INFN Underground Facilities

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Radiation Impact on Superconducting Qubits
Fermilab May 31, 2024

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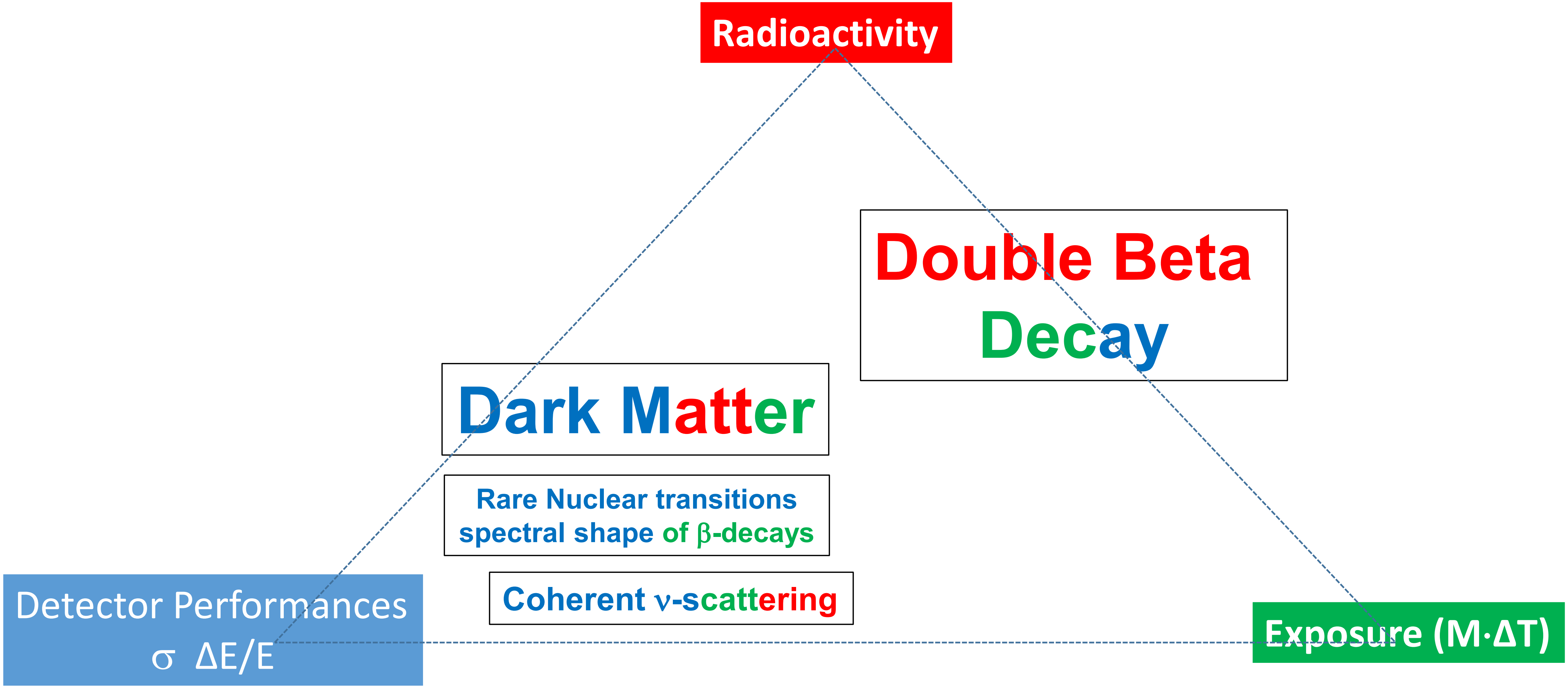
Ministero dell'Università e della Ricerca
Italiadomani Piano Nazionale di Ripresa e Resilienza

SQMS Superconducting Quantum Materials & Systems Center
INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

Underground Labs for Rare Event Physics



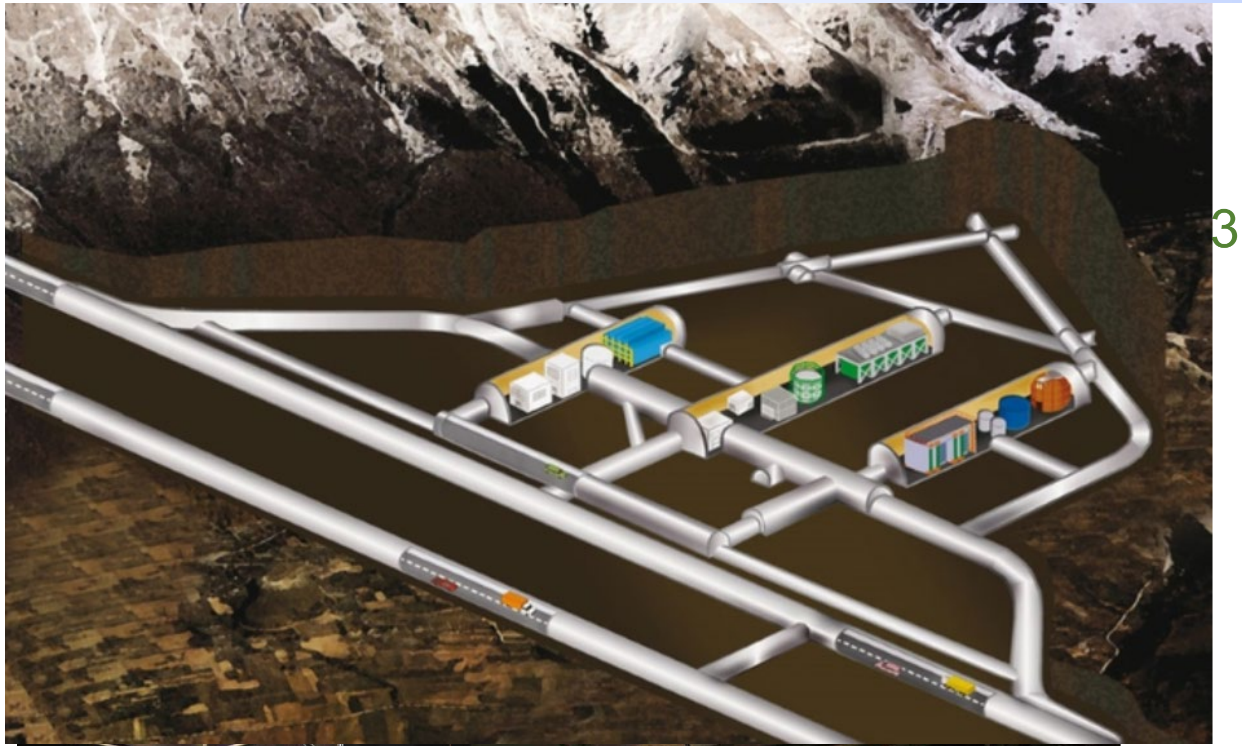
DM detectors "corrected" the strategy (towards lower thresholds rather than Exposure) after the operation of L noble gas detectors

Rare Event Physics…. Underground labs mandatory

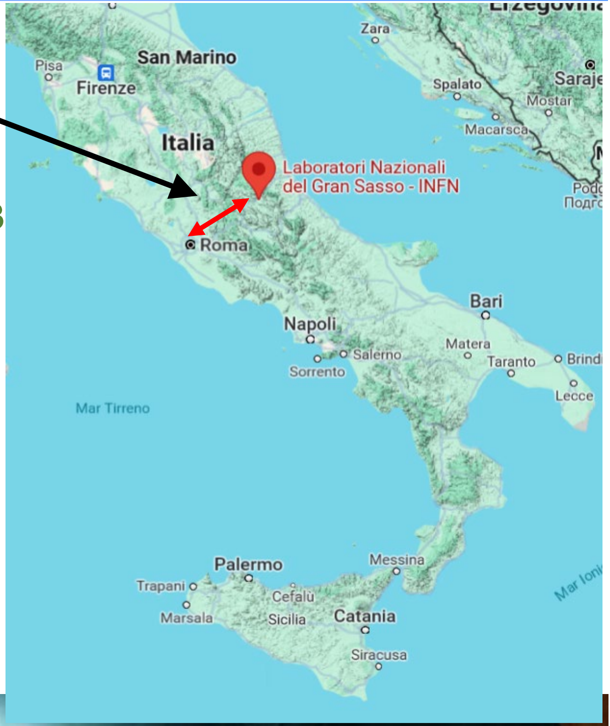
The “natural” radioactivity environmental background is of the order of ~50÷150 Hz /Kg of absorber.
This can be reduced by something like >98% with an appropriate (~ tons) shielding around the cryostat.

But cosmic rays will anyhow release something like 5 ÷10 MeV /cm with a rate of 1 $cm^{-2}\ min^{-1}$.
For this reason it is mandatory to perform these searches underground

Rare Event Physics: INFN-LNGS Underground Lab



1 h driving from Rome
(118 km by Highway)

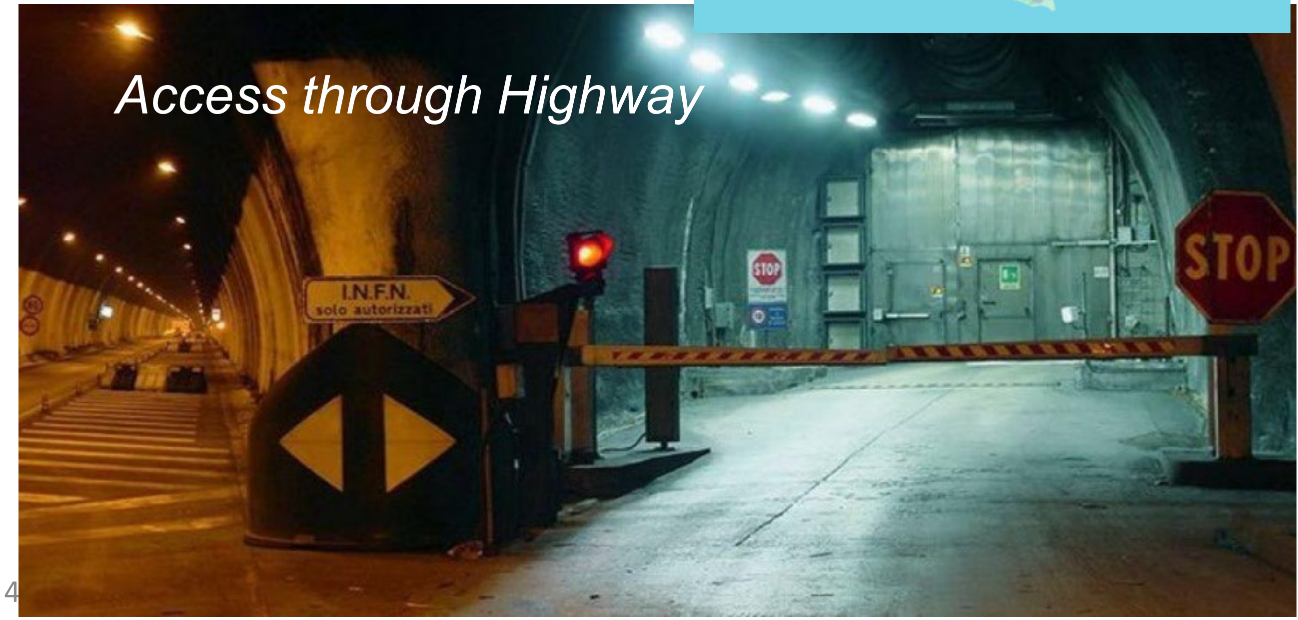


3 main halls ~ 100 x 20 x 18 m^3

~1400 m of rock

3650 m.w.e.

μ-Flux ~1 m^{2}h^{-1}



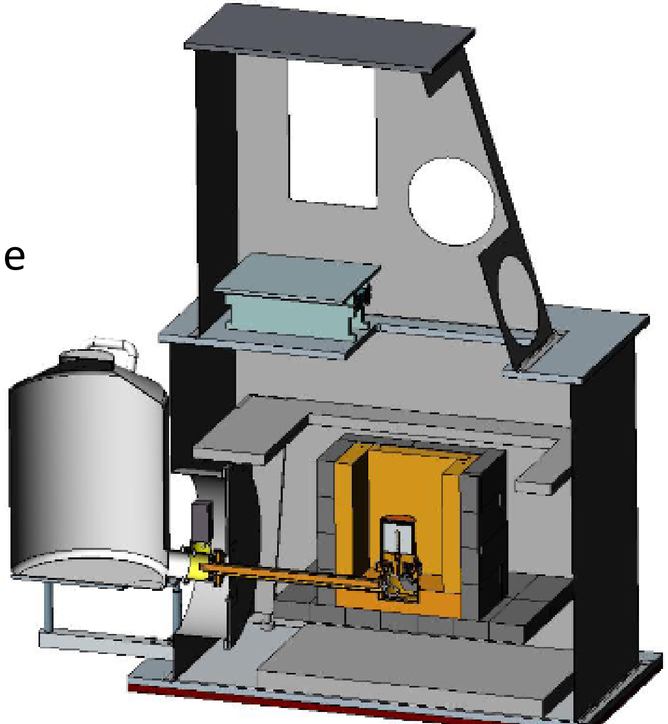
Material screening in Stella

LNGS hosts the most advanced laboratory (open to users) for low background measurement: Stella

- γ spectrometry (with **H**igh **P**urity **Ge** Detectors **HPGe**)
 - 15 detectors installed

Sensitivity (U/Th):
•**6** commercial LB detectors (O(mBq/kg))
•**5** commercial ULB detectors (1 well-type, 1 BEGe, combined 4 p-type coaxial) (O(0.5 mBq/kg))
•**4** custom ULB detectors (MPIK/LNGS) O (10μBq/kg)

✓ Constant N_2 flushing
✓ Pre-chamber for sample Rn degassing
✓ 15 l allowed space



STELLA = <u>S</u>ub<u>TE</u>rranean <u>L</u>ow <u>L</u>evel <u>A</u>ssay

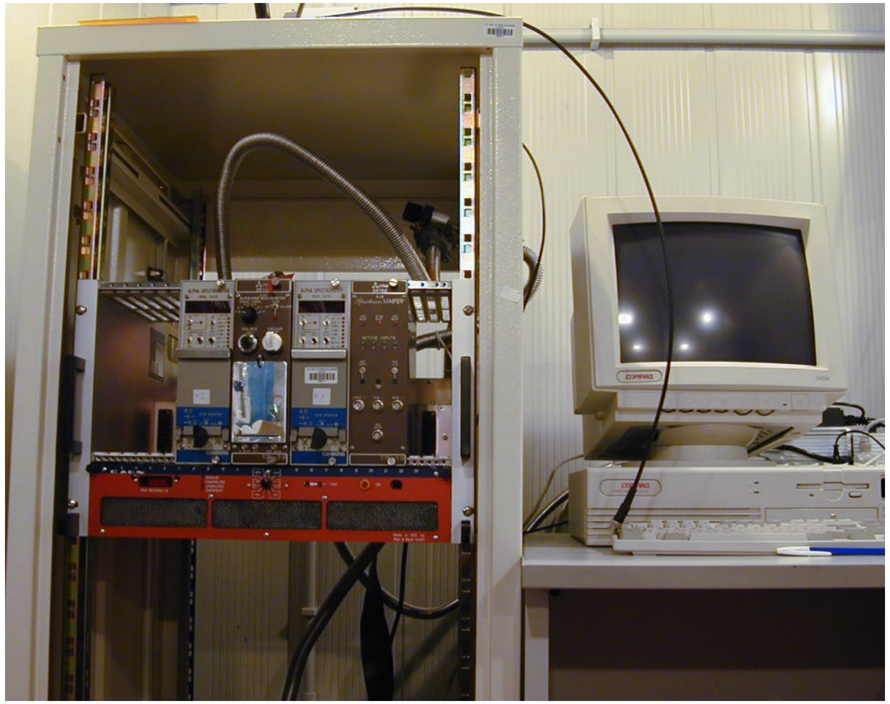
Rare Event Physics: Low Level Radioactivity measurement

Main task is material selection for all experiments installed in the LNGS underground laboratories (on the average about 50-100 samples per year); if there is availability, also for experiments outside of LNGS

Bulk Radioactivity

detector	total and peak background count rate [d^{-1} kg^{-1}_{Ge}]			
	40-2700 keV	352 keV(U)	583 keV (Th)	1461 keV(K)
GeMi	555	4.1	1.4	6.1
GePV	498	2.6	1.8	3.2
GsOr	442	2.0	0.76	4.2
GePaolo	222	1.1	0.31	1.8
GeCris	115	0.29	< 0.13	0.88
GeMPI	71	< 0.07	< 0.06	0.24

Surface Radioactivity with *standard* PIPS



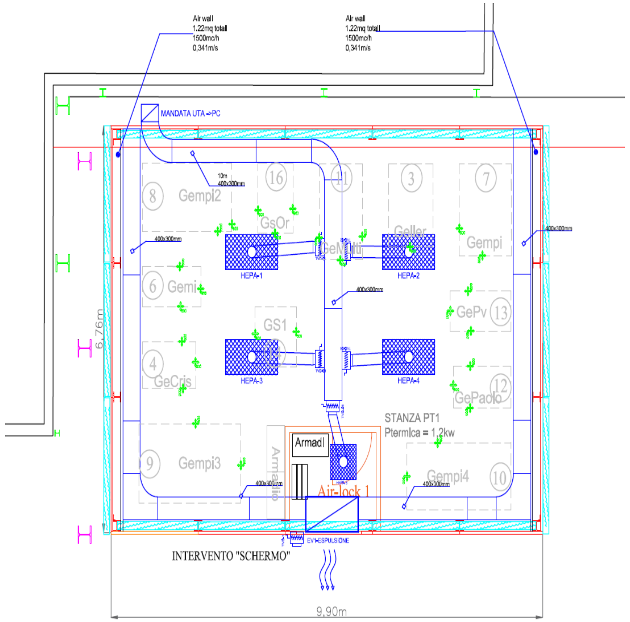
Background level ~ 0.1 c/cm^2/MeV/day (*continuum region*)

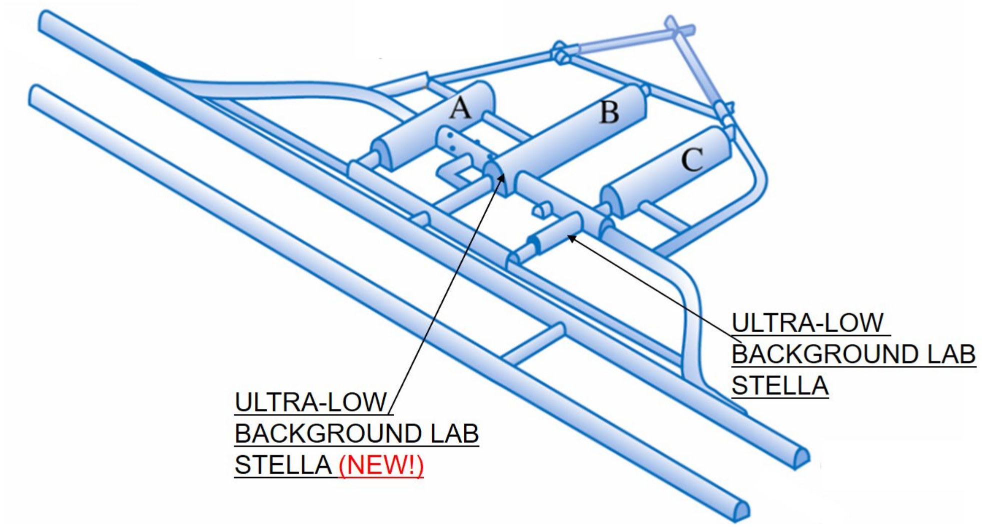
2024-2025 Stella upgrade

- Second floor: small laboratory, offices and warehouse
- first floor: controlled environment: offices and the DAQ room

Ground floor:

- steel structure with wall thick. of 5 cm (70 m^2, ca. 3 m high) (1/10 Radioactivity)
- *controlled environment*, with a class close to ISO 8 standard.
- neutron shielding made with 15 cm of water «tanks» and HDPE slabs (floor)





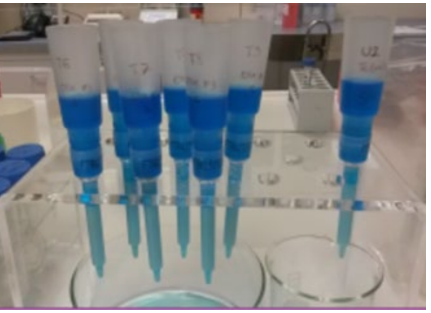
ICP-Mass Spectroscopy

ICP-MS 7500 Quadrupole Mass Analyzer with collision cell (2001)
HR ICP MS Element 2 (Thermofischer) (2010)
TIMS MAT 261 (2013) Isotopic ratio ~ 0.01 %
ICP MS Agilent 7850 (2022)

Instrumentation

Ultra trace

Sample preparation



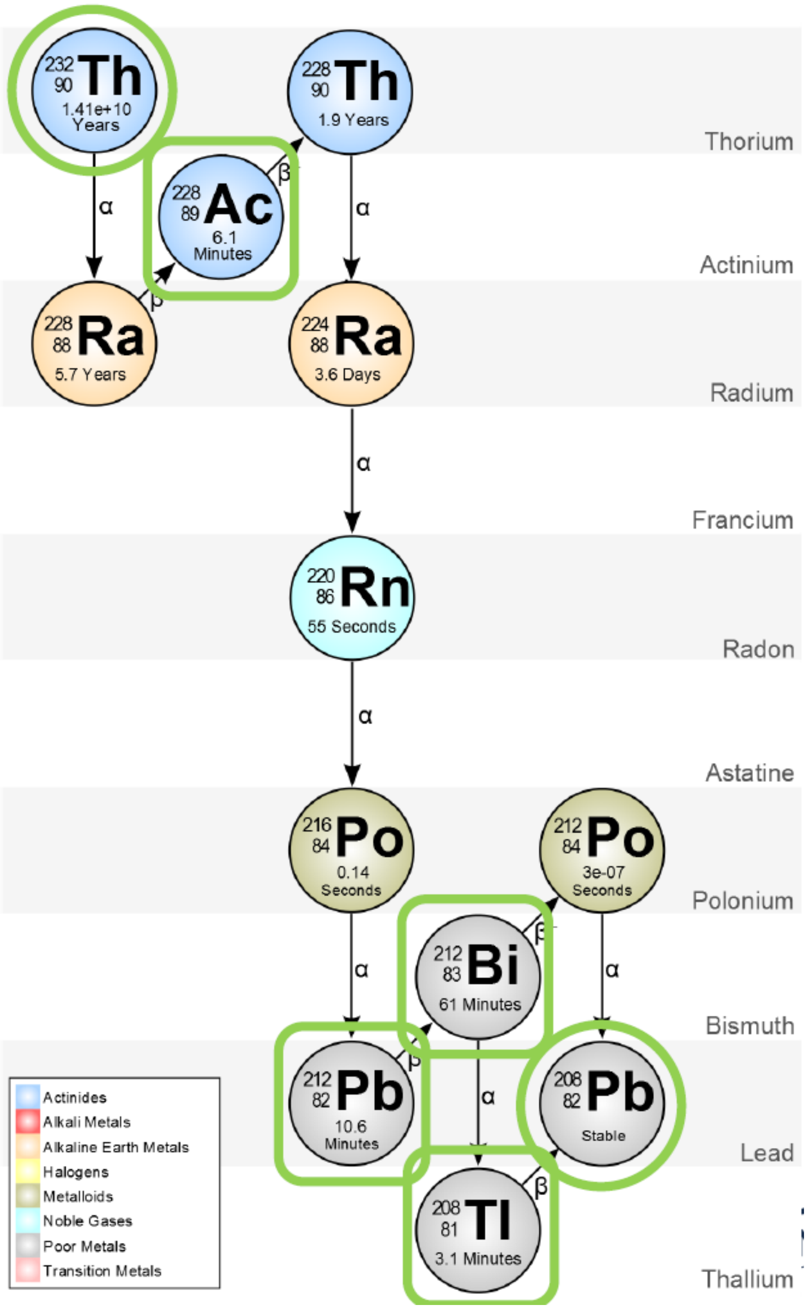
"Clean chemistry"

Mass spectrometry measures the concentration of nuclides (number nuclides/mass)

- ✓ O (grams) sample
- ✓ Sample dissolved in acid
- ✓ **Destructive** measurement
- ✓ Relatively fast measurement
- ✓ easy sample treatment for ppm sensitivity
- ✓ more complex treatment for ppt and O(10) ppq

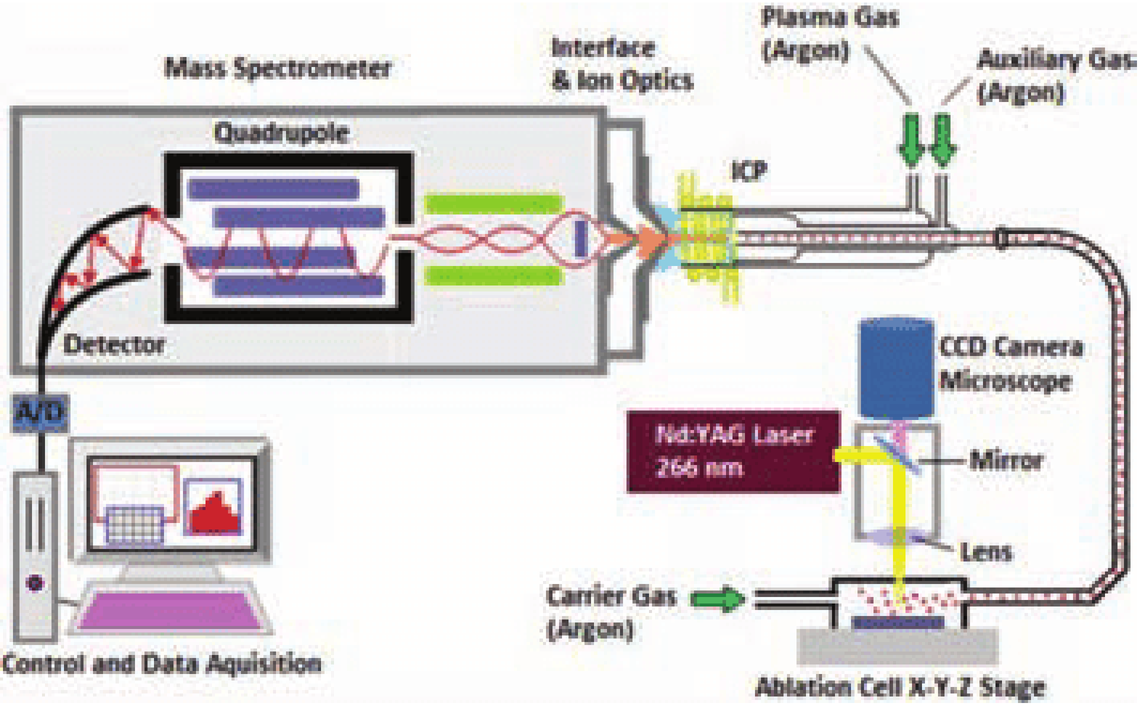
Techniques comparison

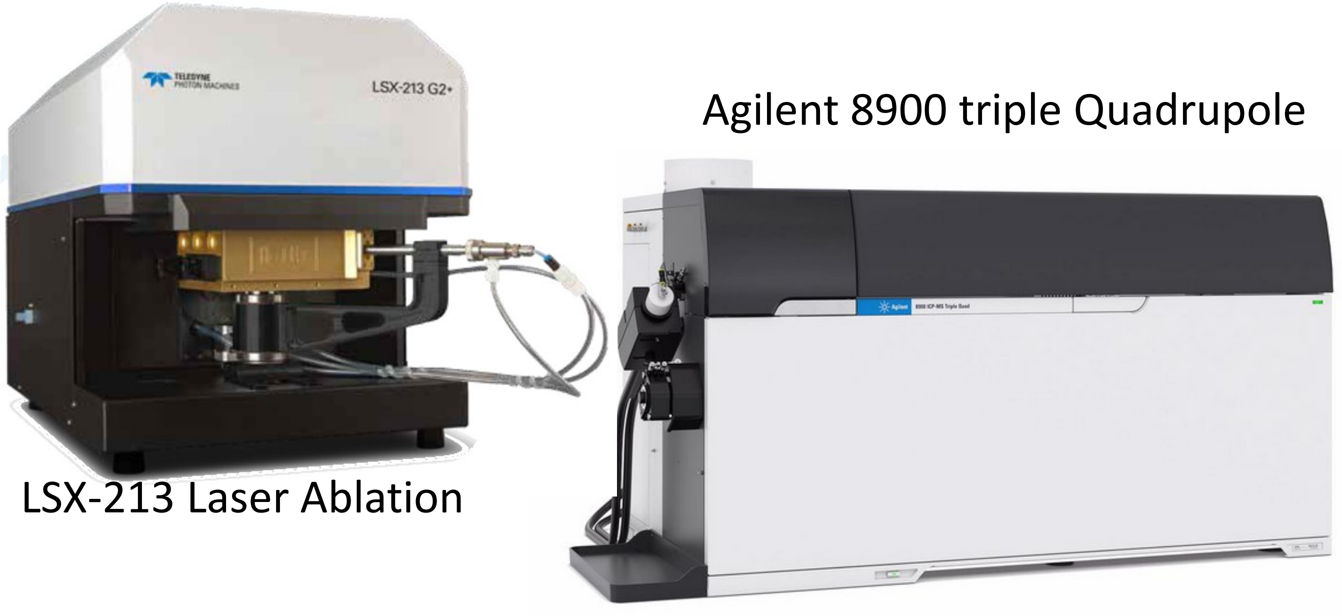
		ICPMS	HPGE
		Primordial parents	ϒ emettitors
		Surface/bulk	BulK
Destructive		**Yes**	No
Detection Limit	[10^{-12}g/g]	Th=0.5 U=0.5	Th= 10-20 U= 10-20
Sample size	[g]	0.1-10	1-10000
Sample treatment		Contamination **risk not negligeble**	Almost free
Analysis Time		days	Weeks/months



HPGE and ICPMS are often applied both to check secolar equilibrium of decay chain. ICP-MS allows to perform the quality control of each single part (or lot)

Laser Ablation + triple quadrupole – Fall 2024





Agilent 8900 triple Quadrupole

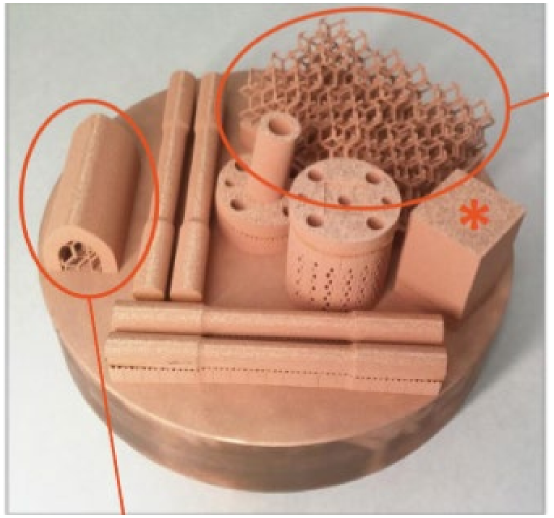
LSX-213 Laser Ablation

The new system combines the advantages of the latest generation triple quadrupole ICP-MS in terms of sensitivity and the ability to reduce interference problems with the possibility of performing punctual analysis (4 to 100 µm spot) and studying the depth profile concentration of impurities

Additive Manufacturing: Future Outlook in Designing Pure Metal Components for Particles Detectors

AM allows to produce parts:

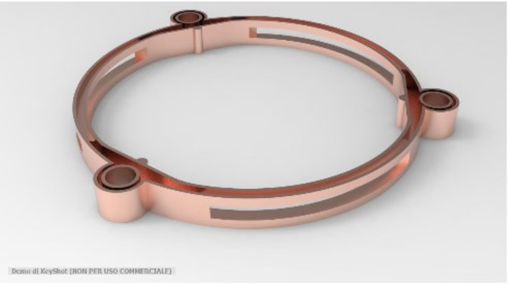
- Complex geometries
- High Resolution
- Hollow components
- W/o final traditional machining
- W/o surface cleaning
- Mass save of a factor about 2-3
- Components number reduction



Crystal Holder

Traditional CNC
mass=27g

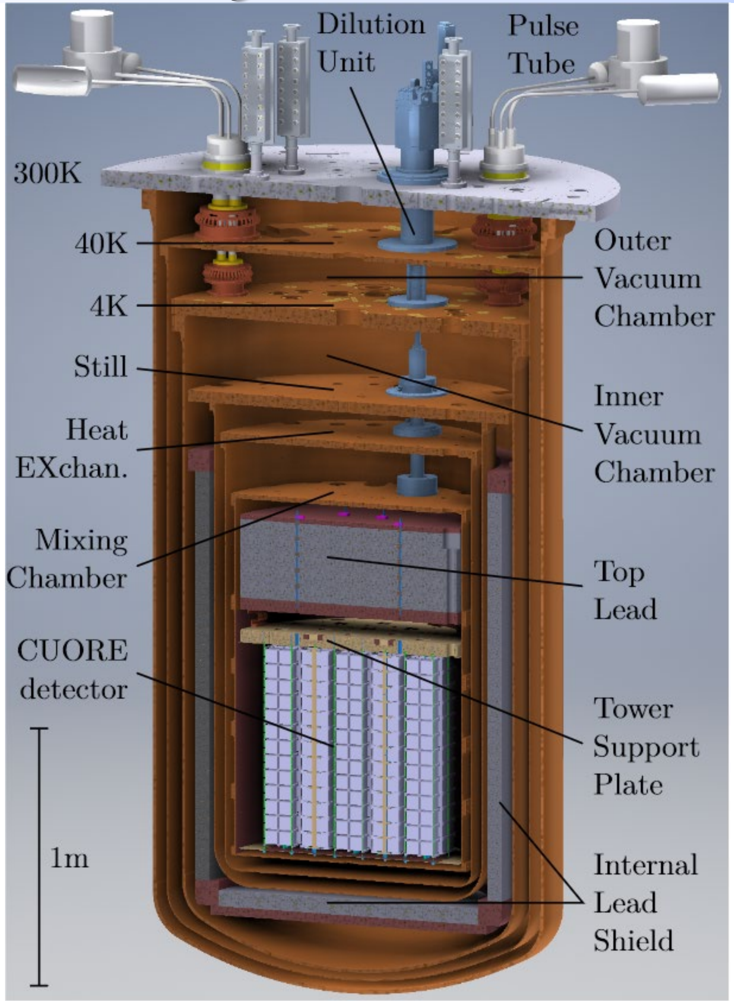
AD same supports
mass=11g

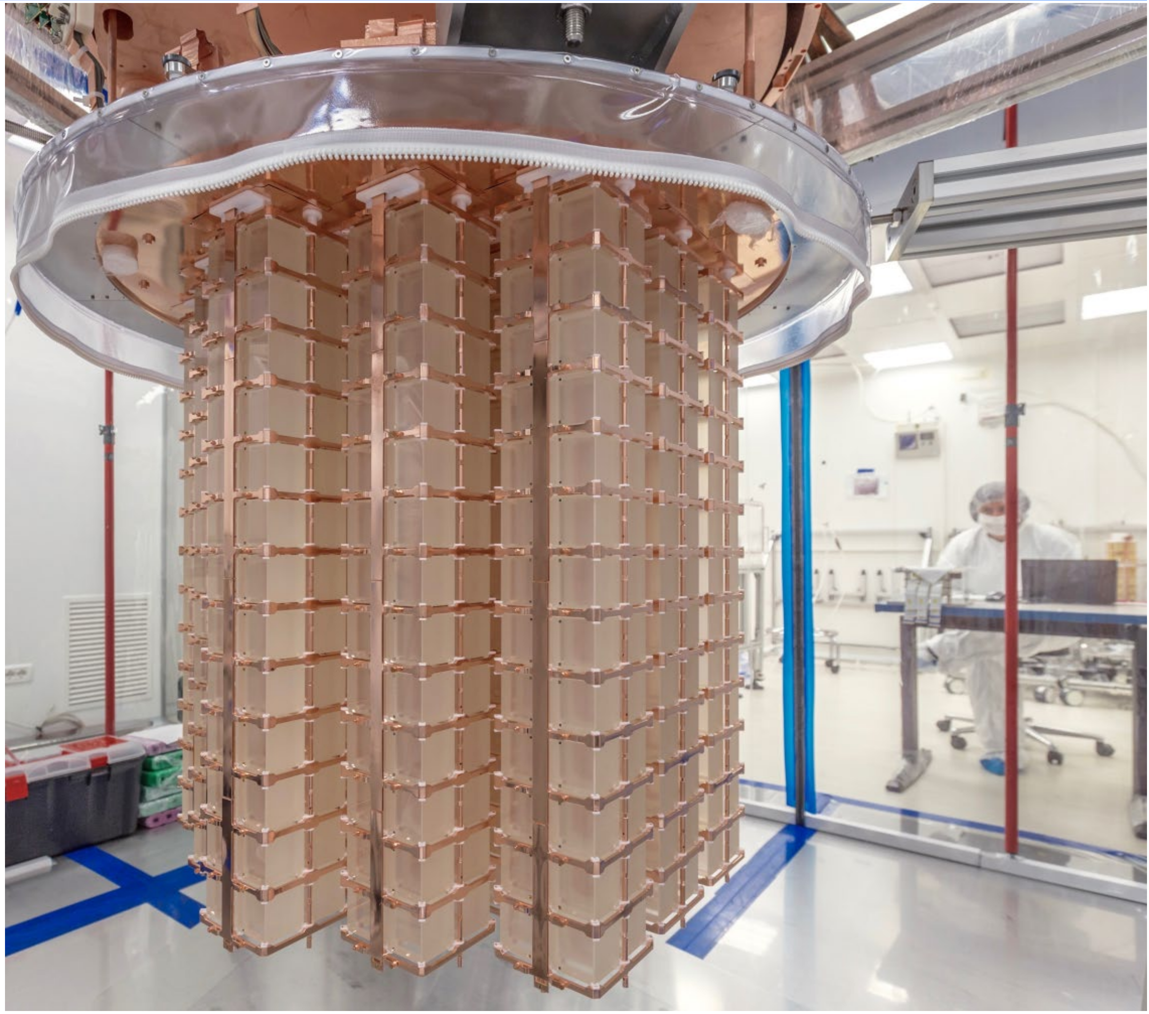


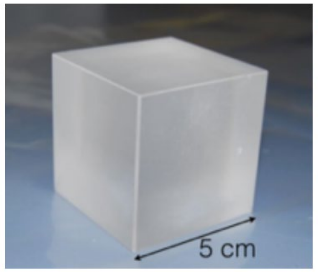
AD new design
mass=9g

M/3 !

Cryogenic Experience : CUORE





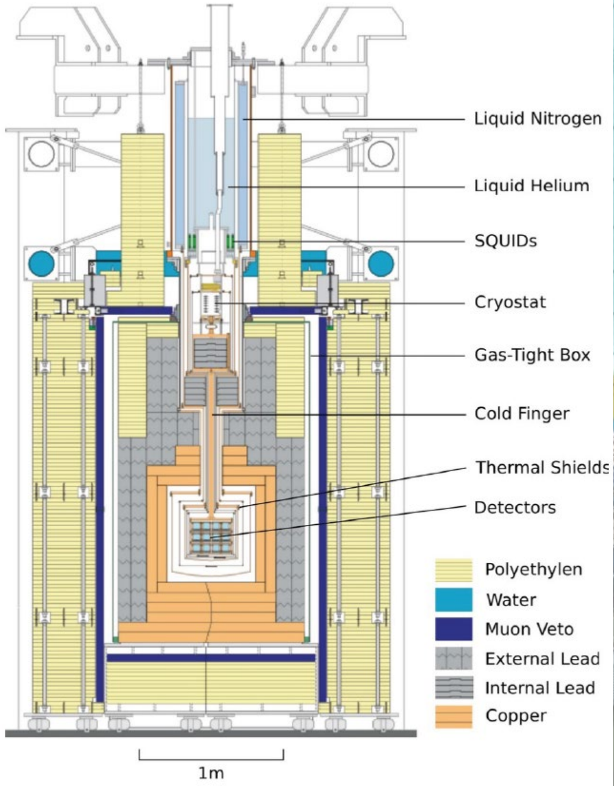


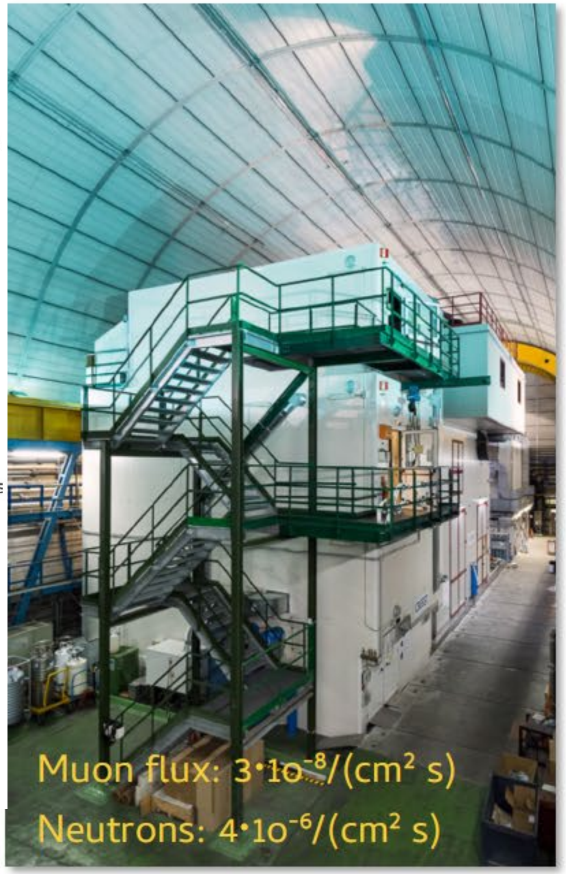
$^{(nat)}TeO_2$ crystal

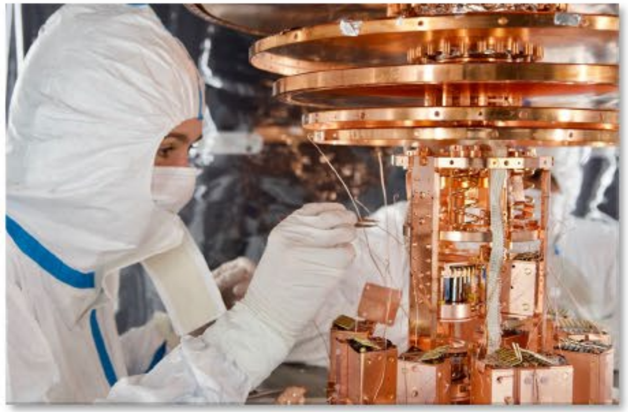
Absorber = 0νββ source
$5.0 \times 5.0 \times 5.0$ cm^3
750 g mass
$C(T) \sim 2.3 \times 10^{-9}$ J/K (@ 10 mK)
$\Delta T_{crystal} \sim 100$ μK/MeV
$\tau \sim 0.1 - 1$ s

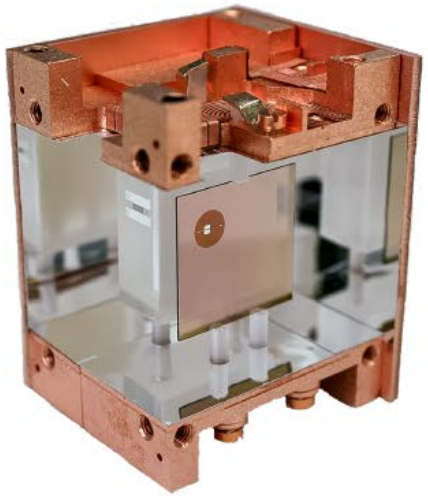
The CUORE cryostat was closed in 2017. It will be reopened to host the CUPID experiment, most probably, in late 2025

Cryoenic Experience: CRESST









The CRESST Experiment is moving (since few years) towards extremely low energy threshold (O(10) eV) therefore renouncing to the double readout technique (Heat+Light). The setup is presently under upgrade. The time-scale for a Physic run is O(2) y

LNGS – CRYO- experiments

There are several $^3He/^4He$ dilution cryostat located deep underground. They are connected with REP experiment/Collaborations

 # 2 *Old* Oxford wet cryostat (Oxford 1000 and Oxford 200) belonging to the CUORE/CUPID collaboration

 # 2 *Old* customized wet cryostats (Oxford 1000 and Leiden MNK-CF-500) belonging to the CRESST collaboration

 # 1 Huge *10 years old* wet cryostat (Leiden DRS-CF-2000) hosting the 1 Ton CUORE bolometric experiment

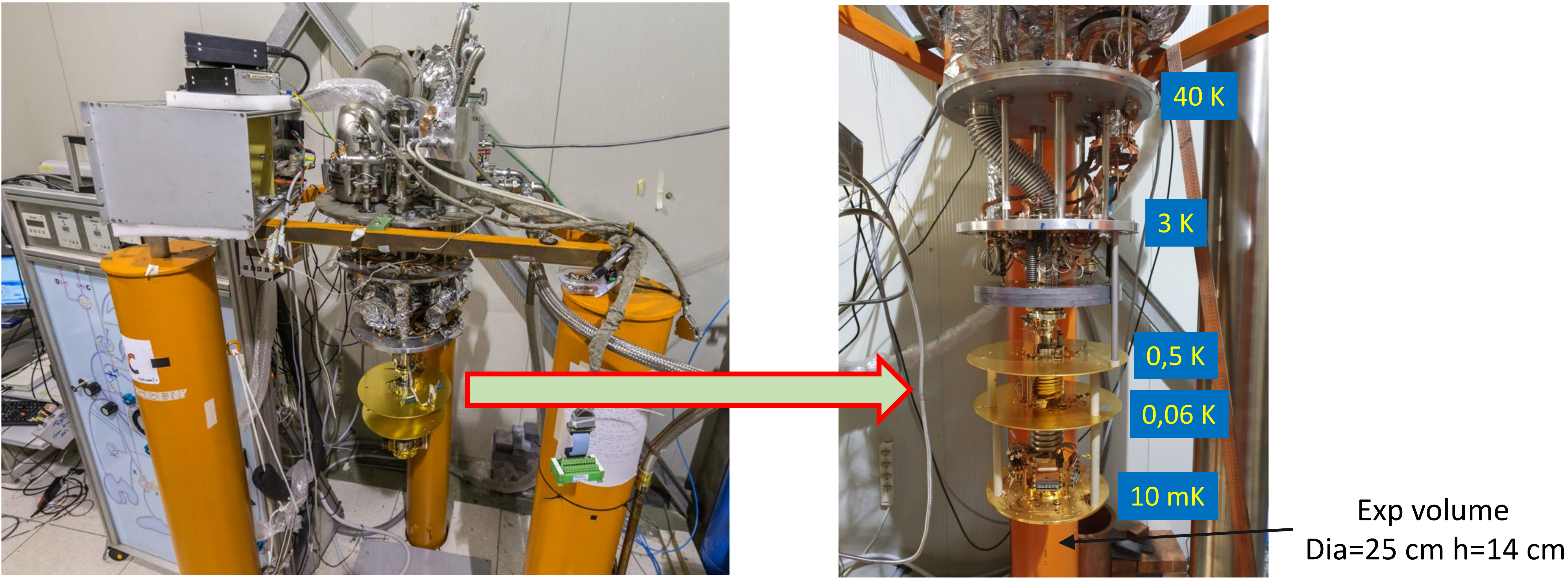
 # 1 brand new custom Cryoconcept HEXA-DRY S hosting the COSINUS experiment

Therefore 6 dilution units are present (and most of them working) deep Underground. But, definitively, none of these installation can be used by external users since the cryostats are "property" of collaboration and / or experiments, not to the Labs.

But, fortunately, there is another dilution unit…….

The IETI Facility

The IETI Cryostat is a dry (Pulse Tube based) $^{3}He/^{4}He$ dilution unit located in the **Hall C** of LNGS. The cryostat is characterized by an extremely low vibration level due to Pulse Tube decoupling and a custom-made 3-stage mechanical decoupling system between cold plates and detectors. Access to this kind of system can be extremely appealing for experimental groups interested in performing small-scale “table-top” low-temperature measurements (e.g. pathfinder or pioneer experiments) in the very peculiar underground site.

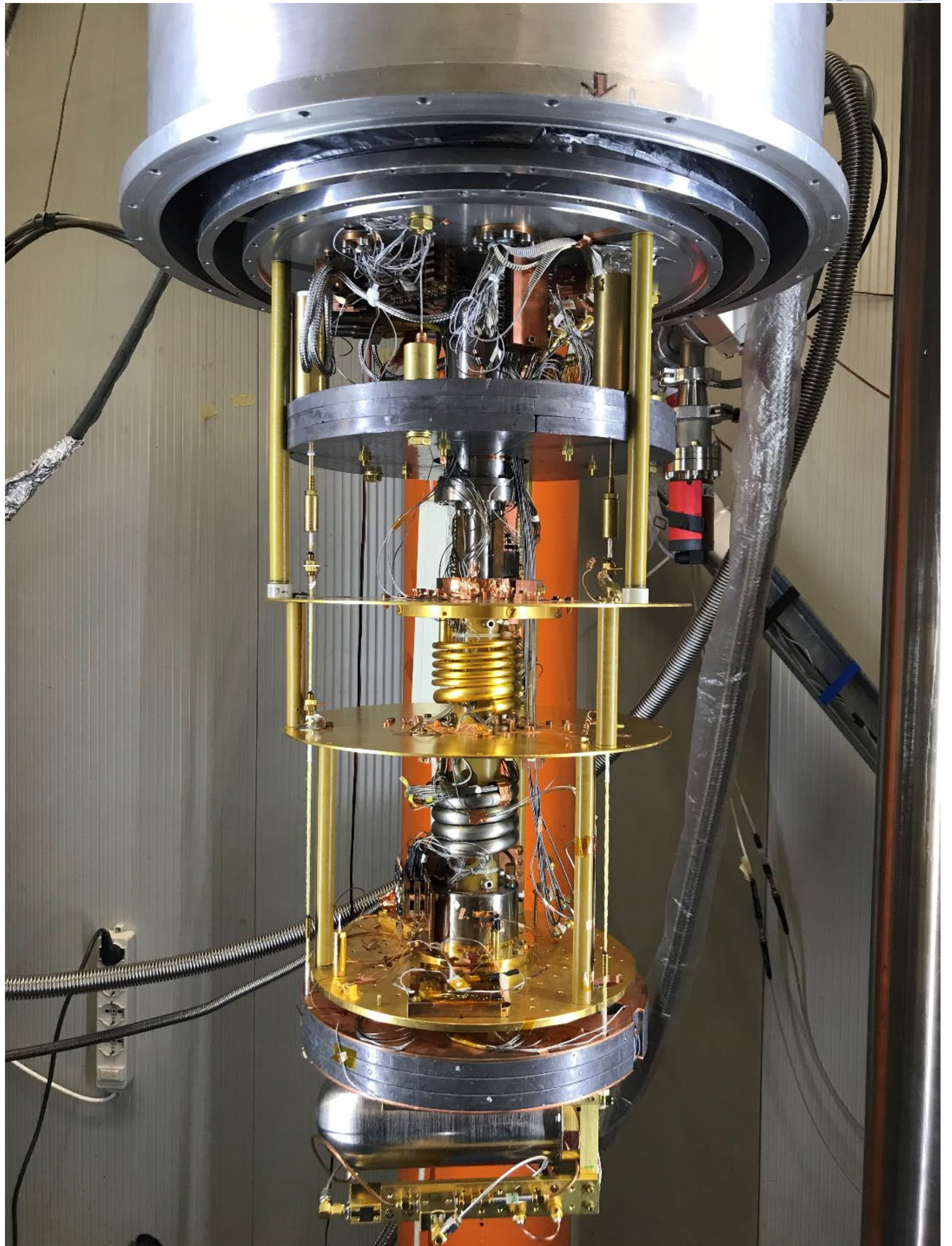


The IETI Facility

The cryostat is equipped with an *internal* lead shielding of **3 cm** below the 3 K Flange and **3 cm** of Lead below the Mixing Chamber (MC). This lead is also integral part of the three-fold mechanical decoupling system.
The outside shielding can be made with **10 cm** of lead surrounding the main 300 K vacuum chamber. This shielding, even if relatively small compared to the standard low-radioactivity cryostats belonging to experiment like CUORE and/or CRESST is sufficient to run even large bolometers (few hundreds of grams) w/o affecting the performances of Energy resolution induced by pile-up.

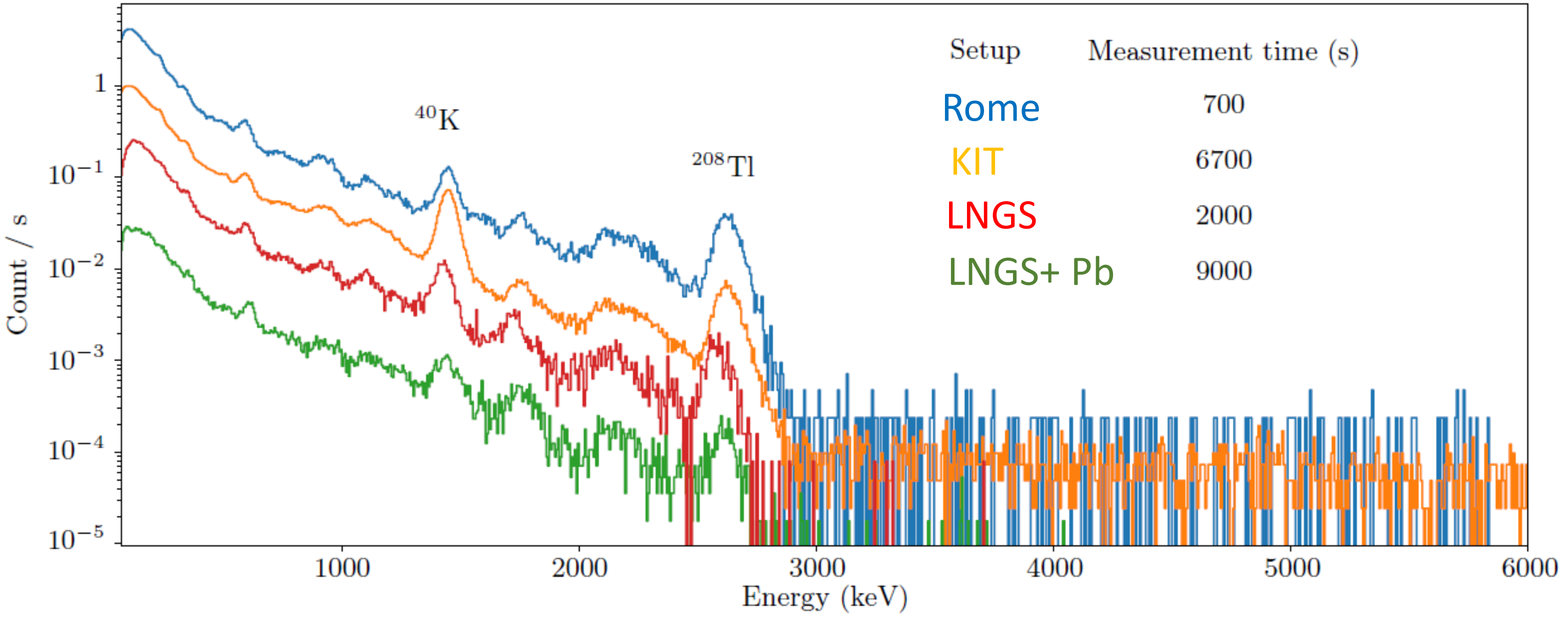
The IETI cryostat is presently equipped with different readout lines

- **12** electronic Channels equipped with low noise voltage preamplifiers (2 nV/√Hz) (**R&D** for CUPID experiment an rare event decays);
- **3** Magnicon SQUIDS   (**R&D** for Cosinus Experiment).
- **8** low attenuation SMA Coax cables   from 300 K to 3K + 8 NbTi
- Superconductive Coax from 3K to MC (**R&D** Demetra/SQMS for Resonators/Qubit applications)
- **48** additional twisted superconductive wires from Room Temperature (RT) to MC.
- A ^{60}Co crystal for absolute thermometry calibration + a Noise Thermometer



The IETI Facility

Going underground results in a abrupt decrease in the environmental radioactivity levels.



Cardani et al., *Nat. Commun.* **12**, 2733 (2021)

Environmental Background measured with the same Detector, 3” NaI
In three different Labs

Advanced Cryogenics Lab

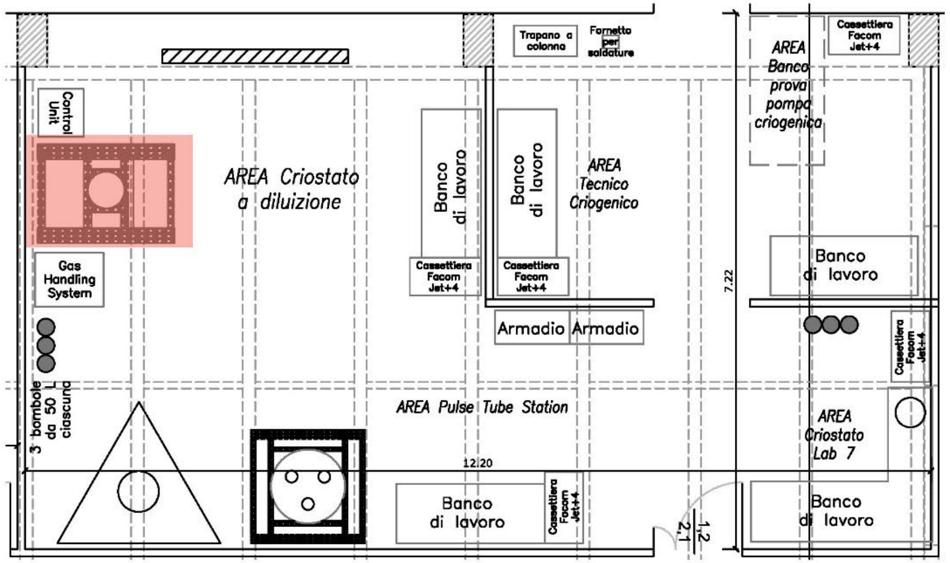
The Advanced Cryogenics Laboratory (Acryl) is a set of new facilities mainly funded by PNRR resources:

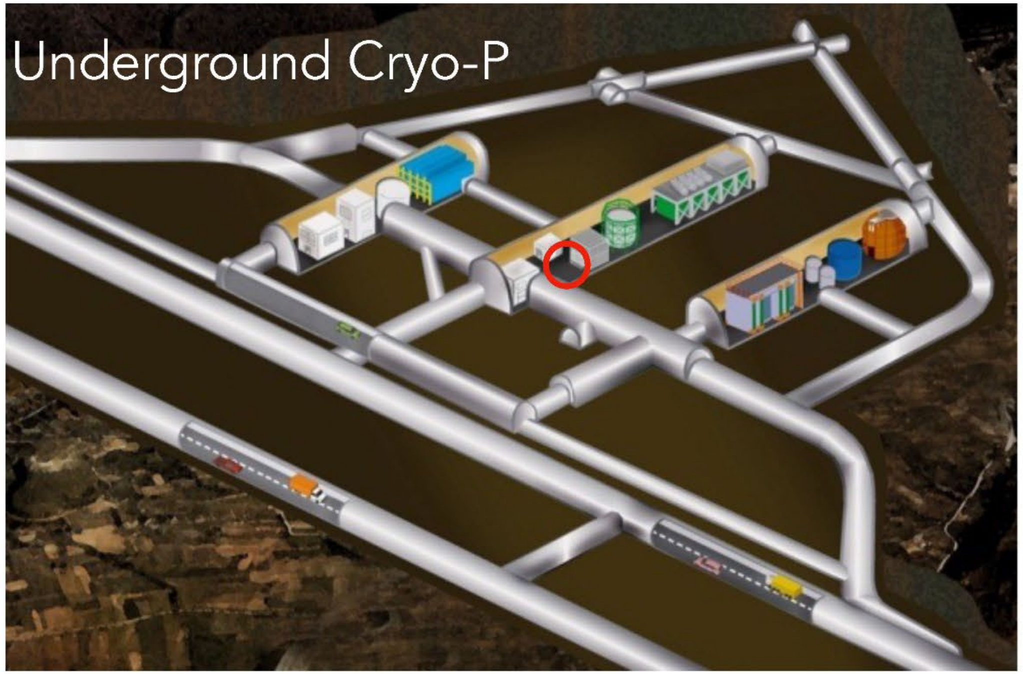
- **<u>CRYO-Lab</u>**: an integrated aboveground cryogenic hub for R&D at different temperature scales

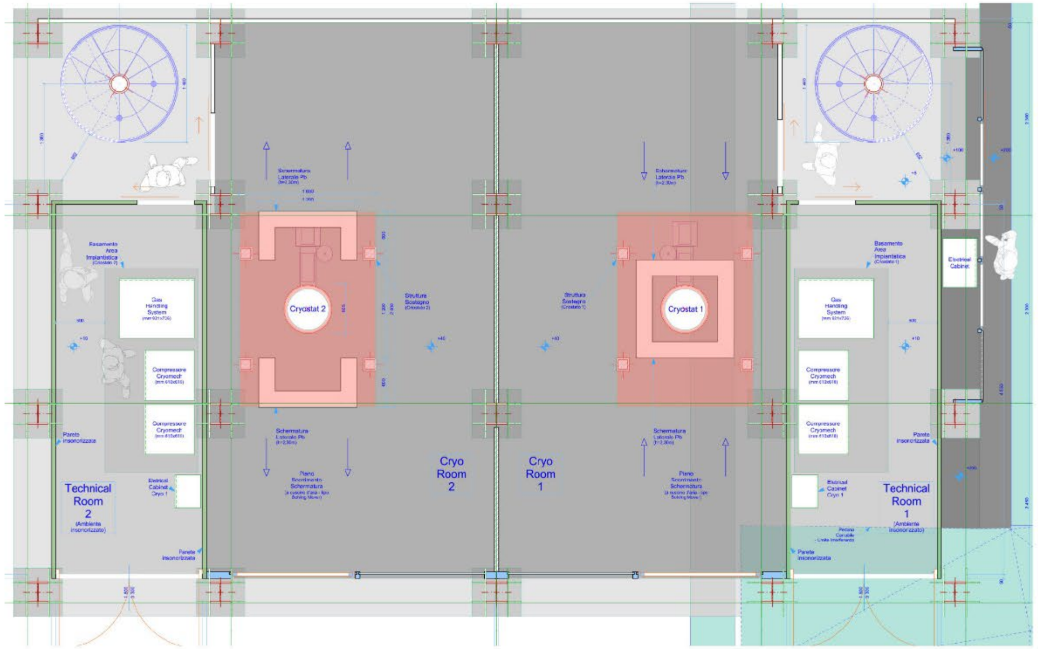
- **<u>CRYO-P</u>**: a cryogenic underground platform for mK applications

3 new dilution cryostats

Aboveground Cryo-Lab

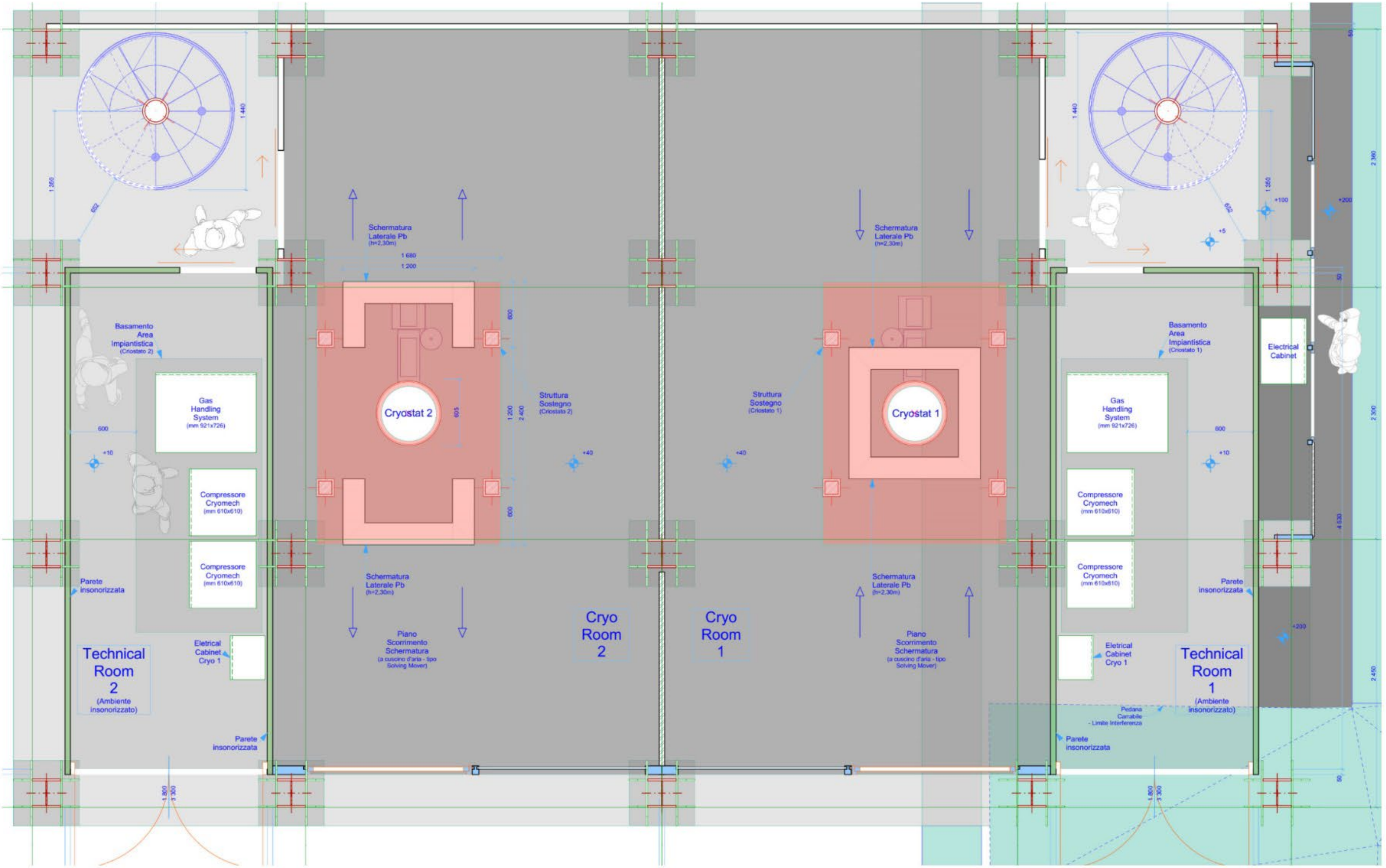






Cryo-P: an underground facility for mK applications

- Two separated experimental areas open to scientific community
- Each equipped with:
  - one dry (PT-based) dilution cryostat
  - sliding room T lead shieldings
  - "service" room for ancillaries, compressors and vacuum systems
  - 1 ton crane
  - 1st floor balcony with working stations
- 2nd floor with control room, small workshop and clean room



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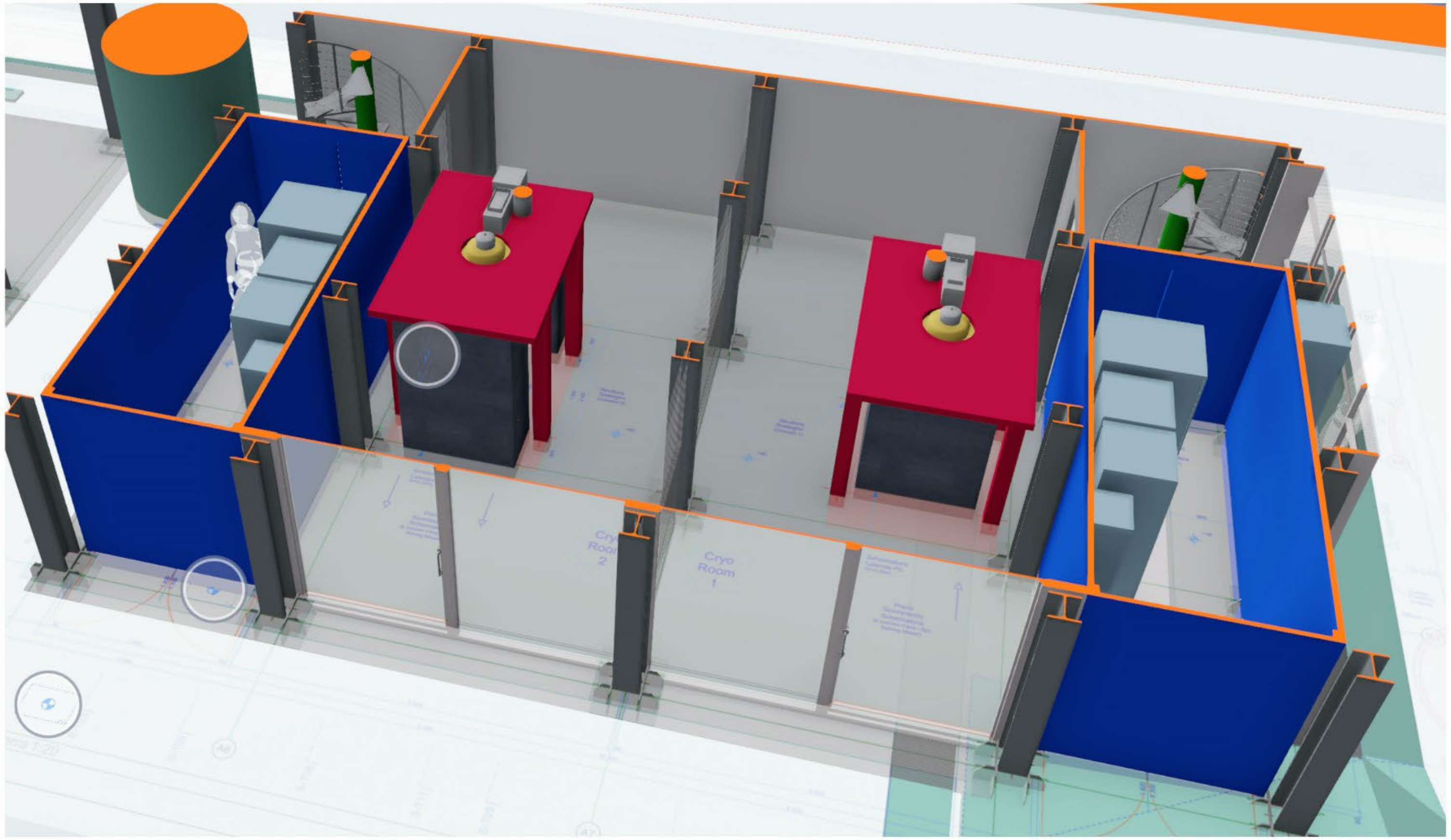

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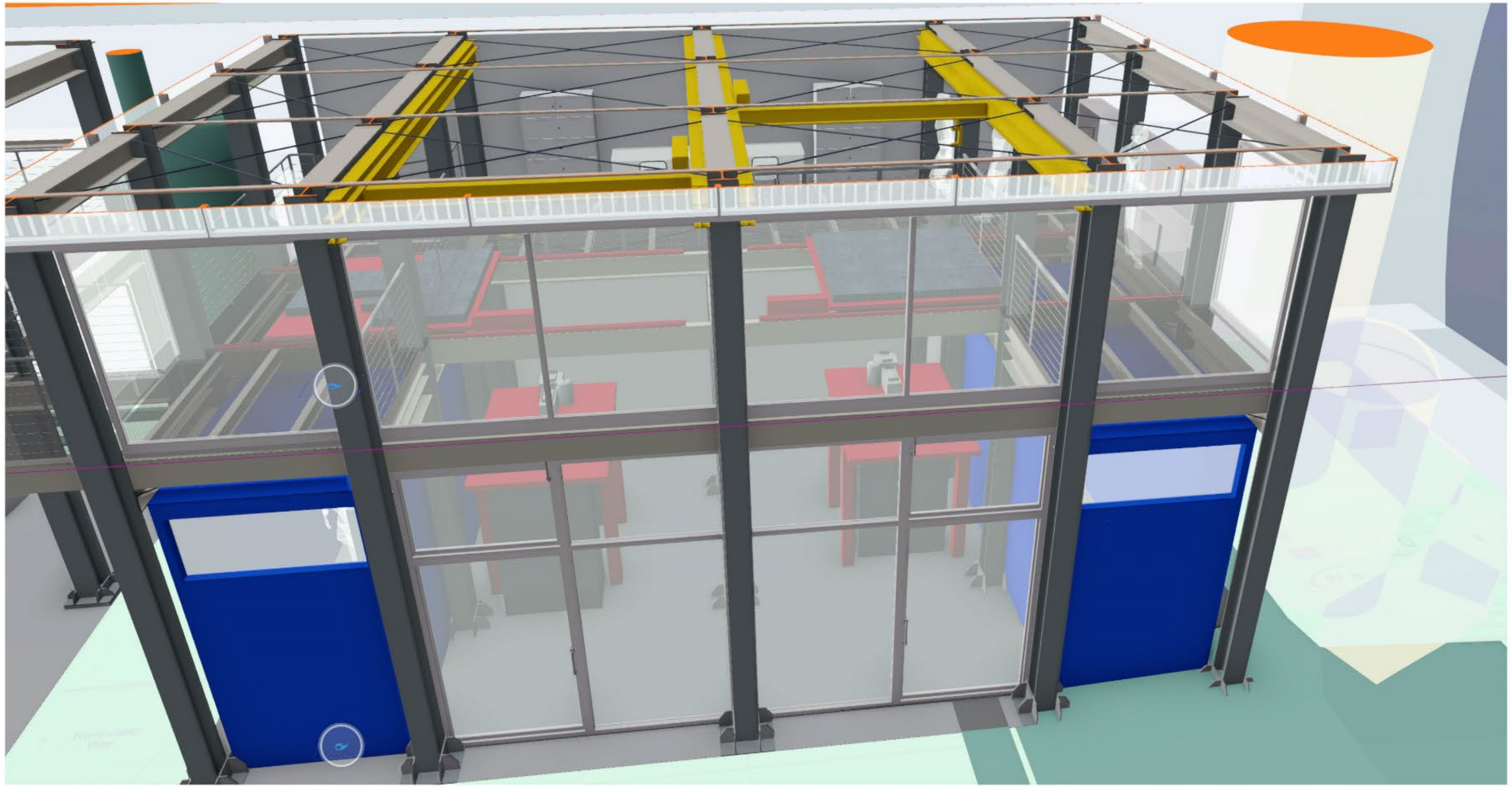

Cryo-P: an underground facility for mK applications

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Cryo-P cryostats

Common features:

- low-background:
  - roomT side and top lead shielding
  - mK top lead shielding hanging below the MC
  - selected materials for vessels and elements in the experimental volume
- single vacuum chamber
- ≥ 6 optical fibers
- ≥ 20 RF lines with LNA, attenuators and circulators
- additional DC wiring (≥ 144 twisted pairs)
- control software

Leiden cryostat

"Large" or "Leiden" cryostat:

- by Leiden Cryogenics
- 50 cm diameter x 100 cm height
- two PT425-RM by Cryomech
- 25 μW @20 mK
- base T ≤ 8 mK
- < 2 weeks to base T
- suitable for 6-12 months runs
- expected delivery: Sep 2024
- expected commissioning: early 2025
- (2025-2028) CUPID, CRESST and SQMS
- (2028->…) opened to scientific community

Specials:

- ≥400 kg mass at base T
- lifting table

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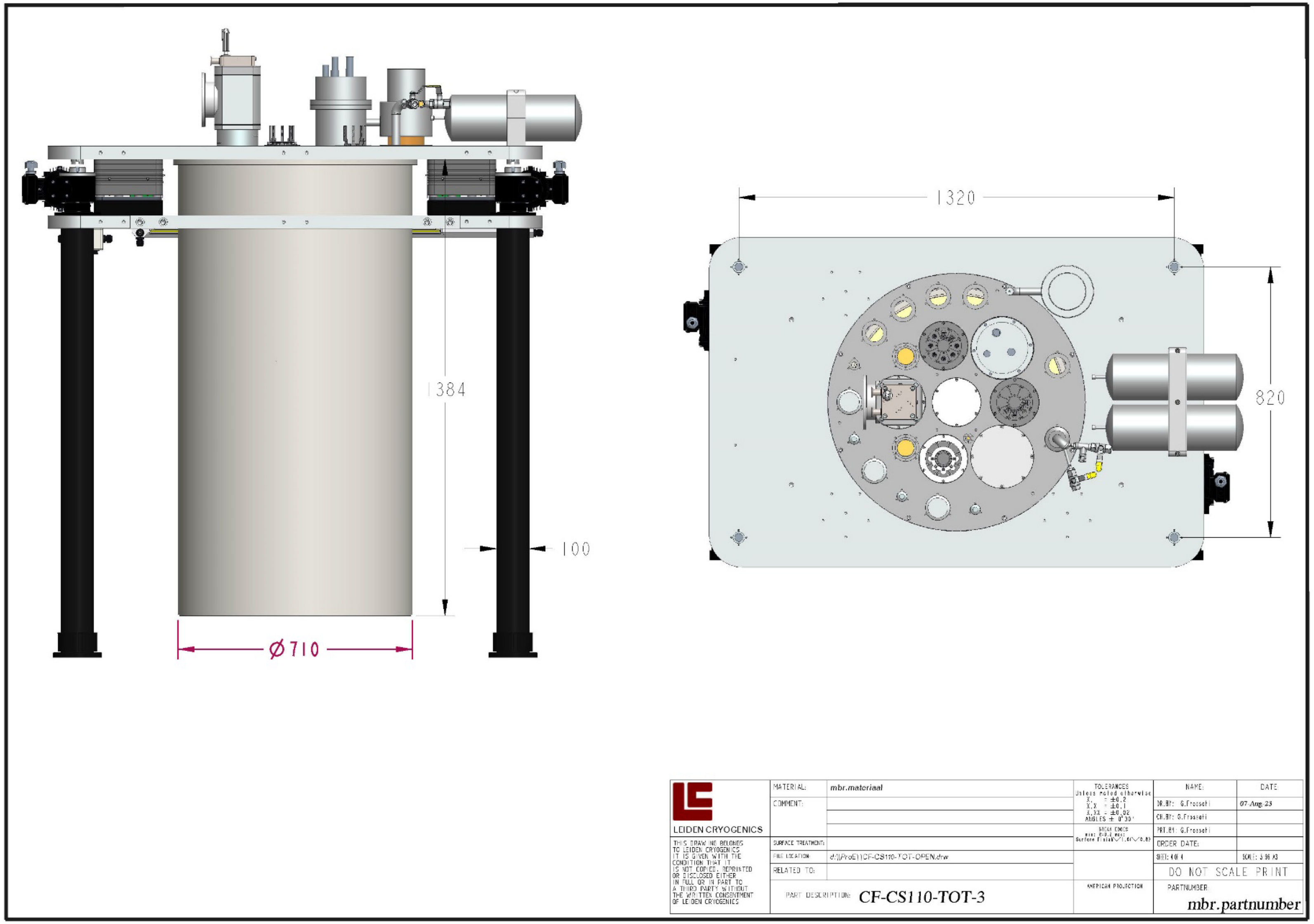


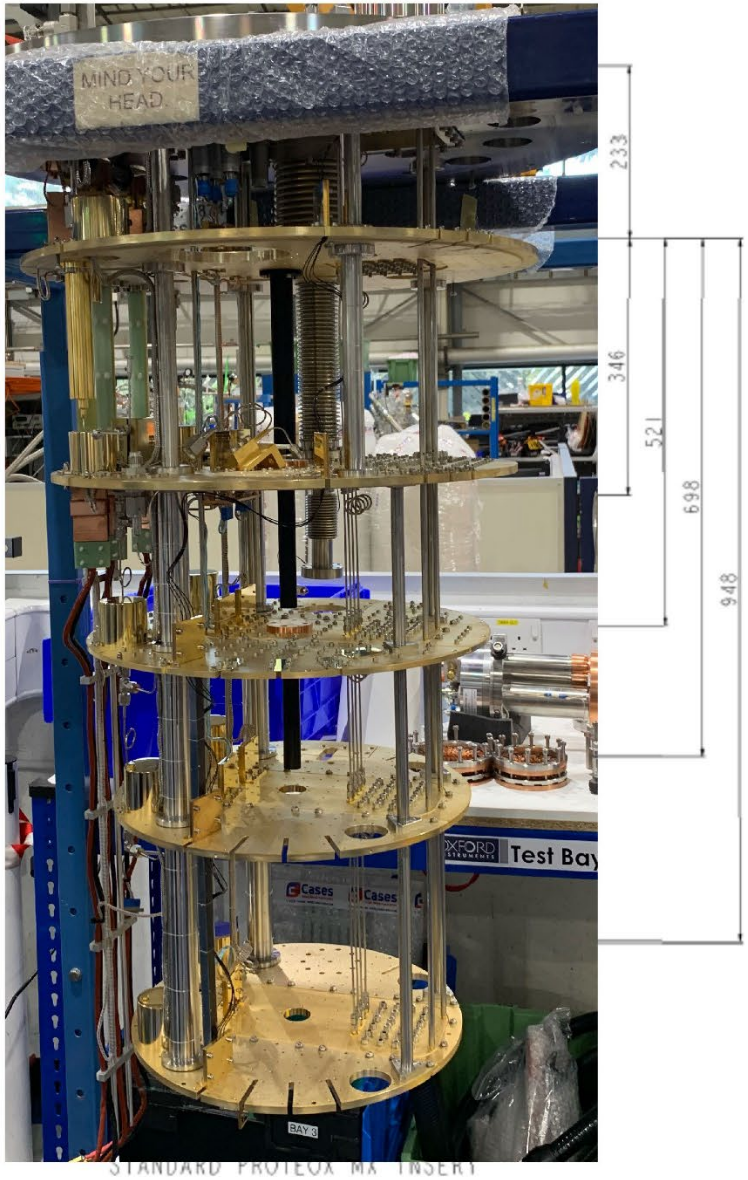
Oxford cryostat

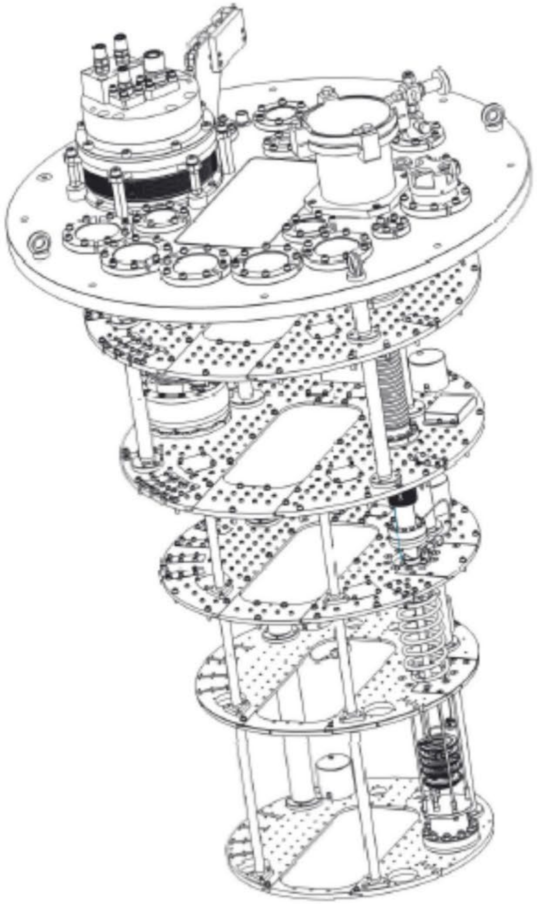
"Small" or "Oxford" cryostat:

- by Oxford Instruments
- 36 cm diameter x 40-50 cm height
- one PT425-RM by Cryomech
- >10 μW @ 20 mK
- base T ≤ 10 mK
- < 10 days to base T
- suitable for 3-6 months runs
- expected delivery: Nov 2024 - Mar 2025
- expected commissioning: mid 2025
- (2025->…) opened to scientific community

Specials:

- ≥220 kg mass at base T
- secondary insert
- 12 T magnet
- sample loader





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