TREX-DM experiment at LSC: status, prospects and low-energy calibration

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StG-2009: T-REX

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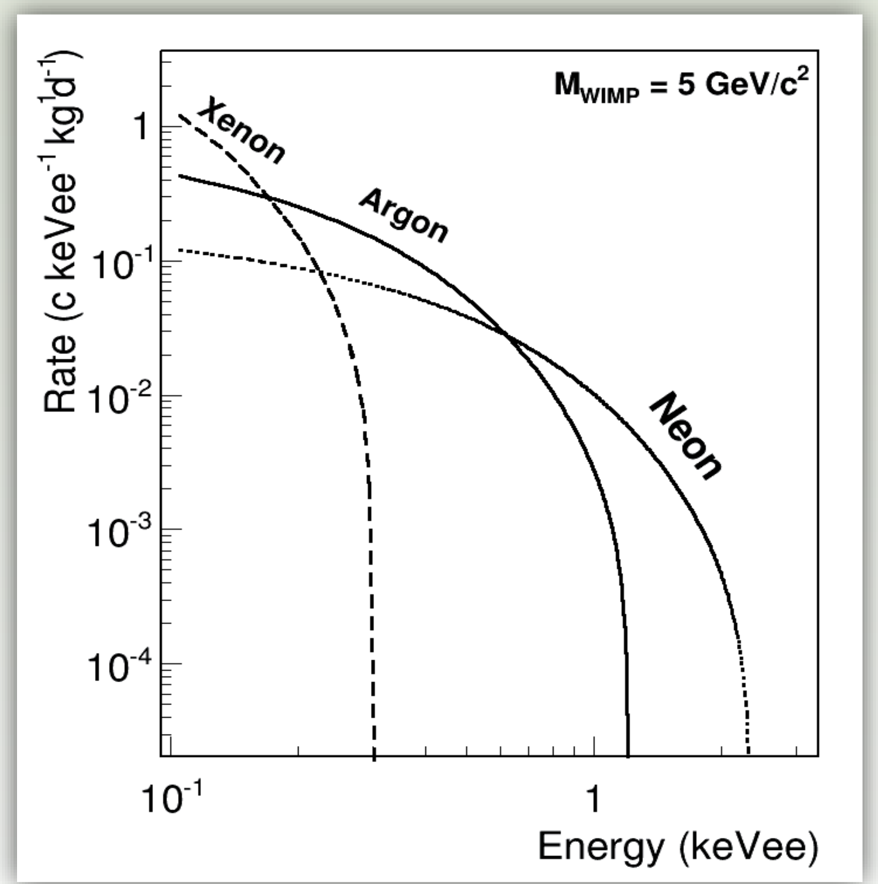
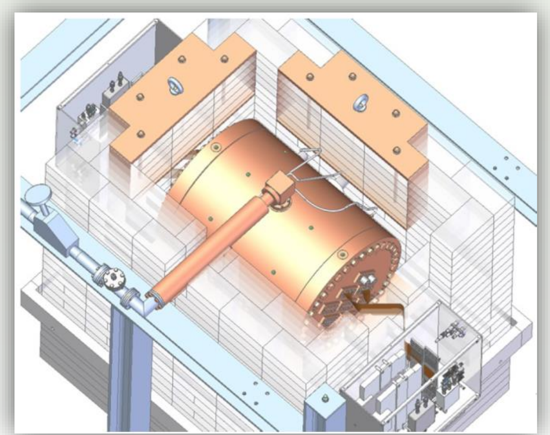
Motivation

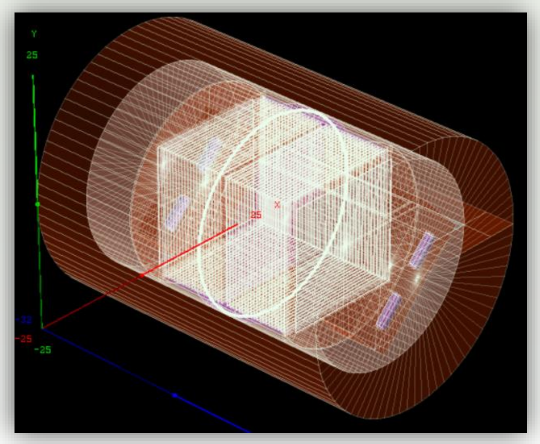
- Dark Matter searches focused on WIMPs are gradually shifting to very low masses (**< 10 GeV/c²**)
- To successfully explore this mass region in direct searches, we need:
  - **Light** nuclei as target
  - Very **low** energy **threshold** (< 1 keV_{ee})
  - **Low background** level

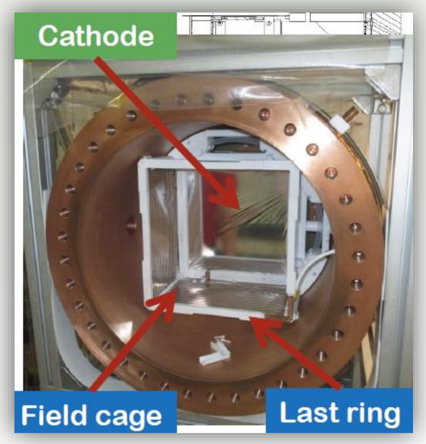


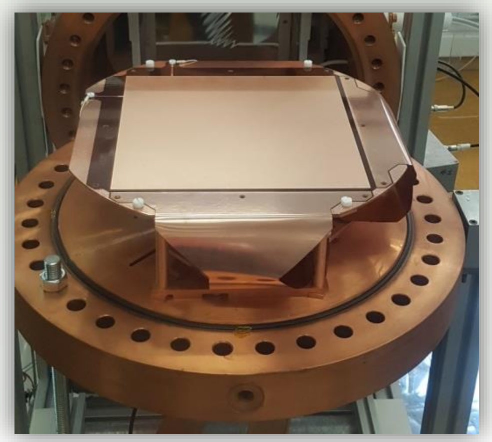
TREX-DM

- **TREX-DM** is an experiment conceived to look for **low-mass WIMPs**
- Gas TPC (cylindrical **copper vessel**) holding **~ 20 liters** of pressurized gas: **~ 0.3 kg Ar** or **~ 0.16 kg Ne @ 10 bar**
- Using novel Micro-MEsh Gaseous Structure (**Micromegas**) readouts
- Located at the Canfranc Underground Laboratory (LSC) with a depth **~ 2400 m.w.e.**

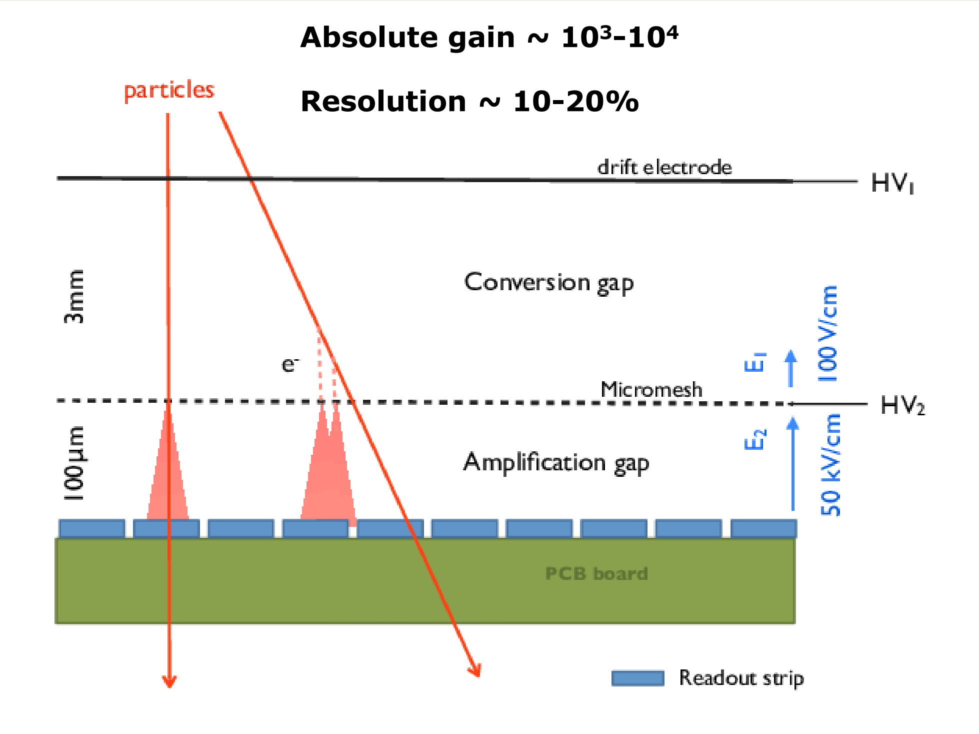


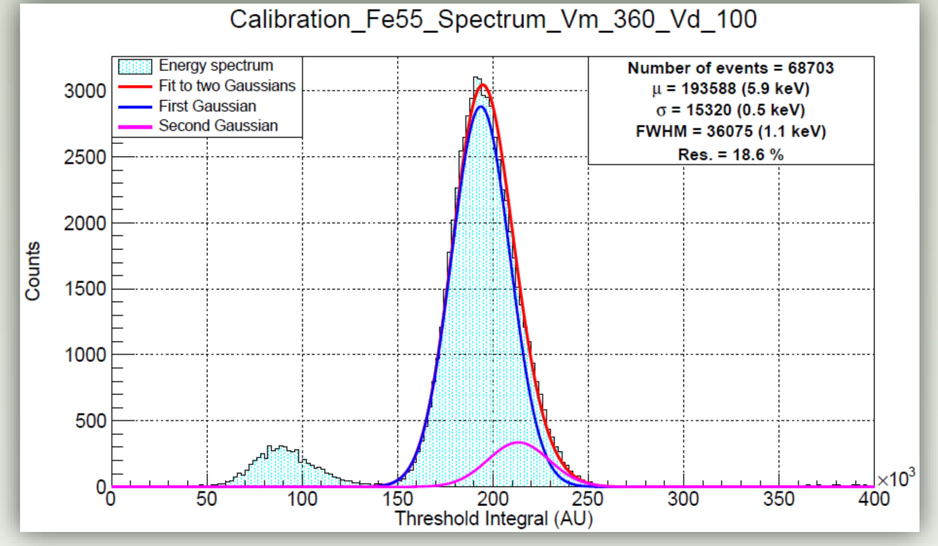




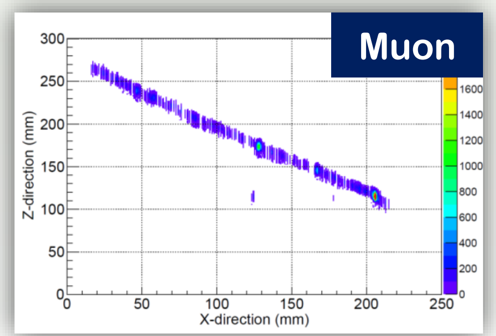


Detector: Micromegas





25 x 25 cm^2 TREX-DM fabricated at CERN

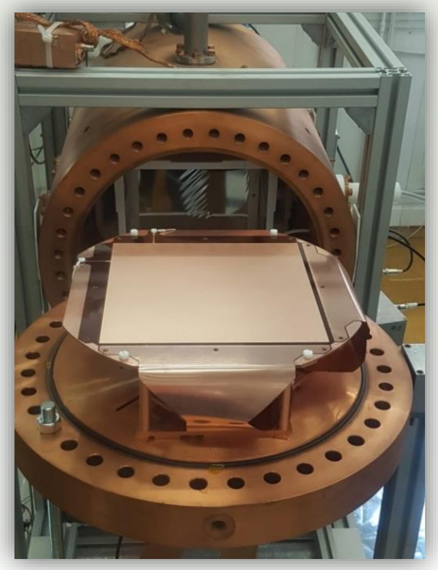


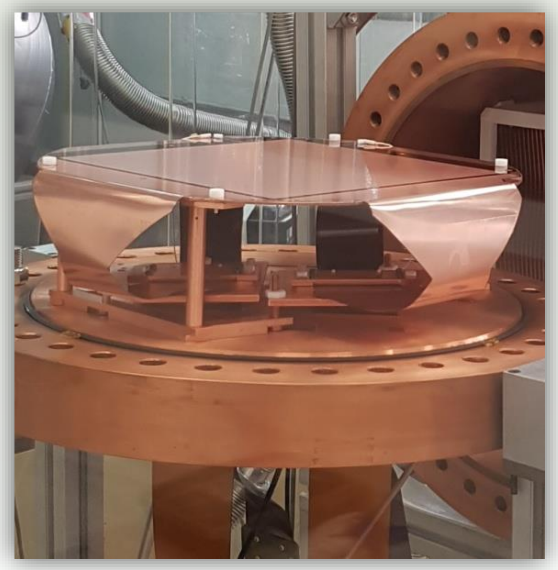
Advantages for **rare-event experiments**:

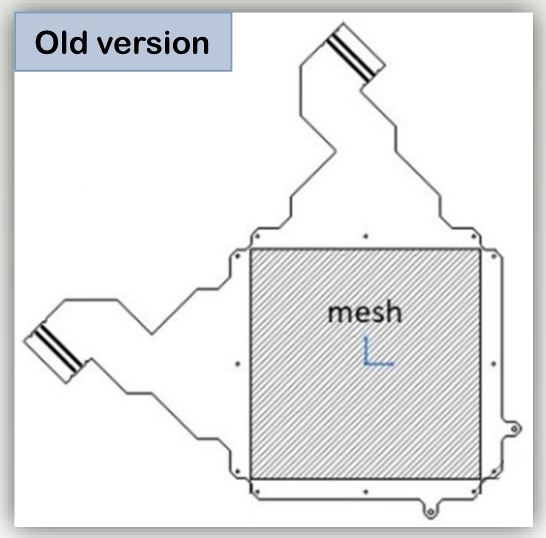
- **Topological information**: to discriminate background from expected signal by dark matter (few microns track → point-like event)
- Use of **radiopure materials**: kapton and copper, potentially very clean → **low background**
- Potential to reach **low energy thresholds**
- **Scaling-up**

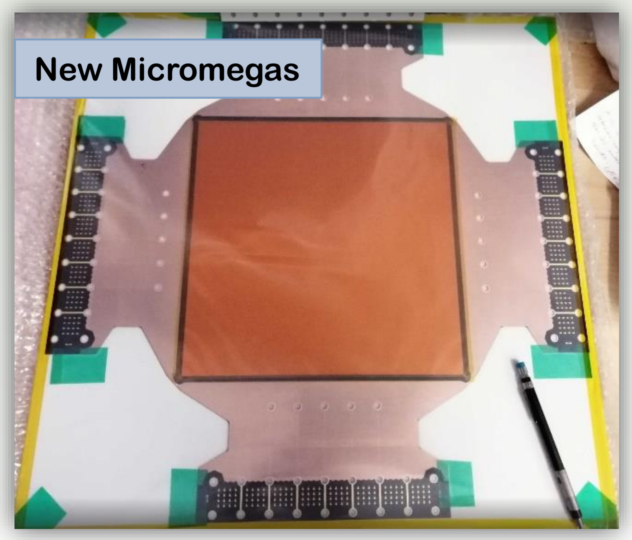
Detector: Micromegas

- **Two Microbulk Micromegas readouts**: the largest surface (**~25x25 cm2**) ever produced with this technology.
- **512 channels**: 256 X strips, 256 Y strips, ~1 mm pitch
- **Flat cables** to extract the signals and **connectors** made of **radiopure** material
- Detectors **upgraded in June 2022:**



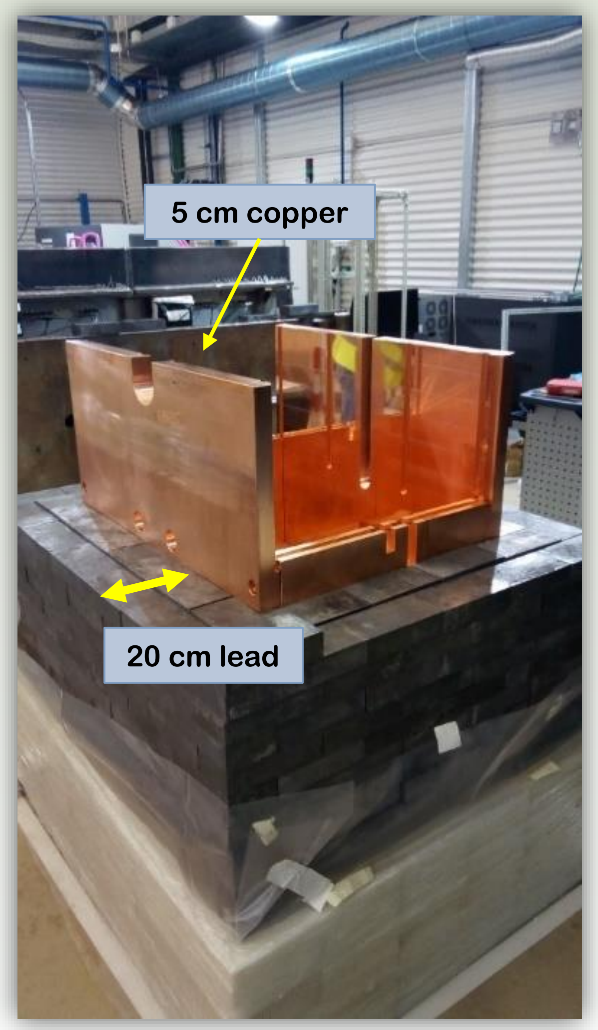




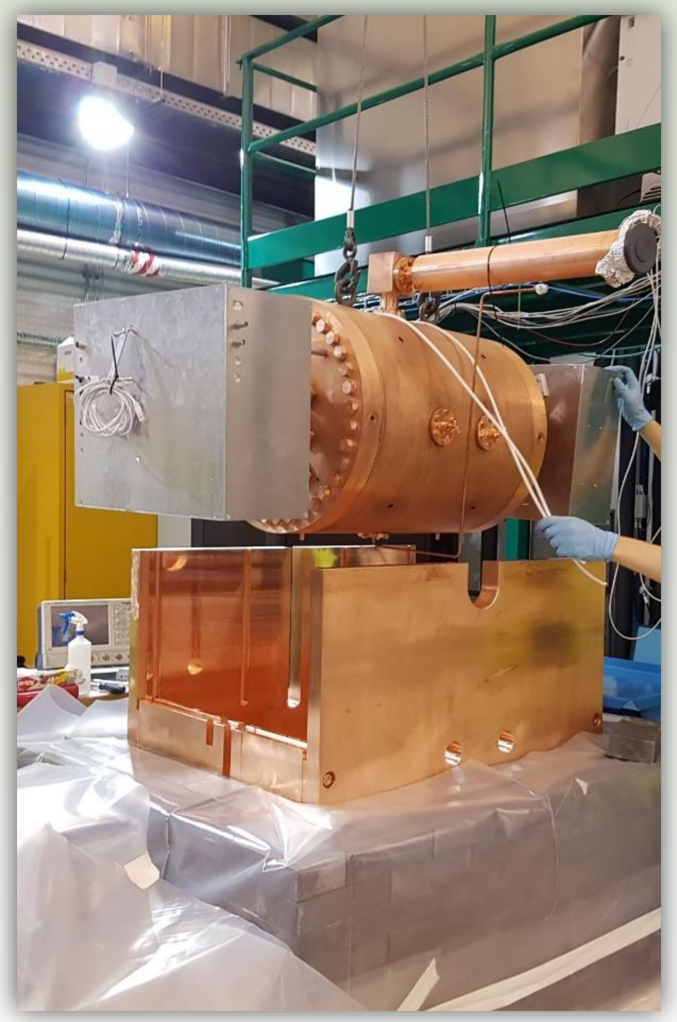


Shielding

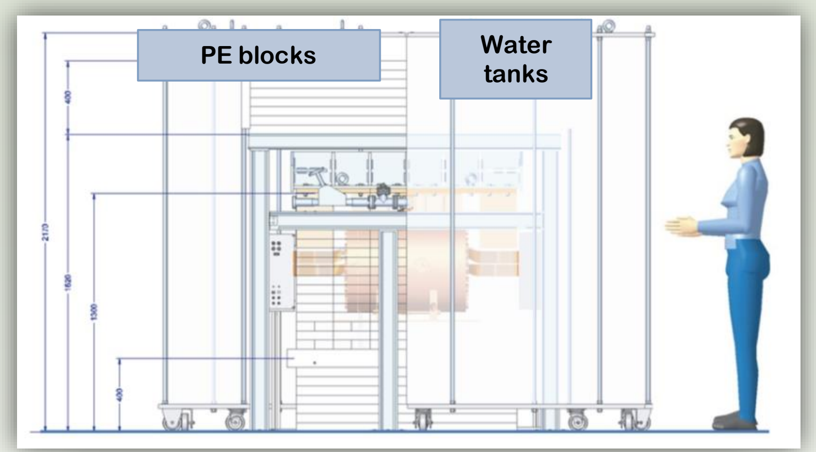
5 cm copper + 20 cm lead



DAQ outside the shielding

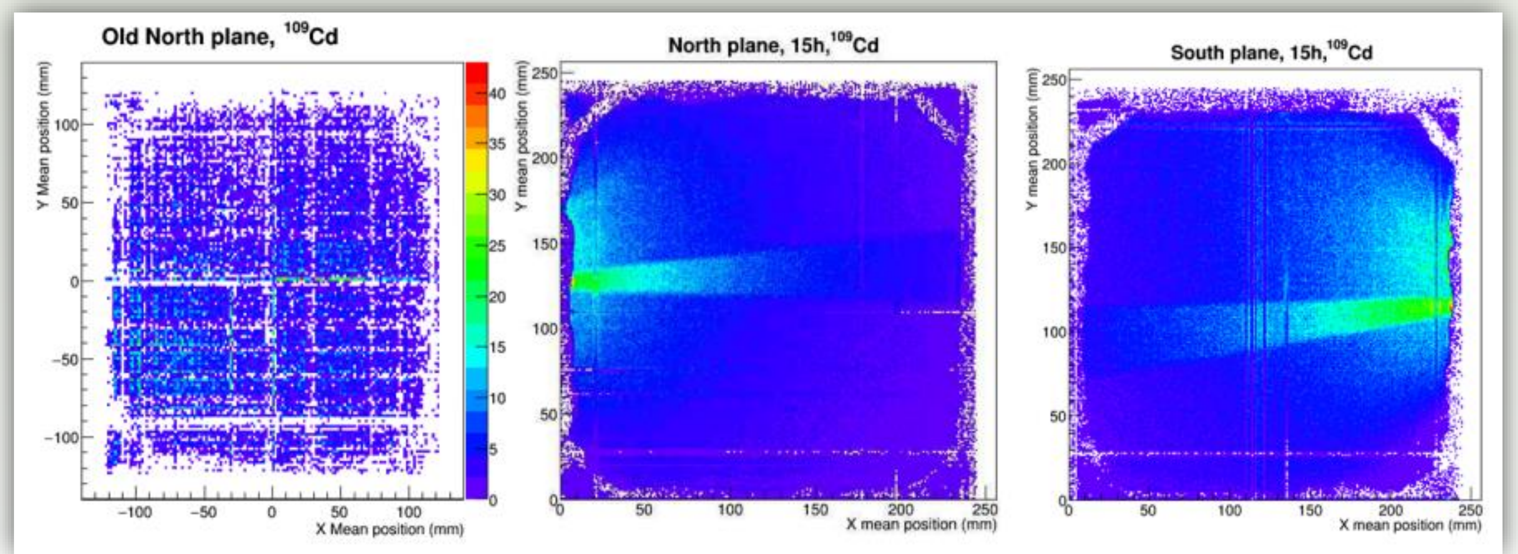


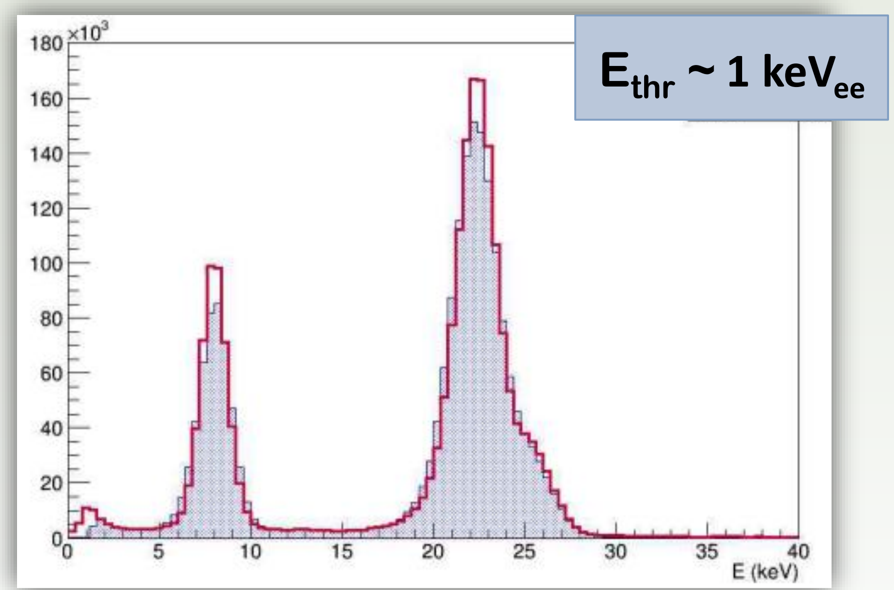
Neutron shielding foreseen: **polyethylene** ceiling + **water** tanks



Status: Energy threshold

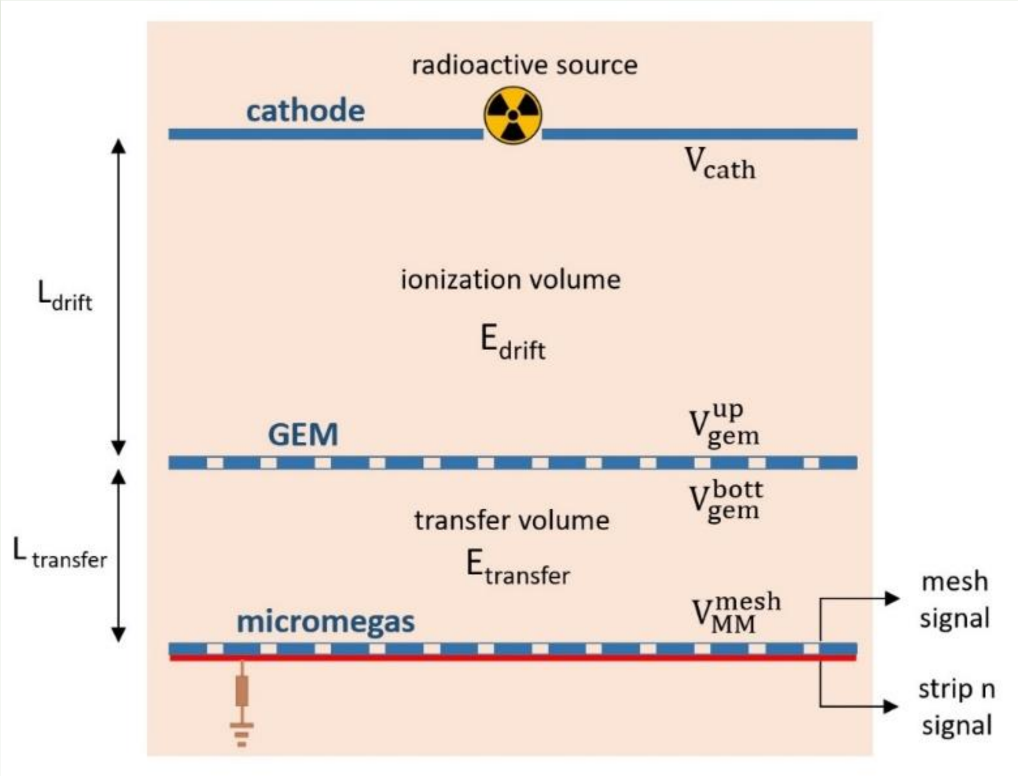
- After detector upgrade in June 2022 → **15-20% fewer dead channels** → improved threshold
- Threshold **~ 1 keV$_{ee}$** is limited by **signal-to-noise ratio** and **trigger efficiency** at low energies

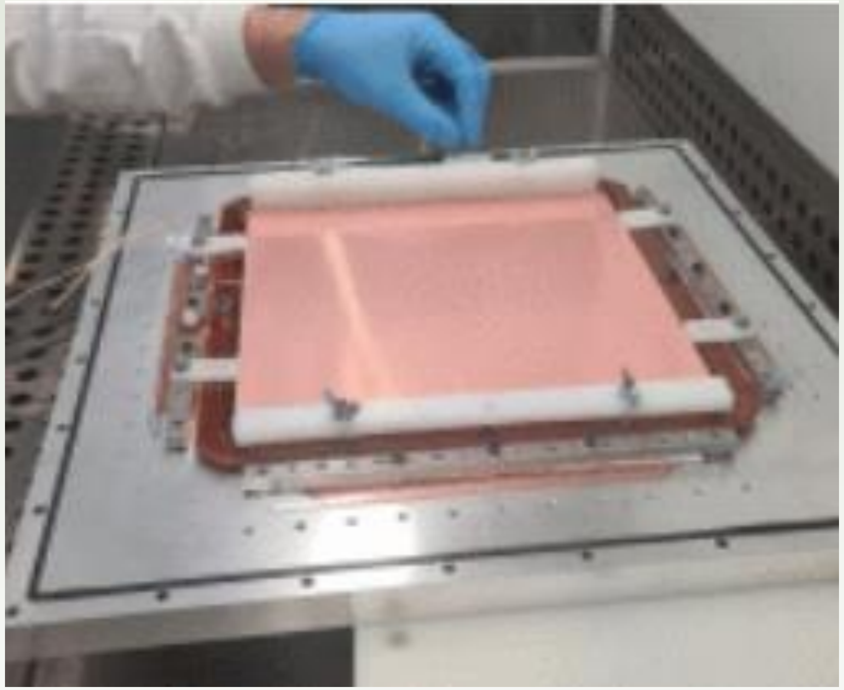




Prospects: Energy threshold

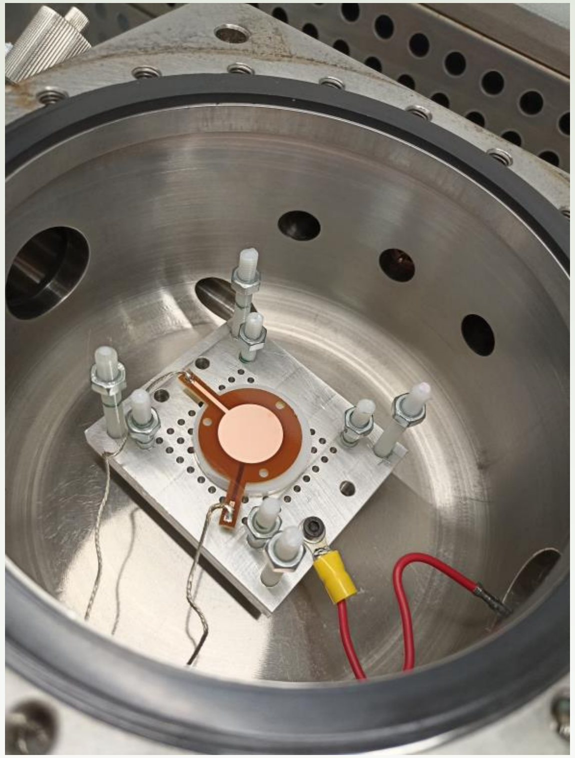
- Idea: improve Micromegas gain **adding a Gas Electron Multiplier (GEM) stage on top** of the Micromegas planes → **increase signal-to-noise ratio**

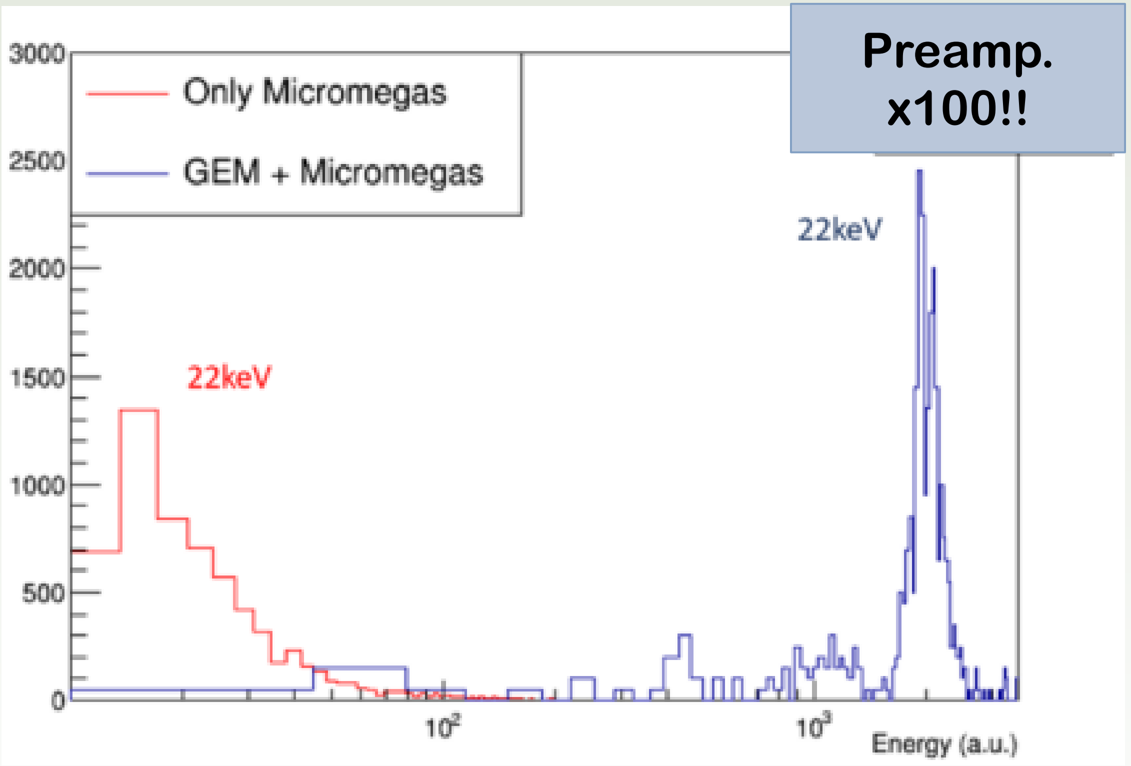




Prospects: Energy threshold

- **Results** in test bench: combined **GEM-MM set-up**: **x10-100** pre-amplification factor → potential to lower E_{thr} down to **single ionization electron** energies (**~ 20 eV_{ee}**)
- Plans to install a GEM foil on top of TREX-DM readout planes in the coming months





Low-energy calibration: why?

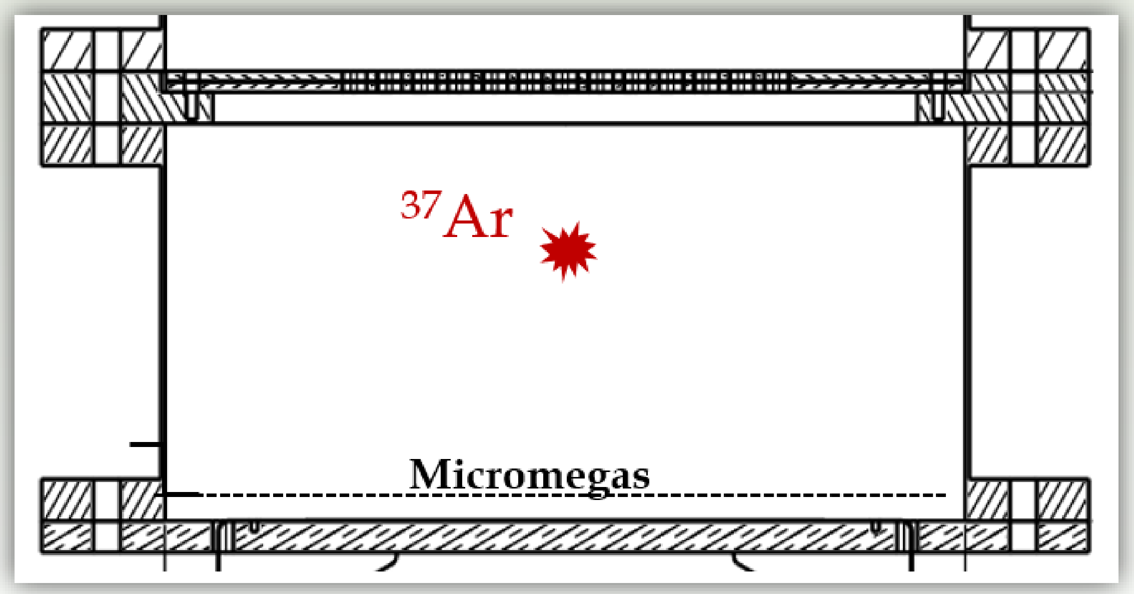
- Dark Matter searches focused on WIMPs are gradually shifting to very low energy thresholds (**sub keV$_{ee}$**)
- Important to understand the behaviour of the detector and the energy reconstruction at those energies ➔ need for a **low-energy calibration** with high statistics

Why 37Ar?

- 37Ar (**$T_{1/2}$ = 35.04 d**) decays by electron capture, and provides two characteristic x-rays for calibration at low energies: **2.82 keV** (K shell, probability 0.90) and **0.27 keV** (L shell, probability 0.09)

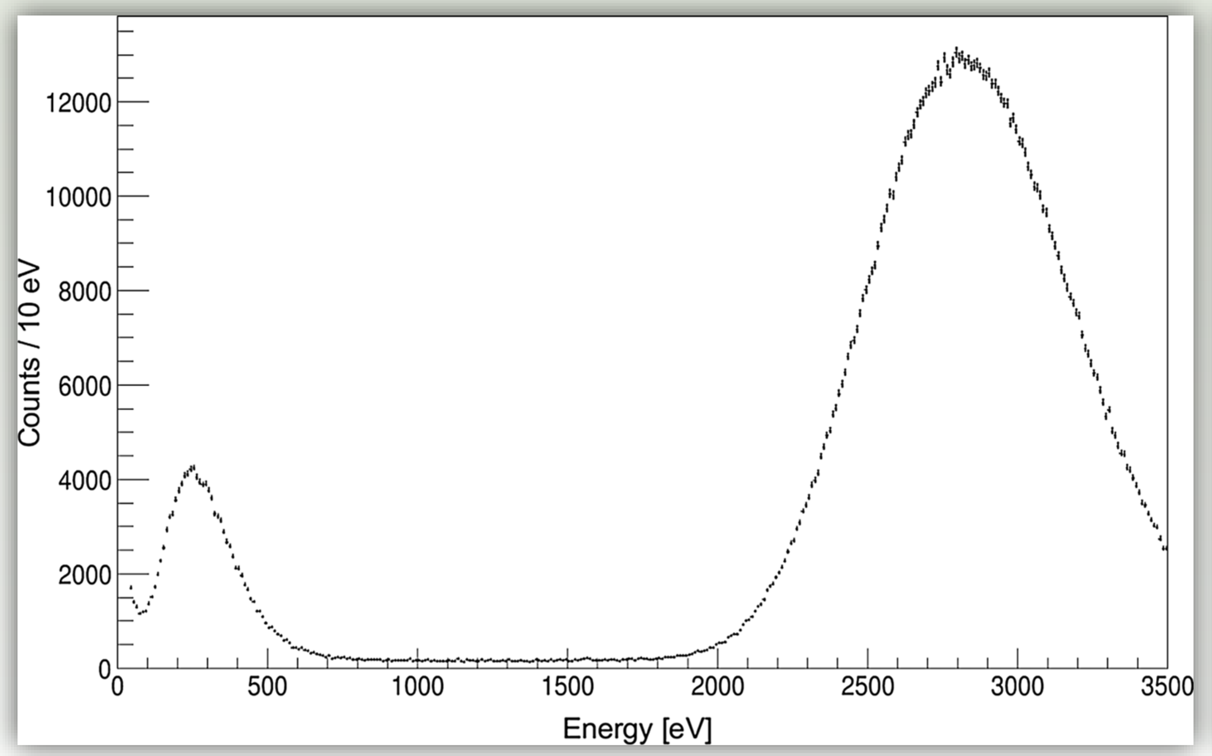
- Gas + mono-energetic spectrum

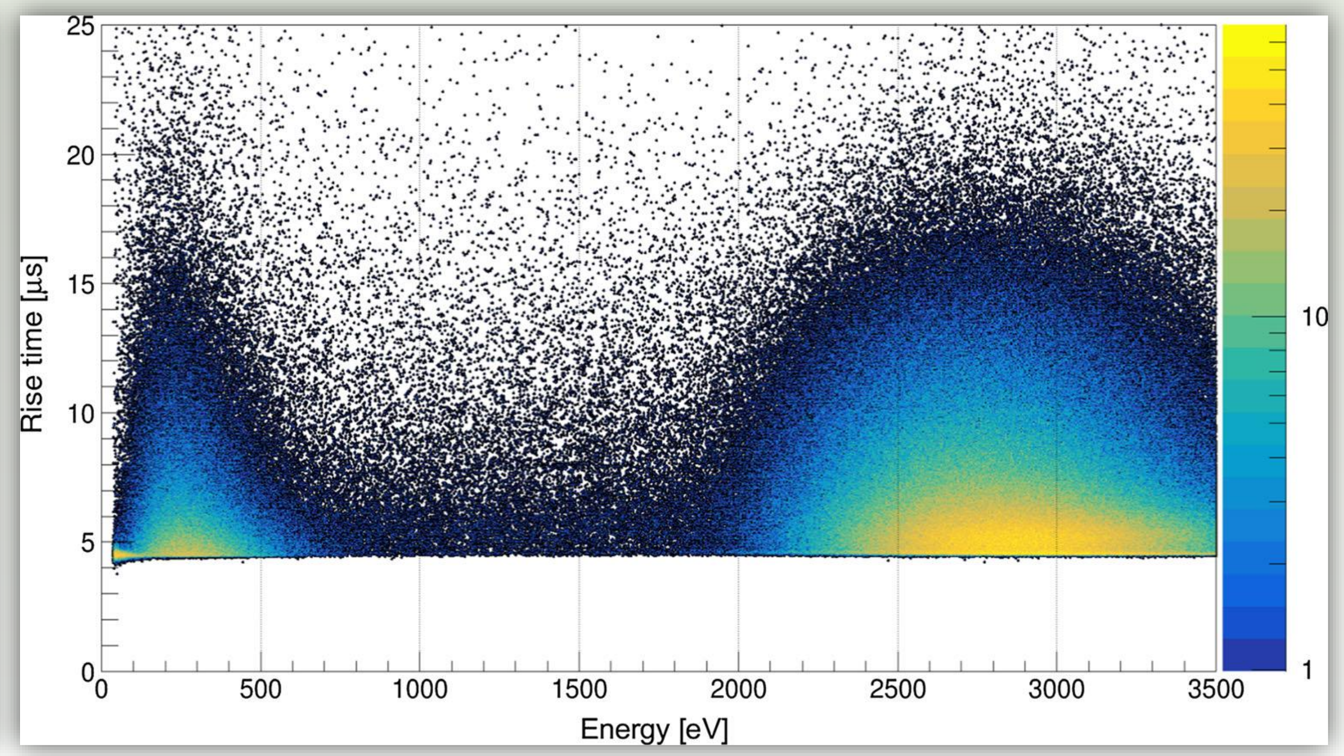
  ➔ calibration that provides a **homogeneous** illumination



Why 37Ar?

- Ultra-low-background experiments such as XENON1T or NEWS-G have successfully used it (https://arxiv.org/pdf/2211.14191.pdf)





37Ar: how to obtain it

- Irradiation with thermal neutrons of Ar enriched with 36Ar: 36Ar(n, γ)37Ar (XENON1T)
- Neutron irradiation of Ca, e.g. in the form of **CaO powder**: 40Ca(n,α)37Ar (NEWSG)

Isotope	Nat. abundance (at.%)	Cross-section (mb)	Reaction	Activation product	Half-life	Product decay γ-rays (keV)*
Argon reactions						
Ar-36	0.337	Thermal: 5000	*n*, γ	Ar-37	35.1 days	None
Ar-38	0.063	Thermal: 800	*n*, γ	Ar-39	269 a	None
Ar-40	99.600	Thermal: 700	*n*, γ	Ar-41	110 m	1293.6 (99.2)
Calcium reactions						
Ca-40	96.941	Thermal: 2.6	*n*, α	Ar-37	35.1 days	None
		Fast: 13				
Ca-42	0.647	Thermal: 680	*n*, γ	Ca-43	Stable	n/a
		Fast: 2.8	*n*, *p*	K-42	12.4 h	1524.7 (17.9)
Ca-43	0.647	Thermal: 6700	*n*, γ	Ca-44	Stable	n/a
		Fast: 1.89	*n*, *p*	K-43	22.2 h	372 (82), 616 (65)
Ca-44	2.086	Fast: 0.003	*n*, α	Ar-41	110 m	1293.6 (99.2)
Ca-46	0.004	Thermal: 740	*n*, γ	Ca-47	4.54 days	1296.8 (75.0)

*Selected γ-rays, branching ratio in parentheses

37Ar: how to obtain it

- **Ca irradiation** has a larger fast-neutron cross section, but thermal neutron reaction can also take place (https://doi.org/10.1007/s10967-018-6130-8)

- Irradiation in a neutron reactor is faster and produces higher activities, but use of a **neutron source** also a possibility (e.g. AmBe source, $\bar{E}$ = 4.2 MeV, at **CEA Saclay facilities**)

Isotope	Nat. abundance (at.%)	Cross-section (mb)	Reaction	Activation product	Half-life	Product decay γ-rays (keV)*
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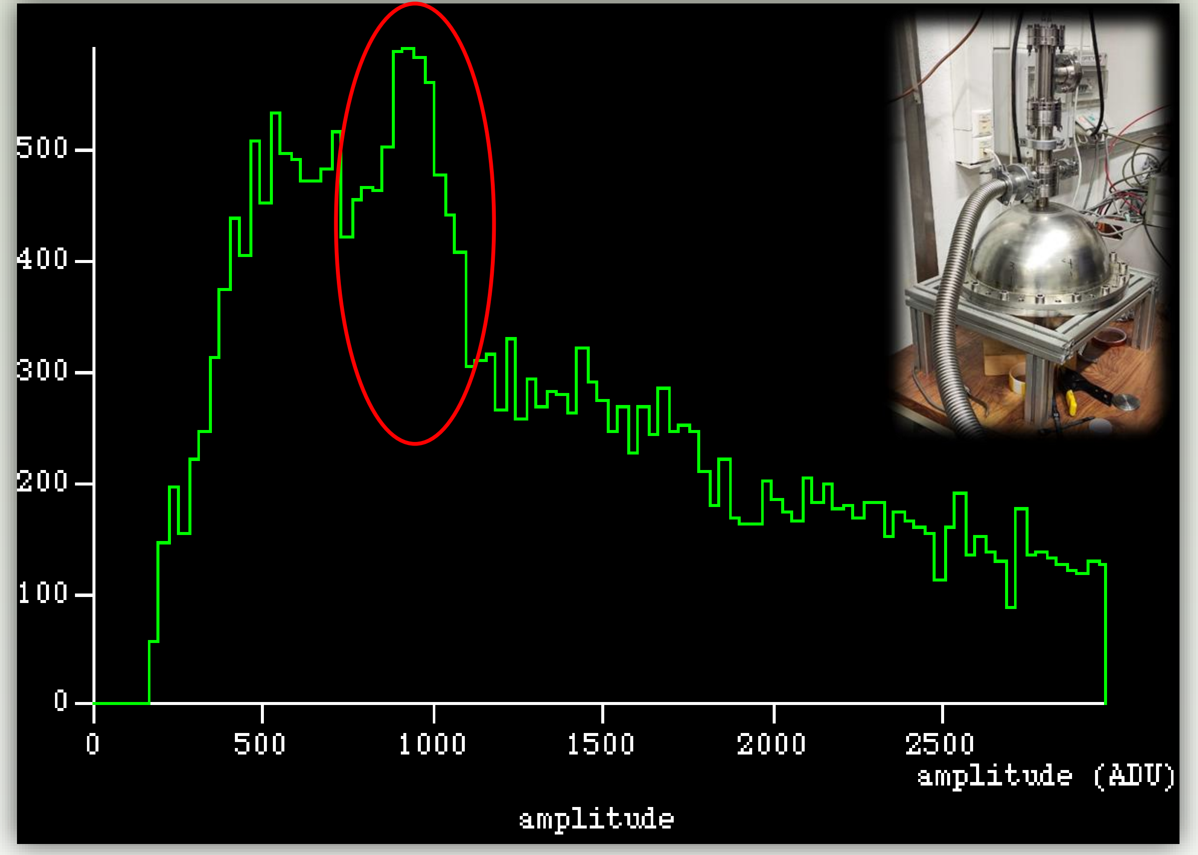
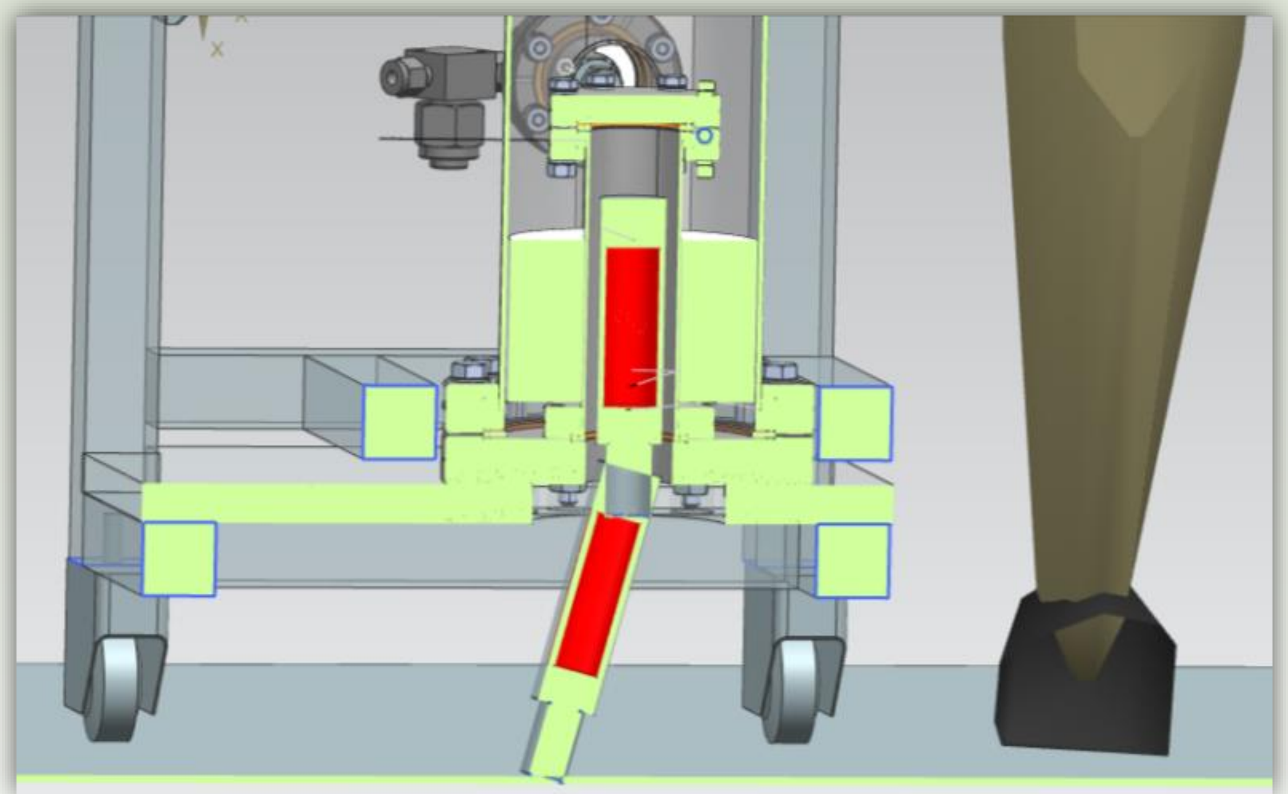
*Selected γ-rays, branching ratio in parentheses

Tests at CEA Saclay (with SPC)



2.82 keV peak at around 1000 ADU: ≈ 1 Hz after 15 days of irradiation

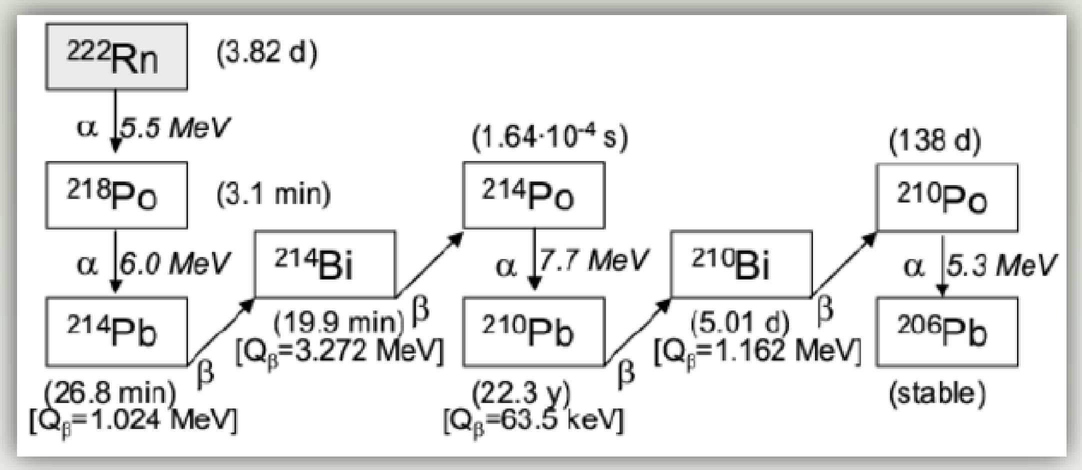
Set-up for TREX-DM



SS vessel with a hole performed to insert the neutron source: **solid angle optimisation** for irradiation (10^2-10^3 Bq)

Status and Prospects: Background

- **2020-2022**, background dominated by **222Rn: 600 c keV^{-1} kg^{-1} day^{-1}** (= dru)
- After a lot of effort, a solution was found: **open-loop operation** bypassing the filters and the recirculation pump → **100 dru** (1-2 orders of magnitude higher than background model)

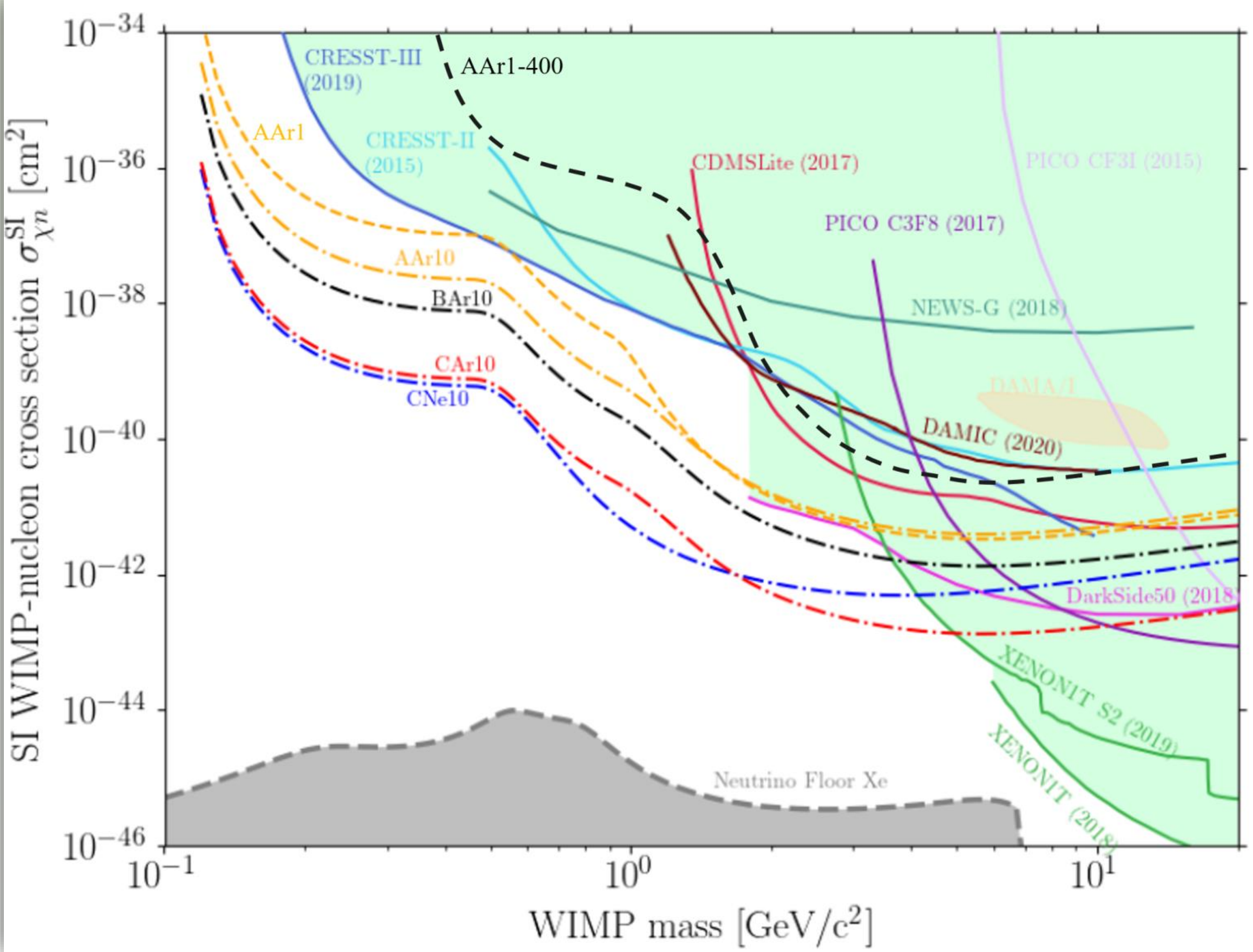


- After installing cleaner detectors in June 2022, data analysis shows **>90% background** comes from **intrinsic 222Rn progeny** contamination on the **surface** of the mylar cathode
- Plans to install a more radiopure cathode in the coming months → background estimate **1-10 dru**

Status and Prospects: Gas mixture

- In 2019-late 2022, **Ne-2%isobutane** was used
- Oct 2022-July 2023, **data taking stopped due to experiment relocation** (from Lab2400 to Lab2500: space restructuring needs from LSC)
- **Ne difficult to acquire** due to war → need to shift to **Ar-based mixtures**
- Ar-1%isobutane currently used, but Lab2500 opens the possibility to go to **lighter mixtures** by **increasing** the **isobutane** content, e.g. **Ar-10%isobutane** (flammable) → **improved sensitivity**

Sensitivity prospects

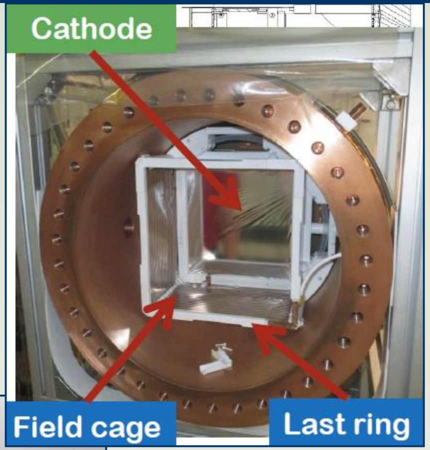


scenario	energy thr (eV_{ee})	backgr level (dru)	isobut (%)	time exposu (year)
AAr1-400	400	10	1	1
AAr1	50	10	1	1
AAr10	50	10	10	1
BAr10	50	1	10	1
CAr10	50	0.1	10	10
CNe10	50	0.1	10	10

Thank you for your attention!!

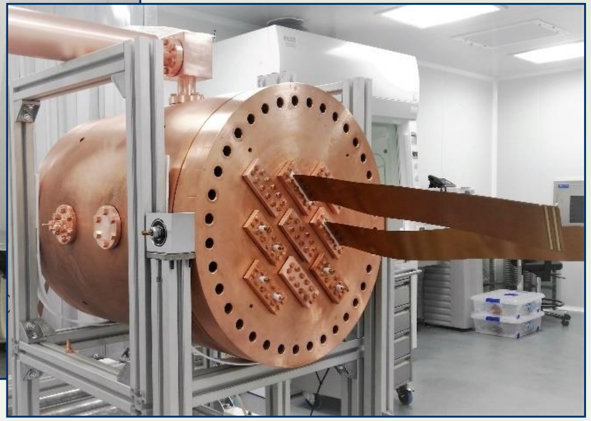
Back-up slides

Detector: vessel & gas system



Vessel:

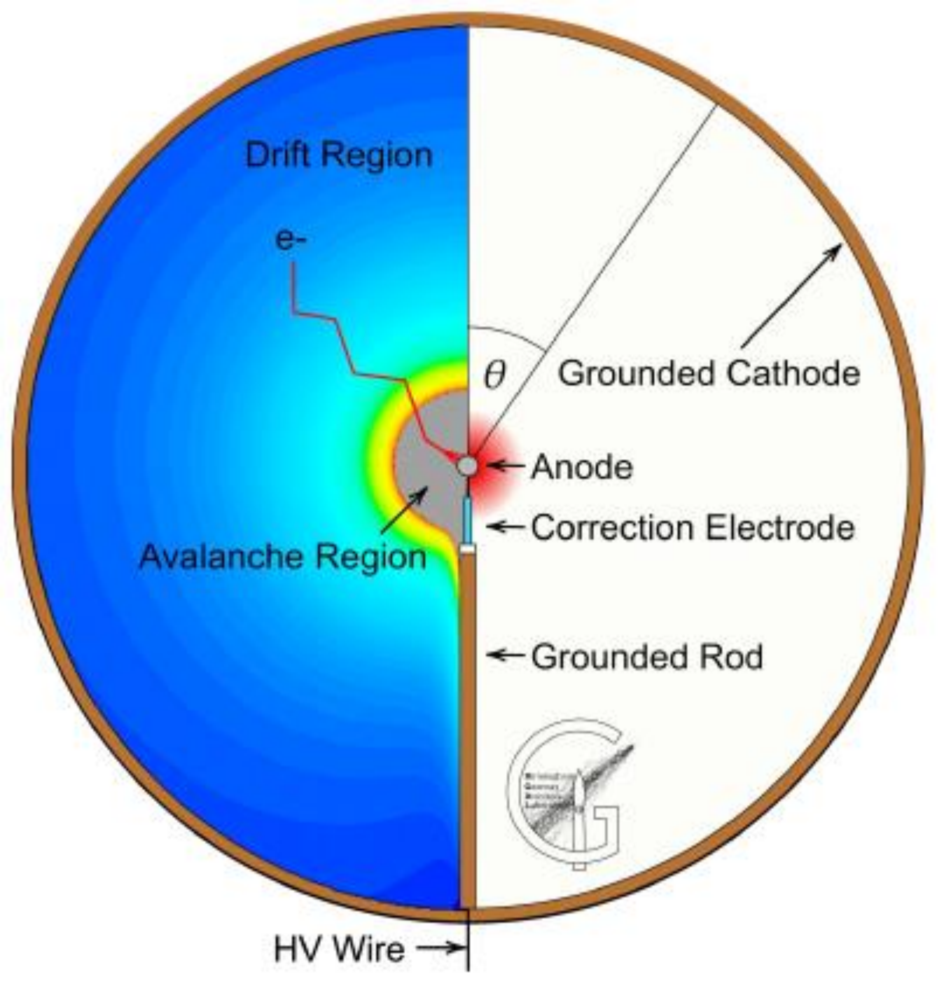
- Cylindrical vessel made of copper
- Designed to operate safely at 10 bar, certified as pressure equipment before installation at LSC



Gas system:

- Designed for non-flammable gases, consisting of recirculation part + purification branch

Spherical Proportional Counter (SPC)

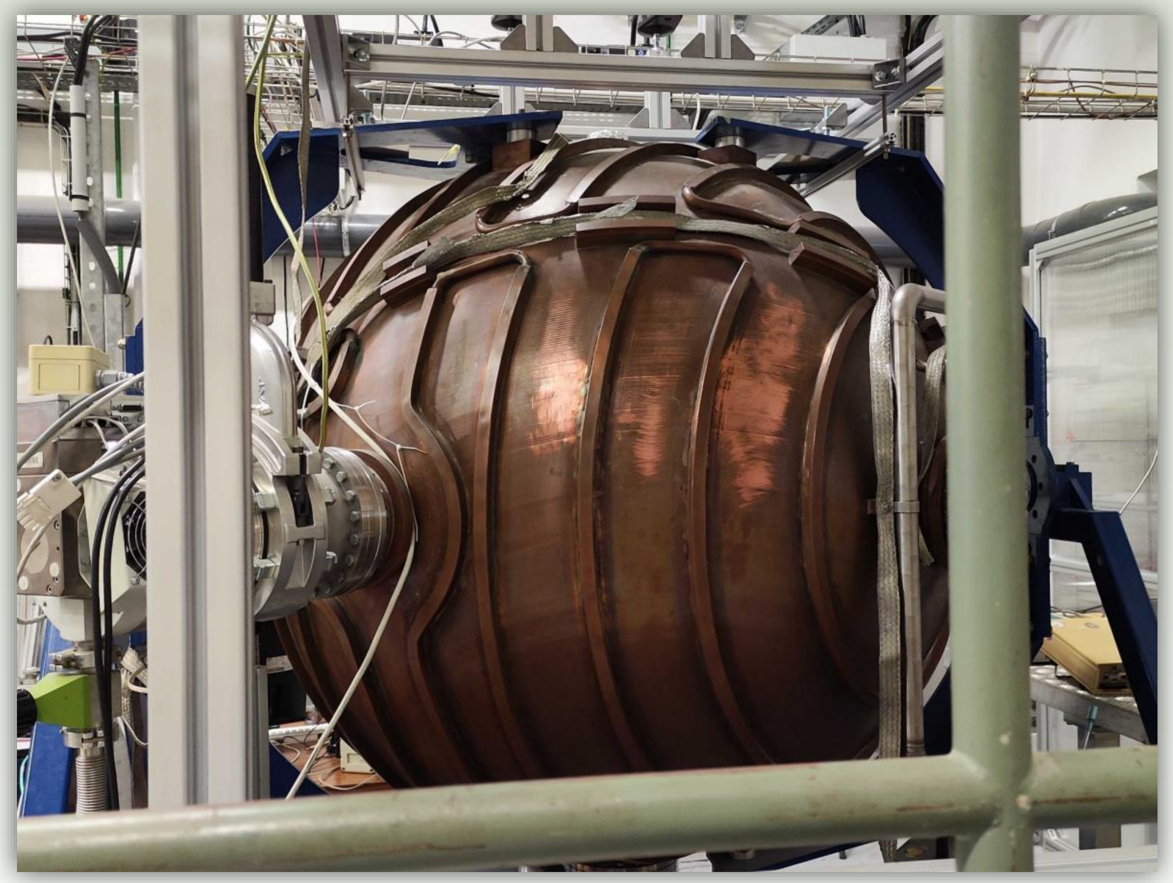


$$E(r) = \frac{V_0}{r^2}\frac{r_A r_C}{r_C - r_A} \approx \frac{V_0}{r^2} r_A$$

r_A = *anode radius*
r_C = *cathode radius*

Near $r = r_A$ ➔ E(r) ↑↑↑ ➔ avalanche region

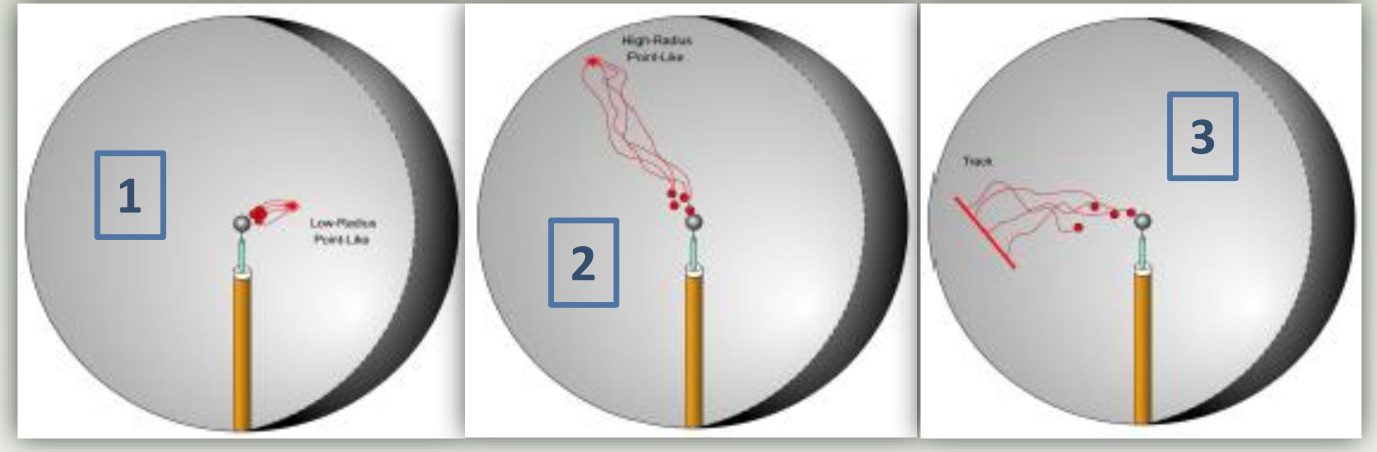
Spherical Proportional Counter (SPC)



Copper SPC at CEA Saclay

Spherical Proportional Counter (SPC)

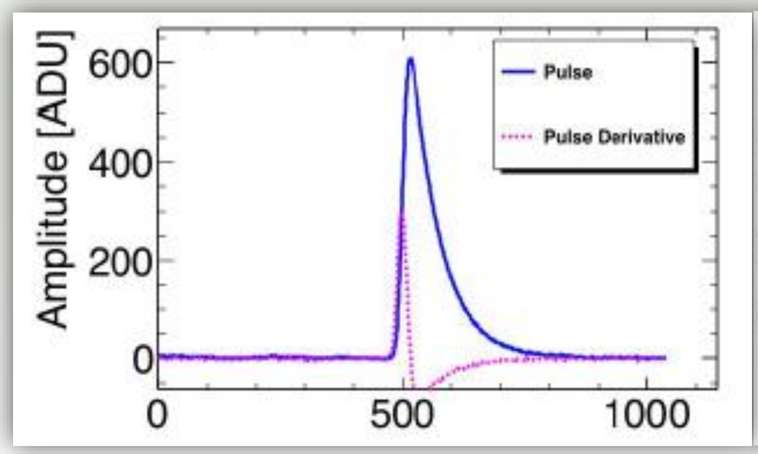
Risetime and falltime ➔ drift time dispersion ➔ event selection: point-like vs. track, fiducialisation

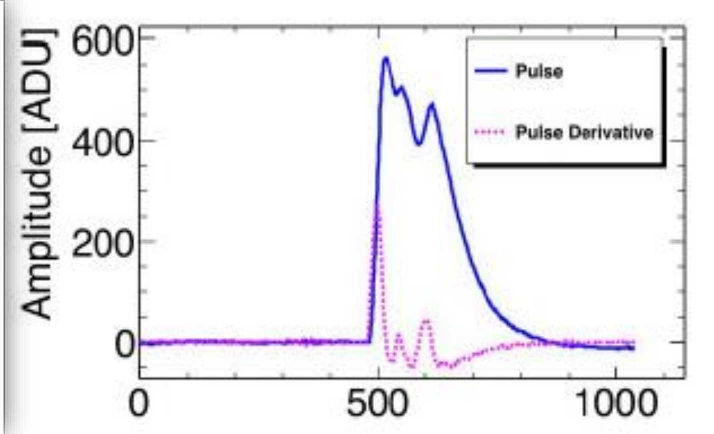


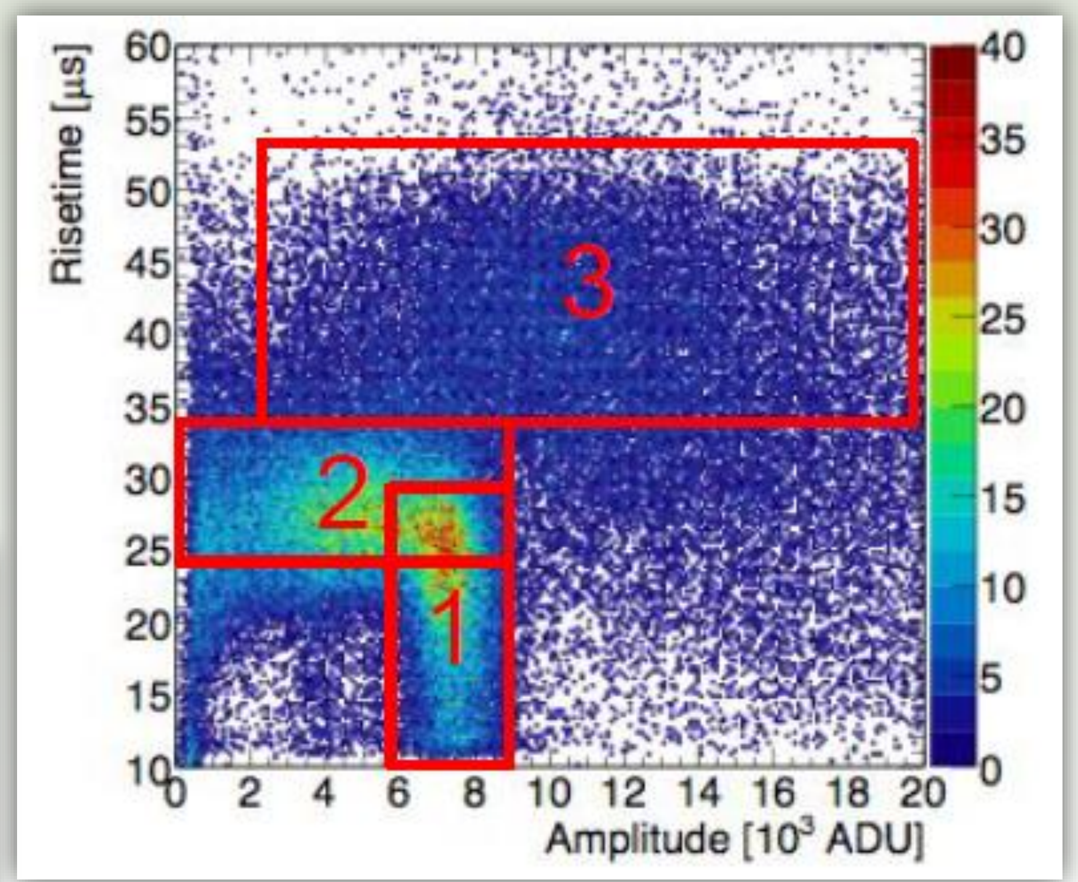
x-ray in the volume

x-ray near cathode

cosmic muon

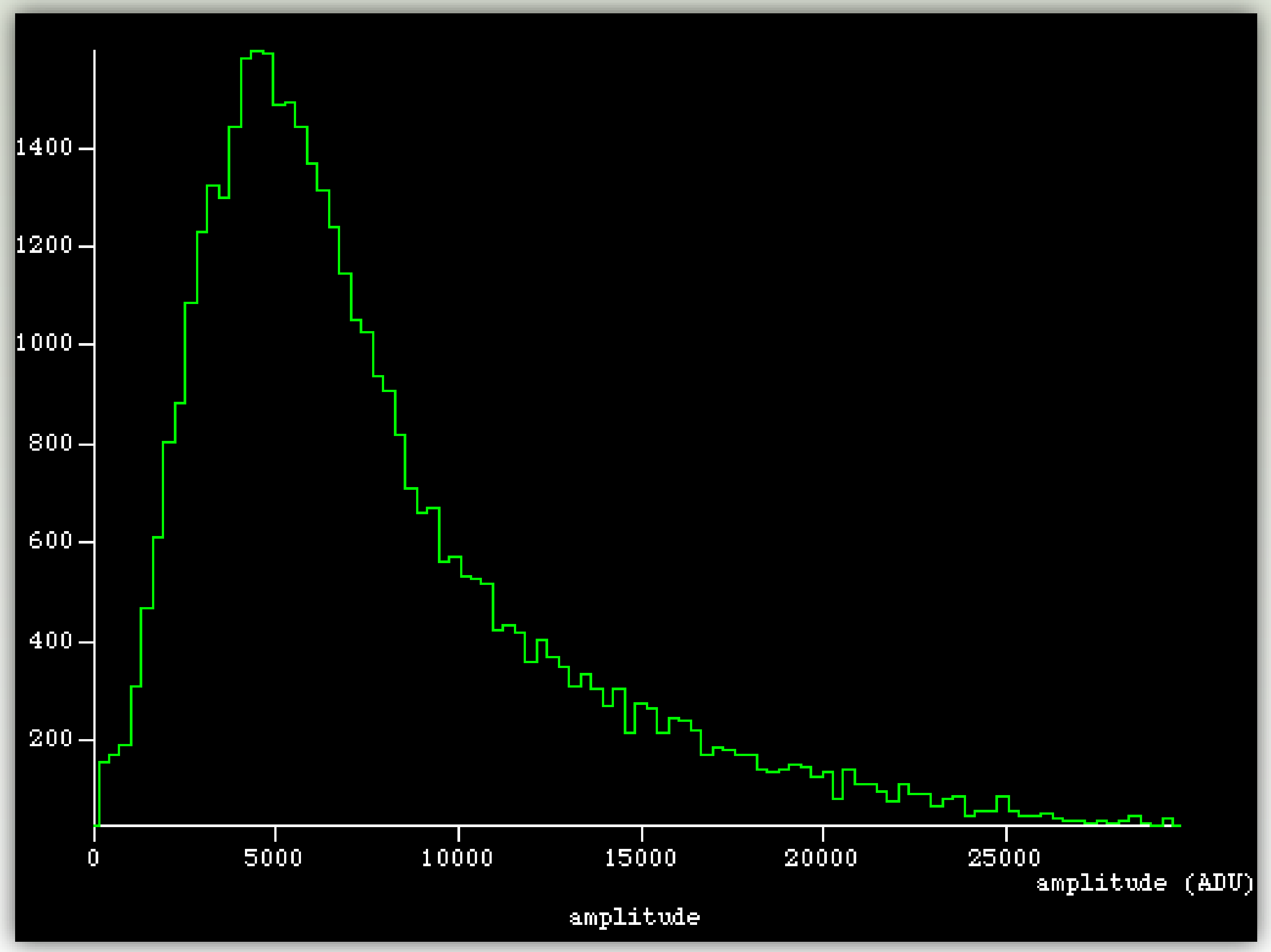




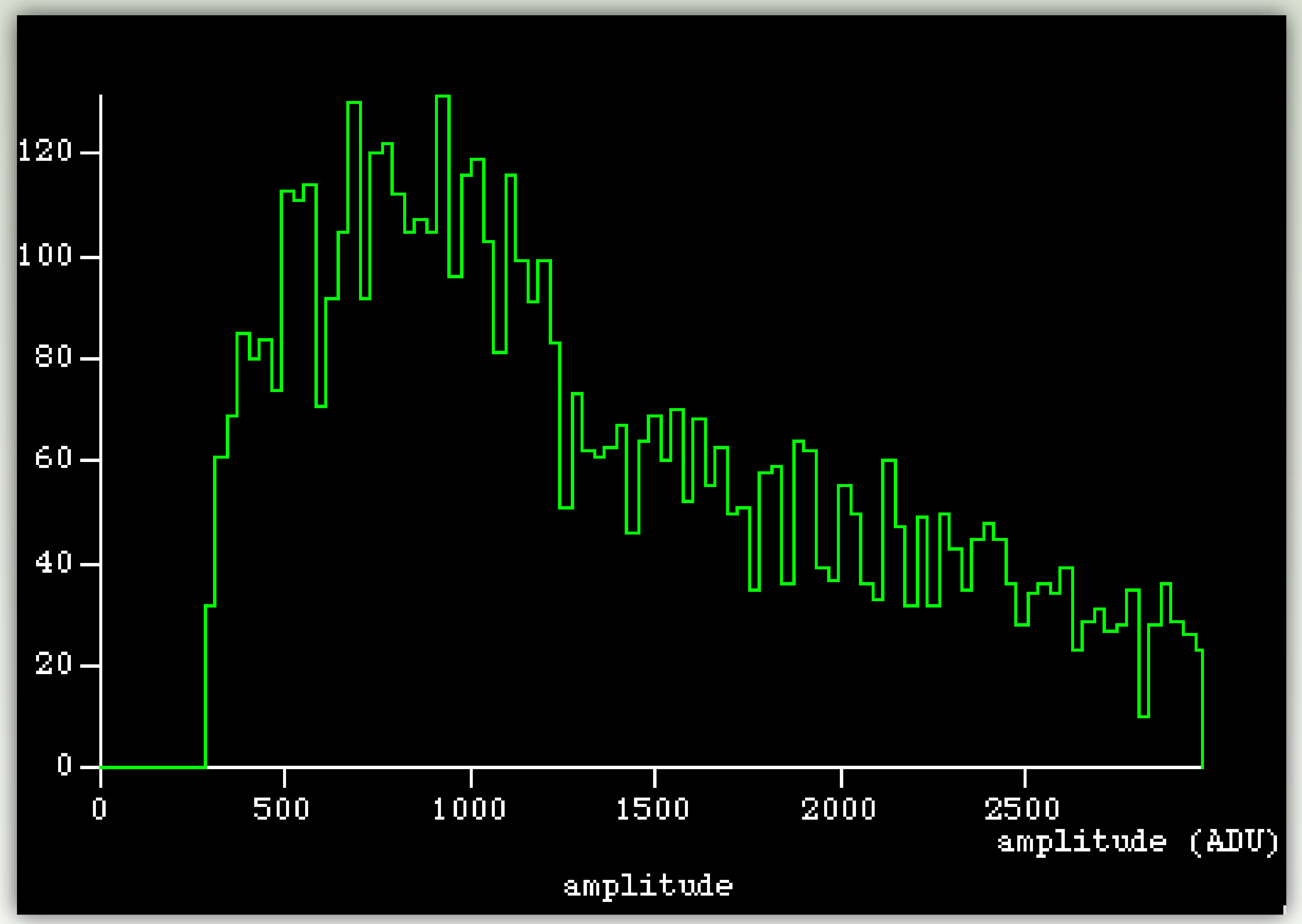


Second try: background run (before 37Ar): cosmic rays

HV: 1600 V, gas Ar-2%CH4, pressure 600 mbar, duration 1300 s

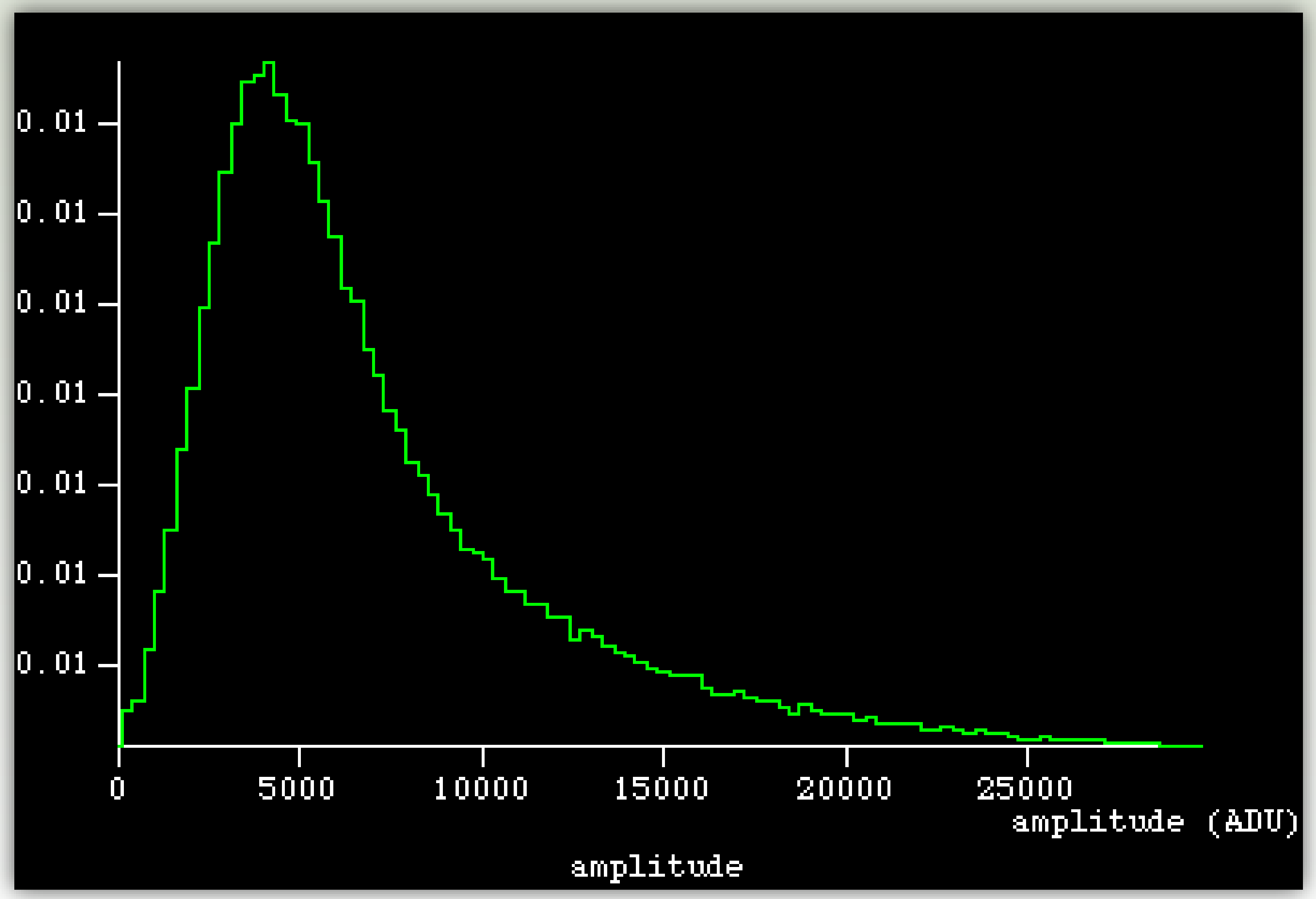


Second try: background run (before 37Ar): LE spectrum

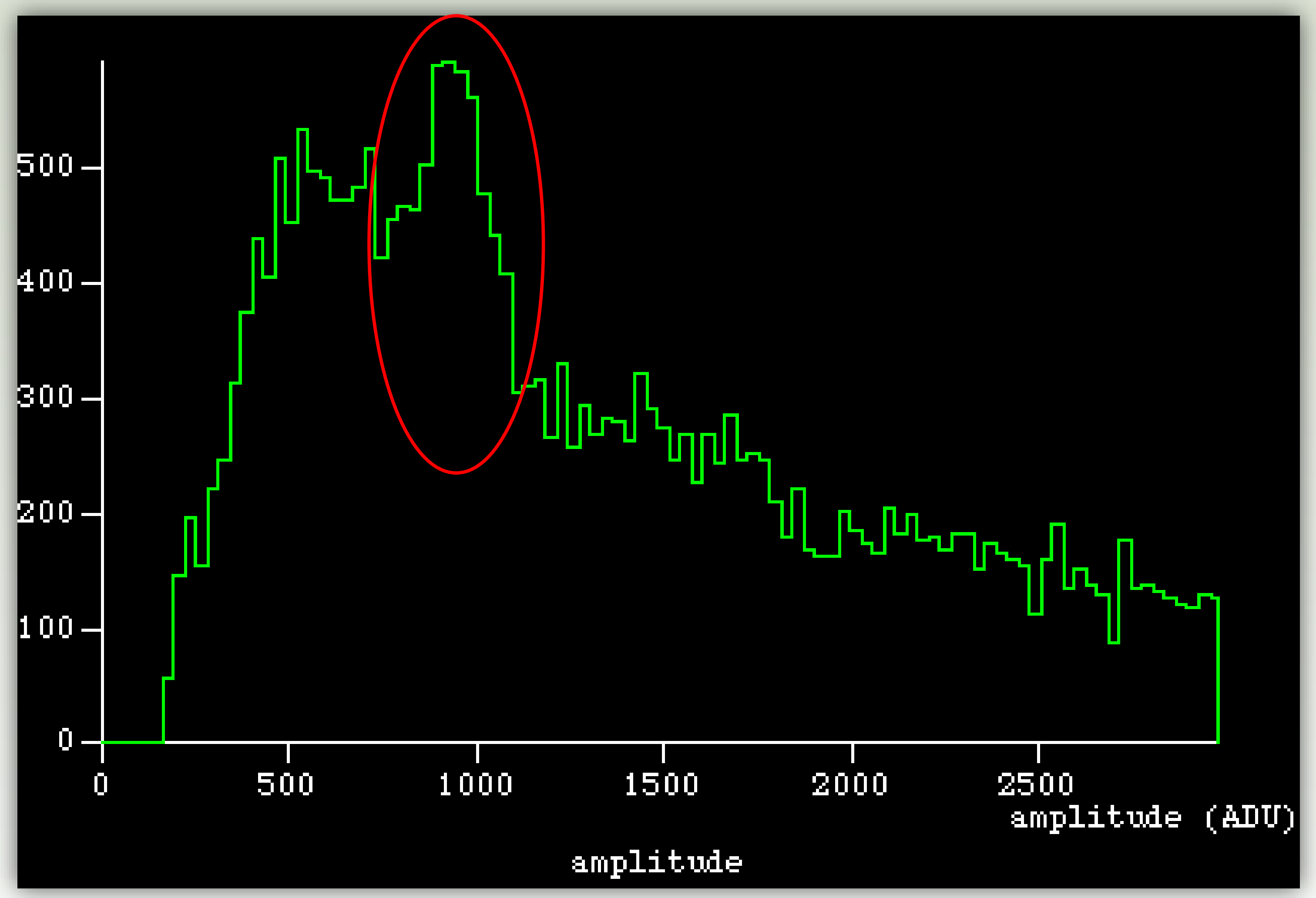


Second try: 37Ar run: cosmic rays (≈ same gain)

HV: 1600 V, gas Ar-2%CH4, pressure 600 mbar, duration 5800 s

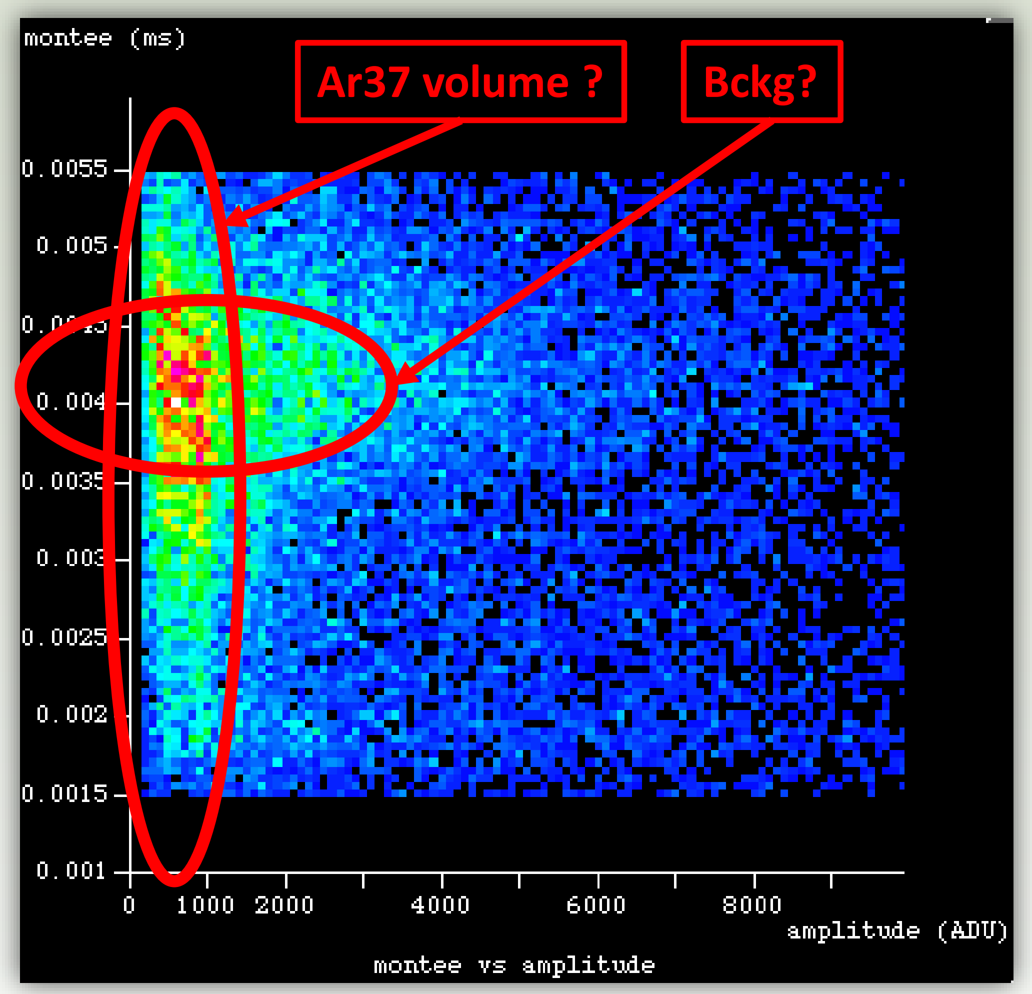


Second try: 37Ar run: LE spectrum

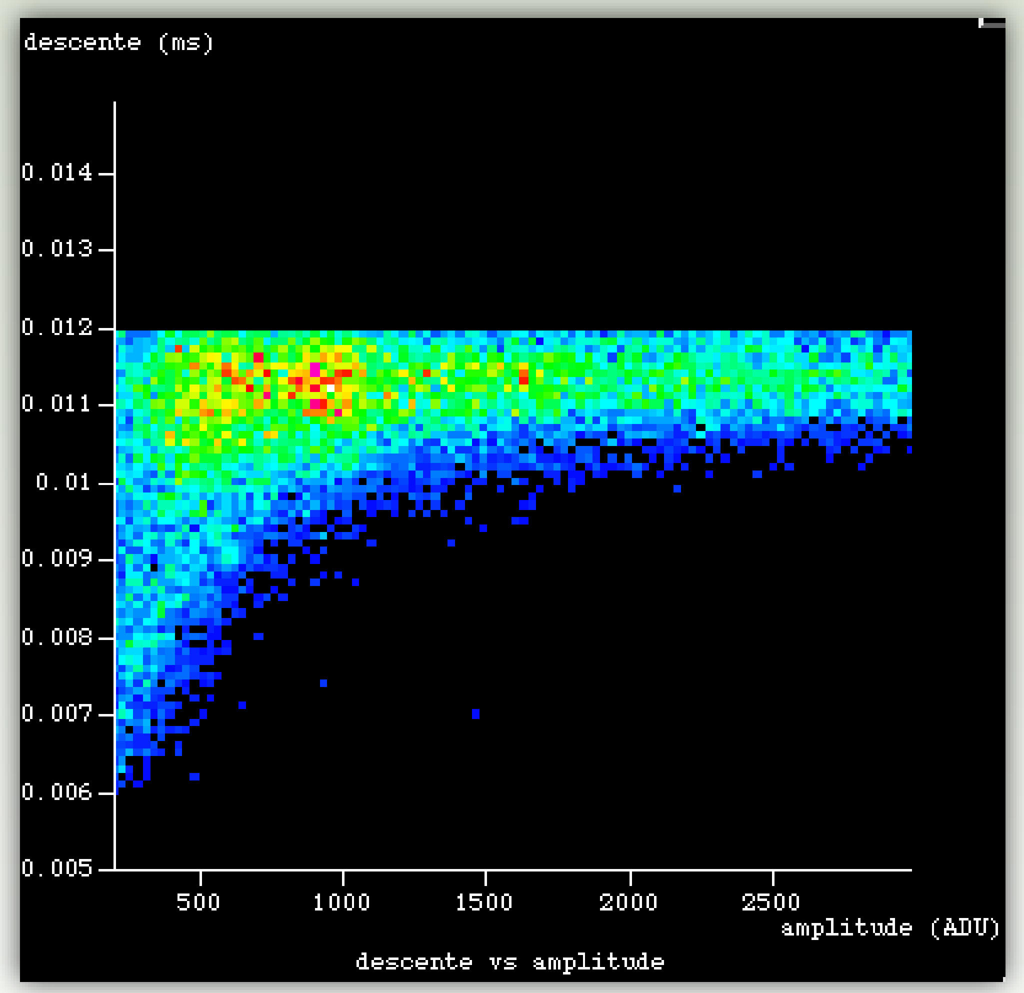


37Ar spectrum: 2.82 keV peak at around 1000 ADU? Rate < 1 Hz…

Second try: 37Ar run: LE part

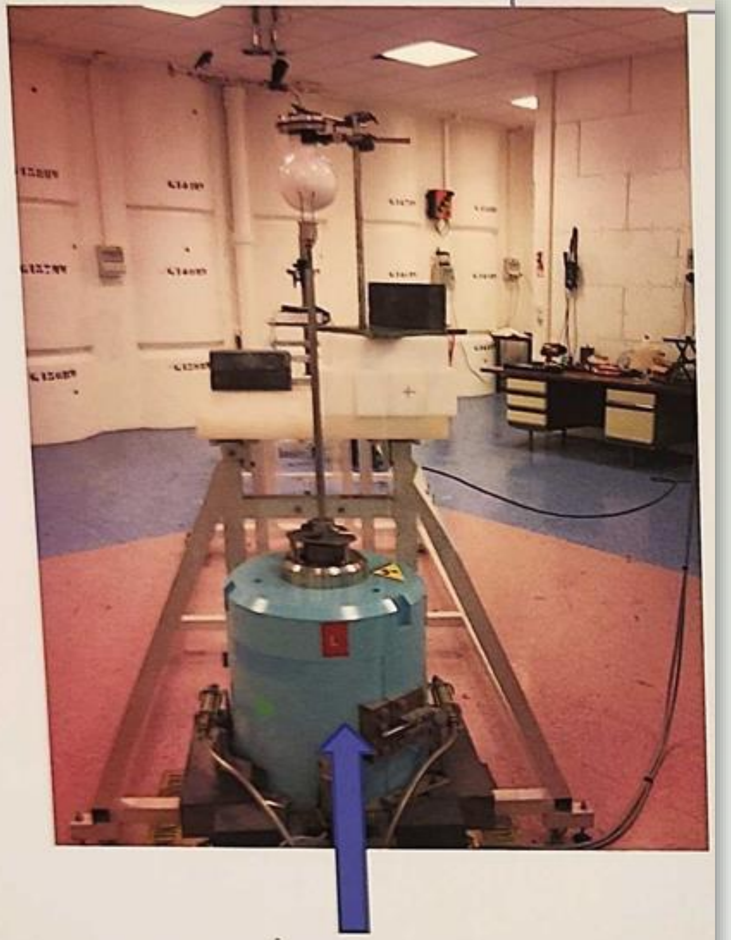


Risetime vs. amp



Falltime vs. amp

Initial results: x2-x3 flux, constant irradiation → higher rate

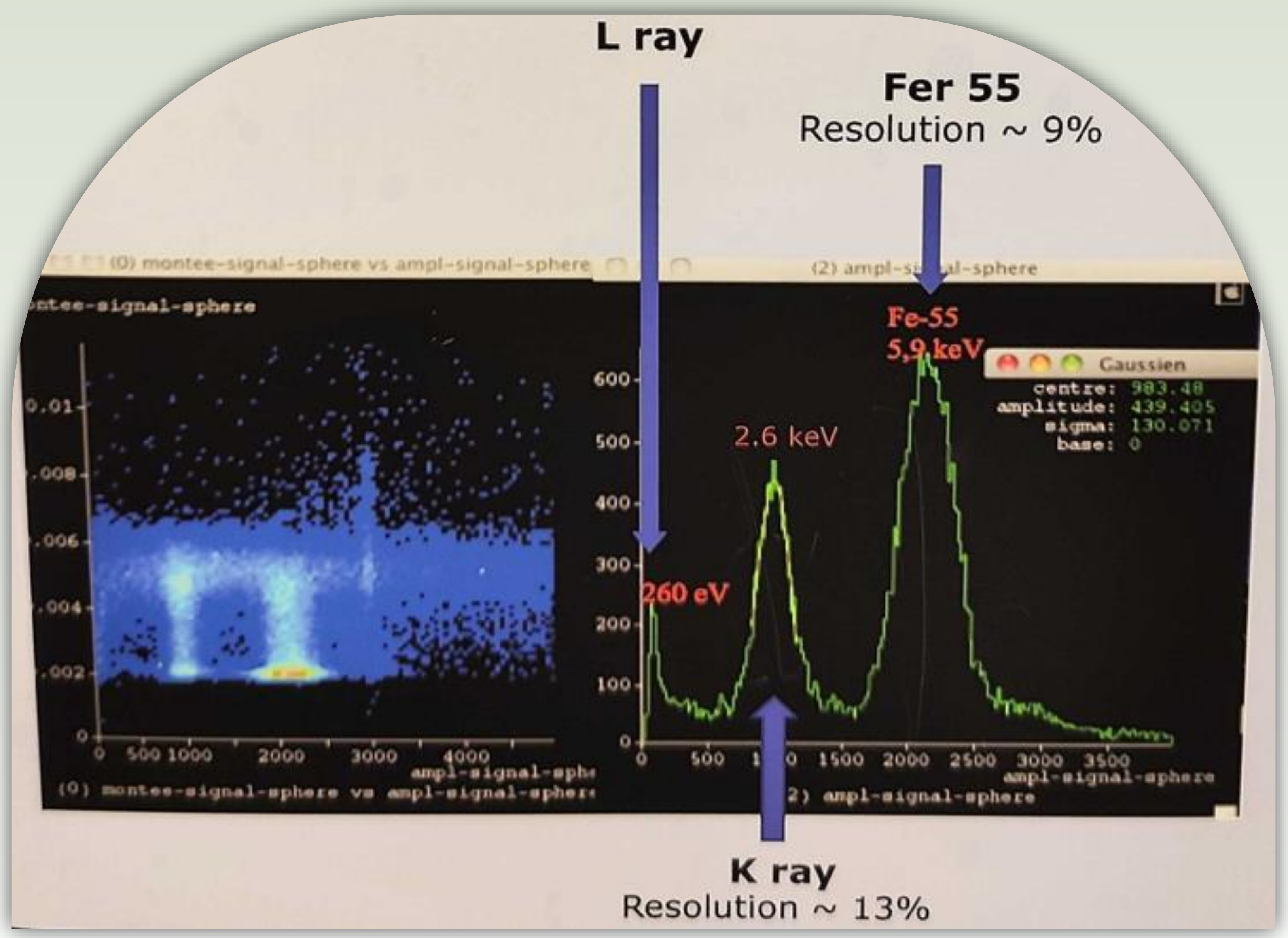


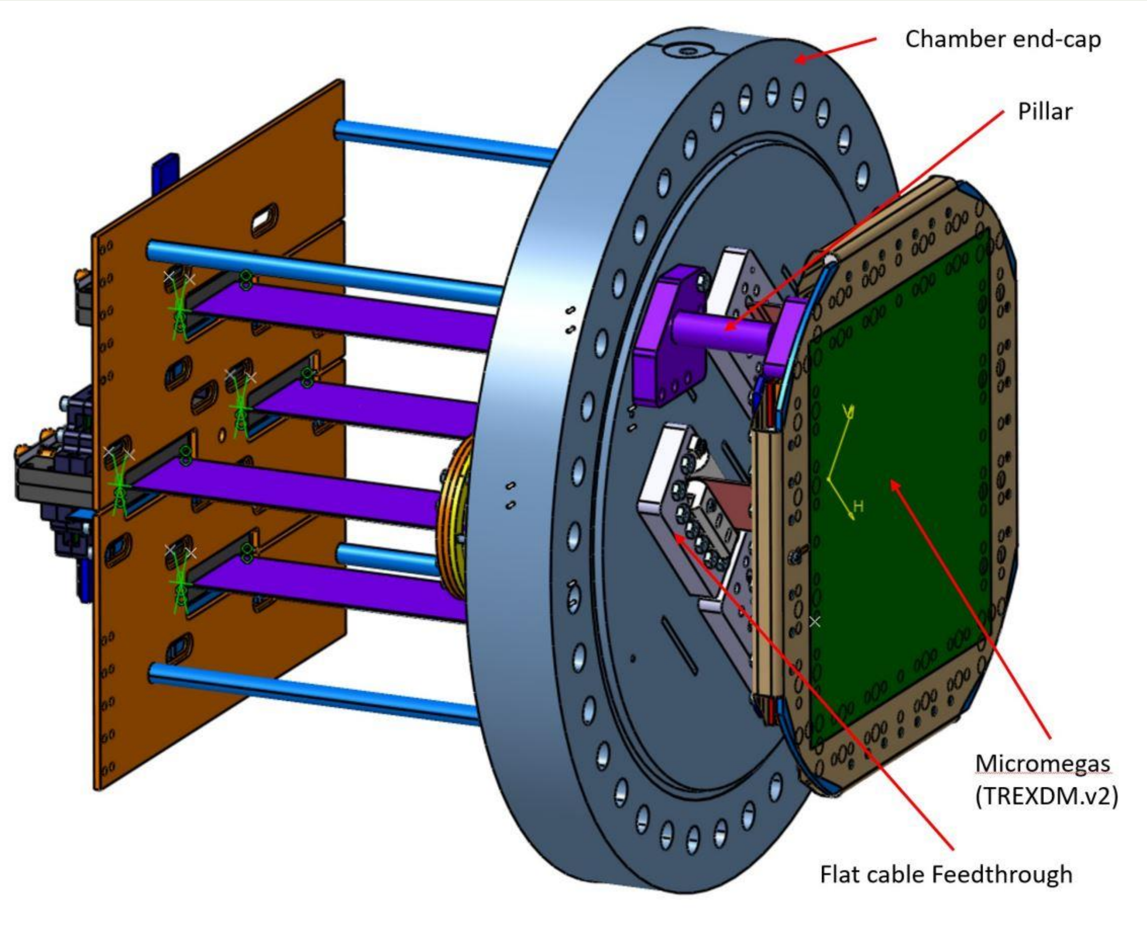
Neutrons source :

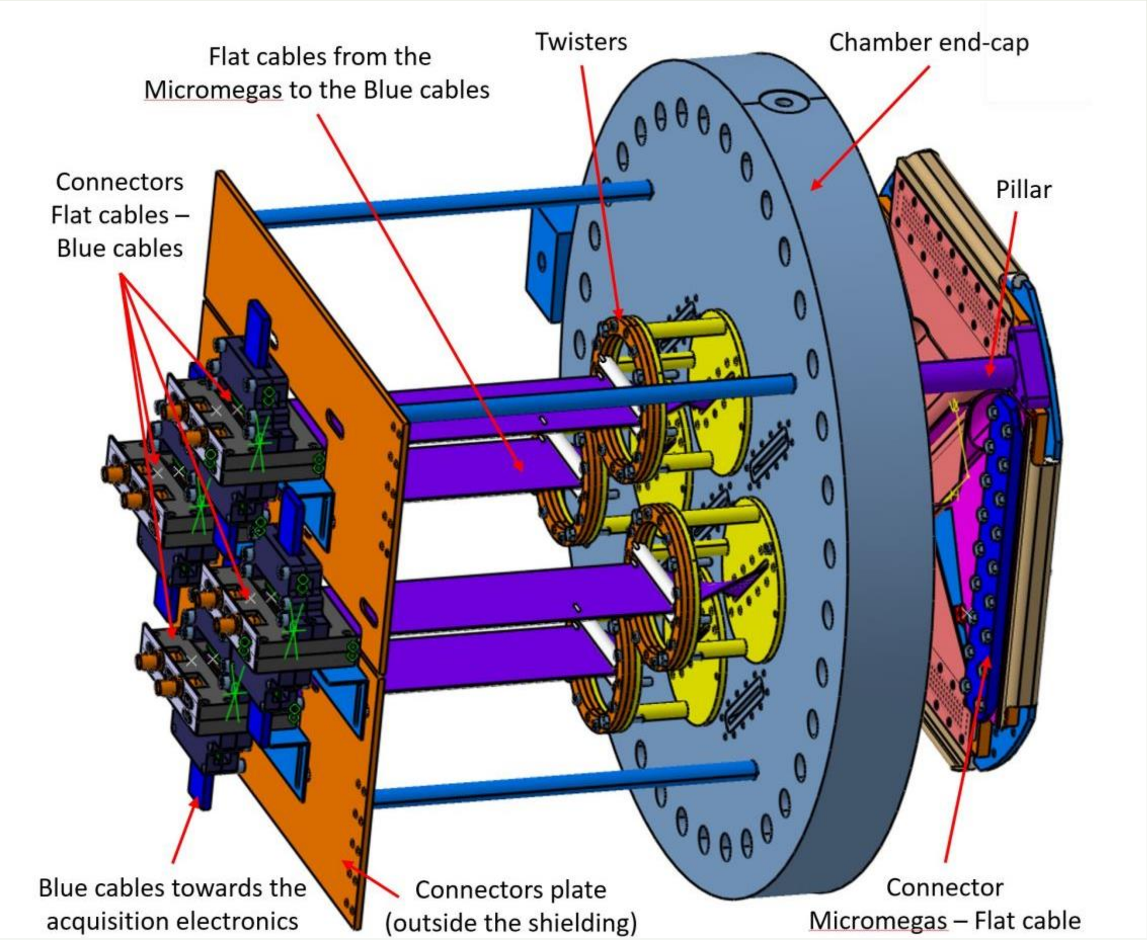
Last success: home made Ar-37 source
Using Ca-40 powder
About 40 hz after 14 days
Of neutron irradiation:
$7x10^6$neutrons/s

Argon 37

Initial results: much better resolution…

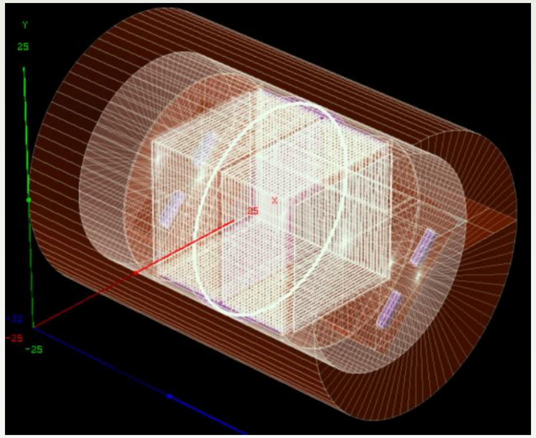



Chamber end-cap
Pillar
Micromegas
(TREXDM.v2)
Flat cable Feedthrough


Flat cables from the
Micromegas to the Blue cables
Twisters
Chamber end-cap
Connectors
Flat cables –
Blue cables
Pillar
Blue cables towards the
acquisition electronics
Connectors plate
(outside the shielding)
Connector
Micromegas – Flat cable

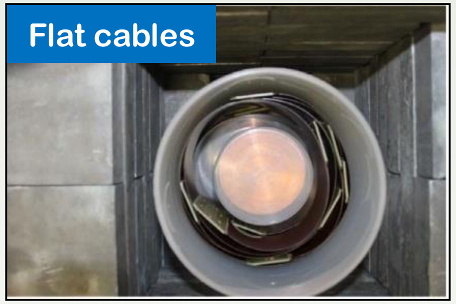
Background model: simulation

- Detailed geometry including shielding
- Based on Geant4 (Physics processes) + REST code (electron generation in gas, diffusion effects during drift, charge amplification at Micromegas, signals at mesh and strips)
- Inputs for main background sources
  - Measured fluxes of environmental backgrounds in Canfranc (γ, neutrons, μ)
  - Activity measurements from an extensive material screening program underway for several years to select components for design of set-up, mainly based on germanium gamma spectrometry at LSC
- Points to 40K in the Micromegas detectors as the main limiting source of background
- The expected background levels are in the range 1-10 c keV^{-1} kg^{-1} day^{-1} (= 1-10 dru)

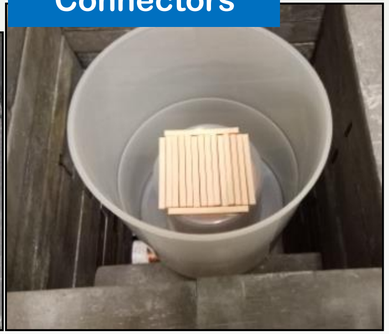


Microbulk Micromegas

Flat cables



Connectors

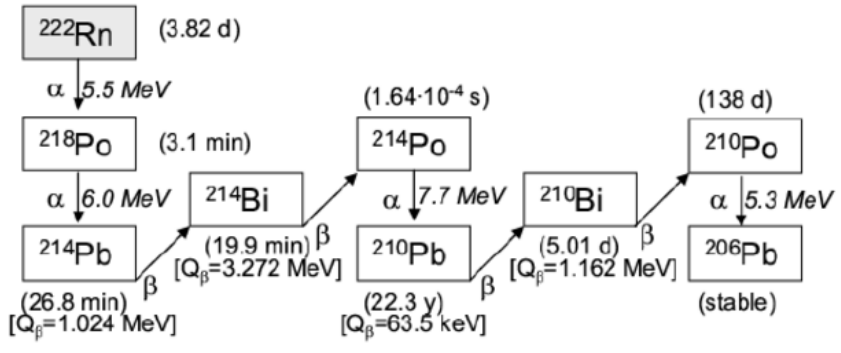


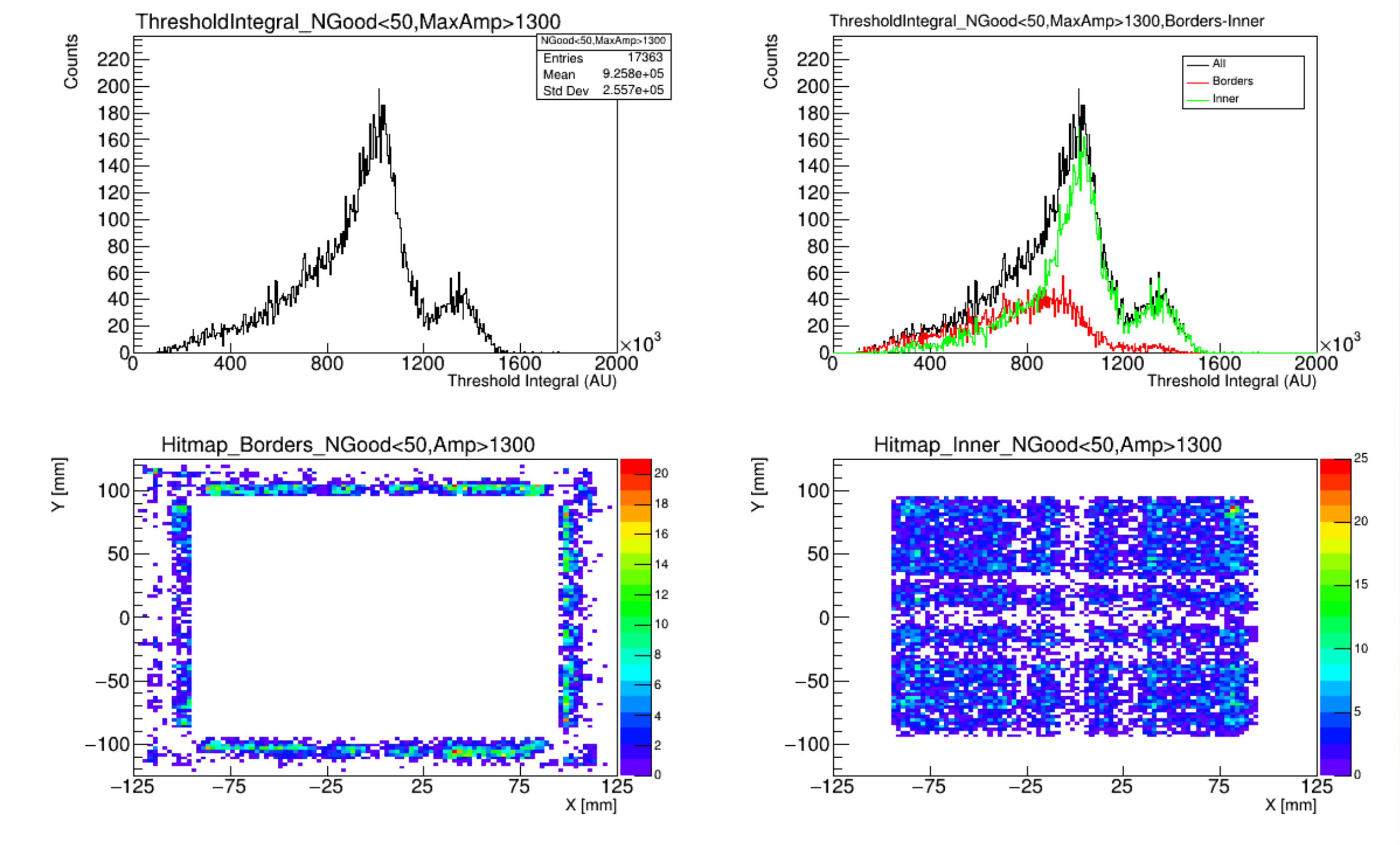
AGET chips

"Background assessment for the TREX Dark Matter experiment"
https://arxiv.org/pdf/1812.04519.pdf

Background status: Rn issue

- Since first runs in 2020, evidence of contamination from Rn.
- Special low gain (HE) runs show alpha events:





- Black: "5 MeV peak" (5.5 + 6.0 + 5.3) and "7 MeV peak" (7.7 MeV)
- Inner: Rn + progeny
- Borders: surface 210Pb (5.3 MeV from 210Po)

Background status: Rn issue

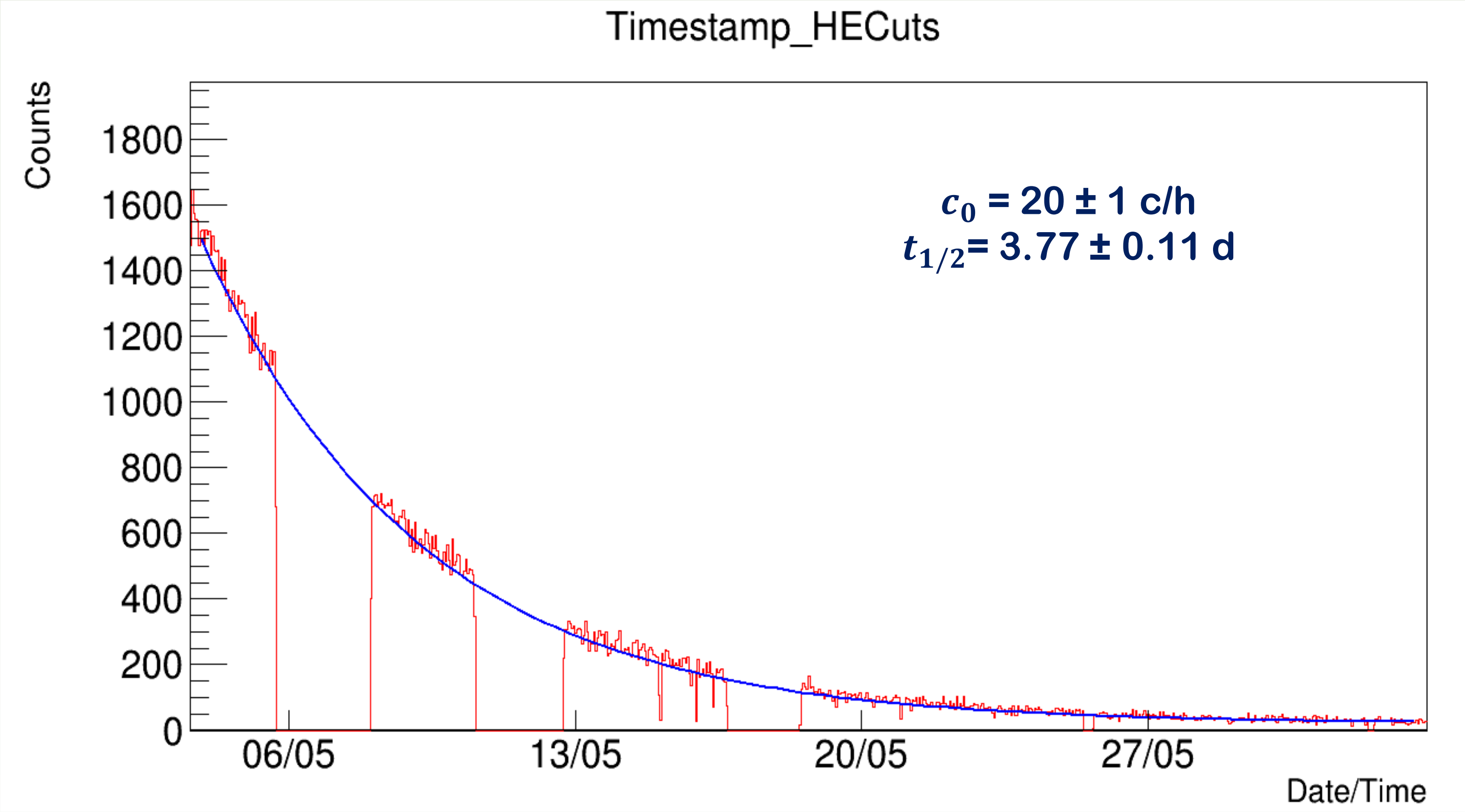
Filters in the gas system

Left: H_2O; right: O_2

Background status: Rn issue

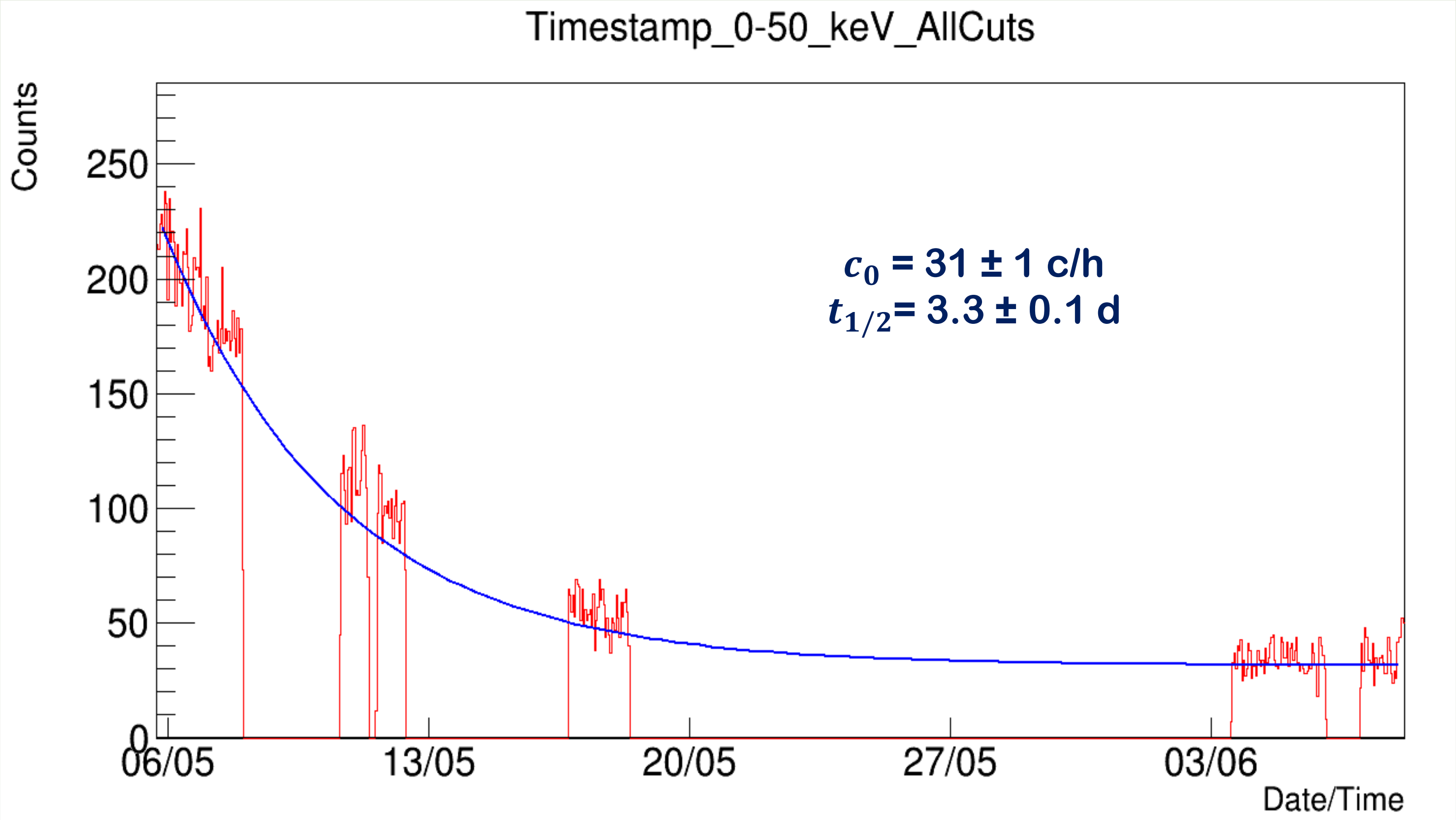
- **LE and HE runs during 1 month in seal mode**
- **They supported the hypothesis of Rn + constant component: decrease in alpha rate and background rate in 0-50 keV after cuts**

Low-gain runs (alphas) $c_0 + c_1 e^{-c_3 t}$



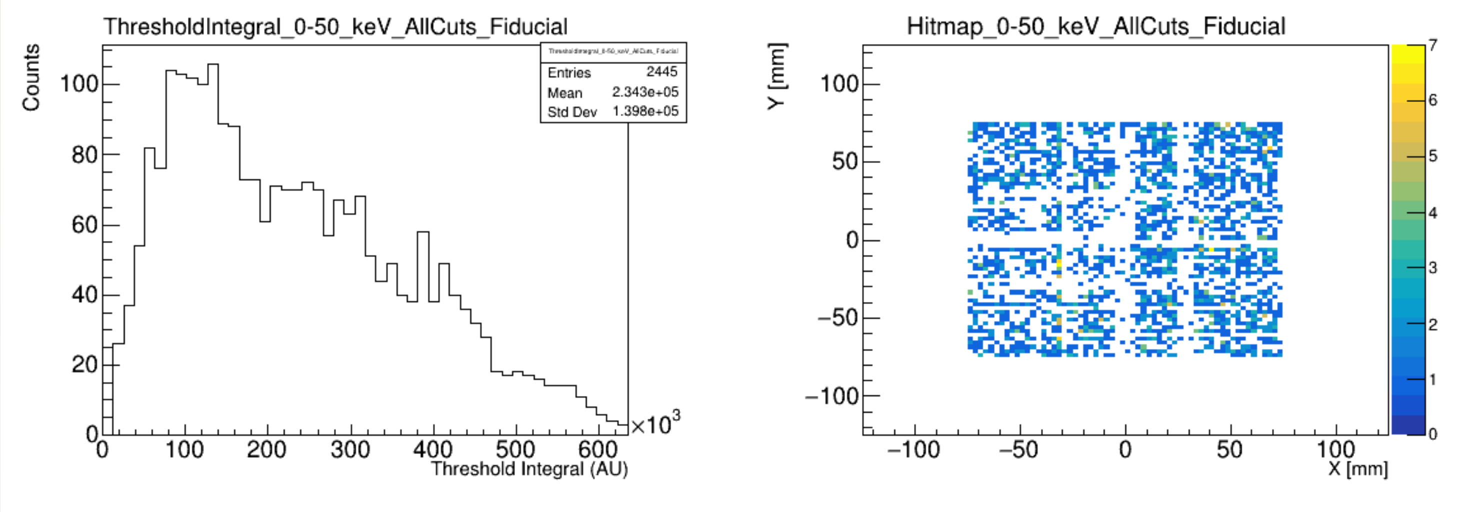
Background status: Rn issue

Nominal-gain runs (low energy) $c_0 + c_1 e^{-c_3 t}$



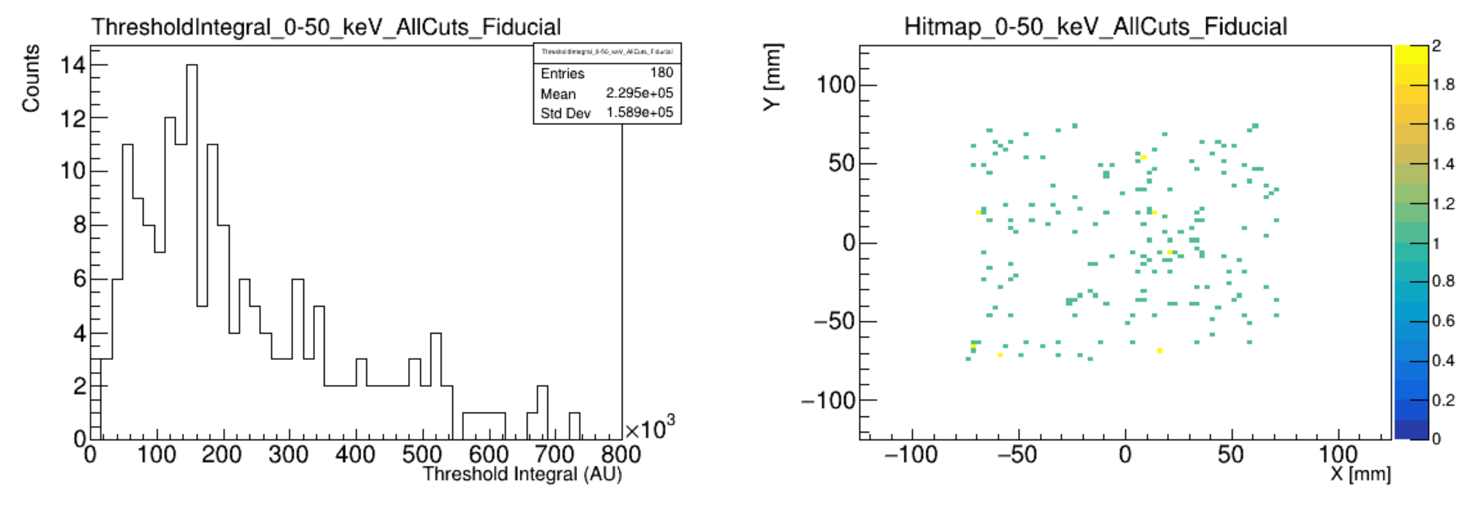
Background status: Rn issue

Background @ low energies



Before Rn decay

0-50 keV → 600 dru



After Rn decay

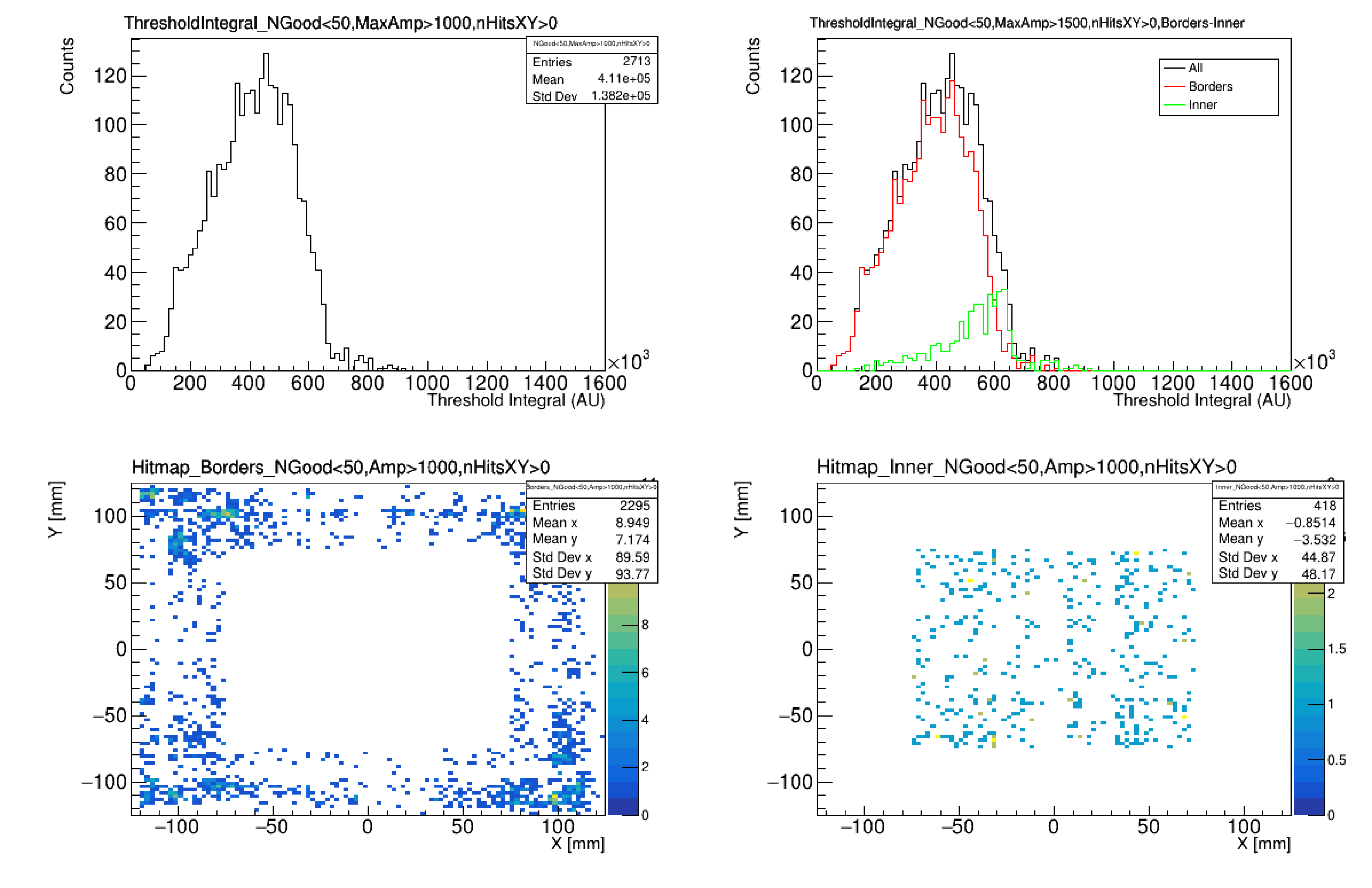
0-50 keV → 100 dru

Background status: Rn issue

- **Internally emanated Radon is the main source of background (removing it takes us from ~600 dru down to ~100 dru in the 0-50 keV range)**
  - **A lot of effort put into removing it from the system:**
    - **Trying with several commercial filters**
    - **Testing 5Å molecular sieves (we found out they do trap Rn, but emanate more than Agilent filters, best commercial filters we have)**
    - **Testing a custom-made O2+H2O filter developed by the University of Birmingham with low-emanation materials (ongoing collaboration with NEWS-G)**
    - **Testing activated carbon filters**
    - **Open-loop operation bypassing the filters and the recirculation pump**

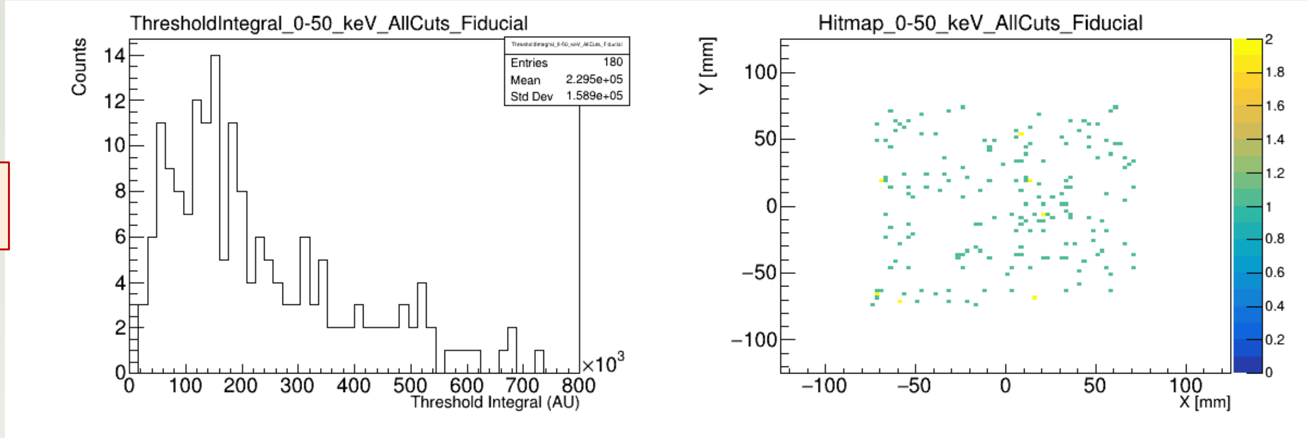
- **Rn progeny surface contamination may well be responsible for the rest of background not accounted for in our background model**
  - **A program to identify alpha surface contaminations + its mitigation is ongoing**

Open loop: no longer a Rn spectrum, only surface contamination



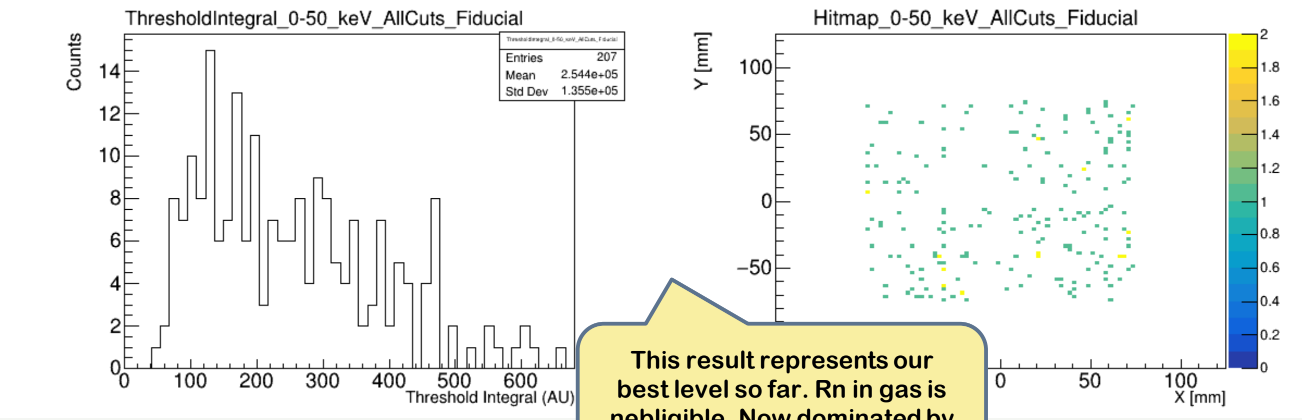
Background level comparison: seal mode in June 2021 vs. open loop

Sealed mode: after Rn decay



0-50 keV: 120 dru

Open loop



0-50 keV: <80 dru

This result represents our best level so far. Rn in gas is nebligible. Now dominated by Pb210 in surfaces

40K issue in microbulks

Micromegas id	40K activity with GeAnayet ($\mu Bq/cm^2$)*	Dead channels number (out of 512)	Maximum voltage reached at mesh
MM4S_1	Not measured but should be like #2 & #3	5	300 V
MM4S_2	1.07 ± 0.23	2	295 V
MM4S_3	1.07 ± 0.23	0	305 V
MM4S_4	< 1.2	3	280 V
MM4S_5	< 1.2	4	285 V

* Previous value of 40K activity (in background model) = 3.45 ± 0.40 $\mu Bq/cm^2$

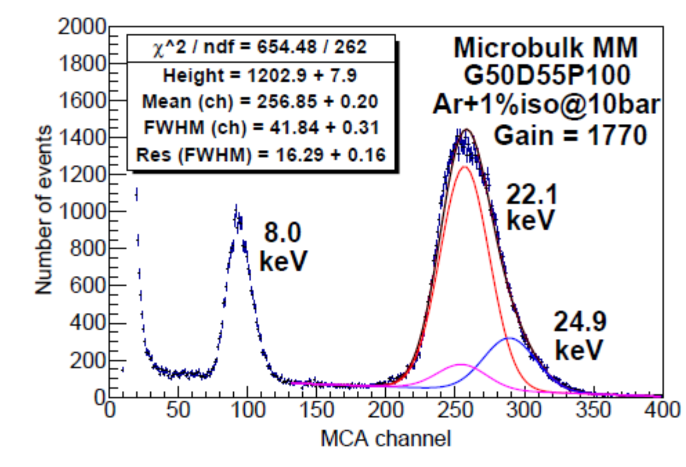
Factor of x4 (probably more) improvement demonstrated (this theoretically brings 40K in back. model to levels well below 1 dru)

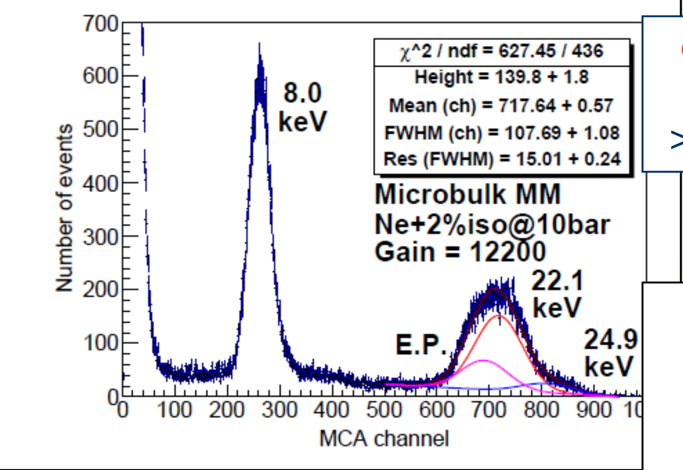
Radiopurity measured on 1m2 witness samples that underwent exactly the same chemical process than the microbulk readouts

Publication on microbulk radiopurity in preparation…

Detector performance

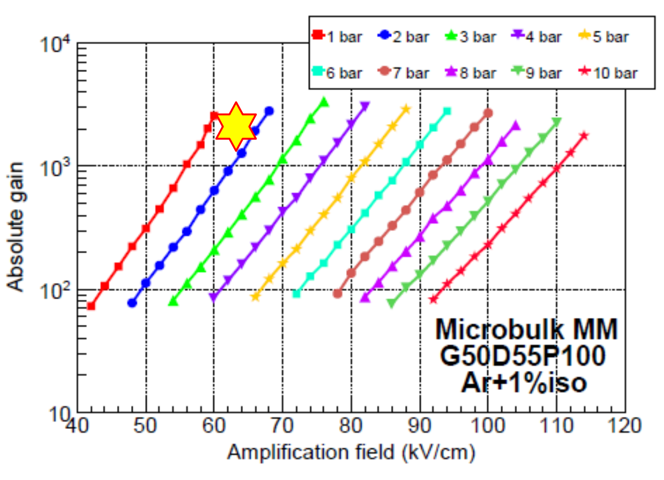
- Characterization of Microbulk Micromegas in non-flammable gases in a simplified set-up
  - Ar+1%iC_4H_{10} and Ne+2%iC_4H_{10} at 1-10 bar
  - Source: ^{109}Cd

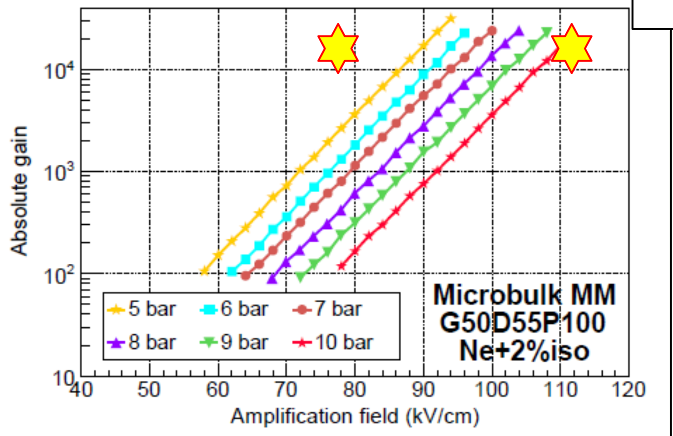




Gain: excellent behaviour, maximum >10^3 in Ar and >10^4 in Ne for all pressures

F.J.Iguaz et al, "Microbulk Micromegas in non-flammable mixtures of argon and neon at high pressure", in preparation

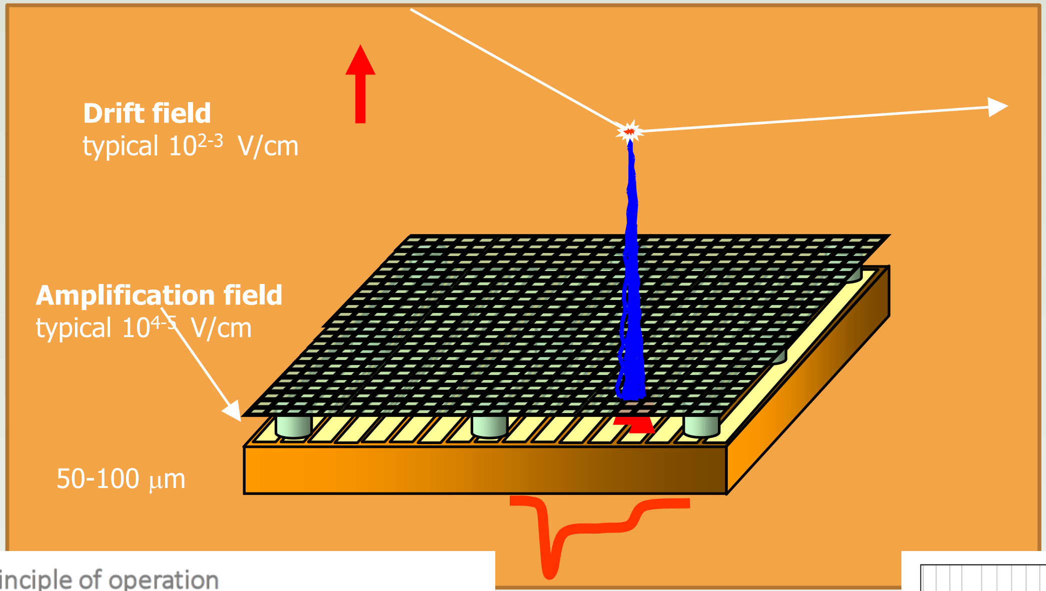




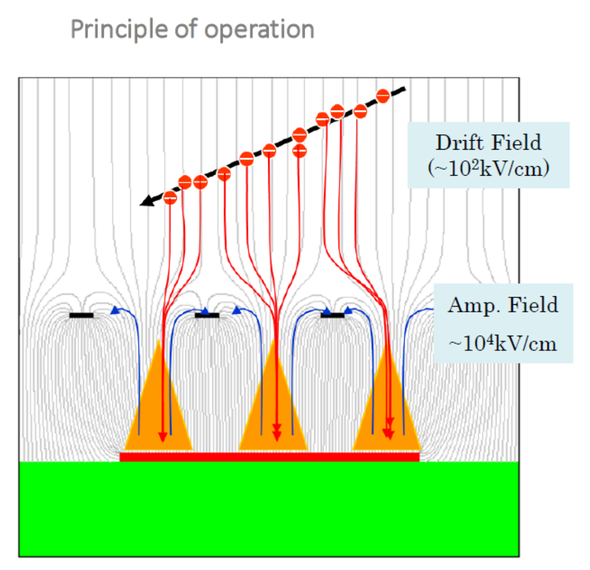
Energy resolution: some degradation with pressure

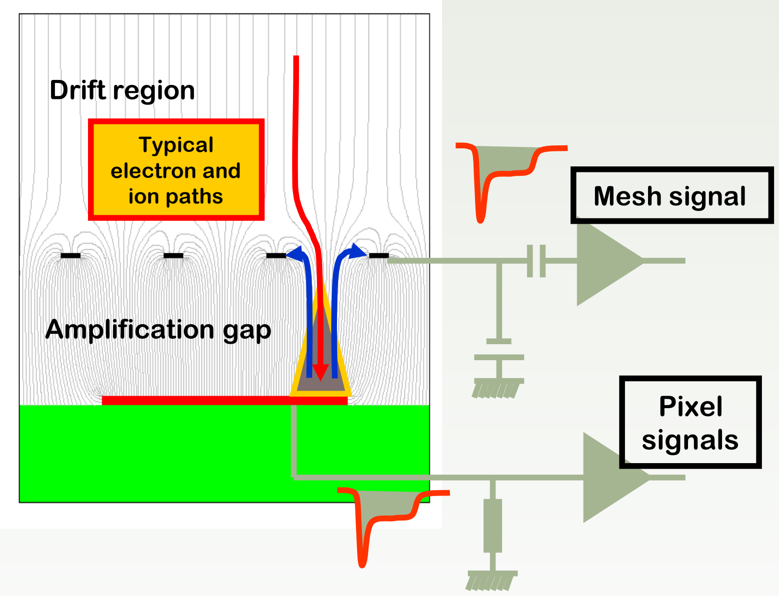
Micromegas readouts

- Giomataris, Charpak (96)



Simplicity
Granularity
Homogeneity
Large areas
…

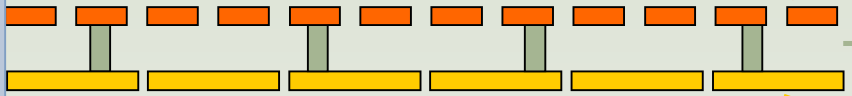




Micromegas readouts

BULK
Robust
Mature
Very large areas available ($2\ m^2$)

Readout plane + mesh all in one



Woven Inox mesh 30 µm

vacrel 128 µm

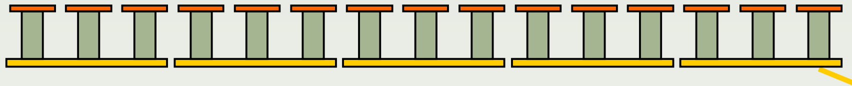
Readout pads

Well established technique

T-REX R&D

•MICROBULK
Higher homogeneity
Light weight, radiopure

Readout plane + mesh all in one



Micromesh 5µm copper

Kapton 50 µm

Readout pads

CERN+CEA+UNIZAR development

See for details:
JINST 5 (2010) P02001

Beyond microbulk?

Microfabricated Micromegas

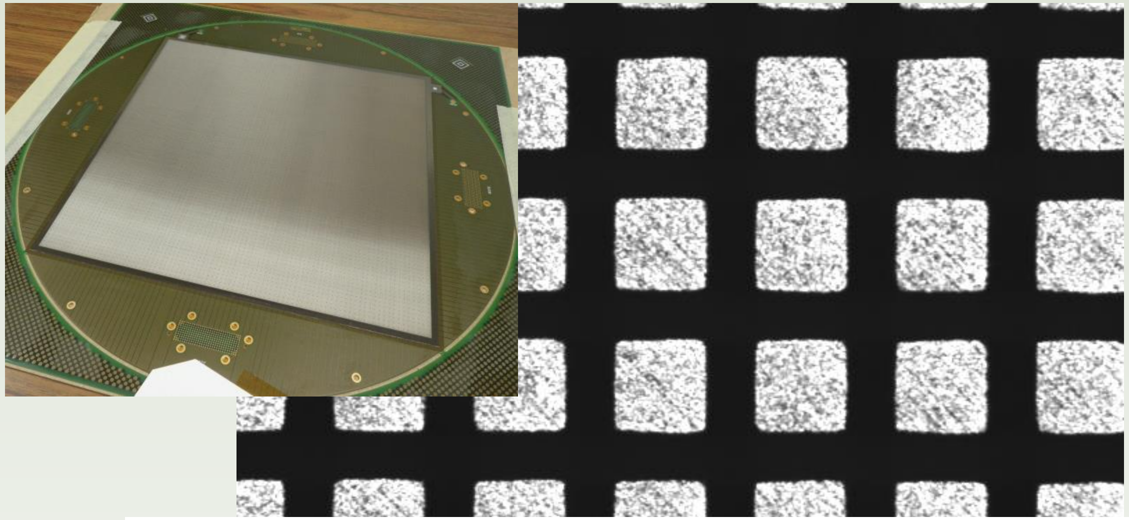
Started development with CNM

Micromegas structures with Si-wafer microfabrication techniques…

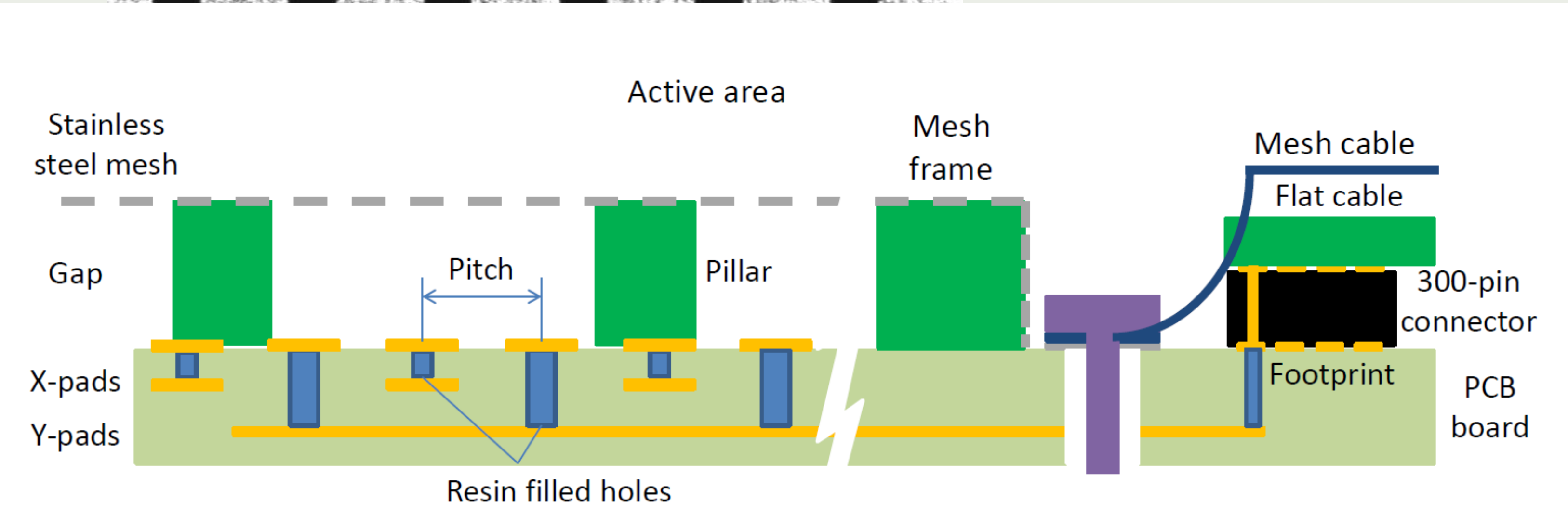
Higher Flexibility & precision in geometrical parameters

Better tailored to application…

Micromegas readout planes

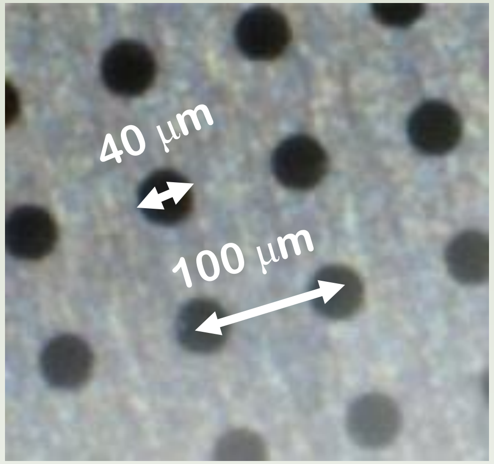


- Bulk @ IRFU/Saclay.
- PCB @ Somacis.
- Area: 25.2 x 25.2 cm^2.
- Squared pads 332 μm, pitch 583 μm.
- Interconnected to 432 strips/direction.

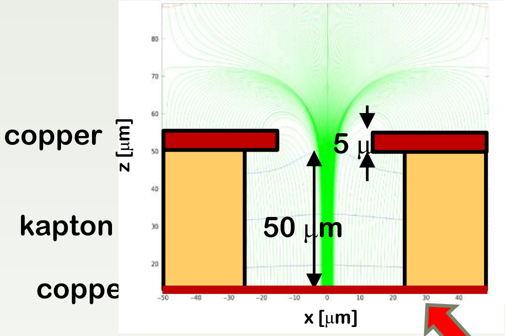


Microbulk Micromegas

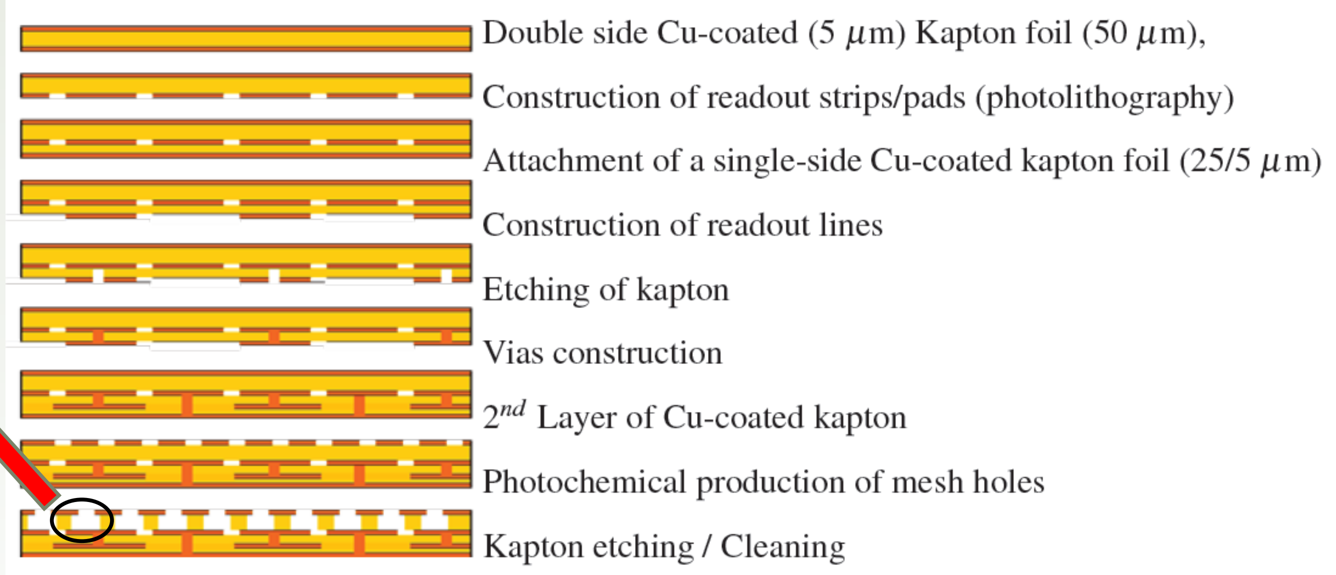
- Made out of copper & polyimide (kapton)
  - potentially very radiopure
- High gap homogeneity
  - good energy resolution
  - Stability/homegeneity in response



Manufactured at Rui de Oliveira's workshop at CERN

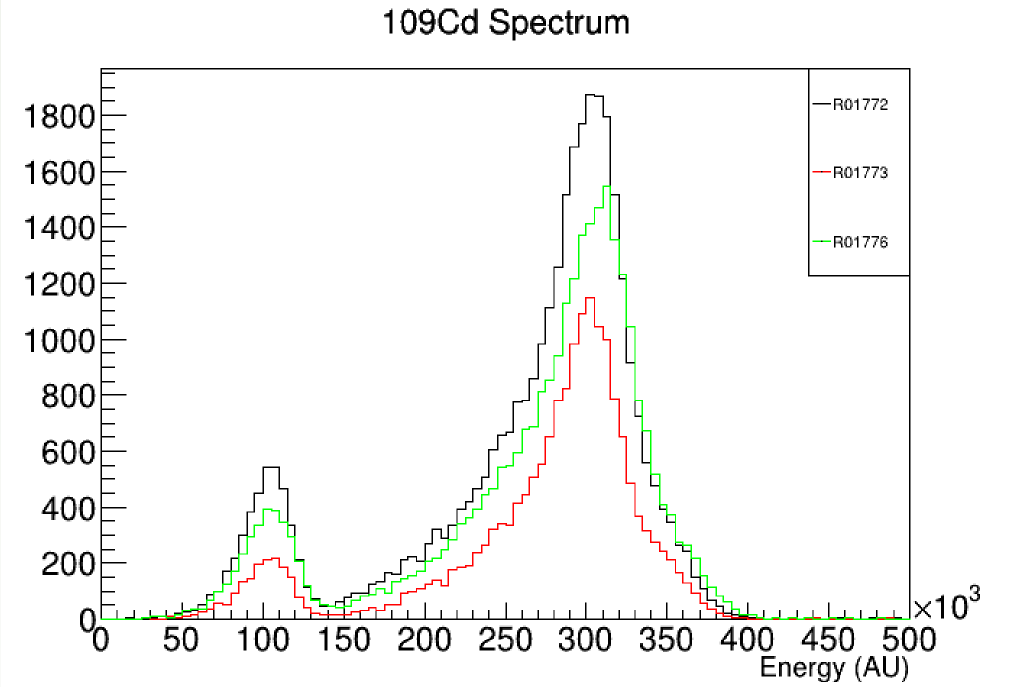


See for details:
JINST 5 (2010) P02001



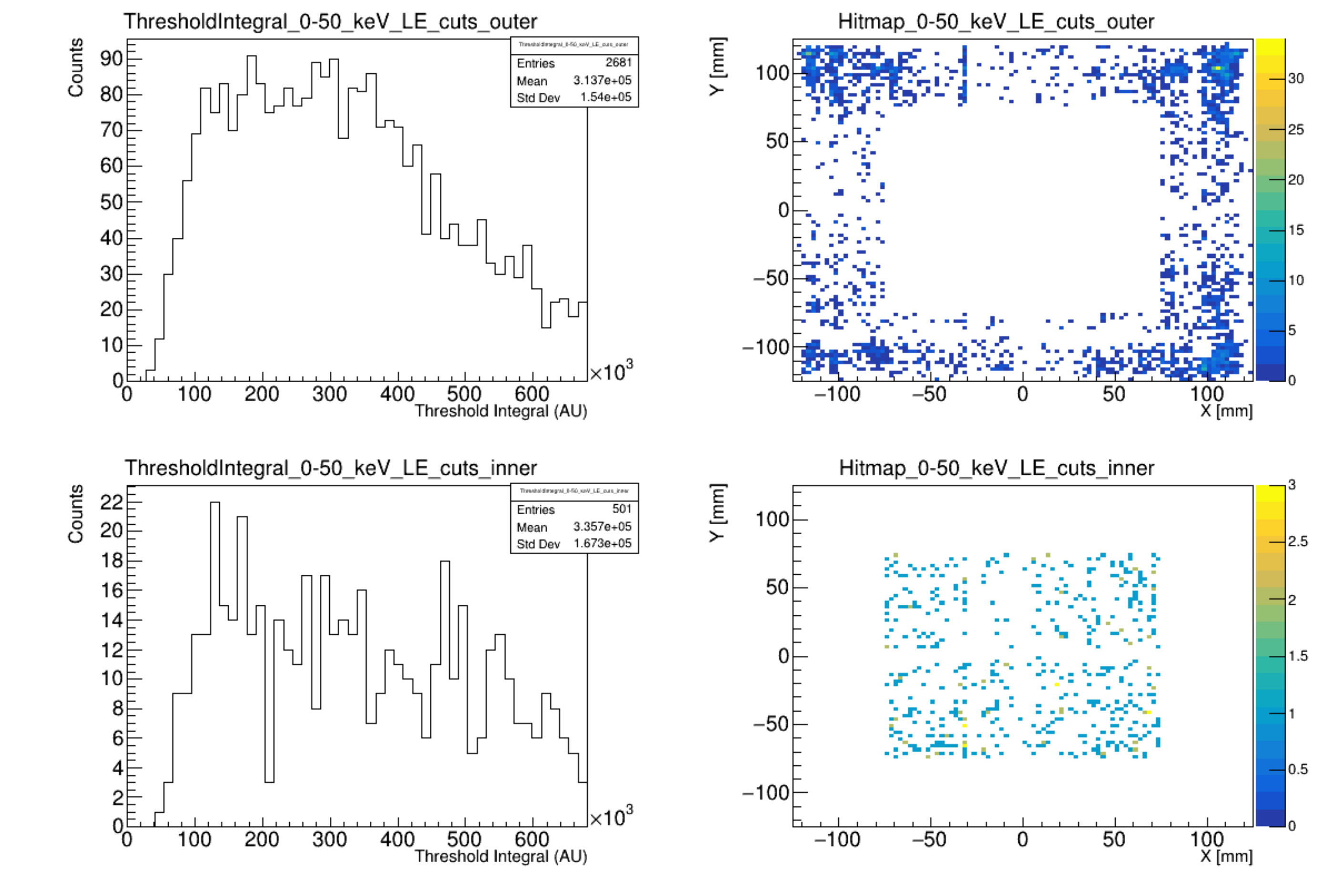
Flow optimisation in open loop: 109Cd calibrations

0.9 ln/h ⟹ one renovation every 11.5 days



Calibrations after 0, 1 and 2 weeks at 0.9 ln/h ⟹ gas is clean with this flow

Vmesh: 365 V (nominal gain), 0.9 ln/h, 4.5 days

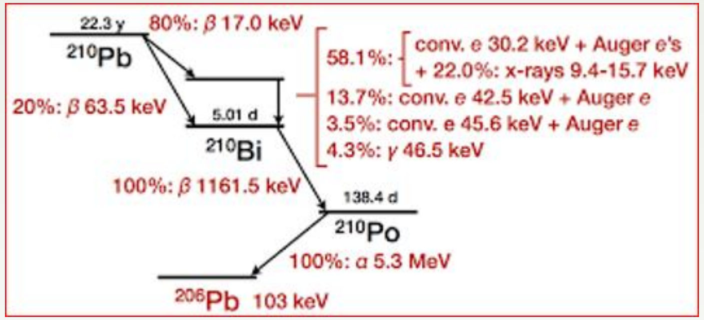


25 c/h

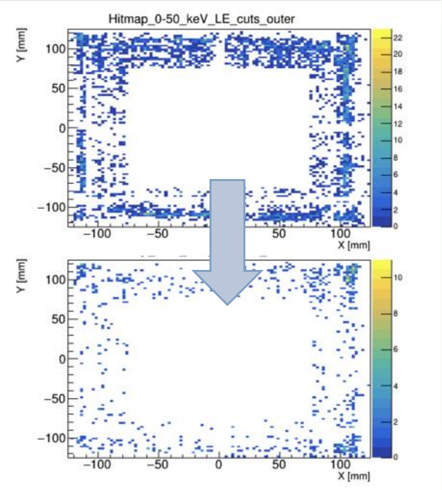
< 5 c/h!

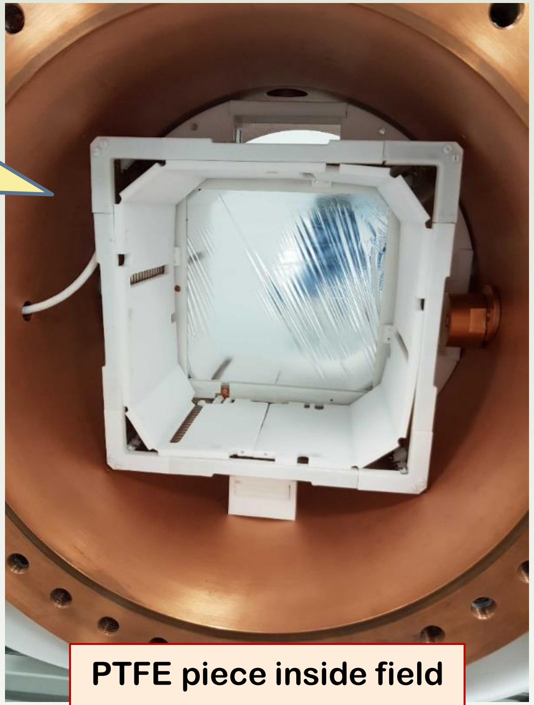
Surface alphas (Rn progeny)

- Rn progeny (Pb210) attached to surfaces (from past exposure) produces alpha events, but also LE events (in similar proportion)



Reminder: machining of the Teflon walls led to reduction of both HE and LE background counts in the outer region

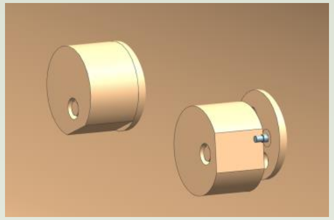


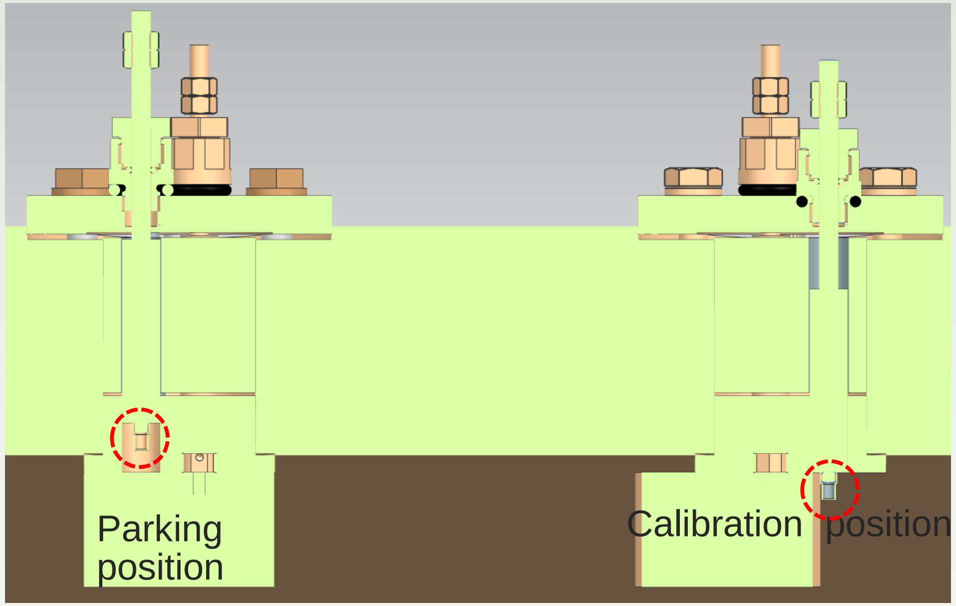


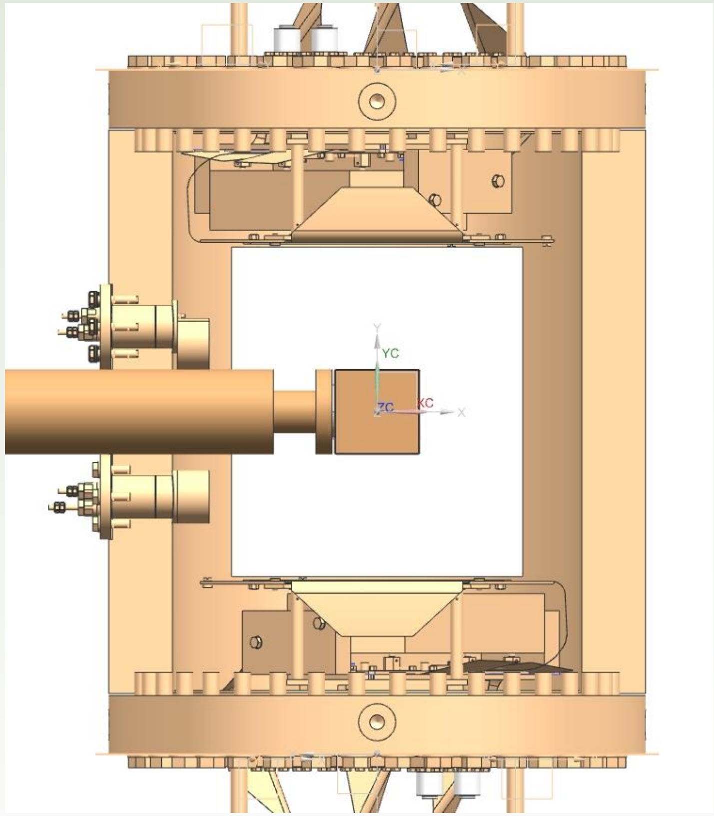
PTFE piece inside field cage

Detector: calibration system

- Design:
  - Two exempt ^{109}Cd sources (8 μCi, emissions at 3, 22, 25 and 88 keV) on the side of the vessel, each facing one detector active volume
  - A lever to move a 6 cm-thick copper piece, which blocks all the radiation emitted by the source.







- Status:
  - Design validated by a leak-test
  - New pieces being built at the LSC workshop