The ASTAROTH Project - a novel technique for NaI(Tl) crystal cool-down

ICNFP 2020, 4-12 Sept. 2020, Crete

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Introduction

ASTAROTH is an R&D project aiming at **lowering the energy threshold down to the sub-keV region** for direct dark matter (DM) detection experiments based on NaI(Tl) scintillating crystals.

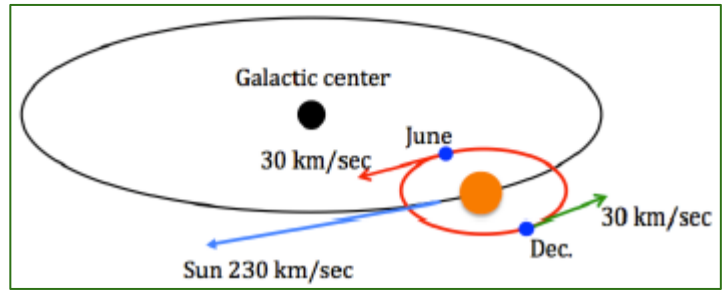
This is of fundamental importance for testing the DM interpretation of the DAMA annual modulation signal, with the same target and technique.

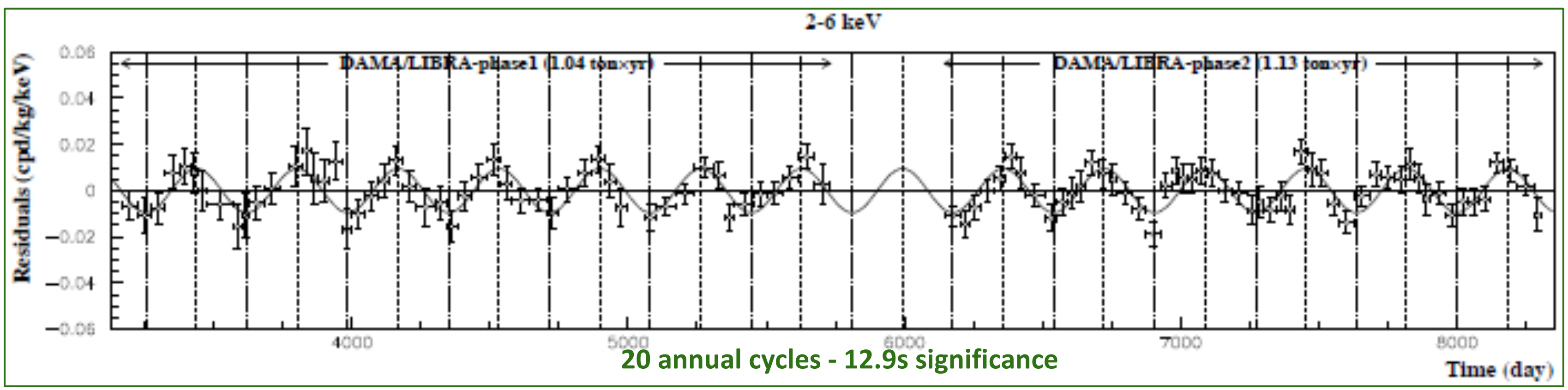
DAMA/LIBRA phase-2

Exposure: 1.13 ton x year (6 years)

Sensitive mass: about 250 kg of radio-pure NaI(Tl) crystals

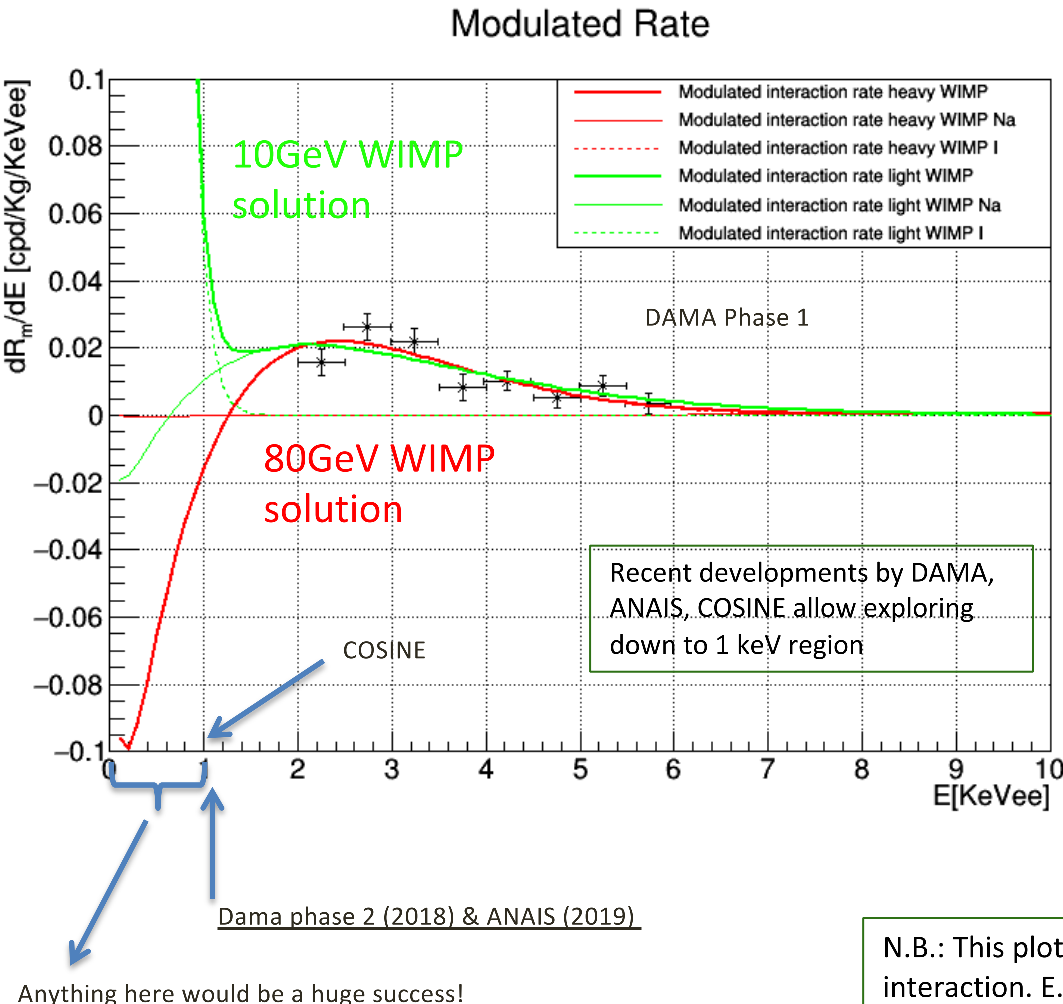
Read-out with PMTs, no veto





20 annual cycles - 12.9s significance

Introduction



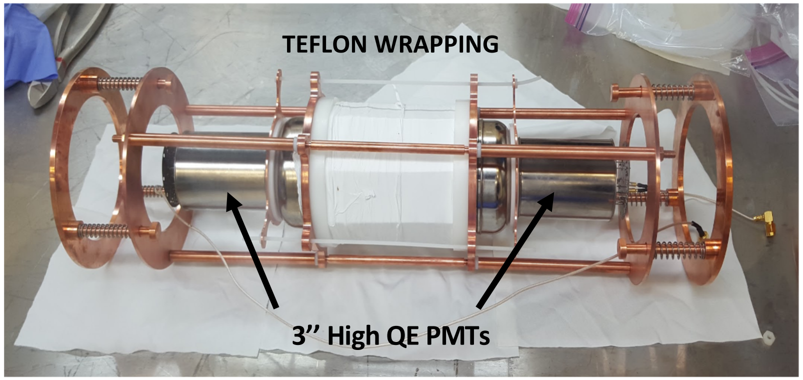
- ASTAROTH proposes a technology development that aims at **lowering the detection energy threshold**, making it possible for the first time to **observe sub-keV recoils**.
- This would allow disentangling different DM-induced modulation models, thus restricting the parameter space of a surviving DM candidate.

N.B.: This plot is made assuming simplest hypotheses for DM and its interaction. E.g.: standard DM halo distribution, spin-independent interaction.

Current technological limitations

A model-independent verification of the DAMA observation requires:

- ultra-low background, superior sensitivity and low energy threshold.
- **NaI(Tl)-based detectors**, SABRE, ANAIS and COSINE, share with DAMA the basic design.



- Limited light collection, ranging from 7 to 15 photoelectrons (phe) per keV.
- Intrinsic high noise and radioactivity of the PMTs.
- Hard to achieve production of very-high-purity crystals with a mass of few kg.

→ **observable recoil energy higher than 1 keV$_{ee}$.**

Some experiments exploit **VETO**:

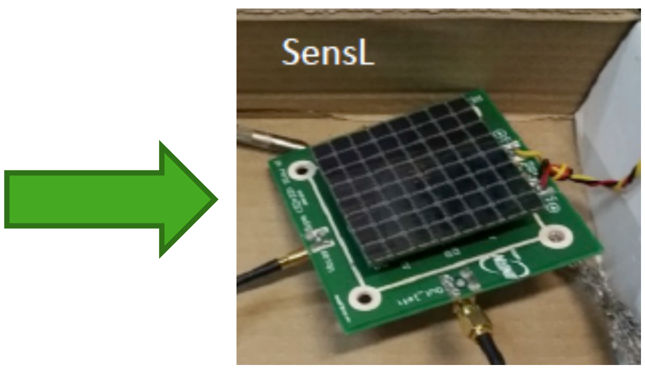
- designed to catch γ's from key backgrounds such as ^{40}K, ^{22}Na.
- Organic liquid scintillators of general use but now hindered in labs due to safety /environmental procedures.

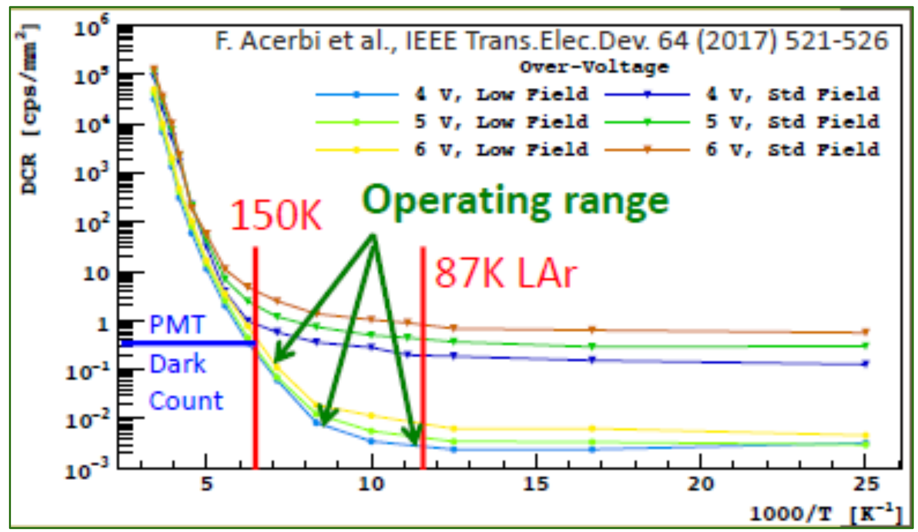
Pictures courtesy of SABRE experiment

ASTAROTH Strategy

- Immersing the target NaI(Tl) crystals in a cryogenic medium -> **Liquid Argon** (LAr), that **doubles as VETO** due to its excellent scintillation properties.

- Reading them out with **Silicon PhotoMultipliers** (SiPM) on all surfaces. SiPM feature lower dark noise than PMTs at **T<150 K** and have higher PDE (55% vs ~30-35% QE of PMTs at 420nm).





Enhanced physics reach

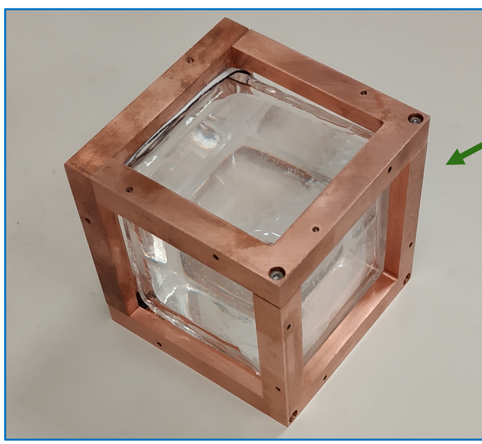
Small high purity cubic NaI(Tl) crystals read on all six surfaces by SiPM matrices, operating at a moderate and tunable cryogenic temperature (87-150K).

-> overcoming the limitations of the present generation DM detectors:

- **Smaller very-high-purity crystals are easier to produce**
- **Maximized sensitive area, higher SiPM PDE -> enhanced light collection**
- **Lower SiPM dark noise at low temperature (<150 K).**
- **ASIC readout and digitalization on board provide compactness and fewer (radioactive) components**

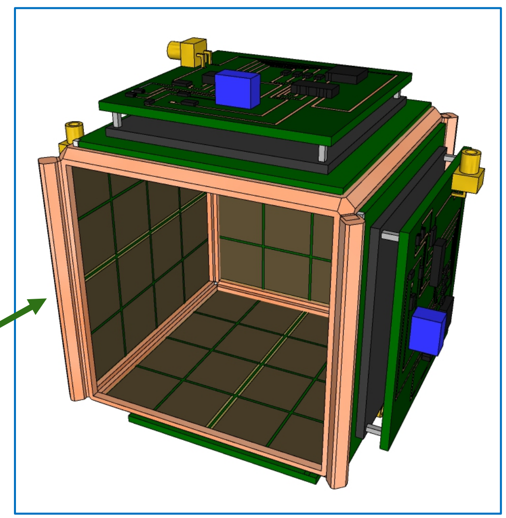
→ more controlled backgrounds and reduced power dissipation

This will allow accessing for the first time the sub-keV recoil energy region for the observation of a DAMA-like annual modulation signal.



Crystal in quartz container, Cu support

SiPM+readout on single PCB mounted on Cu support



Technological advantages

The light detectors to be developed for this purpose will feature:

- SiPM matrices with area of tens of cm^2, read as a single channel by ad-hoc integrated electronics.
- In a second stage, single low-radioactivity PCB hosting both SiPM and ASIC → **compactness**

ASIC readout

Requirements:

- Single photon counting
- Channel/timing info per channel (SiPM)
- Sum waveform digitized on chip (12 bit - 500 MS/s)

→

Advantages:

- Fully digital (optical?) output
- Redundant energy estimators
- Surface background rejection (^{210}Pb from Radon attachment)

The obtained devices aim at replacing traditional PMTs of a similar sensitive surface with a compact light-weight sensor, featuring unmatched low radioactivity for a wide range of applications.

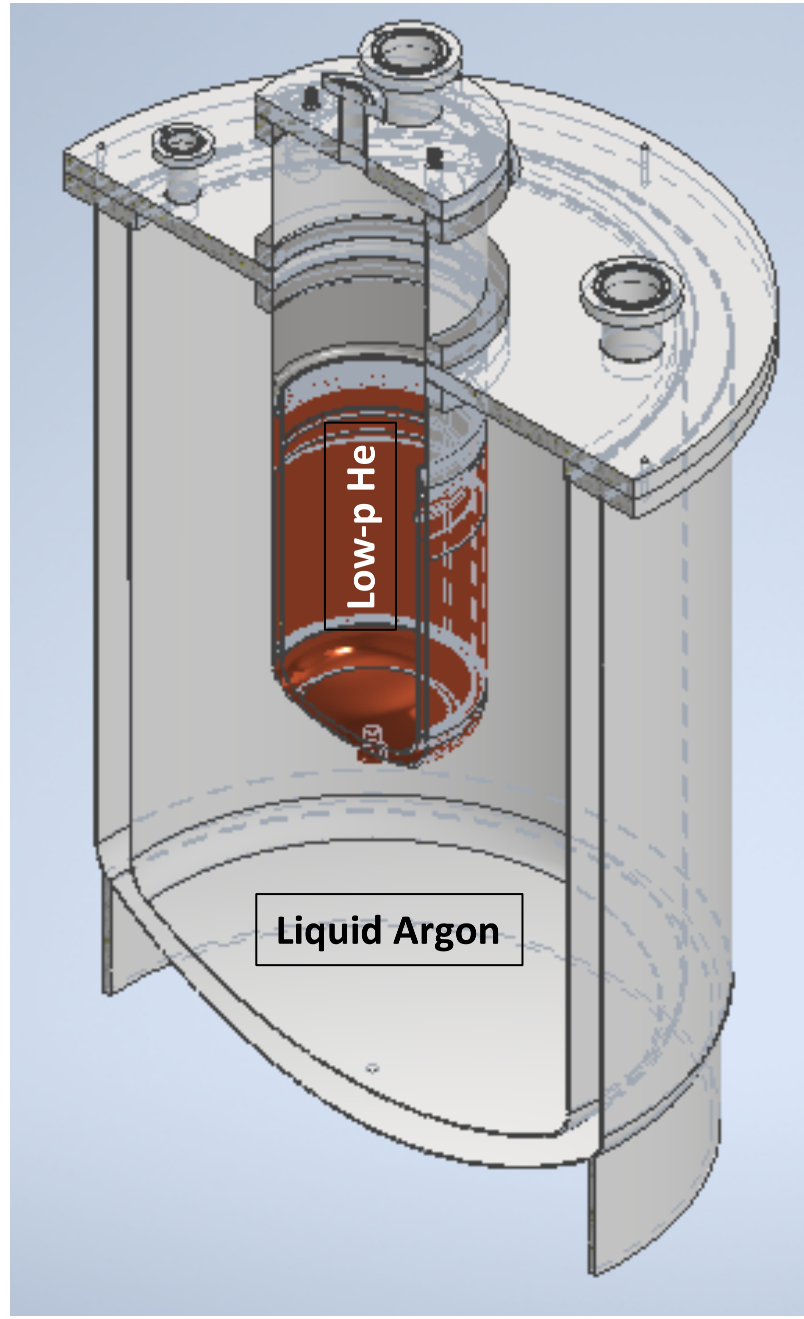
Passive crystal cooling

The design of the NaI(Tl) crystals chamber and cooling system aims at ensuring the crystals survival and stable read-out from the electronics:

- **Temporal gradient limited to <20 K/h.**
- **Spatial gradients (within crystal) < 1 K.**
- **Temperature stability in time, during data taking, within 0.1 K.**

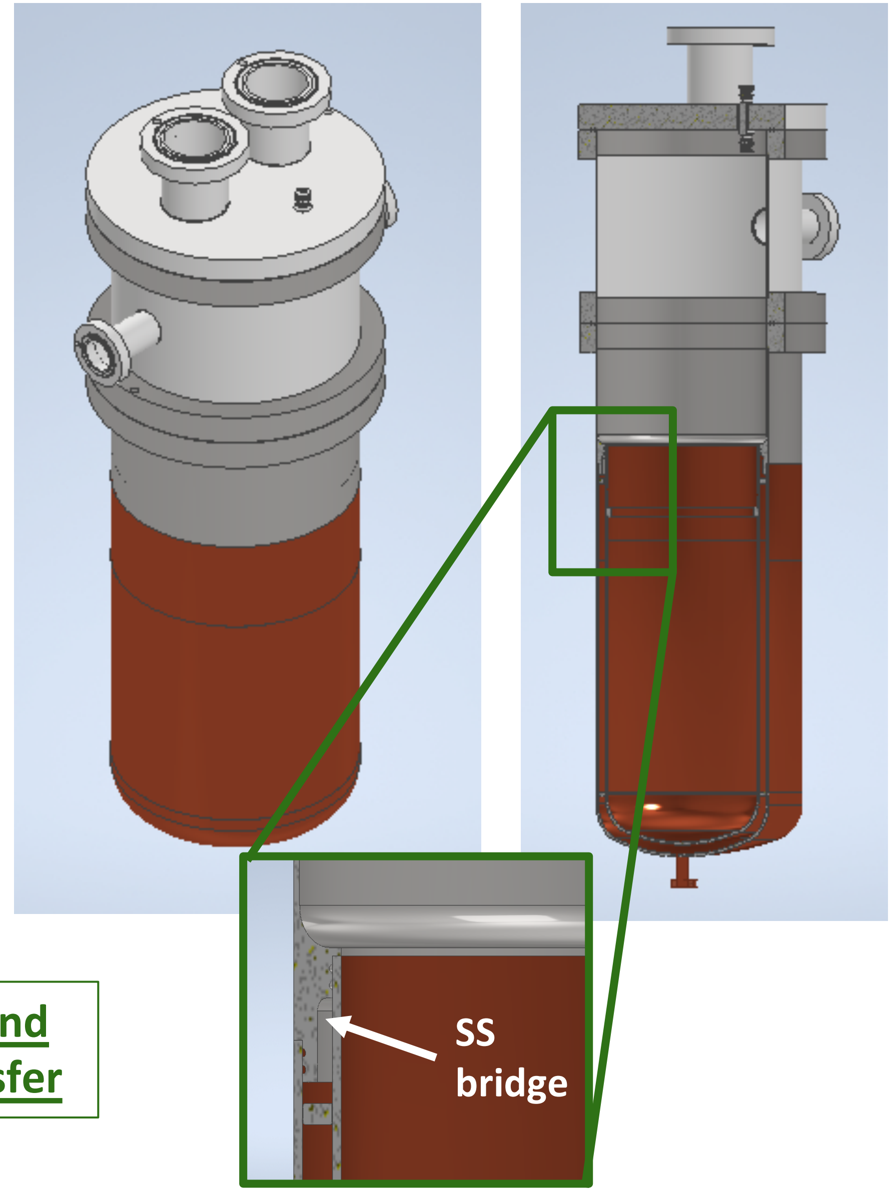
Operating conditions are between 87 K (LAr temp) and 150 K (upper limit for SiPM low dark noise).

The design is optimized to characterize the crystal yield through running it at different temperatures, eventually selecting its best working point.



Passive crystal cooling – inner Cu chamber

- Custom-made **dual-wall, vacuum-insulated** copper chamber, featuring a specially designed **Stainless Steel (SS) thermal bridge** between the two walls.
- The chamber is immersed in a **LAr bath providing cooling power**. Cold power gets to the inner Cu wall only by conduction through the SS bridge.
- This allows cooling the chamber down to 87 K.
- A **tunable power heater** is used to raise and fix the temperature at will up to 150 K.
- **Low pressure Helium gas** fills the inner volume, serving as heat-transfer medium to the crystals, and providing the necessary thermal inertia to ensure the crystals safety.

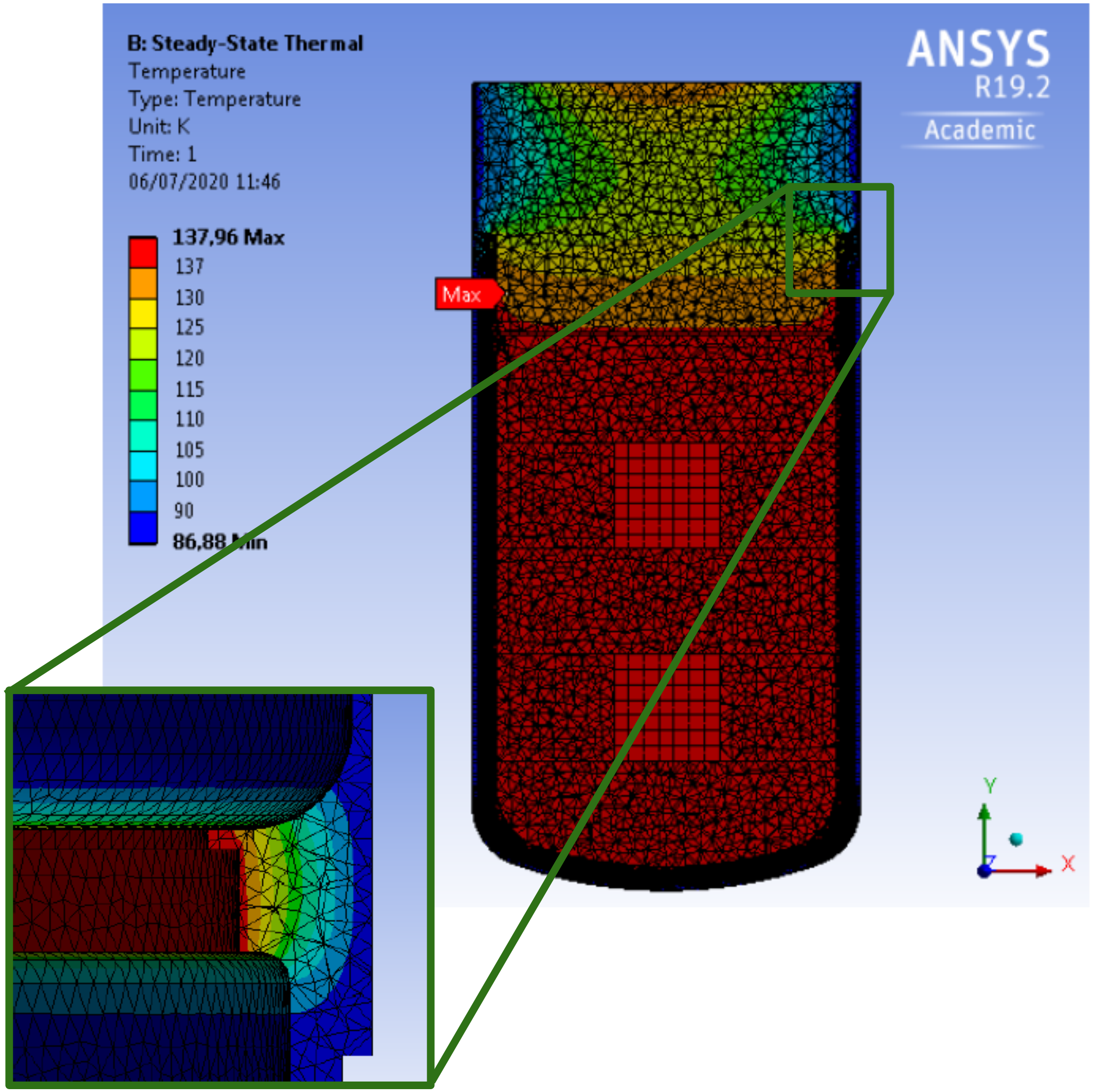


This design makes negligible the effects of radiation and convection, thus maximizing the control on heat transfer

Simulating the cooling system

Thanks to the Mechanical Service of INFN Milano, the new cooling system was fully simulated and tested with a Finite Element Analysis (FEA), following a two-stage approach.

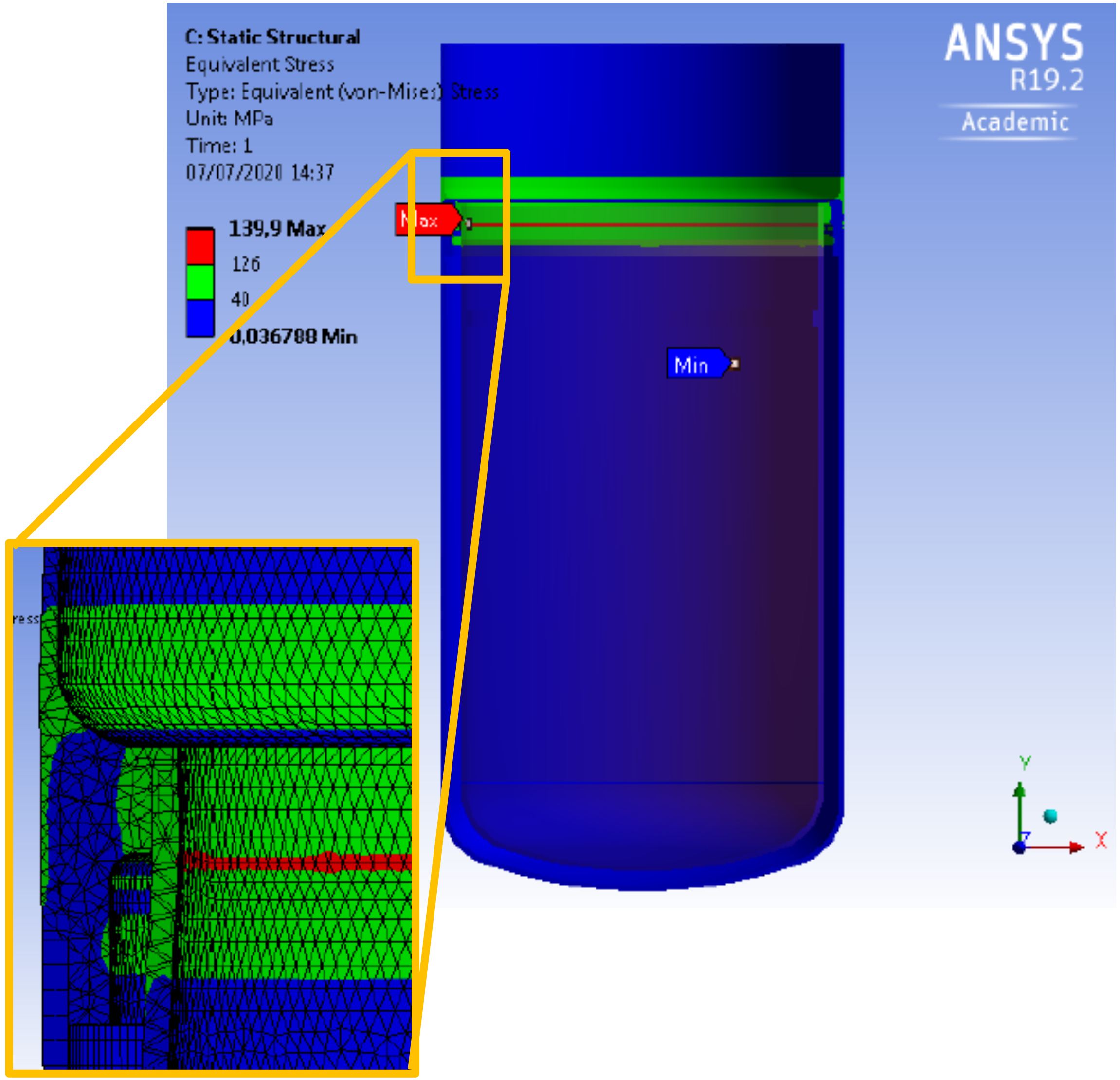
1. **A static thermal simulation** was performed, having as input the LAr cooling power and the power emitted by the heater to obtain a specific temperature in the inner volume (E.g.: 150 K). This demonstrated that the **equilibrium temperature of the chamber is uniform within <0.01 K** over the whole volume.



Zoom on SS bridge temperature distribution

Simulating the cooling system

2. **A mechanical simulation** was implemented, with the temperature maps obtained in the first stage as input. This highlighted the most stressed areas (the thermal bridge) and allowed developing their design.



- Stress on SS bridge and Cu chamber walls.
- Magnified, load-driven distortions in highest-stress operating conditions (Outer Temp=87 K, inner Temp=150 K).
- Stress is below Cu terminal yield.

Outlook

- The ASTAROTH project aims at testing the DM interpretation of the DAMA annual modulation signal.

- The first steps for the project is to develop a new cooling technique for NaI(Tl) crystals and a compact SiPM-based readout technology.

- This will allow characterizing the crystals over a wide rage of temperatures, selecting the best working point to achieve superior sensitivity and ultra-low background.