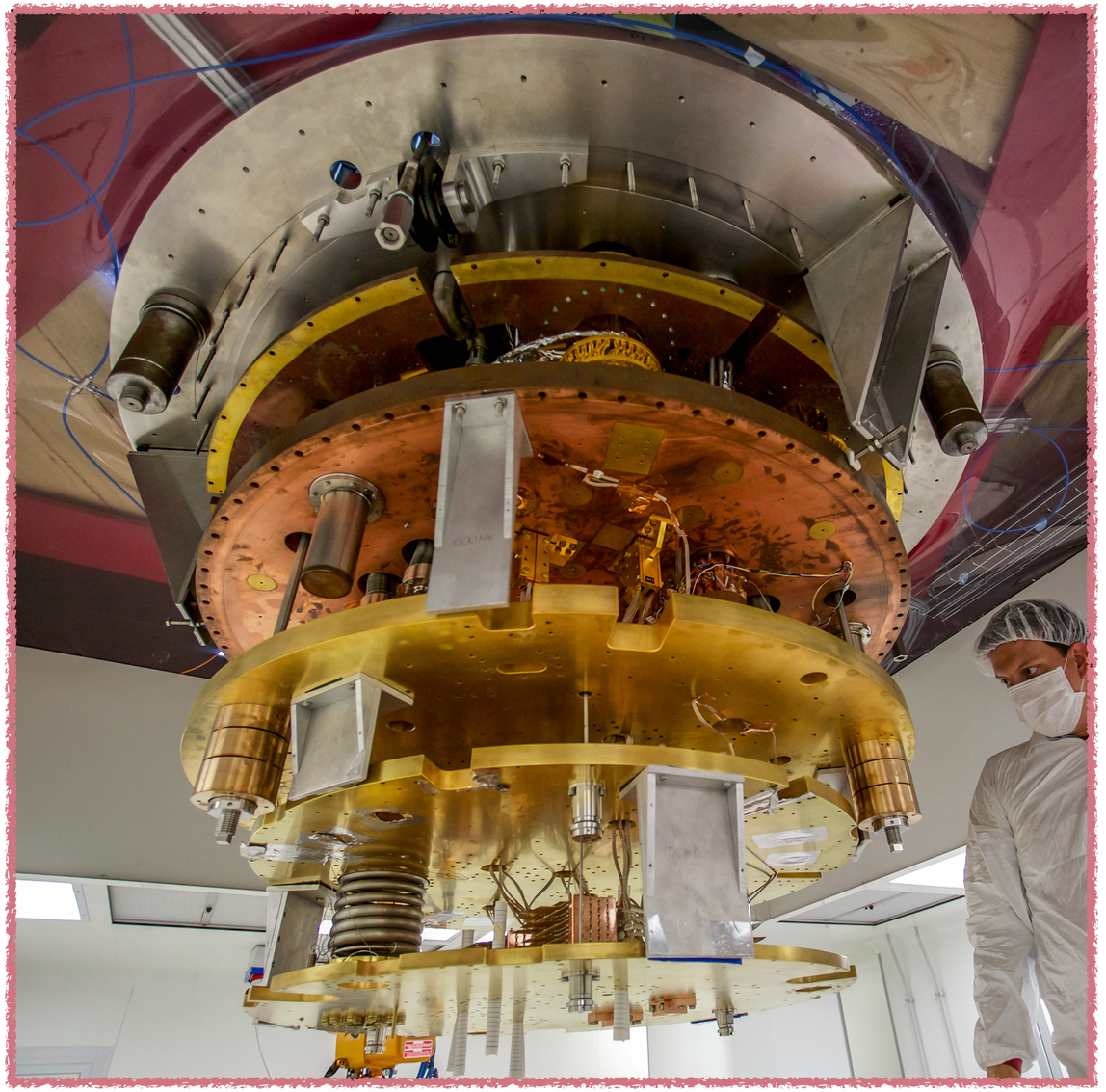
New and advanced technologies for cryogenic infrastructures

APOGEIA WP 5.5

Paolo Gorla

Laboratori Nazionali
del Gran Sasso - INFN

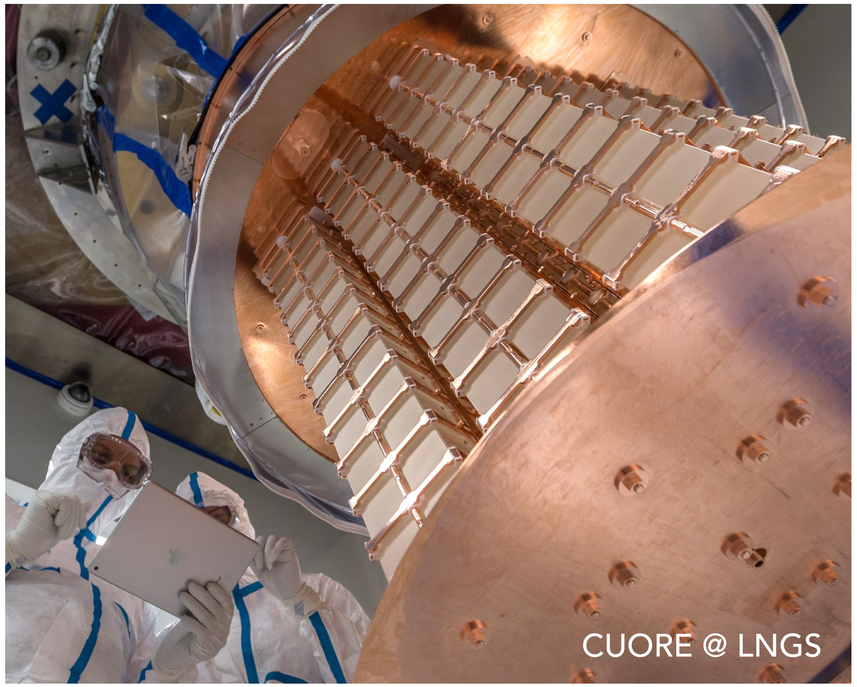


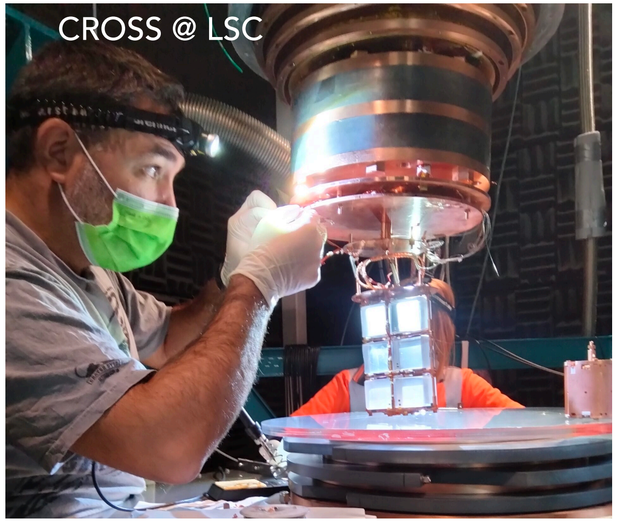
INFN LNGS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Gran Sasso

APPEC

Workshop on EU Underground Laboratories, April 28-29 2022

Cryogenic technologies for particle physics

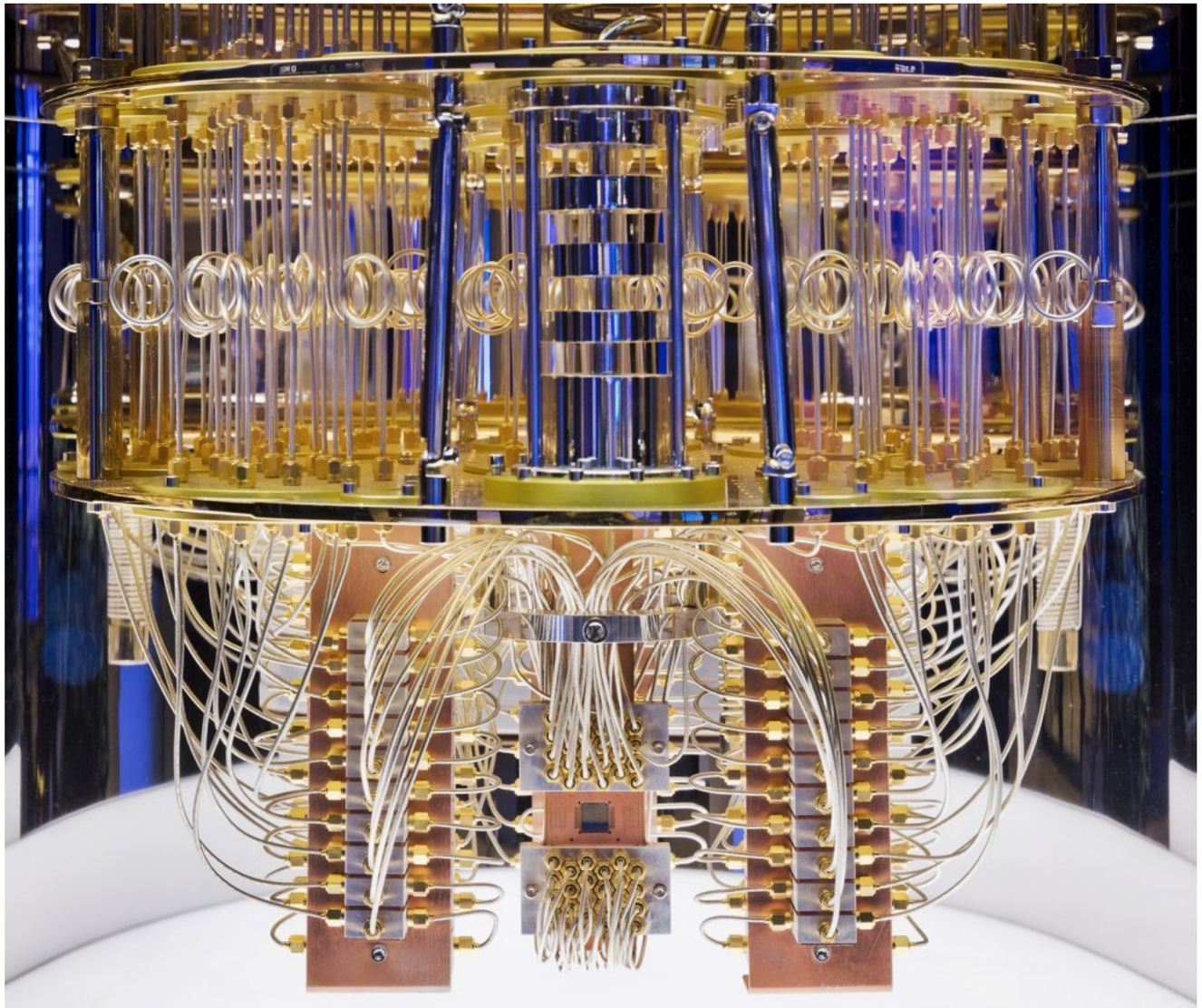




In recent years, cryogenic technologies become more and more relevant in astroparticle physics experiments, due to extreme performances, radio-purity, and low impact on environment.

Technological applications

Quantum computing has boosted the development of a new generation of Dilution Refrigerators to operate Qubits at mK temperature (WP2, talk from J.Pelegrin). In this scenario Underground Laboratories can play a role offering low background, reduced muon flux research environments where the quantum coherence time of qubits is strongly enhanced.

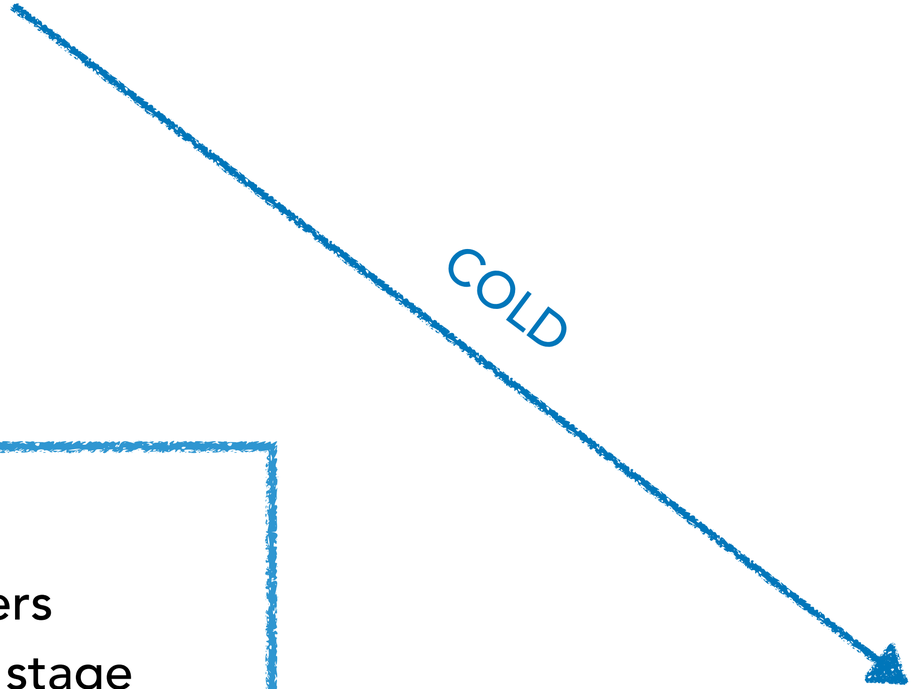


Cardani, L., et al. Reducing the impact of radioactivity on quantum circuits in a deep-underground facility. Nat Commun 12, 2733 (2021).

Temperature scales

Liquefied Gases: 165K - 77K (4.2K)

- Liquefied Noble Gas TPCs (LXe 165K, LAr 87K)



Cold heads: 15K - 2K

- Gravitational Waves Interferometers
- Dilution refrigerators' pre-cooling stage

Dilution refrigerators: 5mK - 30mK

- Criogenic detectors, bolometers, sensors, Qubits

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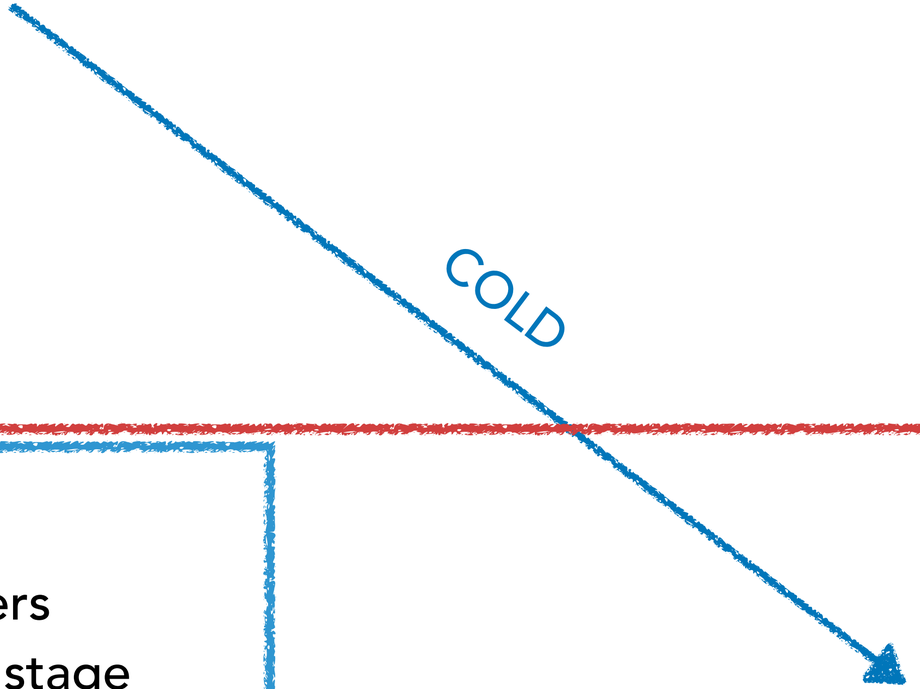

Cryogen-free DRs

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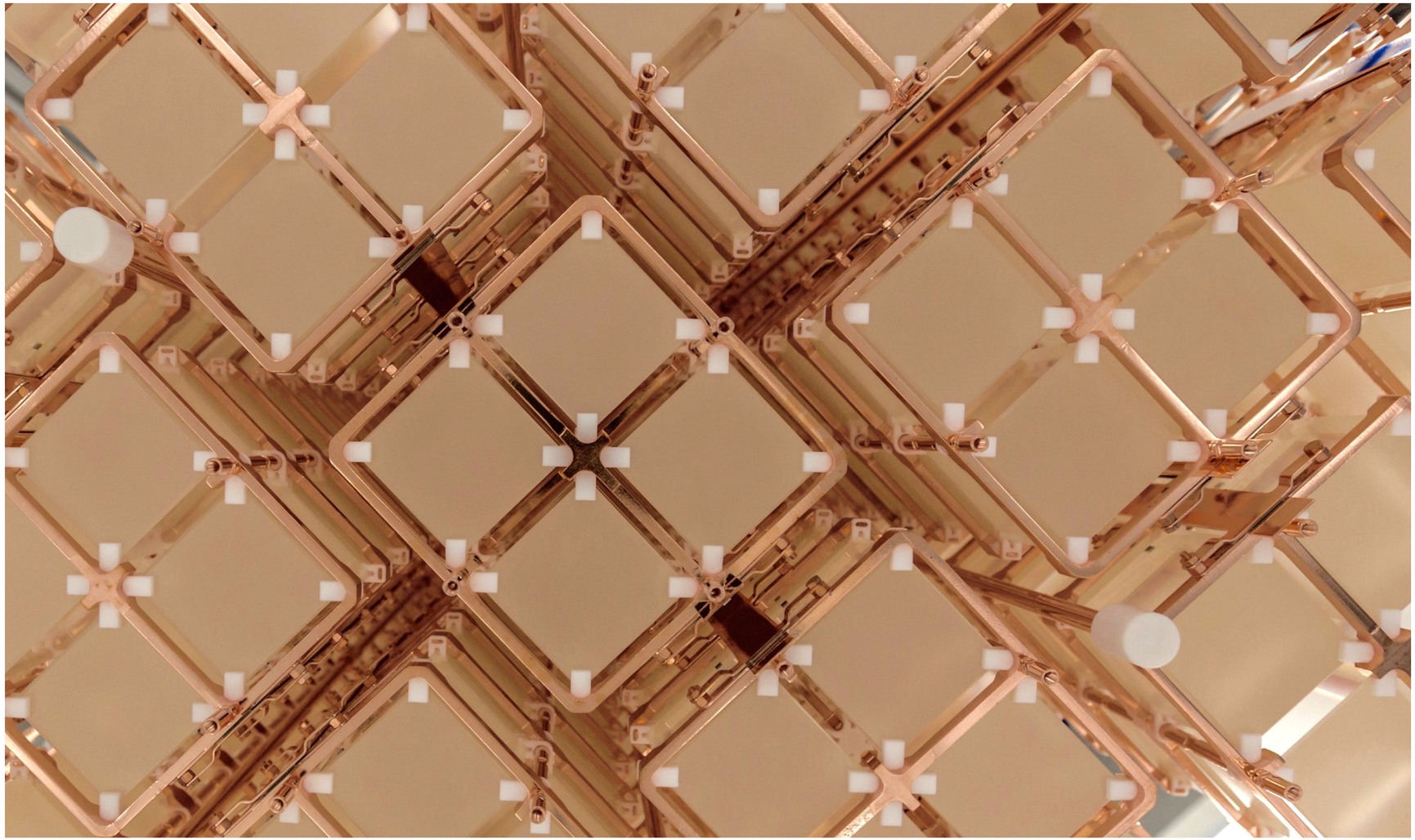
Next-gen cryogenic experiments

Many cryogenic projects are proposing experiments in the tonne-scale of cold mass

Detector:
→ low background
→ high sensitivity

Cryostat:
→ Low temperature
→ Low background
→ Low vibration



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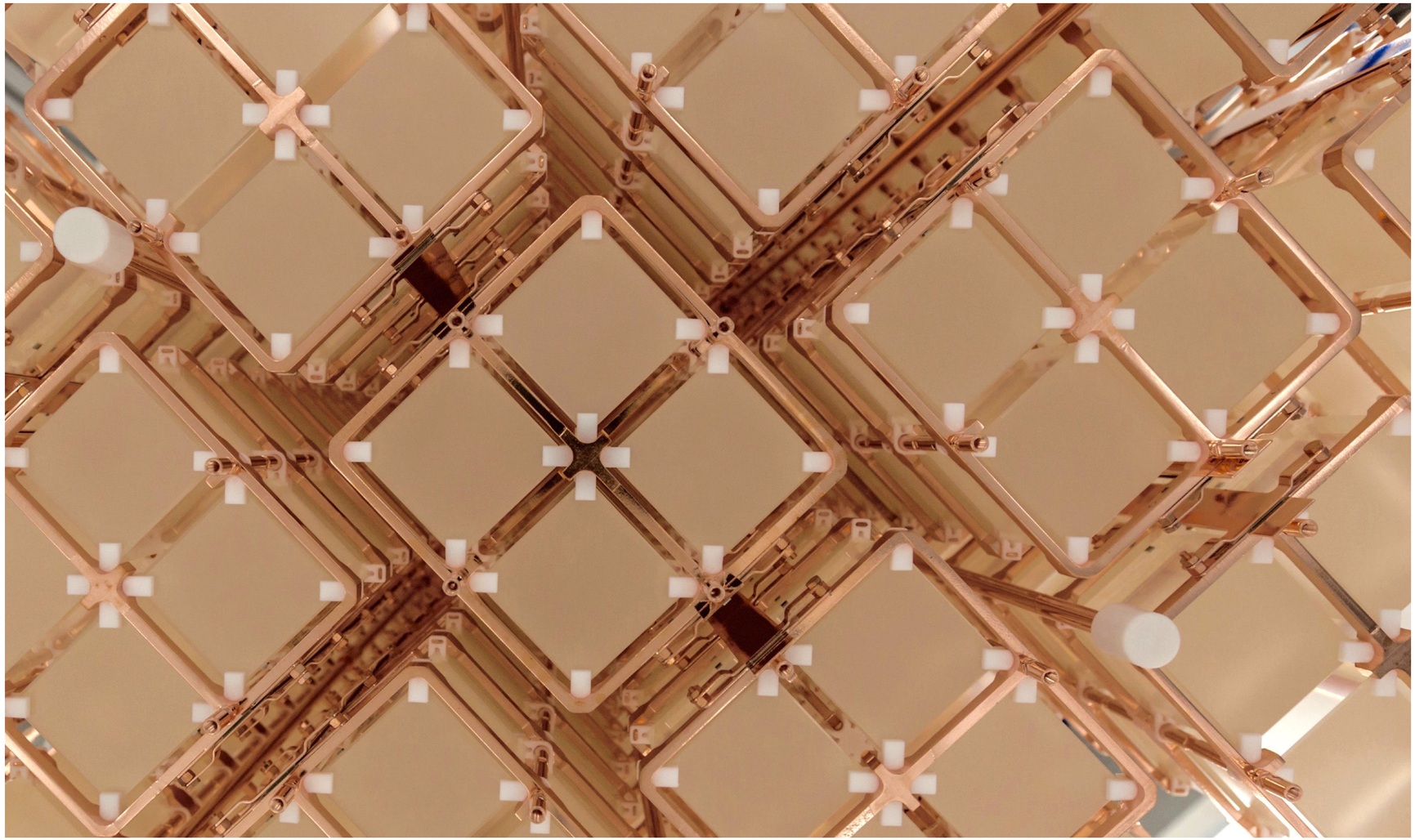


CUORE: the first demonstrator

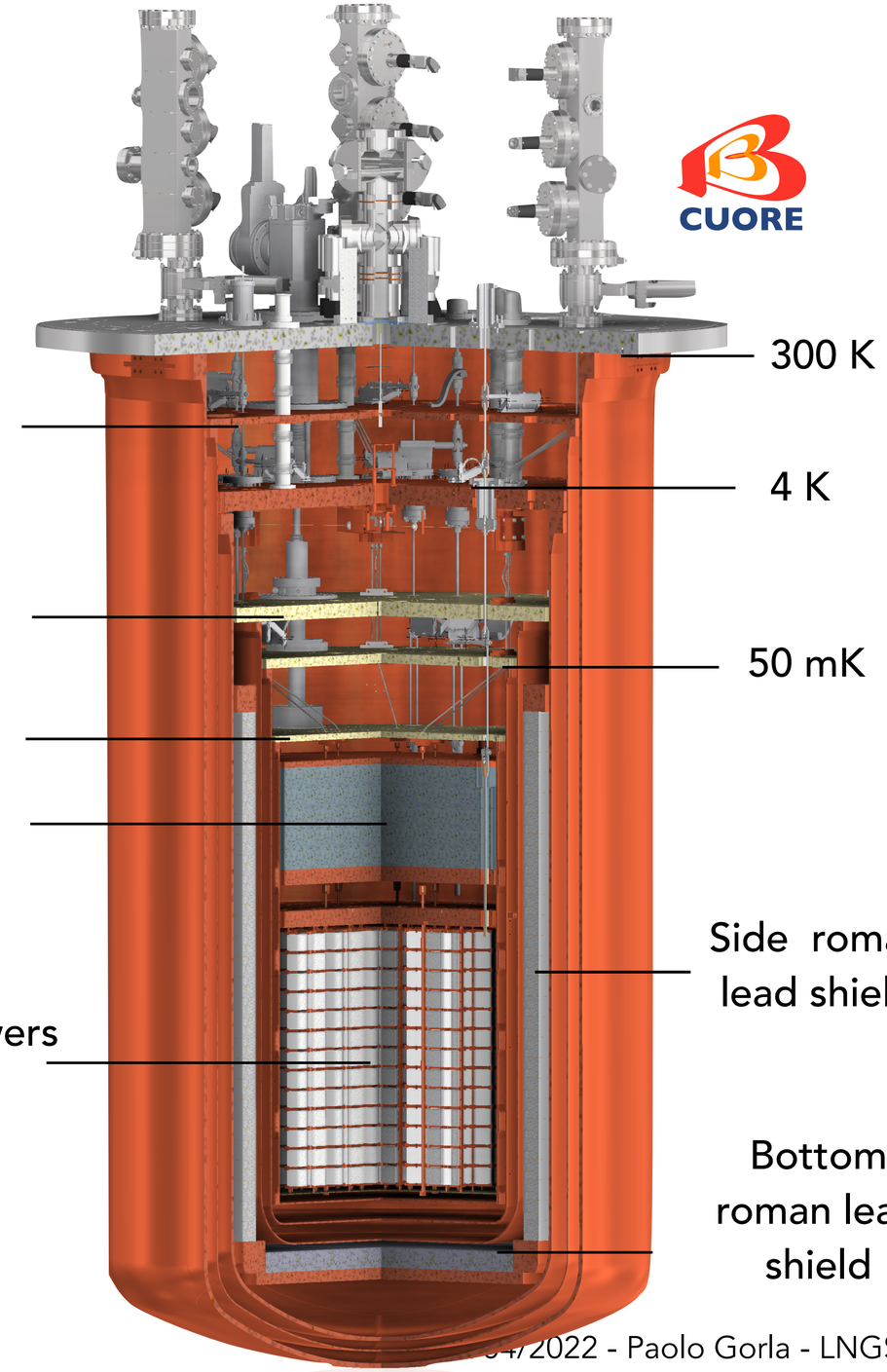
Requirements

The CUORE detector is hosted in a cryogen-free cryostat (mass < 4K: ~15 tons of Pb, Cu and TeO_2):

- Operating temperature 11 -15 mK (base T~7 mK) on an experimental volume of ~1 m^3
- Designed to guarantee extremely low radioactivity and low vibrations environment
  - Energy resolution: goal of 5 keV at $Q_{\beta\beta}$
  - Low background: goal of 10^{-2} cts/(keV·kg·yr) at $Q_{\beta\beta}$
- Low vibrations
- Run for 5 yr

Solutions

- Cryogen free cryostat → Lower downtime
- 5 (4) Pulse Tubes (PT) down to ~4K
- Dilution Unit (DU) down to ~7mK
- PT phase cancellation

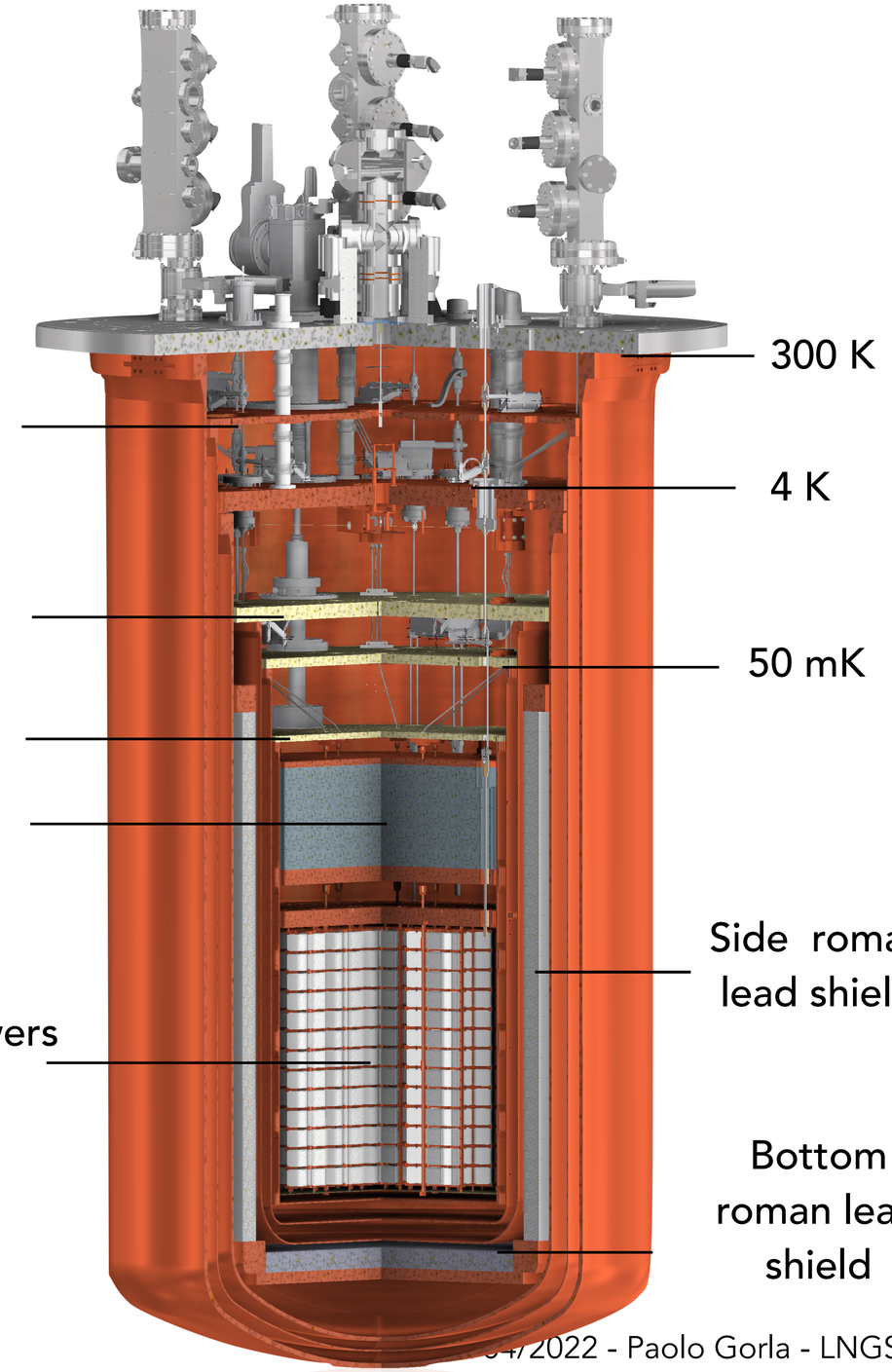


CUORE cryostat

Custom design and commissioning

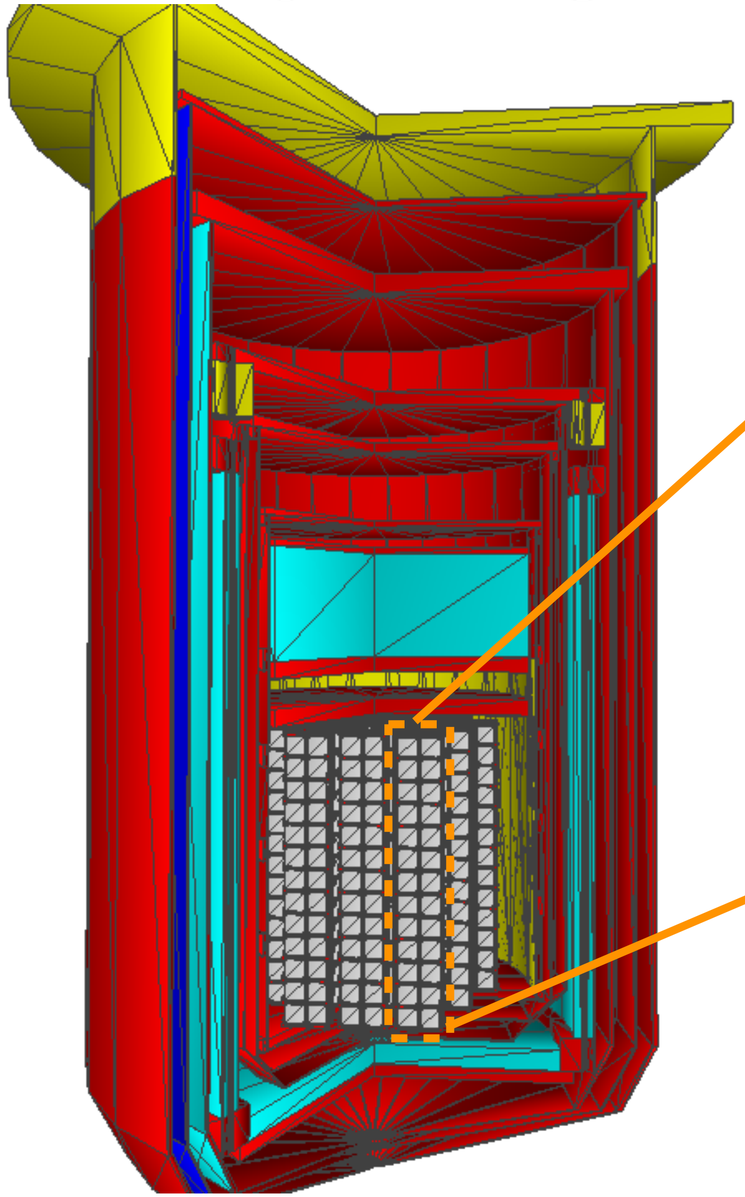
In 2007 no company or engineer available to develop/design the full CUORE cryostat. Most of the work internal to the CUORE collaboration: design took 3 years and commissioning took 4 years but results are impressive.

And now we know how to do it better.

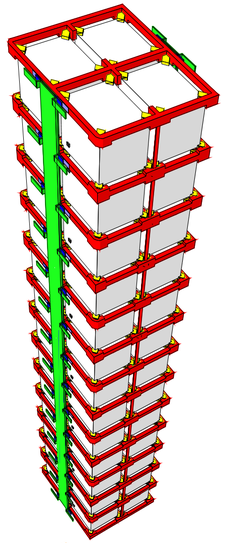


Everything but clean

WP 5.3



Any single CUORE component or part has been selected and validated for low contamination content. The full bkg expectation projected via MC simulations.



Volume	Type	Components
TeO_2	Bulk	$2\nu\beta\beta$, ^{210}Pb, ^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{230}Th ^{226}Ra-^{210}Pb, ^{40}K, ^{60}Co, ^{125}Sb, ^{190}Pt
TeO_2	Surface (0.01 μm)	^{232}Th, ^{228}Ra-^{208}Pb, ^{238}U-^{230}Th, ^{226}Ra-^{210}Pb, ^{210}Pb
TeO_2	Surface (1 μm)	^{210}Pb
TeO_2	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Bulk	^{232}Th, ^{238}U, ^{40}K, ^{60}Co, ^{54}Mn
CuNOSV	Surface (0.01 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (1 μm)	^{210}Pb, ^{232}Th, ^{238}U
CuNOSV	Surface (10 μm)	^{210}Pb, ^{232}Th, ^{238}U
Roman lead	Bulk	^{232}Th, ^{238}U, ^{108m}Ag
Top lead	Bulk	^{232}Th, ^{238}U, ^{210}Bi
Ext. lead	Bulk	^{210}Bi
CuOFE	Bulk	^{232}Th, ^{238}U, ^{60}Co
External	-	Cosmic muons

Crucial contribution from LNGS low background facility (STELLA Lab) and low contaminant traces identification facility (ICPMS Lab)

Dilution unit: hunt for 6 mK

G. Frossati (**Leiden Cryogenics**) developed the DU for the CUORE specifications and advised on how to install and operate it

Leiden Cryogenics
Leader in Low Temperature Techniques

HOME NEWS PRODUCTS COMPANY CONTACT DOWNLOADS LOGIN

Leiden Cryogenics, new Cryogen Free CF-CS110 model

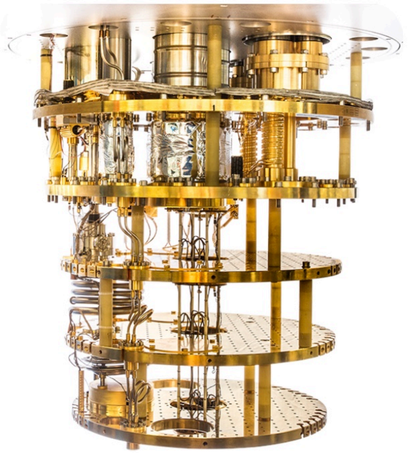
With pride we announce our newest Cryogen Free CF-CS110 model,

this new system with 490mm diameter mixing chamber plate to provide a large sample space.

And the double pulsed tube cooling with an expected Tmin ~ 5 mK,

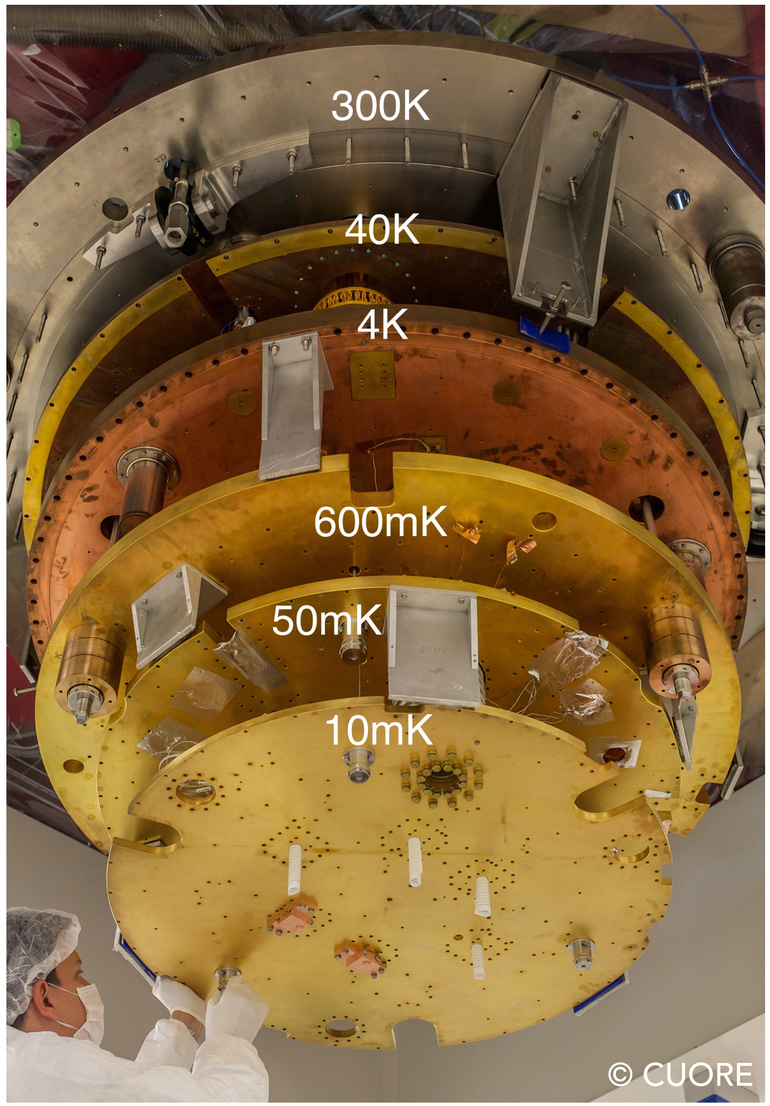
and Cooling power ~ 2500 microW @ 120 mK

LEARN MORE CONTACT



And today you can just buy it! —> not only from Leiden Cryogenics, many players in DRs market today (Bluefors, Oxford Instruments, CryoConcept, etc…)

Cryogen-free DRs



300 K

35 K

3.5 K

800 mK

50 mK

7 mK

Cryogen-free DRs have replaced traditional LHe bath 4.2K stage and 1K stage with Pulse Tube (PTs) cryocoolers at 2.5K-3.5K

PROS

- Improved duty cycle
- High reliability
- Reduced instabilities
- Reduced cost/LHe procurement issues
- Easiness of operation

CONS

- Gas expansion in the PT is an intrinsic source of vibration

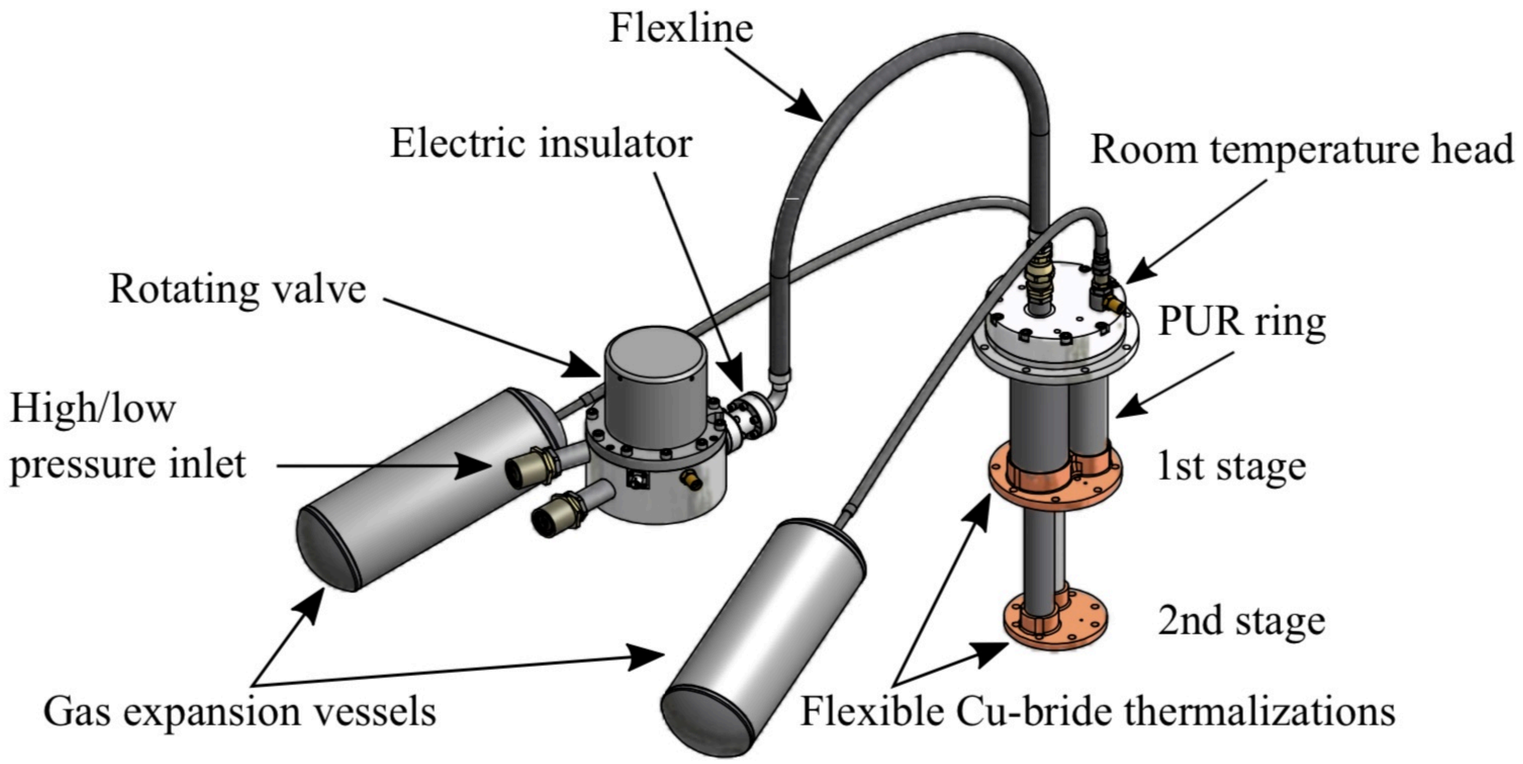
Integrated Cryostat

And then you just need to insert it in a large enough cryostat providing all the proper temperature stages.

To cool down the full CUORE mass you need to **remove ~1*10^9 J of enthalpy.**

Where can you get such an impressive cooling power?

Cryomech pulse tubes



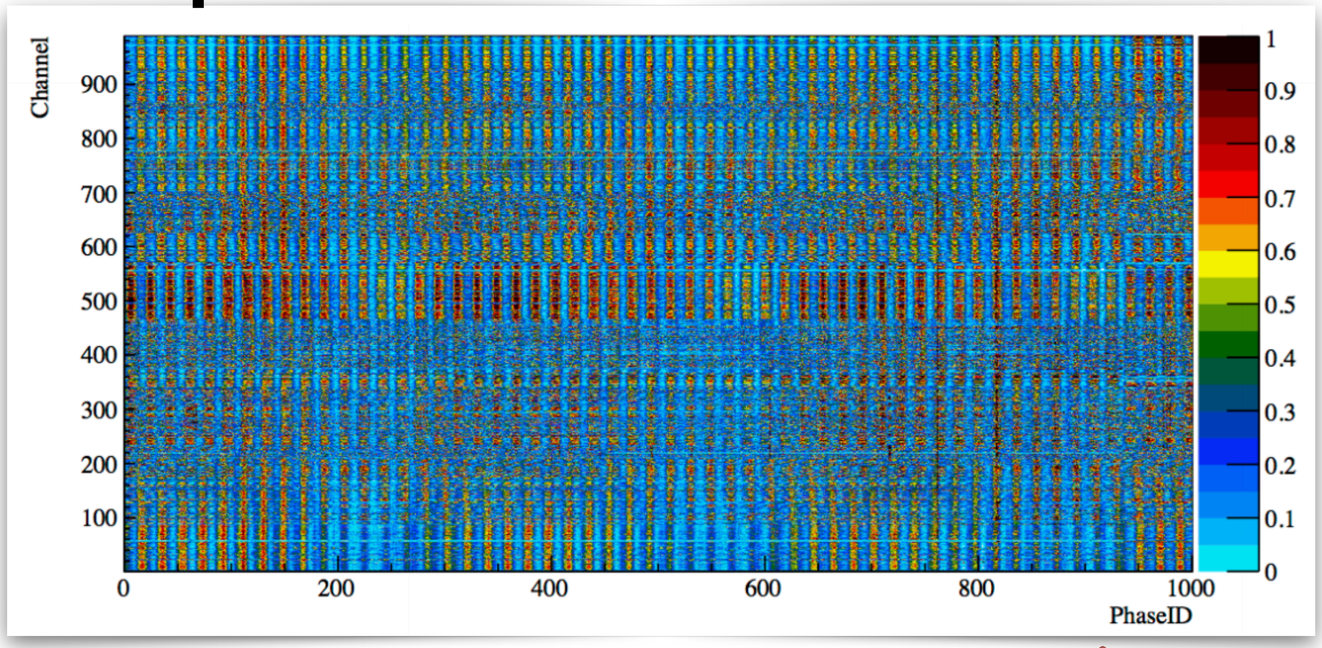
PT415 from Cryomech can provide a cooling power of 1.5W @4.2K W/ 40W @ 45K

CUORE case-study

CUORE cryostat is equipped with 5 (4 operating at the time) Cryomech PT415 Pulse Tubes with remotized rotary valve.

These PTs provide ~3.5 K at the 2nd stage and ~35 K at the 1st stage for the full CUORE cryostat.

PT phase cancellation



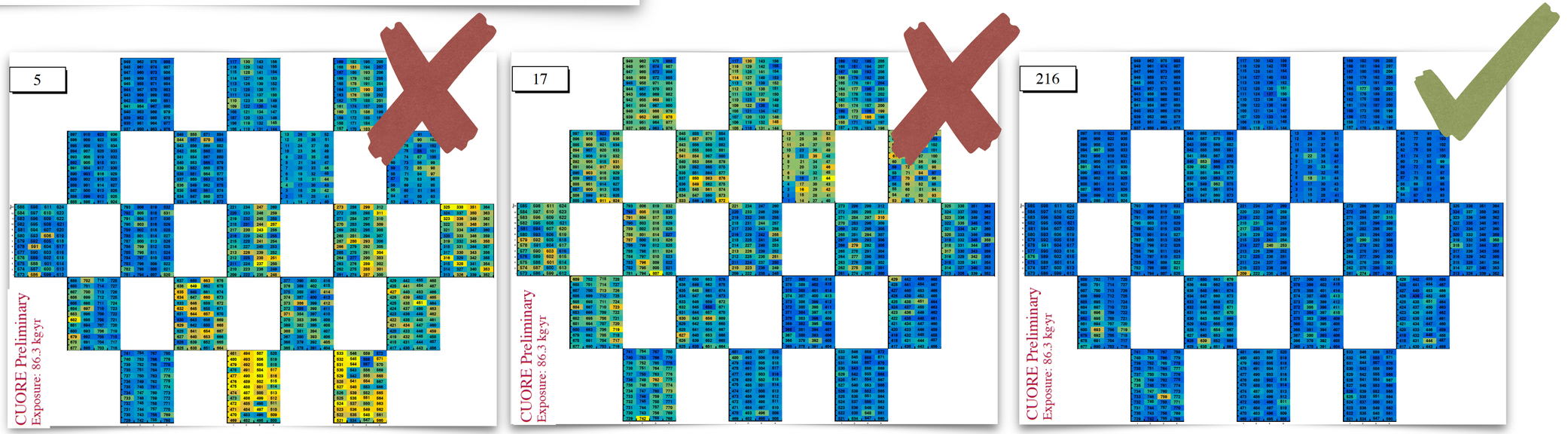
Attenuation of Pulse tube induced vibrations:

(1) Switch to Linear Drives to control PT motor heads -> reduce temperature variations on the Mixing Chamber

(2) PT phase scan to find the phase configuration that actively minimize the PT induced vibrations

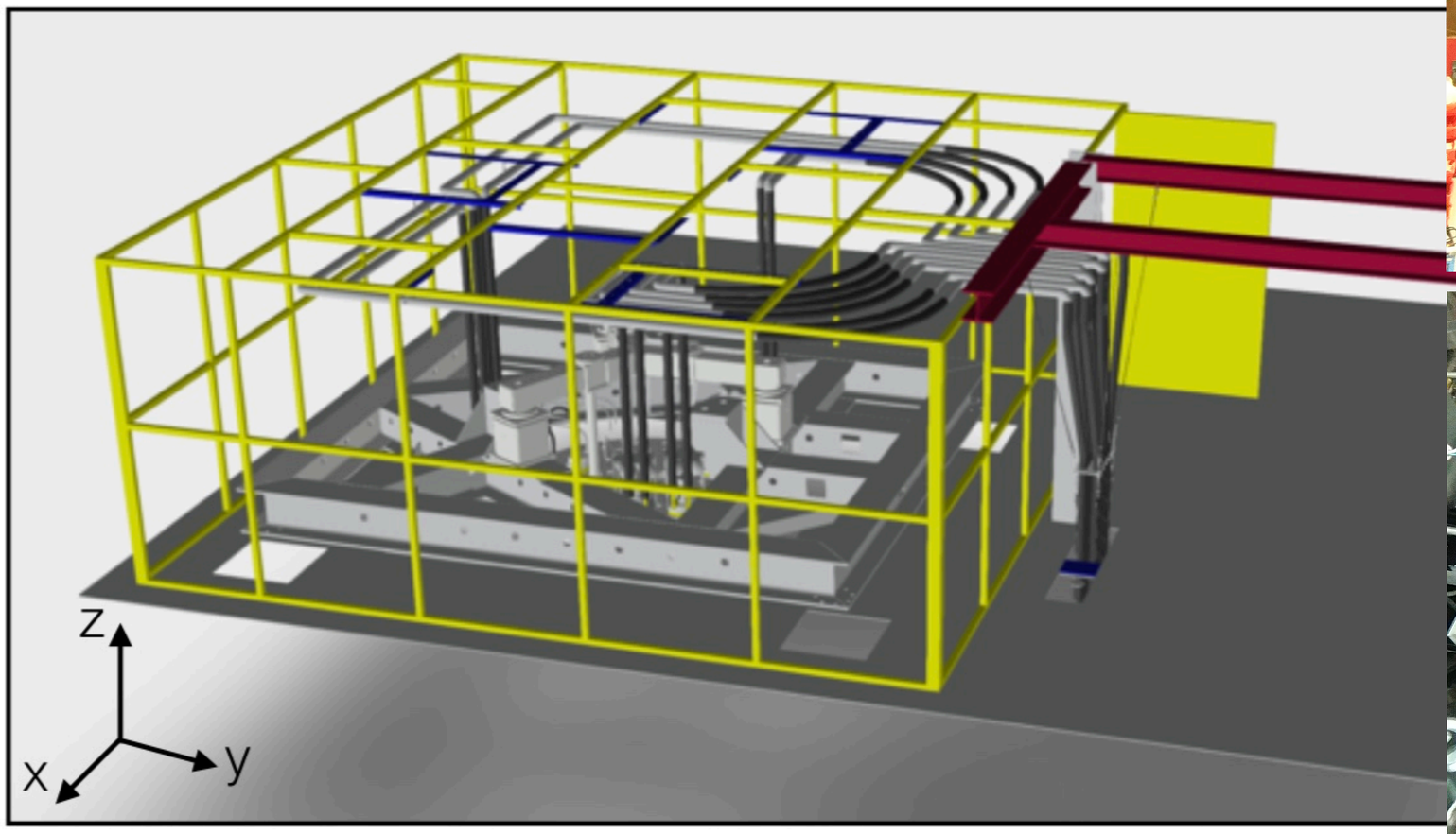
Cryogenics 93 (2018) 56–65
arXiv:1712.02753

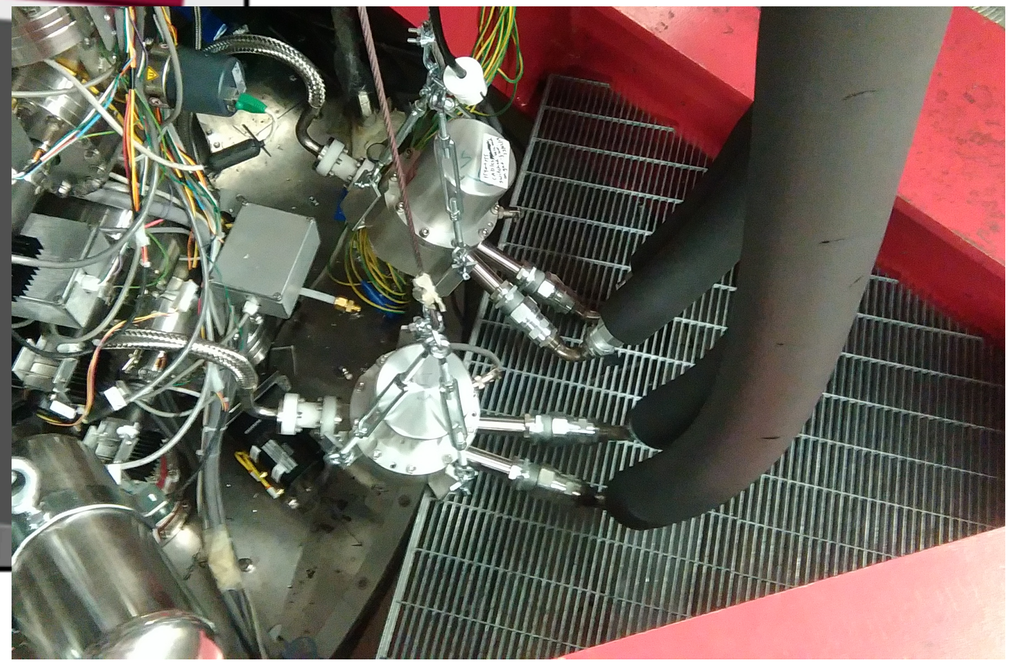
Example of the PT induced noise for three different PT phase configurations



Vibration dissipation

As vibrations from pulse waves are unavoidable, dissipating vibrations far away from the cryostat is crucial





Cold stage thermalizations

In CUORE Currently PTs are connected rigidly to the 300K plate and to trough a system of copper braids the cold stages

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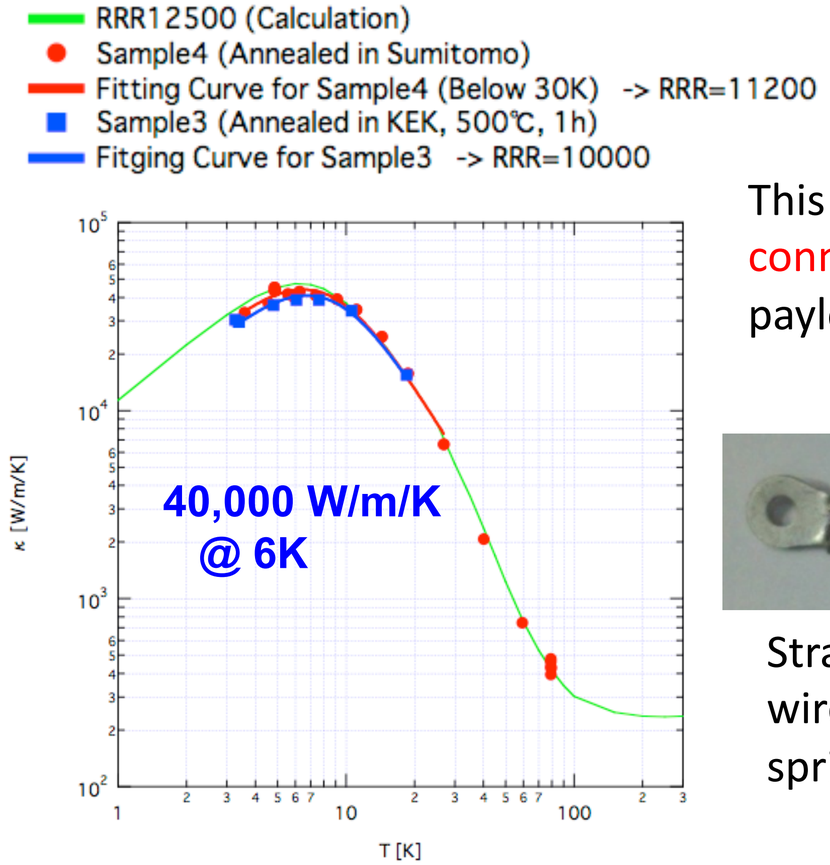
Radical improvement of the noise cancellation will require redesign the cryostat-PT coupling (possible for new cryostats) but optimization of the current system are under investigation

6N Purity Al Heat Link

Extremely soft and good conducting high purity Al braids

KAGRA



Teion Kogaku 46, (2011) 415-420

Thermal / Electrical conductivity at cryogenic temperature proportional to material purity.

This is important to realize weakly connected heat links to cryogenic payload

Stranded cable (made of many thin wires) has advantage to have small spring constant.

$$k = n \times k^{(1)} = \frac{3nE\pi d^4}{64l^3}$$

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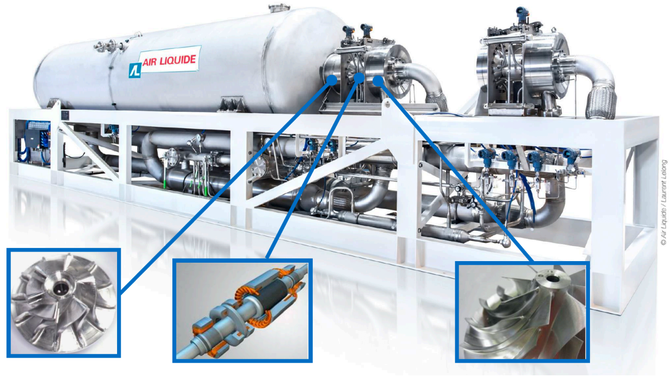
Advance cryogenic Laboratory @ LNGS

Nowadays most experiments @ LNGS utilise cryogenic technologies

- wide range of temperature (from ~ 165 K down to 0.005 K)
- 6 dilution refrigerators presently underground, more in the future
- increased need of cryogenic and vacuum support
- some projects planned to enlarge the cryogenic equipment



LN_2 liquefier & re-liquefier

- will cover the needs of DarkSide and LNGS
- Large power (40 kW @ 68 K)

New LHe liquefier

- Support to the “wet” dilution fridges
- Production rate ~ 20 liters/hour

Testing facilities at “high” temperature

- Pulse Tube based
- GM cold head based
- Characterisation of materials and devices down to ~ 3K

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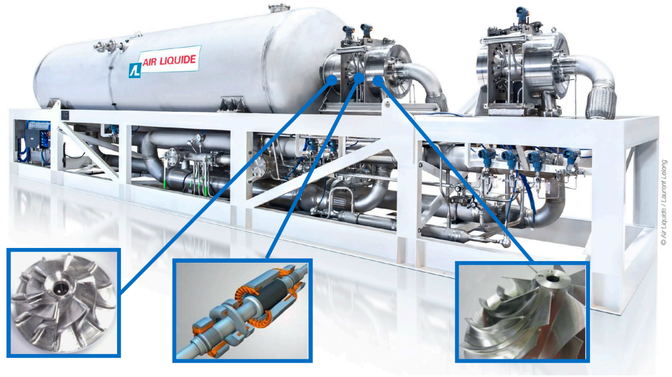

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Available infrastructures (I)

LNGS cryo-platform

A top-class DR (funded by BMBF, INFN, and SQMS) with large experimental space: ⌀ 50 cm, h 100 cm (Base T < 10 mK).
Cryogenic setup conceived to perform measurements of detectors and devices at very low Temperature

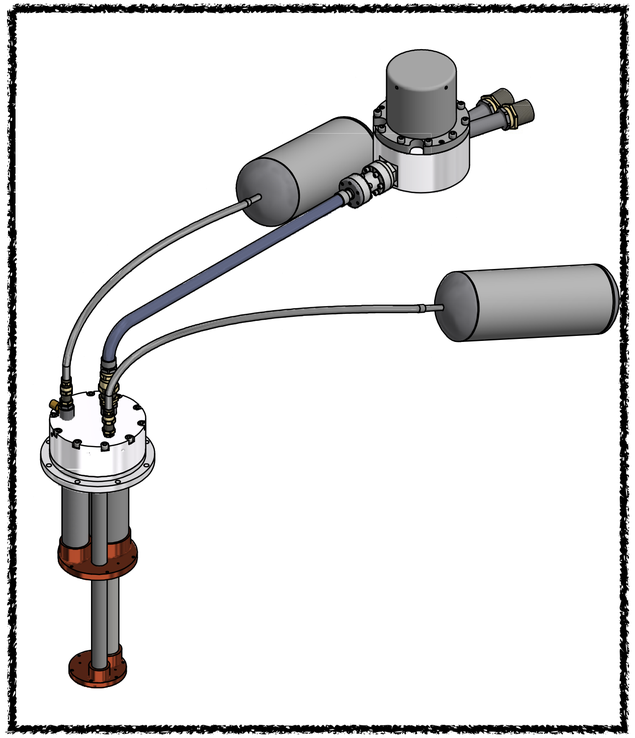
Dry 3He/4He dilution refrigerator developed as broad use facility in the LNGS underground side. The Cryo-Platform facility will be available in 2023. Access procedures regulated by a PAC.

Low radioactivity & low vibration environment
Useful for low-background tests of
Cryogenic detectors equipped with TES, NTD, KID, …
Qubits

Available infrastructures (II)

PT425

PT425 2.7W @ 4.2K W/ 55W @45K (base T 2.8K) represents the newest technological achievement of Cryomech for DR applications (other option: PT310 1.0W @ 3.0K W/ 35W @35K).



2 PTs and a dedicated Test facility will be installed in the new Advanced Cryogenic Lab at LNGS above ground site to test and characterise performance and vibrations (funded by INFN for CUPID, in the upcoming 3 years available for testing) —> soft thermalisation and vibration decoupling program

APOGEIA WP 5.5

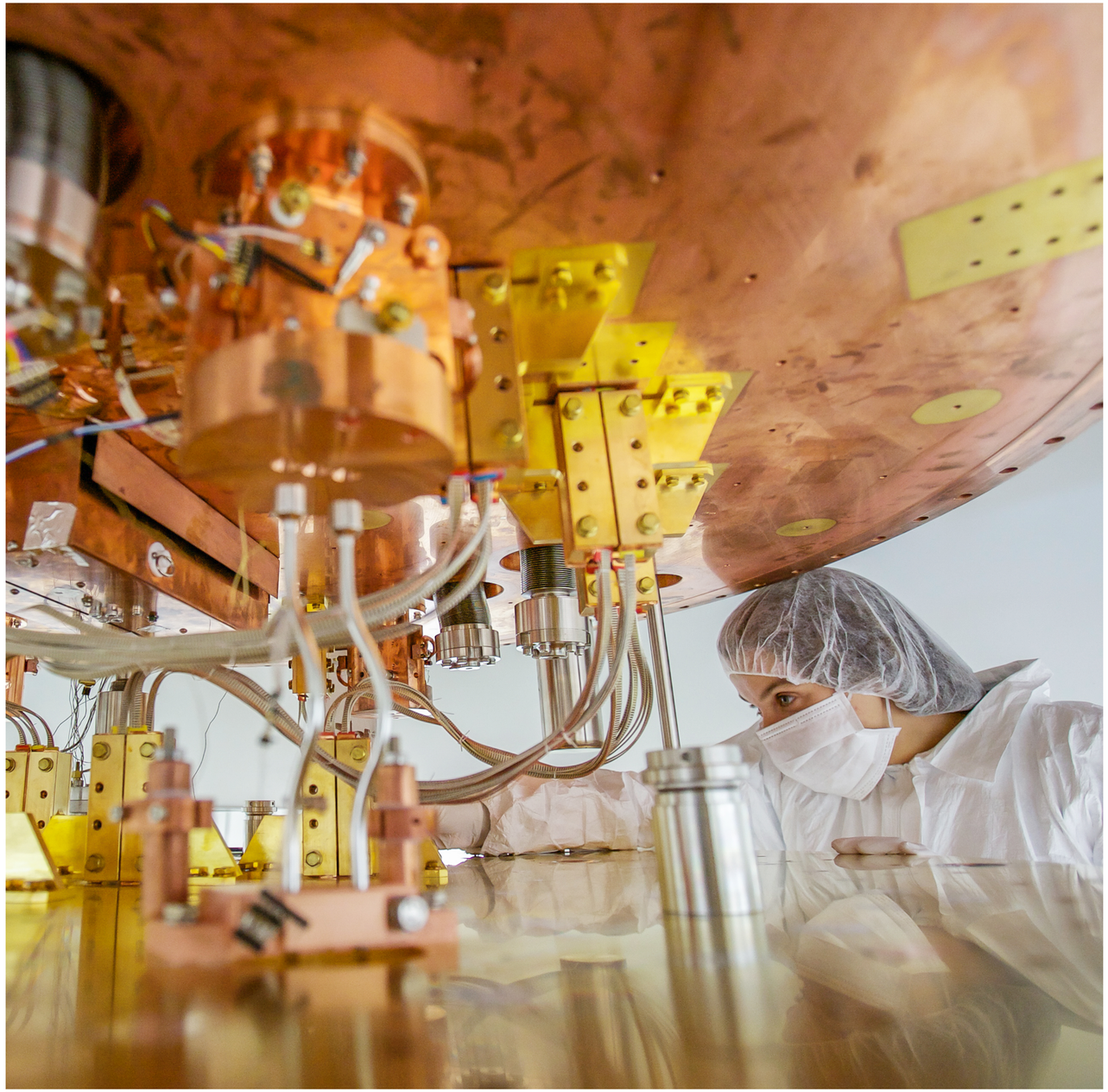
The most advanced research lines in the field focus on the suppression of vibration from PT cryocoolers and on the detector vibration decoupling and sensor optimization. PT induced vibration, which come mainly from the pulsed expansion of high pressure helium in the PT expansion chamber, can be minimized with soft thermalization between PTs and DR plates. Most recent developments include the use of aluminum 6N braids widely used in gravitational wave interferometers. At the detector level both the decoupling from vibration and sensor optimization can be crucial ingredients of the upgraded sensitivities for a variety of sensors, including transition edge sensors (TES) and neutron transmutation doped (NTD) germanium chips. Complementary read out of light or charge offer a fundamental tool for particle discrimination and background rejection. In the LNGS laboratory there are facility already available for the test and characterization and facilities funded on different budget that will be installed in 2023 and will be available for use during the project: liquid helium based DR; 10K GM based cryostat; PT based cryostat; 2 cryogen-free DR.

5.5.1.2 Deliverables :

1. Hire of the personnel that will follow the optimization and testing on the facilities.
2. Acquisition of the electronic instrumentation and sensors to characterize and optimize detectors.
3. Upgrade and commissioning of the PT facility

Take home messages

Next generation of cryogenic projects, both in astroparticle physics and quantum technology, will require large, low background, and low noise cryostats



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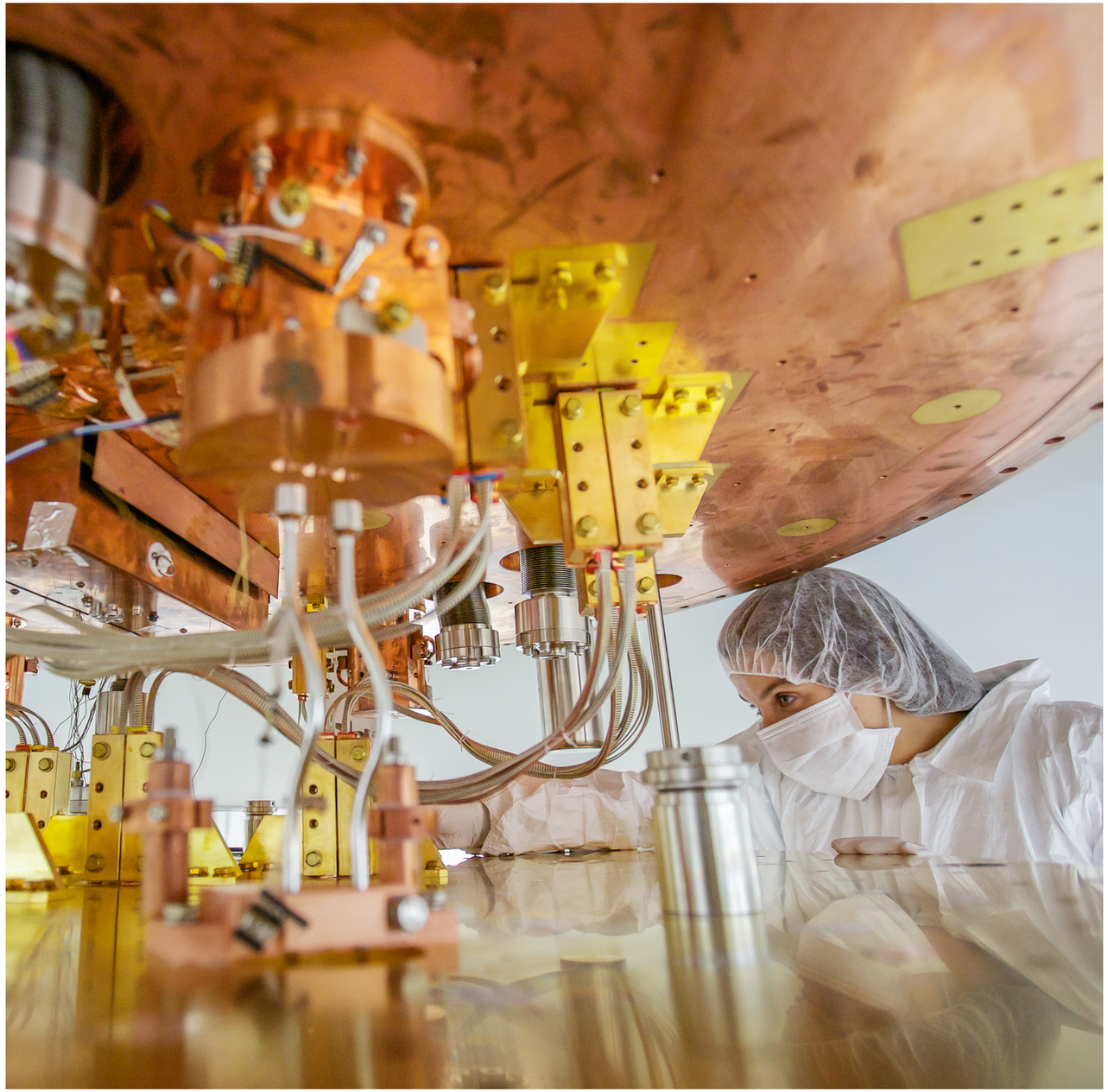

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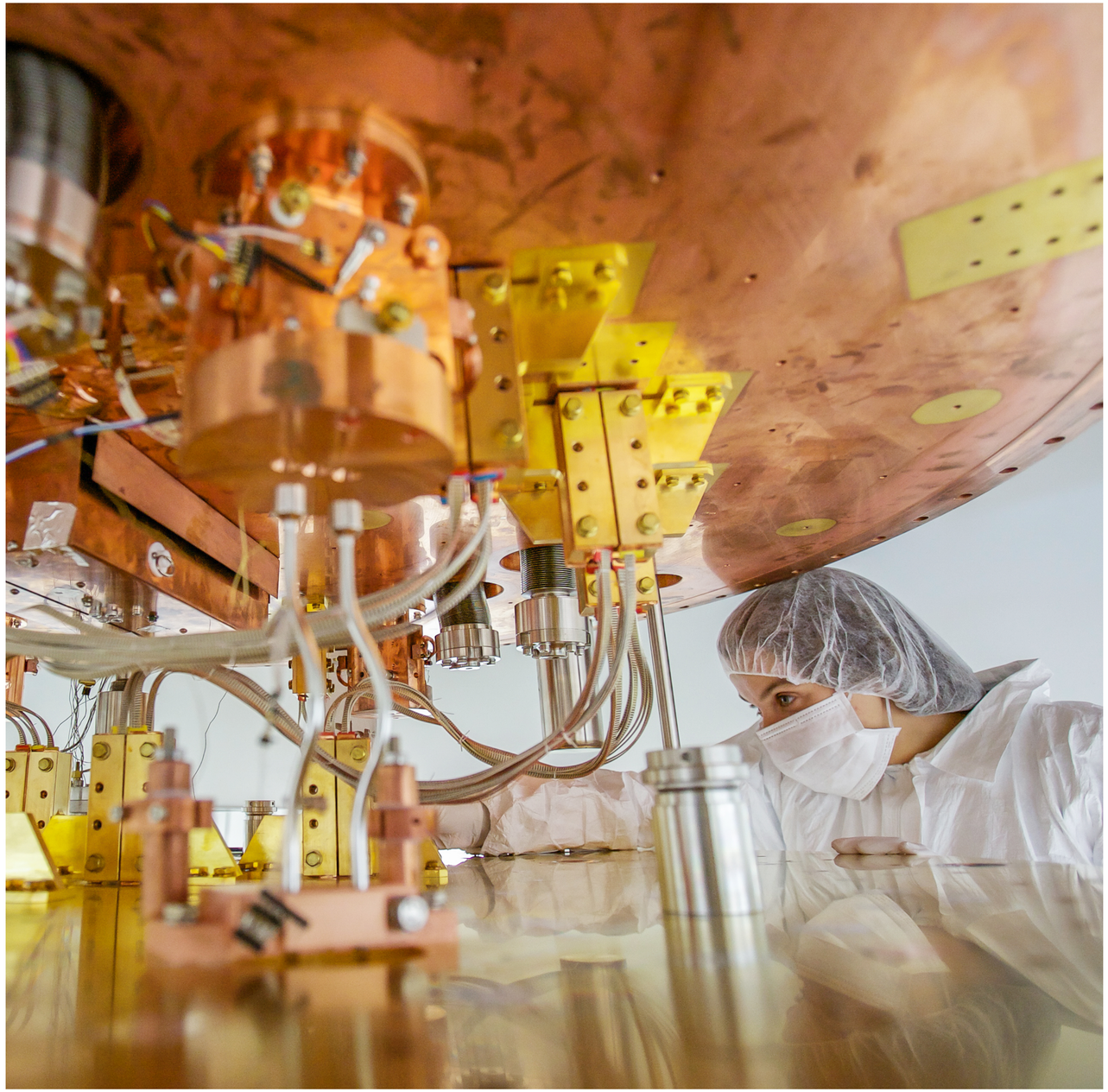

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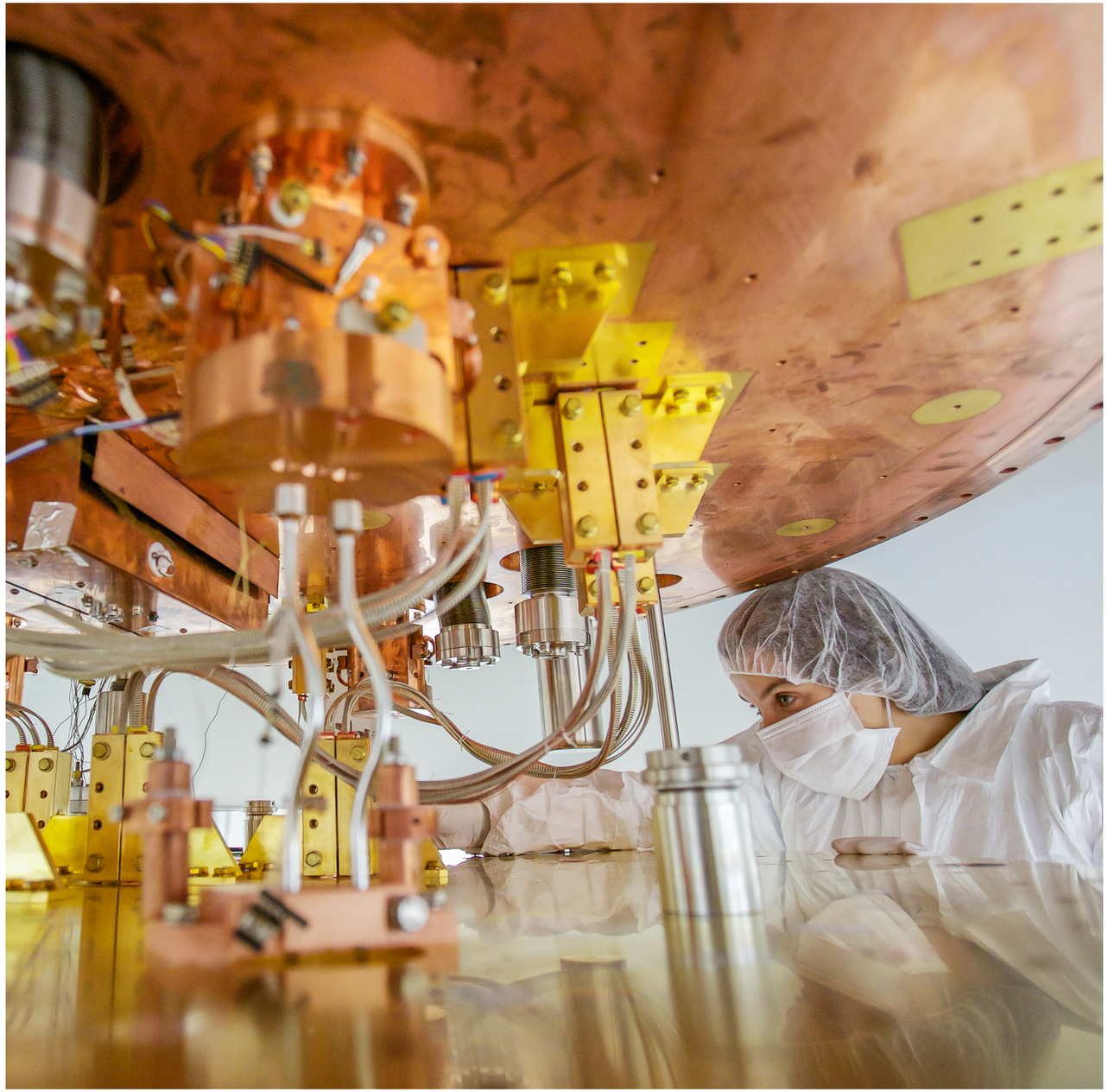

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The technology and knowhow are mature for next generation tonne- or multitonne-scale mK cryostats