

# Pathways to CRNS: evolving detectors and neutron modeling

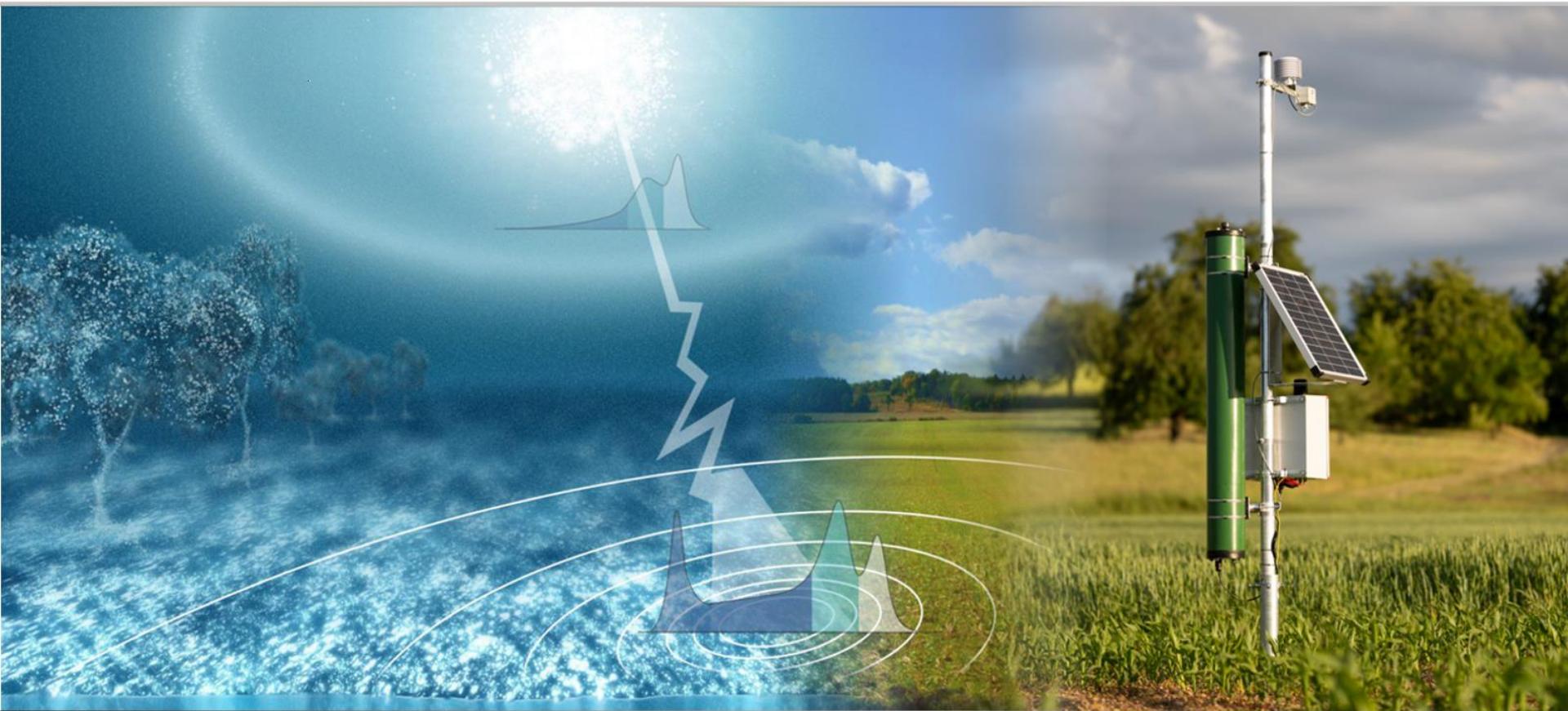
Markus Köhlj<sup>1,2</sup>

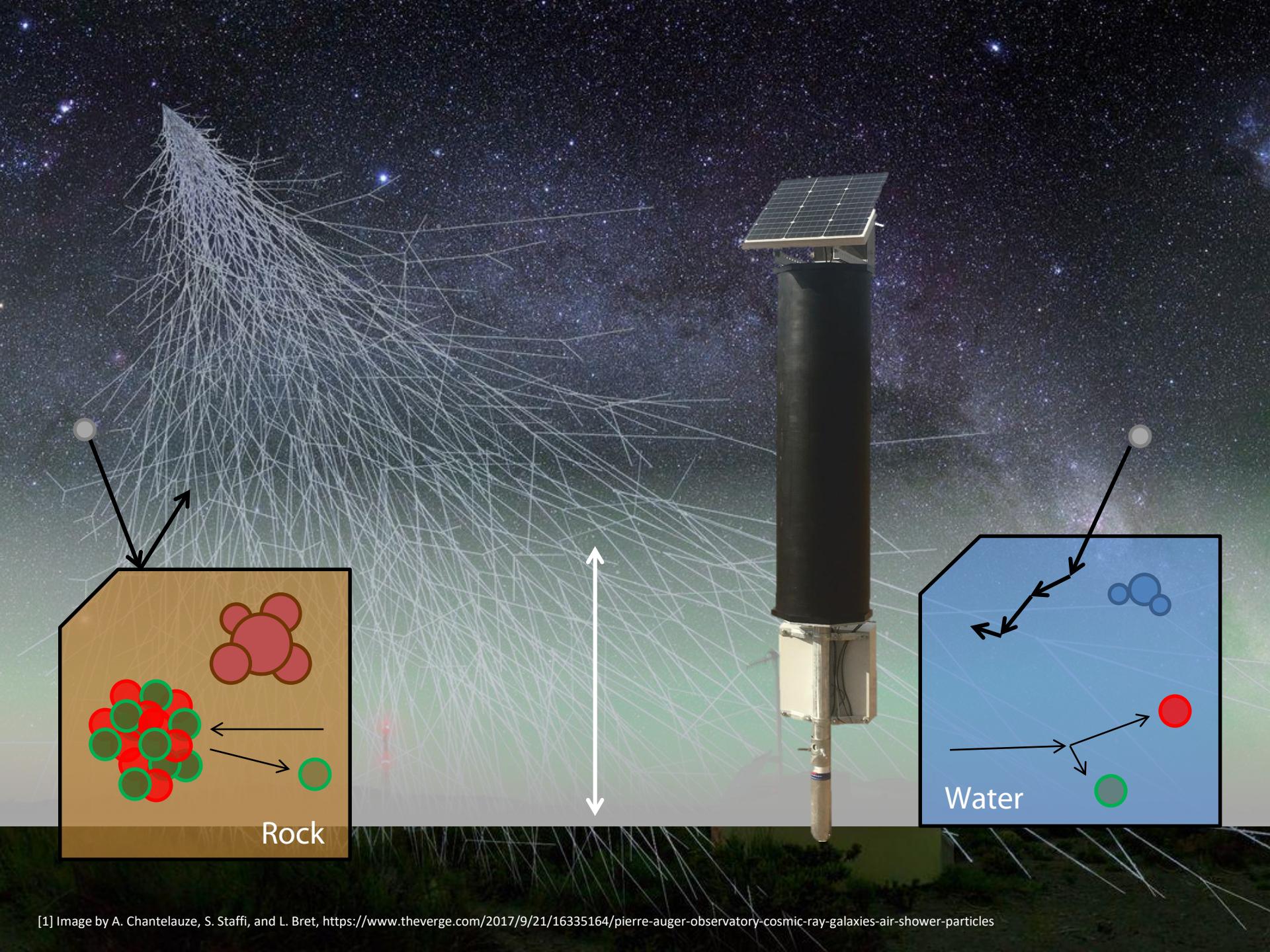
<sup>1</sup> Physikalisches Institut, Heidelberg University, Germany

<sup>2</sup> StyX Neutronica GmbH, Mannheim, Germany



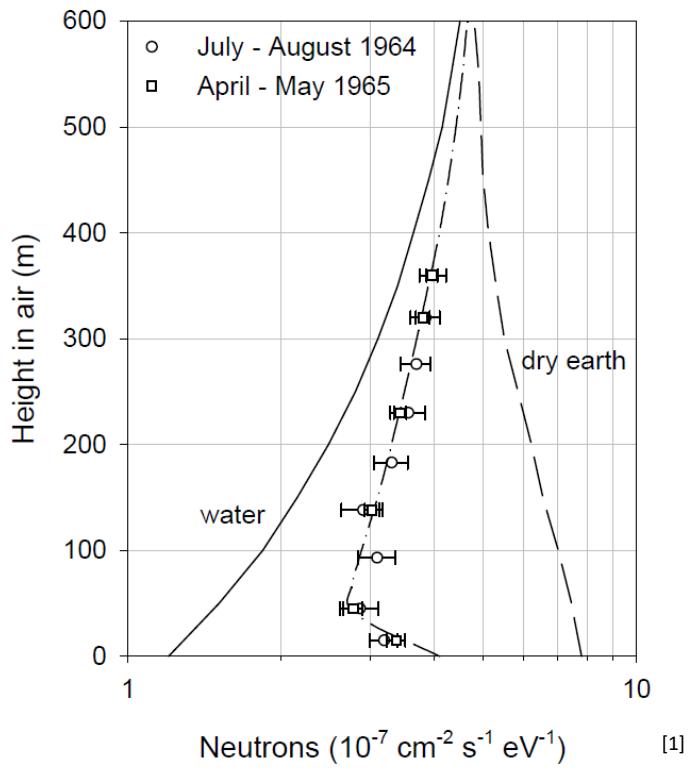
Physikalisches Institut  
Heidelberg University  
Germany





[1] Image by A. Chantelauze, S. Staffi, and L. Bret, <https://www.theverge.com/2017/9/21/16335164/pierre-auger-observatory-cosmic-ray-galaxies-air-shower-particles>

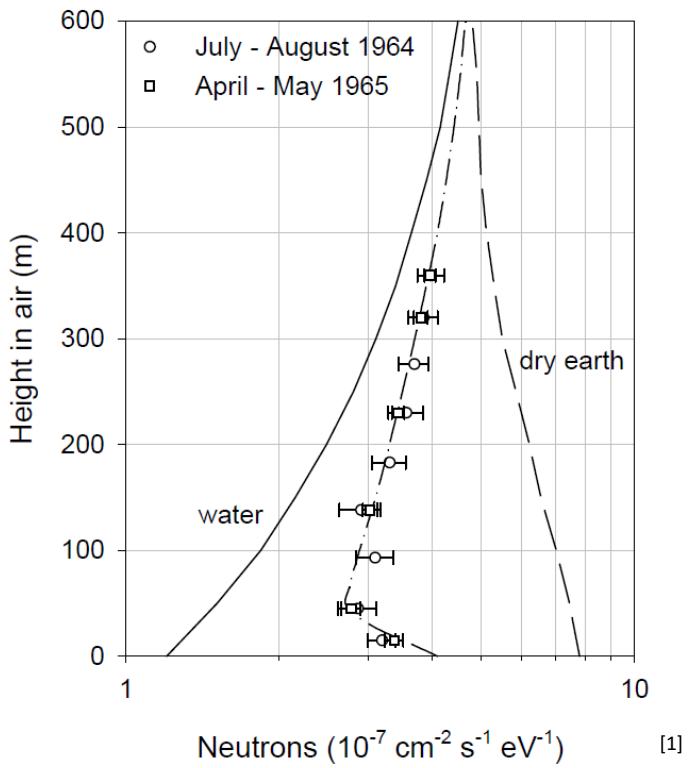
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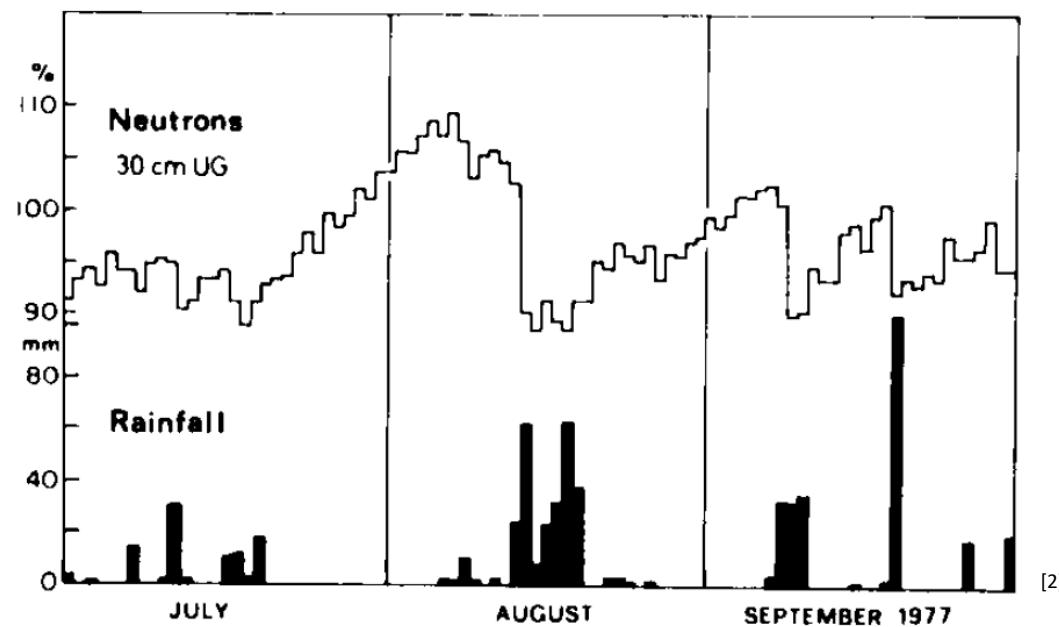
1966

[1] Hendrick, L. D. and Edge, R. D., "Cosmic-ray neutrons near the Earth", Phys. Rev. Ser. II, 145 (1966)  
[2] Kodama, M. et al., "Application of atmospheric neutrons to soil moisture measurement", Soil Sci., 140 (1985)

# » The History Channel



[1]



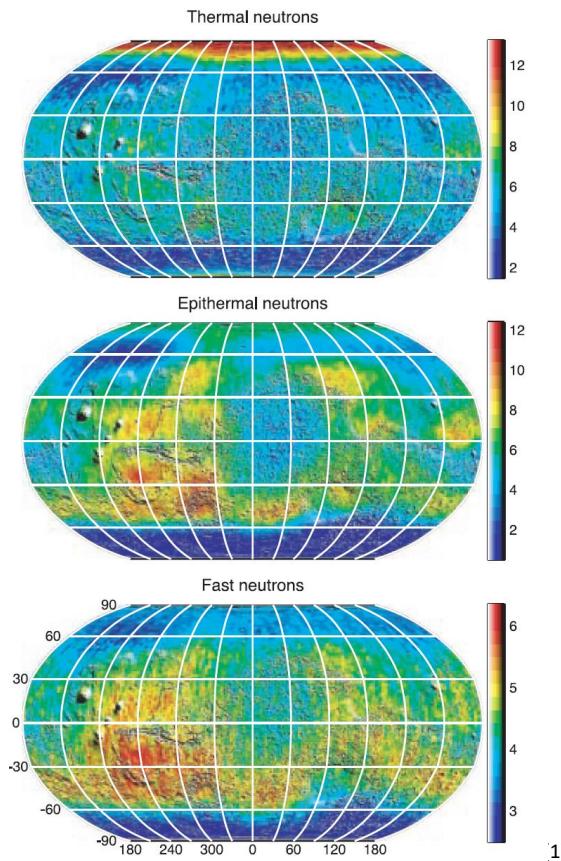
[2]

1966

1985

[1] Hendrick, L. D. and Edge, R. D., "Cosmic-ray neutrons near the Earth", Phys. Rev. Ser. II, 145 (1966)  
 [2] Kodama, M. et al., "Application of atmospheric neutrons to soil moisture measurement", Soil Sci., 140 (1985)

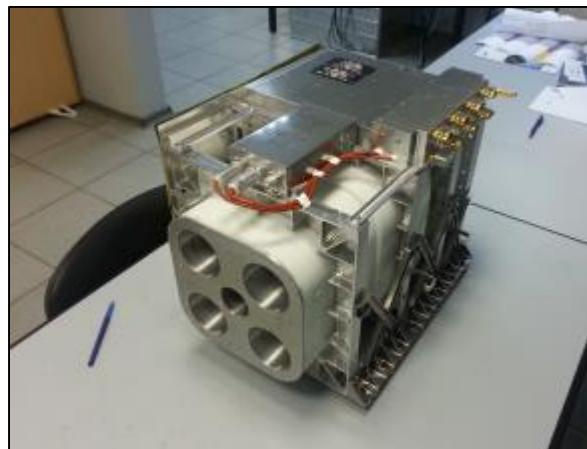
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Curiosity Rover



[2]



Trace Gas Orbiter

1966

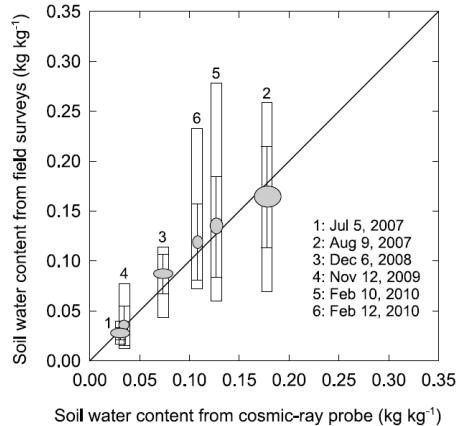
1985

2000

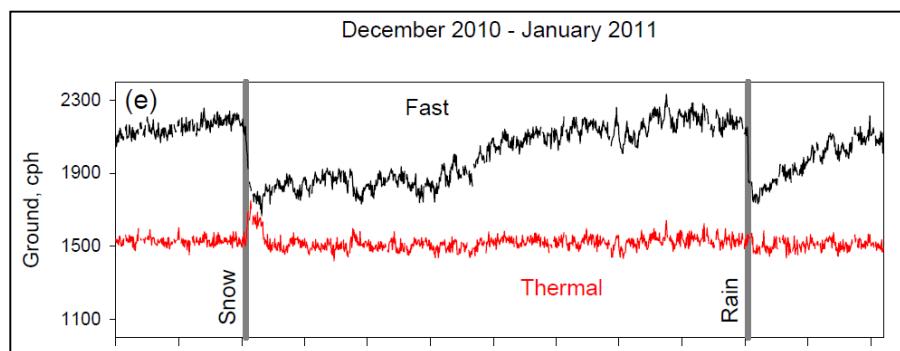
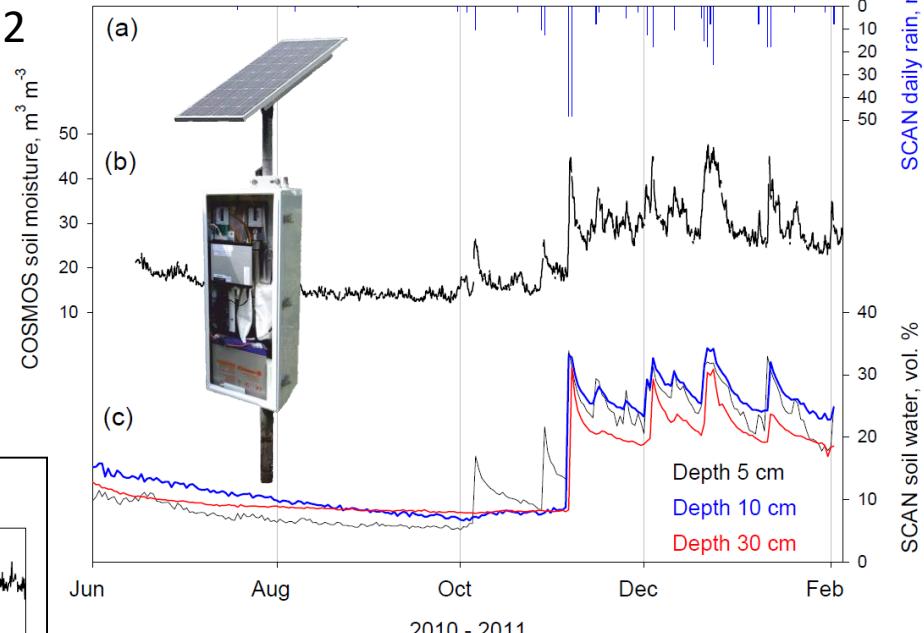
[1] W.C. Feldman, et. al „Global Distribution of Neutrons from Mars: Results from Mars Odyssey“, *Science* 297 (5578) (2002), 75-78.

[2] <http://exploration.esa.int/mars/48523-trace-gas-orbiter-instruments/?fbodylongid=2217>

# The History Channel



2012



[1] Zreda, M. et al., "COSMOS: The COsmic-ray Soil Moisture Observing System." *Hydrology and Earth System Sciences* 16(11) (2012)

[2] Desilets, D. et al., "Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays.", *Water Resources Research* 46(11) (2010)

# » Stationary Instruments



StyX Neutronica SP



Hydroinnova CRS1000

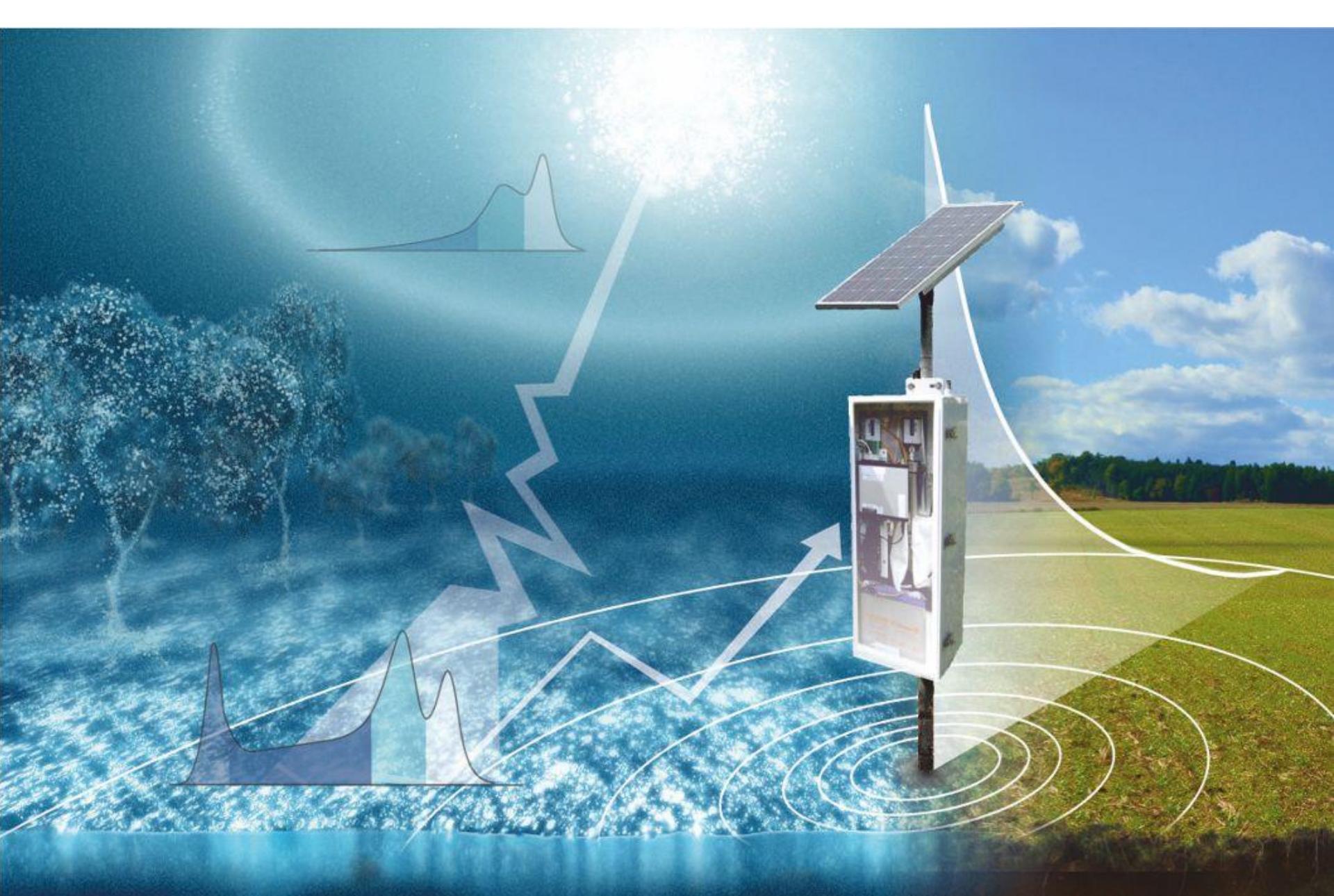


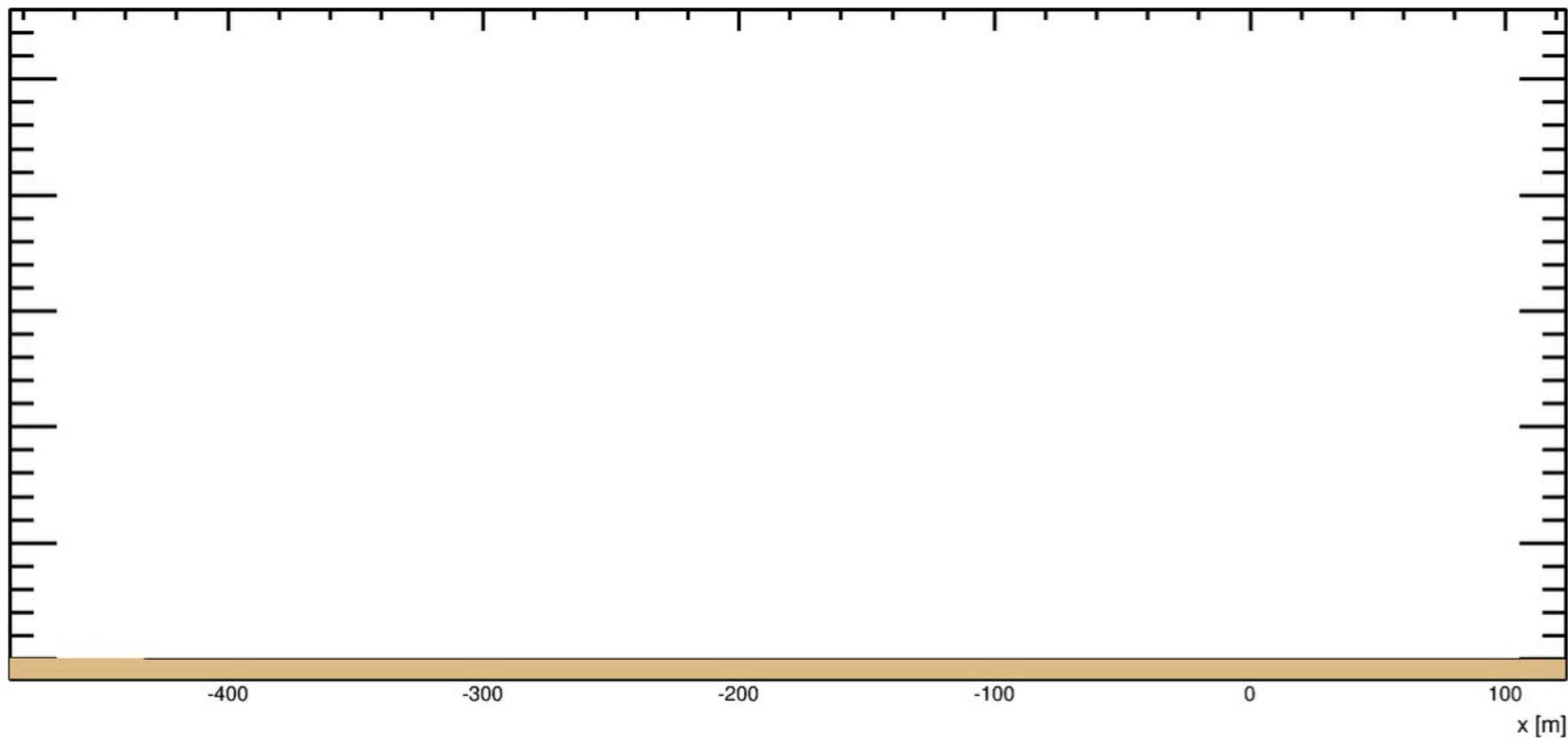
Finapp 3



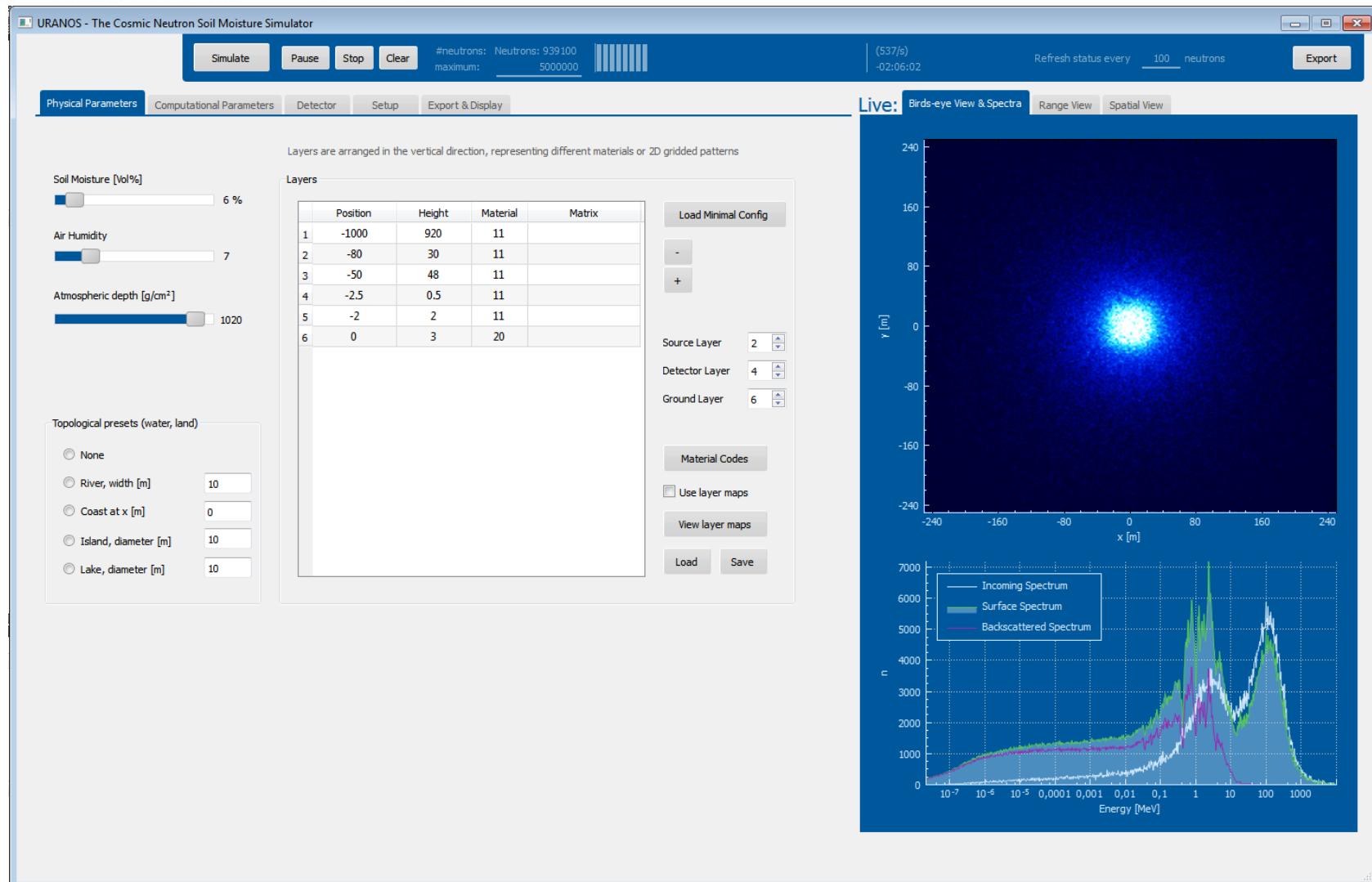
StyX Neutronica S1





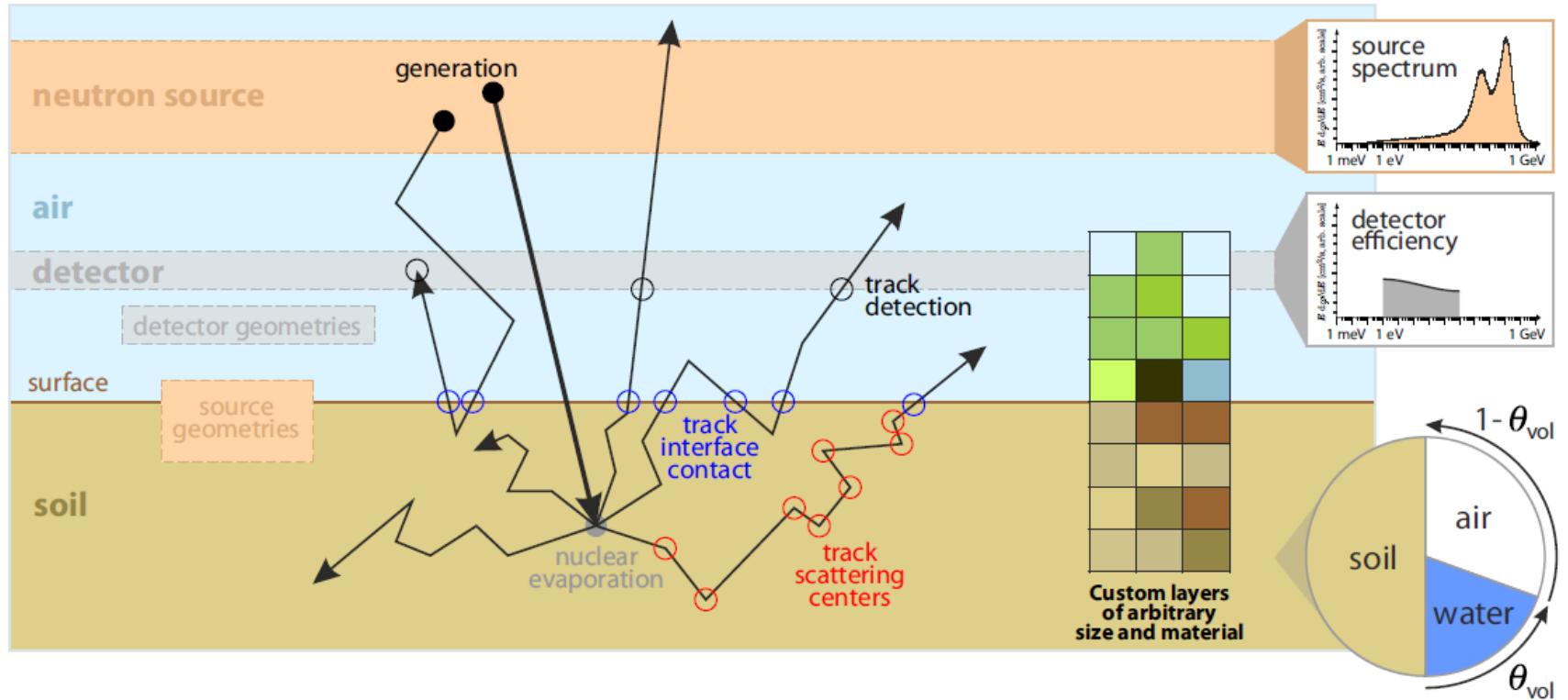


In collaboration with Martin Schrön, UFZ Leipzig



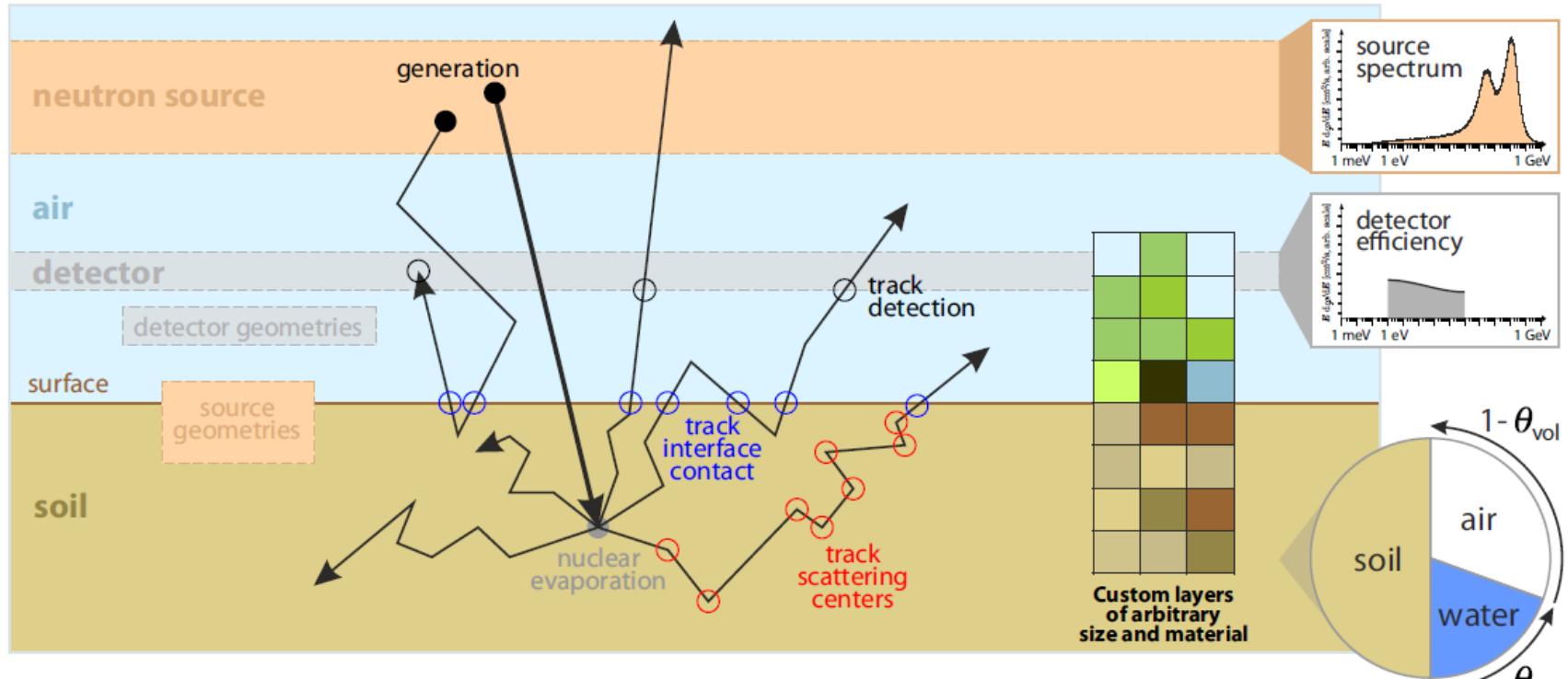
# URANOS Buildup

In collaboration with Martin Schrön, UFZ Leipzig



# URANOS Buildup

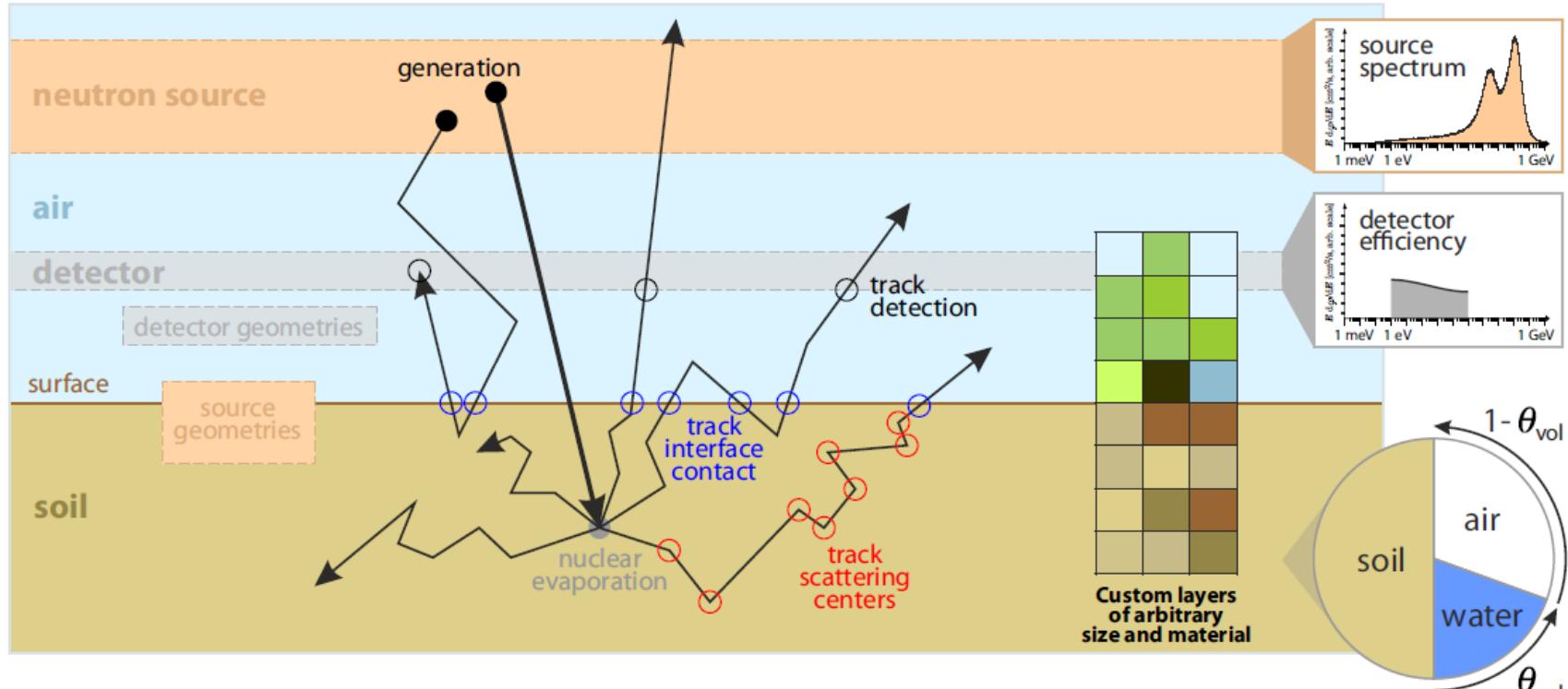
In collaboration with Martin Schrön, UFZ Leipzig



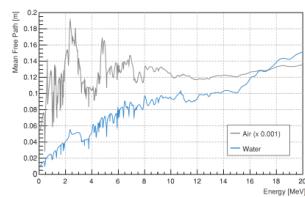
- written in C++
- linked against ENDF data bases

# URANOS Buildup

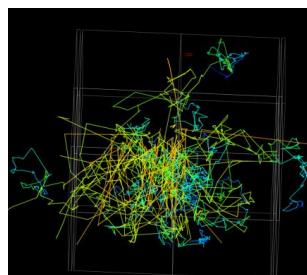
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- written in C++
- linked against ENDF data bases

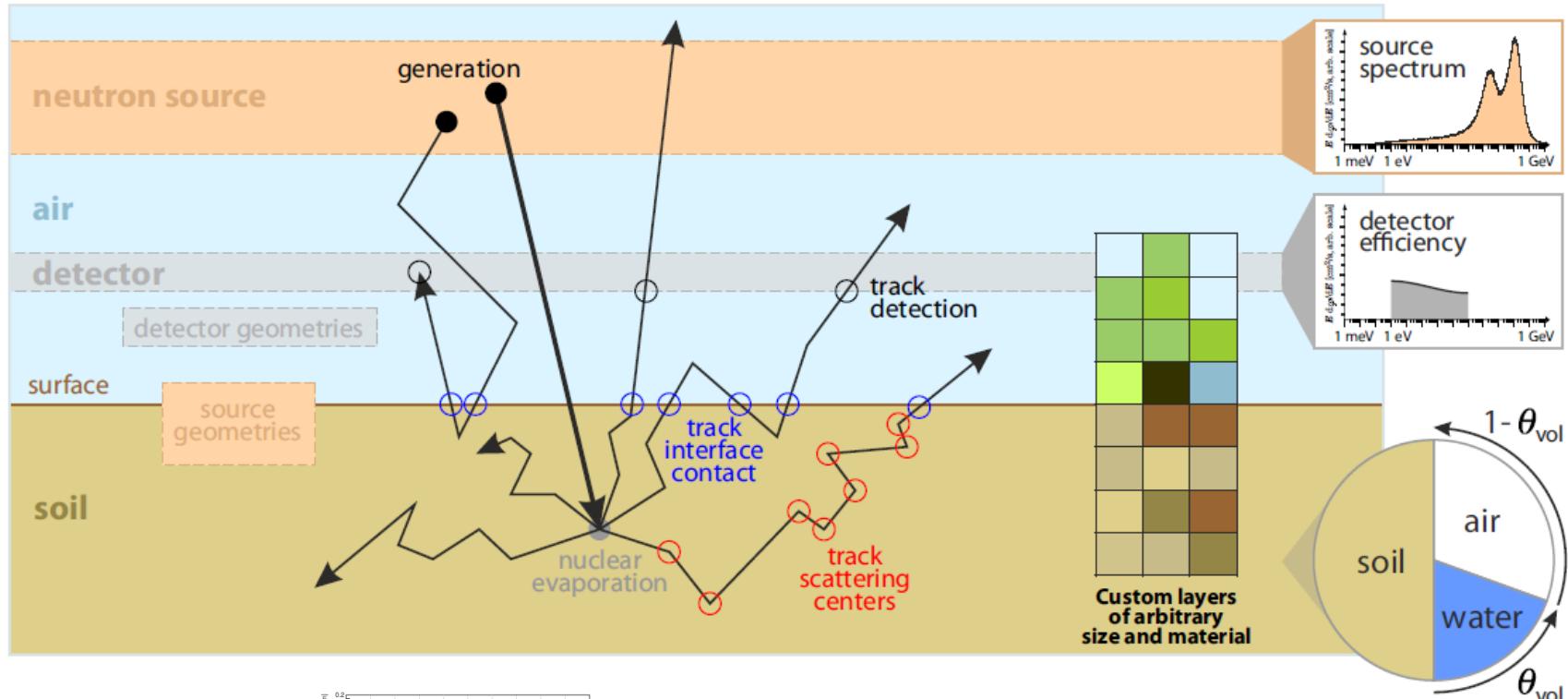


- Ray-Casting

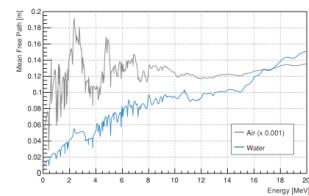


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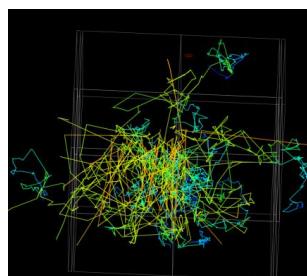


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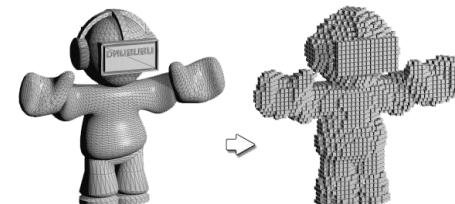


- linked against ENDF data bases

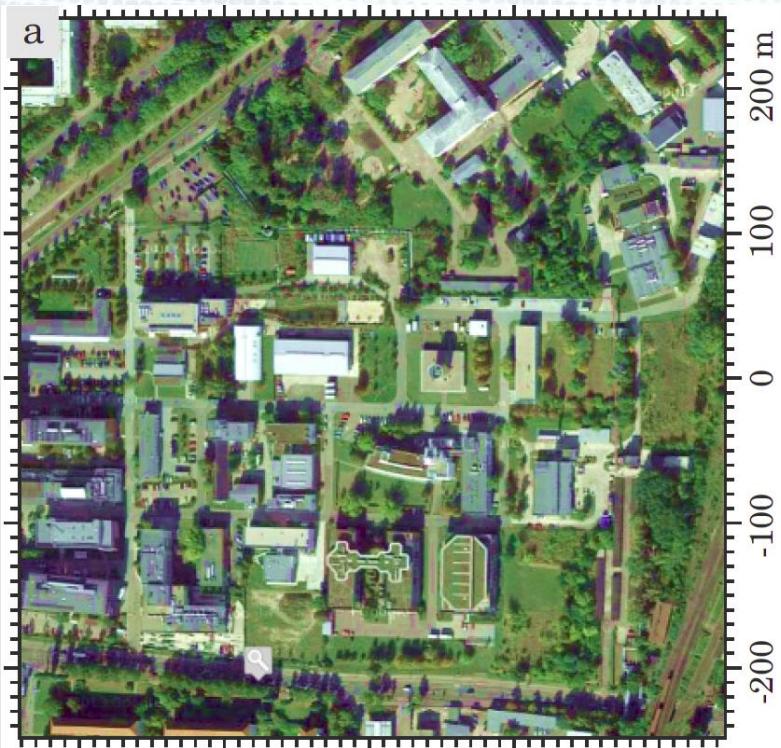
- Ray-Casting



- Voxel Engine

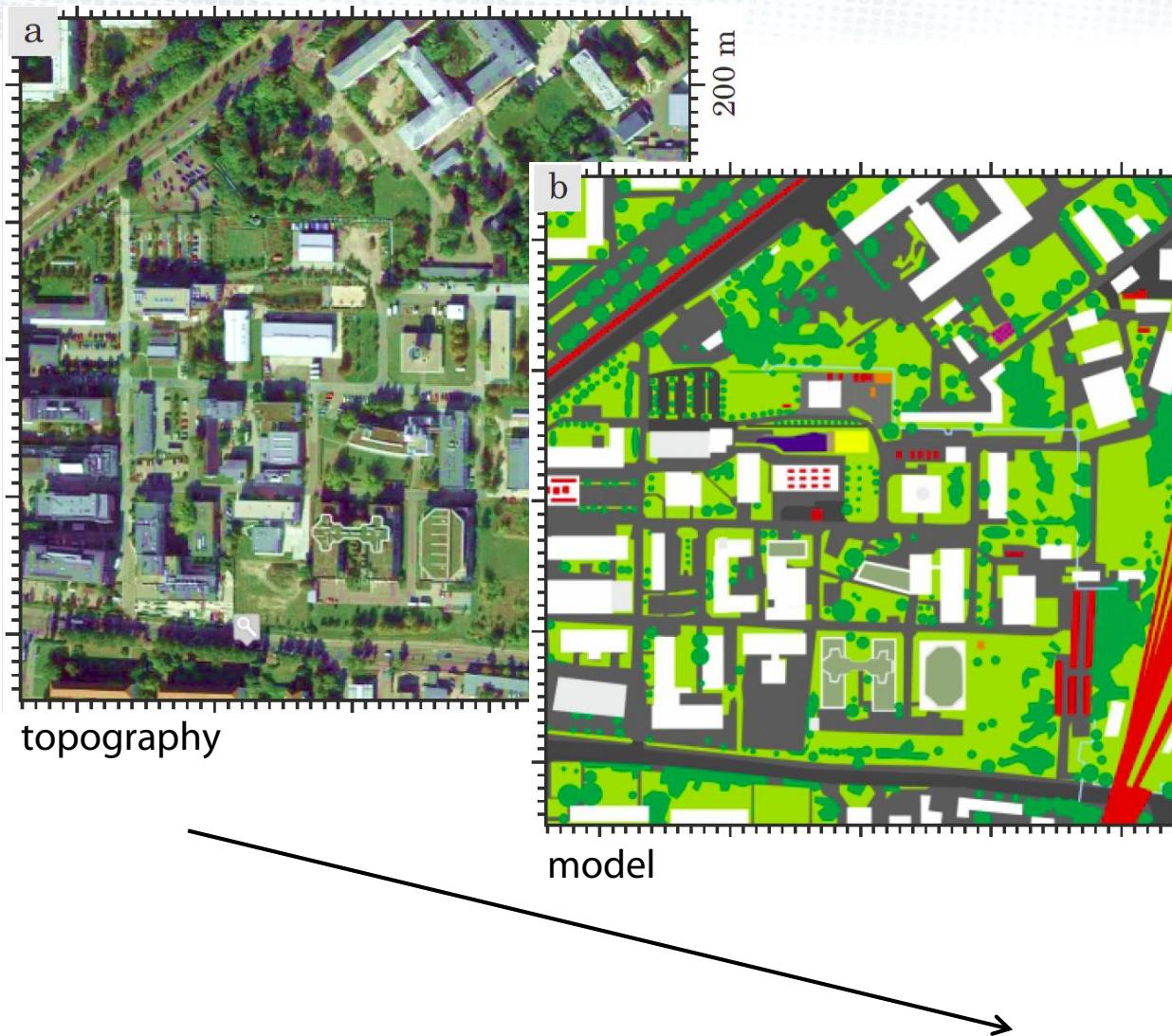


# » URANOS Modeling



topography

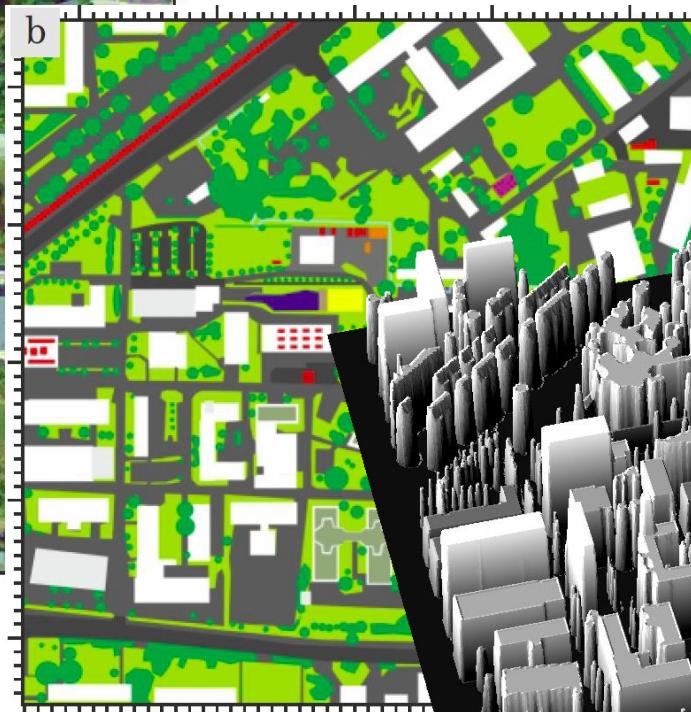
# » URANOS Modeling



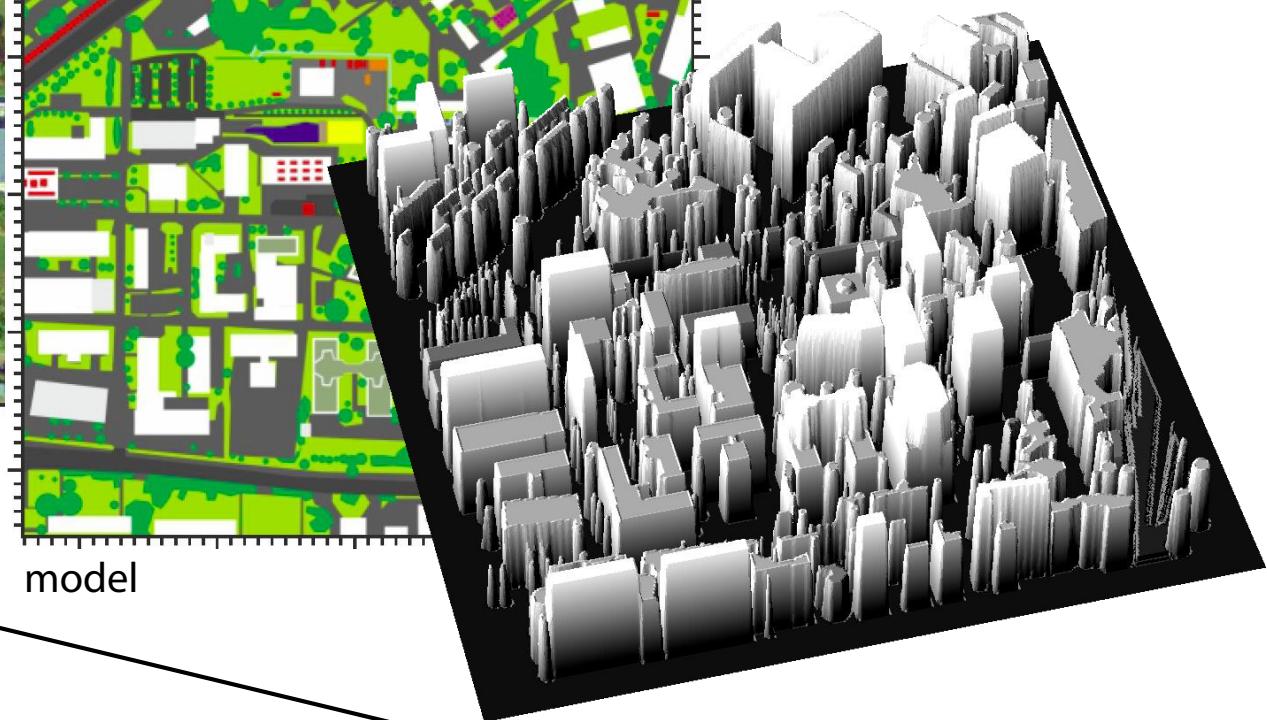
# URANOS Modeling



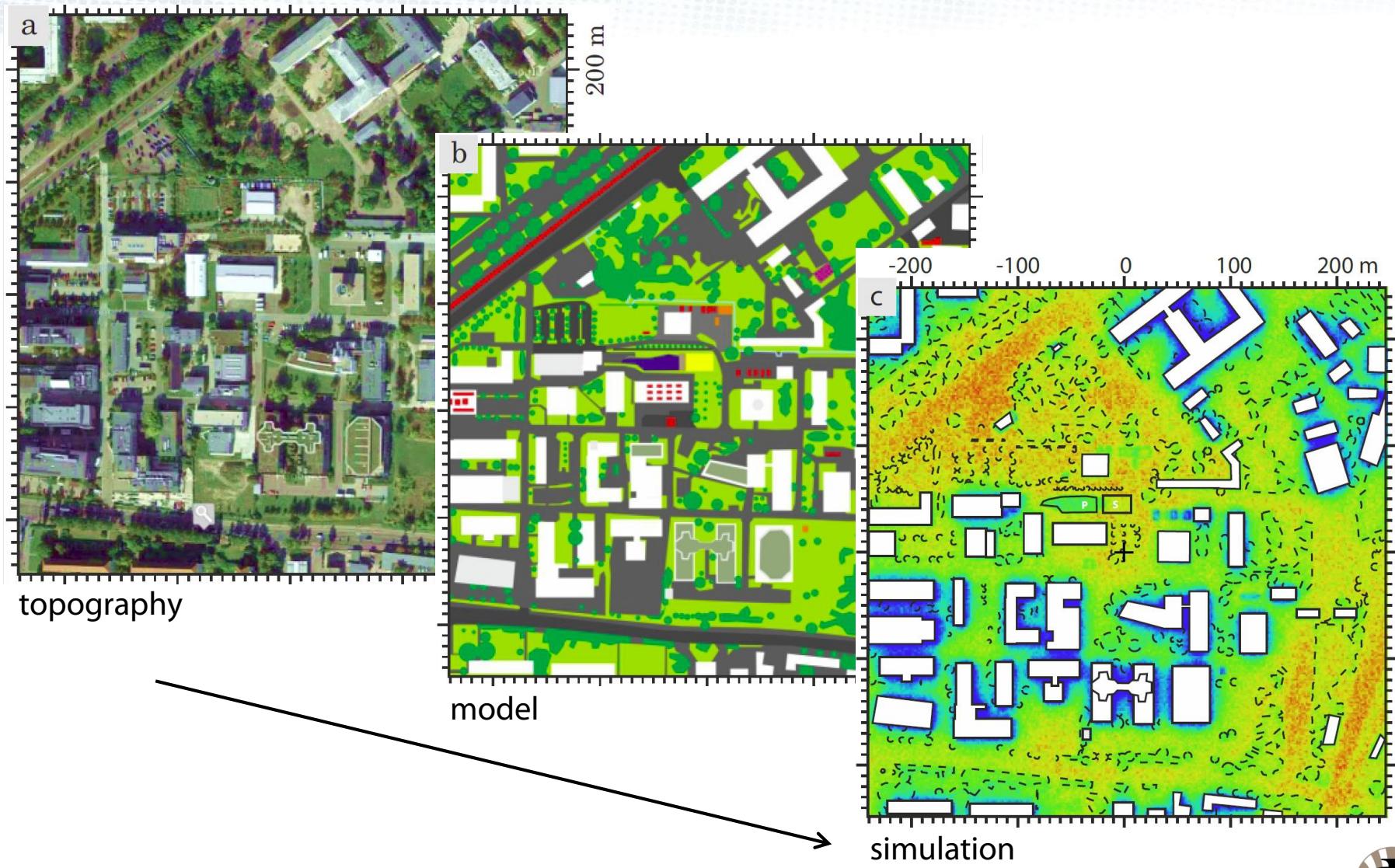
200 m



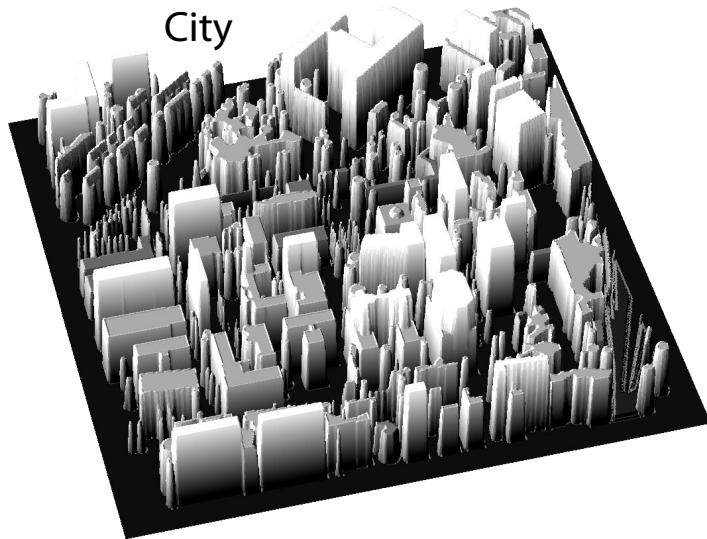
model



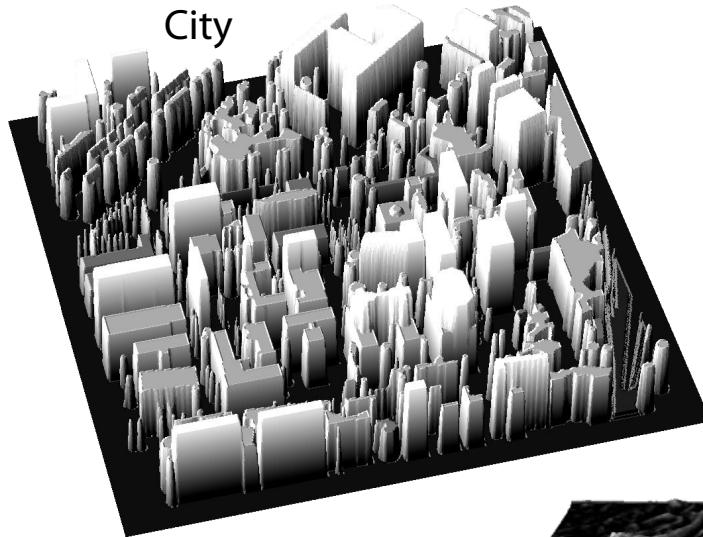
# URANOS Modeling



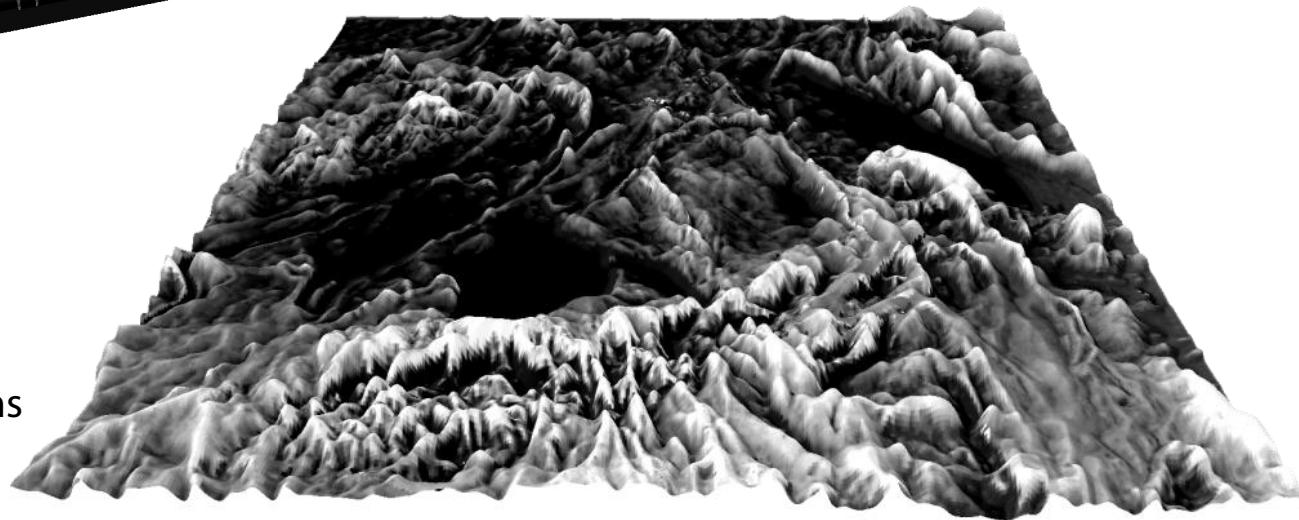
# URANOS Modeling



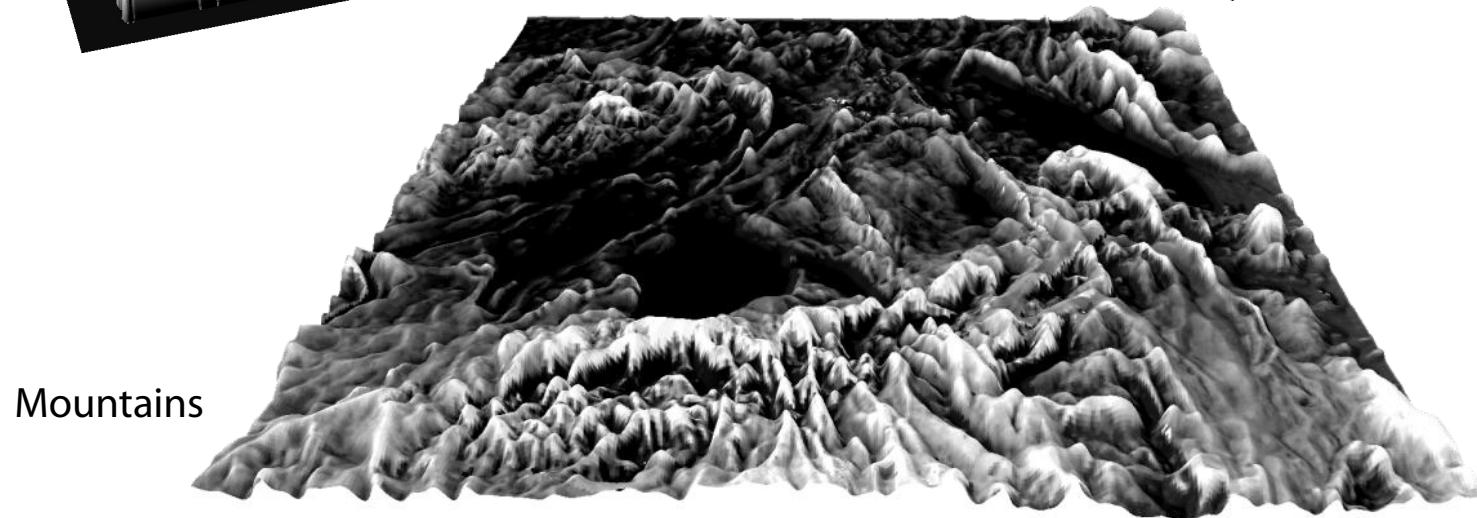
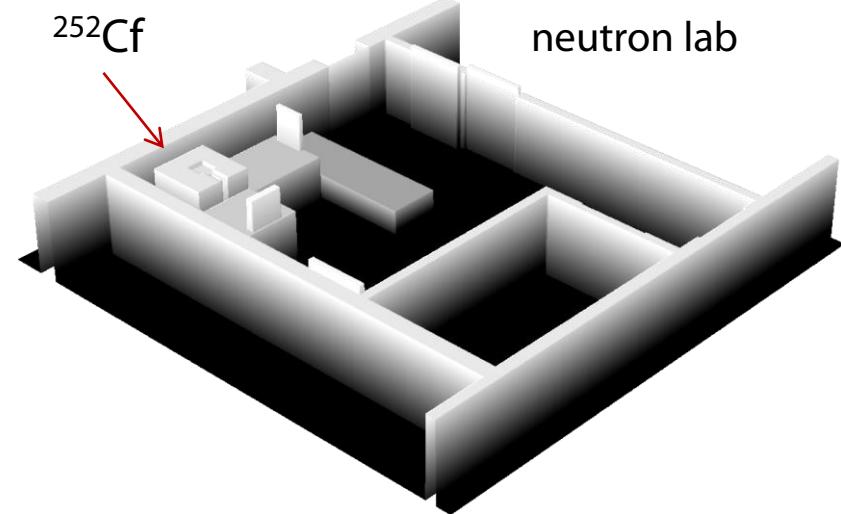
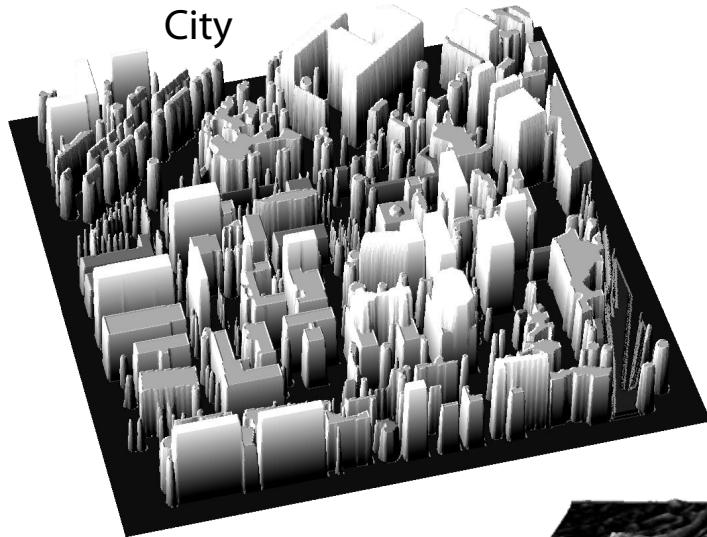
# URANOS Modeling



Mountains

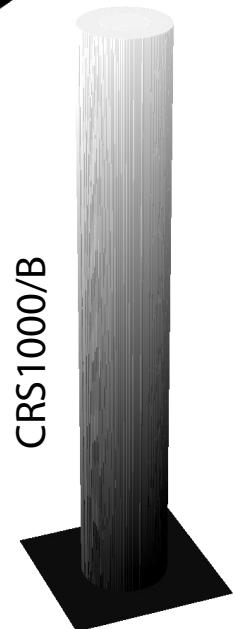
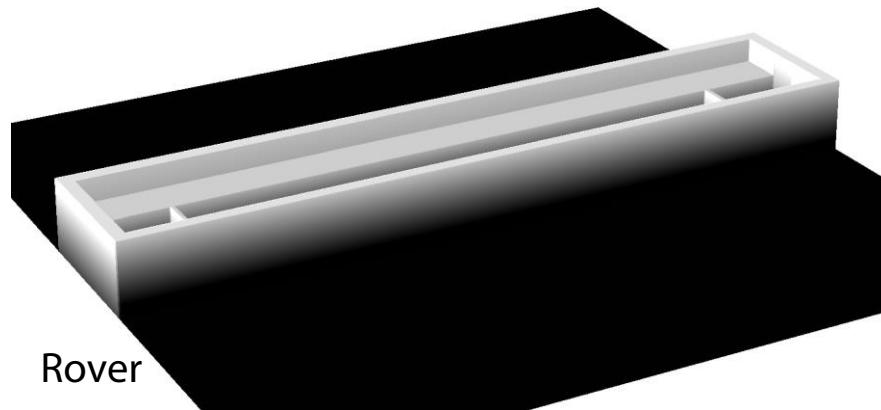
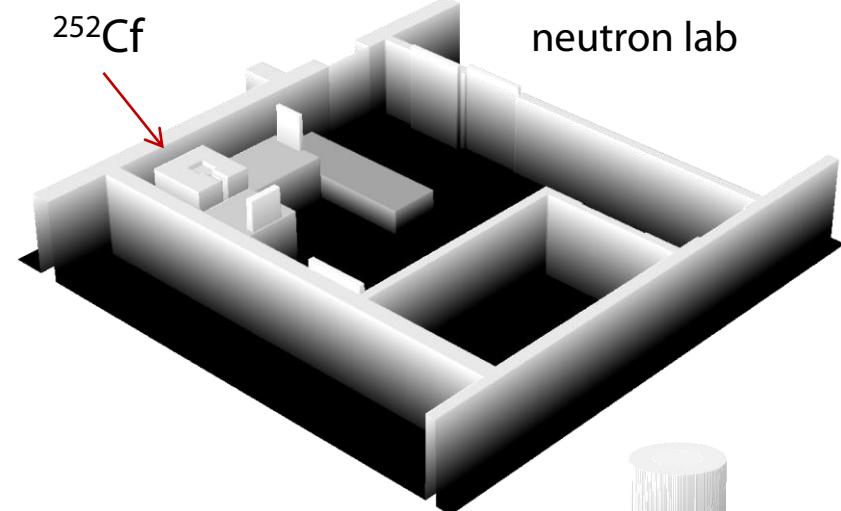
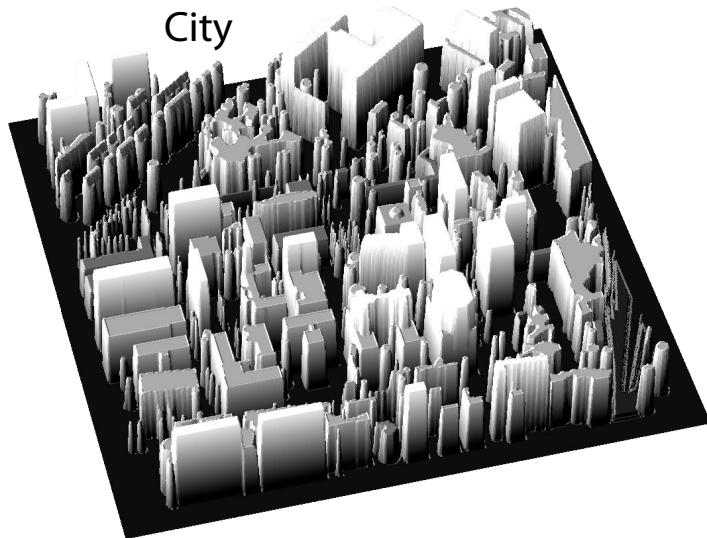


# URANOS Modeling



Mountains

# URANOS Modeling



# URANOS Modeling

URANOS - The Cosmic Neutron Soil Moisture Simulator

The screenshot shows the URANOS software interface. At the top, there are buttons for Simulate, Pause, Stop, Clear, and a status bar showing neutrons/sec (0), Refresh every 1674 neutrons, Save CFG, and Export.

**Physical Parameters:**

- Soil Water Content [Vol%]: 50 %
- Soil Porosity [Vol%]: 50 %
- Air Humidity: 0.33 g/m<sup>3</sup>
- Air Humidity Exponential Length: Inf
- Atmospheric depth: 1013 g/cm<sup>3</sup>
- Cut-off rigidity [GV]: 5

**Computational Parameters:**

Layers are arranged in the vertical direction, representing different materials or 2D gridded patterns. Position z denotes the depth below surface (z=0) in [m] and refers to the upper edge of the layer. Layers override topological presets.

|   | Position | Height | Material | Matrix    |
|---|----------|--------|----------|-----------|
| 1 | -0.1     | 0.1    | 11       |           |
| 2 | 0        | 0.05   | 11       | 2M [1000] |
| 3 | 0.05     | 1.9    | 11       | 3M [1000] |
| 4 | 1.95     | 0.05   | 11       | 4M [1000] |
| 5 | 2        | 2      | 11       |           |

**Layer Control:**

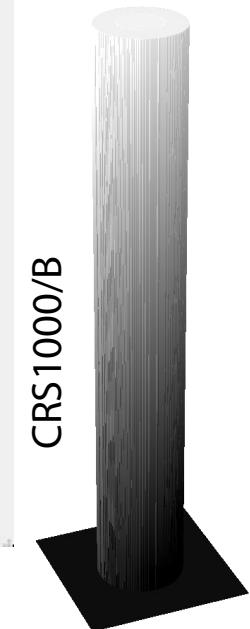
- Minimum Configuration
- Generate
- Source Layer: 1
- Detector Layer: 3
- Ground Layer: 5
- Material Codes
- Use layer maps
- View layer maps
- Layer Configuration: Load, Save

**Live:** Birds-eye View & Spectra, Range View, Spatial View, Detector

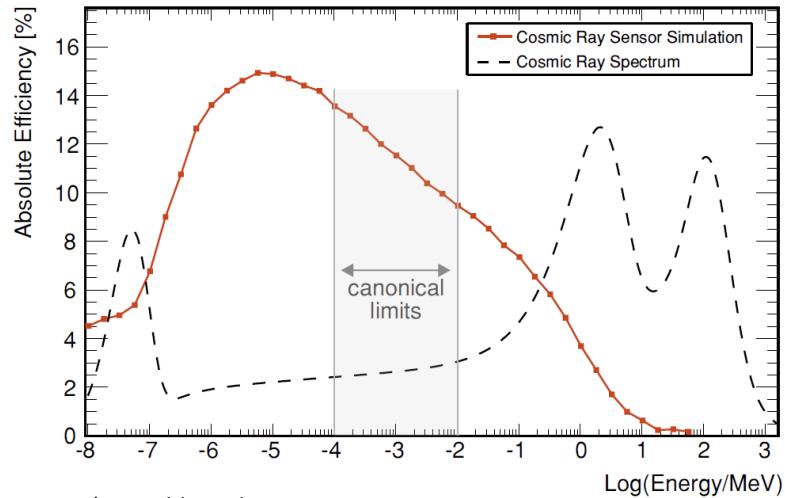
The Birds-eye View & Spectra window displays a heatmap of neutron intensity across a 40x40 m area. The x-axis is labeled 'x [m]' from -40 to 40, and the y-axis is labeled 'y [m]' from -40 to 40. The heatmap shows a gradient from dark blue to light blue, indicating higher neutron counts near the surface and lower counts at greater depths.

The Spectra window shows the energy spectrum with Energy [MeV] on the x-axis ranging from -1 to 1 and Intensity [n] on the y-axis ranging from 0 to 1. It includes three curves: Incoming Spectrum (blue), Surface Spectrum (green), and Backscattered Spectrum (purple).

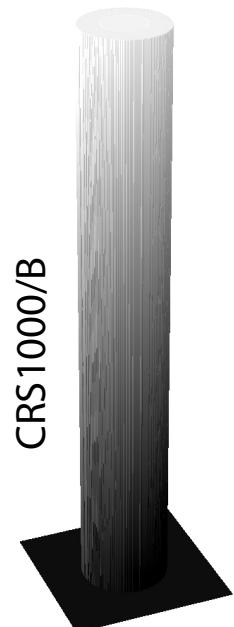
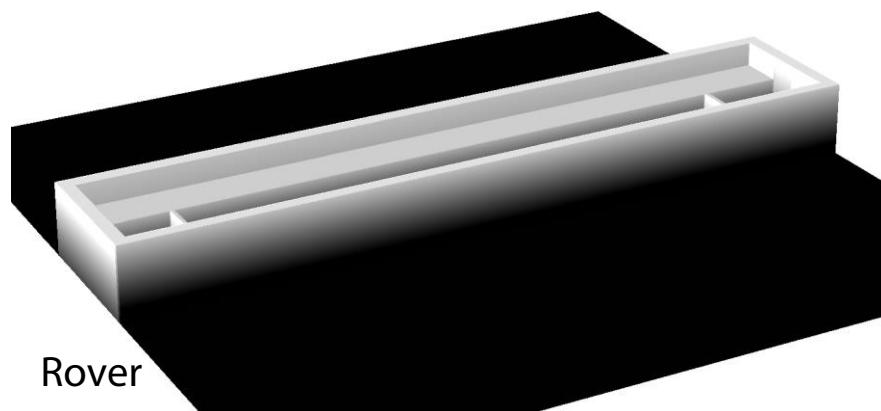
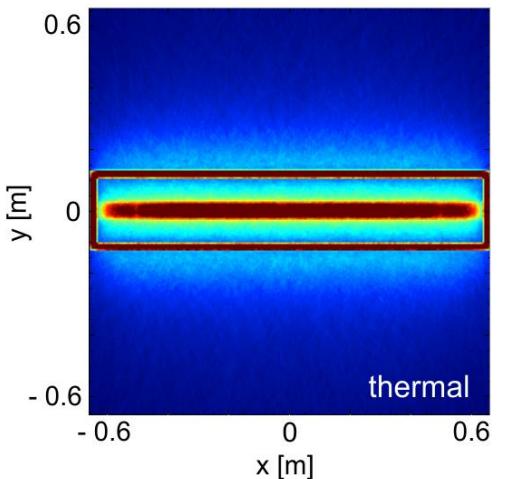
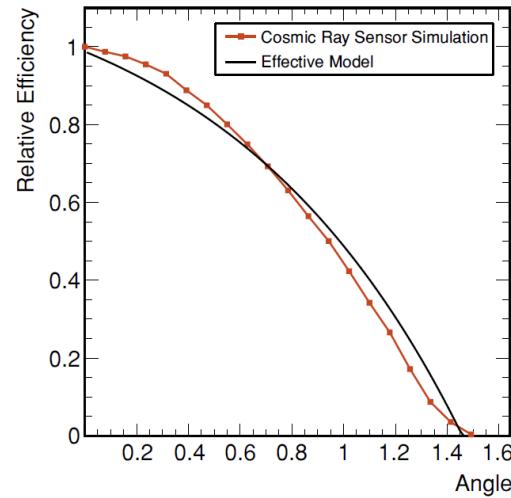
Rover



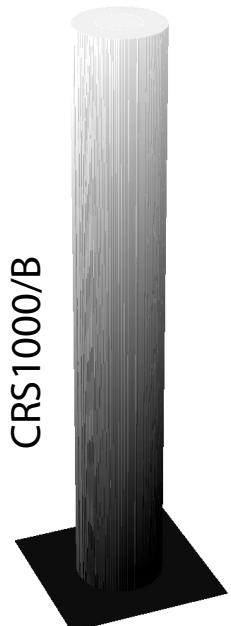
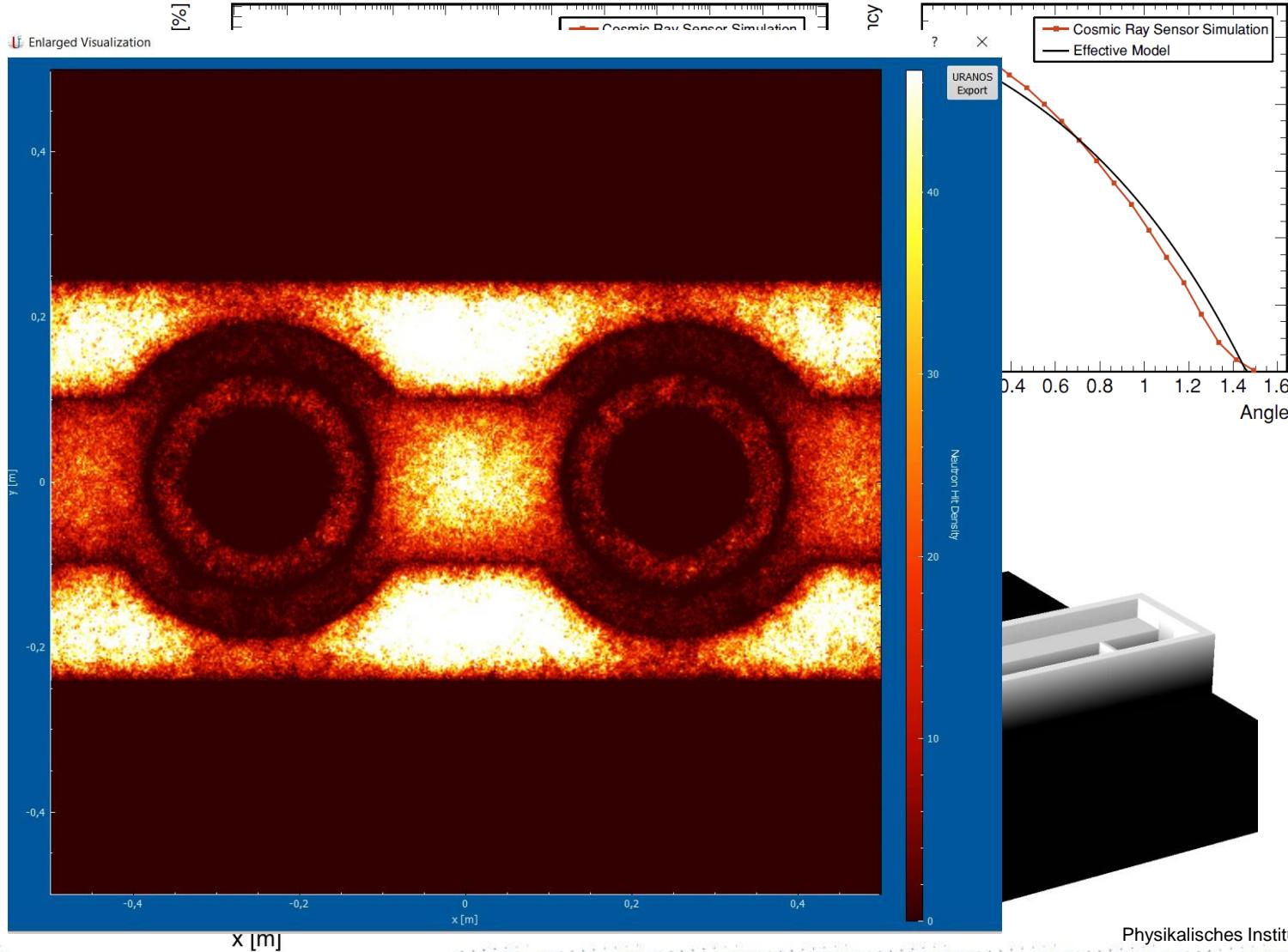
# URANOS Modeling



\*M. Köhli et al.  
Response Functions for Detectors in Cosmic Ray Neutron Sensing



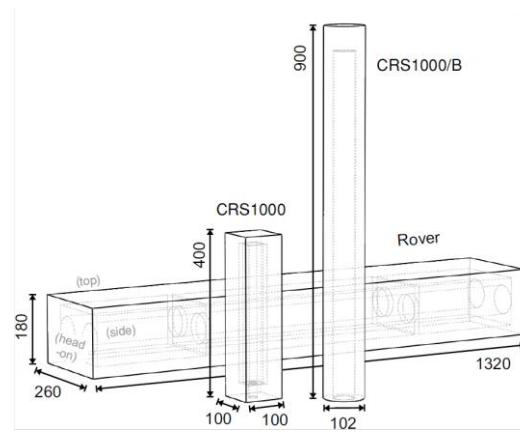
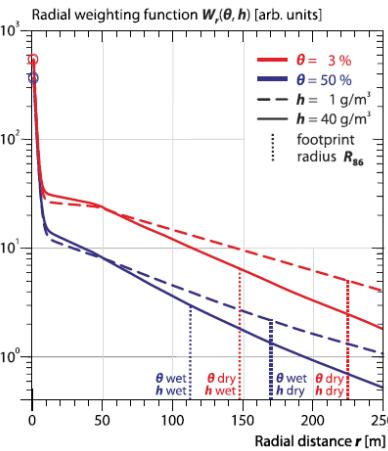
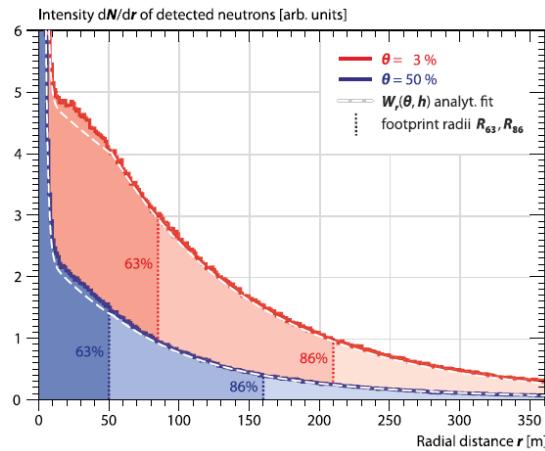
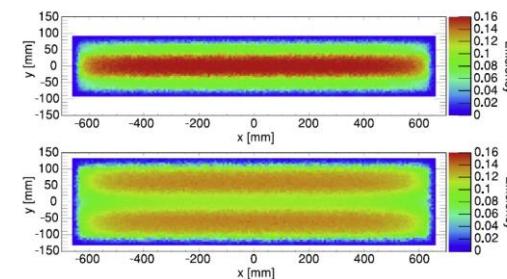
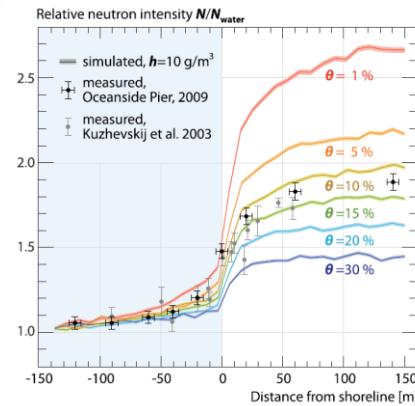
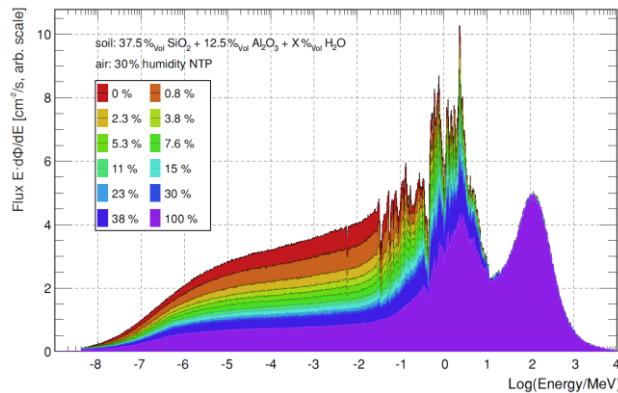
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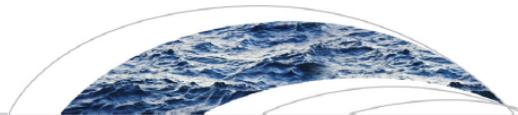
Physikalisches Institut, Universität Heidelberg



# CRNS timeseries



# » 2015 WWR paper



## Water Resources Research

### RESEARCH ARTICLE

10.1002/2015WR017169

M. Köhli and M. Schrön contributed equally to this work.

#### Key Points:

- Neutron transport modeling revised

### Footprint characteristics revised for field-scale soil moisture monitoring with cosmic-ray neutrons

**M. Köhli<sup>1</sup>, M. Schrön<sup>2</sup>, M. Zreda<sup>3</sup>, U. Schmidt<sup>1</sup>, P. Dietrich<sup>2</sup>, and S. Zacharias<sup>2</sup>**

<sup>1</sup>Physics Institute, Heidelberg University, Heidelberg, Germany, <sup>2</sup>Department of Monitoring and Exploration Technologies, UFZ—Helmholtz Centre for Environmental Research, Leipzig, Germany, <sup>3</sup>Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona, USA



# » 2015 WWR paper



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Water Resources Research—hydrology

- New Flood Model Offers National

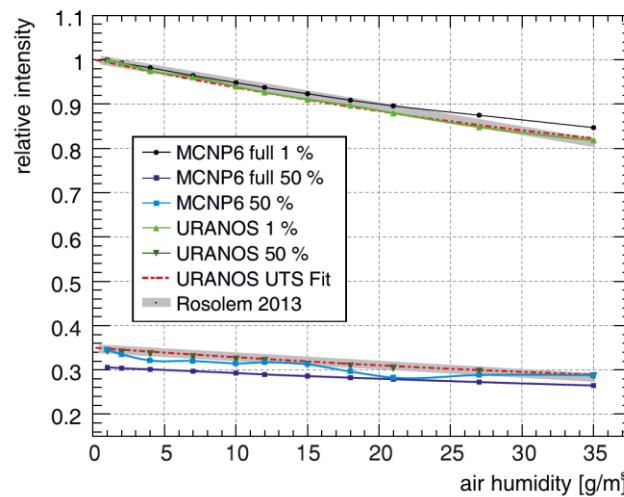
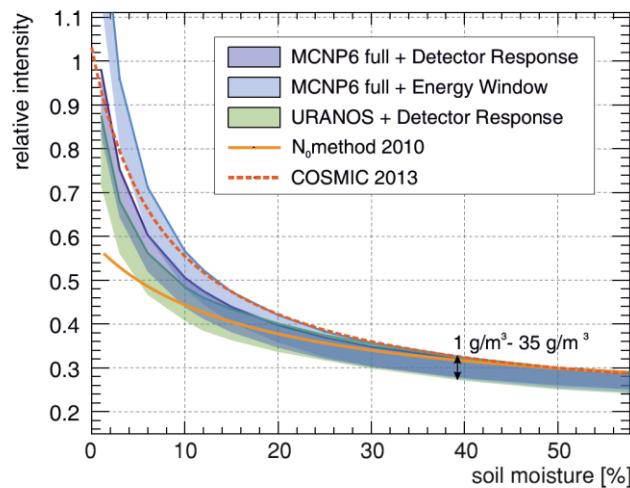


# » 2021 Intensity Relation

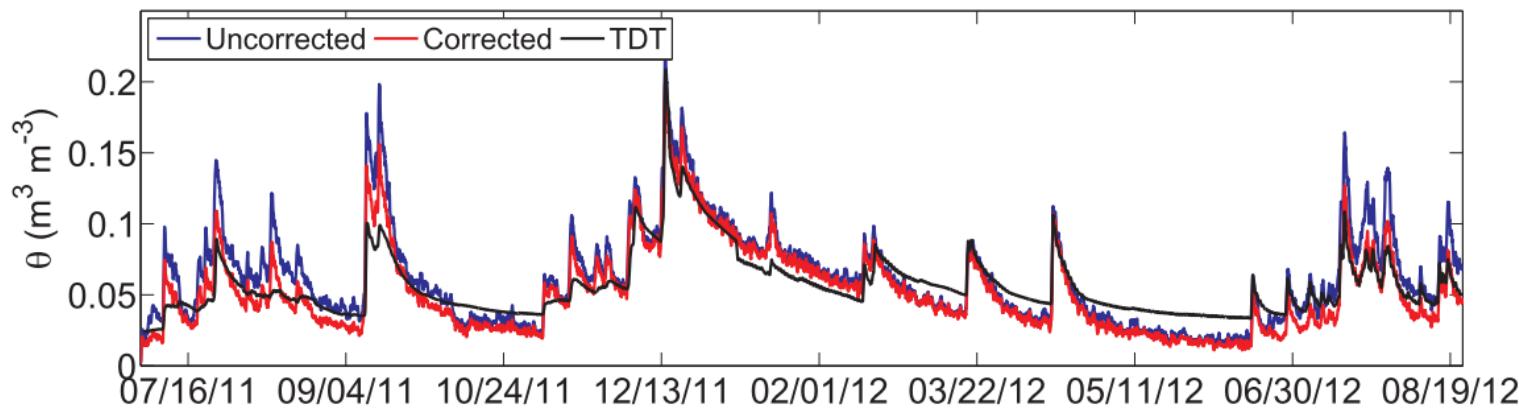
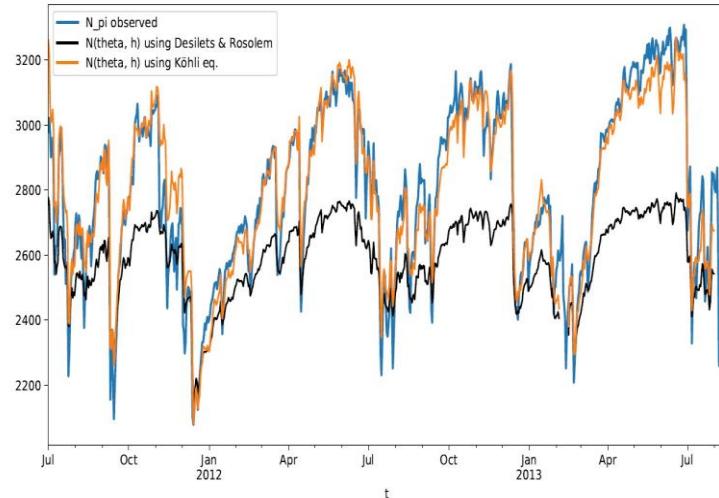
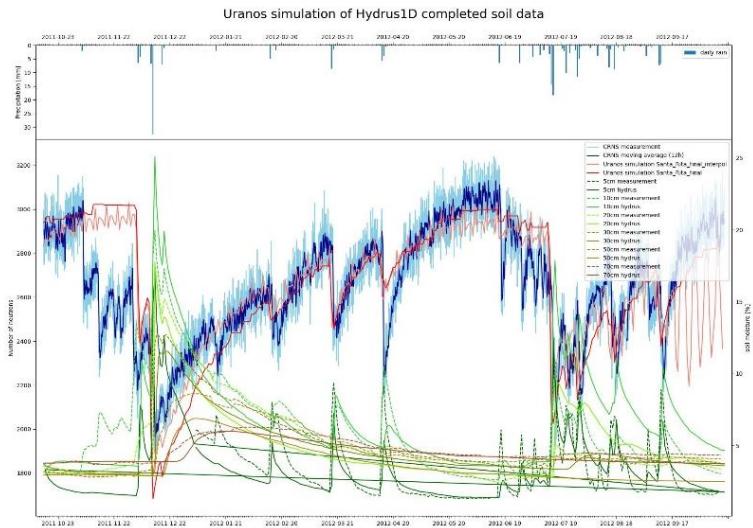
Our proposition: the universal transport solution (UTS)

$$I(\theta, h) = N_D \left( \frac{p_1 + p_2 \theta}{p_1 + \theta} \left( p_0 + p_6 h + p_7 h^2 \right) + e^{-p_3 \theta} (p_4 + p_5 h) \right)$$

Hyperbola                      Exponential  
↑                                  ↑  
air humidity corrections

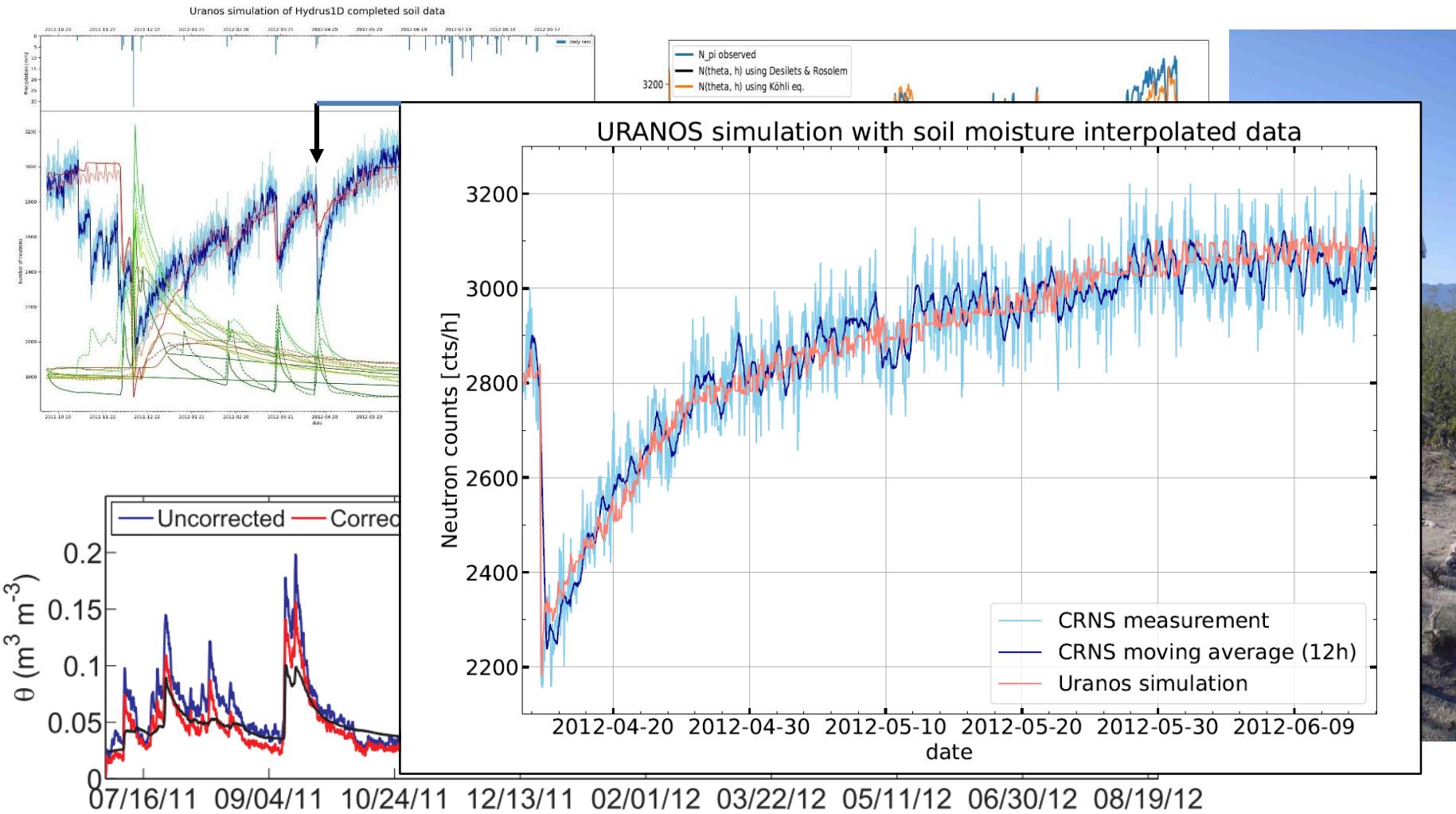


# CRNS timeseries Stanta Rita



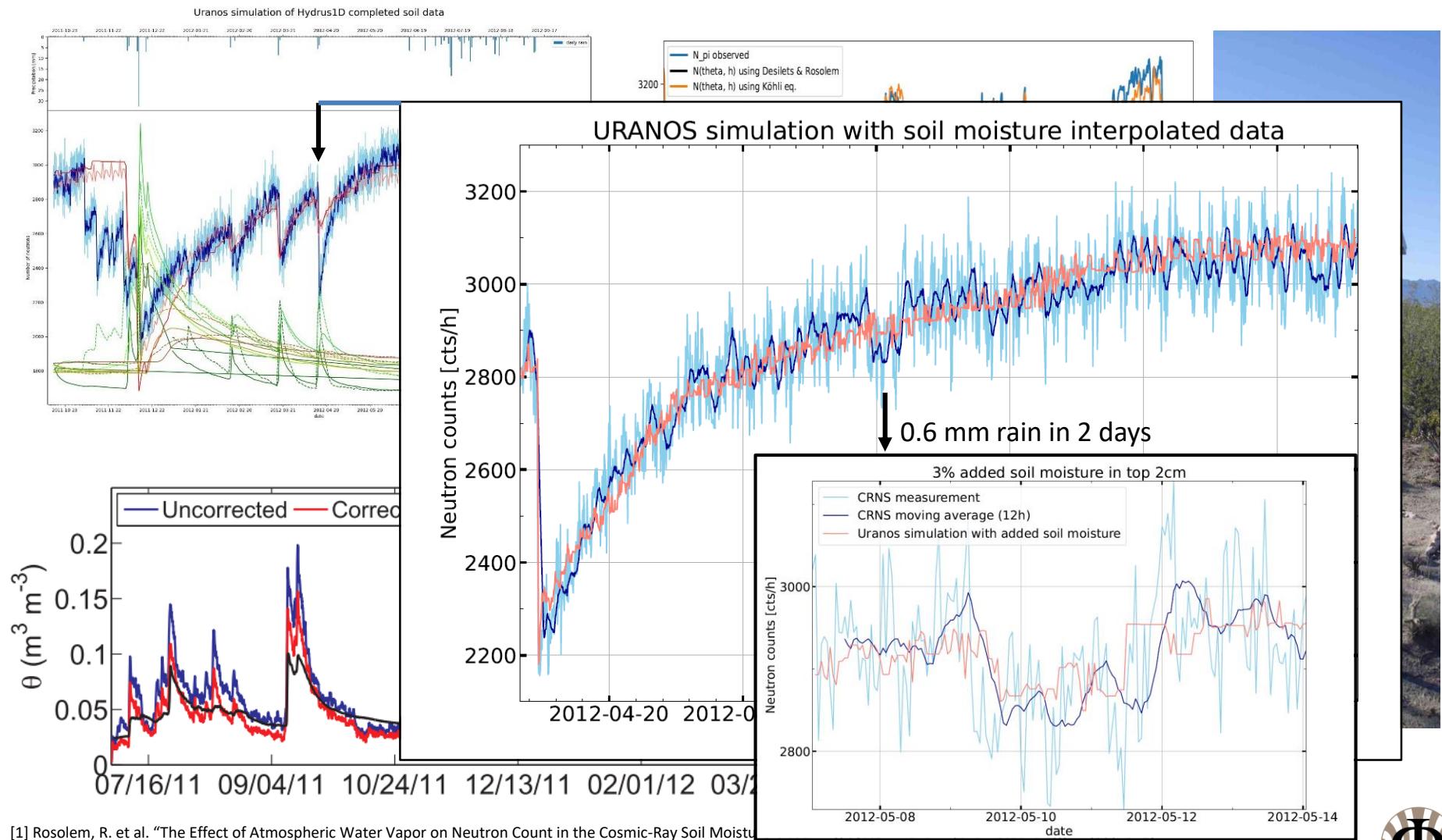
[1] Rosolem, R. et al. "The Effect of Atmospheric Water Vapor on Neutron Count in the Cosmic-Ray Soil Moisture Observing System." J. of Hydrometeorology 14(5) (2013)

# CRNS timeseries Stanta Rita



[1] Rosolem, R. et al. "The Effect of Atmospheric Water Vapor on Neutron Count in the Cosmic-Ray Soil Moisture Observing System." J. of Hydrometeorology 14(5) (2013)

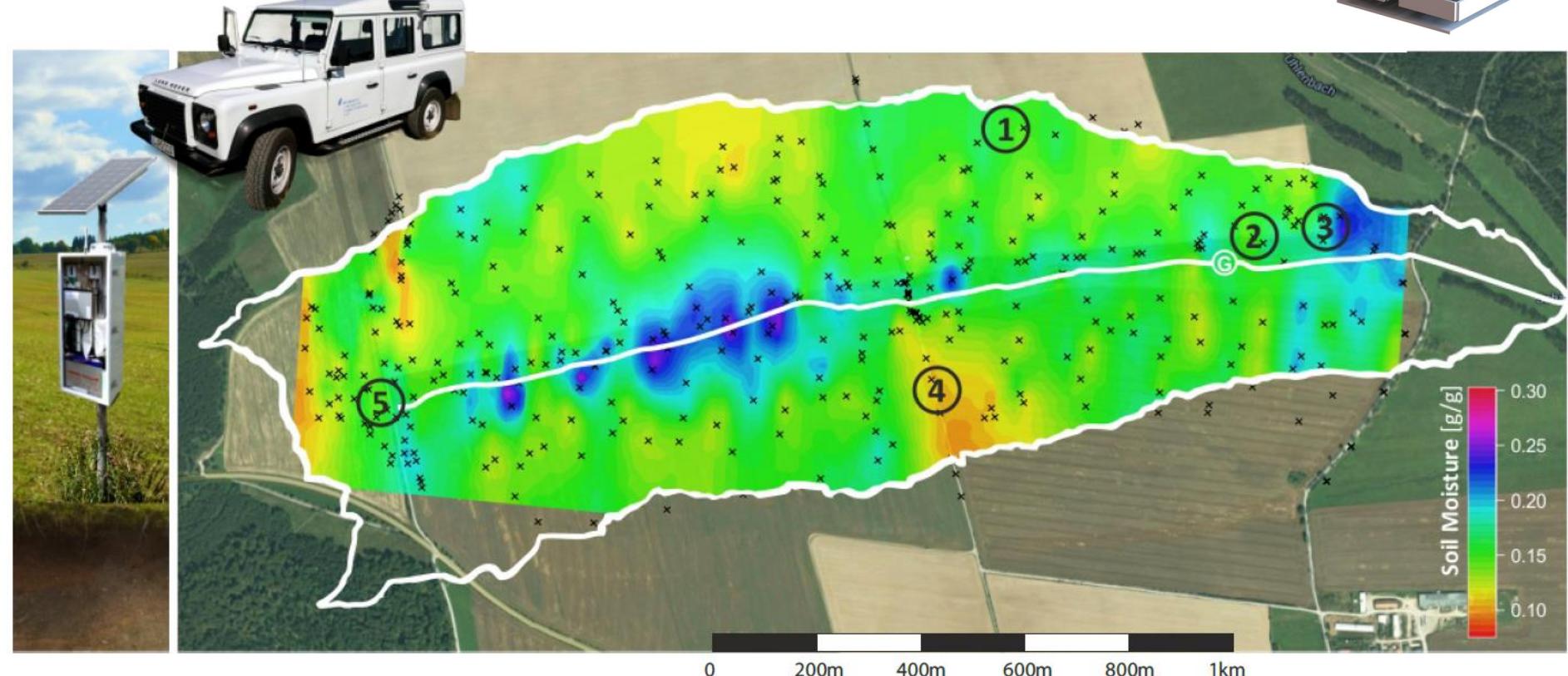
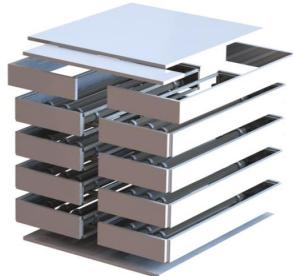
# CRNS timeseries Stanta Rita



[1] Rosolem, R. et al. "The Effect of Atmospheric Water Vapor on Neutron Count in the Cosmic-Ray Soil Moisture Sensor".

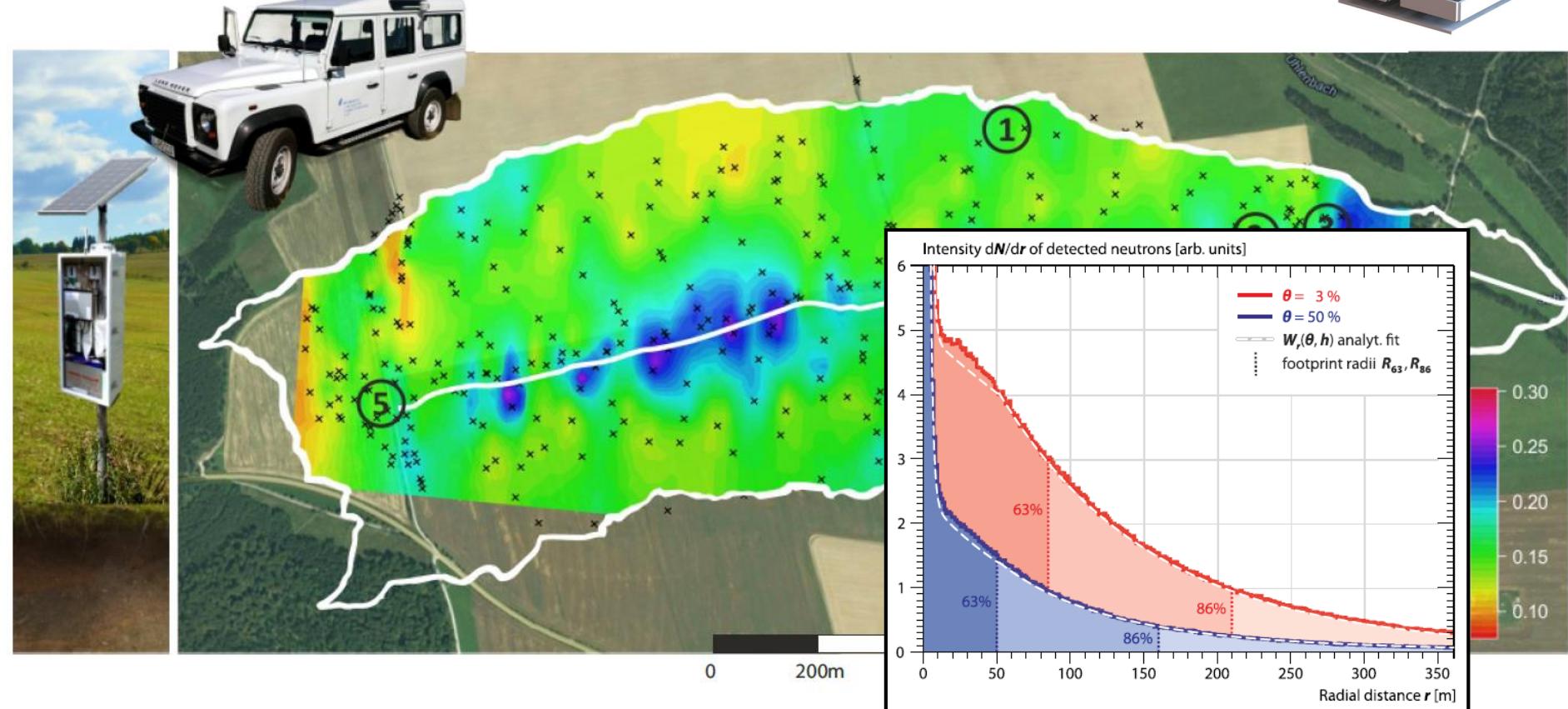
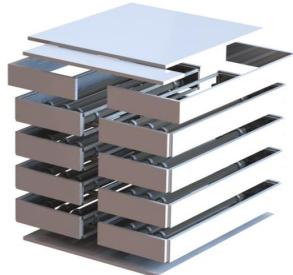
# » Stationary and Roving

In collaboration with Martin Schrön, UFZ Leipzig



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# » Stationary Instruments



Stationary - small



Stationary - large



Roving

# » Tubes and Frontend Electronics



| Type*                          | Costs** | Abs. Eff.*** |
|--------------------------------|---------|--------------|
| $^3\text{He}$                  | 2500 €  | 60 %         |
| $^{10}\text{BF}_3$             | 1500 €  | 20 %         |
| $^{10}\text{B}_4\text{C}$ conv | 1000 €  | 12 %         |

\*Proportional counter tubes examples of different sizes to match similar instrument performances. Commercial tubes He: 2" x 12",  $\text{BF}_3$ : 2" x 30". Conventional sputter-coated  $\text{B}_4\text{C}$  tube 2.3" x 47".

\*\*Costs for a proportional counter, for He mainly the gas filling, for  $\text{BF}_3$  (hazardous) 1000 € for the tube, others 300 €.

\*\*\*thermal neutron absorption efficiency.

# » Tubes and Frontend Electronics



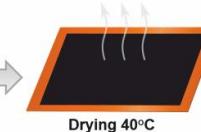
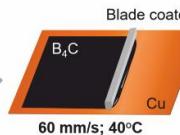
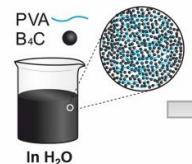
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| <b><math>^6\text{LiF}</math> printed</b>            | 700 €   | 12 %         |
| <b><math>^{10}\text{B}_4\text{C}</math> printed</b> | 400 €   | 11 %         |

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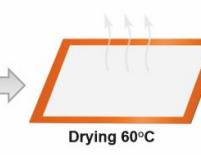
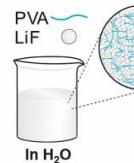
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\*\*\*thermal neutron absorption efficiency.

## Printed neutron converters



## Sample preparation



# » Tubes and Frontend Electronics

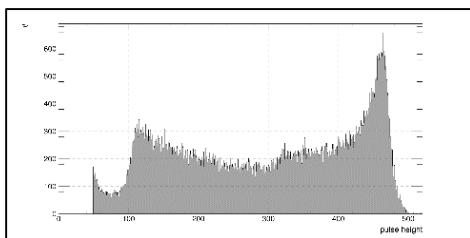
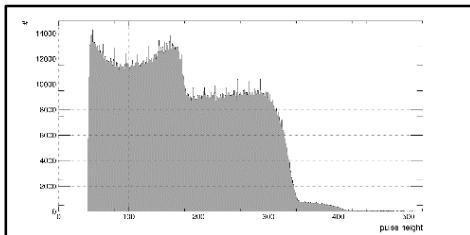


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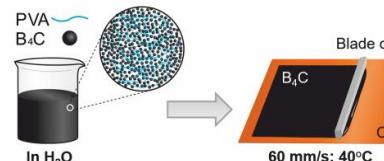
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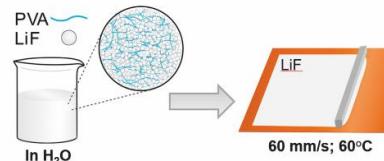
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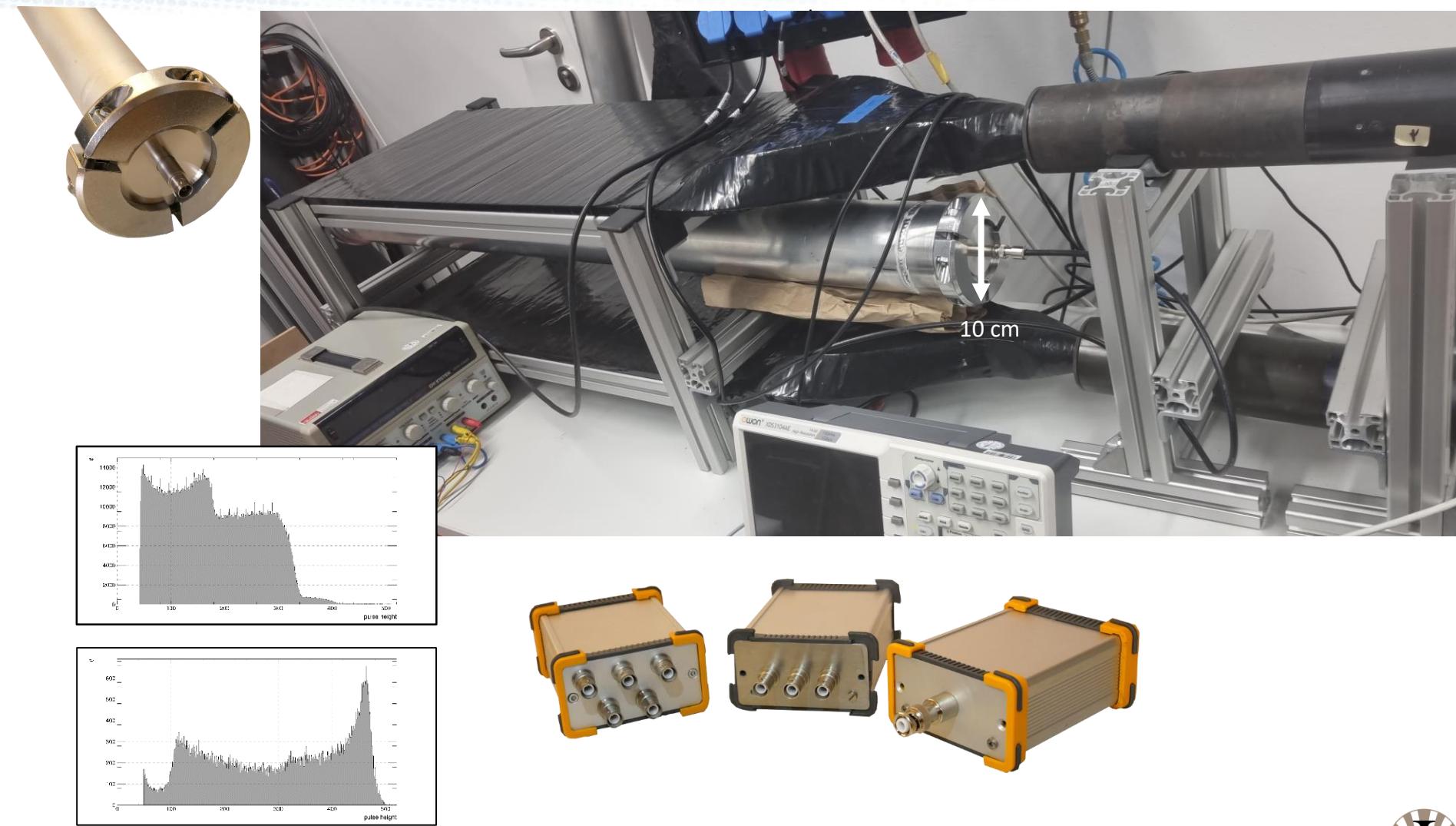
## Printed neutron converters



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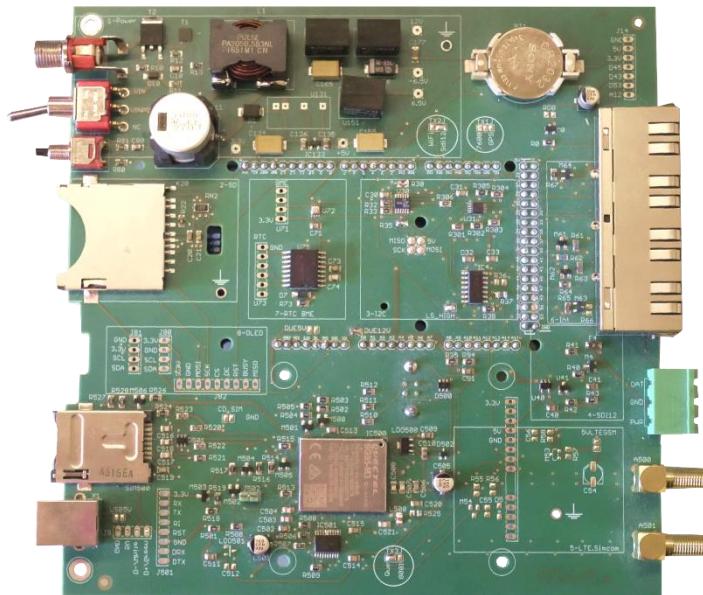
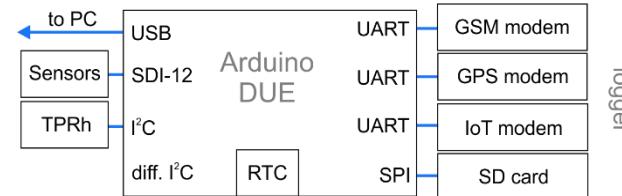
# » Tubes and Frontend Electronics



# » Data Logger

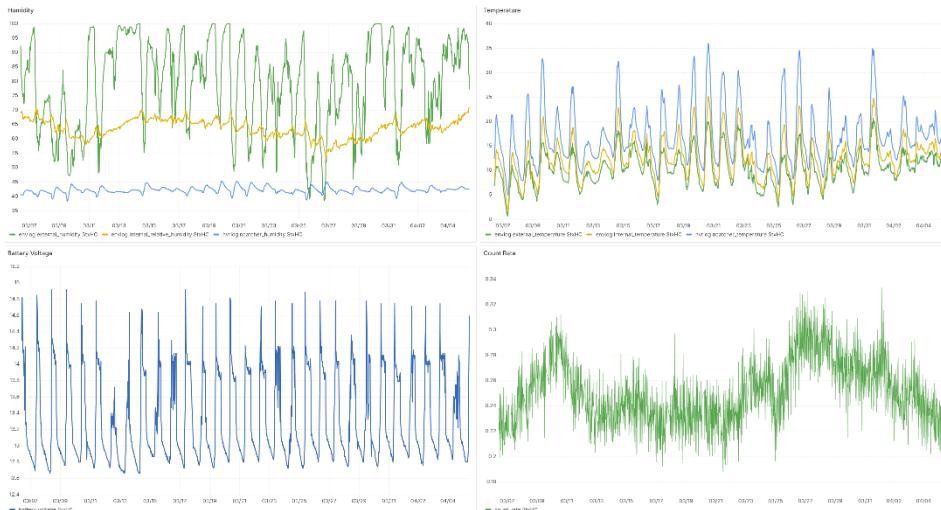


- Low temperature dependence
- Display: RL, p, event info
- High resolution for environmental variables
- Battery/voltage monitoring
- Multi-purpose RJ45 Connector
- SD card
- SDI-12 / RS485 implementation

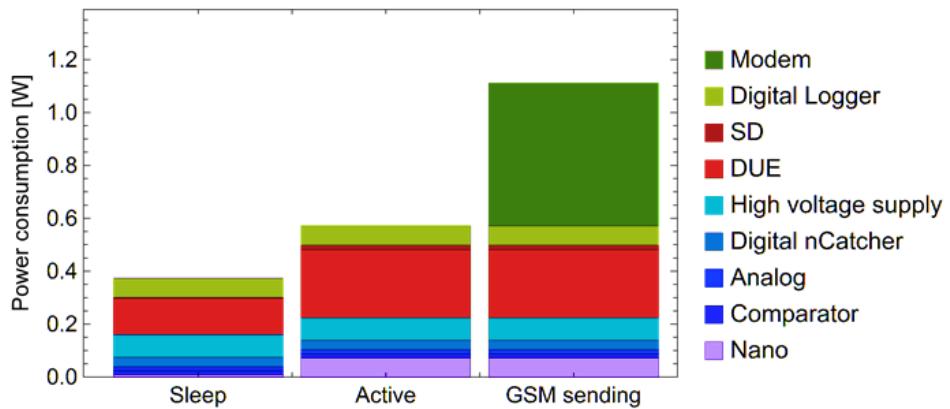


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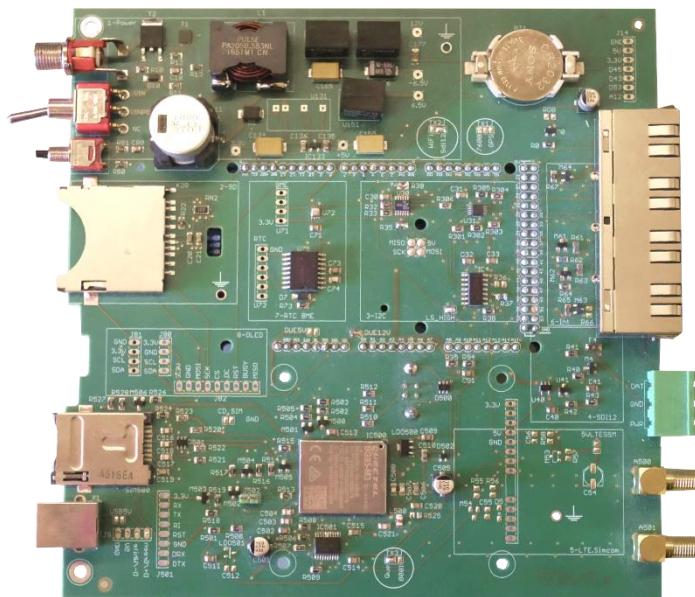
## Real-time data interface



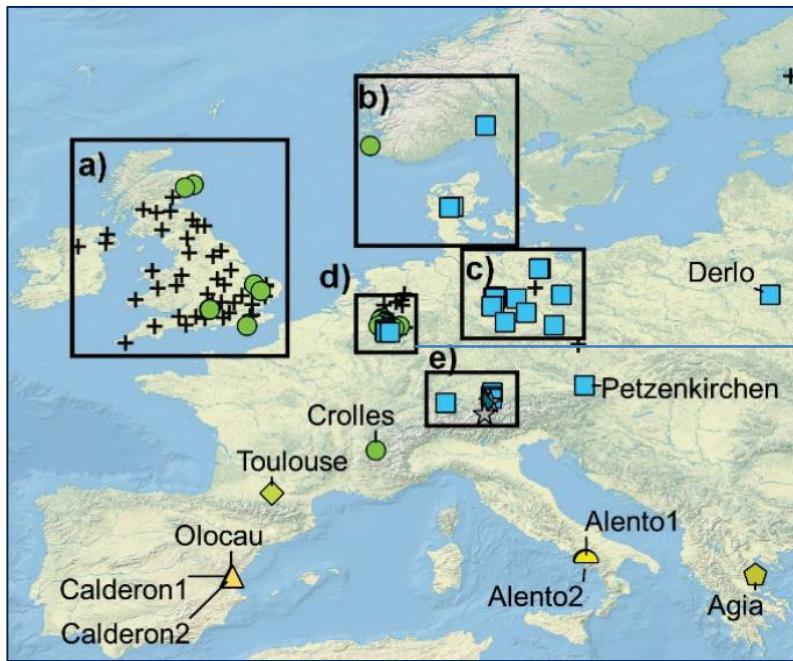
## Power Consumption



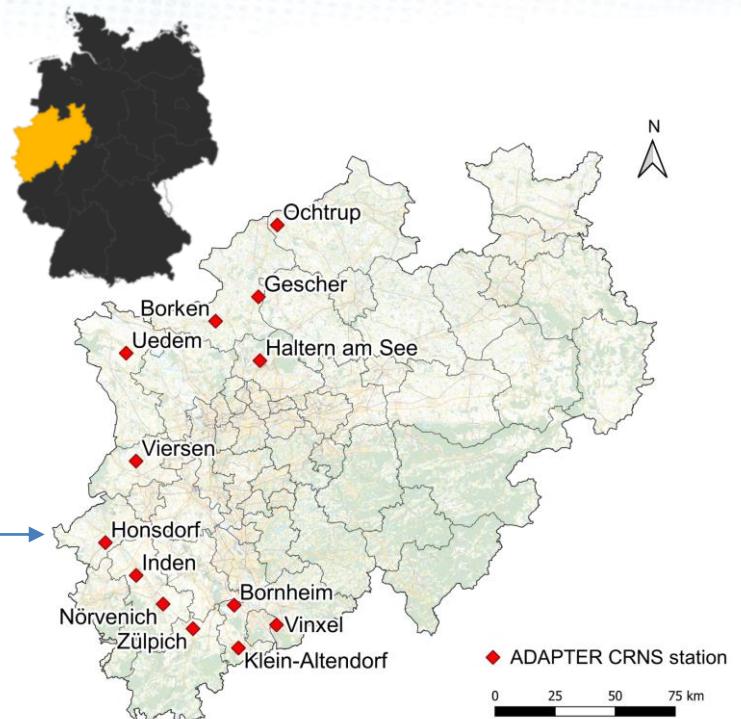
- Low temperature dependence
- Display: RL, p, event info
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- Multi-purpose RJ45 Connector
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- SDI-12 / RS485 implementation



# » CRNS Networks



COSMOS-Europe sites (Bogena 2021, ESSD)



ADAPTER sites (Ney 2021, MetroAgriFor)



# » The ADAPTER Network



Devices with  
NB-IoT modems

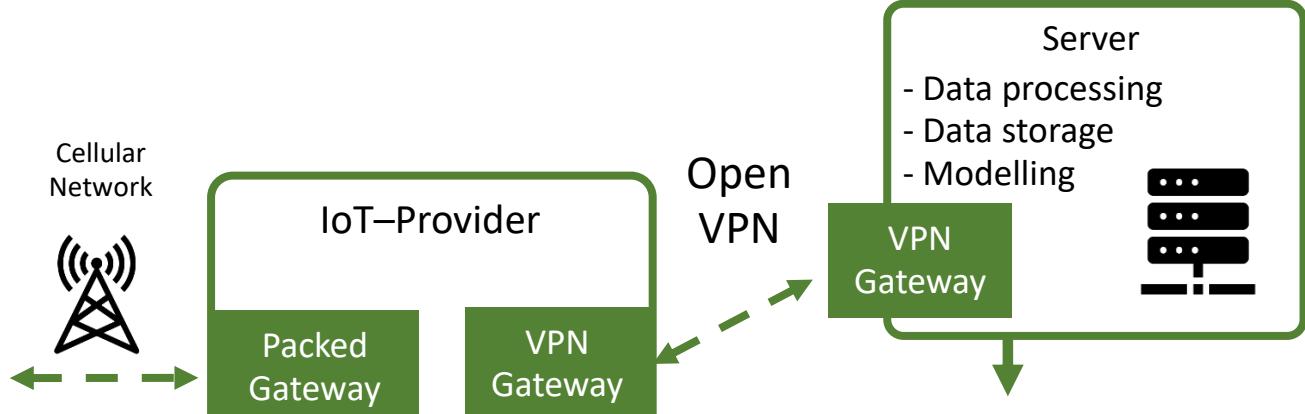


In collaboration with  
Patrizia Ney  
FZ Jülich

Physikalisches Institut, Universität Heidelberg



# » The ADAPTER Network



- ❖ transmission of the observation data via **Narrow Band Internet of Things (NB-IoT)** in near real-time

In collaboration with  
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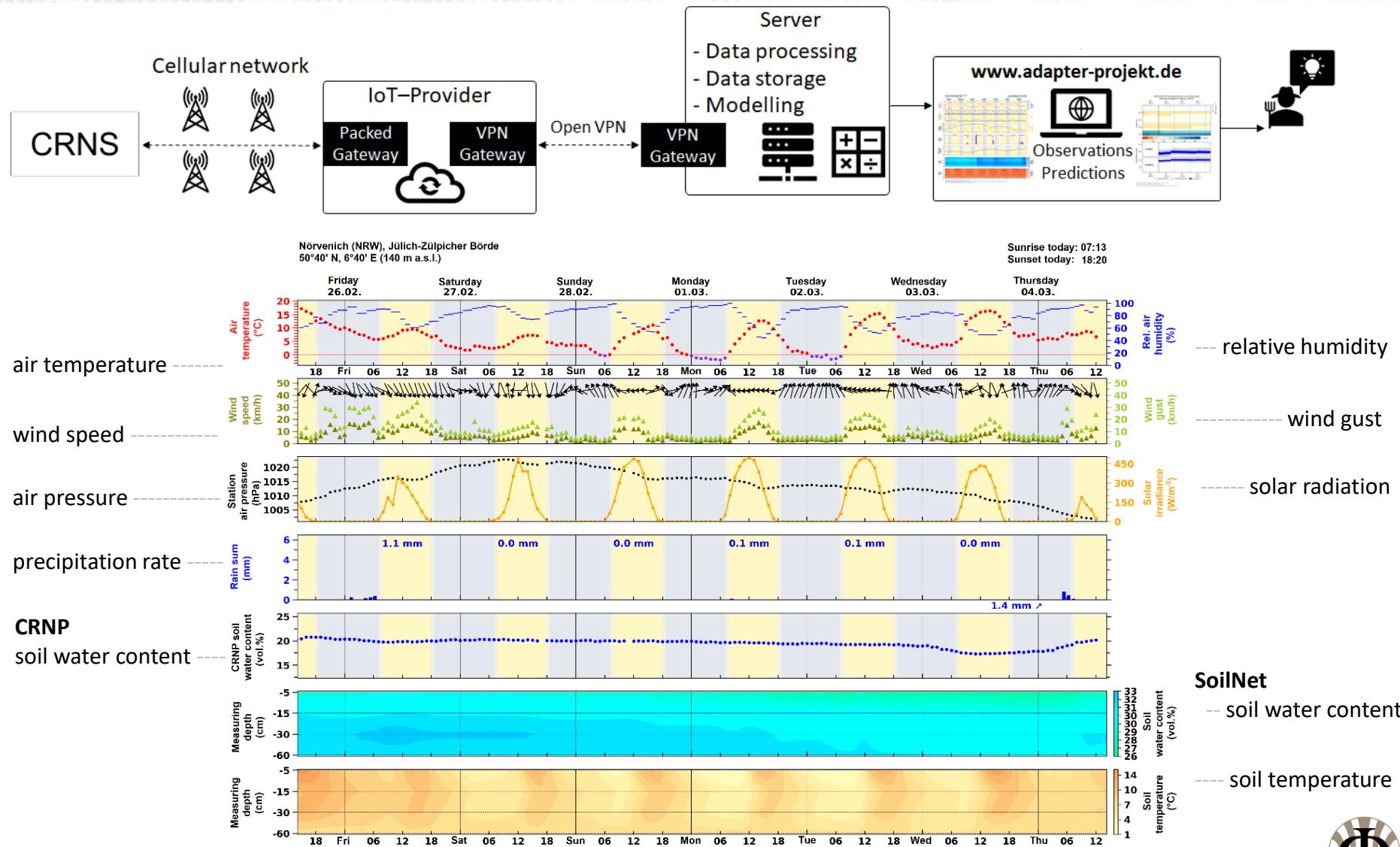
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Patrizia Ney  
FZ Jülich

# Telemetry Integration



# » SOMMET: Standardization



## PROJECT PARTNERS:



**IRSN**  
INSTITUT DE RADIODÉPROTECTION  
ET DE SÉCURITÉ NUCÉAIRE

**Ciemat**  
Centro de Investigaciones  
Energéticas, Medioambientales  
y Tecnológicas



**CZECH METROLOGY INSTITUTE**

**INRIM**  
ISTITUTO NAZIONALE  
DI RICERCA METROLOGICA

Lead WP5

**DANISH TECHNOLOGICAL INSTITUTE**  
Lead WP1

Justervesenet



**Universität**  
Potsdam  
Lead WP2



UK Centre for  
Ecology & Hydrology



ALMA MATER STUDIORUM  
UNIVERSITÀ DI BOLOGNA  
Lead WP3



CTU  
CZECH TECHNICAL  
UNIVERSITY IN PRAGUE



Lead WP4



POLITECNICO  
MILANO 1863



HELMHOLTZ  
Zentrum für Umweltforschung

## IMPACT & SUPPORT:



Agenzia Spaziale Italiana



United Nations  
Educational, Scientific and  
Cultural Organization



International Centre  
for Water Resources and Global Change  
under the auspices of UNESCO



Deutscher Wetterdienst  
Wetter und Klima aus einer Hand



AHDB  
AGRICULTURE & HORTICULTURE  
DEVELOPMENT BOARD



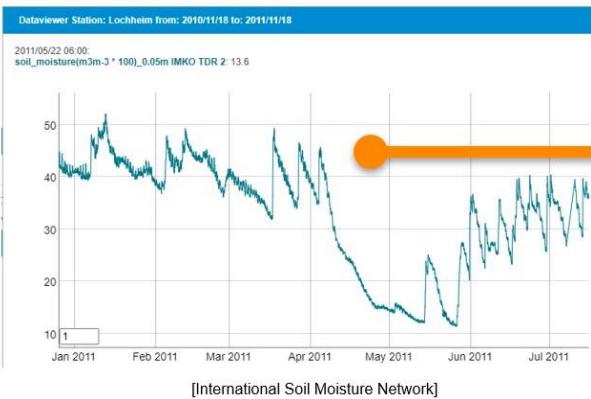
# » Multiple scales of SOMMET

Comparison and harmonization of soil moisture measurement methods at multiple spatial and temporal scales

- Comparison of methods, their constraints and different spatial and temporal characteristics
- Development of an approach to harmonize point scale, field scale and remote sensing

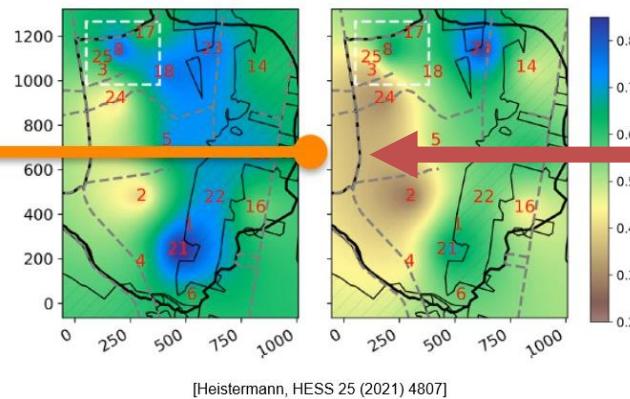
## Point-scale *in situ* measurements

Example: Time series of a single sensor



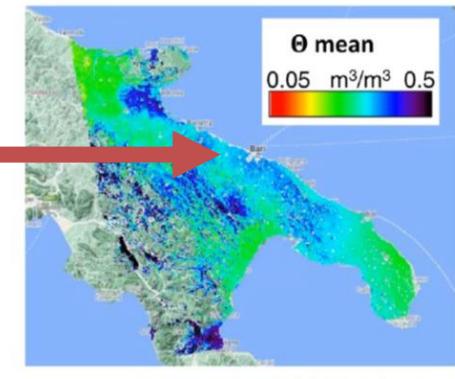
## Cosmic-ray neutron sensing

Example: Daily average soil moisture at catchment scale



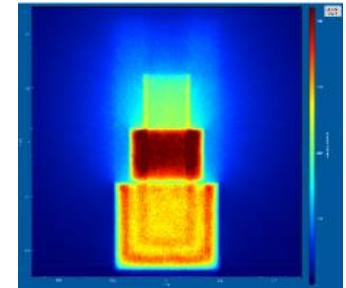
## Satellite remote sensing

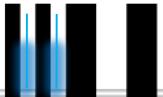
Example: Sentinel-1 surface soil volumetric water content product



# » SI-traceable measurements

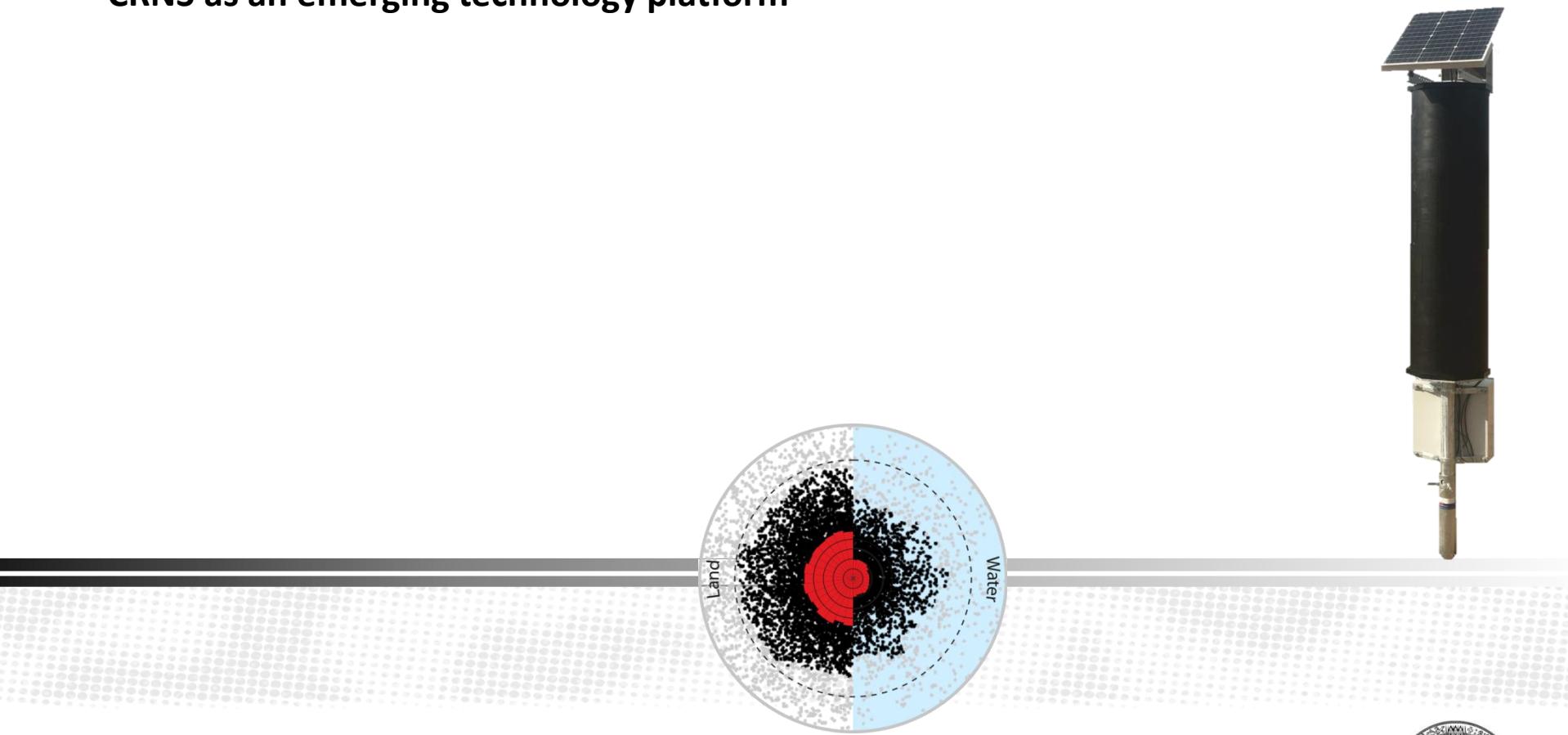
- Calibration facilities for point scale sensors
- Primary measurement methods and transfer standards
- Provide a traceability scheme to CRNS





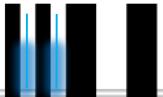
# Pathways to CRNS: evolving detectors and neutron modeling

CRNS as an emerging technology platform



Physikalisches Institut  
Heidelberg University  
Germany

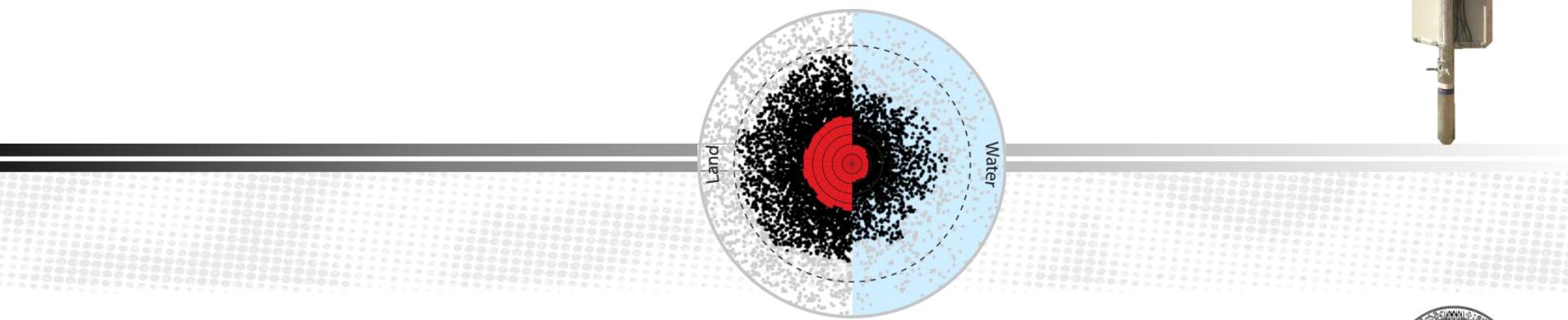


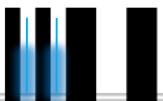


# Pathways to CRNS: evolving detectors and neutron modeling

## CRNS as an emerging technology platform

- Independent modeling and simulation results

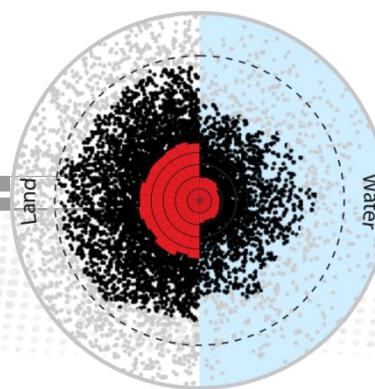


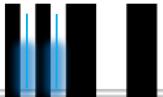


# Pathways to CRNS: evolving detectors and neutron modeling

## CRNS as an emerging technology platform

- Independent modeling and simulation results
- Solutions for detection systems
  - Independent, non-invasive sensor operation and low maintenance

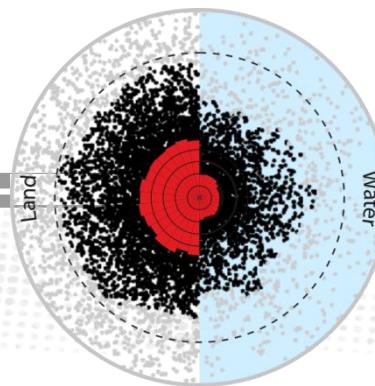




# Pathways to CRNS: evolving detectors and neutron modeling

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- Different Networks (COSMOS, UK, EU, Germany) - different telemetry solutions (IoT-Integration / LTE / LoRa)



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- SOMMET (PTB): SI-traceable standardization of soil moisture measurements

