D-A-CH Conference
26.06.2025
17.2

Soil moisture measurements on the intermediate scale between Remote Sensing products and point probes: Cosmic-Ray Neutron Sensing

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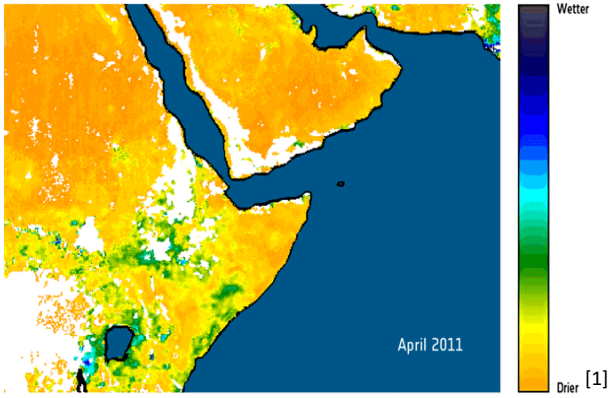
[4]Helmholtz-Centre for Environmental Research – UFZ, Leipzig, Germany

Physikalisches Institut
Heidelberg University
Germany

Soil Moisture Measurement Gap

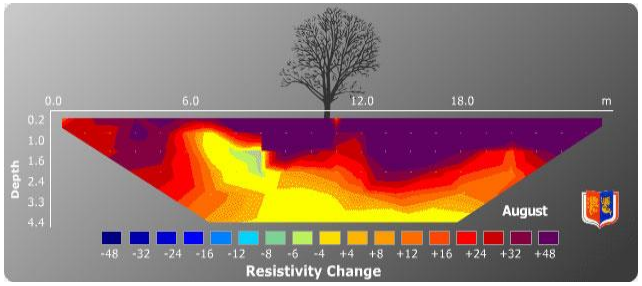
~ 1 km



[1]

via
satellite remote sensing
(optical, microwave)

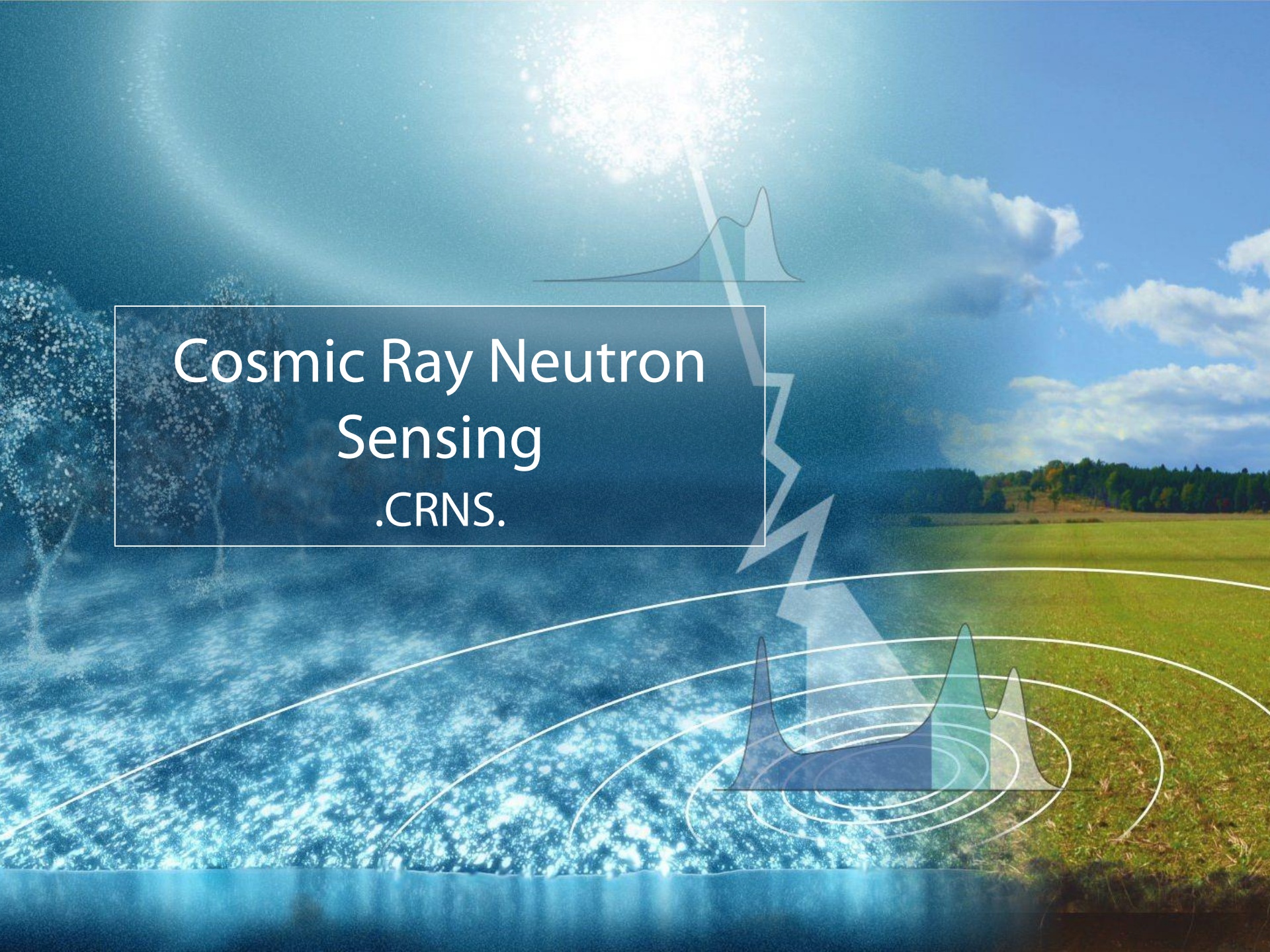
< 10 m



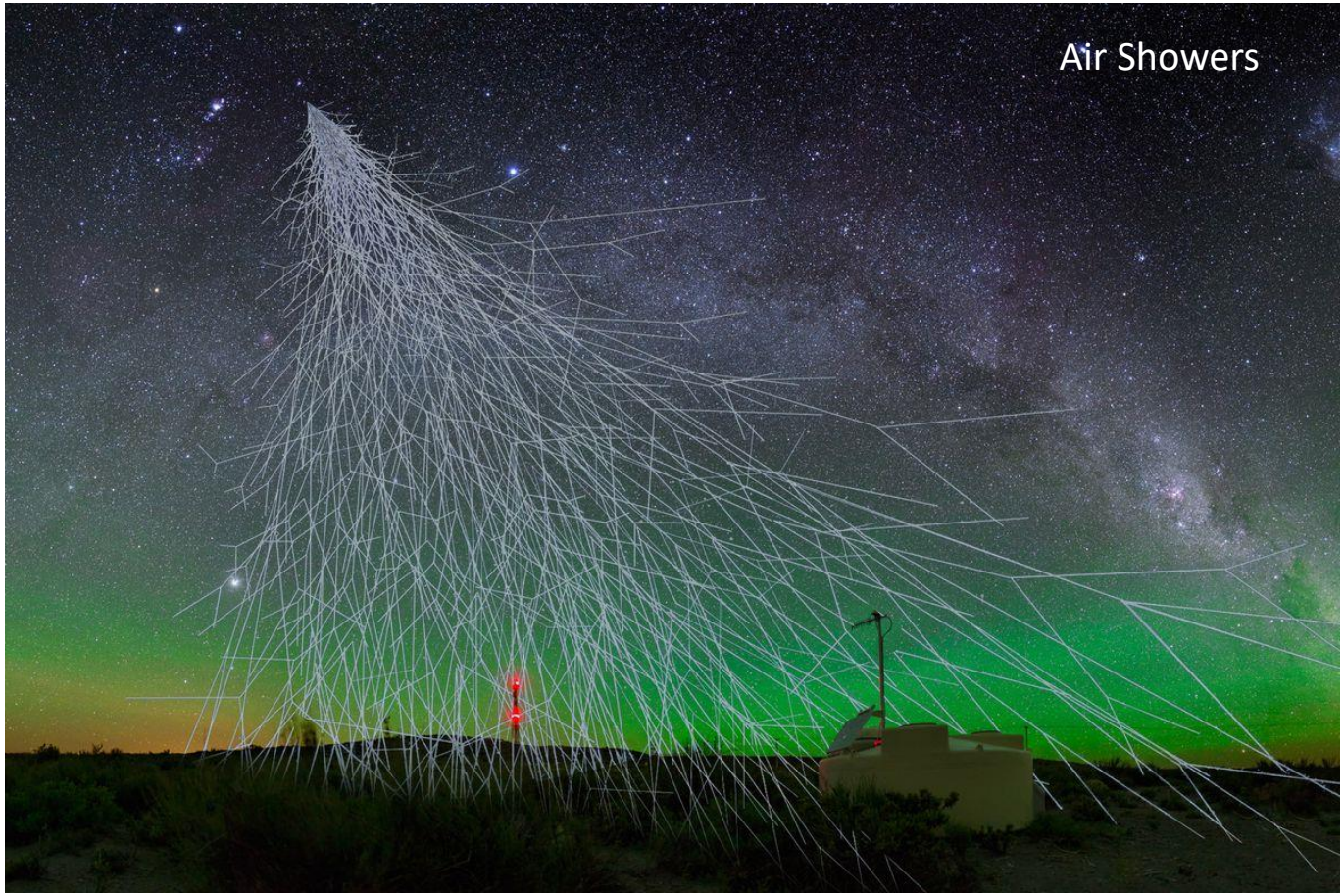
[2]

via
local techniques
(electrical resistivity, capacitance, etc)
(even neutrons…)

[1] ESA SMOS (http://www.esa.int/Our_Activities/Observing_the_Earth/SMOS/Horn_of_Africa_drought_seen_from_space)
[2] The Clay Research Group (http://www.theclayresearchgroup.org/images/ert.jpg)


Cosmic Ray Neutron Sensing
.CRNS.

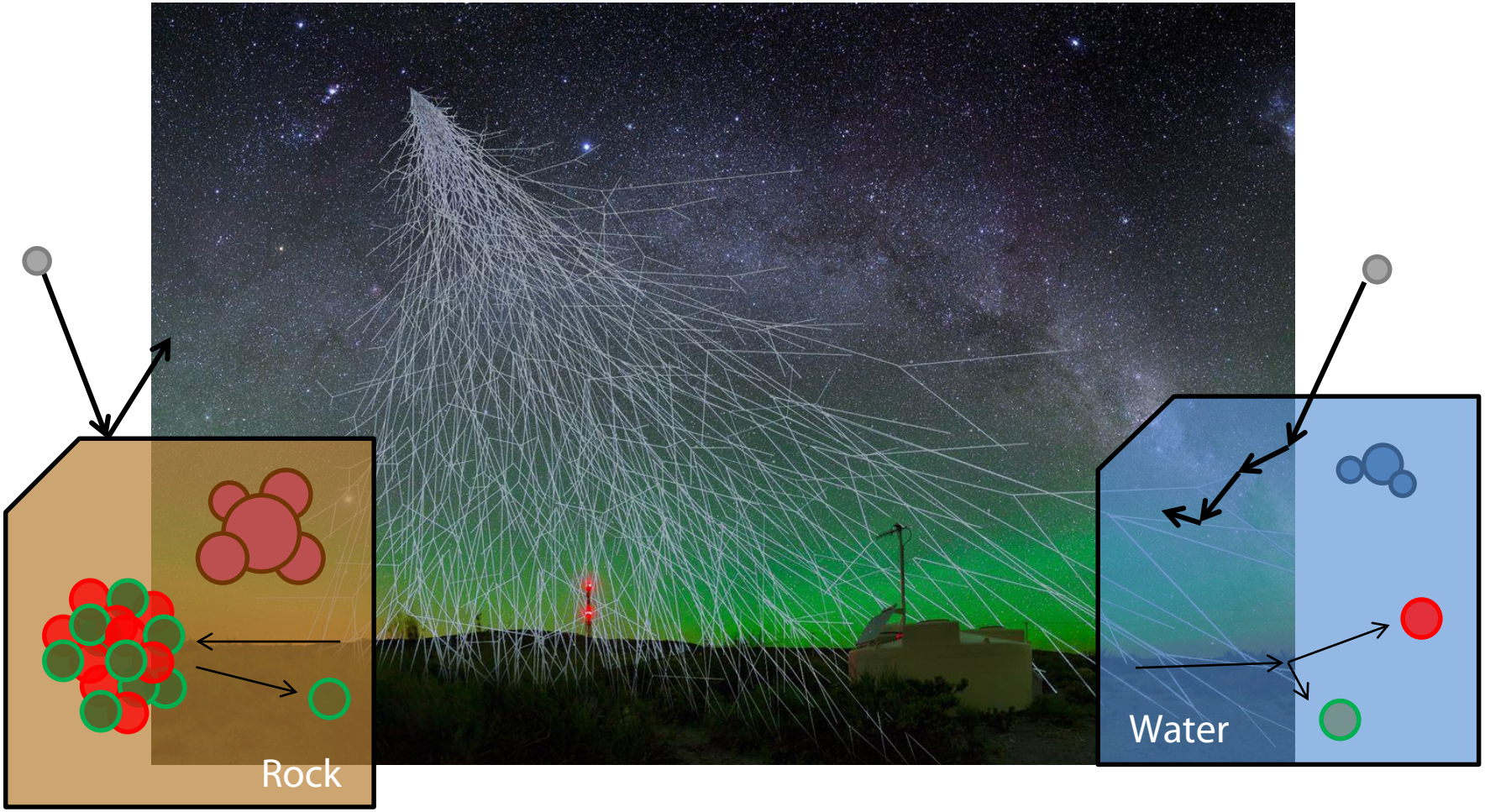
Cosmic Neutron Basics



[1]

[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

Neutron interaction with water



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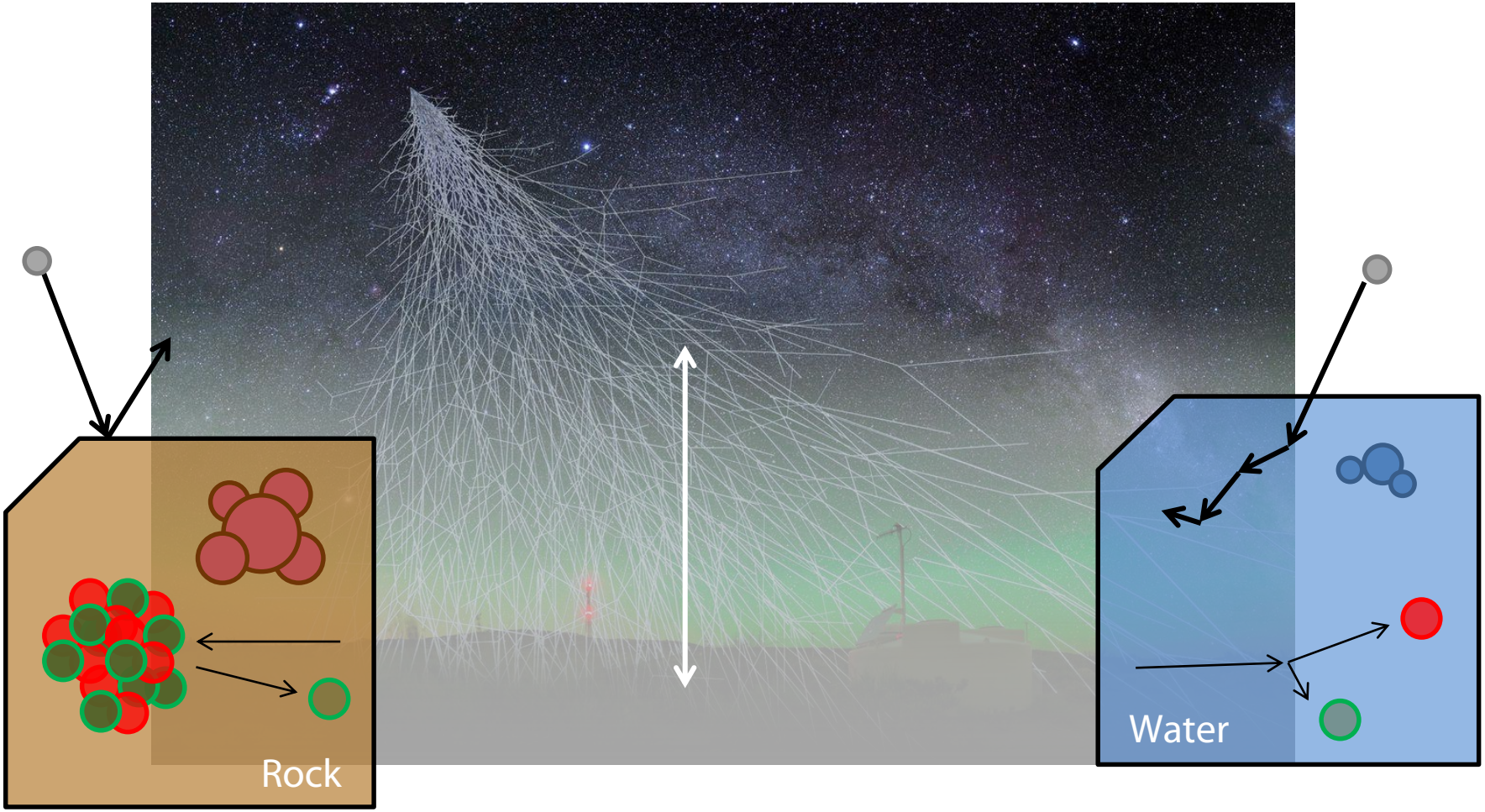
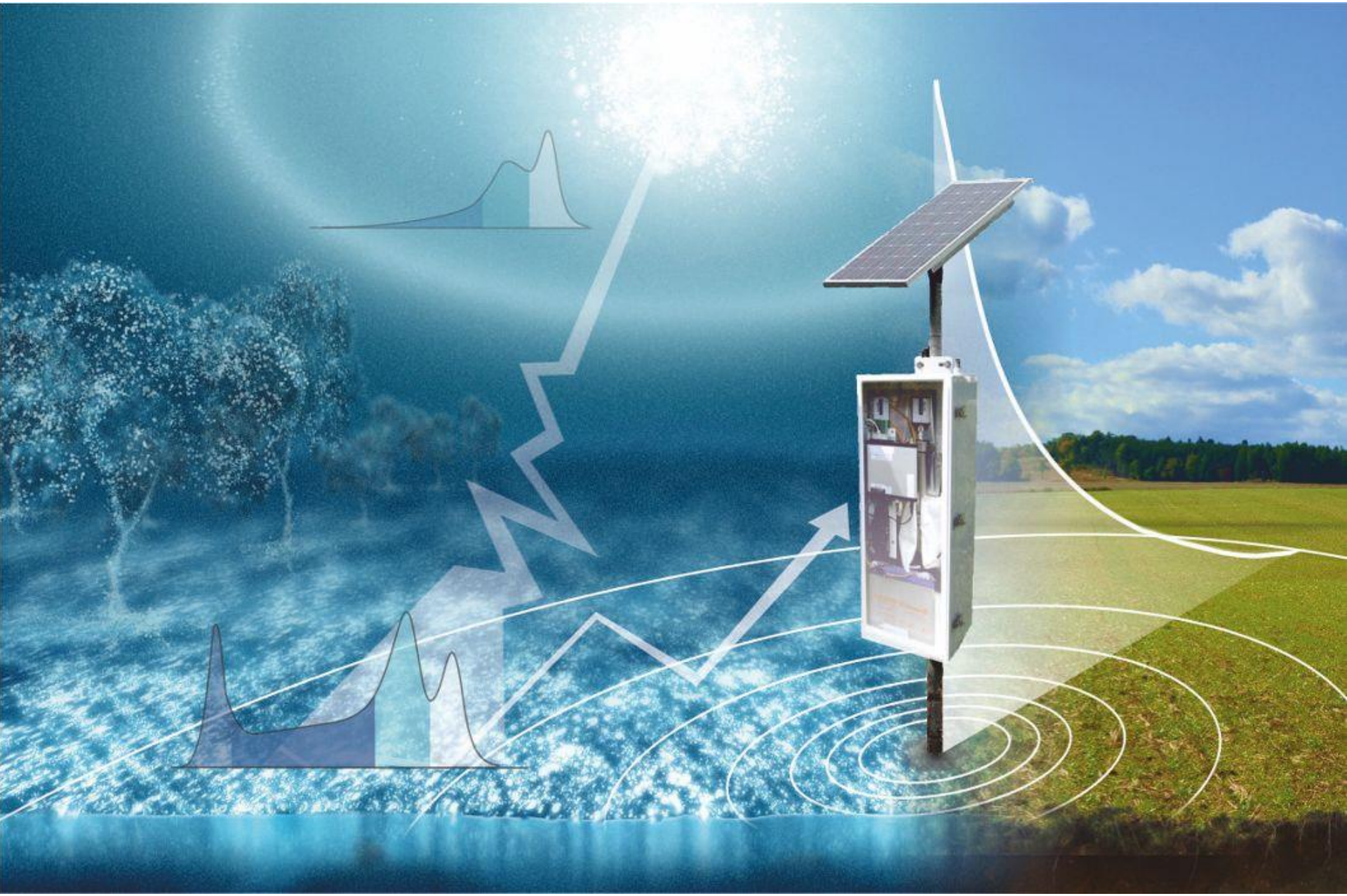
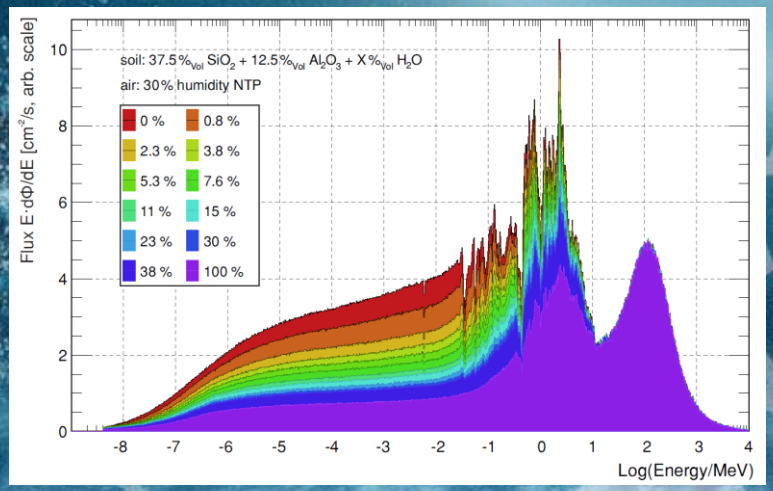
Neutron interaction with water



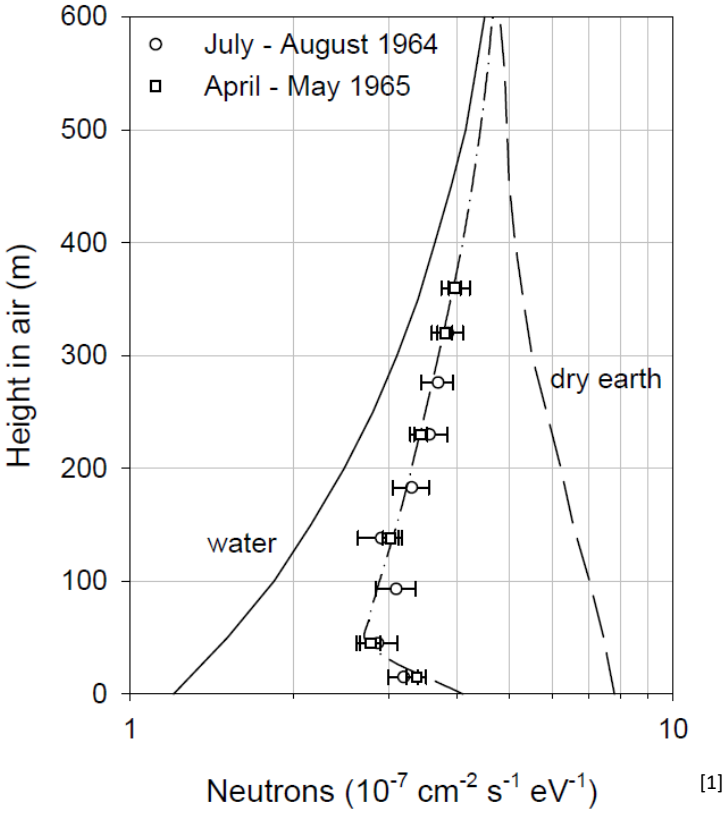
[1] Image by A. Chantelauze, S. Staffi, and L. Bret, https://www.theverge.com/2017/9/21/16335164/pierre-auger-observatory-cosmic-ray-galaxies-air-shower-particles




soil: 37.5%Vol SiO2 + 12.5%Vol Al2O3 + X%Vol H2O
air: 30% humidity NTP
0 %
0.8 %
2.3 %
3.8 %
5.3 %
7.6 %
11 %
15 %
23 %
30 %
38 %
100 %
Flux E·dΦ/dE [cm⁻²/s, arb. scale]
Log(Energy/MeV)

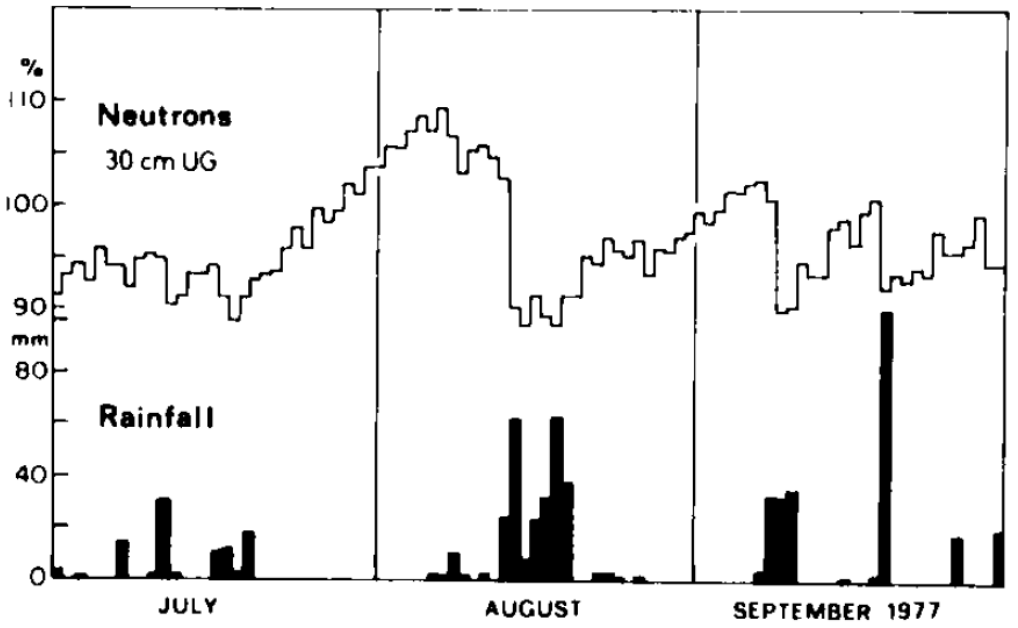
The Historical Channel

1966



[1]

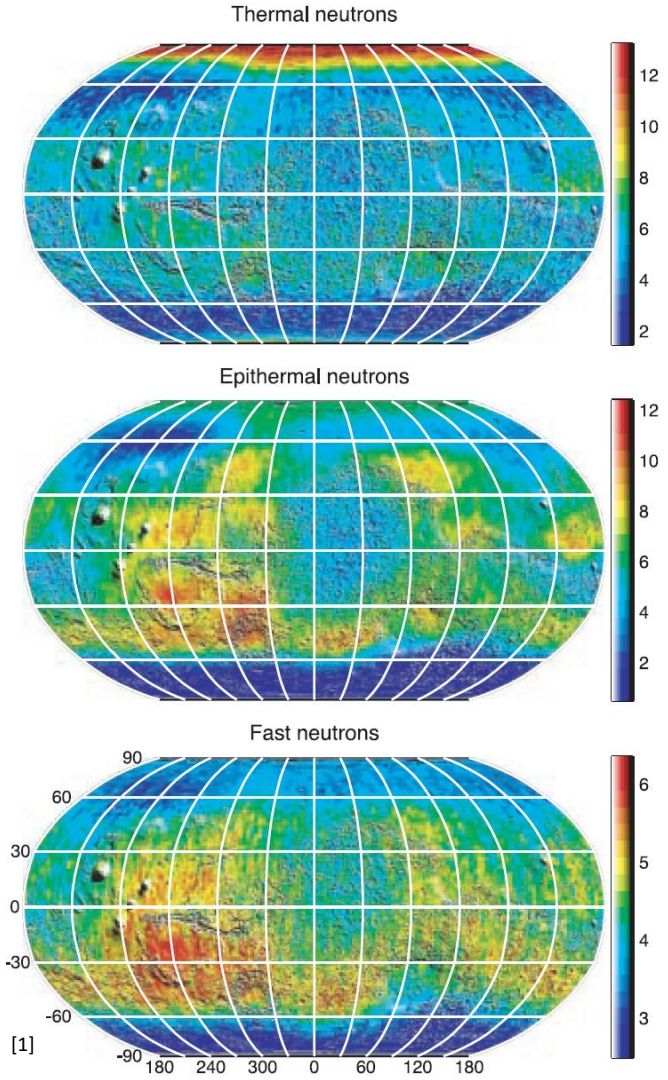
1985



[2]

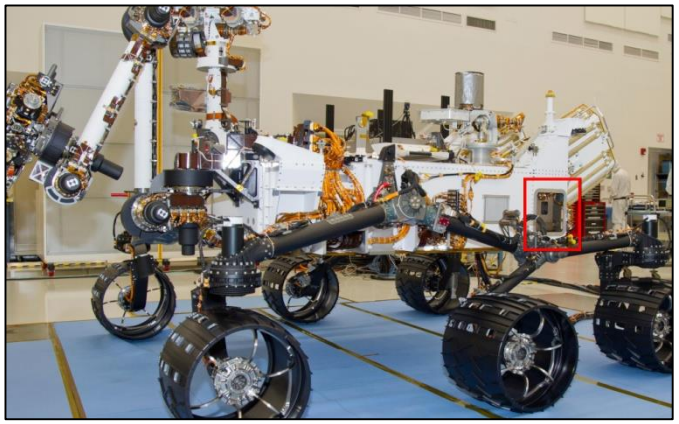
[1] Hendrick, L. D. and Edge, R. D., "Cosmic-ray neutrons near the Earth", Phys. Rev. Ser. II, 145 (1966)
[2] Kodama, M. et al., "Application of atmospheric neutrons to soil moisture measurement", Soil Sci., 140 (1985)

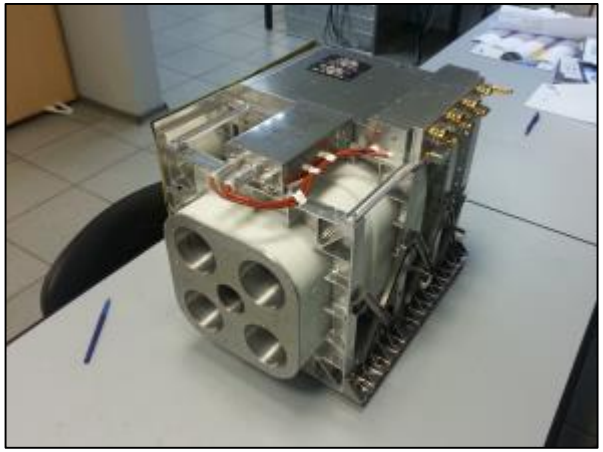
Water on Mars



[1]

Curiosity Rover





[2]

Trace Gas Orbiter

[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

Stationary Instruments

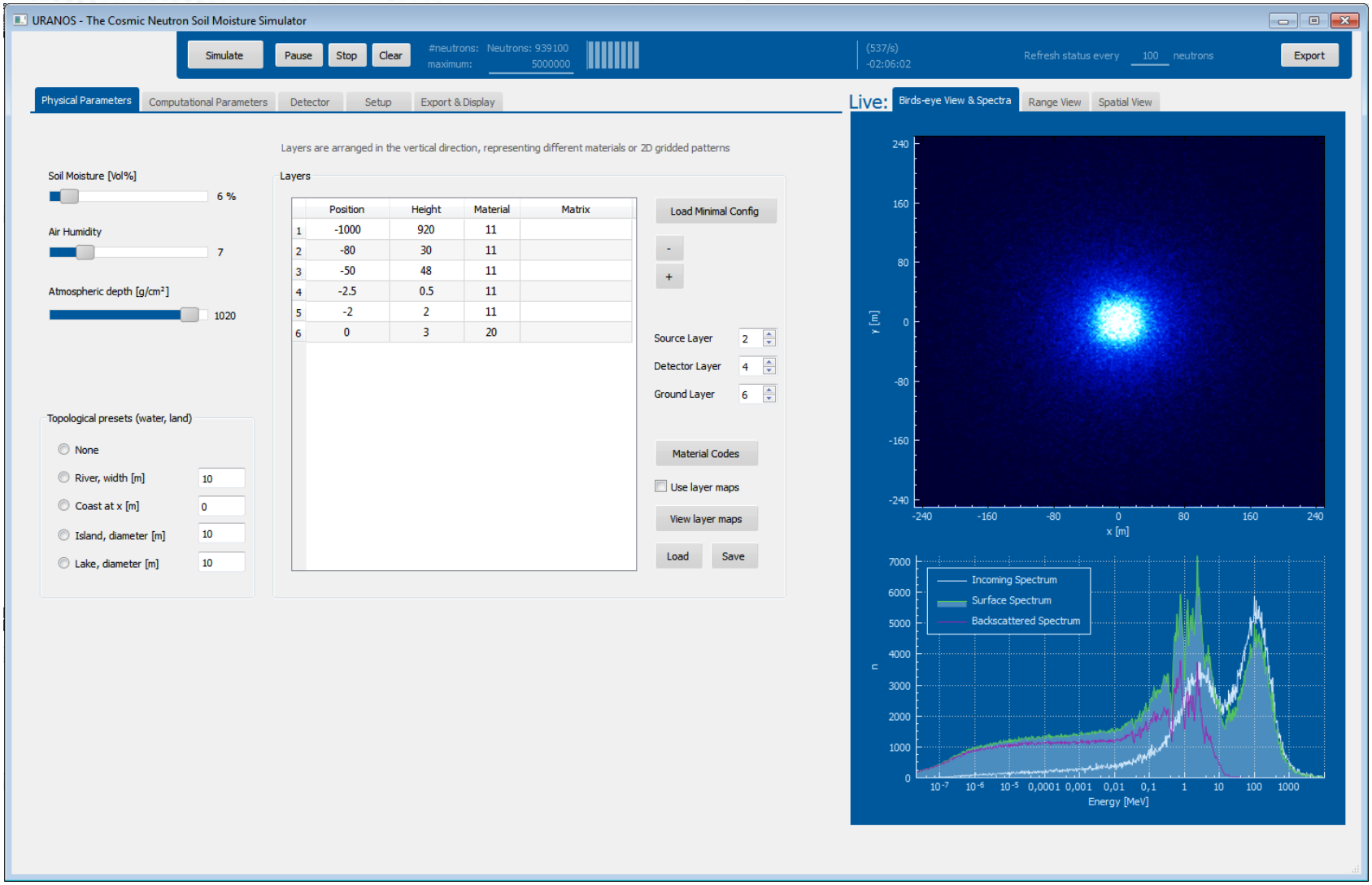
StyX Neutronica SP

Hydroinnova CRS1000

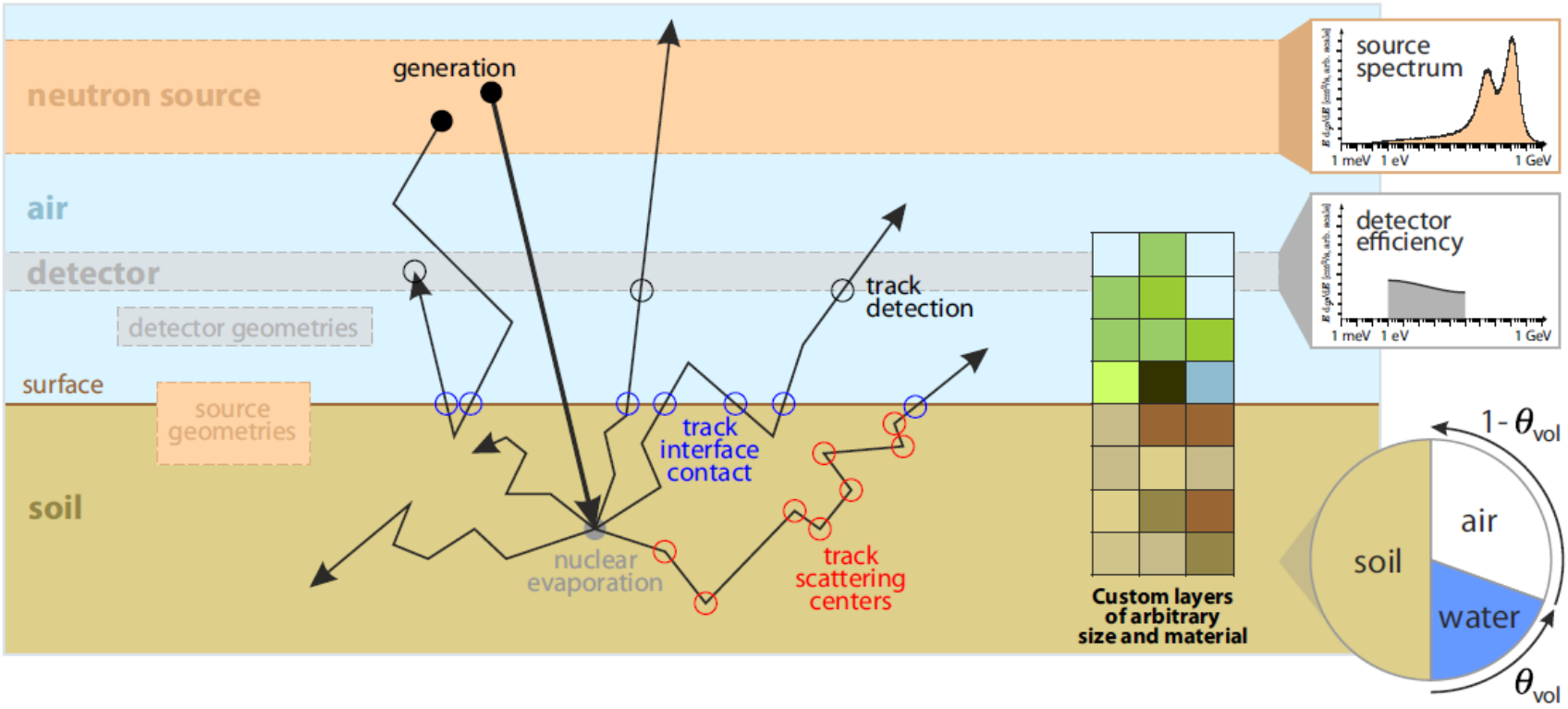
Finapp 3

StyX Neutronica S1

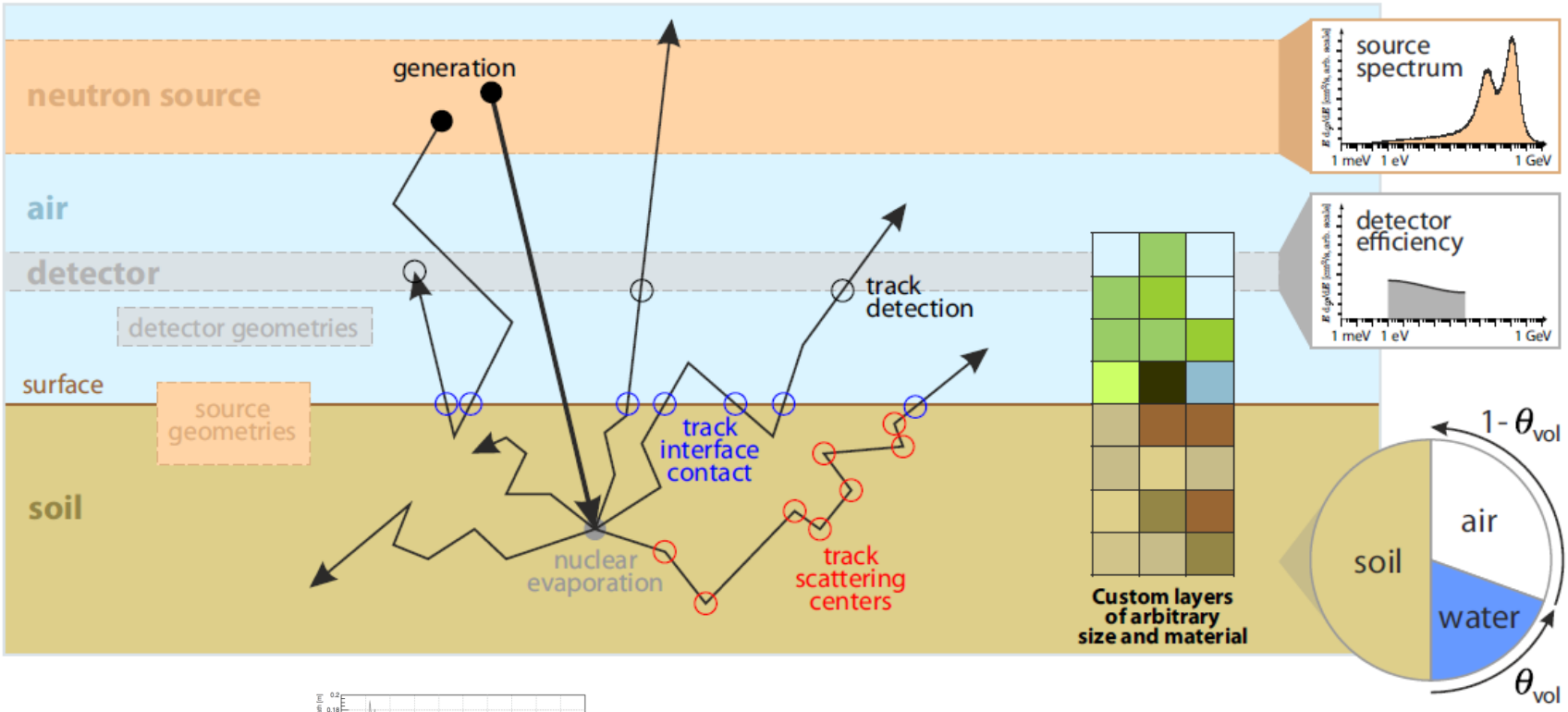
URANOS

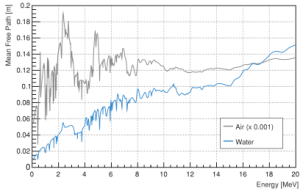

URANOS - The Cosmic Neutron Soil Moisture Simulator
Simulate
Pause
Stop
Clear
#neutrons: Neutrons: 939100
maximum: 5000000
(537/s)
-02:06:02
Refresh status every 100 neutrons
Export
Physical Parameters
Computational Parameters
Detector
Setup
Export & Display
Layers are arranged in the vertical direction, representing different materials or 2D gridded patterns
Soil Moisture [Vol%]
6 %
Air Humidity
7
Atmospheric depth [g/cm²]
1020
Topological presets (water, land)
None
River, width [m] 10
Coast at x [m] 0
Island, diameter [m] 10
Lake, diameter [m] 10
Layers
Position Height Material Matrix
1 -1000 920 11
2 -80 30 11
3 -50 48 11
4 -2.5 0.5 11
5 -2 2 11
6 0 3 20
Load Minimal Config
-
+
Source Layer 2
Detector Layer 4
Ground Layer 6
Material Codes
Use layer maps
View layer maps
Load
Save
Live:
Birds-eye View & Spectra
Range View
Spatial View
y [m]
x [m]
n
Incoming Spectrum
Surface Spectrum
Backscattered Spectrum
Energy [MeV]

URANOS Buildup



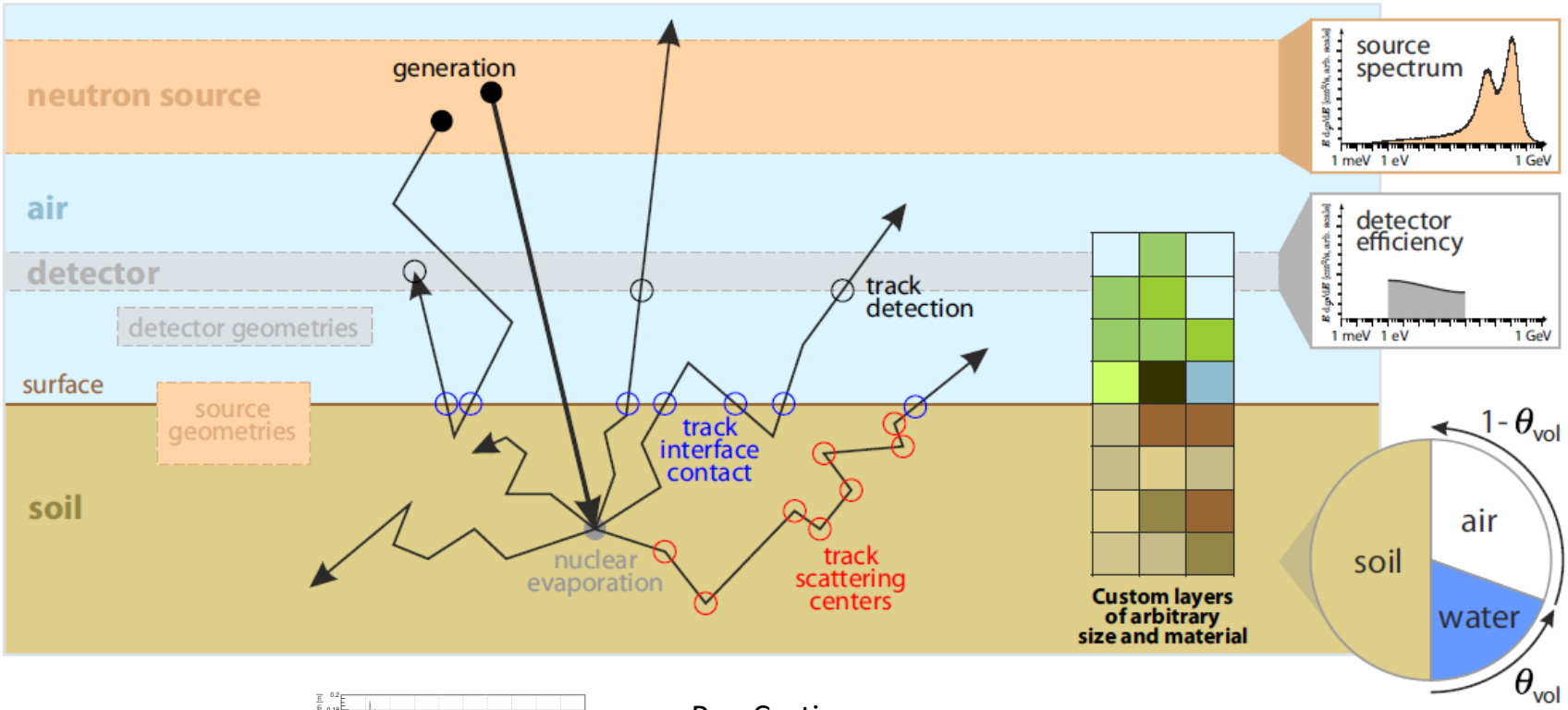
URANOS Buildup



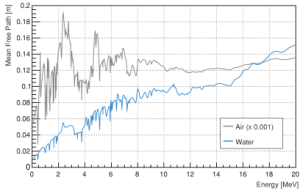


- written in C++
- linked against ENDF data bases

URANOS Buildup

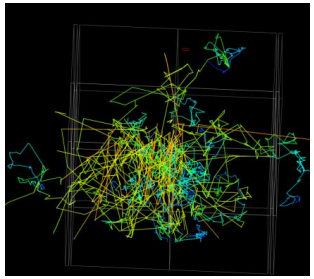


- written in C++

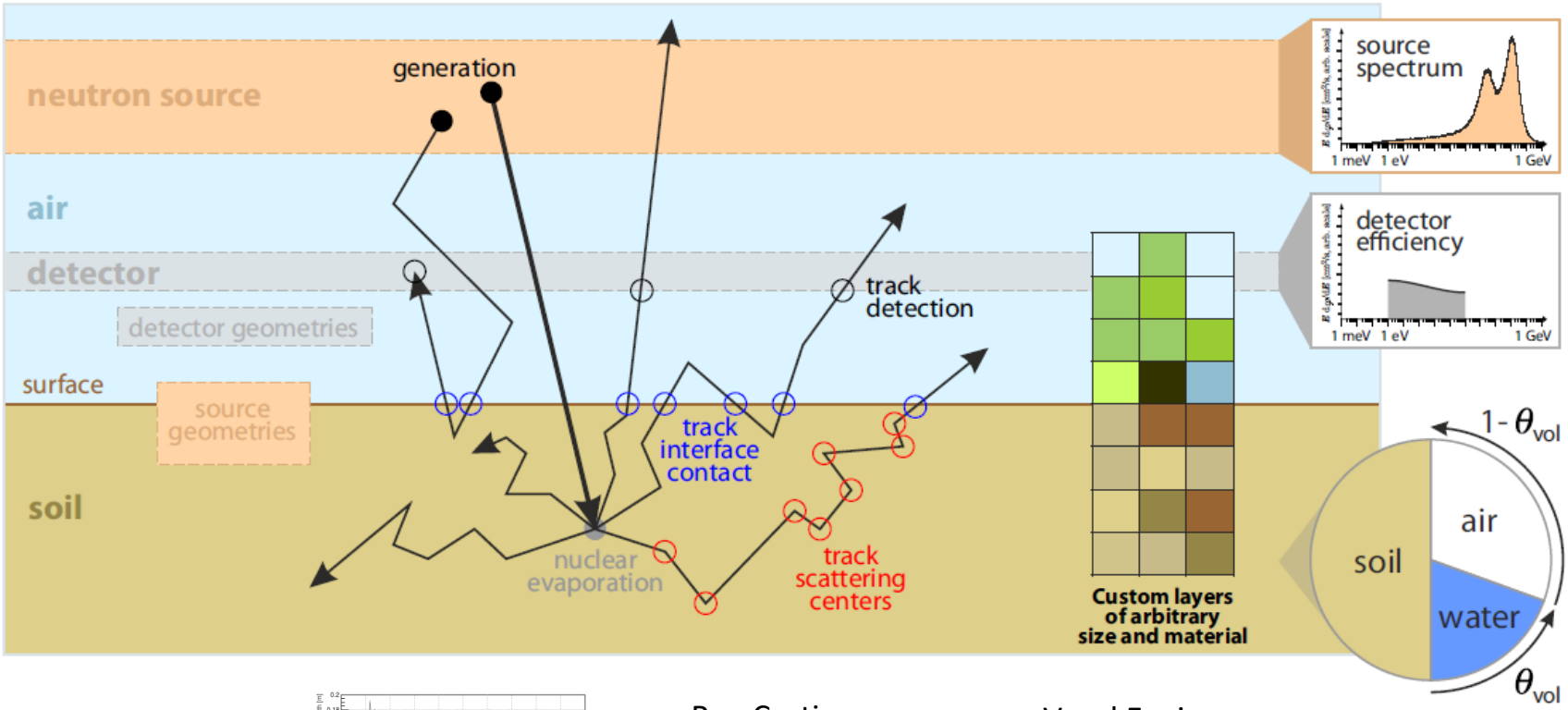


- linked against ENDF data bases

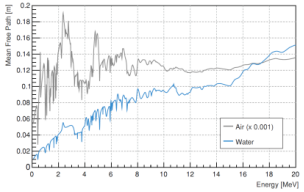
- Ray-Casting



URANOS Buildup

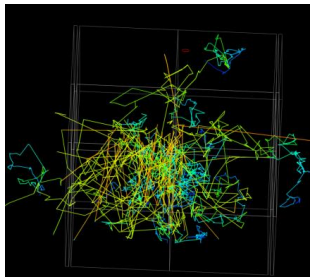


- written in C++

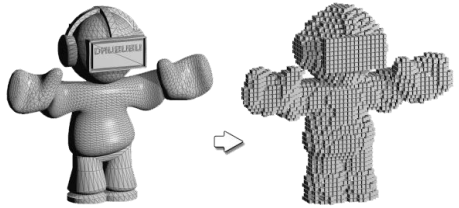


- linked against ENDF data bases

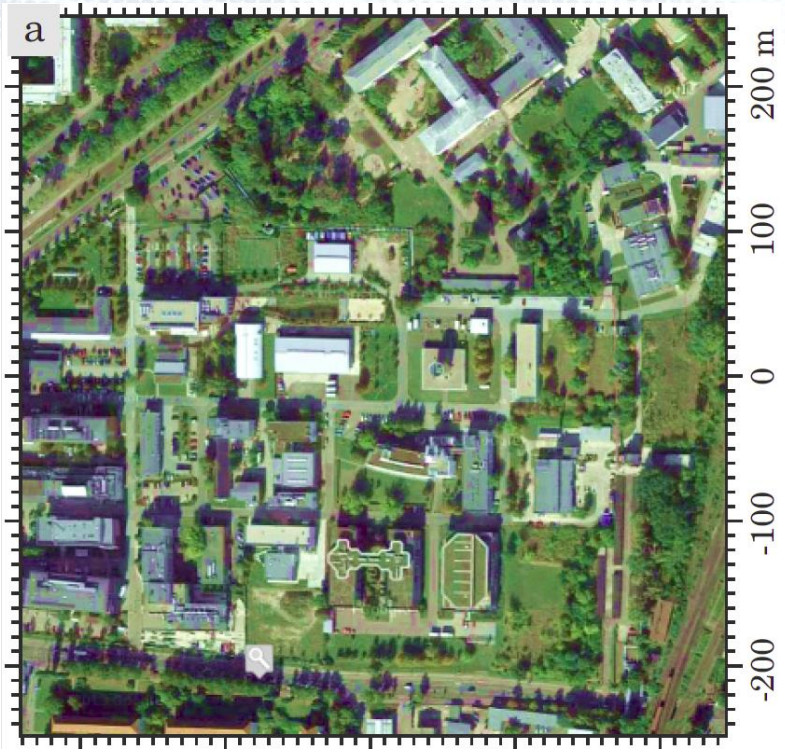
- Ray-Casting



- Voxel Engine

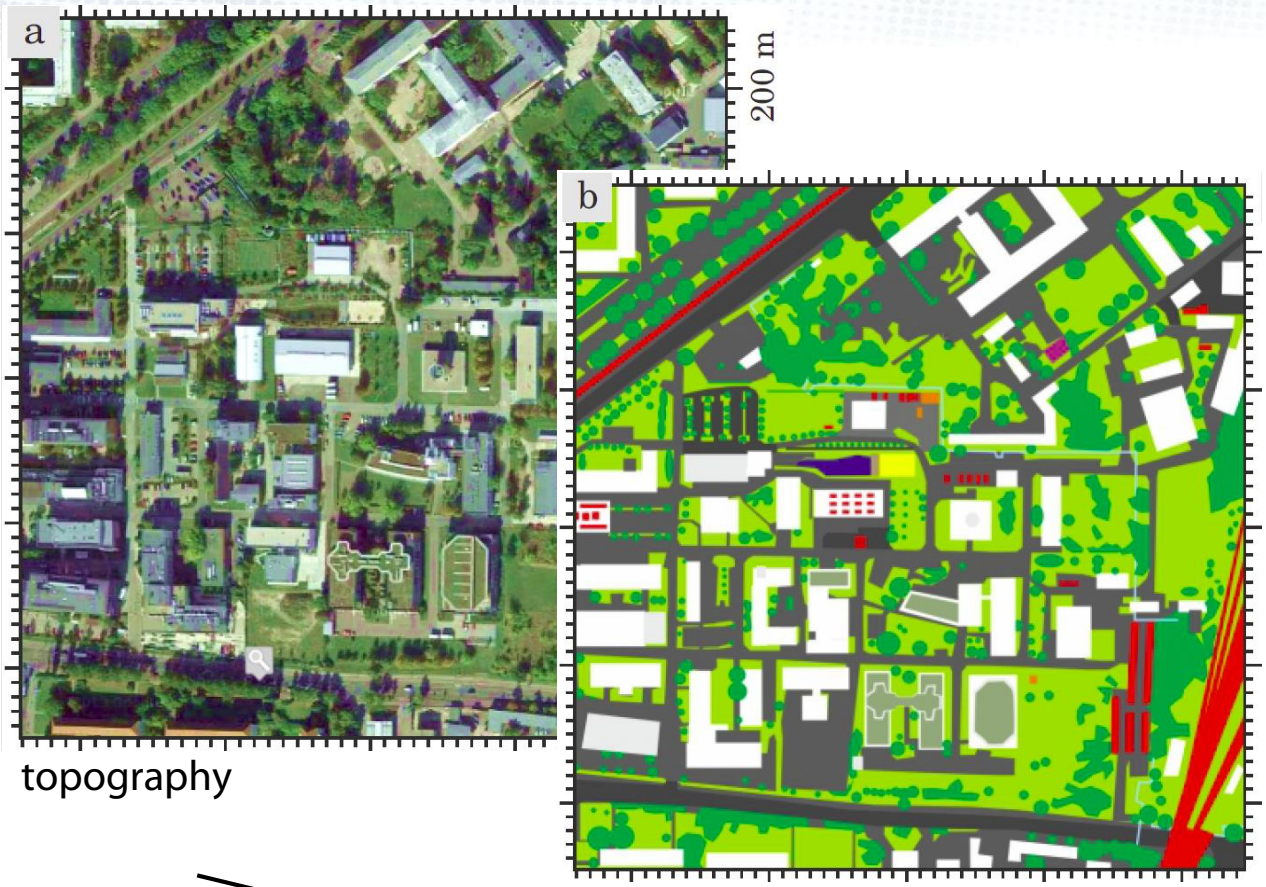


URANOS Modeling

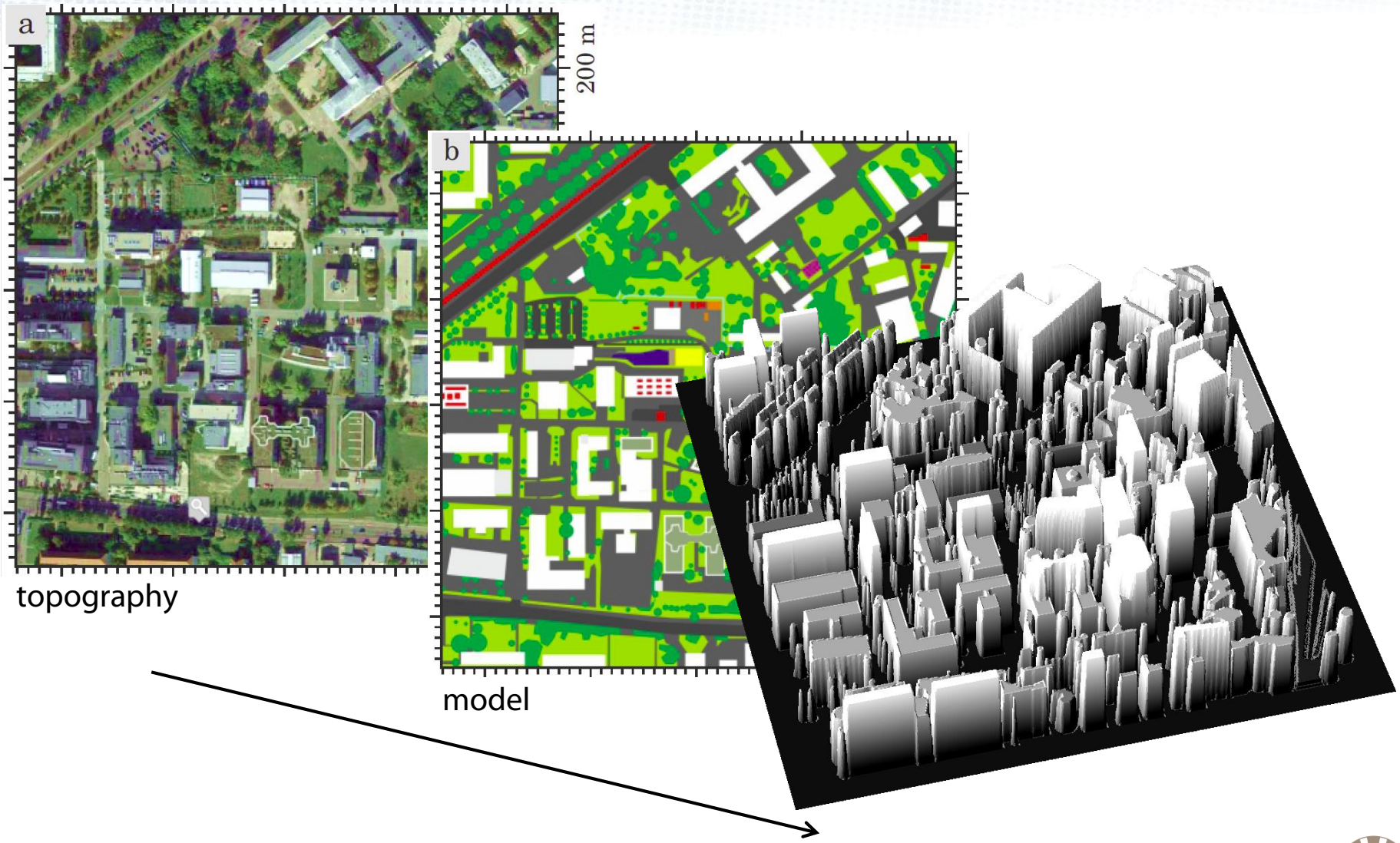


topography

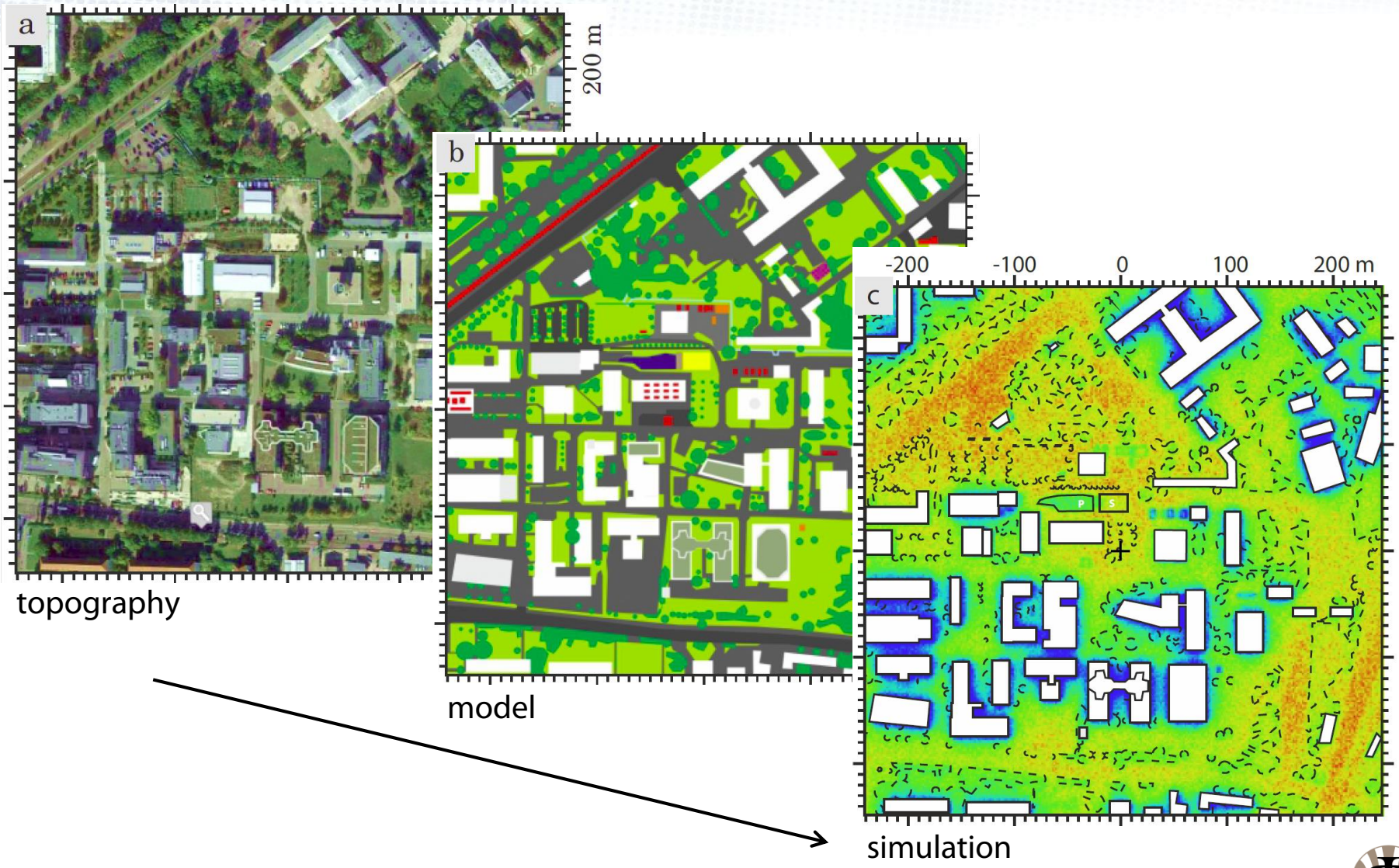
URANOS Modeling



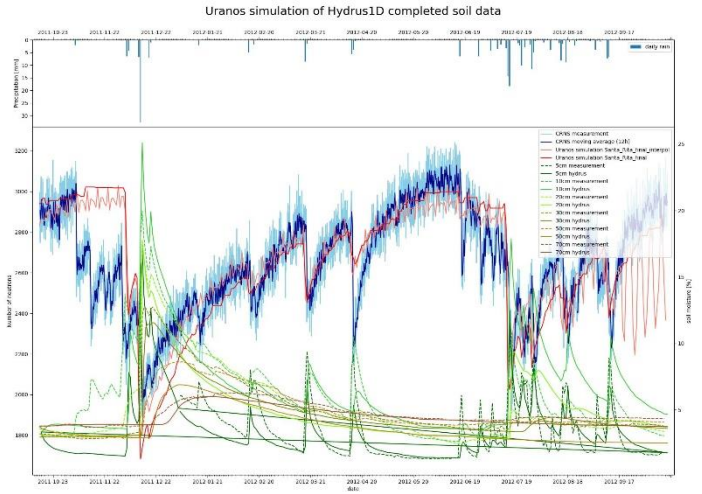
URANOS Modeling

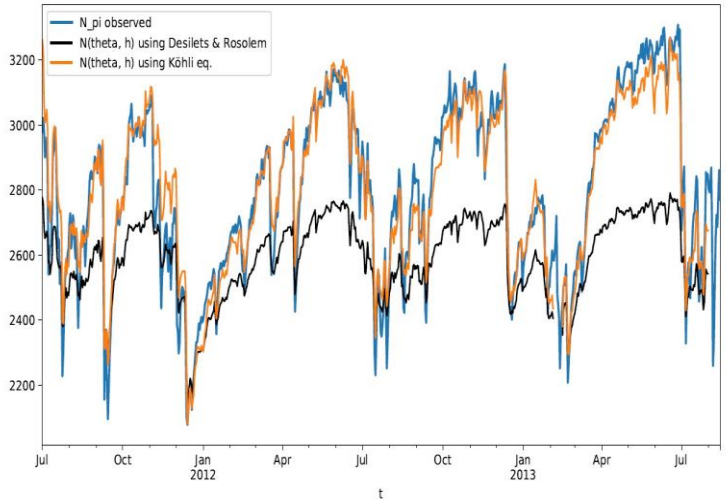


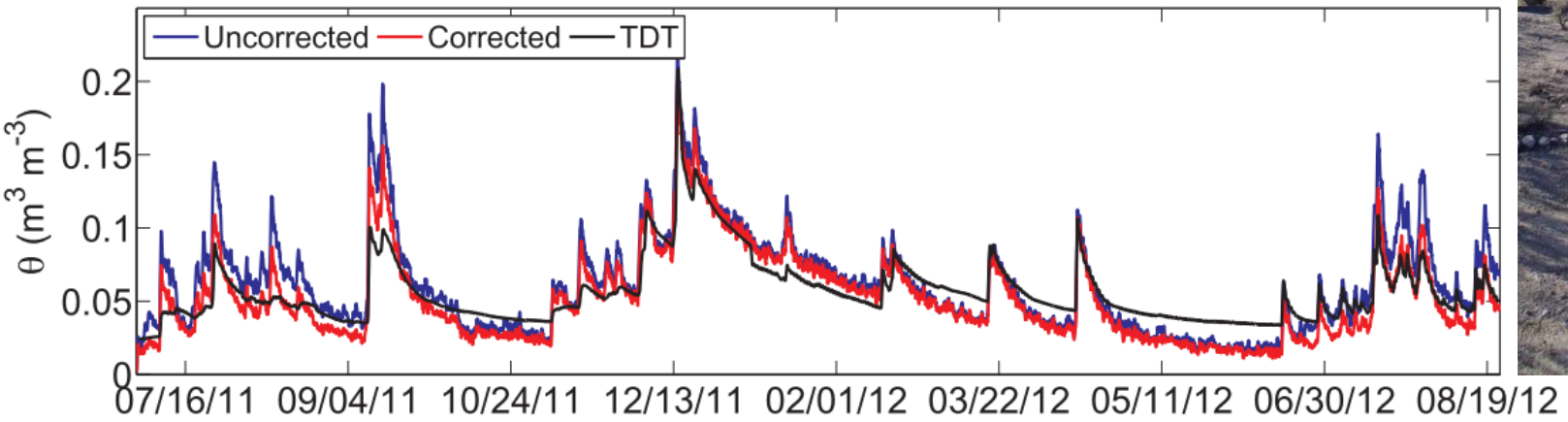
URANOS Modeling



CRNS timeseries



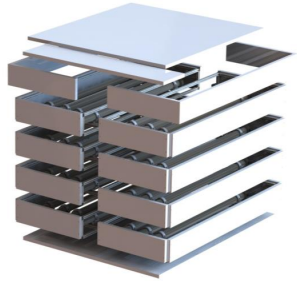




[1] Rosolem, R. et al. "The Effect of Atmospheric Water Vapor on Neutron Count in the Cosmic-Ray Soil Moisture Observing System." J. of Hydrometeorology 14(5) (2013)

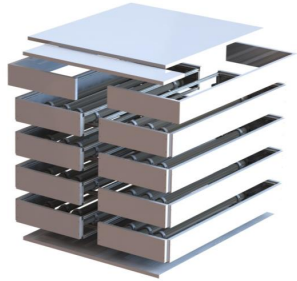
Stationary and Roving

In collaboration with Martin Schrön, UFZ Leipzig



Stationary and Roving

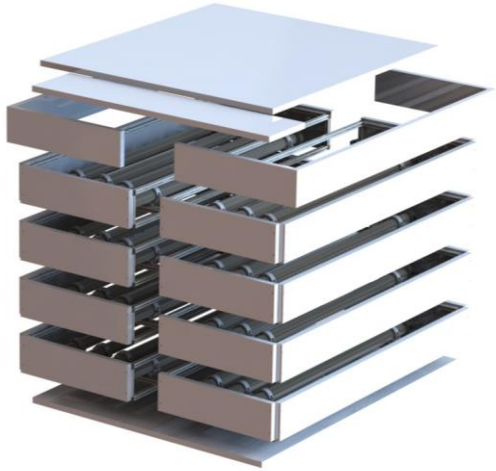
In collaboration with Martin Schrön, UFZ Leipzig



Stationary Instruments

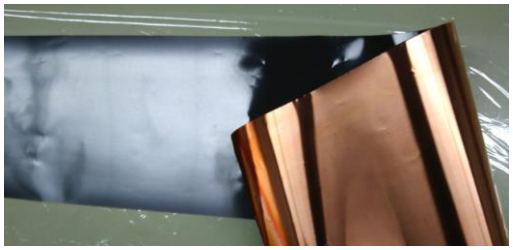
Stationary - small

Stationary - large

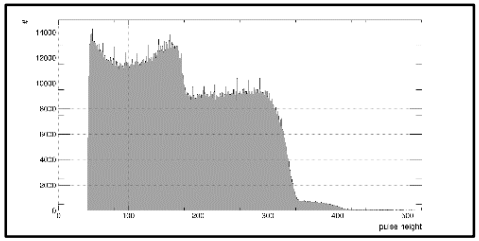


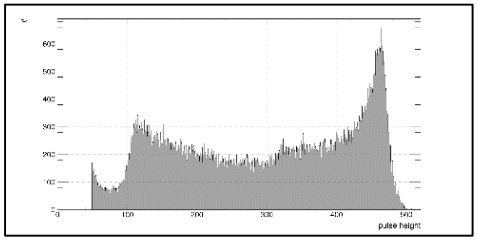
Roving

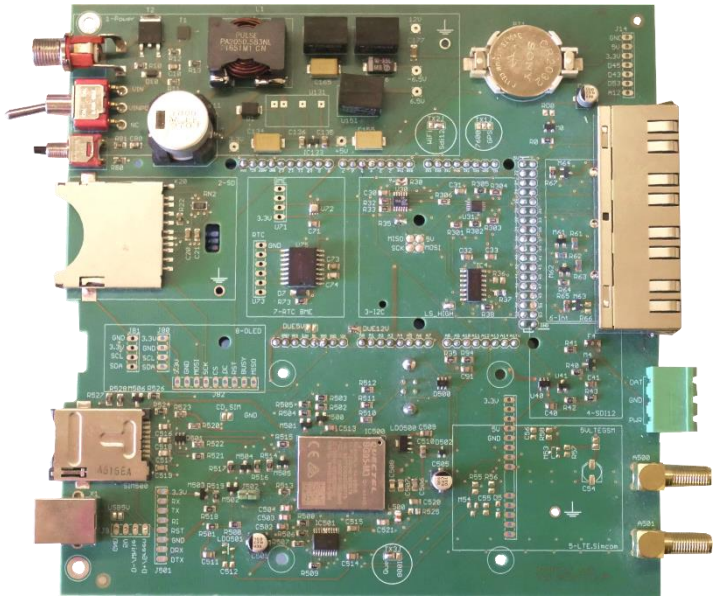
Instrument Development



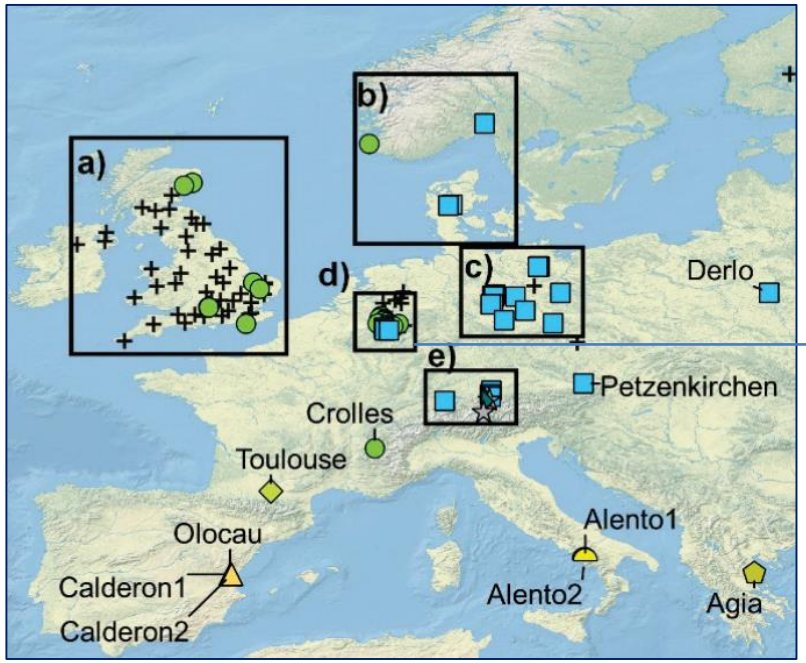
- Low temperature dependence
- Display: RL, p, event info
- High resolution for environmental variables
- Battery/voltage monitoring
- Multi-purpose RJ45 Connector
- SD card
- SDI-12 / RS485 implementation
- GPS Modem
- 4G Modem
- LoRa Modem



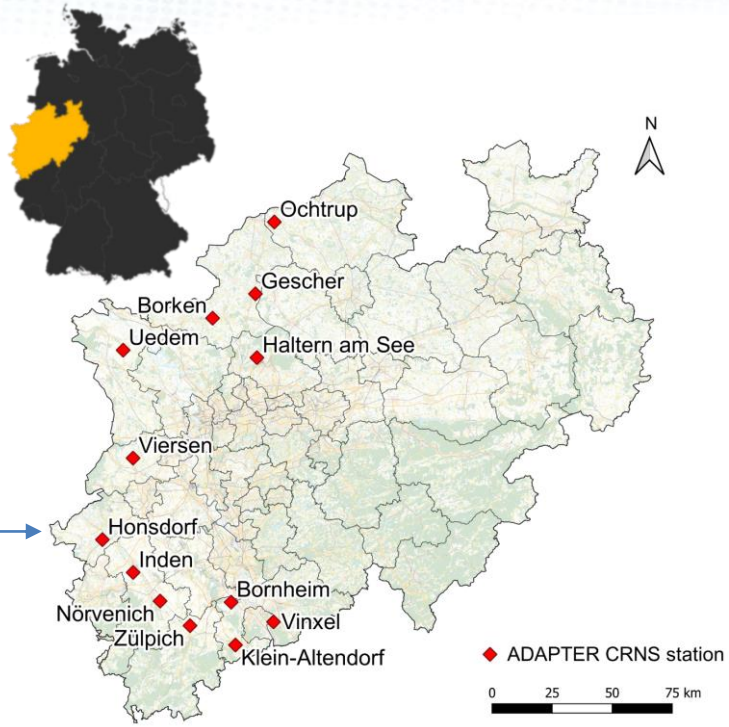




CRNS Networks

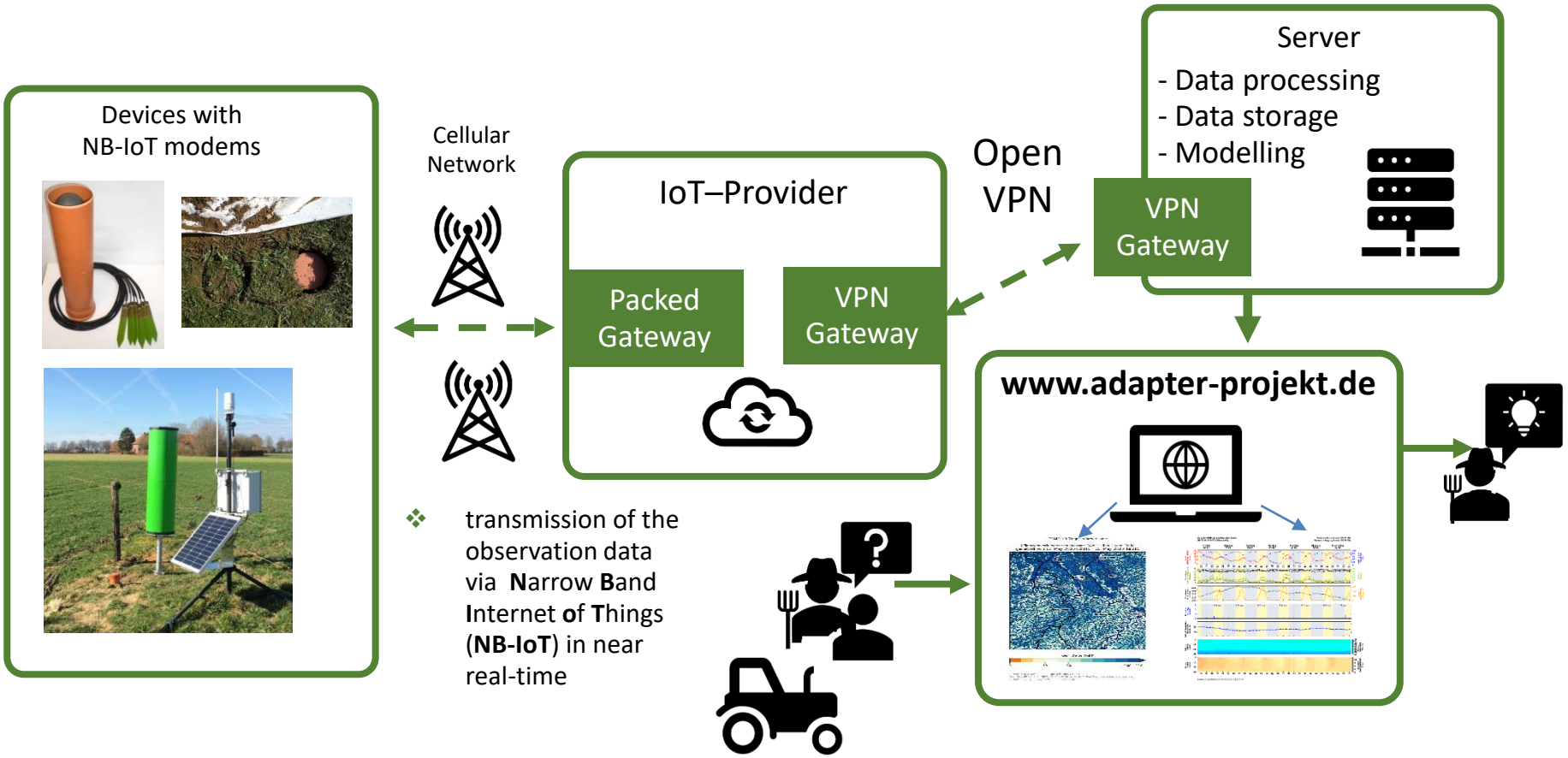


COSMOS-Europe sites (Bogena 2021, ESSD)



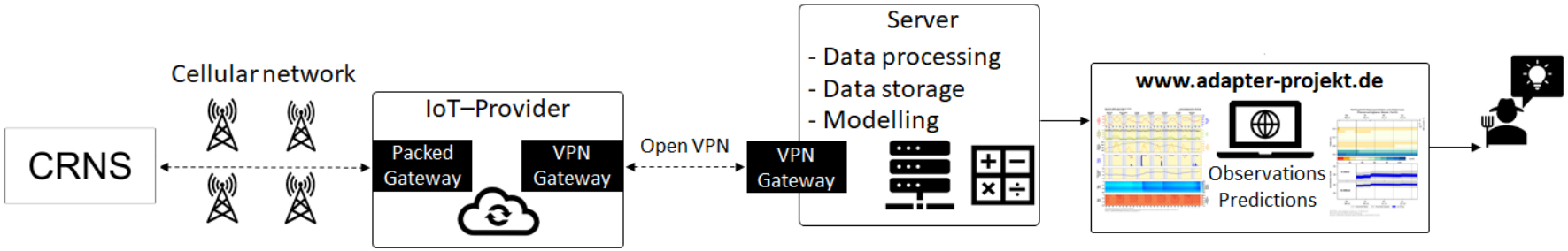
ADAPTER sites (Ney 2021, MetroAgriFor)

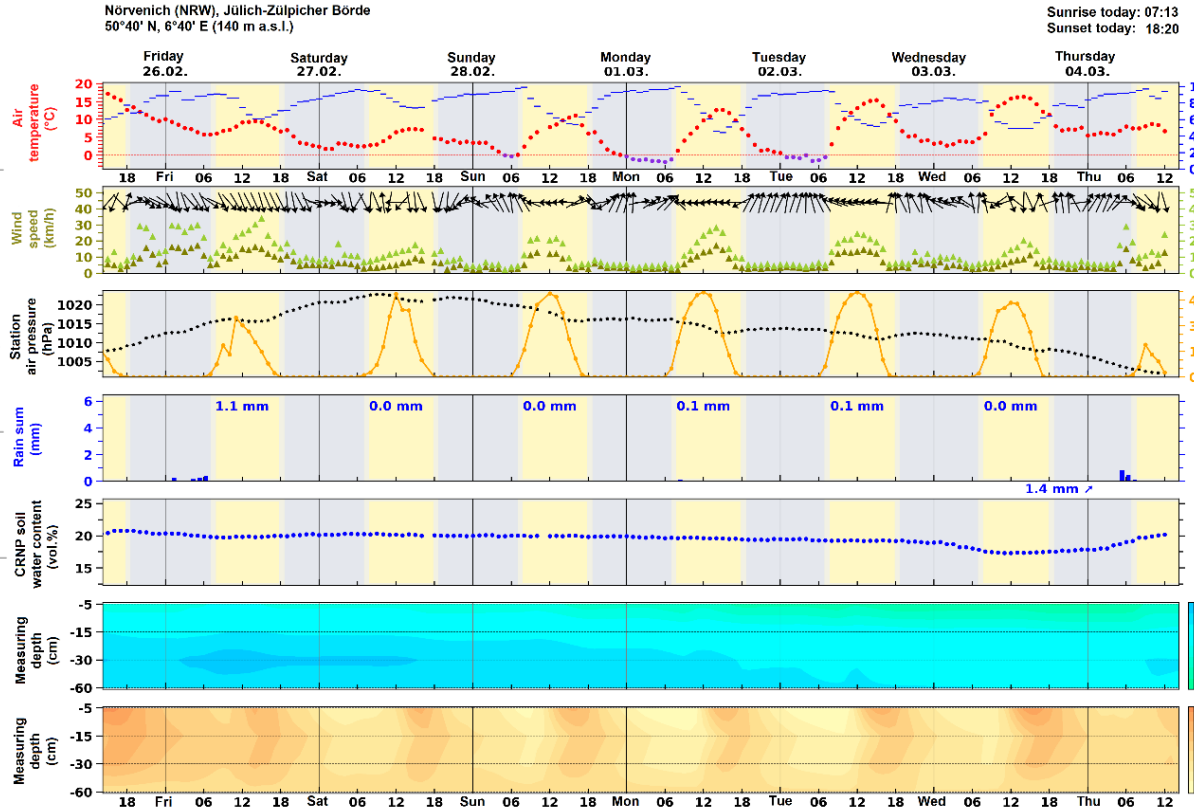
The ADAPTER Network



In collaboration with
Patrizia Ney
FZ Jülich

Telemetry Integration





air temperature

wind speed

air pressure

precipitation rate

CRNP
soil water content

relative humidity

wind gust

solar radiation

SoilNet
soil water content

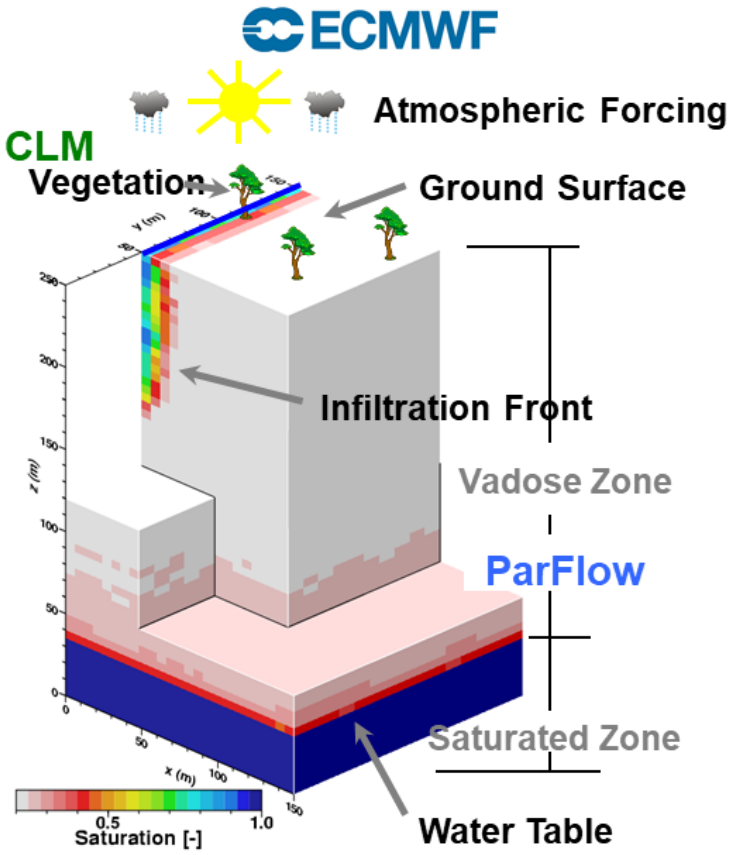
soil temperature

Forecast Model

High-resolution soil moisture forecast

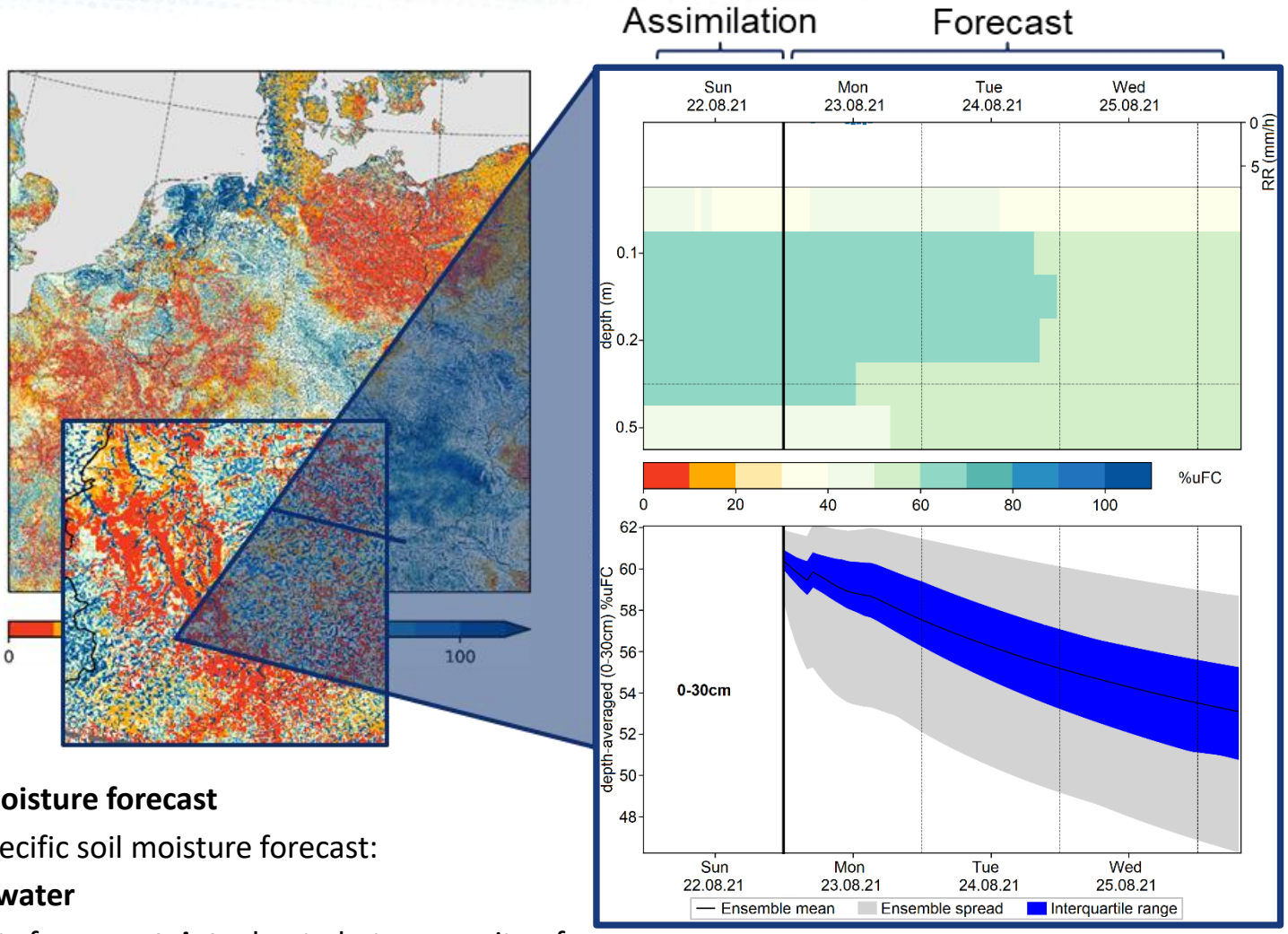
- Focus on **soil water states** and **fluxes**
- **ParFlow** hydrological model for the complete dynamical representation of the subsurface and surface hydrological processes, coupled with
- **CLM** (**C**ommon **L**and **M**odel) for the interactions at the surface
- Atmospheric forcing: forecasts from ECMWF
- Assimilation of observed soil moisture

→ **Initialization closest to reality**



Parflow

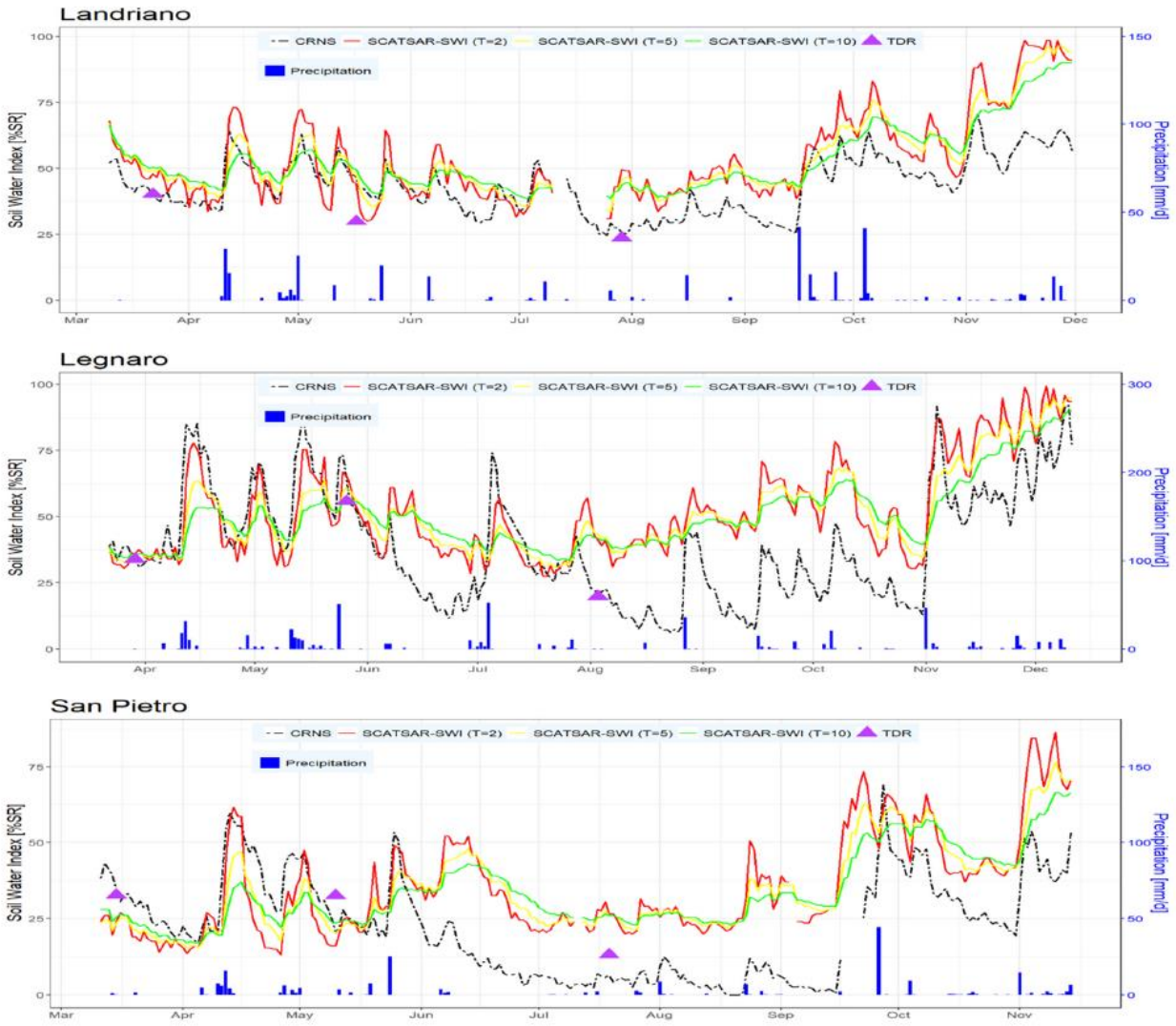
Model: ParFlow/CLM
Forcing: ECMWF HRES



High-resolution soil moisture forecast

- Prototype: site specific soil moisture forecast:
  e.g., **plant available water**
- Ensemble accounts for **uncertainty** due to heterogeneity of soil hydraulic properties

Remote Sensing Comparison



CRNS footprint

NDVI

- 0 - 0.1
- 0.1 - 0.2
- 0.2 - 0.3
- 0.3 - 0.4
- 0.4 - 0.5
- 0.5 - 1

S. Emamalizadeh et al. (2024): „Comparison of SoilWater Content from SCATSAR-SWI and Cosmic Ray Neutron Sensing at Four Agricultural Sites in Northern Italy: Insights from Spatial Variability and Representativeness“

SOMMET: Standardization

PROJECT PARTNERS:

PTB — Coordination, Lead WP6

Ciemat — Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

CZECH METROLOGY INSTITUTE

DANISH TECHNOLOGICAL INSTITUTE — Lead WP1

IRSN — INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

SMU

INRiM — ISTITUTO NAZIONALE DI RICERCA METROLOGICA — Lead WP5

Justervesenet

TÜBİTAK

Universität Potsdam — Lead WP2

CTU — CZECH TECHNICAL UNIVERSITY IN PRAGUE

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA — Lead WP3

POLITECNICO MILANO 1863

ifac — istituto per il rilevamento elettromagnetico dell'ambiente — Lead WP4

UK Centre for Ecology & Hydrology

UFZ HELMHOLTZ Zentrum für Umweltforschung

INSTITUTE OF AGROPHYSICS PAS

IMPACT & SUPPORT:

esa

asi Agenzia Spaziale Italiana

UNESCO — United Nations Educational, Scientific and Cultural Organization

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

WMO

eLTER

Deutscher Wetterdienst — Wetter und Klima aus einer Hand — DWD

ECMWF

THE UNIVERSITY OF ARIZONA

AHDB — AGRICULTURE & HORTICULTURE DEVELOPMENT BOARD

LANDBRUG FØDEVARER

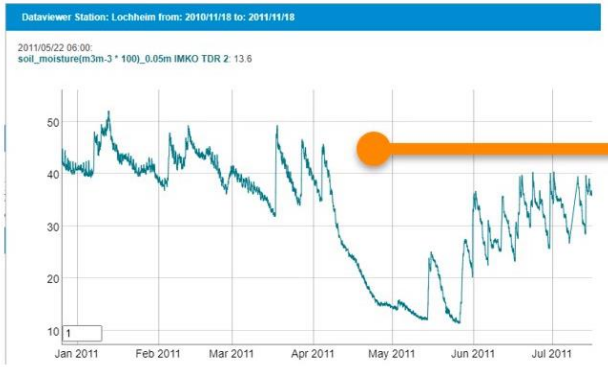
NMBU — Norwegian University of Life Sciences

Multiple scales of SOMMET

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

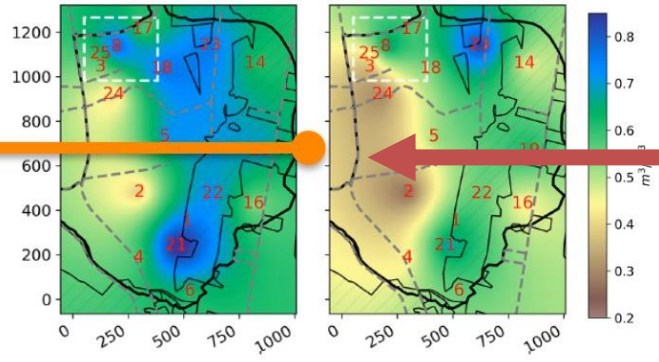
- Comparison of methods, their constraints and different spatial and temporal characteristics
  - Development of an approach to harmonize point scale, field scale and remote sensing

Point-scale *in situ* measurements
Example: Time series of a single sensor



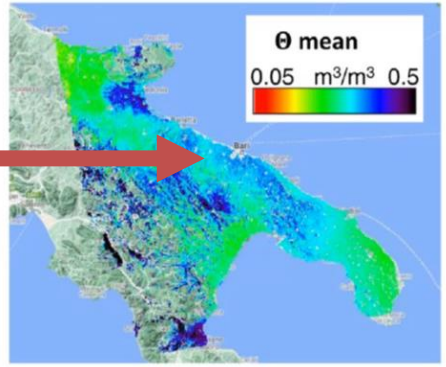
[International Soil Moisture Network]

Cosmic-ray neutron sensing
Example: Daily average soil moisture at catchment scale



[Heistermann, HESS 25 (2021) 4807]

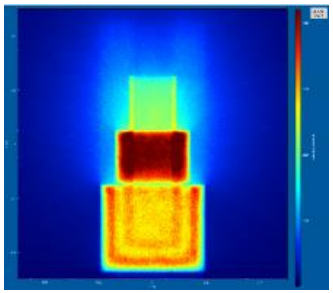
Satellite remote sensing
Example: Sentinel-1 surface soil volumetric water content product

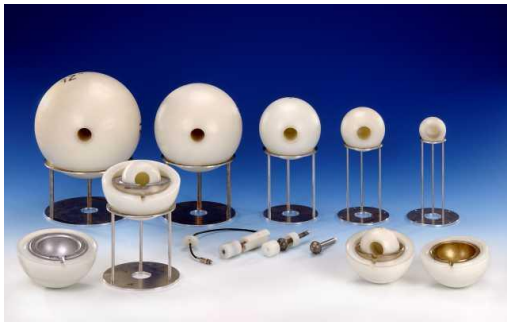


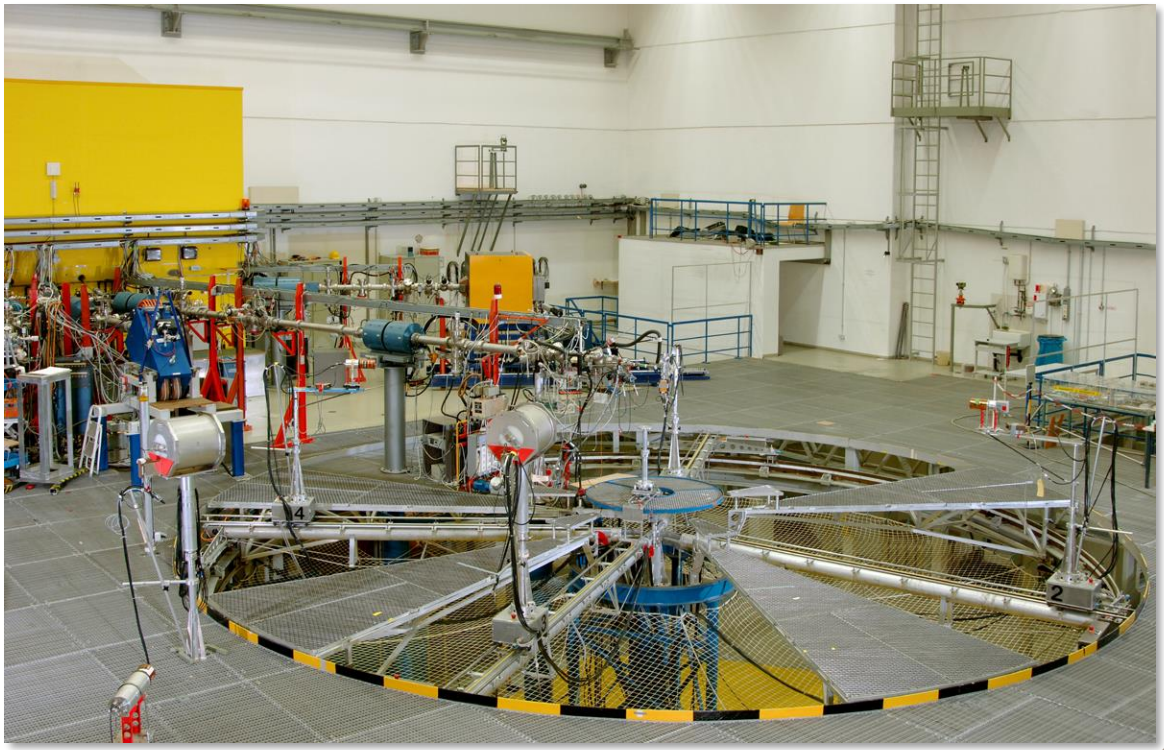
[Balenzano *et al.*, Data in Brief 38 (2021) 107345]

SI-traceable measurements

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

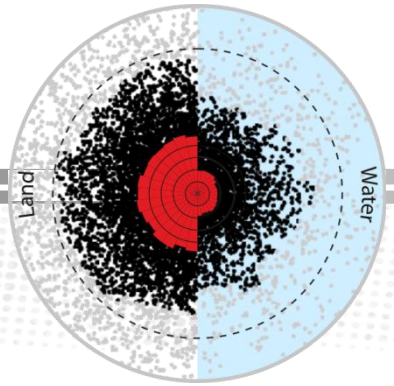






CRNS is an emerging technology

- **Bridges the scale** between remote sensing and local probes
- Provides an **area-averaged soil moisture** estimate on **10 ha** and max. 50 cm depth



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Heidelberg University
Germany

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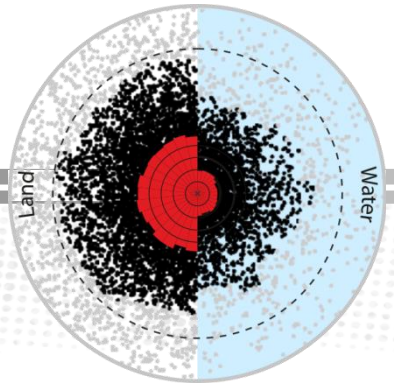

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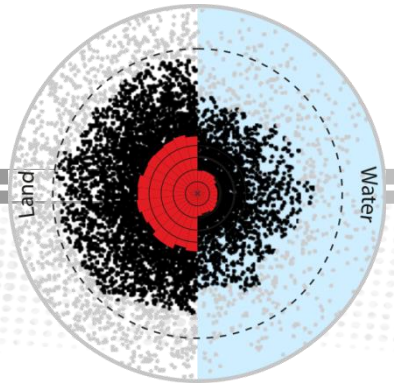

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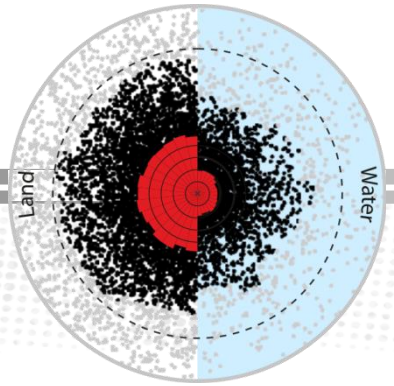

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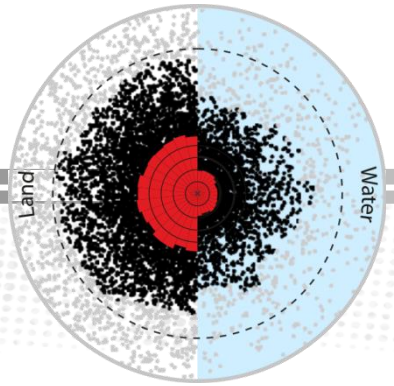
- **SOMMET (PTB): SI-traceable standardization of soil moisture measurements**



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