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The ASTAROTH project

Davide D'Angelo[1,3], Andrea Zani[1],
F. Alessandria[1], A. Castoldi[1,4], S. Coelli[1], D. Cortis[2], G. Di Carlo[2], L. Frontini[1,3], N. Gallice[1,3], C. Guazzoni[1,4], V. Liberali[1,3], M. Monti[1], D. Orlandi[2], M. Sorbi[1,3], A. Stabile[1,3], M. Statera[1]

[1]INFN Milano; [2]INFN LNGS; [3]Università degli Studi di Milano; [4]Politecnico di Milano

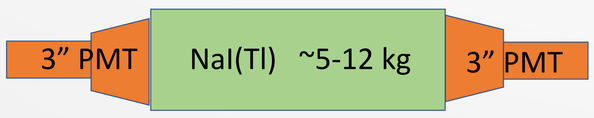
INTRODUCTION

ASTAROTH is an **R&D project** for improving the sensitivity of **direct dark matter (DM) detection** experiments based on **NaI(Tl) scintillating crystals**. These are of fundamental importance for testing the DM interpretation of the DAMA annual modulation signal [1], with the same target and technique. ASTAROTH's **technology development** aims at clearing the low energy spectral region of interest from PMT-related noise and background that limit the sensitivity of current generation experiments. It would also lower the detection threshold, observing for the first time sub-keV recoils where a large portion of signal potentially lies, so far undetected. ASTAROTH's strategy consists in reading the scintillation light with **arrays of Silicon PhotoMultipliers (SiPMs) on all crystal surfaces**. SiPMs have several advantages over PMTs if operated **at cryogenic temperatures**. We have developed an innovative cryogenic system able to cool and operate the detectors in a wide range of temperatures. The cooling power is obtained by a **liquid Argon (LAr) bath** that can also be exploited as a veto detector against irreducible radio-impurities.

I. MOTIVATION

All current generation NaI(Tl)-based detectors share concept and limitations:

Energy region of interest: up to 6 keV$_{ee}$



(e.g. DAMA [2], SABRE [3], ANAIS [4], COSINE[5])

1. Emitted: 40-42 photons / kev — Detected: 7-15 ph.e. / kev.
2. High noise from PMTs at low energy [partly "after-glow" but not well understood]
   ↳ resulting spectrum dictated by PSD efficiency

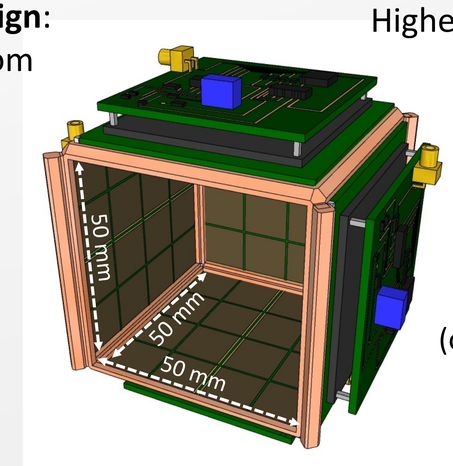
The observable recoil energy is only higher than 1 keV$_{ee}$.

3. *Challenging* to achieve ultra-high purity crystals of this length (≳ 20 cm)
4. Surrounding veto to catch key backgrounds (^{40}K, ^{22}Na):
   ✗ organic liquid scintillators increasingly difficult to use due to stricter safety/environmental procedures

II. INNOVATION

ASTAROTH aims to overcome these limitations in the next generation detectors:

***All-sensitive* design**: light read-out from every face



Higher conversion efficiency
SiPM **PDE: up to 55%**
PMT QE: 30-35% @420nm NaI(Tl) peak emission

Six 25 cm^2 SiPM matrices

Aim to > 20 ph.e. / keV (optical simulations ongoing)

Single channel (sum) read-out

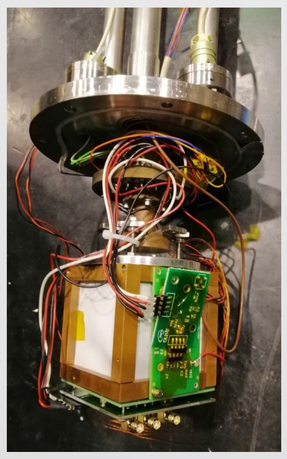
No "after-glow"

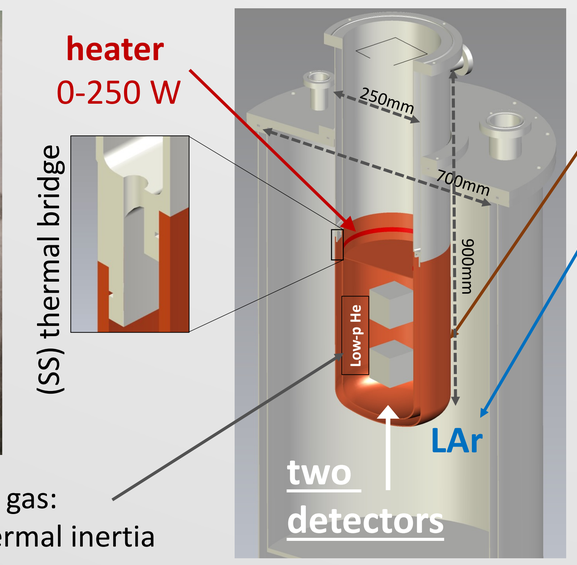
Lower dark count than PMTs at low temperature (<150 K) [6]

Negligible sensor radioactivity (i.e. dominated by electronics)

SiPM require cryogenic operation

III. CRYSTAL COOLING - Custom design for a *wide* range of temperatures





copper chamber vacuum-insulated dual wall

Liquid Argon bath excellent **scintillator**

Instrument the outer volume as **veto**!

[negligible radiation convection]

low pressure Helium gas: heat conduction, thermal inertia

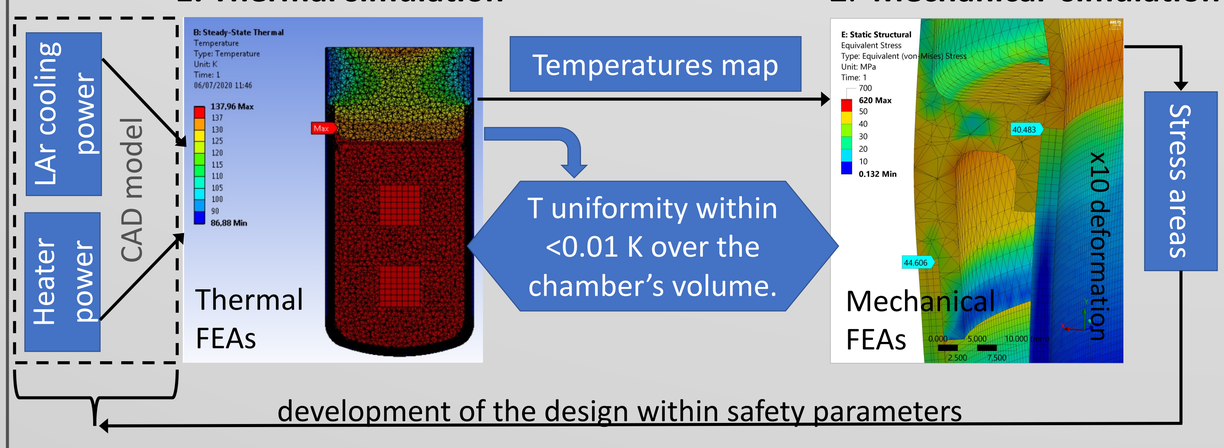
Heating power (tunable heater) → Dynamic equilibrium ← through the bridge ← Cooling power (LAr)

87 K < *tunable* working temperature < 150 K

choose the optimal working point for both crystals and SiPM

✓ Finite Element Analysis (FEA) of the full model with a two-stage approach:

1. Thermal simulation — **2. Mechanical simulation**



✓ Cross-check by independent approaches
↳ mechanical service of INFN Milano and LNGS
✓ Copper properties at low temperature independently determined
↳ ad-hoc strain & rupture tests (LASA laboratory)

IV. R&D COMPARING TECHNICAL DESIGN SOLUTIONS

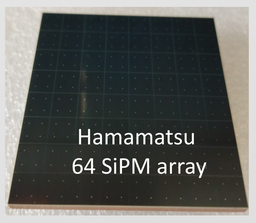
Challenge: fully transparent moisture-tight case

1. Fused silica (soldered vs. glued solution)
2. Acrylic by Univ. of Alberta (DEAP coll.)

ASTAROTH size: 5x5x5cm
Future physics phase of 8-10cm: ultra-high-purity crystals are within the reach of manufactures [6]

Compare SiPM from two vendors:

1. FBK NUV-HD-Cryo [7] pitch 40 µm, Low Field, wire bonded.
2. Hamamatsu S13361-6050 series pitch 50 µm, TSV technology



Compare two array layouts:

1. 8x12 mm^2 (24 devices) "2s3p" ganging on array; front-end: 4 channels + sum [8]
2. 6x6 mm^2 (64 devices) variable ganging on the front-end (in development)

V. TECHNOLOGICAL OUTLOOK

ASIC readout: compact, low power, low radioactivity

- Starting point: analog chip and board for 24 SiPM array courtesy of INFN Torino/Genova (DarkSide-20k collaboration)
- Development ongoing for **digitalization** on chip
- First goal: characterize 110nm LFoundry technology for digital applications
  - Test structures chip *submitted* in Dec 2021
- Final goal: single low-radioactivity (Arlon?) PCB hosting both SiPM and ASIC no radioactive connectors
  - Bonus: optical output; single device charge information (redundant energy estimator w.r.t. full array sum)

Aim beyond ASTAROTH: replace PMTs of similar sensitive surface with a compact, light-weight sensor. Unmatched low radioactivity and noise for a *wide range* of cryogenic applications in Astroparticle physics.

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