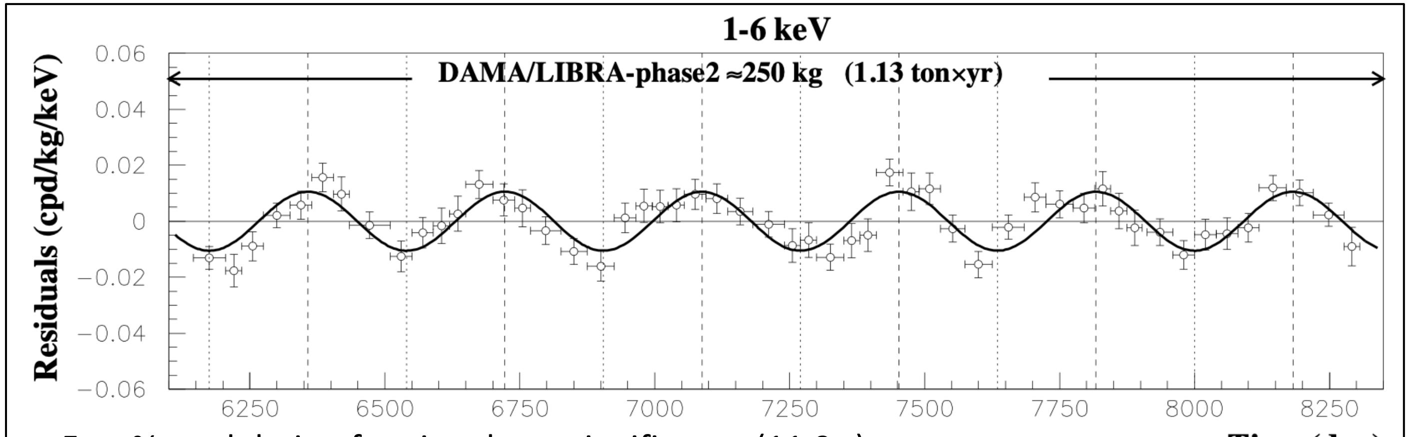
ASTAROTH:
All Sensitive crysTal ARray with lOw Threshold

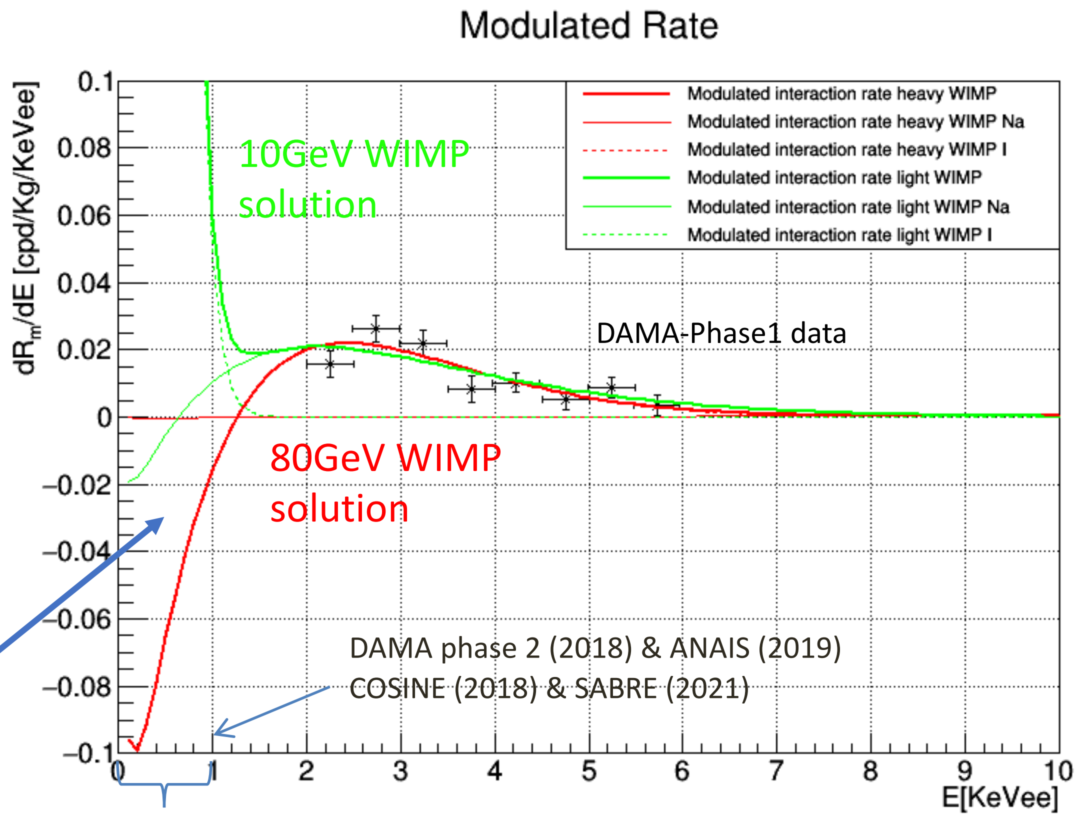
Meeting SABRE – Roma 1-2 Marzo 2023

Introduction - Physics Case



Few % modulation fraction; large significance (11.9σ)

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

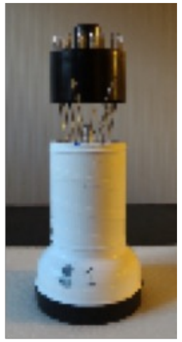


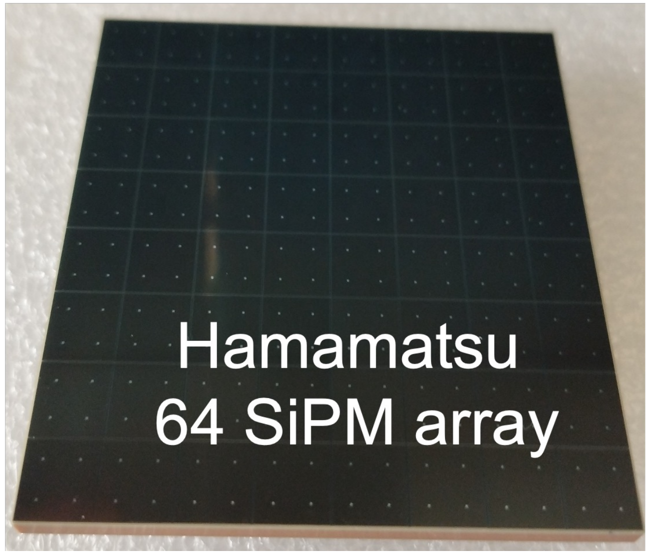
Simplified scenario - basic hypotheses on DM interaction (standard Halo distribution, spin-independent coupling).

- **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.

Overcoming the limitations

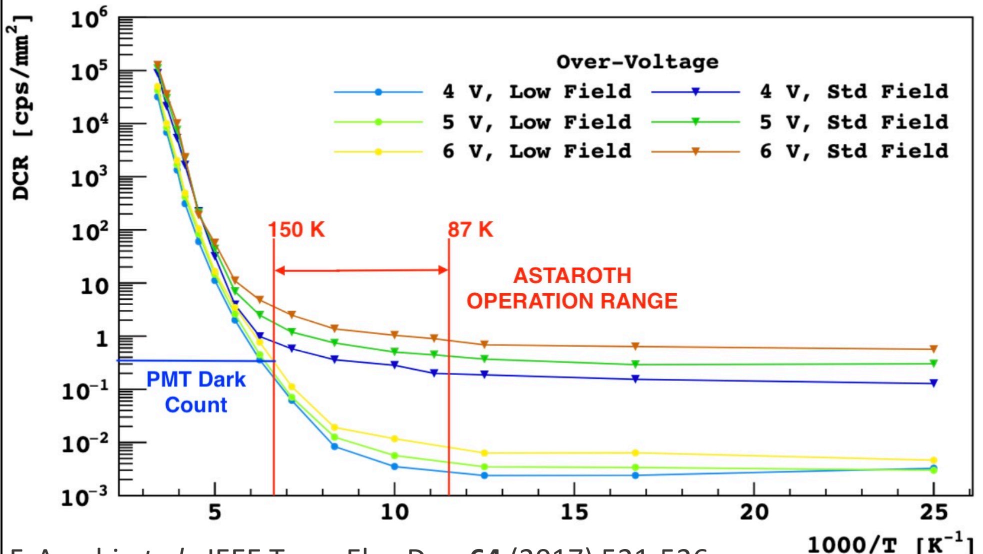
A next-generation detector should:
- **surpass PMT technology to reduce intrinsic backgrounds;**
- **enhance Light Yield (collected phe/keV).**





Use of SiPMs implies the need of a cryogenic environment:
- scintillating **Liquid Argon** (LAr, 128 nm) provides cooling power and can double as VETO detector if equipped with PMTs/SiPMs.

Silicon PhotoMultipliers (SiPMs) can replace PMTs:
- 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

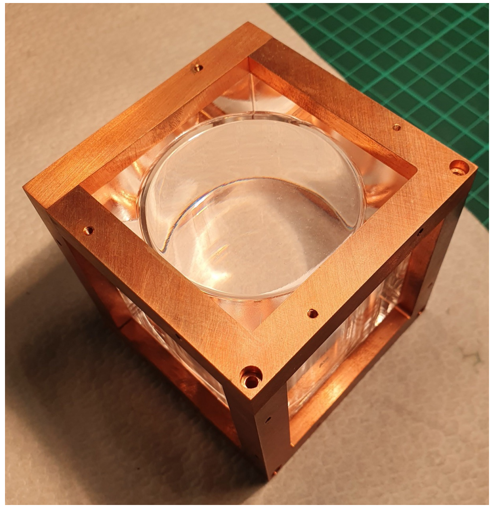
The strategy for an enhanced physics reach

ASTAROTH proposes to employ **small high-purity cubic** NaI(Tl) crystals (presently: 5x5x5 cm^3) read on all six surfaces by SiPM matrices, operating at a tunable cryogenic temperature in the range 87-150 K.

- Use of encapsulated crystals (fused silica, neon atmosphere) for easier manipulation and installation.
- **Investigate the 87-150 K range, to find the optimal operation point**, given crystal and SiPM properties.
  → Not a consistent picture about NaI(Tl) crystals properties at low-Temp (crystal/set-up-dependent results)
- **Extremely-high purity is more easily attainable with smaller crystals.**
- **Enhance light collection thanks to SiPMs: 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

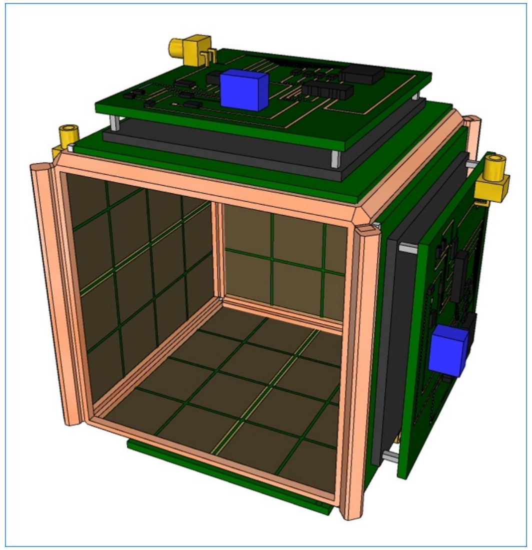
→ Allow for the first-time access to sub-keV recoil energies for the observation of a DAMA-like annual modulation signal.

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



Crystal in quartz container, Cu support

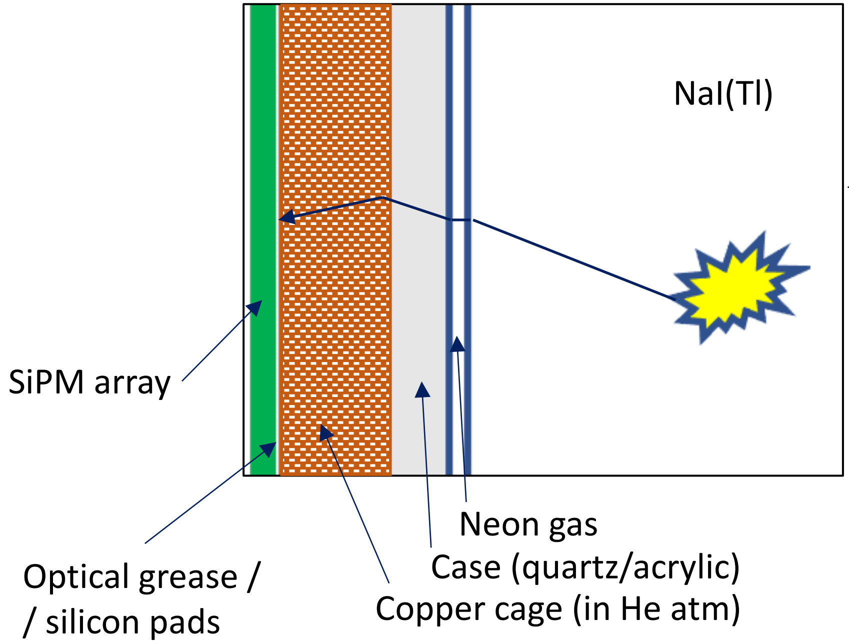
SiPM+readout on single PCB mounted on Cu support

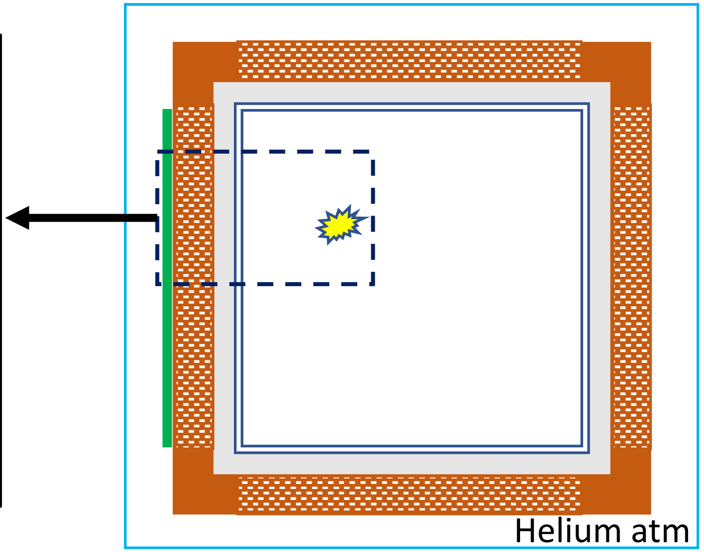


Setup simulation

ASTAROTH can operate 2 encapsulated 5x5x5 cm^3 NaI(Tl) crystals (0.46 kg each).

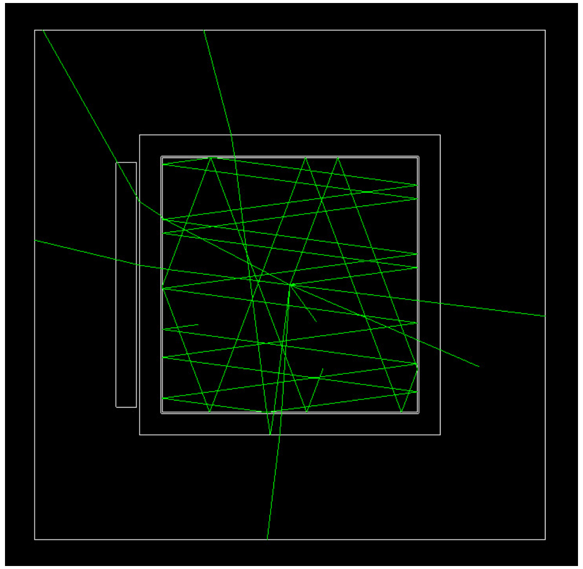
- Goal: collect ~ 20 ph.e./keV out of ~42 γ/keV emitted by the crystal -> **~50% collection efficiency**
- **Very challenging**





GEANT4 simulations (M. Galli) of optical photon tracking, reproducing the present design.

- evaluation of collection efficiency;
- modify details to optimize design:
  - Cubic vs cylindrical crystal
  - Distance SiPM – case
  - Distance case – crystal
  - Surface polished/rough



Conclusions:

1. Cylinder slightly better than cube
2. Surface not relevant
3. <u>Neon layer induces several total reflections -> light absorbed on the crystal</u>
4. Importanto to keep SiPM close to case

Case alternatives

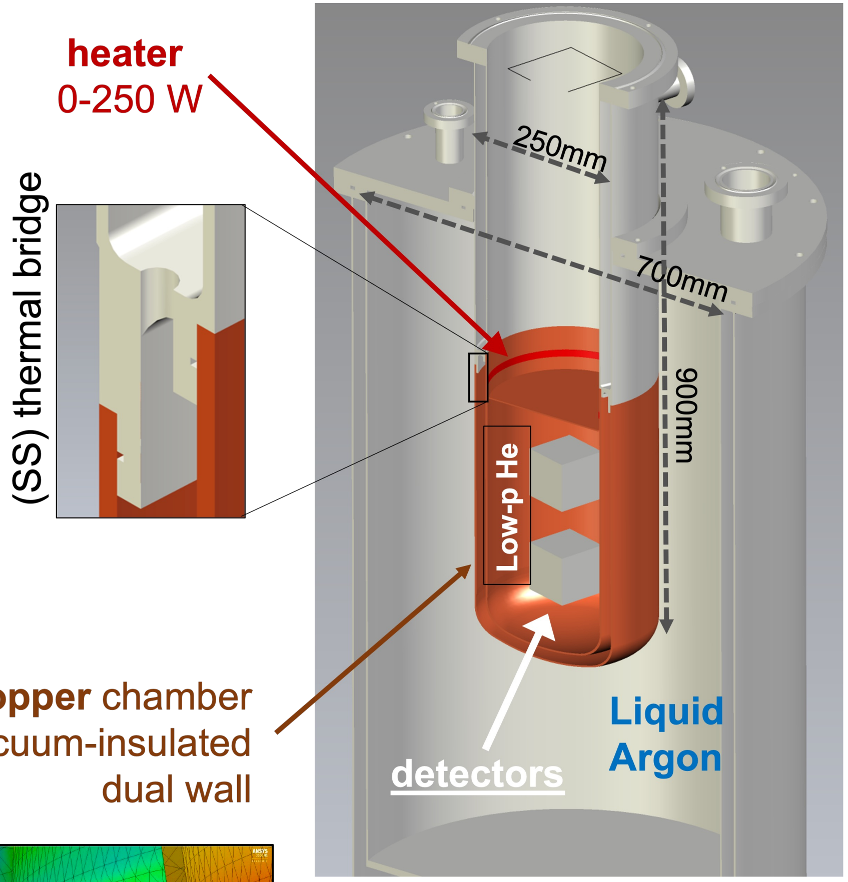
- Current case design has three major problems:
    1. Hilger company is not able to make the cubic case gas tight
    2. The neon gas layer kills light by total reflection
    3. In low pressure environment (200mbar He) the case could explode (inner pressure 1 atm).
- Work on a different design: coat the crystal with (epoxy?) resin
    - Same CTE as crystal
    - Cryogenic-rated resin by Masterbond, very expensive
    - Use resin that coats FBK SiPM
    - Others…
- Which container
    - a permanent quartz cuvette (Hellma)
        - But glass shirks less at cold
        - But how to suspend the crystal?
    - 3D-printed (PLA, ABS) cast
        - But need to polish surfaces
- Tests planned with C. Cattadori @Bicocca
    - Asked also Hilger and RMD to try

Detector Design - mechanics

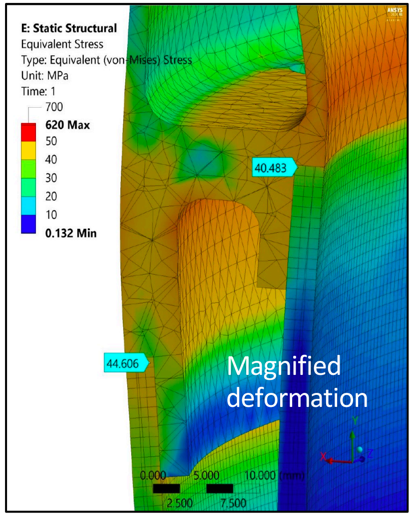
Design requirement: ensuring crystals survival and stable read-out from the electronics.

- **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.**

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



- **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.



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

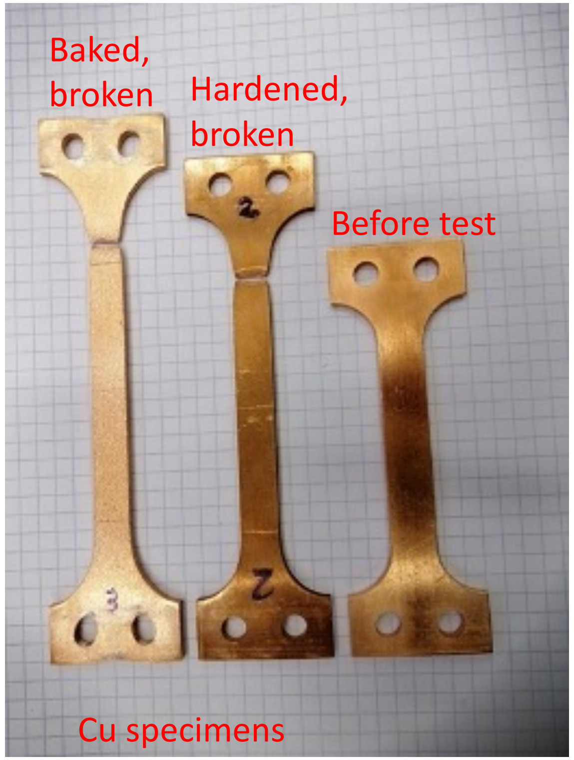
Crygenic tests of materials

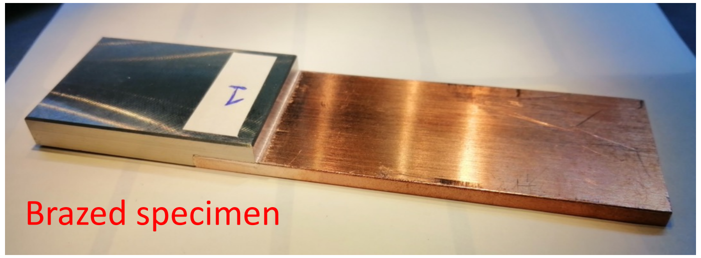
Completed mechanical tests of material samples to optimize simulations and validate chamber design:

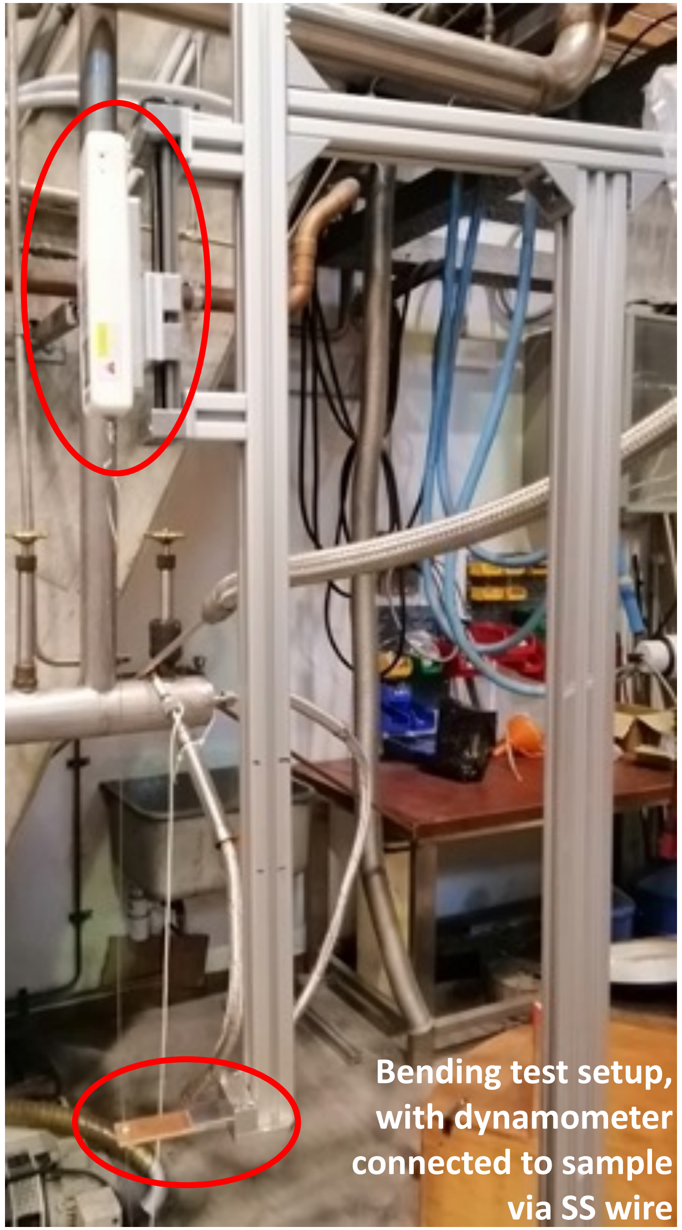
- **baking of two copper samples**, to reproduce mechanical state of copper in the chamber (@UniMi oven);
- **tensile tests** (strain, rupture) **of copper samples at 77 K** at LASA, to derive material properties;
- **bending tests of samples of brazed connections** (SS-copper) **in LN2**, to test their survival in working conditions.

Completed FEA simulations of chamber behavior in working conditions.

Paper/technical note in preparation.

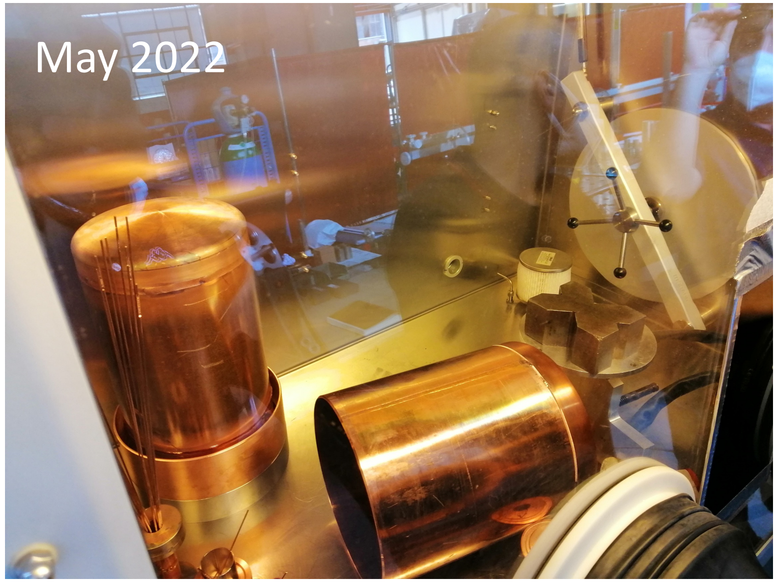






Detector chamber

Long job: 1 year design + 1 year construction
Chamber delivered in June 2022
Commissioning delayed (mostly due to A. Zani other commitments), hopefully soon.

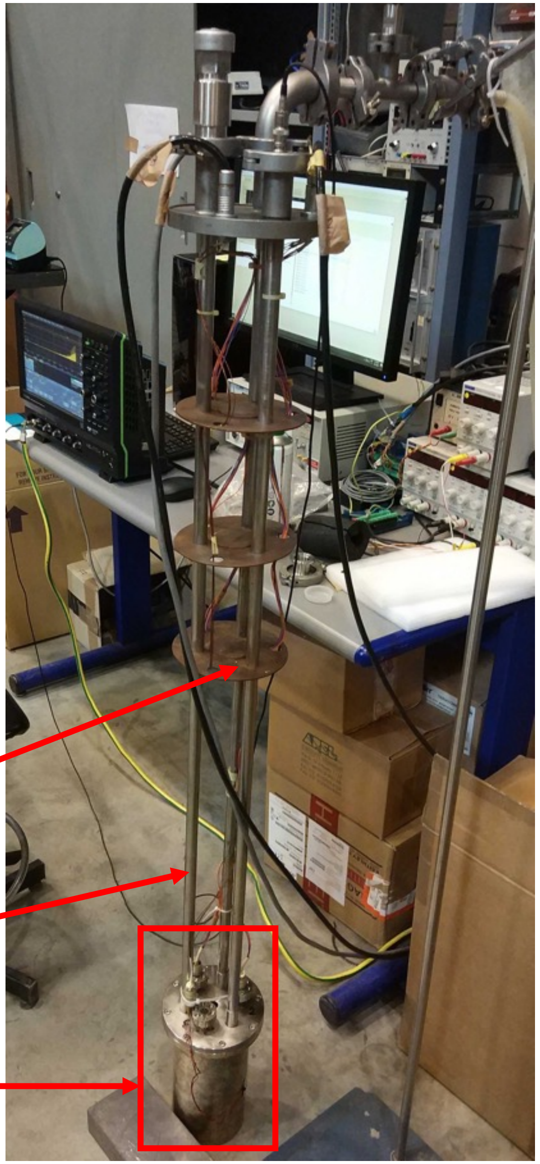


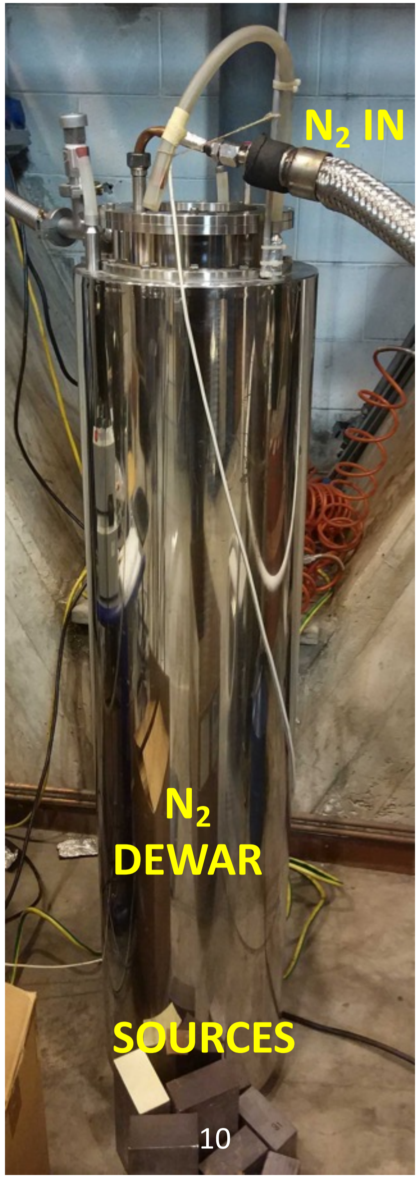
@ Saes Rial Vacuum (PD)

Production company visited in May, to witness copper welding and validate chamber leak testing.

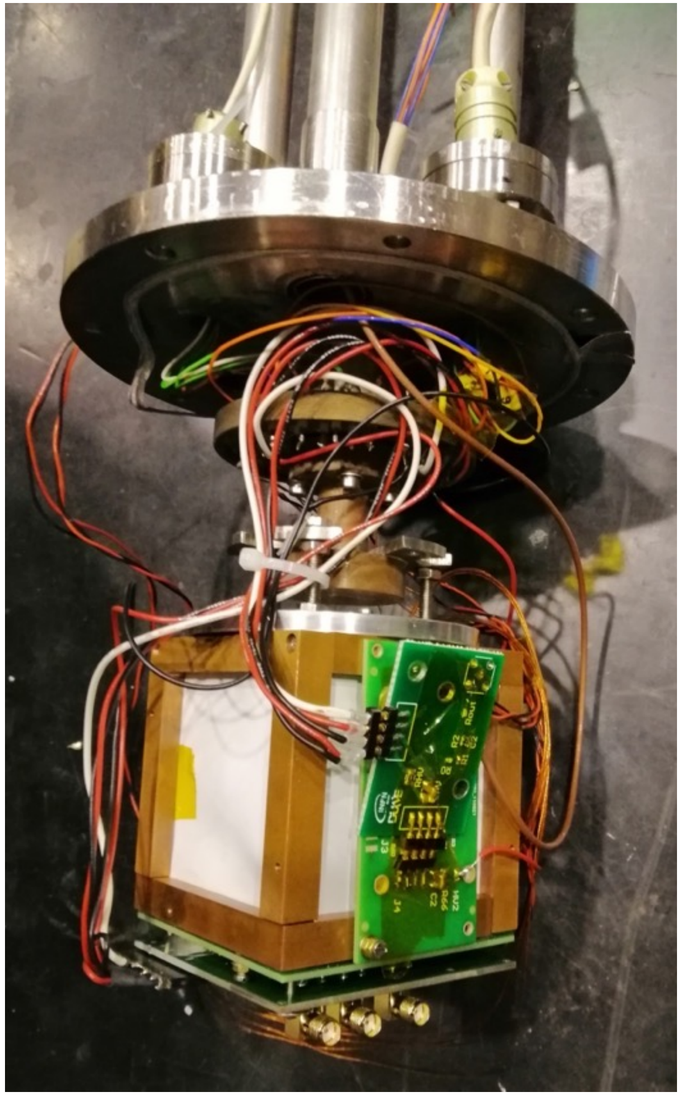
Integrated cryogenic tests at INFN LASA Milano

- Goal: test for the first time the NaI+SiPM detector
- Data taking: April 2021 @LASA in our temporary setup.
  - Used in 2019, to successfully cool down to 110K a test crystal in a controlled way, w/o light read-out.
- A SS single-wall chamber containing the crystal in dry He atmosphere is inserted in a dewar
- Cooling with a N_2 mixer, exploiting liquid and warm gas to produce a gas mixture at a tunable temperature.
- 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.
- Data analysis is in progress





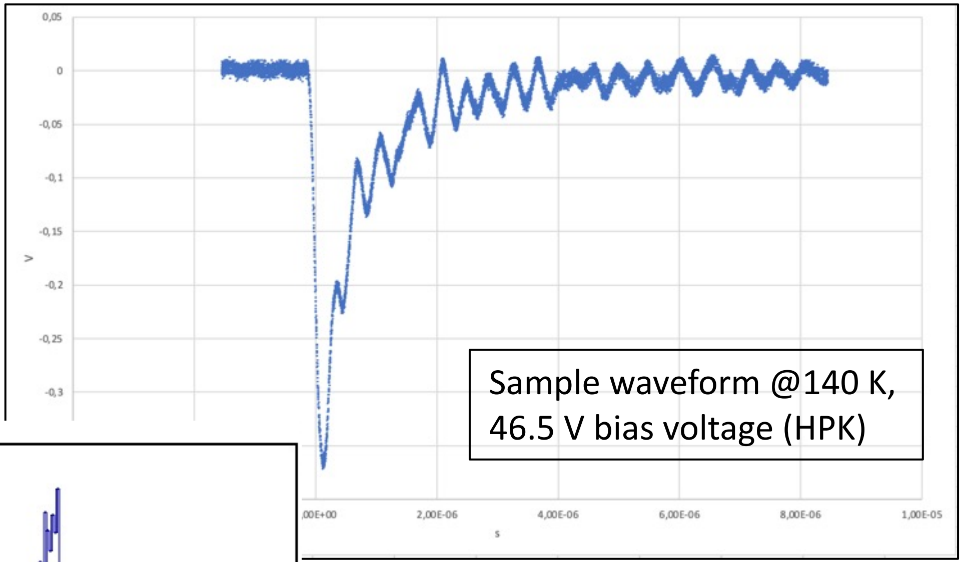
Integrated cryogenic tests at INFN LASA Milano



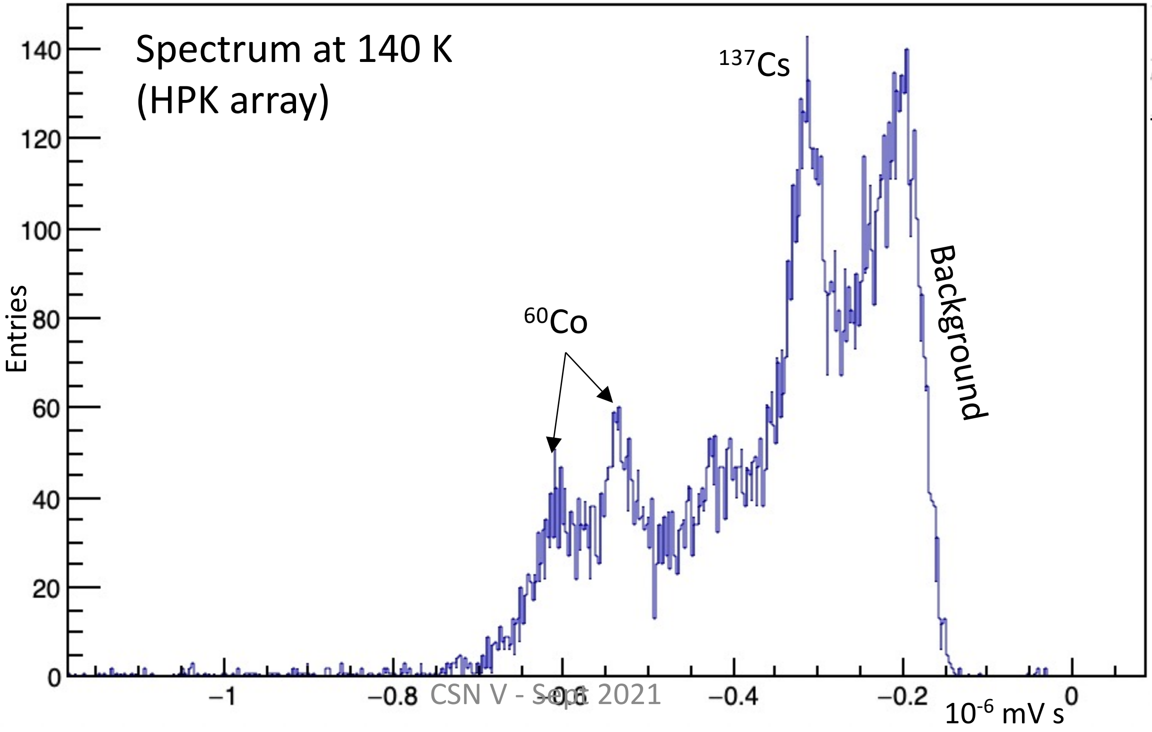
Crystal wrapped in Lumirror™ and equipped with HPK (1'', side) and fake FBK (2'', bottom) SiPM arrays.

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

Multiple PT100's monitor T map around crystal.

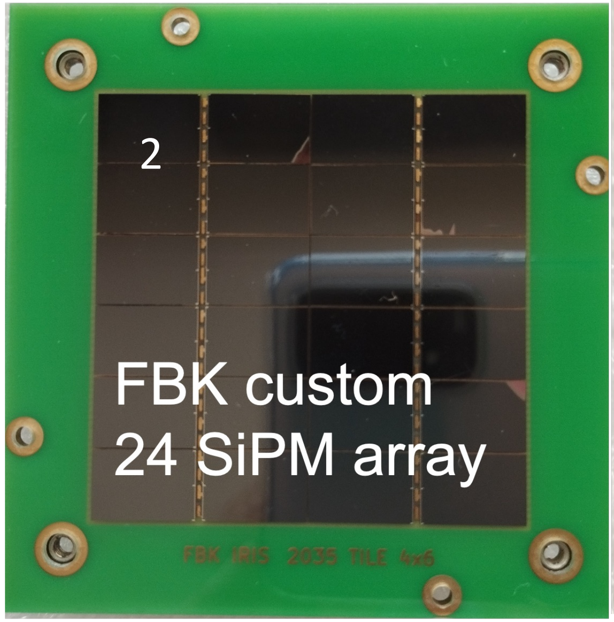


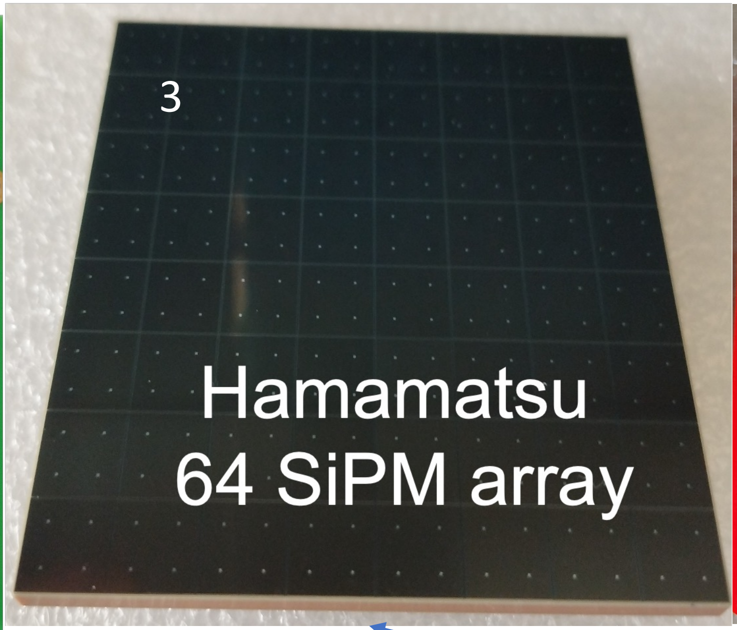
Sample waveform @140 K, 46.5 V bias voltage (HPK)

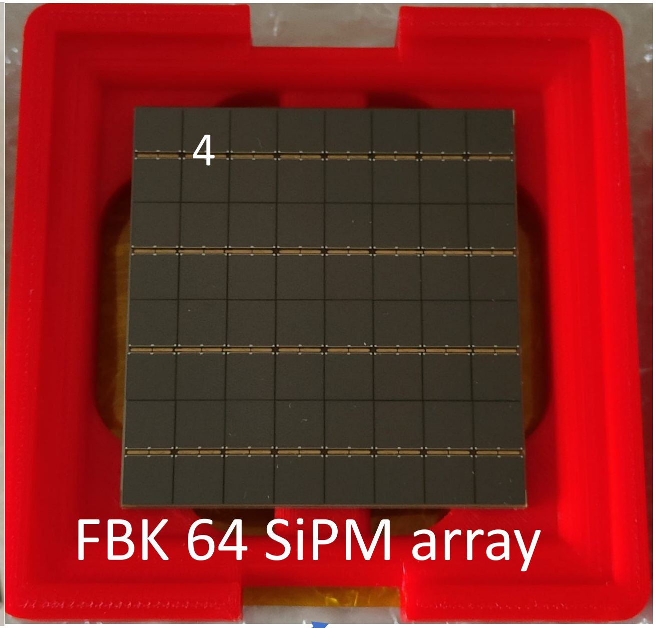


	Firm	Tech	Model	Avail.	Tile size (mm²)	Devices	Area (mm²)	Also used	Pitch (mm)	Route	Gang	Ch	Resin	Tested
1	HPK	S13361	3050AS-08	2021	25x25	64	3x3		50	TSV	no	64	silicon	yes
2	FBK	NUV-HD-Cryo	custom	Jun-22	50x50	24	8x12	DS-20k	35	Wire bond	2s3p	4	epoxy	yes
3	HPK	S13361	6050AS-08	Mar-22	50x50	64	6x6	Dune	50	TSV	no	64	silicon	no
4	FBK	NUV-HD-Cryo	custom	Jan-23	50x50	64	6x6	Dune	30	Wire bond	no	64	epoxy	no

SiPM arrays







Same connectors

SiPM readout - discrete

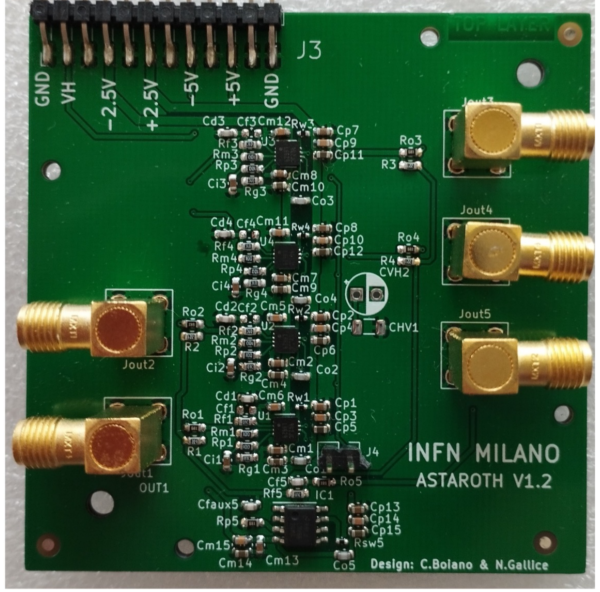
Frontend board for FBK-1 24-SiPM array (Internal design):

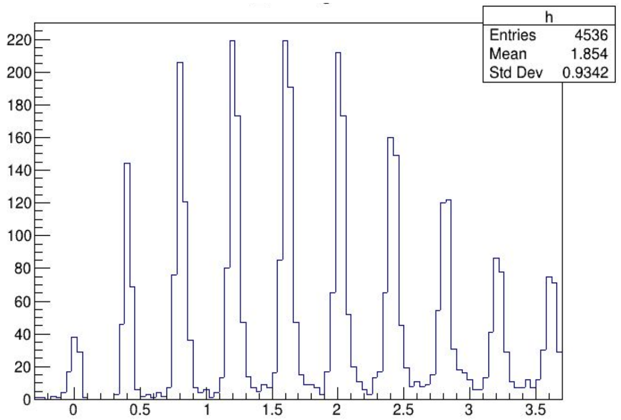
- 4 channels + SUM.
- Designed internally (N. Gallice), based on design of DS-20k.
- Characterized (M. Galli) at room and LN2 temperature with laser.
- More tests to come.

Frontend board of 64-SiPM arrays (HPK & FBK-2)

- More versatile design: 1 motherboard + 4 piggy boards with variable ganging : 1, 4, or 16 SiPM. 4 channels out, differential.
- Cryogenic test for some SiGE Op-amp
- Designed finalized, PO placed. To be produced.

R/O board for FBK 24-SiPM array





ASIC-based compact read-out

One further step towards **compact, low-power, radio-pure read-out** is employing ASIC chips.

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)

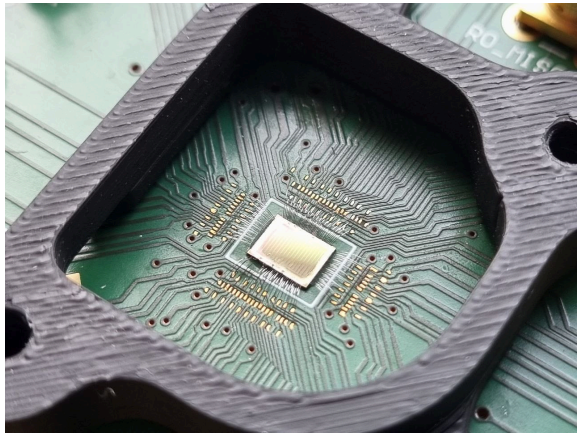
The outcome for these light detectors would be:
- SiPM arrays with area of tens of cm^2, read as a single channel by ad-hoc integrated electronics.
- At a later stage, single low-radioactivity PCB hosting both SiPM and ASIC → **compactness**

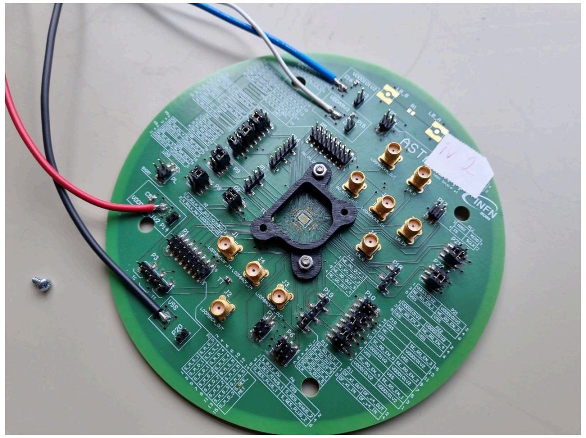
Such devices could replace traditional PMTs of a similar sensitive surface with a compact light-weight sensor, featuring unmatched low radioactivity for a wide range of applications.

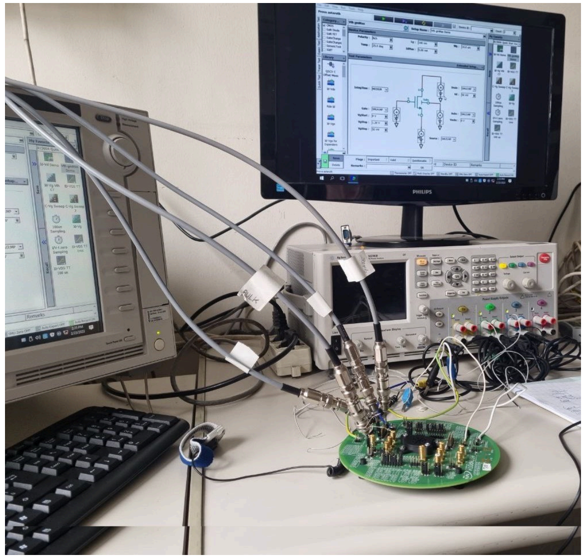
SiPM readout - ASIC

Received in 2022 a frontend board from INFN Genova
- Based on analog ASIC developed in Torino for DS-20k
- Compatible with FBK-1 24 SiPM array
- To be tested yet…

Working on **digital** ASIC
- Designed a test chip based on Lfoundry 110nm tech for testing timing properties at (variable) cryogenic temperatures.
- Delivered Jul 2022. Test board developed, constructed and bonded.
- Currently under test at room T and LN2
  -> then move it to ASTAROTH cryostat at LASA.
- This work is of interest by itself for IC community -> publish it.
- Final Goal: ASIC with digitization on chip, single device charge, optical out.
- Note: not funded by CSNV but by INFN-Mi & UNIMI.

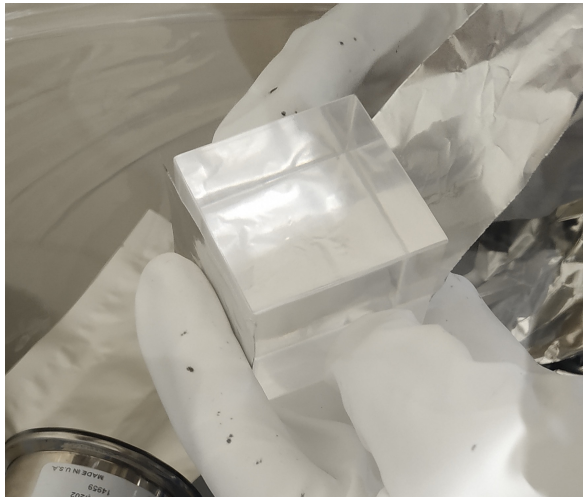






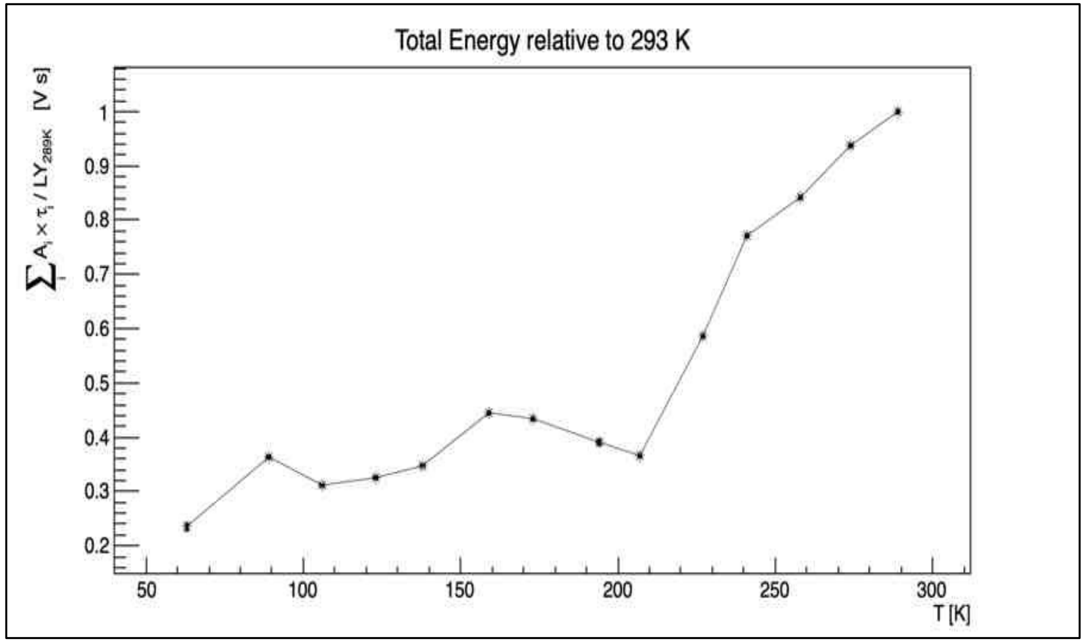
(V. Liberali, A. Stabile, L. Frontini, V. Trabattoni)

Crystal characterization at LNGS



- A **naked NaI(Tl) cubic crystal**, 2’’-side, was characterised with a cryo-cooler at INFN LNGS.
- Crystal wrapped in Aluminum and **cooled under vacuum** with a cold-head. Readout with an external 2’’ PMT, at room temperature. Data collected at **30 -> 300 K**, with ^{137}Cs source.
- **Crystal response vs T** is isolated, **excluding photon detector effects** -> Data analysis shows light reduction and stretching of scintillation waveform profile (up to 1.5 μs).

- **Feb. 2022: third data taking campaign**, with perfected temperature measurement on crystal:
  - Produced in Milan components to improve crystal-cold head thermal contact;
  - demonstrated need to tune DAQ window w.r.t. temperature, due to scintillation profile stretching;
  - derived need to repeat test with multiple crystals (reproducibility of results) and different dopings (effect of Tl concentration on Light Yield);
  - under way: ordered three sets of five crystals with different dopings: 250, 750, 1500 ppm.



Use of COSINUS set-up @ LNGS and support from local personnel

Anagrafica 2023

Personale	Ruolo	% impegno	Sezione	FTE
D. D'Angelo (RN)	PA	30%	Milano	**2.2**
A. Zani	Tecnologo	10%		
V. Toso	AdR UNIMI	40%		
A. Stabile	RTD-B	30%		
M. Sorbi	PA	10%		
Chiara Guazzoni	PA Polimi	20%		
Andrea Castoldi	PO Polimi	30%		
Niccolò Gallice	Dottorando	20%		
G. Di Carlo§	Ric.	30%	LNGS	

- No sigla LNGS, Di Carlo afferisce su Milano

Wide support from INFN Structures/Services:

- Strong collaboration with LASA laboratory (Segrate, MI) infrastructure and personnel.
- Strong involvement of Servizi Meccanici of INFN-Mi & INFN-LNGS, for what concerns detector simulations (FEA).

Synergies with:

- Nu@FNAL group (SiPM R&D and characterization in cold; ^{241}Am cryogenic source purchase).
- SABRE (scope, crystal characterization).
- Genova/Roma3 (SiPM read-out electronics).

Financial plan CSNV

year	Funding k€ (CSNV only)
2020	46.5
2021	34.5
2022	61 (- 27.5 returned)
2023	*29.5 (if all SJ will be released)*
Totale	**144**

+ 40k Transition grant D. D’Angelo (2017-2019)
+ 23k Fellini A. Zani (2021-22)
+ 16k UNIMI PSR (2019, 2021)
+ director’s funds for ASIC line

What happens in July 2023?
- extension?
- new proposal?

… to be decided with referees

Activities 2023

Activities

- Cryogenic chamber commissioning
  - Installation of pumping group
  - Cold cycle without crystals
- To be delivered soon: 15 50x50x50mm naked crystals with different Tl concentration: 250, 750, 1500ppm
  - @LNGS: Understand temperature dependence of crystal Light Yield and scintillation profile
- [Obtain and test functionality of acrylic case for a crystal (if ever…)]
- Test epoxy resin coating of crystals on small and full scale
  - With or without glass container
- Complete GEANT4 simulation of optical photons transport in the new design
- Completion of design of crystal supports – and purchase
- Characterize readout board for 64-SiPM arrays
- Test ASIC front-end from Genova
- Test ASIC test chip for timing performance
- Characterization vs temperature of available SiPMs in Milano Politecnico setup (PDE measurement vs T)
- Acquire 3 more SiPM arrays to complete coverage of one crystal
- Perform characterization of one fully-equipped crystal in cryo-chamber @ LASA, with ^{241}Am source

Back Up

Introduction - Physics Case

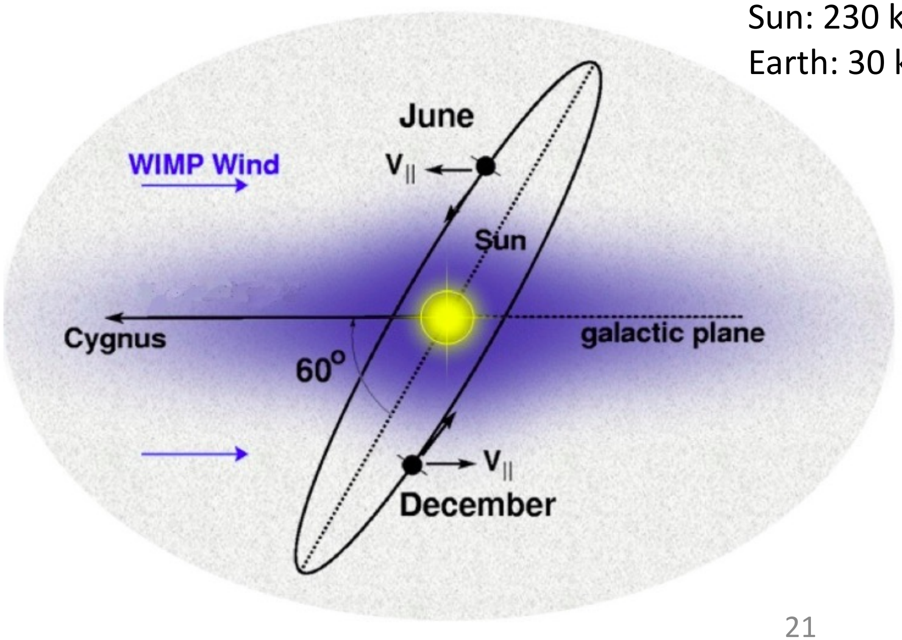
ASTAROTH

- INFN 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 2nd.

- 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.

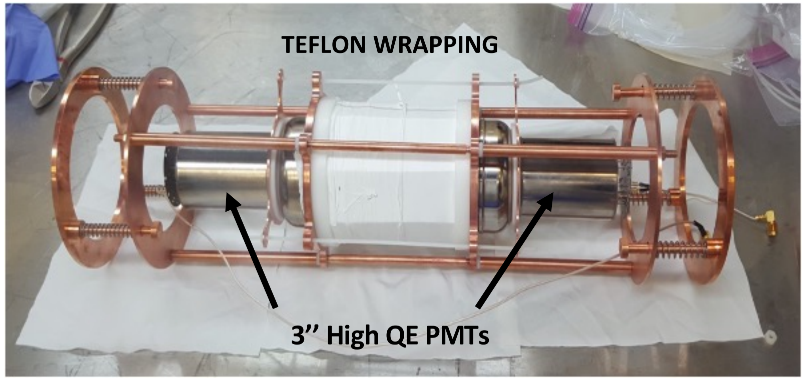
Sun: 230 km/s
Earth: 30 km/s



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.



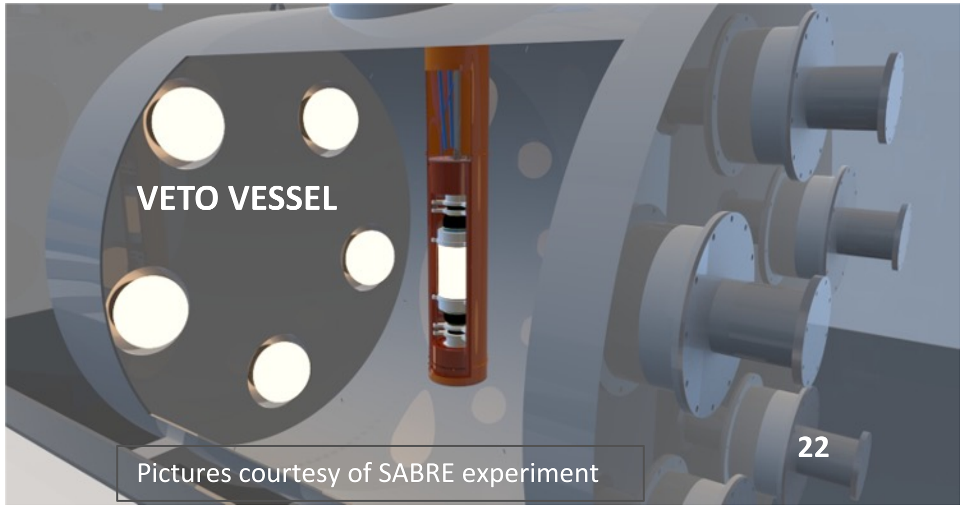
- Detector: parallelepipedal crystals, wrapped in reflector and coupled with high-QE* PMTs.
  - Light collection is limited to 7-15 photoelectrons (phe) per keV.
  - PMTs feature intrinsic high noise and radioactivity.
- Large, few-kg mass crystals: hard to achieve very-high-purity production.

  → **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