MUOGRAPHY AND GEOLOGY – DOES IT MATTER WHICH CONTINENT YOU STAND ON?

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MuoN solutions

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Introduction

- Q: Does it matter which continent you stand on? We found this an interesting question and conducted a relatively extensive simulation in order to understand how this question can be approached

- Tools:
  - Extensive Air Showers (EAS):
    - CORSIKA (proton for simplicity)
      - Muon angular and energy distributions on the ground level
    - Single muons (energy and angular distributions) can also be taken from Gaisser-like formula
      - One example is Guan et al.[1] that has improved parametrization for the low-energy part
  - Muon propagation:
    - MMC code[2]
      - Based on parametrization (unlike GEANT4)
      - Simple to simulate very high-energy muons

    - Geant4 (version 10.5.1)
      - Standard tool for muon propagation in the material
      - Validate MMC results

[1]Guan et al. A parametrization of the cosmic-ray muon flux at sea-level. arXiv:1509.06176v1 [hep-ex] 21 Sep 2015.
[2]Chirkin, D. & Rhode,W., Propagating leptons through matter with Muon Monte Carlo (MMC). arXiv:hep-ph/0407075v3 3 Aug 2016.

Introduction

- Five different types of real-world continental and oceanic crustal and mantle materials were simulated
  - Studied continental geological models were:
    1) upper continental crust
    2) bulk continental crust
    3) lower continental crust
    4) oceanic crust
    5) oceanic upper mantle
  - In addition, we simulated water and standard rock for comparison

Geological background

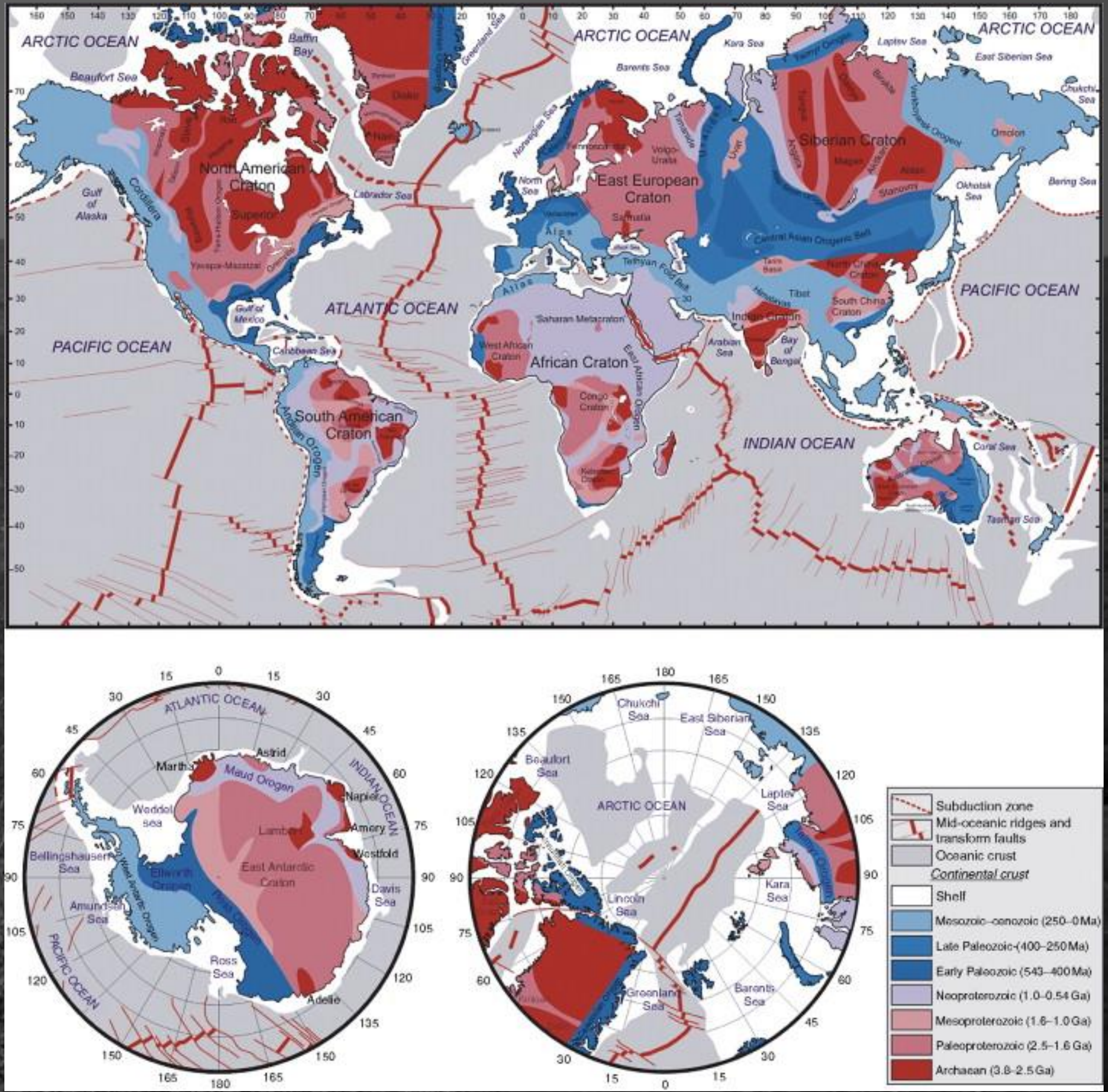
Earth's crust is a collage of rock domains of different age and composition

Due to tectonic forces and different levels of erosion, also crustal depth varies from place to place

Hence, from the viewpoint of simulations, it indeed matters where exactly muography is applied to

Local (geological) details may vary significantly

Our work will provide the first-level approximations of muon propagation simulations in global scale. However, local geology may still require knowledge of the local average rock compositions



An example: Average upper-crustal composition

Several compositional models have been proposed for the upper continental crust. The example given here is the upper-crustal model we used

The main components of rock geochemical data are presented as oxides

Recommended composition of the upper continental crust (Rudnick & Gao, 2014)

Element	Units	Upper crust	1 Sigma	%	Source[a]	Element	Units	Upper crust	1 Sigma	%	Source[a]
SiO_2	wt%	66.6	1.18	2	1	Ag	ng g^{-1}	53	3	5	4
TiO_2	"	0.64	0.08	13	2	Cd	µg g^{-1}	0.09	0.01	15	4
Al_2O_3	"	15.4	0.75	5	1	In	"	0.056	0.008	14	4
FeO_T	"	5.04	0.53	10	1	Sn	"	2.1	0.5	26	14
MnO	"	0.10	0.01	13	1	Sb	"	0.4	0.1	28	12
MgO	"	2.48	0.35	14	1	I	"	1.4		50	5
CaO	"	3.59	0.20	6	1	Cs	"	4.9	1.5	31	15
Na_2O	"	3.27	0.48	15	1	Ba	"	628	83	13	16
K_2O	"	2.80	0.23	8	3	La	"	31	3	9	4
P_2O_5	"	0.15	0.02	15	1	Ce	"	63	4	6	4
Li	µg g^{-1}	24	5	21	11	Pr	"	7.1			4
Be	"	2.1	0.9	41	4	Nd	"	27	2	8	4
B	"	17	8	50	4	Sm	"	4.7	0.3	6	4
N	"	83			5	Eu	"	1.0	0.1	14	4
F	"	557	56	10	4	Gd	"	4.0	0.3	7	4
S	"	621	322	53	4	Tb	"	0.7	0.1	21	4
Cl	"	370	382	103	4	Dy	"	3.9			17
Sc	"	14.0	0.9	6	6	Ho	"	0.83			17
V	"	97	11	11	6	Er	"	2.3			4
Cr	"	92	17	19	6	Tm	"	0.30			17
Co	"	17.3	0.6	3	6	Yb	"	1.96	0.4	18	4
Ni	"	47	11	24	6	Lu	"	0.31	0.05	17	4
Cu	"	28	4	14	7	Hf	"	5.3	0.7	14	4
Zn	"	67	6	9	7	Ta	"	0.9	0.1	13	11
Ga	"	17.5	0.7	4	8	W	"	1.9	1	54	18
Ge	"	1.4	0.1	9	4	Re	ng g^{-1}	0.198			13
As	"	4.8	0.5	10	9	Os	"	0.031	0.009	29	13
Se	"	0.09	0.05	54	4	Ir	"	0.022	0.007	32	13
Br	"	1.6			5	Pt	"	0.5	0.5	95	13
Rb	"	84	17	20	10	Au	"	1.5	0.4	26	4
Sr	"	320	46	14	4	Hg	µg g^{-1}	0.05	0.04	76	4
Y	"	21	2	11	4	Tl	"	0.9	0.5	57	4
Zr	"	193	28	14	4	Pb	"	17	0.5	3	4
Nb	"	12	1	12	11	Bi	"	0.16	0.06	38	19
Mo	"	1.1	0.3	28	12	Th	"	10.5	1.0	10	20
Ru	ng g^{-1}	0.34	0.02	6	13	U	"	2.7	0.6	21	20
Pd	"	0.52	0.02	3	13						

The five geological models

Element	Upper continental crust[a] (juvenile 2.5-1.8 Ga)	Bulk continental crust[b] (irrespective of age)	Lower continental crust[c] (irrespective of age)	Oceanic crust[d]	Oceanic upper mantle[e]
SiO_2	66.86	57.24	53.4	49.77	45.61
TiO_2	0.64	0.90	0.82	1.51	0.06
Al_2O_3	15.26	15.88	16.9	16.09	2.65
FeO	4.90	9.09	8.57	10.56	-
Fe_2O_3	-	-	-	-	8.01
MnO	-	-	0.10	-	0.13
MgO	2.26	5.29	7.24	7.74	41.13
CaO	3.57	7.39	9.59	11.36	2.34
Na_2O	3.34	3.10	2.65	2.82	0.06
K_2O	3.02	1.10	0.61	0.15	-
P_2O_5	0.14	-	0.10	-	0.01

Results

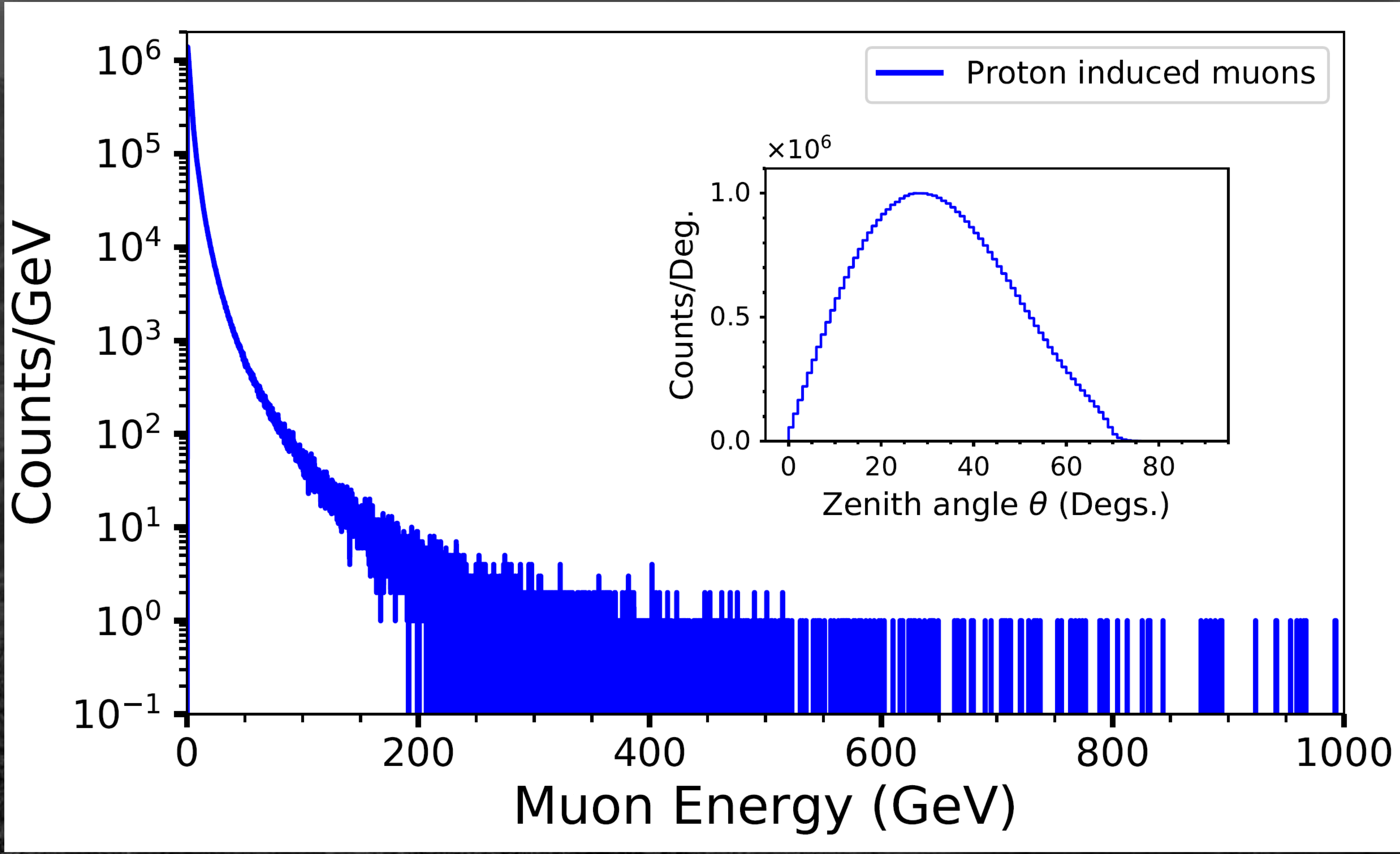
The initial energies for proton-primaries range from 1.3 GeV to 10^7 GeV with the spectral index of -2.7

~80% of primaries producing muons most relevant in muography are protons (mainly those below the knee energies)

A simple rule of thumb for the standard rock: 10 GeV gets to 20 m, 100 GeV to 150 m and 1000 GeV to 1000 m

Muons in those of the latter are scarce

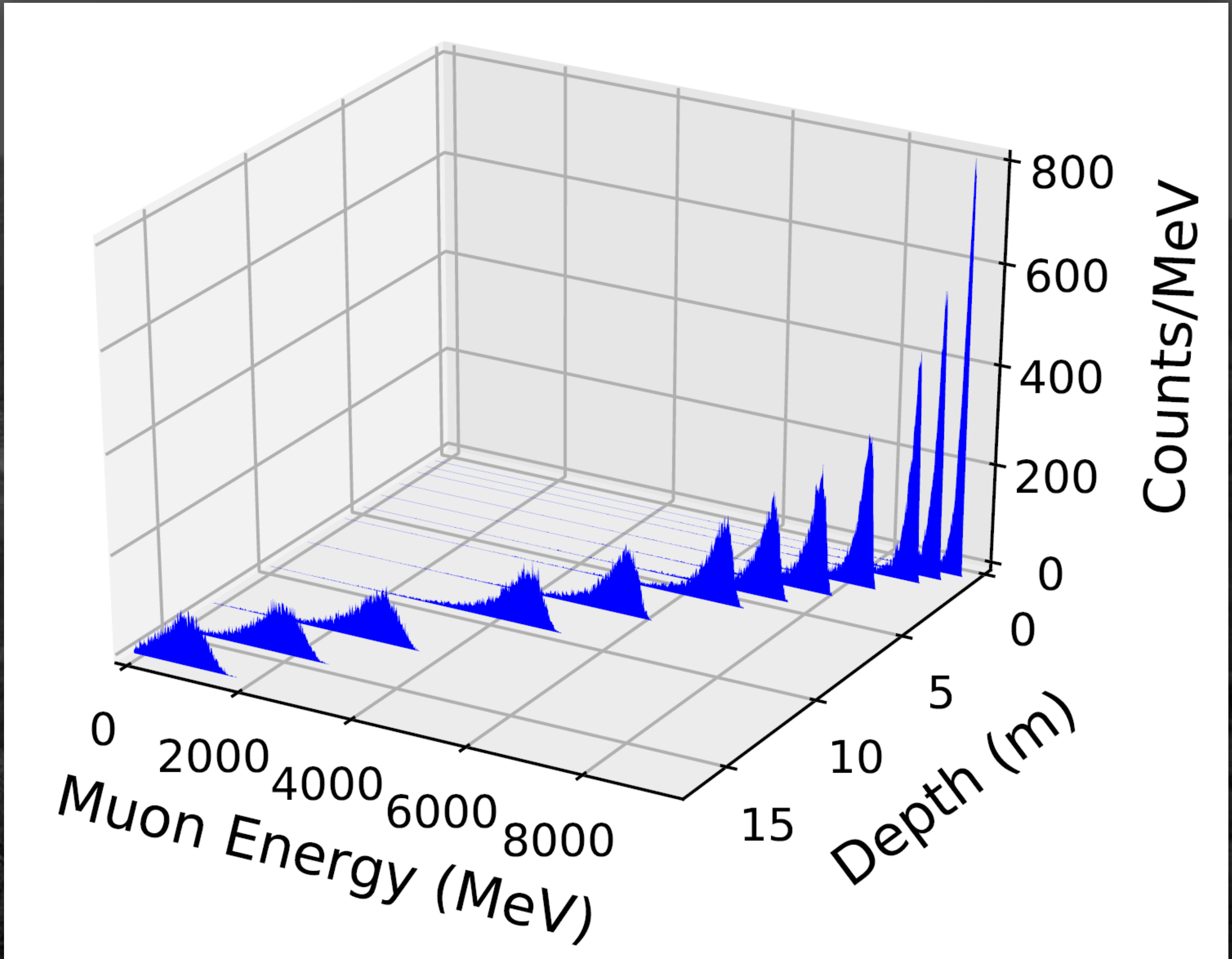
Fig. 1. Simulated muon energy and angular distributions (zenith angle, inset) for 10^8 proton-induced extensive air showers according to the CORSIKA cosmic-ray software package (Heck et al., 1998)



Results

Simulations have been performed with the Geant4 software package

Fig. 2. Simulated muon energy distributions of initially 10 GeV muons at twelve different (for clarity not equally divided) depths in standard rock

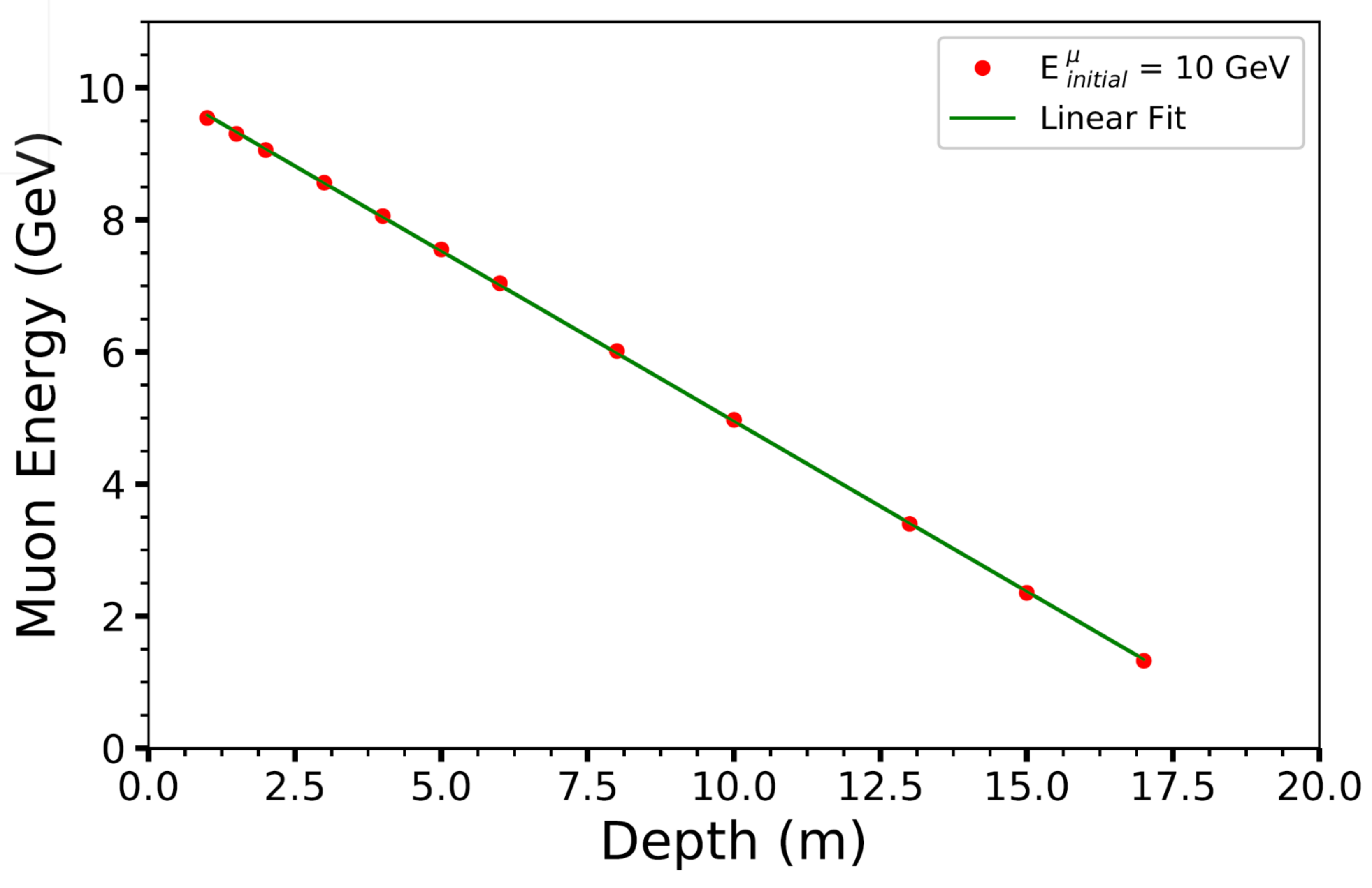


Results

Prior to their decay these muons have lost ~90% of their initial energy at the end of their path

However, a small fraction is lost all the time as soon as the muons hit the ground

Fig. 3. Simulated means of energy distributions of initially 10 GeV muons at twelve different depths in standard rock (red dots) together with a linear fit (green line)



Results

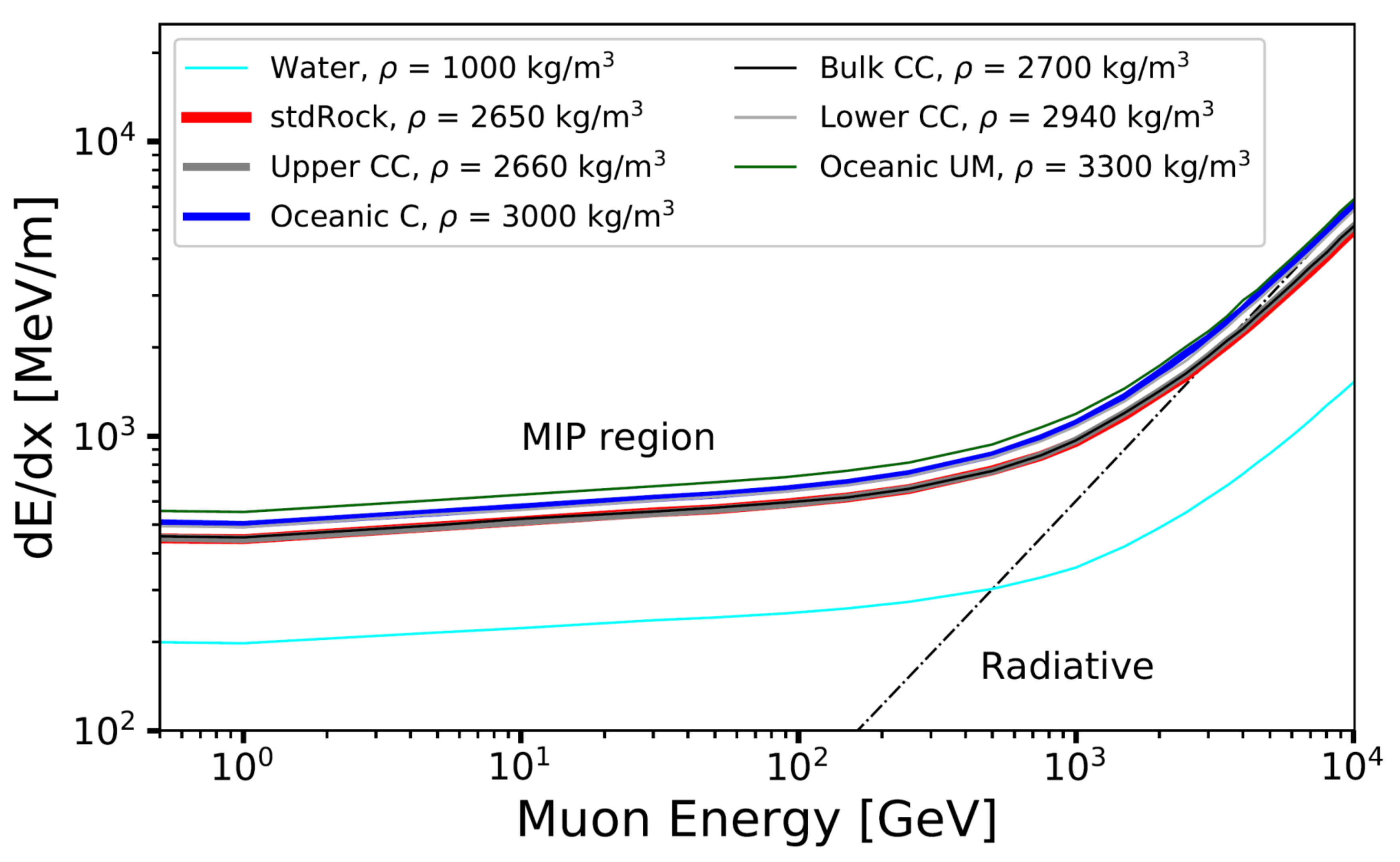
Water and standard rock are plotted for comparison

Simulations have been performed with the Geant4 software package

The MIP region (minimum ionizing particle), the stopping power is only weakly sensitive to the energy or speed of the particle) is indicated

The dashed line indicates the radiative component that enters increasingly in at high muon energies

Fig. 4. Simulated muon stopping powers, i.e., energy losses per unit distance, in five earth continental materials



Results

The number was limited to three for clarity

One notes that 'Upper CC' almost overlaps with 'Bulk CC' although the former get generally slightly deeper

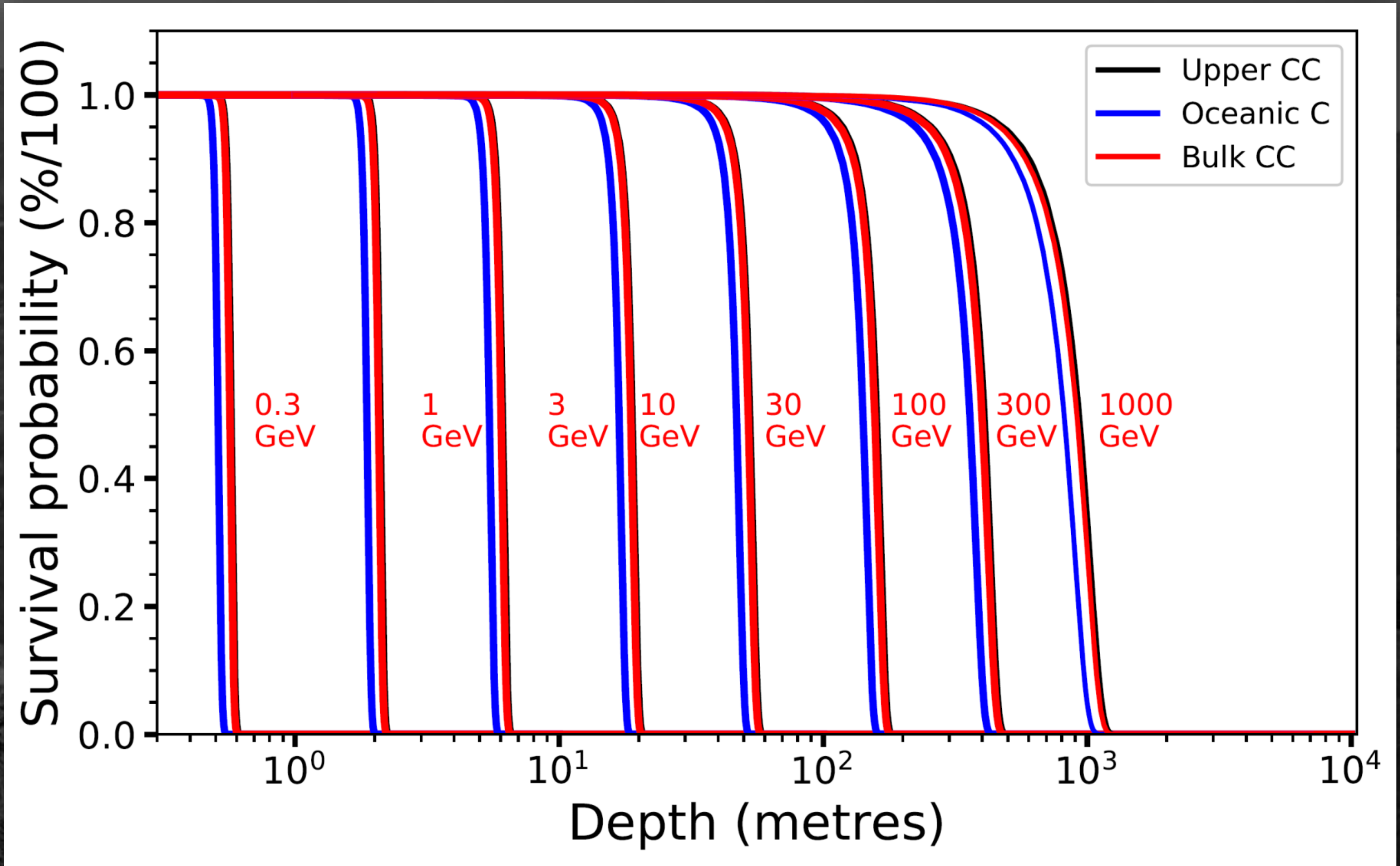
The simulations have been carried out using the Geant4 software package

A simple rule of thumb: 10 GeV muons get to 20 m, 100 GeV to 150 m and 1000 GeV to 1000 m of standard rock

The shape of the curves is not constant (the deeper the muons get the broader is the energy distribution)

The probability is actually not 1 till it begins to collapse but a small fraction (of muons) is lost once the muons hit the ground

Fig. 5. Simulated muon survival probabilities as a function of depth for three common layers of the earth's crustal materials for selected (logarithmic) muon energies



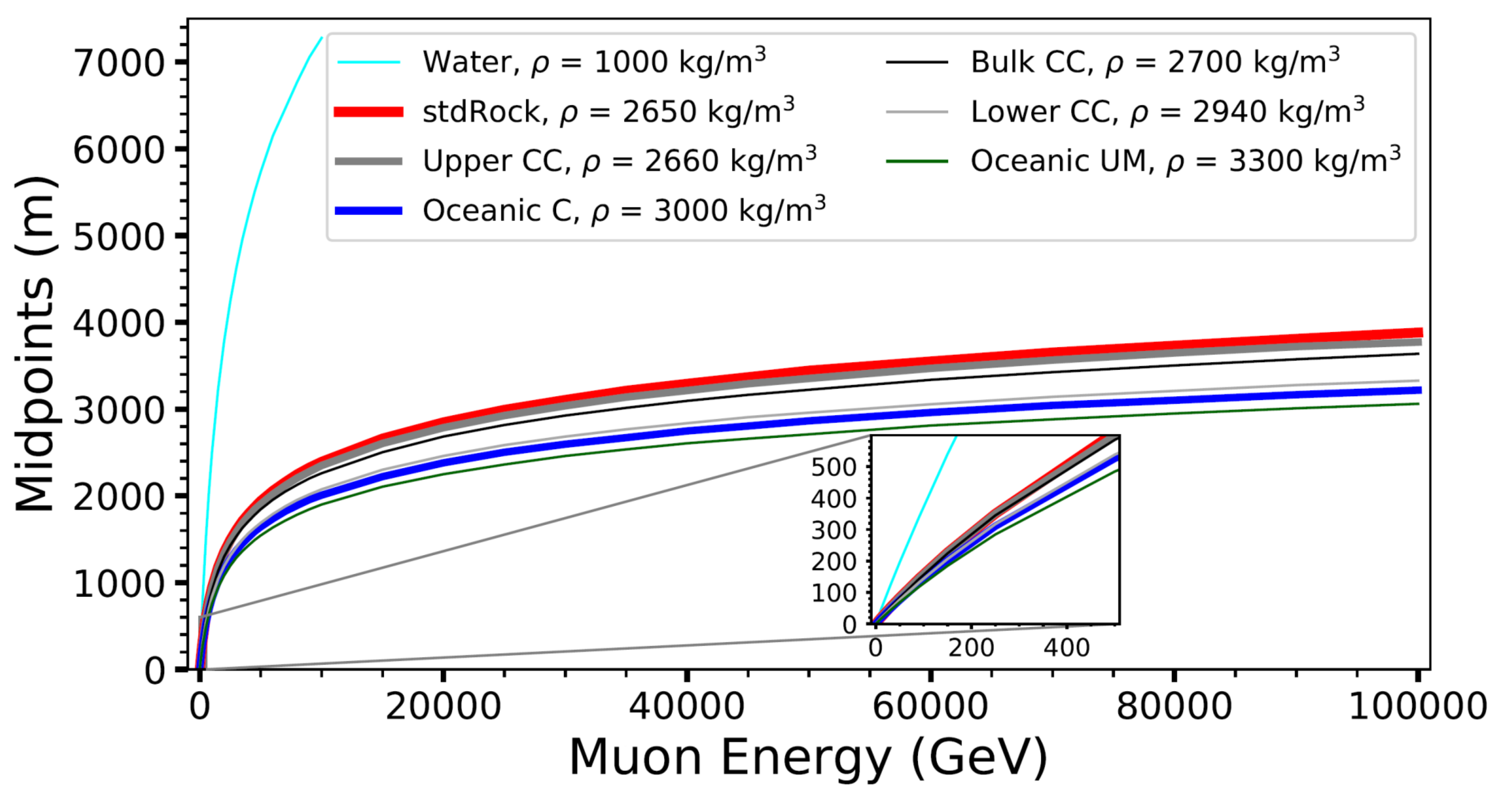
Results

Those of water and the standard rock for comparisons

Simulated with the Geant4 (Allison et al., 2016) software package

One notes that the range in water is significantly longer than that of any given solid material

Fig. 6. Muon ranges (mid-points) for five common earth continental materials



Results

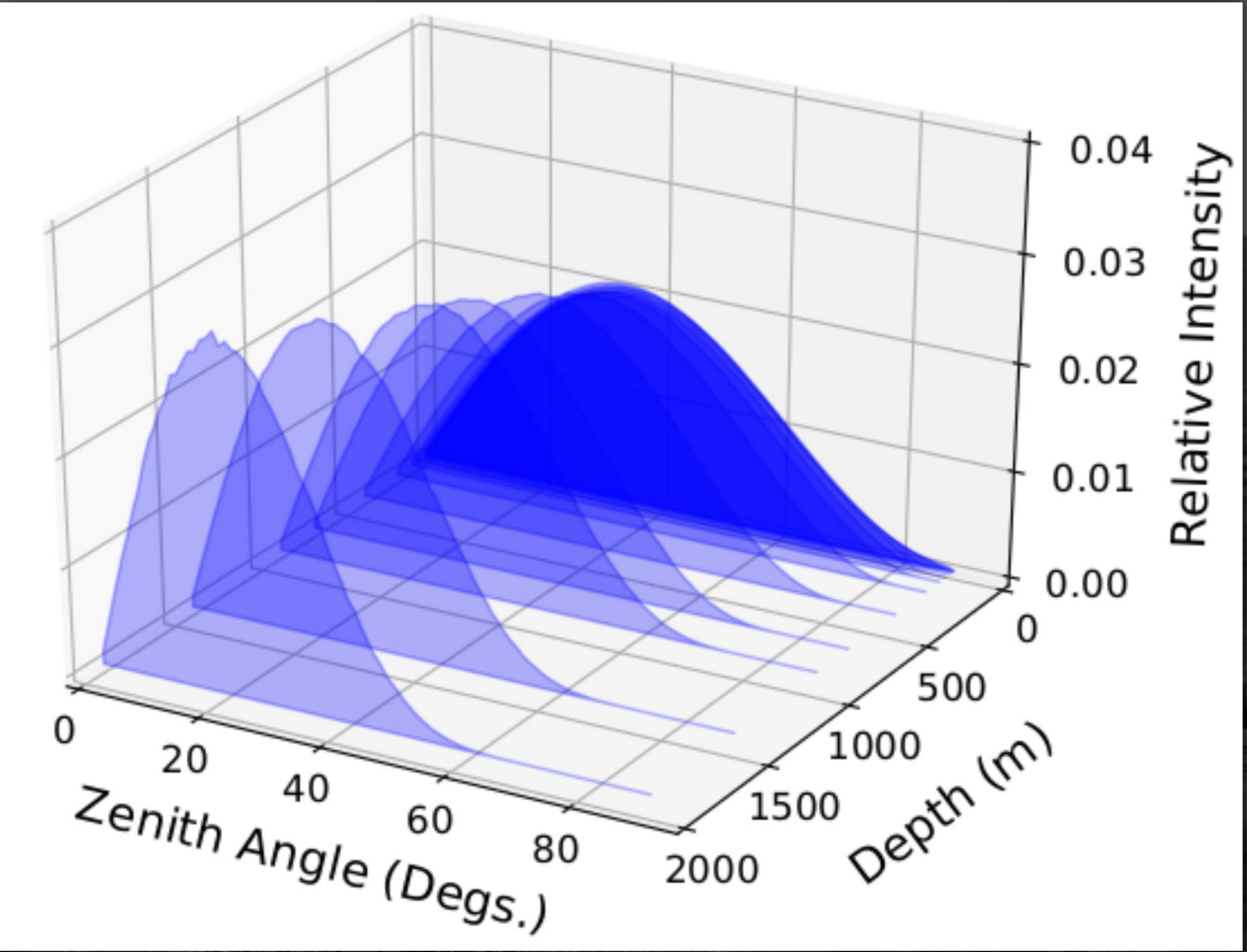
Note that for clarity the area of each distribution is normalized to 1

This (obviously) results from initial muon energy distribution which is not flat (and of geometry)

The distribution is proportional to $\cos^n\theta$ where n is close to 2 on the ground but for large depths, the exponent n gets very large

Note that parameter n in $\cos^n\theta$ determines the width of the distribution

Fig. 7. Simulated muon angular (zenith) distributions of standard rock at the selected twelve depths



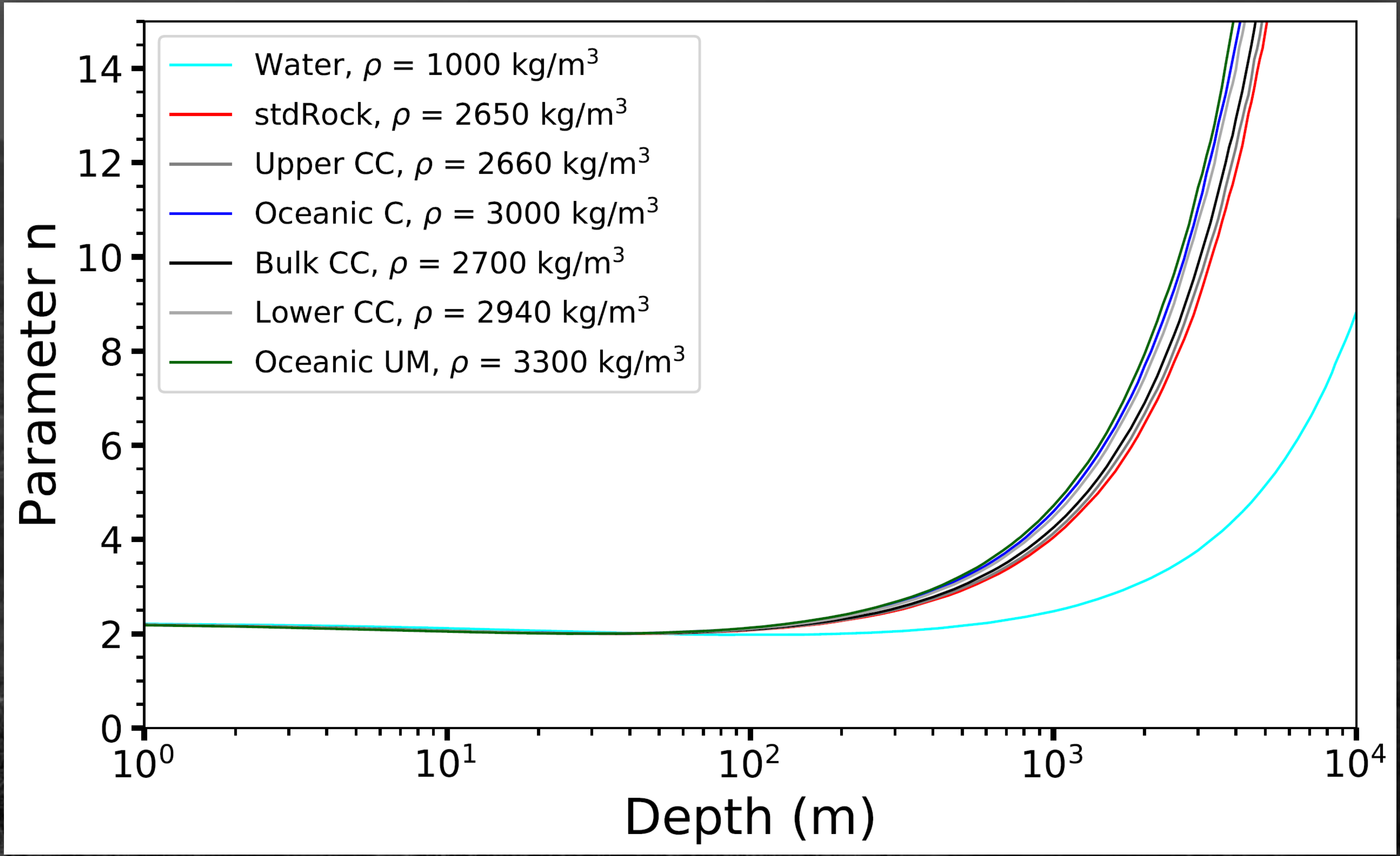
Results

Those of standard rock and water are for comparison.

The parameter n is clearly density dependent and increases faster with higher densities

However, below 100 m it seems constant regardless of density

Fig. 8. Simulated (MMC) parameter n of $\cos^n\theta$ fitted at different depths for a thick column of rocks

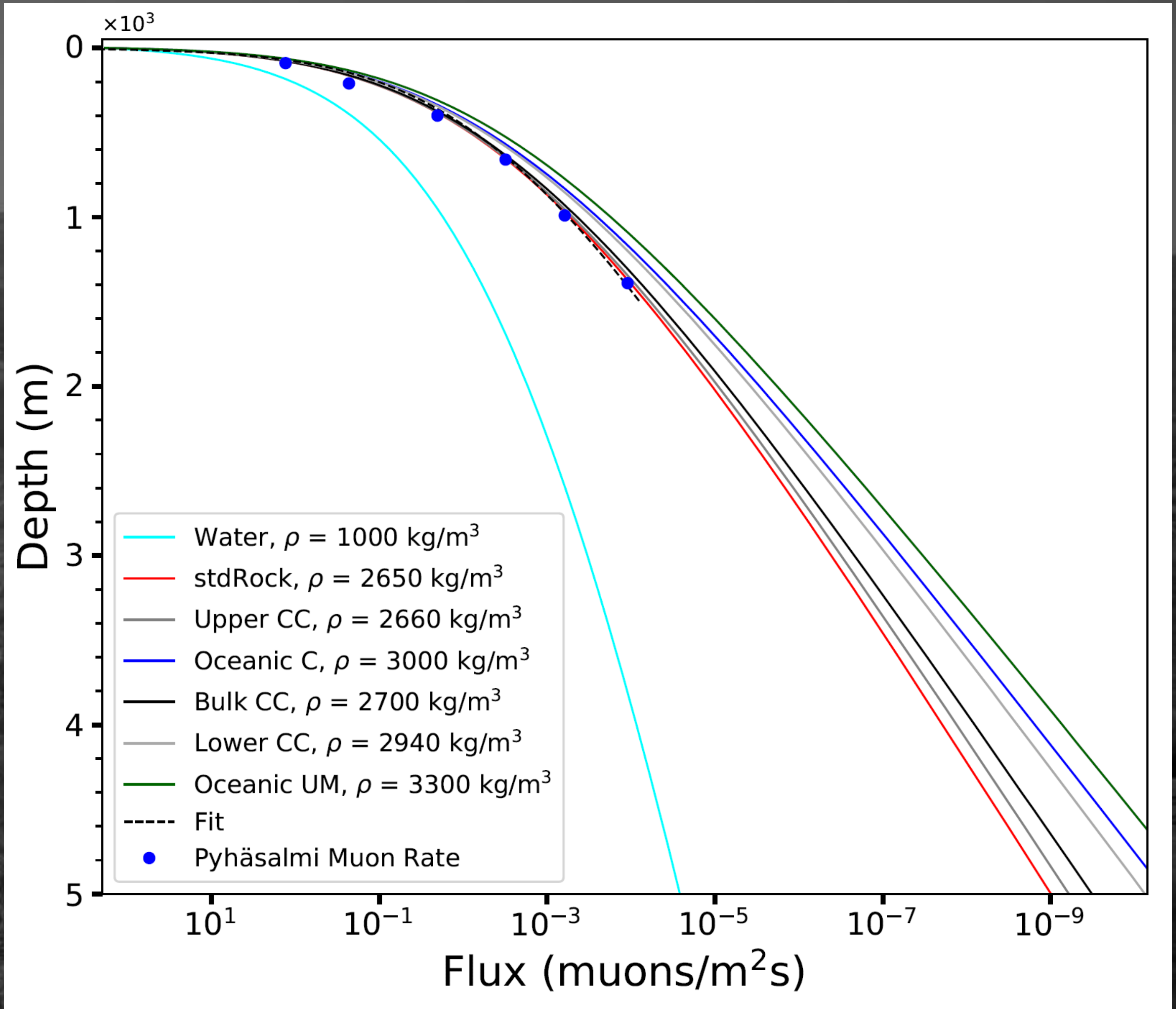


Results

Water and standard rock are for comparison

Simulations have been performed using the approach by Chirkin and Rhode (2016), or the MMC code, while the experimental data for the Pyhäsalmi mine are from Enqvist et al. (2005)

Fig. 9. Simulated and measured relation between the depth (in metres) and the muon rate in five continental materials



Conclusions

- Different materials result in significantly different muon distributions and rates
  ➡ Cannot be neglected in muographic surveys

- Standard Rock is actually a not-so-good example of a common ("standard") rock

- Energy loss is surprisingly linear practically till muons decay

- Angular distribution ($\sim\cos^n\theta$) is somewhat surprising
  - Down to 100m practically constant and independent on density/material
  - May be useful to remember in, e.g., groundwater studies

- We are preparing a longer paper to be published next year
  - Stay tuned!

Thank you !

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