Modern approaches in ultra-low background experiments at the LSM underground laboratory

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What is connection of high energy physics and investigation of rear processes underground ?

Underground physics

- Physics beyond the standard Model, search for rare events or decays

- Proton decay GeV

  Origin of the creation of deep underground labs

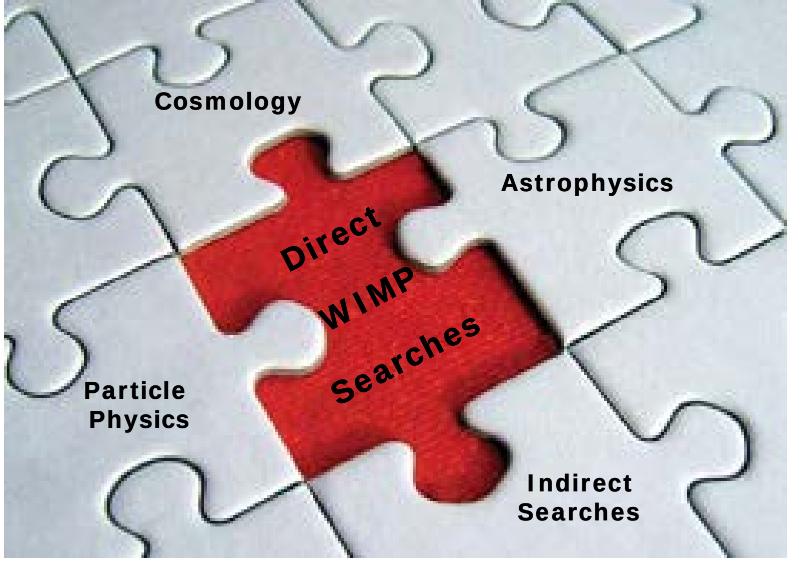
  - ❑ SUSY

- Neutrino oscillations and astronomy MeV - GeV
  - ❑ Solar neutrinos
  - ❑ Atmospheric
  - ❑ Accelerators
  - ❑ SuperNovae

- Neutrino properties MeV
  - ❑ Double beta decay Nature of neutrino and mass

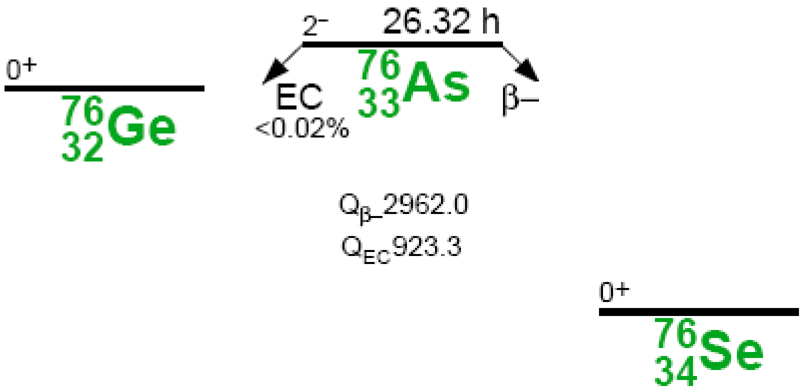
- Dark matter keV
  - ❑ Universe content

Dark Matter puzzle



- Cosmology
  - non-baryonic DM in the early Universe *[WMAP, Planck, …]*
- Astrophysics
  - Gravitational probes at galactic/cluster sizes
  - WIMPs present in our Galaxy with density ~0.3 GeV/cm^3
- Particle Physics
  - **Thermal relics WIMPs appear as natural consequence of SUSY *[LHC]***
- Indirect Searches
  - Annihilation decay products:
    too many phenomena too be decisive (?),
    many experiments with different approaches
- **Direct Searches**:
  - background free measurements
  - winter/summer modulation measurements
  - Is DM particles of the halo are those can be produced at LHC?

Neutrinoless Double Beta Decay, and its importance for Neutrino Physics and Astrophysics



In the Standard Model this process cannot occur without neutrinos

Observation at any level would imply:

- Lepton number L is not conserved
- Neutrinos have *Majorana masses* — masses with a different origin than the quark and charged lepton masses
- Neutrinos are their own antiparticles

Observation of 0νββ would make more plausible:

- The See-Saw model of the origin of neutrino mass
- Leptogenesis, an outgrowth of the See-Saw, which may be the origin of the baryon-antibaryon asymmetry of the Universe

General opinion of the particle physics community:

A non-zero signal for 0νββ would be a tremendously important discovery

2 tasks for any modern experiment:

- **Target mass (i.e. expected number of "good" events)**
- **Reduction and understanding of backgrounds**

  - **Cosmic rays and cosmic activation**

  - **Ambient natural radioactivity**
    - **Radioactivity of materials**
    - **Radioactive dust**
    - **Radioactive gases**

  - **Exotic (neutrino induced background, etc)**

  …

Very performant detector(s)
Energy threshold, good resolution(s), selection power

Large volume
10 kg – 1 ton

Efficient shielding,
Underground lab,
material selection, …

Shield/ underground

Primary cosmic rays composed essentially of all periodic elements:

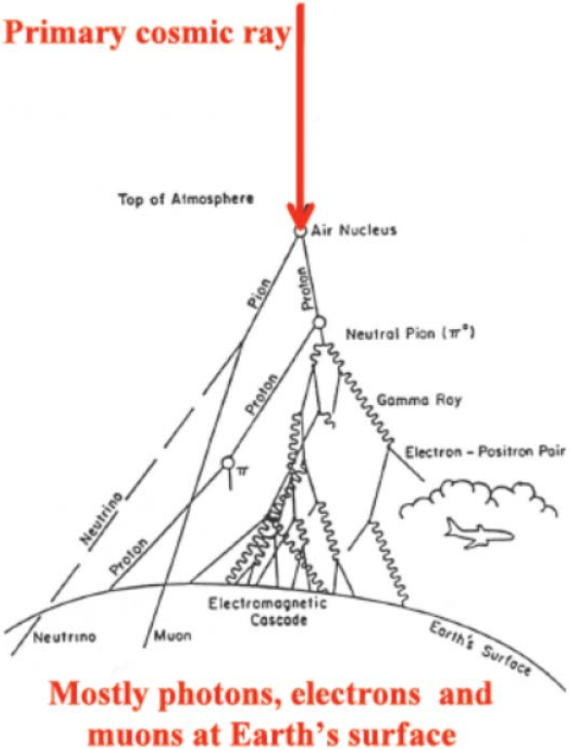
~ 89% protons, ~ 10% helium nuclei

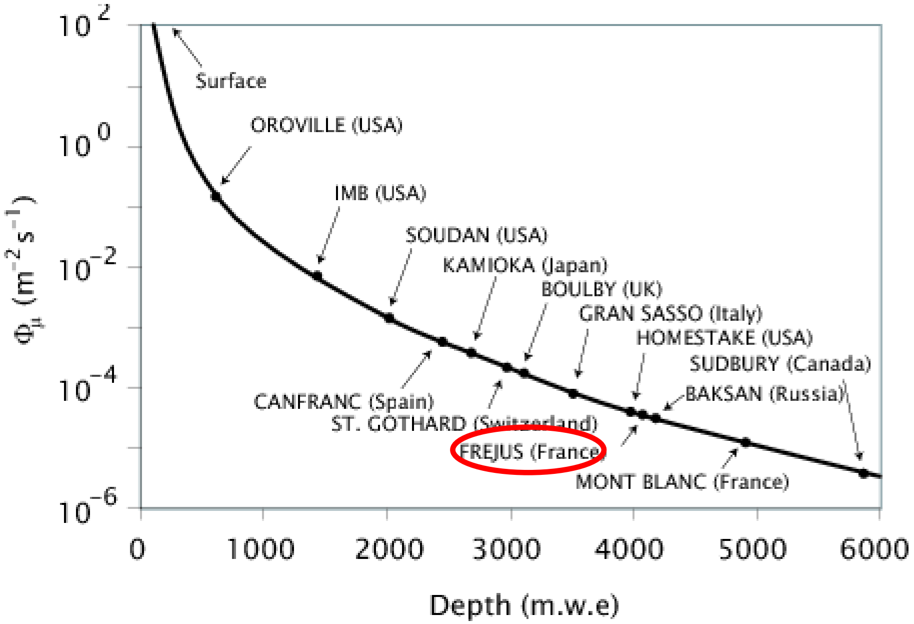
~1% heavy elements (C, O, Si, …)

• At sea level, most are muons with mean energy at 4 GeV, but there are also much higher energies

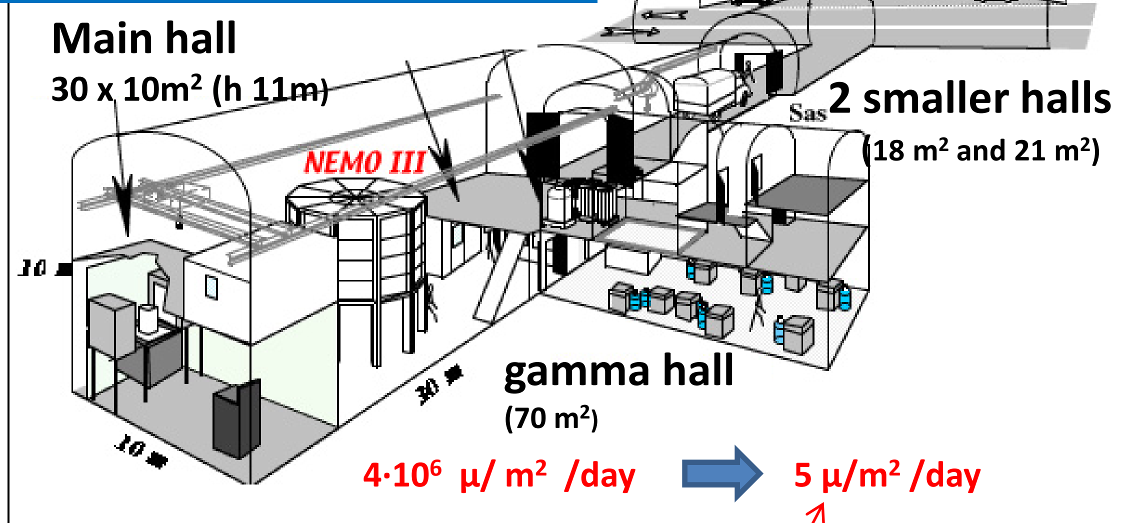
• Also, about 20% are fast neutrons

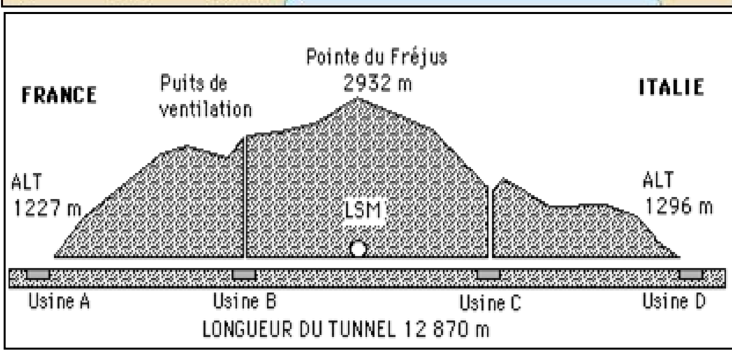
• Only deep underground laboratories can provide effective shield from the cosmic





LABORATOIRE SOUTERRAIN DE MODANE





Operators	CEA/DSM & CNRS/IN2P3
Location	Fréjus Tunnel (Italian-French border)
Excavation	1983
Underground area	main hall (30x10x11 m) + γ-spectroscopy hall (70 m²) + 2 secondary halls of 18/21 m²
Depth	1700 m (4800 mwe)
Surface	> 400 m²
Permanent staff	10
Scientists users	100+

Modane Underground Laboratory (LSM)

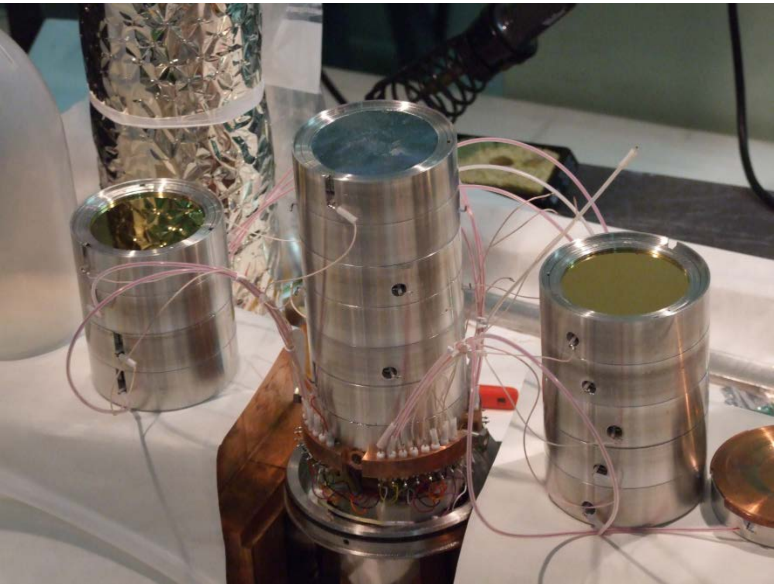
LSM / experiments

Direct DM search EDELWEISS

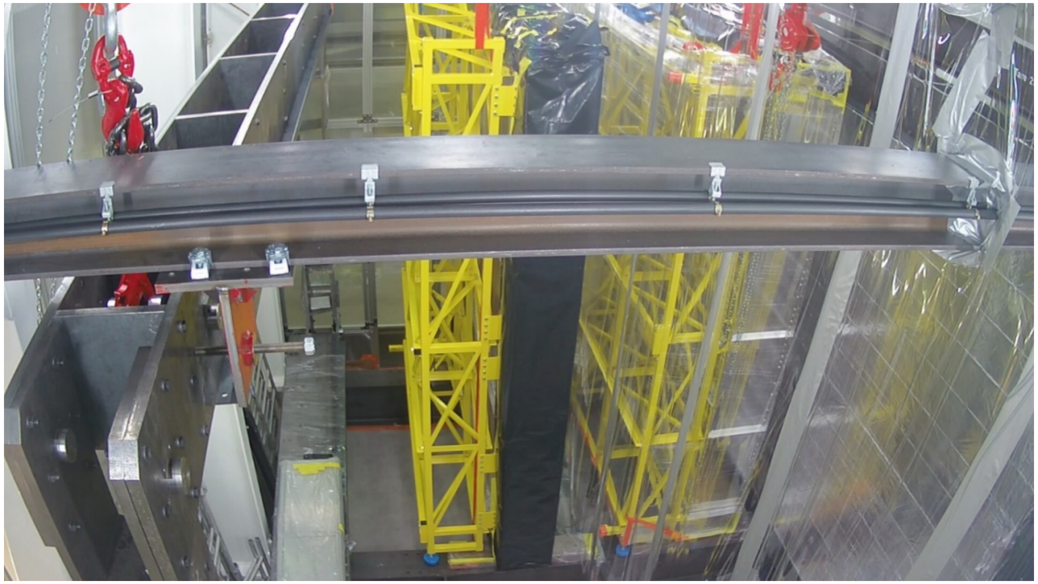
Doble beta decay with scintillating bolometers CUPID

Heavy elements in nature SHIN

Double EC TGV-II



World leading double beta decay identification NEMO



Traditional methods for reduction of backgrounds

- Underground laboratory
- Low radioactive materials
  - Material selection
  - Clean rooms
  - Clean conditions, (include air) during all phases of the experiment
- Multi layer passive and active shields (include shields from radioactive gases in air, from dust, etc)
  - New bigger detectors provides effective self-shielding

Background / γ (β)

Natural radioactivity is presented everywhere,

High penetration power

Connected problem – radioactive gases in the atmosphere (Rn, Kr, Ar)

Connected problem – radon progenies, ^{14}C, …

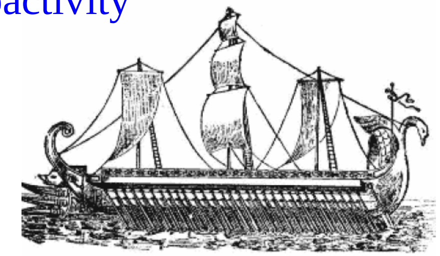
• Ultra pure materials (screening facilities, distillation and purification of liquids, radon free clean rooms for storage / assembly/ run).

• Shields

• Special methods (γ/nuclear recoil discrimination, fiducial cut, etc)

Shields / γ

This days background requirement: <1 event per kg per year
For example human body has: ~100 Bq/kg
Need to reduce by 10^9 times (minimum)
All construction materials have to be selected by their low radioactivity

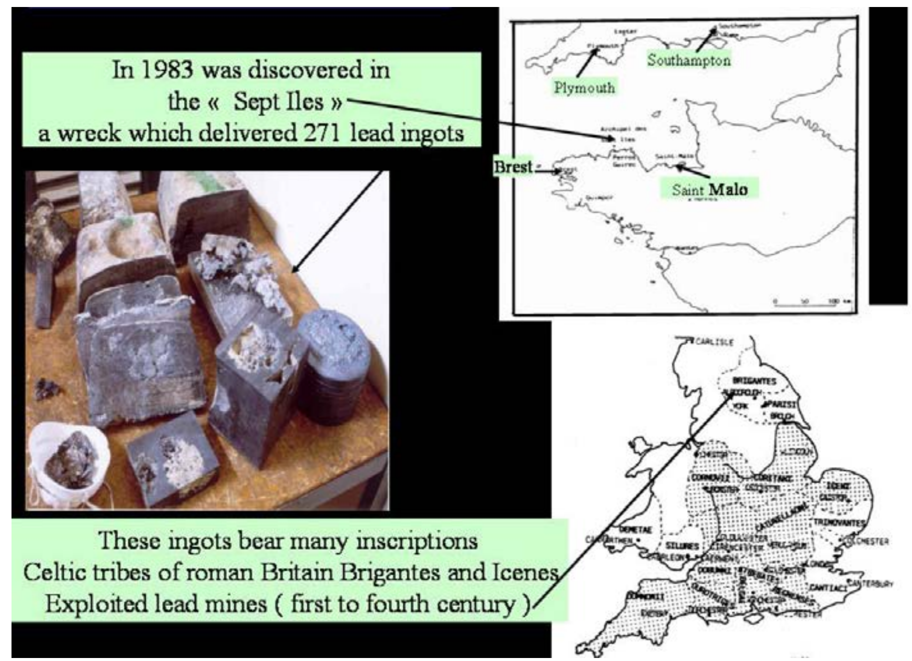


γ - using of multi layer shielding,
need high Z, less-radioactive, easy for mechanical treatment,
not very expensive.

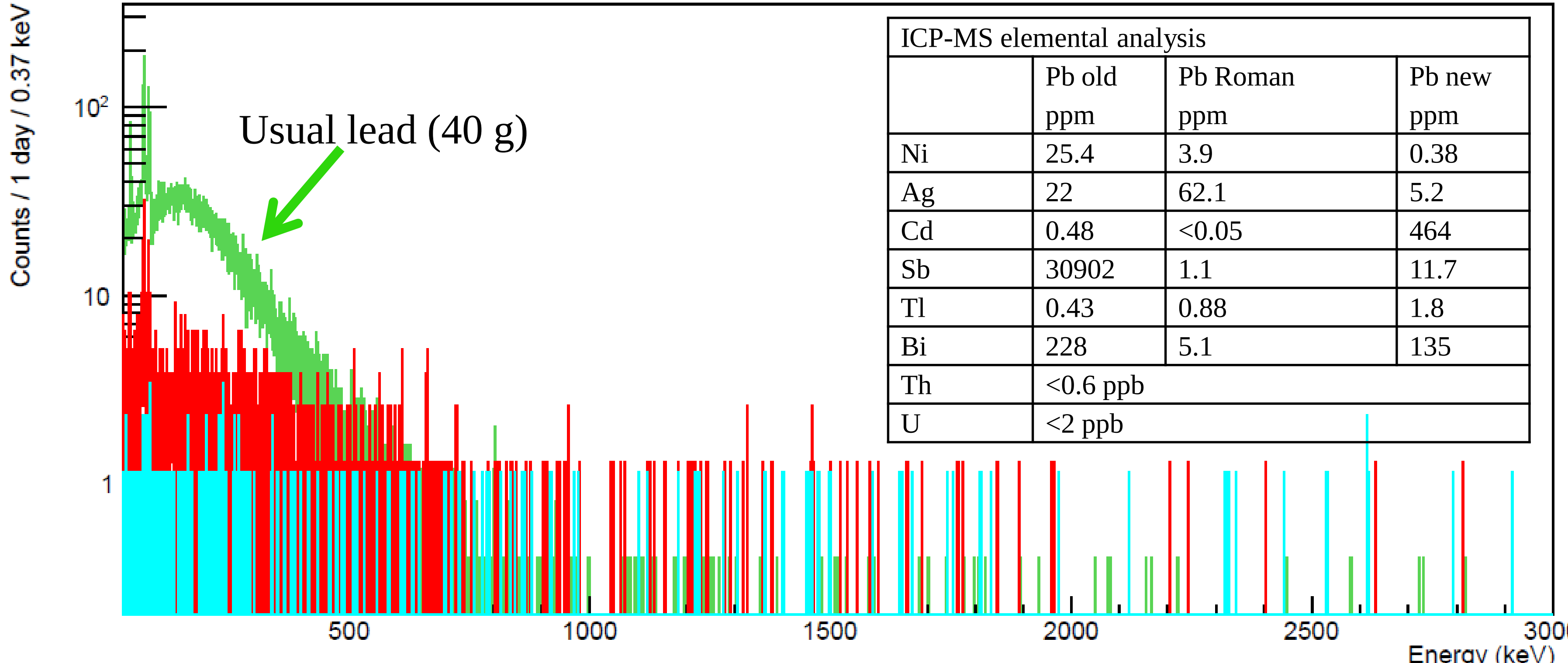
Lead is good, but has problem
with ^{210}Pb and it decay chain

Usual lead radioactivity:
20-100 Bq/kg

Solution: archeological lead,
2 centuries reduce ^{210}Pb activity by
1000 times



Measurements of Pb samples with the OBELIX (600 cm^3 HPGe) spectrometer (LSM)



ICP-MS elemental analysis			
	Pb old ppm	Pb Roman ppm	Pb new ppm
Ni	25.4	3.9	0.38
Ag	22	62.1	5.2
Cd	0.48	<0.05	464
Sb	30902	1.1	11.7
Tl	0.43	0.88	1.8
Bi	228	5.1	135
Th	<0.6 ppb		
U	<2 ppb		

Material selection

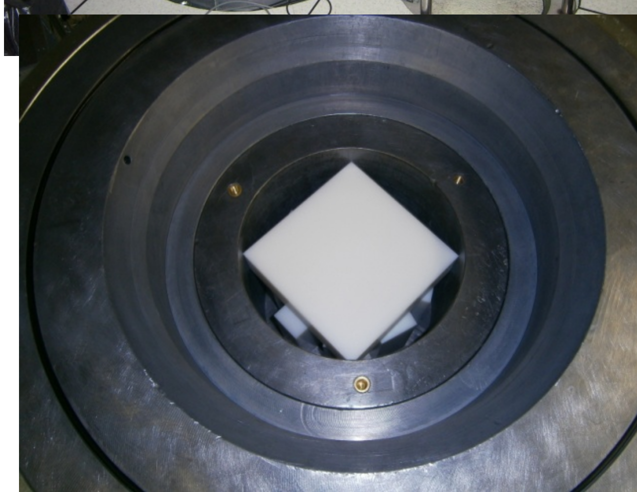
- Low background detectors are required (usually located in underground and special low background laboratories). Very often only limits of contaminations can be obtained

HPGe detectors in the LSM underground laboratory

- Prototype of setup is required

- Impossible to make final phase without phase1, phase2, …,

LSM experiments:
HPGe detectors in the underground lab
Two from them: Low background HPGe detectors with a sensitive volume of 600 cm^3; Relative efficiency: 160%;



NEMO, NEMO-2, NEMO-3, SuperNEMO
EDELWEISS-1, 2 now 3
with continuous increasing of mass target and reduction of backgrounds

Dominant radioactivity gases

Radon

- Natural decay chains (^{235}U, ^{238}U, ^{232}Th)
- ^{222}Rn dominant, 1-1000 Bq/m³ in air (depends on season, place, etc)

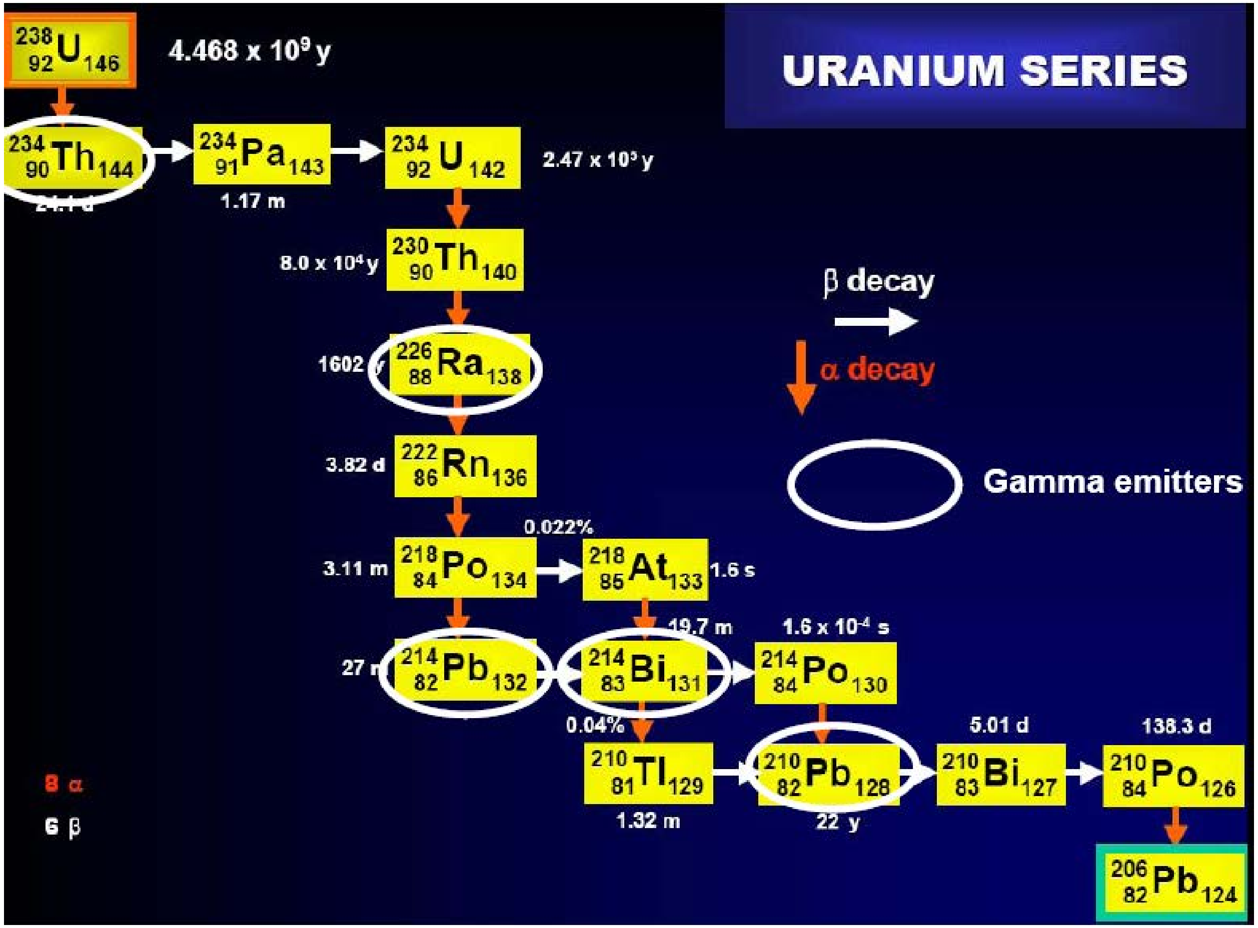
Krypton

- Anthropogenic origin (nuclear fuel reprocessing)
- ^{85}Kr $\Rightarrow$ 1 Bq/m³ in air (slowely rising with time)

There are also other radioactive gases (Tritium, Ar, gases with carbon (^{14}C), …)

Their impact depends from particular experiment …

Radon in nature / ^{222}Rn



LS (commercial)	**10^{-13} g/g**
Acrylic	**10^{-12} g/g**
Teflon	**10^{-10} g/g**
Stainless S	**10^{-9} g/g**
Glass	**10^{-7} g/g**
Welding rod	**10^{-6} g/g**
Rock	**10^{-6} g/g**

^{238}U decay rate= 12400 Bq/g

For example, rock has ^{238}U activity at ~10 Bq/kg

Radon important properties

Boiling point 211K, Freezing point 202K

In normal condition: gas (radioactive gas!)

Radon is noble gas! ⇒ main ”unfavourable” property is high penetrability in many medias (plastics, some glasses, etc), non transparent for “usual” gases

WARNING: If there is a weak point in your system, radon (unfortunately) will find it !

It has 3.8 days life time, long enough for it!

Important: metals non transparent for radon!

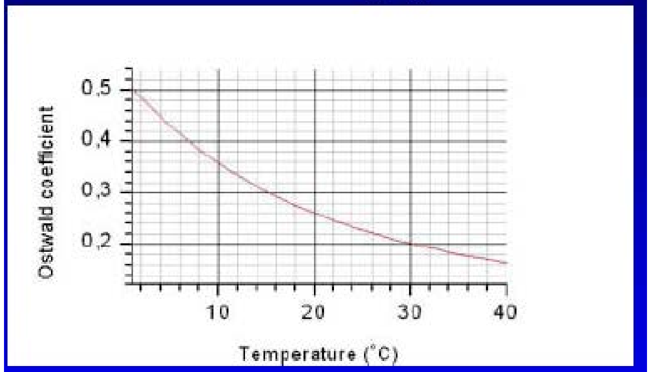
Radon can escape from metals only due recoil energy after alpha decay of radium

⇒ natural radioactivity of surface layer (10-30 nm) of metal is important

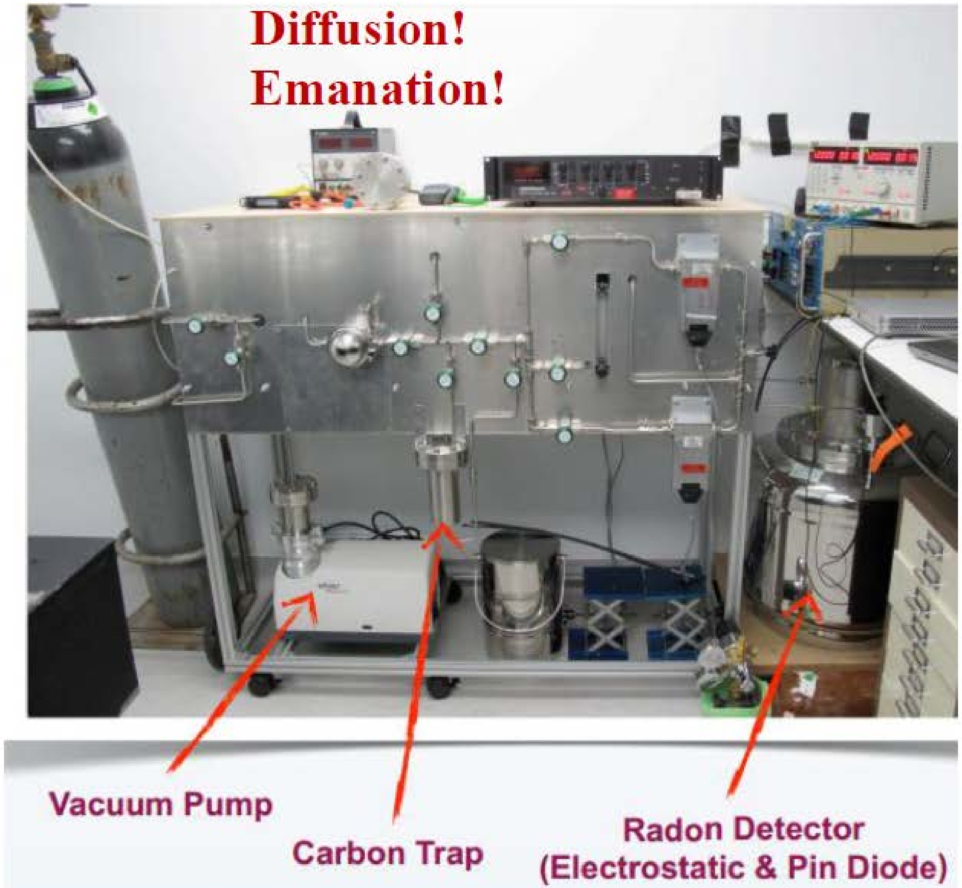
⇒ it is important to know, that radium go to surface when a metal is melting (need to remove surface layer by chemical or other way to lower radon emanation from metal surface)

Compound	Ostwald coefficient (L)
Water	0.285
CS_2	23.14
$CHCl_3$	15.08
Benzene	12.82
Toluene	13.24
Hexane	16.56
Xylene	15.4
Di-ethyl-ether	15.08
Petroleum	9.01
1-Pentanol	10.6
2-Butanol	7.58
Methanol	5.4

Solubility of radon in water (1)



The fight against radon



Radon line to work with tracker

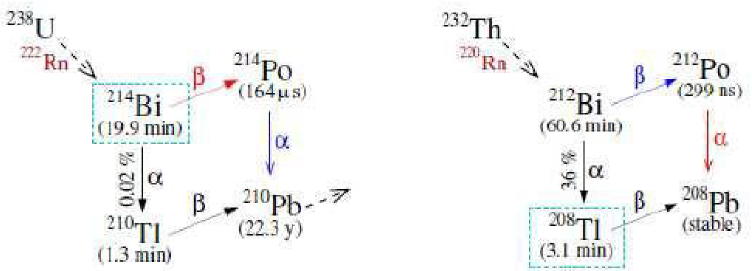
Radon emanation setup.

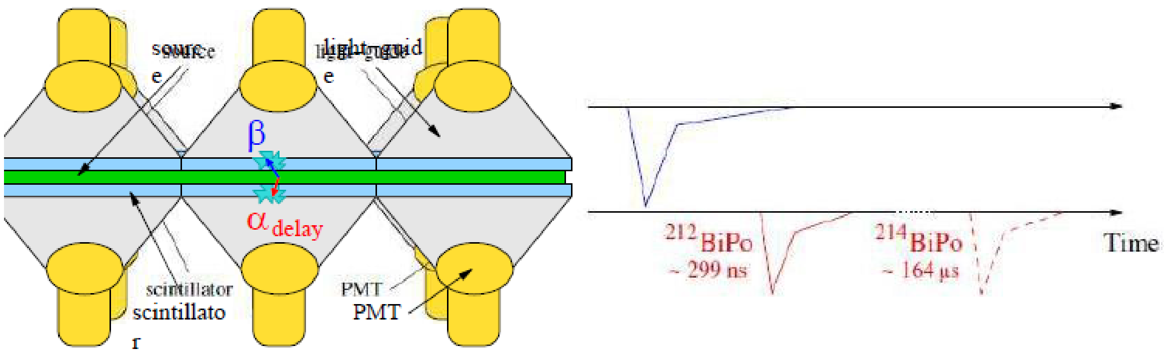
Tracker module under Rd measurement

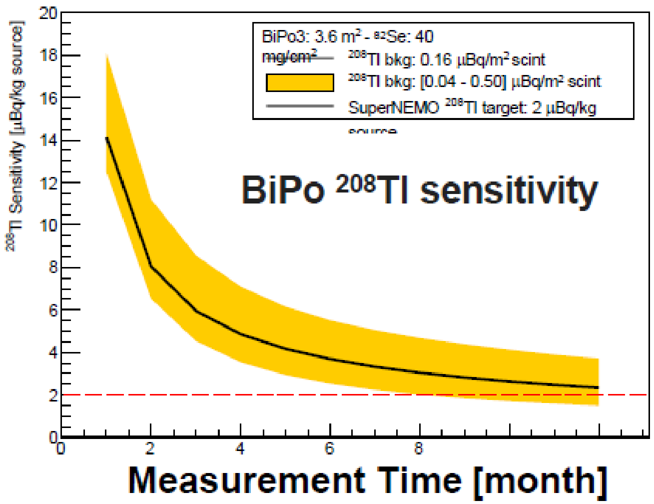
SuperNEMO example

The Bi-Po 3 detector

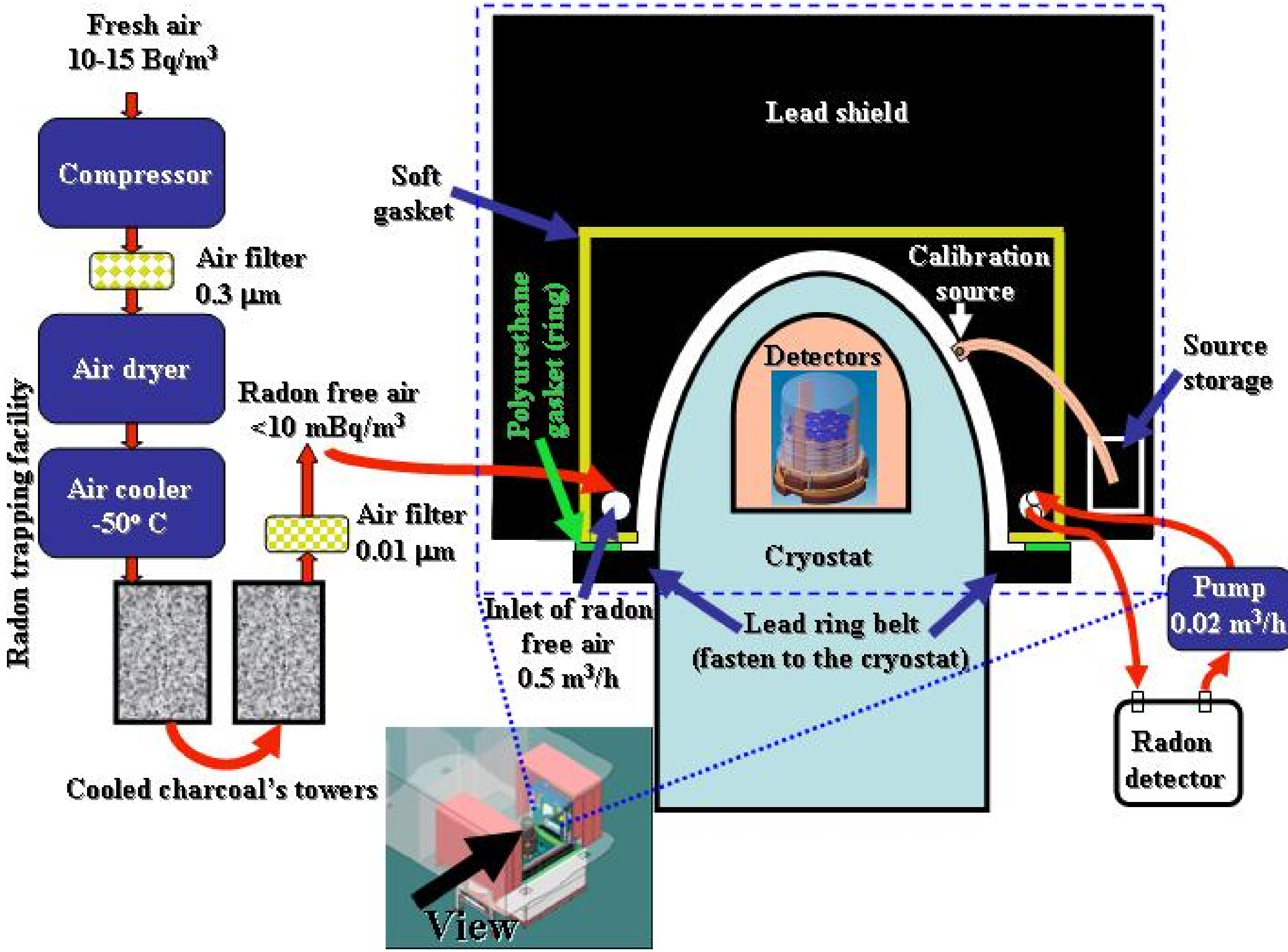
- HPGe spectroscopy not sensitive enough to reach few µBq/Kg: BiPo-3 dedicated setup at Canfranc underground lab
- 2 modules of 3.0x0.6 m^2 can measure up to 1.4 kg of ^{82}Se foil with thickness of 40 mg/cm^2
- ^{214}Bi and ^{208}Tl measured trough process from natural radioactivity chain
- Thin radiopure plastic scintillators coupled to lightguides and low radioactivity PTMs

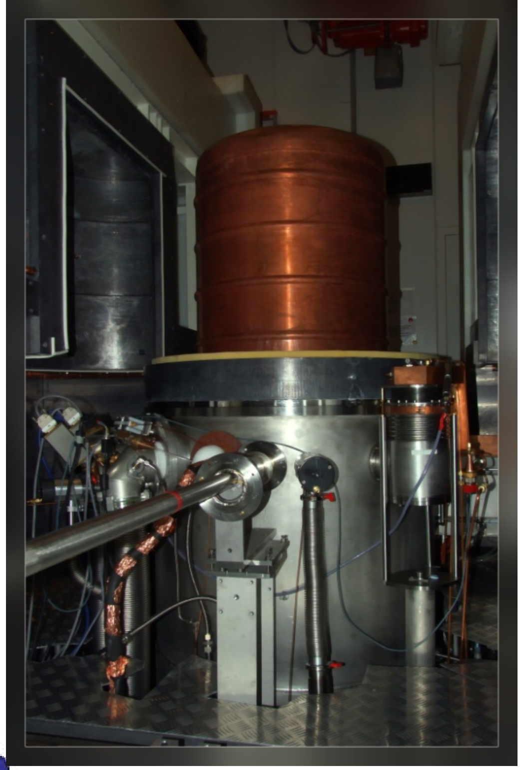






Shields / radon





Radon level at cryostat proximity < 50 mBq/m^3, thanks to anti-radon factory
Continuous control with high sensitive radon detector

Before of building of modern low background experiment we have to solve the radon problem:

- Radon free air

- Radon free clean rooms for storage/assembly

- Distillation and purification of liquids / gases

- Radon control measurements everywhere (not only at the setup)

Neutron background sources underground:

Low energy neutrons induced by U/Th activities

- fission and (α,n) reactions in the surrounding rock/concrete
- fission reactions in detector shield

High energy neutrons induced by muons

Fight with neutron background:

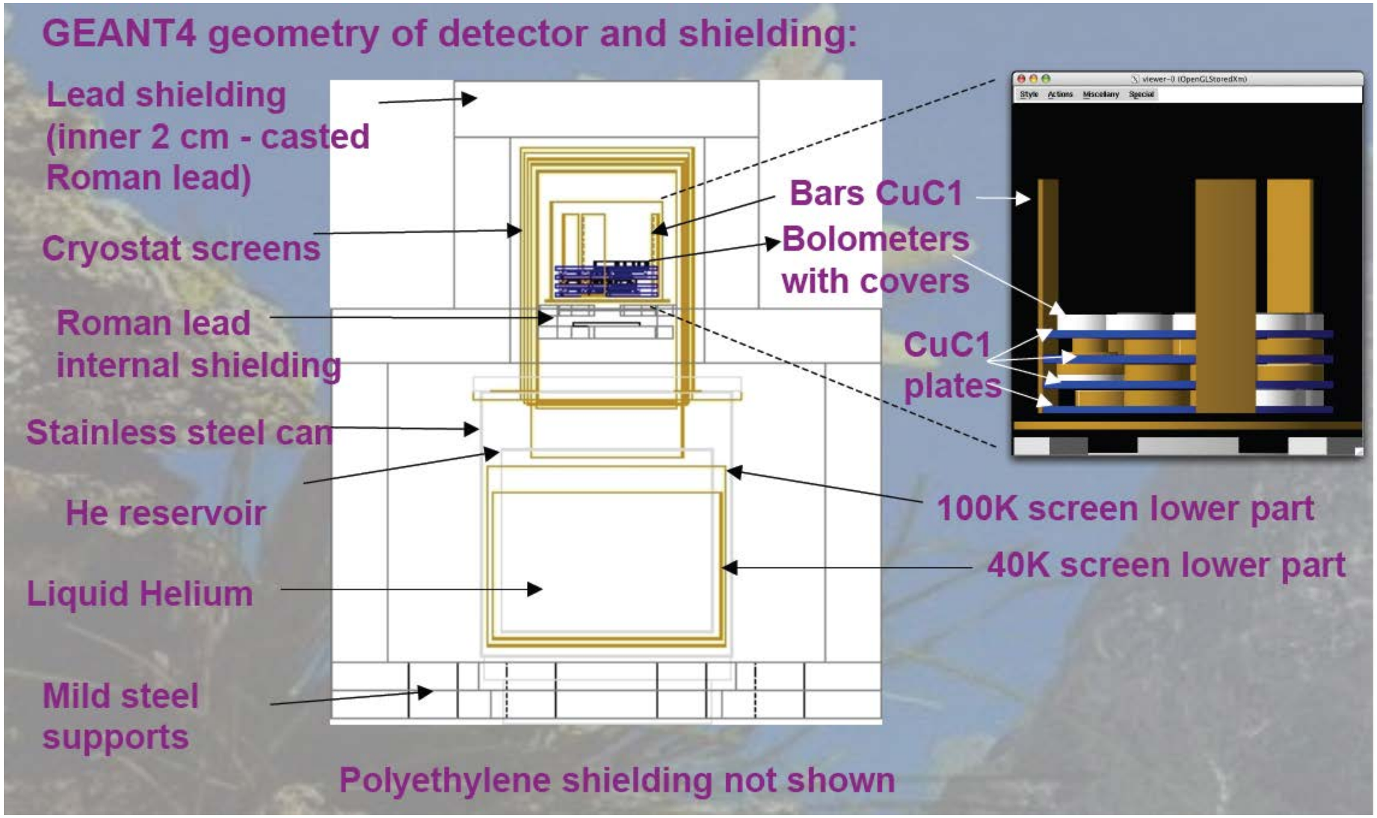
1) Go underground laboratory / reduce neutron flux by 4+ orders
2) Material selection
3) Muon veto system
4) Passive neutron shield
5) Multi-detector assembly / neutron background identification

Background model / agreement with experiment

Check in advance main parameters of the setup

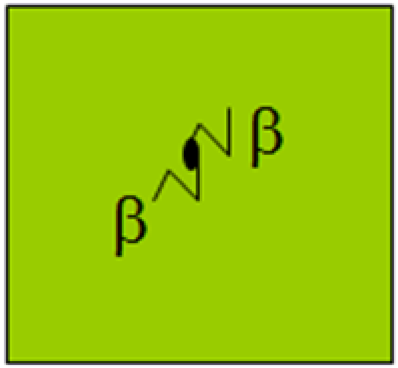
Challenge: Complicated devices with many parts are difficult to implement, not always all contaminations are known

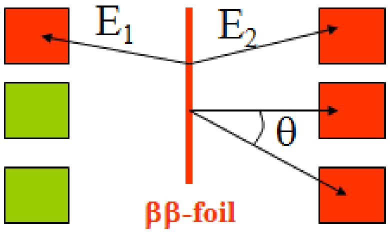
Gain: Reliability of experiment / agreement of the background model and experimental data, examination of systematic uncertainties

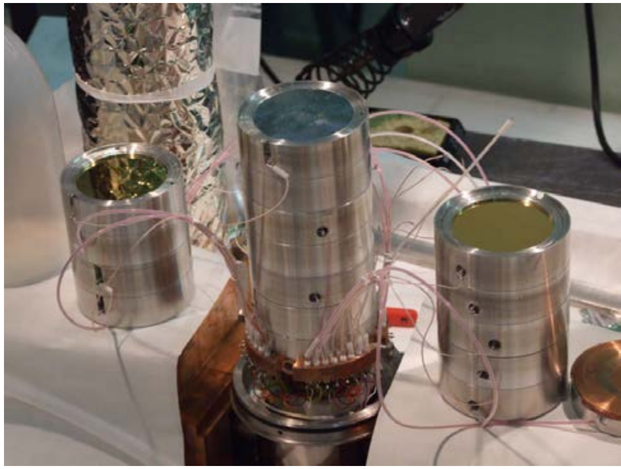


Additional criteria for signal selection / events identification

- Pulse shape discrimination
- Combination of methods for measurements (Ionization, Heat, Light)
- Space / time discrimination (see for example surface background reduction in next talk about the EDELWEISS experiment)
- Multi-detector assembly
- Specific behavior (seasonal variations)







The SuperNEMO Demonstrator

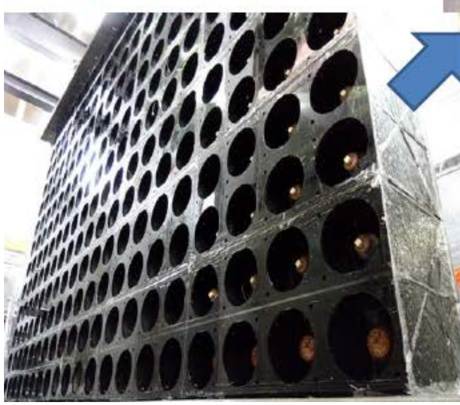
Source: 7kg of ^{82}Se

Calorimeter R&D
Optical unit

Tracker R&D:
Wiring robot

CO: 1 quarter of tracker

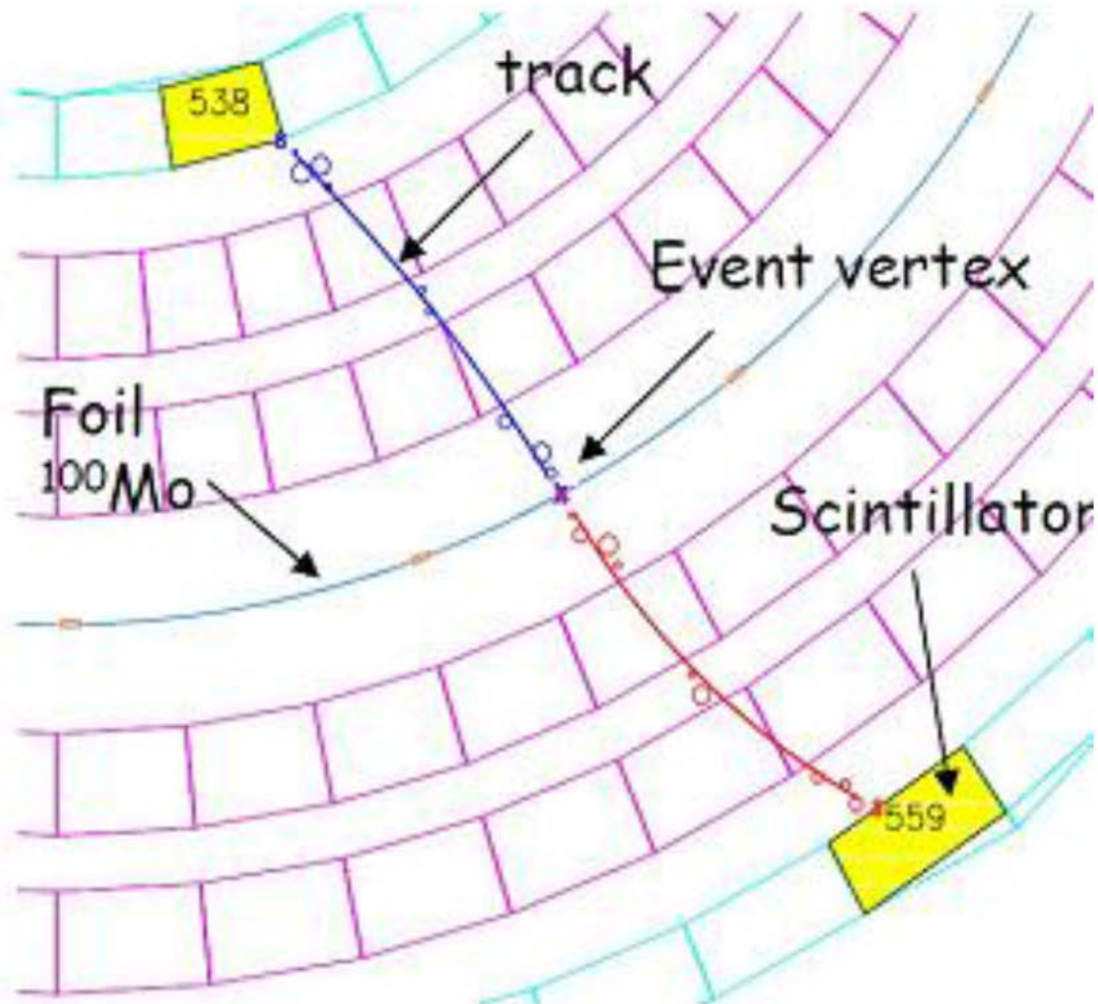
Calorimeter wall



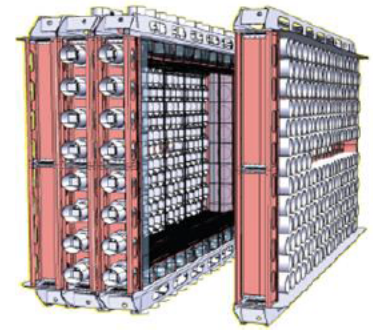
Low background R&D: BiPo-3

The current goal: the start of the first module, which should achieve the claimed background conditions.

The ββ-decay pattern in the NEMO-3 detector



$$T_{1/2}^{0\nu}(y) \propto \frac{a\varepsilon}{W} \times \sqrt{\frac{M \times t}{N_{BGR} \times \Delta E}}$$

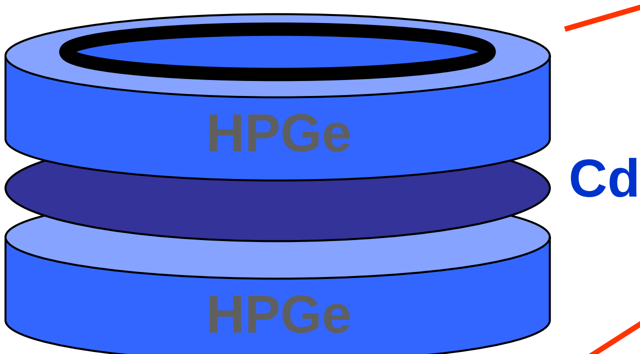


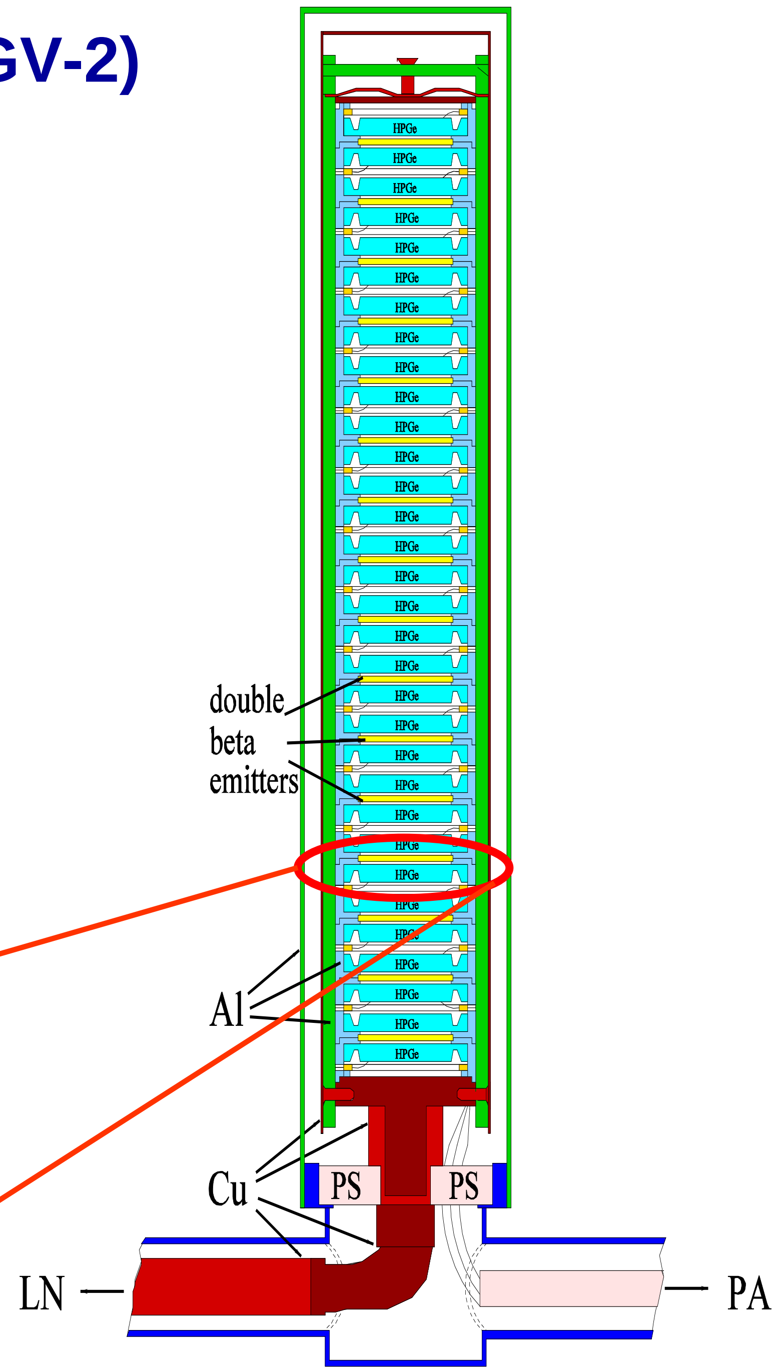
NEMO-3	$\Rightarrow$	SuperNEMO
^{100}Mo, 7kg	Isotope, mass	^{82}Se,100-200 kg
^{208}Tl: < 20 μBq/kg ^{214}Bi: < 300 μBq/kg	Background in ββ-foil	^{208}Tl: < 2 μBq/kg ^{214}Bi: < 10 μBq/kg
8%	Efficiency	30%
8% @ 3 MeV	Energy resolution (FWHM)	4% @ 3 MeV
$T_{1/2} > 2 \times 10^{24}$ y $<m_\nu> < 0.3 – 0.6$ eV	Sensitivity	$T_{1/2} > 1\text{-}2 \times 10^{26}$ y $<m_\nu> < 40 – 110$ meV

Clean room for ^{82}Se purification (DLNP JINR)

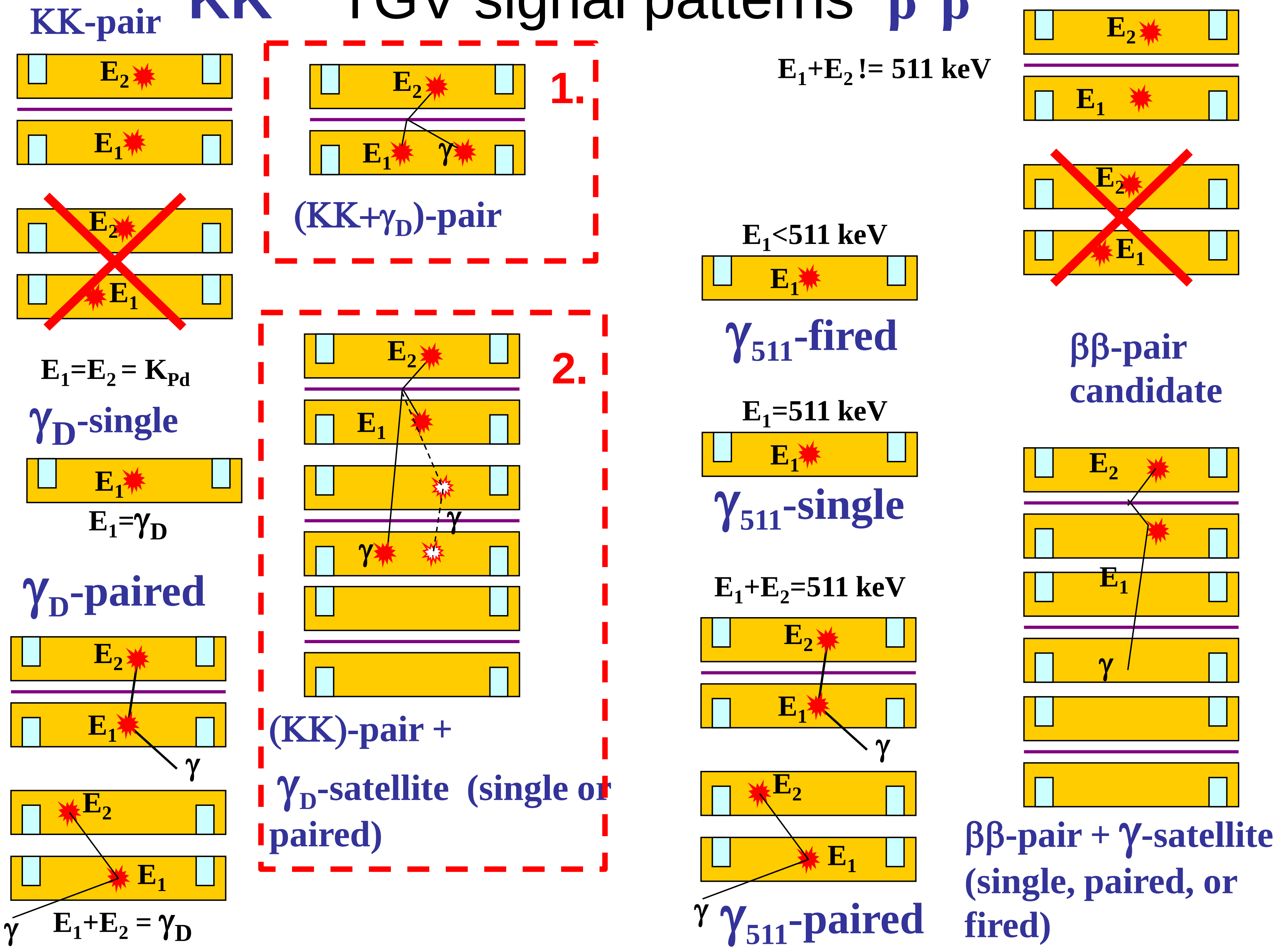
Telescope Germanium Vertical (TGV-2)

32 HPGe planar detectors ∅60 mm x 6 mm
with sensitive volume: 20.4 cm^2 x 6 mm
Total sensitive volume: ~400 cm^3
Total mass of detectors: ~3 kg
Total area of samples : 330 cm^2
Total mass of sample(s) : 10 ÷ 25 g
Total efficiency : 50 ÷ 60 %
E-resolution : 3 ÷ 4 keV @ ^{60}Co
LE-threshold : 40÷50 keV (5 ÷ 6 keV)
Double beta emitters:
16 samples (~ 50 µm) of ^{106}Cd (enrich.75%)
13.6 g ~ 5.79 x 10^{22} atoms of ^{106}Cd

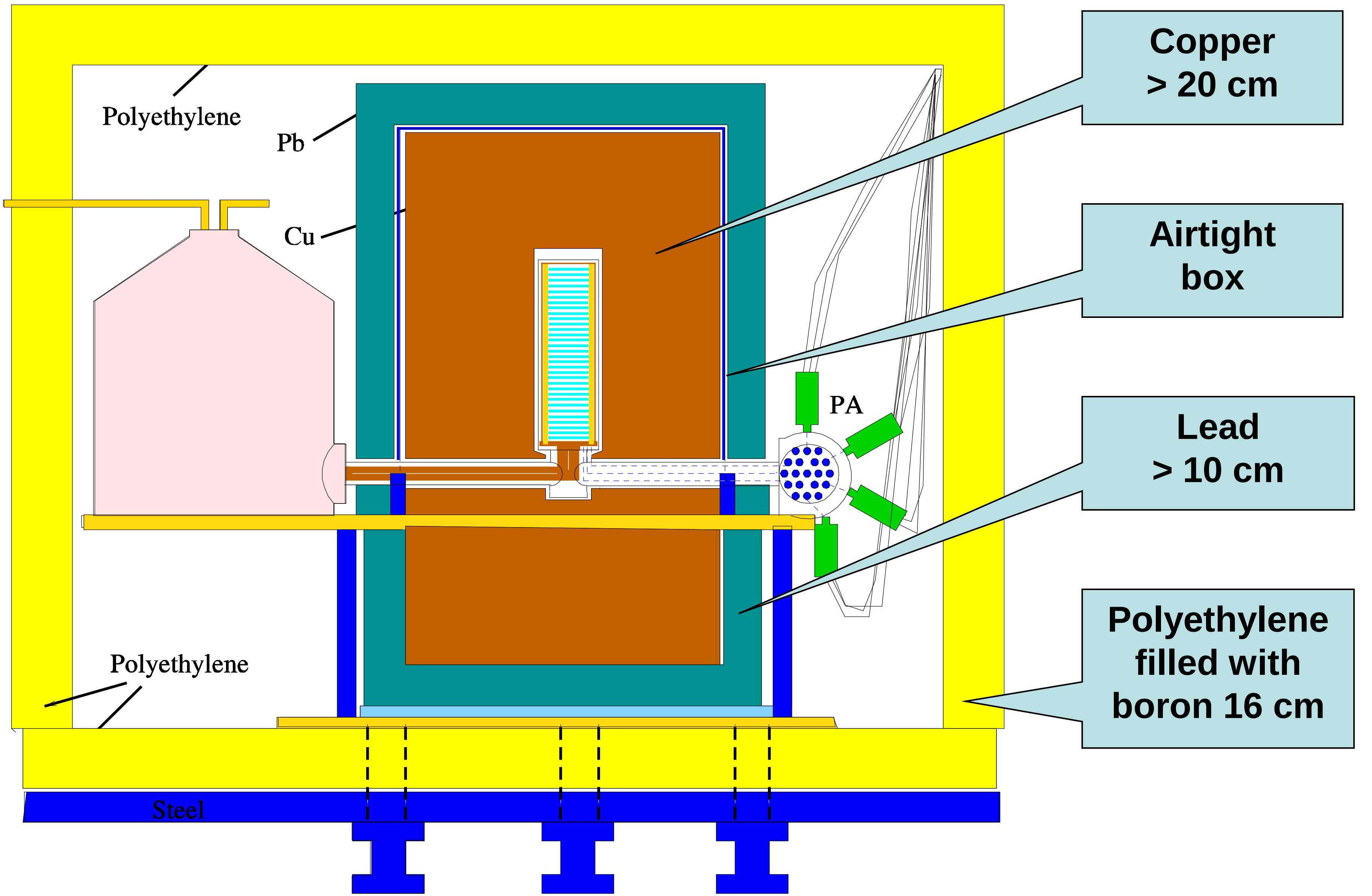


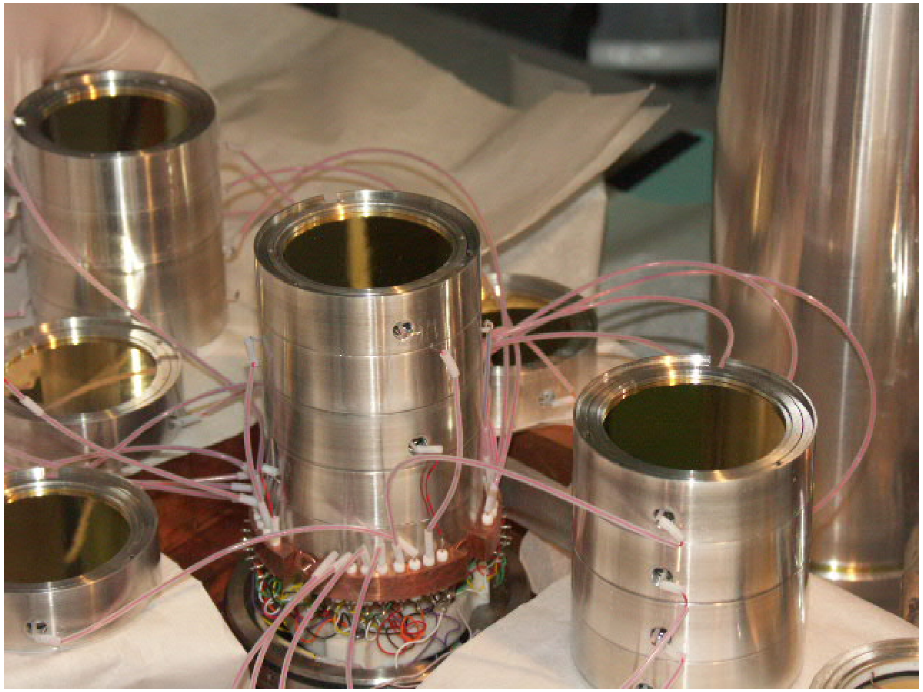


KK TGV signal patterns $\beta^+\beta^+$



PASSIVE SHIELDING

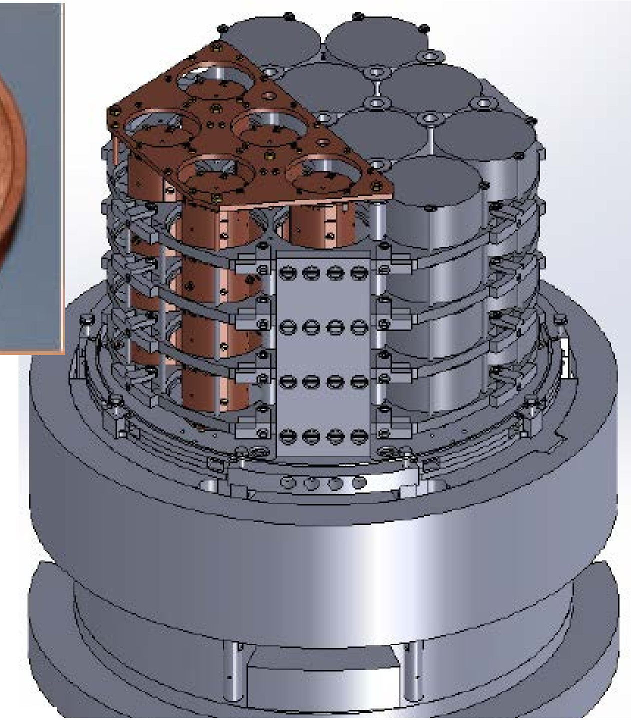





SHIN

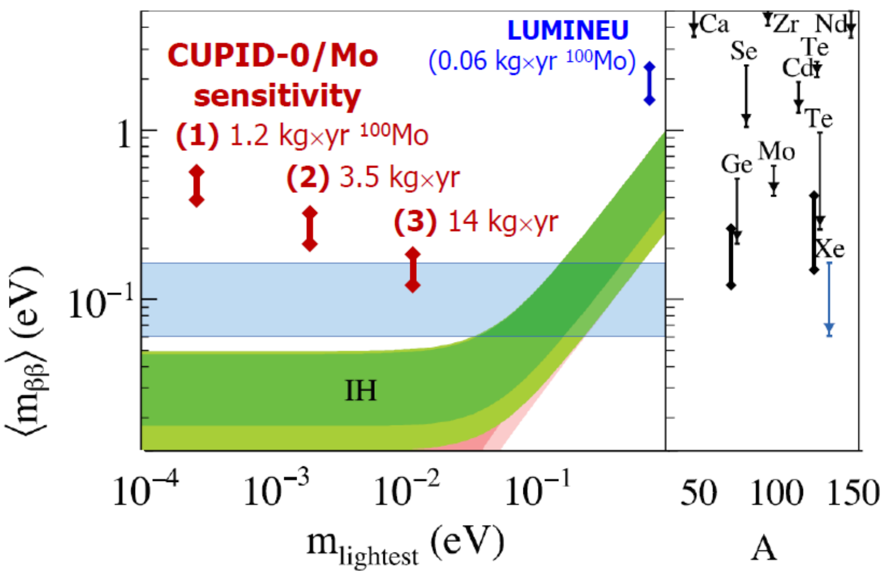
The SHIN experiment is aimed at searching for EkaOs (Z=108 element) in an Osmium sample by measuring its spontaneous fission (or/and that of its descendants) by the detection of the multiple neutron emission following the SF. A neutron multi-detector developed at FLNR-JINR is now in operation in the (LSM), Modane Underground Laboratory (60 detectors (3He filled) in a polyethylene moderator). The sample to be measured is placed in the central cavity.

CUPID / EDELWEISS



Another important trend:
synergy

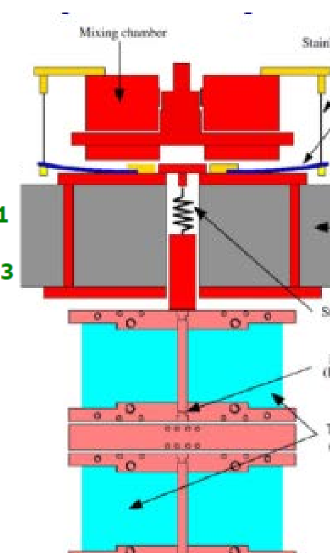
In the LSM, the excellent example of the synergy is search for 0γ2β decay of ^{100}Mo with the scintillating bolometer approach: the CUPID experiment ($Li_2{}^{100}MoO_4$ bolometers) in the EDELWEISS cryostat

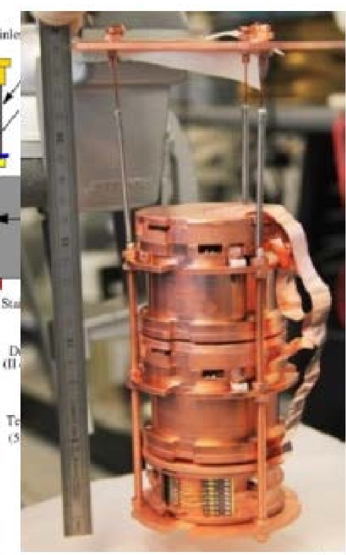


ββ Nuclide	Exposure [kg×yr]
^{130}Te	32
^{100}Mo	34
^{76}Ge	41
^{136}Xe	504

^{130}Te: arXiv:1710.07988
^{100}Mo: PRD 92 (2015) 072011
^{76}Ge: arXiv:1710.07776
^{136}Xe: PRL 117 (2016) 082503
NME: RPP 80 (2017) 046301

CUPID/Mo in EDELWEISS





Conclusion and outlooks

• **The aim of this talk was to reveal some details about underground physics for high energy community;**

• **In general, all modern methods of nuclear physics have to be applied to achieve the sensitivity levels that are interesting now for particle physics;**

• **JINR (Dubna) conducts modern world leading experiments in LSM underground laboratory dedicated to search and investigation of rear processes by means of nuclear physics methods.**

Roman lead

We drill a hole in the ingot and collected samples from different depth

ICP-MS elemental analysis						
	Pb Hellas ppm	Pb *ingot* 0-1.5 cm ppm	Pb *ingot* 1.5-3.7 cm ppm	Pb *ingot* 3.7-5.4 cm ppm	Pb *ingot* 5.4-7.15 cm ppm	Pb *ingot* 7.15-9.15 cm ppm
Ni	3.9	10.2	10.6	12.5	9.5	18.6
Ag	62.1	80.7	90.7	98.2	69	158
Cd	<0.05	<0.1				
Sb	1.1	79.2	71.6	83	56.5	104
Tl	0.88	<0.7				
Bi	5.1	<4				
Th	Limit (<0.6 ppb Hellas, <0.2 ingot)					
U	Limit (<2 ppb Hellas, <5 ppb ingot)					

Archeological Pb ingot are clean, attention to contamination during a treatment!

Fission yields of krypton-85

Nuclide	Fission yield (%) thermal	fast
232Th		4.14
233U	2.28	2.12
235U	1.32	1.33
238U		0.74
239Pu	0.558	0.62