FACULTY
OF SCIENCES

DEPARTMENT OF PHYSICS AND ASTRONOMY
EXPERIMENTAL PARTICLE PHYSICS AND GRAVITY

PROBING SOIL MOISTURE USING SCINTILLATION DETECTORS

Aiko Decaluwe / 14-03-25

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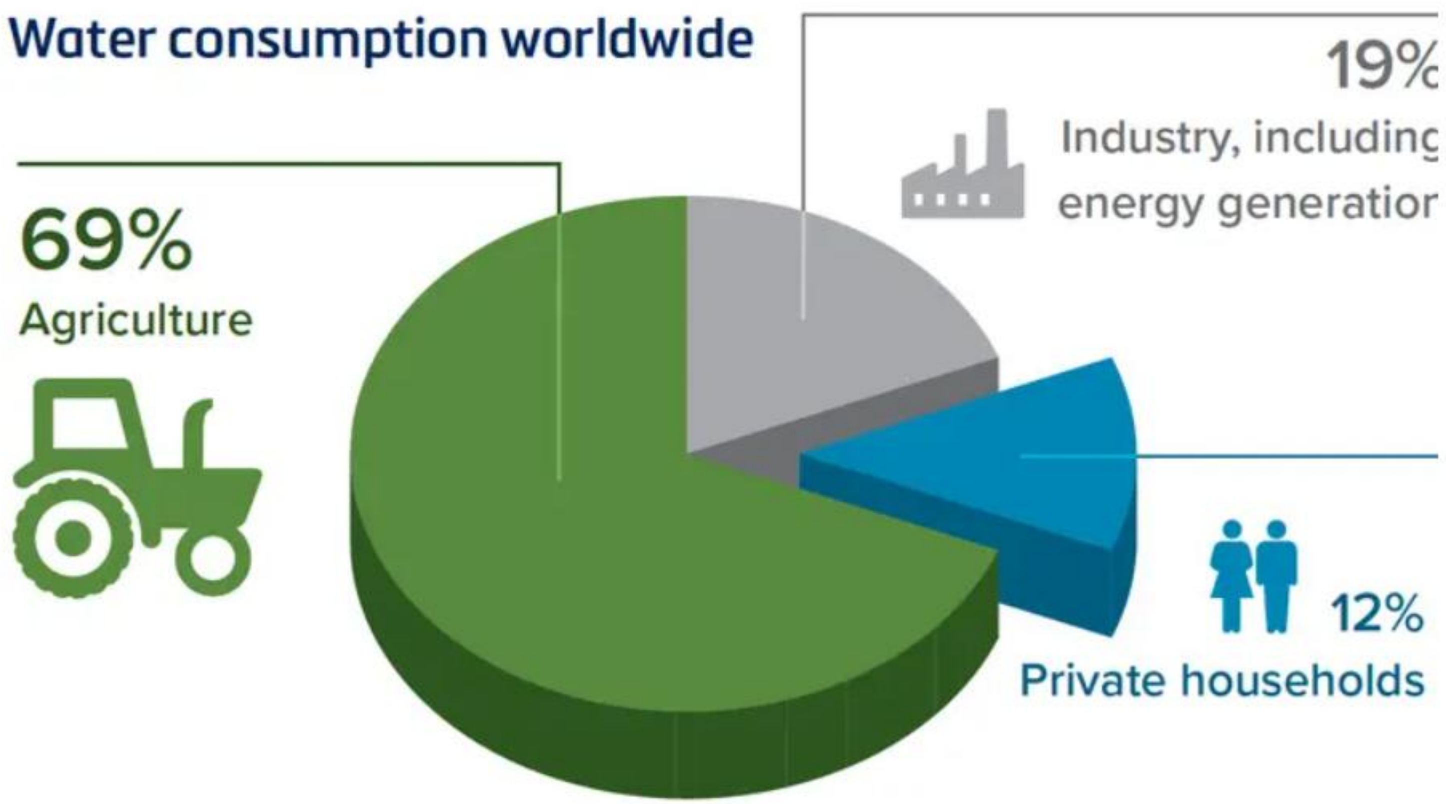
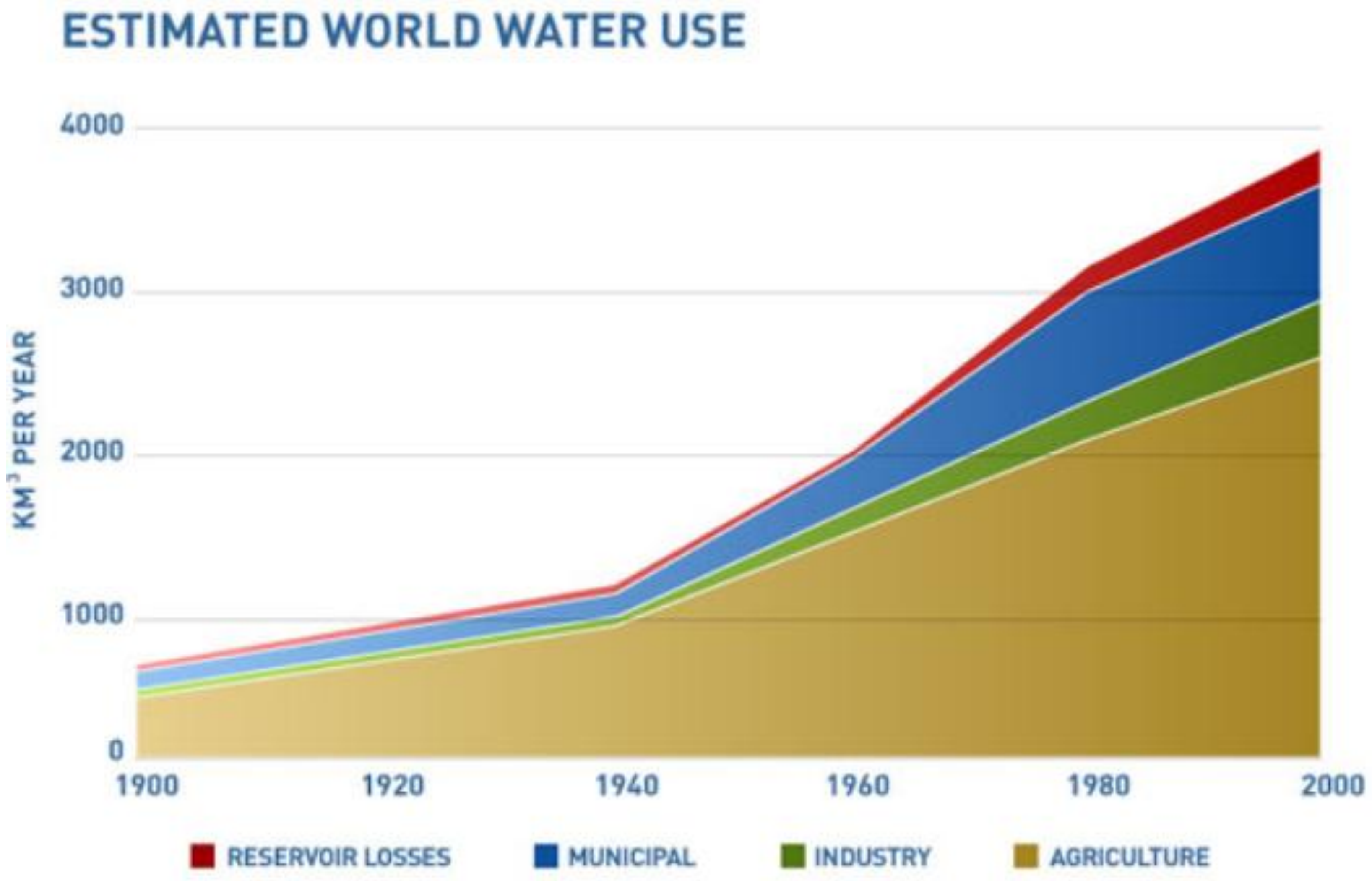
INTRODUCTION

WHY STUDY SOIL MOISTURE?

- Water scarcity
- 70% fresh water used for agricultural production
- SM measurements
- CRNS



(TECE)



(food and agriculture organization of the united states)

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COSMIC RAY NEUTRONS

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COSMIC RAY NEUTRONS

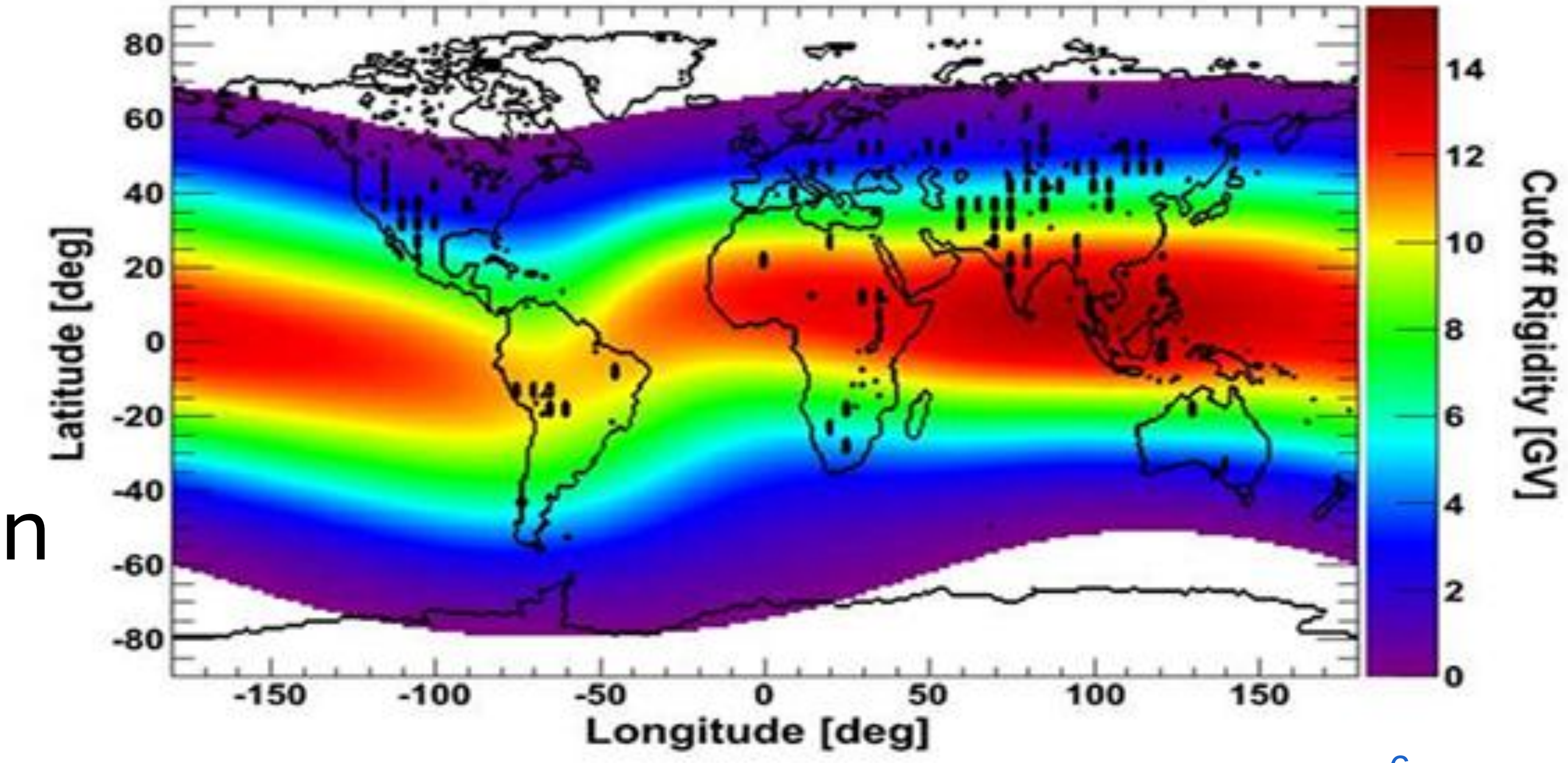
Origin: cosmic rays

→ First protective layer: geomagnetic field

- Shielding: cut-off rigidity (0-17 GV)

→ Second protective layer: atmosphere

- primary cosmic rays interact with air molecules atmosphere
- secondary cosmic rays (p, n, other)
- fast neutrons (E≈1MeV) through nuclear evaporation process



(O. Adriani et al., 2016)

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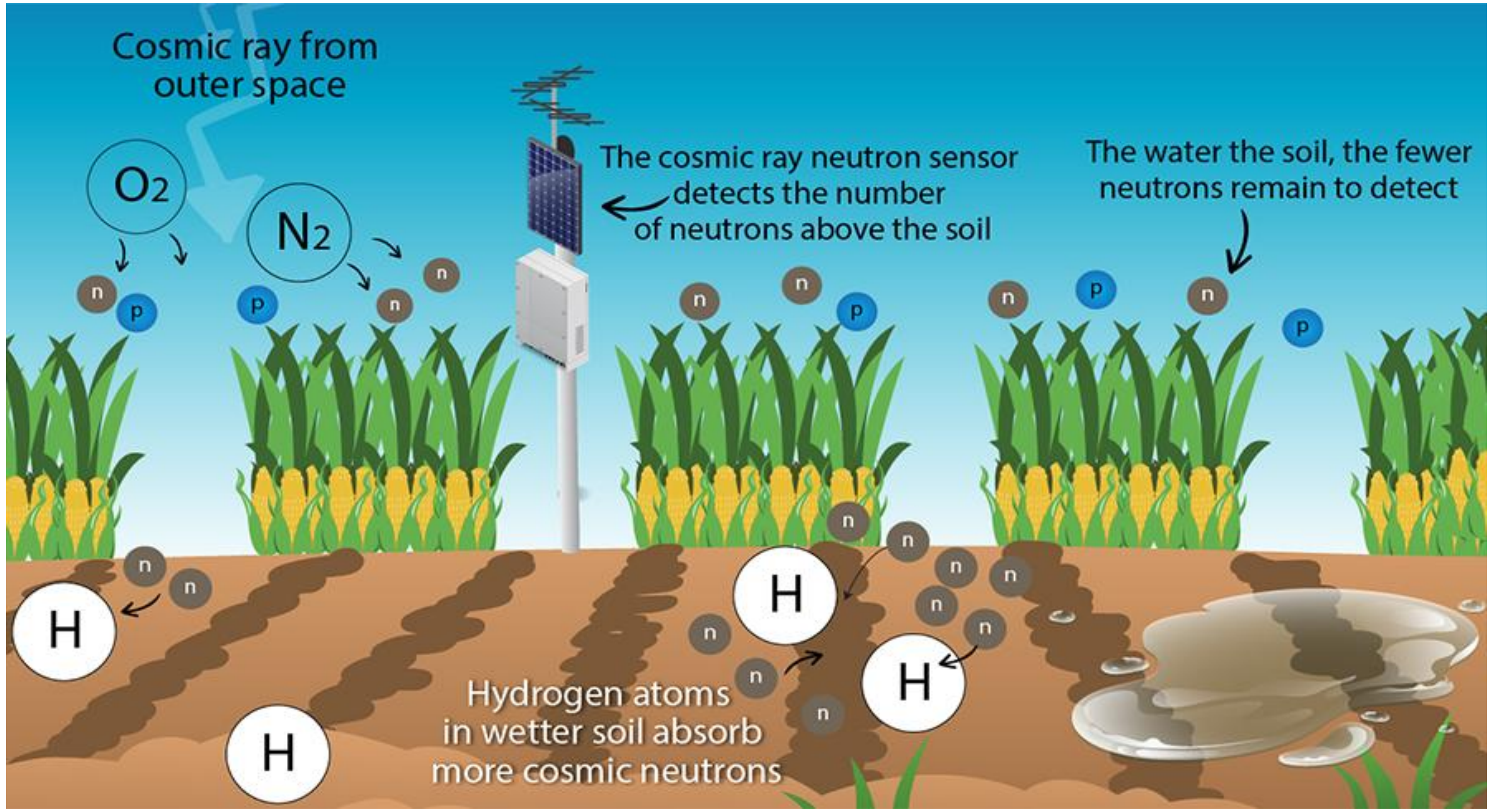
CONNECTION WITH SOIL MOISTURE

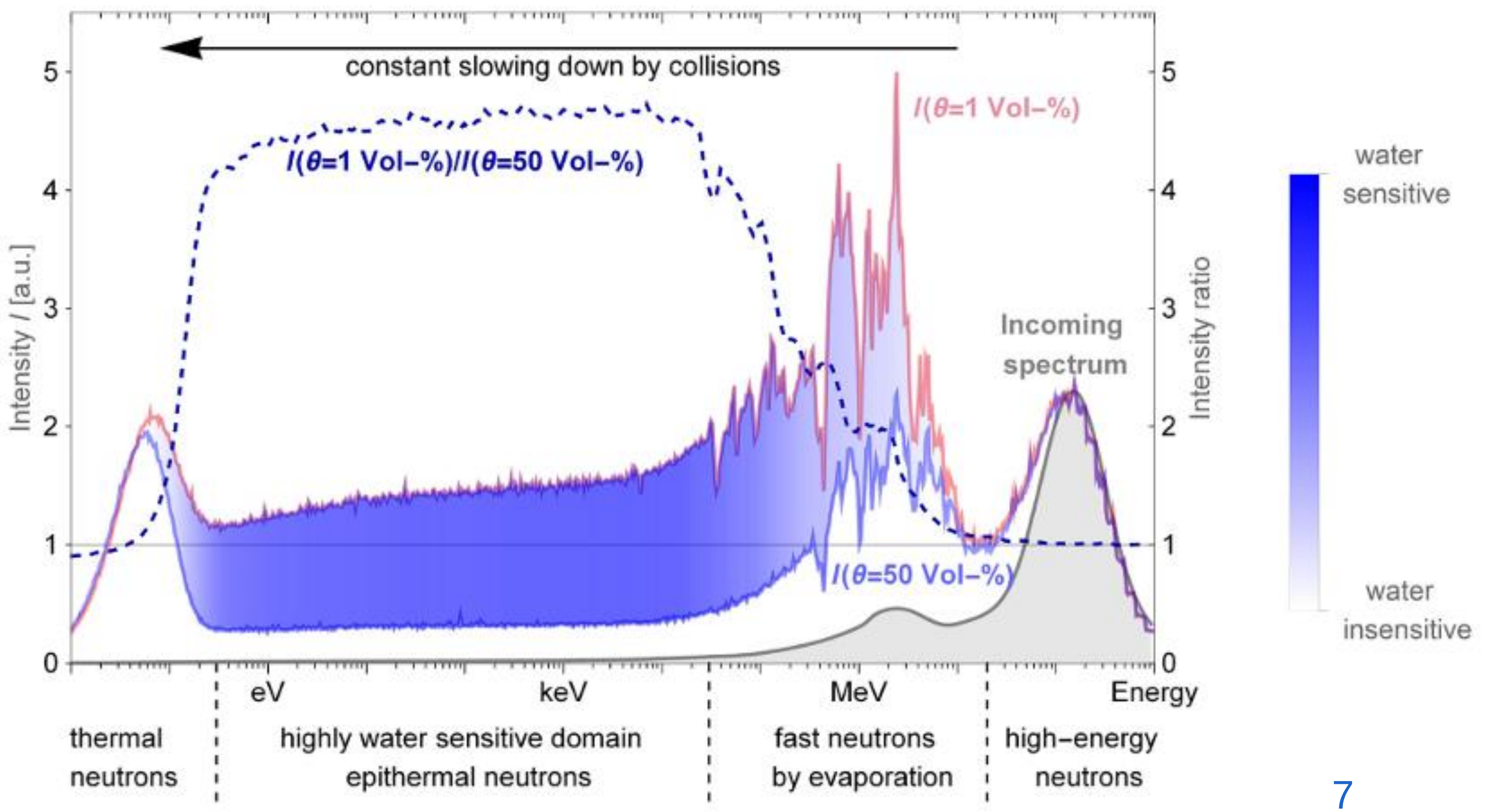
Fast neutrons moderated by hydrogen atoms in soil

→ captured or diffused back into air as low energy neutrons

→ dry/wet soils = many/few neutrons



(International atomic energy agency, 2018)



(Weimar et al., 2020)

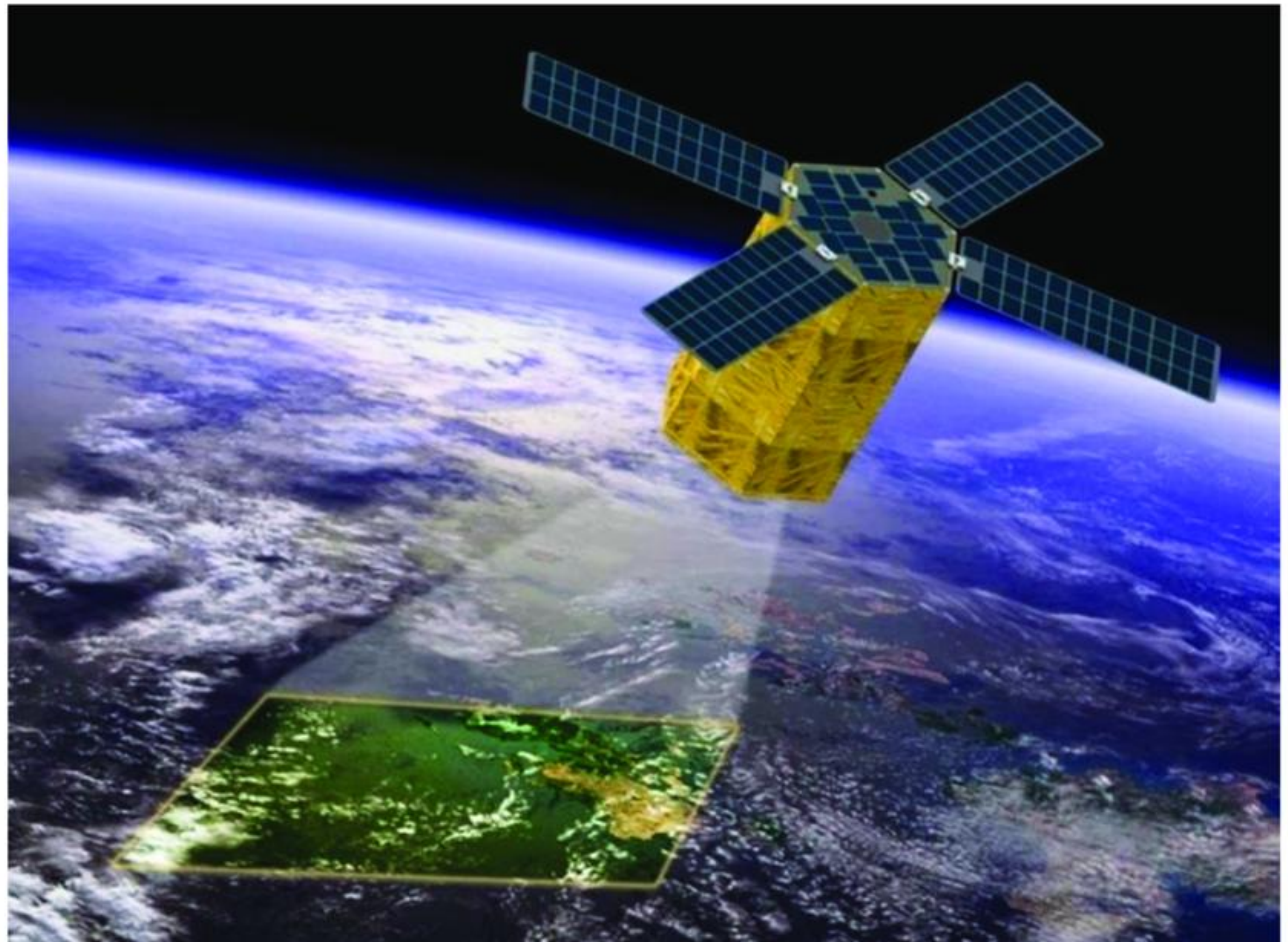
HOW TO MEASURE SOIL MOISTURE?

Soil moisture measurements

→small scales: visual, gravimetric method, invasive sensors

→ large scales: remote sensing using satellites

→ field scale: CRNS



(Svynchuk et al., 2021)

(Deyan Georgiev, 2024)

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COSMIC RAY NEUTRON SENSING (CRNS)

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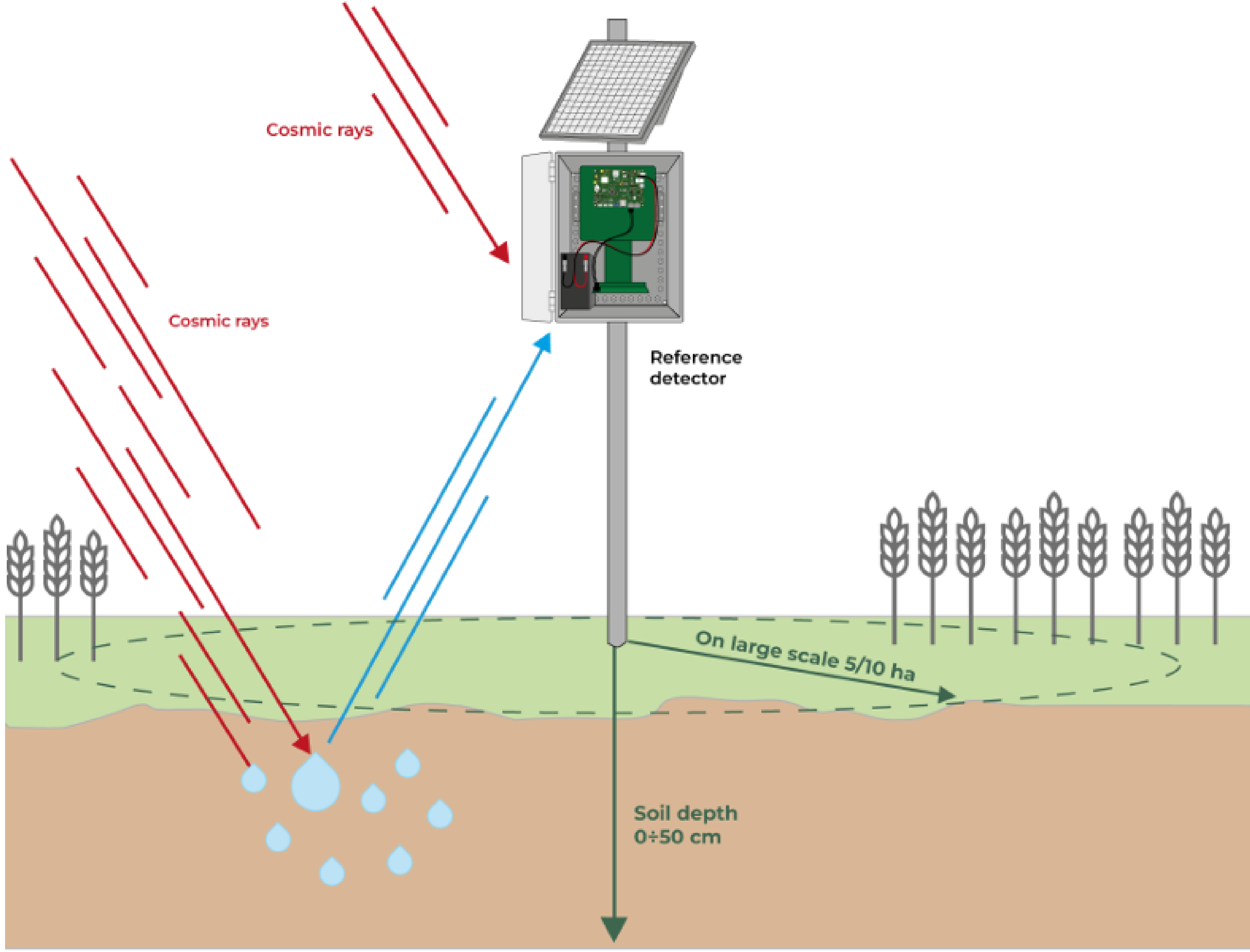
FINAPP CRNS DETECTOR

- Counts low energy neutrons
- Radius: 125 m
- Depth: 0-50 cm depth
- Average soil moisture measurement

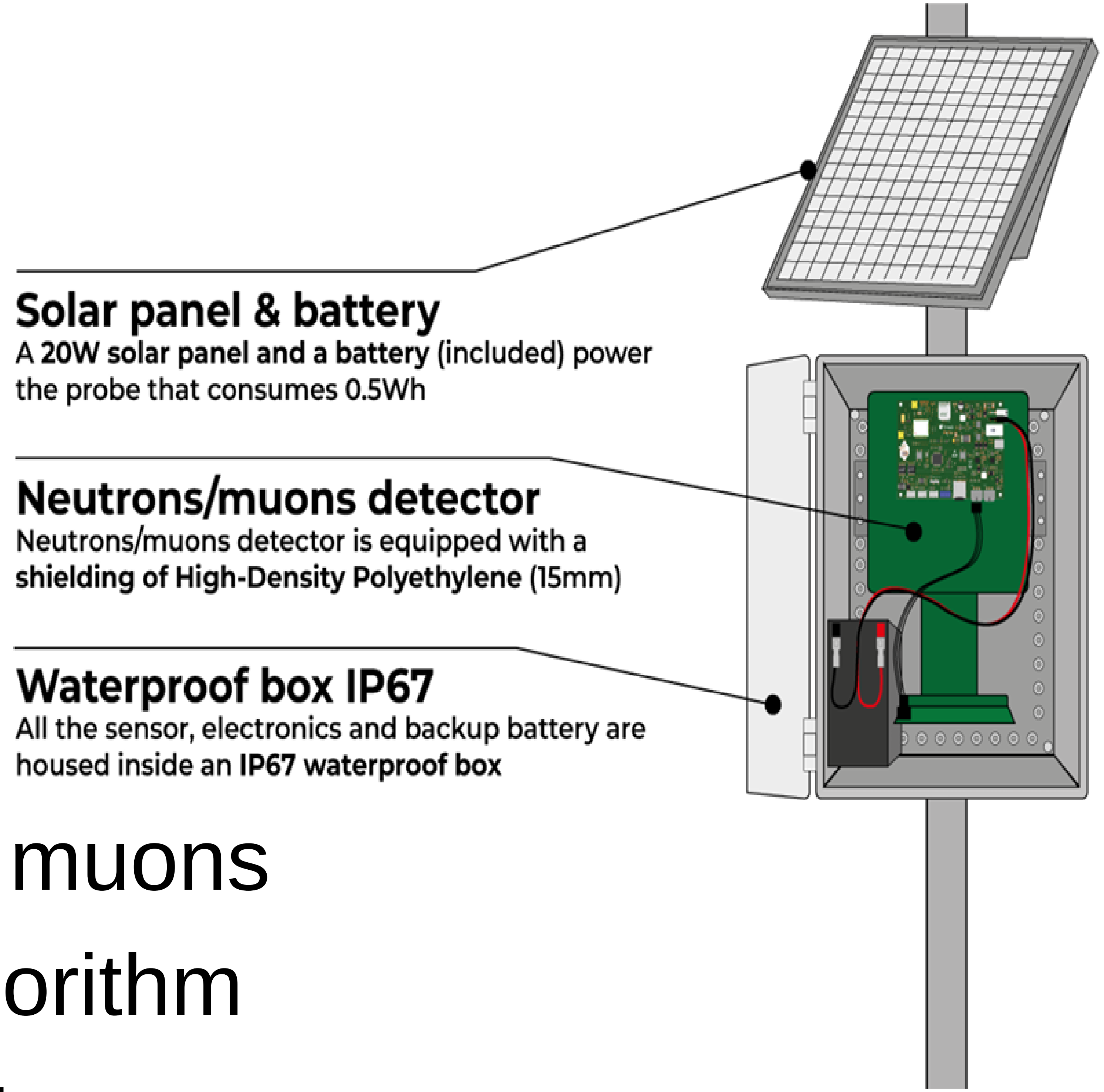


(Finapp, 2024)

FINAPP CRNS DETECTOR

- Detector
  - → sheets:
    - ^{6}LiF: thermal neutrons

$$^{6}\text{Li} + {}^{1}\text{n} \rightarrow {}^{3}\text{H} + {}^{4}\text{He} + 4.78\ \text{MeV}$$



(Finapp, 2024)

    - ZnS:Ag (scintillator): ^{3}H, ^{4}He, muons
  - → Pulse Shape Discrimination algorithm
- Powered by solar panel and battery

FROM NEUTRON COUNT TO SOIL MOISTURE

Soil moisture

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

Neutron count

Neutron count over dry soil

But calibration and corrections needed!

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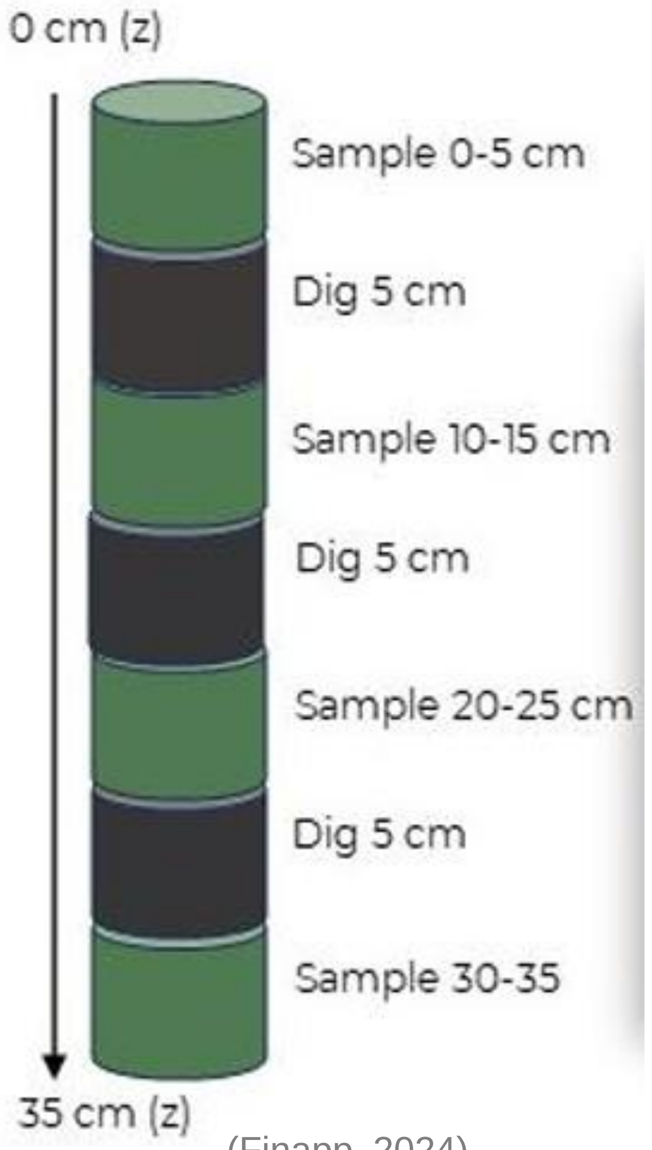
CALIBRATION

- Gravimetric method: 16 samples
- Weighted average: θ = 31,6%
- $N_0 = 2309$



(Finapp, 2024)

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CORRECTIONS

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

1) Atmospheric pressure
2) Air humidity
3) Incoming cosmic radiation

$$N = N_{\mathrm{raw}} \cdot C_{\mathrm{p}} \cdot C_{\mathrm{h}} \cdot C_{\mathrm{inc}}$$

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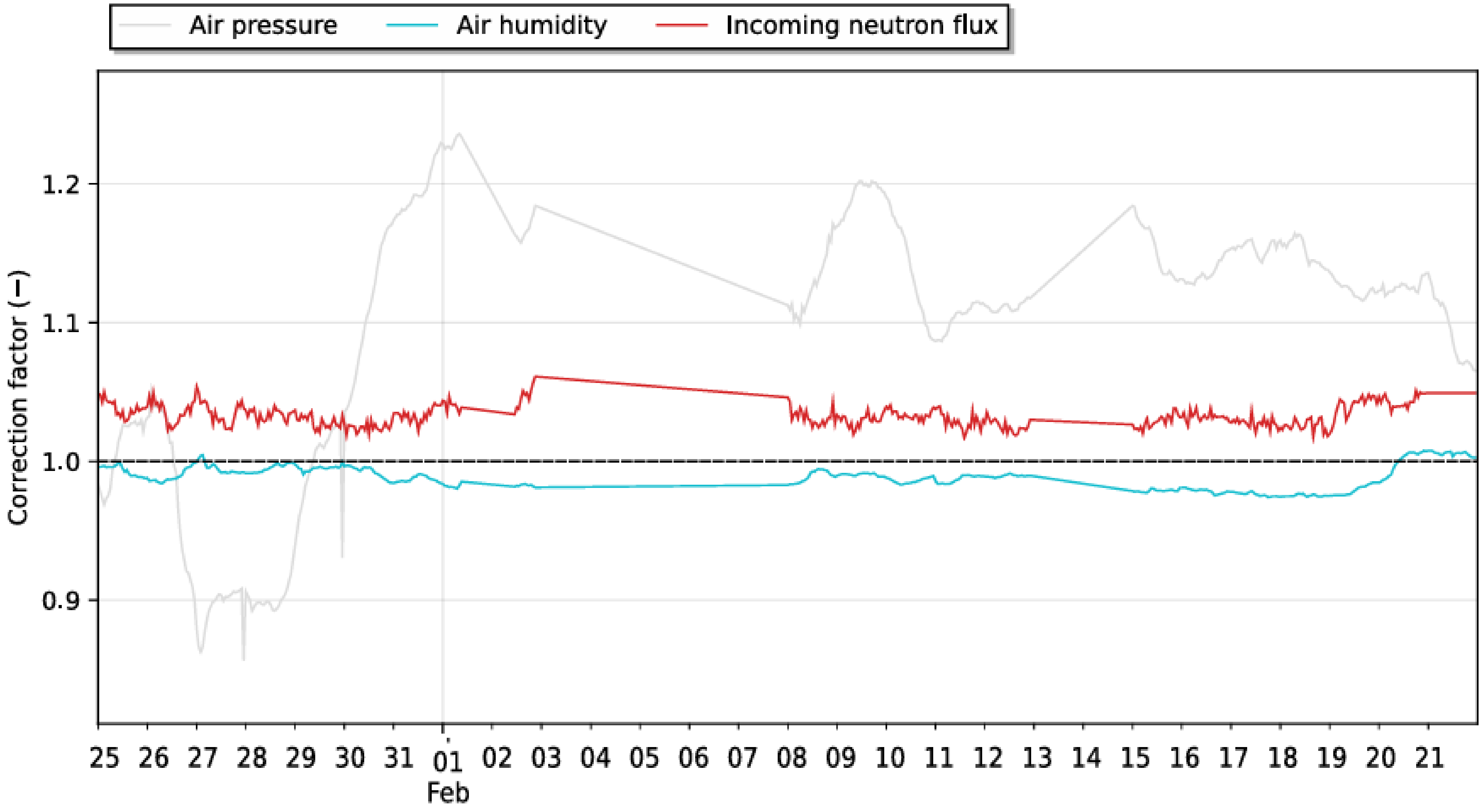
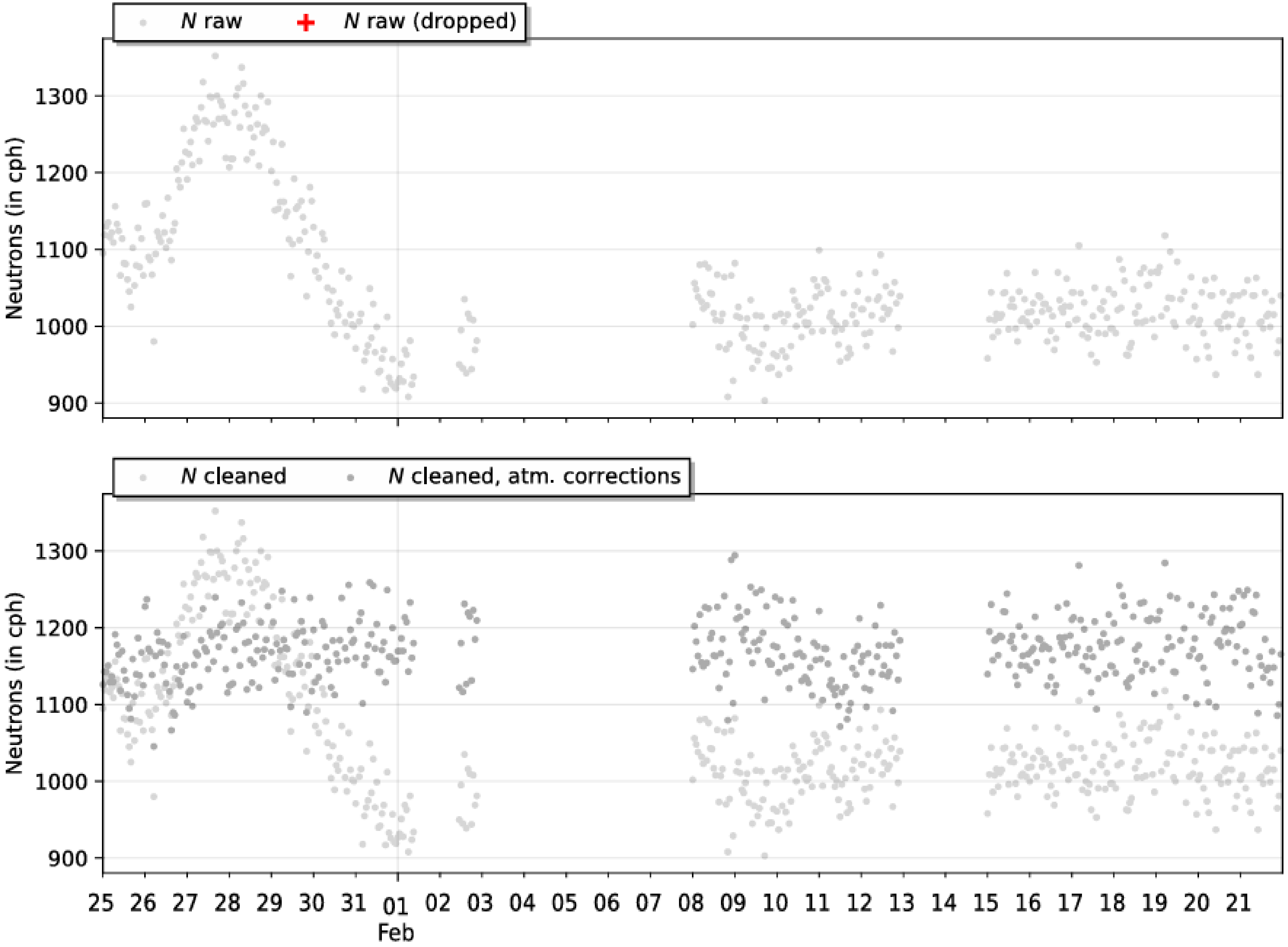
RESULTS

- Data: weather station and CRNS (25/01 – 21/02)
- CoRNy: A Cosmic-Ray Neutron processing toolbox for pythonData
- Corrections:



RESULTS



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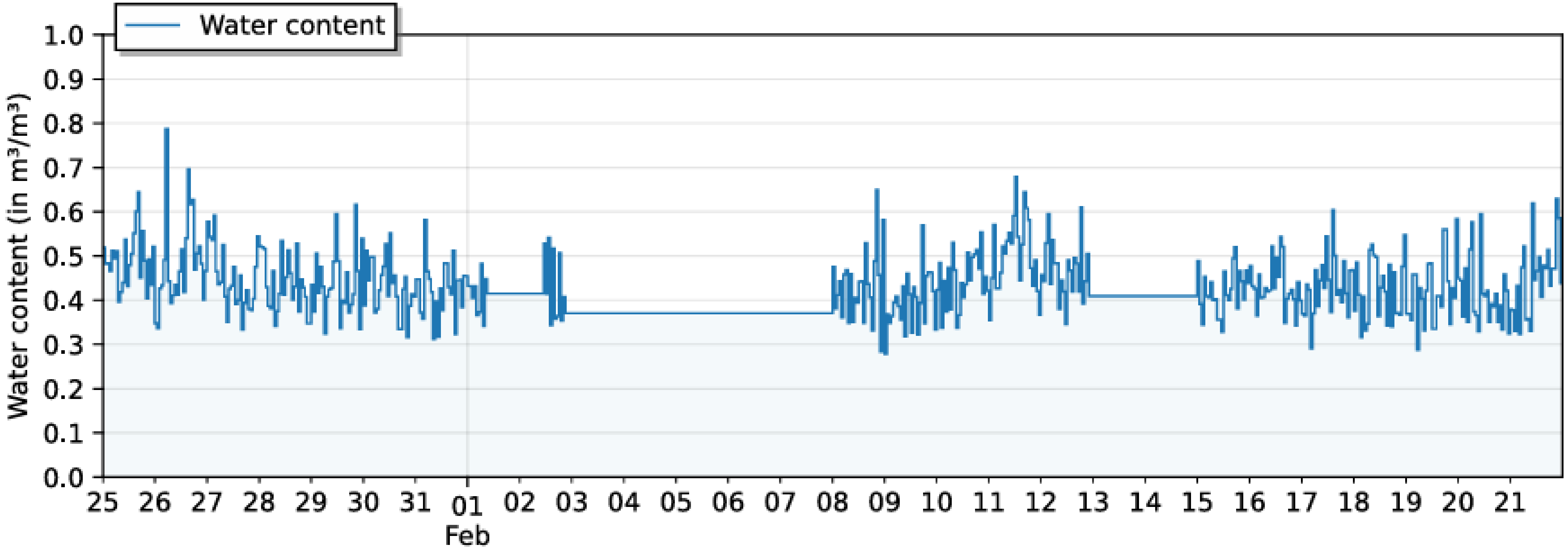
RESULTS



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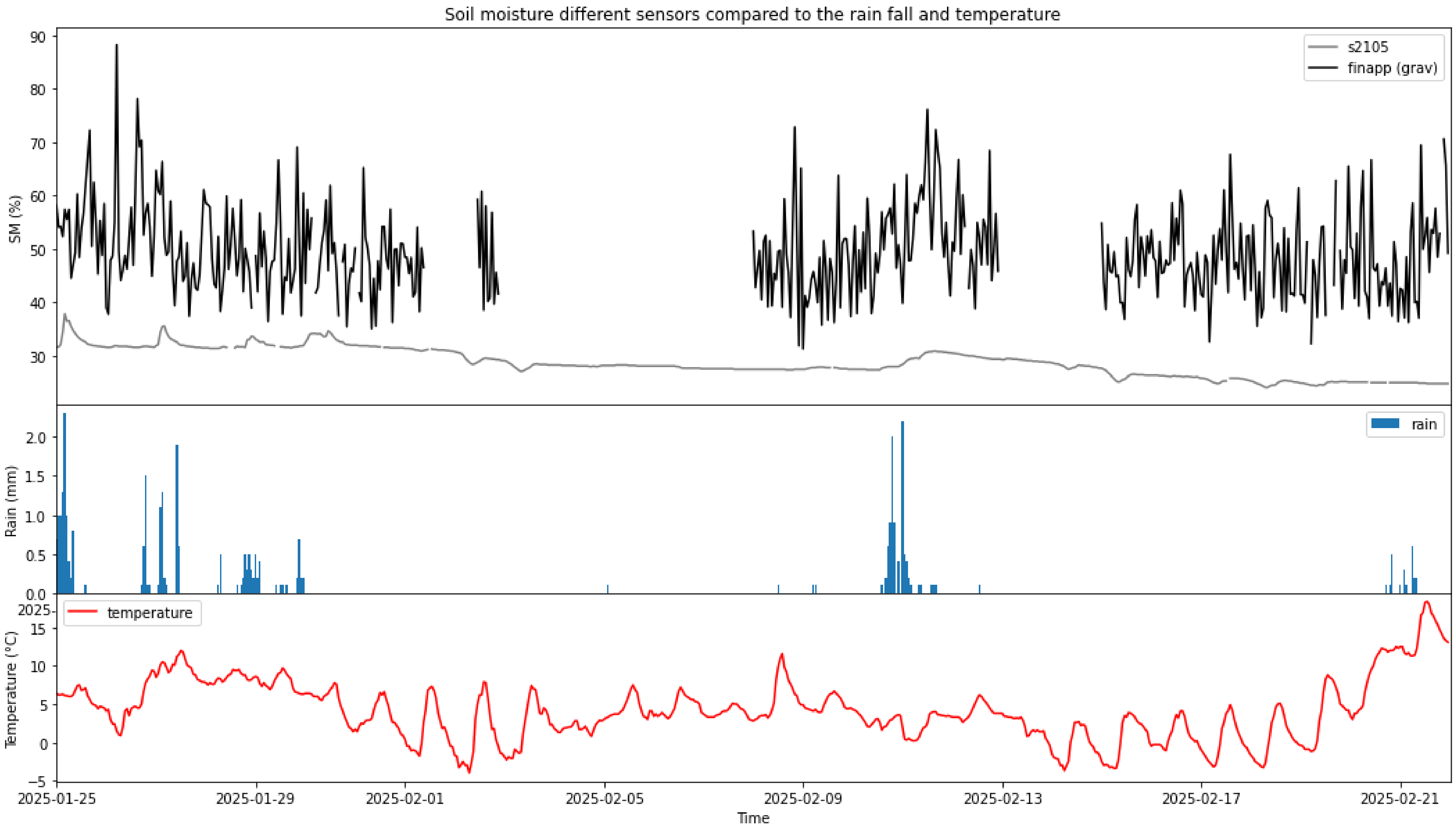
RESULTS



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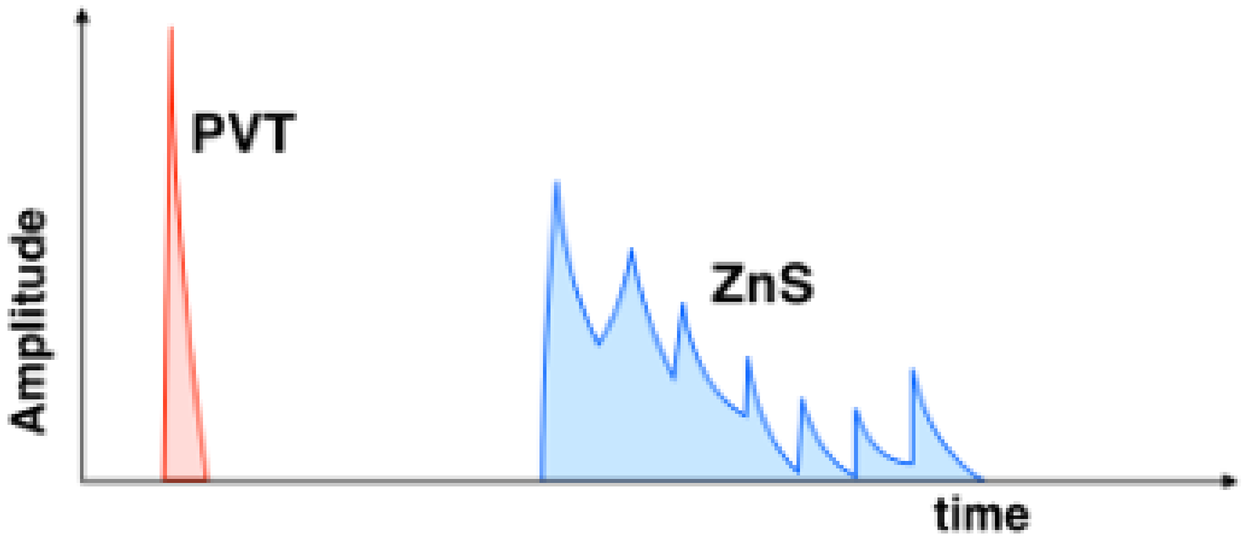
SCINTILLATION DETECTOR

SCINTILLATION DETECTORS

– Set-up 1:
  → 4 plastic scintillator cube
  → neutron screens

$$^{6}Li + {}^{1}n \rightarrow {}^{3}H + {}^{4}He + 4.78\ MeV$$

  → wavelength shifting fiber
  → SiPM
  → oscilloscope



(Y. Abreu et al 2017)

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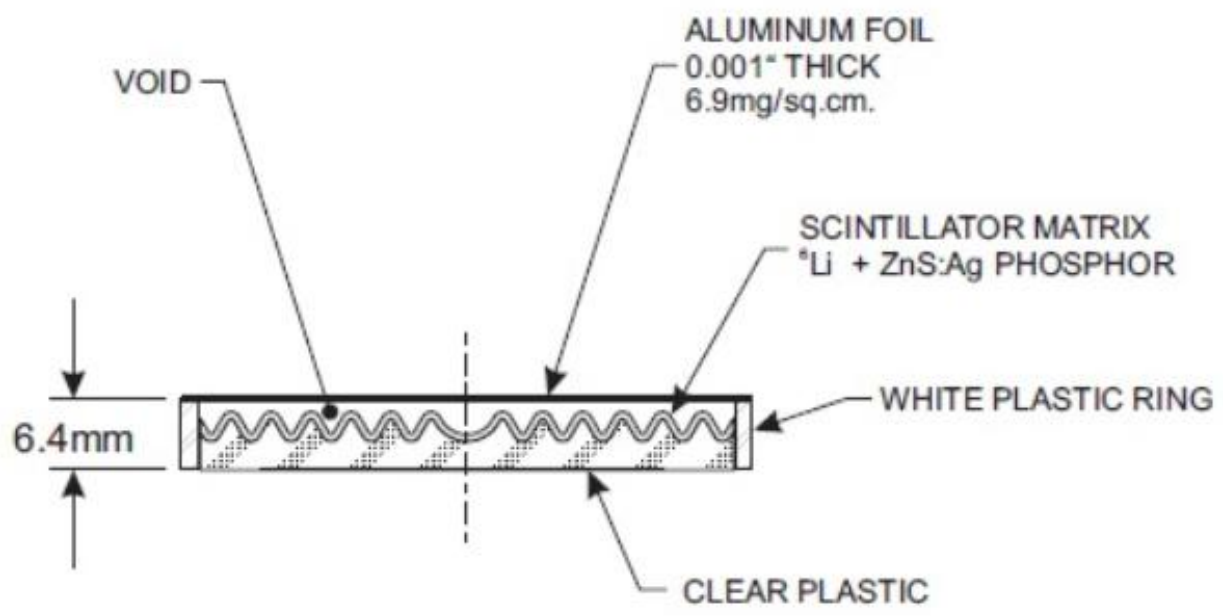
SCINTILLATION DETECTORS

– Set-up 2

→ small thermal neutron detector



(Eljen technology)

– Set-up 3

→ flat scintillation cube

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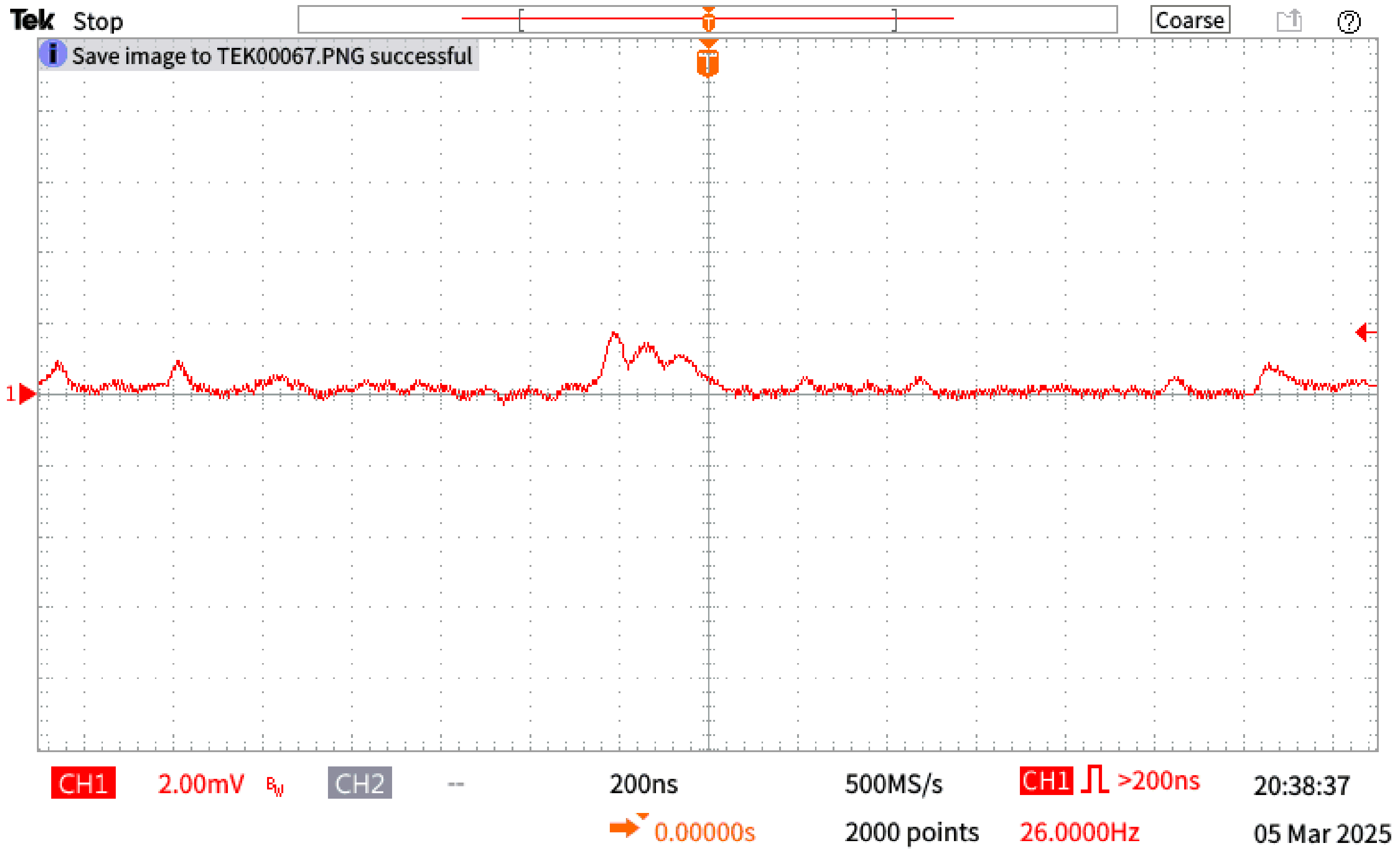
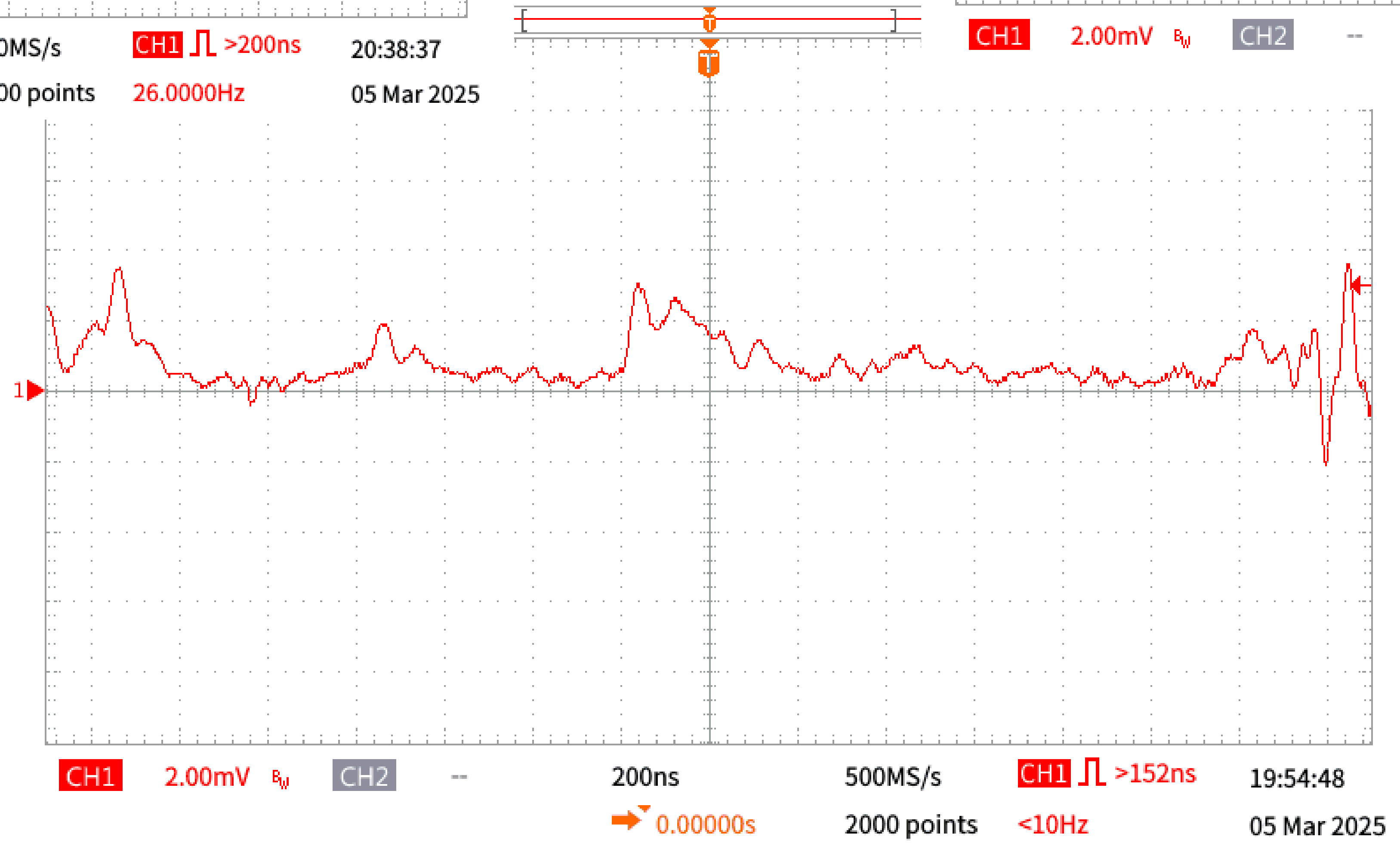
RESULTS





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APPROACH BY SIMULATIONS

URANOS

- Ultra Rapid Adaptable Neutron-Only Simulation for Environmental Research
- Physical parameters: θ, R_c , h
- Layers:

Layers

	Position	Height	Material	Matrix
1	-1000	350	11	
2	-650	100	11	
3	-550	510	11	
4	-40	38	21	
5	-2	0.4	11	
6	-1.6	1.6	21	
7	0	0.5	20	

Source Layer 2

Detector Layer 5

Ground Layer 7

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URANOS

– Computational parameters: area and source size
  → 50 m^2
– Detector: geometry
  → CRNS: 20x20cm screen
  → self-made detector: 10x10cm screen
– #neutrons: 120n/m^2/s → 360 000 n/m

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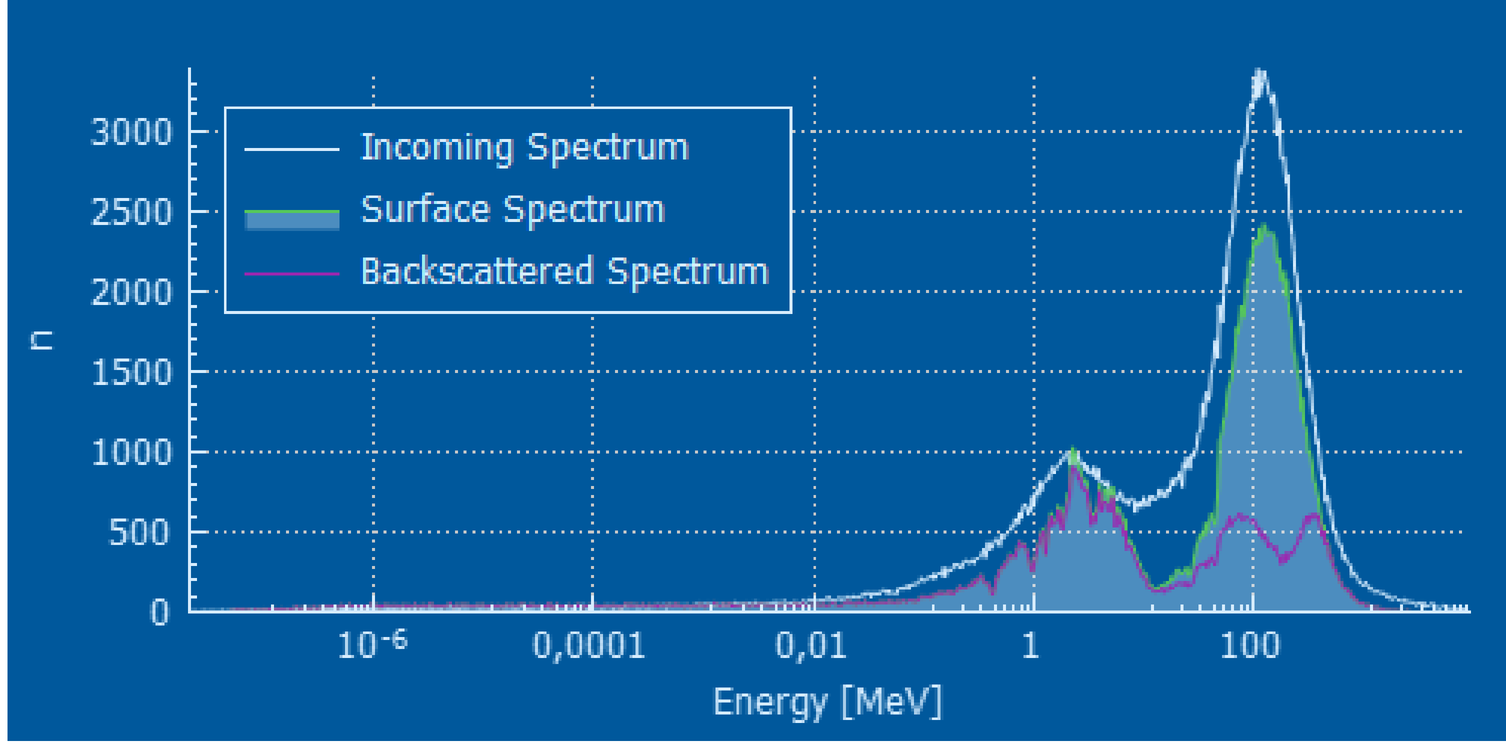
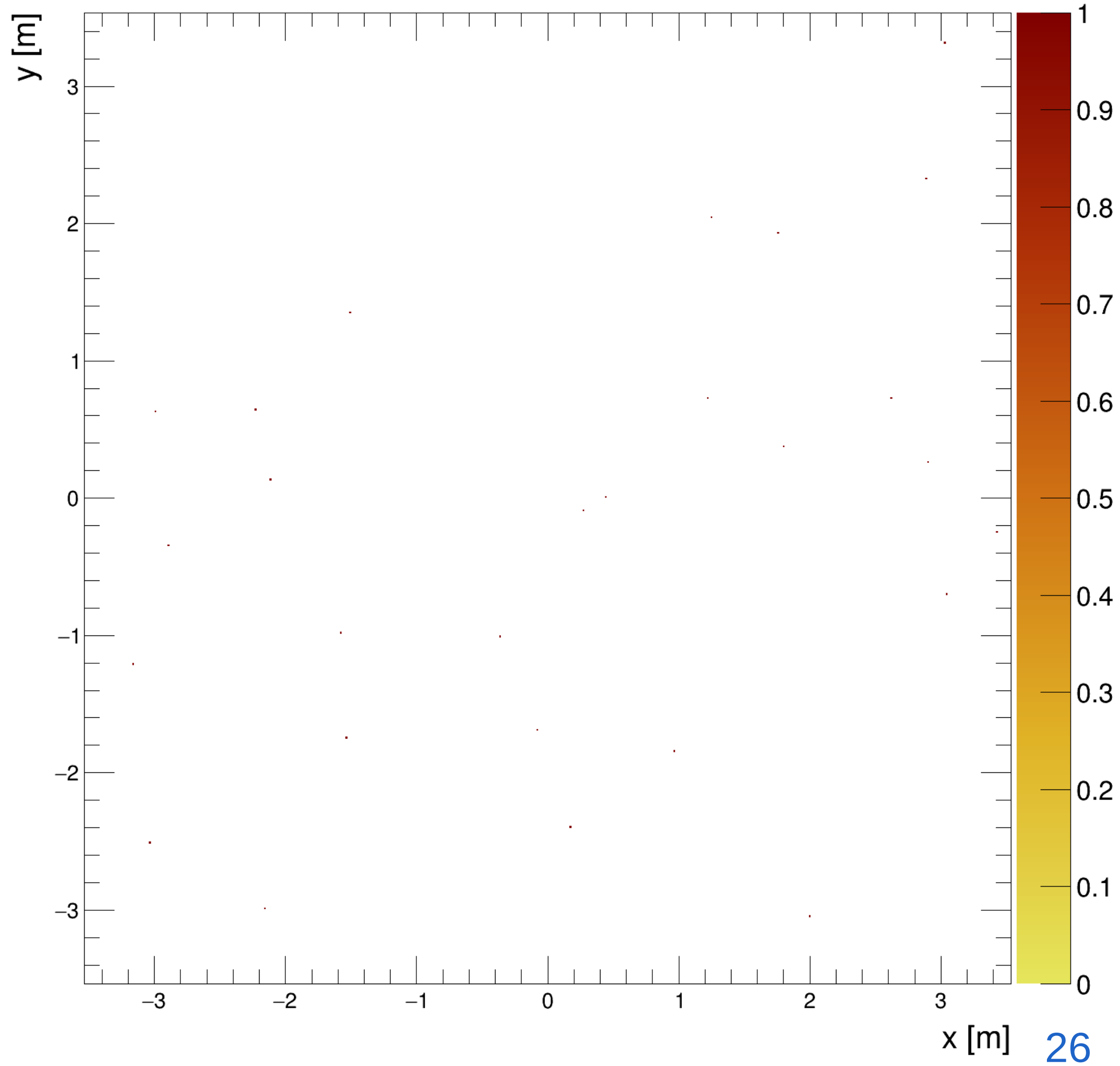
RESULTS

SM	Finapp (n/min)	Self-made (n/min)
1%	98	52
30%	45	24
43%	35	22
50%	31	18





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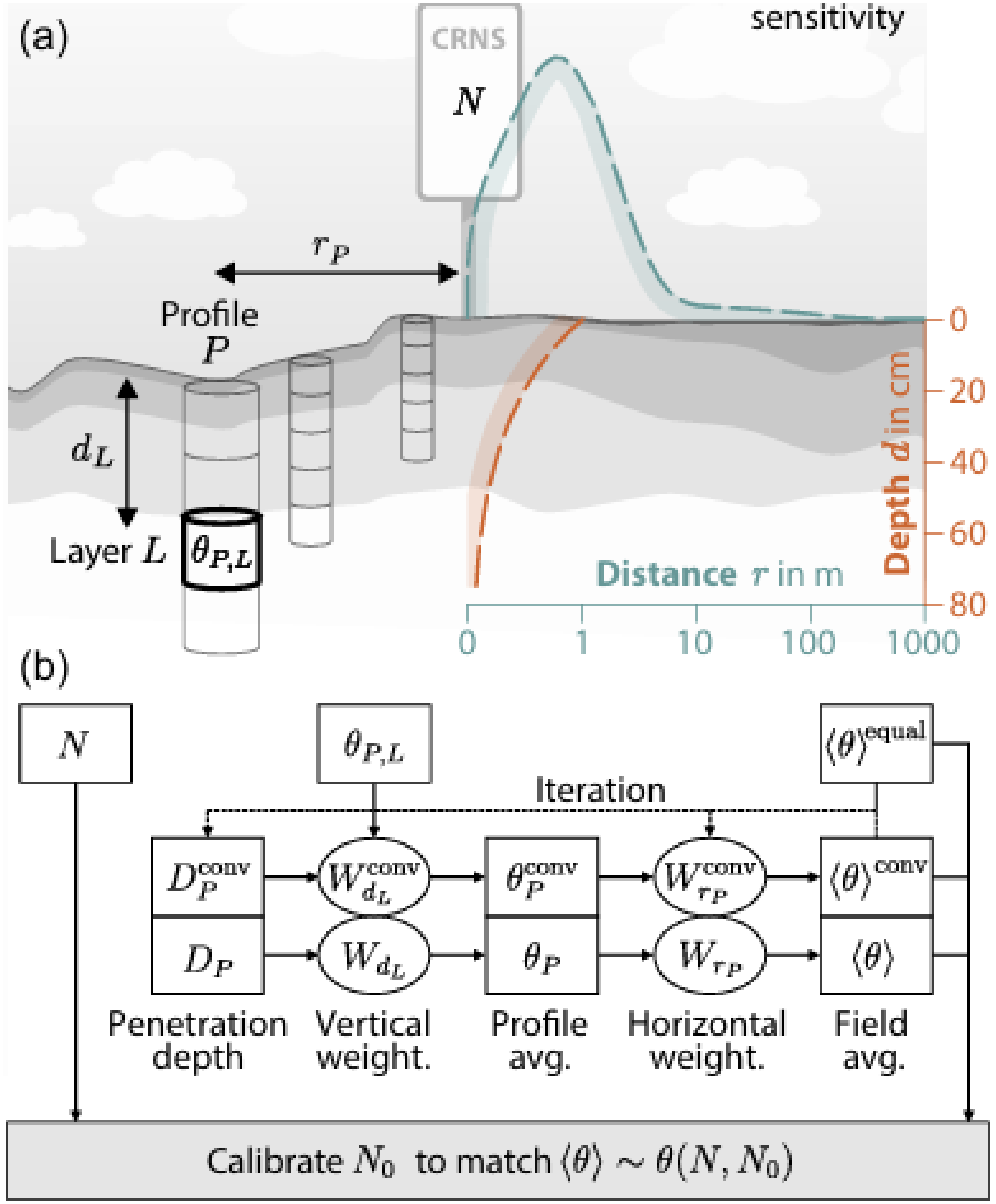
CALIBRATION: WEIGHTED AVERAGE

1) Estimate average value
2) Calculate the penetration depth D of the neutrons for each profile P
3) Vertically average the values $\theta_{P,L}$ over layers L, to obtain a weighted average for each profile P

$$W_d = e^{-2d/D}$$

$$\theta_P = \frac{\sum_i w_i \theta_i}{\sum_i w_i}$$



(M, Shrön et al., 2017)

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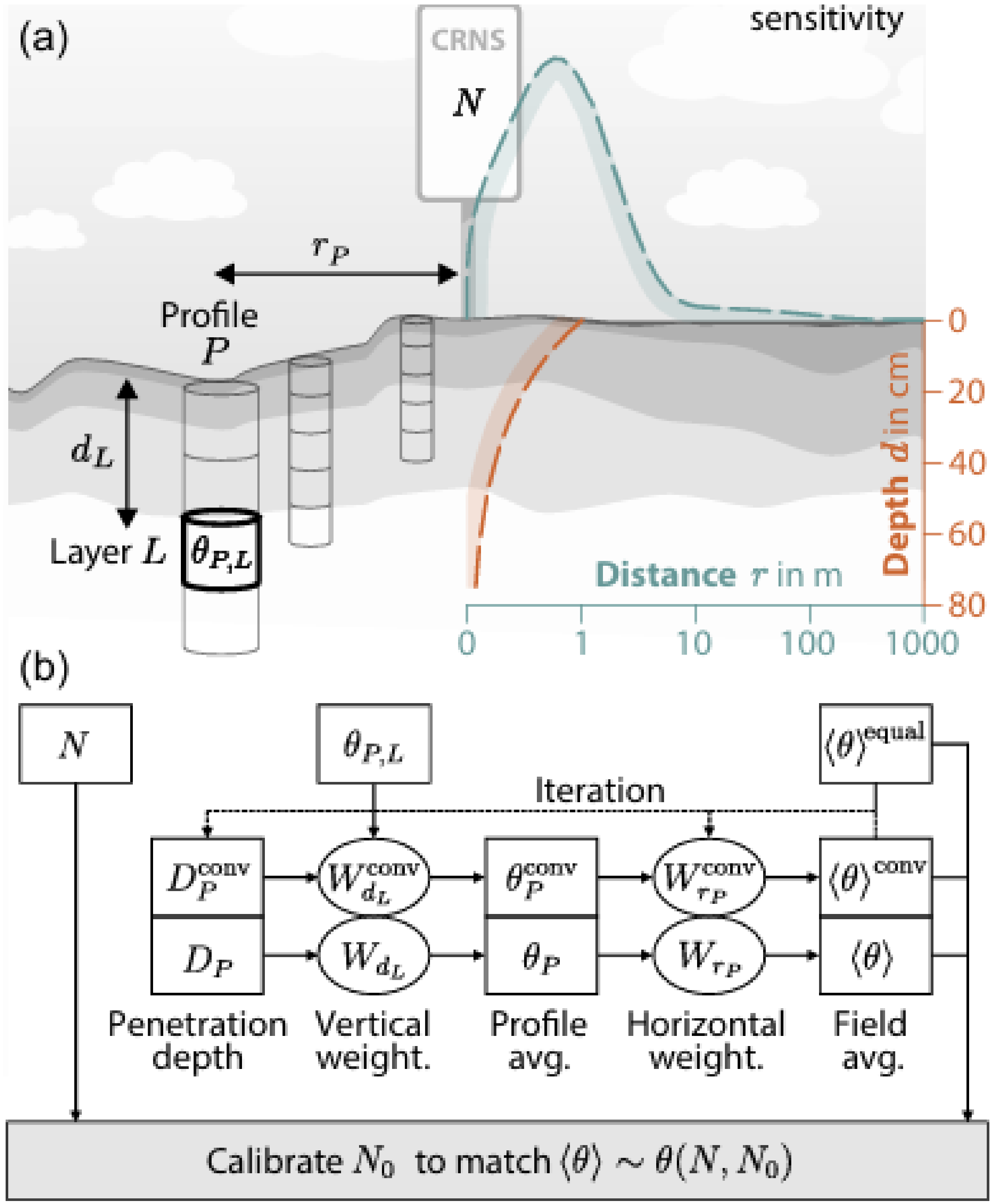
CALIBRATION: WEIGHTED AVERAGE

4) Horizontally average the profiles θ_P

$$W_r = \begin{cases} \left(F_1 e^{-F_2 r^*} + F_3 e^{-F_4 r^*}\right)\left(1 - e^{-F_0 r^*}\right), & 0\,\mathrm{m} < r \leq 1\,\mathrm{m} \\ F_1 e^{-F_2 r^*} + F_3 e^{-F_4 r^*}, & 1\,\mathrm{m} < r \leq 50\,\mathrm{m} \\ F_5 e^{-F_6 r^*} + F_7 e^{-F_8 r^*}, & 50\,\mathrm{m} < r < 600\,\mathrm{m} \end{cases}$$

$$\langle\theta\rangle = \frac{\sum_i w_i \theta_i}{\sum_i w_i}$$

5) Use the new ⟨θ⟩ to reiterate through steps 1–5 until value converges



(M, Shrön et al., 2017)

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ATMOSPHERIC PRESSURE CORRECTION

$$C_\mathrm{p} = e^{\beta(P-P_0)}$$

– P_0 =reference atmospheric pressure (time calibration)
– P = actual atmospheric pressure
– β= barometric coefficient that is related to the local mass attenuation length of neutrons in air (0,0076)

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AIR HUMIDITY CORRECTION

$$C_{WV} = 1 + 0.0054\Delta\rho_{v0}$$

$$\Delta\rho_{v0} = (\rho_{v0} - \rho_{v0}^{REF})$$

$\Delta\rho_{v0}$ = Difference in the absolute humidity at the time of measurement (ρ_{v0}) and at the reference time ($\rho^{ref}{}_{v0}$) in gm^{-3} (time of calibration)

INCOMING NEUTRON CORRECTION

1) The effect of changes to incoming neutron intensity

→ I = neutron monitor count at the time of interest

→ I_{ref} = neutron monitor count at calibration time

2) Effect geomagnetic cutoff rigidity

→ neutron monitor at different location

→ Rc = rigidity CRNS

→ $R_{c,ref}$ = rigidity neutron monitor

$$f_{inc,2} = \left[1 + \gamma\left(\frac{I}{I_{ref}} - 1\right)\right]^{-1}$$

$$\gamma = 1 - 0.075(R_c - R_{c\_ref})$$

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