Ultra-sensitive Rn detection and its suppression

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IEAP CTU was found in 2002 as a scientific and educational institute of the CTU in Prague, focusing on a research in the field of particle and subatomic physics performed in an international experiments

105 people (38 from abroad)

1) Brief introduction of IEAP CTU (main research topics)
2) Why we need to suppress Rn caused background?
3) Rn detection (ultra-low concentrations)
4) Rn suppression
5) Rn in education

Main research subjects in IEAP CTU:

(1) CERN – experiments ATLAS (ATLAS TPX – radiation field measurement, luminosity monitoring, theory, data processing), MoEDAL, AFP, ISOLDE (nuclear physics at CERN)

(2) Neutrino physics – 2νEC/EC decay of ^{106}Cd (experiment TGV – necessity to upgrade), experiment COBRA (close to end), detection of 0ν and 2νββ decay of ^{82}Se (experiment SuperNEMO), experiment LEGEND (USA/Germany – 0νββ decay of ^{76}Ge); detection of atmospheric neutrinos in experiments KM3NeT and Baikal-GVD); detection of reactor antineutrinos

(3) Detection of dark matter – experiment PICO in SNOLAB (Canada), detection of neutralino

(4) Detection of high-energy cosmic rays – detection of radiation from universe (8 Timepix detectors on ISS, NASA; Timepix detector on Proba-V and RISESAT satellites; small unit VZLUSat), new projects with ESA (HardPix on-board GOMX-5 Cubesat mission, 12U, 20 kg. Launch 2023; 2x HardPix outside Lunar Gateway as part of ESA ERSA. Launch 2024).

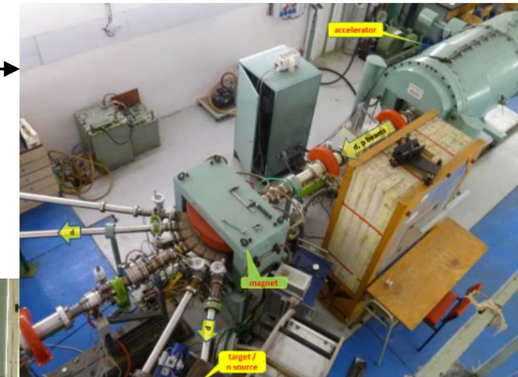
(5) Structure of atomic nuclei and nuclear reactions – fission, radioactive nuclei decay, super heavy nuclei, astrophysical reactions

(6) Applications – pixel and strip detectors, imaging (X-rays and neutrons), biomedicine, hadron therapy, study of material…..

All our activities are based on international cooperation

Research infrastructure of IEAP CTU

- Van de Graaff accelerator

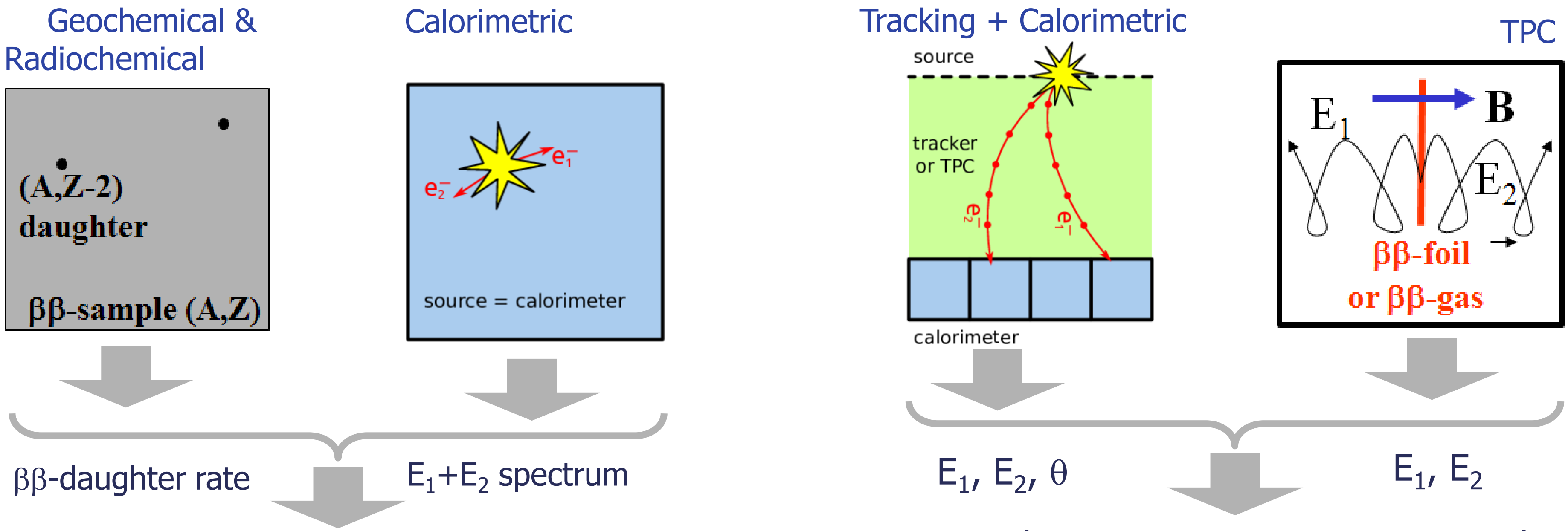


- Underground laboratory LSM in Modane, France
- Small underground laboratory in Prague in a nuclear shelter
- 2 electron microscopes
- Laboratory for high-resolution X-ray radiography, 3D X-ray tomography and neutronography in IEAP,

- Specialized laboratory for experimental imaging – common laboratory of IEAP and 3rd faculty of medicine of CU
- Radon laboratory (ultrasensitive measurement, radon-free chambers) – common laboratory of IEAP and the National Radiation Protection Institute;

- Tunable electron source and equipment for scintillators measurements – common laboratory of IEAP and the NUVIA company.

Experimental techniques to observe ββ-decay (no method is perfect)



Energy resolution, High (~ 100%) efficiency

Precise ββ-observation, Any ββ-source can be measured (test nuclear models), Potentially zero-background, Test of ββ0ν mechanisms

Formula of experimental sensitivity

$$T_{1/2}^{0\nu} = \ln(2) N_A \times \frac{a\varepsilon}{m_{mol}} \times \sqrt{\frac{M \times t}{N_{bkg} \times \Delta E}}$$

N_A : Avogadro number

M : source mass

ε : **efficiency**

m_{mol} : molar mass

t : time of measurement

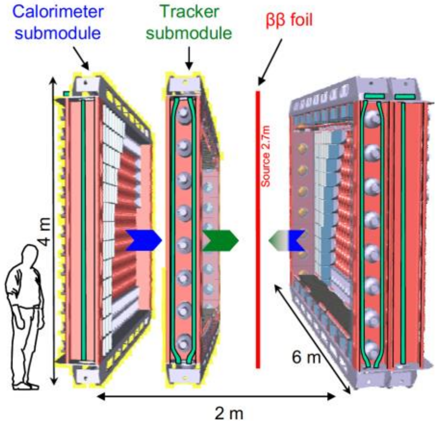
a : **Isotope abundance**

N_{BGR} : **background rate**

ΔE : **energy resolution**

Ultra low background experiments (neutrino physics, DM)

SuperNEMO: measurement of double beta decay in the LSM underground laboratory in Modane, France (4 800 m w.e.) – cooperation of institutions (France, UK, Czechia, Slovakia, Russia, Ukraine, JINR)

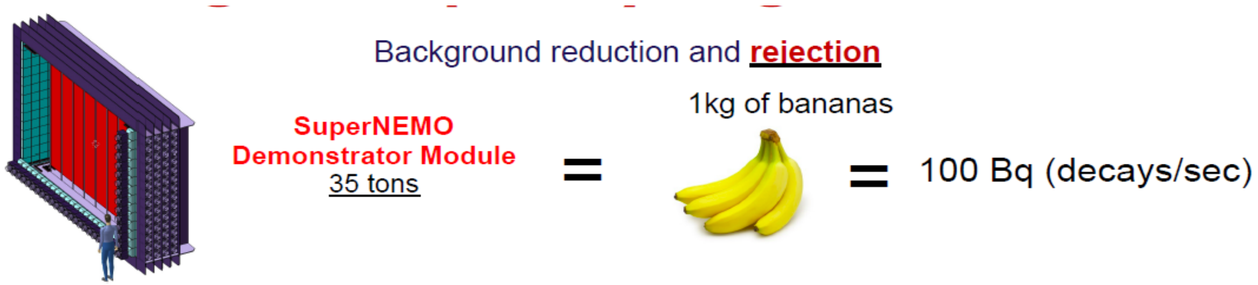


DEMONSTRATOR = 1 module (7 kg of ^{82}Se)

The goal is to reach a zero background level in the region of interest of 0νββ.

Demonstrator sensitivity for 0νββ:

$T_{1/2} > 5.9 \times 10^{24}$ y (90% C.L.) and $\langle m \rangle < 0.2 - 0.55$ eV



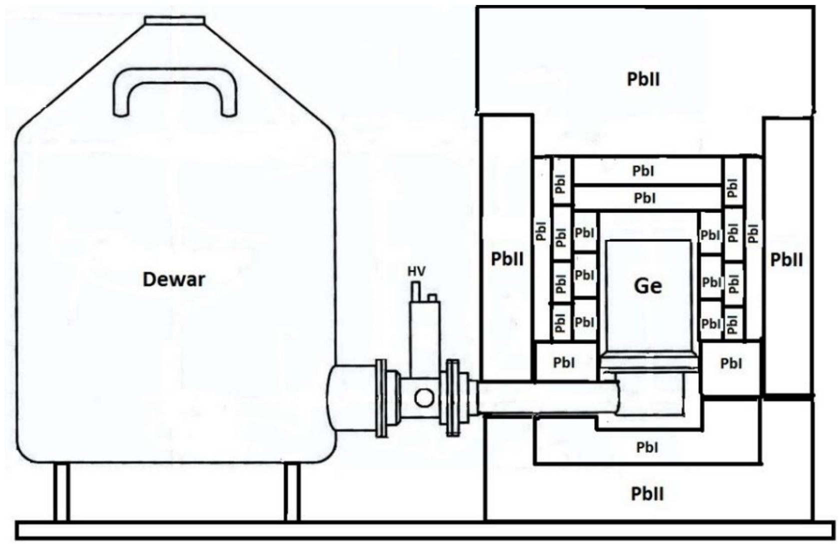
Calorimeter (712 Optical Modules, plastic scintillator, PMT) is ready. Tracking detector (2034 cells running in Geiger mode and filled with a gas mixture (95% He, 4% ethanol, 1% Ar) is ready. A coil producing a 25 G magnetic field is installed.

We need gamma and neutron shielding. Data taking.

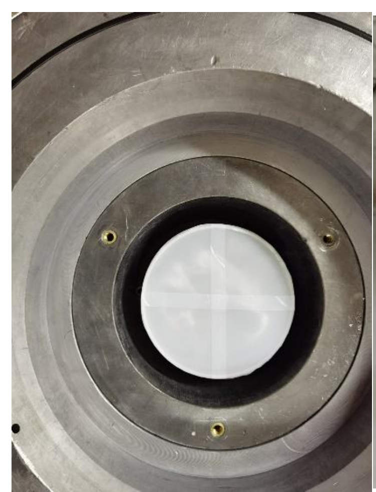
Why we need to suppress Rn caused background?

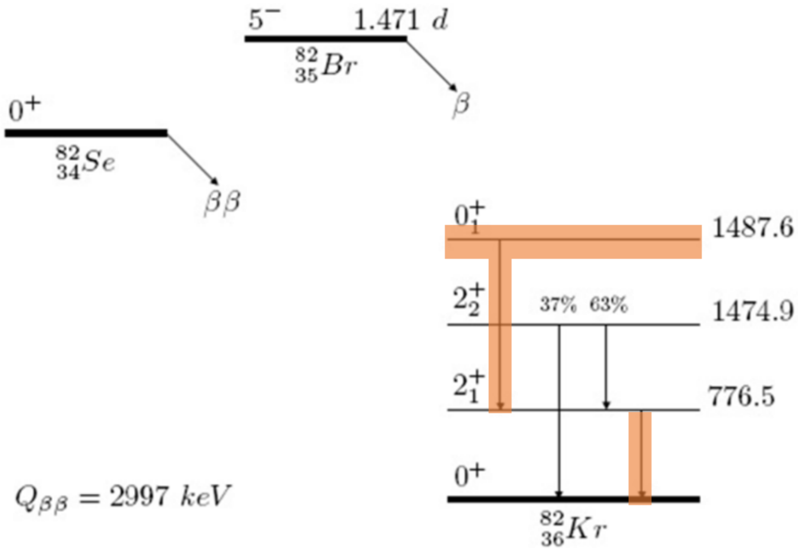
Search for ββ decay on excited levels of ^{82}Se with the OBELIX spectrometer and the influence of radon background

- **OBELIX is a unique ultra-large volume HPGe spectrometer**
- **Volume is 600 cm^3, Mass is 3.2 kg**
- **Relative detection efficiency is 160% and energy resolution is 2.2 keV @ 1332 keV**
- **Record ultra-low radioactive background level due to specially constructed individual multilayer passive shield**
- **Location: LSM (Modane, France, 4800 m.w.e.)**



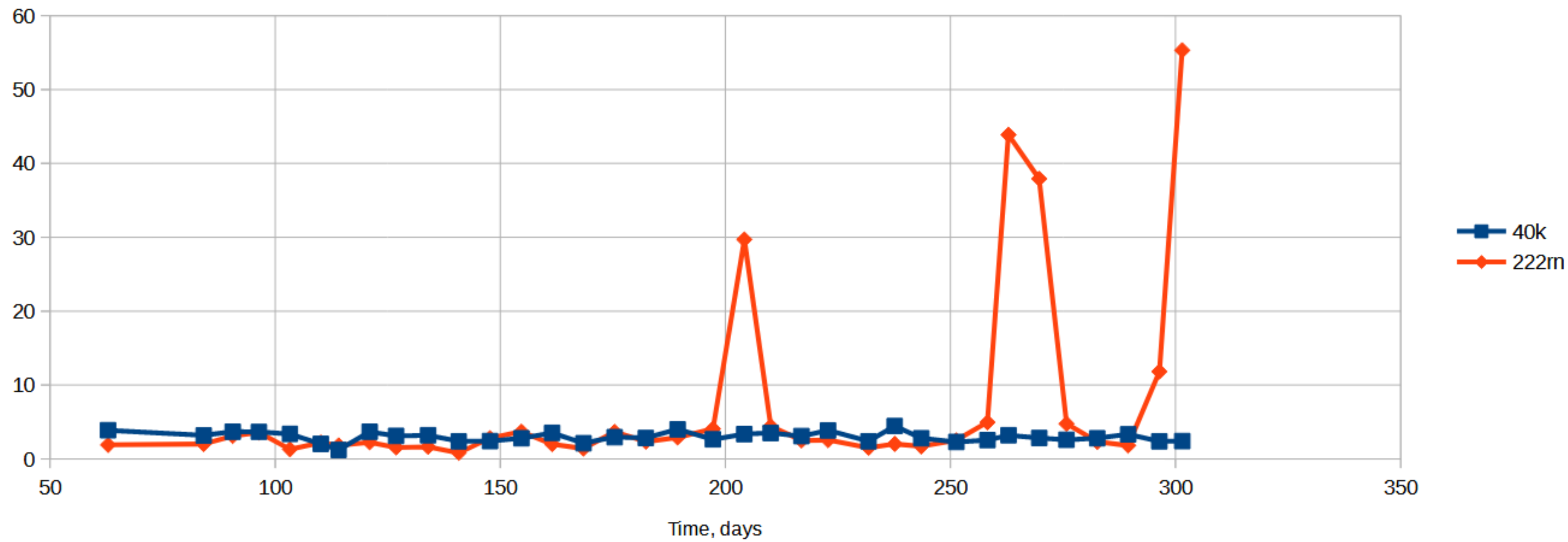
A source in Marinelli vessel with 6 kg of ^{82}Se was installed on OBELIX (October of 2021) for long-term measurements in order to search for double beta decay into excited states of the daughter nucleus ^{82}Kr, which have not yet been observed by anyone.



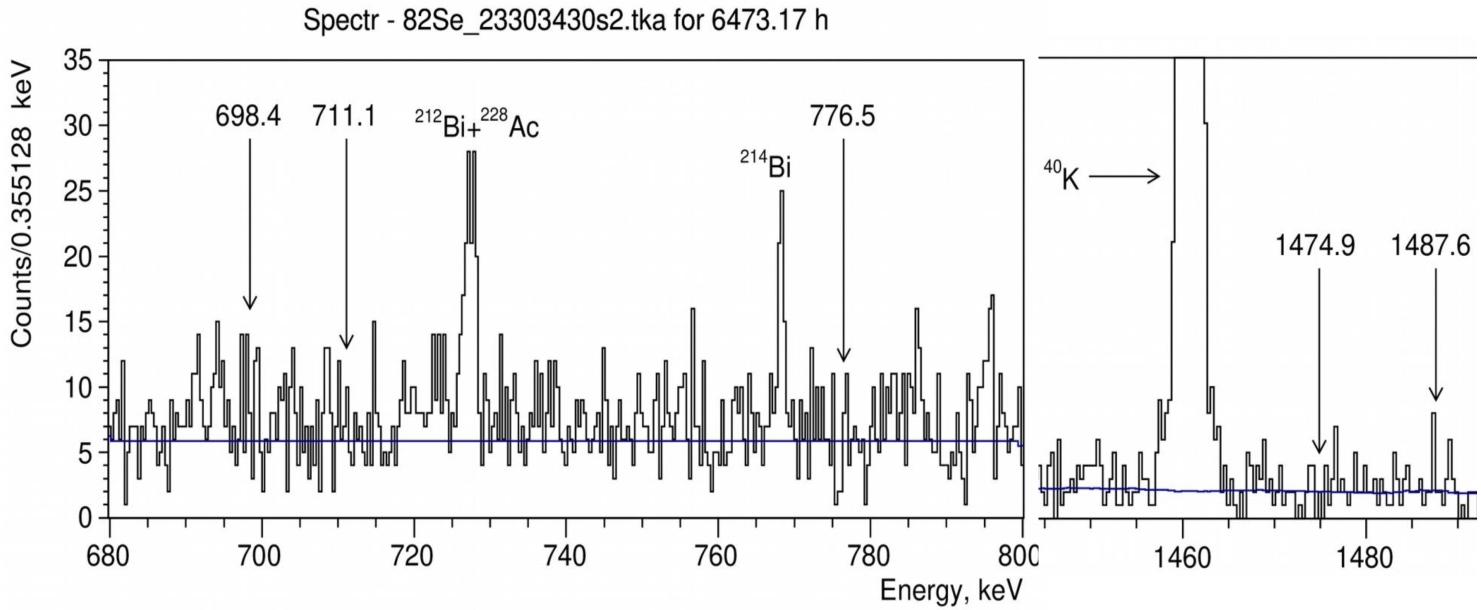


- **Theoretical expectations of transition to 0^+_1 exited state are at the level of $T_{1/2}$ ~ 5-7.5 x 10^{22} y (A. Barabash, F. Šimkovic).**
- **After 10 months of exposure, OBELIX has achieved this level of sensitivity!**

- Look at radon peaks (the sum of the 351 keV, ^{214}Pb, and 609 keV, ^{214}Bi, lines from the ^{222}Rn) we observe anomalous spikes.
- **The reason is unknown (open shielding, stop clean air flushing???), but it cost us a month of exposure, which we had to reject.**



Current results



- **No effect was observed in 12 months of measurement**
- **We reached sensitivity level $T_{1/2}$ ~ 5 x 10^{22} y (see the table below).**
- **Measurements are in progress to reach $T_{1/2}$ ~ 10^{23} y…**

Level	Gammas with efficiencies	Limit $T_{1/2}$ (90% CL), 10^{22} y		
		present	MPI	[1]
2^+_1 (776.5 keV)	776.5 (2.416%)	5.89	1.19	1.3
2^+_2 (1474.9 keV)	776.5 (1.341%)+1474.9 (0.756%)	4.53	1.02	1.0
0^+_1 (1487.6 keV)	711.1 (2.129%)	2.39	0.95	
	776.5 (2.076%)	5.06	1.10	
	711.1 (2.129%) + 776.5 (2.076%)	4.29	1.38	3.4

[1] J. W. Beeman et al., Eur. Phys. J. 75 (2015) 591.

- Long-term studies of rare processes continue on the OBELIX
- The sensitivity level of $T_{1/2} \sim 5 \times 10^{22}$ y for the double decay of ^{82}Se into excited levels has been reached on the OBELIX spectrometer.
- Within 2 years of additional measurements, it is planned to reach the level of $T_{1/2} \sim 10^{23}$ y.
- Radon is a serious problem, so protection and control is essential.

Main sources of the radon:

- Diffusion of the Rn from outside the detector
- Rn emanation of materials inside the detector.

What is needed:

- Rn detectors sensitive to ~0.1 mBq/m^3 – Rn detector
- Isolation of the detectors using thin foils, glue... with low radon diffusion coefficient - Rn diffusion apparatus
- Emanation measurements of parts inside the detector - Rn emanation apparatus

Radon activity measurement method	Detection limit
Charcoal trap method	0.05 Bq/m^3
Electrostatic collection method	1 mBq/m^3
Filter method	0.1 Bq/m^3
Liquid scintillation method	3 Bq/m^3
Bare method (solid flight trace detector)	5 Bq/m^3
Cup method (solid flight trace detector)	10 Bq/m^3
Scintillator cell method	20 Bq/m^3
Ionization chamber method	20 Bq/m^3

Rn detection (ultra-low concentrations)

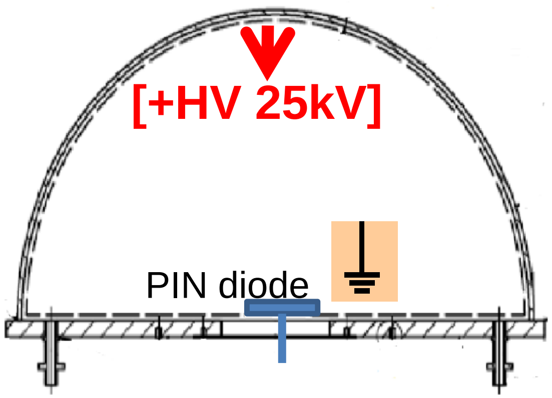
- hemisphere stainless steel, volume = 50L
- Electrostatic collection, PIN diode.

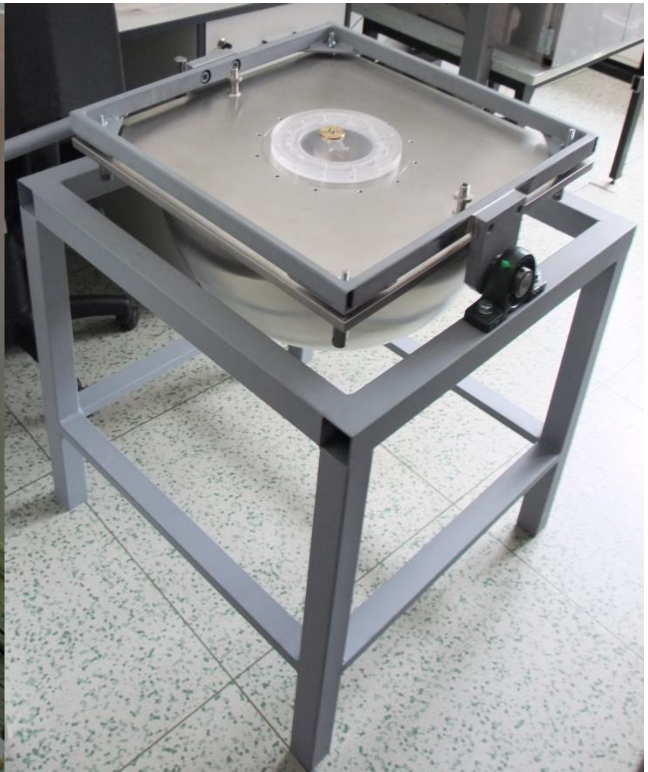
Results

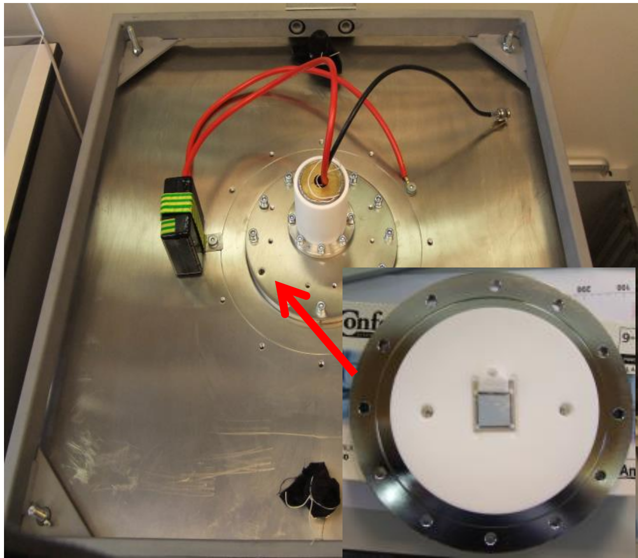
- HV = 12 kV, efficiency ~ 25%
- Measurement of background

Remark

- 1 mBq/m^3 means 86 decays of Rn in m^3 per day

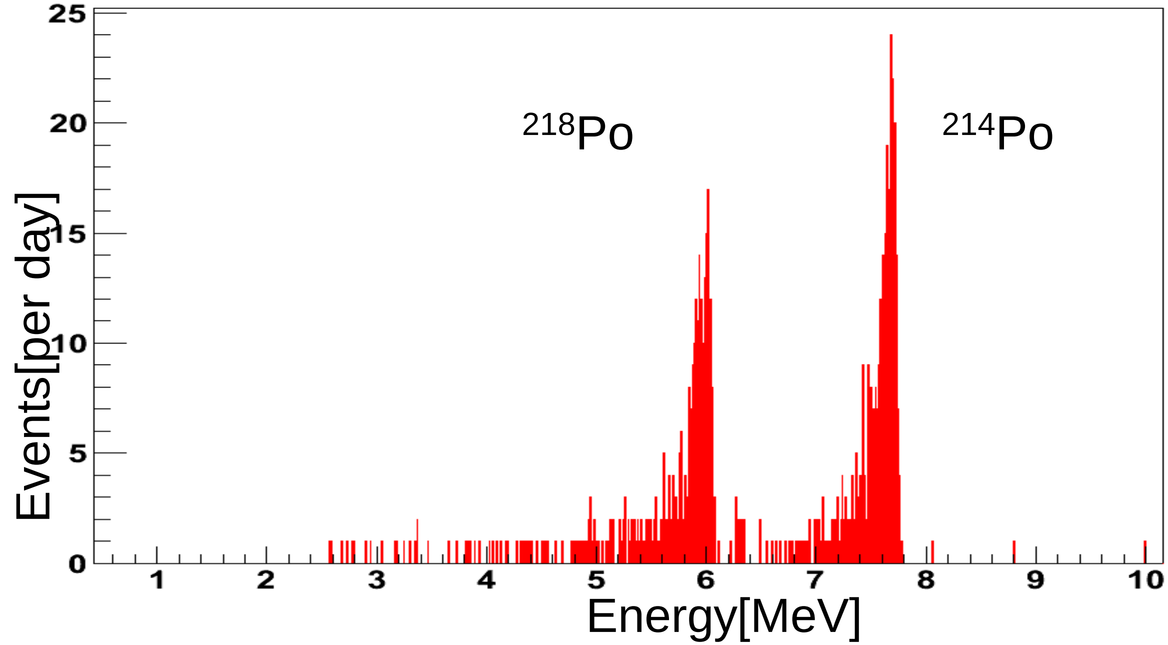


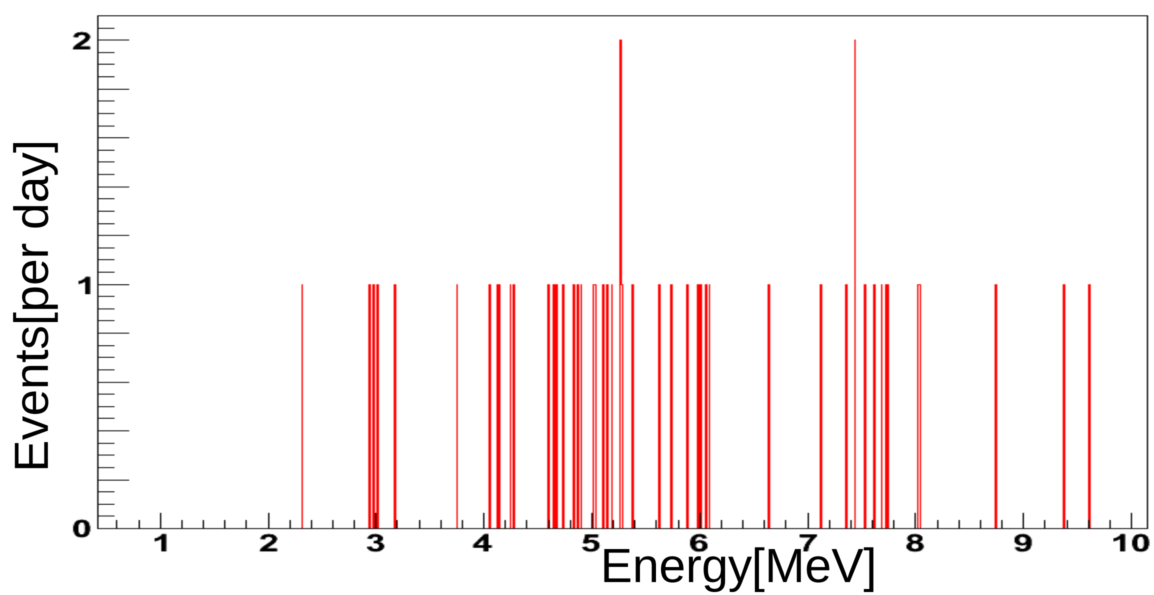




Energy spectrum measured at the beginning of background measurement (5 Bq/m^3)

Time of measurement [day]	Sensitivity [mBq/m^3]
1	11
7	3.5
30	1.6
75	1





Background after 2 months is 11±1 events/day in the ROI (6.2-7.8 MeV, ^{214}Po)

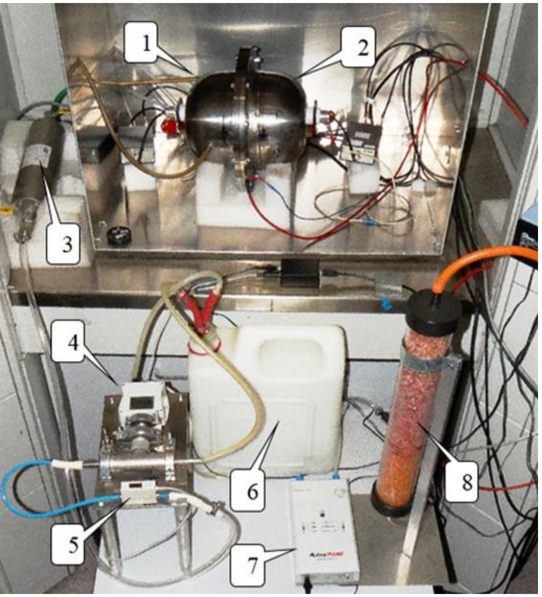
Honeycomb Rn detector (Volume 300 L = 6 ×50 L)

- HV (-7 kV) – noise at 150 keV, Efficiency of ~ 33%
- Stainless steel thickness - 2 mm
- Background of construction materials: $^{226}Ra < 0.1$ Bq/kg
- Software, simultaneously data analysis (6 detectors)
- Expected sensitivity of the Radon detector ~ mBq/m^3

Radon concentration line

- ✓ Adsorbent – active charcoal K48
- ✓ Adjustable temperature of adsorbent – cooling up to - 180 °C
- ✓ Disadsorbtion of Rn from adsorbent – heating up to +135 °C
- ✓ Expected sensitivity ~ 10 μBq/m^3

Radon diffusion apparatus

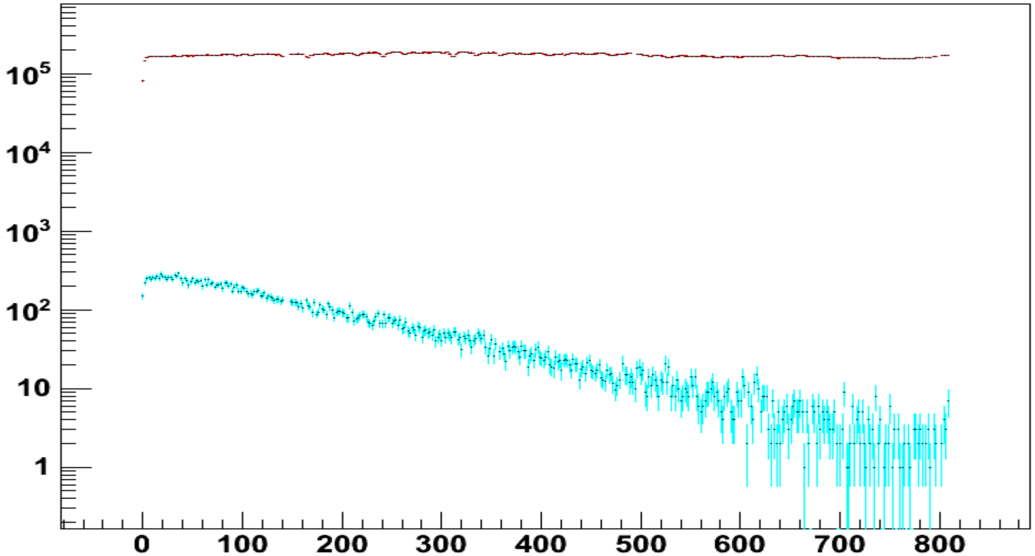


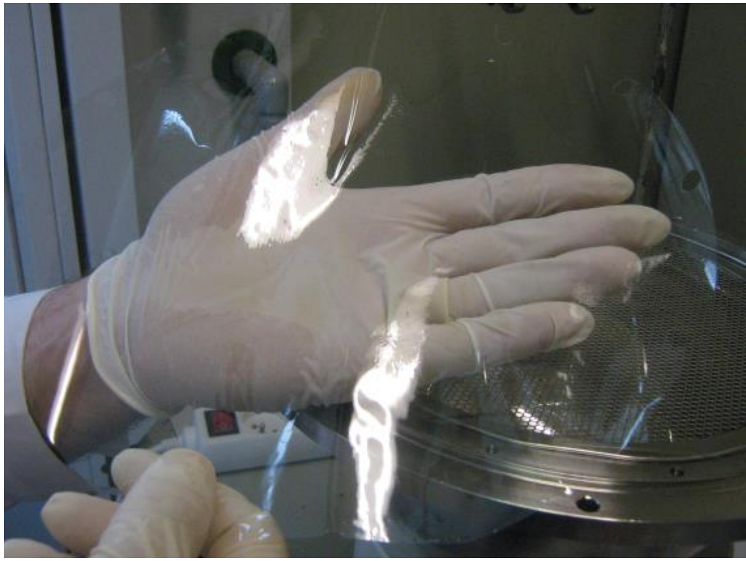
2 hemispheres separated by tested material foil (left hemisphere with high Rn activity, *38 kBq/m³*; Rn penetrates into right hemisphere*)*

1/2 - Left/right vessel; 3 - Radon source; 4 - Sensors of temperature, humidity, and pressure; 5 - Flow-meter; 6 - Air buffer; 7 - Air pump, 0.34 L /min; 8 - Air dryer

Measurement of Rn diffusion through 50 µm NYLON film

Rn suppression factor C1/C2 > 76 500; **Diffusion coefficient** D $=4.7\cdot10^{-16}$ m^2s^{-1}

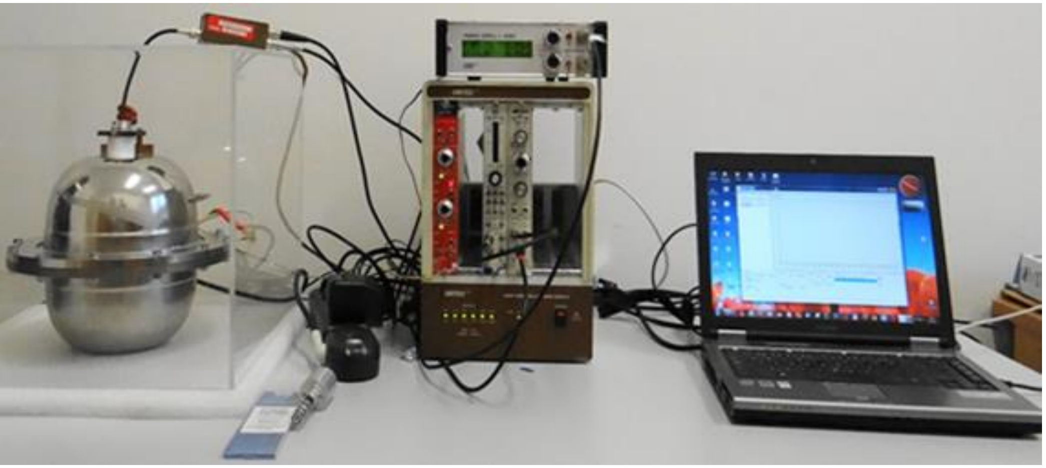


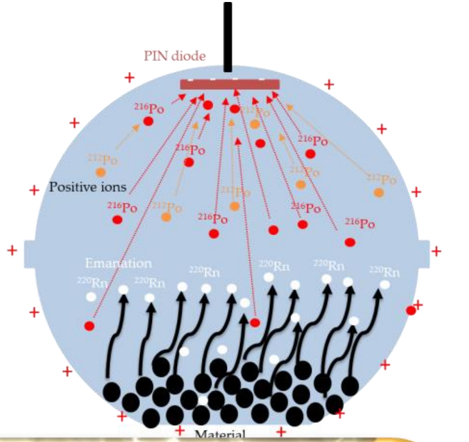


Summary of results for different materials (foils) for the SuperNEMO detector from the radon-tightness point of view.

Foils	Thickness [μm]	C1/C2	C_1/C_2 normalized to 15 μm	Diffusion coefficient D [10^{-12} m^2s^{-1}]	Diff. length L [μm]
HDPE (2 layers)	2×144	3.5	1.1	19	3 000
TROPAC III	102	> 8 300	> 600	< 0.0043	< 46
TROPAC junction	102	> 6 300	> 500	< 0.0051	< 50
Bovlon film	0.015	4.0	4.0	0.84	633
Mylar (2 layers)	2×20	> 9 100	> 2 300	< 0.0012	< 24
Mylar junction	20	110	85	0.030	120
EVOH (2 layers)	2×15	> 31 000	> 8 900	< 0.00035	< 13
EVOH + PE	125	165	20	0.013	254
Nylon	50	76 500	6 380	0.00047	15
PET	1 000	> 41 136	> 35	< 0.076	< 190

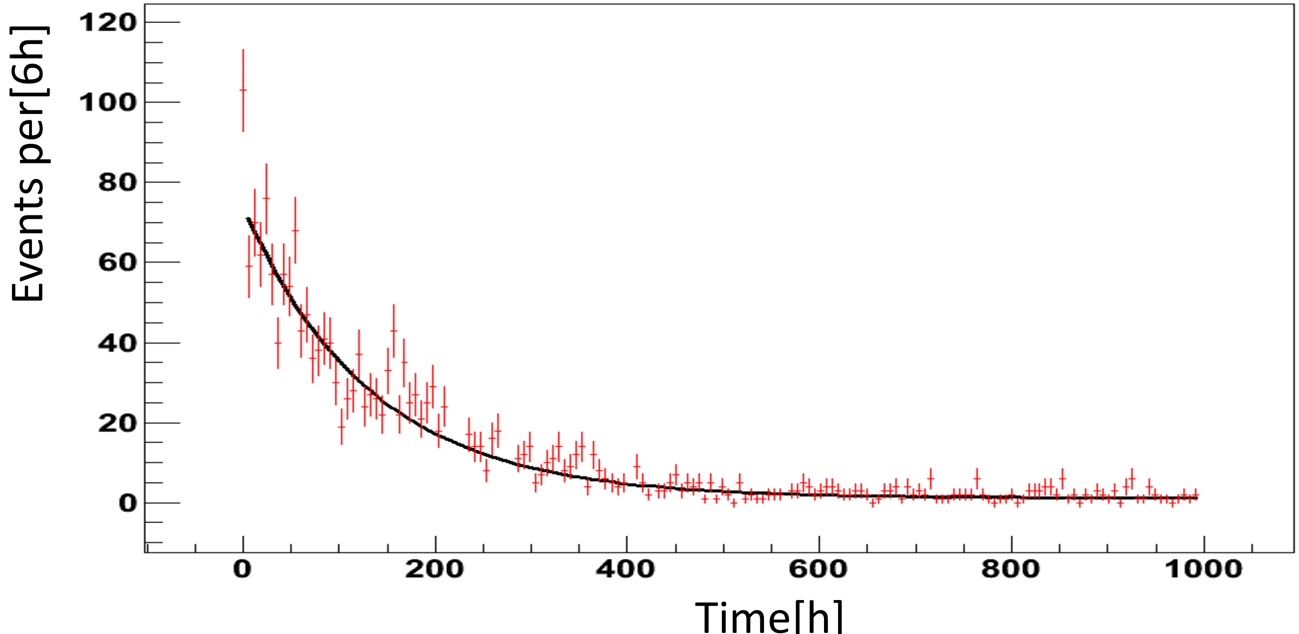
Apparatus for measurement of Rn emanation





Measurements of Rn emanation from glass pellets

Rn from glass pellets < 1.3 x 10^{-9} Bq/kg/s



Suppression of Rn from air

Radon trapping on charcoal => Radon decays during trapping

reduction factor 100 => „retention time" T = 606 hours (~ 25 days)

T (hours) = K (m^3/kg) * m (kg) / f (m^3/hour)

T – retention time of Radon in charcoal; m – mass of charcoal

f – flux of gas

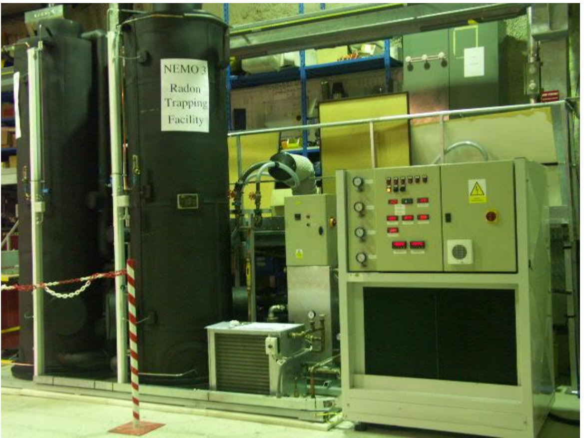
K – depends on charcoal type, temperature, pressure (J. Busto, CPPM):

t (°C)	20	0	-30	-40	-50	-60
K(m^3/kg)	4	12	53	78	152	272

A(222Rn) in LSM ~ 10-20 Bq/m^3

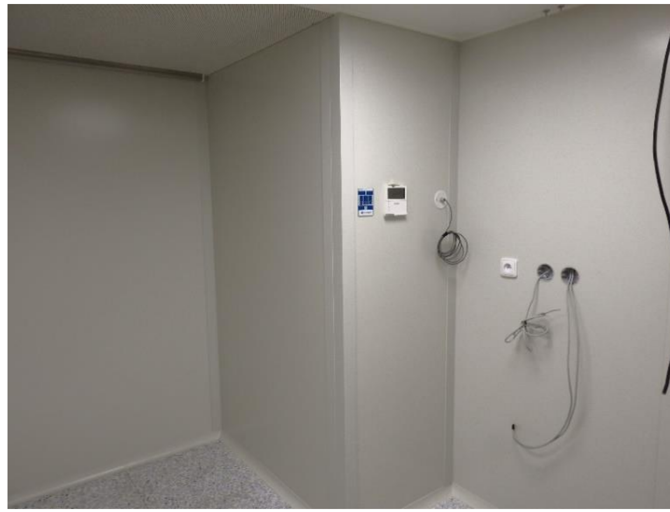
Antiradon setup: 500 kg charcoal @ -50°C, 7 bars

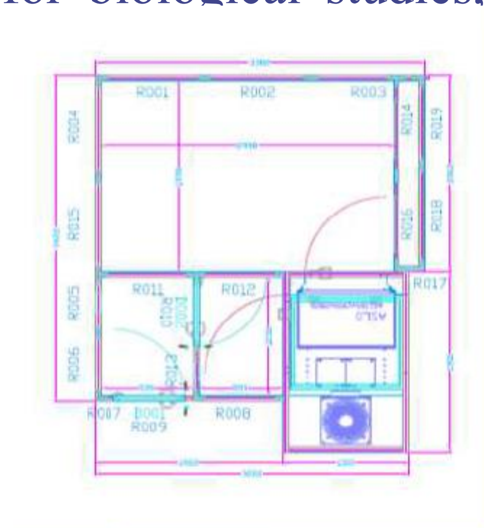
Activity: A(^{222}Rn) < 10 mBq/m^3 !!! Flux: 150 m^3/h (produced by ATEKO company, Czech Republic)



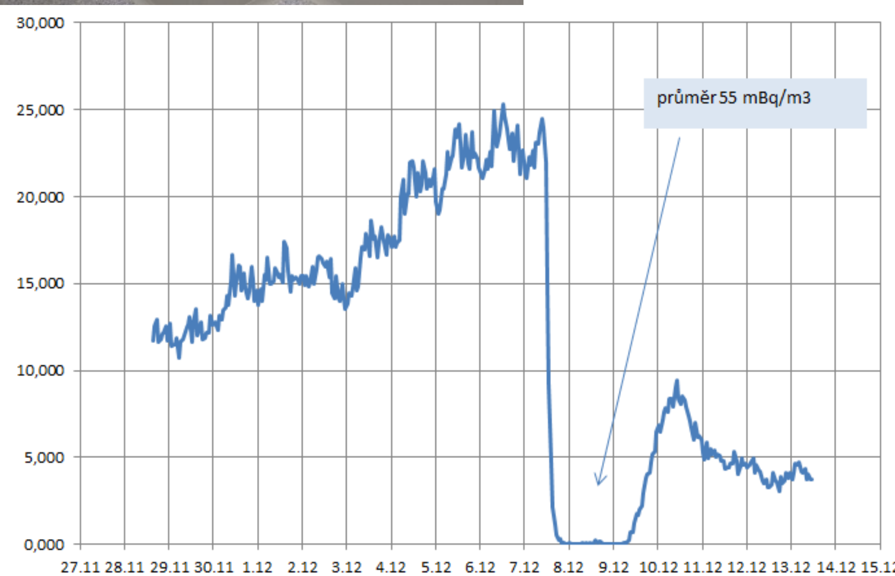
Clean rooms in SURO and LSM (ISO 5, zero-dose environment)

- Anti-radon system and clean room (ISO 5) is installed in SURO and in LSM
- Suppression of all types of radioactivity (including Radon) for biological studies, preparation of detectors, enriched foils…..

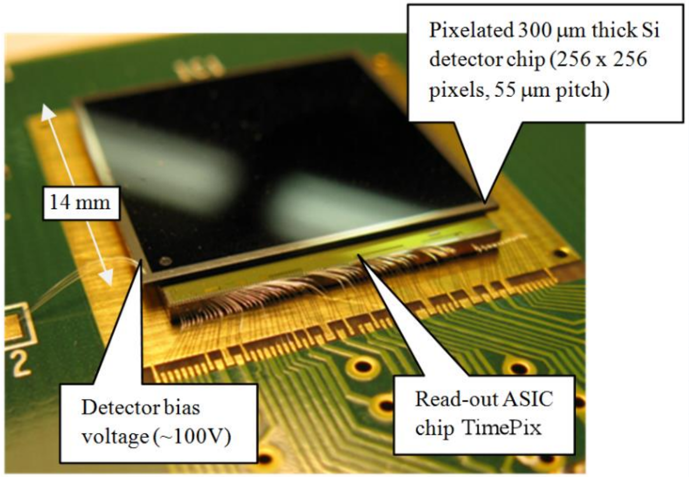


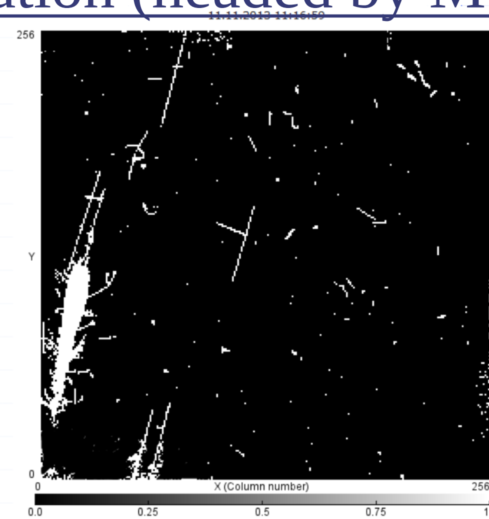


3) v čisté místnosti po finálním
vzduchu (20 m3/h) dne 7.12.



Medipix/Timepix collaboration (headed by M. Campbell, CERN):





e.g. Timepix3

Each pixel can be configured to operate in different mode independently to other pixels

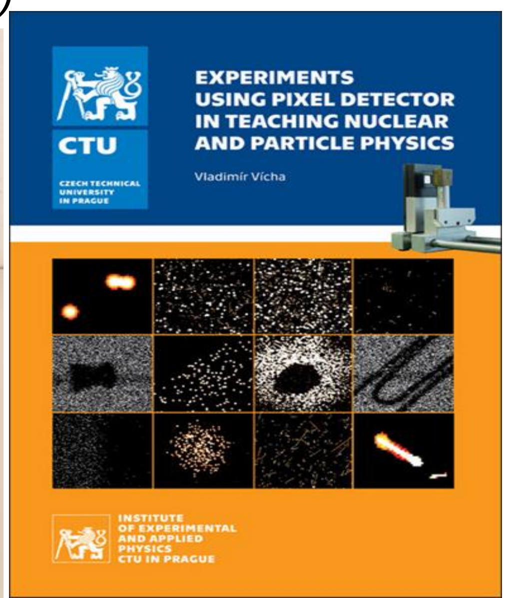
Measuring Energy (TOT, dead time per pixel 475 ns) and Time-stamping (TOA, 1.56 ns) simultaneously

Readout modes: a) Frame-based mode (max~1300 fps); b) Data-driven mode (~40Mhits/s), dead time per pixel min. 475ns

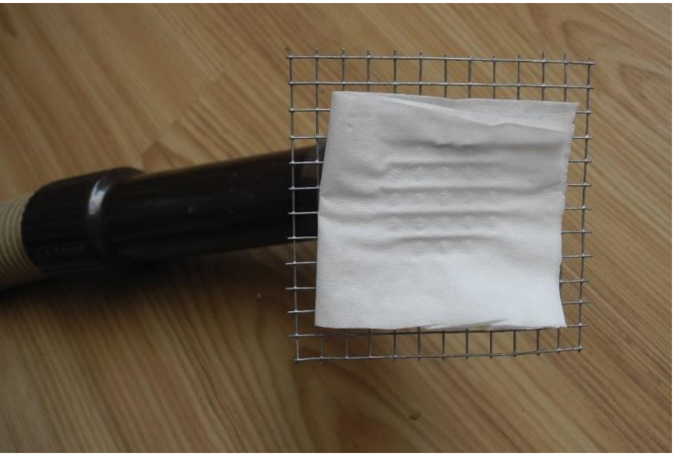
Output data: up to 8 serial lines, 640MHz => max. data rate= 5.12 Gbps

SESTRA - **S**chool **E**ducation **S**et with **T**imepix for **R**adiation **A**nalysis

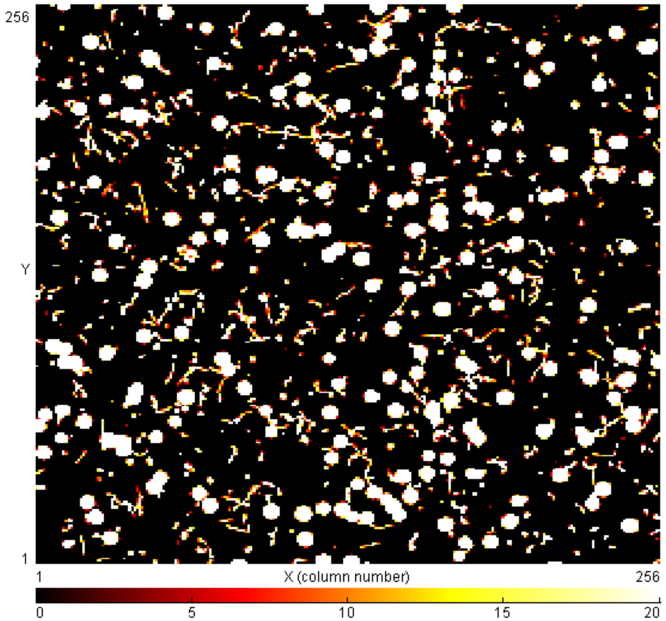
- Particle Camera MiniPixEDU
  (Timepix detector, calibrated)
- Control Software
  Pixelman Simple preview & Pixet basic
  (acquisition, online visualisation, etc.,)
- Alfa source
  (241Am, α and γ source, 9.5 kBq)
- Gamma source
  (241Am, γ source, 300 kBq, optional)
- Potassium Salt
  (β and γ source)
- Thoriated Tungsten Electrode
  (α, β and γ source)
- Uranium Glass *(α, β and γ source)*
- Mounting Rails
- Source Holder
- Camera Holder
- Aluminium, Stainless, Copper, Brass and Lead Shielding Plates
- Radiography Adapter Head
  +Samples with Hidden Patterns
- Vacuum Cleaner Grate Adapter
- USB Cable
- Book of detailed guidelines
  "Experiments Using Pixel Detector in Teaching Nuclear and Particle Physics"



DEMONSTRATION OF BACKGROUND RADIOACTIVITY CAUSED BY RADON

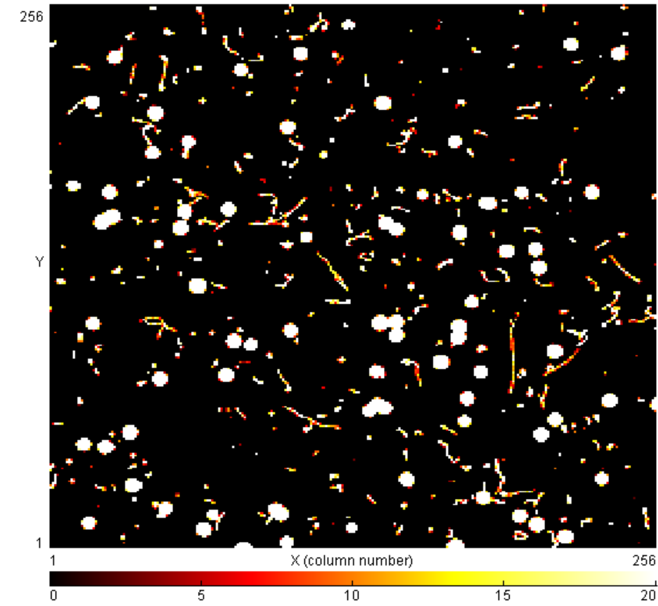


Visualizations of the Rn caused radioactivity of the paper tissue used as an air filter at home. The filtering took 5 minutes and exposure time was 10 minutes in both cases.



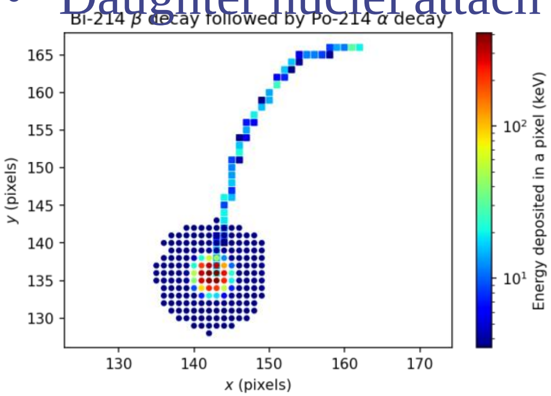
Not-ventilated (left) room

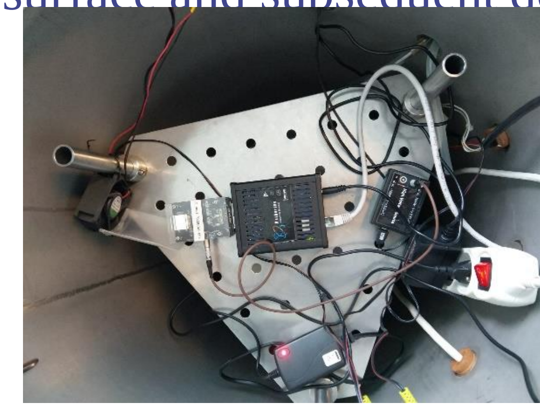
Ventilated (right) room

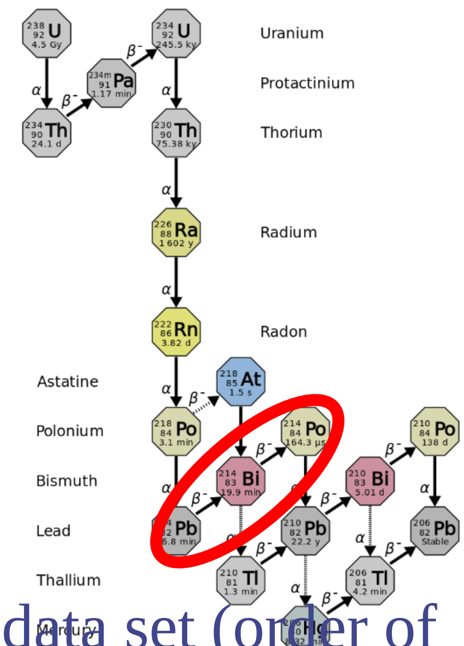


Measurement of half-life time of Po-214 (also Po-212) with high precision using TPX3 detector (student J. Jelínek)

- Measurement was done in SURO, Timepix3 into barrel with high activity of Rn-222 (units to tens of MBq m^{-3}) for 140 hours
- Daughter nuclei attach to Timepix3 surface and subsequent decays were observed







The overal result of measurements is:

$$T_{1/2} = 163{,}565 \pm 0{,}034(\text{stat}) \pm 0{,}022(\text{syst})\ \mu\text{s}$$

Other recent experimental values:

$T_{1/2} = 163{,}58 \pm 0{,}29(\text{stat}) \pm 0{,}10(\text{syst})\ \mu\text{s}$ (Bellini et al., 2013)

$T_{1/2} = 163{,}47 \pm 0{,}03\ \mu\text{s}$ (Alexeyev et al., 2020) – no proper error discussion

Spatial resolution of Timepix3 allowed to collect large data set (order of 10^7 events) in short time (approx. 6 days) while maintaining reasonable signal to noise ratio.

Millennium Institute for Subatomic Physics at the High Energy Frontier, SAPHIR is based on the similar way and it looks that you are going on proper way in science:

- Instrumentation R&D
- International cooperation based on reciprocity
- Precisely defined responsibility of your team in the collaborative research
- Support of local research infrastructure
- Strong theoretical team.

<u>Posssible areas of cooperation:</u>

1) Detector technologies (scintillating detectors, strip, pixel…)

2) Deep underground laboratories (ANDES – technologies of ultra-low background)

3) Space (payloads based on pixel detectors, Chile has ambitious program to space)

4) Detection of radiation (HPGe spectroscopy)

Thank you for your attention

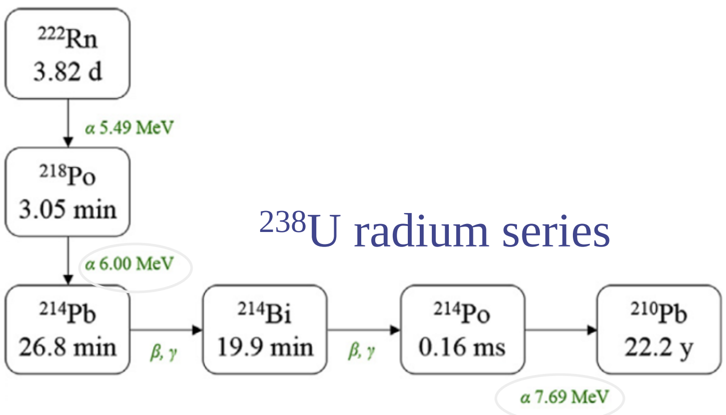
Radon

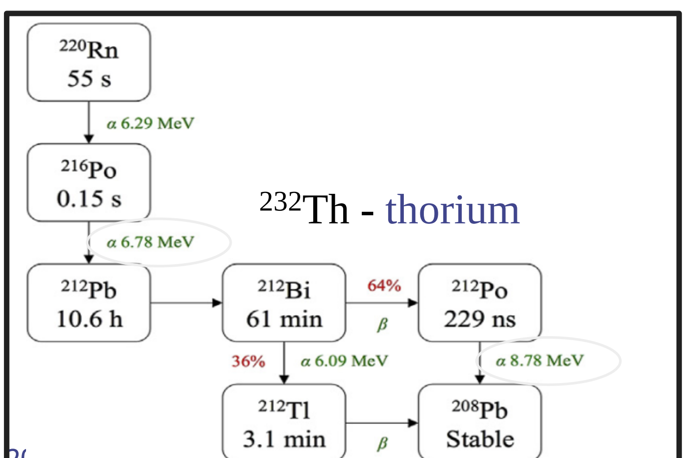
There are three decay "chains" that occur in nature:

1. the uranium series, beginning with ^{238}U,
2. the thorium series, which originates with ^{232}Th,
3. the actinium series, which originates with ^{235}U.

Radon

- Inert noble gas,
- belongs to the ^{238}U chain (present in any material),
- high diffusion and permeability
- wide range of energy of emitted radiation (with the daughters),
- surface contaminations with radon daughters (heavy metals),
- broken equilibrium in the chain at ^{210}Pb level.





Radon ^{222}Rn and its daughters form one of the most dangerous source of background in many experiments

Author	Isotope		Time of delay [s]	Relative humidity	Charge [%]		
					Pos+	Neg-	Neutral
Renoux (1965)	^{218}Po	air filter	180	standard air	81.5		18.5
Rabbe (1968)	^{218}Po	air	330	13 & 33			100
Postendorfer (1979)	^{218}Po	air	at the time formation	≥ 95	88		12
Dua (1981)	^{222}Rn progeny	air	0.046	16-19	90.8	3.9	5.30
Dankelmann et al. (2001)	^{218}Po	air filter	120	50	49		51
Postendorfer (2005)	^{214}Po	air	-	30-95	48		52
	^{214}Pb				45		55

Different experimental results of radon decay progenies charge obtained by different authors

Detector "Obelix" (JINR/IEAP CTU/LSM)

P type coaxial HPGe detector (U-type ultra low background cryostat located at LSM (4800 m w.e.)

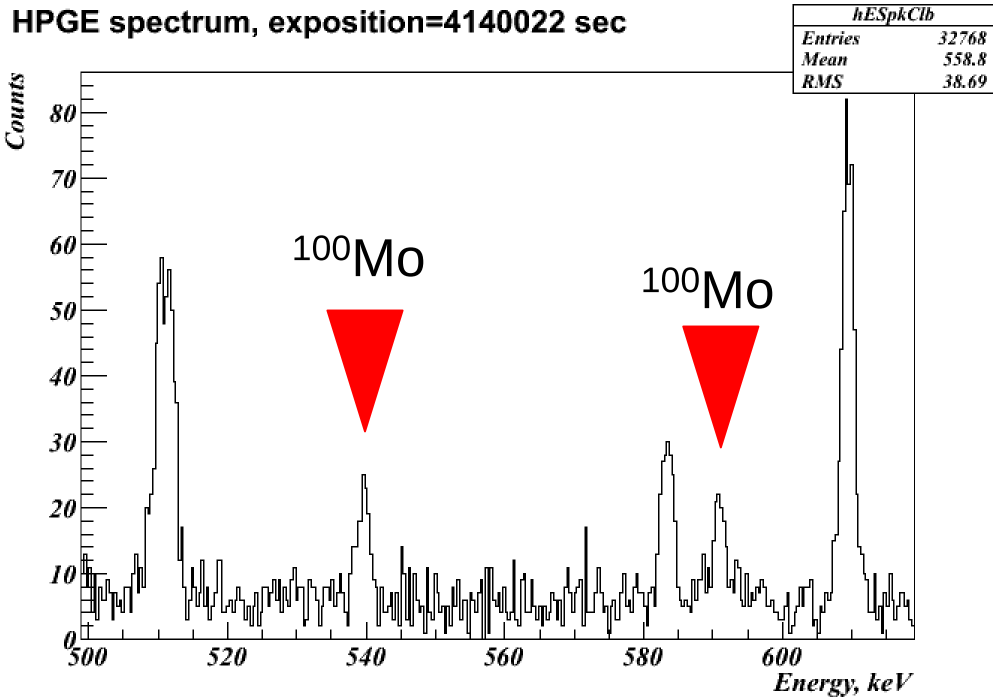
Sensitive volume 600 cm^3 Efficiency 162%

Energy resolution ~1.2 keV at 122 keV (^{57}Co), ~2 keV at 1332 keV (^{60}Co)

12 cm of arch. Pb, 20 cm of low active Pb, Radon free air

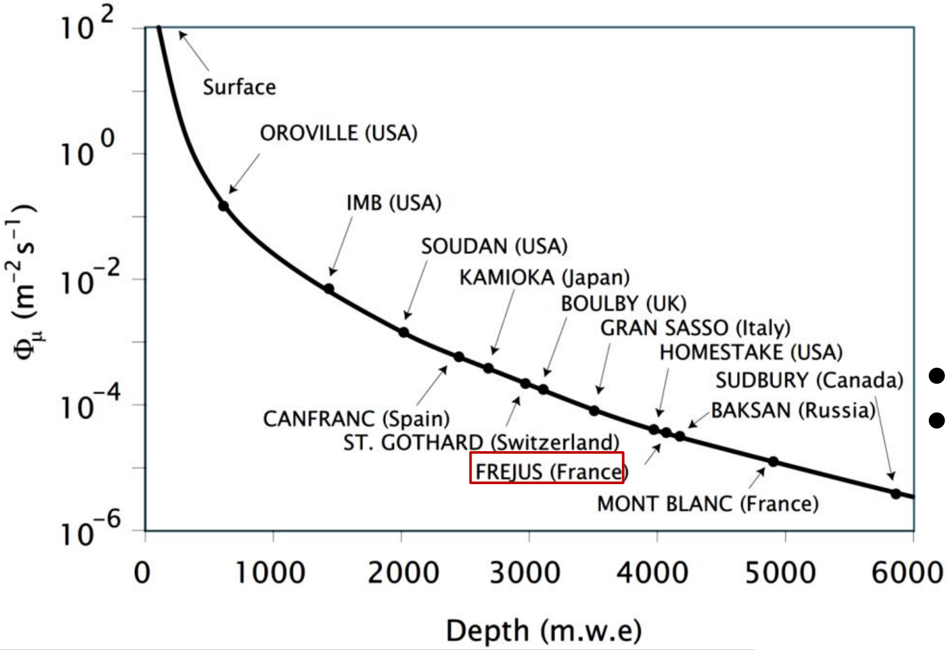
Process	$T_{1/2}$ [years]
$2\nu2\beta^-$ decay to 0^+_1 [1130 keV]	7.5×10^{20}
$2\nu2\beta^-$ decay to 2^+_1 [540 keV]	$> 2.5 \times 10^{21}$

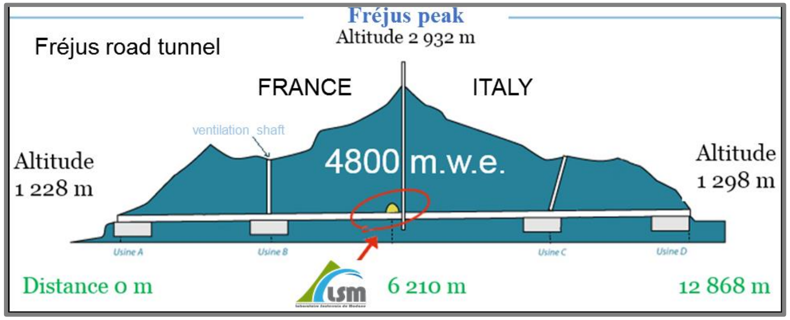
- **Mass of ^{100}Mo – 2517,15 g**
- **Total measurement time – 2288 h**



The price of such detector is 250 kEUROs => you need international cooperation

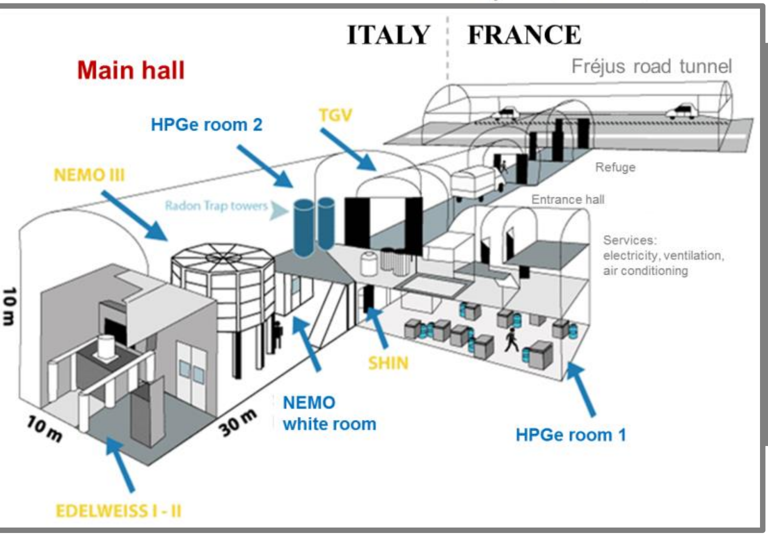
Laboratoire Souterrain de Modane





- Road tunnel Fréjus (France – Italy border)
- Depth of ~ 4800 m.w.e. (muon suppression factor ~ 10^6)

    - Muon flux: 4×10^{-5} μ.m^{-2}.s^{-1}
    - Neutron flux: 4×10^{-2} n.m^{-2}.s^{-1}(fast); 1.6×10^{-2} n.m^{-2}.s^{-1} (thermal)
    - Radon: 15 Bq.m^{-3}

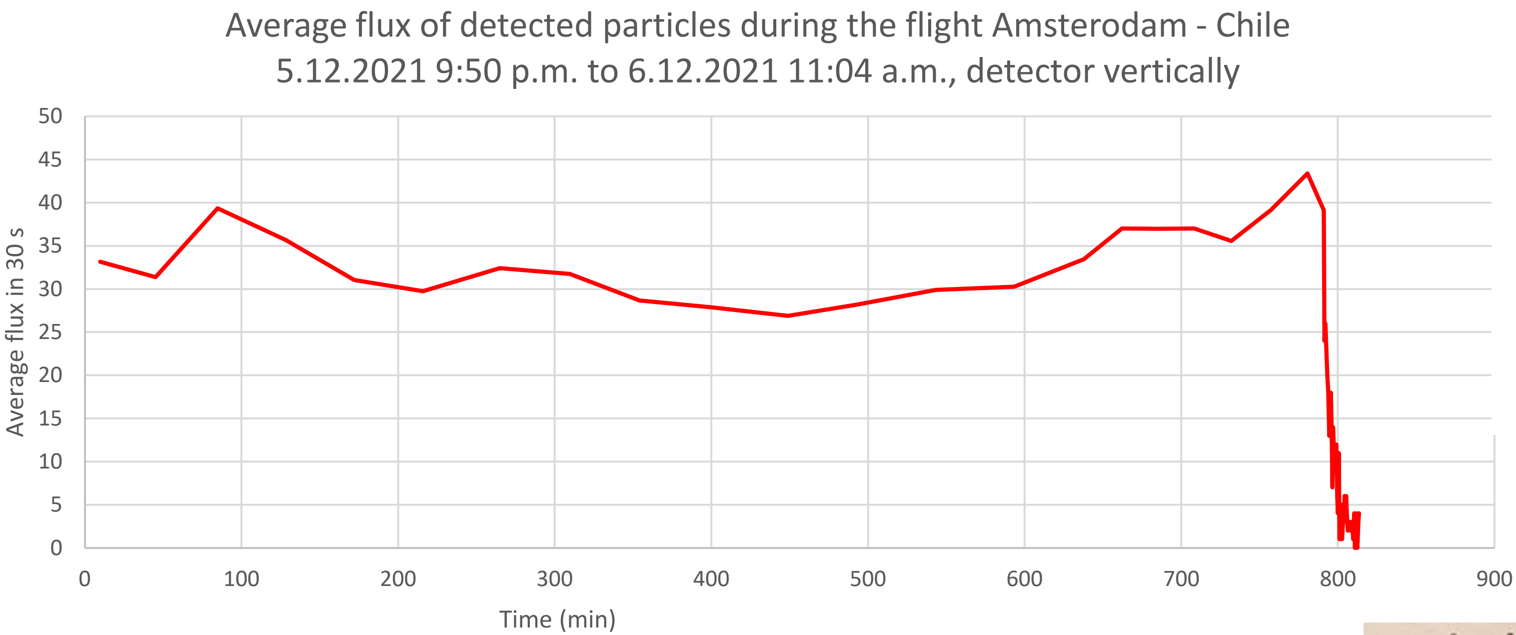


Main hall

HPGe room 1

Flight Amsterodam – Santiago, 5. - 6. 12. 2021

Measurement by pixel detector during flight (only during take-off it was impossible)



a) 1st local maximum: appr. 80 minutes after take-off (11 p.m.)

b) 7 hours flux is relatively stable

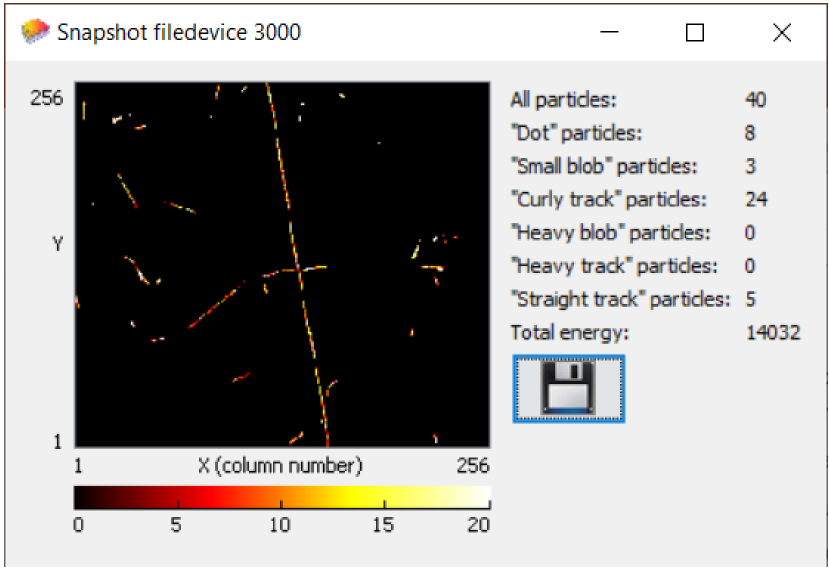
c) After 600 minutes of flight (8:30 a.m.) flux is increasing. The second maximum is in time 730-780 minutes of flight (10 a.m.- 10:50 a.m.)

d) Landing is clearly visible

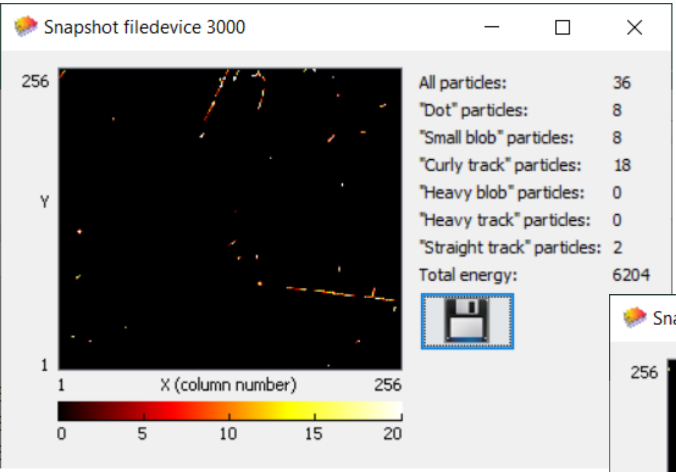
Detection of muons during flight:

In vertical position: total number 674 (1 per 45s)

In horizontal position: total number 169 (1/170s)

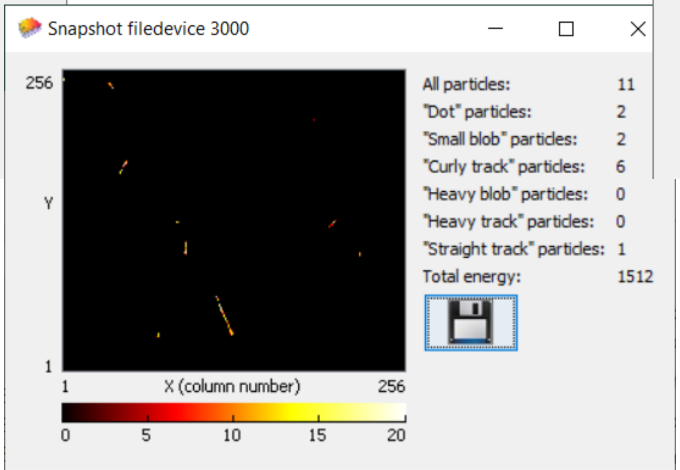


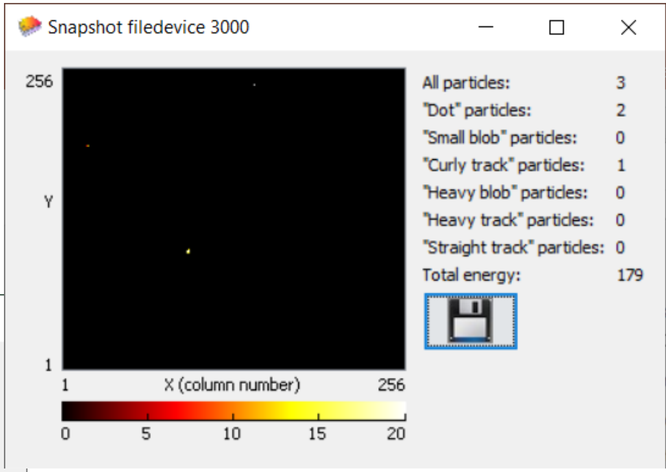
Measurements during landing (last 36 minutes) – decreasing of flux is clearly visible



Time before landing = 36 minutes

Time before landing = 18 minutes





Time before landing = 3 minutes

Experiments in high radiation environment: i) activities in space, ii) LHC (MoEDAL, ATLAS-TPX)

International Space Station | In orbit since 3Q 2012 | 380 km

5 Timepix-Lite detectors placed on ISS since 2012 (collaboration with NASA and the University of Houston).

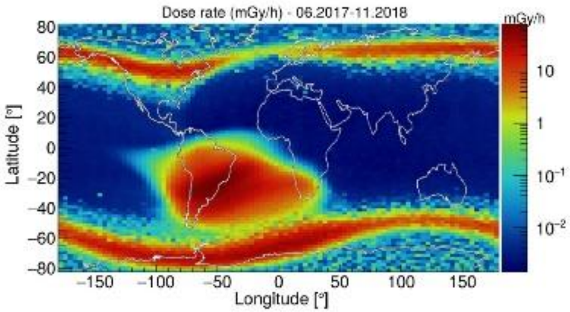
USB-Lite interface developed at IEAP.

ESA Proba V satellite | Launched 7th May 2013 | 820 km

SATRAM module with Timepix detector onboard ESA satellite Proba-V.

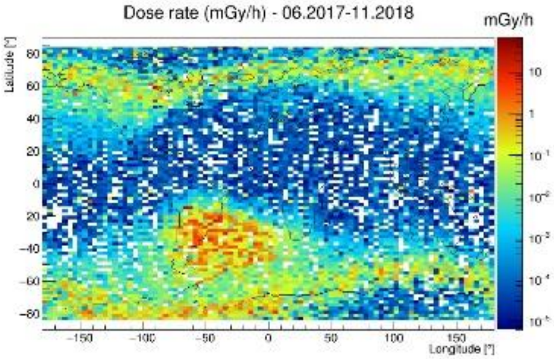
Characterization of space radiation at LEO. TPX in open space.

Developed by IEAP and BD Sensors.



SATRAM

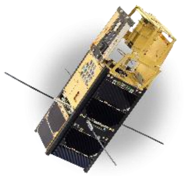
detector life time: ≈ 340 days



VZLUSAT-1

detector life time: ≈ 11 hours

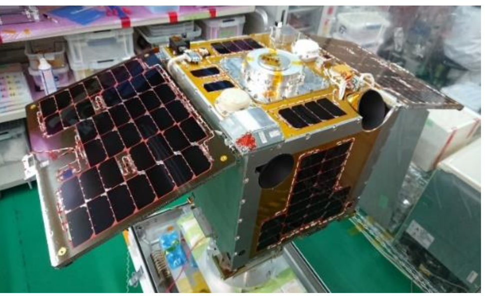
VZLUSAT-1 | Launch 2017 | 500 km



Timepix detector as part of miniature X-ray telescope onboard VZLUSAT-1 cubesat since 2017.

The first Czech satellite since 1996.

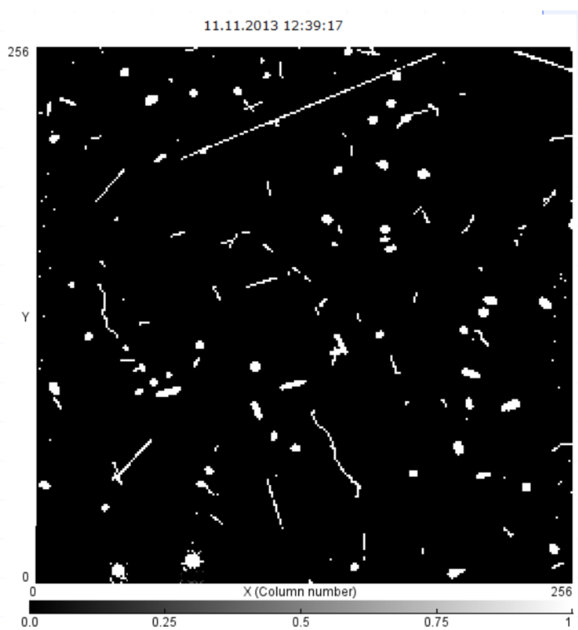
RISESAT satellite | Launch 2019 | 500 km

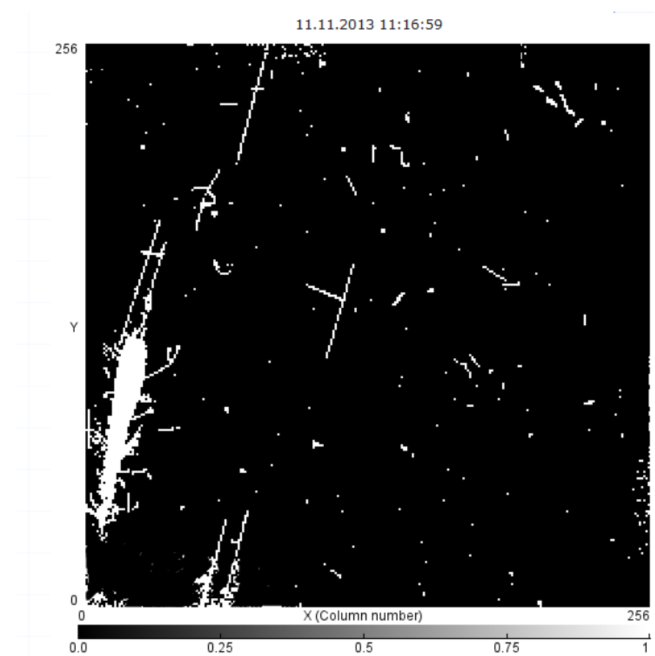


東北大学
TOHOKU UNIVERSITY

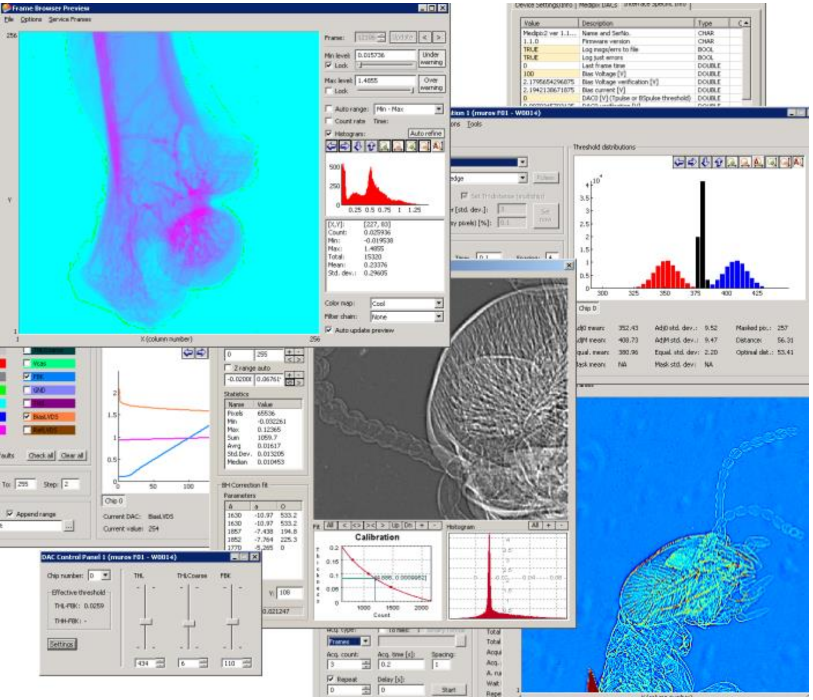
Japanese microsatellite RISESAT (Rapid International Scientific Experiment Satellite); dimensions 50x50x50 cm, weight ~50 kg

Development led by Tohoku University and Hokkaido University





Data Acquisition Control Software



PIXELMAN – *IEAP CTU*

Acquisition and control tool for Medipix & Timepix detectors

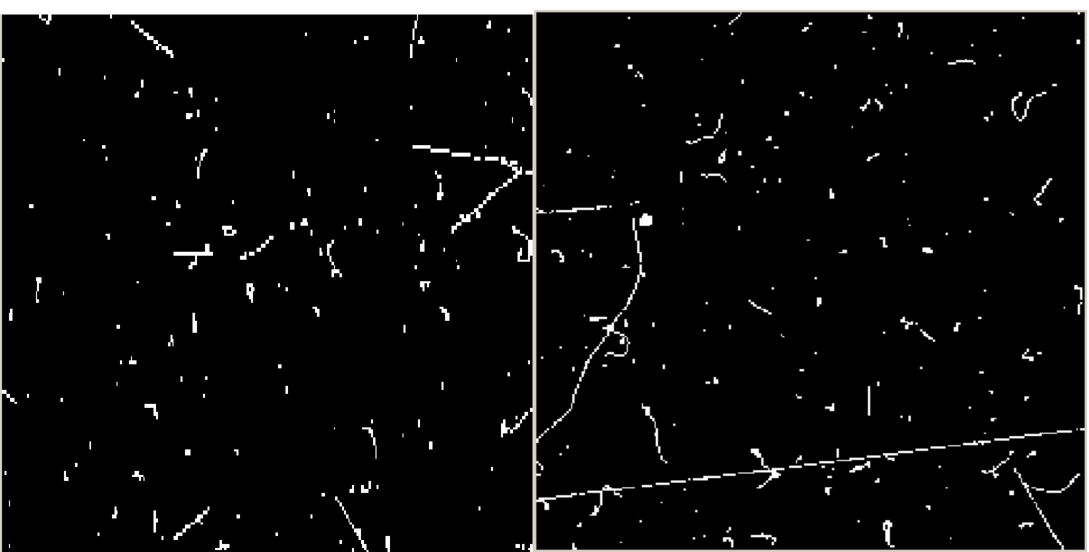
PIXET - *ADVACAM*

Acquisition and control tool for Timepix & Timepix 3 detector

J-PIX – *IEAP CTU*

Acquisition and control tool for Timepix 3 detector currently under development fully designed in Java to be multi-platform

Typical response of Timepix device to natural background radiation:



Clearly recognizable tracks and traces of

- X-rays
- electrons
- alpha particles
- muon
- electron-positron pair, … .