Soil Moisture Measurements with Cosmic-Ray Neutrons

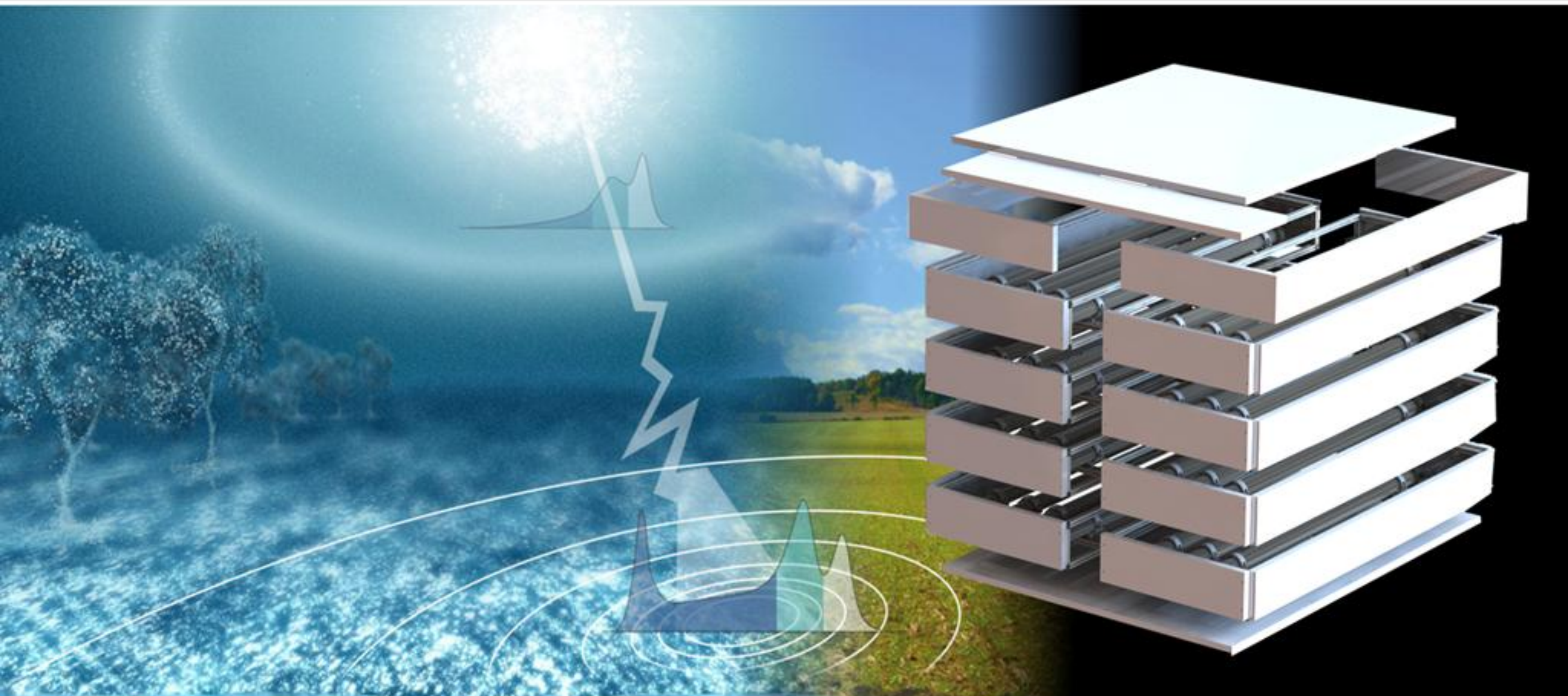
Particle Physics Colloquium
November12th 2019

Physikalisches Institut

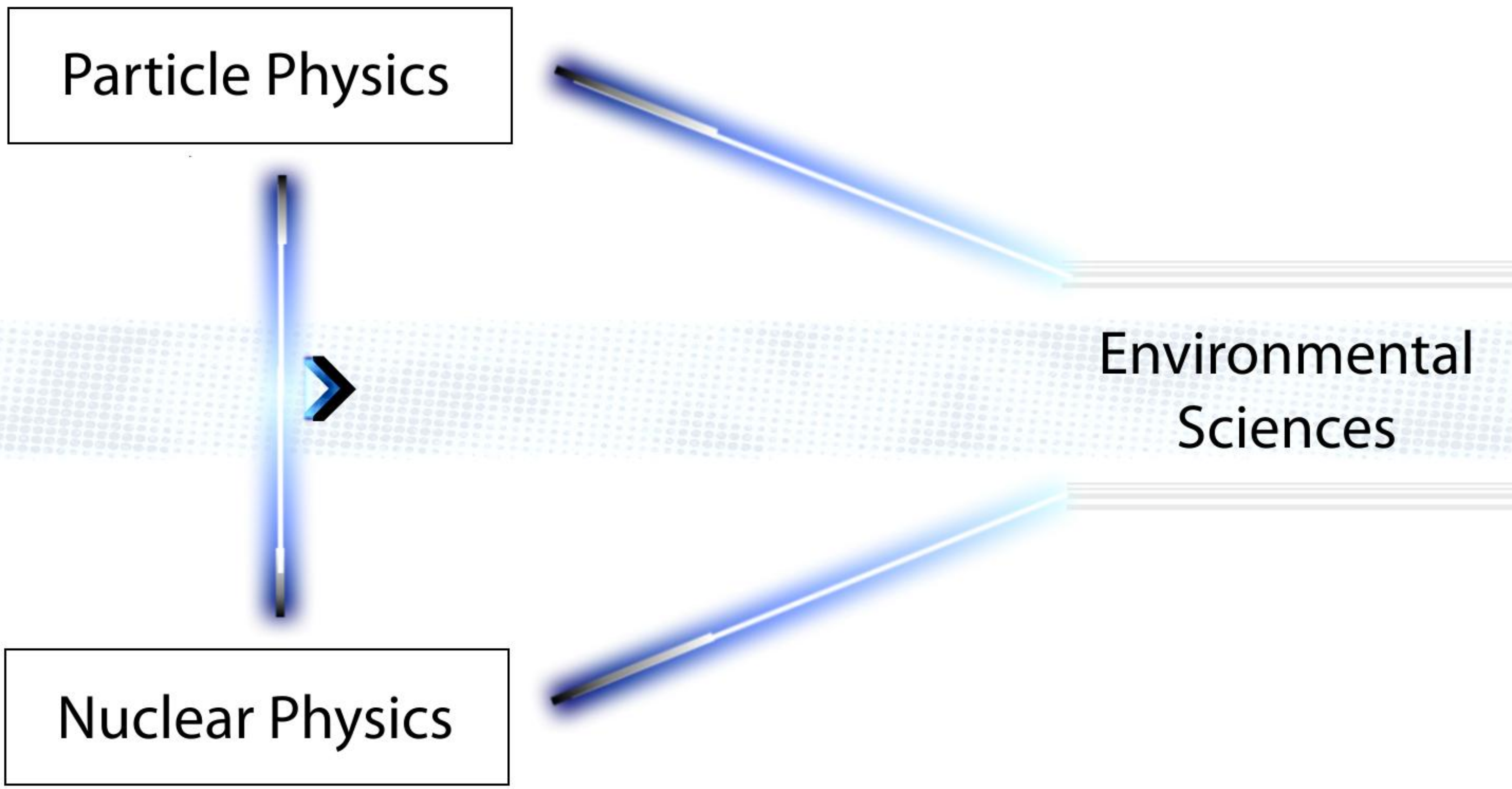
Ruprecht-Karls-Universität Heidelberg

Markus Köhli

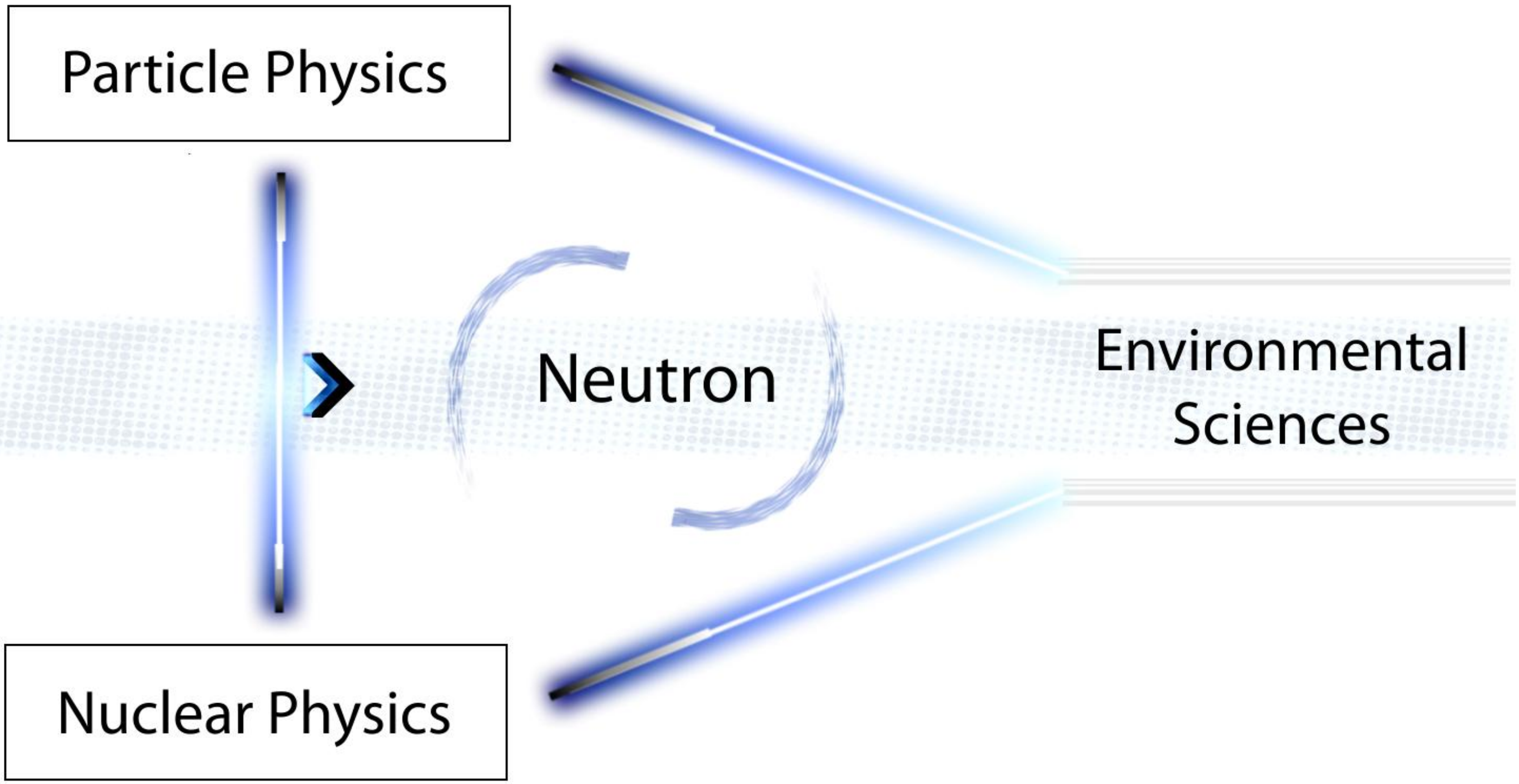
AG Schmidt
ANP-PAT



An interdisciplinary spin-off



An interdisciplinary spin-off



CNCS inelastic spectrometer, SNS

[1]

[1] http://www.iso.org/iso/2012_iso-in-action_water_vignette.jpg

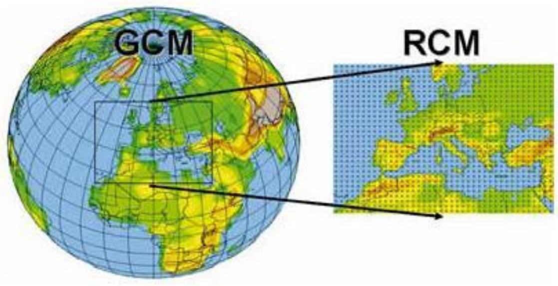
[1]

Where? When? How much?

[1] http://www.iso.org/iso/2012_iso-in-action_water_vignette.jpg

[3]

[2]

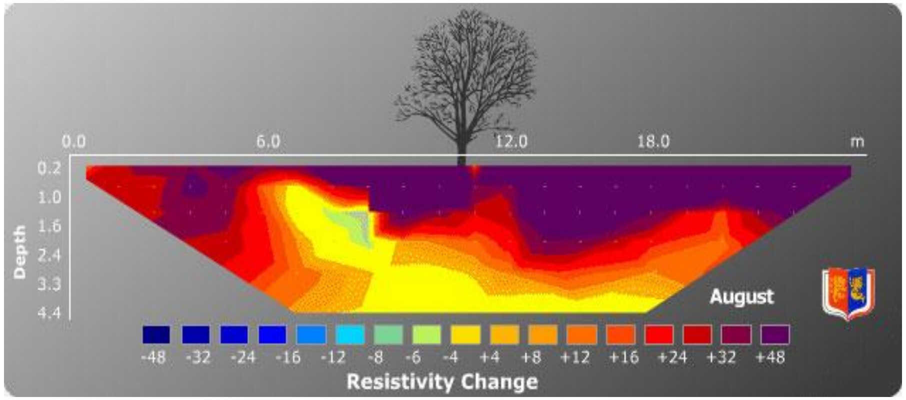


[1]

[1] http://www.wmo.int/pages/themes/climate/images/figures/ClimateModelnesting.jpg
[2] http://www.livetradingnews.com/wp-content/uploads/2014/04/precisionag.jpg
[3] http://upload.wikimedia.org/wikipedia/commons/3/37/Nam_steppe.jpg

< 10 m

~ 1 km



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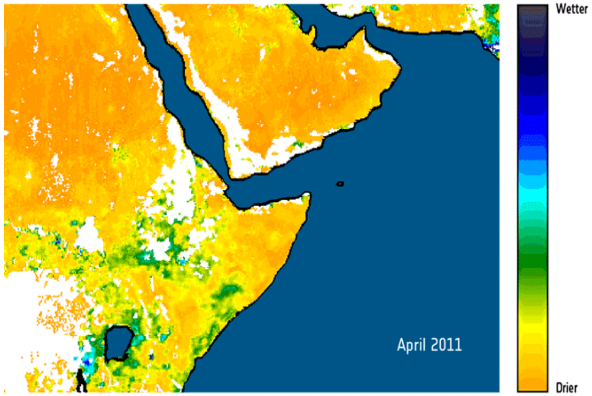


[1]

via

local techniques

(electrical resistivity, capacitance, etc)

(even neutrons…)

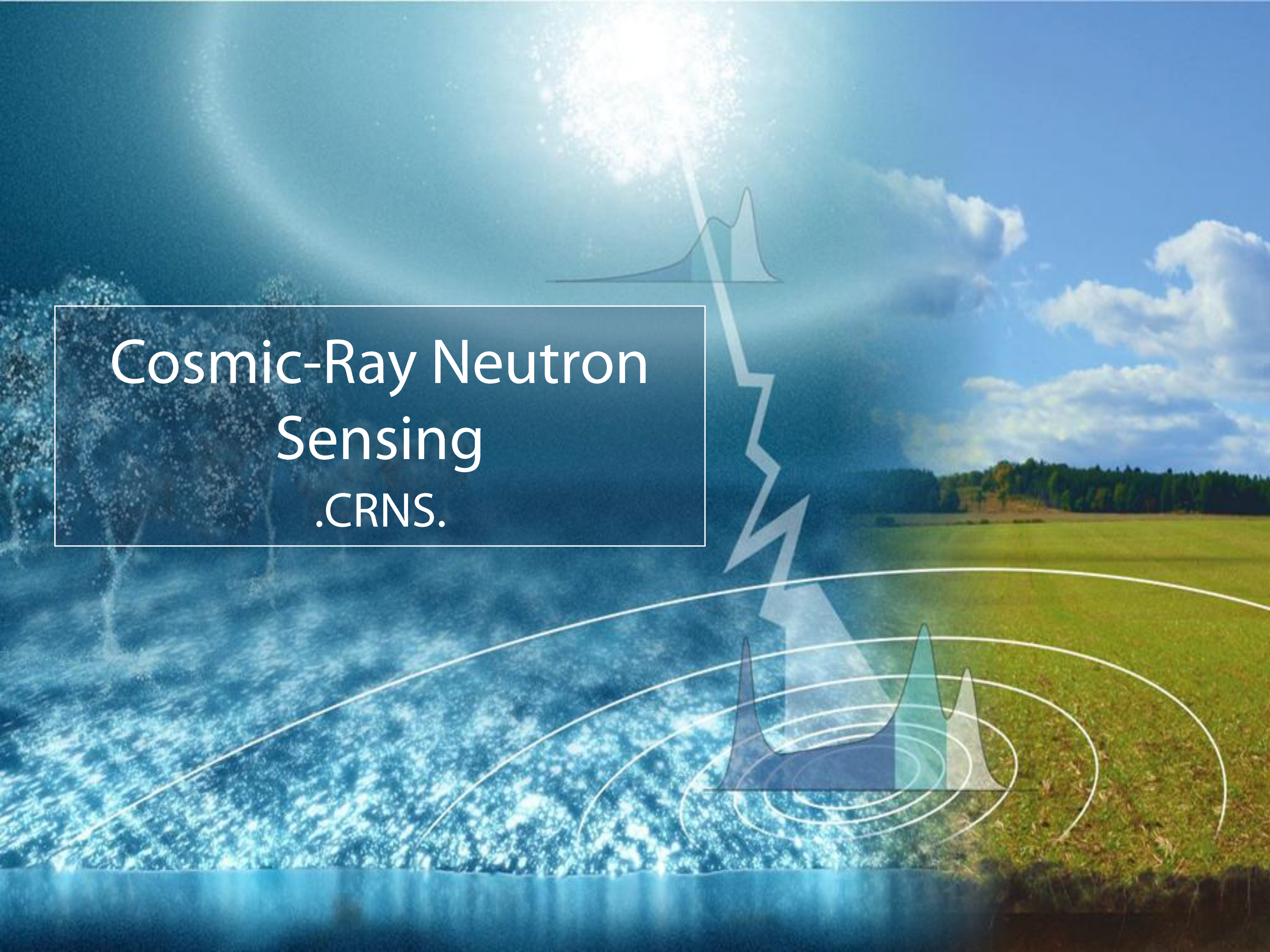
via

satellite remote sensing

(optical, microwave)

[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.

A talk of ~3 neutron lifetimes

Part I

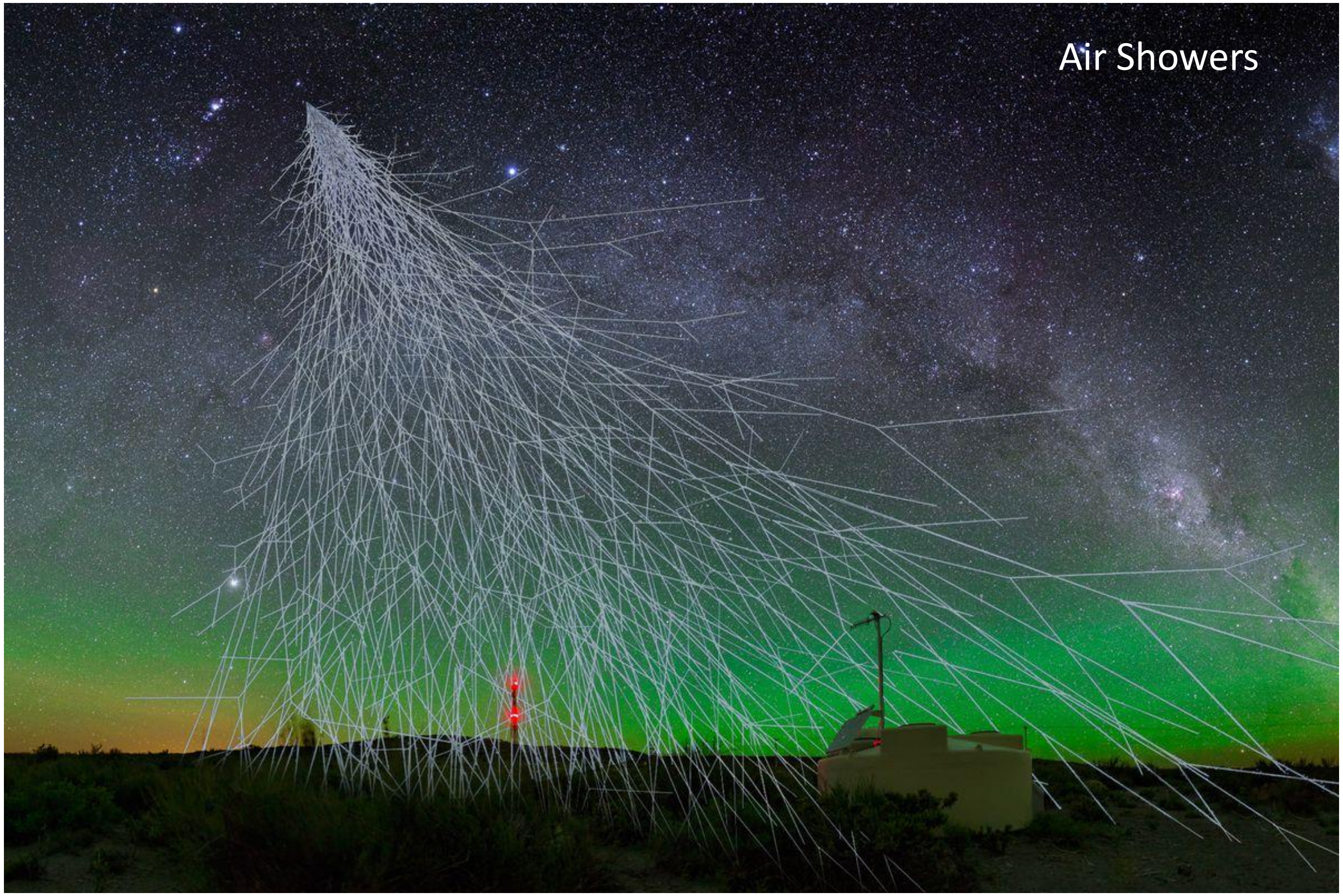
- Cosmic-Ray Neutron Basics
- Measure Water With Neutrons

Part II

- Neutron Detection Principles
- Detector Developments

CRNS

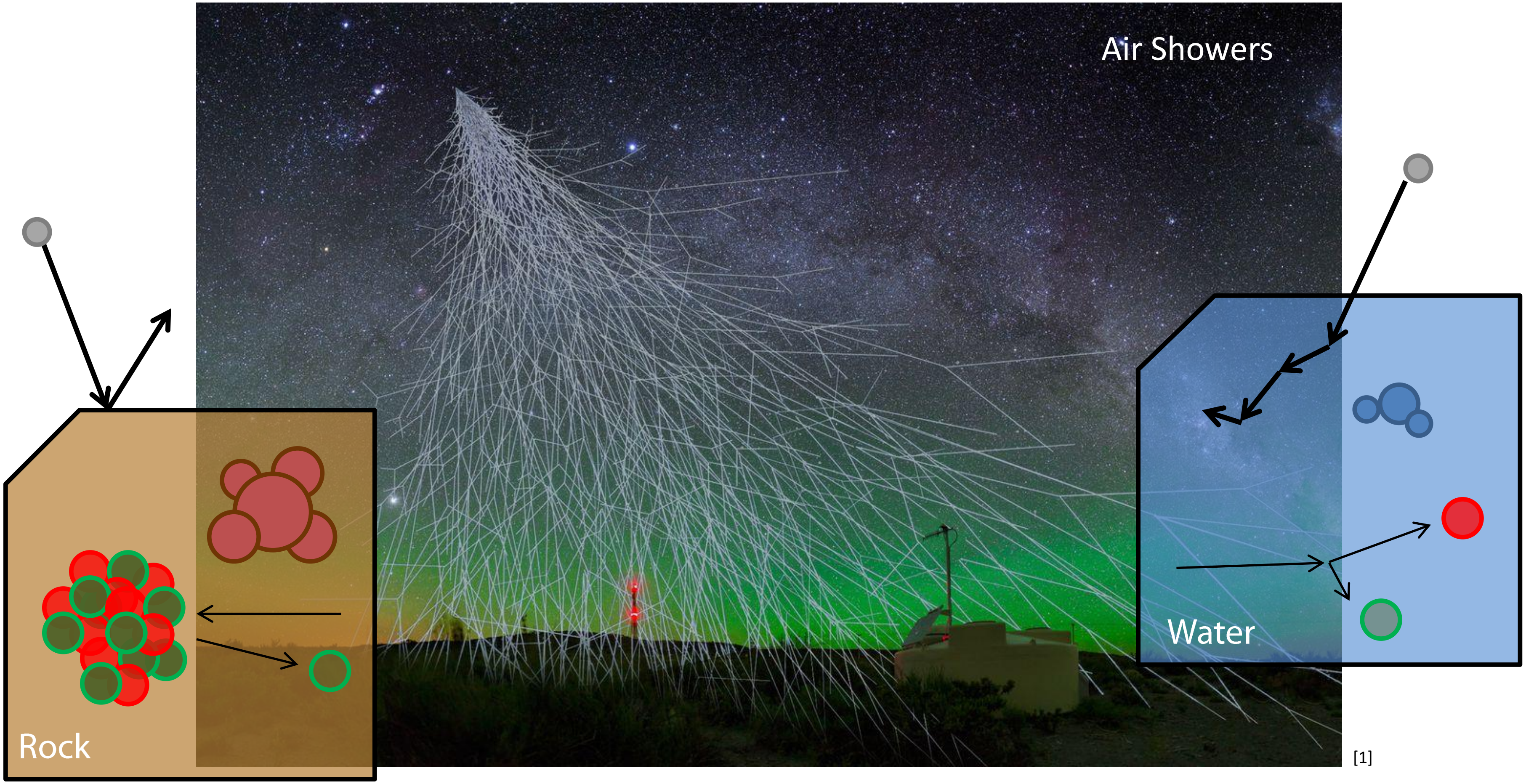
The Cosmic Neutron Basics



[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

The Cosmic Neutron Basics



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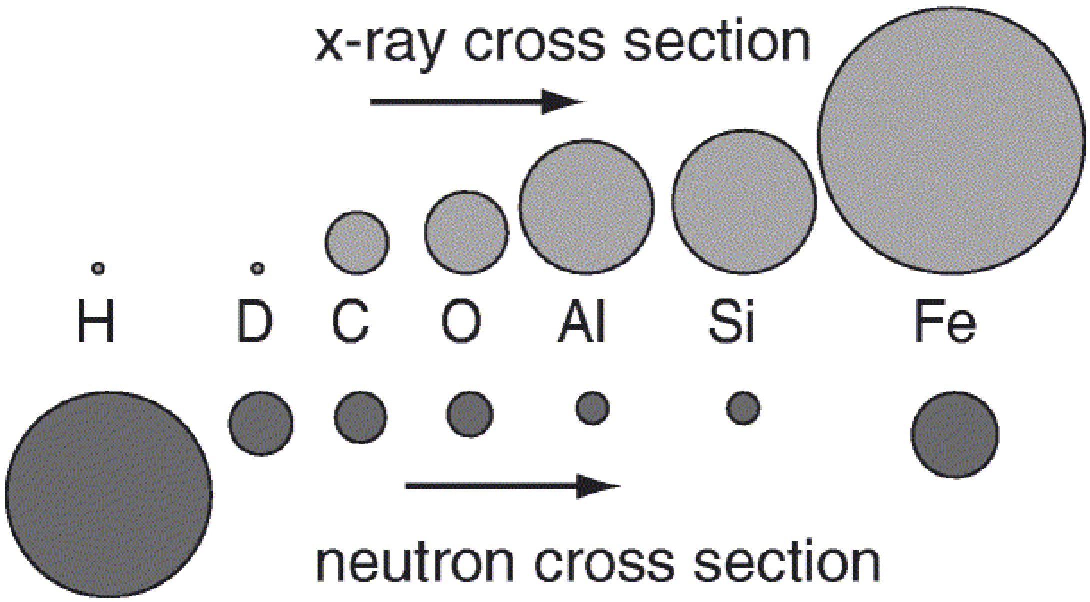
Cross Sections

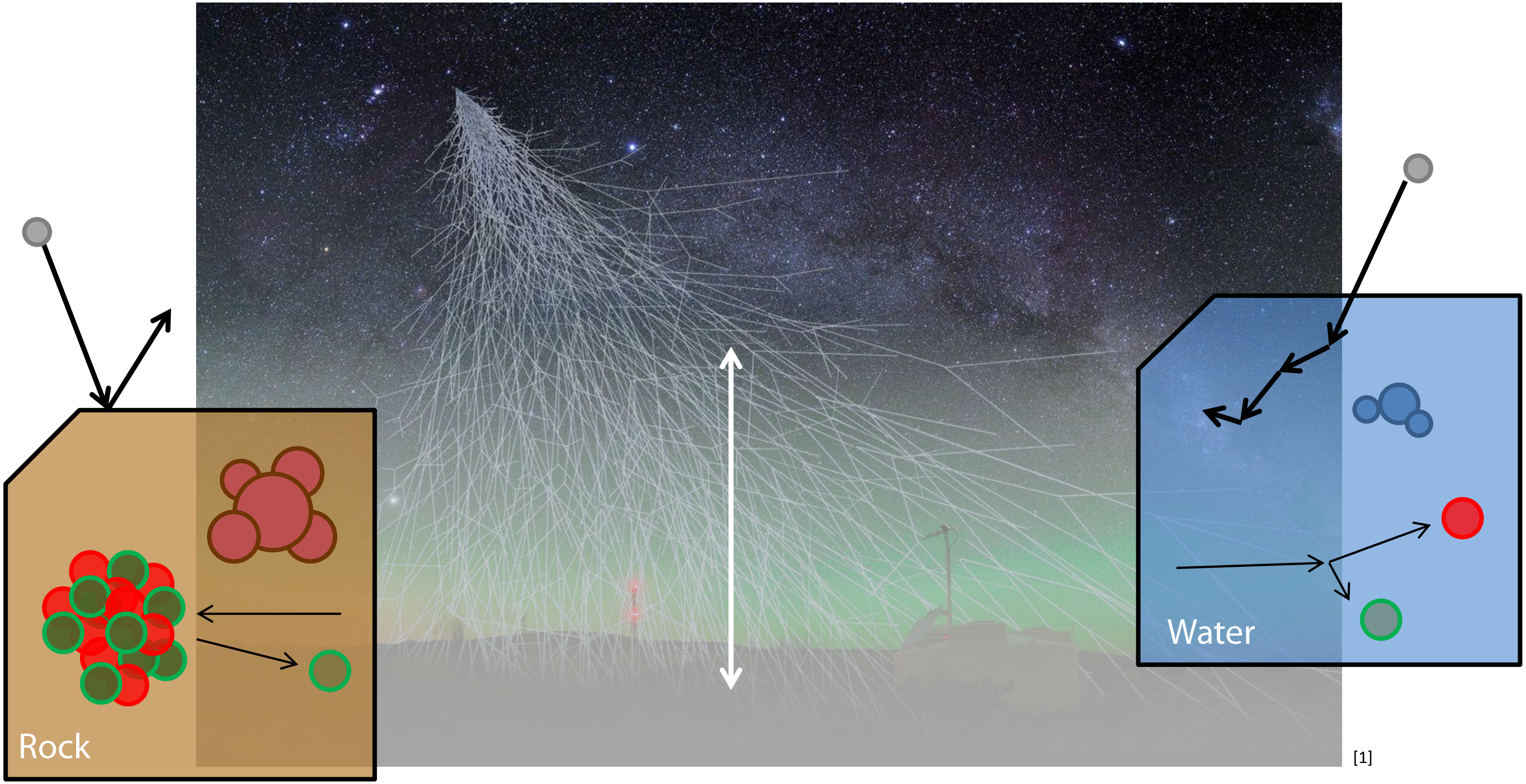


- **X-Ray** cross section depends on Z
- **neutron** cross section varies over periodic table

Neutron imaging

Courtesy: PSI

The Cosmic Neutron Basics



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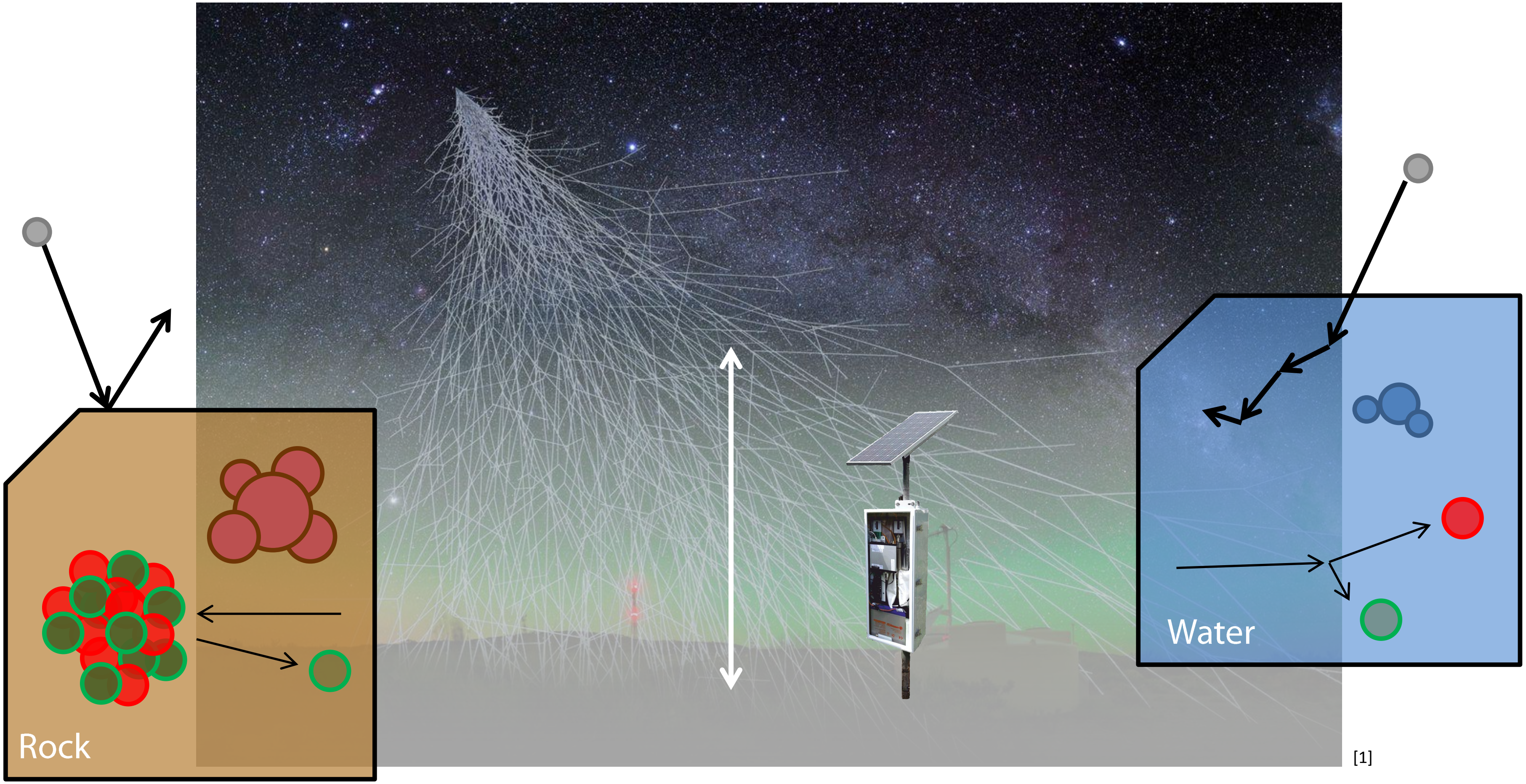

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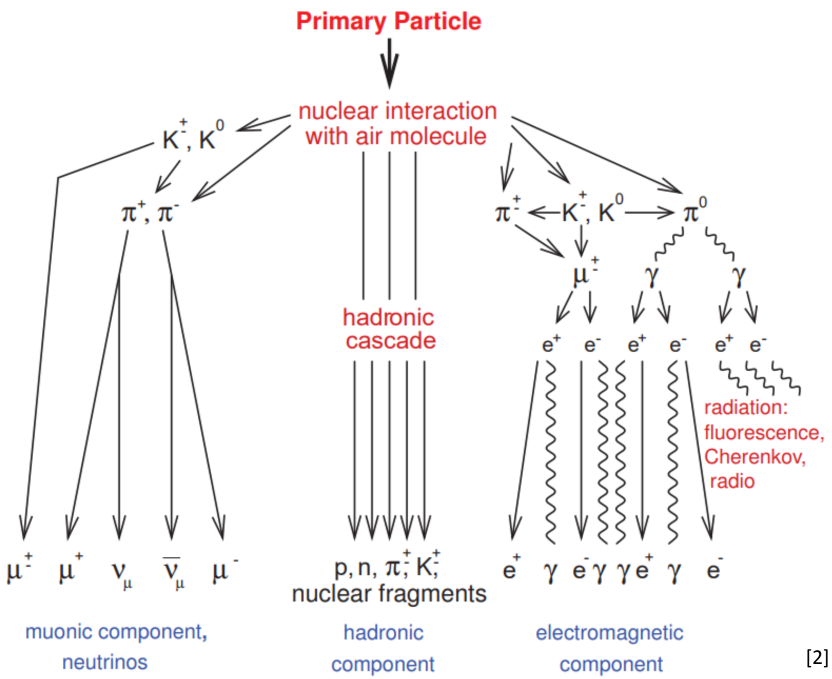
More details please...

The Cosmic Neutron Basics



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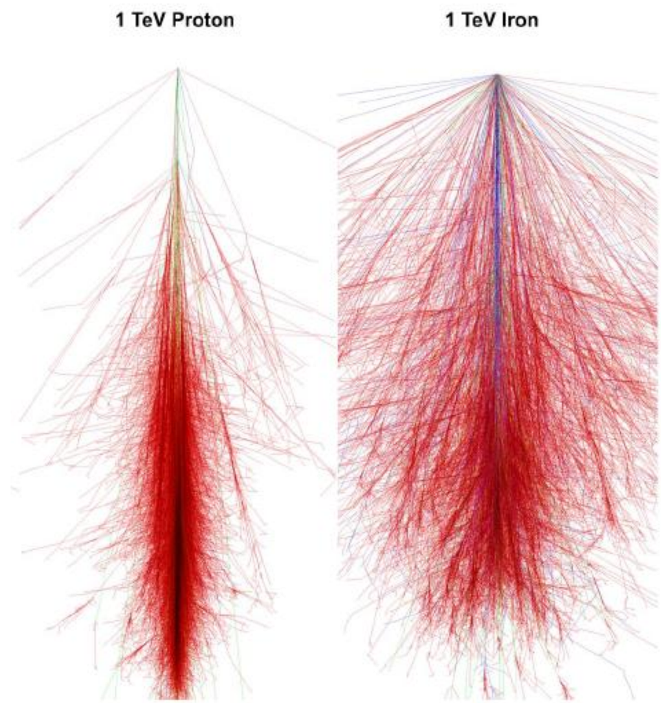
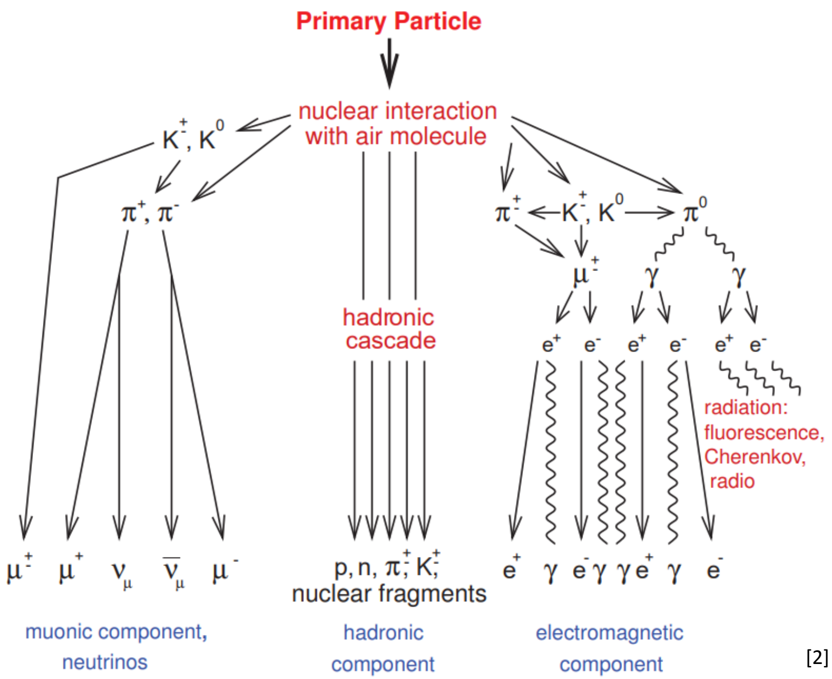


[3]

[2] Haungs , A. et al., „Energy spectrum and mass composition of high-energy cosmic rays." Rep. Prog. Phys., 66 (7) (2003)
[3] Heck, D. et al., „CORSIKA: A Monte Carlo code to simulate extensive air showers." FZKA 6019. Forschungszentrum Karlsruhe (1998)

The Cosmic Neutron Basics



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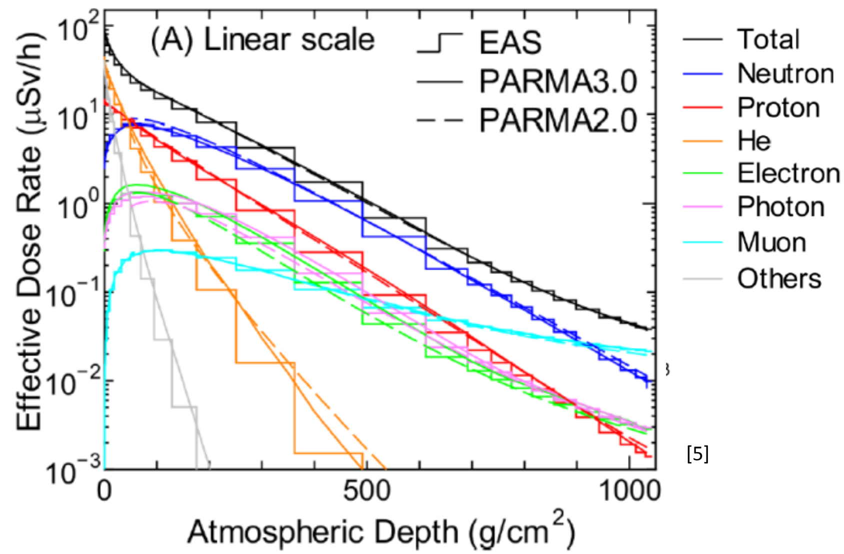

[5]

[2] Haungs , A. et al., „Energy spectrum and mass composition of high-energy cosmic rays.” Rep. Prog. Phys., 66 (7) (2003)
[5] Sato, T., “Analytical Model for Estimating Terrestrial Cosmic Ray Fluxes Nearly Anytime and Anywhere in the World: Extension of PARMA/EXPACS.”, PLOS ONE 10(12) (2015)

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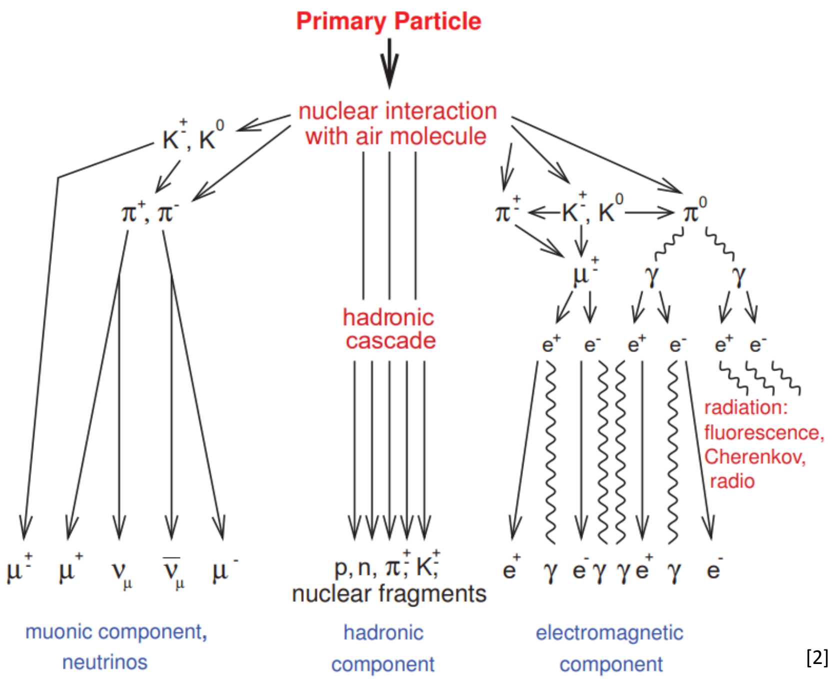

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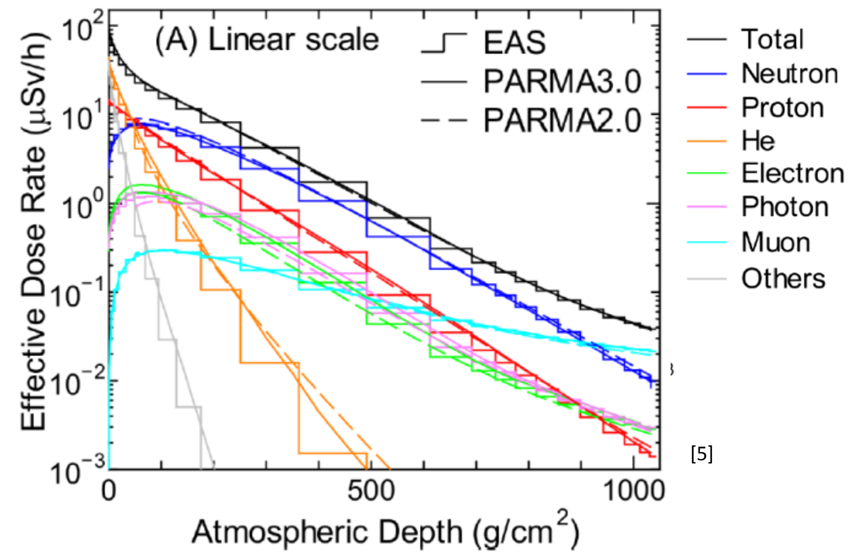

[5]

Sea-level particle absorption lengths.

Particle	*Length L* (g/cm^2)
Electrons	100
Protons	110
Pions	113
Neutrons	136
Muons and muon capture	261

[4]

[2] Haungs et al., „Energy spectrum and mass composition of high-energy cosmic rays." Rep. Prog. Phys., 66 (7) (2003)
[4] Ziegler, J.F., "Terrestrial cosmic ray intensities." IBM Journal of Research and Development 42(1) (1998)
[5] Sato, T., "Analytical Model for Estimating Terrestrial Cosmic Ray Fluxes Nearly Anytime and Anywhere in the World: Extension of PARMA/EXPACS.", PLOS ONE 10(12) (2015)

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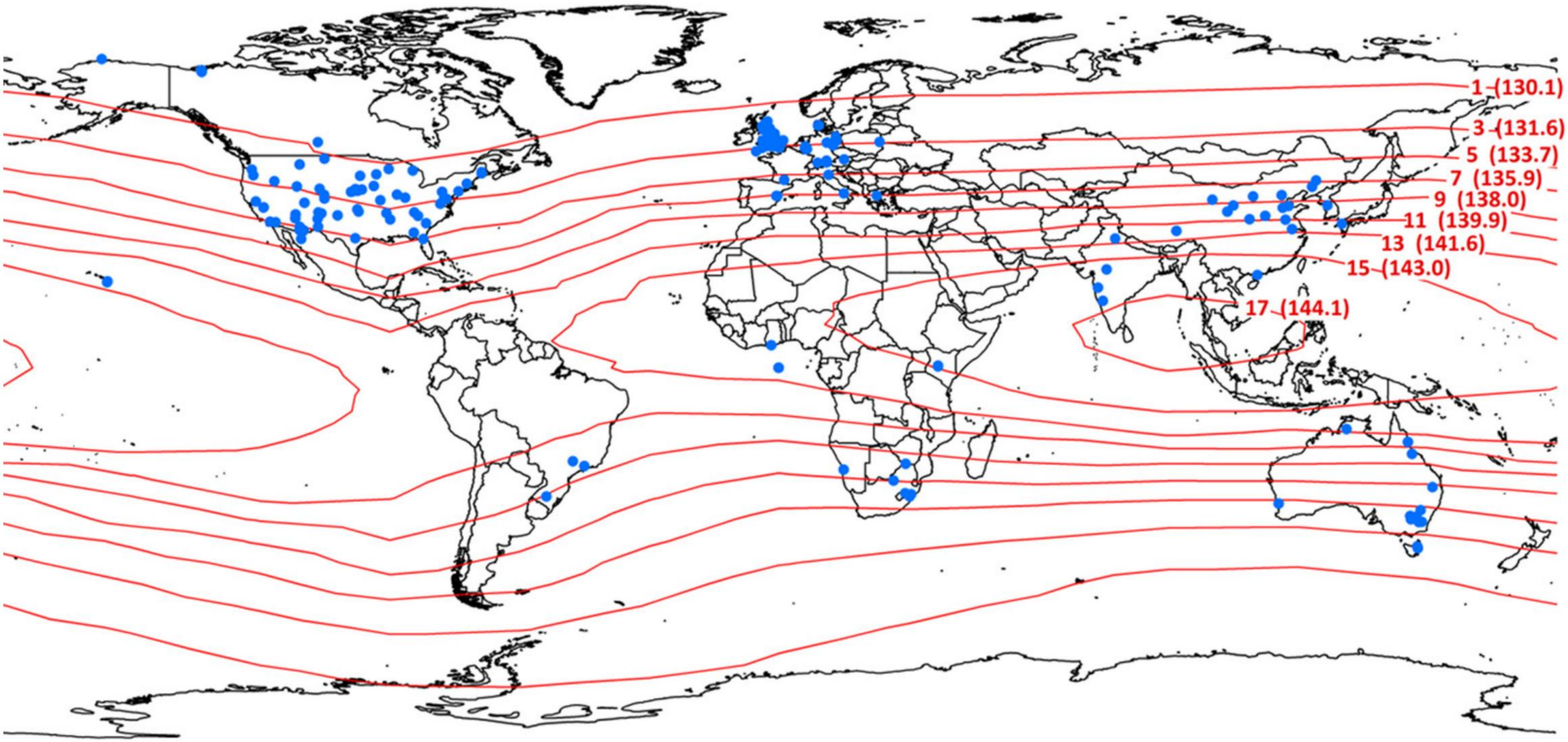

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[5] Andreasen, M. et al. "Status and Perspectives on the Cosmic-Ray Neutron Method for Soil Moisture Estimation and Other Environmental Science Applications." Vadose Zone Journal 16(8) (2017)

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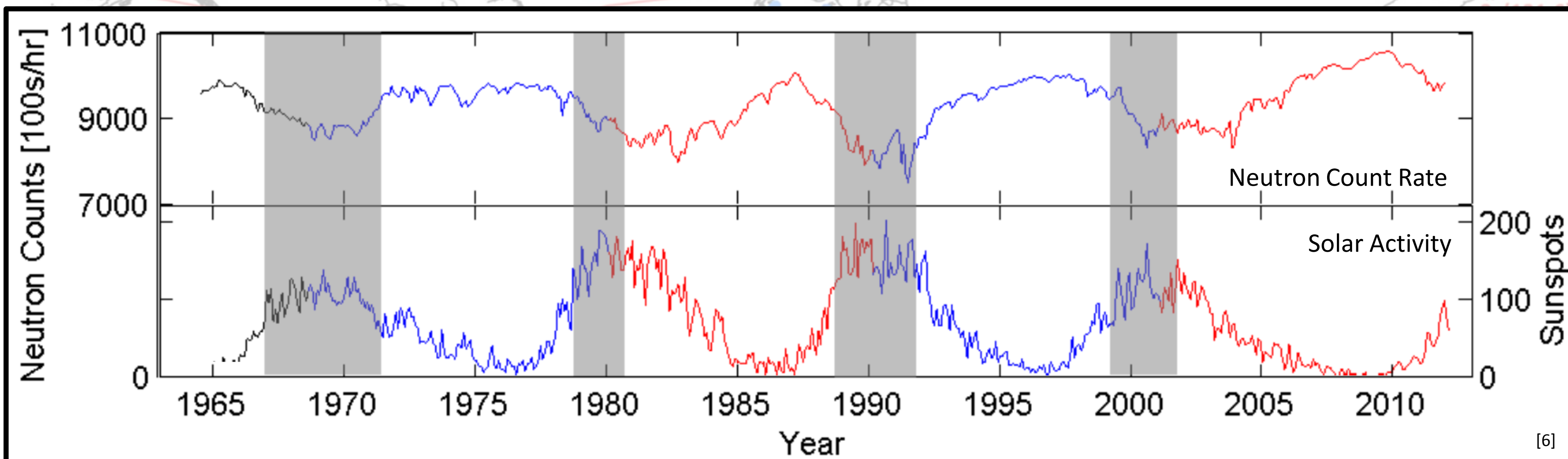

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[5] Andreasen, M. et al. “Status and Perspectives on the Cosmic-Ray Neutron Method for Soil Moisture Estimation and Other Environmental Science Applications.” Vadose Zone Journal 16(8) (2017)
[6] Thomas, S.R. et al. “The 22-Year Hale Cycle in Cosmic Ray Flux -Evidence for Direct Heliospheric Modulation.” Solar Physics 289(1) (2014)

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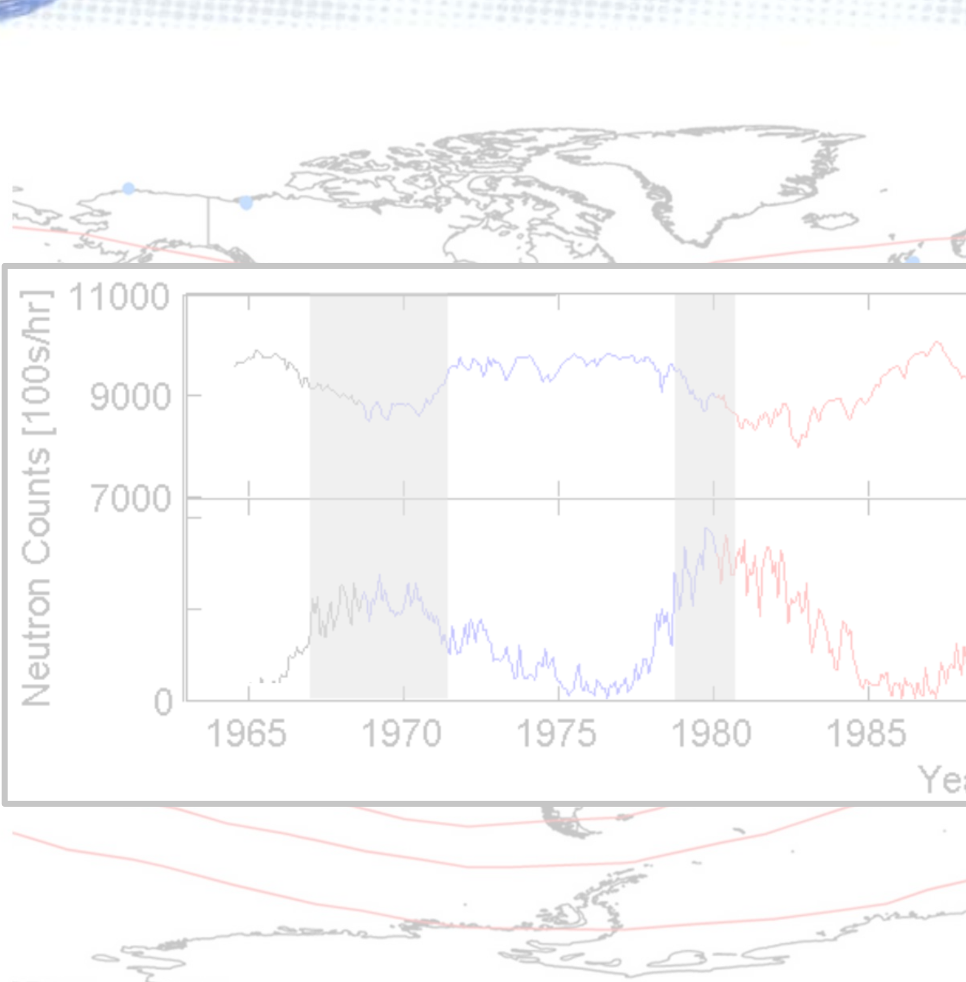

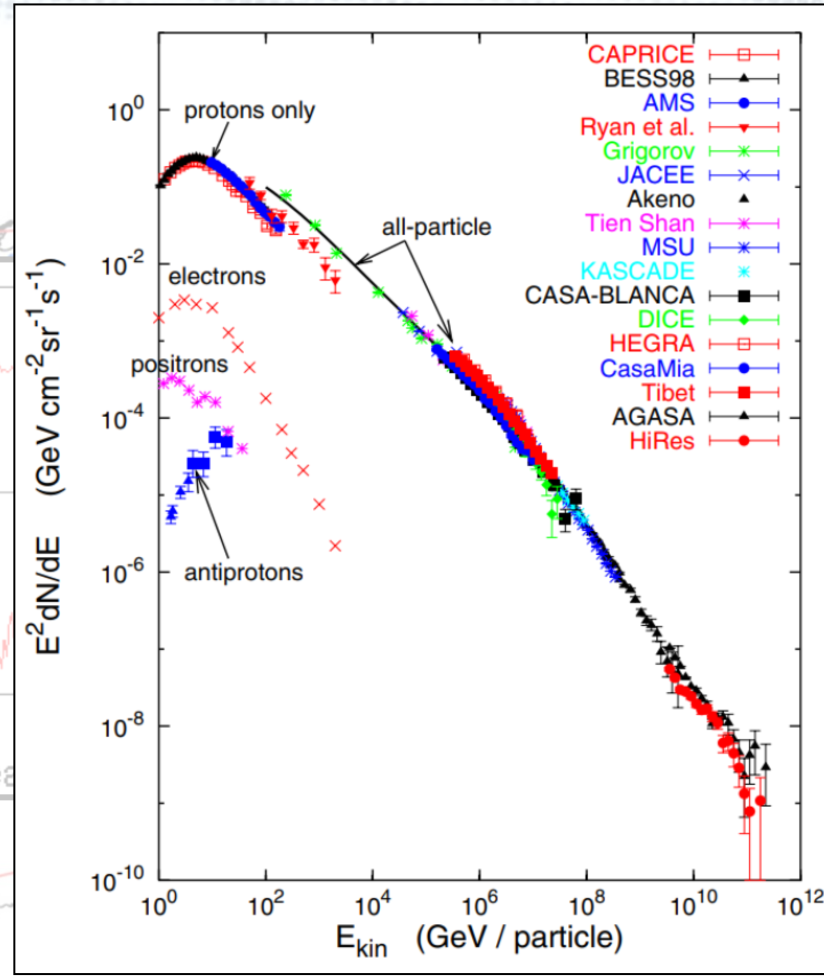

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[6] Thomas, S.R. et al. "The 22-Year Hale Cycle in Cosmic Ray Flux -Evidence for Direct Heliospheric Modulation." Solar Physics 289(1) (2014)

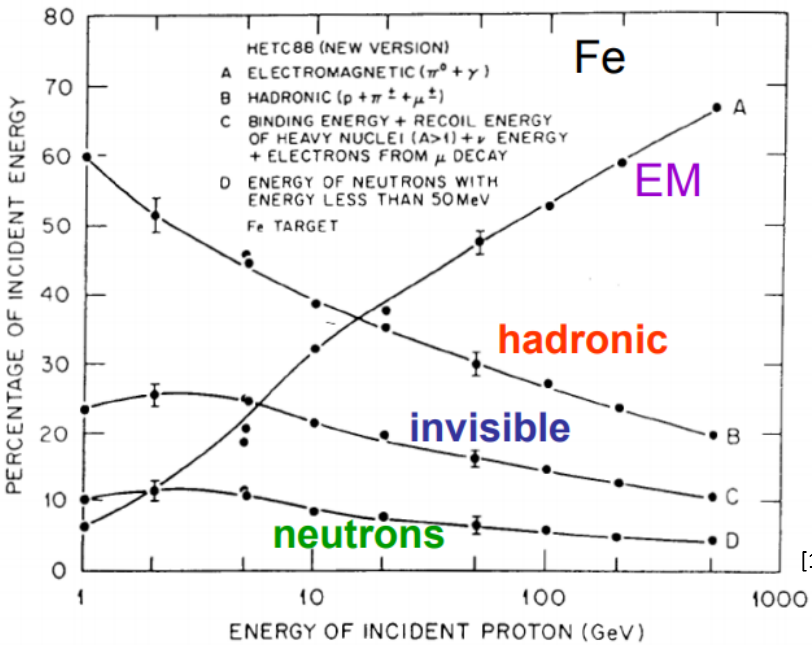
[7] Gaisser, T.K. "The Cosmic-ray Spectrum: from the knee to the ankle." Journal of Physics:Conference Series 47(1) (2006)

Neutrons in Calorimeters

Deposited Energy

$$E_p = f_{em} e + (1 - f_{em}) h$$

$$h = f_{rel} \cdot rel + f_p \cdot p + f_n \cdot n + f_{inv} \cdot inv$$



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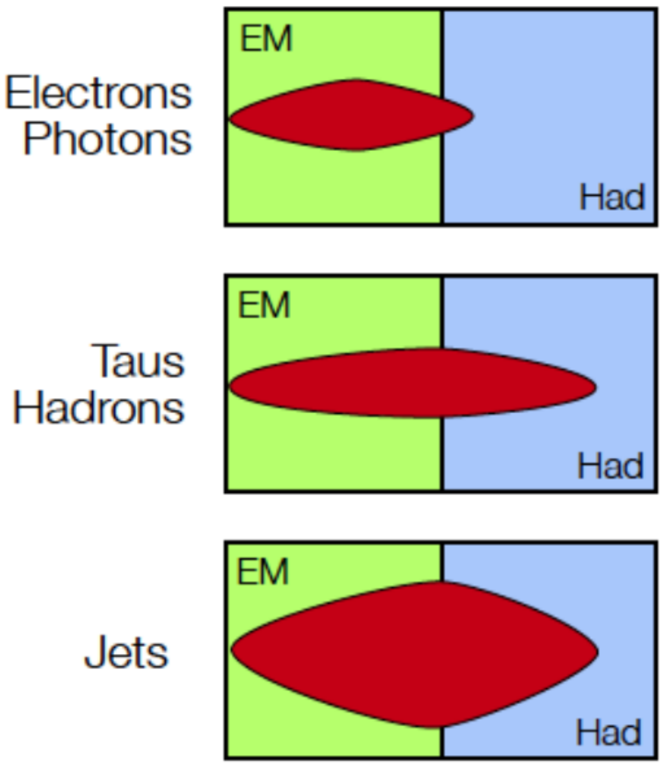
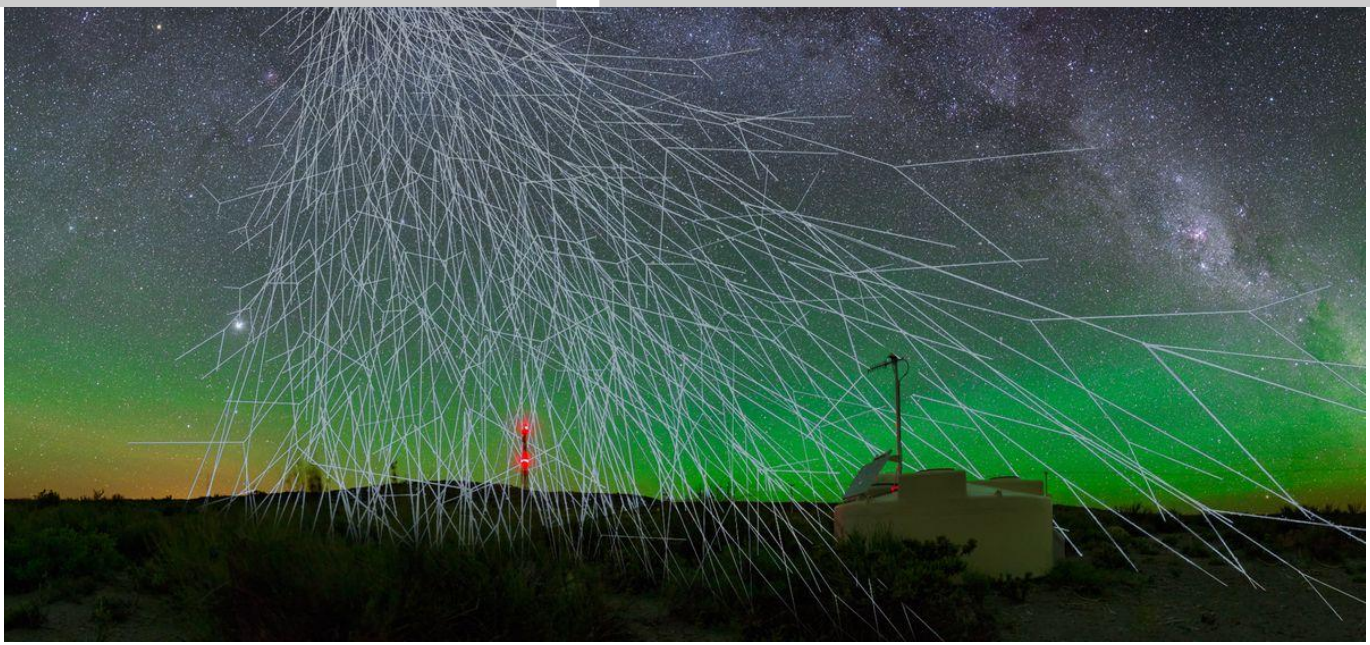


[2]

[1] Anderson, D.F. et. al. „Proceedings Of The First International Conference on Calorimetry In High Energy Physics" (1991)
[2] Schlepper, „Hadron Calorimeters" http://www.desy.de/~schleper/lehre/Det_Dat/SS_2018/06_lecture_calorimetry_HAD.pdf

The Cosmic Neutron Basics

Scattering			Absorption			
coherent	elastic	inelastic	photonic	charged	neutral	fission
	(n,n)	(n,n‘)	(n,γ‘)	(n,p) (n,d) (n,α)	(n,2n) (n,3n)	(n,f)



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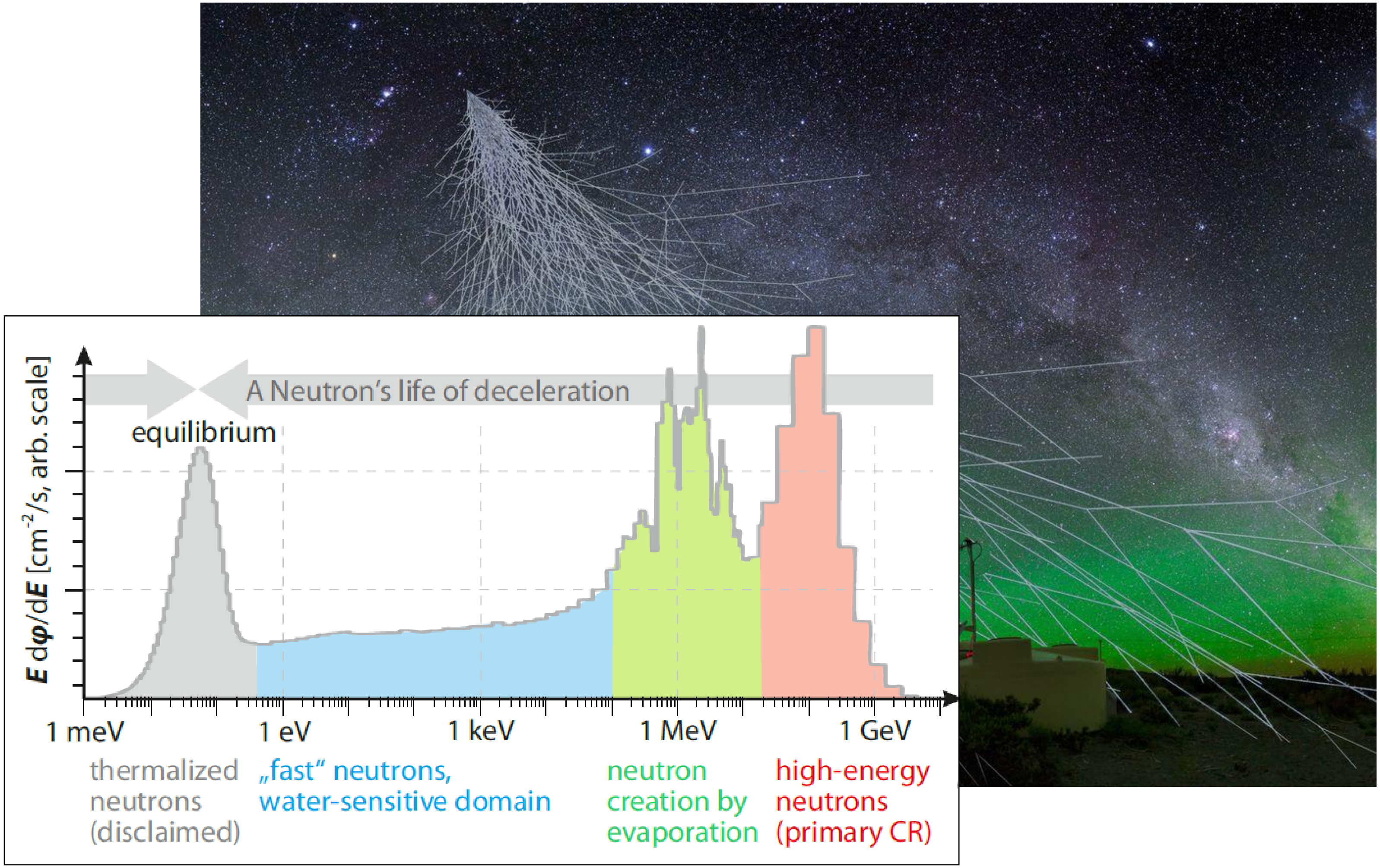
	(n,n)	(n,n‘)	(n,γ‘)	(n,p) (n,d) (n,α)	(n,2n) (n,3n)	(n,f)

Cold — Thermal — Epithermal — Fast — Medium Energy — High Energy

- Diffraction: Cold to Thermal
- Fission: Thermal to Fast
- Elastic Scattering: Cold to High Energy
- Capture: Cold to Fast
- Inelastic Scattering: Medium Energy to High Energy

< 1meV — < 0.5 eV — > 50 keV — > 1 MeV — > 10 MeV

The Cosmic Neutron Basics



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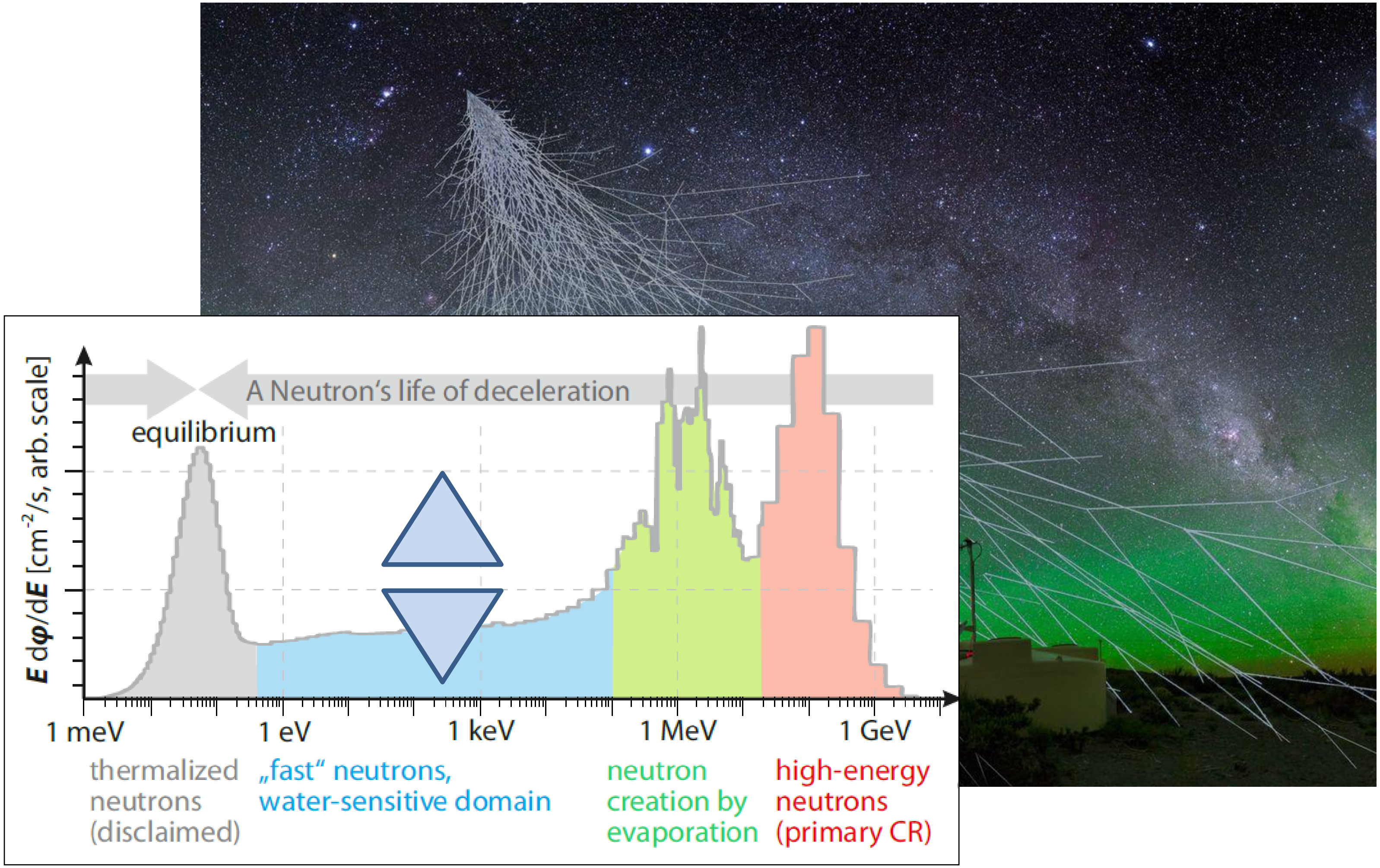
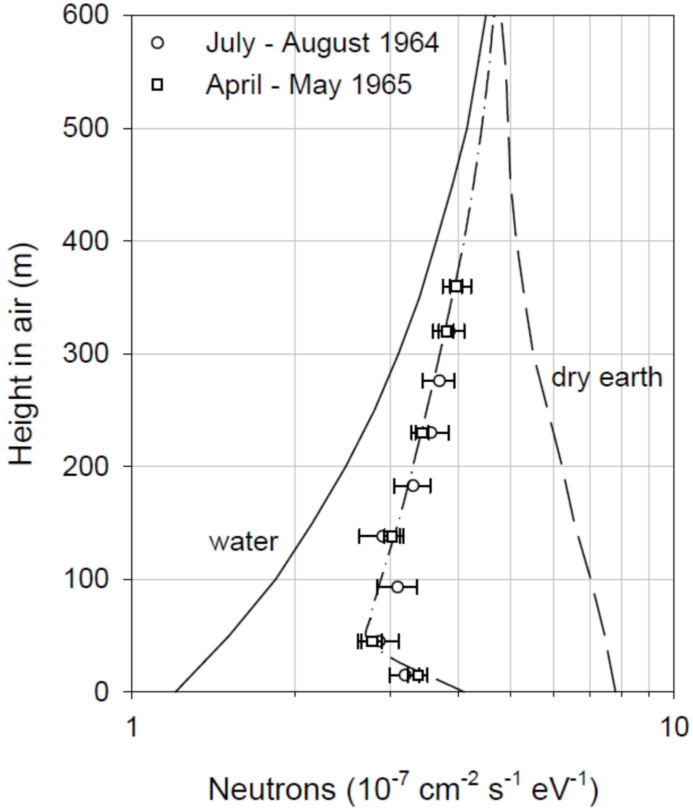


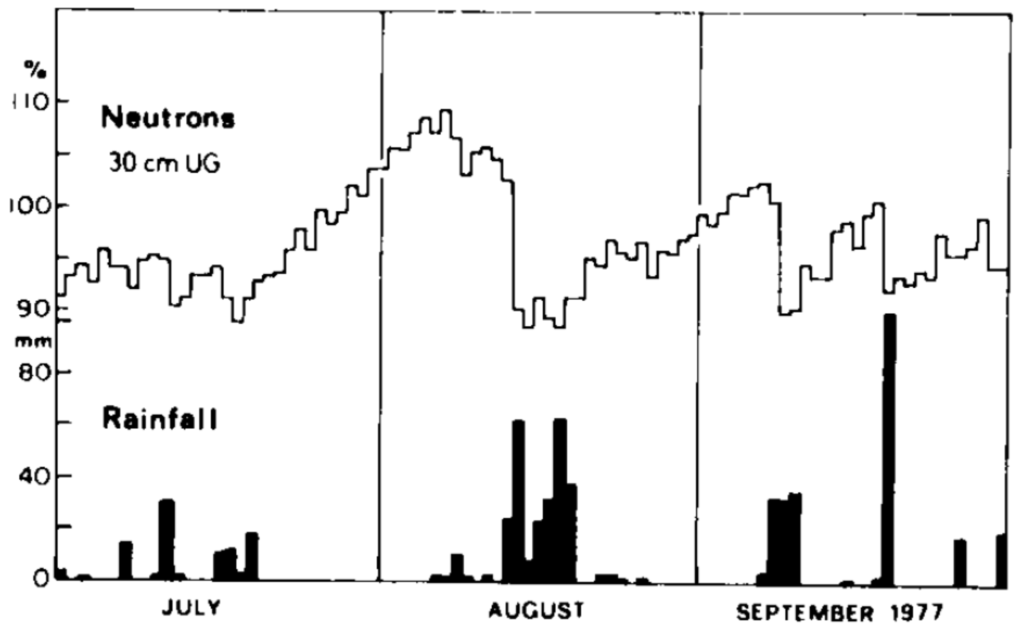
Historical References

1966



[1]

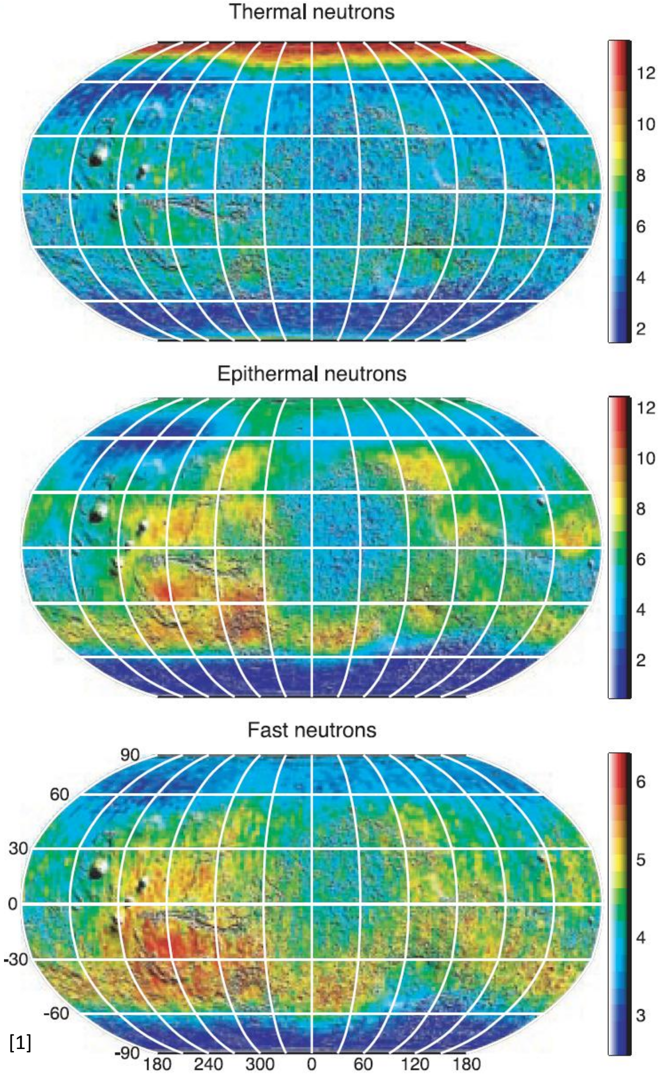
1985



[2]

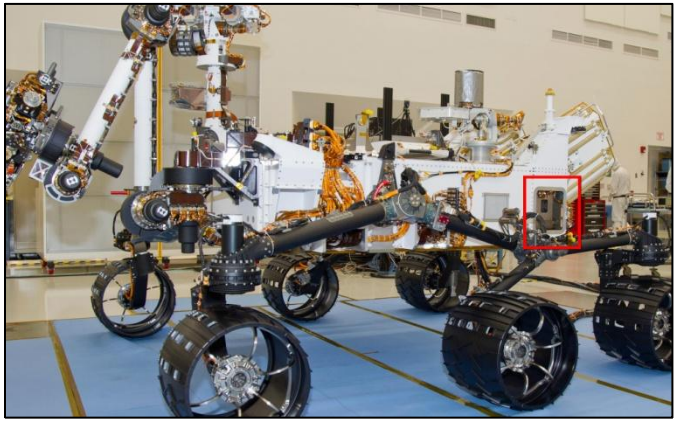
[1] Hendrick, L. D. and Edge, R. D., "Cosmic-ray neutrons near the Earth", Phys. Rev. Ser. II, 145 (1966)
[2] Kodama, M. et al., "Application of atmospheric neutrons to soil moisture measurement", Soil Sci., 140 (1985)

Water on Mars



[1]

Curiosity Rover



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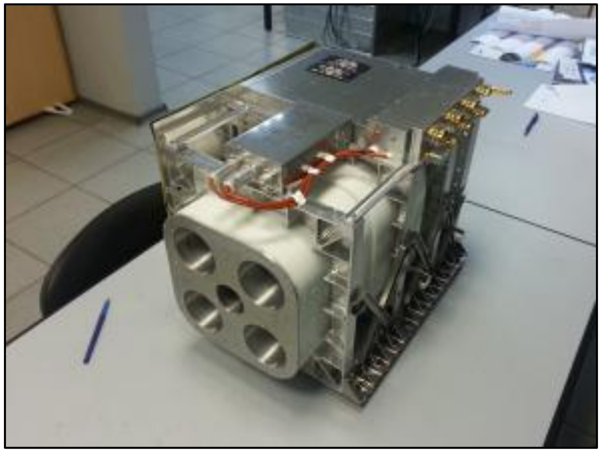
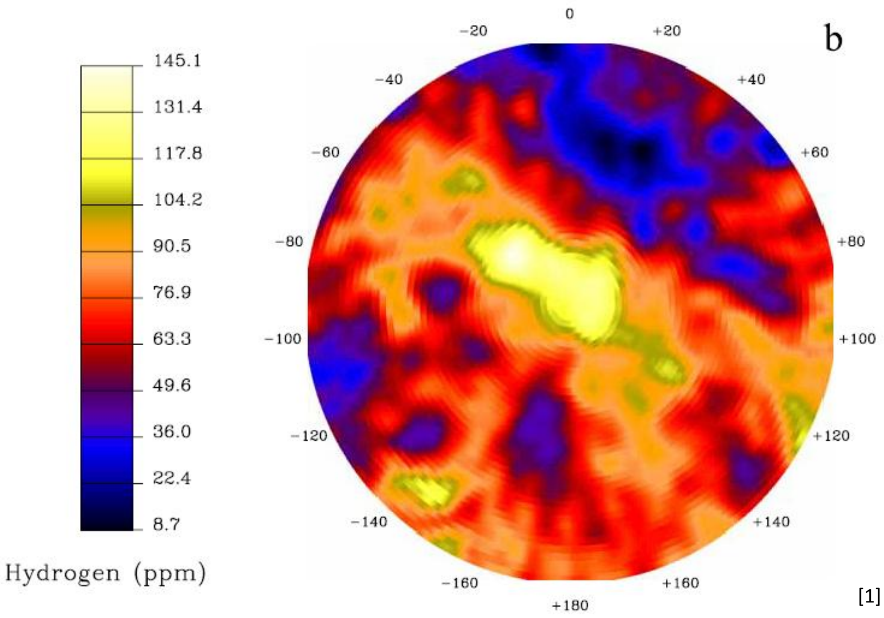


Trace Gas Orbiter

[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

Water on Moon

2002+



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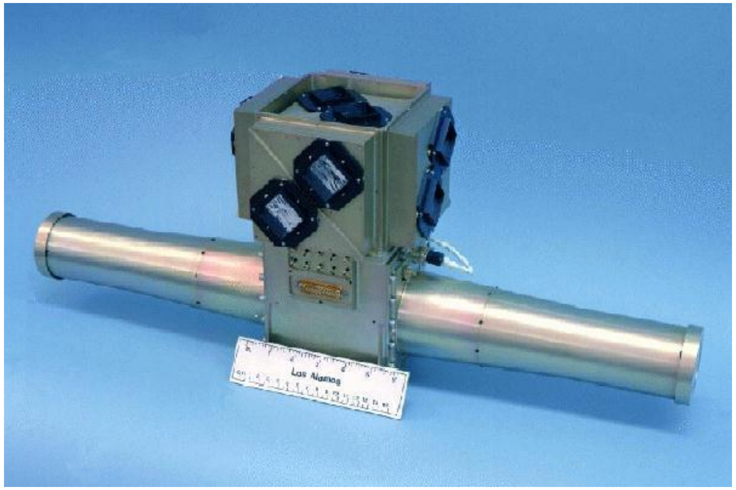
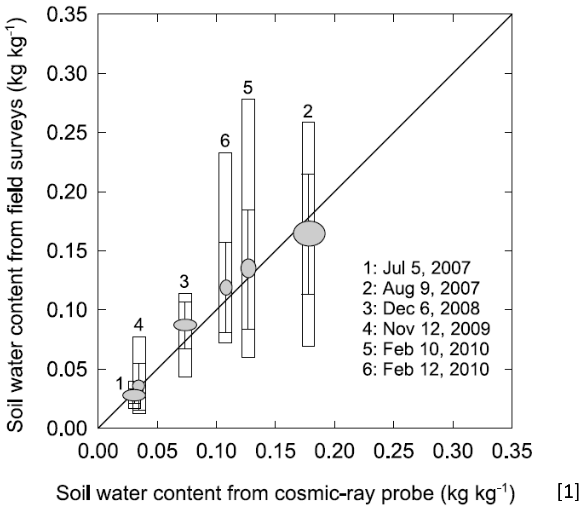


[2]

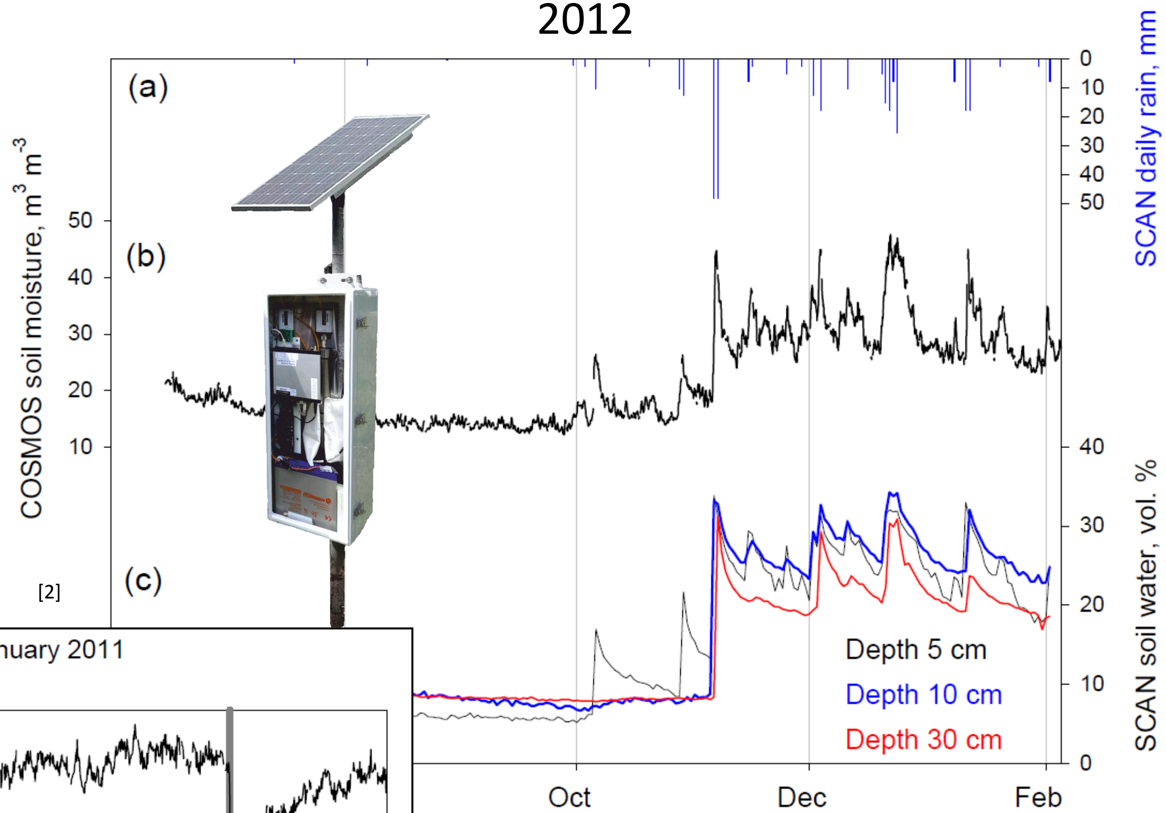
[1] Lawrence, D.J. et al., „Improved modeling of Lunar Prospector neutron spectrometer data: Implications for hydrogen deposits at the lunar poles“, Journal of Geophysical Research, 111 (2006)
[2] http://www.tsgc.utexas.edu/spacecraft/lunar_prospector/ns.html

The Birth of CRNS

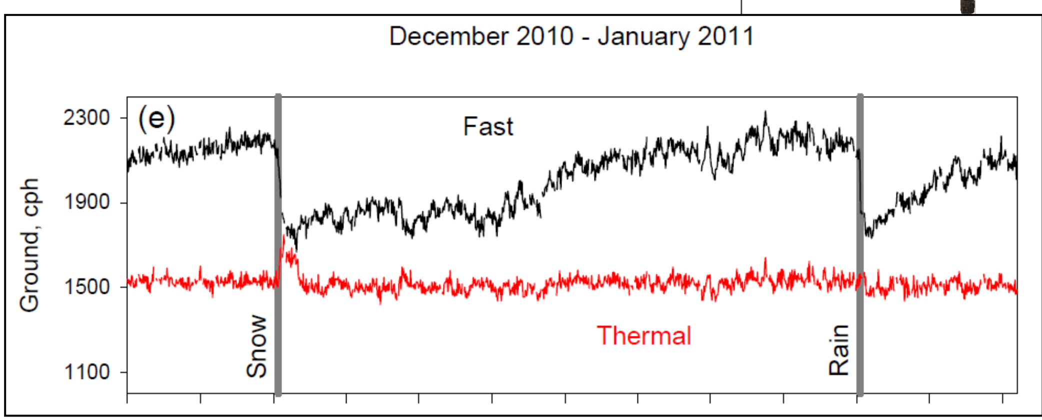
2010



2012



2010 - 2011



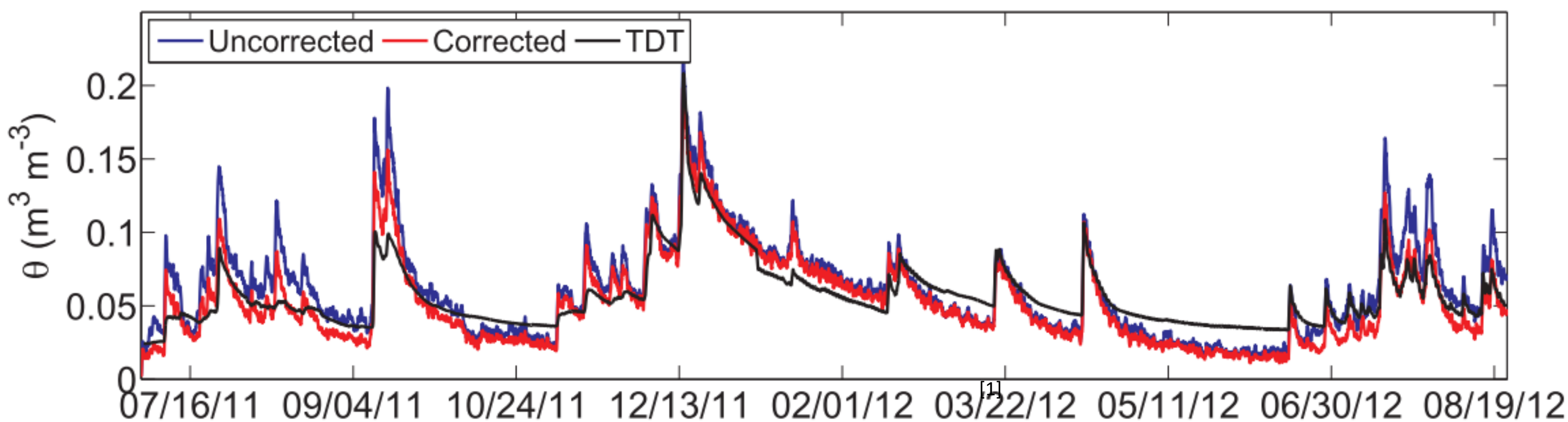
[1 Zreda, M. et al., "COSMOS: The COsmic-ray Soil Moisture Observing System." Hydrology and Earth System Sciences 16(11) (2012)
[2] Desilets, D. et al.,"Nature's neutron probe: Land surface hydrology at an elusive scale with cosmic rays.", Water Resources Research 46(11) (2010)

The Birth of CRNS

2013

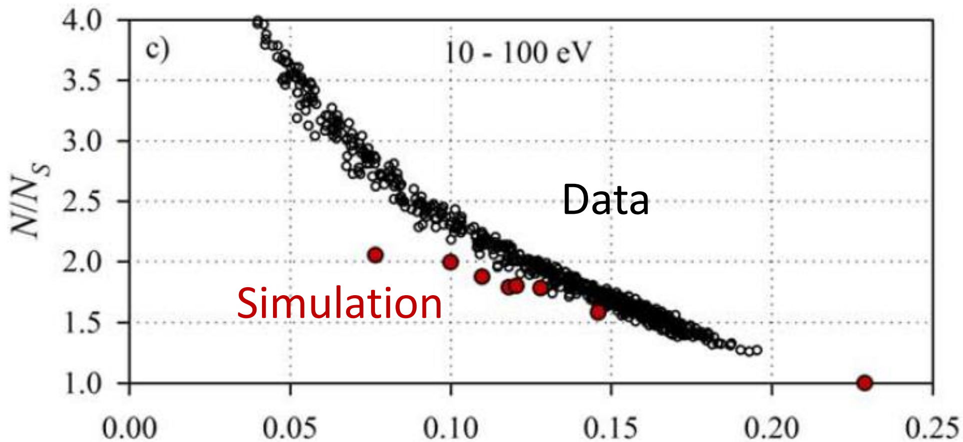
(b)

Arizona



[1]

2014



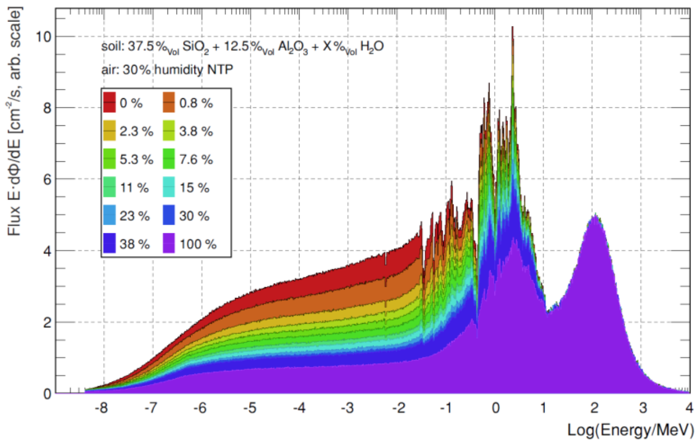
[2]

[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)

[2] McJannet, D. et al.,"Field testing of the universal calibration function for determination of soil moisture with cosmic-ray neutrons." Water Resources Res. 50(6) (2014)

The Birth of CRNS

2015



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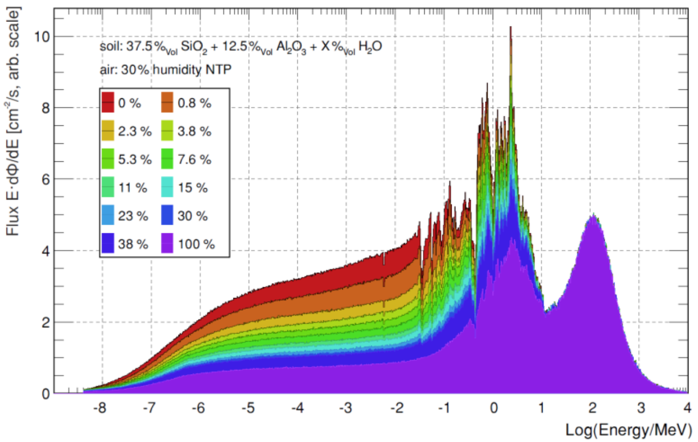
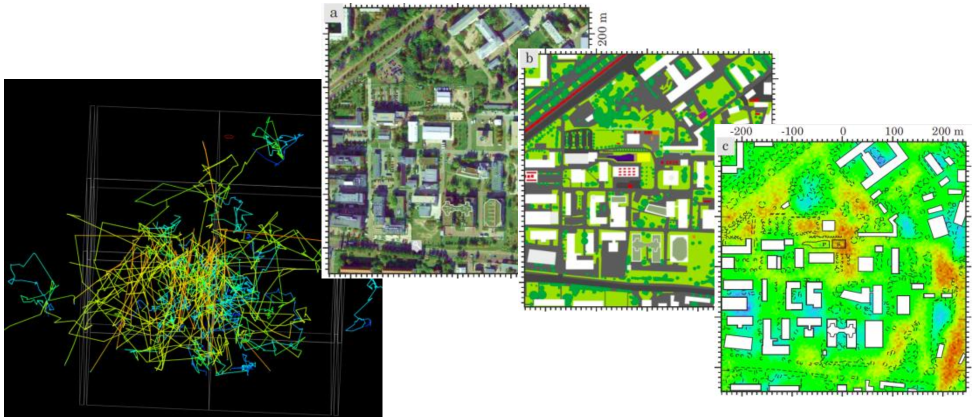
2015



URANOS

Ultra Rapid Adaptable Neutron-Only Simulation *for Environmental Research*

- Neutron Transport Monte Carlo
- Voxel Engine
- Ray-Casting
- Cosmic Neutron Source Option
- written in C++
- linked against ENDF data bases



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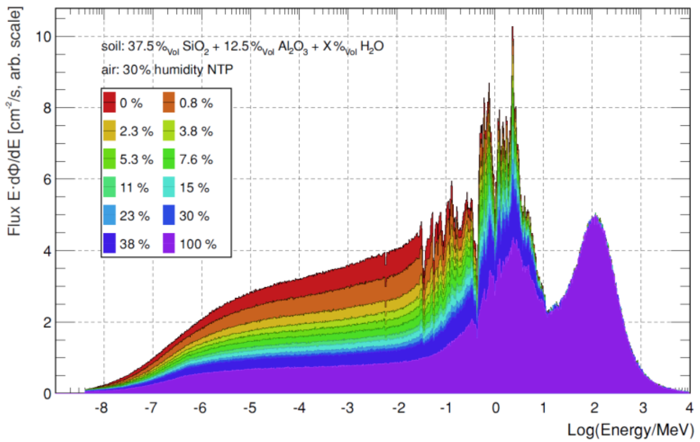
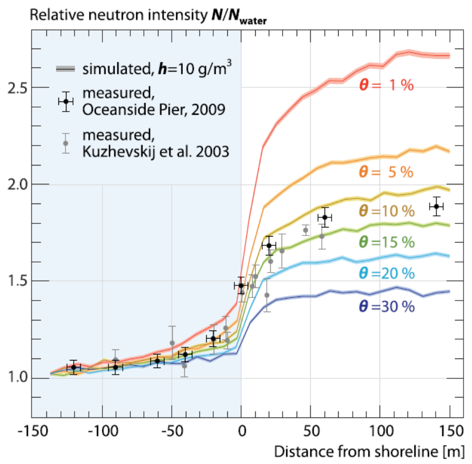
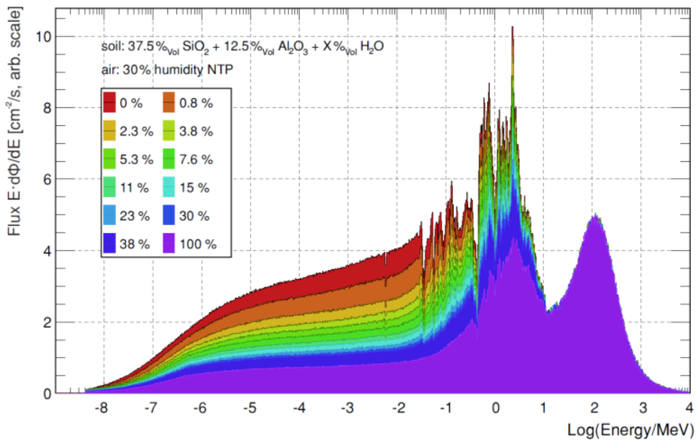
2015

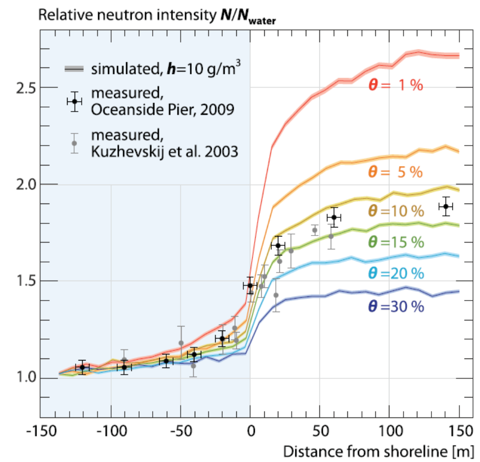


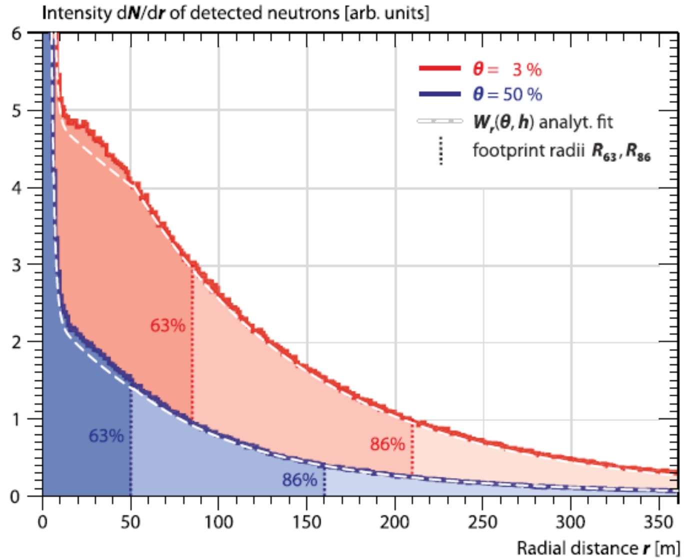


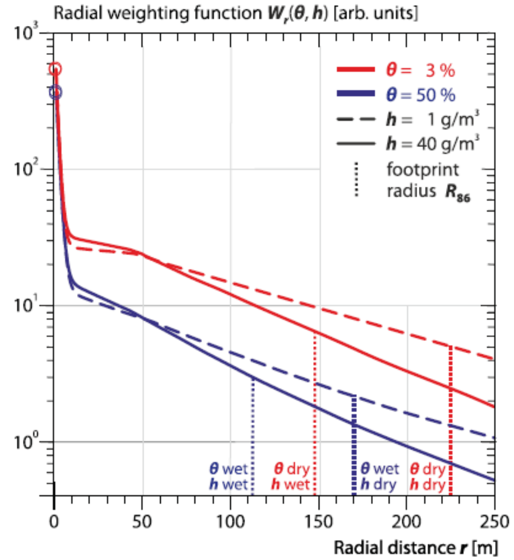
The Birth of CRNS

2015





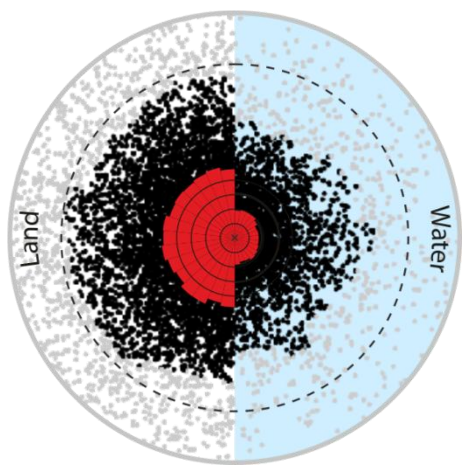




Cosmic Neutron Propagation

dry land

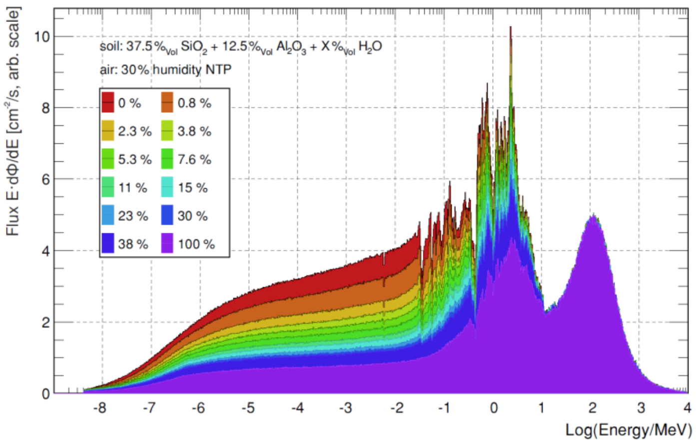
water

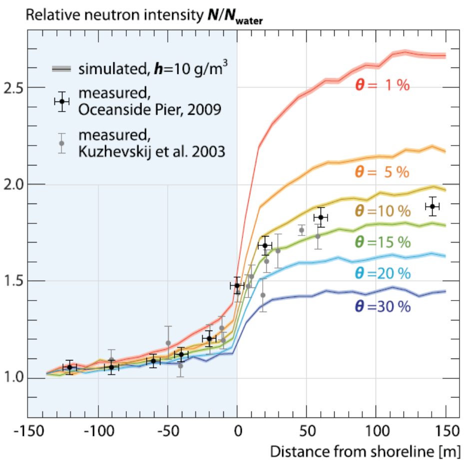


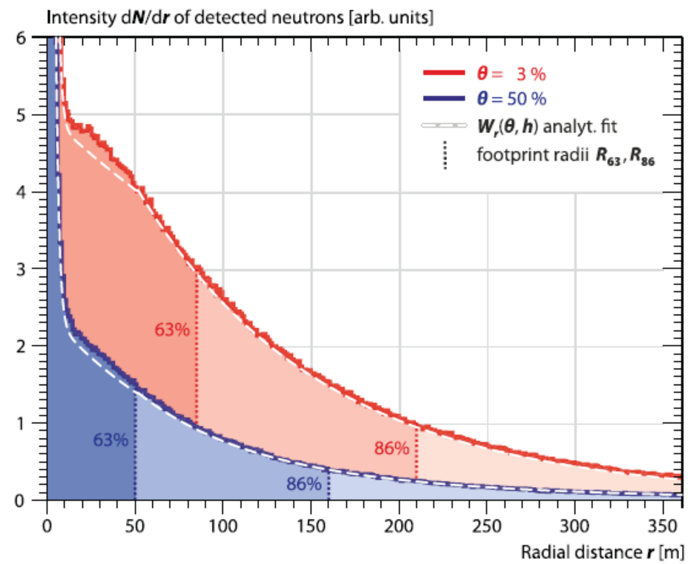
Footprint

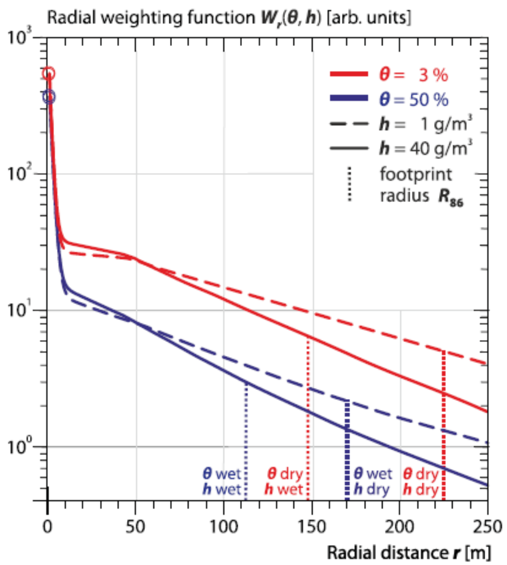
The Birth of CRNS

2015



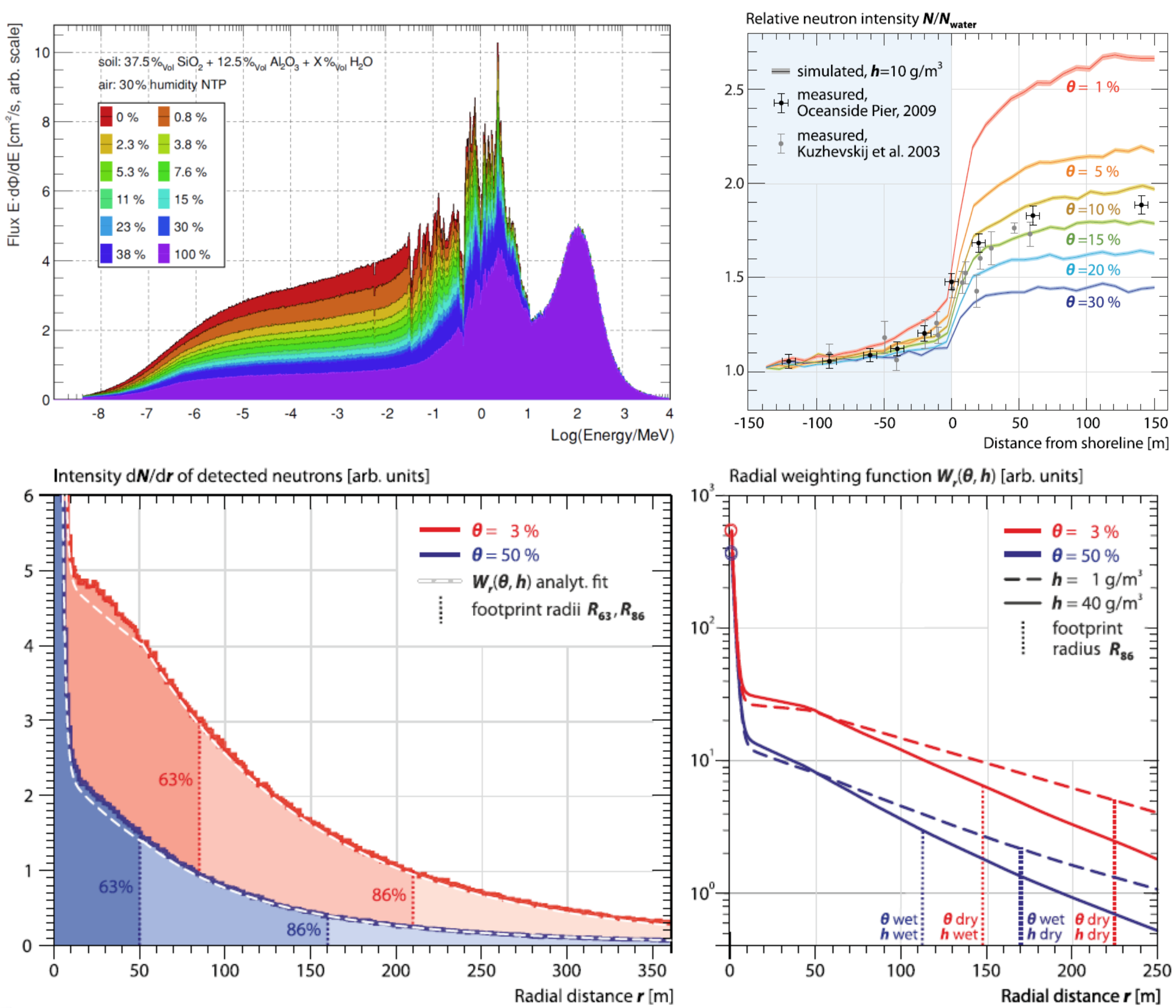


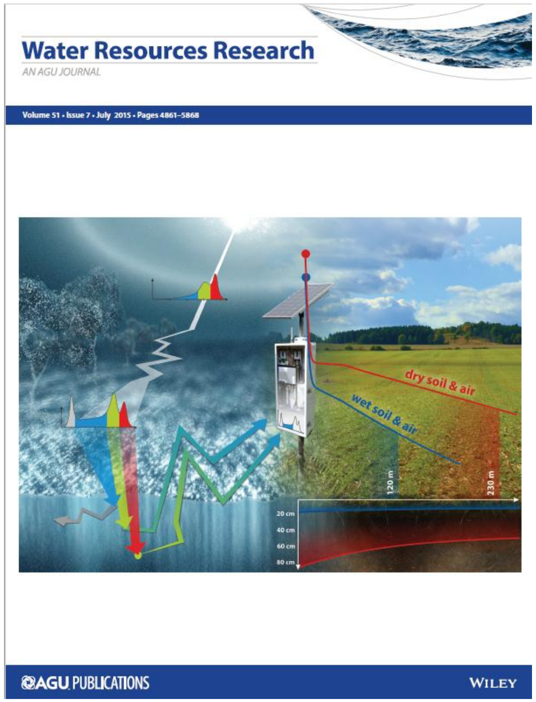




The Birth of CRNS

2015





The Birth of CRNS

gu/journal/10.1002/(ISSN)1944-7973/issues/2007/

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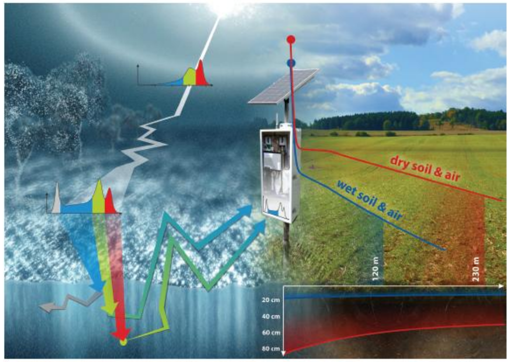

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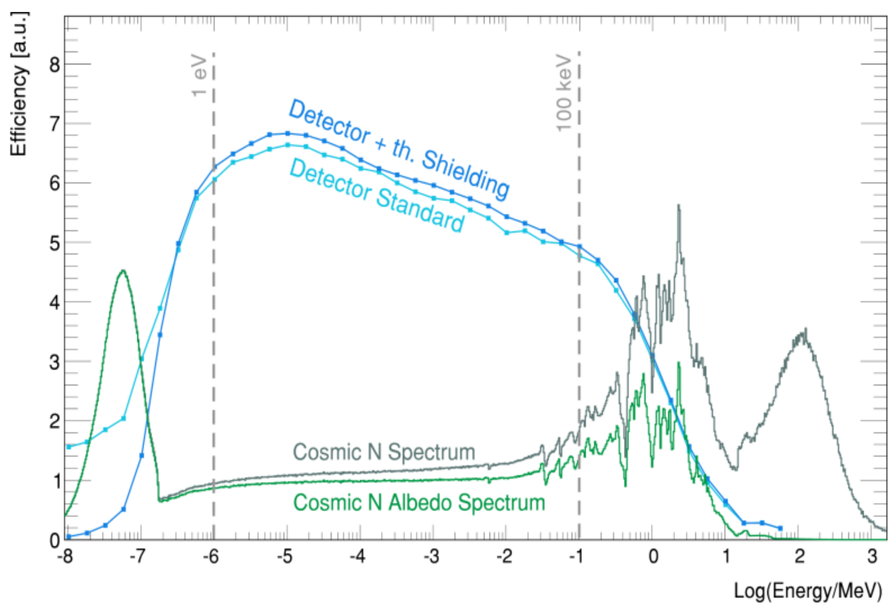
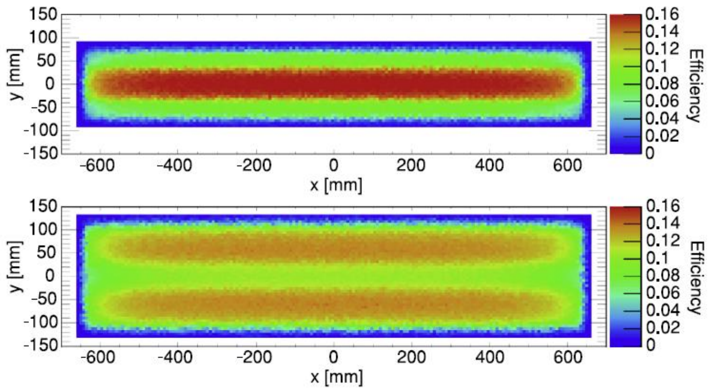
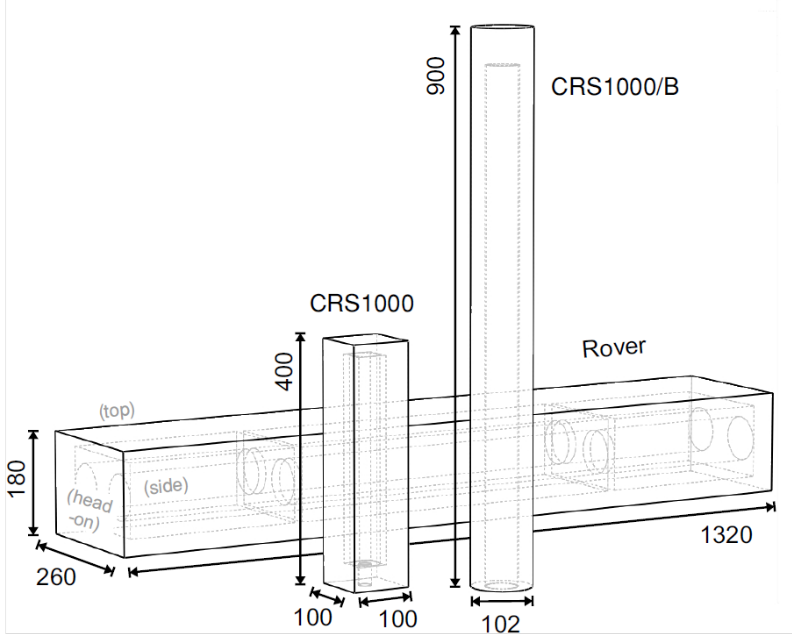
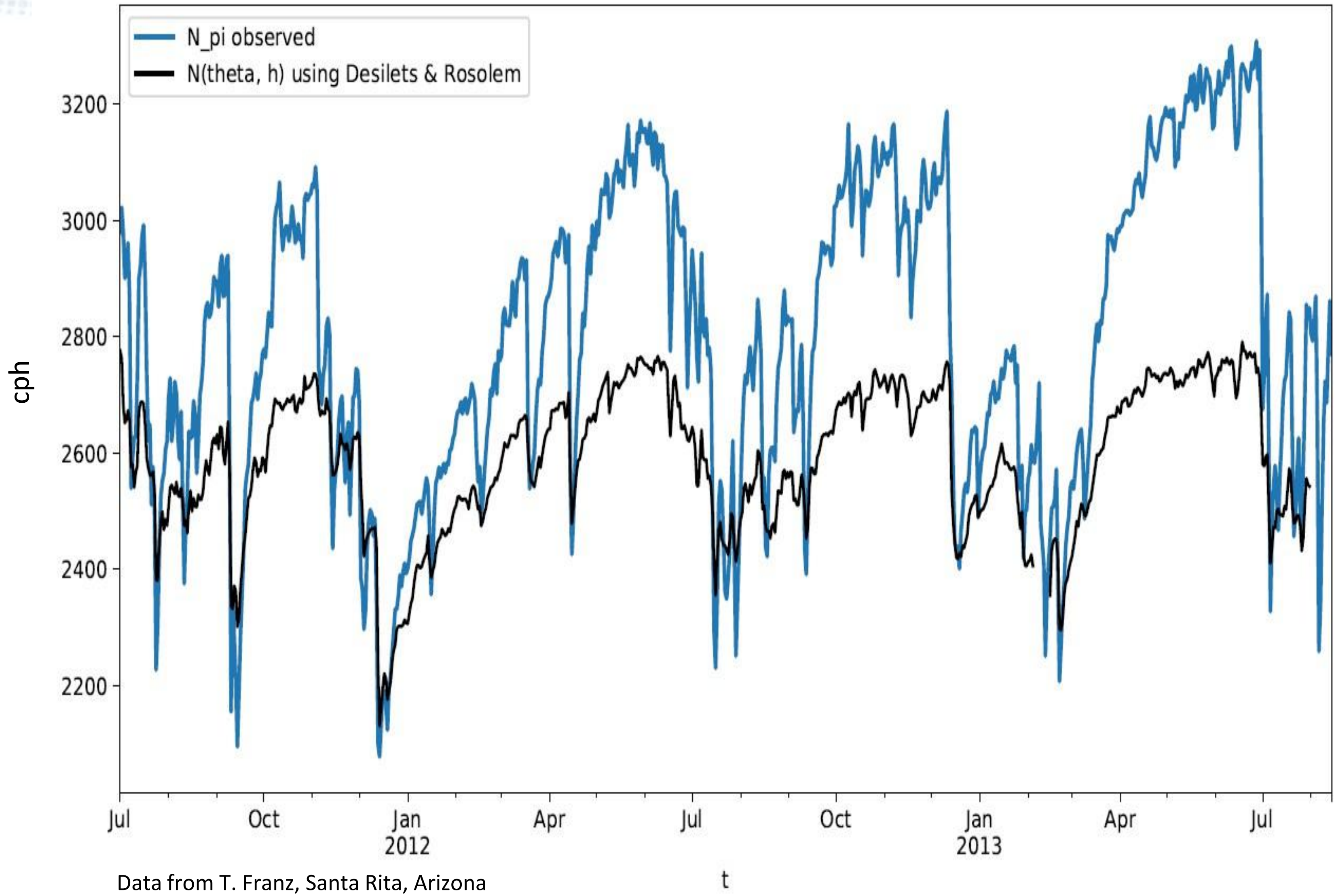
Detector Response Function





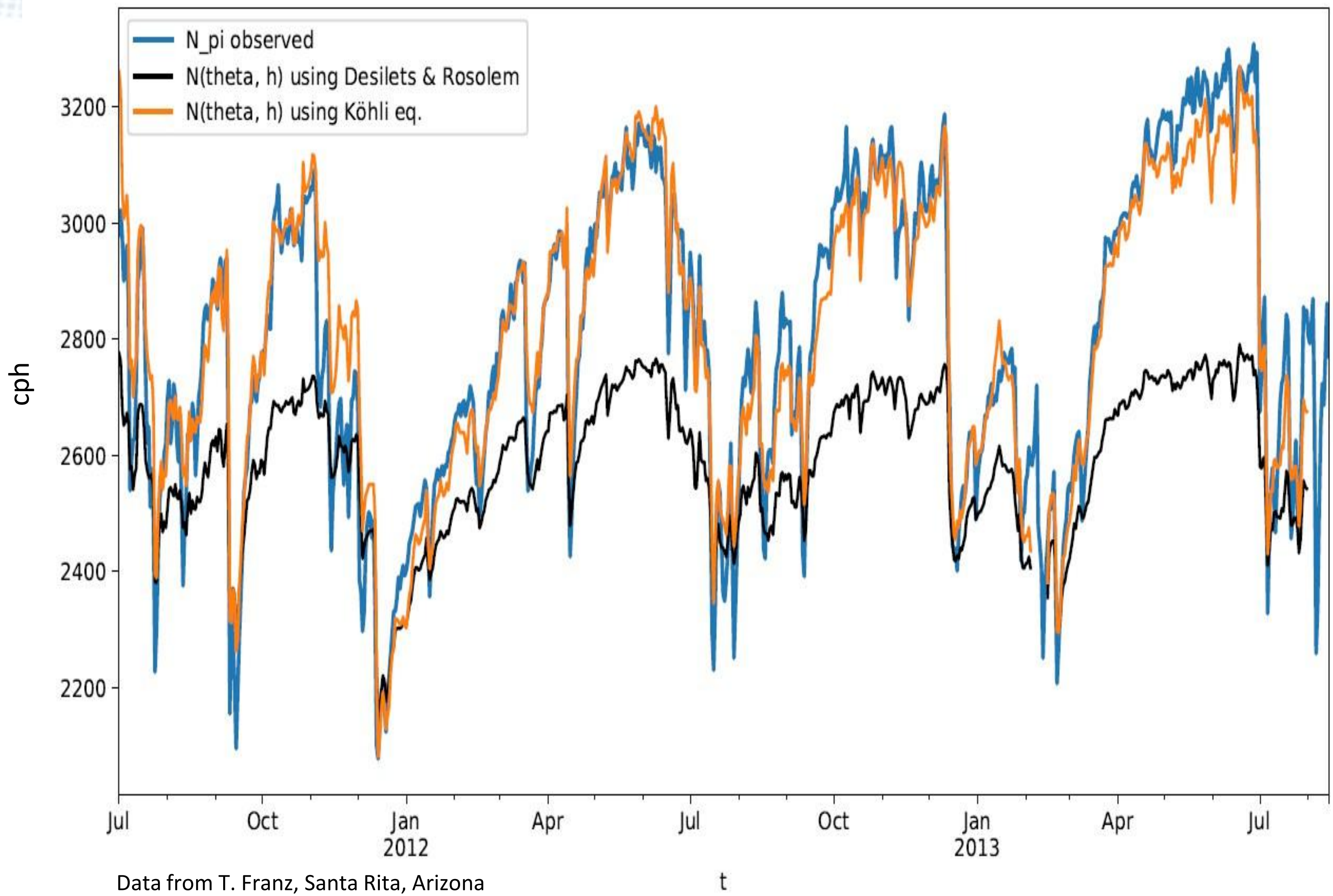


Intensity Function



Data from T. Franz, Santa Rita, Arizona

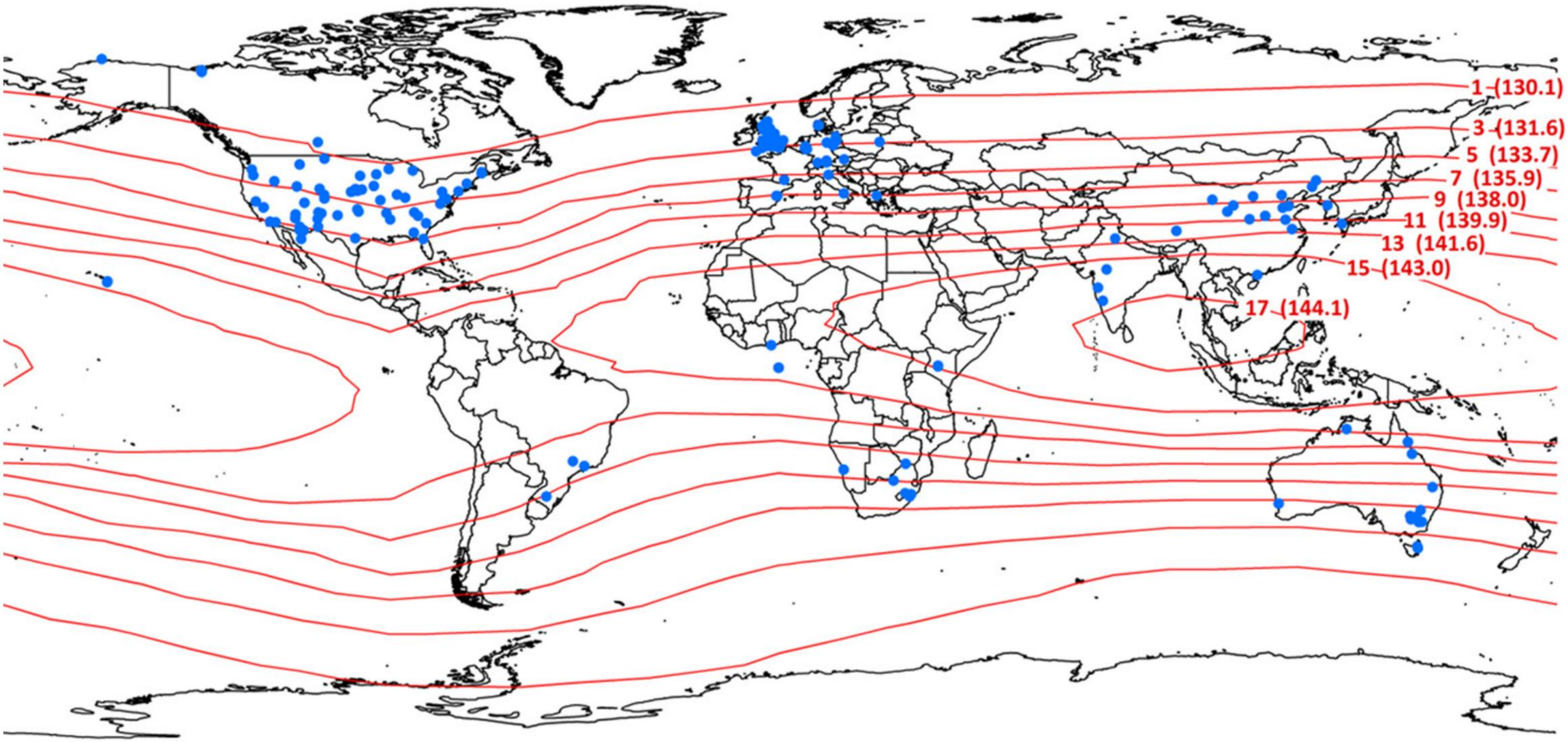
Intensity Function Revised



Data from T. Franz, Santa Rita, Arizona

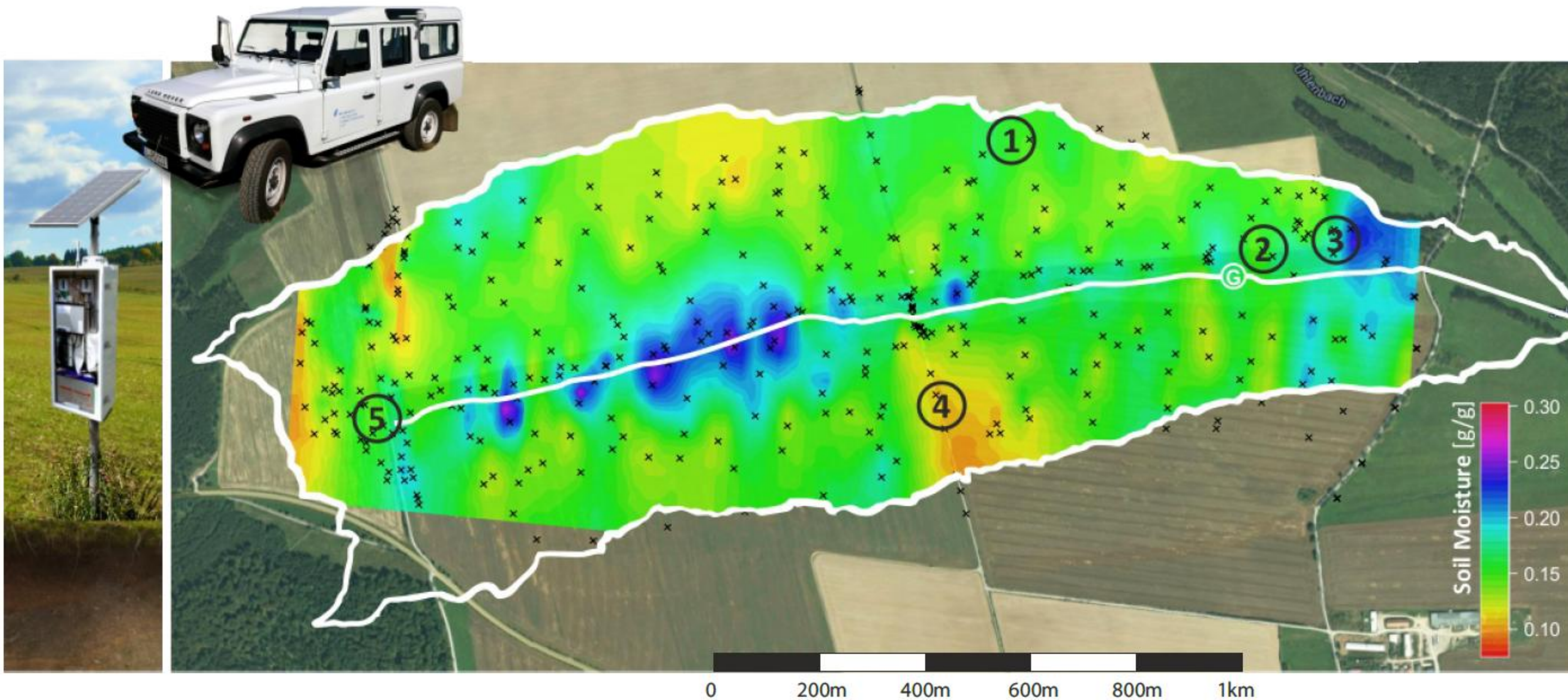
Examples and Recent Studies

COSMOS Probe Deployment

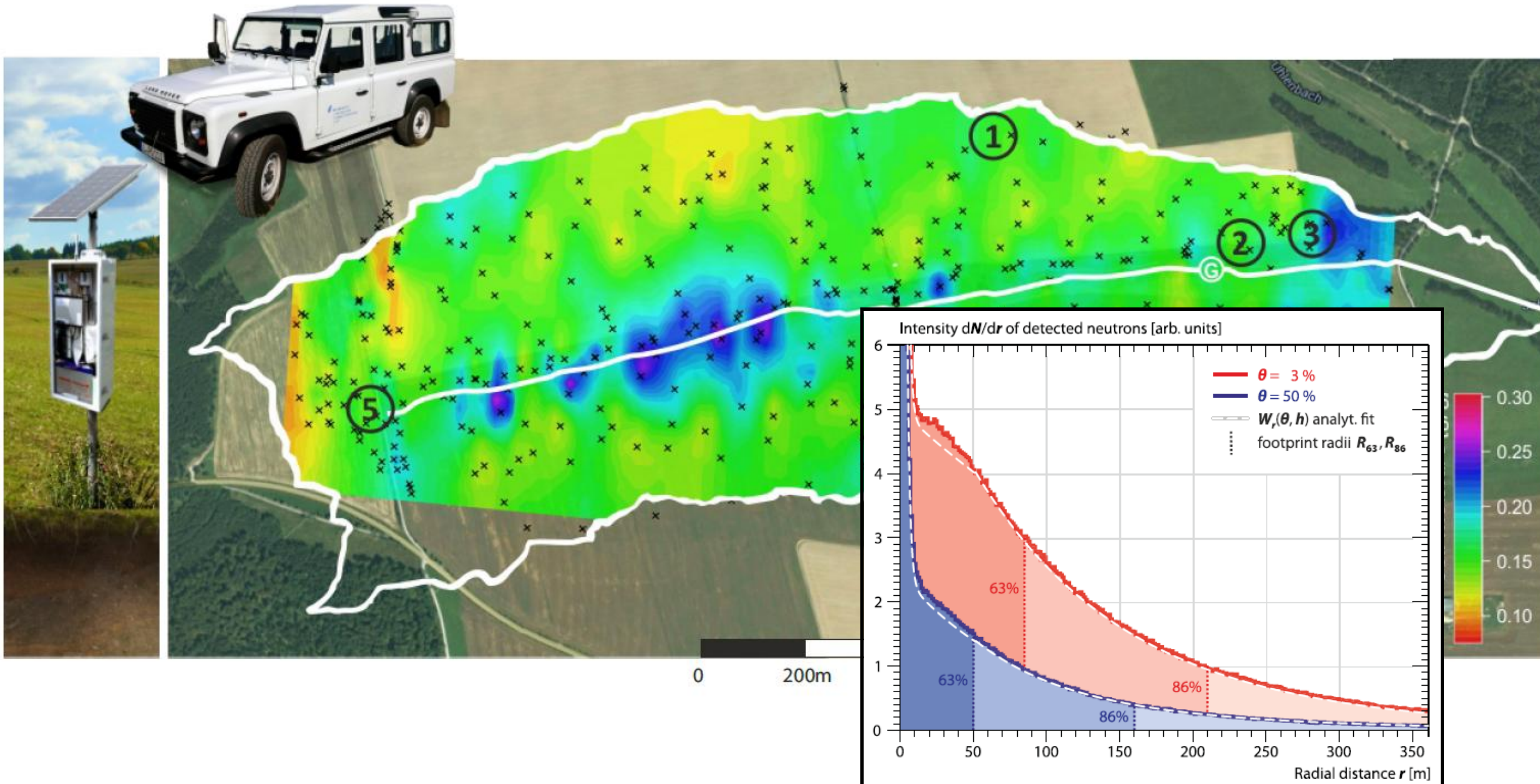


[5] Andreasen, M. et al. "Status and Perspectives on the Cosmic-Ray Neutron Method for Soil Moisture Estimation and Other Environmental Science Applications." Vadose Zone Journal 16(8) (2017)

Roving


1
2
3
4
5
G
Soil Moisture [g/g]
0.30
0.25
0.20
0.15
0.10
0
200m
400m
600m
800m
1km

Roving

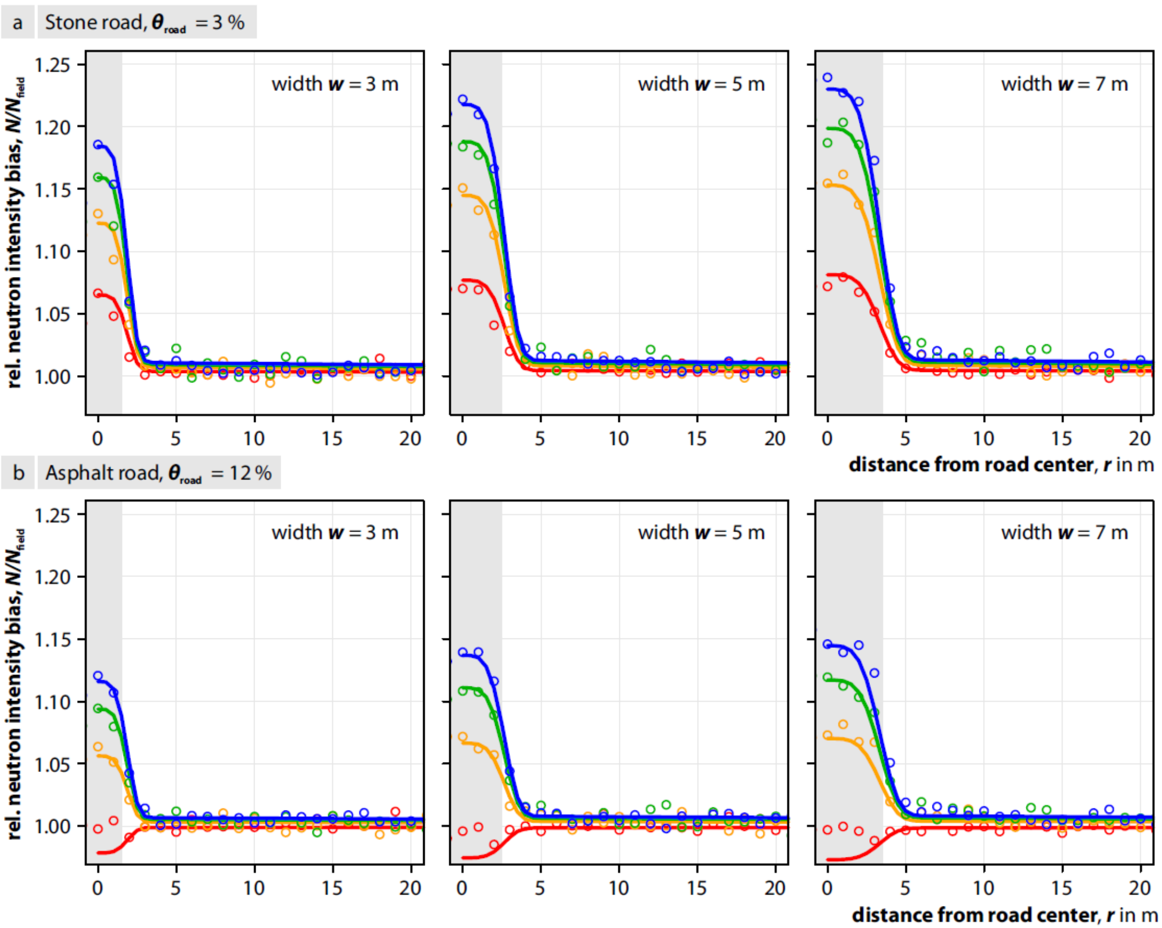


1
2
3
5
G
Uhlenbach
0
200m
0.30
0.25
0.20
0.15
0.10
Intensity dN/dr of detected neutrons [arb. units]
θ = 3 %
θ = 50 %
W_r(θ, h) analyt. fit
footprint radii R63, R86
63%
86%
63%
86%
0
1
2
3
4
5
6
0
50
100
150
200
250
300
350
Radial distance r [m]

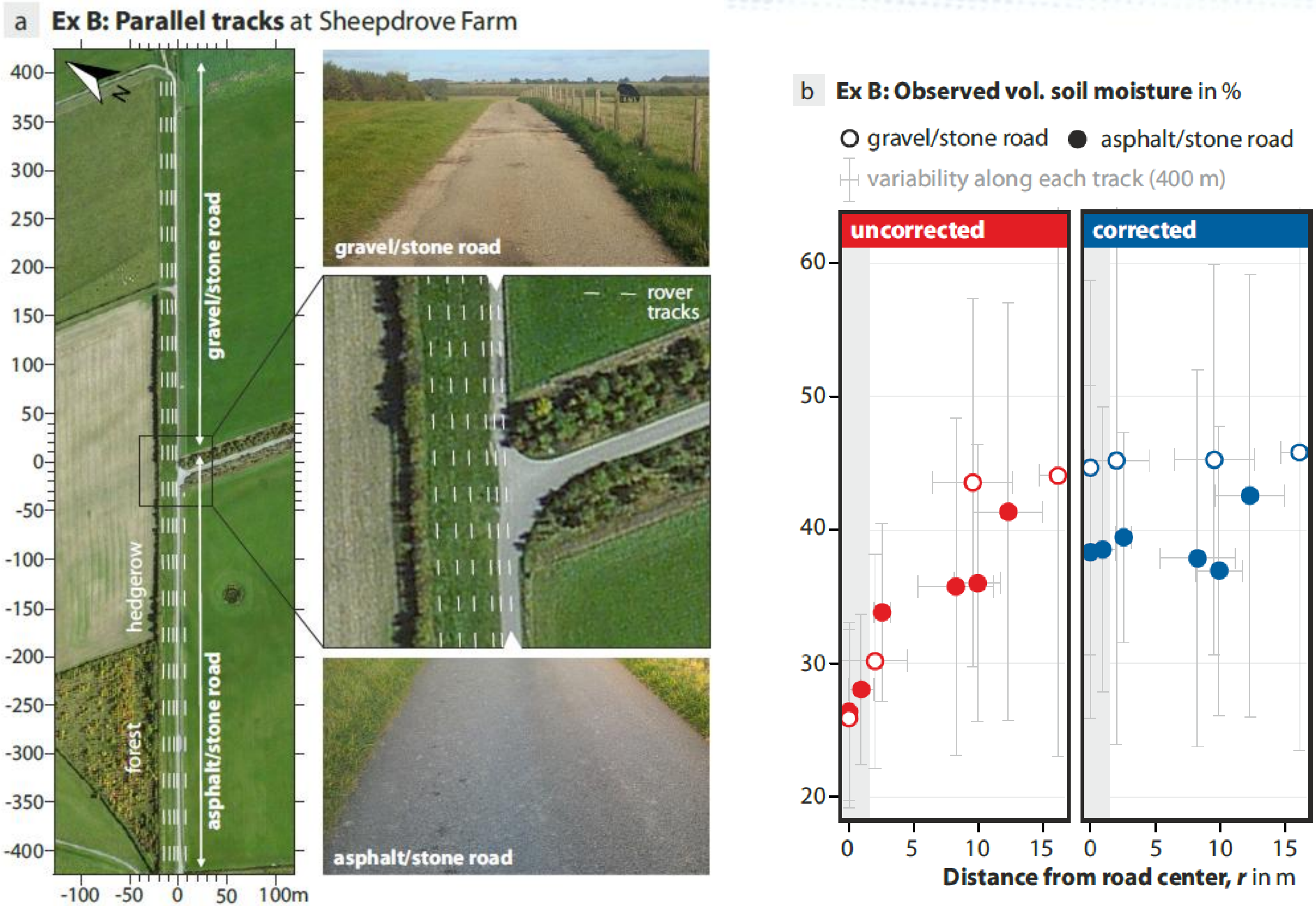
The Road Effect

HELMHOLTZ
CENTRE FOR
ENVIRONMENTAL
RESEARCH – UFZ

In collaboration with
Martin Schrön
UFZ Leipzig

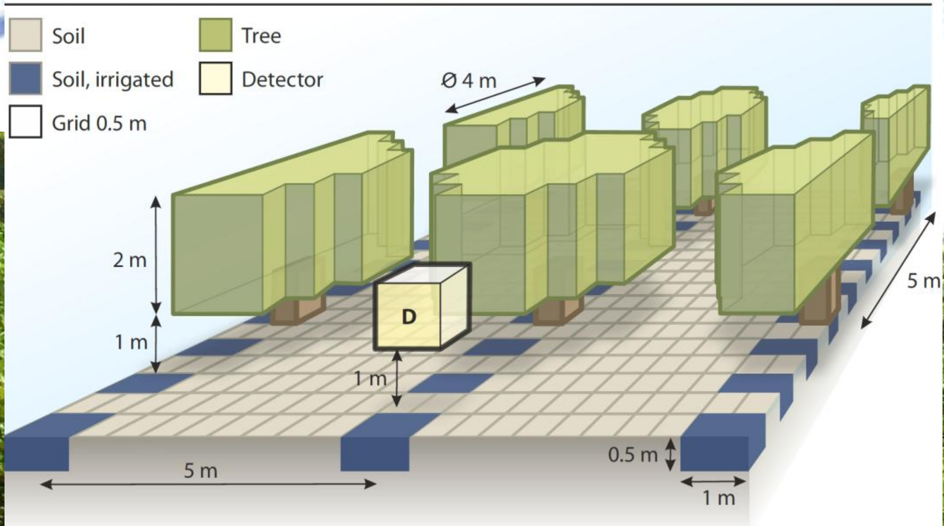


The Road Effect



Drip Irrigation

Schematical segment of the URANOS setup, total extent: 500 m

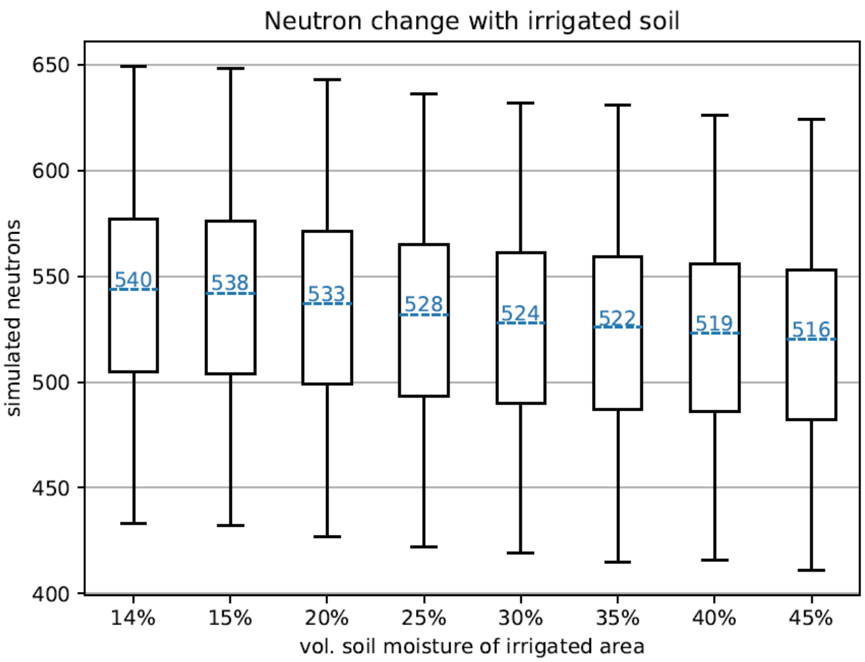


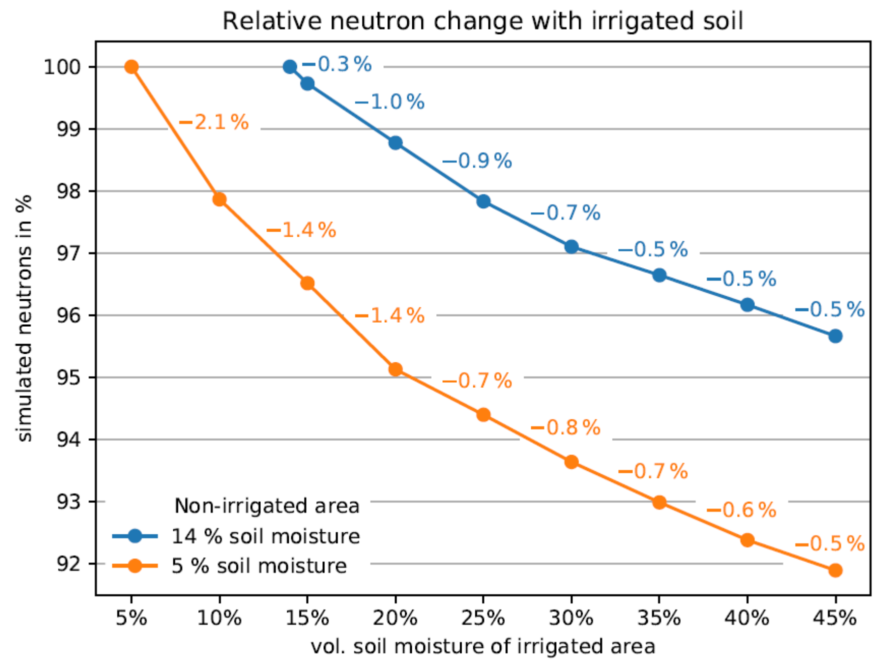
D. Li et al., to be published

Drip Irrigation

In collaboration with
Dazhi Li
FZ Jülich

Lemon trees: 3 kg/m^3 biomass
8 % of soil irrigated

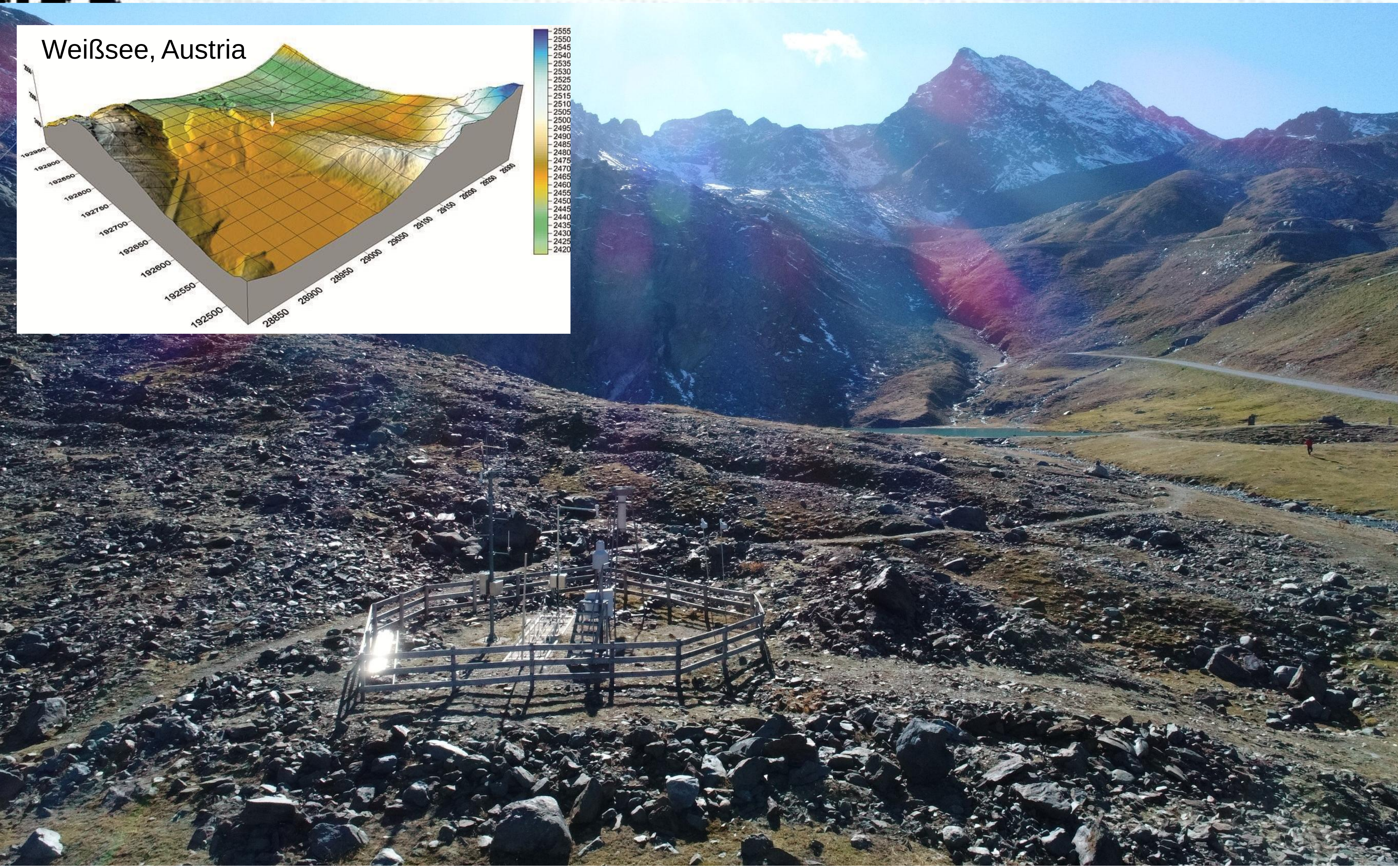




Only a few percent change -> needs large sensor

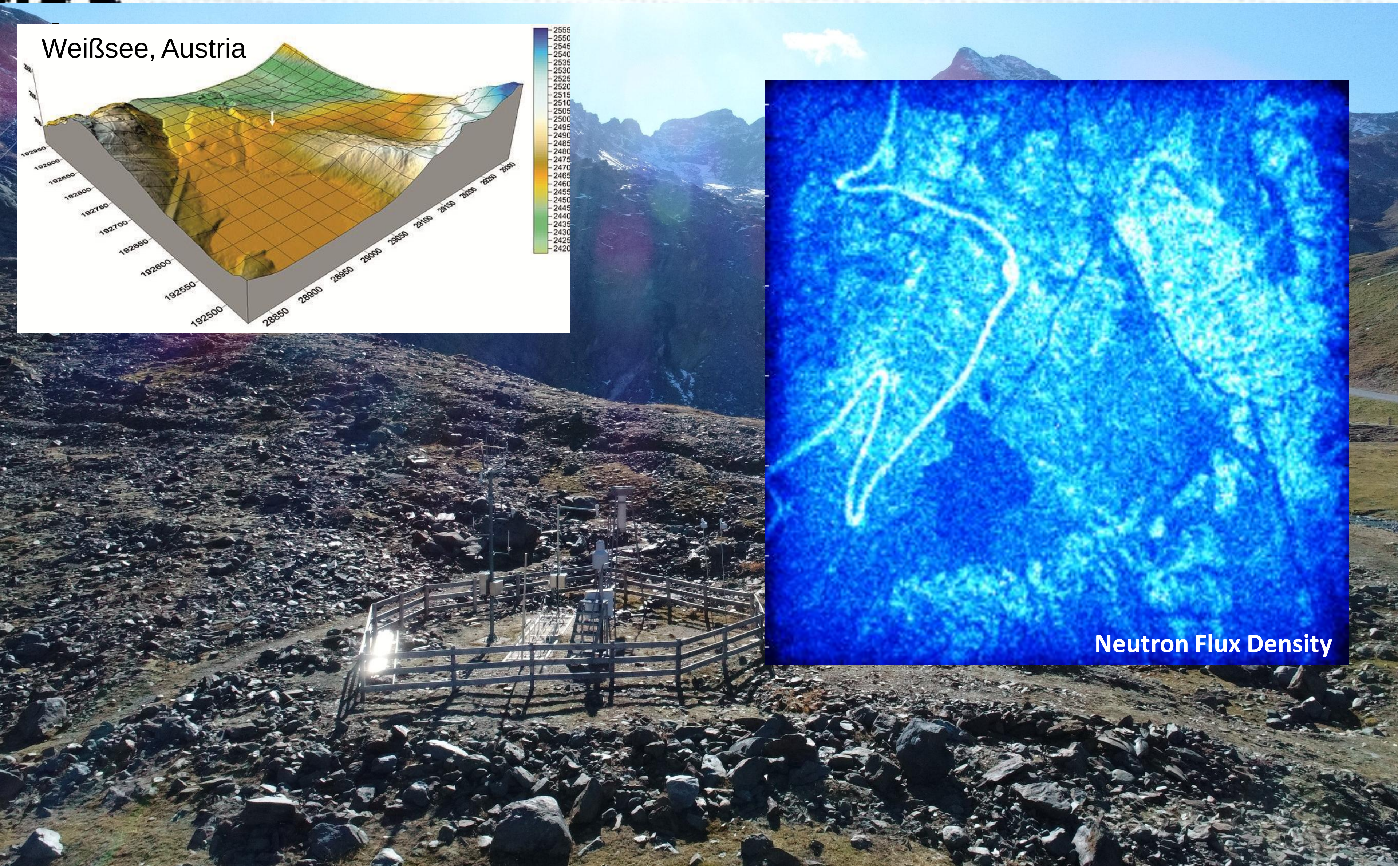
D. Li et al., to be published

Snow Water Equivalent



P. Schattan et al., to be published

Snow Water Equivalent

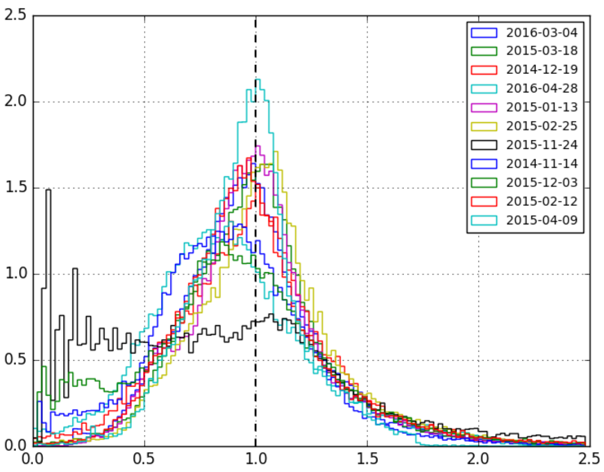


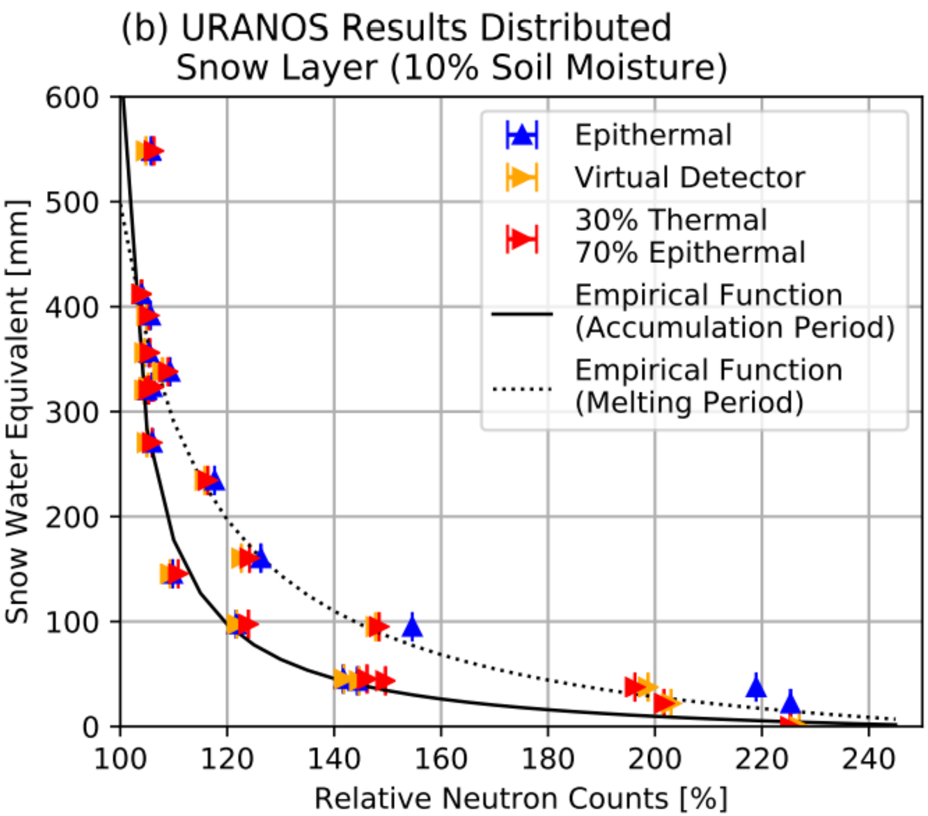
P. Schattan et al., to be published

Snow Water Equivalent

In collaboration with
Paul Schattan
Uni Insbruck

3D Laser scanner
snow distribution measurements





P. Schattan et al., to be published

Neutron Detection

Basics

Neutron Detection

- No charge
- „Low“ energies - as low as thermal ($k_B T$ = 25 meV)

  MeV ⟶ neV

- **Scattering**
  - coherent
  - elastic: (n,n)
  - inelastic: (n,n‘)
- **Absorption**
  - photonic: (n,γ‘)
  - charged: (n,p), (n,d), (n,α)
  - neutral: (n,2n), (n,3n)
  - fission: (n,f)

Neutron Detection

- No charge
- „Low“ energies - as low as thermal ($k_B T$ = 25 meV)

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Scattering

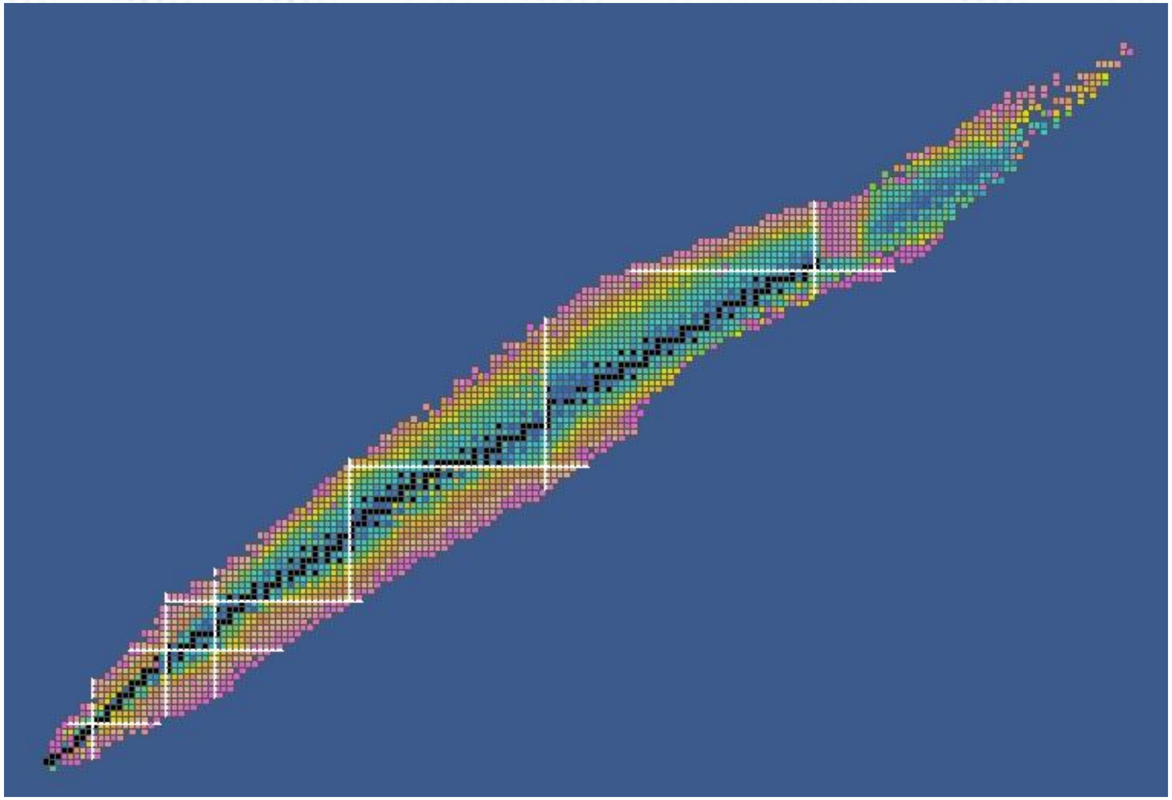
- coherent
- elastic (n,n)
- inelastic (n,n‘)

Absorption

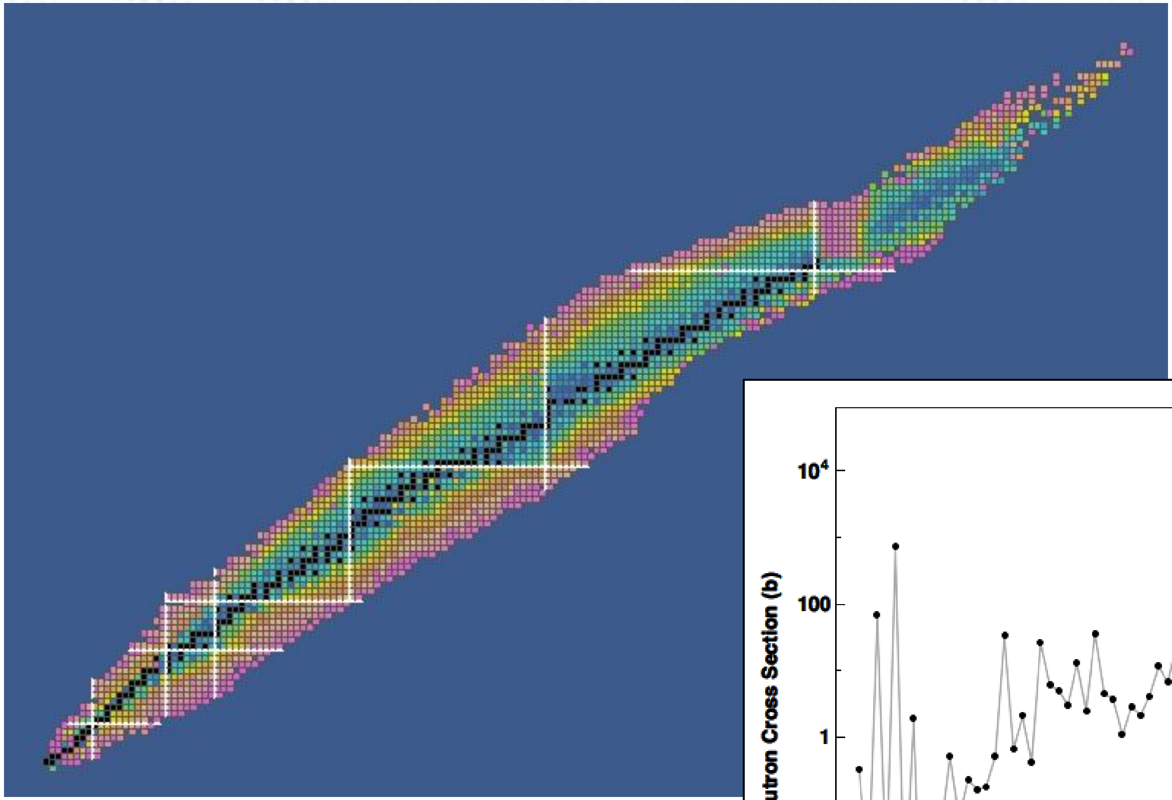
- photonic (n,γ‘)
- charged (n,p) (n,d) (n,α)
- neutral (n,2n) (n,3n)
- fission (n,f)

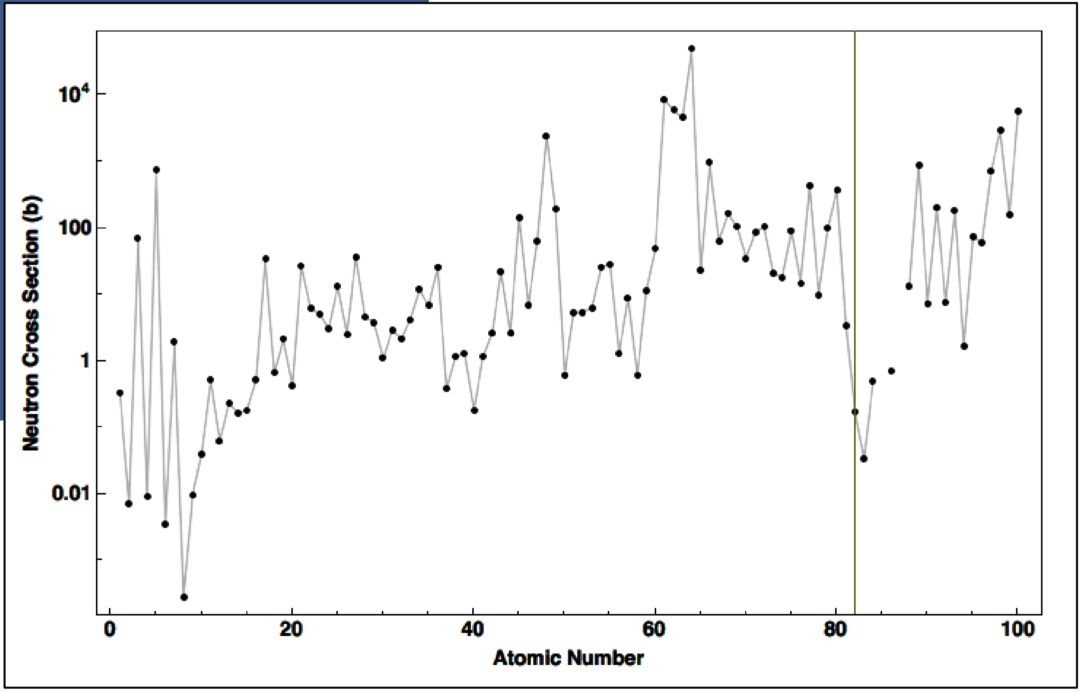
‚converters‘

Neutron Detection



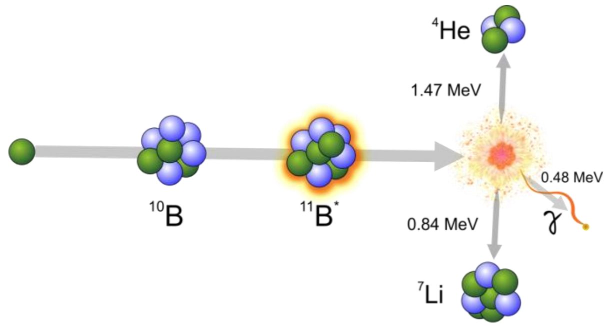
Neutron Detection



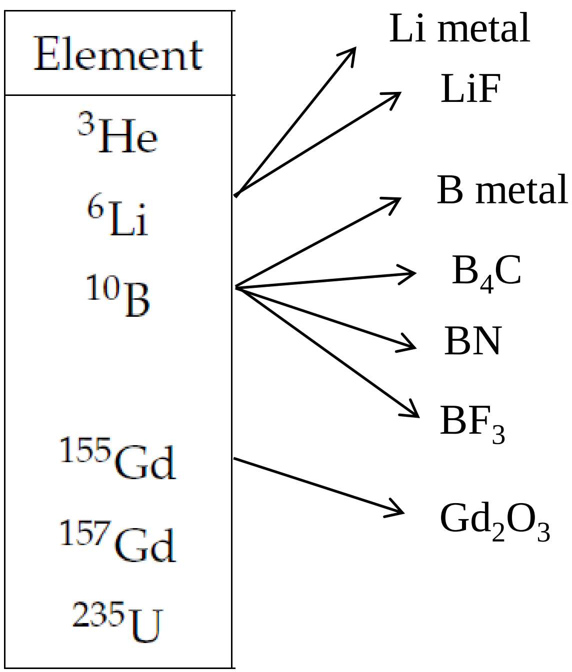


Neutron Converters

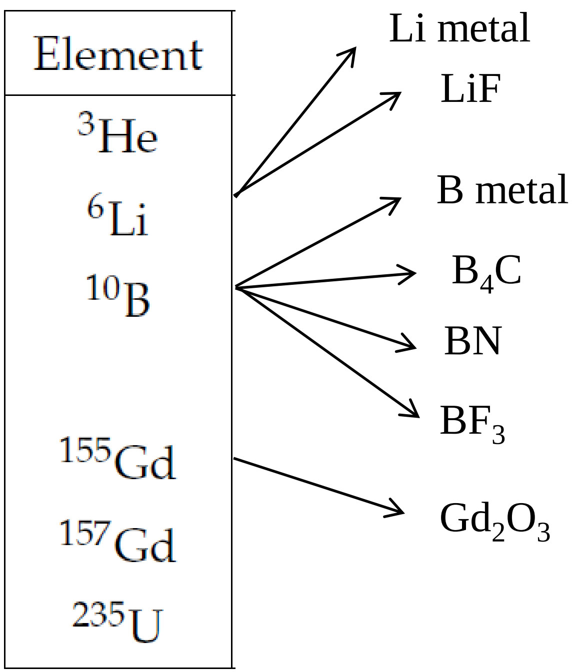
Element	Reaction		CS at 25.2 meV
^{3}He	^{3}He+n $\longrightarrow$	^{3}H+764 keV +p	5327 b
^{6}Li	^{6}Li+n $\longrightarrow$	^{3}H+α + 4.78 MeV	940 b
^{10}B	^{10}B+n $\longrightarrow$	^{7}Li+α + 2.79 MeV (6 %)	3837 b
	^{10}B+n $\longrightarrow$	^{7}Li*+α + 2.31 MeV (94 %)	
^{155}Gd	^{155}Gd+n $\longrightarrow$	^{156}Gd+γ + e^- + (30 − 180) keV	61000 b
^{157}Gd	^{157}Gd+n $\longrightarrow$	^{158}Gd+γ + e^- + (30 − 180) keV	254000 b
^{235}U	^{235}U+n $\longrightarrow$	fission fragments + 160 MeV	584 b

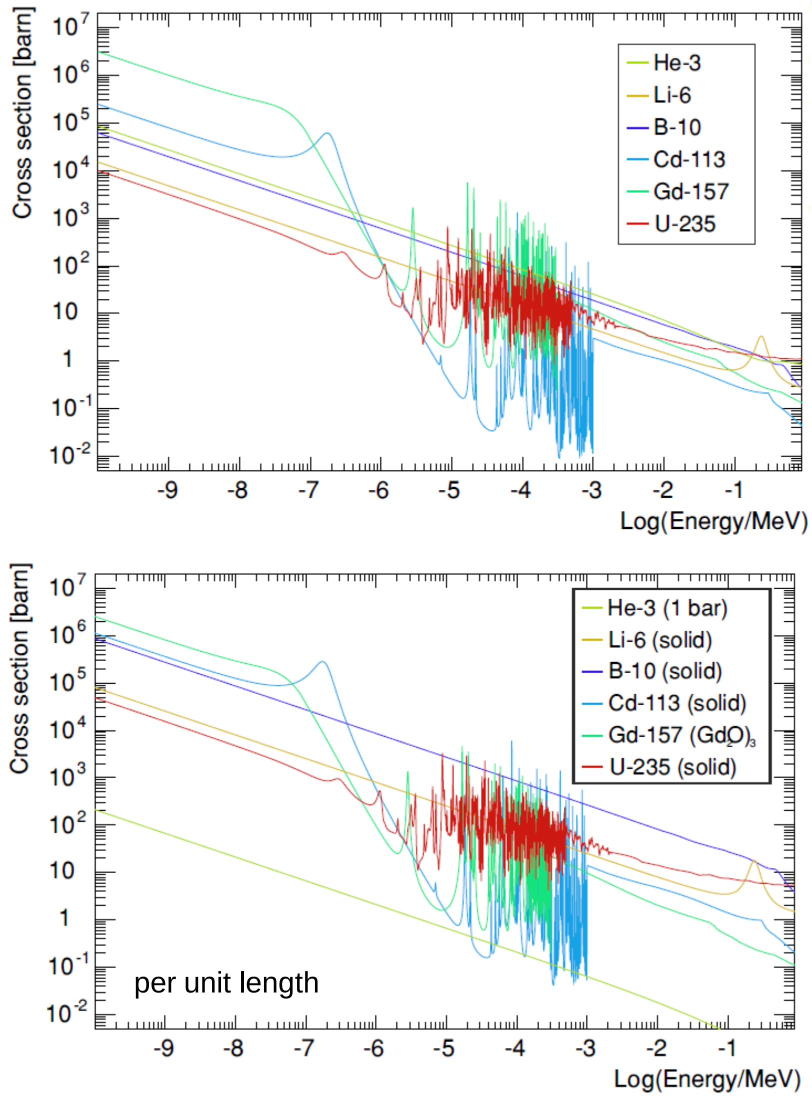


Neutron Converters

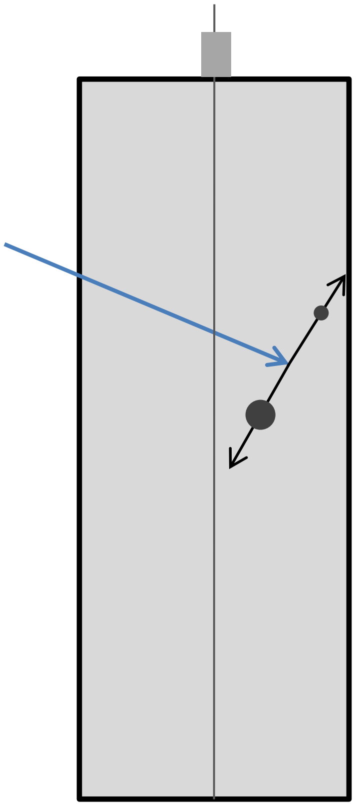


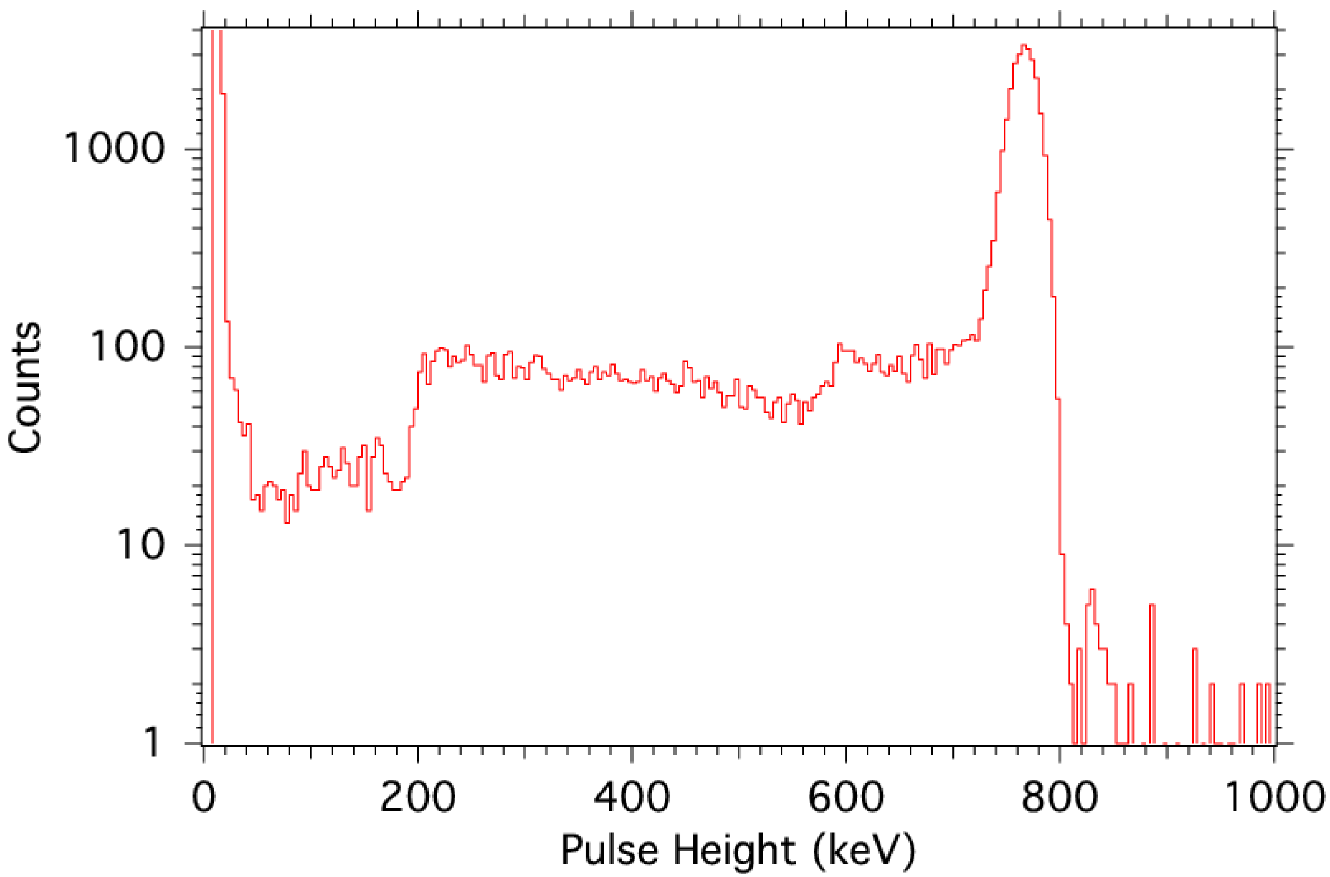
CS vs. absorption coefficient





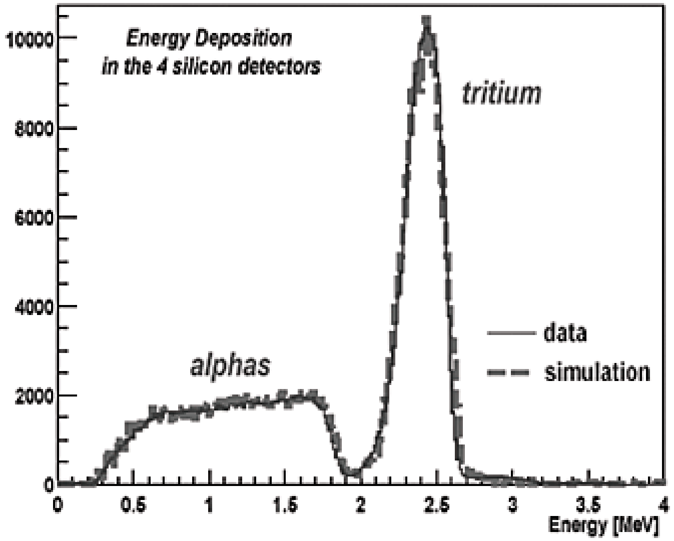
Conversion in ^{3}He

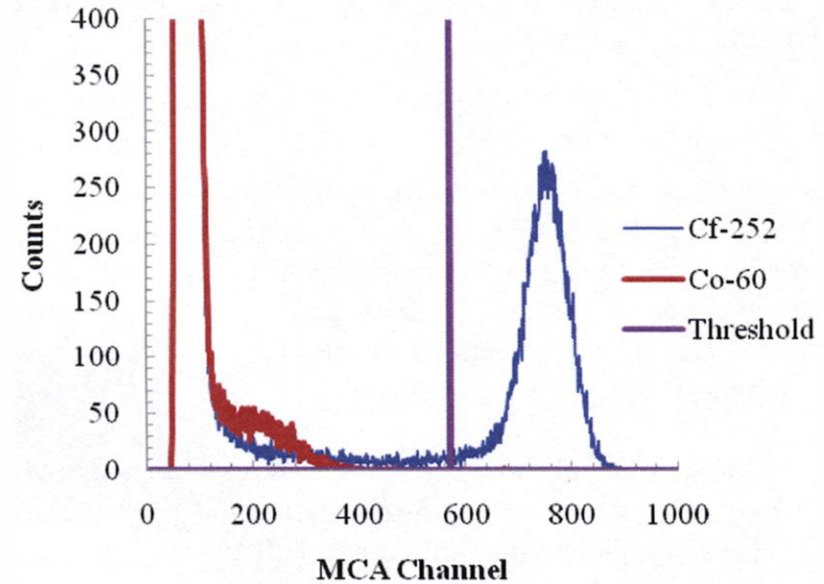


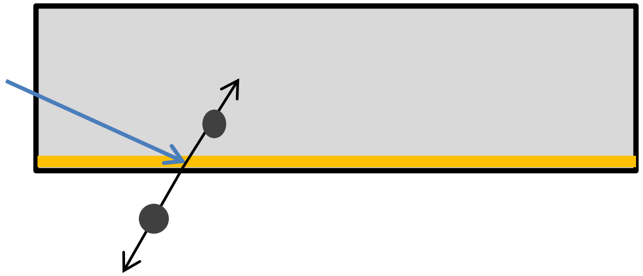


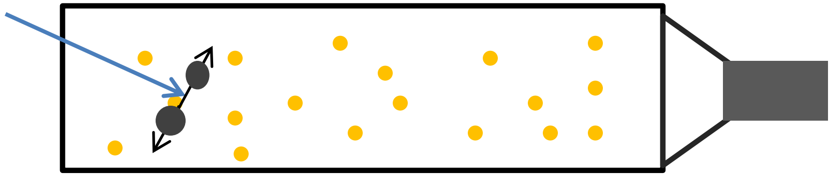
Langford et al., “Event Identification in 3He Proportional Counters Using Risetime Discrimination” arXiv:1212.4724v1

Conversion in ^{6}Li



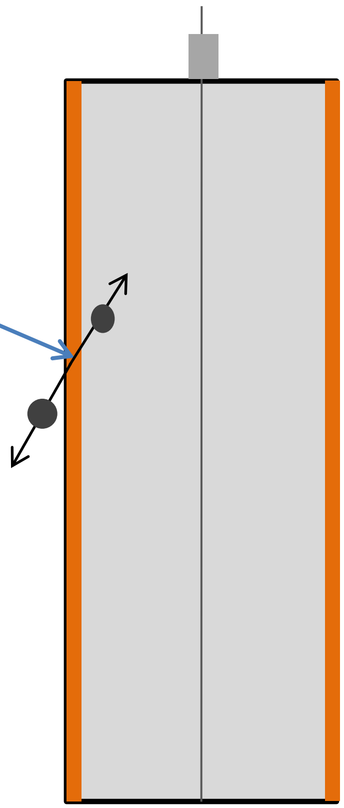




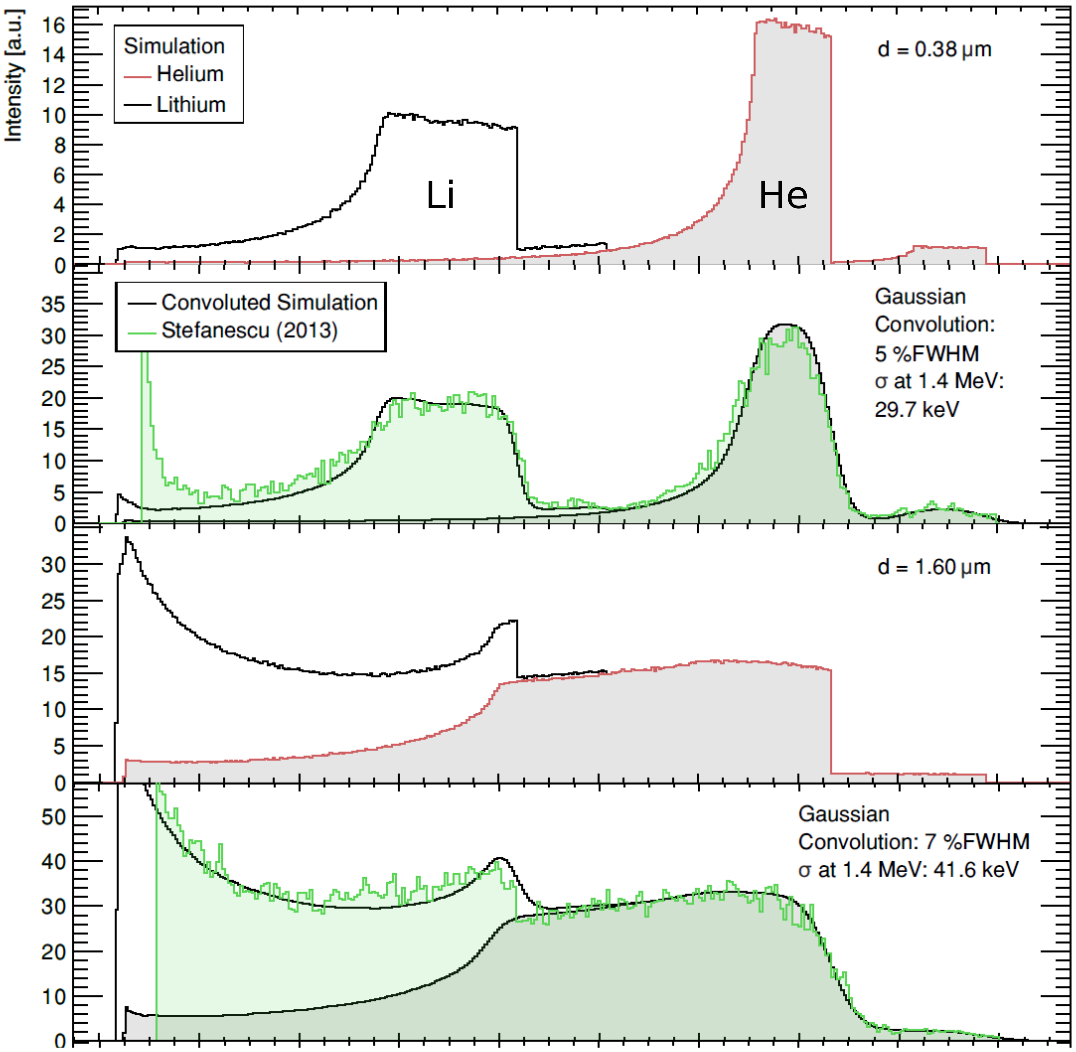


[1] P.F. Mastinu et al., “A low-mass neutron flux monitor for the n _TOF facility at CERN”, Braz. J. Phys. vol.34 no.3, 2004
[2] “A Compact Neutron Detector Based on the use of a SiPM Detector”, IEEE Nuc. Spring Symp., 2008

Conversion in ^{10}B



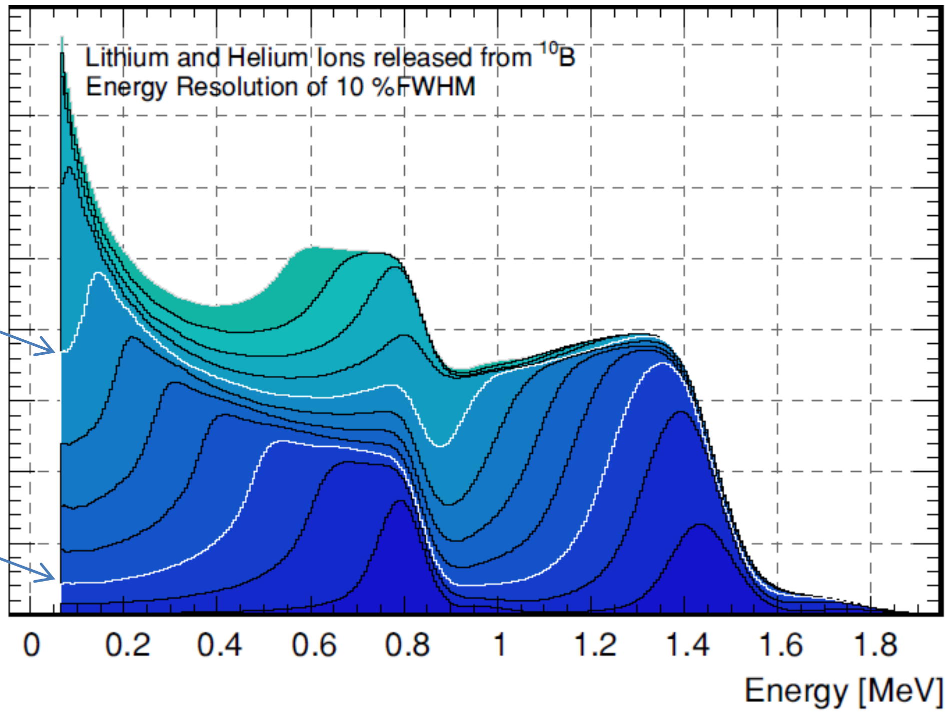
0.035 mm ^{10}B

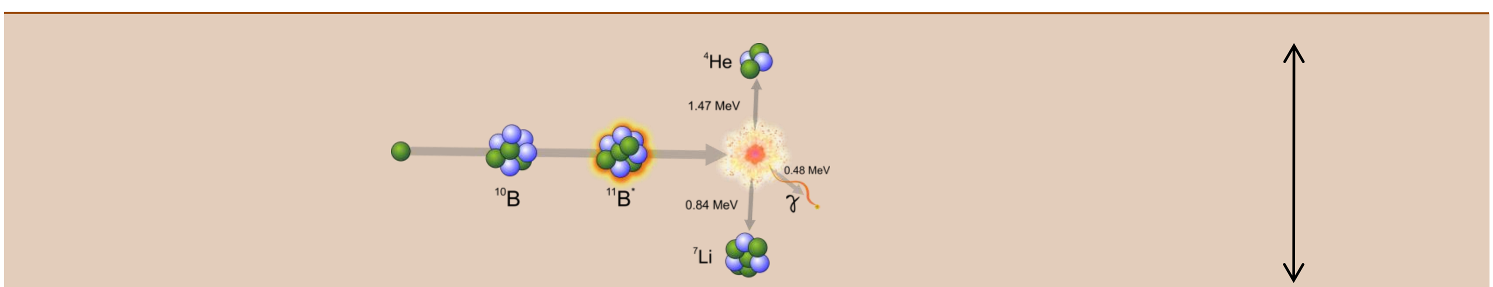


Conversion Products: Energy Spectra

thick converter

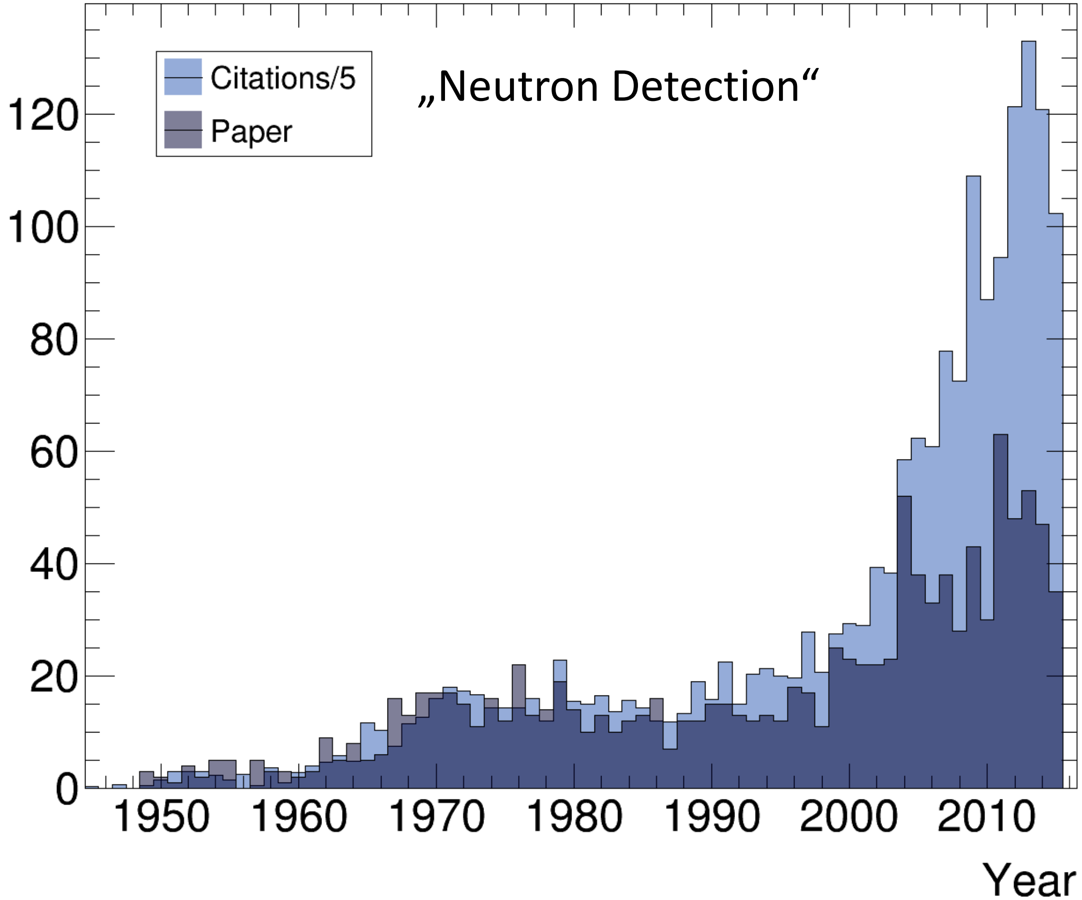
thin converter





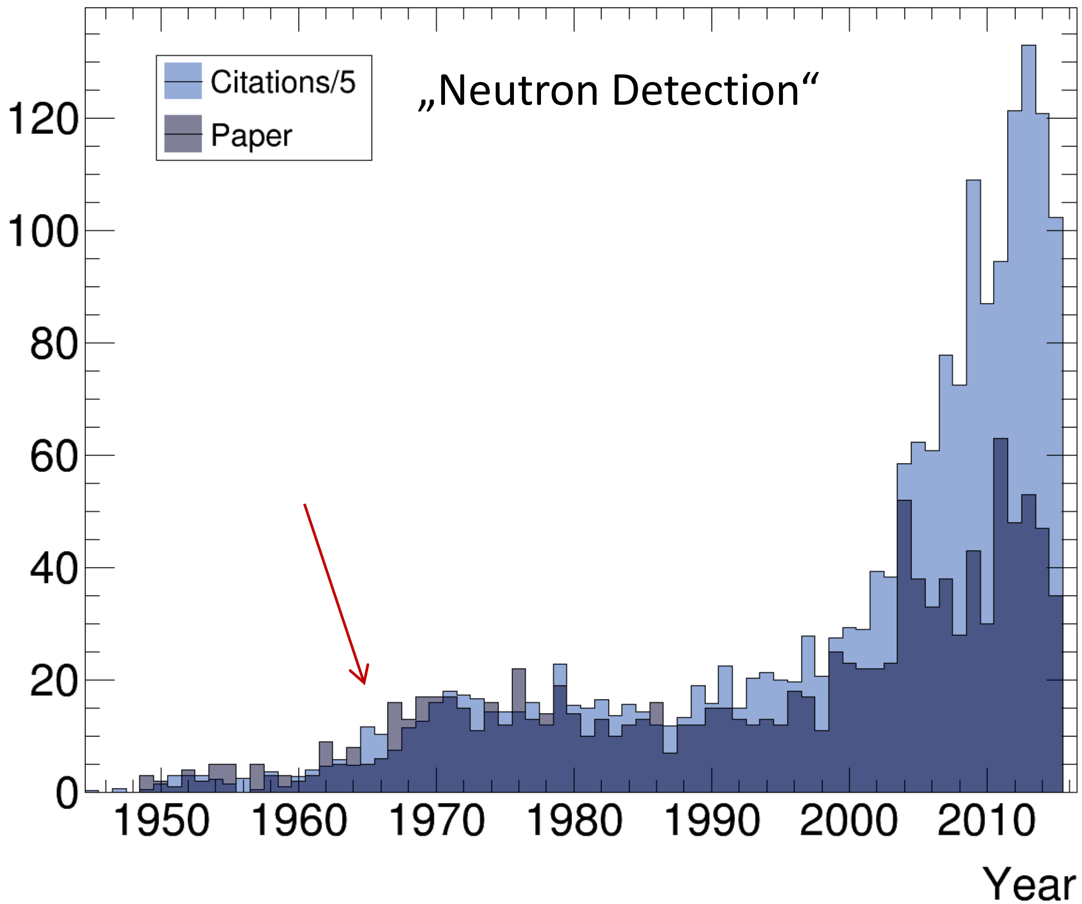
The rise and rise of citatation analysis

Citatation Analysis



Web of Science Citation Reports

Citatation Analysis



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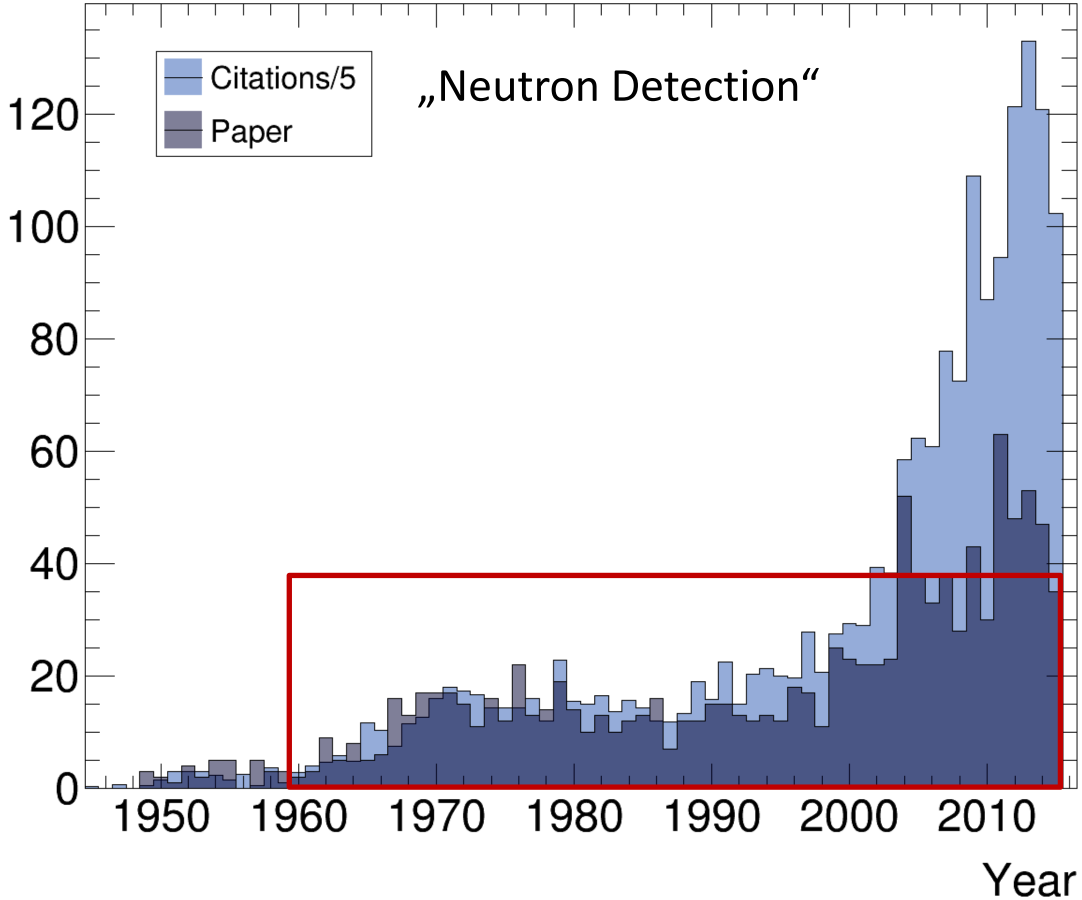
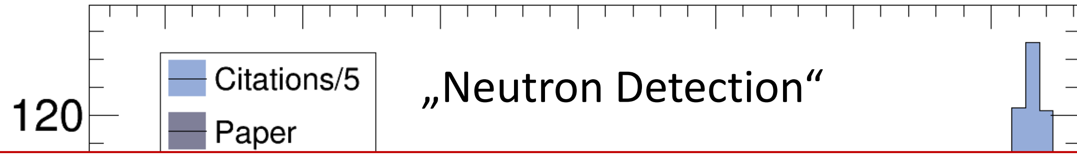
Citatation Analysis



Web of Science Citation Reports

Citatation Analysis



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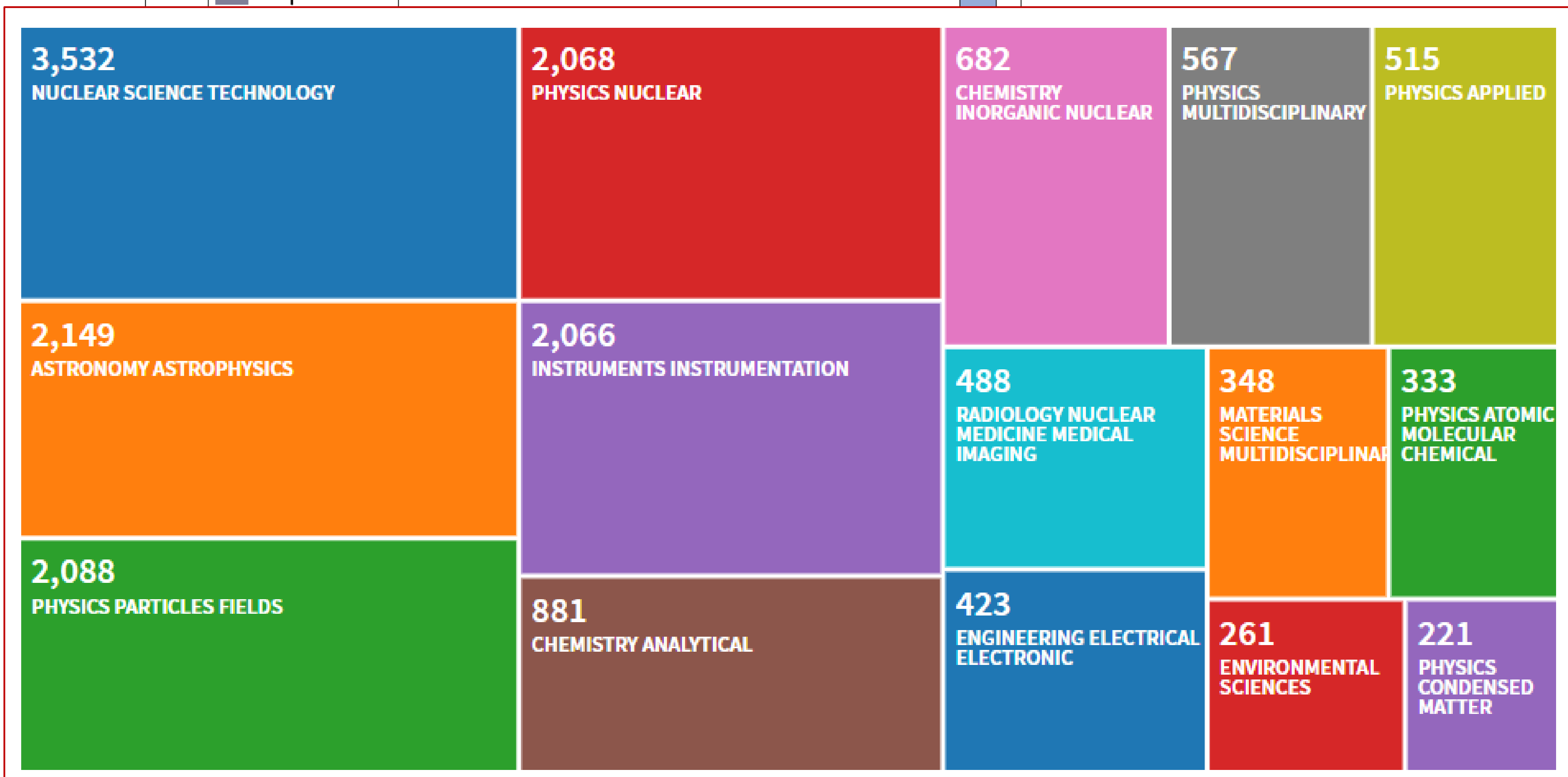
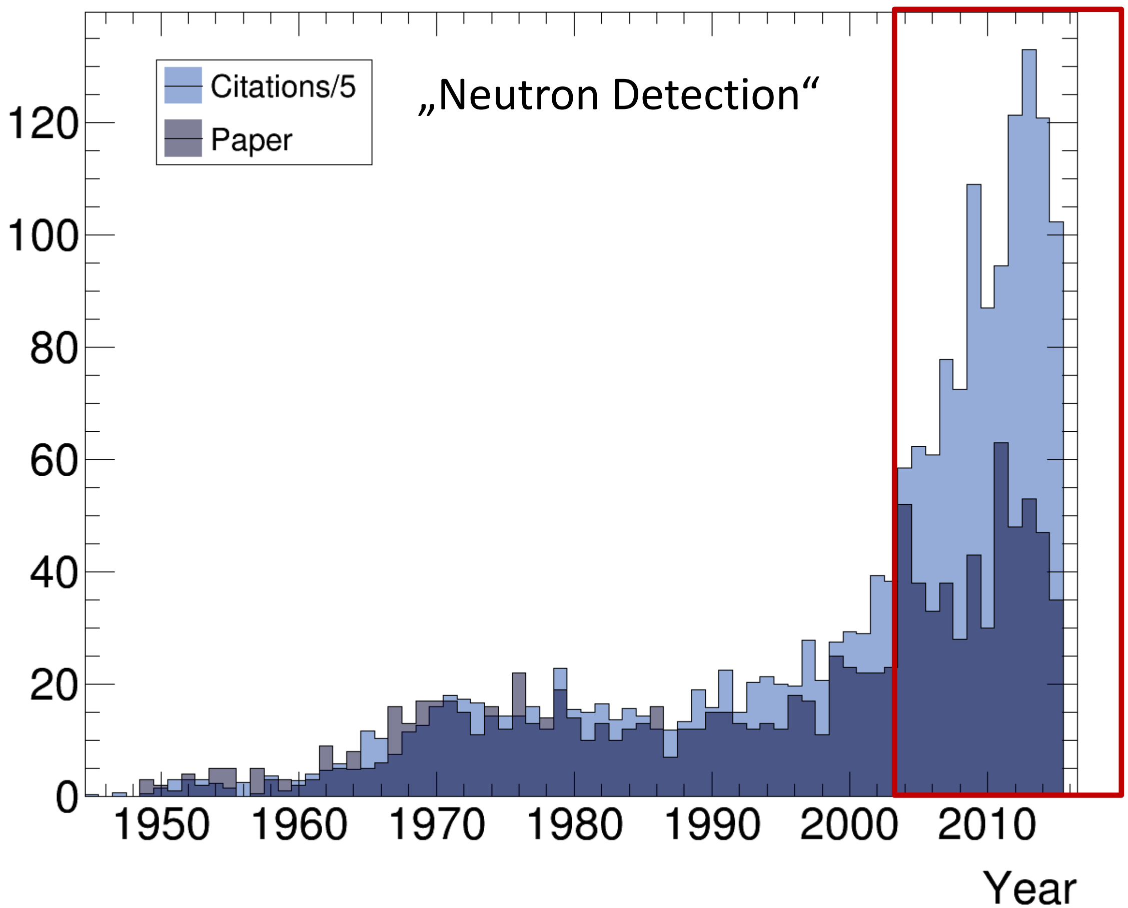


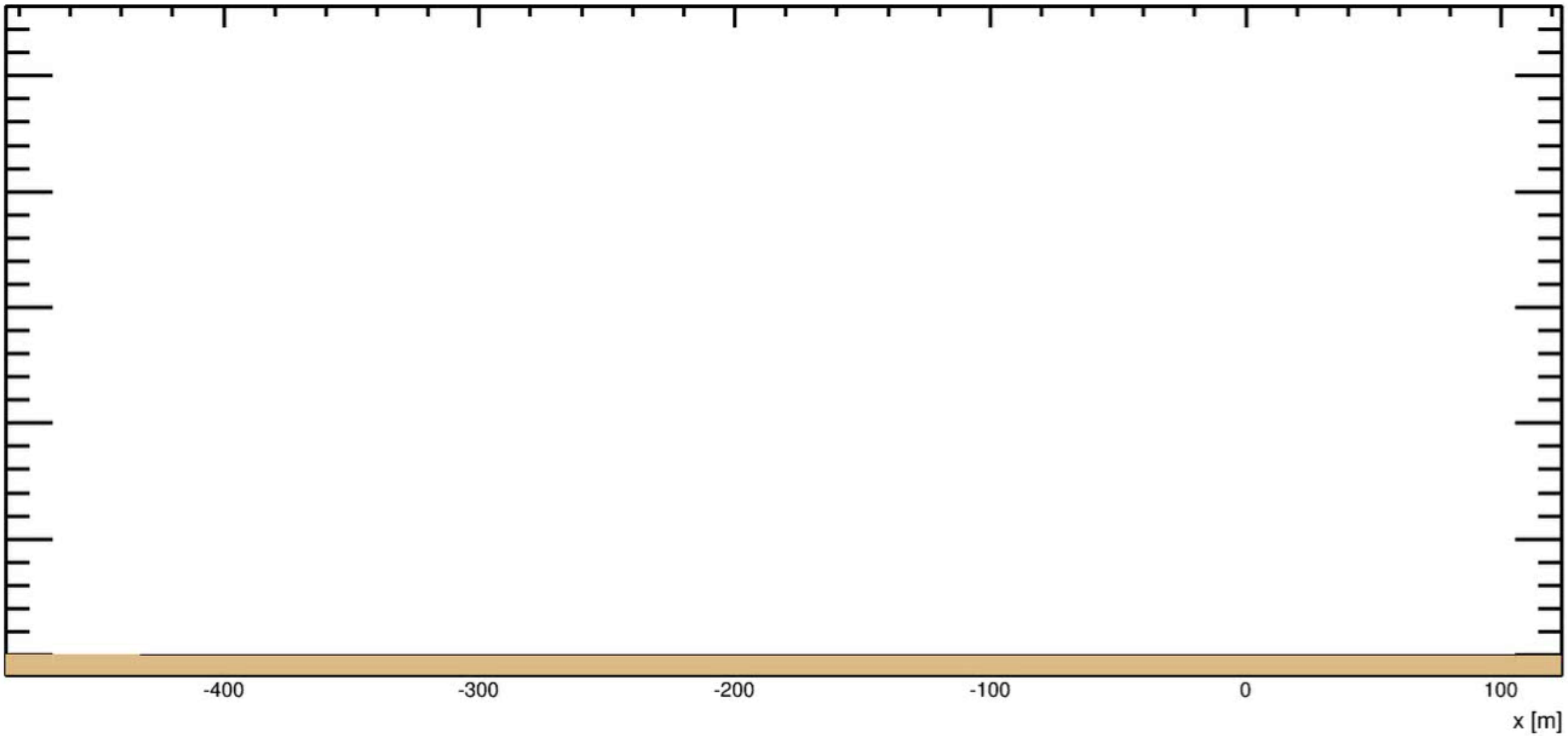
Citatation Analysis



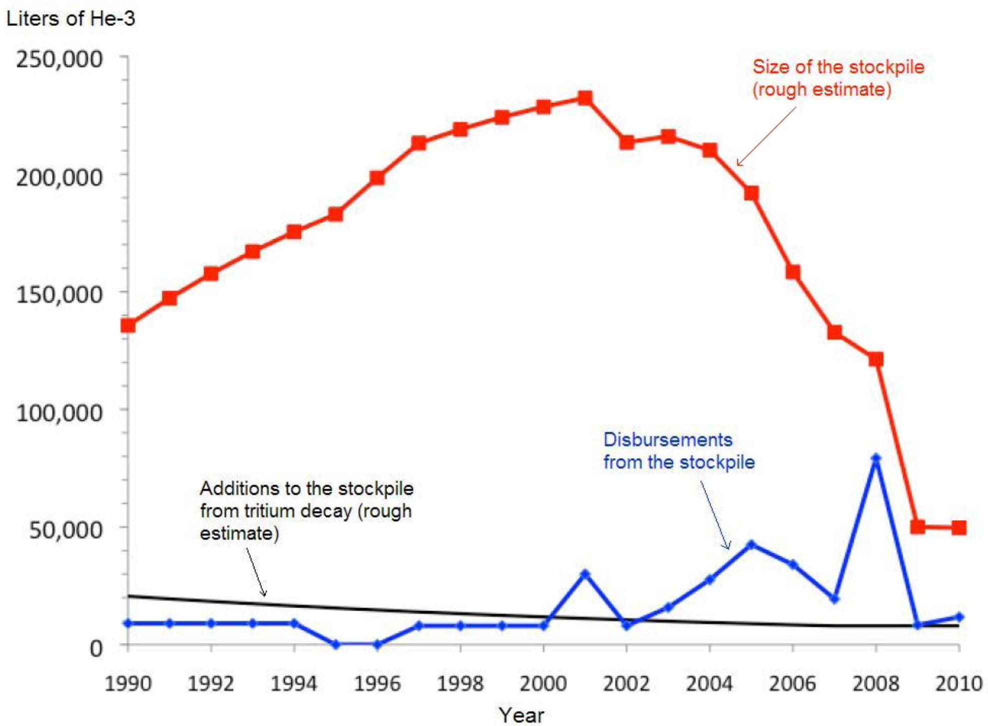
Web of Science Citation Reports

Titan II Rocket in Launch Silo, Arizona State Museum

Where does the He-3 come from?



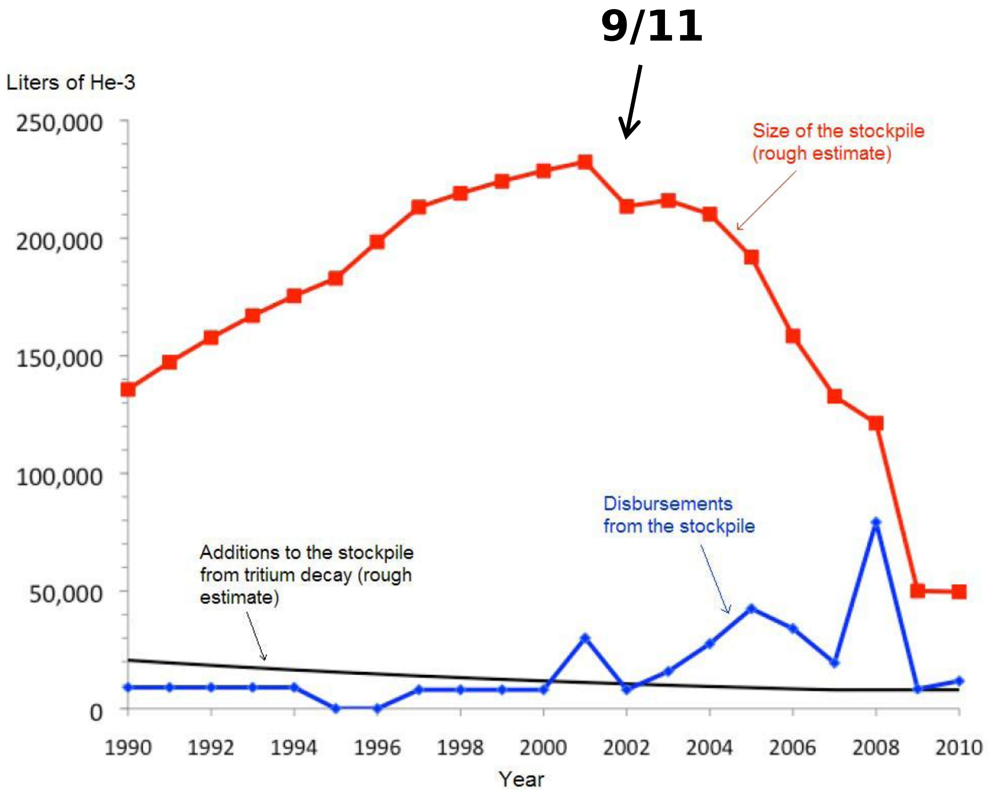
The Helium-3 Crisis



AAAS, Overview of Helium-3 Supply and Demand

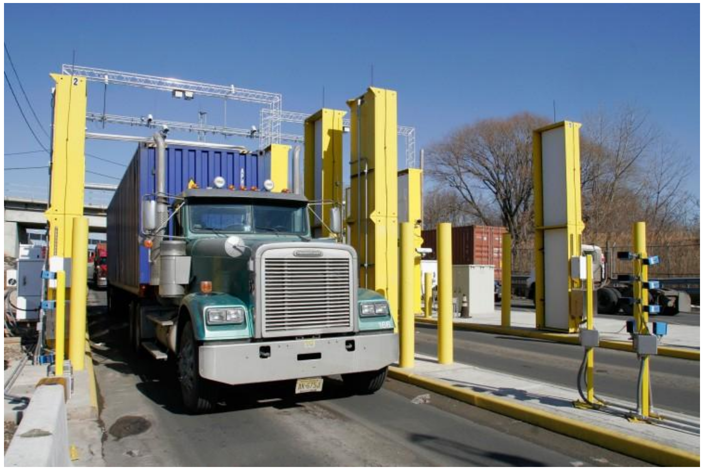
[1] http://www.saphymo.com/photos/ecatalogue/116-2/access-control-clearance-monitors-rcp-radiological-control-for-pedestrian.jpg
[2] http://cits.uga.edu/uploads/1540compass/1540images/_compass750/RPM1.jpg

The Helium-3 Crisis



AAAS, Overview of Helium-3 Supply and Demand

[1]

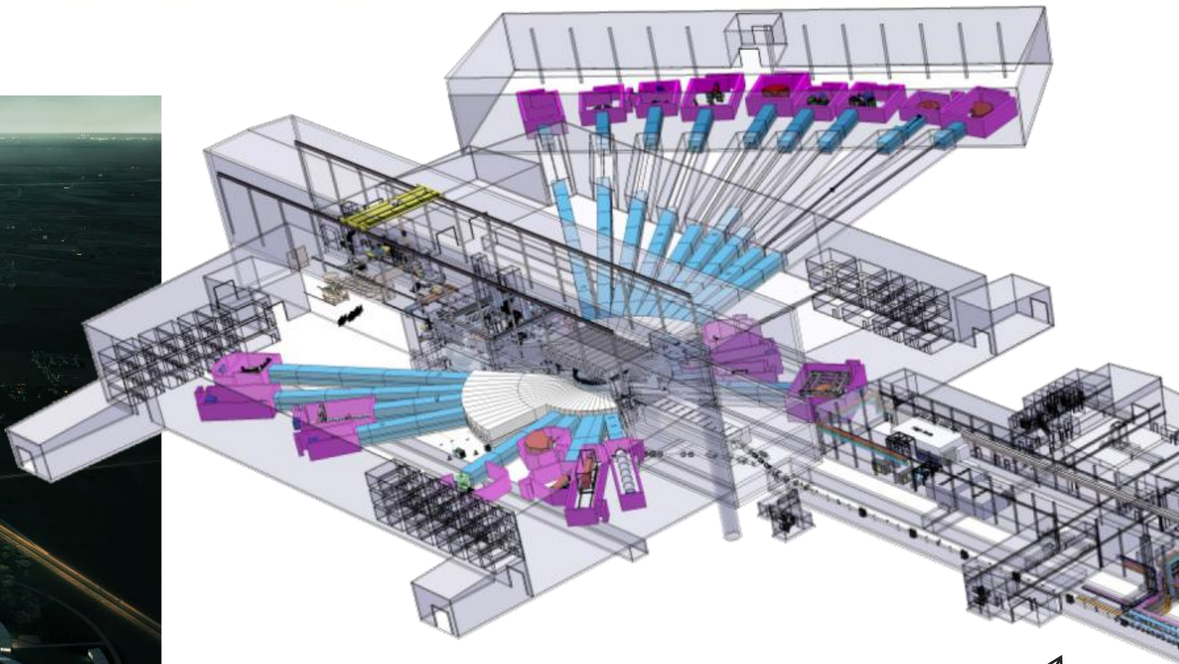


[2]

[1] http://www.saphymo.com/photos/ecatalogue/116-2/access-control-clearance-monitors-rcp-radiological-control-for-pedestrian.jpg
[2] http://cits.uga.edu/uploads/1540compass/1540images/_compass750/RPM1.jpg

The European Spallation Source

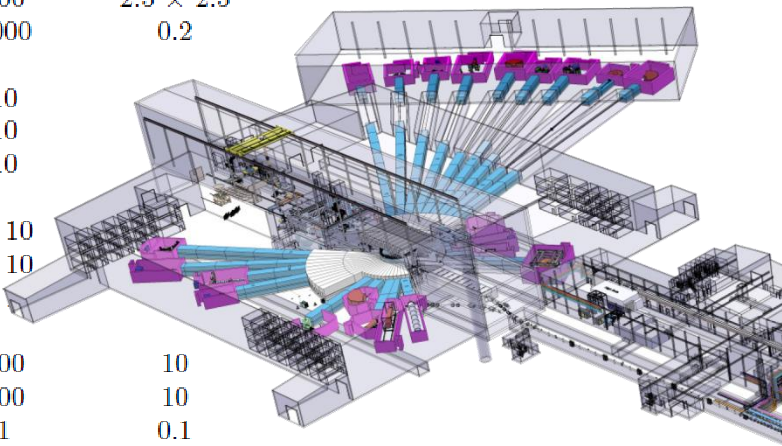
ESS TDR 2013
Lund, Sweden



Linear Accelerator
2 GeV
3 ms Pulse
62.5 mA

ESS Instrumentation

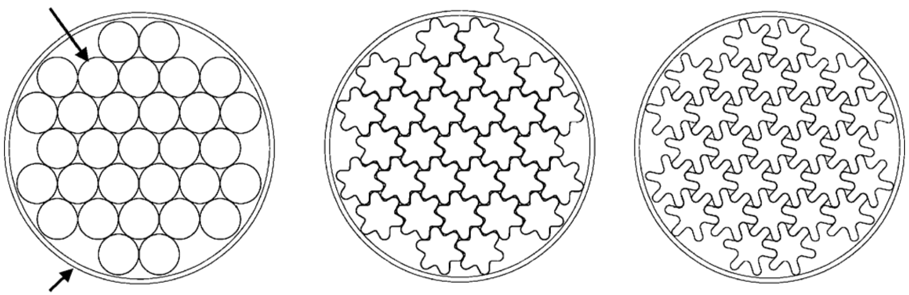
Instrument	Detector area [m^2]	Wavelength range [Å]	Time resolution [μs]	Spatial resolution [mm]
Multi-purpose imaging	0.5	1 - 20	1	0.001 - 0.5
General purpose polarised SANS	5	4 - 20	100	10
Broad-band small sample SANS	14	2 - 20	100	1
Surface scattering	5	4 - 20	100	10
Horizontal reflectometer	0.5	5 - 30	100	1
Vertical reflectometer	0.5	5 - 30	100	1
Thermal powder diffractometer	20	0.6 - 6	< 10	2×2
Bi-spectral powder diffractometer	20	0.8 - 10	< 10	2.5×2.5
Pulsed monochromatic powder diffractom.	4	0.6 - 5	< 100	2×5
Material science & engineering diffractom.	10	0.5 - 5	10	2
Extreme conditions instrument	10	1 - 10	< 10	3×5
Single crystal magnetism diffractometer	6	0.8 - 10	100	2.5×2.5
Macromolecular diffractometer	1	1.5 - 3.3	1000	0.2
Cold chopper spectrometer	80	1 - 20	10	
Bi-spectral chopper spectrometer	50	0.8 - 20	10	
Thermal chopper spectrometer	50	0.6 - 4	10	
Cold crystal-analyser spectrometer	1	2 - 8	< 10	
Vibrational spectroscopy	1	0.4 - 5	< 10	
Backscattering spectrometer	0.3	2 - 8	$<$ [illegible]	
High-resolution spin echo	0.3	4 - 25	100	10
Wide-angle spin echo	3	2 - 15	100	10
Fundamental & particle physics	0.5	5 - 30	1	0.1
Total	**282.6**			



ESS TDR 2013

Alternative detection technologies

New Detectors – Tube Replacement



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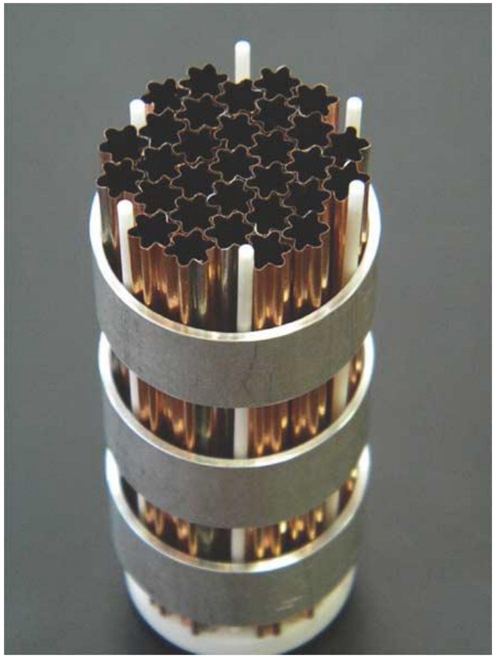

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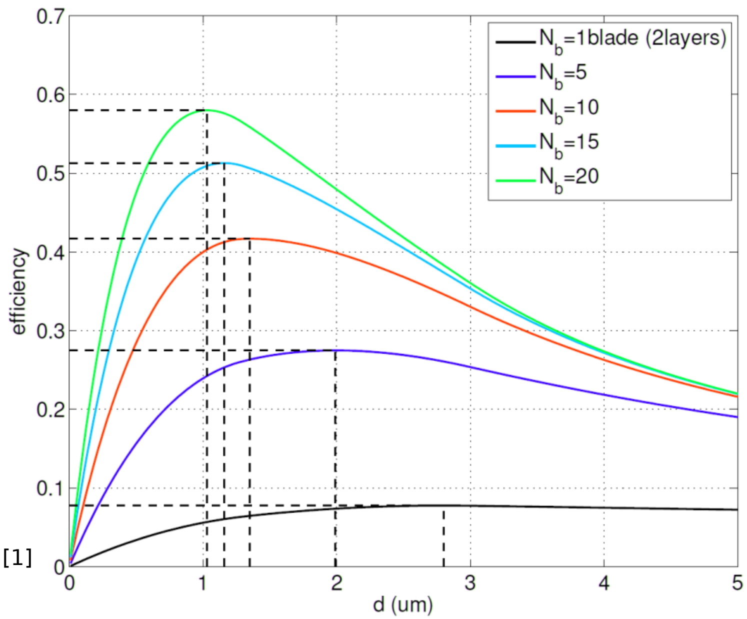
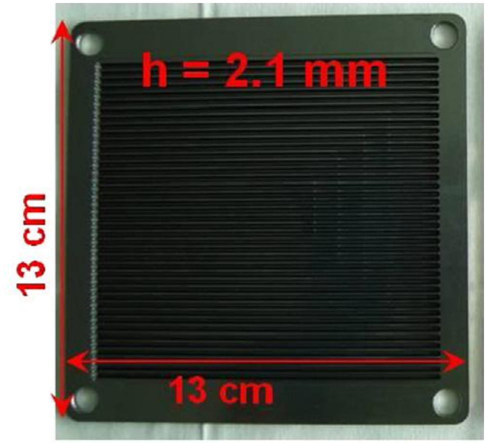


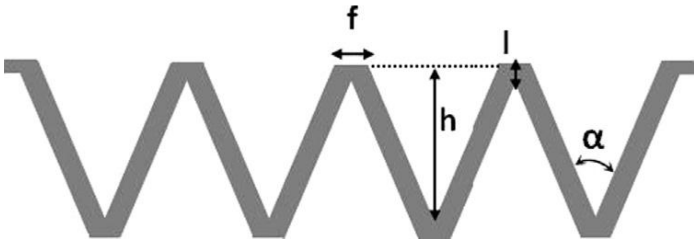
[1]

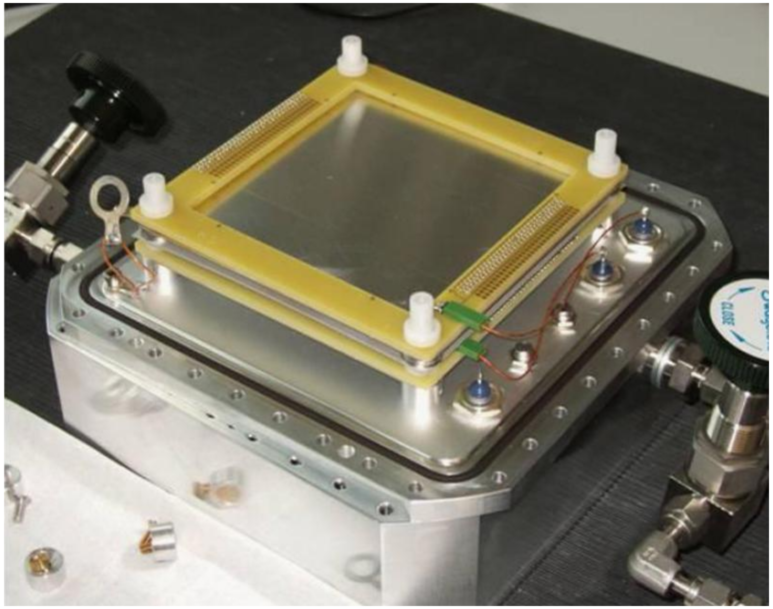
[1] F. Piscitelli, "Boron-10 layers, Neutron Reflectometry and Thermal Neutron Detectors", PhD Thesis 2014

[2] J. L. Lacy et al., "The Evolution of Neutron Straw Detector -Applications in Homeland Security", IEEE Transactions on Nucl. Science, 60,2 (2013)

New Detectors – Cathode Structures

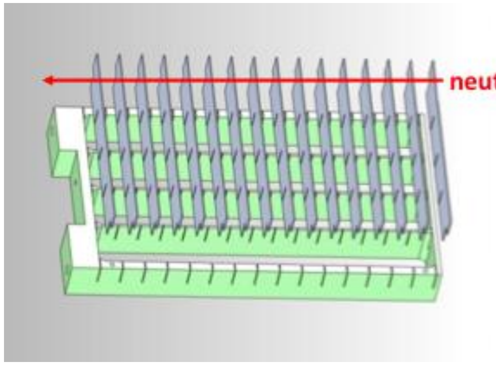


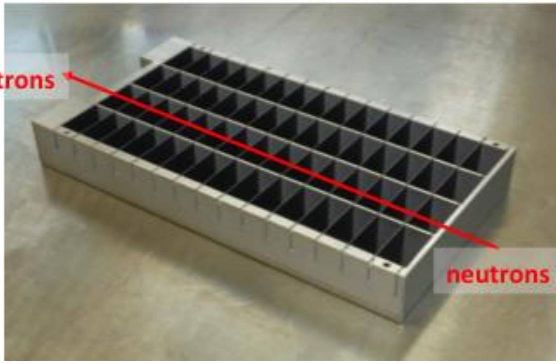


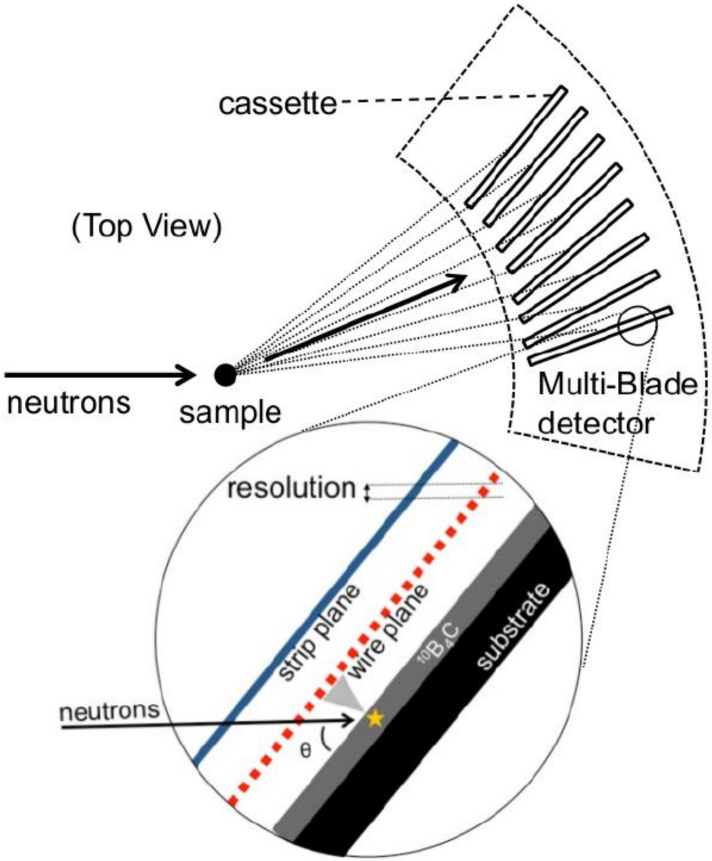


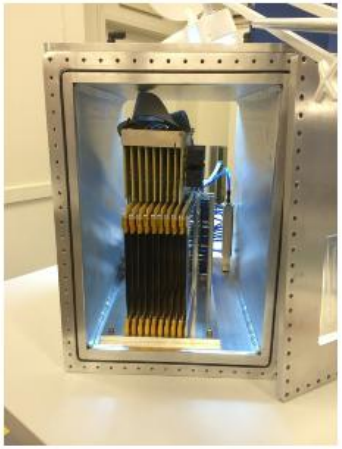
I. Stefanescu et al., „Development of a novel macrostructured cathode for large-area neutron detectors based on the 10B-containing solid converter", NIMA 727 (2013)

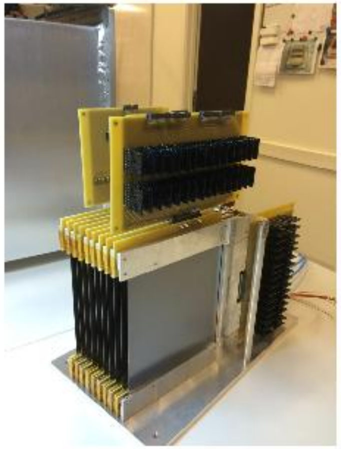
New Detectors – He-3 Replacements





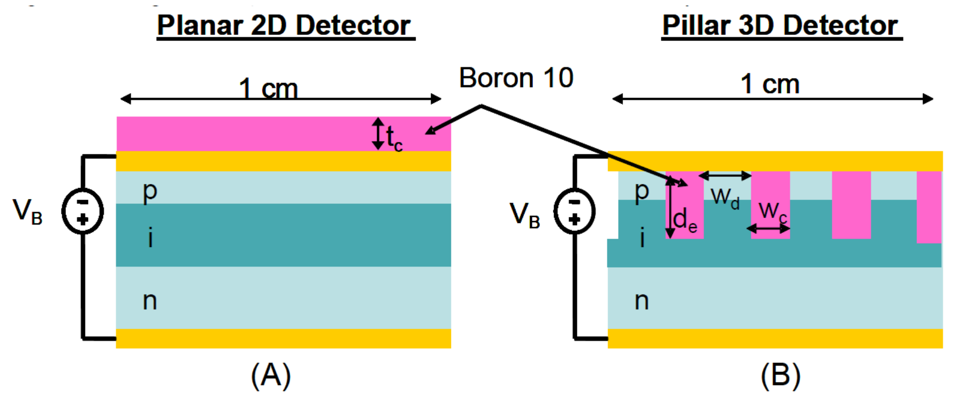






F. Piscitelli et al., "Novel Boron-10-based detectors for Neutron Scattering Science" arXiv:1501.05201v1 (2015)

New Detectors – 3D Silicon



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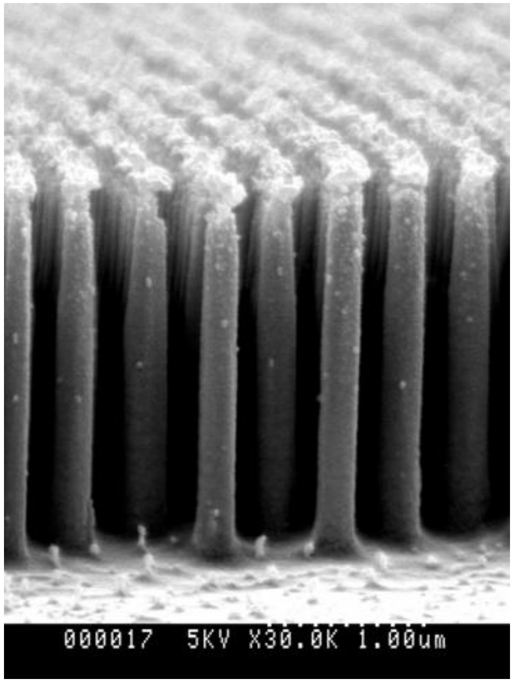

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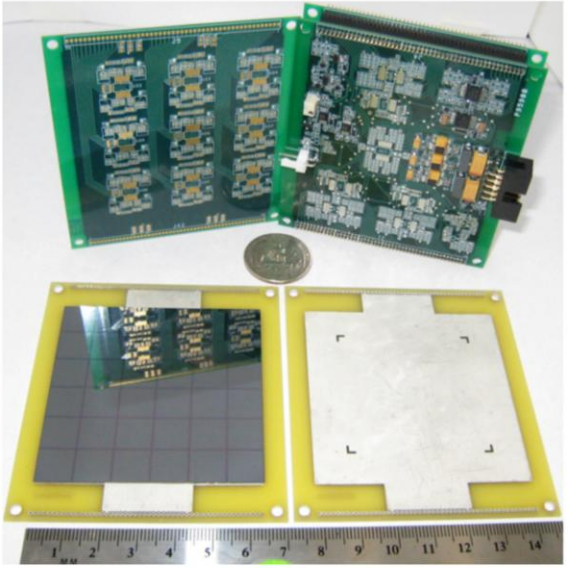
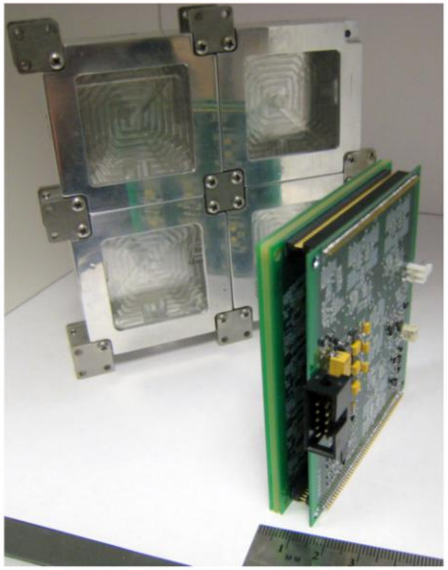
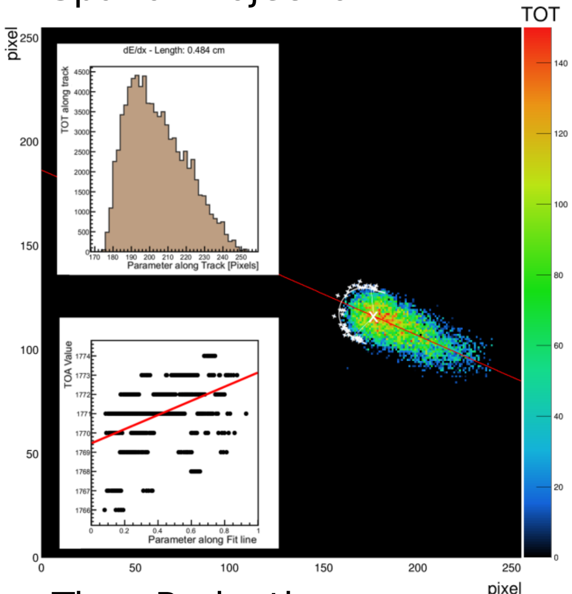




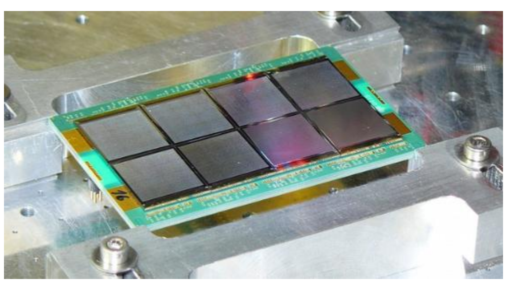
[1] R.J. Nikolic et al. "Roadmap for High Efficiency Solid-State Neutron Detectors", Barry Chin Li Cheung Publications, 15 (2005)
[2] D.S. McGregor et al., „High-efficiency microstructured semiconductor neutron detectors that are arrayed, dual-integrated, and stacked ", Applied Radiation and Isotopes 70 (2012)

New Detectors – Time Projection

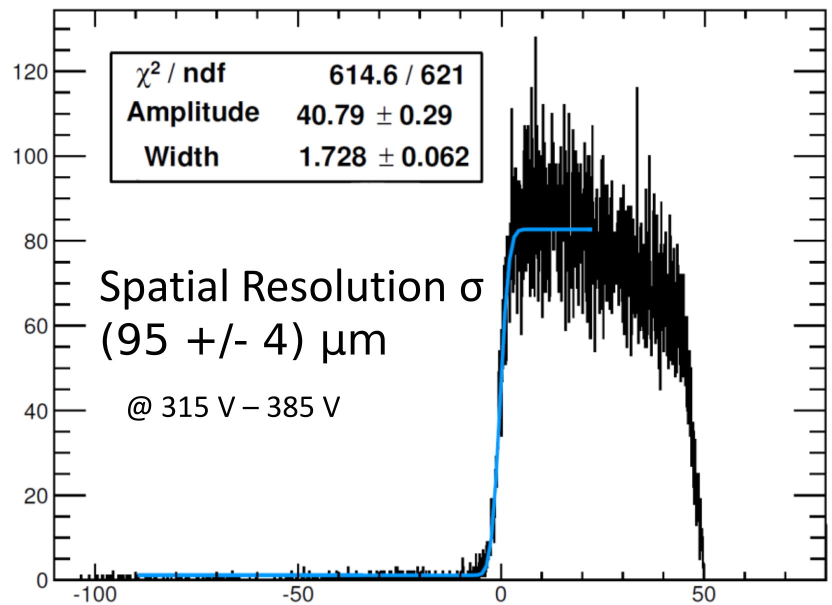
Spatial Projection

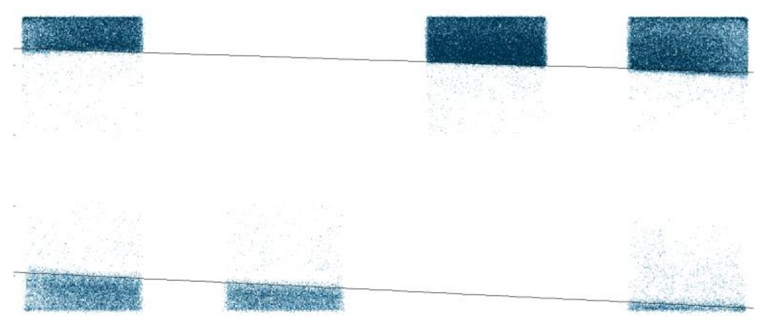


Time Projection

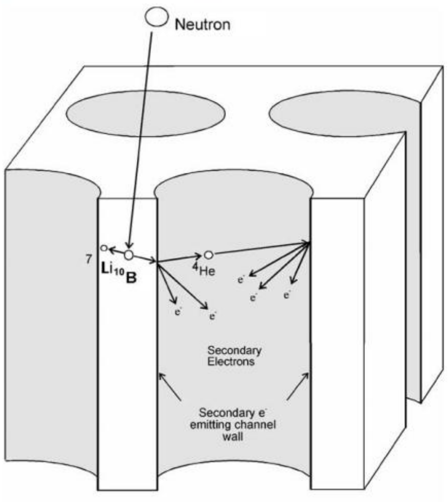


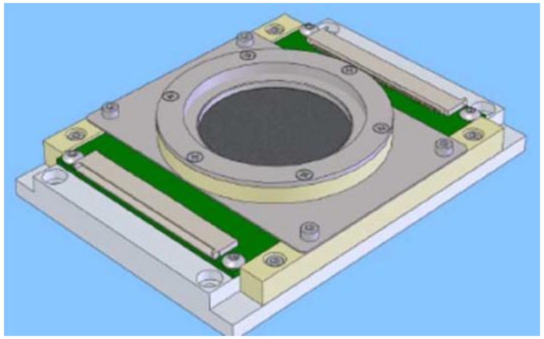
Edge Projection

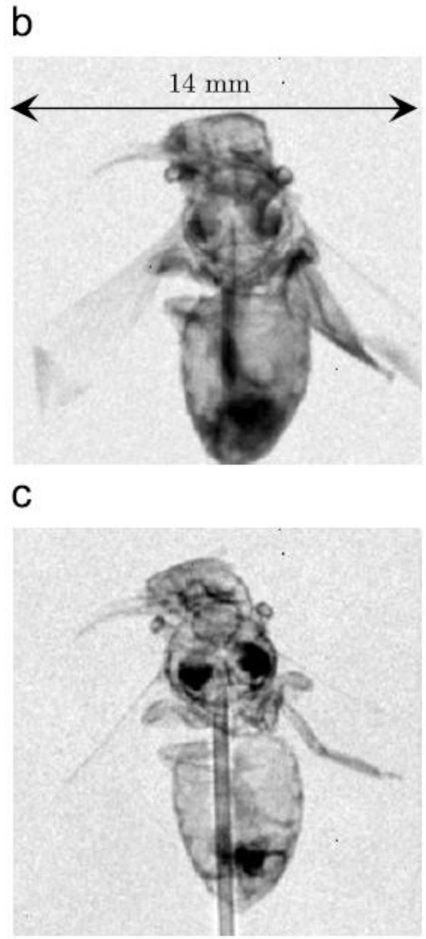




New Detectors - MCP



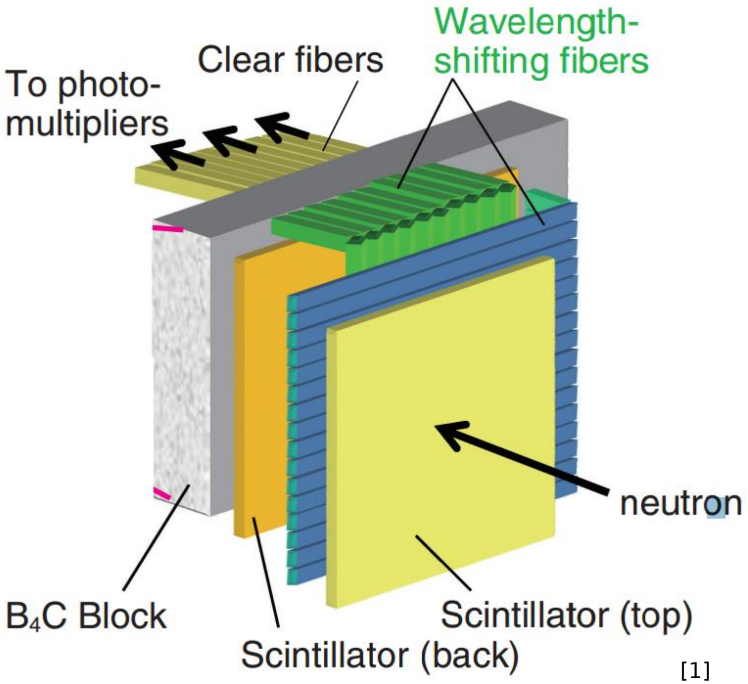




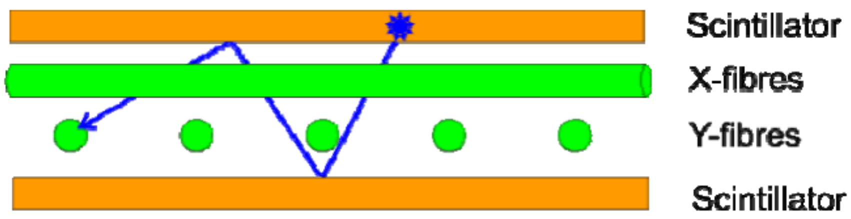
A. Tremsin et al., "High-resolution neutron radiography with microchannel plates: Proof-of-principle experiments at PSI", NIM A, 605 (2009)
A. Tremsin et al., „Efficiency optimization of microchannel plate (MCP) neutron imaging detectors. I. Square channels with 10B doping", NIM A, 539 (2005)

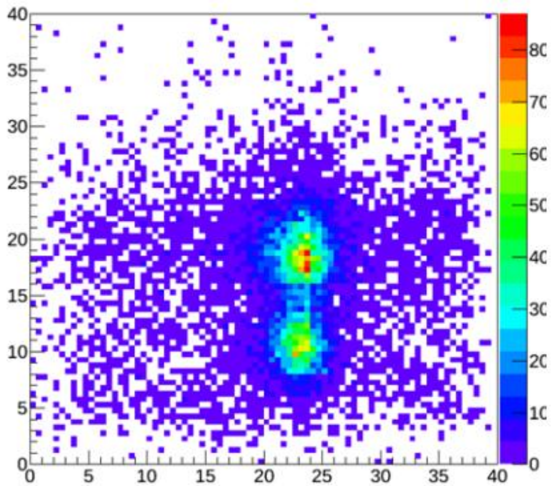
Fig. 3. Photograph (a) and neutron radiographic images of a bee; (b) thermal neutron beamline NEUTRA, acquisition time 15 min; (c) cold neutorn beamline ICON, acquisition time 3 min. The edges of the hypodermic needle show some diffraction enhancement.

New Detectors - WLSF



[1]





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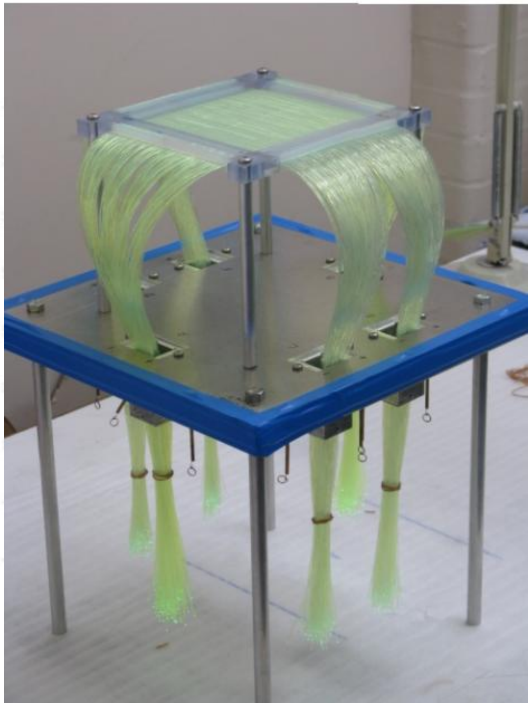
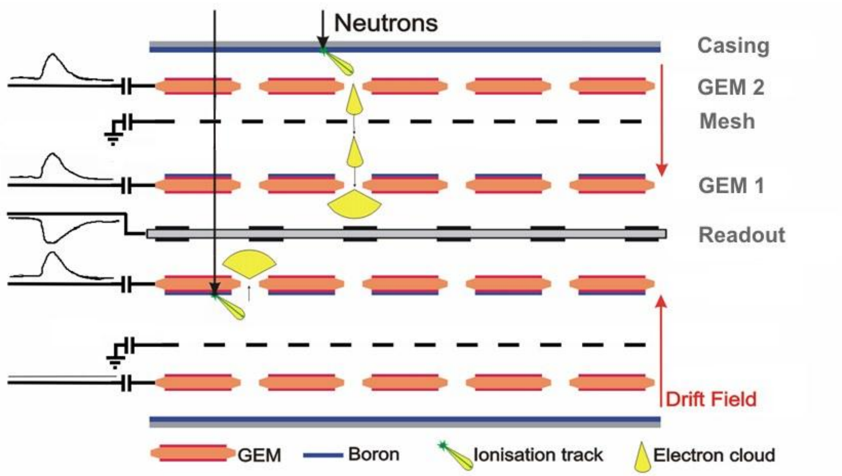
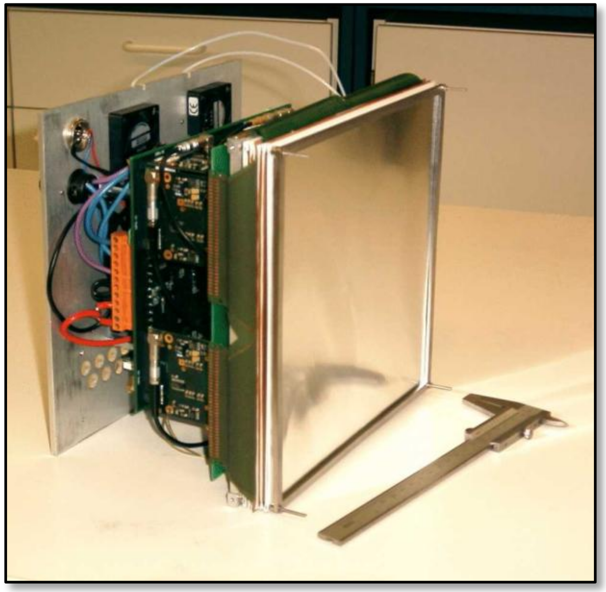


[3]

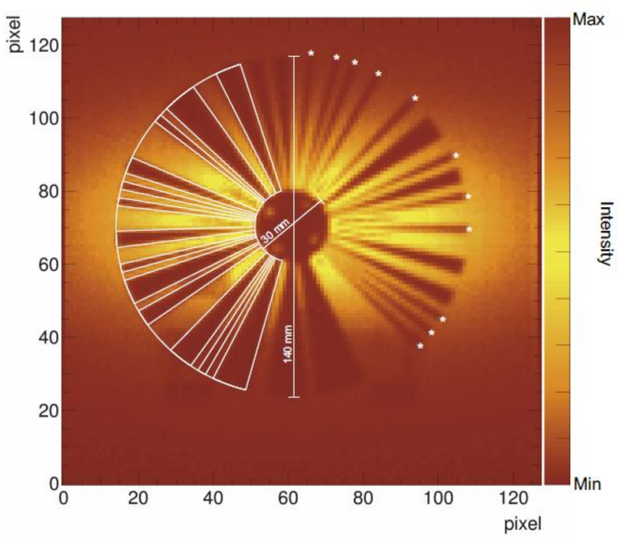
[1] J. Sykora, "WLSF detector status and future plans at ISIS" (2013)
[2] R. Engels "Status WLSF Neutron Detector Prototype from FZJ" (2012)
[3] Nakamura, T. et al., "A Large-Area Two-Dimensional Scintillator Detector with a Wavelength-Shifting Fibre Readout for a Time-of-Flight Single-Crystal Neutron Diffractometer", NIM A, 686, issue 1 (2012)

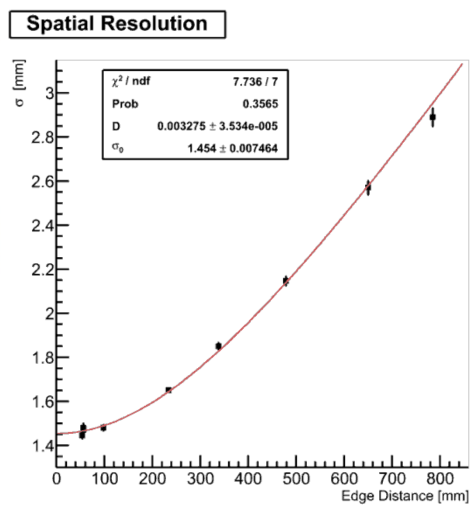
„New“ Detectors – CASCADE





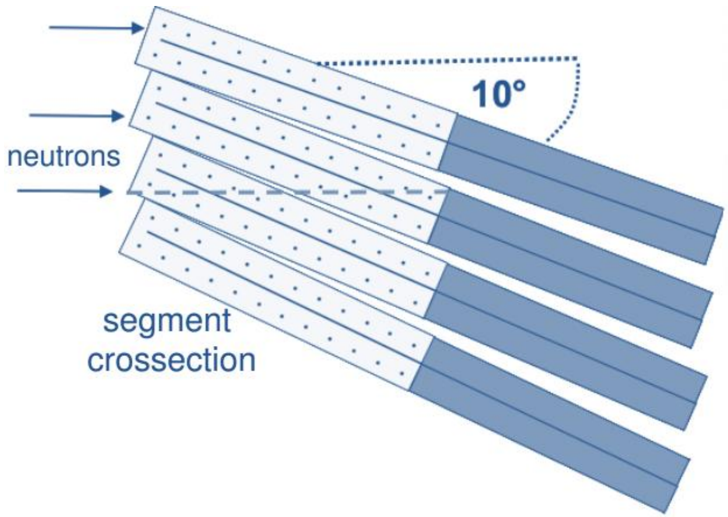
for RESEDA
FRM II, TU Munich

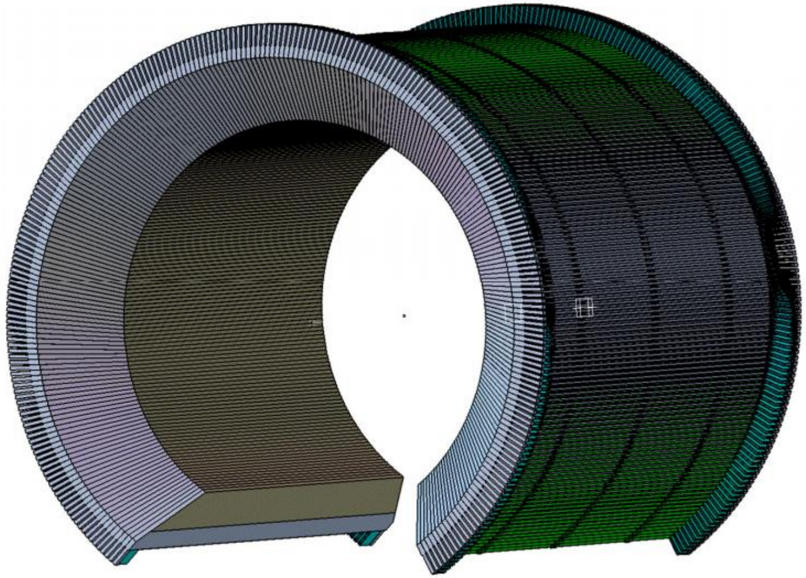




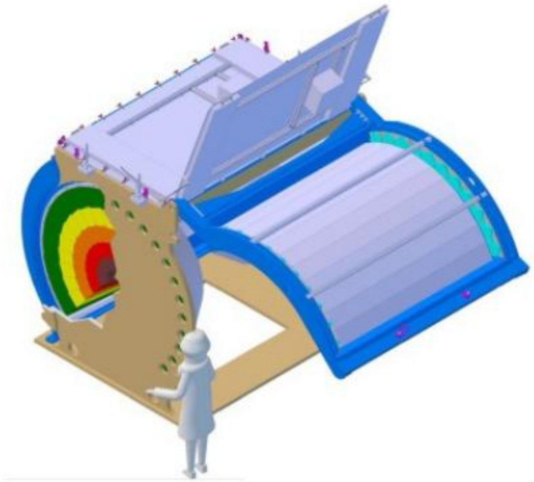
Spatial Resolution σ
(1.4) mm

„New" Detectors – Jalousie





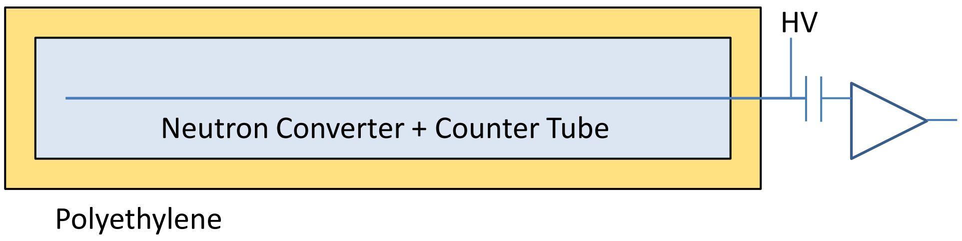
The Jalousie Detector Concept
for Powtex (FZJ @ FRM II, Munich)
and DREAM (FZJ @ ESS, Sweden)



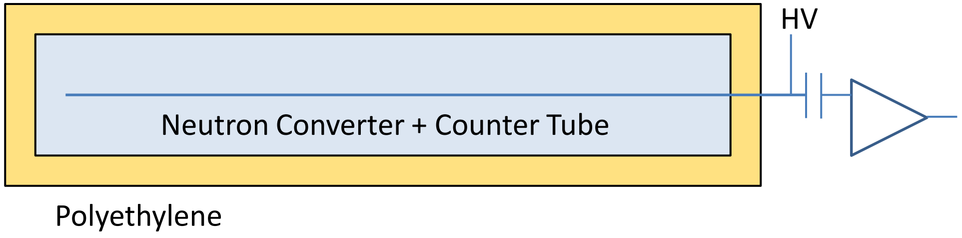
Ch. J. Schmidt, "The 10B-based Jalousie Neutron Detector", DENIM 2015

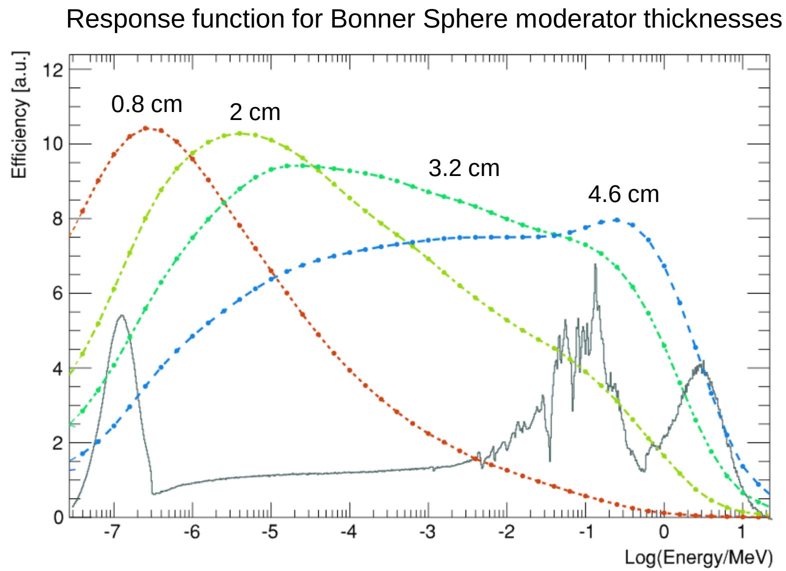
CRNS Inhouse Developments

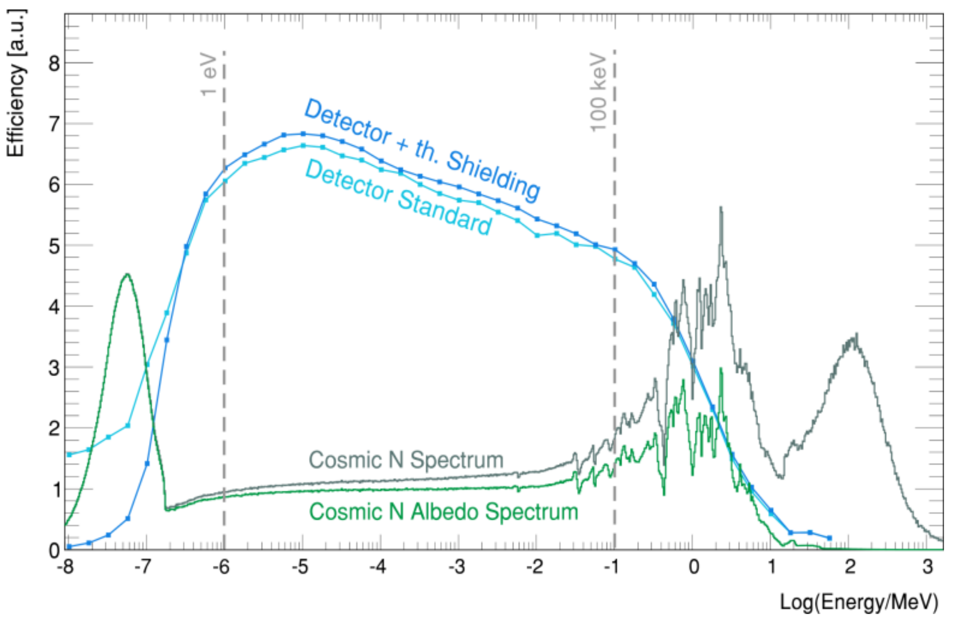
CRNS Detectors



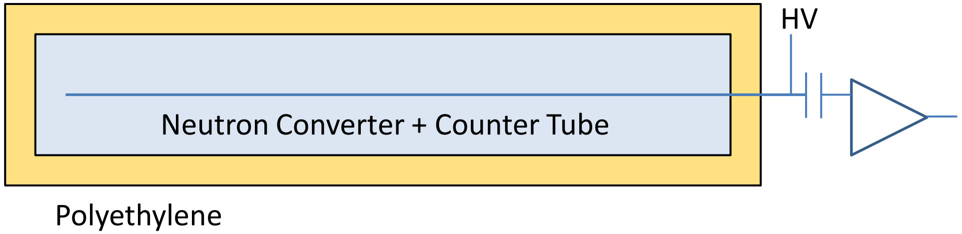
CRNS Detectors

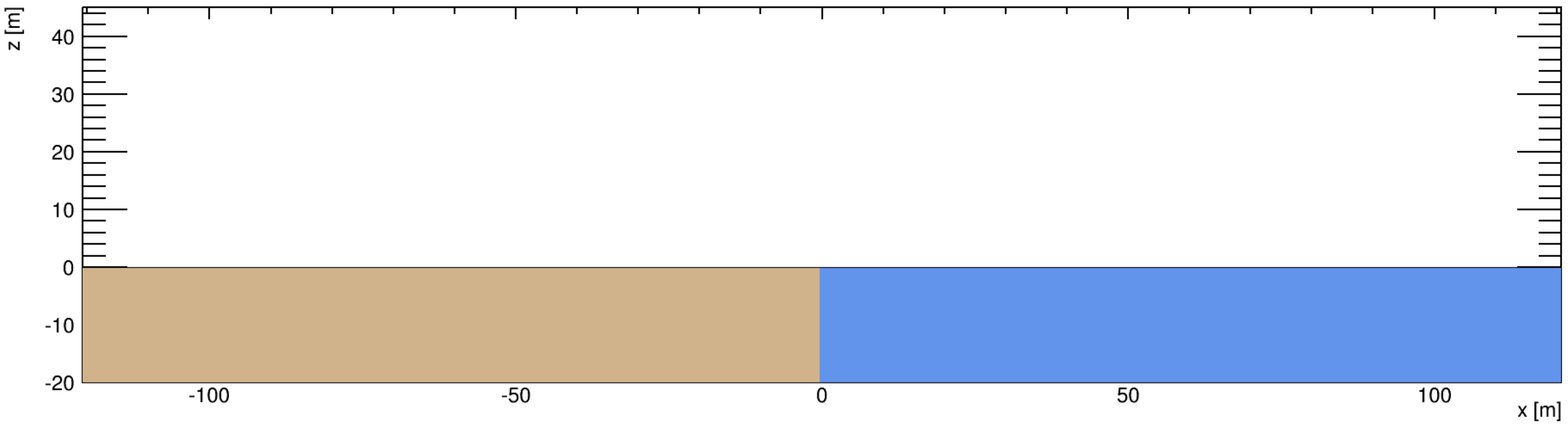






CRNS Detectors





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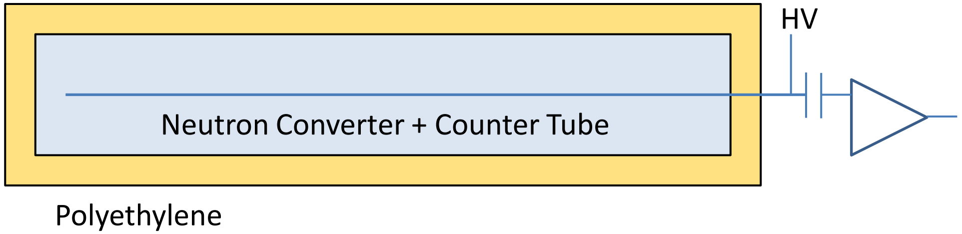
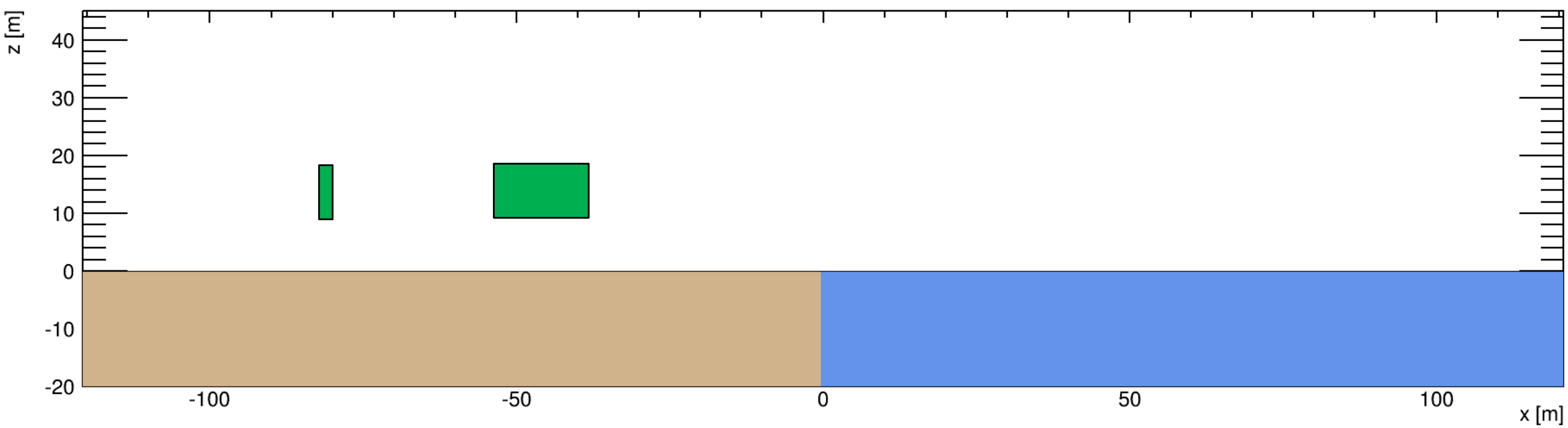
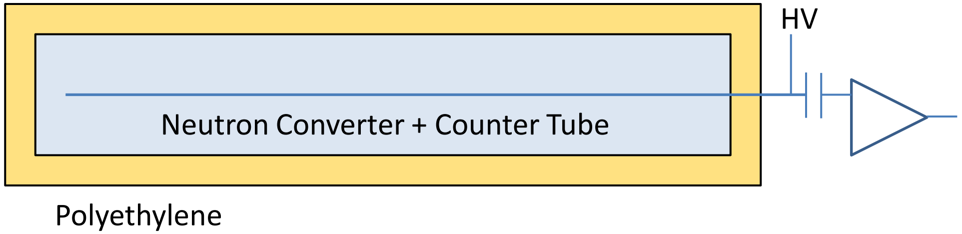




CRNS Detectors



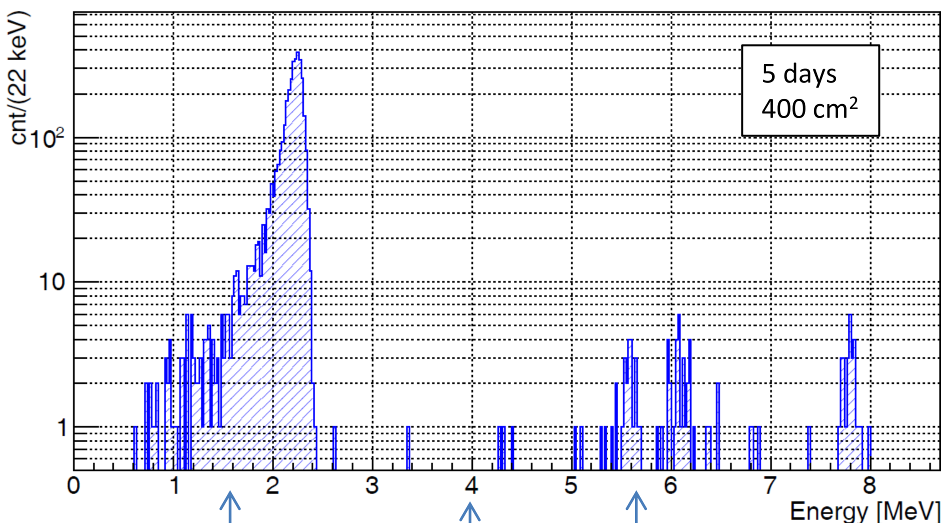
Challenges:

- radiopure materials
- good background suppression
- independent 24/7 operation
  - over months and years
- low power consumption
- wireless data transmission

Radiopurity of tube materials

In collaboration with
Heinrich Wilsenach
IKTP, TU Dresden

Measured sample of high purity copper foils

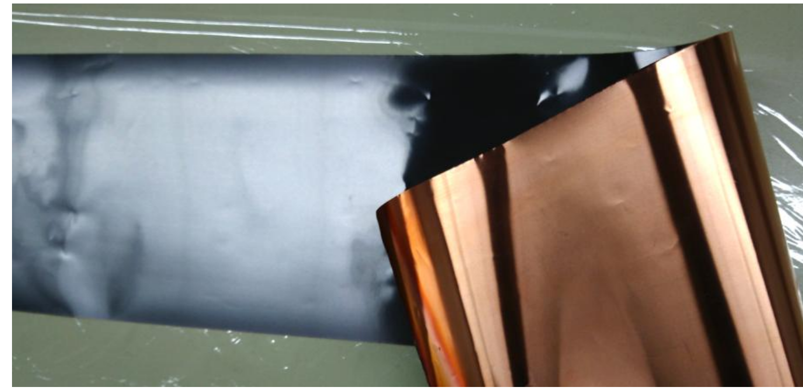


Calibration Source

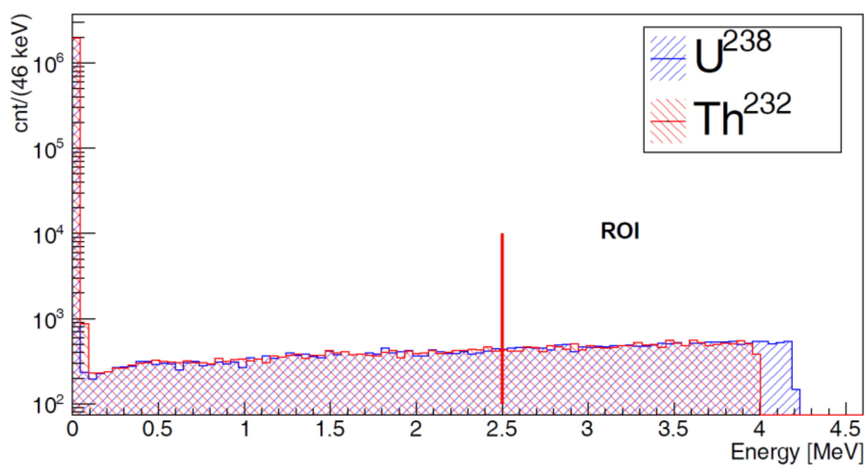
ROI

Rn-222 Traces

(1.05 +/- 0.1) /h/m^2
in (2.6-5.0) MeV



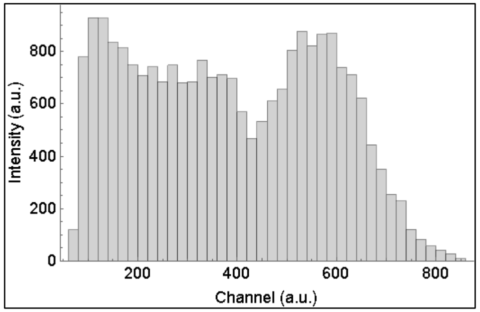
Simulated U+Th Spectra

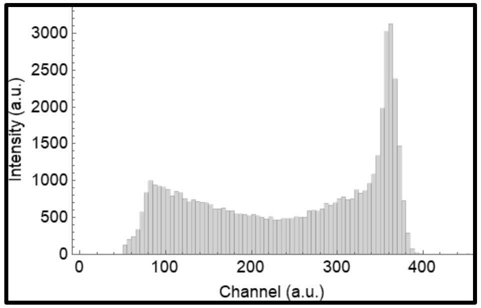


Microcontroller Readout Electronics

nCatcher

HV unit

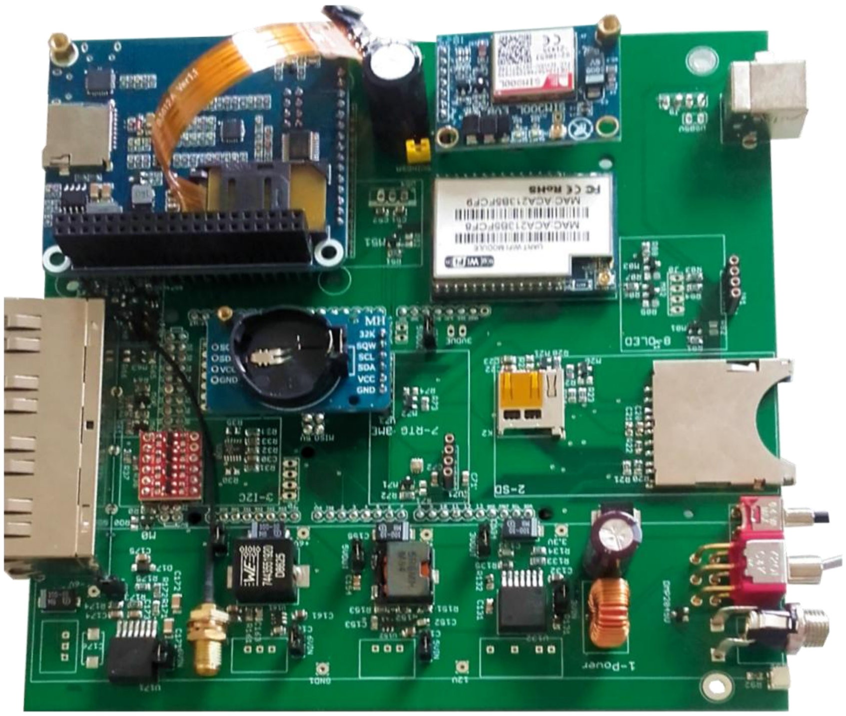




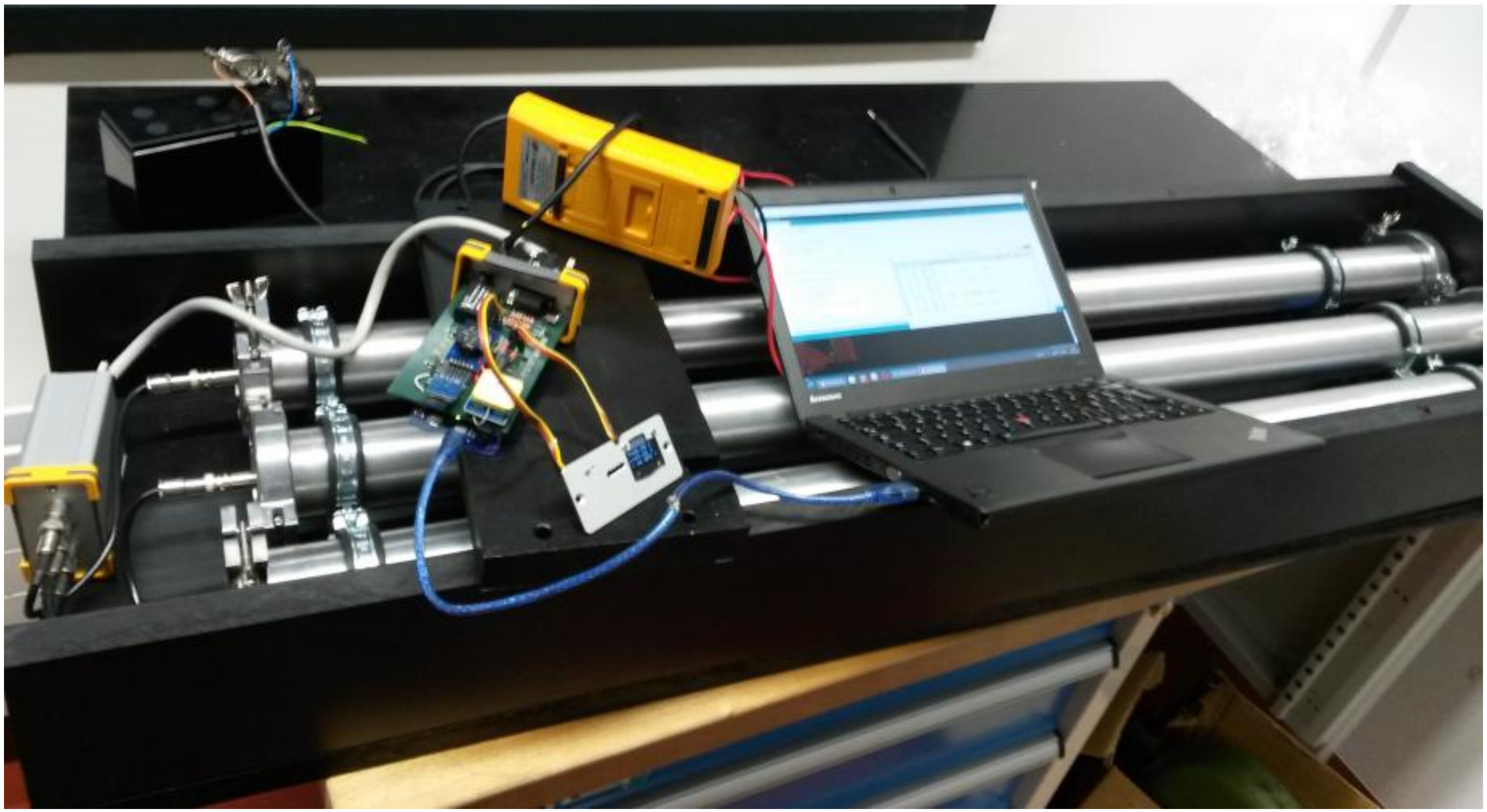
Improvements/Features:

- Low temperature dependence (Remaining drift can be corrected by the firmware)
- Display: RL, p, event info
- High resolution for environmental variables (especially pressure)
- Battery/voltage monitoring
- Multi-purpose RJ45 Connector
- (SDI-12 implementation to come)

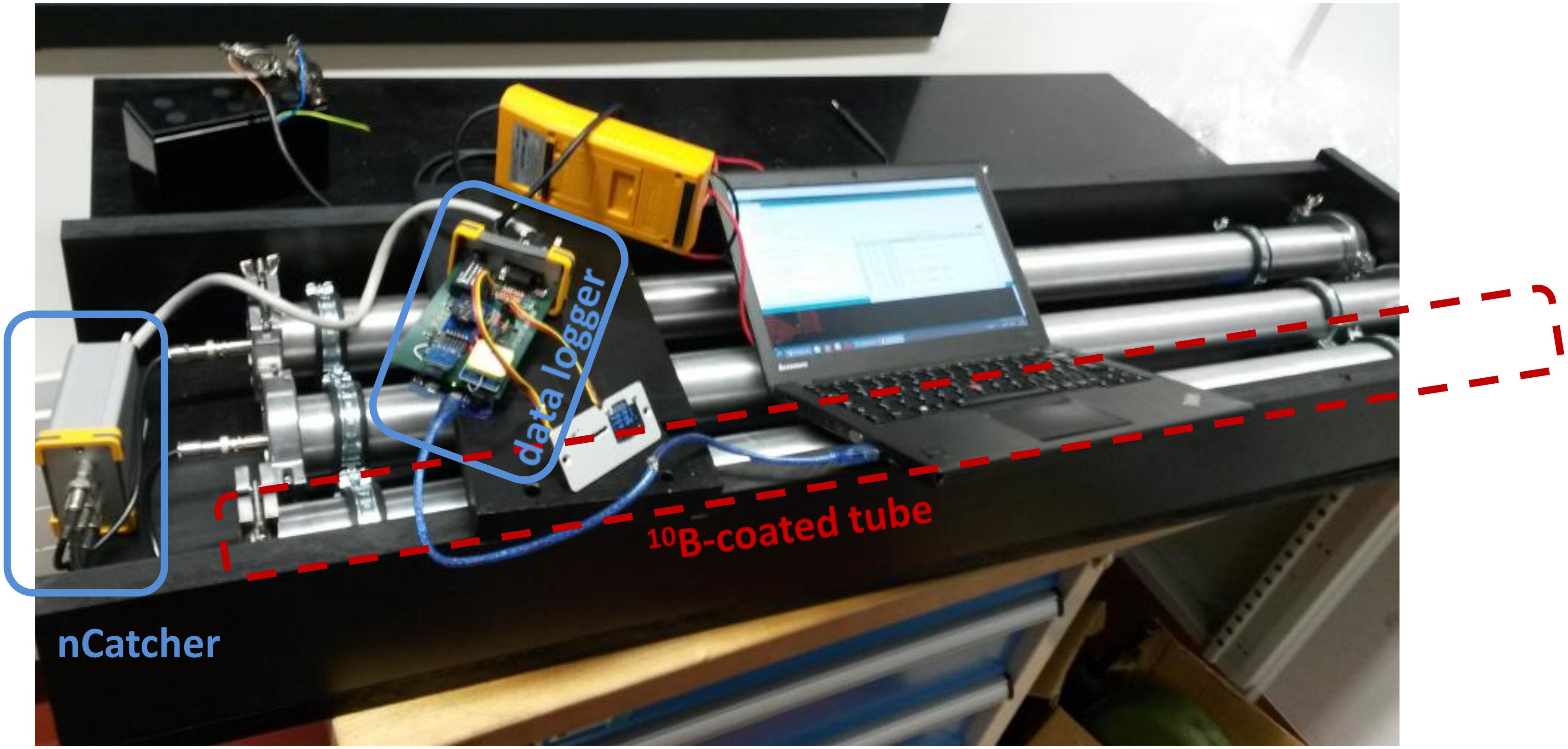
Data logger



^{10}B CRNS Detectors - Prototype



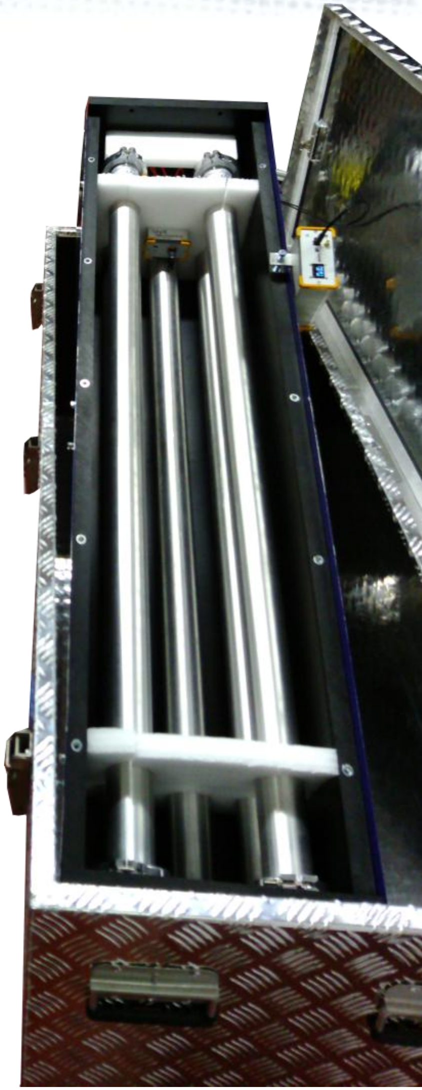
^{10}B CRNS Detectors - Prototype



^{10}B CRNS Detectors - Prototype

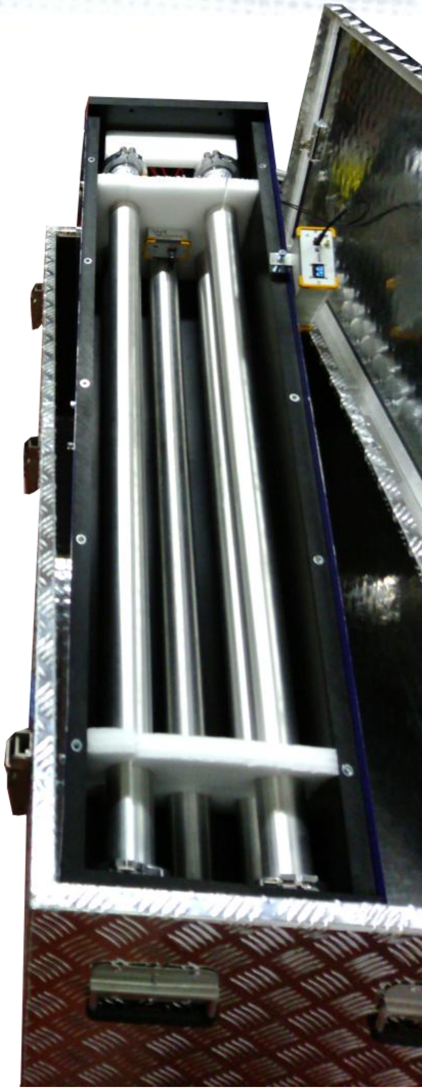
In collaboration with
Heye Bogena and Jannis Jakobi
FZ Jülich

Measurements @ Wüstebach (Eifel)

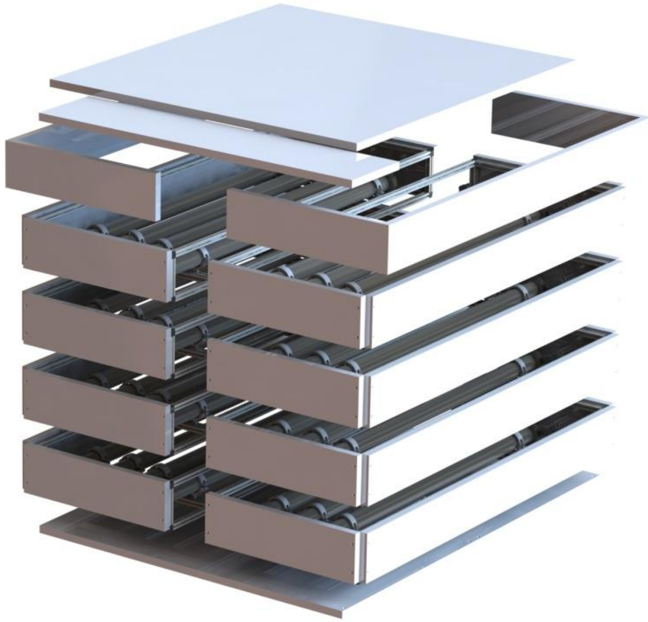


^{10}B CRNS Detectors – Full Size

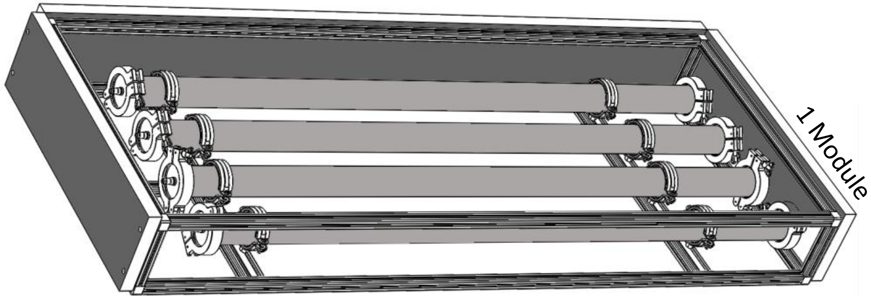
Measurements @ Fendt (Bavaria)



The largest CRNS Detector



Team: Jannis Weimar, Fabian Allmendinger, Matthias Janke, Markus Köhli



First Data:

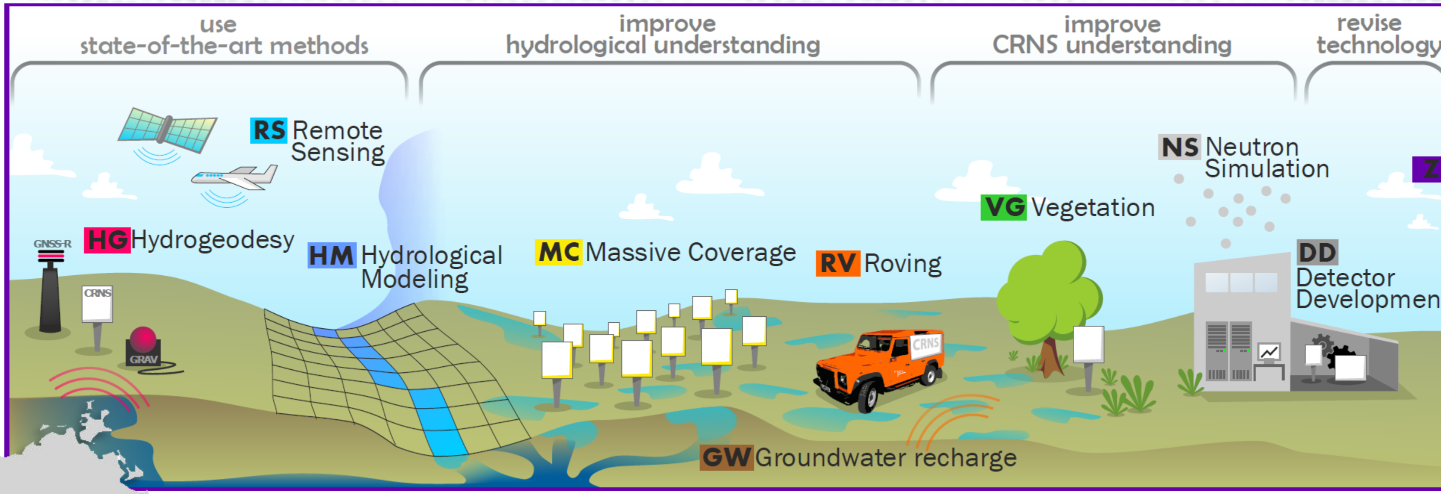
Standard Sensor:	600 /h
Heidelberg Rover:	18000 /h

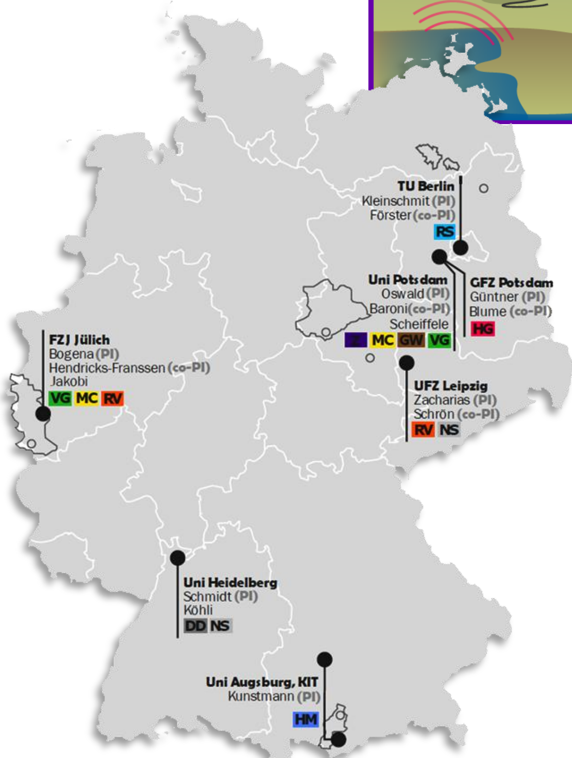
An interdisciplinary Collaboration

Cosmic Sense

DFG

FOR 2694





DFG Research Group

https://www.uni-potsdam.de/de/cosmicsense.html

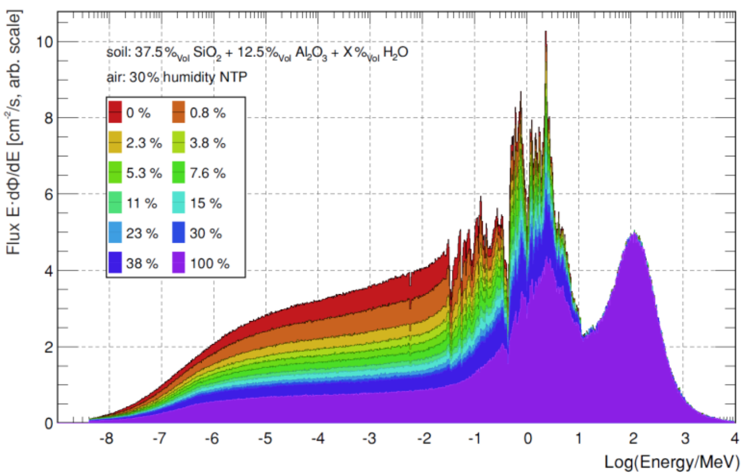
Neutron Physics

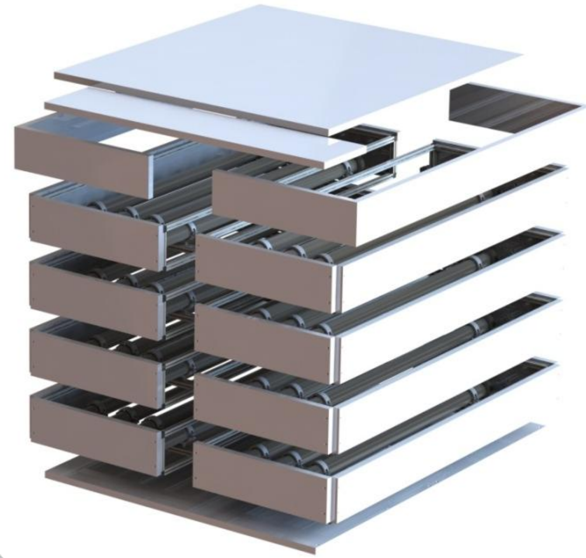
across the scales
and disciplines

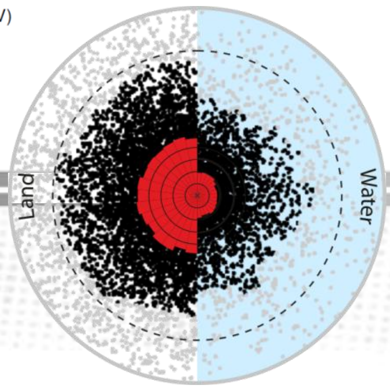
(detection)

Particle Physics Colloquium
November12th 2019

Soil Moisture Measurements with Cosmic-Ray Neutrons







Physikalisches Institut

Ruprecht-Karls-Universität Heidelberg

Markus Köhli

AG Schmidt
ANP-PAT