Markus Köhli

UP 16.2

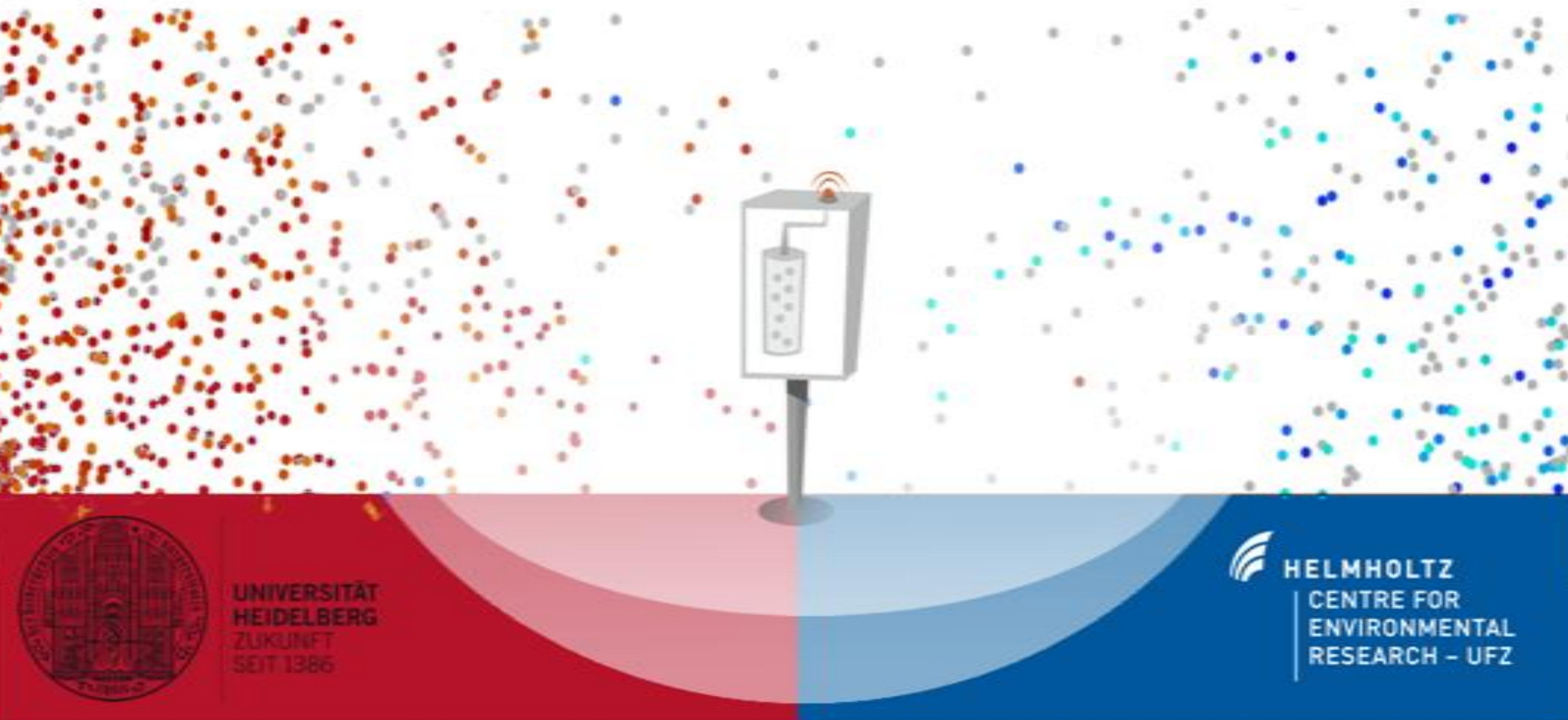
Martin Schrön Ulrich Schmidt Peter Dietrich Steffen Zacharias

27.03.2015

Soil moisture sensing

with

cosmic-ray induced neutron showers



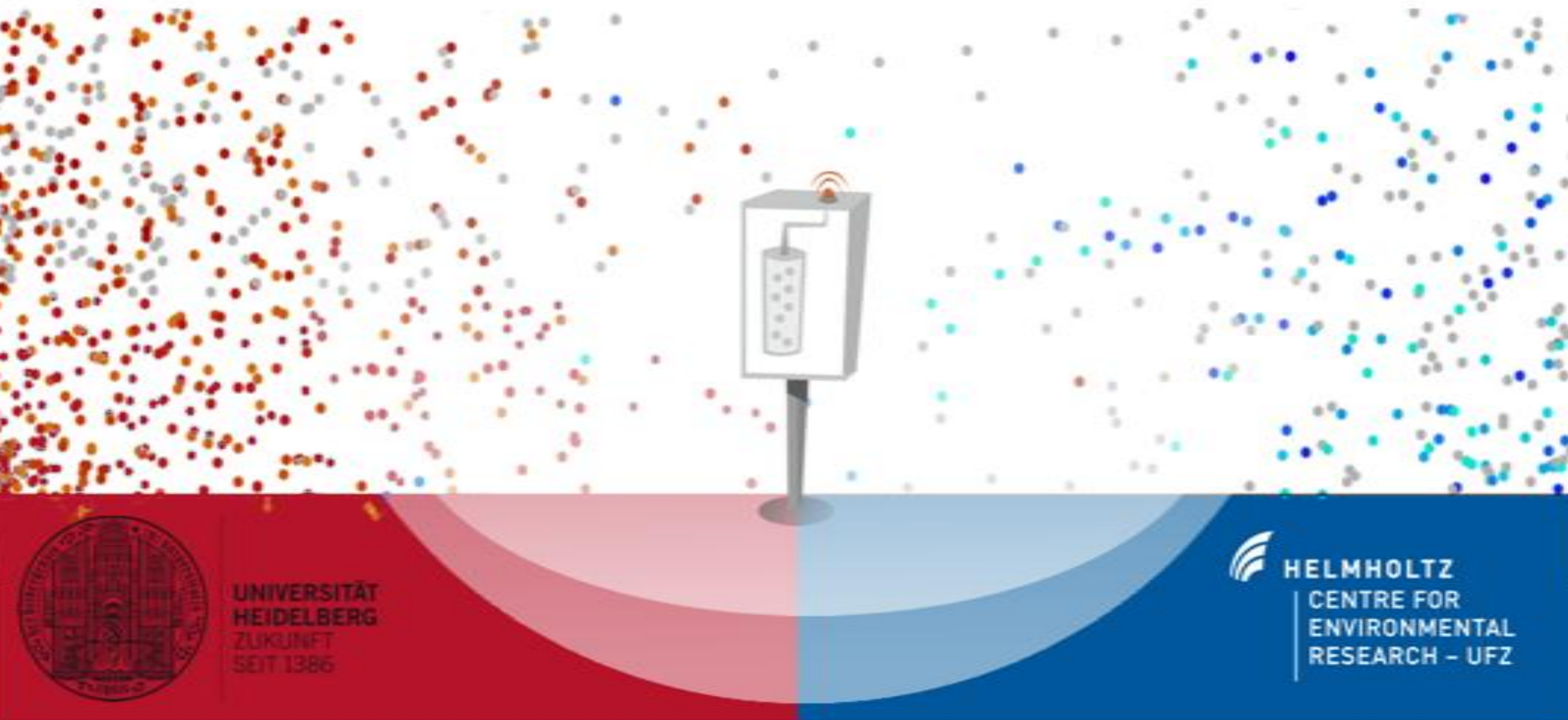
Markus Köhli
UP 16.2
Simulation

Martin Schrön
UP 16.4
Application

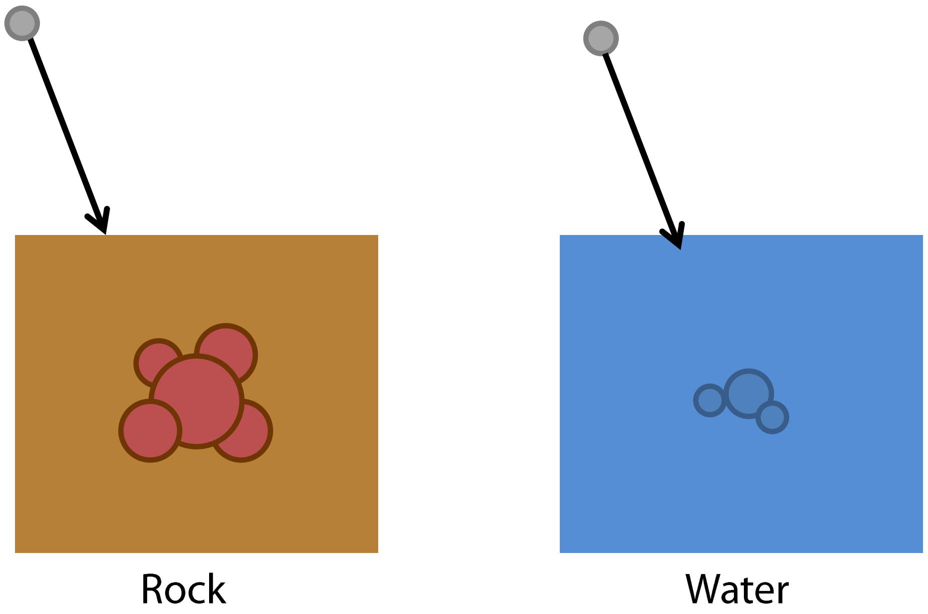
Ulrich Schmidt Peter Dietrich Steffen Zacharias

27.03.2015

Soil moisture sensing
with
cosmic-ray induced neutron showers



Neutron response to water



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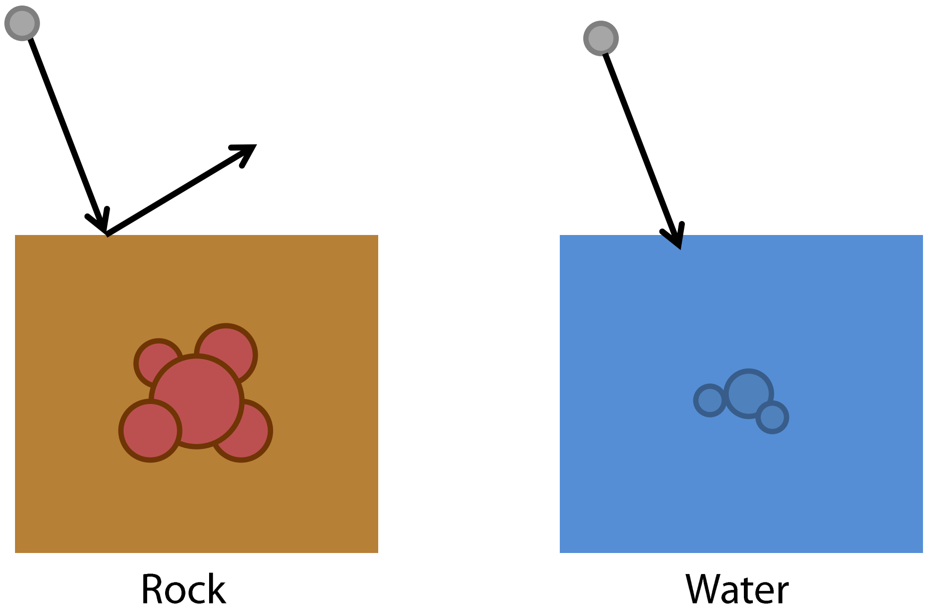

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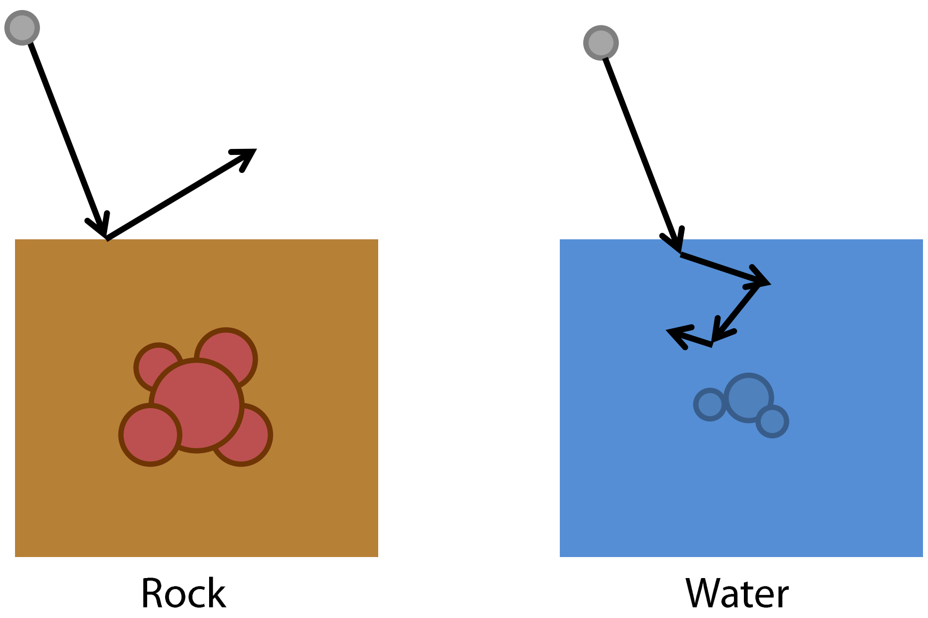
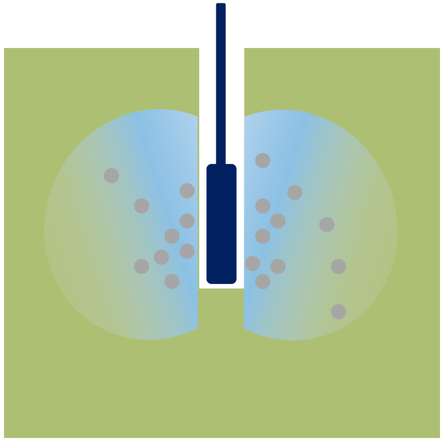


Neutron response to water

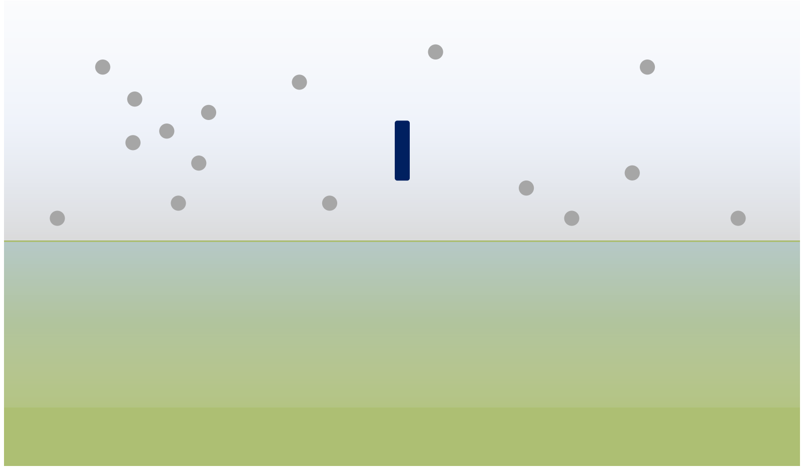
active

small distinct domain



passive

large area, diffusive



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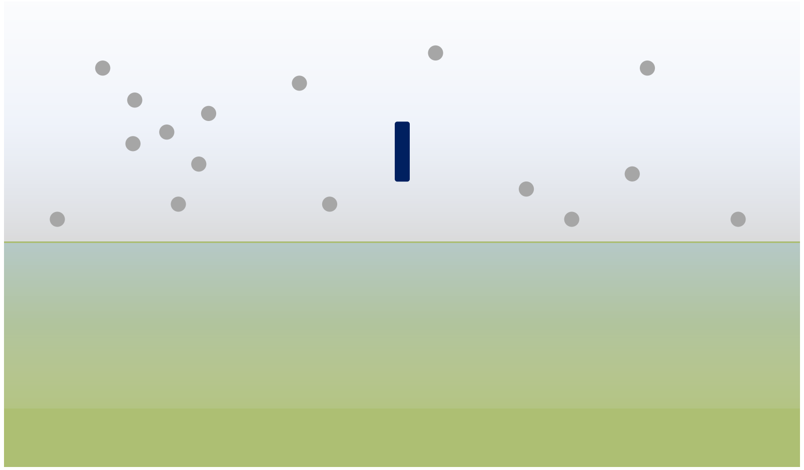
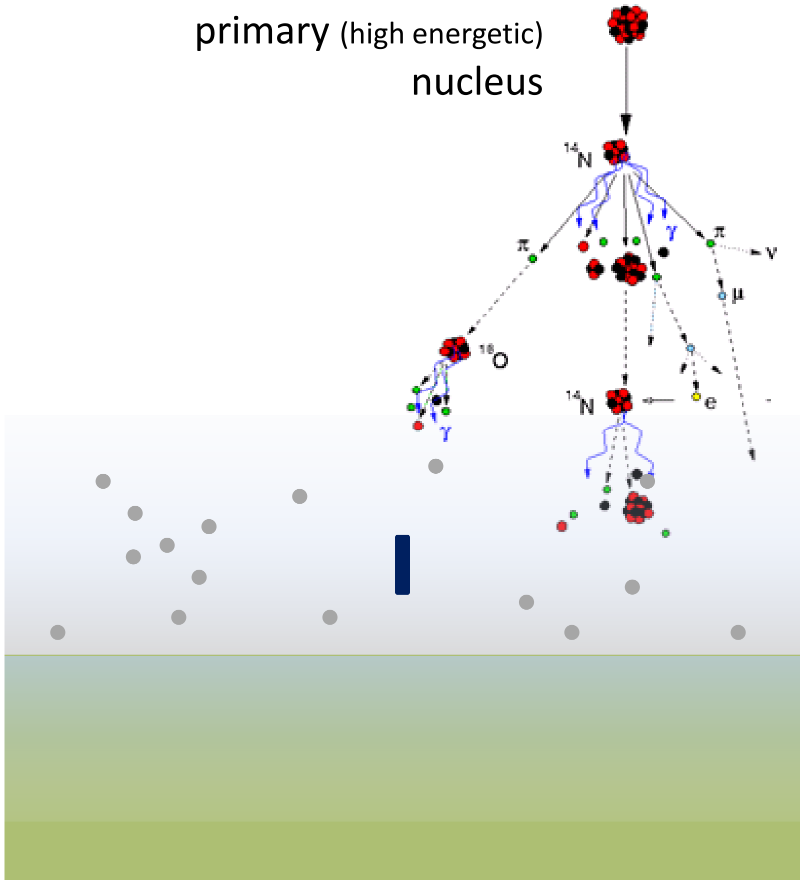
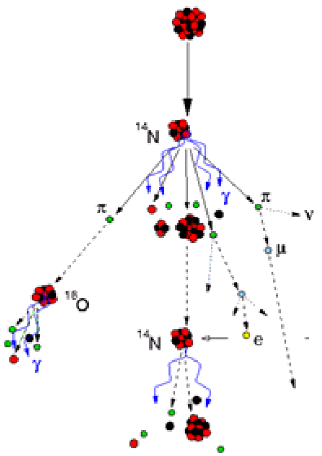
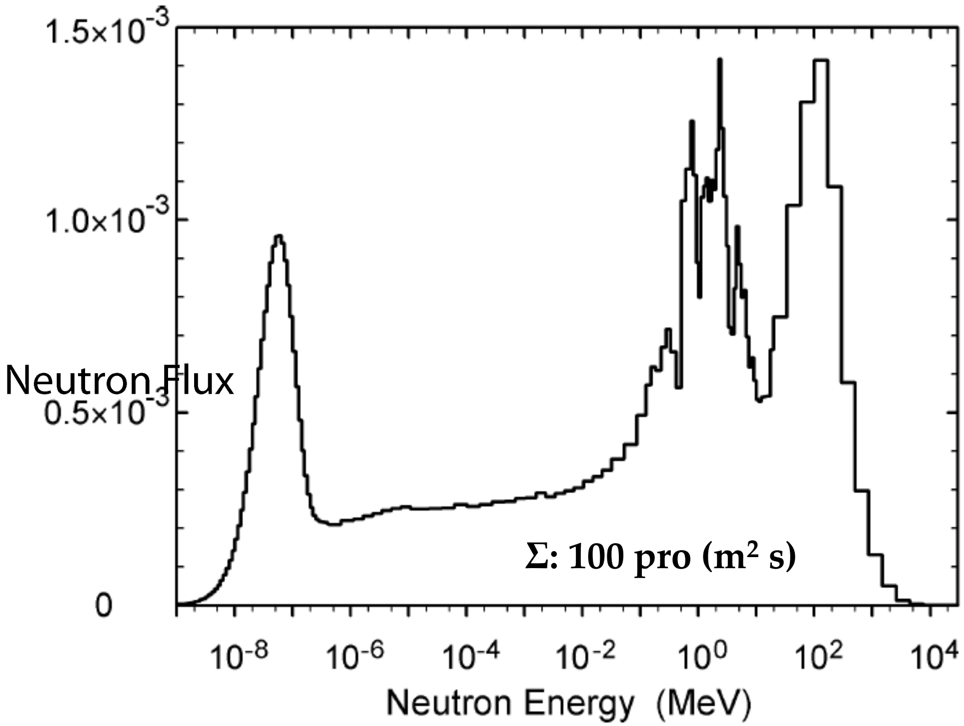


Cosmic Neutrons

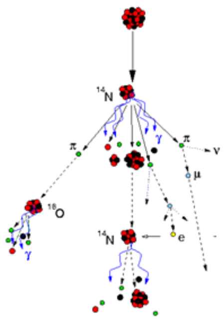


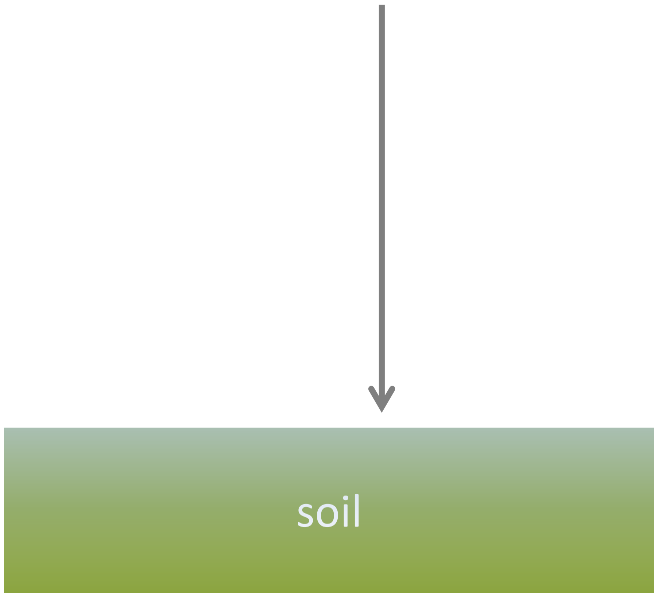
The Cosmic Neutron Spectrum

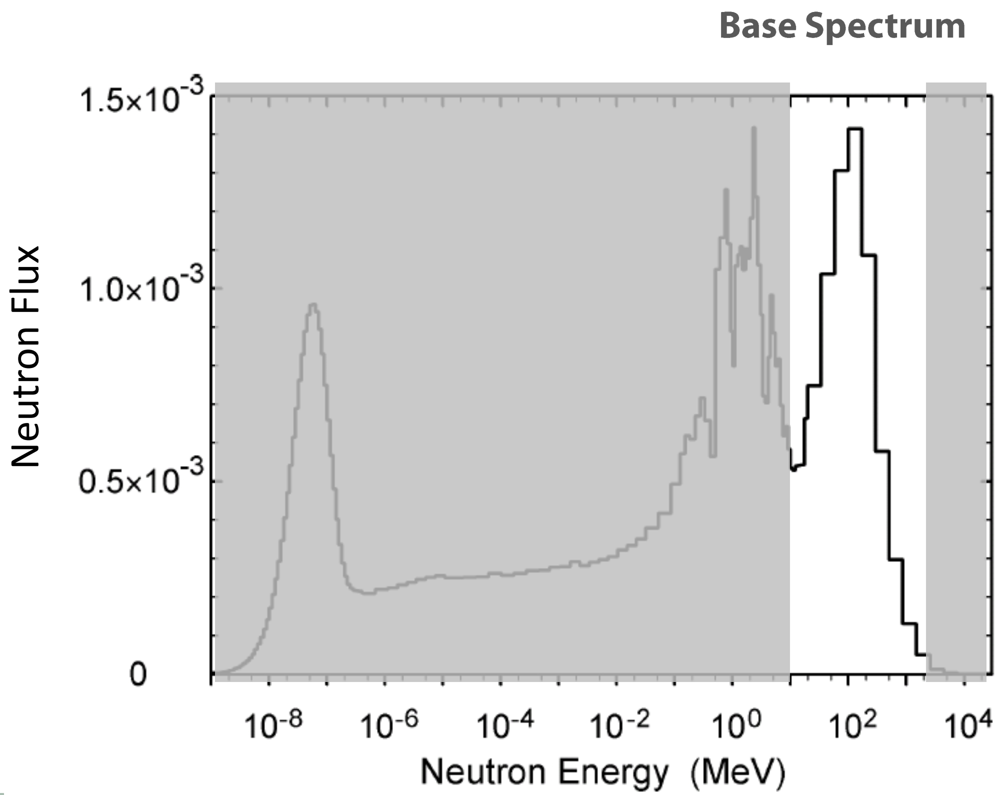




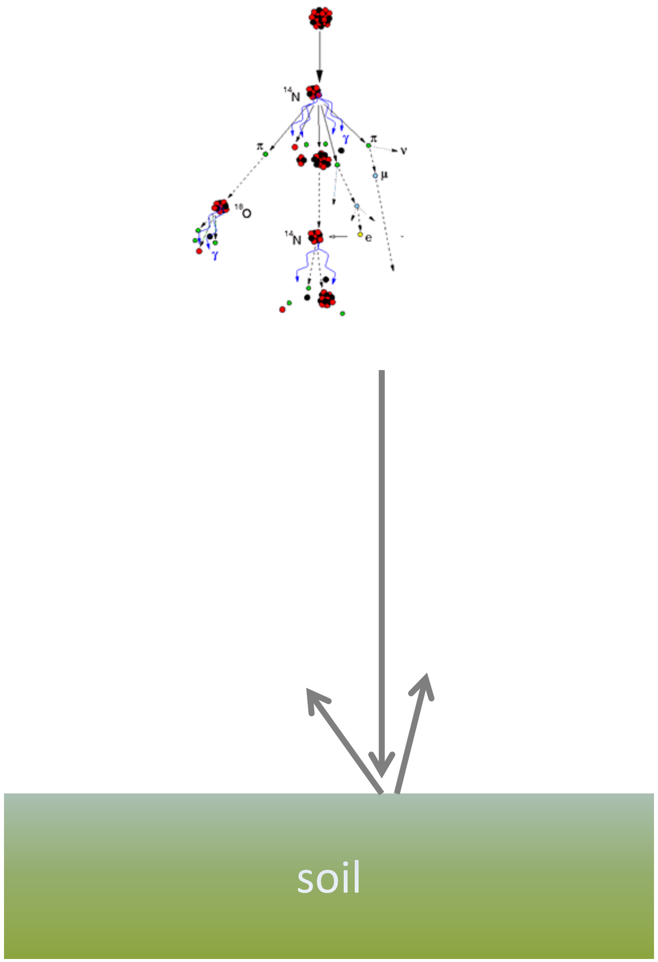
The Cosmic Neutron Spectrum

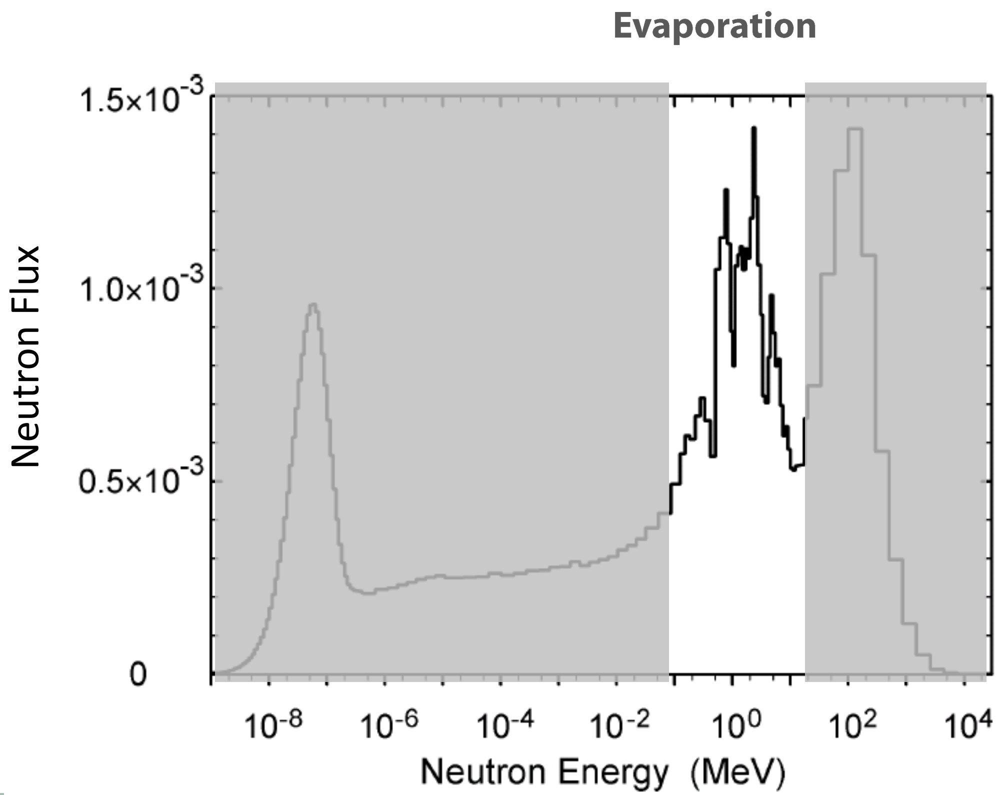






The Cosmic Neutron Spectrum





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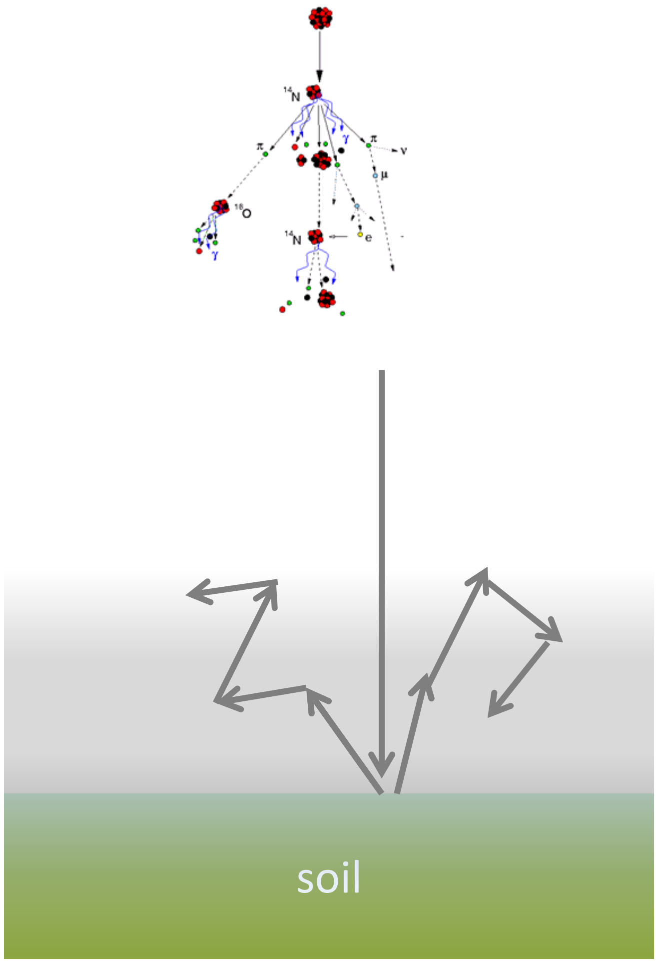

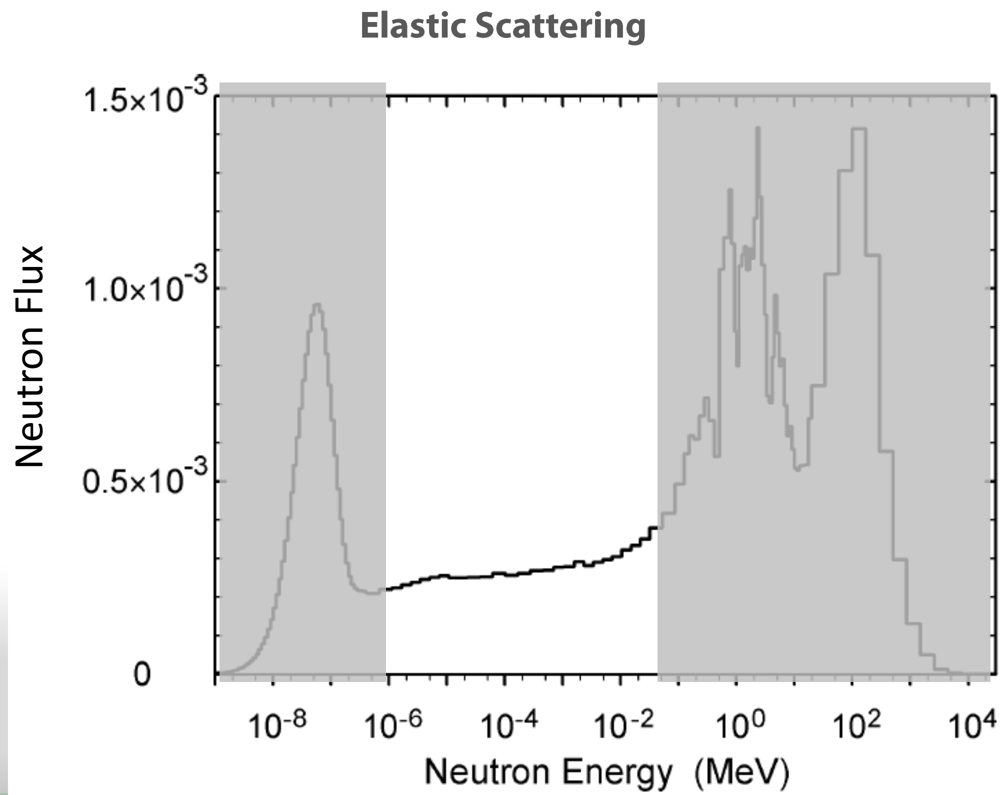

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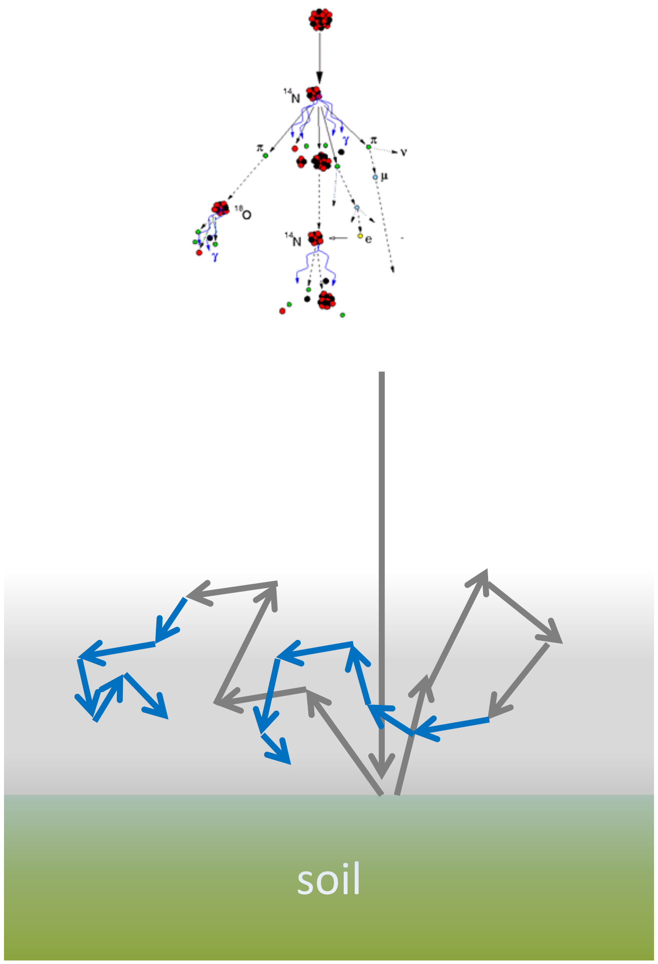

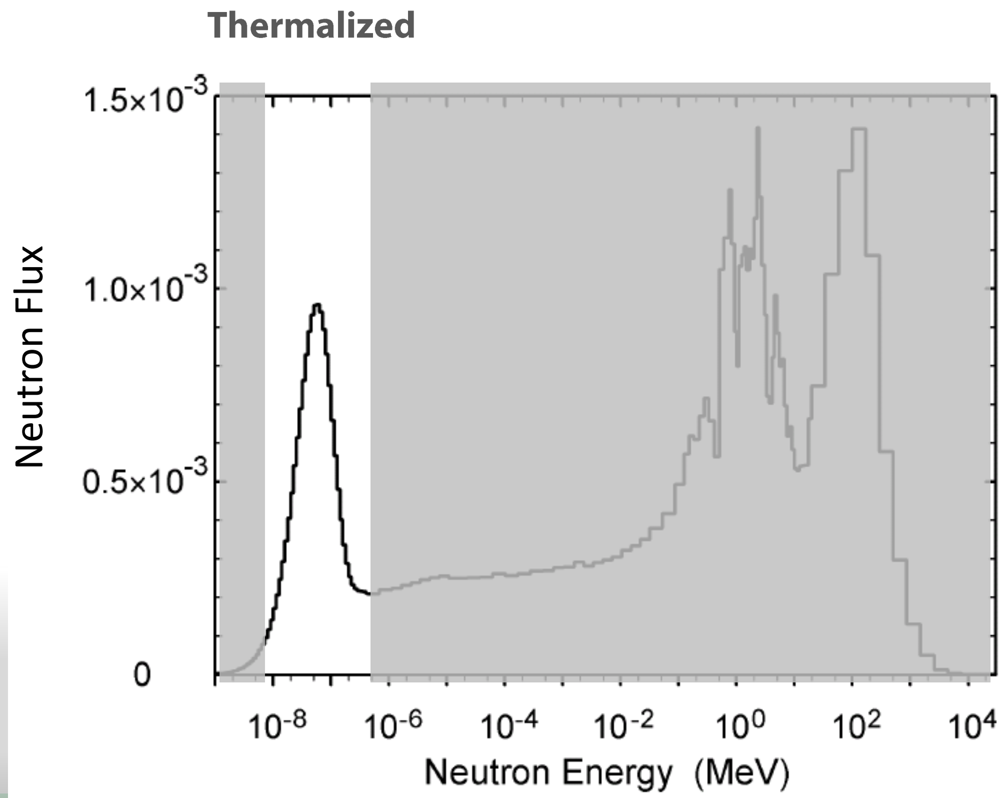

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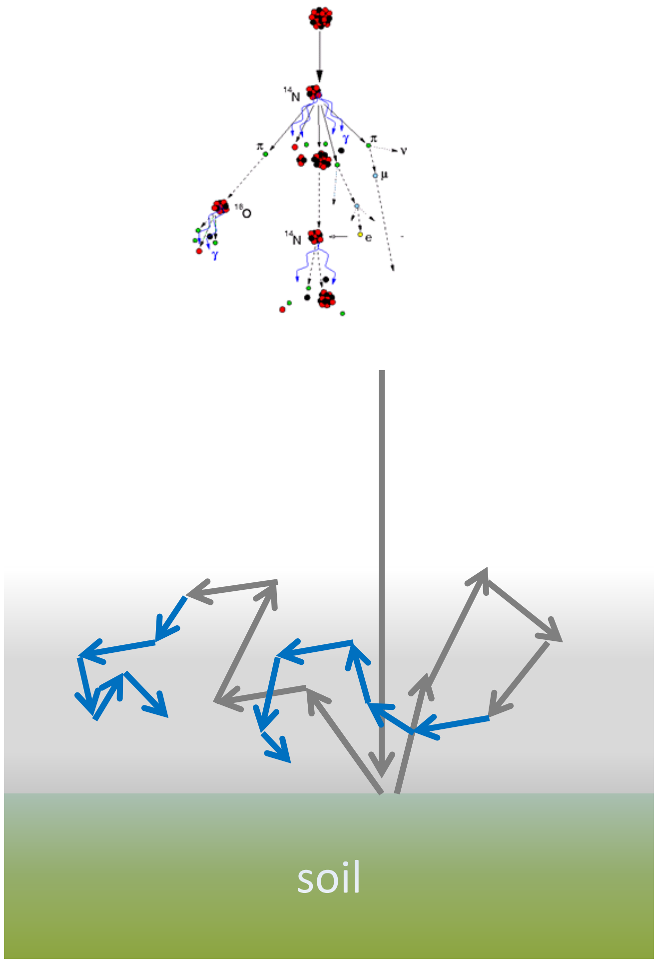
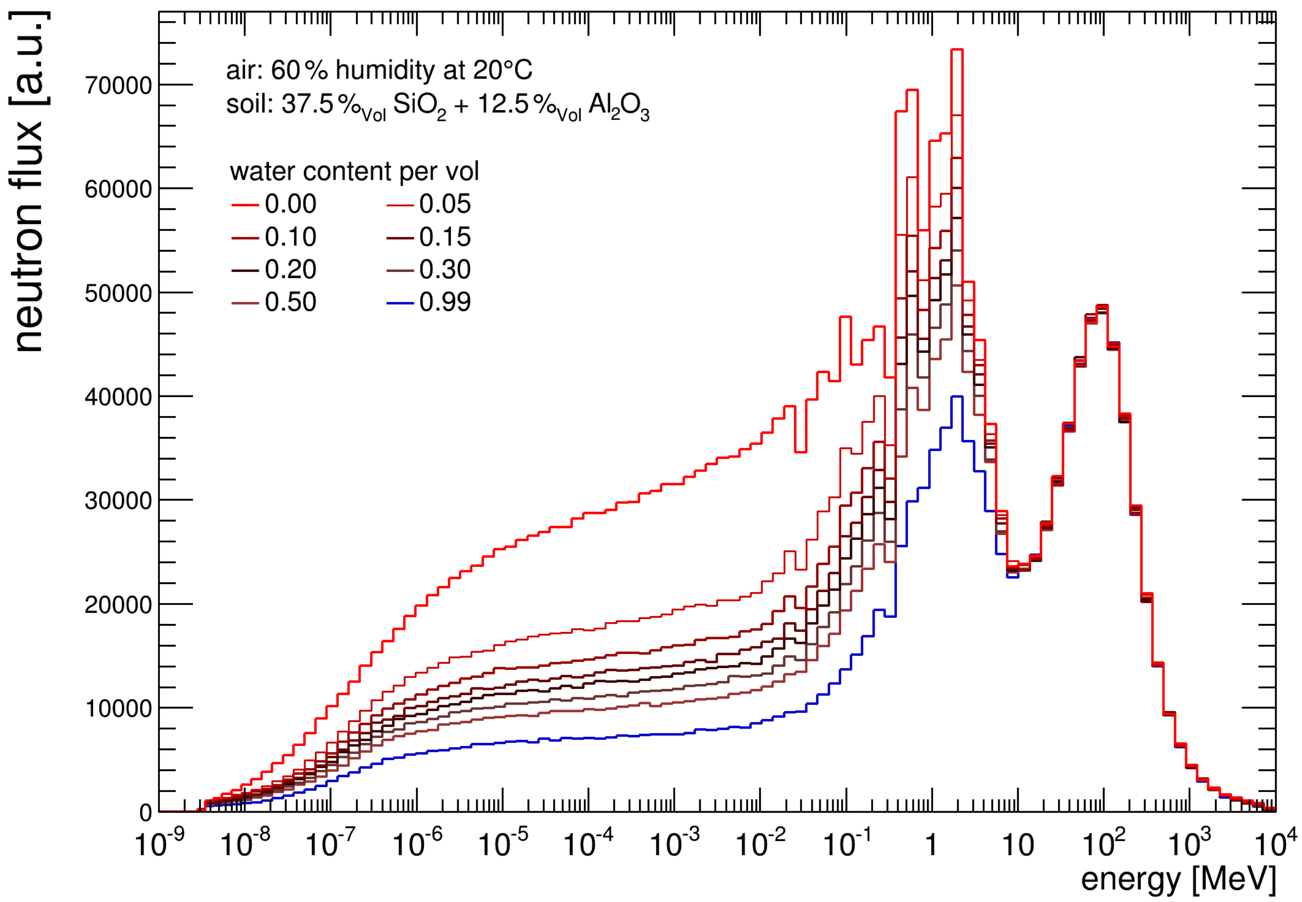
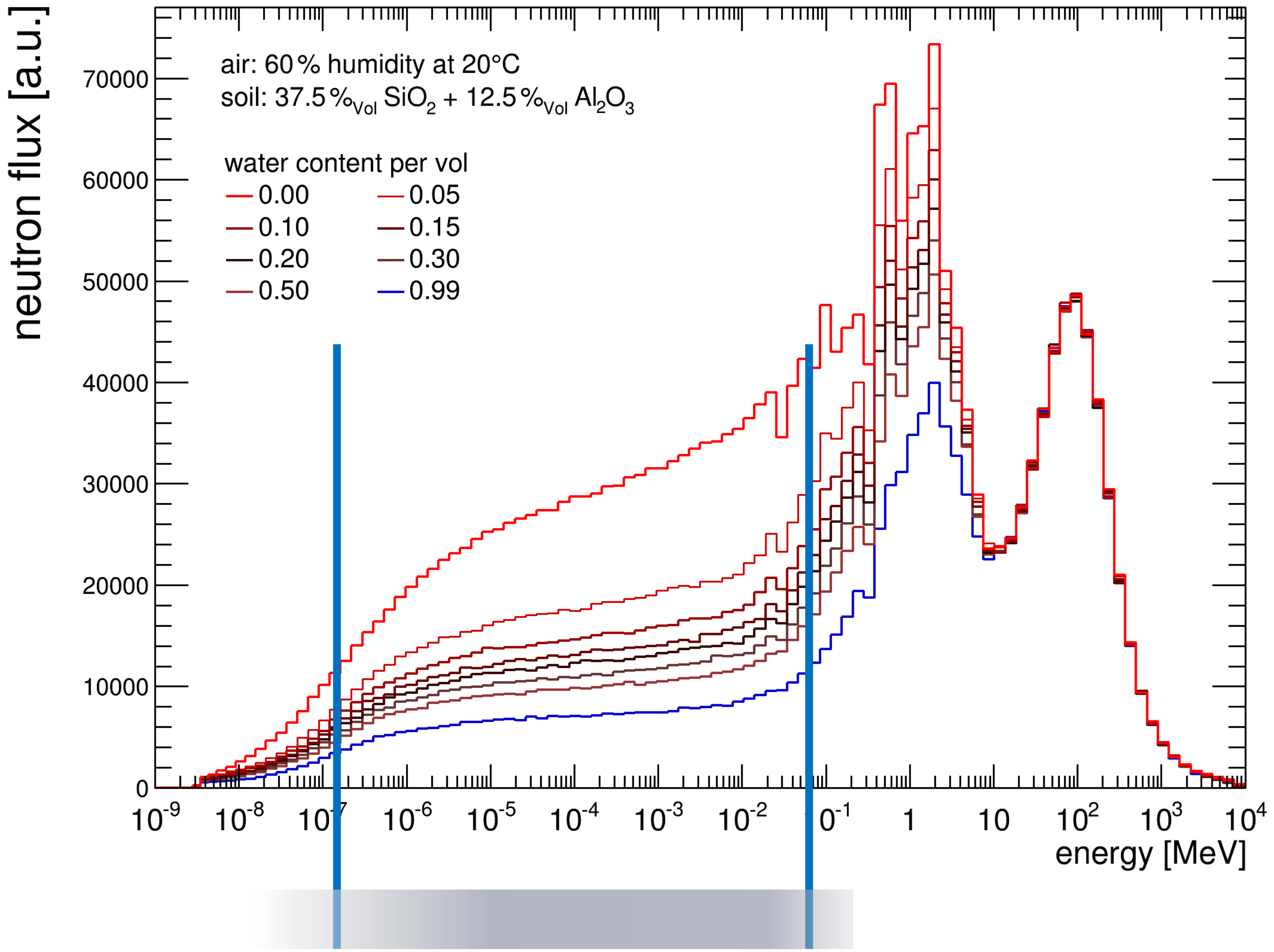


The Cosmic Neutron Spectrum

The Cosmic Neutron Spectrum

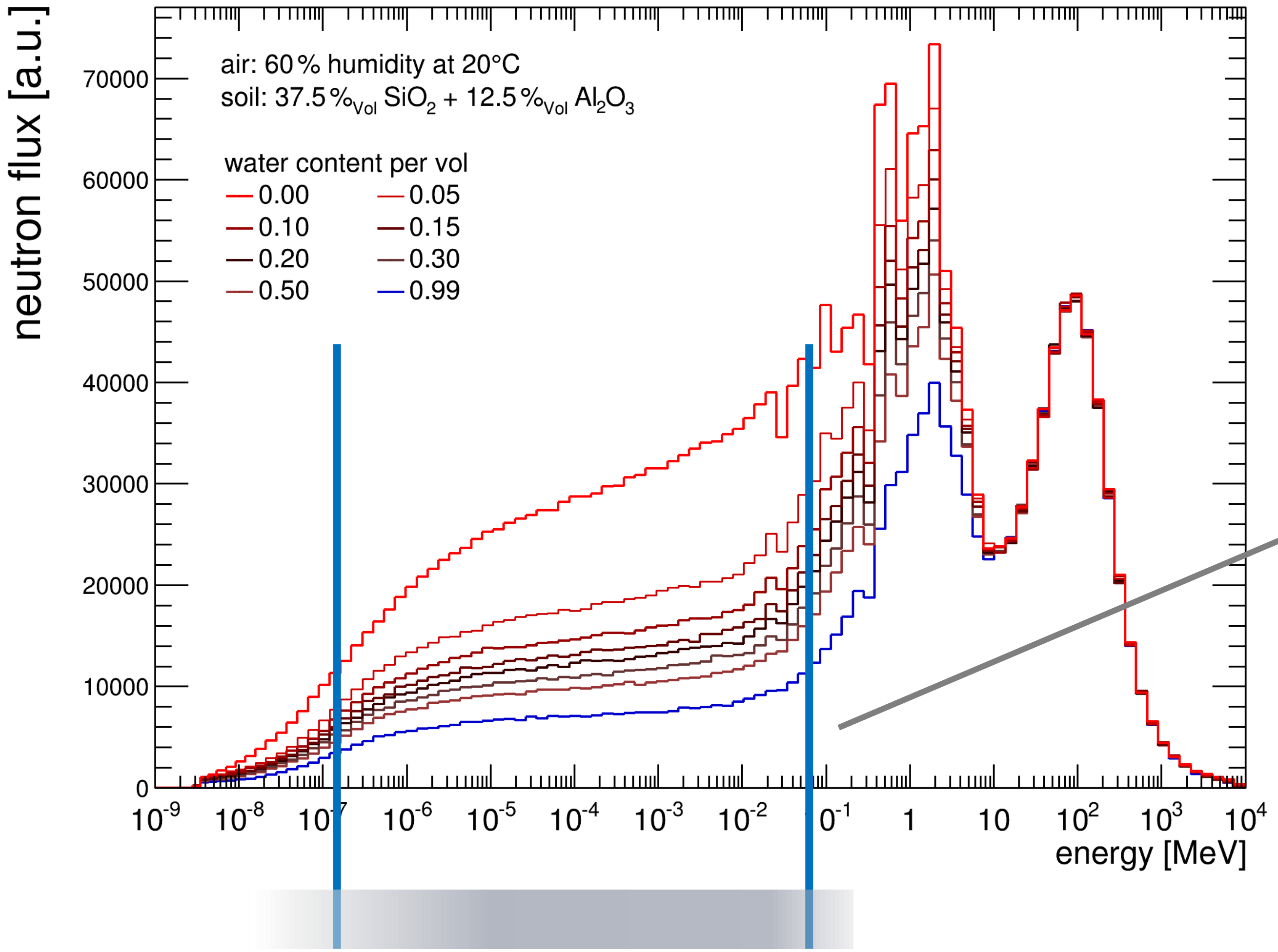


The Cosmic Neutron Spectrum



M. Köhli, M. Schrön, U. Schmidt, P. Dietrich, S. Zacharias

The Cosmic Neutron Spectrum



UP 16.4

Soil moisture sensing by cosmic ray induced showers

M. Köhli, M. Schrön, U. Schmidt, P. Dietrich, S. Zacharias

HELMHOLTZ CENTRE FOR ENVIRONMENTAL RESEARCH – UFZ
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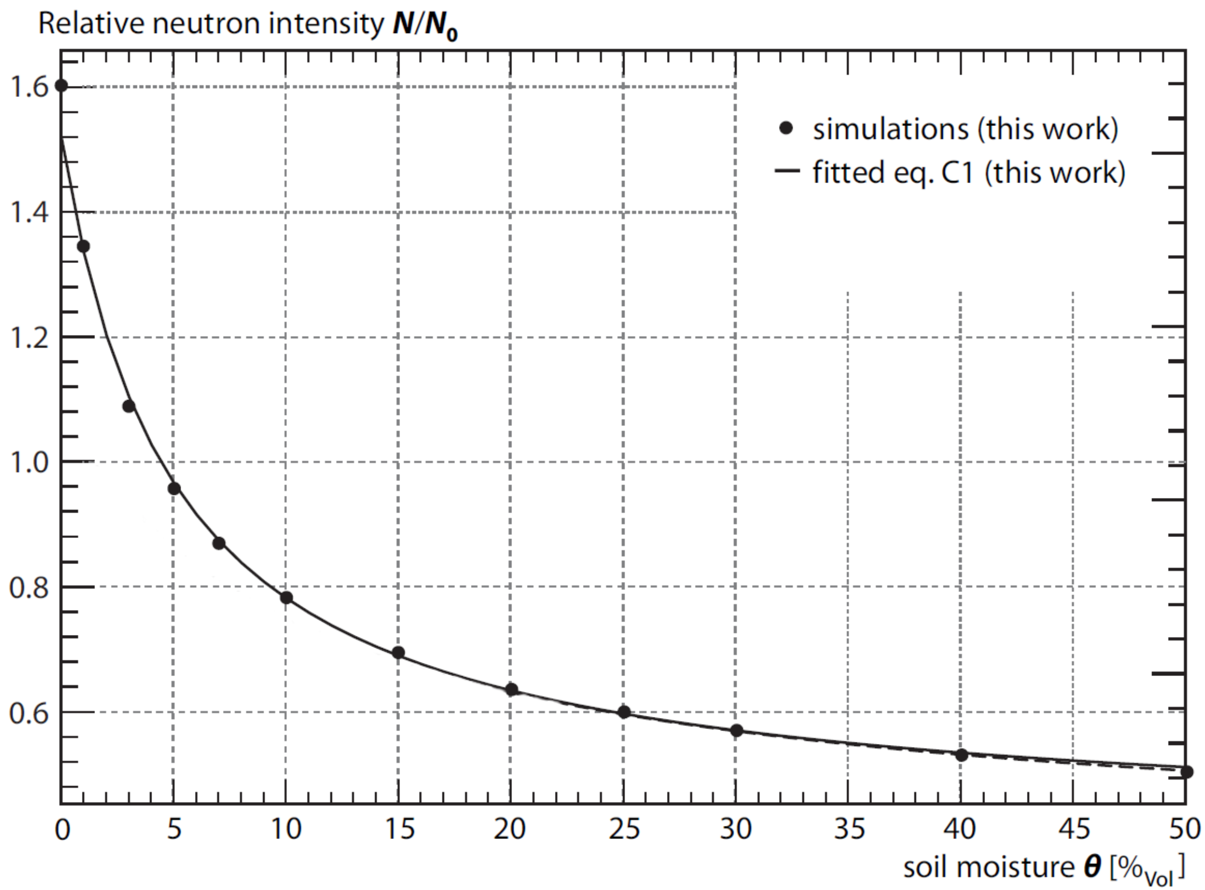
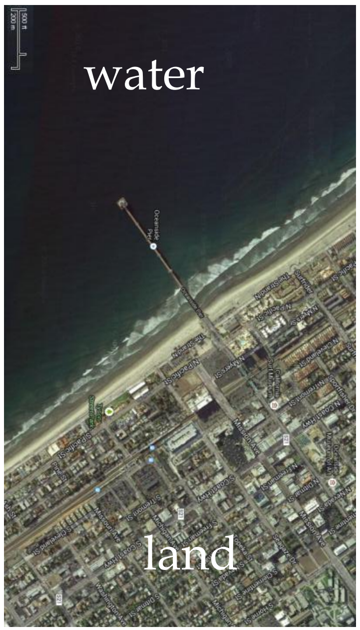
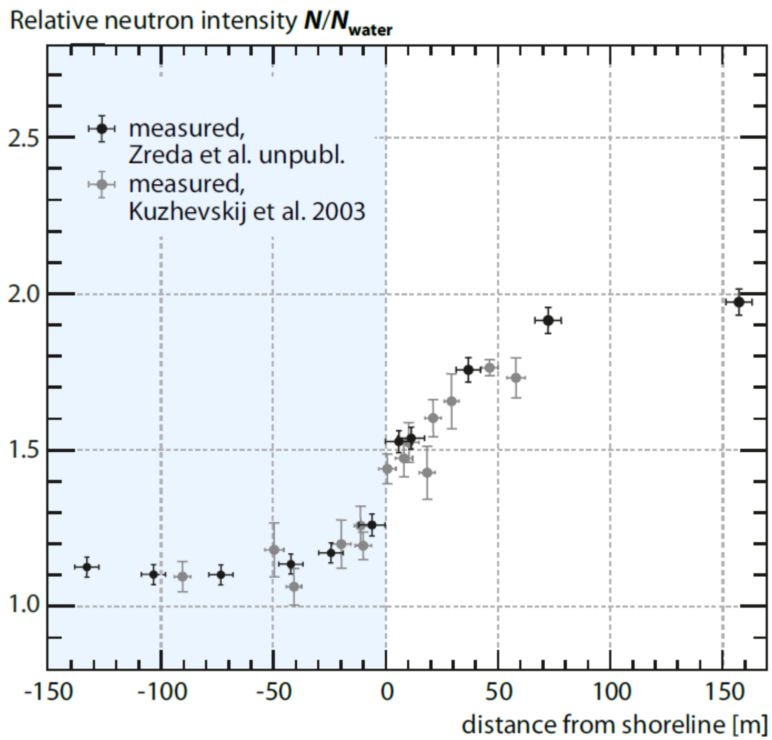
The Cosmic Neutron Spectrum



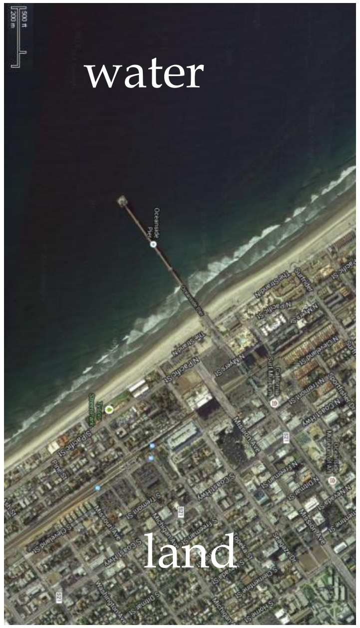
Coastal Transect

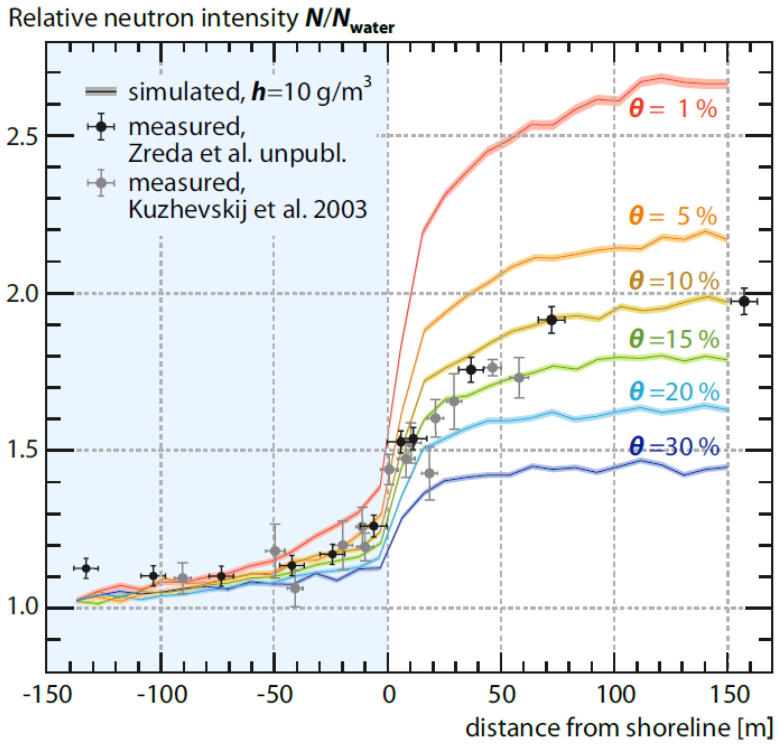




water land

Costal Transect





water land

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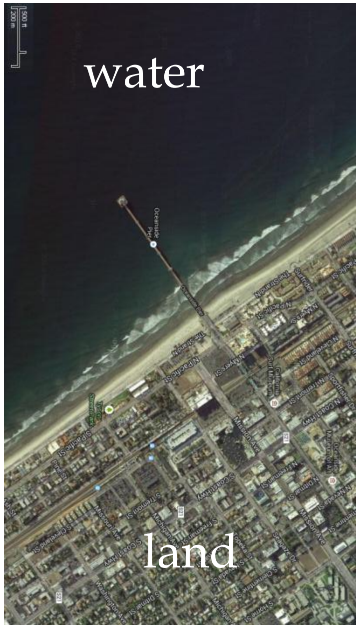

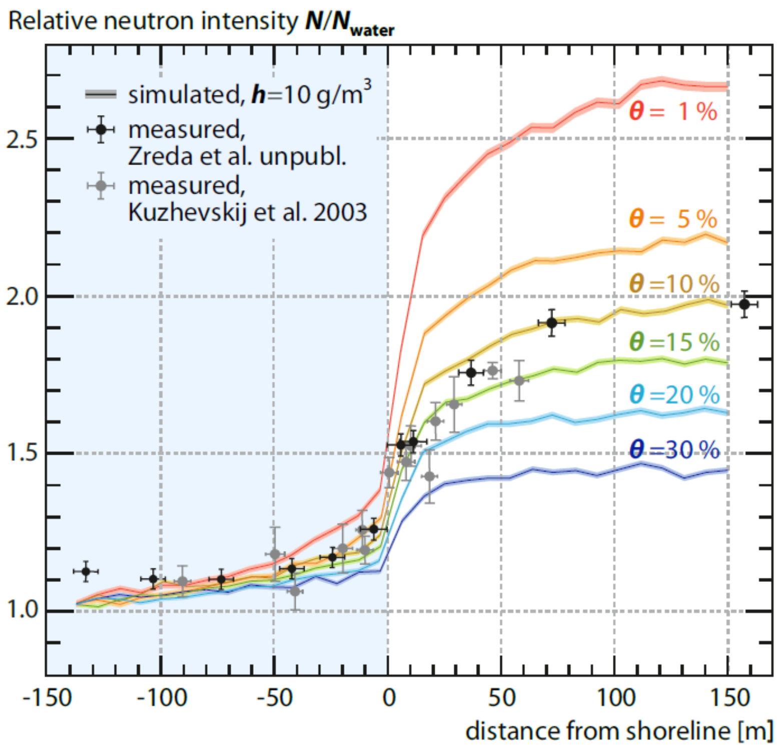

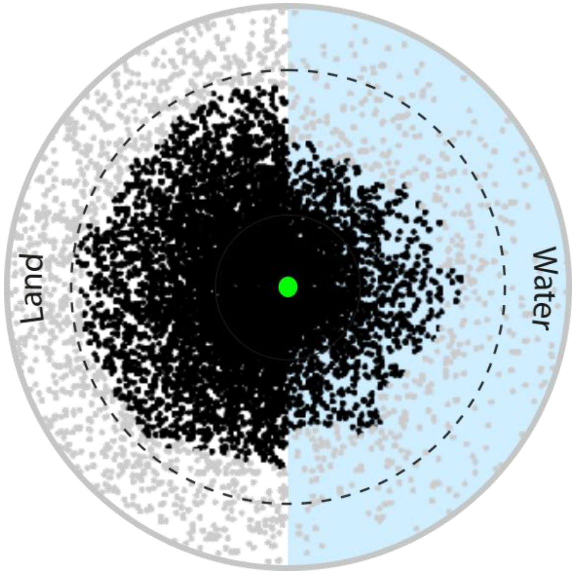

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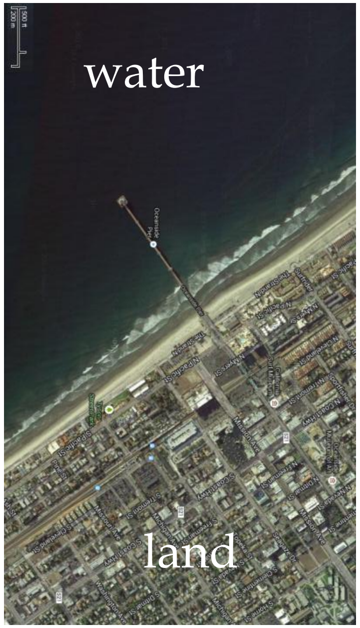
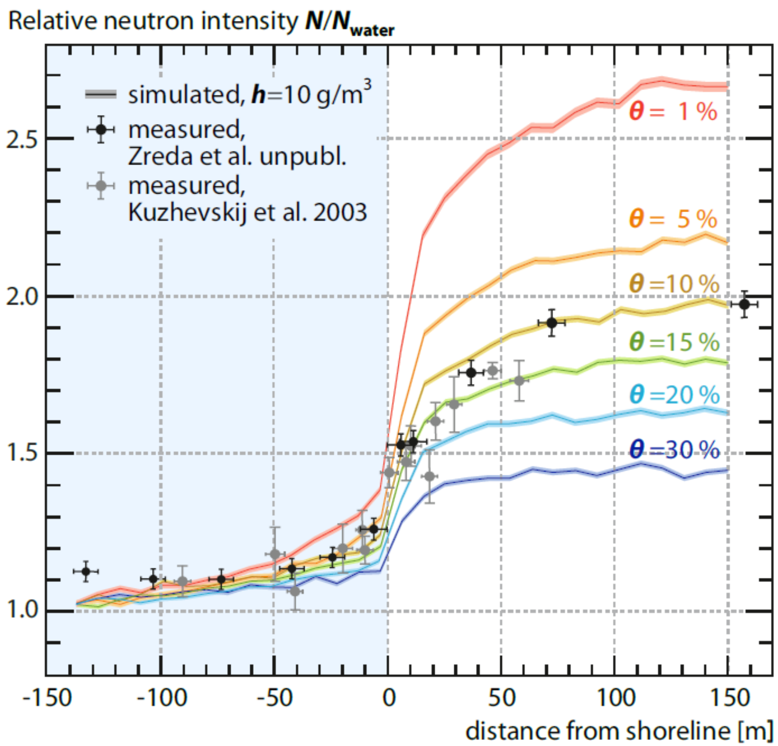
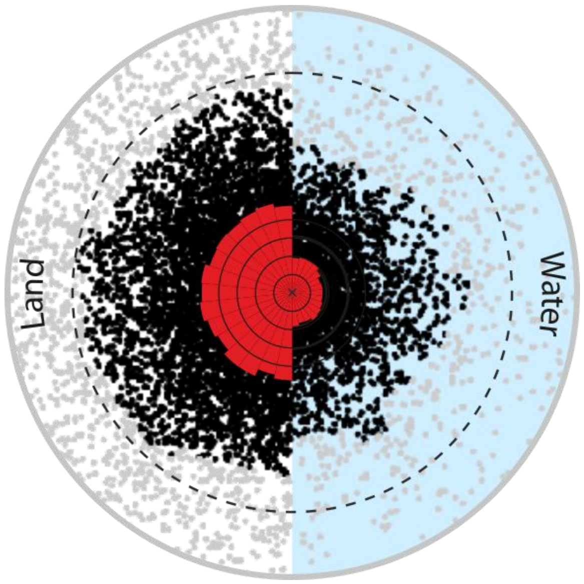


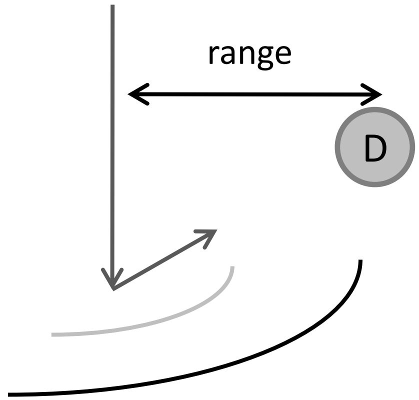


water land



Detected neutron origins (first contact to soil)
Closest 86% of neutron origins for each 12° sector
Neutron intensity for each 12° sector [arb. units]
Footprint R_{86}(5g/m^3, 5 %)=210m for homogeneous soil

How far do reflected neutrons travel?



The Footprint

How far do reflected neutrons travel?

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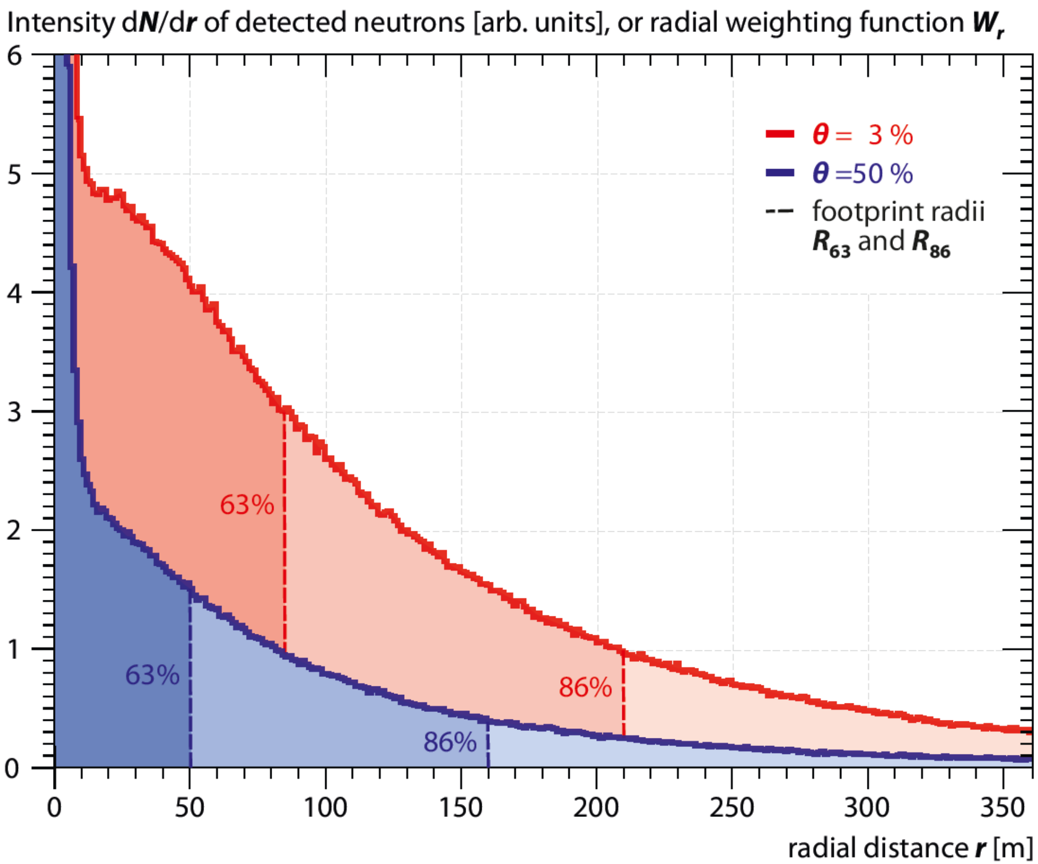
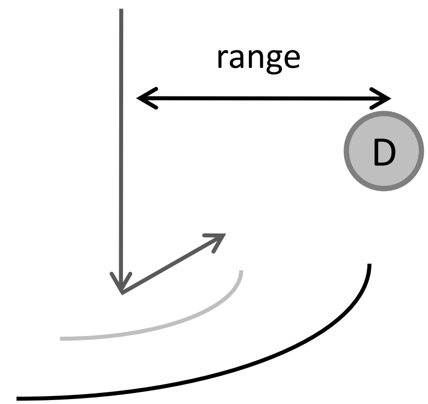
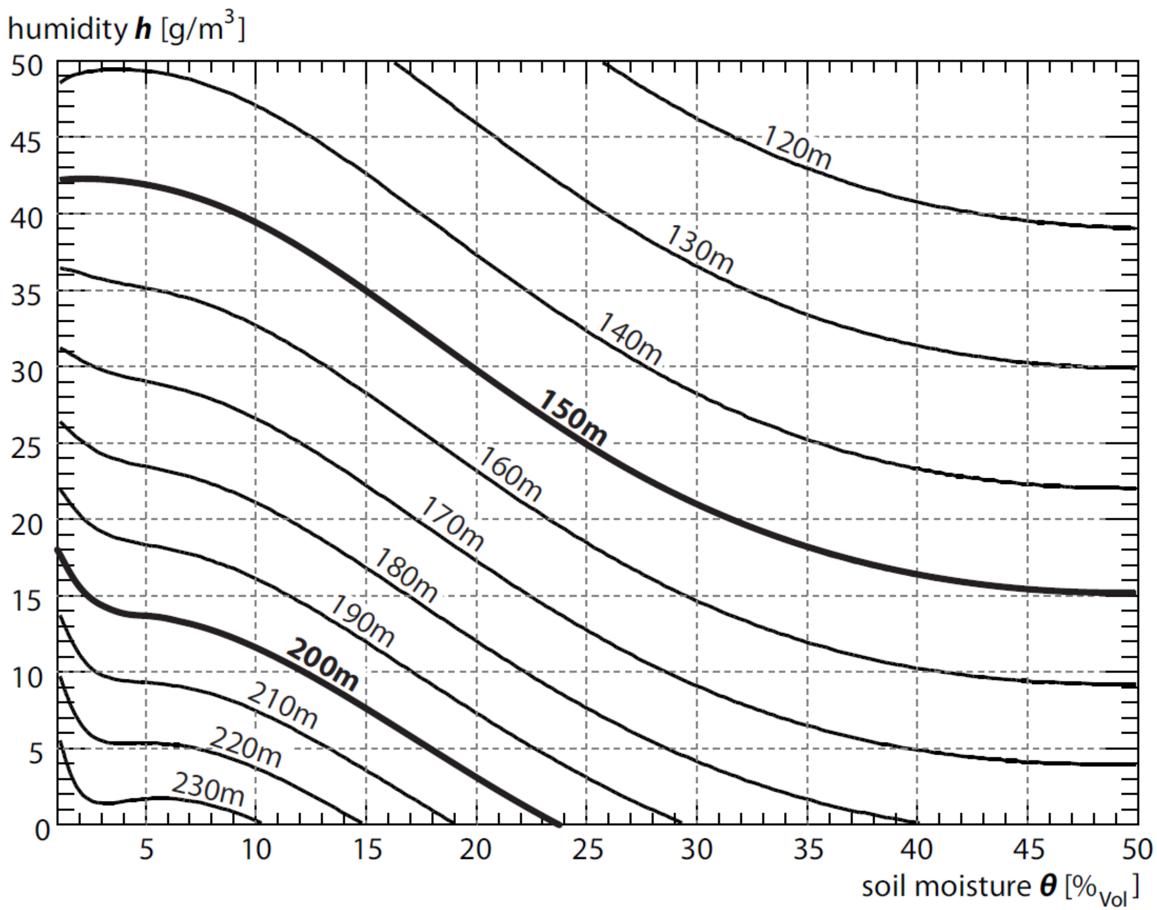
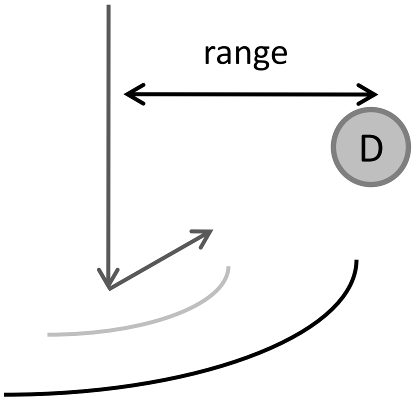




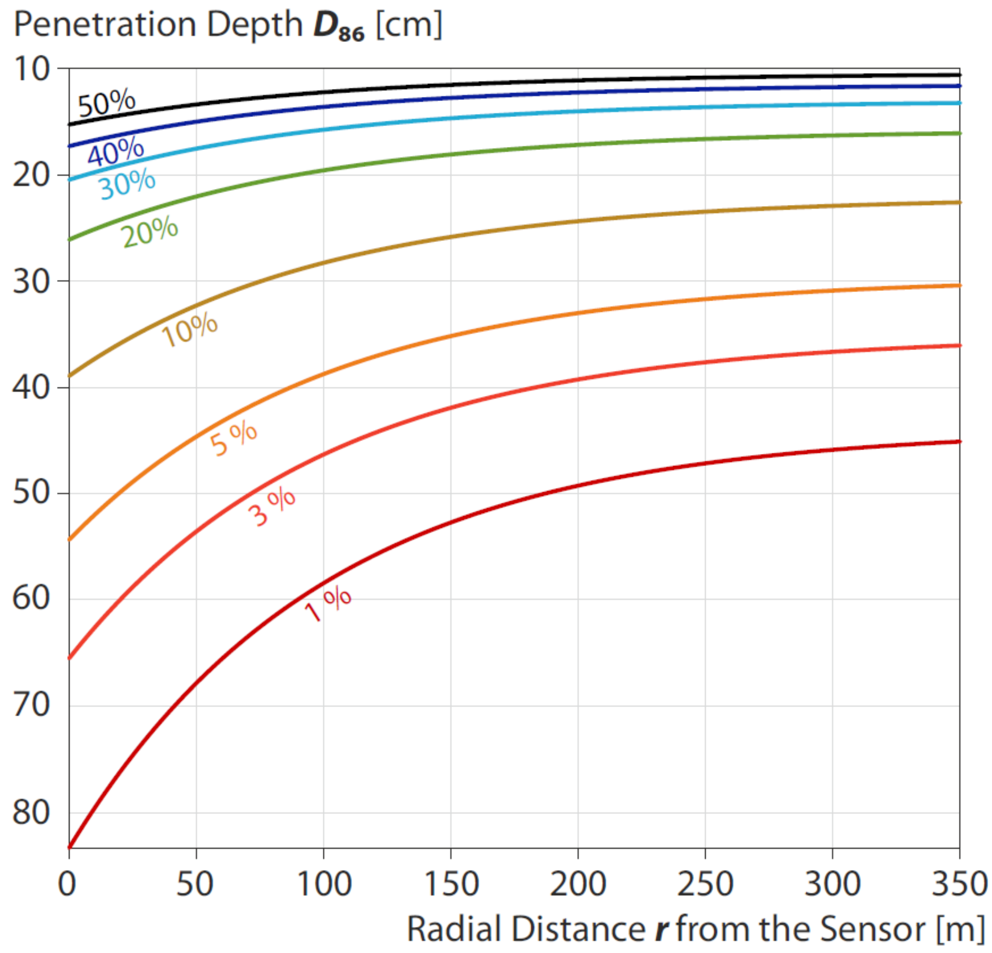
The Footprint – Analytical Description

How far do reflected neutrons travel?





Footprint Penetration Depth



The Cosmos Collaboration

a worldwide network of sensors

M. Zreda et atl. (2008)

Summary

- Cosmic-Ray Neutrons

- Monte-Carlo neutron transport modelling methods

Summary

- **Cosmic-Ray Neutrons can be used to measure soil moisture**

averaged over several hectares
and decimetres of depth

- **Monte-Carlo neutron transport modelling methods**

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lead to the understanding of this technology

Summary

- **Cosmic-Ray Neutrons can be used to measure soil moisture**

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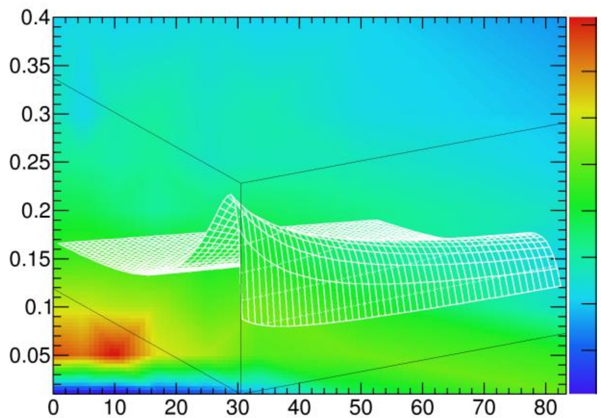
lead to the understanding of this technology

to be continued
M. Schrön

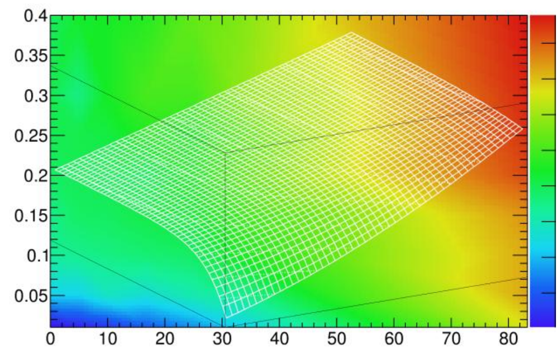
UP 16.4

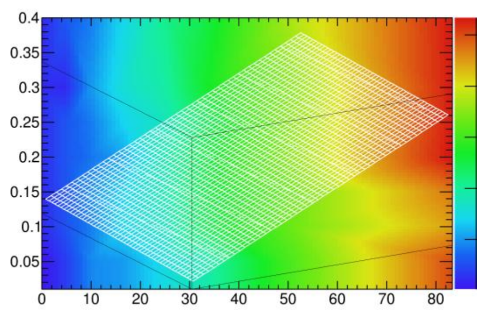
Footprint: Analytical Function

Parameter 1

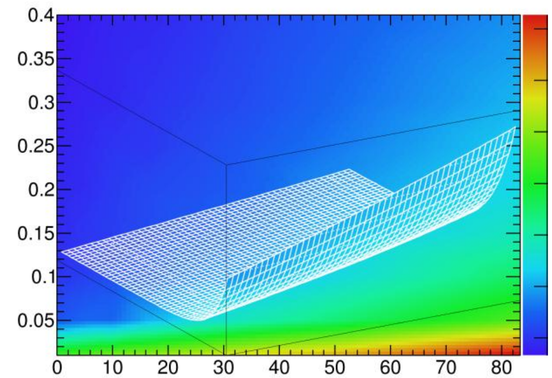


Parameter 2





Parameter 3



Parameter 4

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Footprint: Analytical Function

$$W_r(h,\theta) \approx \begin{cases} F_1\, e^{-F_2 r} + F_3\, e^{-F_4 r}\,, & r \leq 50\,\mathrm{m} \\ F_5\, e^{-F_6 r} + F_7\, e^{-F_8 r}\,, & r > 50\,\mathrm{m} \end{cases}$$

$$\begin{aligned}
F_1 &= p_0\,(1+p_3 h)\exp\left(-p_1\theta\right) + p_2\,(1+p_5 h) + p_4\theta, \\
F_2 &= \left((1+p_4 h)\exp\left(-\frac{p_1\theta}{1+p_6\theta}\right) + p_2\right)(1+p_3 h)\,, \\
F_3 &= p_0\exp\left(-p_1\theta\right) + p_2 + p_4\theta + +p_5 h, \\
F_4 &= p_0\,(1+p_3 h)\exp\left(-p_1\theta\right) + p_2 + p_4\theta \\
F_5 &= p_0\left(0.02 + \frac{1}{p_5(p_5+p_6\theta+h)}\right) \\
&\quad \cdot(\theta-p_4)\exp(-p_1(\theta-p_4)) + p_2\,(0.7+h\theta p_3)\,, \\
F_6 &= p_0(h-p_1) + p_2\theta, \\
F_7 &= \left((p_0+p_4 h)\exp\left(-p_1\frac{\theta}{1+p_5 h+p_6\theta}\right) + p_2\right) \\
&\quad \cdot(2+hp_3), \\
F_8 &= \left(p_0\,(1+p_6 h)\exp\left(-p_1\theta\left(1+p_4\frac{h}{\theta}\right)\right) + p_2 + p_5\theta\right) \\
&\quad \cdot(2+p_3 h)\,.
\end{aligned}$$

F_1	$p_0 = 8735$	± 30
	$p_1 = 17.1758$	± 0.0873
	$p_2 = 11720$	± 21
	$p_3 = 0.00978$	± 0.00014
	$p_4 = -7045$	± 56
	$p_5 = 0.003632$	± 0.000026
F_2	$p_0 = -2.79257 \cdot 10^{-5}$	$\pm 1.52 \cdot 10^{-8}$
	$p_1 = 5.0399$	± 0.0134
	$p_2 = 2.85445 \cdot 10^{-5}$	$\pm 1.27 \cdot 10^{-8}$
	$p_3 = 0.002455$	$\pm 6 \cdot 10^{-5}$
	$p_4 = 6.8517 \cdot 10^{-8}$	$\pm 5.5 \cdot 10^{-10}$
	$p_6 = 9.2927$	± 0.0382
F_3	$p_0 = 5.4818 \cdot 10^{-5}$	$\pm 9 \cdot 10^{-7}$
	$p_1 = 15.921$	± 0.421
	$p_2 = 0.0006373$	$\pm 3.155 \cdot 10^{-7}$
	$p_4 = -5.99 \cdot 10^{-5}$	$\pm 1.3 \cdot 10^{-6}$
	$p_5 = 5.425 \cdot 10^{-7}$	$\pm 1.28 \cdot 10^{-8}$
F_4	$p_0 = 247970$	± 1695
	$p_1 = 17.63$	± 0.21
	$p_2 = 374655$	± 1098
	$p_3 = 0.00191$	± 0.00022
	$p_4 = -195725$	± 2840
F_5	$p_0 = -1383701$	± 143180
	$p_1 = 4.155$	± 0.574
	$p_2 = 5324$	± 543
	$p_3 = -0.00238$	± 0.00105
	$p_4 = 0.0156$	± 0.0014
	$p_5 = -0.130$	± 0.026
	$p_6 = 1520$	± 289
F_6	$p_0 = -1.543 \cdot 10^{-5}$	$\pm 1.6 \cdot 10^{-6}$
	$p_1 = 10.06$	± 0.94
	$p_2 = 1.807 \cdot 10^{-5}$	$\pm 1.6 \cdot 10^{-6}$
	$p_3 = 0.0011$	± 0.0007
	$p_4 = 8.81 \cdot 10^{-8}$	$\pm 3.9 \cdot 10^{-9}$
	$p_5 = 0.0405$	± 0.0049
	$p_6 = 20.24$	± 1.57
F_7	$p_0 = 6.031 \cdot 10^{-8}$	$\pm 4.37 \cdot 10^{-10}$
	$p_1 = -98.5$	± 0.93
	$p_2 = 1.0466 \cdot 10^{-6}$	$\pm 7.1 \cdot 10^{-8}$
F_6	$p_0 = 11747$	± 208
	$p_1 = 41.66$	± 1.7
	$p_2 = 4521$	± 49
	$p_3 = 0.01998$	± 0.00055
	$p_4 = -0.00604$	± 0.00034
	$p_5 = -2534$	± 127
	$p_6 = -0.00475$	± 0.00026

The Cosmic Neutron Spectrum