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

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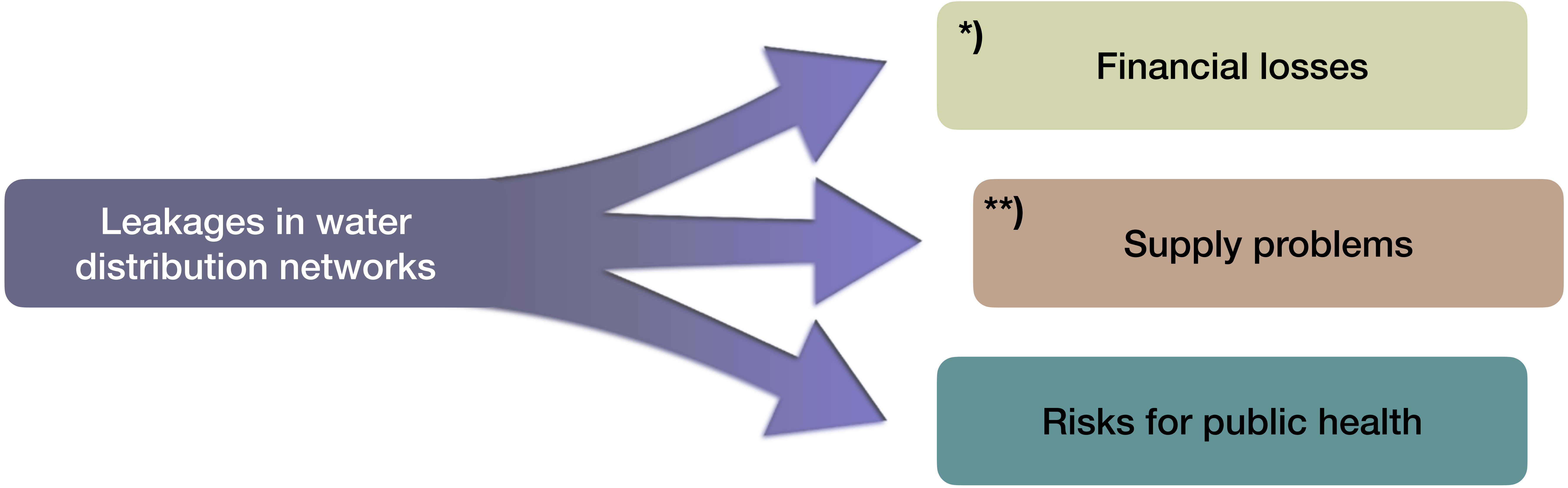
Leakages in water distribution networks

- The three-fold problem with water leakages in distribution networks

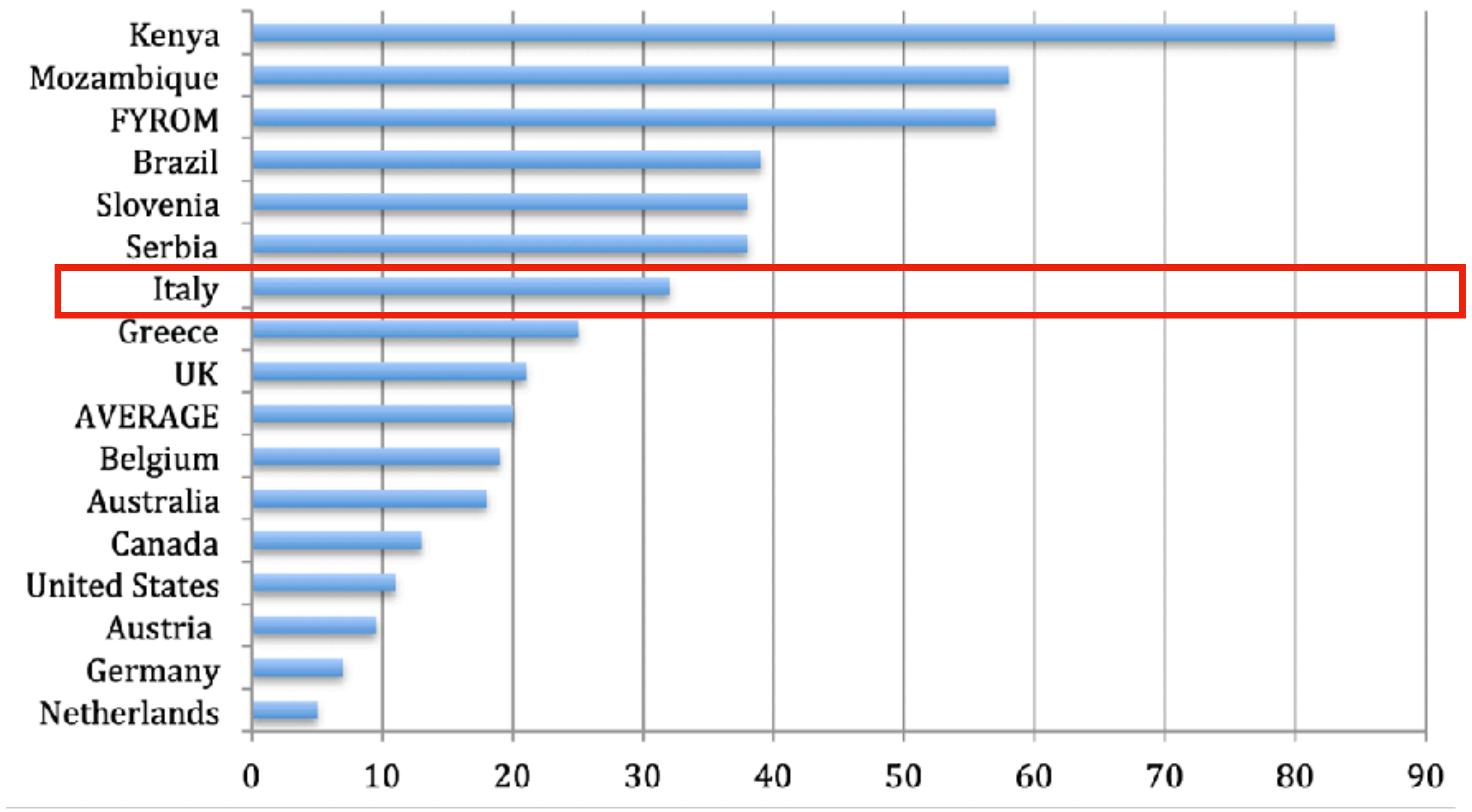


* example: a 5 mm hole @ 5 bar leakages 32000 liters of water per day

** example: in Italy still 11 municipalities ration water (latest data from ISTAT)

Leakages in water distribution networks

- Leakage rate in water distribution networks
  (data from Global Water Intelligence, 2008)



Leakages in water distribution networks

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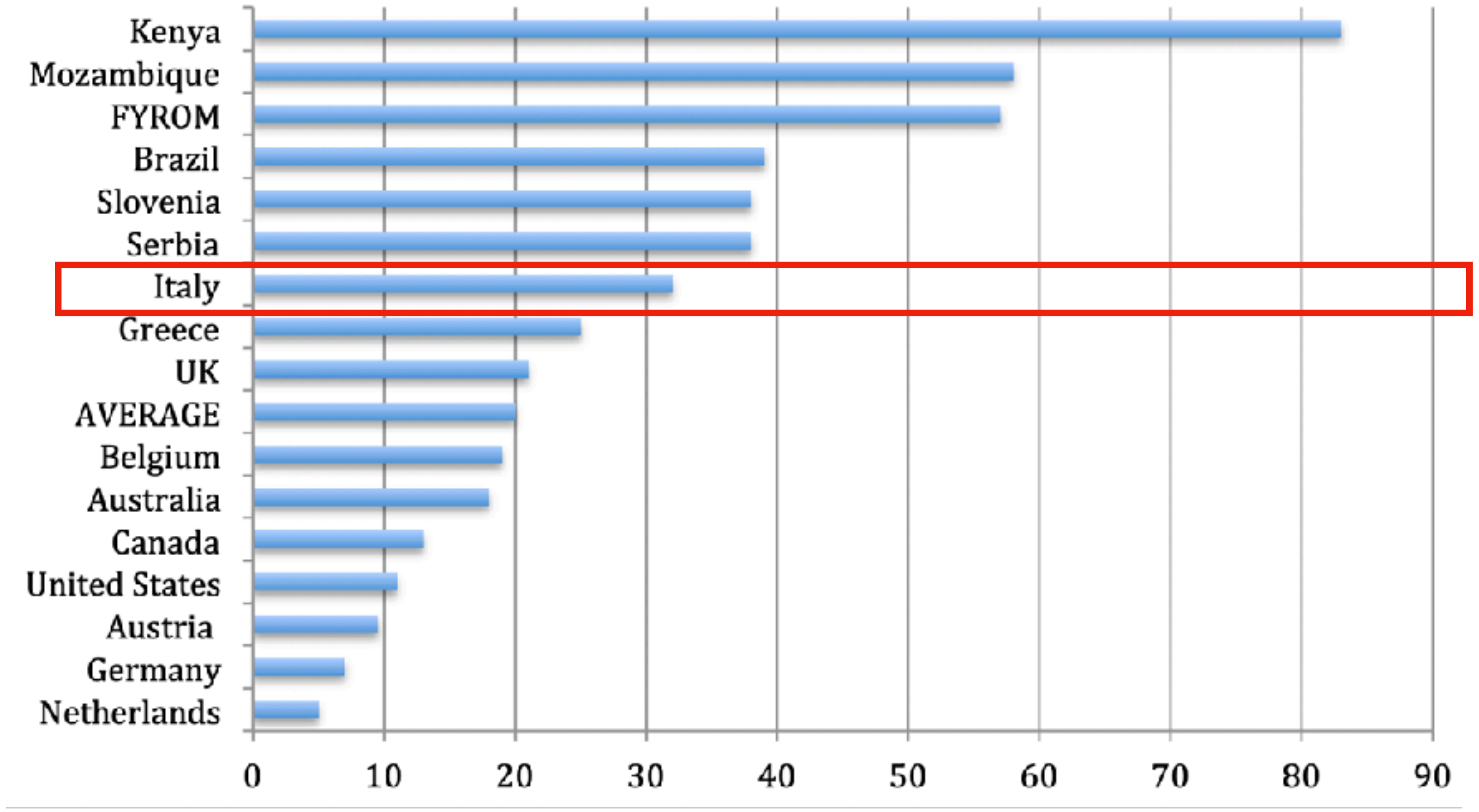
- Did things get better for Italy 15 years later?



Leakages in water distribution networks

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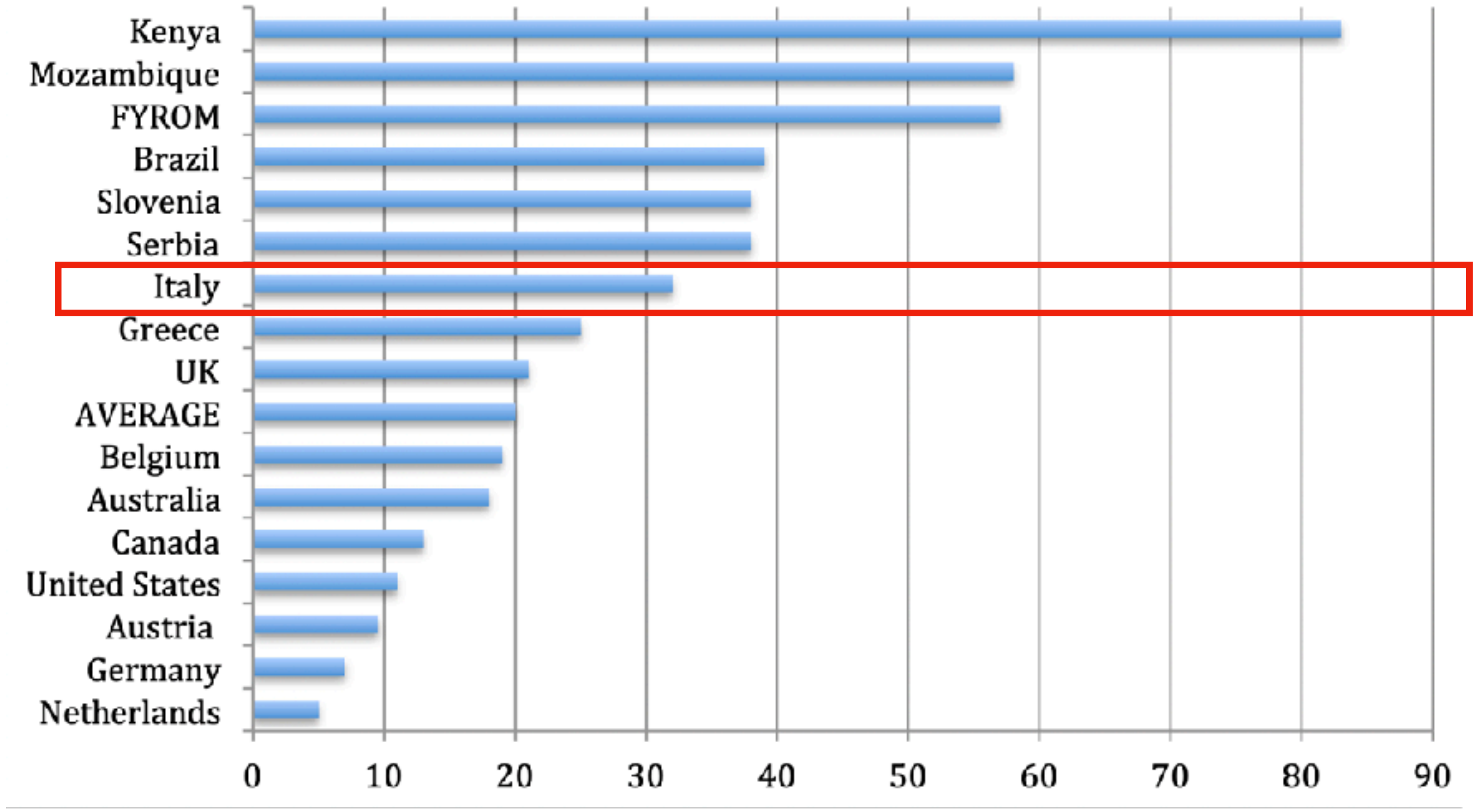
- Did things get better for Italy 15 years later?

- ISTAT (Italian national institute of statistics):
  36.2% of the water in the distribution networks is loss every year



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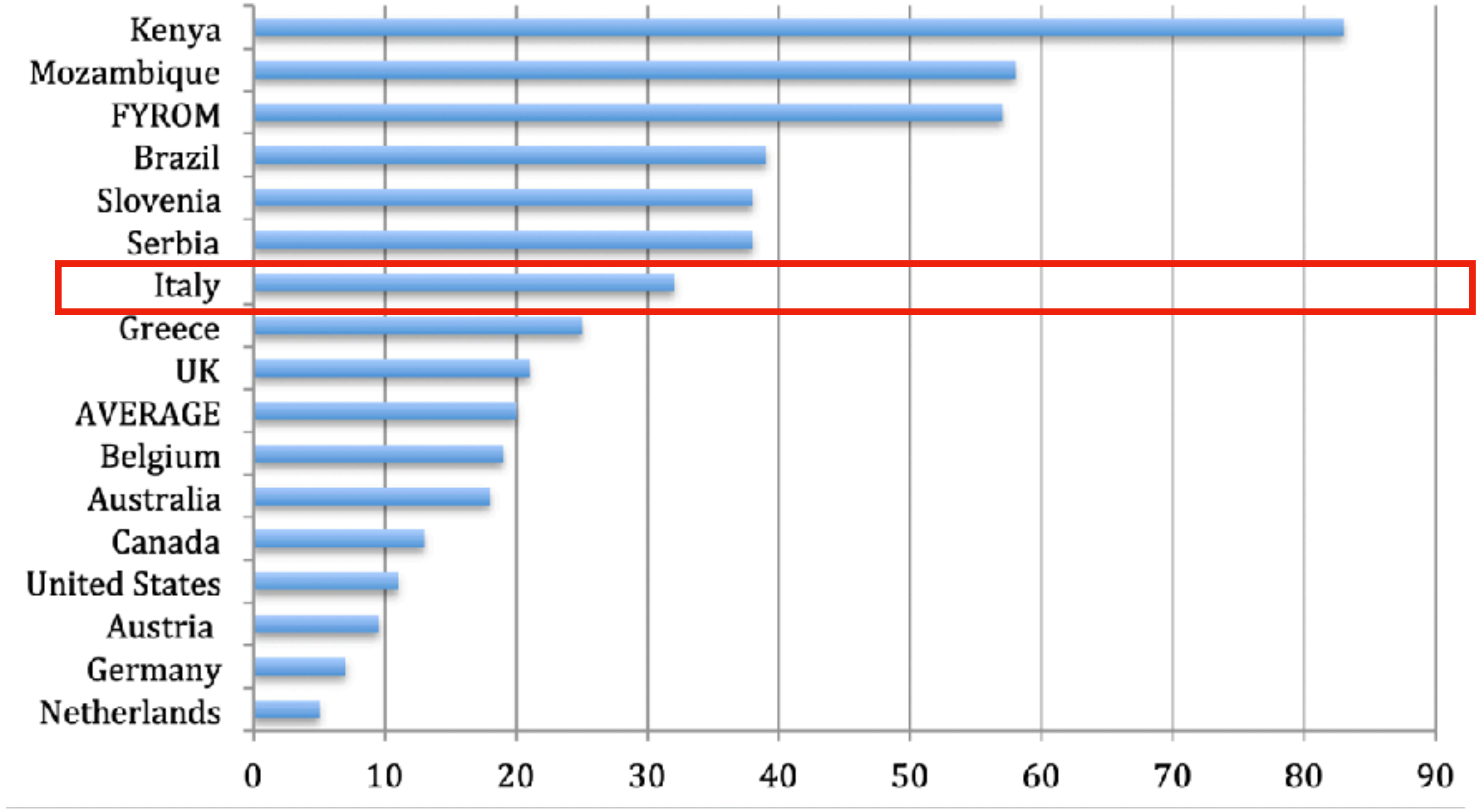
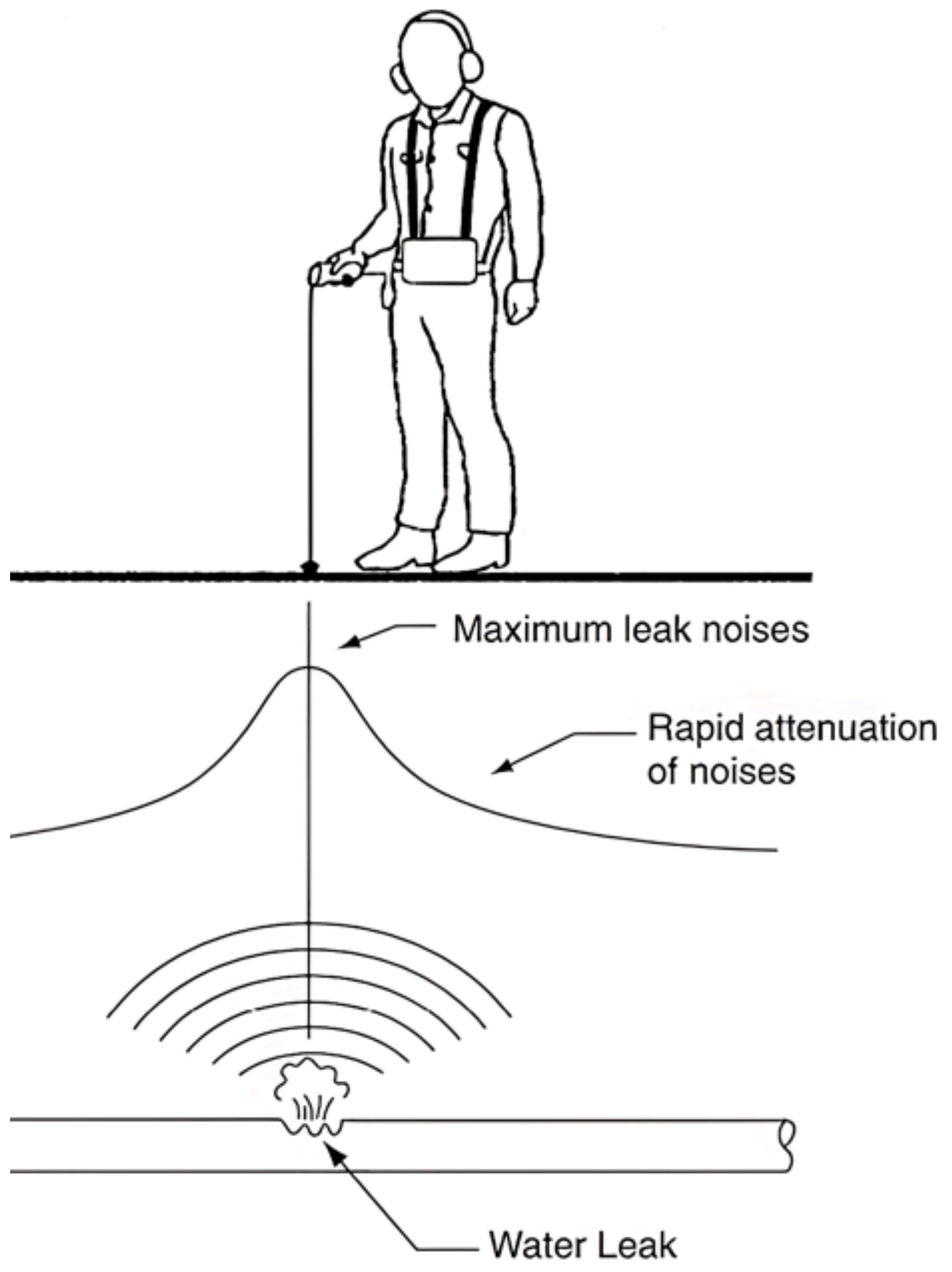
- What are the mostly used techniques to identify leakages in distribution networks?



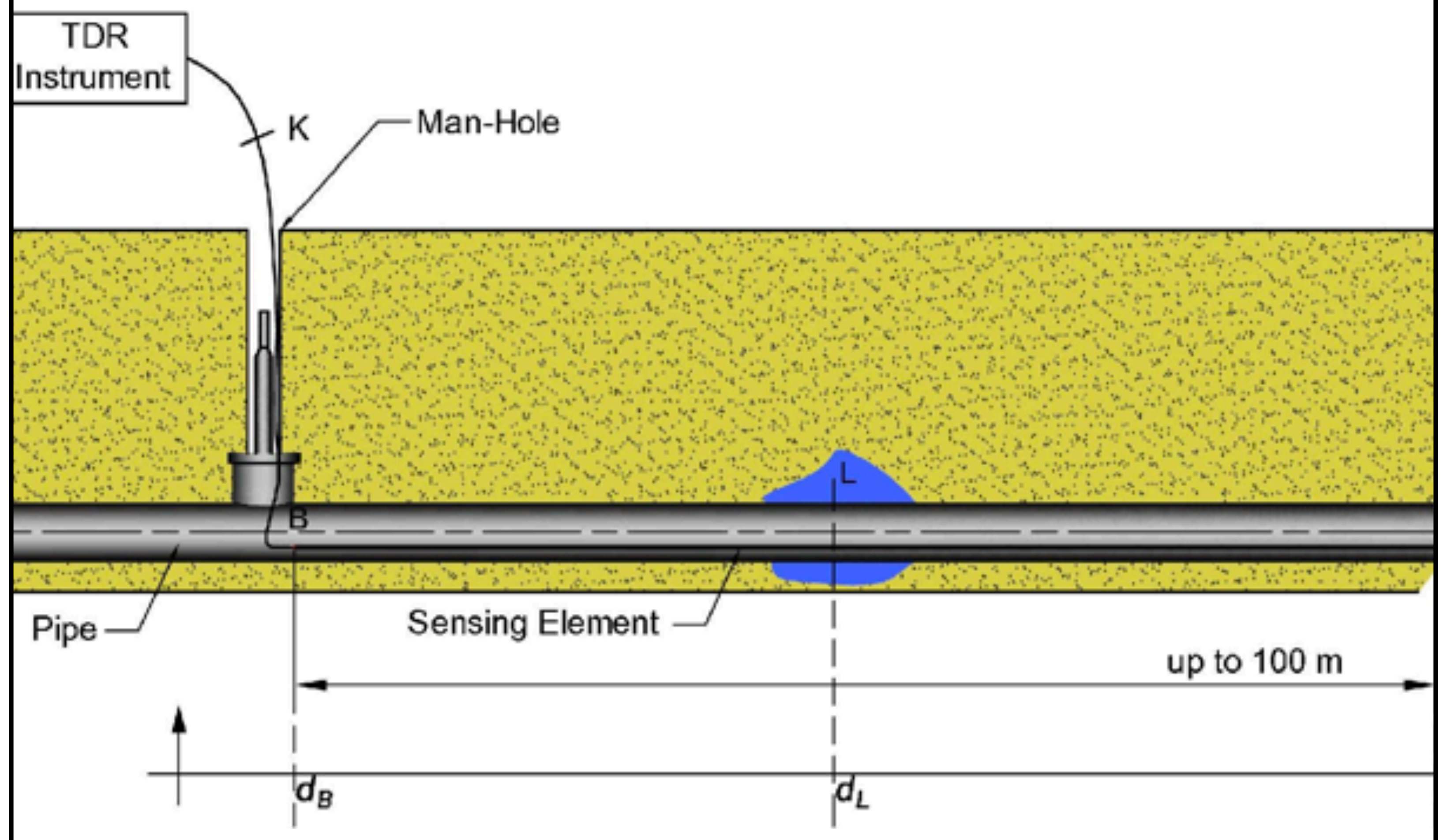
Common techniques for leakages detection

Sounding/acoustic devices



https://www.subsurfaceleak.com/

Noise correlator sensors



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Ground penetrating radars

Cosmic-ray neutrons and water content of soil

- The Cosmic Ray Neutron Sensing (CRNS) technique was originally proposed for hydrological and environmental applications

- CRNS capability already demonstrated by few research groups and it has also found commercial applications in agriculture

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doi:10.1002/2015GL063963
doi:10.2136/vzj2017.04.0086
doi:10.3390/agriculture9090202

The principle

- Secondary CR neutrons, produced by primary cosmic rays, can be categorized as:
  - $O(GeV)$ high-energy cascade neutrons , from the split of atmospheric nuclei
  - $O(MeV)$ fast neutrons from neutron evaporation induced by high-energy neutrons
  - low-energy thermal and epithermal neutrons from moderation of fast neutrons

Cosmic-ray neutrons and water content of soil

- Fast neutrons penetrate a few tens of g cm^{-2} of matter, that is some hundreds (tens) of meters (cm) of air (soil) before being thermalized

- An equilibrium concentration of neutrons is established in both air and soil, depending on:
  - the production rate of fast neutrons
  - the efficiency of moderating of fast neutrons, that is the content of hydrogen

- From the intensity of fast (or epithermal) neutrons, the hydrogen content is inferred

- Because of the dependence on air pressure, air humidity, vegetation, soil composition, etc., a reliable assessment of the soil water content requires the applications of corrections, filters and calibration functions

Cosmic-ray neutrons for leakage detection

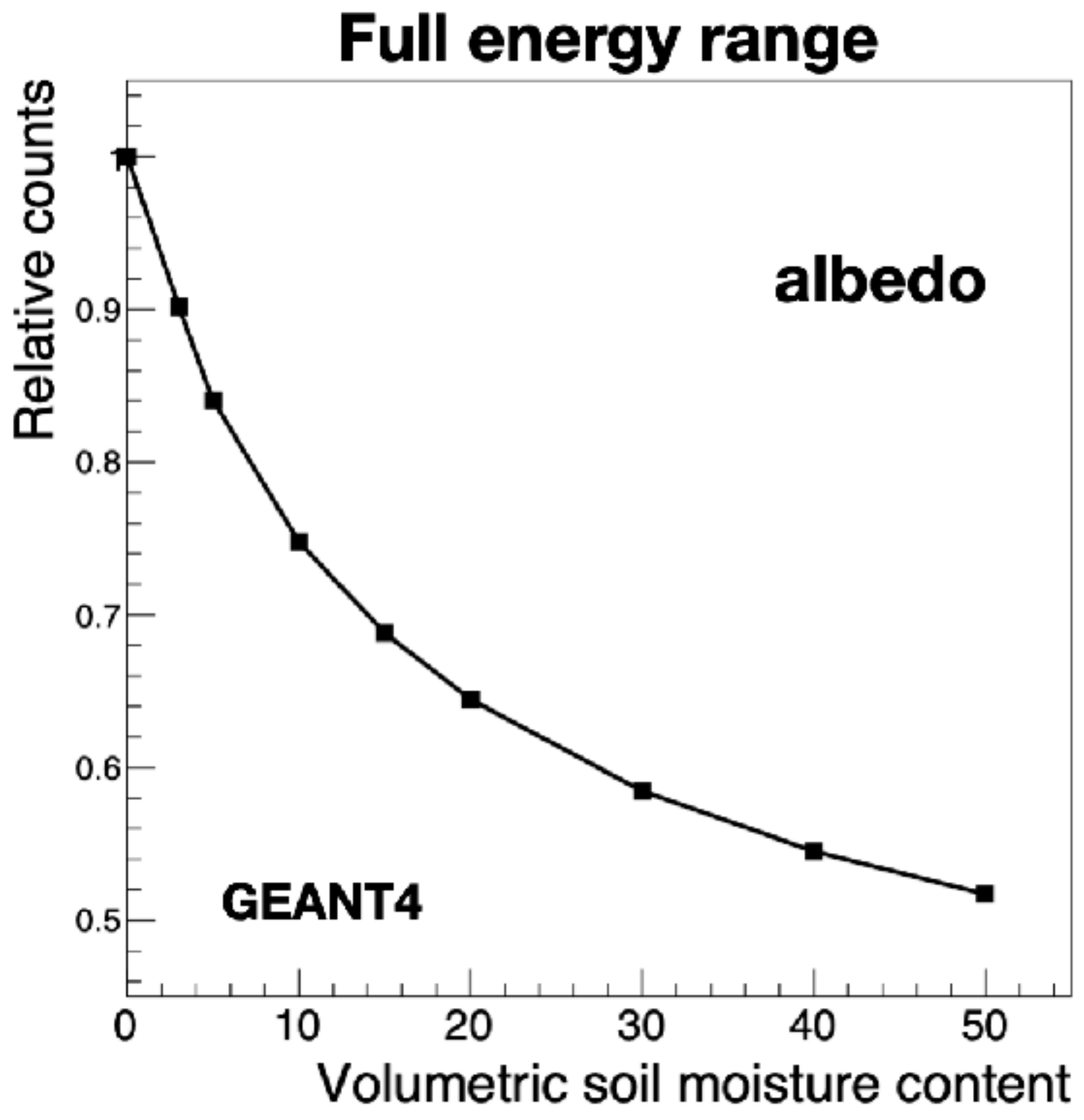
- We are investigating the possibility of using CR neutrons for subsoil leakages detection
  - small signals but no absolute need for an actual assessment of the soil water content

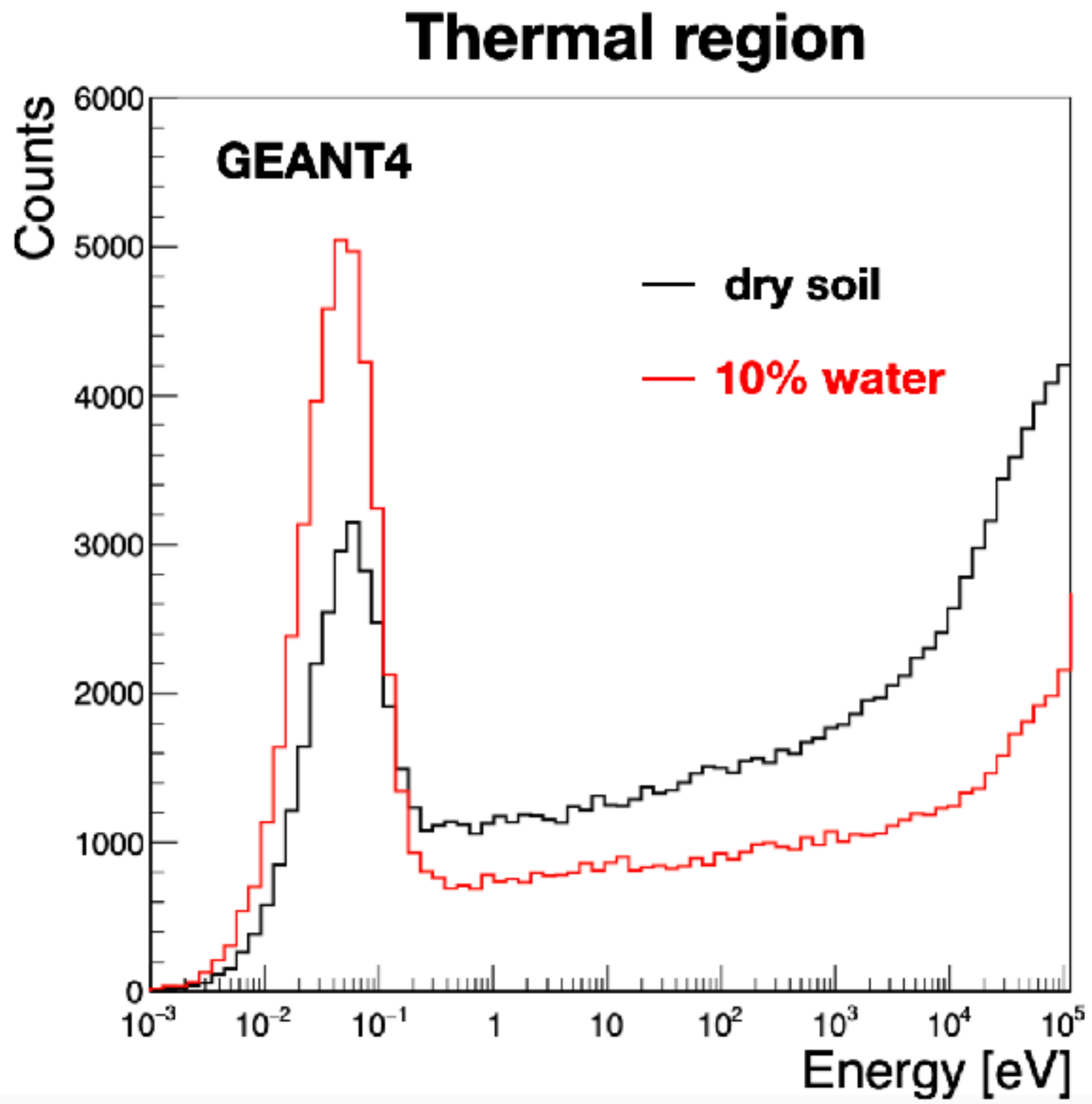
- Our approach involve two important differences w.r.t. what currently used in this field:
  - the use of two sensitive layers for neutrons
  - the detection of neutrons in the thermal region

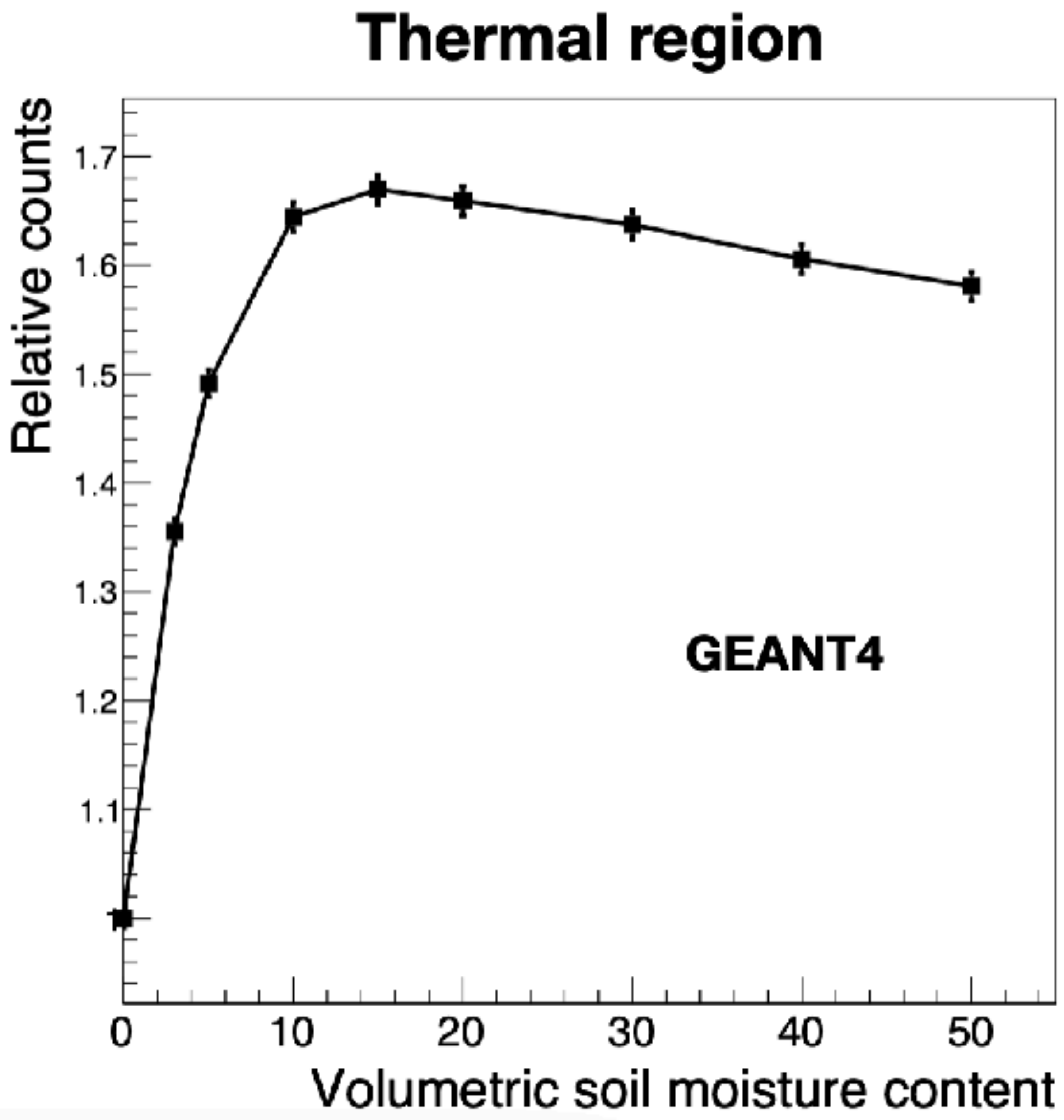
- Expected main advantages/drawbacks of this approach:
  - less sensitivity to calibration functions, thanks to a relative measurement between the two sensitive layers
  - possible higher sensitivity to small signals
  - worse capability of an absolute measurement of the water content in soil

Neutrons flux and water soil content

- The albedo neutron flux decreases for increasing values of the water soil content
- Decrease driven by epithermal to fast neutrons, whereas thermal neutrons show a different behavior (depending on the soil composition and water content)

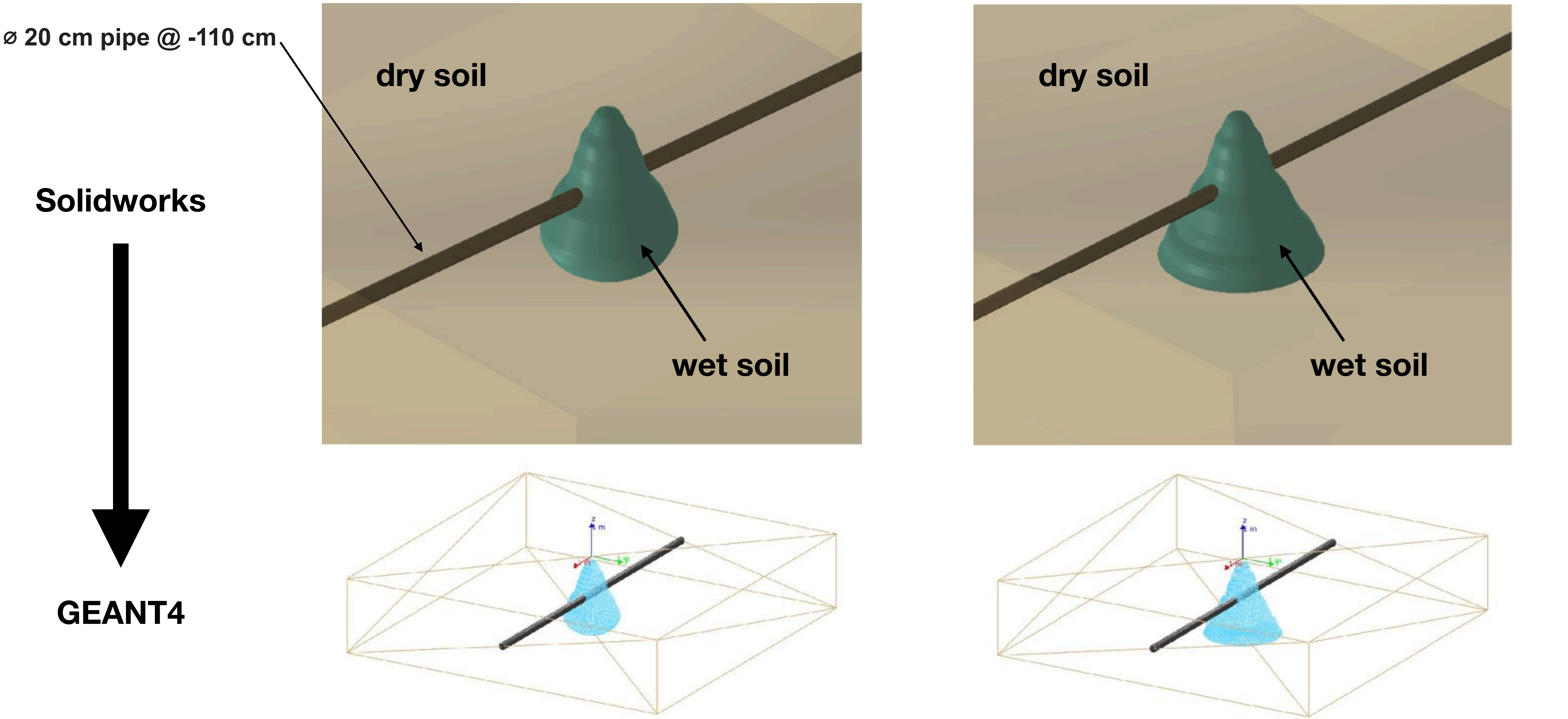






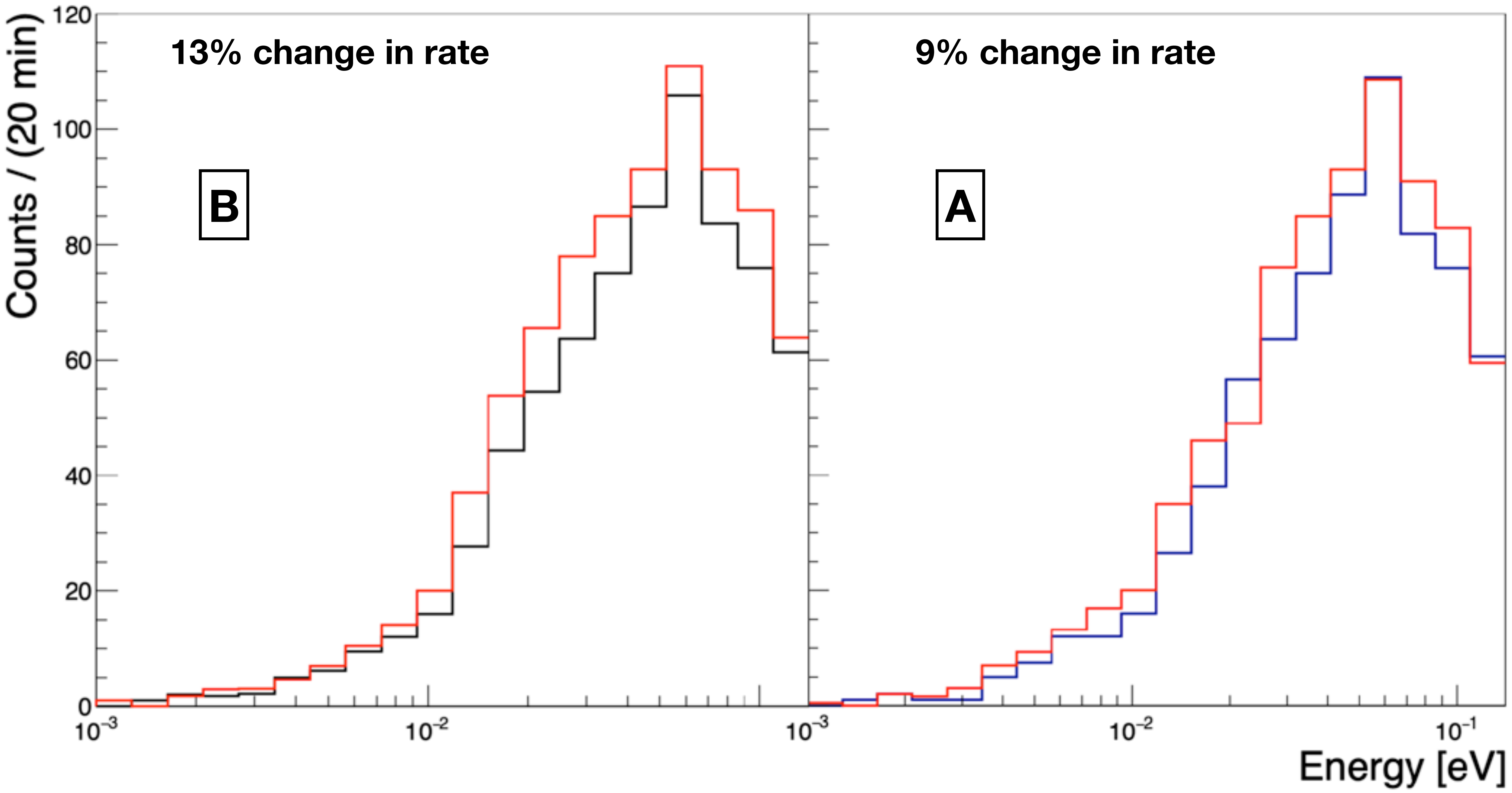
Some simulation results

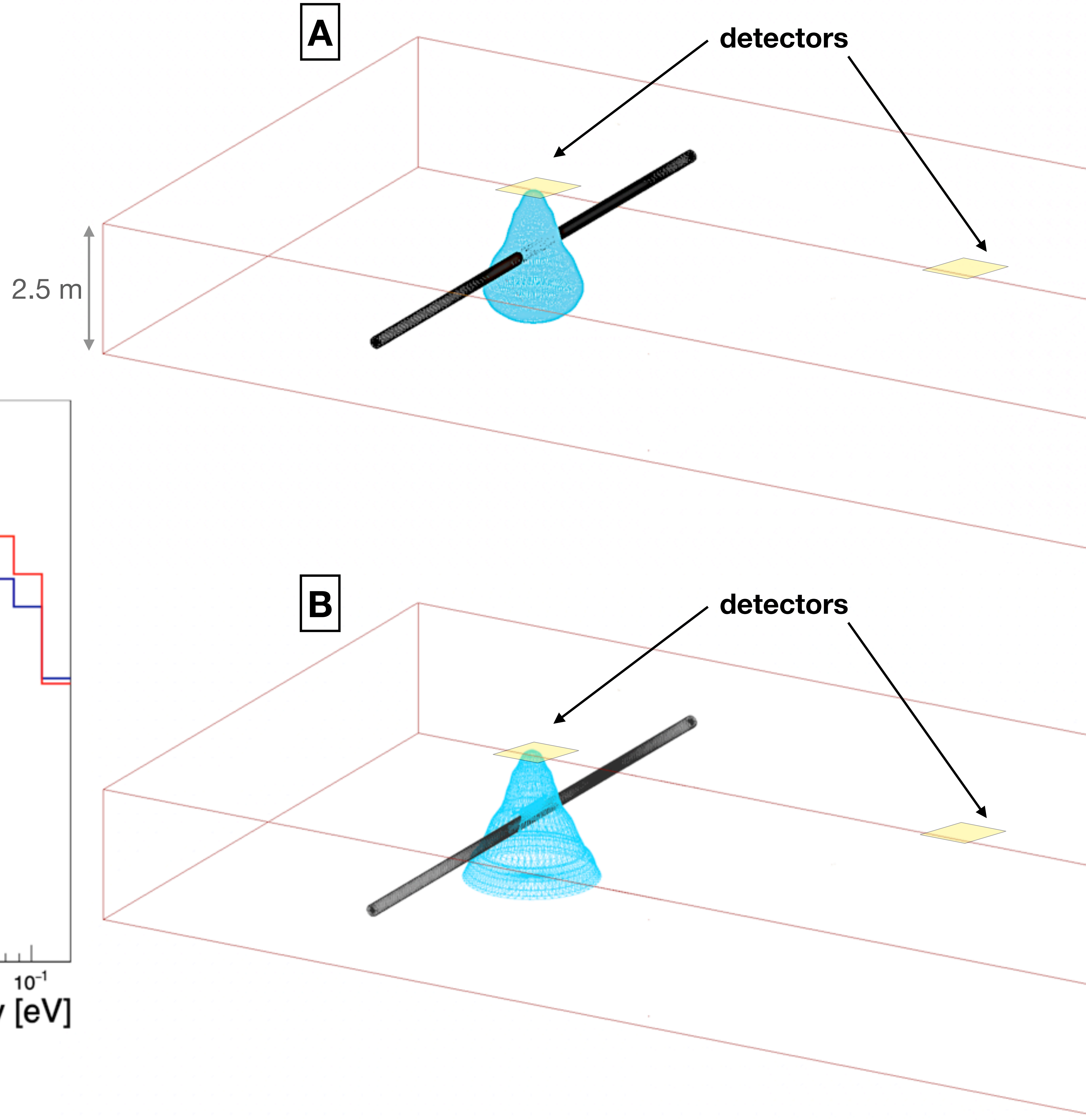
- Some (realistic) scenarios of subsoil leakages from pipes were simulated



Some simulation results

- Note: in water distribution networks, the position of pipes is known





Simulation results

- Many additional effects to take into account (atmospheric pressure, air humidity, presence of vegetation, soil composition, etc.)

- How much can we trust simulation results to claim the feasibility of the technique?
  - ...fairly little...

- This is why we decided to build a new detector to be (also) used to test the technique with field measurements

- Note: in the design of the detector we also wanted to maximize its possible applications
  - Indeed, our laboratory (which I am head of) is also involved in other activities involving cosmic rays: *muography* and studies on the interplay between cosmic rays and climate

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ANPLab

Laboratory of Applied Nuclear Physics

anplab.unibs.it

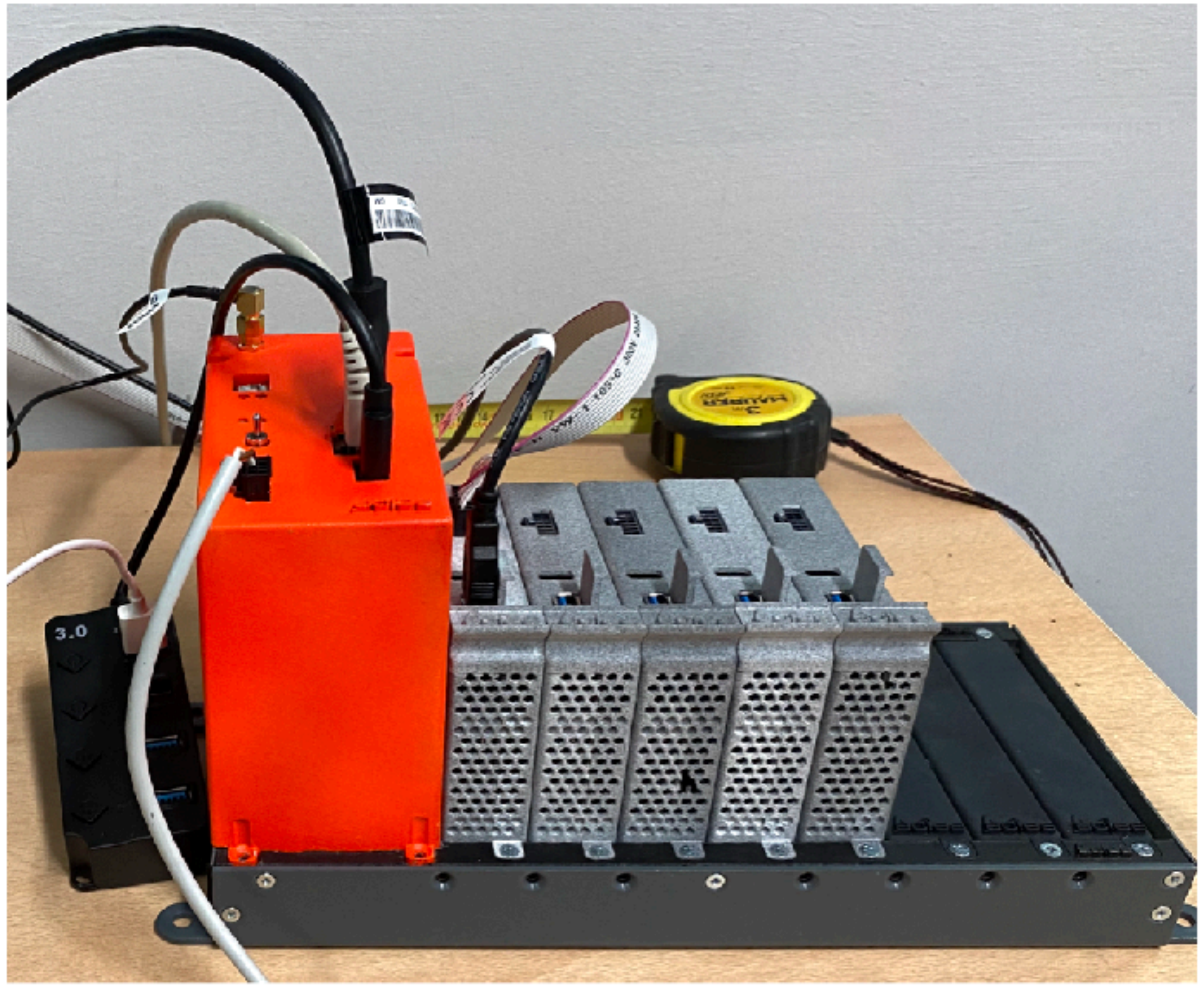
The detector

The detector

- 3 layers for muons
  - scintillating fibers coupled to SiPM
- 2 layers for thermal neutrons
- Shells for all modules from addictive manufacturing
- PLC for DAQ, calibration, storage, etc.
- Car battery (70 Ah) for expected operability ~ 24 h

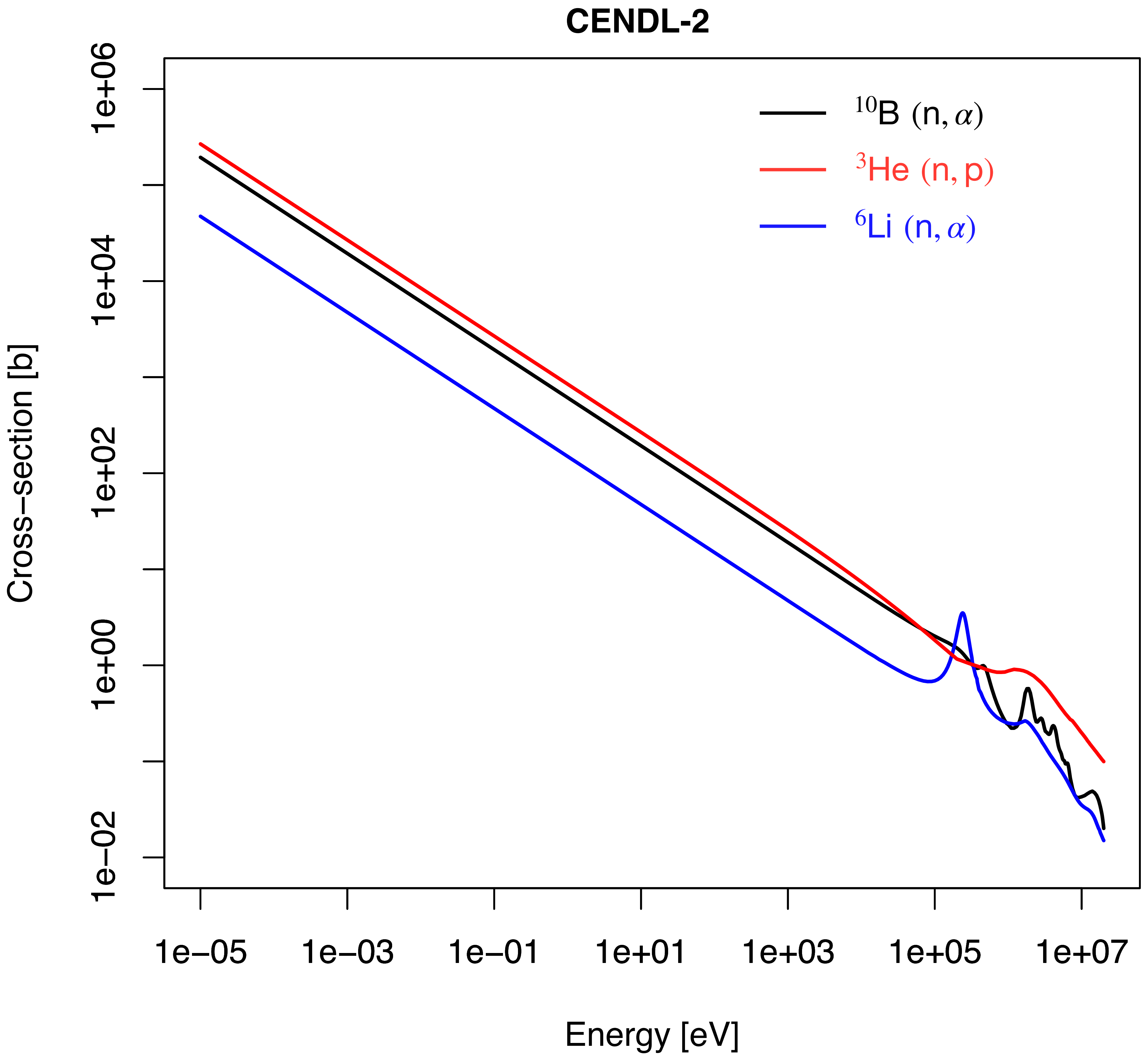
Modular design

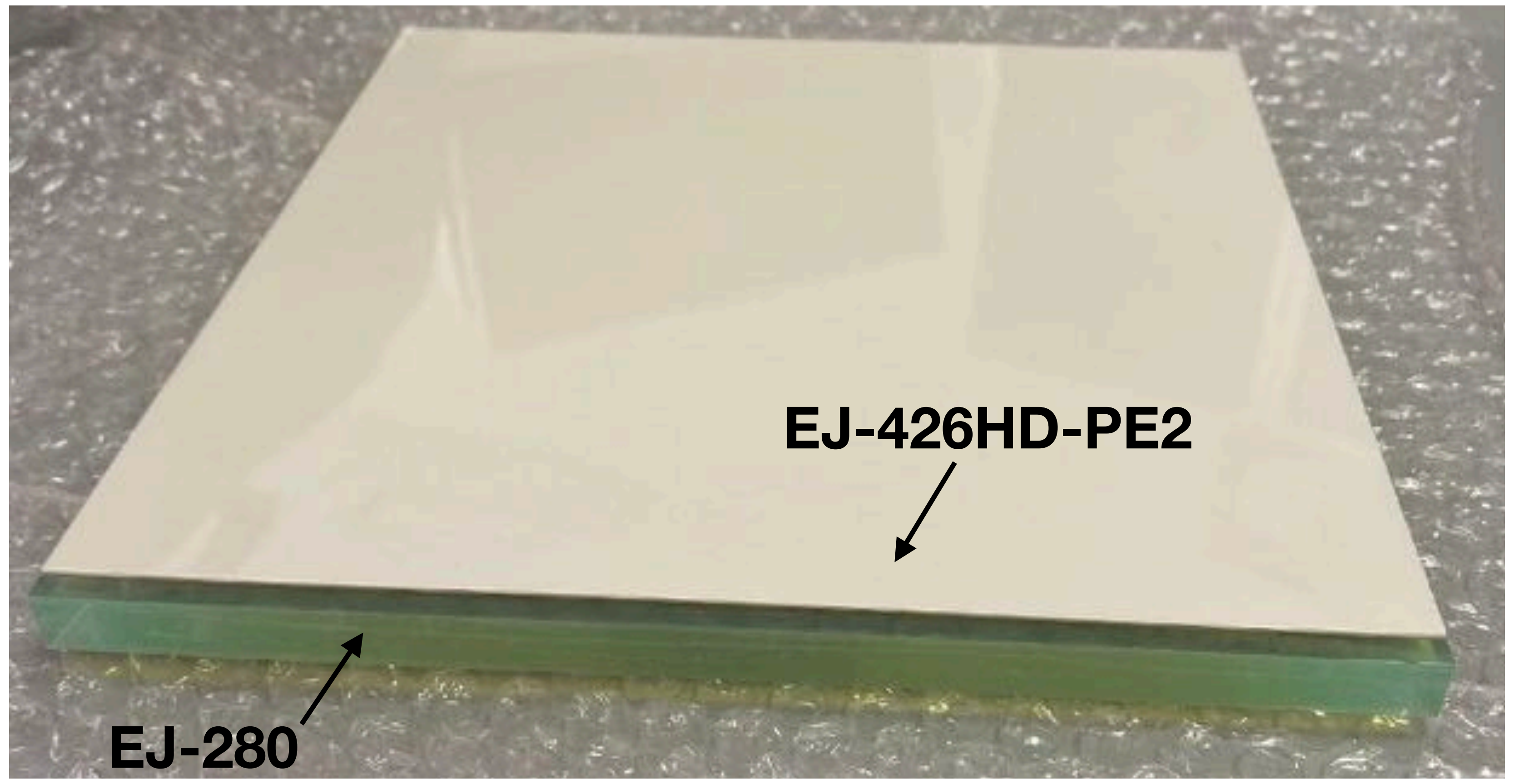
- All modules are plug-and-play (even with on-going data taking)
- Two cables: one usb cable (for data) and one flat cable (for power supply)



Detection of thermal neutrons

- Detection of slow neutrons generally based on the following processes
  - $^{10}\mathrm{B}\ (\mathrm{n},\alpha)$ reaction: $^{10}\mathrm{B} + {}^{1}\mathrm{n} \rightarrow {}^{7}\mathrm{Li}^{*} + {}^{4}\alpha + 2.31\ \mathrm{MeV}$
  - $^{3}\mathrm{He}\ (\mathrm{n},\mathrm{p})$ reaction: $^{3}\mathrm{He} + {}^{1}\mathrm{n} \rightarrow {}^{3}\mathrm{H} + {}^{1}\mathrm{p} + 0.764\ \mathrm{MeV}$
  - $^{6}\mathrm{Li}\ (\mathrm{n},\alpha)$ reaction: $^{6}\mathrm{Li} + {}^{1}\mathrm{n} \rightarrow {}^{3}\mathrm{H} + {}^{4}\alpha + 4.78\ \mathrm{MeV}$
- We chose the EJ-426HD-PE2 from Elijen Technology coupled to a WLS
- ^{3}He and $^{4}\alpha$ detected by ZnS:Ag phosphor matrix with a broad blue fluorescent spectrum



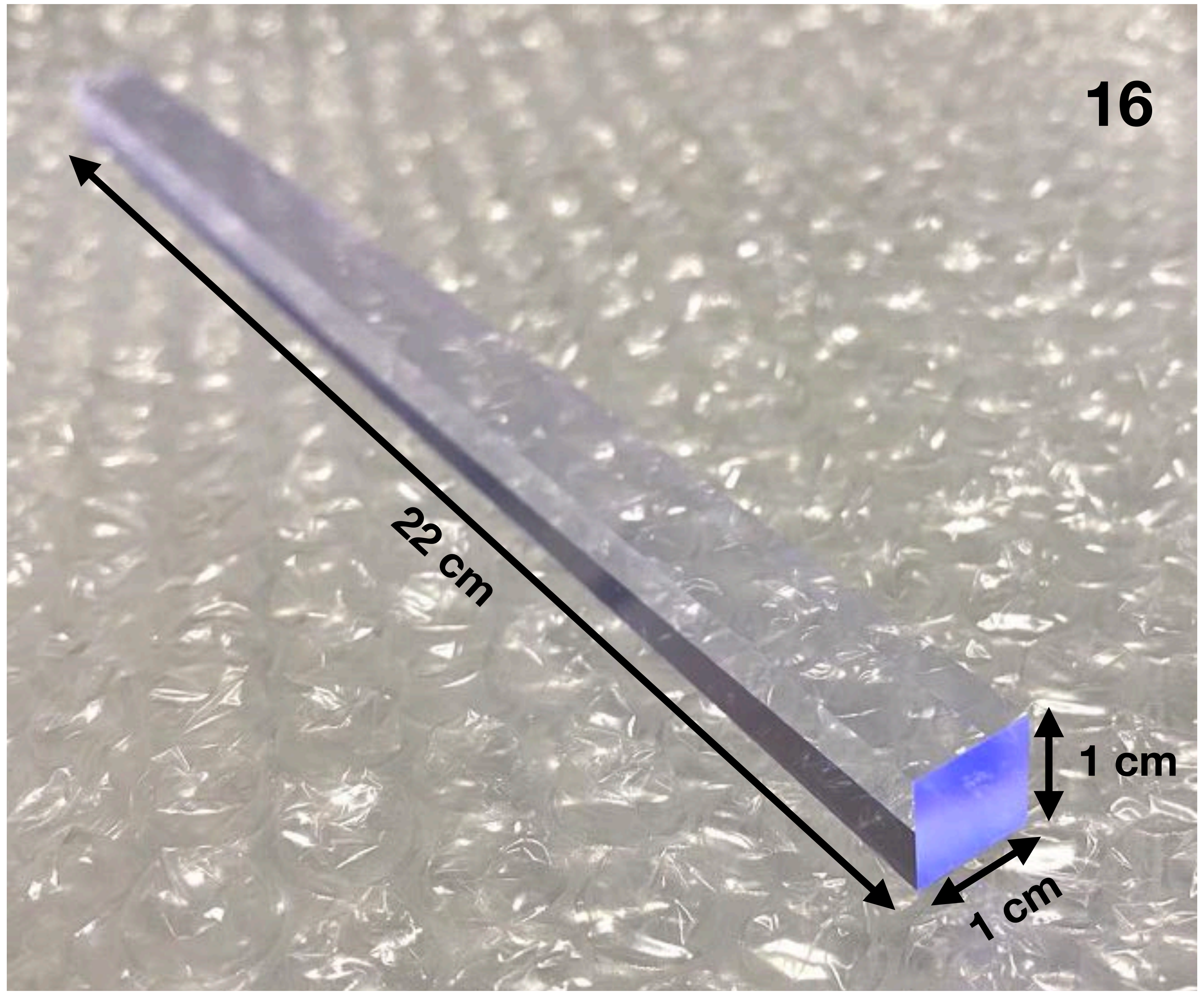


Muon module

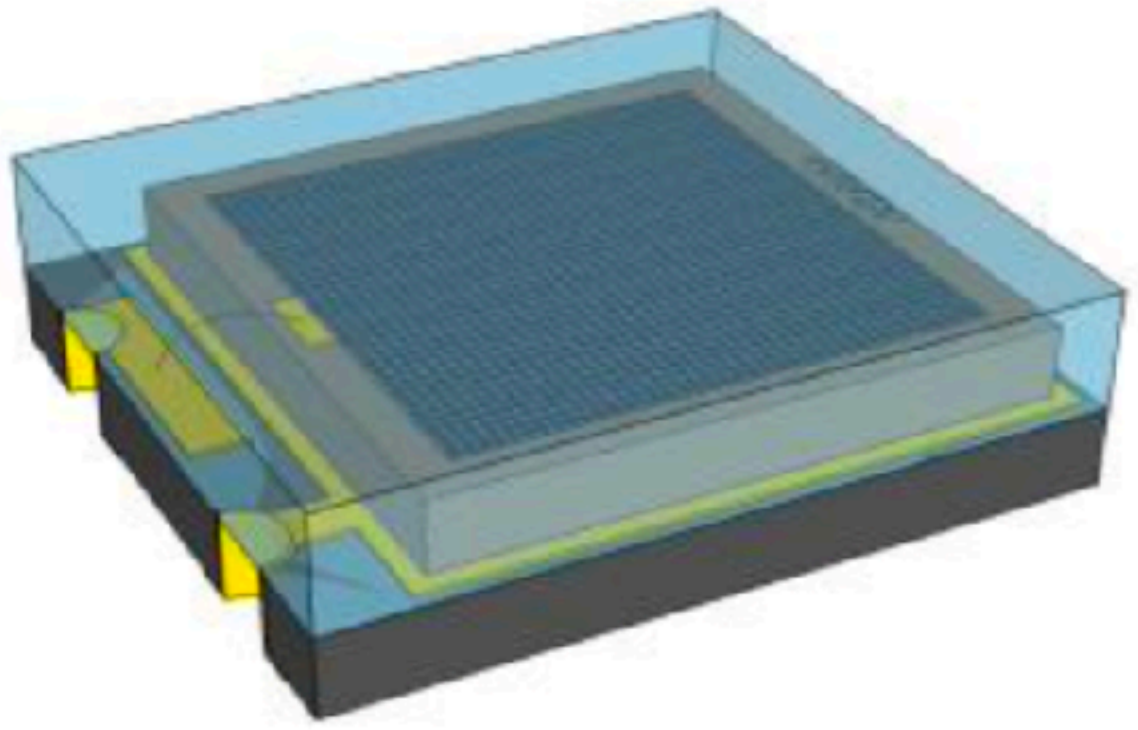
- Each module consists of 22 scintillating fibers (EJ-200 from Elijen Technology) of size (1 x 1 x 22) cm^3

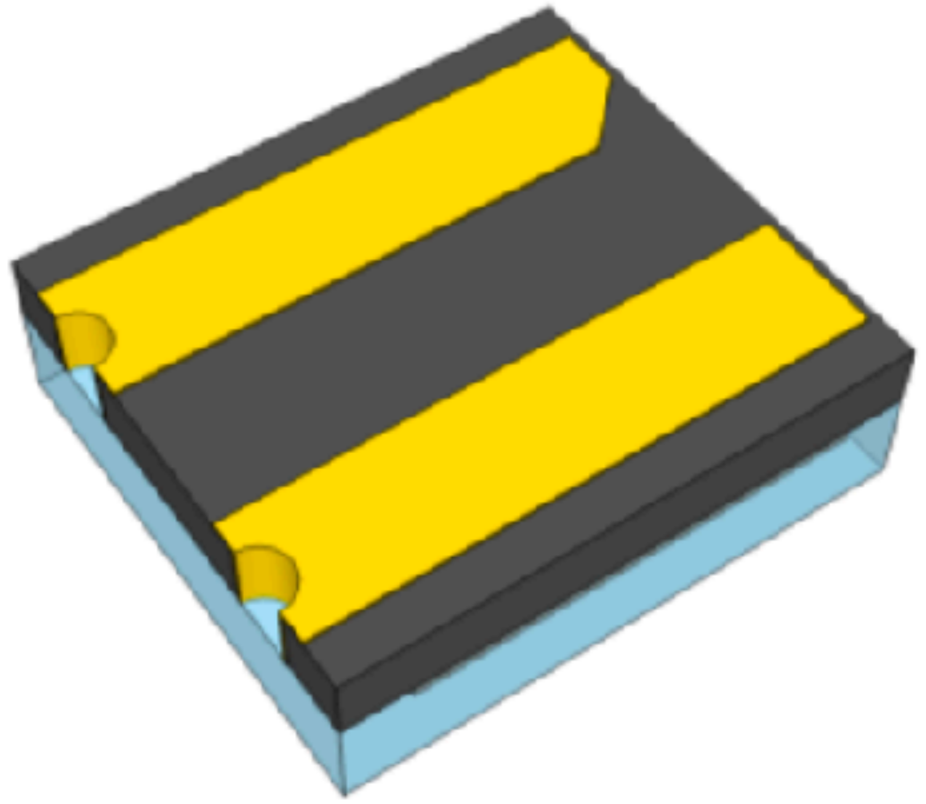
- Each fiber is coupled to a (4 x 4) mm^2 SiPM (ASD-NUV4S-P from AdvanSiD)

- No WLS and no mirror at the opposite end of the fiber



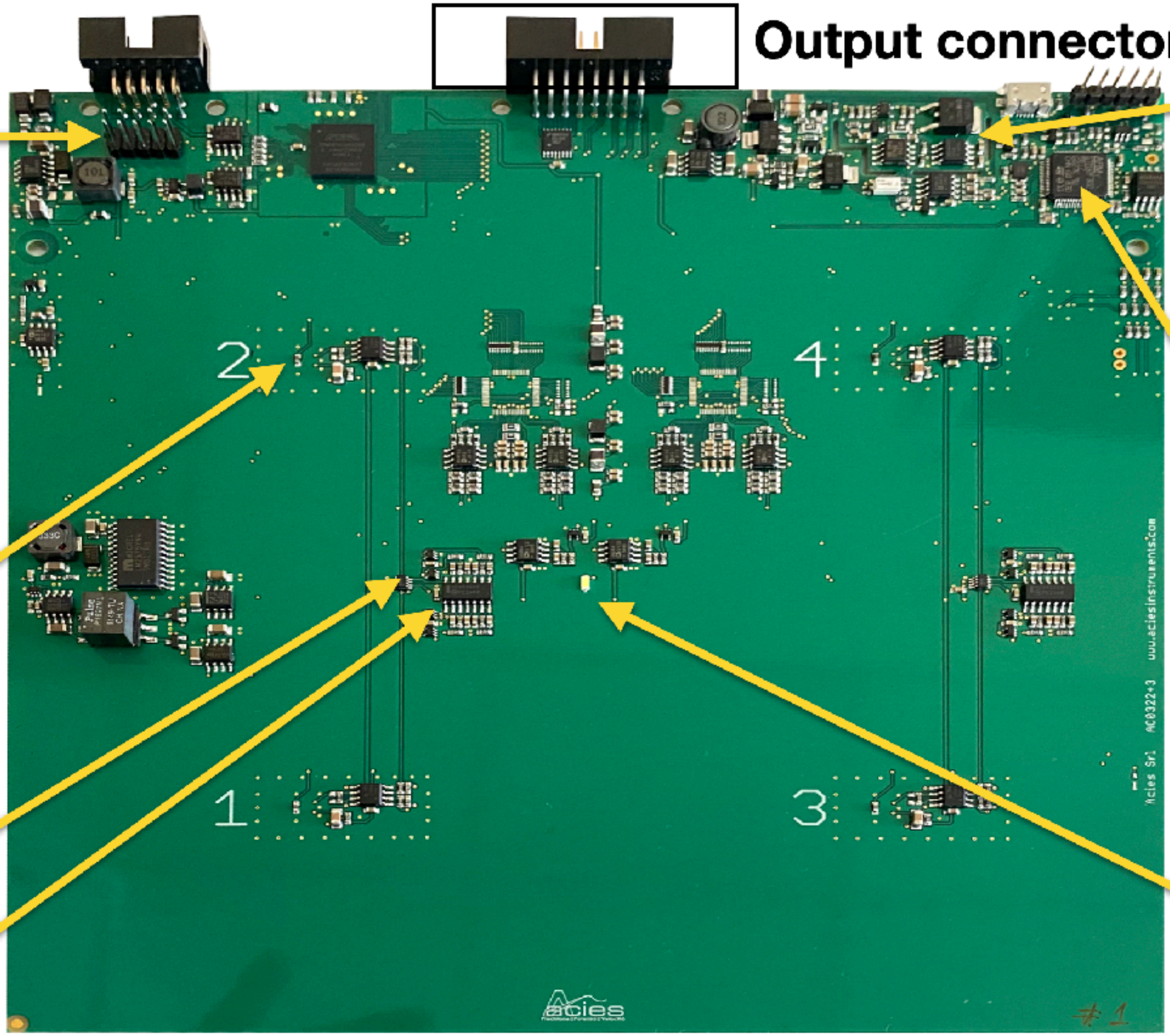
PROPERTIES	EJ-200
Light Output (% Anthracene)	64
Scintillation Efficiency (photons/1 MeV e-)	10,000
Wavelength of Maximum Emission (nm)	425
Light Attenuation Length (cm)	380
Rise Time (ns)	0.9
Decay Time (ns)	2.1
Pulse Width, FWHM (ns)	2.5
Density (g/cm^3)	1.023
Refractive Index	1.58
Light Output vs. Temperature	At 60°C, 95% of that at 20°C No change from 20°C to -60°
Temperature Range	-20°C to 60°C





Front-end electronics: muon modules

Front-end electronics: neutron modules



Output connector

Supply and control connector

Global V_b generator

SiPM (opposite side)

Cortex-M
- SEPIC control
- UART
- USB 2

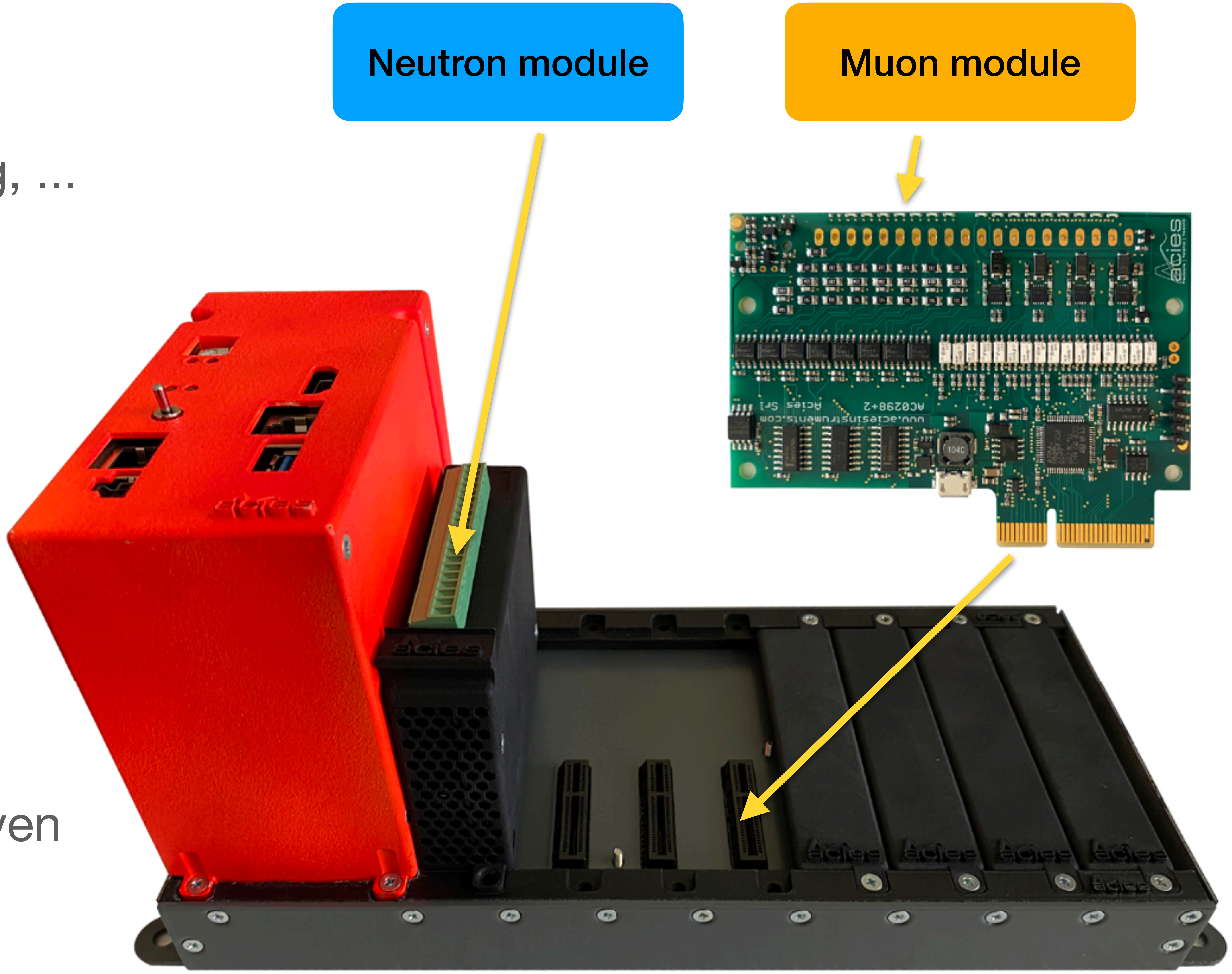
Discrimination

16-bit trim

LED

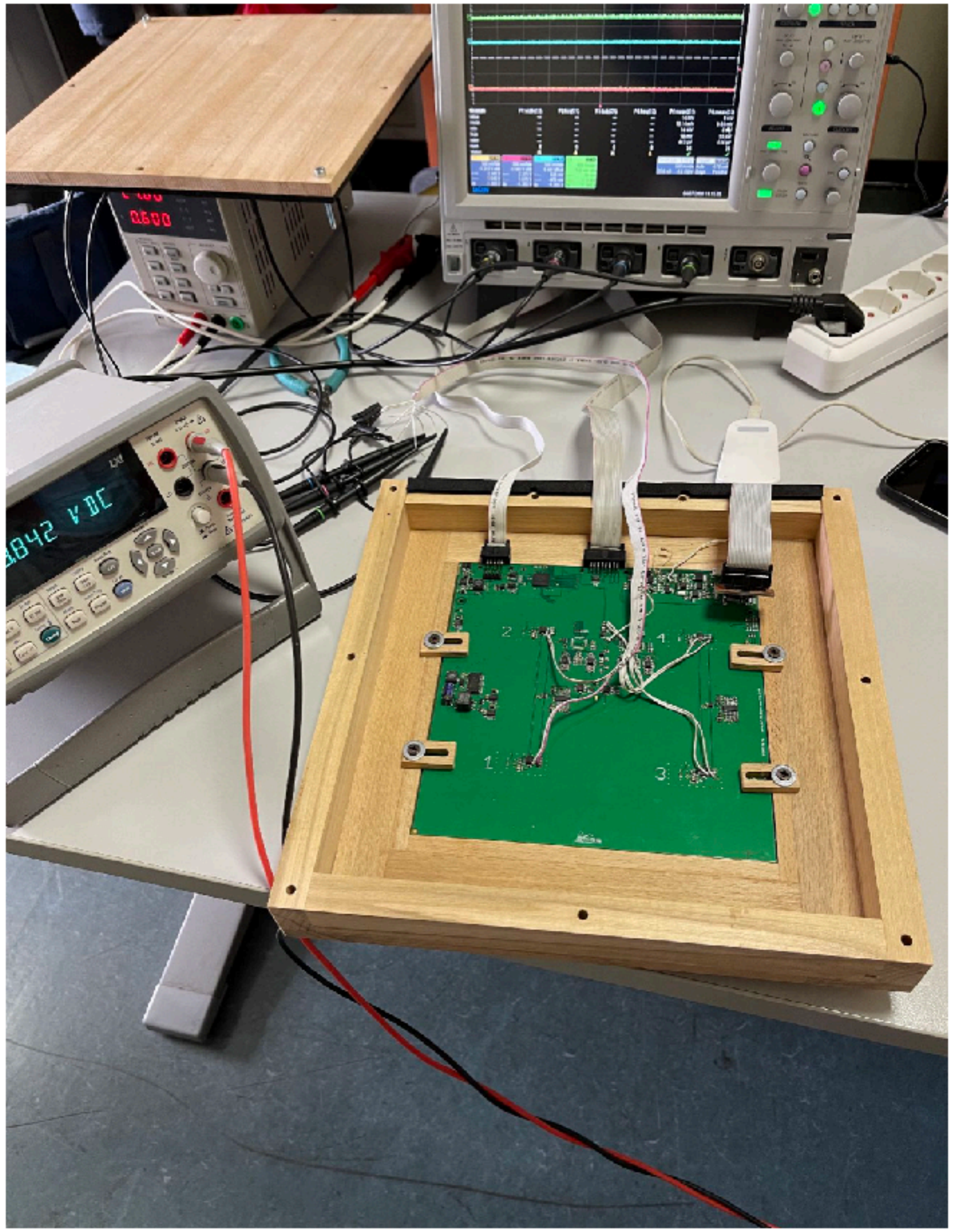
DAQ electronics

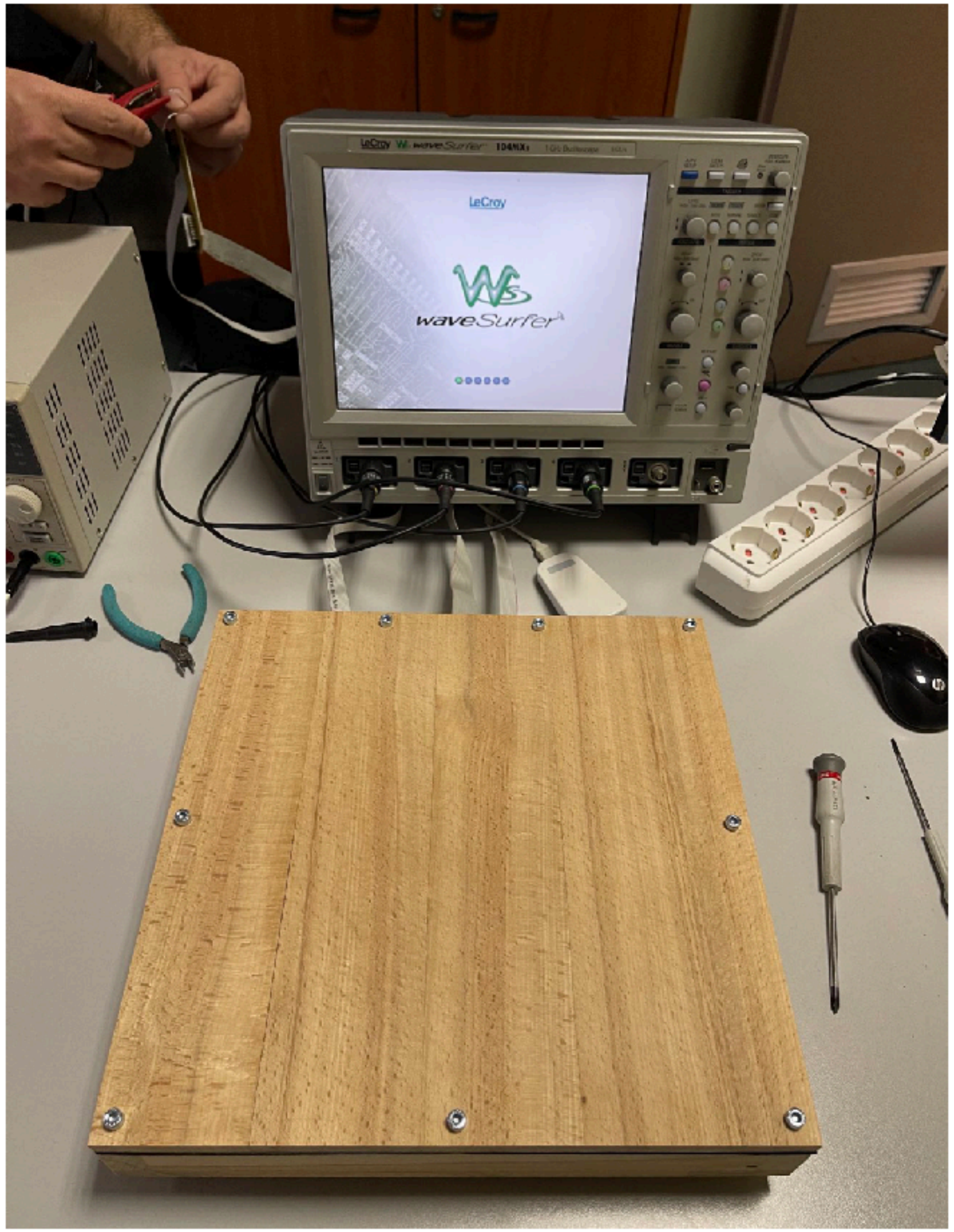
- Dual core CPU with on USB3
  - Real-time: timing, time-stamping, ...
  - SBC running ARC Linux: data acquisition, storage, network interface, ...
- GPS module
- WiFi + ethernet communication
- Supply management
  - If plugged into the socket can even charge the battery



Tests of the modules

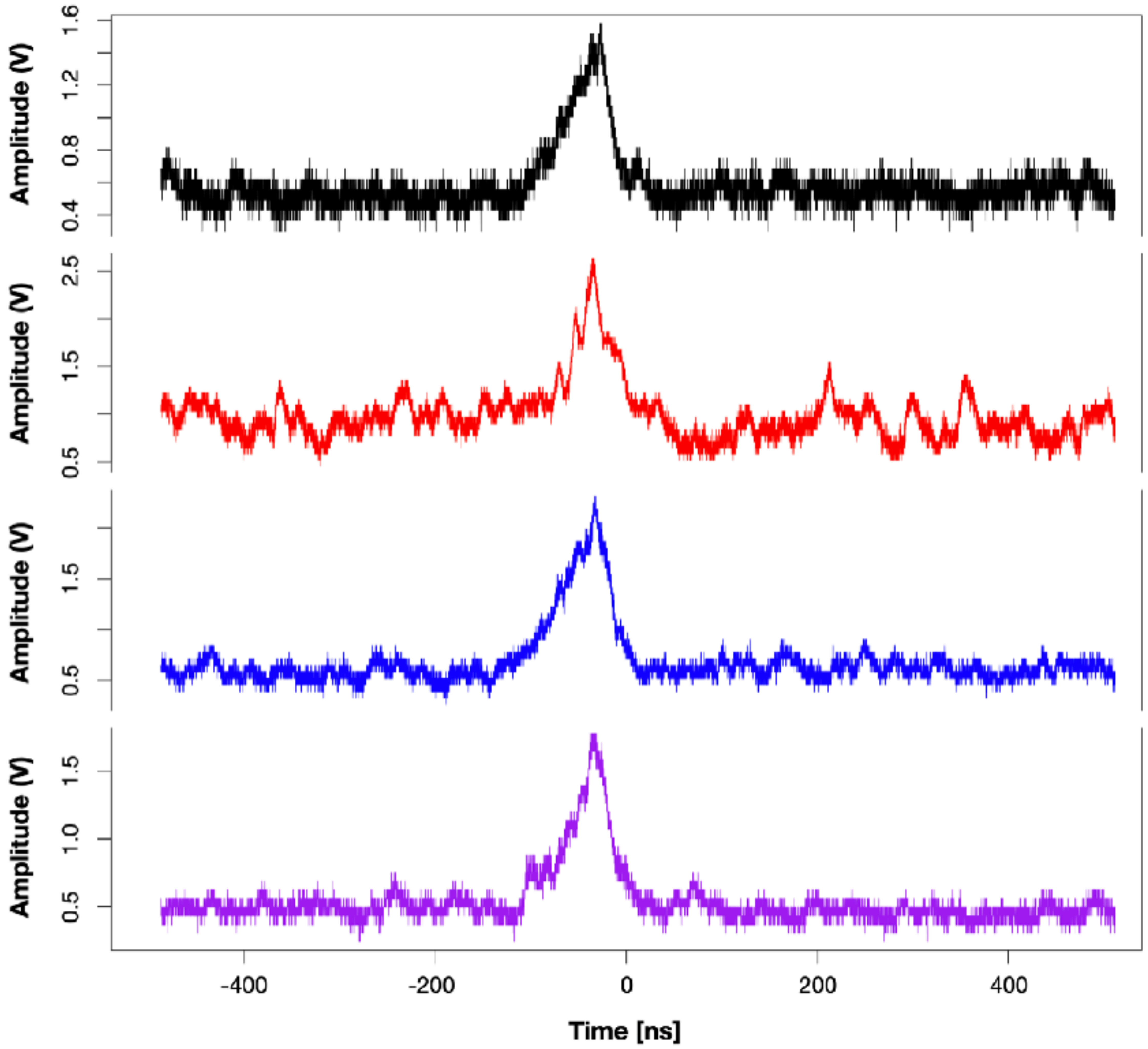
- Each module is under testing with a dedicated setup
- Oversize light-proof wooden boxes are used of the tests
- Boxes are sealed with neoprene





Signals from the neutron modules

candidate neutron event



onboard LED events

Conclusions

- We are investigating the possibility of using cosmic-ray neutrons for the identification of subsoil leakages
- While simulations with both GEANT4 and PHITS seems encouraging, field measurements are necessary to prove the feasibility of the technique
- A new detector has been designed and realized with some innovative solutions, from the the use of additive manufacturing, to the design of the electronics
  - based on a USB3 backplane with realtime time-stamping and triggering
  - programmable bias for SiPMs, and low-noise/high-speed analogue front-end
  - on battery operation (70 Ah ~ 24 h)
- Laboratory tests are ongoing, whereas first field measurements are planned from March