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Investigating the possibility of leakage detection in water distribution networks using cosmic ray neutrons in the thermal region

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ICHEP 2024
PRAGUE
ichep2024.org
42nd International Conference on High Energy Physics
July 17-24 · 2024 · Prague · Czech Republic

Outline

- Problem of leakages in water distribution network
- Common techniques for leakage detection
- Cosmic-ray neutrons for leakage detection
- Monte Carlo simulations
- COMMAND detector

Leakages in water distribution network

- Leakages in distribution networks represent ~80% of the total water loss:

1. R. Liemberger, Water Supply 19 (3), 2018. 2. World Water Assessment Programme, 2018. 3. C.M. Fontanazza, et al., Procedia Eng. 119, 2015

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  - Financial problem:
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    → >50% of population will suffer from water scarcity at least one month each year by 2050[2]

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  - ➢ Supply problem:
    - → >50% of population will suffer from water scarcity at least one month each year by 2050[2]
  - ➢ Risk for public health:
    - → pollutants can contaminate drinkable water through leakages[3]

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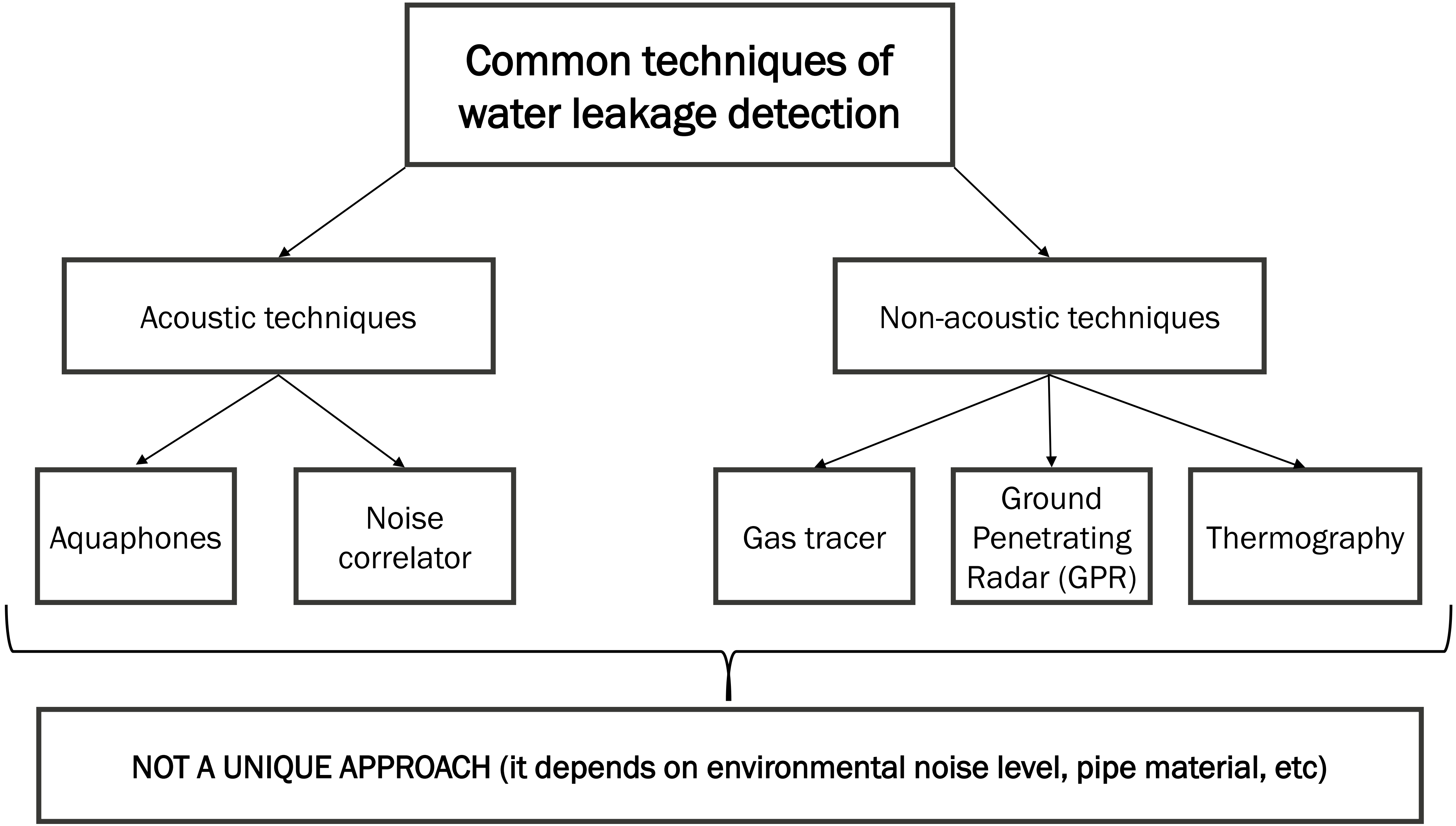
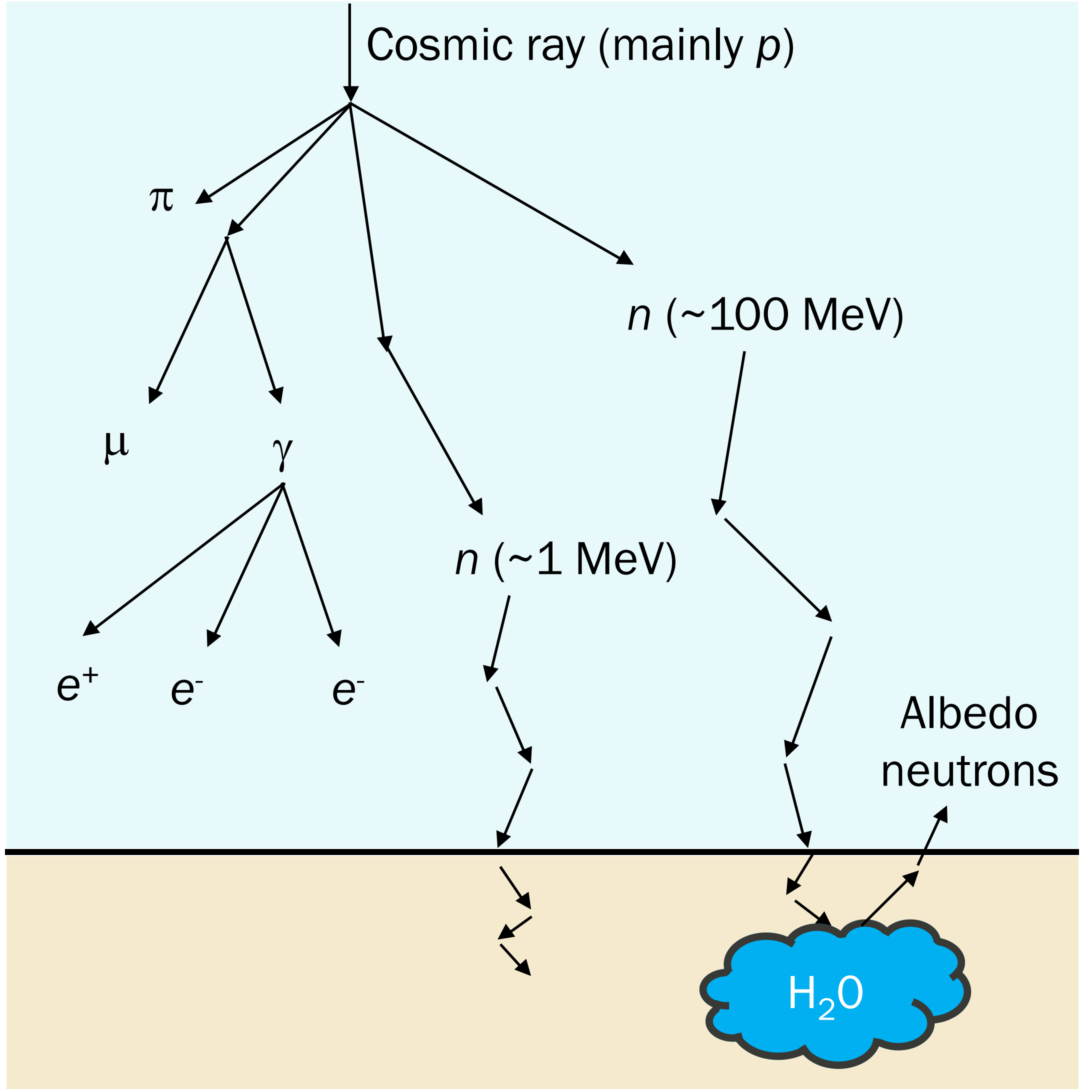

Common techniques of water leakage detection
Acoustic techniques
Non-acoustic techniques
Aquaphones
Noise correlator
Gas tracer
Ground Penetrating Radar (GPR)
Thermography
NOT A UNIQUE APPROACH (it depends on environmental noise level, pipe material, etc)

Cosmic-ray neutrons and water content of soil



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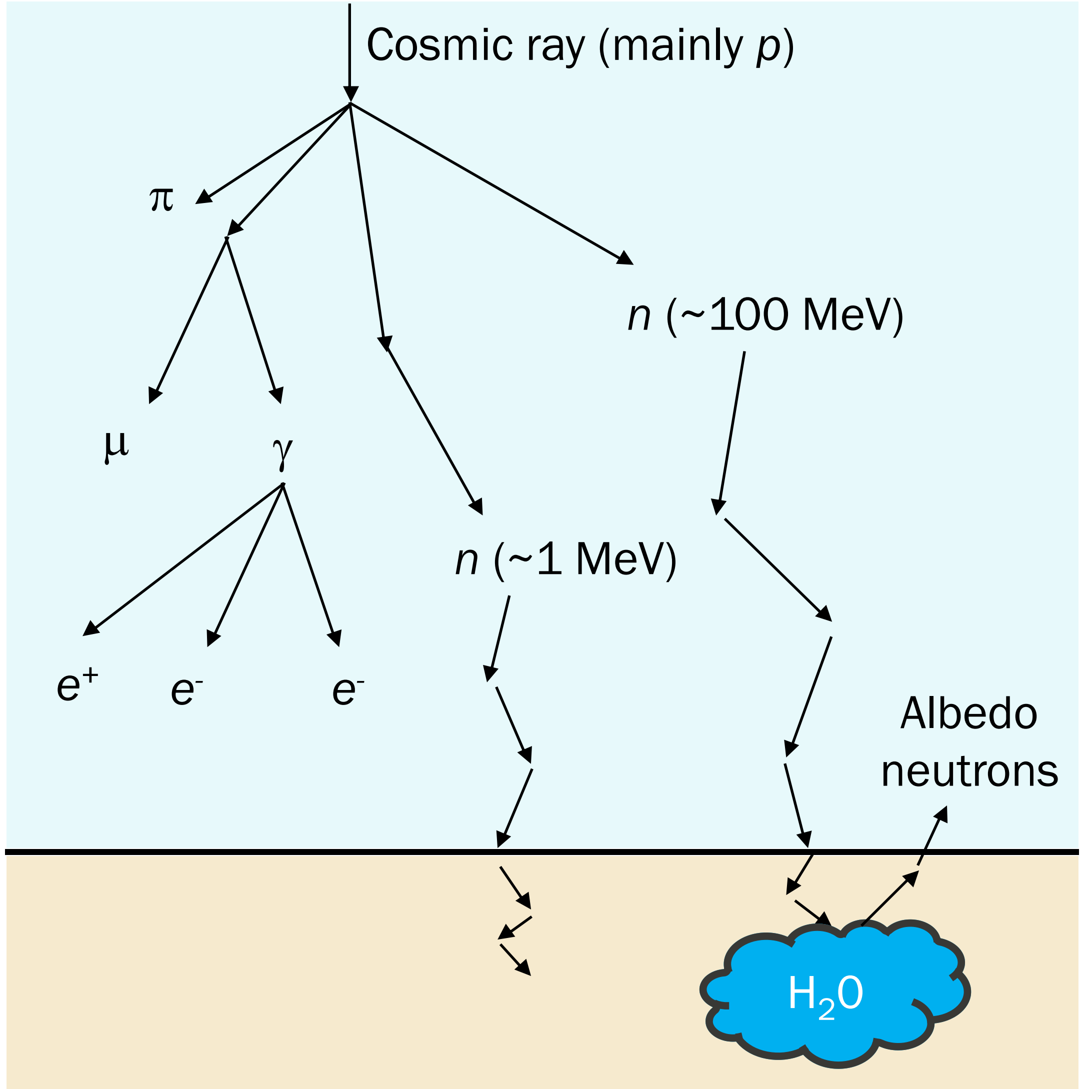

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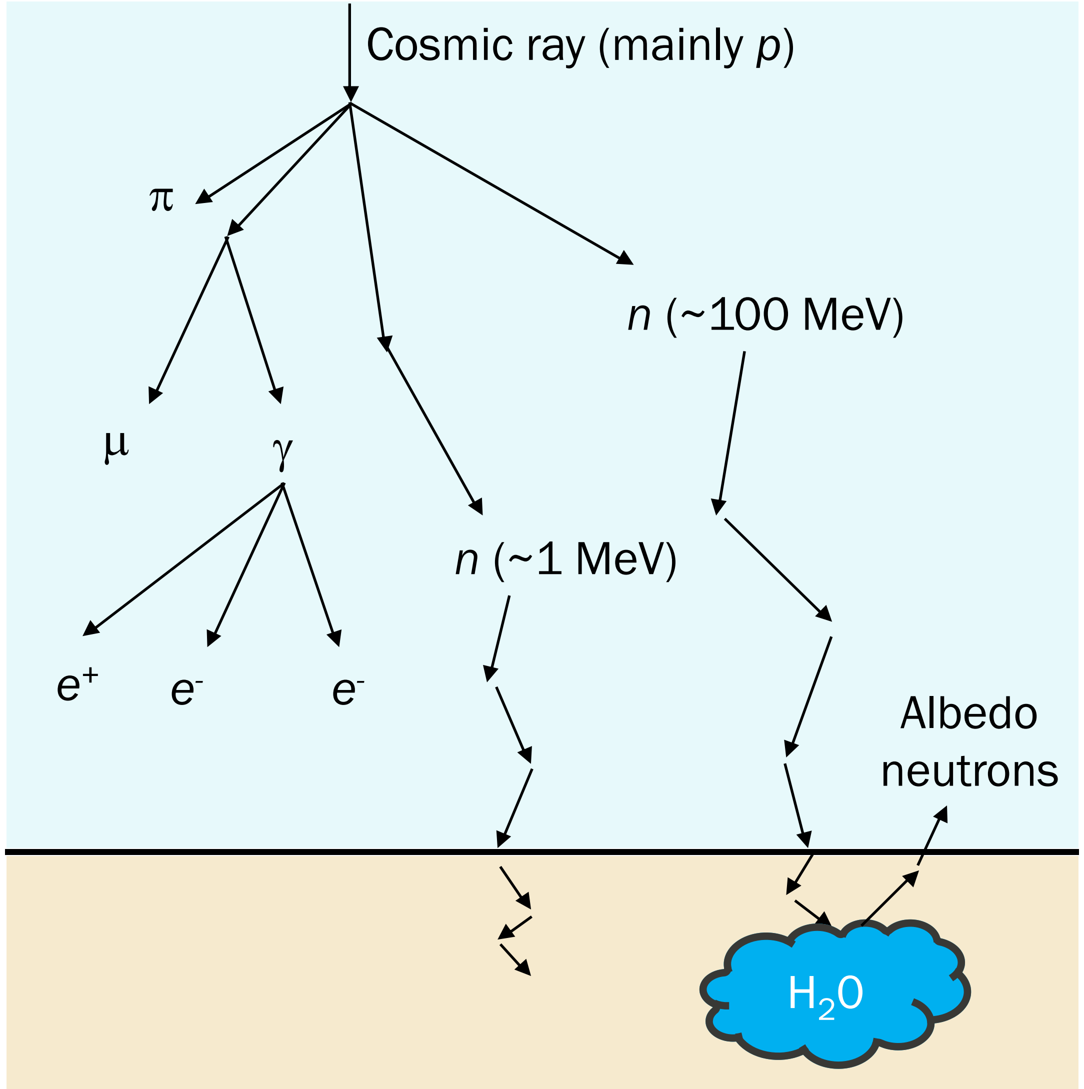

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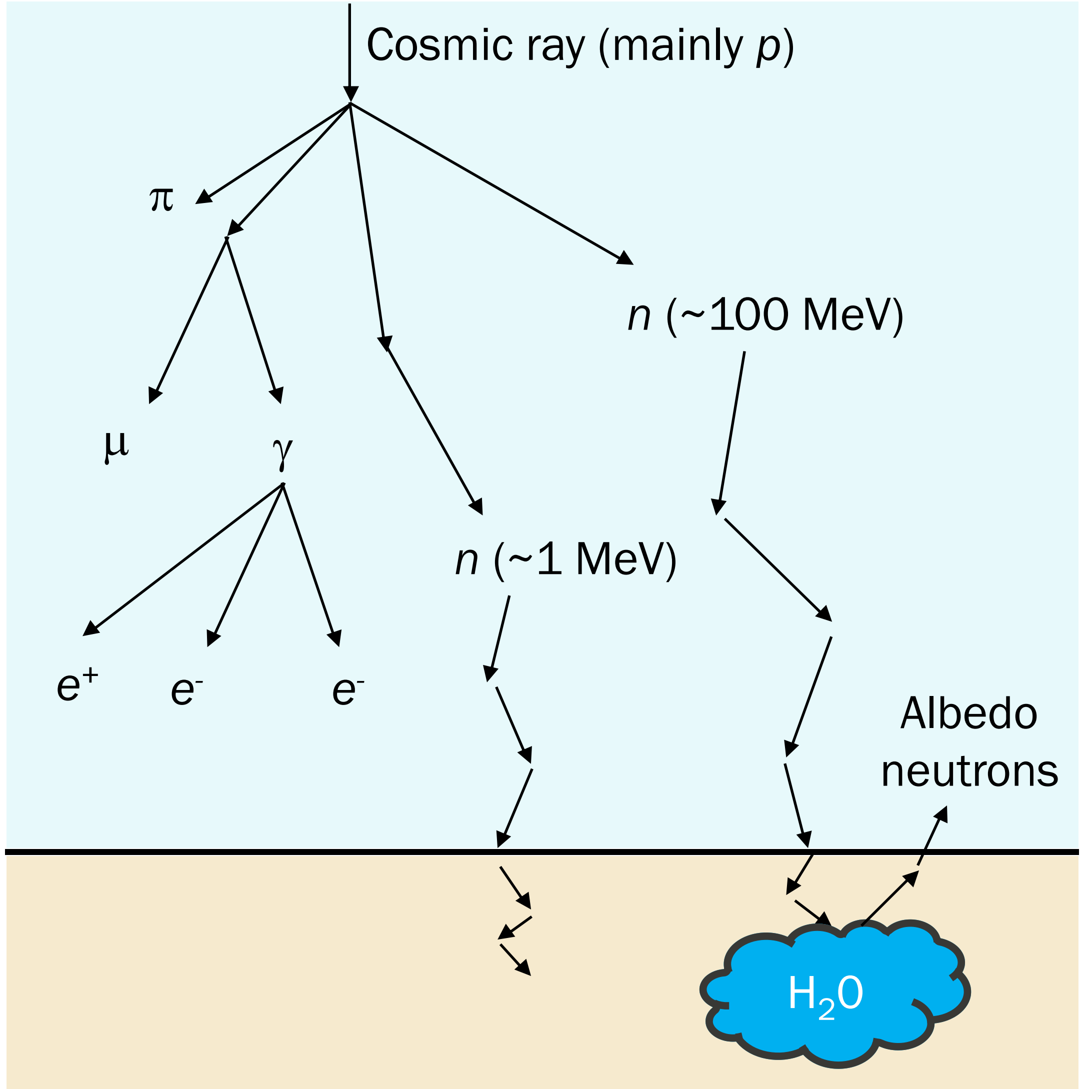

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- Soil further moderates neutrons, which may diffuse back to air (*albedo* neutrons)
- Above ground neutron flux depends on soil composition and moisture:
  - H effectively moderates neutrons → increase in soil moisture results in a decrease Φ_{epi} in favor of Φ_{th}
  - Thermal neutrons are also absorbed in soil → decrease of Φ_{th}

Cosmic-ray neutrons for leakage detection

- The Cosmic Ray Neutron Sensing (CRNS[4]) technique has been developed for above ground monitoring of the environmental humidity:

  → Absolute assessment of water content in soil

  → Elaborate multivariate models are needed

4. M. Zreda et Al., Res. Lett. 35 (21), 2008. 5. L. Sostero, et al, NIM-A, Volume 1059, 2024.

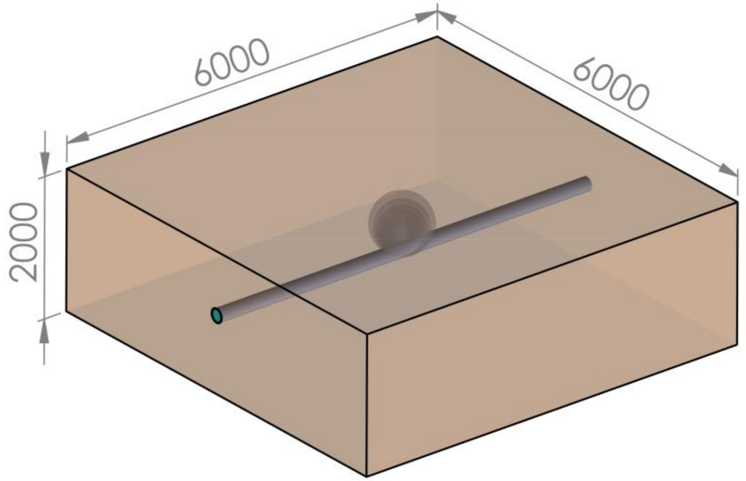
Cosmic-ray neutrons for leakage detection

- The Cosmic Ray Neutron Sensing (CRNS[4]) technique has been developed for above ground monitoring of the environmental humidity:
  - → Absolute assessment of water content in soil
  - → Elaborate multivariate models are needed
- We propose an innovative non-invasive technique to identify water leakages in underground pipelines:
  - → Relative variations with respect to a reference position in the above ground neutron flux along the pipe
  - → Data-driven measurement
  - → Based on thermal neutrons
  - → Results published in Nuclear Inst. and Methods in Physics Research, A (2024)[5]

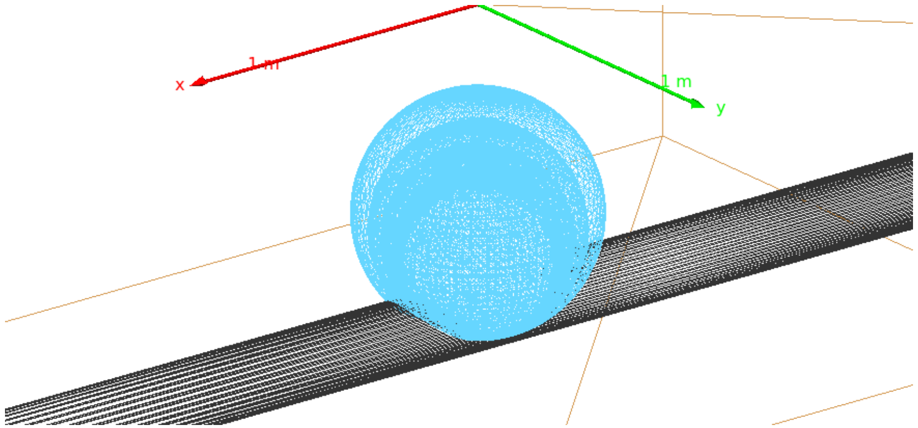
4. M. Zreda et Al., Res. Lett. 35 (21), 2008. 5. L. Sostero, et al, NIM-A, Volume 1059, 2024.

Monte Carlo simulations

- To investigate the potential of the technique, a set of Monte Carlo simulations, based on GEANT4 was performed
- Some (realistic) scenarios of water leakages were simulated

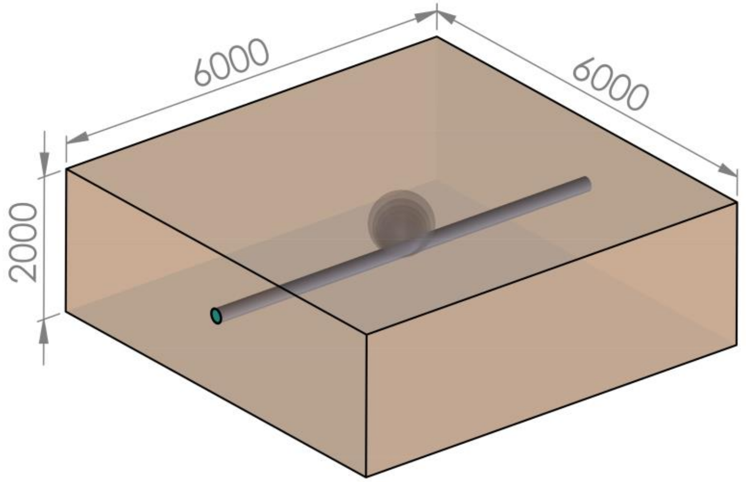


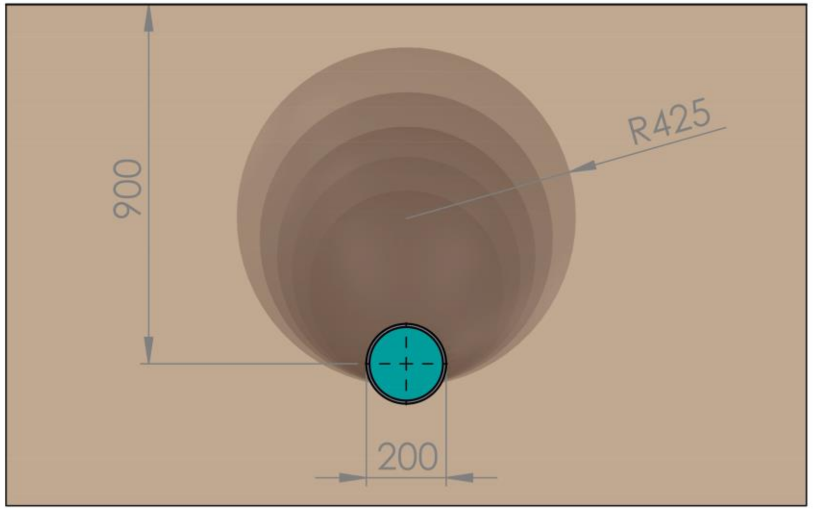
CAD Software → GEANT4



Monte Carlo simulations: geometry

- Soil composition is 90% SiO_2 and 10% Al_2O_3, with a porosity of 50% (sandy soil)
- Pore space filled with air and eventually with water (environmental or leakage)
- Leakage on the top of the tube modelled as a distribution of soil moisture that varies from 50% to 10% in volume of water[6]

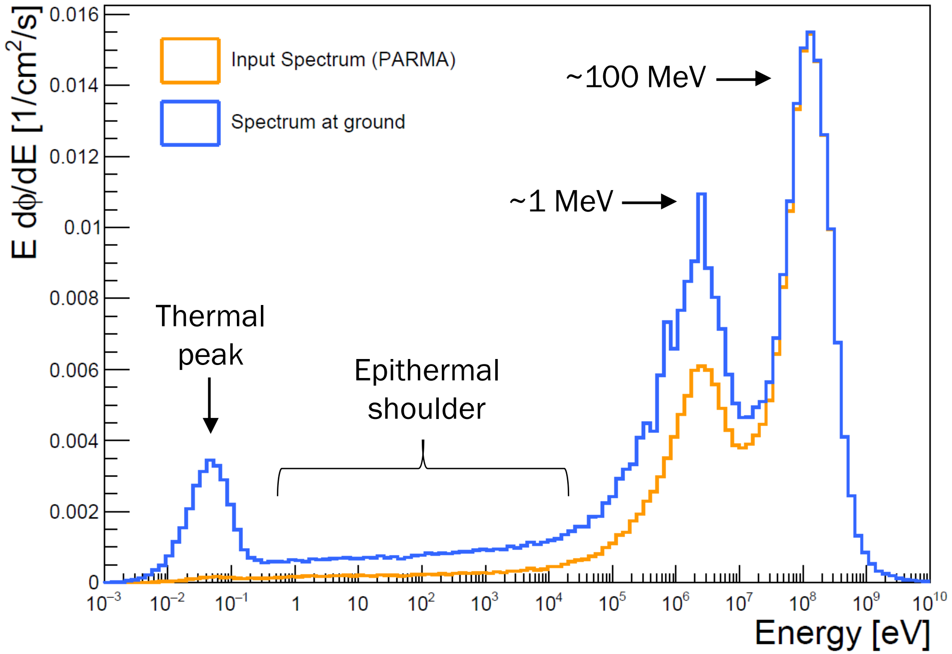


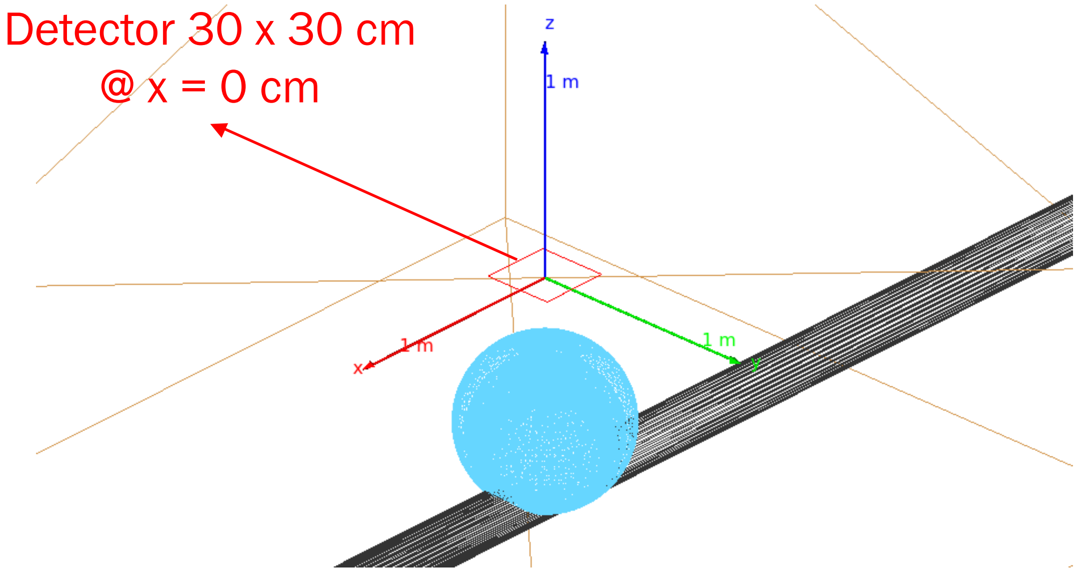


6. X. Wang, et al., J. Clean. Prod. 406, 2023.

Monte Carlo simulations: source and scoring

- Cosmic ray neutrons from a planar source, according to the PARMA analytical model[7]
- Scoring of neutrons with a sensible volume of air above ground
- Counts are corrected by the efficiency of the COMMAND detector





7. T. Sato, PLoS One 10 (12), 2015.

Simulations: sandy soil in dry condition

- For a sandy soil in dry condition (soil moisture 2%), max variation of 26% in correspondence of the centre of the leakage (x = 0 cm)
- The generated statistics corresponds to a data taking of 30 min
- FWHM of ~ 50 cm (good localization)

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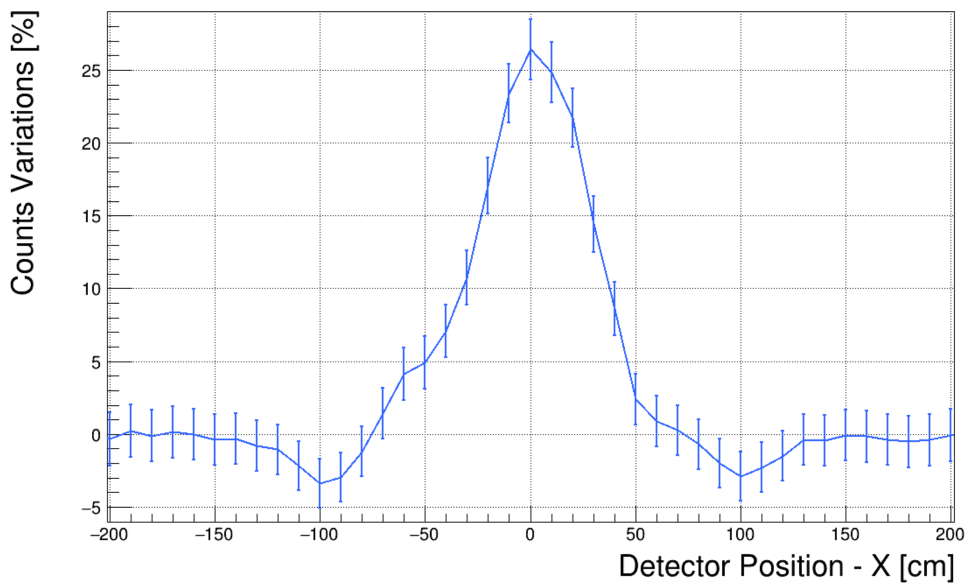

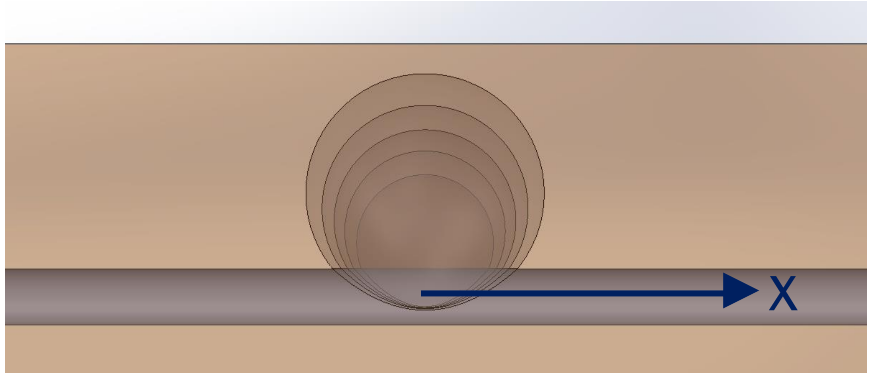

Limits of the technique

- The proposed scenario of dry sandy soil is one of the most favourable for leakage detection using cosmic ray neutrons.
- The limits of the technique might come from:
  - *the chemical composition of soil*
  - *the initial water content in soil (environmental soil moisture)*
  - *the leaked water distribution around the pipe*
  - *the acquisition time*

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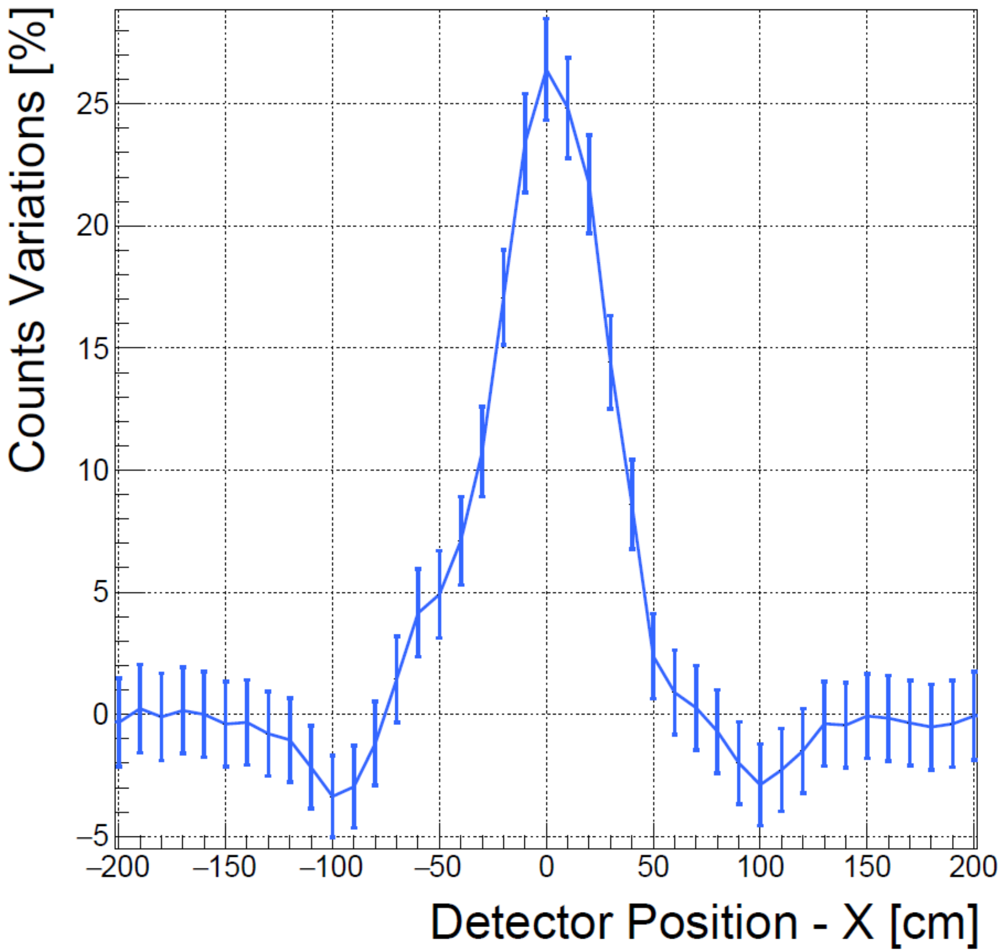
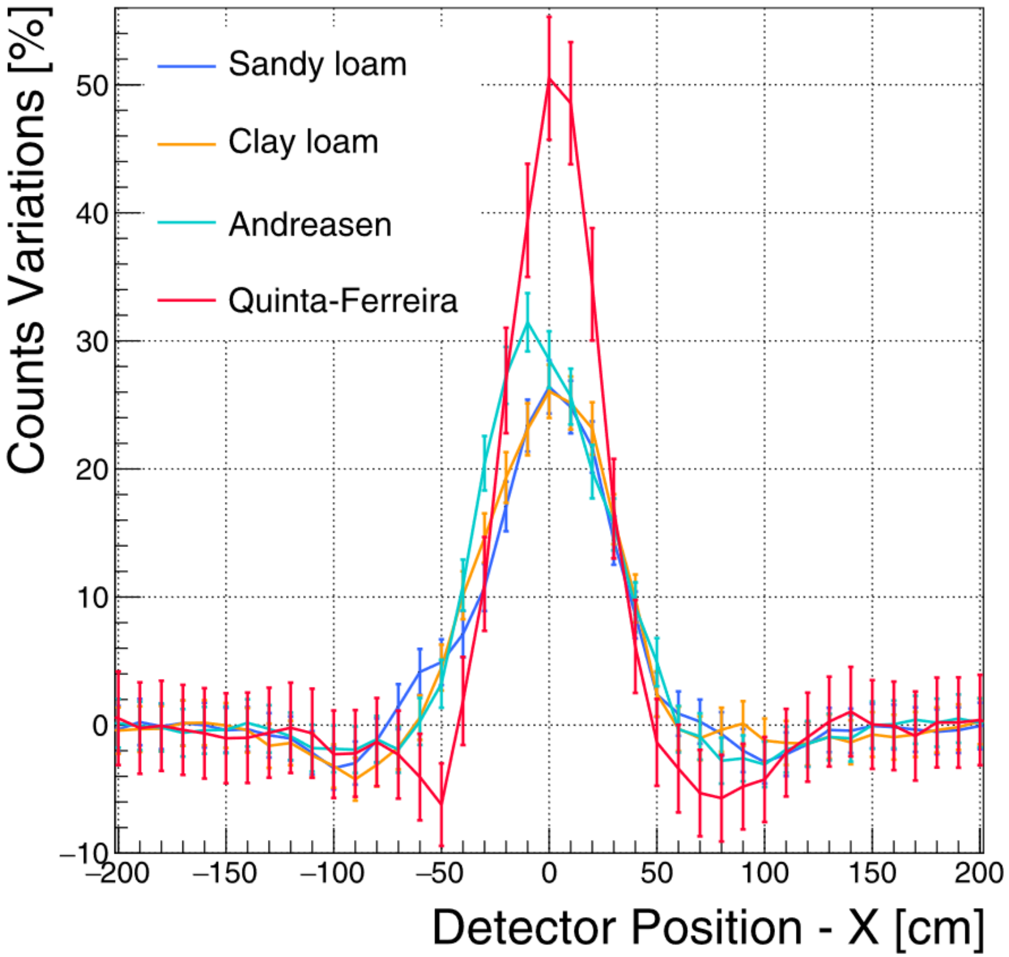


Simulations: impact of soil composition

- We compared:
  - *Sandy loam*
  - *Clay loam*
  - *“Andreasen” soil: with P, K, Ca, Ti, Fe and traces of* ***Gd*** [8]
  - *“Quinta-Ferreira” soil: with P, K, Ca, Ti, Fe,* ***Cl, Mn, U*** *and* ***Cd*** [9]
- Small influence of the soil composition in absence of thermal neutron absorbing elements

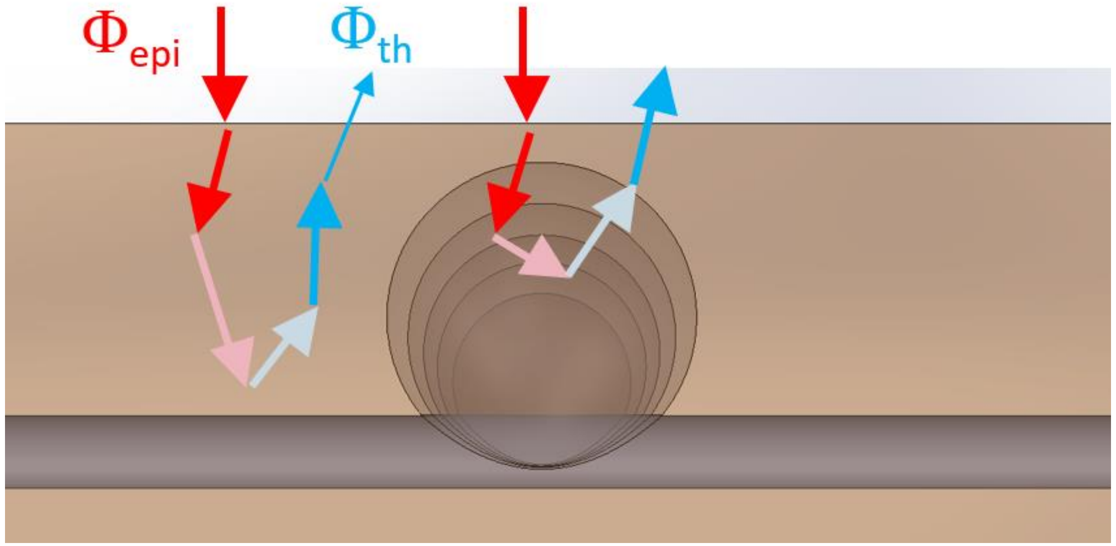
L. Sostero, et al, NIM-A, Volume 1059, 2024



8. M. Andreasen et al., Water Resour. Res. 56 (11), 2020. 9. M. Quinta-Ferreira et al., Environ. Earth Sci. 75 (14), 2016.

Simulations: impact of soil composition

- Far from the leakage (reference position), Φ_{epi} is thermalized more in depth → more absorption of Φ_{th}
- Higher count variation, although lower counts in absolute terms (larger error bars)



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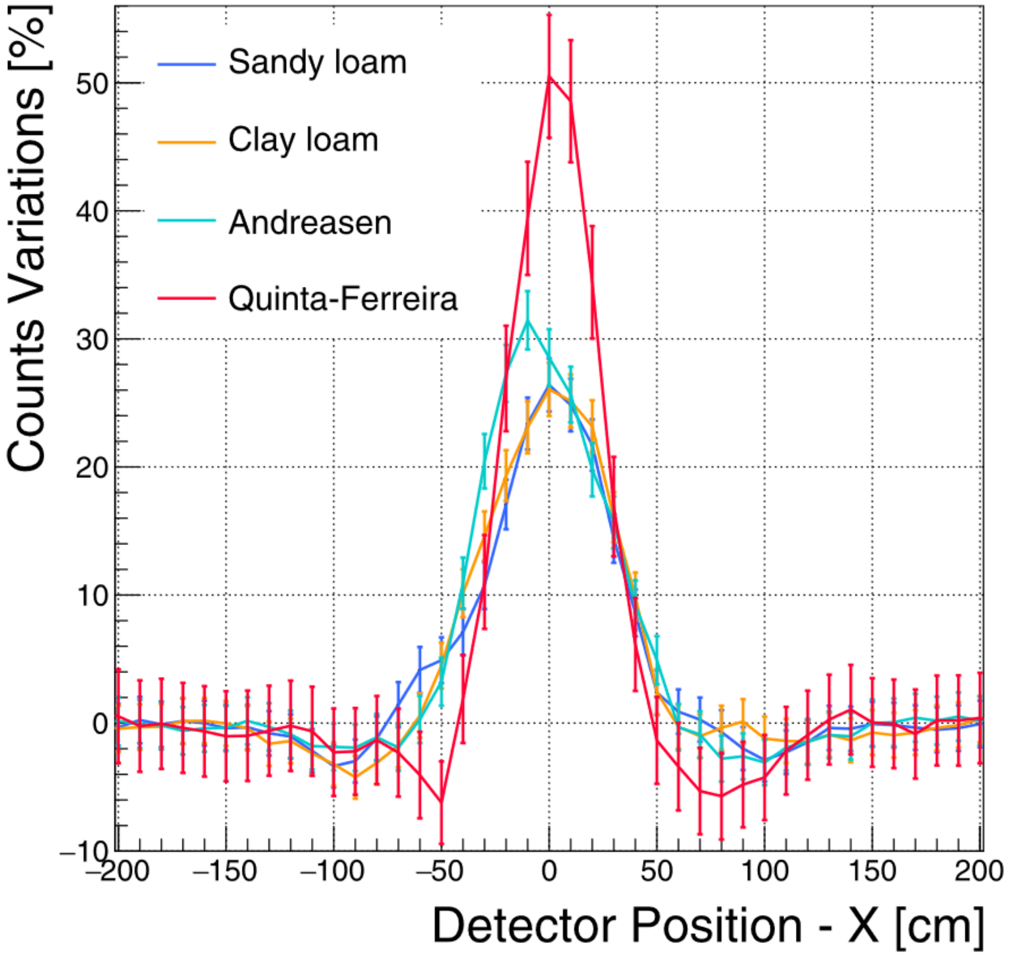
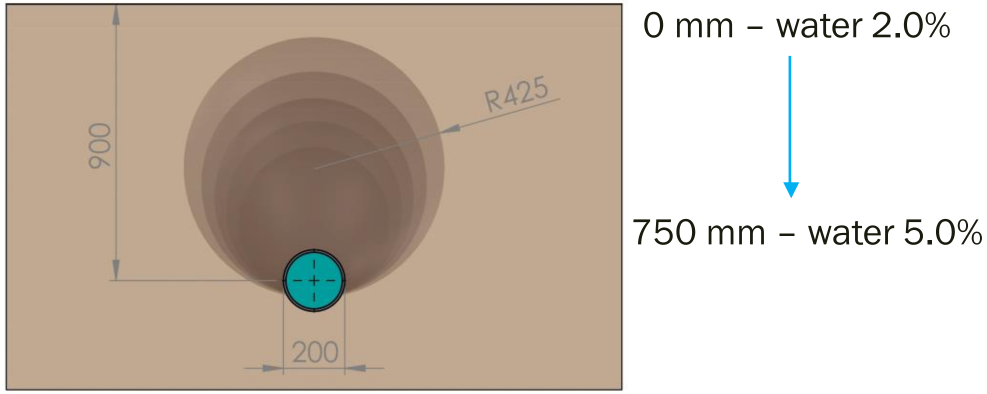


Simulations: impact of soil moisture

- Linear gradient of soil moisture from 0 mm to 750 mm in depth in a sandy soil



- Environmental water makes the local excess of moisture around the leakage less significative

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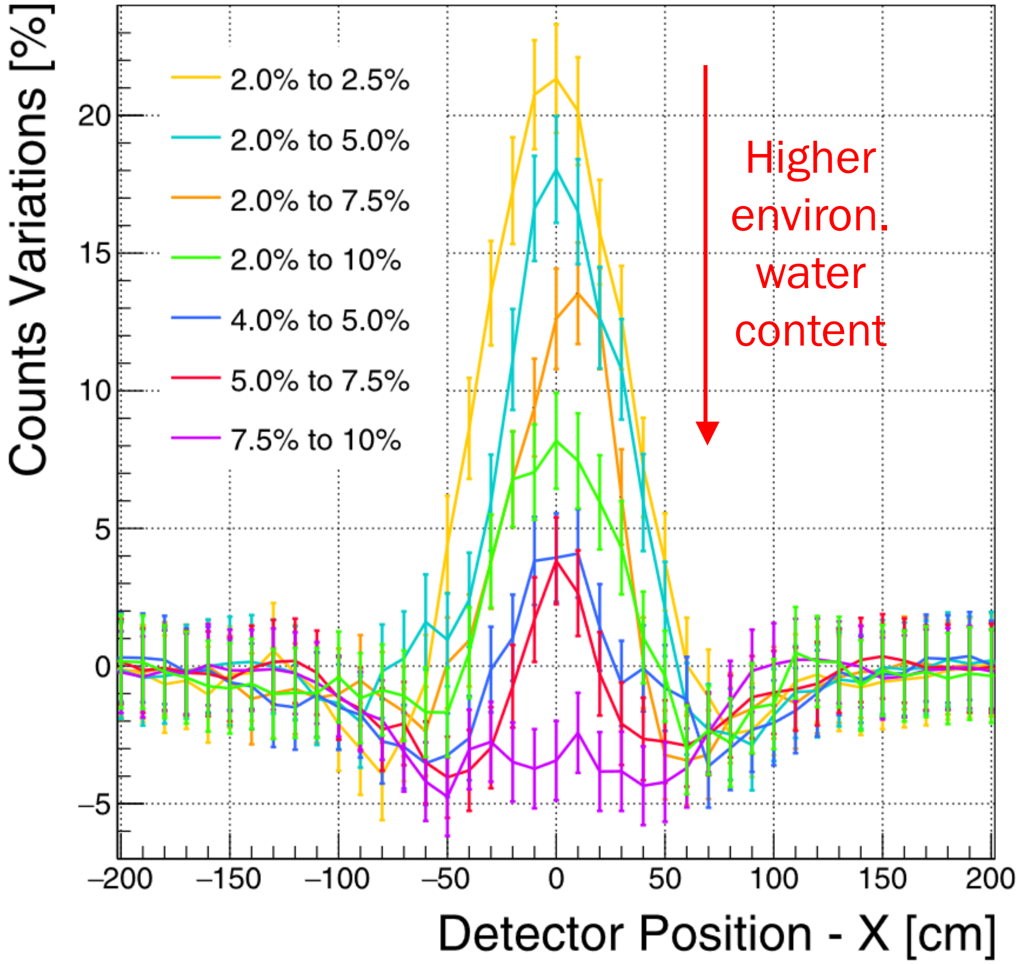
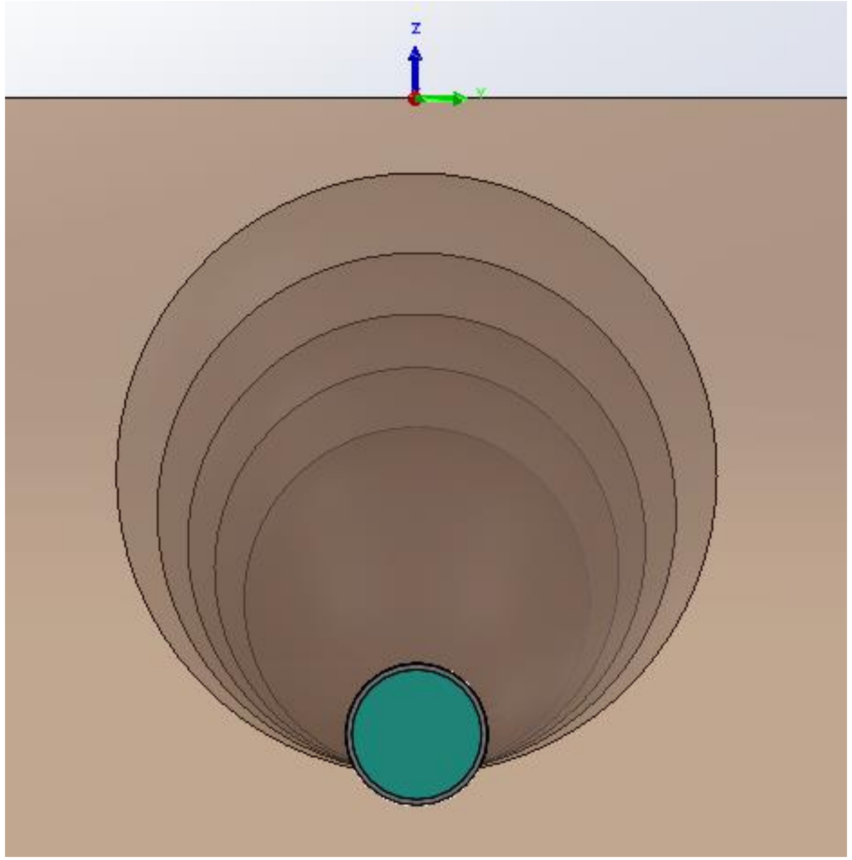


Simulations: impact of leaked water distribution

- We considered other two additional models of leaked water distribution:
  - *Case #1: leakage from an orifice on the top of the tube (as before)*



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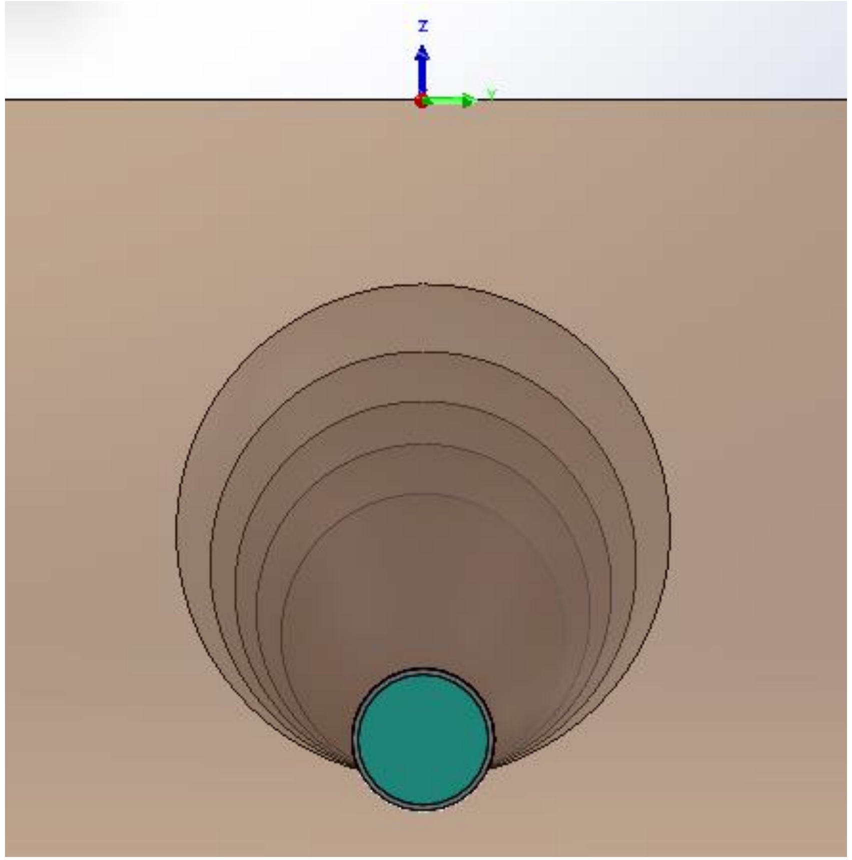

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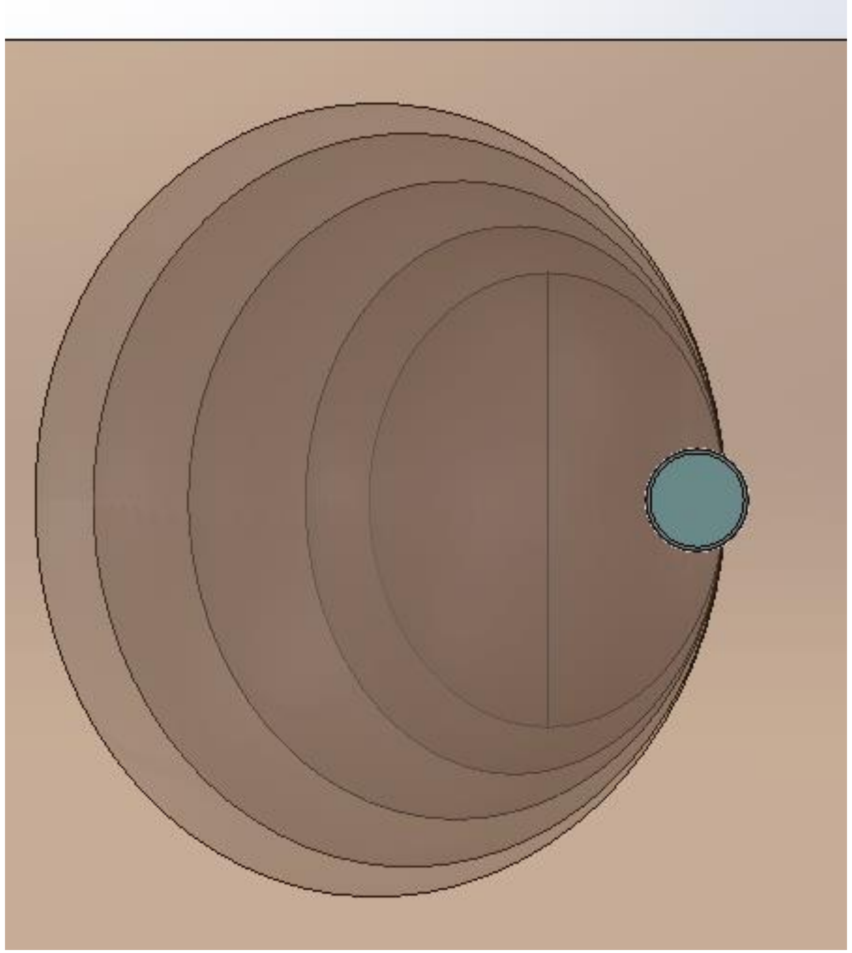

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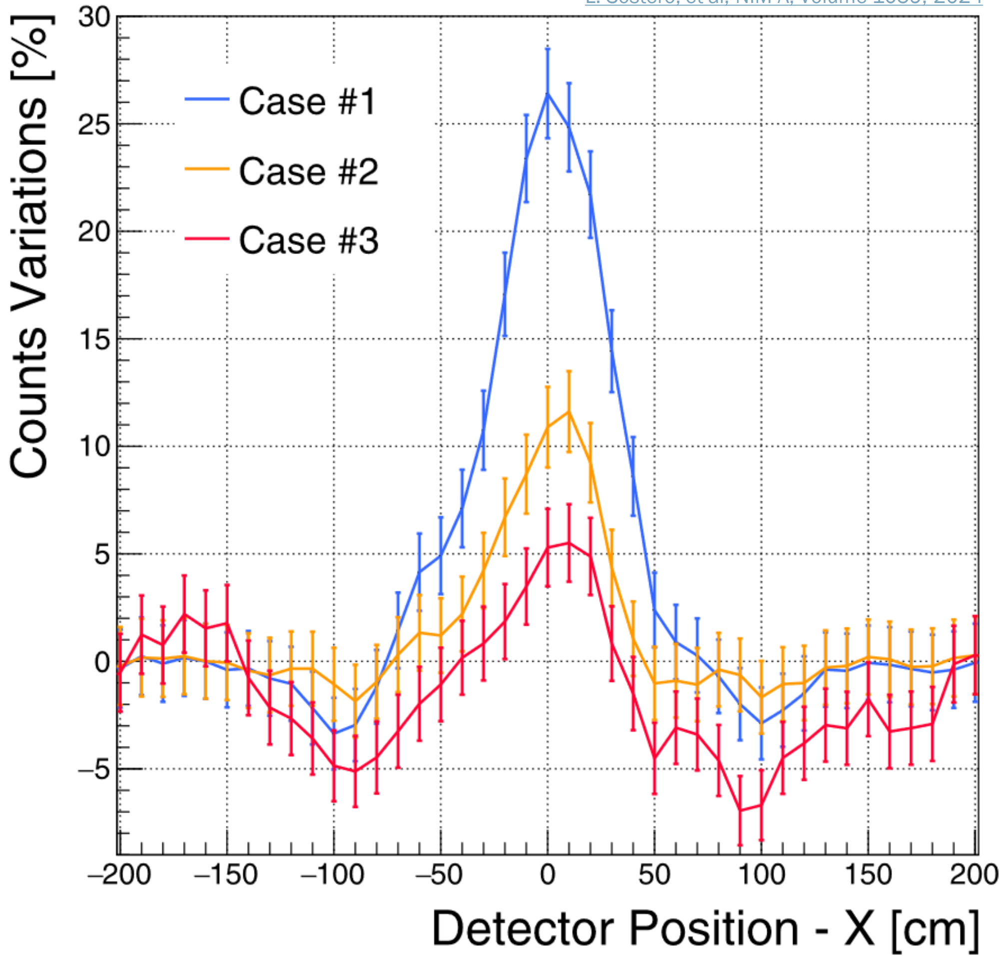
  - *Case #2: as #1, but with a leakage 50% in volume smaller*
  - *Case #3: leakage from an orifice on the side of the tube*
- Shape and position of the leakage, which evolve with time, have an impact on the count variations.

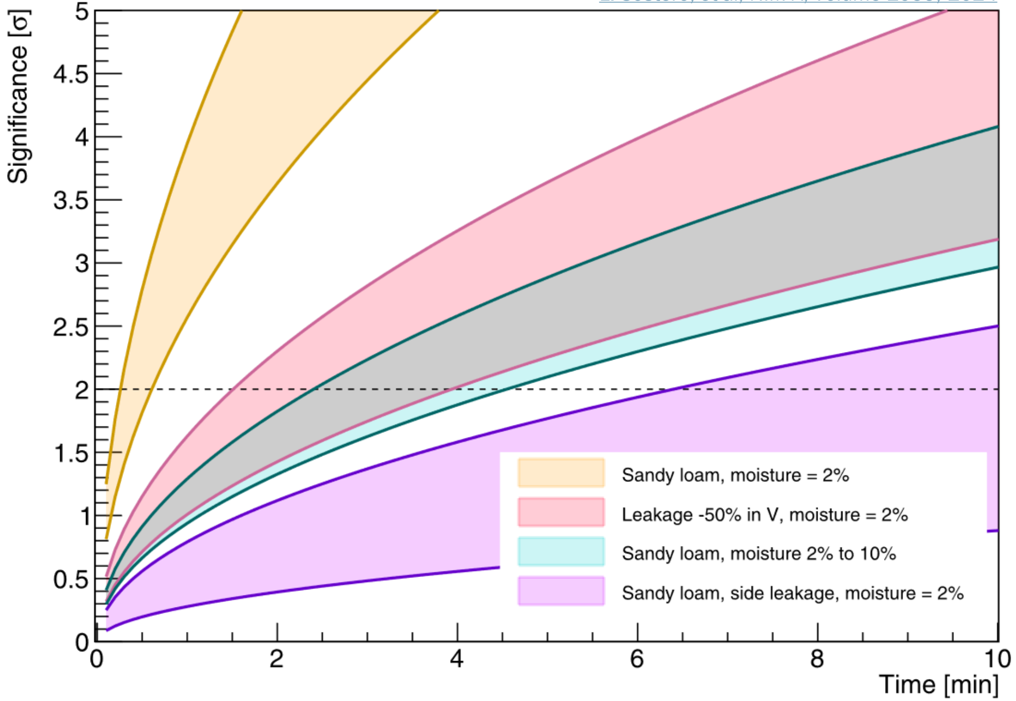
L. Sostero, et al, NIM-A, Volume 1059, 2024



Simulations: impact of acquisition time

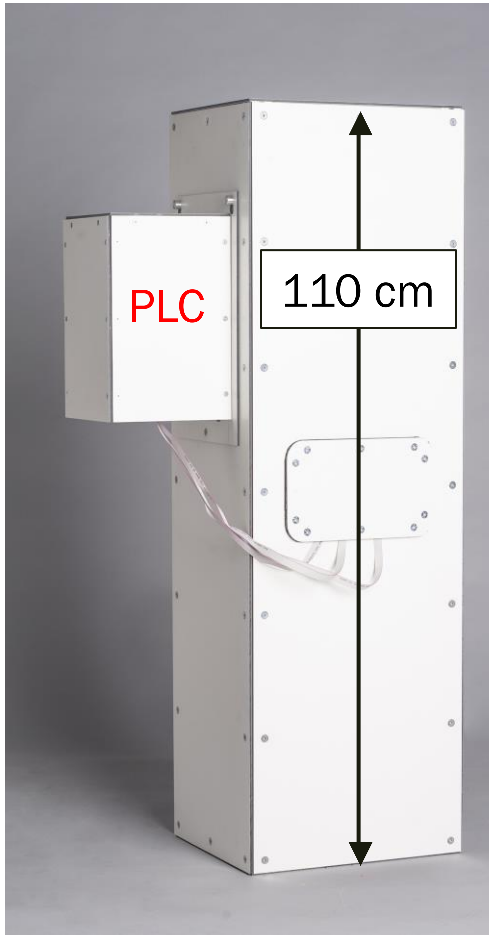
- Band of significance (signal/uncertainty) for difference scenarios, accounting for a maximum displacement of the detector of 20 cm from the leakage point.
- In most of the cases here presented, a data-taking of 5 minutes would be enough to achieve a significance level of 2σ.

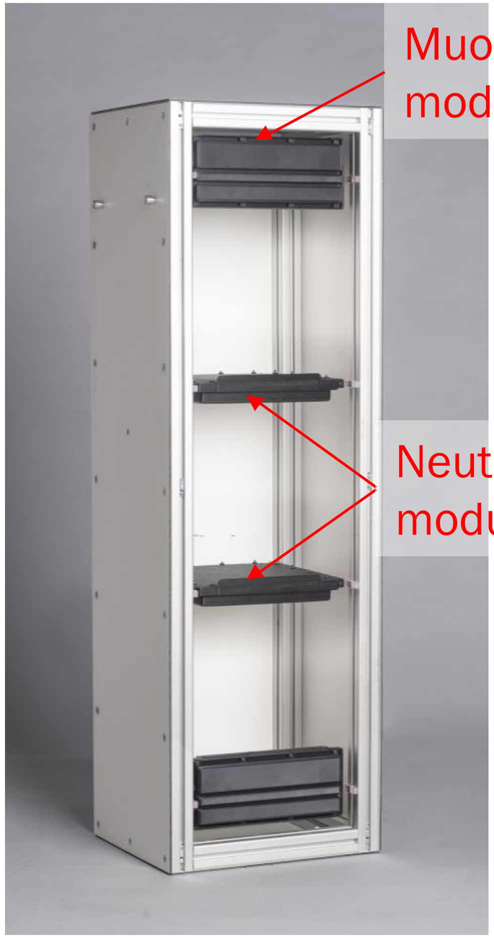
L. Sostero, et al, NIM-A, Volume 1059, 2024



COMMAND detector

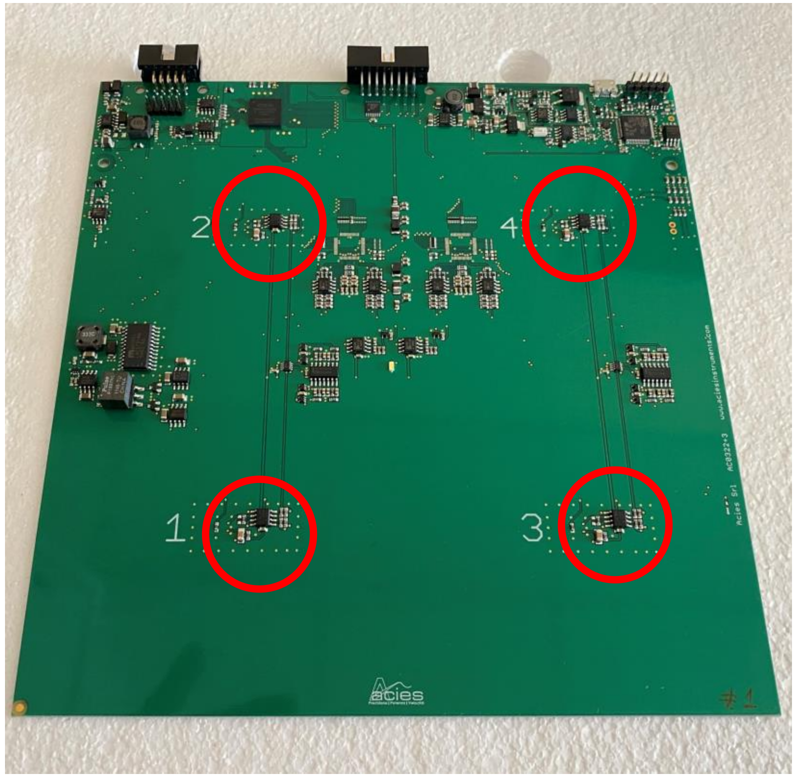
- COMMAND detector: **COM**pact **M**uon **a**nd **N**eutron **D**etector for the identification of (also) underground water leakages
- Thermal neutron detection based on a lithium enriched phosphor detector (ε_{th}~36%) enclosed in a 3D printed shell





COMMAND detector

- Scintillation light collected by an array of four silicon photomultipliers (SiPMs)
- Data acquisition on-board through a dedicated PLC



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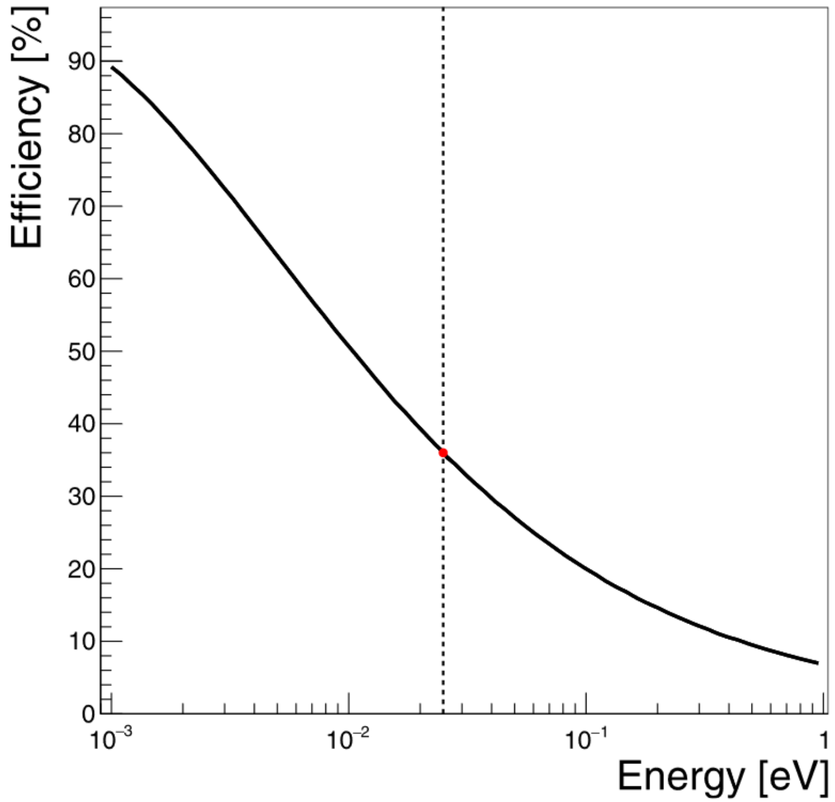
- We designed a low-cost detector, suitable for the identification of underground leakages: the COMMAND detector
- First field measurements are ongoing

Backup slides

Efficiency of Li-6

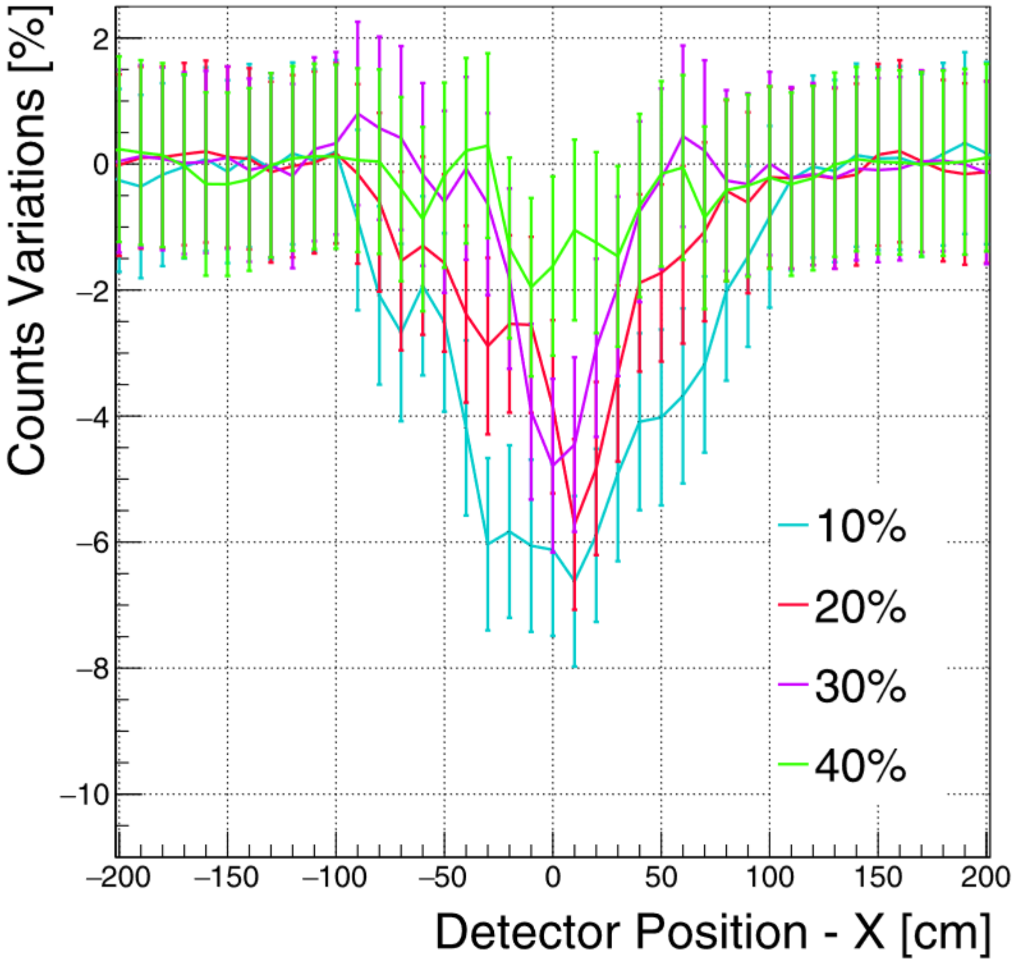
- The counts from simulations were corrected by the estimated efficiency of the EJ-426HD-PE2 detector from Eljen Technology, which is the one chosen for COMMAND.



Simulations: impact of soil moisture

- Uniform wetter conditions (typical of clay soils)
- Negative variation of counts, since such wet conditions leads to the same level of moderation, and the increased water content due to leakage leads only to a further absorption of neutrons
- Water leakage detection still possible

L. Sostero, et al, NIM-A, Volume 1059, 2024



Thermal neutrons cross-section

Element	Weight fractions of earth's crust	Collisions to thermalization	Thermal absorption cross section TACS (barn)[a]
Hydrogen	0.0014	19.0	0.33
Boron	[b]	109.2	759.00
Carbon	[b]	120.6	0.0034
Nitrogen	[b]	139.5	1.90
Oxygen	0.466	158.5	0.002
Sodium	0.028	224.9	0.53
Magnesium	0.021	237.4	0.063
Aluminum	0.081	262.8	0.23
Silicon	0.277	273.3	0.16
Phosphorus	0.001	300.8	0.19
Sulfur	[b]	311.1	0.51
Chlorine	[b]	343.3	33.00
Potassium	0.026	378.0	2.10
Calcium	0.036	387.3	0.43
Titanium	0.004	461.6	6.10
Manganese	0.001	528.5	13.30
Iron	0.050	537.2	2.53
Cadmium	[b]	1074.6	2390.00
Lead	[b]	1975.5	0.17
Uranium	[b]	2268.6	4.20

M. Quinta-Ferreira et al., Environ. Earth Sci. 75 (14), 2016.

XRF soil composition

	Voulund Farmland (mass%)	Harrild Heathland (mass%)	Gludsted Plantation (mass%)
O	52.32	52.76	52.78
Si	42.65	44.71	44.86
Al	3.29	1.74	1.54
K	0.86	0.56	0.53
Ti	0.20	0.23	0.29
Ca	0.33	bdl	bdl
P	0.24	bdl	bdl
Fe	0.12	bdl	bdl

+0.5 ppm Gd

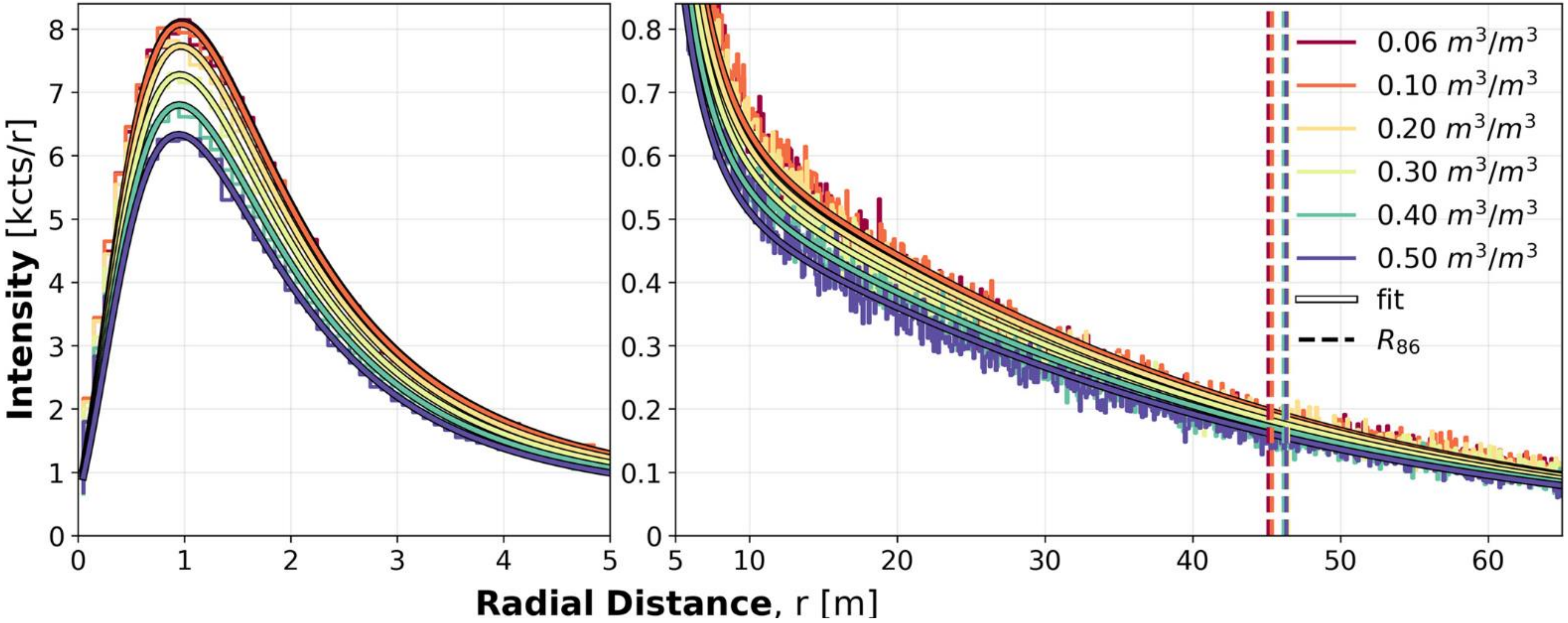
Chemistry	Sample		
	S1	S2	R
(%)			
SiO_2	55.76	26.50	26.04
TiO_2	0.58	0.36	0.55
Al_2O_3	9.07	6.74	8.16
Fe_2O_3	2.92	4.61	4.13
FeO	2.62	4.15	3.72
MnO	0.00	0.02	0.03
MgO	1.13	1.09	0.74
CaO	0.07	0.24	0.36
K_2O	2.38	1.64	2.67
P_2O_5	0.32	0.87	0.51
(ppm)			
Magnesium	6791	6593	4461
Aluminum	48,013	35,664	43,174
Silicon	260,674	123,880	121,746
Phosphorus	1408	3781	2229
Sulfur	1893	95,264	1580
Chlorine	8424	729	562
Potassium	19,795	13,600	22,192
Calcium	535	1703	2596
Titanium	3467	2138	3289
Manganese	0	138	238
Iron	20,398	32,231	28,881
Cadmium	0	104	0
Lead	84	10,809	31
Uranium	0	63	0

M. Andreasen et al., Water Resour. Res. 56 (11), 2020

M. Quinta-Ferreira et al., Environ. Earth Sci. 75 (14), 2016.

Thermal neutrons footprint

Horizontal intensity of simulated thermal neutrons as a function of distance from the first interaction in the soil (detector at 2 m from ground)



Jakobi et al., Geophysical Research Letters (2021)