CRNS - new insights from modeling soil moisture measurement at the hectometer scale

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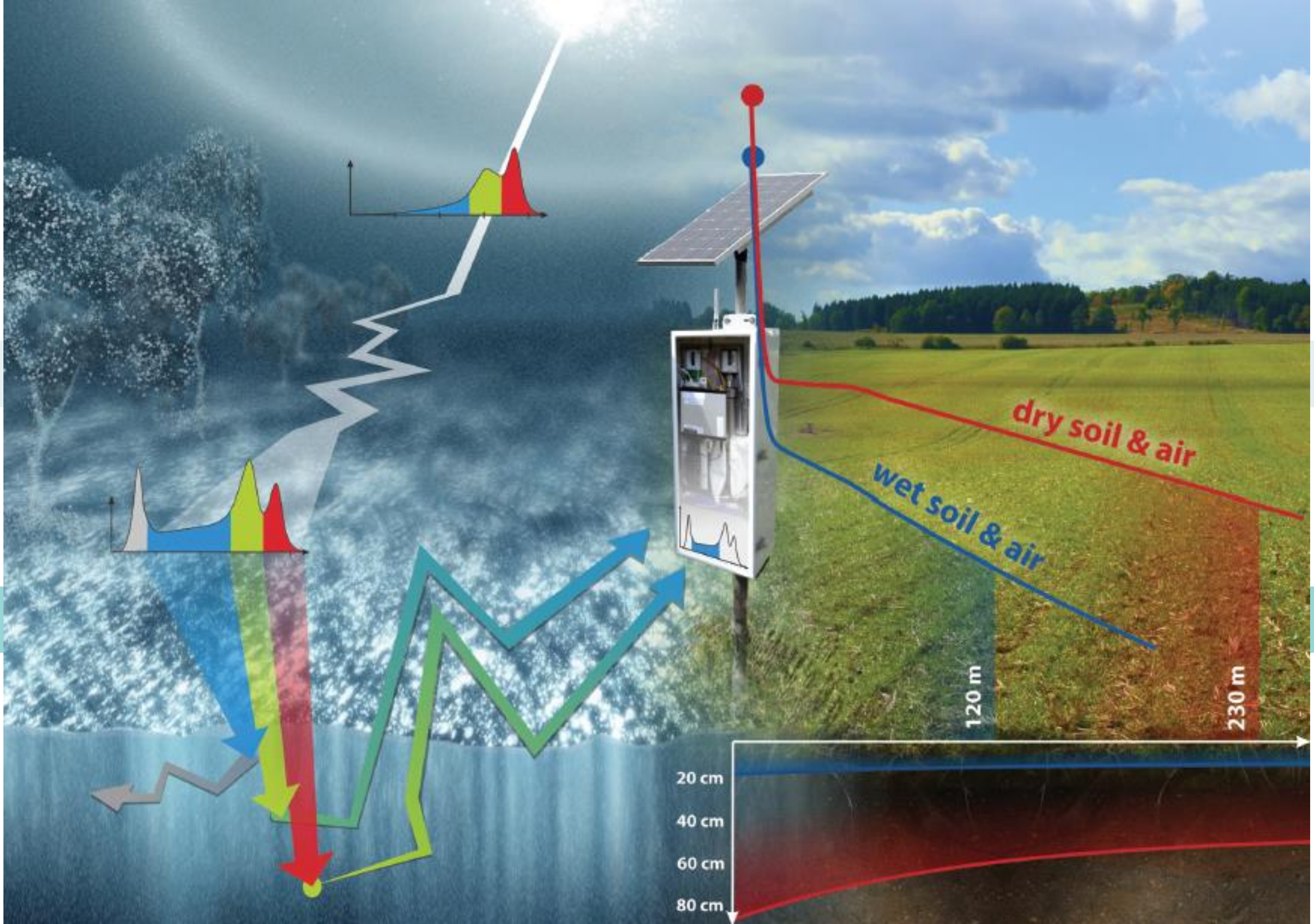
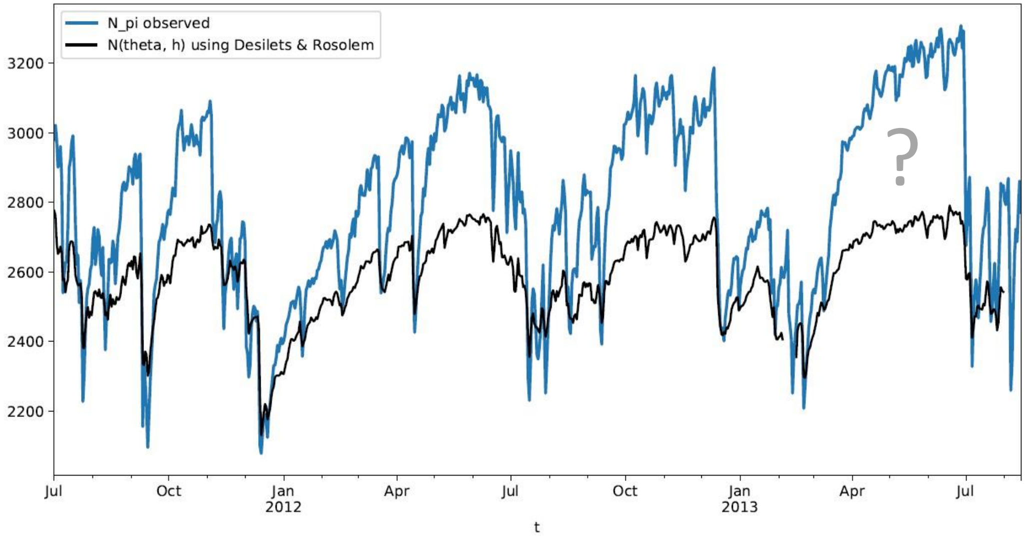

dry soil & air
wet soil & air
120 m
230 m
20 cm
40 cm
60 cm
80 cm

Motivation

Many studies were carried out for **finding a sensor calibration routine** and to compare the performance to conventional instruments…
Rivera Villarreyes et al., 2011; Franz et al., 2012a; Hawdon et al., 2014; Almeida et al., 2014; Coopersmith et al., 2014

with a good agreement between measured neutron flux and soil moisture values

Santa Rita



Motivation

However, unexplained features in the CRNS data could not be described by the Desilets equation

$$\theta(N) = \frac{0.0808}{\left(\frac{N}{N_0}\right) - 0.372} - 0.115$$

Then,

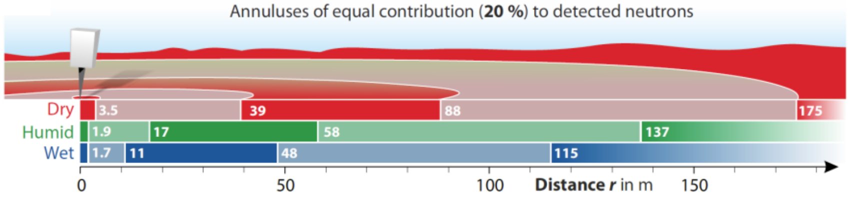
groups tried to **fit the parameters** of the hyperbola to their data
Rivera Villarreyes et al., 2011; Lv et al., 2014; Heidbüchel et al., 2016; Sigouin and Si, 2016

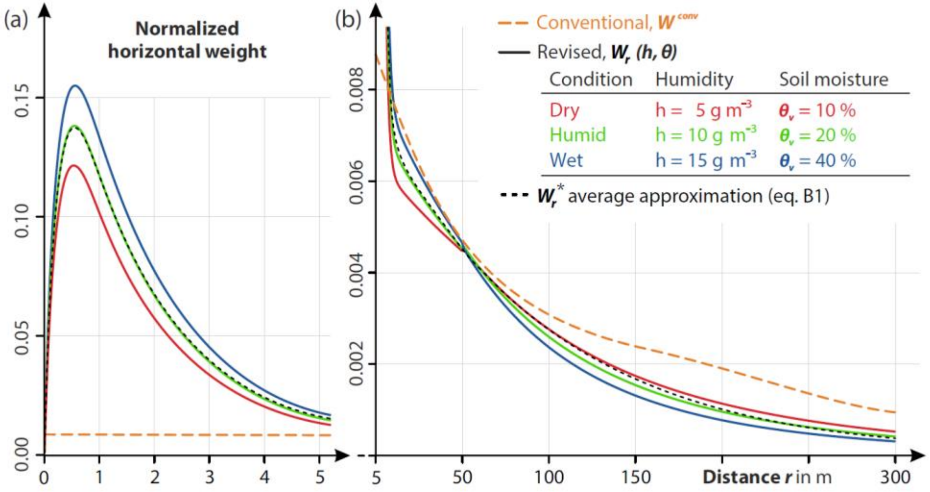
with a better correlation **at the cost of site-specific calibrations**

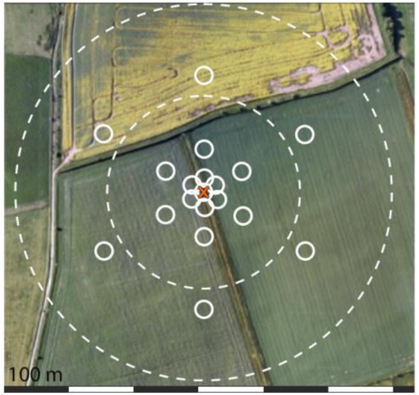
NS > Footprint

One reason:
different weighting strategy needed

→ Footprint revision
Köhli et al. 2015; Schrön et al. 2017



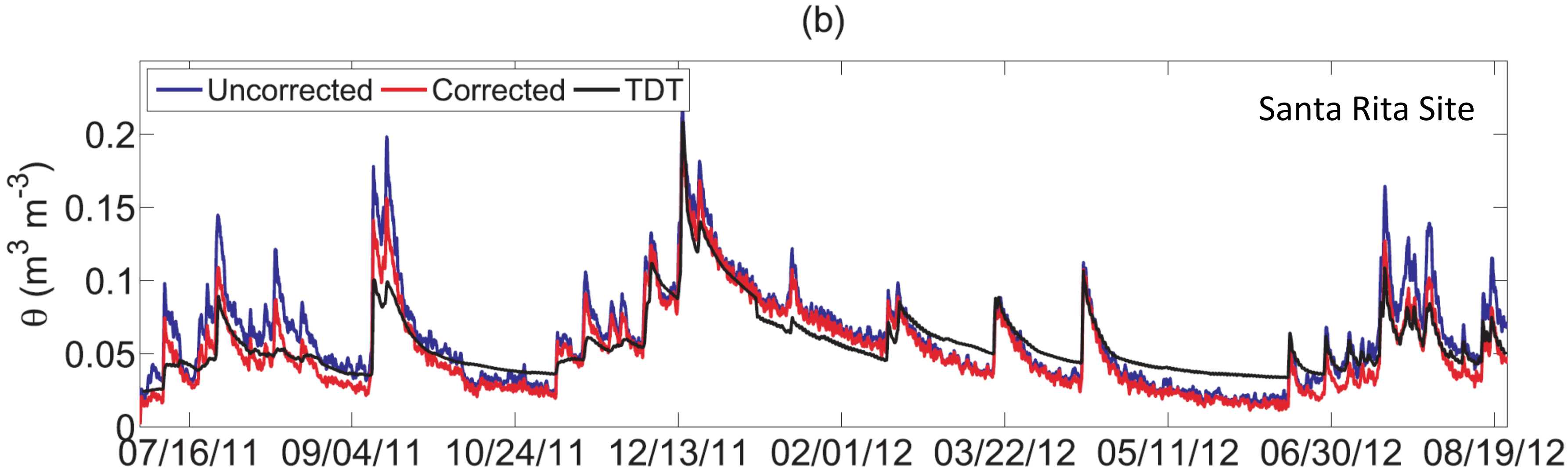




Motivation

But still:

Desilets equation / N0 method: bad performance under dry conditions



R. ROSOLEM, et al. “The Effect of Atmospheric Water Vapor on Neutron Count in the Cosmic-Ray Soil Moisture Observing System.” *Journal of Hydrometeorology* 14(5), 2013, 1659–1671.

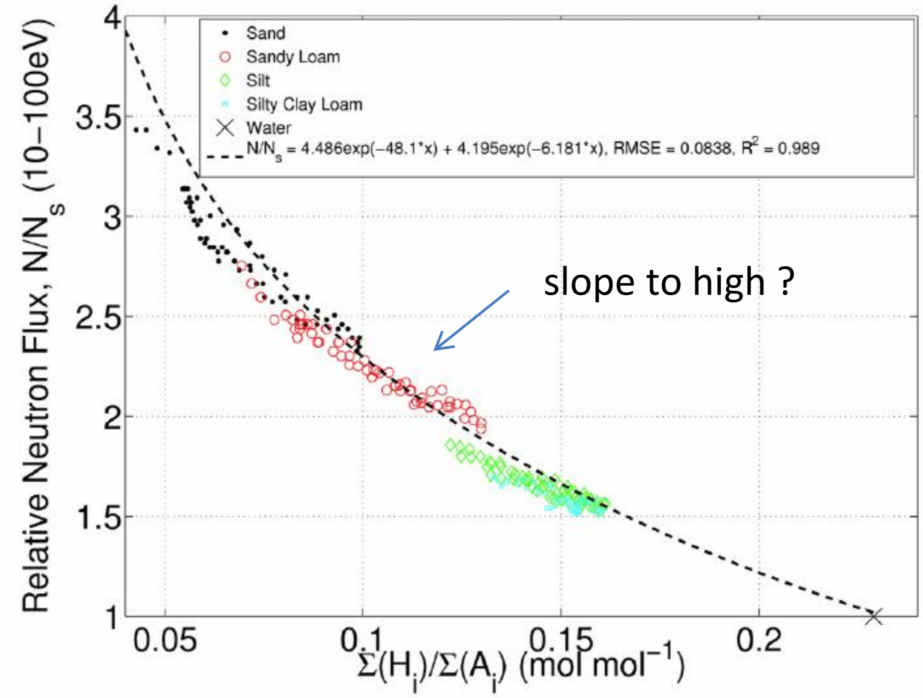
Different Intensity Models

Other intensity description approaches

Universal calibration function (UCF) / HMF method

$$\text{hmf} = \frac{\sum H_i}{\sum A_i}$$
$$= \frac{H_\tau + H_{\text{SOC}} + H_\theta + H_{\text{AGB}}}{\text{NO} + \text{SiO}_2 + \text{H}_2\text{O}_\tau + \text{H}_2\text{O}_{\text{SOC}} + \text{H}_2\text{O}_\theta + \text{C}_6\text{H}_{10}\text{O}_5 + \text{H}_2\text{O}_{\text{AGB}}}$$

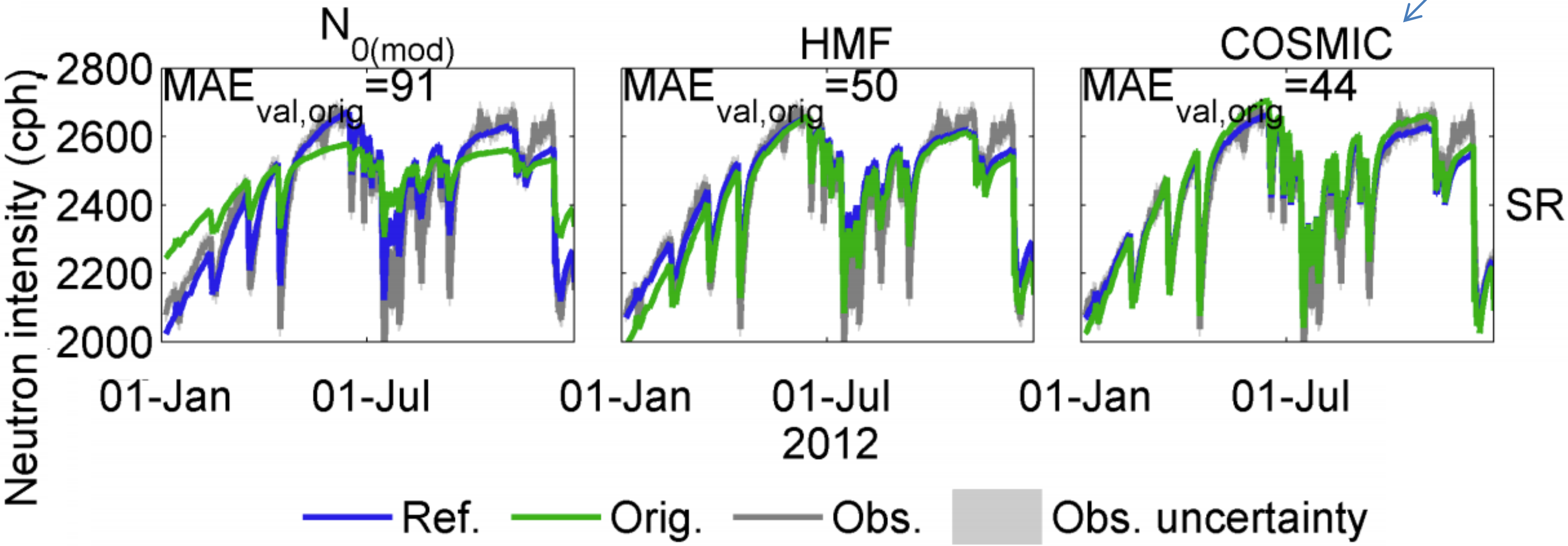
$$\frac{N}{N_s} = 4.486\exp(-48.1\cdot\text{hmf}) + 4.195\exp(-6.181\cdot\text{hmf}).$$



T. FRANZ, et al. “A universal calibration function for determination of soil moisture.” *HESS 17*(5), 2013, 453-460.

Comparison

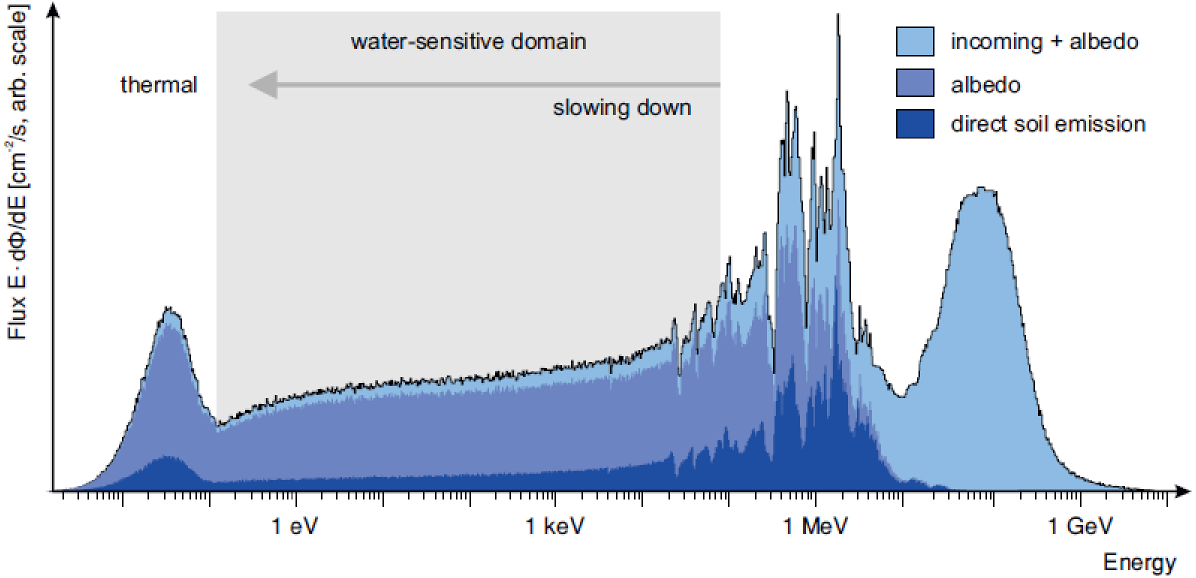
not analytical



J. IWEMA et al. "Investigating temporal field sampling strategies for site-specific calibration of three soil moisture–neutron intensity parameterisation methods." *Hydrology and Earth System Sciences* 19(7), 2015, 3203–3216.

Above-ground neutron flux

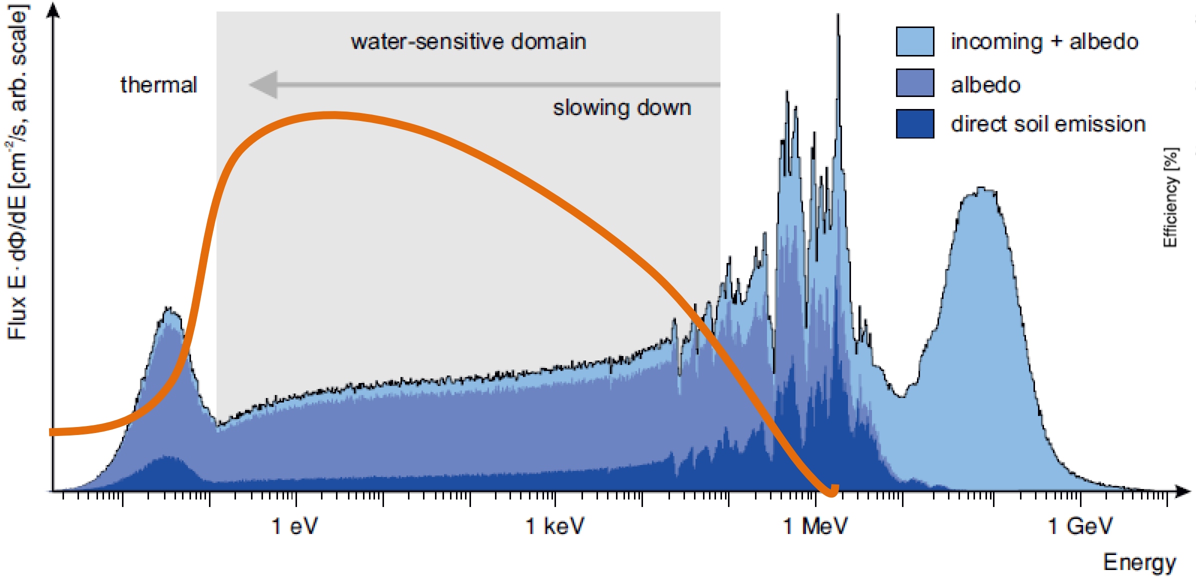
Epithermal flux is not the result from one single process

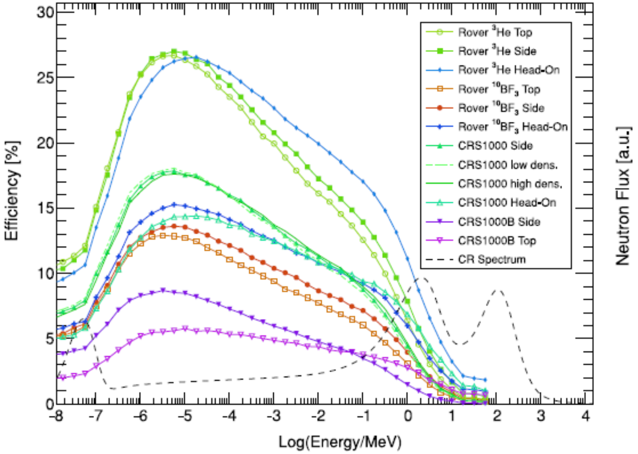


- generation in the air
- generation in the ground
- slowing down by hydrogen
- absorption

Above-ground neutron flux

Take into account the relative detection efficiency

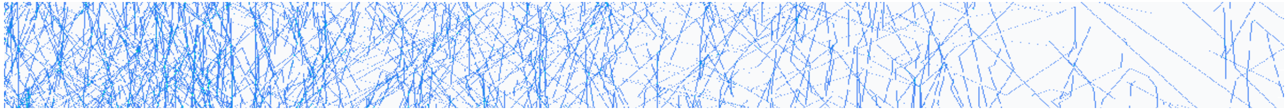




Köhli et al. 2018

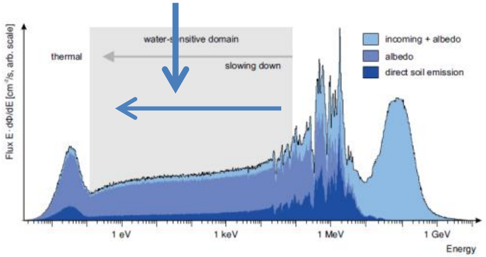
Mathematical description

Understand the mathematics of neutron transport:



Theoretical considerations

The neutron intensity is proportional to the number of collisions within the water-sensitive domain



Theoretical considerations

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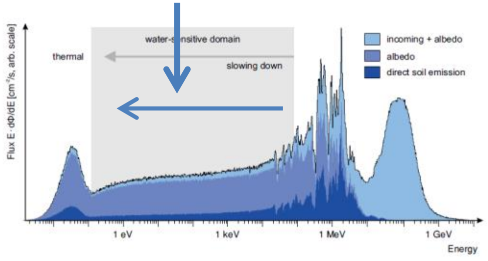
$$I(\theta) \propto \Phi_{\mathrm{epith}}(\mathrm{H_2O}) \propto n_{\mathrm{col}}^{\mathrm{ground}} \propto \frac{\Sigma^{\mathrm{soil}} + w\,\Sigma^{\mathrm{water}}}{\Sigma^{\mathrm{soil}}\,\xi^{\mathrm{soil}} + w\,\Sigma^{\mathrm{water}}\,\xi^{\mathrm{water}}}$$

Hyperbola-shaped



weight fraction of water w
cross section Σ
logartithmic energy decrement per collision ζ

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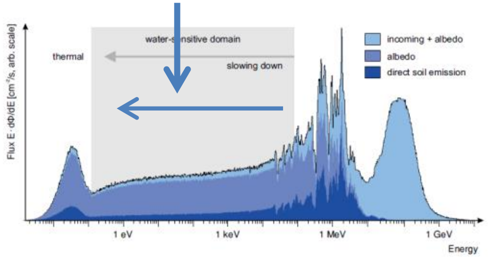

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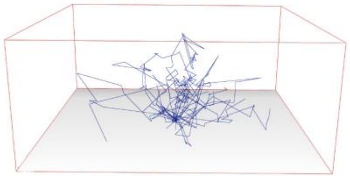
+ Diffusive Transport



$$\Phi \propto \exp(-r)/r^2$$

$$\Phi \propto \exp(-r)/r$$

exponentially shaped

Intensity Function

Our proposition: the universal transport solution (UTS)

$$I\left(\theta, h\right) = N_D \left(\frac{p_1 + p_2\,\theta}{p_1 + \theta} \qquad\qquad + e^{-p_3\,\theta} \qquad\qquad \right)$$

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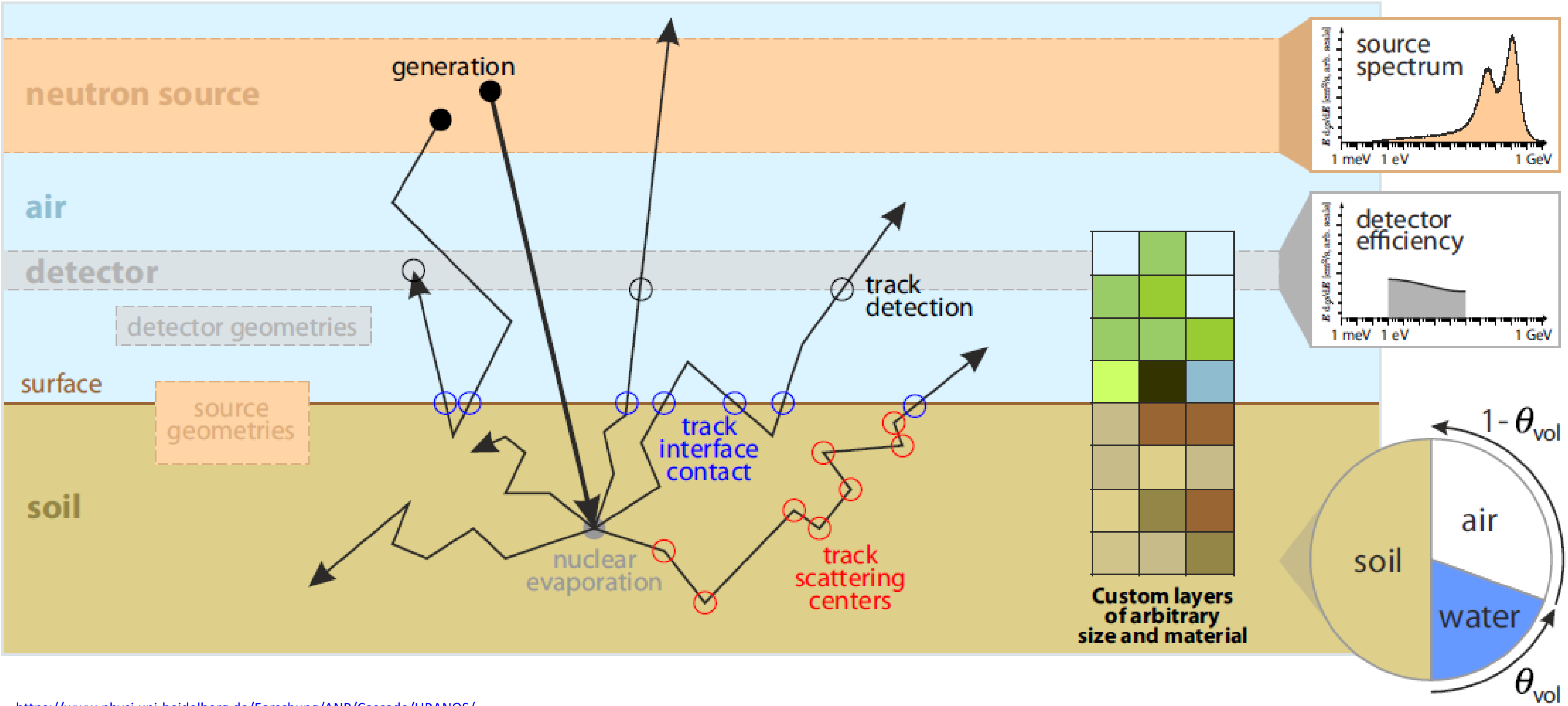
Hyperbola

Exponential

air humidity corrections

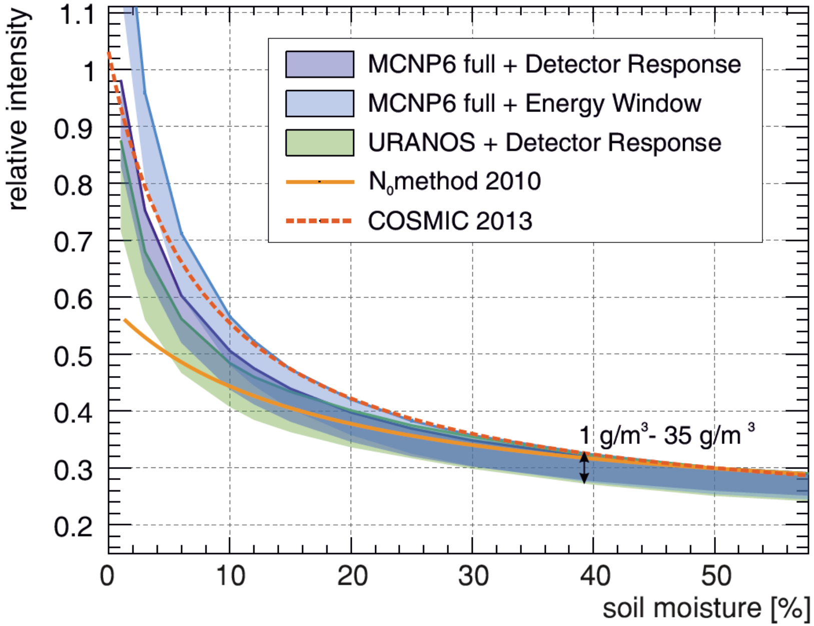
Simulating the above-ground intensity

The simulation toolkits used in this study are MCNP 6.2 and URANOS. The air medium consists of 78% nitrogen, 21% oxygen and 1% argon usually at a pressure of 1020 mbar. The soil consists of 50%Vol solids and a scalable amount of H2O. The solid domain is comprised of 75%Vol SiO_2 and 25%Vol Al_2O_3 at a compound density of 2.86 g/cm^3. The input spectrum used in this work relies on the cosmic-ray propagation models by Sato et al.



https://www.physi.uni-heidelberg.de/Forschung/ANP/Cascade/URANOS/

Simulation results



-N0 method is not steep enough in dry regions
- Exponential methods like Cosmic are more suitable for low soil moisture values
- Using fixed lower and upper bounds for scoring leads to a significantly steeper soil moisture relation. The detector response icludes thermal and MeV neutrons, both scaling less good then the epithermal range.

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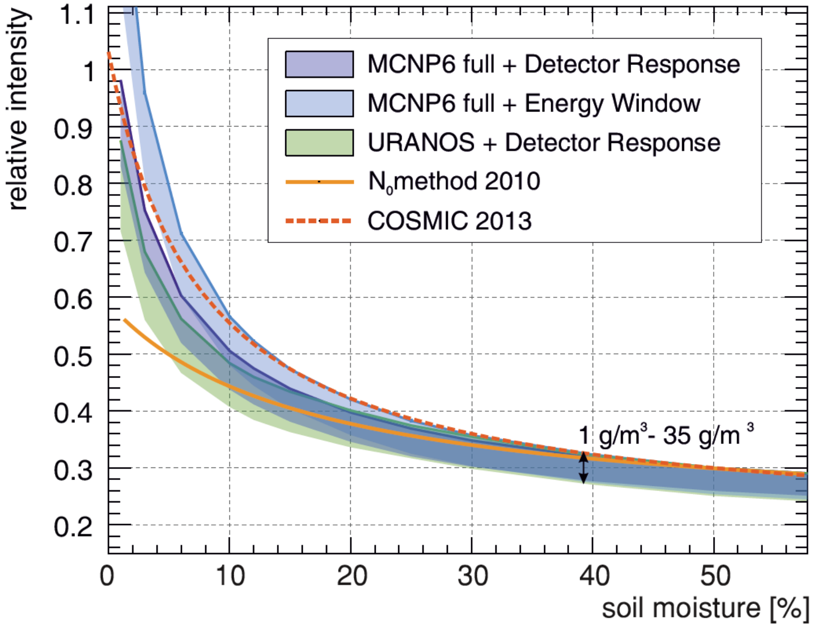

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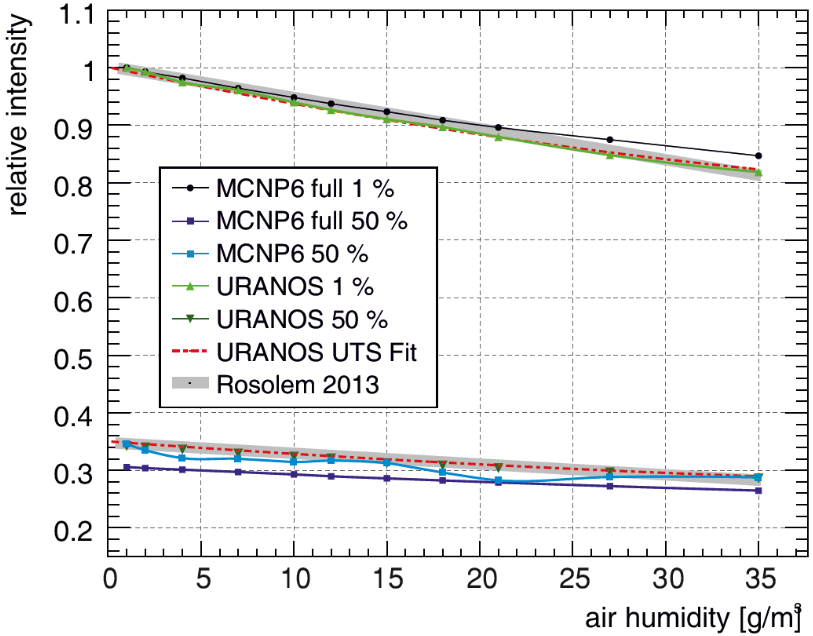
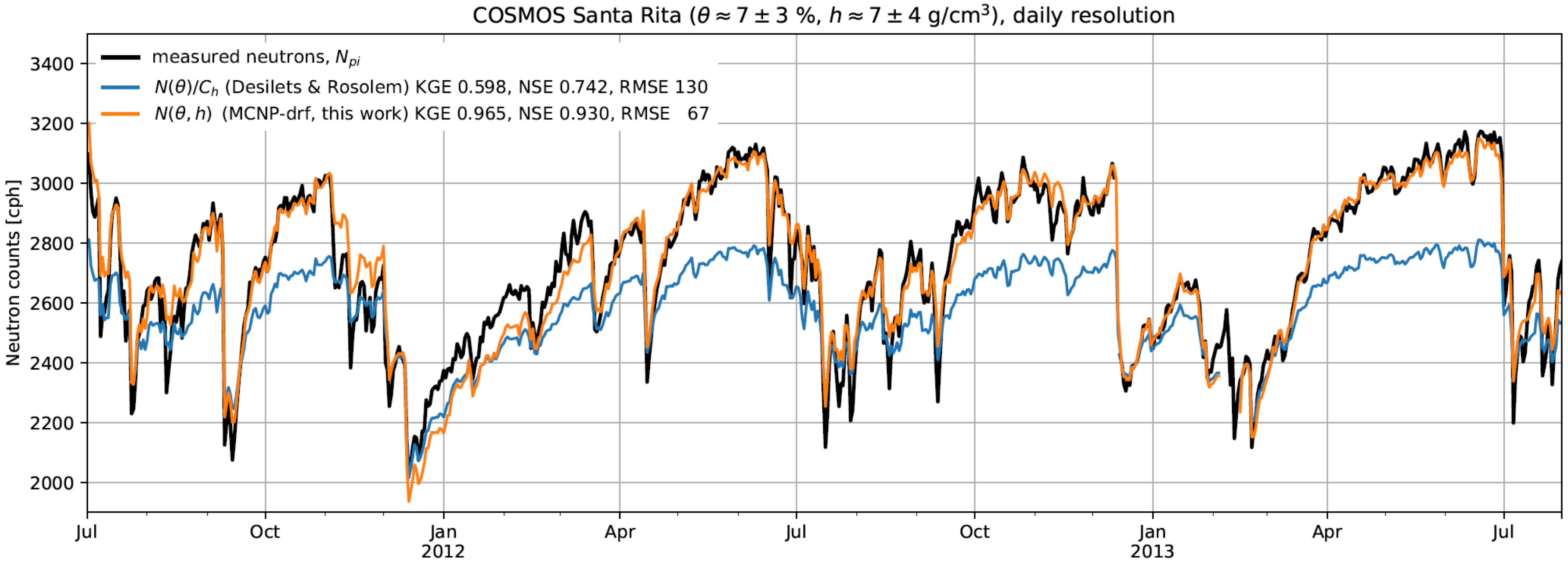


For humid compared to dry air the maximum achievable count rate is reduced by 20 %. This quantitatively agrees with Rosolem et al. (2013) who studied the change from dry to 22 g/m^3. However, a strictly linear relationship for water vapor cannot be verified. The presented reduction rate of 0.0054 per gram air humidity seems to hold only for dry conditions.

Experimental evidence – dry conditions

M. Köhli et al. "*Soil Moisture and Air Humidity dependence of the above-ground cosmic-ray neutron intensity*" Front. Water, **2**, 2021.



Caution! Here: soil moisture converted to neutron counts

Data from Santa Rita (T. Franz)

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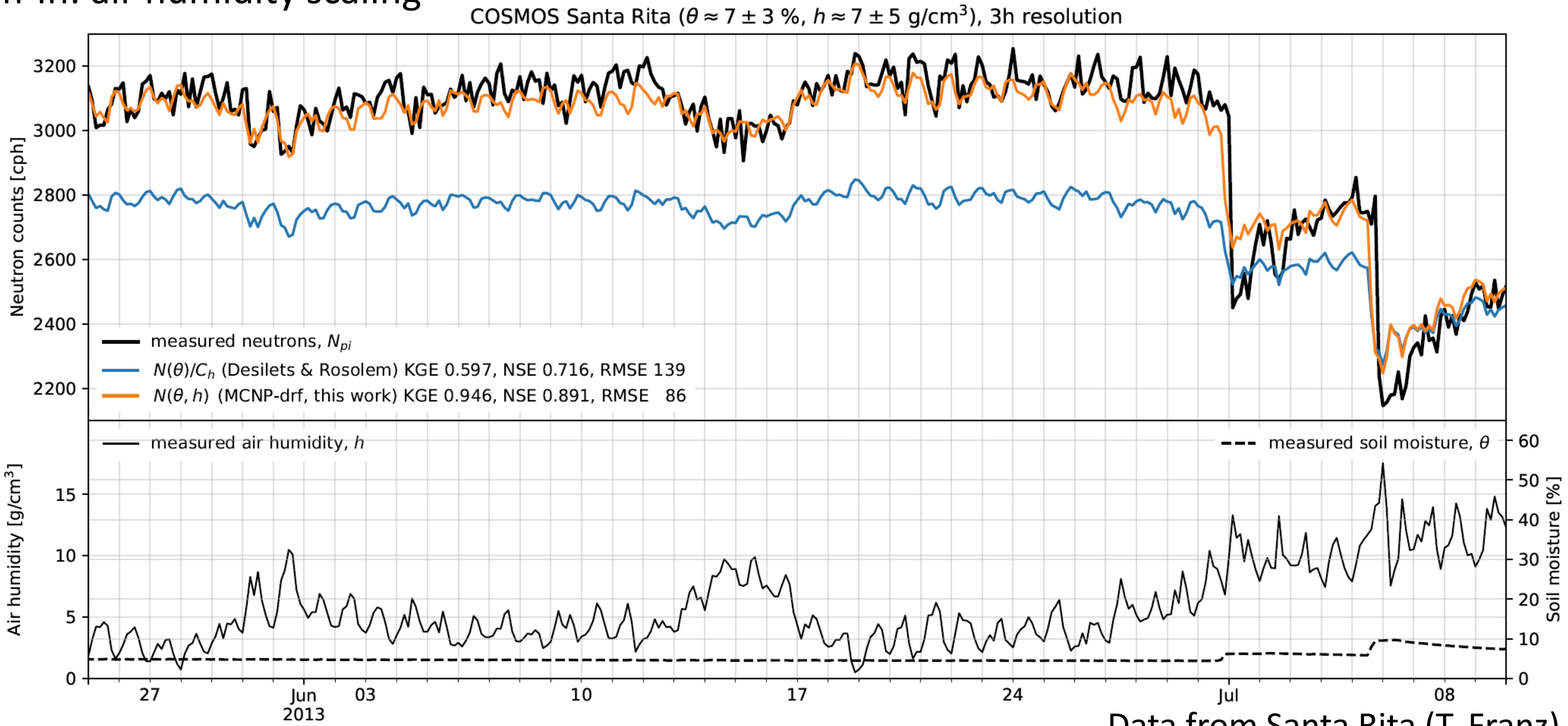
Zoom-In: air humidity scaling



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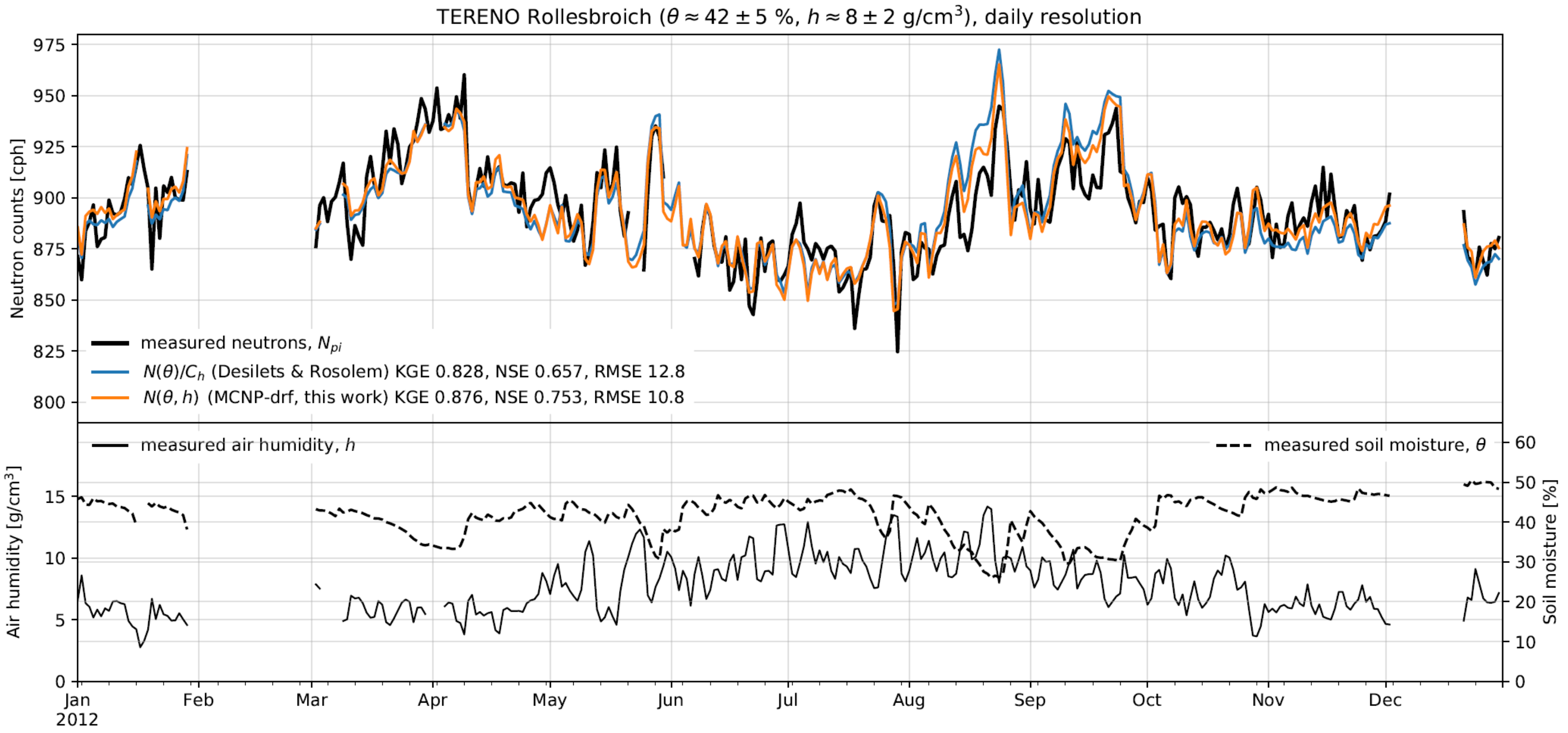
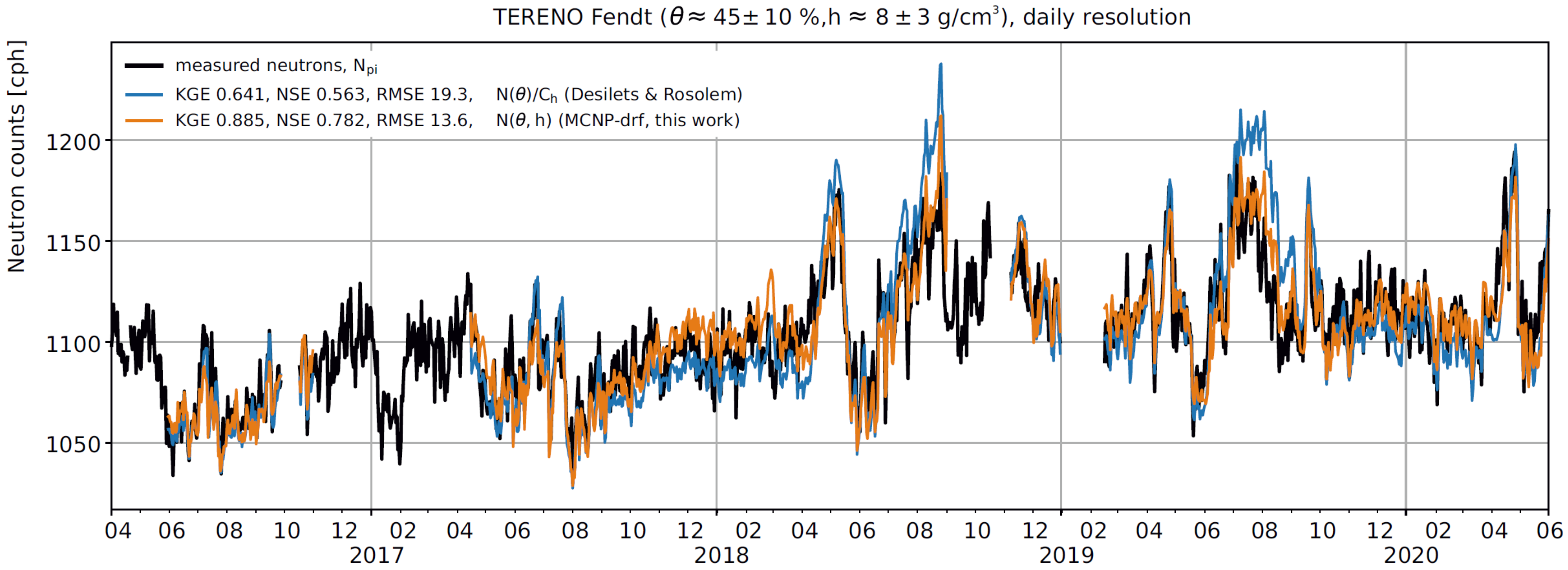
Experimental evidence – wet conditions



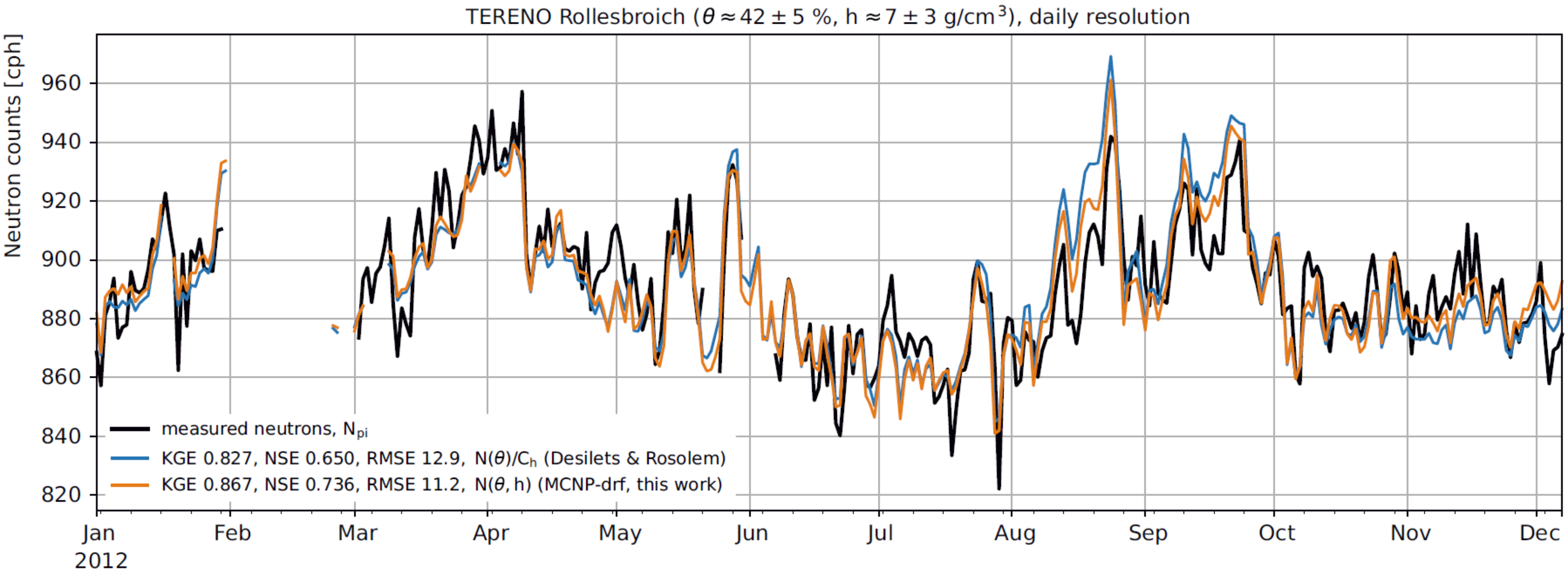
Data from Rollesbroich (R. Baatz)

Experimental evidence – wet conditions



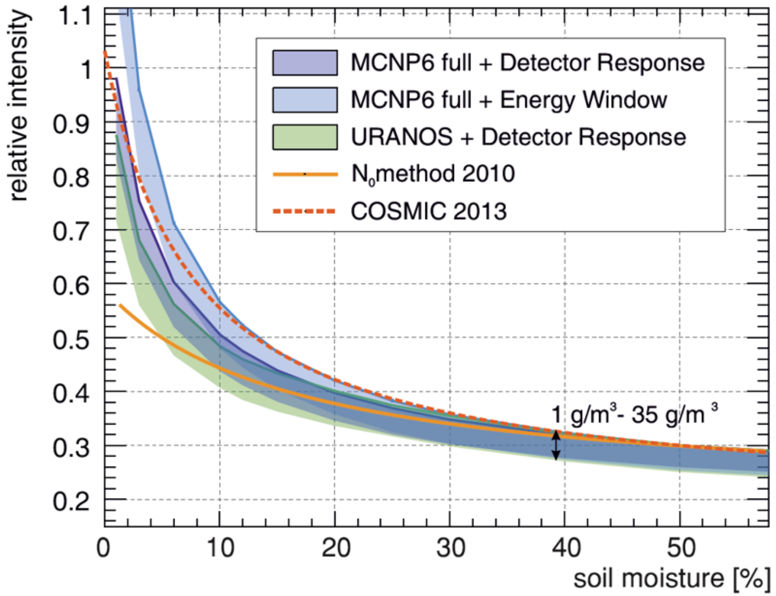
Data from Fendt (B. Fersch, KIT)

Experimental evidence – wet conditions



Data from Rollesbroich (R. Baatz, FZJ)

Thermal Shielding



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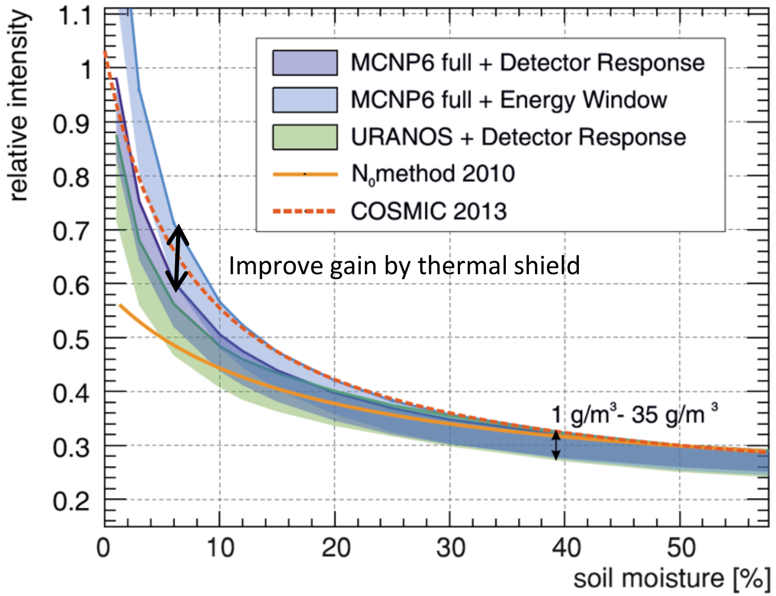

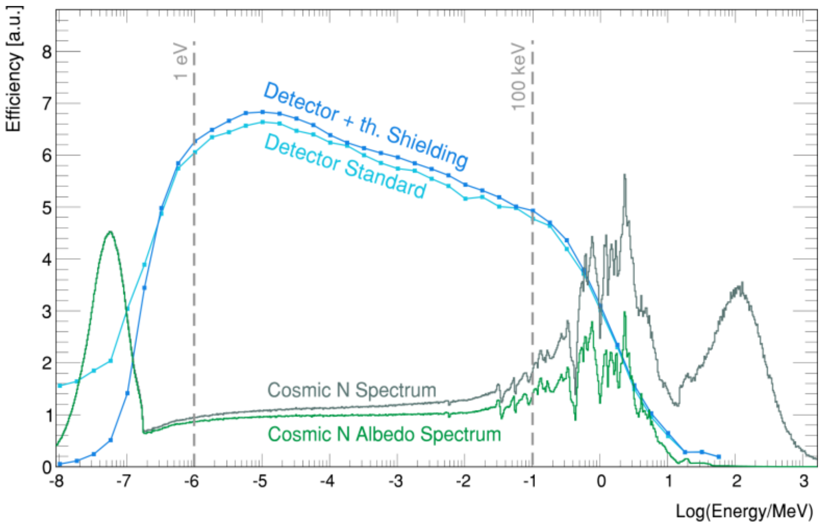

Gadolinium Coating

approx. 90 % absorption efficiency
to cadmium cutoff (0.5 eV)
equals ~95 % in thermal regime (< 0.1 eV)

Overview

- **Site-specific calibrations** are most probably a result of not optimal fit functions

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- New **CRNS intensity function** found by understanding **the contributions** and **improving the corrections of CR neutrons to the signal.**

Combined function for soil moisture and humidity:

$$I\left(\theta,h\right)=N_{D}\left(\frac{p_{1}+p_{2}\,\theta}{p_{1}+\theta}\,\left(p_{0}+p_{6}\,h+p_{7}\,h^{2}\right)+e^{-p_{3}\,\theta}\,\left(p_{4}+p_{5}\,h\right)\right)$$

NS > Overview

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- Thermal shields can significantly improve the signal response

Backup

UTS fit results

Set	p_0	p_1	p_2	p_3	p_4	p_5	p_6	p_7
1: MCNP drf (full)	1.0940	0.0280	0.254	3.537	0.139	−0.00140	−0.0088	0.0001150
2: MCNP ewin (full)	1.2650	0.0259	0.135	1.237	0.063	−0.00021	−0.0117	0.0001200
3: URANOS drf	1.0240	0.0226	0.207	1.625	0.235	−0.00290	−0.0093	0.0000740
4: URANOS ewin	1.2230	0.0185	0.142	2.568	0.155	−0.00047	−0.0119	0.0000920

Results for the parameters p0 - p7

NS > Intercomparison