LITESABRE:
Liquid argon Immersion Technology Enhancement for SABRE

Fellini General Meeting, Ferrara 30-31 May 2022

Fellowship for Innovation at INFN

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Istituto Nazionale di Fisica Nucleare

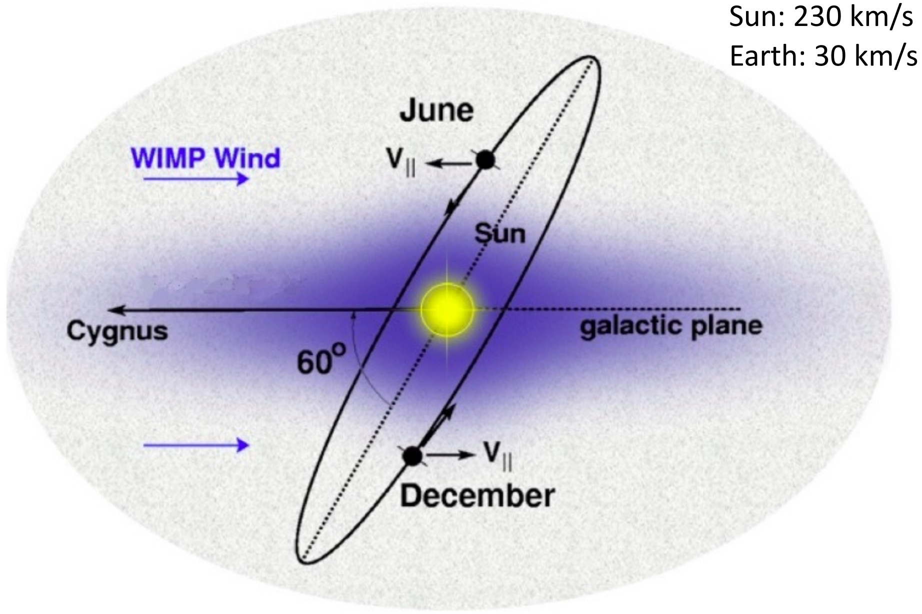
Fellow:
Andrea Zani (INFN Mi)

Supervisor:
Davide D'Angelo (Uni Milano)

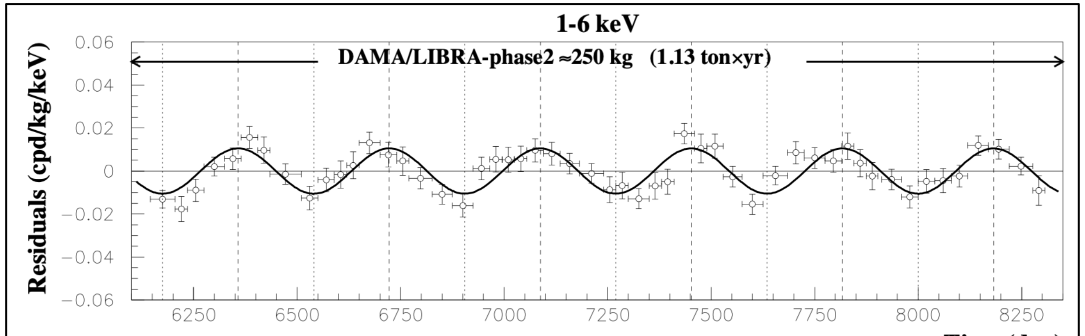
The "DM-modulation" case

Sun: 230 km/s
Earth: 30 km/s

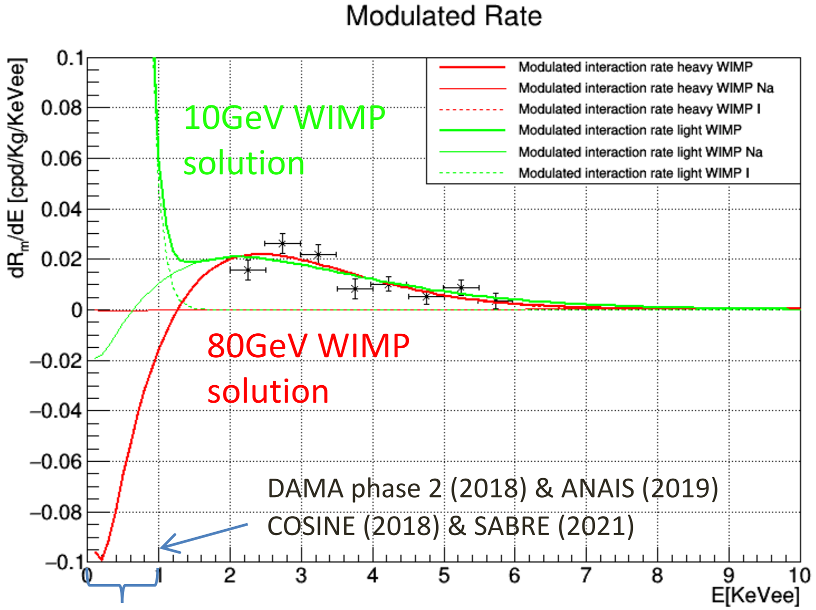
- WHO → DAMA (plus SABRE, ANAIS, COSINE), NaI(Tl) crystals
- WHAT → Dark-Matter induced modulation in the interaction rate
- WHY → Single positive DM signal, never confirmed otherwise; very close to detector threshold
- WHEN → for the last 20 years and counting
- WHERE → Underground lab (LNGS, …)



- HOW → Lower energy threshold; reduce backgrounds
  → increase sensitivity to different DM-models (& restrict parameter space)



Few % modulation; large significance (11.9σ)

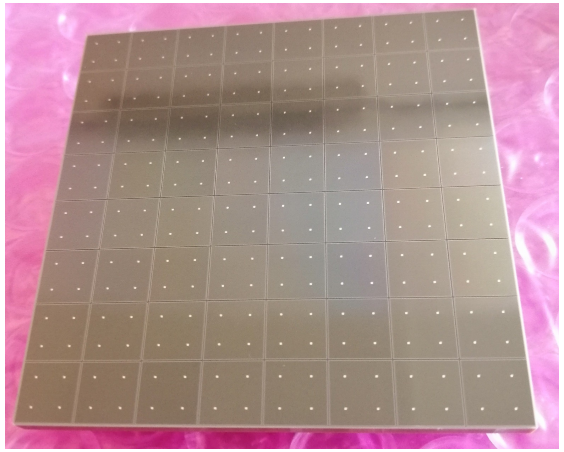


In practice…

Upgraded detection techniques

Any next-generation detector should:

1) Reduce readout-related intrinsic backgrounds;
2) enhance Light Yield (collected phe/keV) w.r.t. present solutions
3) Improve active background rejection



Use of SiPMs implies the need of a cryogenic environment:

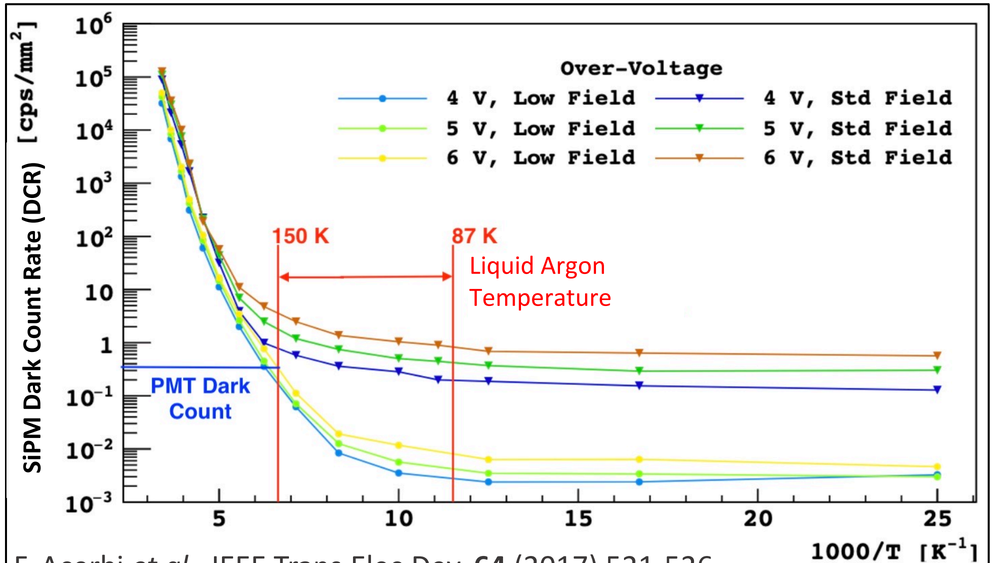
(1,3)

- scintillating **Liquid Argon** (LAr, 128 nm) provides cooling power and can double as **VETO detector** if equipped with PMTs/SiPMs.

(1,2)

Silicon PhotoMultipliers (SiPMs) can replace PMTs for crystal readout:

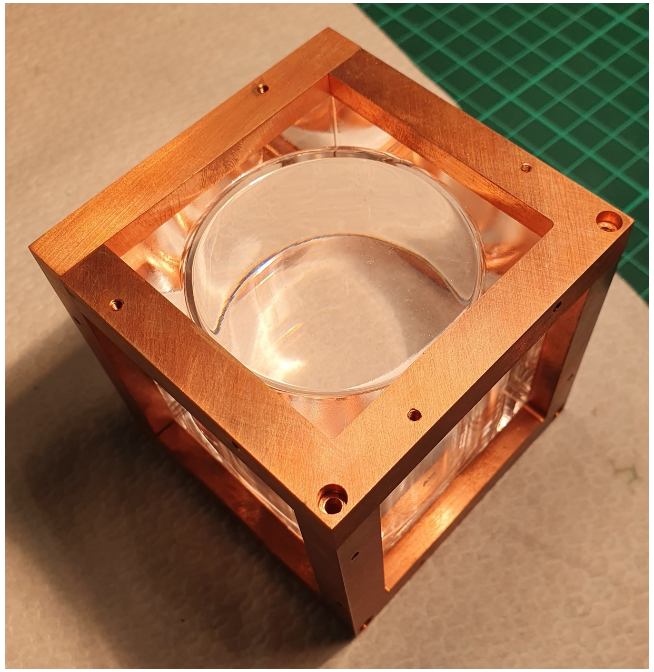
- arrays have smaller transverse dimensions and can be equipped on all crystal surfaces.
- SiPM technology features lower dark noise than PMTs at **T<150 K.**
- Lower intrinsic radioactivity.
- SiPMs have higher PDE (55%), w.r.t. ~30-35% max QE of PMTs at NaI(Tl) scintillation light wavelength (420 nm).



F. Acerbi *et al.*, IEEE Trans.Elec.Dev. **64** (2017) 521-526

The strategy for an enhanced physics reach

- Smaller **high-purity cubic** NaI(Tl) crystals (presently: 5x5x5 cm^3)
- **Extremely-high purity** is more easily attainable with smaller crystals.
- **Encapsulation** (fused silica, neon atmosphere) for easier manipulation and installation
- **Tunable Temperature,** to find the optimal operation point
  - → Not a consistent picture about NaI(Tl) crystals properties at low-Temp (crystal/set-up-dependent results)
- **Enhance light collection** thanks to SiPMs: all six faces R/O maximized sensitive area, higher PDE
- **Push compactness** even further with ASIC readout and digitalization on board (fewer radioactive components)
  - → more controlled backgrounds and reduced power dissipation (later stage, further in time)



Cylindrical test crystal, easier to encapsulate, used for initial cooling cycles

Crystal in quartz container, Cu cage for mechanical support

<u>This will allow first-time access to sub-keV recoil energies for the observation of a DAMA-like annual modulation signal</u>

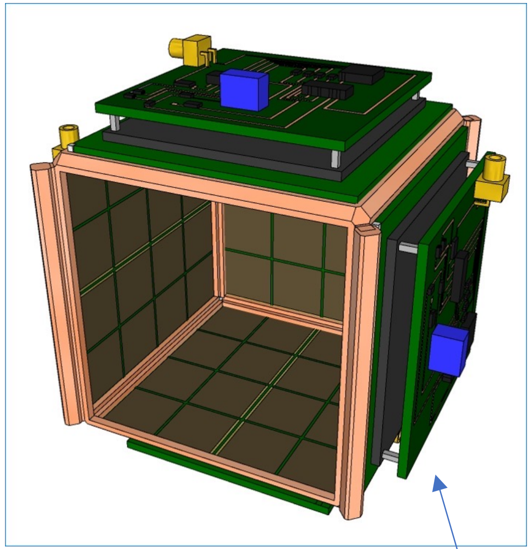
Back to square 1 – HOW ?

LITESABRE strategy is to lower energy threshold for DM recoils detection, by reading-out NaI(Tl) crystals with SiPMs at low temperature in a LAr veto

LITESABRE goal is to prove the feasibility of the said strategy, by:

- **Characterizing crystal and SiPM operation at low temperature independently**, in a wide range of T, to find the respective optimal operation points
- Performing **MonteCarlo** simulation of the crystal-SiPM system to **optimize** their **optical coupling**
- Designing and operating a **dedicated cryogenic chamber** that would allow testing the integrated setup at different temperatures.
- **Characterize the response of the integrated system with γ-sources and neutron beams**, to extract crystal physics parameters of interest for Dark Matter searches

Demonstration of feasibility – MonteCarlo studies

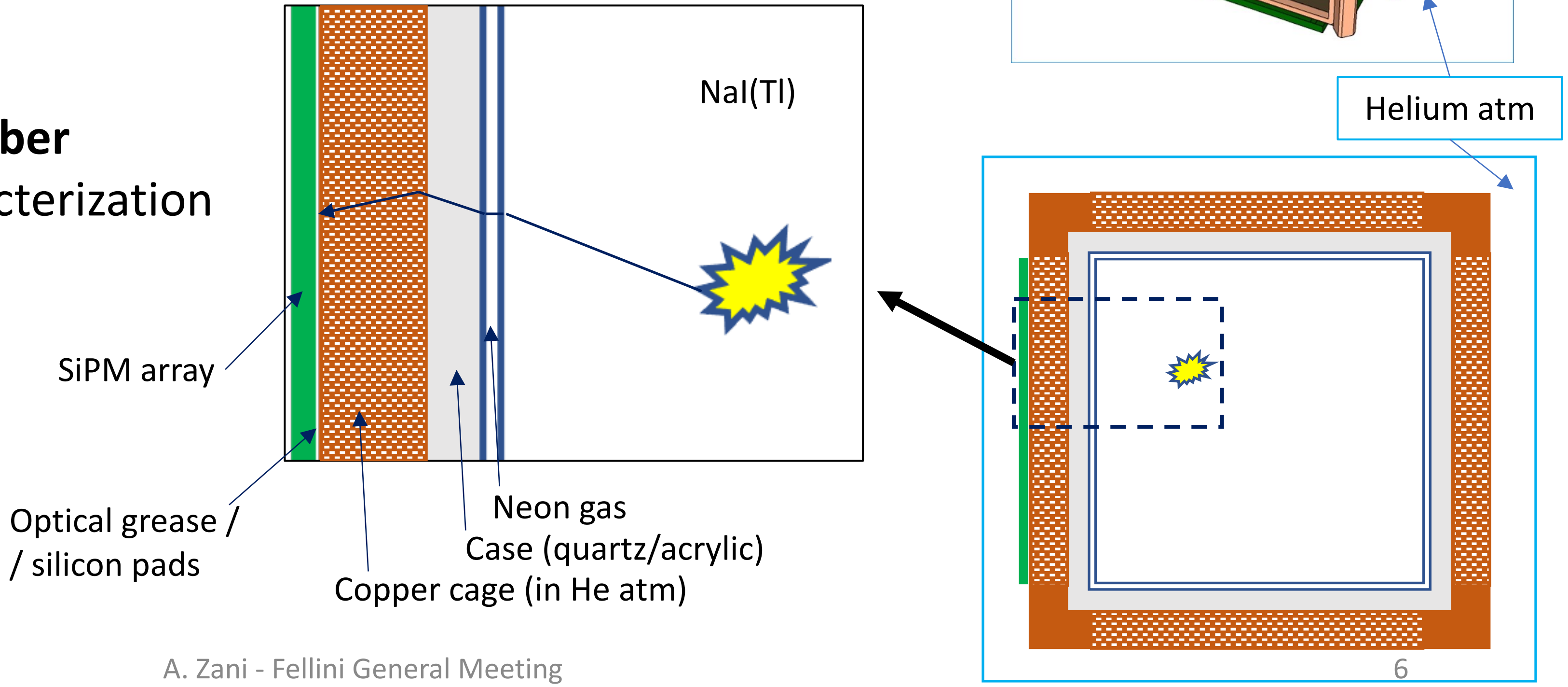


Optical MonteCarlo simulations of light collection efficiency

- starting now, with a Master Thesis student,
- reproducing the crystal-SiPM coupling, complete with case, helium atmosphere and possible optical grease,
- vary conditions (SiPM-crystal distance, case material, …) to **study light transport** and **ensure maximization of light collection** on each tile.

Second step

- **simulating the full cryogenic chamber**
- **Background study** in view of characterization with sources and neutron beams.

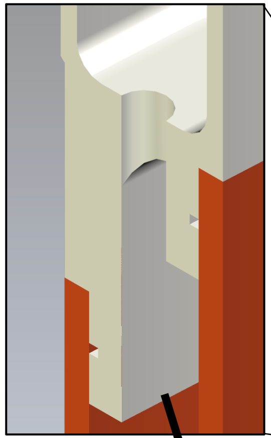


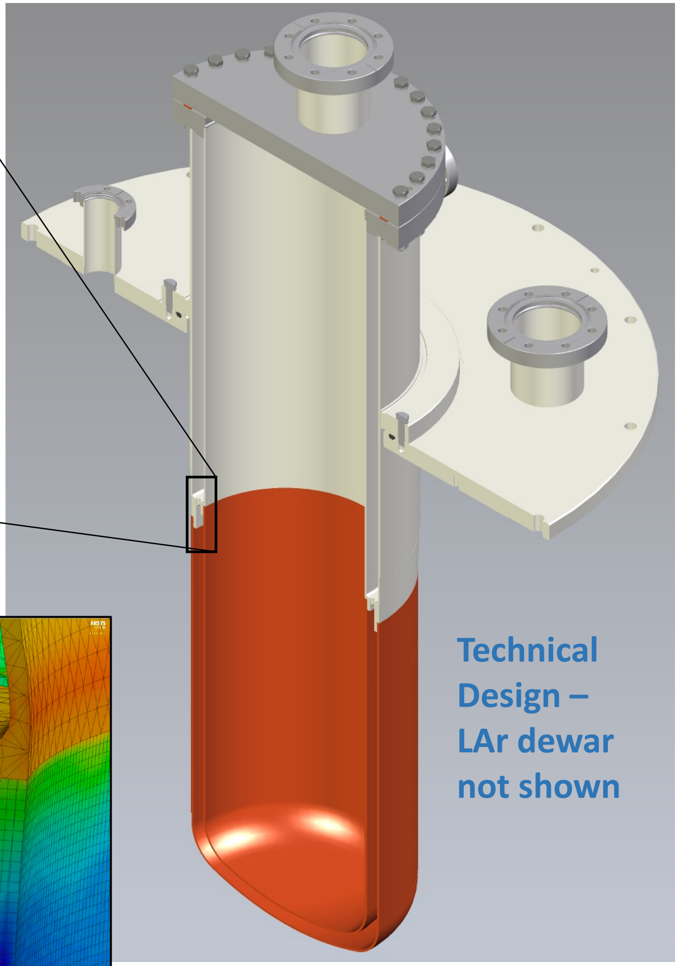
Detector Design

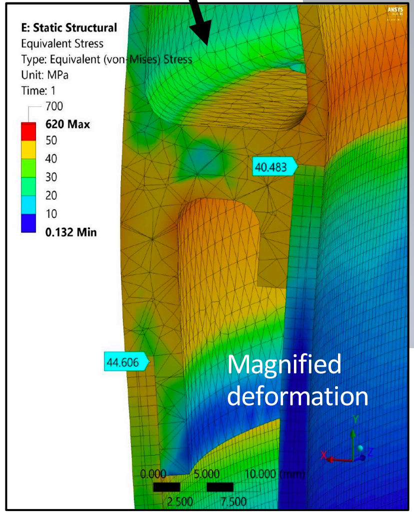
GOAL: ensuring crystals survival and stable read-out from the electronics.
- **Investigate range: 87-150 K**
- **Temporal gradient limited to <20 K/h**
- **Spatial gradients (over crystal dimensions) < 1 K**
- **Temperature stability in time, during data taking, within 0.1 K**

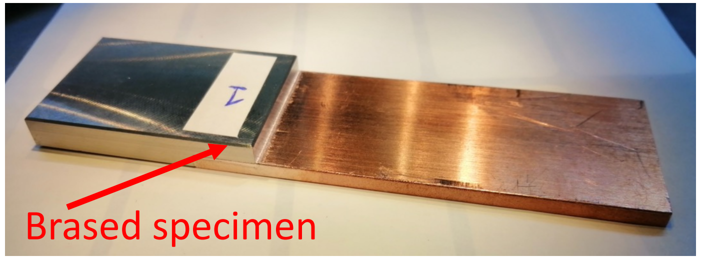
<u>The design is optimized to select the crystals best working point.</u>

MEANS to obtain the goal:
- **Active temp. control in the inner chamber**
- **Thermo-mechanical simulations to validate design/cooling scheme**
- **Mechanical characterization of material properties**



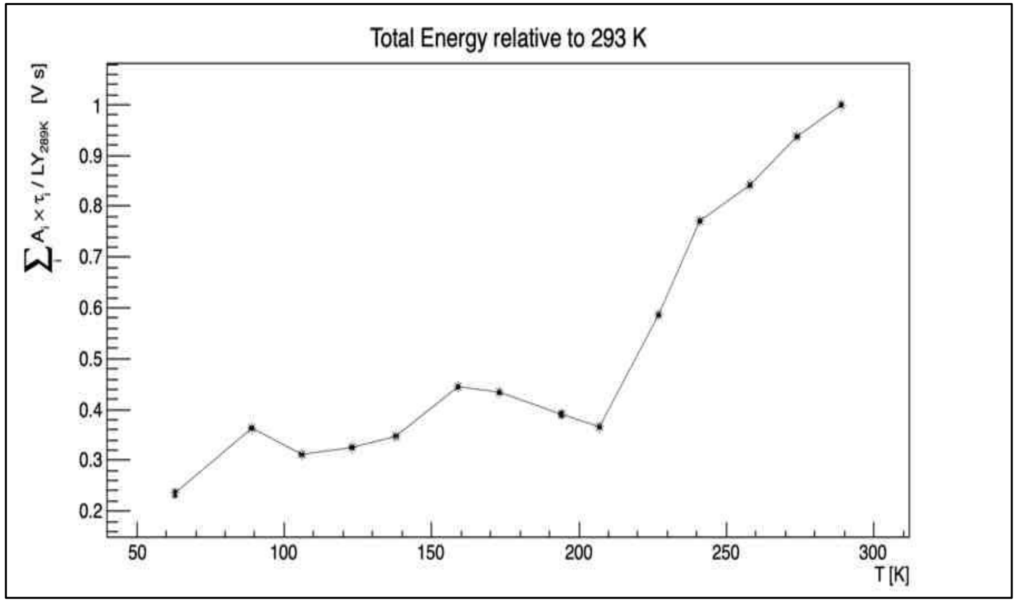






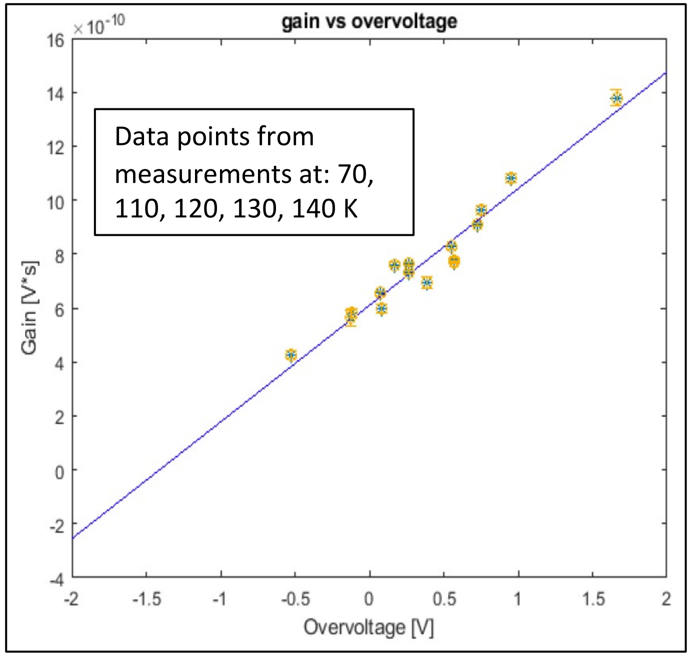
Strong collaboration with:
- **<u>INFN LASA personnel for design/test</u>**
- **<u>INFN MI/LNGS Servizi Progett. Mecc. for design/simulations</u>**

Standalone characterizations



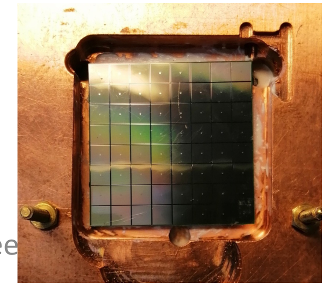
@ LNGS

- **Naked** crystal characterization (Light Yield), in **30-300 K** range, with roomT PMT read-out and γ-source
- Isolated temperature dependence of crystal, no light-detector effects
- **Scintillation light time-profile changes significantly with T**



@ Milano Politecnico

- Characterization of a **1'' Hamamatsu SiPM array** (S13361-3050 series; 64, 3x3mm SiPMs; 50μm pitch)
- **Gain** measurement with dedicated light source, in **77-140 K** range
- Set-up under optimization for Gain, PDE measurement of **upcoming 2'' SiPM arrays**



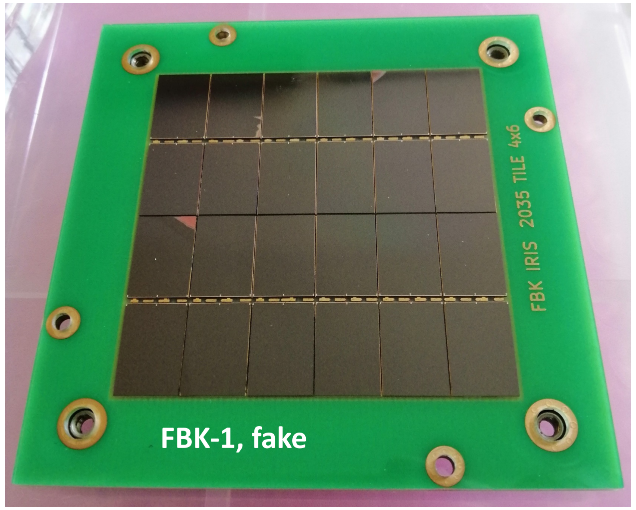
Searching for the best solution

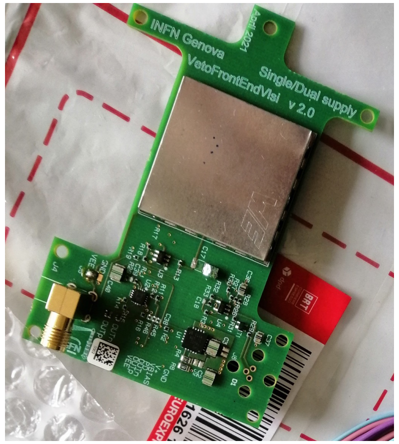
- Hamamatsu arrays:
  - 1'' array (S13361-3050 series; 64, 3x3mm SiPMs; 50μm pitch) used so far.
  - Two more, 2'' Hamamatsu arrays in 2021-22, based on S13361-6050AS-08 devices.

- FBK arrays (two 5x5 cm^2 being delivered, based on NUV-HD-Cryo technology) :
  - First one features 24, 8x12 mm SiPMs, same as DarkSide 20k devices.
  - Second one will feature 64, S13360-6075 HQR, 6x6 mm SiPMs, same as for DUNE.

READ-OUT (In-house design and characterization)

- Analog board for FBK-1 built, to be tested (two versions)
- Development of board with PoliMi for FBK-2, Hamamatsu
- Development of integrated read-out by UniMi colleagues (test chips under production)
- Received analog Front-End from colleagues of INFN GE (for DarkSide 20k Veto) – second to latest version, to test.





Project next steps

Short-term plan (next months)

- Receive cryogenic chamber (01/06), assemble and test leak tightness (cold cycle with no crystals)
- Commission active temperature control (no crystal)

- Bench test of acquired SiPM arrays with available electronic boards
- Bench test of crystal coupled with SiPMs and readout

- First run with one crystal in cryo chamber (1 or 2 faces read-out)

N.B.: All these cold cycles will use LN_2 instead of LAr, since there is no need to use the veto so far.

Long-term plan (till end of project)

1) Monte Carlo simulations
    - second step: integrating the full design for background and sensitivity estimation

2) Crystal characterization with γ's @ LASA.
    - 37 kBq ^{241}Am source, rated for cryogenics, for crystal and LAr veto

3) Characterization on neutron beams
    - Discussions for beam time to start **now***, with possible sites: Louvain (B); CHARM (CERN, CH); INFN LNS
    - Beam energy – few to tens of MeV
    - In the meantime: develop specs for chamber transport

*= requests must be filed ~one year in advance

Status & Perspectives

- LITESABRE project started in Oct. 2021 – Line of research was actually launched in early 2020 with INFN CSN V funded project ASTAROTH
  - End of project in Dec. 2023
- LITESABRE first months were heavily dedicated to the cryogenic chamber for crystal tests

- Experimentally:
  - We have almost all components in our hands (crystal, chamber, SiPM read-out, services)
  - Characterization of crystal with ^{241}Am source feasible in the next eight months (early 2023)
  - Organization starting now for test on neutron beams (to happen within fall 2023)

- MC/Analysis
  - MC simulation (optical – full design) to start now with Master Thesis student
  - Data analysis of previous tests performed with PhD student, will continue

Thank you

Back Up

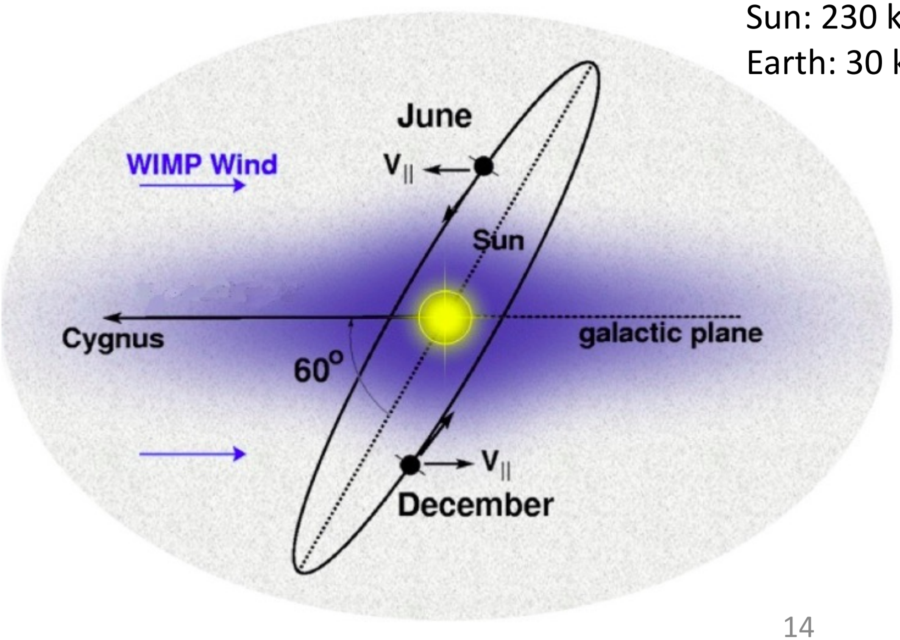
Introduction - Physics Case

- 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.
- DM-Model independent measurement: the combination of the Earth's motion around the Sun and of the Sun's motion around the galactic centre is expected to induce an annual modulation of the DM interaction rate on an Earth-based detector.

- DM interaction rate depends on Earth velocity w.r.t. galactic halo:
  → expected modulated spectrum, with one year period and phase around June 2^{nd}.

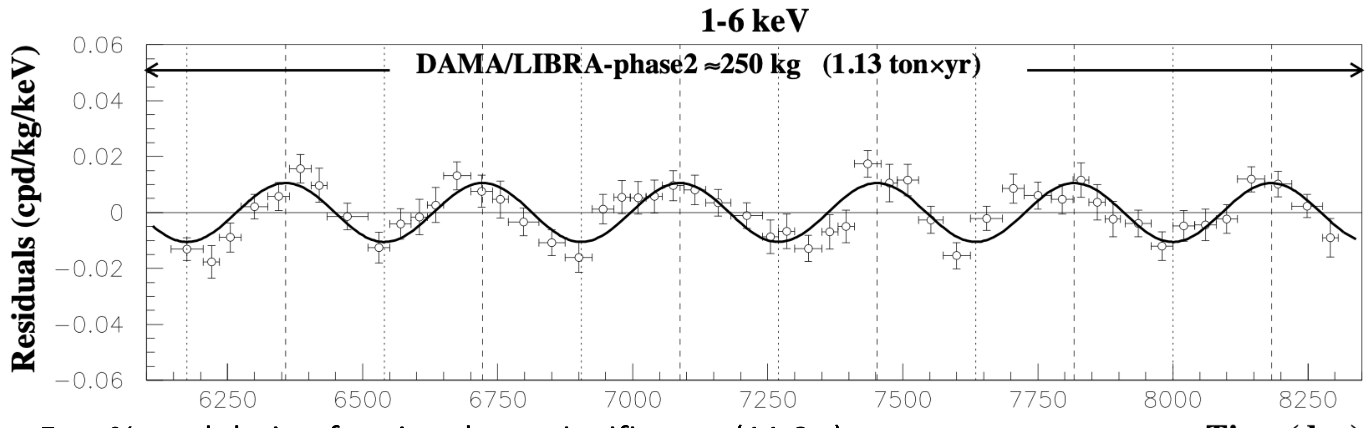
- Elastic scattering of DM particles (e.g., WIMPs) on target material.
  → Very low energy recoil expected, < 50 keV .
  → Very low expected rates: 10^{-1} to 10^{-6} events/day/kg.

Sun: 230 km/s
Earth: 30 km/s

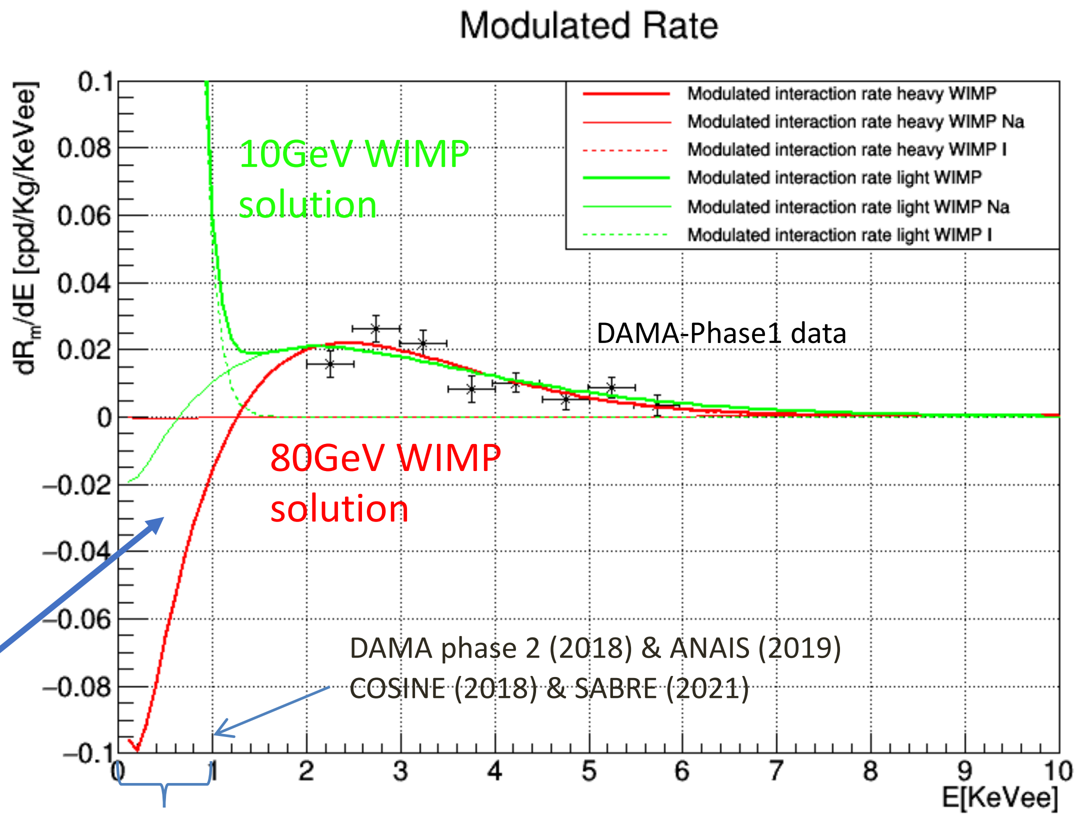


Introduction - Physics Case

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



Few % modulation fraction; large significance (11.9σ)



Simplified scenario - basic hypotheses on DM interaction (standard Halo distribution, spin-independent coupling).

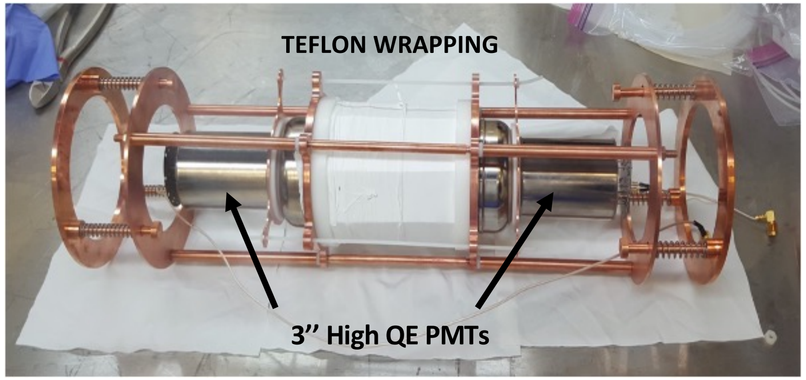
- **Pushing the detection energy threshold below the 1 keV limit** is of fundamental importance to test the positive observation of the DAMA experiment, with the same target material.

- This would allow **disentangling different DM-induced modulation models**, thus restricting the parameter space of a surviving DM candidate.

Current Technological limitations

A model-independent verification of the DAMA observation requires ultra-low background, superior sensitivity and low energy threshold.

Existing **NaI(Tl)-based detectors**, SABRE, ANAIS and COSINE, share the DAMA basic design.



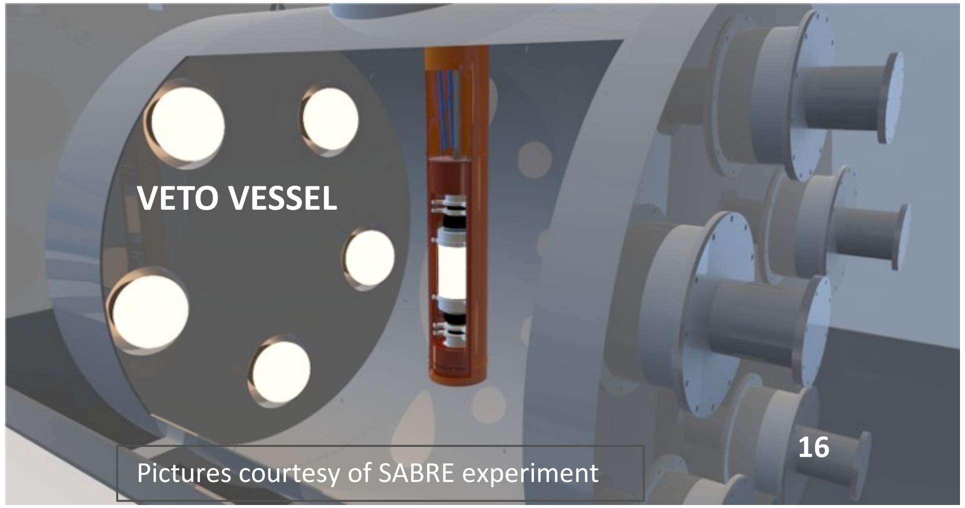
- Detector: parallelepipedal crystals, wrapped in reflector and coupled with high-QE* PMTs.
  - Light collection is limited to 7-15 photoelectrons (phe) per keV.
  - PMTs feature intrinsic high noise and radioactivity.
- Large, few-kg mass crystals: hard to achieve very-high-purity production.

  → **So far, observable recoil energy limited to $\gtrsim$ 1 keV$_{ee}$.**

*QE = Quantum Efficiency

Background rejection can be enhanced with **VETO** detector:

- designed to tag γ's from key backgrounds in the Region of Interest (ROI), such as ^{40}K, ^{22}Na.
- Organic liquid scintillators read by PMTs are main solution.



Pictures courtesy of SABRE experiment

From ASTAROTH to LITESABRE

Since the Fellini submission in 2019, the ASTAROTH project was submitted and funded within INFN CSN V, with the more general scope of carrying on the R&D about various technological aspects of the proposal:

- Crystal safe cool-down;
- Implementation of precise temperature control;
- Crystal characterization at low temperature;
- SiPM characterization at low temperature (various models).

ASTAROTH is a CSN V three-year project, started in February 2020 and therefore in its closing year. **LITESABRE is meant to be in direct continuity with ASTAROTH, sharing the same goal**.
(Davide D'Angelo is ASTAROTH PI)

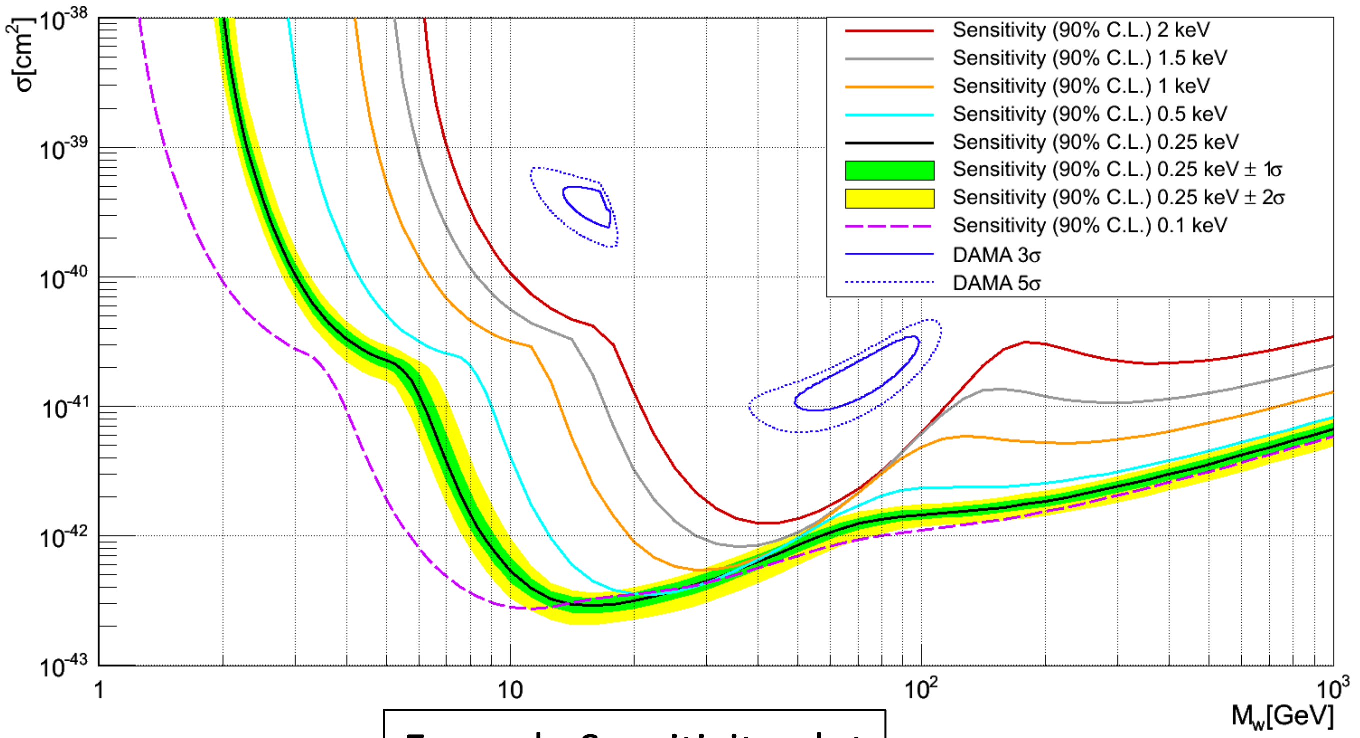
Preliminary sensitivity studies

The ASTAROTH/LITESABRE technology demonstrator will feature 1-2 encapsulated, 5x5x5 cm^3 NaI(Tl) crystals (0.46 kg each), operated on the surface.

- Initial simulations of optical photons transport yield a collection of around 20 phe/keV, vs 40 γ/keV emitted by the crystal -> **50% collection efficiency**

Early sensitivity studies, performed on an older-design full-scale detector featuring 8 encapsulated, 10x10x10 cm^3 NaI(Tl) crystals operated underground.

- In the plot, 0.19 events/kg/day/keV (dru) in the [0.2-6.0] keV window are assumed.
- Within ASTAROTH scope (?), these simulations should be re-run to adapt them to the new demonstrator design



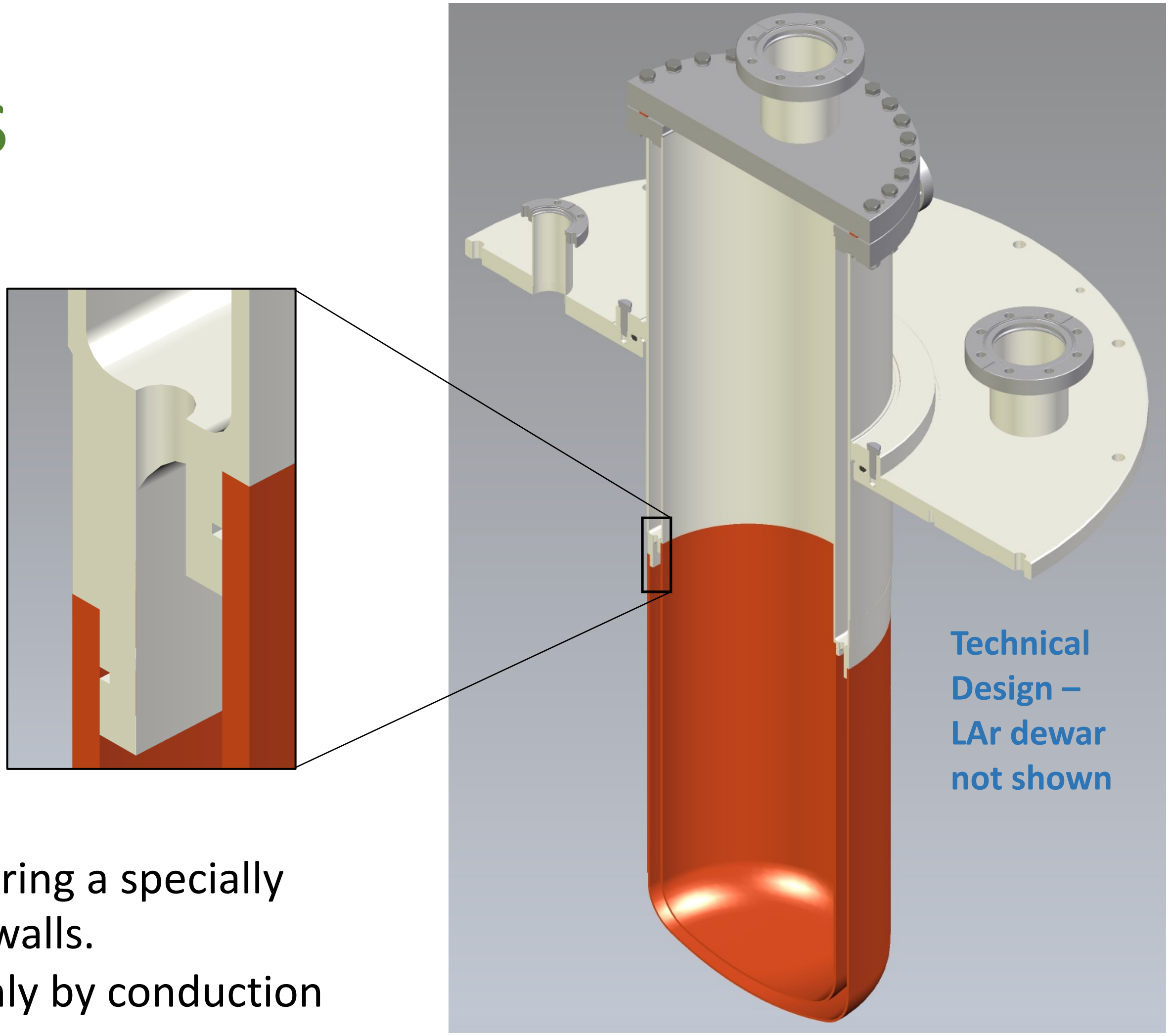
Example Sensitivity plot
Exposure: 30 kg x 3 y

Detector Design I - mechanics

Design requirement: ensuring crystals survival and stable read-out from the electronics.

- **Investigated range: 87-150 K.**
- **Temporal gradient limited to <20 K/h.**
- **Spatial gradients (over crystal dimensions) < 1 K .**
- **Temperature stability in time, during data taking, within 0.1 K.**

The design is optimized to change and select the crystals best working point.



- **Dual-wall, vacuum-insulated** radio-pure copper chamber, featuring a specially designed **Stainless Steel (SS) thermal bridge** between the two walls.
- Chamber is immersed in a **LAr bath providing cooling power** only by conduction through the SS bridge.
- This allows cooling the chamber down to 87 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.

Strong collaboration with INFN LASA personnel for the design

Detector Design II – active temp. control

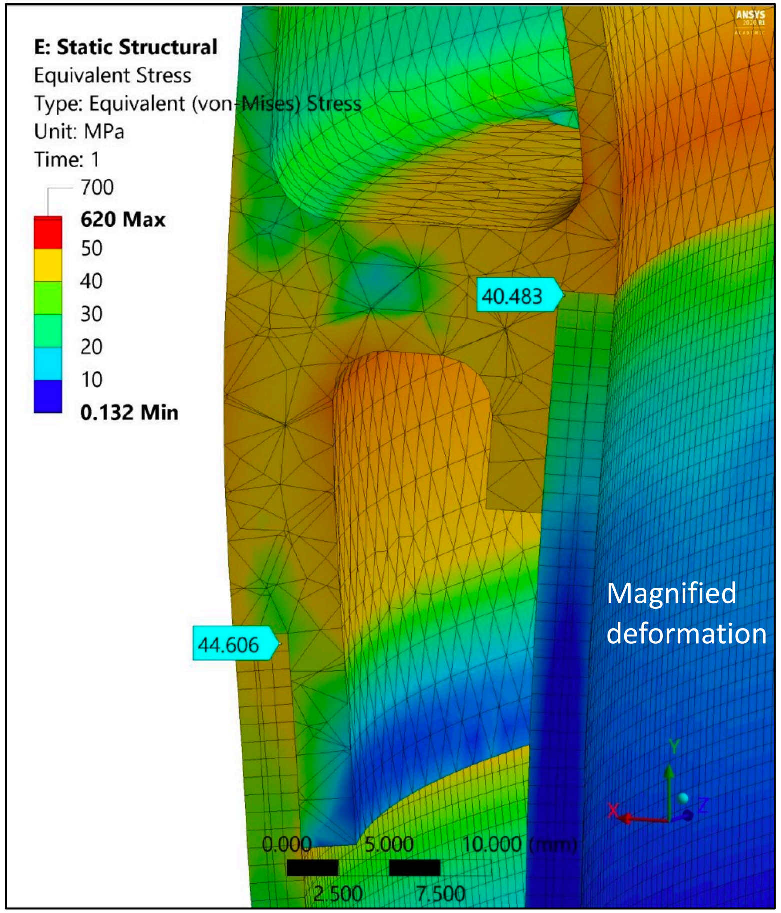
A **tunable power heater (flex Kapton)** is used to raise and fix the temperature at will up to 150 K.
The active temperature control was fully simulated and tested with a **Finite Element Analysis (FEA)**, along with the overall detector design

Static thermal simulation

- Inputs: LAr cooling power and desired heater power (e.g.: around 250 W to obtain 150 K on the inner walls).
- Equilibrium temperature of the chamber is uniform within <0.01 K over the whole volume.

Mechanical simulation

- Inputs: temperature maps obtained in the first stage.
- This highlighted the most stressed areas (the thermal bridge) and allowed developing their design to maximize resistance



- 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.

Strong collaboration with Servizi Meccanici INFN-Mi & INFN-LNGS

Material characterization - I

The thermal bridge is a critical detail for the operation of the chamber.
Need to mechanically characterize copper batch and brazed connection

Tensile tests @ LASA, with a dedicated cryogenic traction machine operated by INFN-LASA personnel, on copper specimens **@ 77 K** .

- **Yield strength** test, followed by **breaking** test (ultimate strength)
- Two strain-hardened specimens and two baked specimens

Specimens baked in house according to instructions given by the company producing the cryogenic chamber (8h cycle @ T_{max} = 850 °C).

Strain gauges for Young modulus and Yield strength evaluation (first leg only)

Material characterization - II

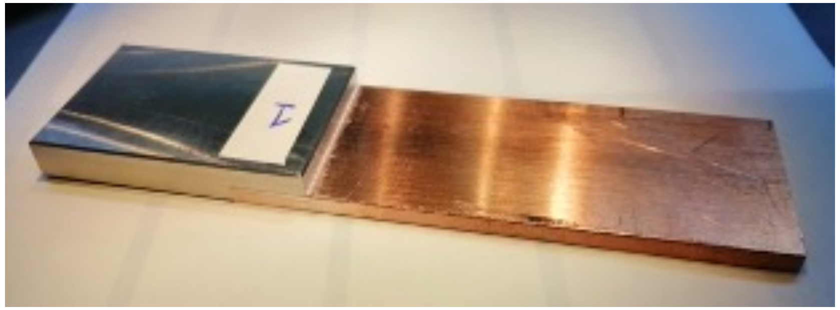
Bending tests @ LASA in LN_2

- dedicated structure built with the INFN-MI Servizio Meccanico:
- **four brazed specimens**, on which bending is applied.

Results of the tensile tests imported into thermo-mechanical simulations, to extract the stress and force applied to the brazed connection.

Force is applied to the specimens, to verify the macroscopic survival of the brazing.

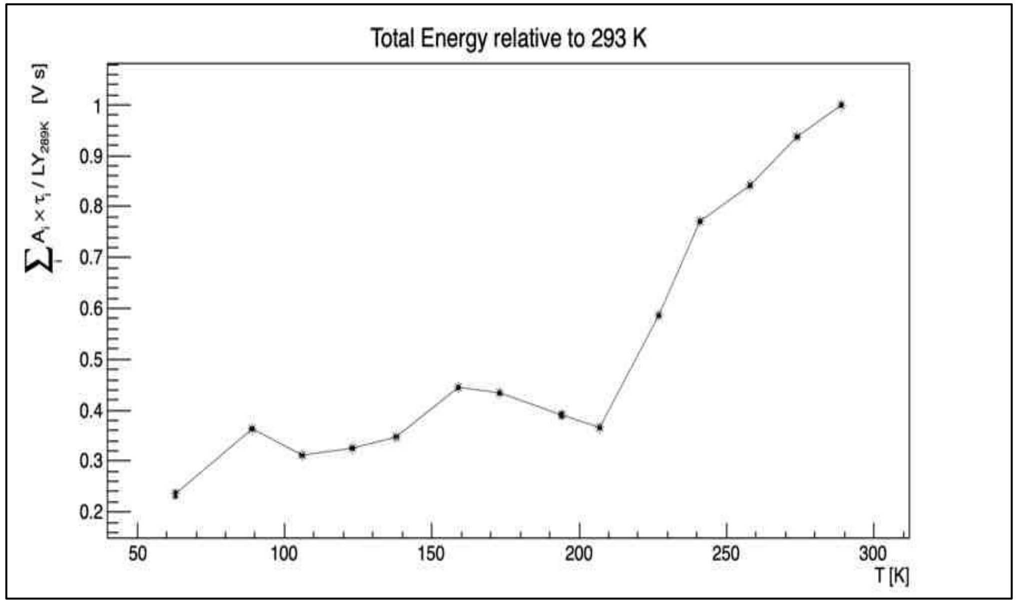
- **microscope check and radiography** to search for microfractures (none found so far).

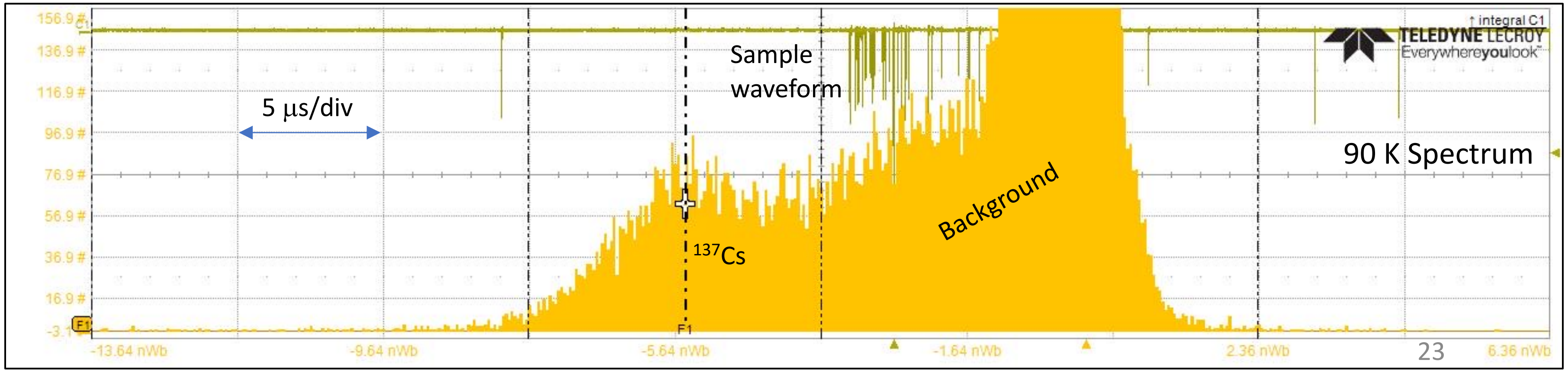


Movable dynamometer to quantify applied force

Crystal characterization at LNGS

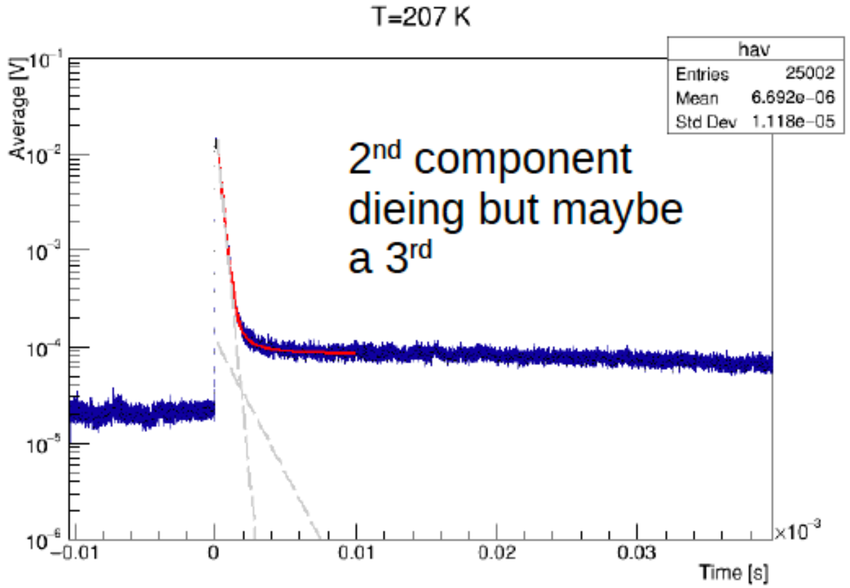
- A **non-encapsulated NaI(Tl) cubic crystal**, 2’’-side, was characterised with a cryo-cooler at INFN LNGS.
- Crystal wrapped in Teflon tape and **cooled under vacuum** with a cold-head. Readout with a 2’’ PMT, at room temperature.
- Waveforms at various temperatures (**77 -> 300 K**) were acquired w/ and w/o a ^{137}Cs source placed on top of the cryo-cooler.
- **Crystal response vs T** is isolated, **excluding photon detector effects** -> Data analysis is in progress.
- **Scintillation time-profile changes with temperature**, the decay constant τ going from ~250 ns (@300 K) to around ≈1.5 μs (@77 K).

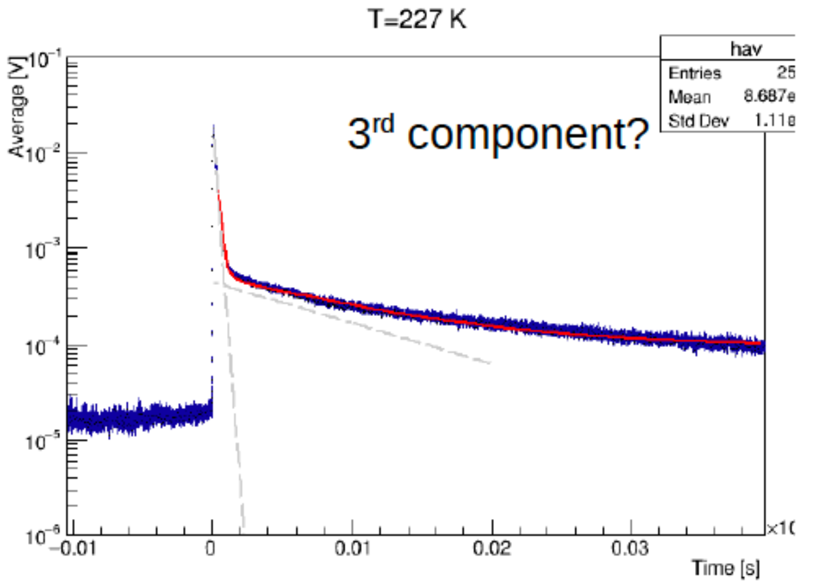


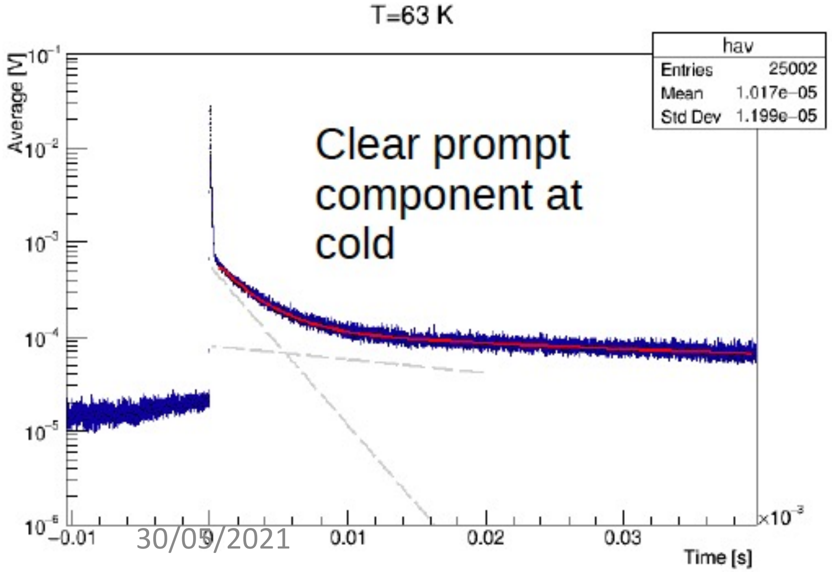


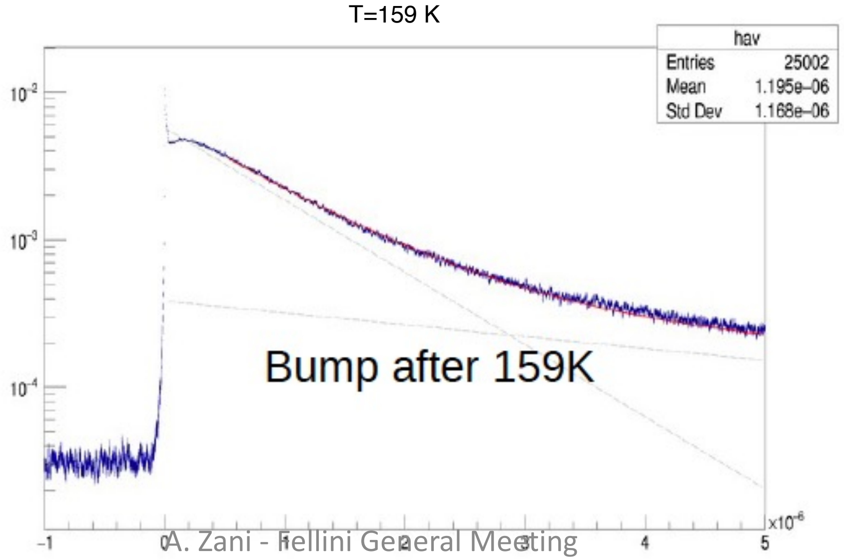
@ LNGS - waveforms

Many features to understand at different temperatures



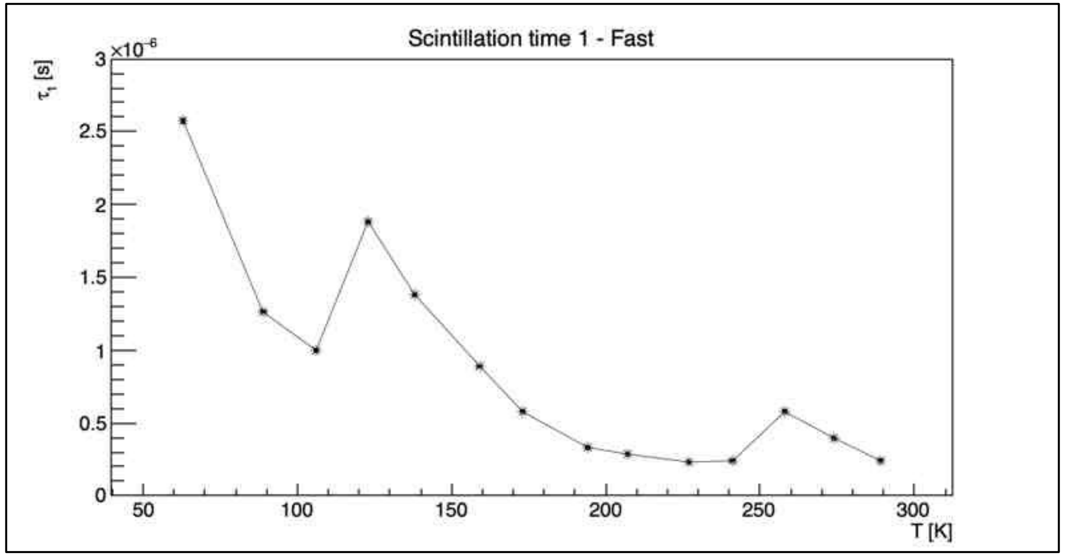


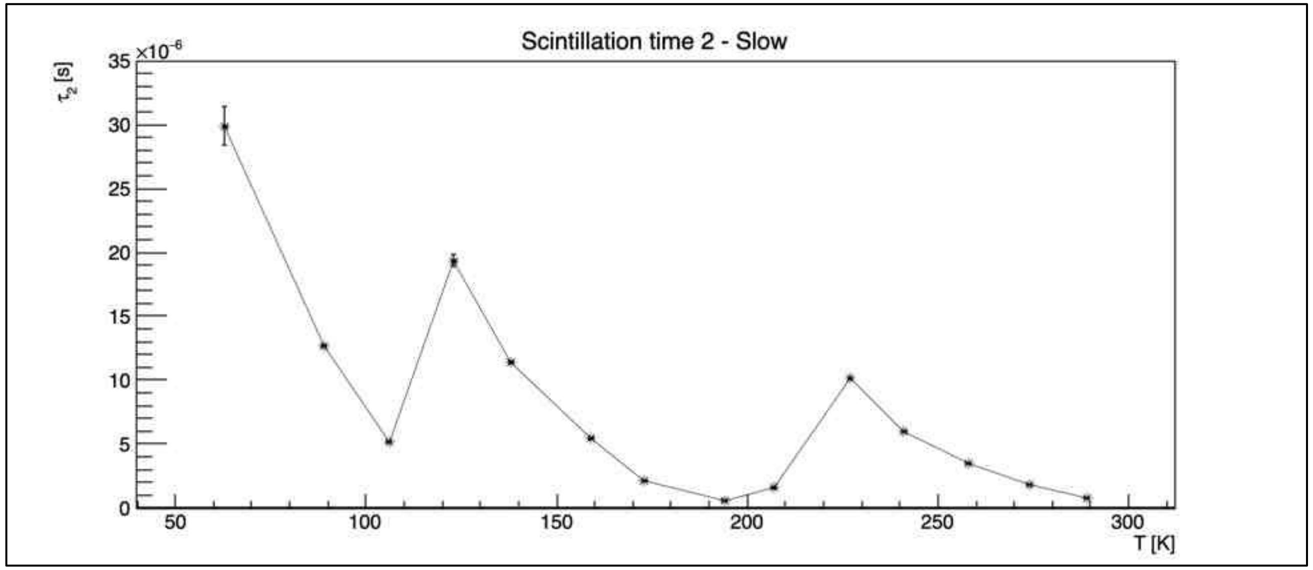


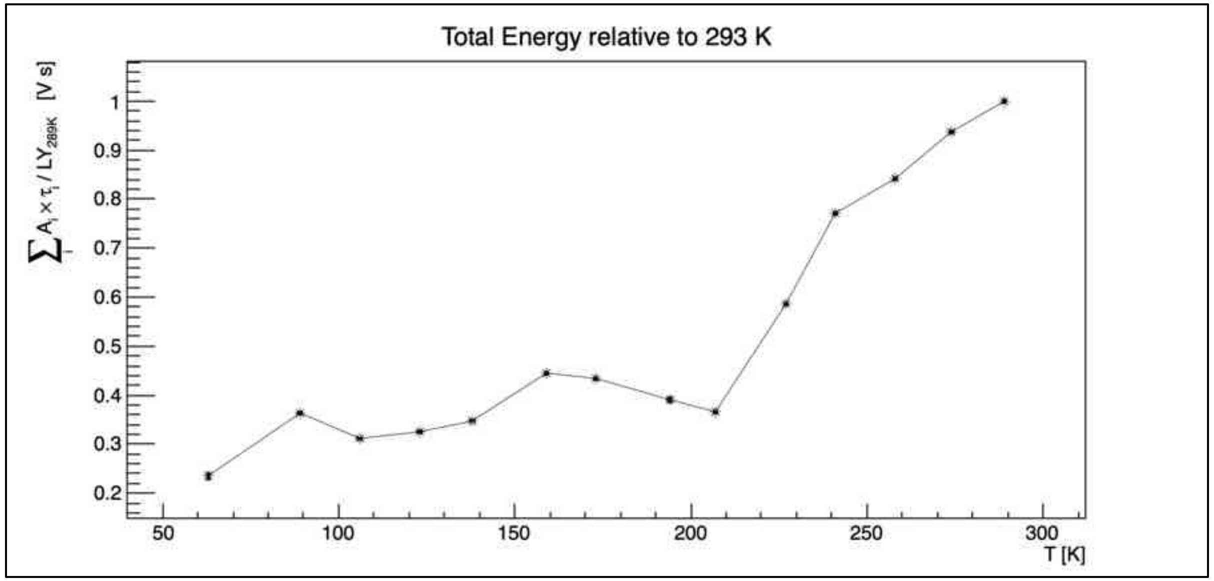


Data analysis mainly carried out by PhD student Niccolò Gallice

@ LNGS – τ's and energy



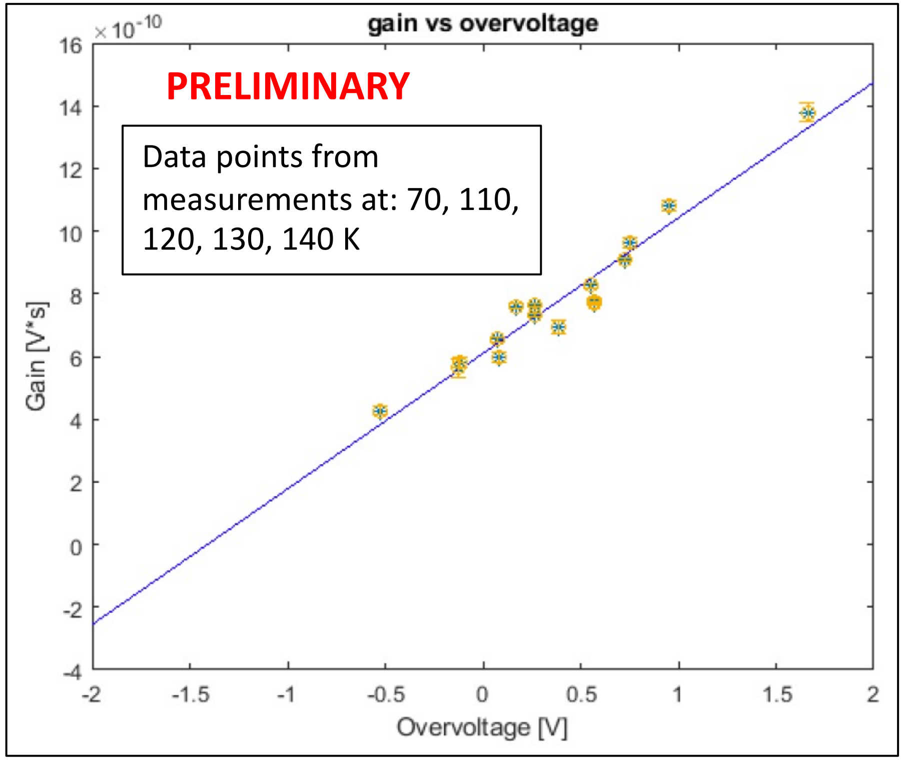




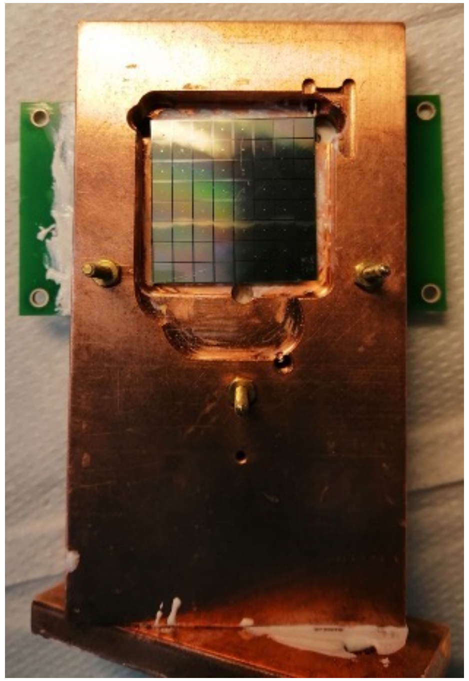
Data analysis mainly carried out by PhD student Niccolò Gallice

SiPM characterization at Milano Politecnico

- The first operative SiPM array used to readout a crystal was an Hamamatsu (HPK) **1'' array** (S13361-3050 series; 64, 3x3mm SiPMs; 50μm pitch).
- Four more arrays from FBK and HPK (5x5 cm^2) are expected in 2021-22.
- 1'' Hamamatsu array was **characterized at Milano Politecnico with a cryo-cooler, cooling it in vacuum on a cold head**.



- Array equipped with a custom cold amplifier. Access to:
  - full device as a single channel;
  - individual SiPMs.
- Measurements were performed **with a dedicated light source** (Hamamatsu PLP-10 high precision laser head, 405 nm), **over a temperature range of 70-140 K**.
- Analysis is in progress and will serve to calibrate data collected with the LASA set-up (see next slides).

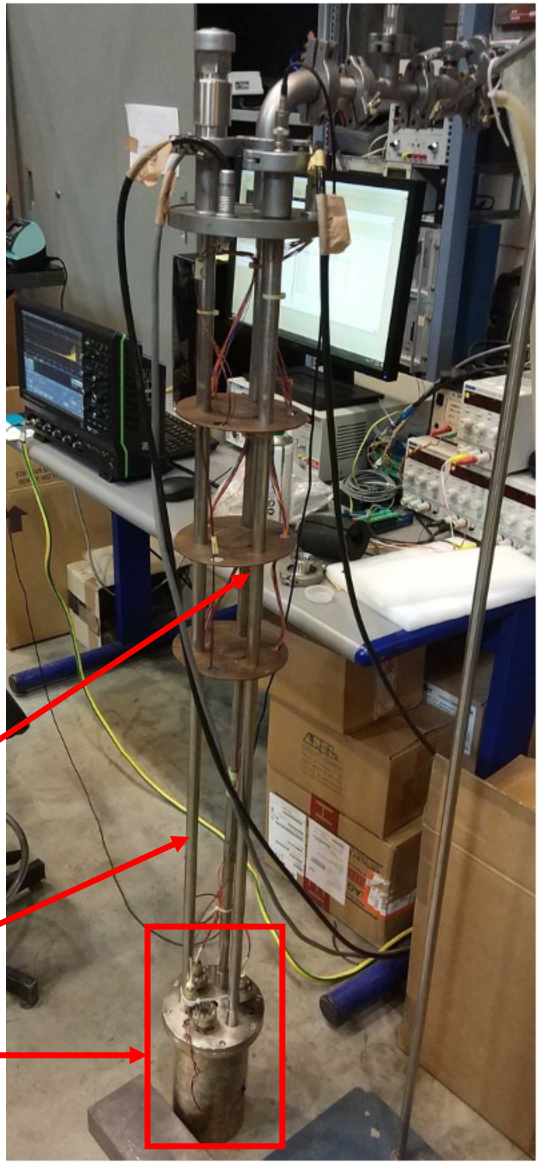


SiPM array and ganging board connected to Cu holder with thermal conductive paste, before installation on cold head

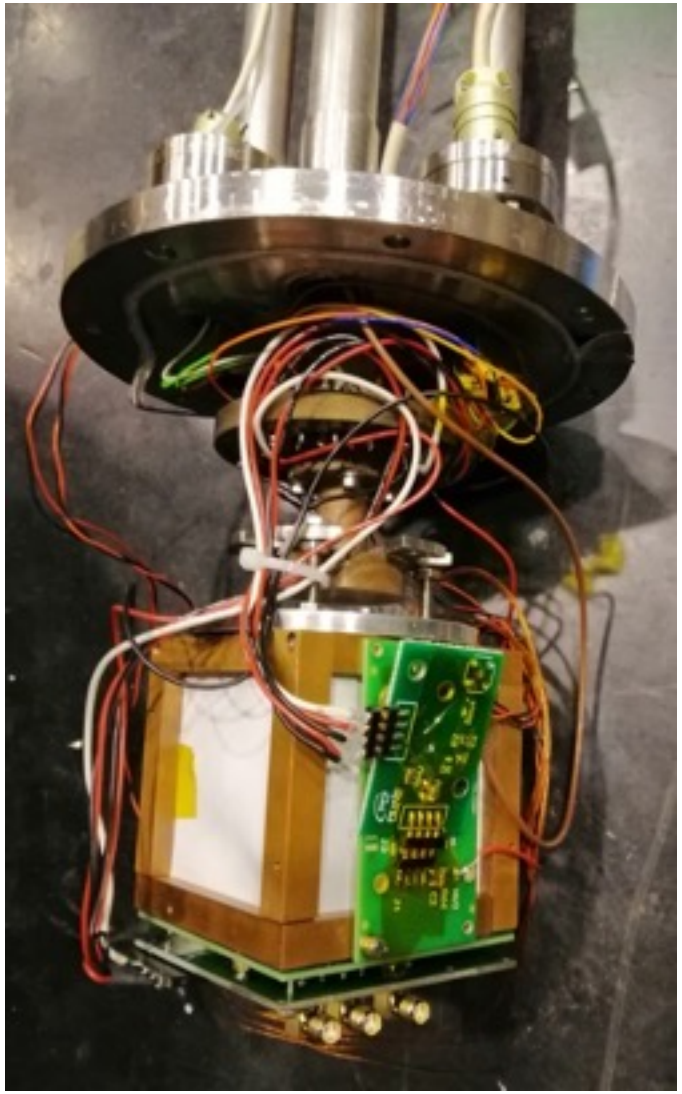
Integrated cryogenic tests at INFN LASA Milano

- ASTAROTH scope – early integration test, meant to yield qualitive results (while waiting for the cryogenic chamber - useful input to simulations

- A SS single-wall chamber containing the crystal in dry He atmosphere is inserted in a dewar and cooled with a N_2 mixer, exploiting liquid and warm gas to produce a cold gas mixture at a tunable temperature.
- In 2019, the system was employed to successfully cool down a test crystal in a controlled way, down to around 110 K.
- In 2021, a cylindrical 5x5 cm crystal (H x ⌀) was equipped with one active SiPM tile (HPK 1'' S13361-3050 array) and cooled in a controlled way.
- Data were collected with ^{137}Cs, ^{60}Co and ^{241}Am γ-sources, placed outside the dewar.



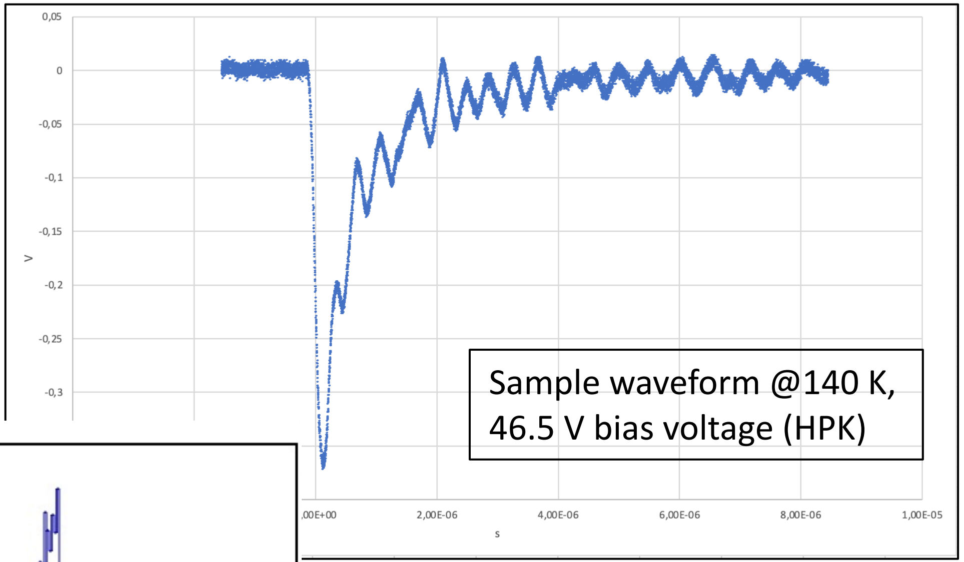
Integrated cryogenic tests at INFN LASA Milano



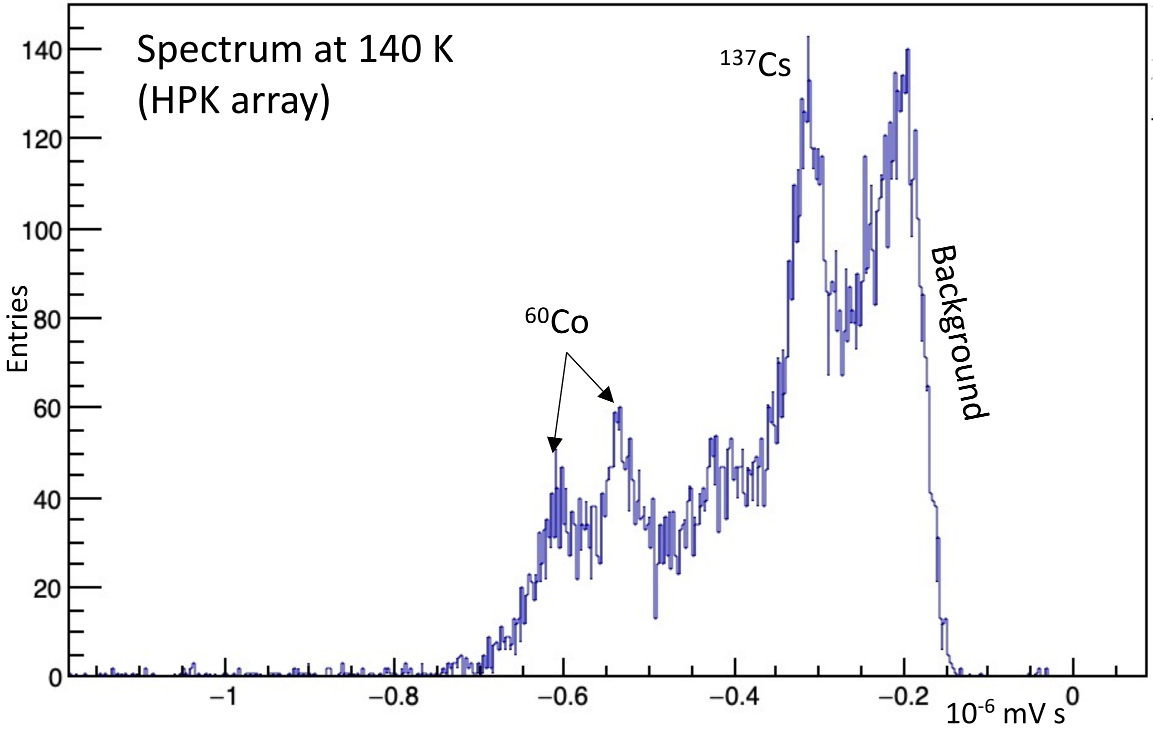
Crystal wrapped in Lumirror™ and equipped with HPK (1'', side) and fake FBK (2'', bottom) SiPM arrays.

Each array has its ganging/amplifying board, and it is independently biased.

Multiple PT100's monitor T map around crystal.



Sample waveform @140 K, 46.5 V bias voltage (HPK)



ASIC-based compact read-out

One further step towards **compact, low-power, radio-pure read-out** is employing ASIC chips.
Activity carried out with external funds in connection with UniMi

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

ASIC READ-OUT →

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

The outcome for these light detectors would be:
- SiPM arrays with area of tens of cm^2, read as a single channel by ad-hoc integrated electronics.
- At a later stage, single low-radioactivity PCB hosting both SiPM and ASIC → **compactness**

Such devices could replace traditional PMTs of a similar sensitive surface with a compact light-weight sensor, featuring unmatched low radioactivity for a wide range of applications.

Collaboration w/ V.Liberali/A. Stabile group (UniMi)