles) | 21.2 NR = 4.8 4.47 evts (0 singles) | 787 NR = 5.4 145.6 evts (8 singles) |

Thus, the biggest difference is obtained in going from the Isotropic cavern to the Full Sim.
By neglecting secondary neutrons, hadronic and EM showers, and muons in cavern,
One predicts far fewer recoils and a lower multiplicity than you will really get.

Final step: Send Neutron files to Pangilinan – Redo LZ20 Sim to close the circle.

# Eventual Goal

1. Cosmogenic Generation of Hadronic Showers
    1. Move from Muon Parameterization to Muon propagation code (MUSUN)
       *Already in use at Soudan, Gran Sasso, Modane, Boulby*
    2. Geography and geology info being gathered for Homestake (Zhang, Mei)
       *Validate with muon measurements for slant paths, normalization*
    3. Create new site-specific neutron flux and multiplicity files

2. Radiogenic Backgrounds included for all spaces
    1. Gamma, neutron from rock samples
    2. Measurements in situ
    3. Radon monitoring

# Start with Homestake: Standardized Monte Carlo FRAMEWORK

Each experiment has its own strengths and physics modules

*Glean useful information from them, e.g.*

MaGe has a waveform library

DEAP/CLEAN incorporated RAT (Reactor Analysis Tool – Braidwood)

SuperCDMS phonon physics add-on

Many experiments pushing on cross sections relevant to their experiment

Each experiment has evolved specific classes and macros for running jobs

*Choose one of the good ones*

Workshop defined what we mean by "good"

Examples: LUXSim (Kareem Kazkaz)

New SuperCDMS Framework (SLAC, Mike Kelsey)

We (Chao Zhang) will adopt a framework similar to LUXSim

*BUT Generalize*

e.g. LUXSimDetectorComponent fully usable without the rest of the LUXSim management

Additional Jobs

- extend G4 materials to have associated properties in a common way
- develop an even more general "object library" of things like PMT structures, etc.
- develop a general-purpose TPC track reconstruction library (LLNL/NNSA money!)

# RADIOGENICS & SCREENING

## Materials Database (James Loach – Majorana)

-begin with a database “Couchdb” and a search engine “Lucene”
-structure has a main database – this database copied and sync to institutions
-“users” and “developers” write code to access information for their purpose

## Decision taken (Feb 2011) to adopt it and add

-new counted materials (by experiment)
-legacy materials (e.g. ILIAS database)
  need volunteers/resources
-Organizing entities: AARM, LRT Workshop, SNOLab
-functionality,
  e.g. contaminated materials automatically incorporated into Geant4

## Software with a “sanctioned” database made available Loach → Villano

- begin software distribution, starting with a “test” database from Majorana

# Some Details about the Materials Database

Open source non-relational database

A flat collection of JSON **documents** of named fields

```
"sample": {
    "name":          "Fused silica",
    "description":   "Corning 7940, lot 56667",
    "source":        "Mark Optics Ltd.",
    "owner":         "LBNL LBF",
}
```

Data aggregated and displayed using **views**

Schema-free so structure can be varied and extended

Distributed (can self-replicate between machines)

Speaks HTML

Widely-used (CERN, BBC etc.)

Future-safe data format (JSON text)

Commercial online hosting services available

http://couchdb.apache.org

http://guide.couchdb.org/

http://www.couchbase.com

http://www.cloudant.com

MAJORANA
Material Assay
Database

tin

- Tin, LANL
- Tin, LANL
- Tin, Canberra

MAJORANA
Material Assay
Database

tin

⊟ Tin, LANL

| | | | | | | |
|---|---|---|---|---|---|---|
| sample | description | Tin, 99.9998% purity | | | | |
| measurement | technique | Gamma | | | | |
| | results | U chain | < | 1.7 | | mBq/kg |
| | | Th chain | < | 3.1 | | mBq/kg |
| | | K-40 | | 25 | (14) | mBq/kg |
| | | Co-60 | < | 1.5 | | mBq/kg |

⊞ Tin, LANL
⊞ Tin, Canberra

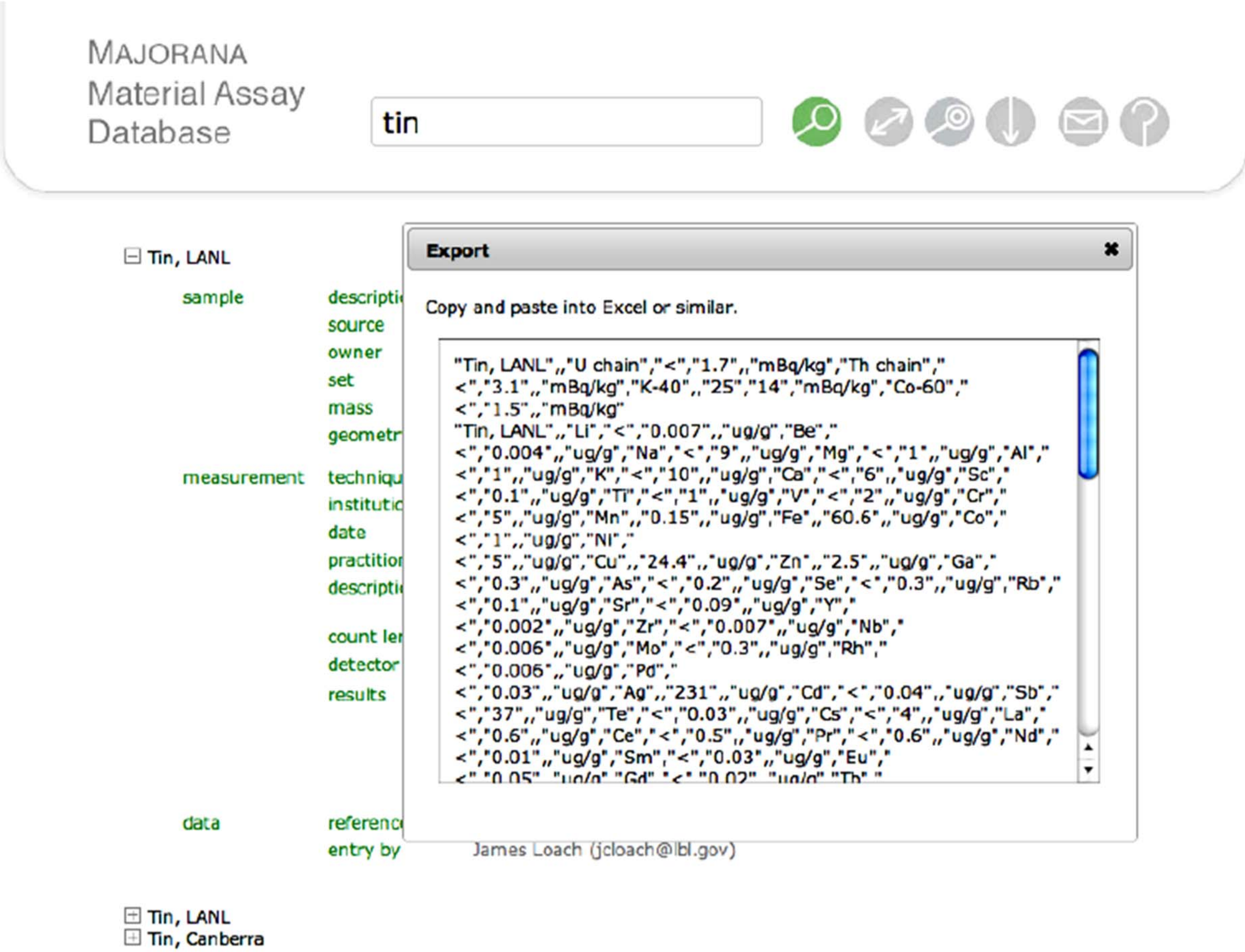
MAJORANA
Material Assay
Database

tin

⊟ Tin, LANL

| | | |
|---|---|---|
| sample | description | Tin, 99.9998% purity |
| | source | Adam Montoya, LANL |
| | owner | LANL |
| | set | Majorana |
| | mass | 710 g |
| | geometry | Block of metal |
| measurement | technique | Gamma |
| | institution | LANL / WIPP |
| | date | 5 / 2010 |
| | practitioner | Steve Elliot, LANL (elliotts@lanl.gov) |
| | description | The tin was placed inside two nested plastic bags and put inside the WIPP-n cavity. Background spectrum 66.78 days. |
| | count length | 99.2 d |
| | detector | WIPP-n |
| | results | U chain < 1.7 mBq/kg |
| | | Th chain < 3.1 mBq/kg |
| | | K-40 25 (14) mBq/kg |
| | | Co-60 < 1.5 mBq/kg |
| data | reference | Majorana report M-TECHDOCDET-2010-110 |
| | entry by | James Loach (jcloach@lbl.gov) |

⊞ Tin, LANL
⊞ Tin, Canberra



MAJORANA
Material Assay
Database
tin
Tin, LANL
sample
descripti
source
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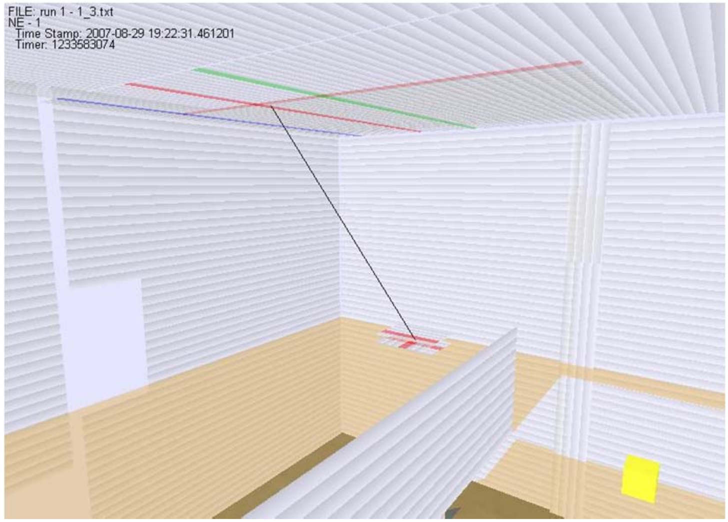
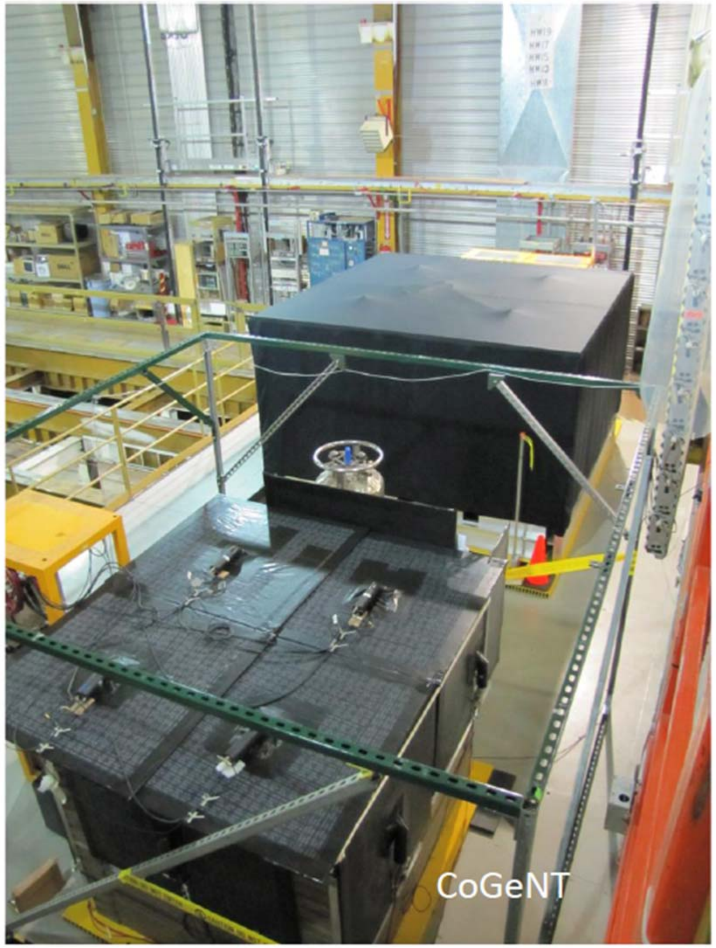
referenc
entry by
James Loach (jcloach@lbl.gov)
Tin, LANL
Tin, Canberra
Export
Copy and paste into Excel or similar.
"Tin, LANL",,"U chain","<","1.7",,"mBq/kg","Th chain","
<","3.1",,"mBq/kg","K-40",,"25","14","mBq/kg","Co-60","
<","1.5",,"mBq/kg"
"Tin, LANL",,"Li","<","0.007",,"ug/g","Be","
<","0.004",,"ug/g","Na","<","9",,"ug/g","Mg","<","1",,"ug/g","Al","
<","1",,"ug/g","K","<","10",,"ug/g","Ca","<","6",,"ug/g","Sc","
<","0.1",,"ug/g","Ti","<","1",,"ug/g","V","<","2",,"ug/g","Cr","
<","5",,"ug/g","Mn",,"0.15",,"ug/g","Fe",,"60.6",,"ug/g","Co","
<","1",,"ug/g","Ni","
<","5",,"ug/g","Cu",,"24.4",,"ug/g","Zn",,"2.5",,"ug/g","Ga","
<","0.3",,"ug/g","As","<","0.2",,"ug/g","Se","<","0.3",,"ug/g","Rb","
<","0.1",,"ug/g","Sr","<","0.09",,"ug/g","Y","
<","0.002",,"ug/g","Zr","<","0.007",,"ug/g","Nb","
<","0.006",,"ug/g","Mo","<","0.3",,"ug/g","Rh","
<","0.006",,"ug/g","Pd","
<","0.03",,"ug/g","Ag",,"231",,"ug/g","Cd","<","0.04",,"ug/g","Sb","
<","37",,"ug/g","Te","<","0.03",,"ug/g","Cs","<","4",,"ug/g","La","
<","0.6",,"ug/g","Ce","<","0.5",,"ug/g","Pr","<","0.6",,"ug/g","Nd","
<","0.01",,"ug/g","Sm","<","0.03",,"ug/g","Eu","

Maybe we eventually agree on Simulations … But are we right?

New experiments at Soudan to characterize hadronic showers underground

Muon proportional tubes lining walls & ceiling




Combined with Neutron Multiplicity Meter (UCSB, Case, Davis)
and LS neutron detectors (USD)

# Summary

**Some funding exists over the next year to make good progress on**

Improving Geant4 Code for Underground Physics
Benchmarking: FLUKA vs Geant4 and Simulation vs Data
Generic studies of the effect of depth (multiplicity, shower topology, veto efficiency)
Universal Materials Database

**A Geant4 Monte Carlo will be developed for Homestake**

has a framework which is easily transferrable to other labs
includes both radiogenic and cosmogenic backgrounds as input modules

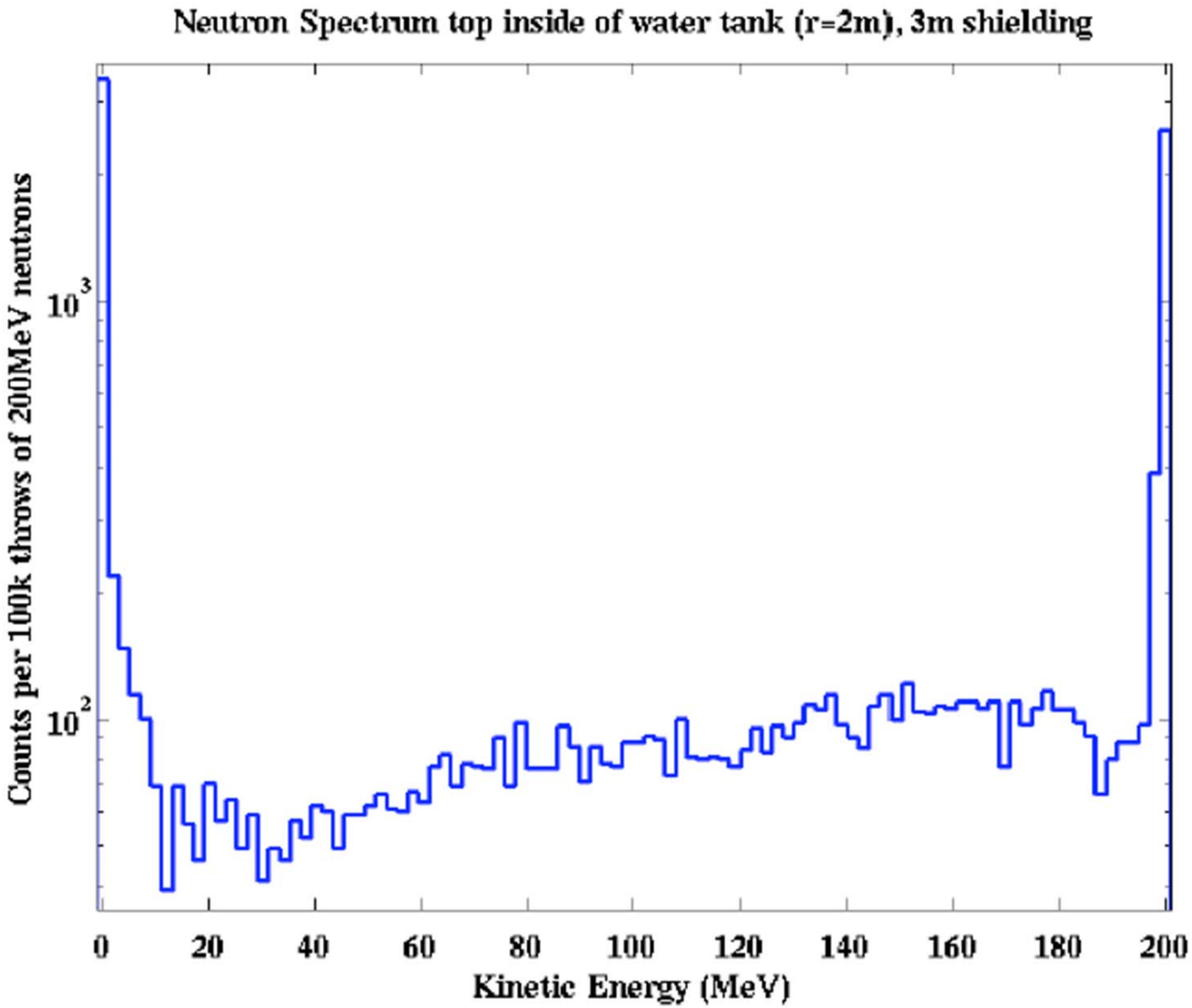
**This may form the basis for a Standard Underground Simulation**

Each lab will contribute background data, coded into the standard framework
Users can request the Background Module for their lab
Enter your experiment's geometry
Press go

You are invited to participate.
We should consider funding structures for the future.

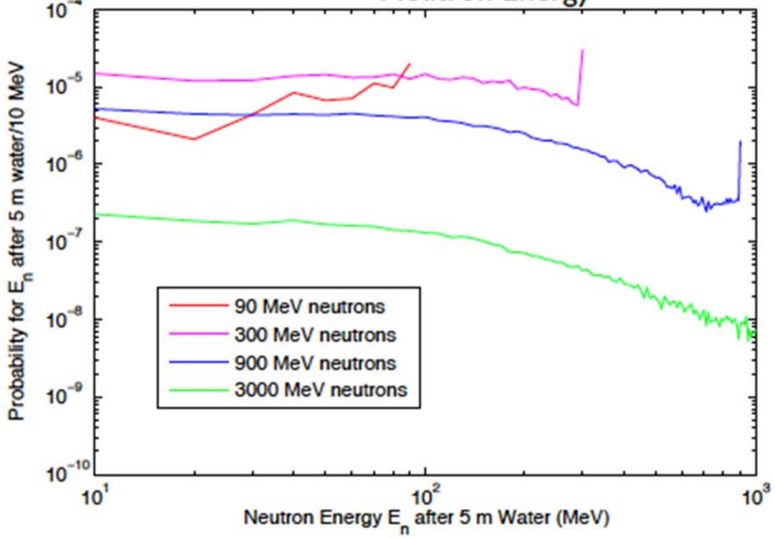
# Backup Slides

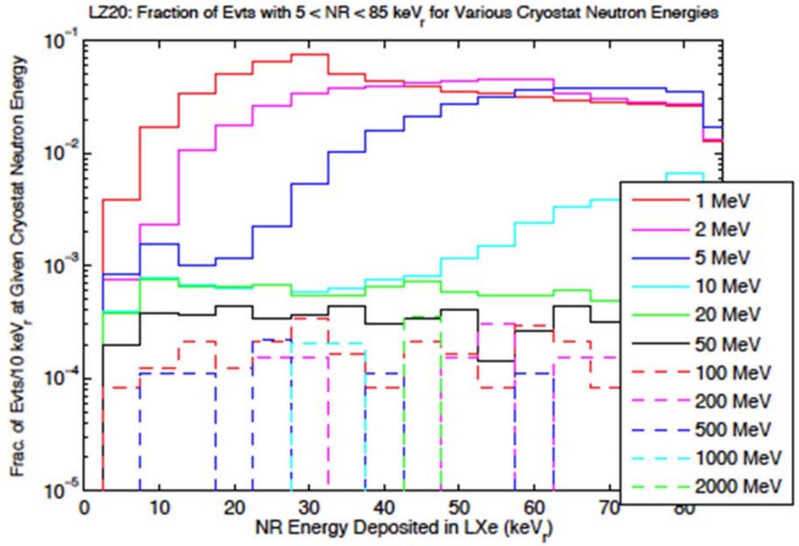
# Effectiveness of 3m Water Shield III

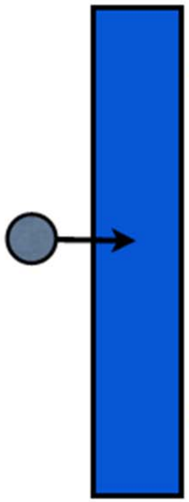


# Cryostat Neutrons

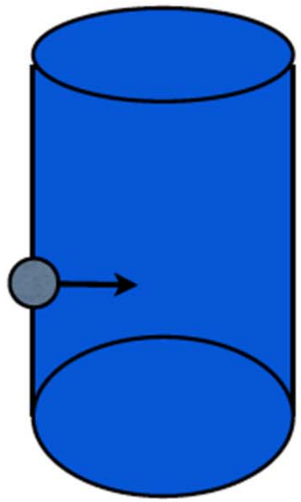
Probability for Cryostat Neutron at En for a Given Primary Neutron Energy



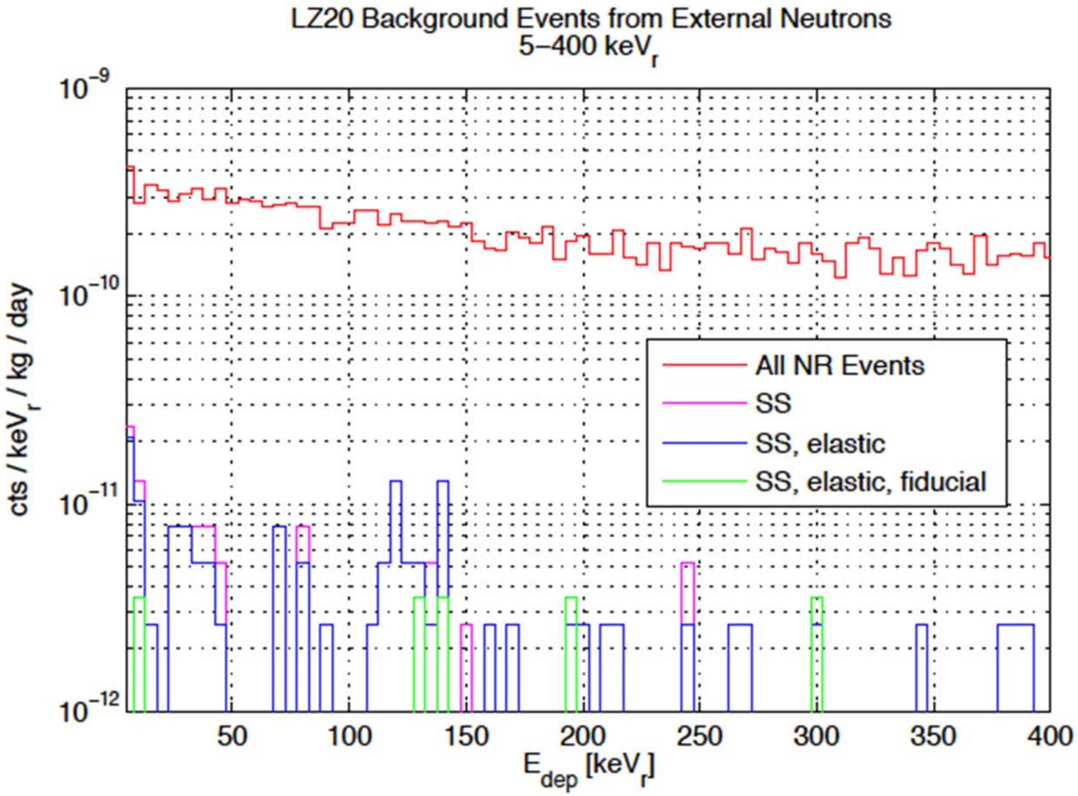



- Cryostat Neutrons: neutrons at cryostat boundary
- Probability for primary neutron producing cryostat neutron with an energy $E_n$ convolves Mei-Hime spectrum and linear water attenuation
    - 300 MeV primary neutron predominantly contributes to cryostat neutrons
- Low energy cryostat neutrons ( < 10 MeV) predominantly produce 5 keV$_r$ < NR < 85 keV$_r$



# Muon-Induced Neutrons: Background Rate




1 dru = 1 ct/keV$_r$/kg/day

- ~ 1.7 billion neutrons generated or ~ 22,000 years of running LZ20 at 4850 ft. level
- LZ20 background goal is 1 background event in 13.5 T in 1,000 live days or 4 ndru$_r$ in 5 - 25 keV$_r$
  - 0.3 ndru$_r$ background rate for NR events from muon-induced neutrons
  - Analysis cuts (single scatter, elastic, fiducial) reduce background by 2 orders of magnitude