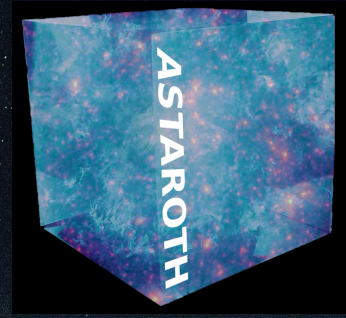




Cryogenic SiPM readout of NaI(Tl) dark matter detectors within the ASTAROTH project

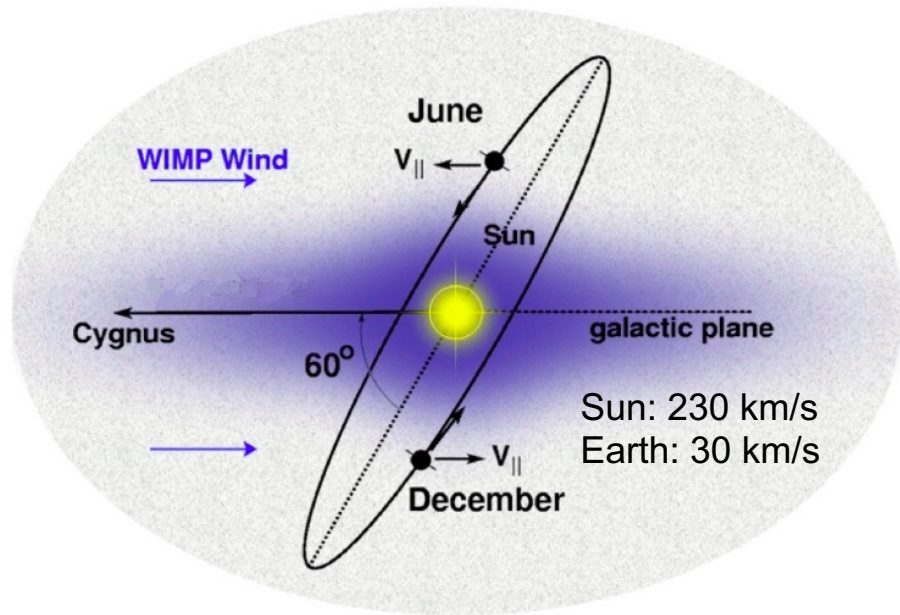
Davide D'Angelo, Edoardo Martinenghi, Valerio Toso

Università degli Studi di Milano and INFN

photo: Valerio Toso
(Campo Imperatore)



Physics Case

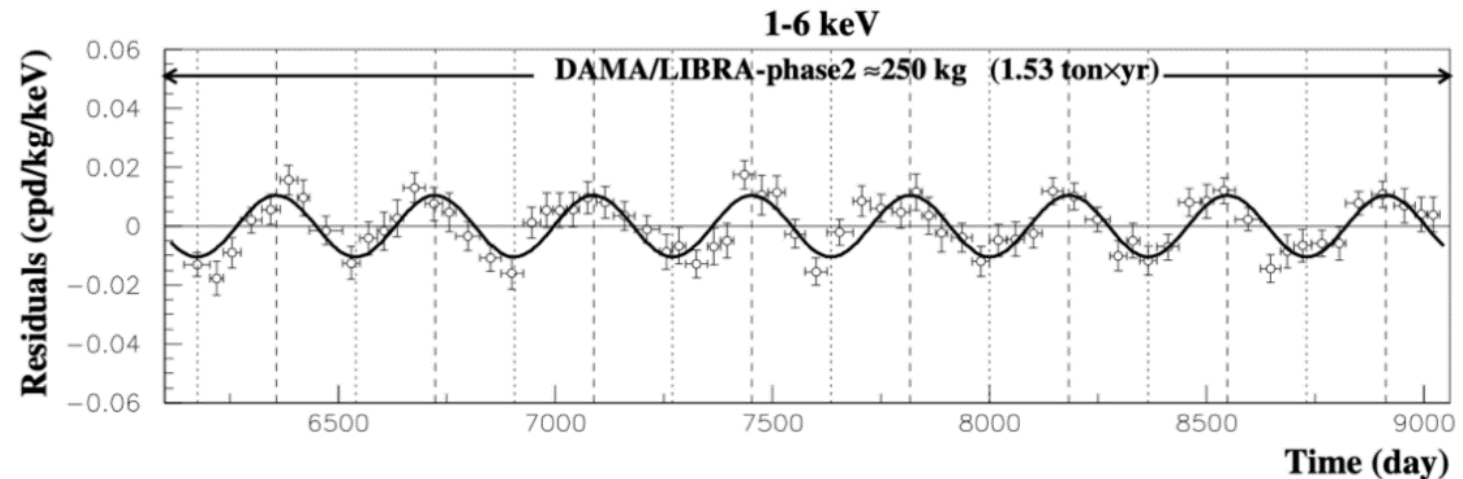


- Challenges:
 - Energy ROI: up to 6 keV recoils
 - Low rates: ~ 1 events/day/kg
 - Radiopurity of crystals and all materials is key to sensitivity
 - Noise from photo-sensors is limiting S/N in the ROI and energy threshold

Direct search for dark matter with NaI(Tl) crystals

- Annual modulation expected: the Earth's motion around the Sun combines with the Sun's motion around the galactic centre.
- Annual modulation detected: DAMA/LIBRA (concluded in 2024), unverified!

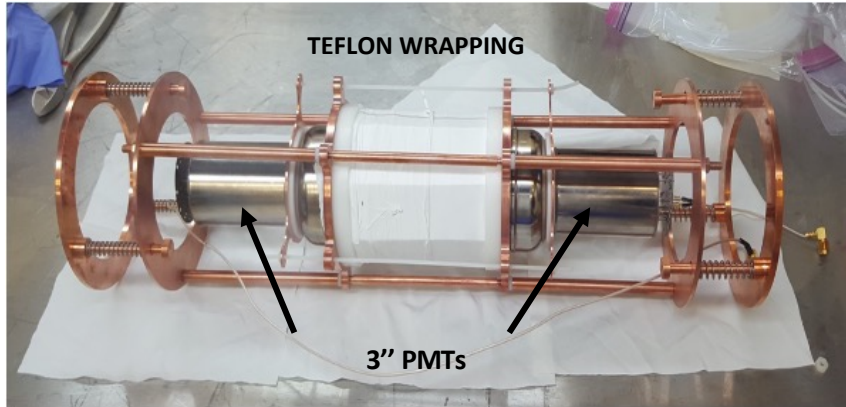
Few % modulation fraction; large significance (11.9σ)



[Nucl. Phys. At. Energy 2021, vol. 22, iss. 4, p 329-342]

Current technological scenario

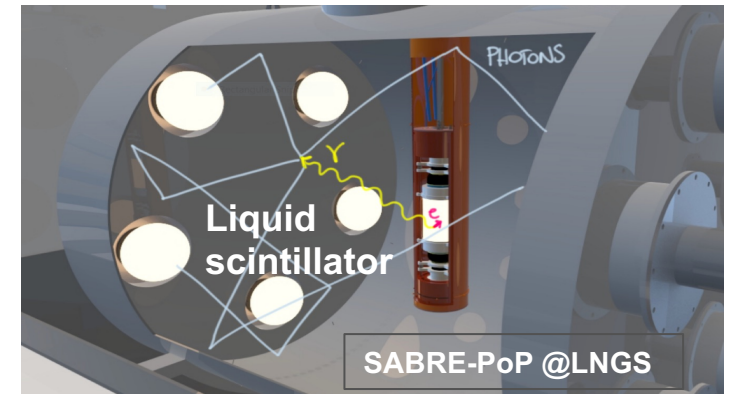
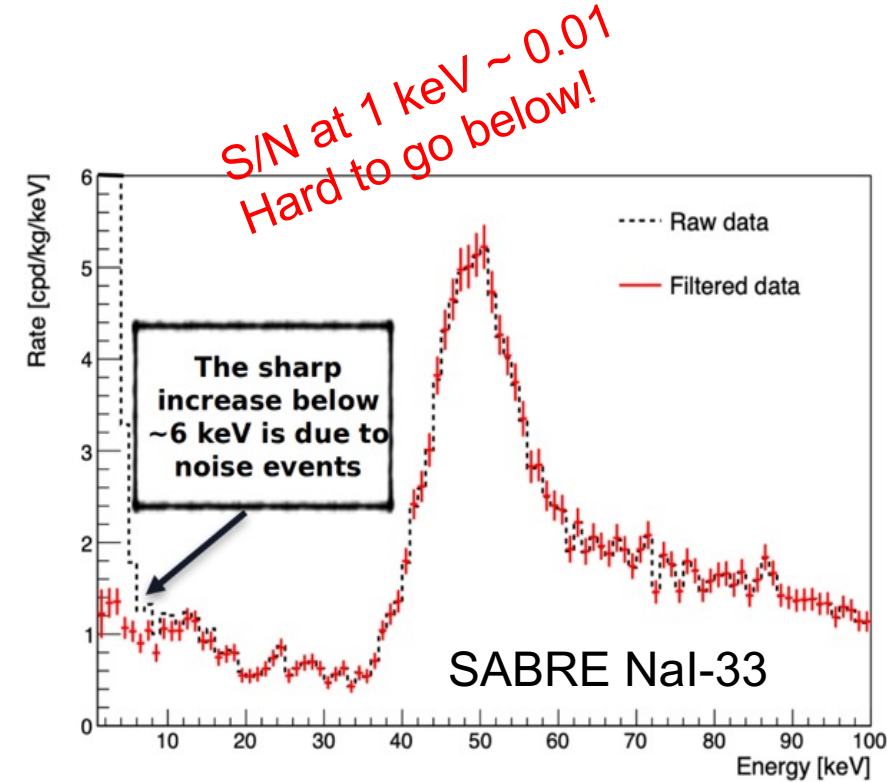
Existing **Nal(Tl)-based detectors**: DAMA, SABRE, ANAIS and COSINE



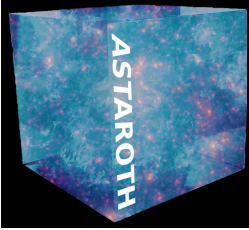
Elongated crystals, wrapped in reflector and coupled with PMTs.

1. Mass of crystals $\sim 5\text{-}12$ kg: hard to achieve with very high purity.
 2. Light collection limited to 7-15 ph.e./keV.
 $\hookrightarrow$ Out of 40-42 ph./keV
 3. Reflector can be a source of surface contamination
 4. PMTs feature intrinsic **high noise** and radioactivity.
5. Background rejection strategy with **VETO** detector:
 - designed to tag γ 's from key backgrounds in the ROI: ^{40}K , ^{22}Na .
 - Organic liquid scintillators used so far by COSINE and SABRE-North PoP
 - **Safety and environmental issues: phased out at LNGS**

ASTAROTH surpasses all 5 limitations!



Overcoming the limitations: ASTAROTH



A next-generation detector should **surpass PMT technology**:

- **reduce noise**
- enhance Light Yield (collected ph.e./keV)

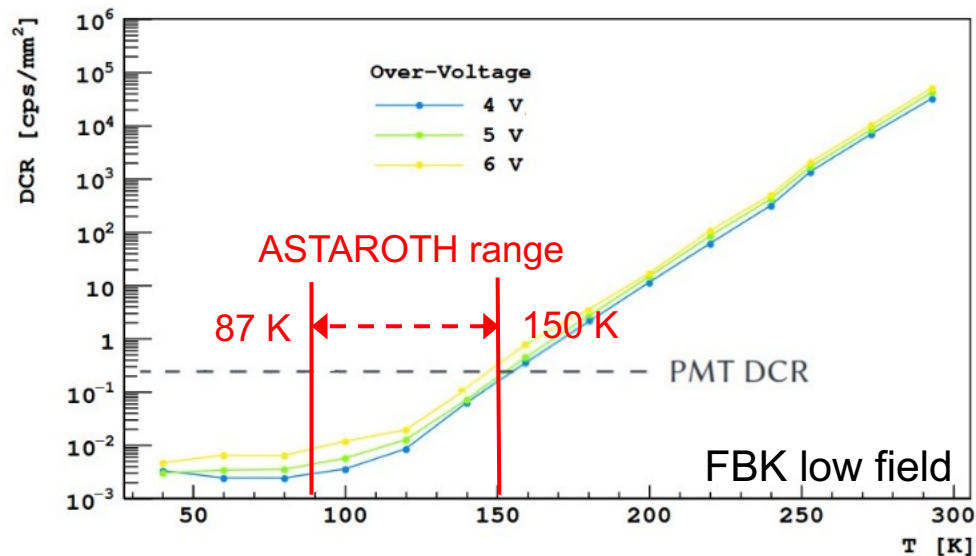


Silicon PhotoMultipliers (SiPMs) can replace PMTs:

- higher PDE (55%), w.r.t. ~30-35% max QE of PMTs at 420 nm (peak NaI(Tl) emission).
- arrays have smaller transverse dimensions.
- lower intrinsic radioactivity.
- SiPM technology features lower noise than PMTs at **T<150 K**.

Use of SiPMs implies the need of a cryogenic environment:

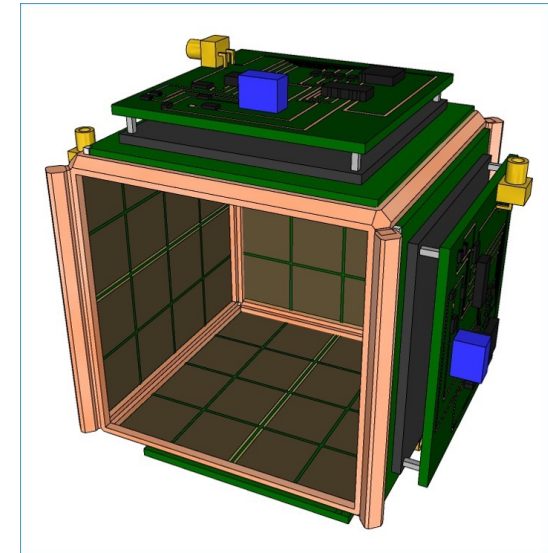
- scintillating **Liquid Argon** provides cooling power and can double as VETO detector if equipped with PMTs/SiPMs.



adapted form: IEEE Trans.Elec.Dev. **64** (2017) 521-526

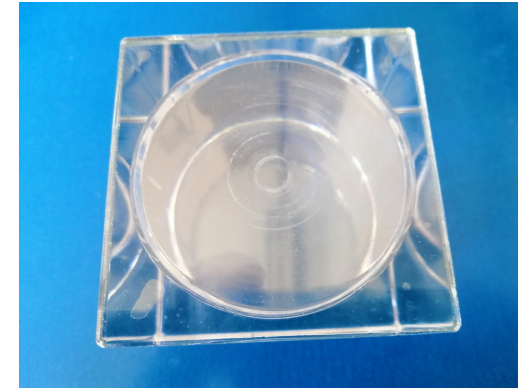
- **Small cubic** crystals (5x5x5 cm³)
- read on **all six surfaces** by SiPM matrices
- operating at a tunable temperature **in the range 87-150 K**, to find the optimal operation point for crystal and SiPM

→ [Access to sub-keV recoil energies](#)

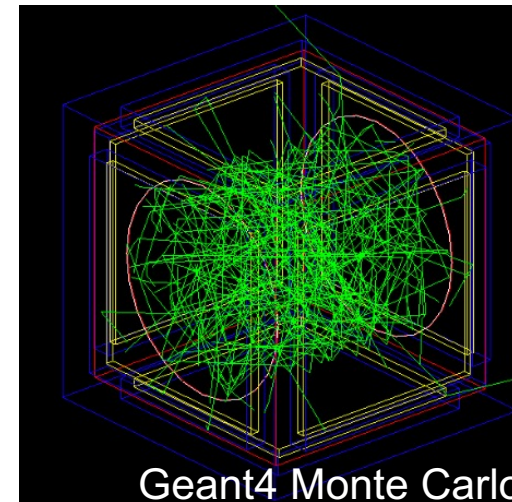


Crystal detector design

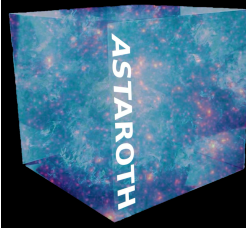
- NaI is **hygroscopic**
- ASTAROTH operates in a cryostat, need a case with several requirements:
 - [withstand vacuum]
 - withstand **several thermal cycles** to LAr T
 - **fully transparent** at LAr T
 - low radioactivity materials
- Present results with a **fused silica** case
 - 1-mm **neon gas gap** to accommodate for different CTE (NaI $\neq$ quartz)
 - **50x50 mm cylinder-in-a-cube** temporary solution
 - Problem: **only a fraction of light exits**

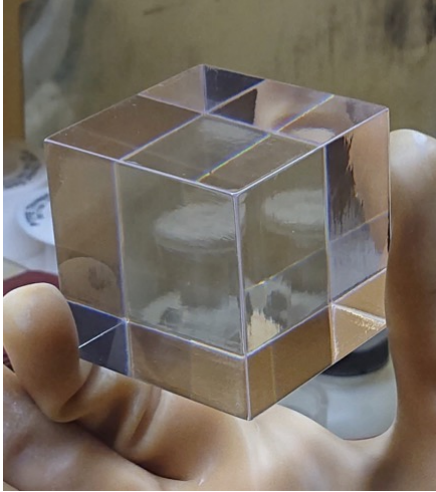


Hilger Crystals, UK

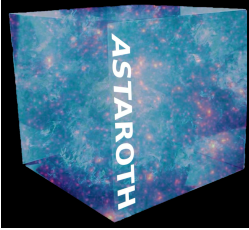


Geant4 Monte Carlo

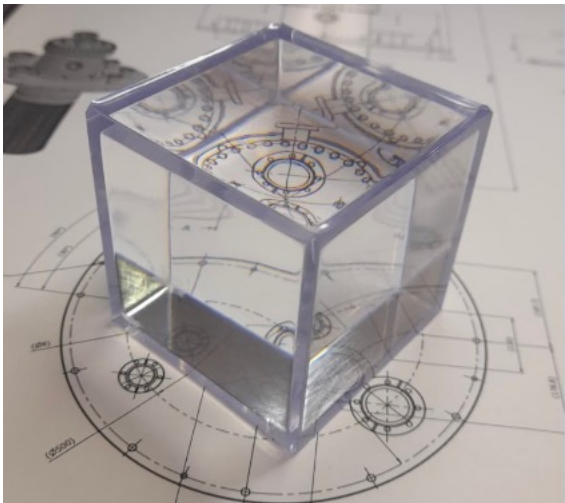
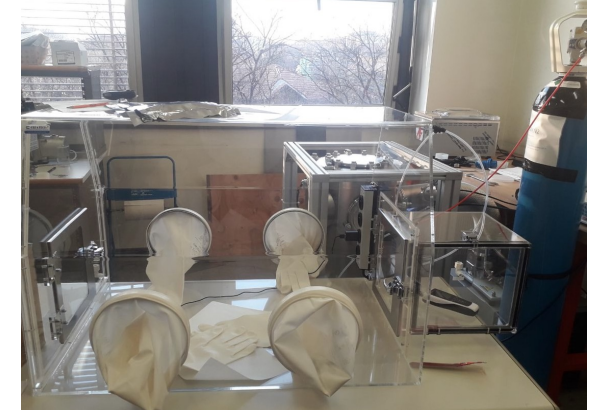




First epoxy-coated NaI(Tl)



- A revolution in handling of hygroscopic crystals
- Works with two resins: Epo-tek and Stycast
- First *fully transparent cold-compliant* **50-mm in 2025**
- *Operated with SiPMs* in July 2025



All the details in poster # 120 By V. Toso



An innovative encapsulation technique for NaI(Tl) scintillating crystals

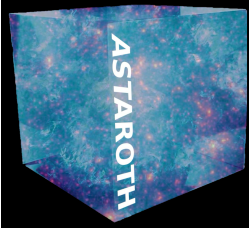
Valerio Toso^{1,2}, for the ASTAROTH collaboration

Ideantification of Dark Matter
1 - 5 Jun 2026
Zaragoza, Spain

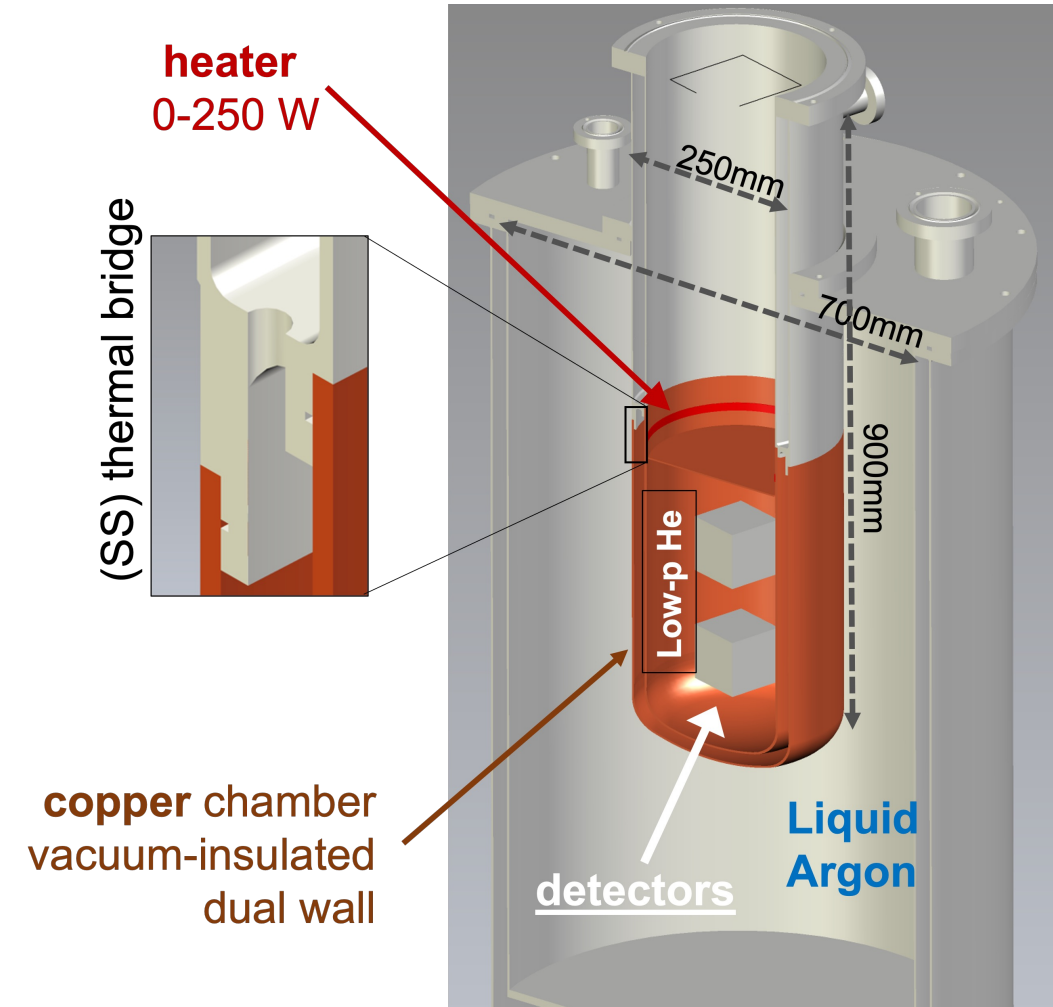
¹INFN Milano; ²Università degli Studi di Milano



ASTAROTH cryostat

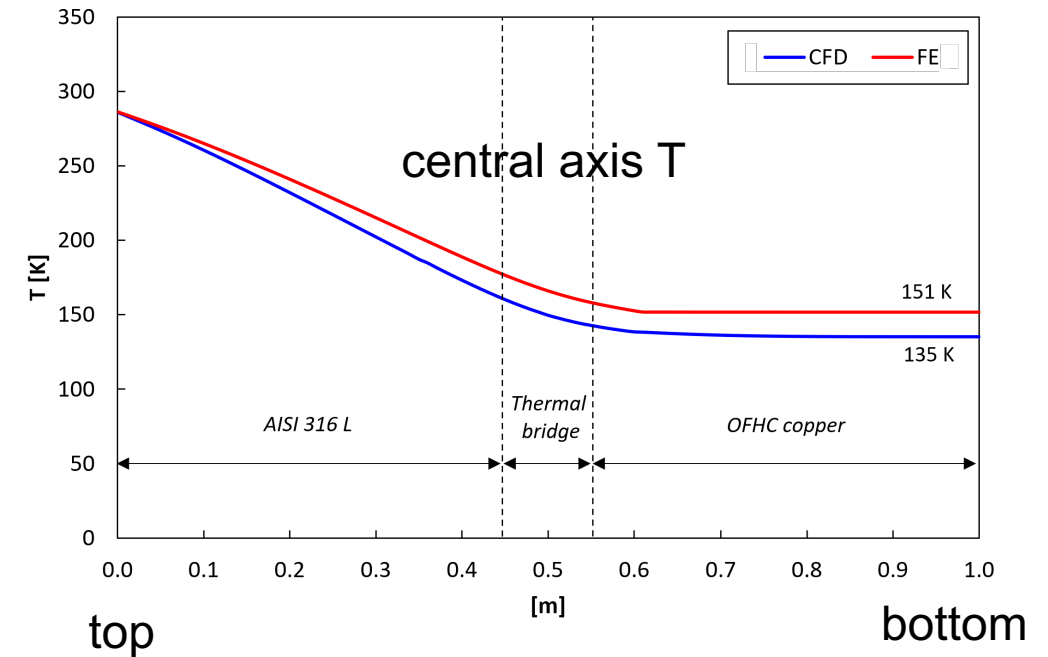
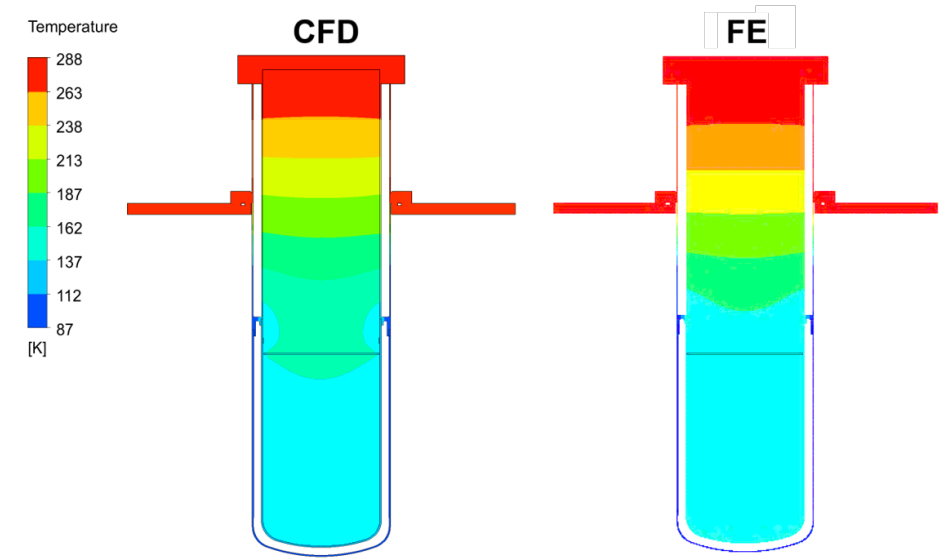


- **Dual-wall, vacuum-insulated** radio-pure copper chamber, immersed in a **cryogenic bath**
- **Cooling power** through a specially designed **Stainless Steel (SS) thermal bridge**.
- Heater raises and stabilizes the temperature above that of cryogenic fluid.
- **Investigated range: 87-150 K.**
- **Helium gas** fills the inner volume, serving as heat-transfer medium to the crystals and SiPMs.



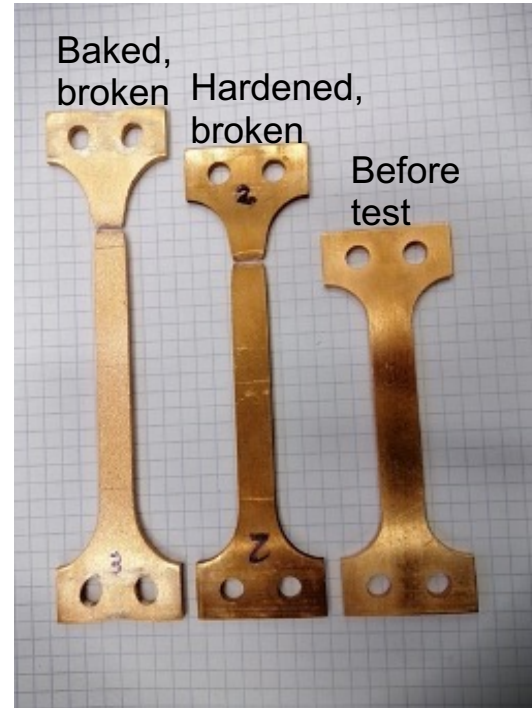
Cryostat thermal simulation

- Thermal field simulated with Ansys at the most stressing temperature: 150 K
- Redundant approaches:
 1. Computational Fluid Dynamics
 2. Finite Element
- Parallel work of two INFN mechanical services:
 - A. Milano (M. Monti)
 - B. LNGS (D. Orlandi)
- The heat map is passed on to the structural analysis



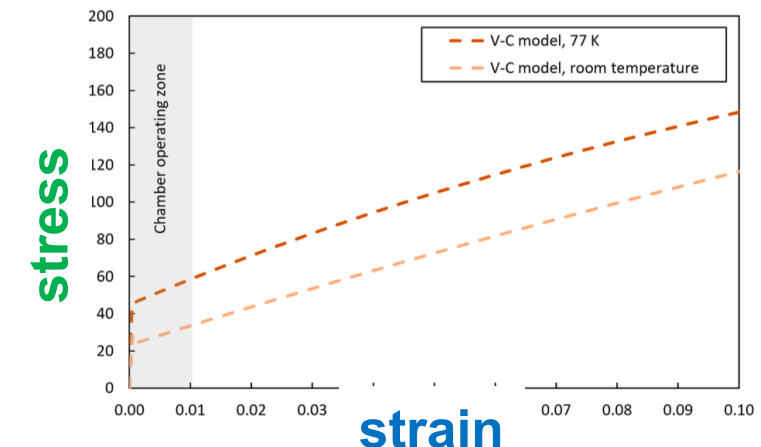
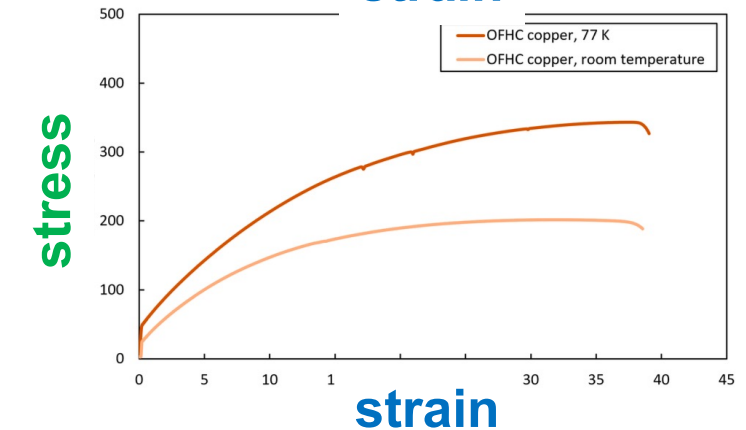
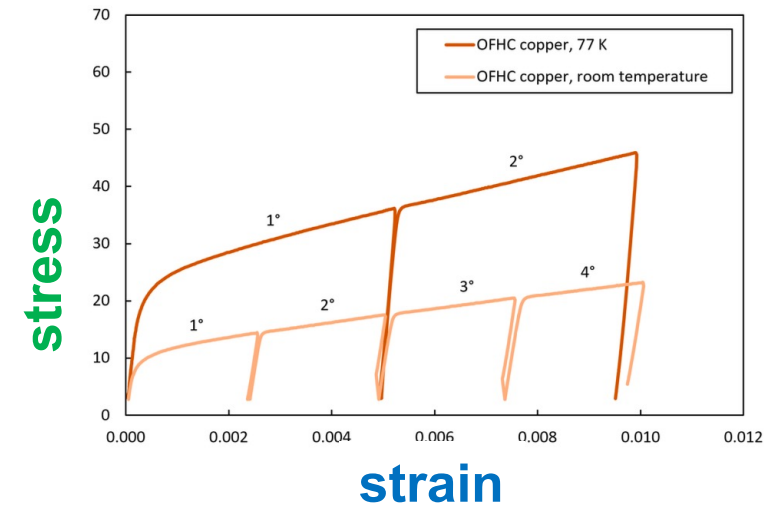
Cryogenic tests of materials, tensile

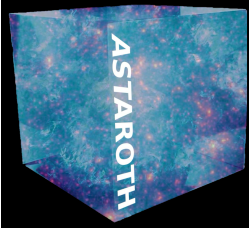
- copper samples were first baked, to reproduce mechanical state of copper in the chamber.
- tensile tests (strain, rupture) of copper samples with an INSTRON test machine at RT and 77K.
- material parameters derived
- Voce-Caboche parametrization
- Results used for the structural analysis



$$\sigma_{\text{model}}^t = c_1 + c_2 \left(1 - e^{-c_3 \varepsilon_p^t} \right) + c_4 \varepsilon_p^t$$

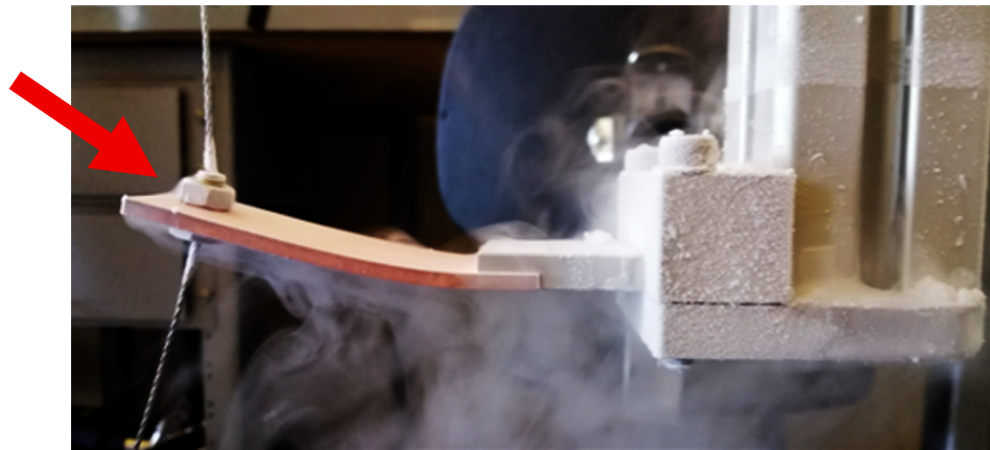
	c_1	c_2	c_3	c_4	r
295 K	25.3	443.1	2.4	0.0	0.5
77 K	47.8	214.7	6.4	0.0	0.6





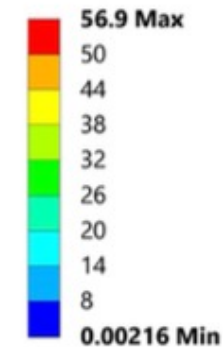
Cryogenic tests of materials, bending

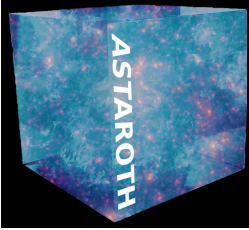
- 4 samples of brazed connection
- Ansys Finite Element simulation of the most stressing operational condition
- bending tests in LN2, subject to the force computed by the simulation
- X-ray scan *before* and *after* the tests: **no difference**



c)

Equivalent Stress Copper
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 2 s



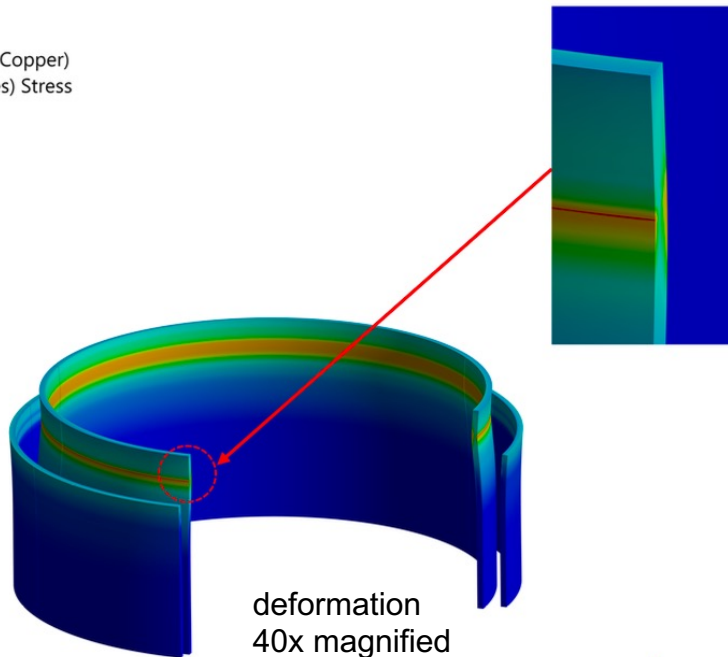
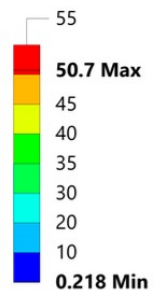


Cryostat structural simulation

- Finite Element Structural Analysis starting with
 - a. The heat map from thermal analysis
 - b. Material properties as a function of T derived from tensile tests
 - c. Other boundary conditions (bolts, weight, ...)

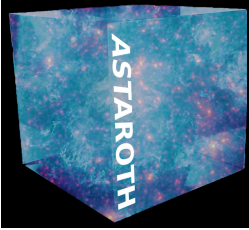
H: Static Structural

Equivalent Stress (Bridge - Copper)
Type: Equivalent (von-Mises) Stress
Unit: MPa



ASTAROTH cryostat

JINST 21 P01038 (2026)



- Installed and commissioned in 2023
- **Temperature stable < 0.1K !!!**
- Over 30 cycles, still going!

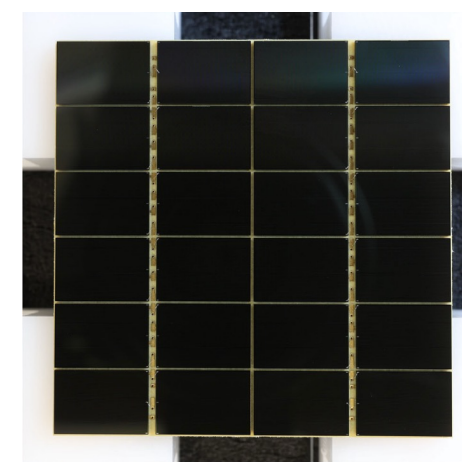
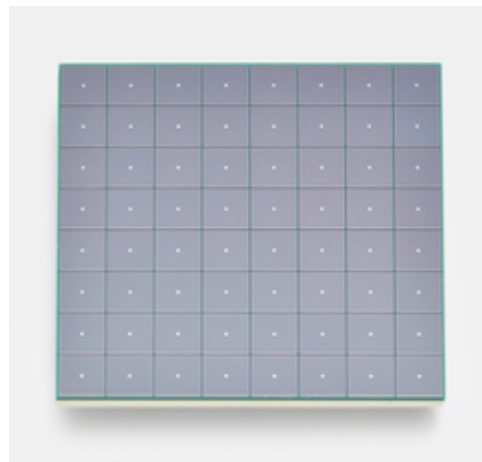
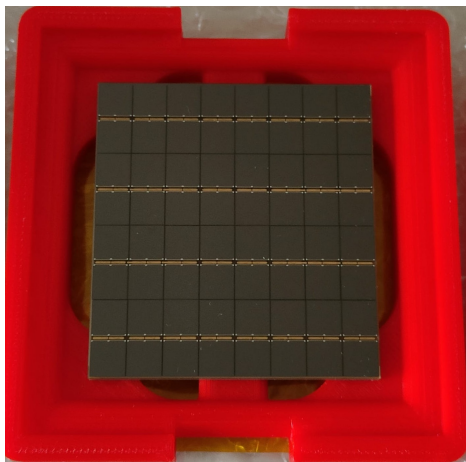


A nonlinear multiphysics model for the design validation of the ASTAROTH copper-steel cryogenic chamber

F. Alessandria,^a F.B. Armani,^{b,a} S. Coelli^{ib,a}, D. Cortis^{ib,c}, D. D'Angelo^{ib,b,a},
E. Martinenghi^{ib,a}, M. Monti^{ib,a}, D. Orlandi^{ib,c}, M. Sorbi^{ib,b,a}, V. Toso^{ib,b,a} and A. Zani^{ib,a,*}



SiPM arrays

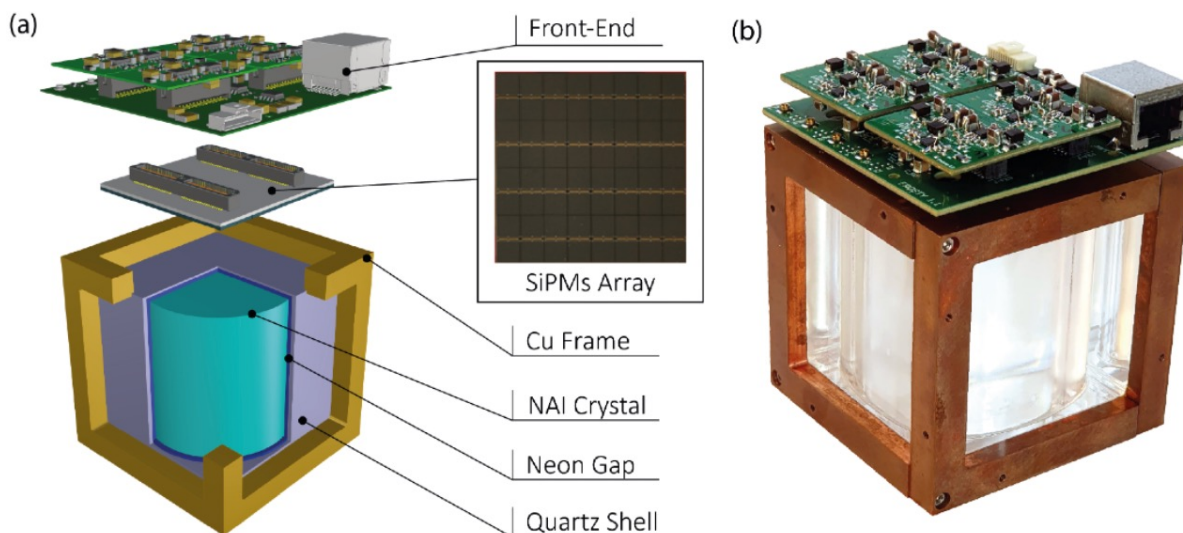
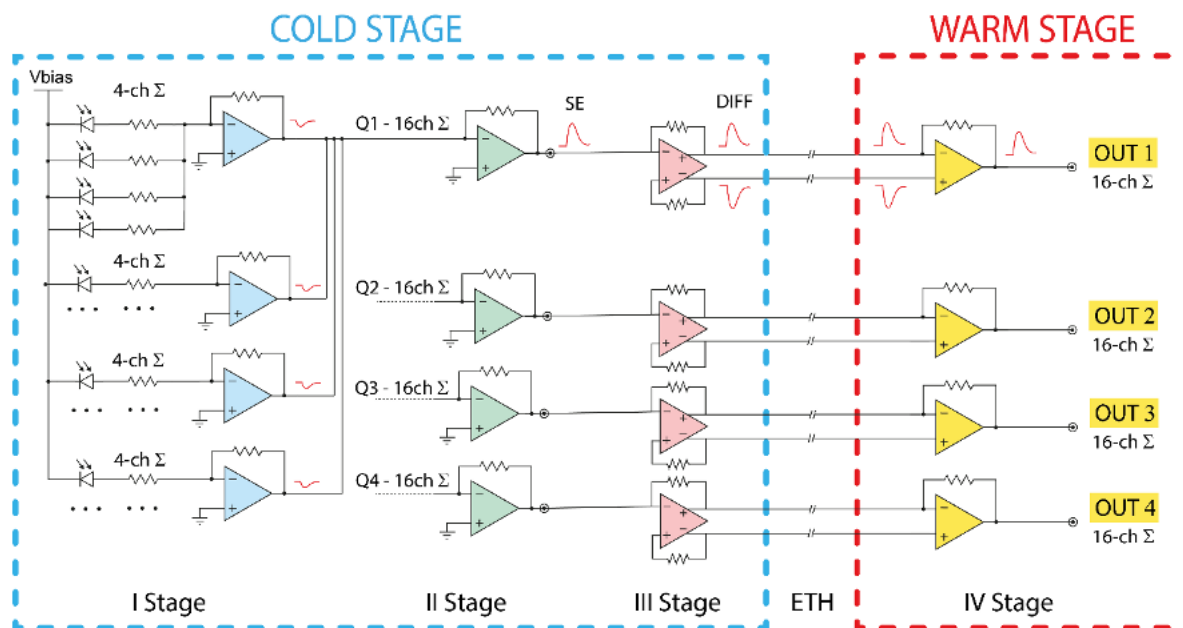


Producer	FBK	Hamamatsu (HPK)	LFoundry / NOA
Technology	NUV-HD-Cryo	S13361	NUV-HD-Cryo
Model	Custom	6050AS-08	DS-20k
Tile Size	50 x 50 mm ²	50 x 50 mm ²	50 x 50 mm ²
Devices	64	64	24 (1 channel)
D. Area	6 x 6 mm ²	6 x 6 mm ²	8 x 12 mm ²
Pitch	30 μm	50 μm	30 μm
Route	Wire bond	TSV	Wire bond
PDE @420nm	~ 55 %	~ 45 %	~ 55 %
Coating	Epoxy resin	Silicone resin	none
# available	1 (+ 1 Metal Trench)	2	4

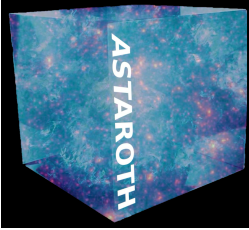
SiPM readout for 64 ch arrays

Developed a custom cryogenic front-end to read out 64-SiPM arrays, both HPK & FBK

- Selection of components after cryogenic test for some SiGe Op-amp
- Cold section: Motherboard + 4 piggy boards: 3-stage amplifier
- Directly coupled to SiPM array
- 4 channels out: differential signals on CAT7 ethernet cable.
- Warm board to convert back differential -> single-ended
- DAQ with a commercial 14-bit, 500 MS/s waveform digitizer

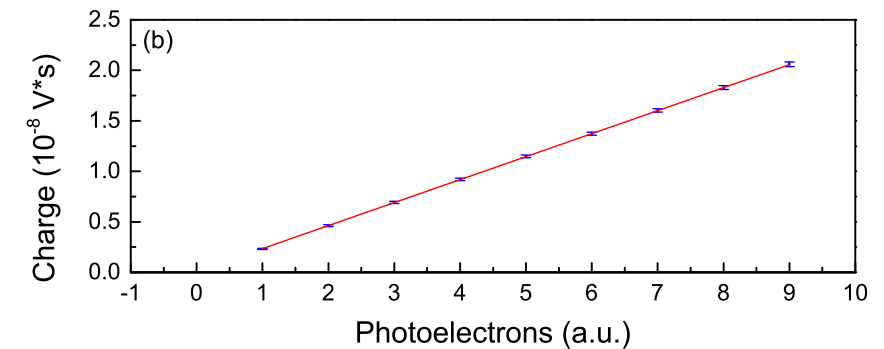
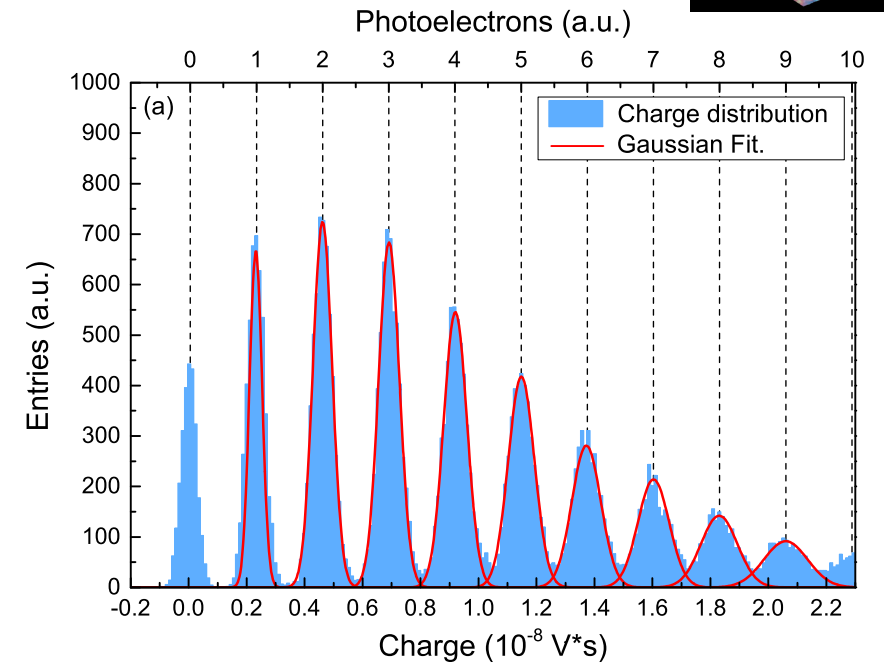
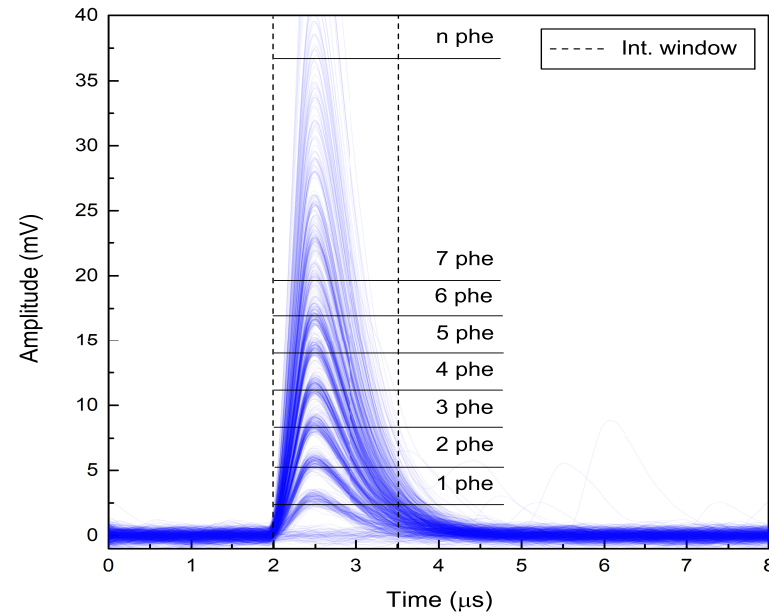


Laser calibration (FBK)



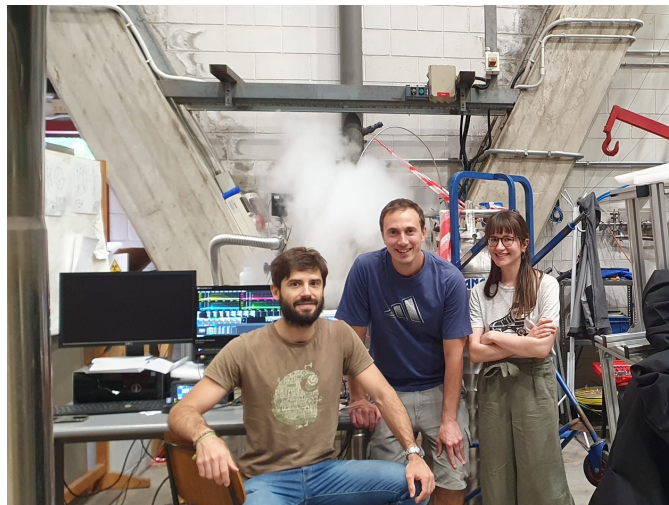
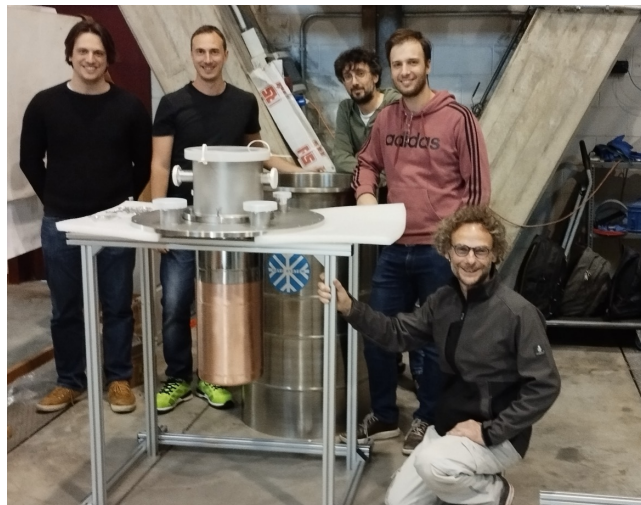
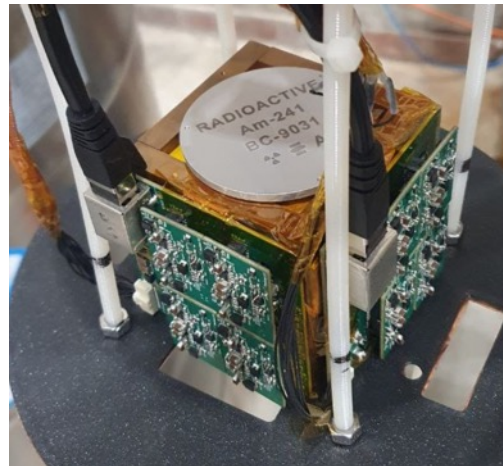
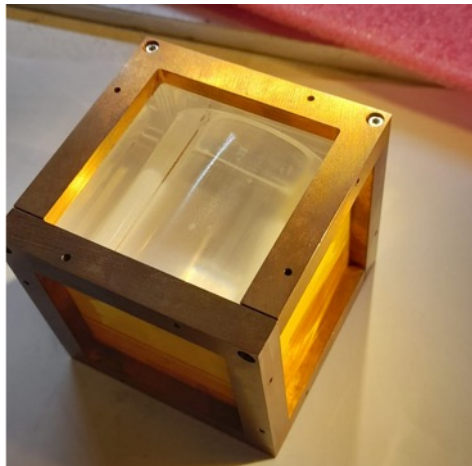
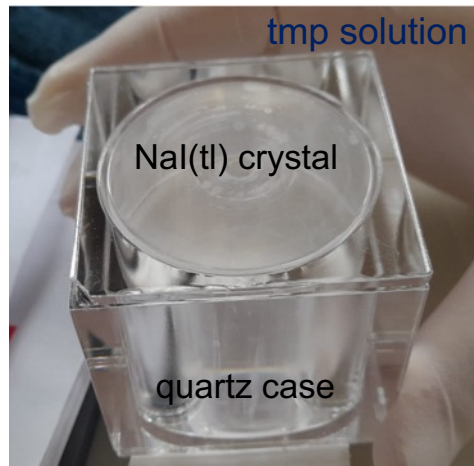
- 405 nm picosecond-pulsed laser (Hamamatsu C10196)
- 200 µm multimodal fiber

- PTFE diffuser
- In liquid nitrogen
- In Faraday cage



Excellent performance of FBK SiPMs + custom electronics

^{241}Am cryogenic source runs



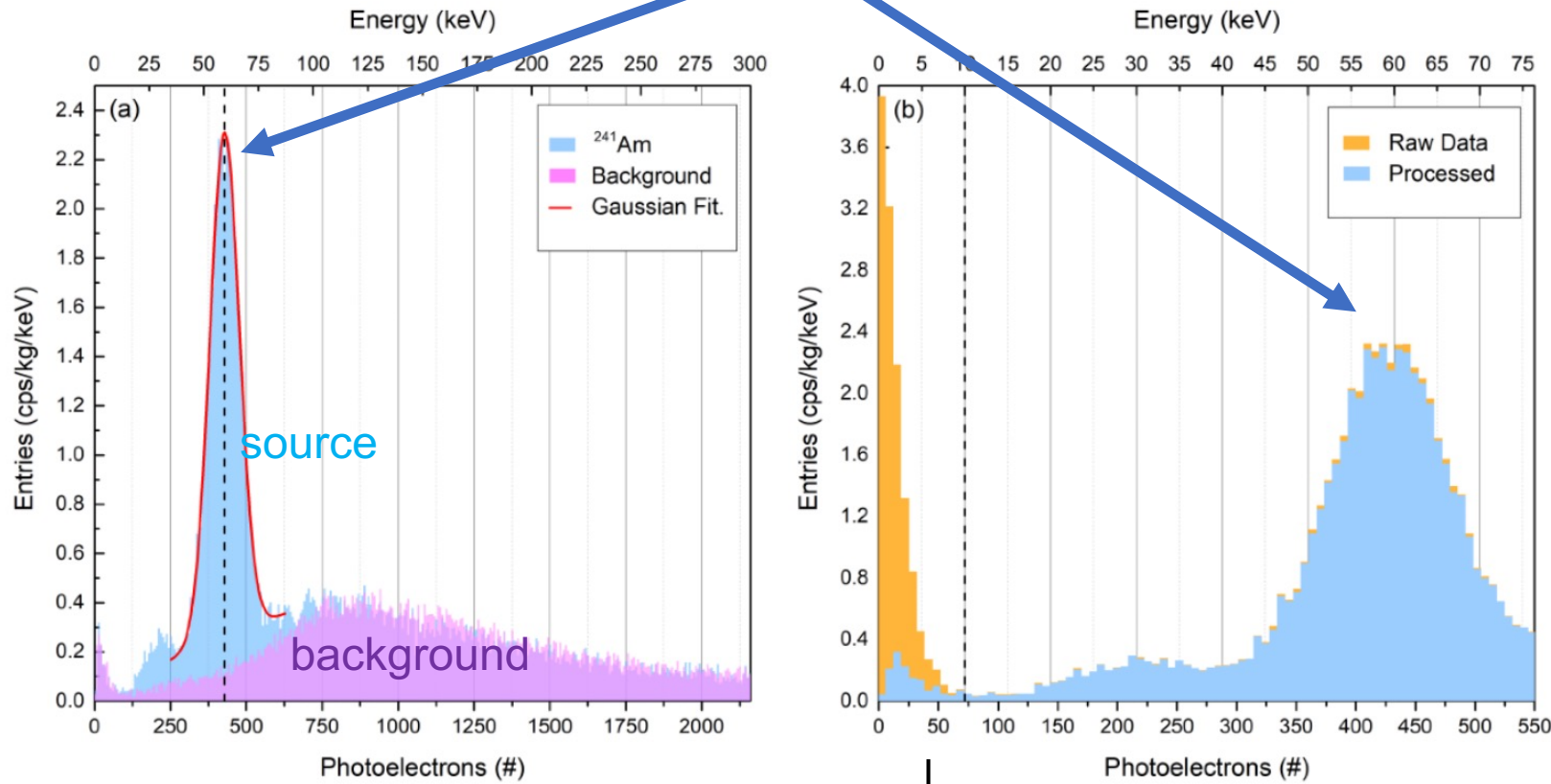
- 1 or 2 sides instrumented
- teflon on other 4 or 5 sides
- ^{241}Am source rated for cryogenic use





Energy spectrum (FBK)

59.5 keV ^{241}Am Source

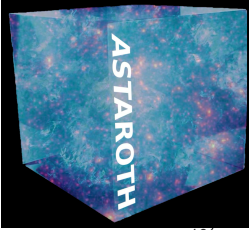


quality cuts to remove artifact triggers

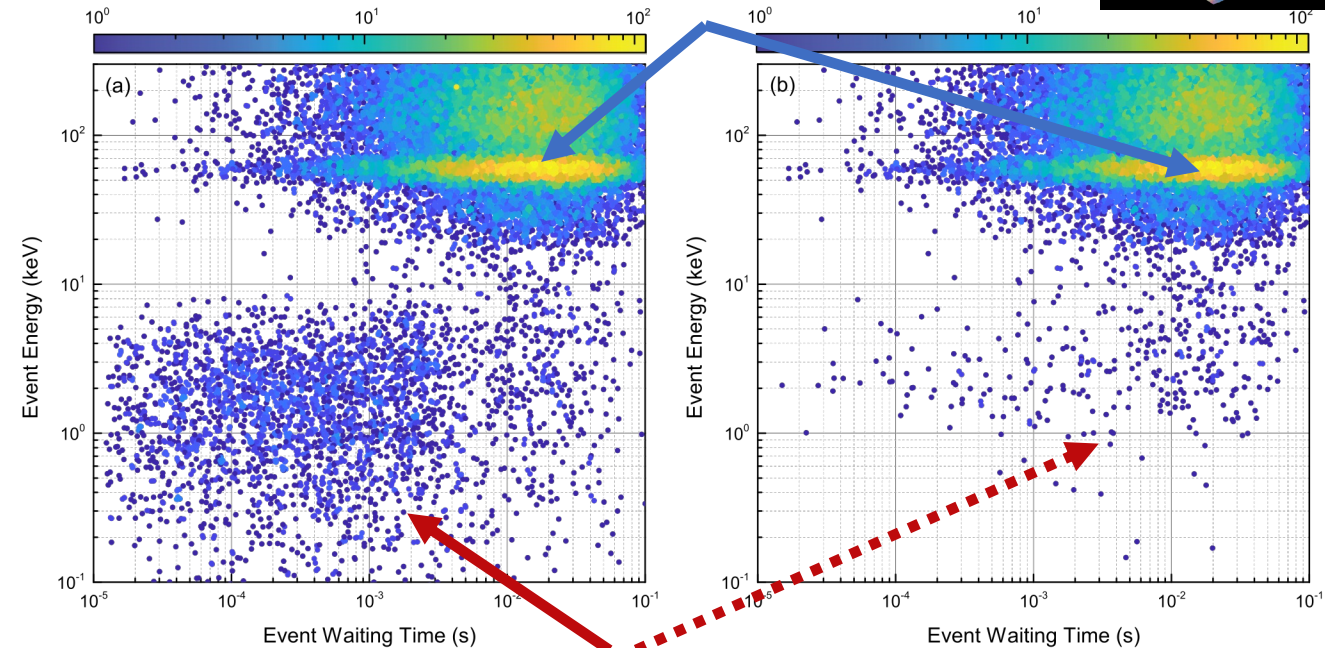
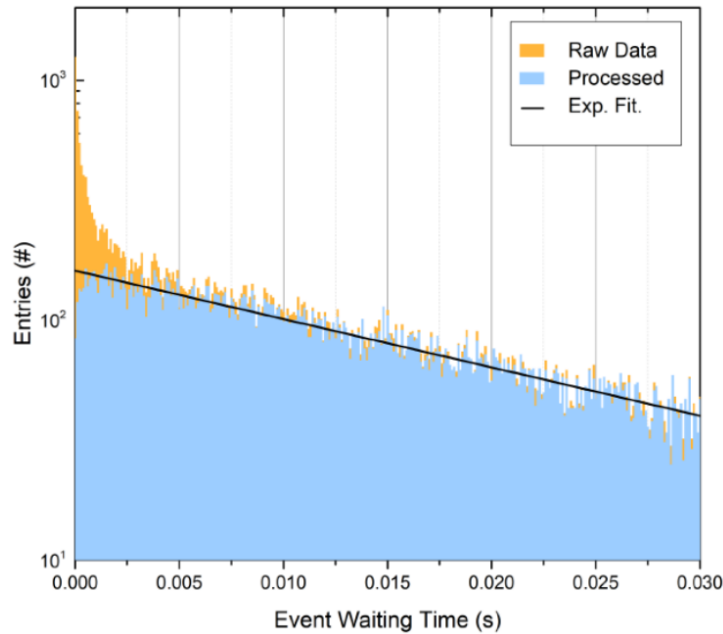
- Ph.e. yield:
~ 7.2 ph.e./keV gross
~ 4.5 ph.e./keV
(past cross-talk correction)
- Considering:
 - only 1 array
 - case with gas gap
 - no optical coupling case/SiPM
- **Several ways to improve!**
- FWHM: 27 %
- Trigger thresh: 0.5 keV

Data quality selection

Eur. Phys. J. C 85, 1444 (2025)



59.5 keV ^{241}Am Source



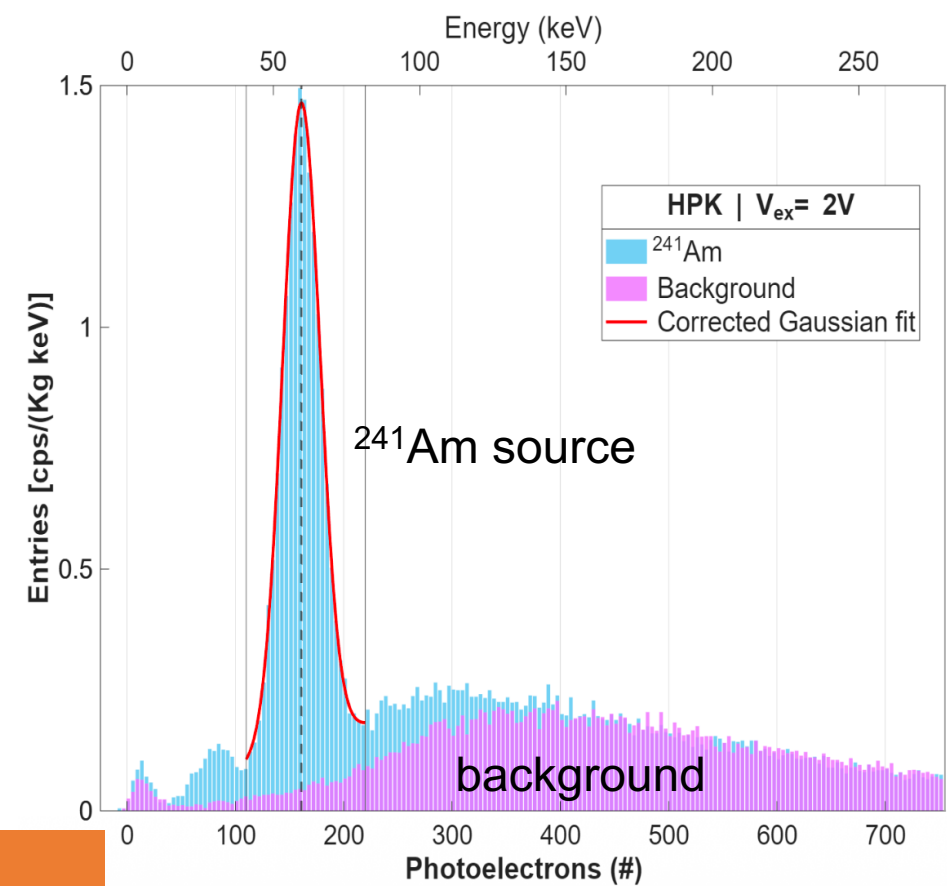
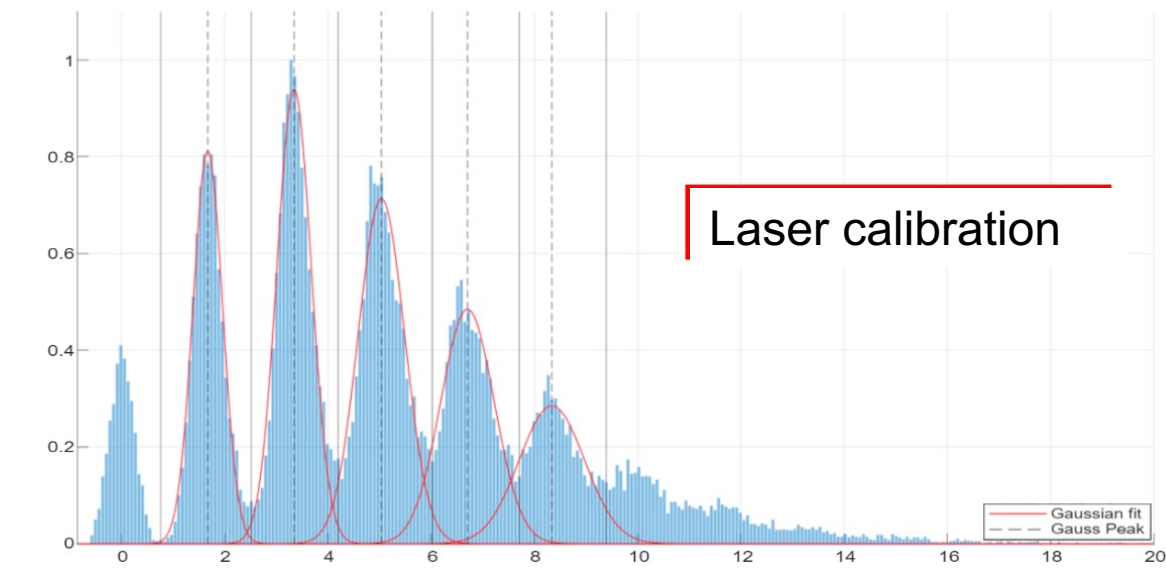
“noise”

Problem	Origin	Solution	Discards
Fake triggers	Tail of preceeding event contributes to trigger	Discard events with wrong baseline computation	12.9 %
High frequency 20 MHz noise	External equipment at LASA	Low-pass filter	1%
Retriggering events	Muons?	500 ms veto after a saturating event	0.25 %

Efficiency: 93.5 % of evts < 10 keV removed

Acceptance: 98.5 % of evts > 10 keV retained

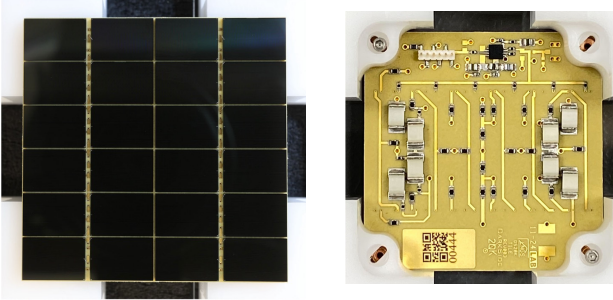
Hamamatsu (HPK) array



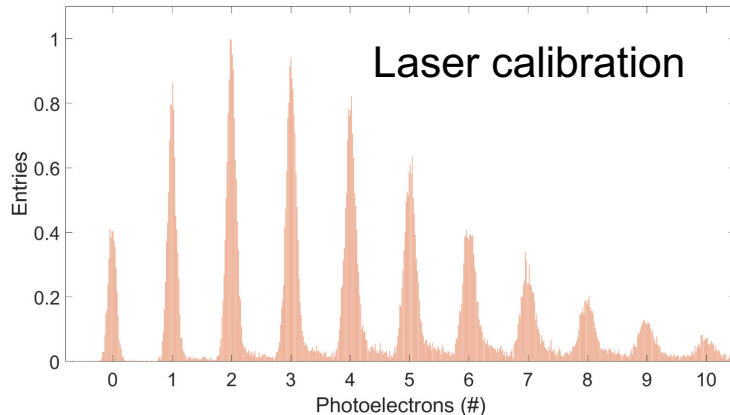
	FBK	HPK
Over-voltage	7 V	2 V
SNR	6.7	6.7
Light yield (CT-corrected)	✓ 4.5 ph.e./keV	2.4 ph.e./keV
Resolution (FWHM at 60 keV)	26 %	25 %
# of resol. peaks (afterpulses, ...)	✓ > 9	5
Cross-talk (from Vinogradov)	36%	12% ✓

HPK is a valid alternative!

NOA arrays



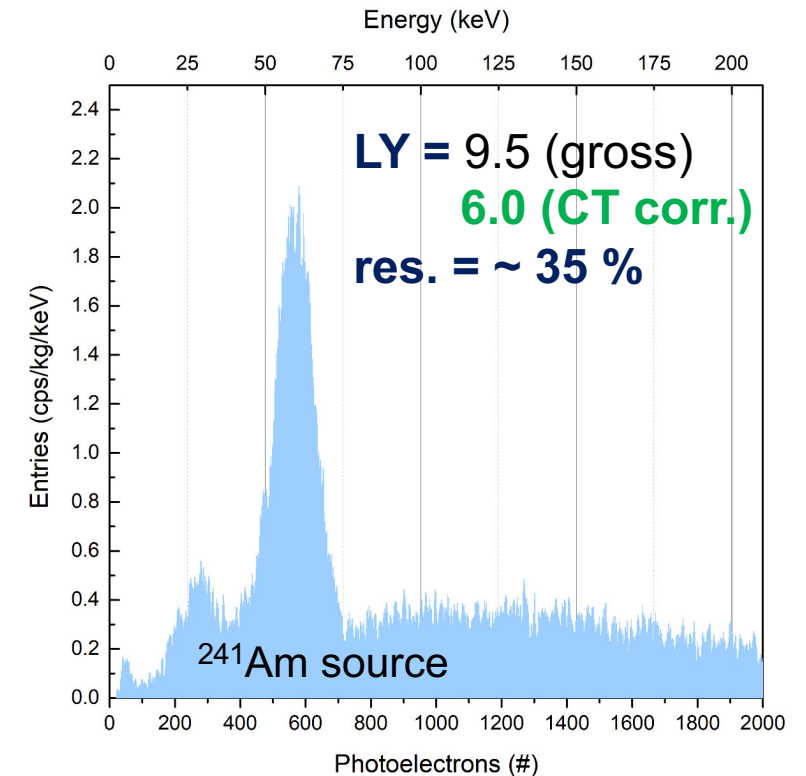
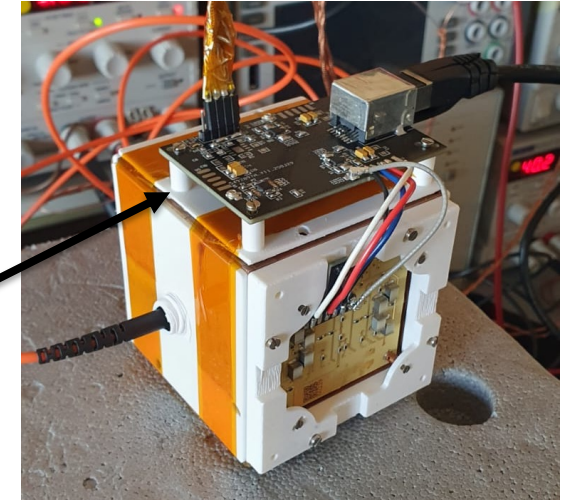
DarkSide coll., Eur. Phys. J. C (2025)
85:1334



- 4 slightly out-of-spec DS-20k arrays
- Single low radioactivity arlon PCB
 - Back mounted front-end
 - Only 1 channel OUT!
- Designed a second stage amplifier reading 3 arrays
- Trigger on two opposing arrays
- Background run still missing
- Data quality cuts to be retuned (faster FE)
- Work in progress

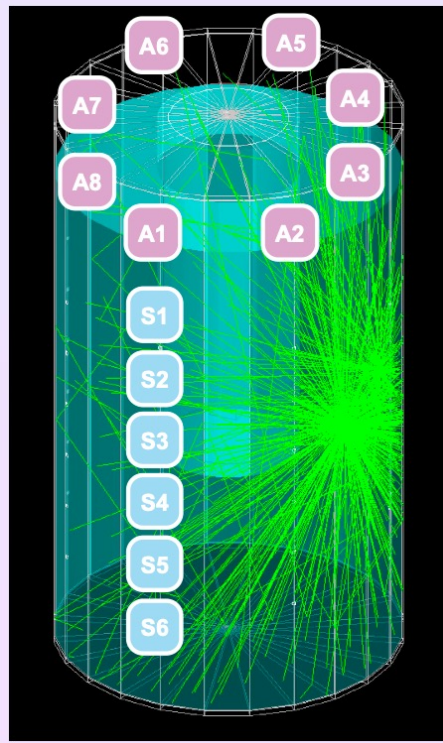
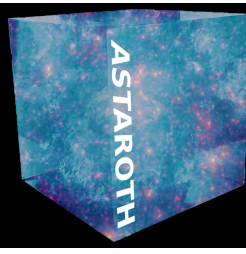
A big thanks to the NOA crew:

- ❖ Lucia Consiglio
- ❖ Andrea Marasciulli
- ❖ George Korga
- ❖ Davide Sablone

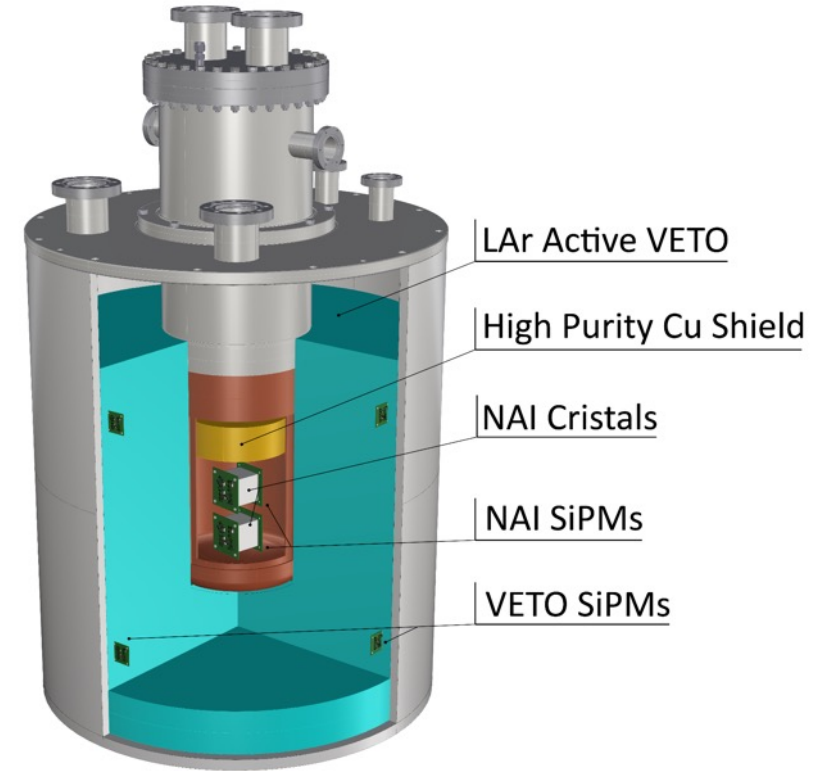


Preliminary

Liquid Argon Veto detector



- Switch from LN_2 to LAr
- Instrument outer volume with SiPM
- Geant4 (and Fluka) simulation to understand coverage and disposition
- Surround with a lead castle (~10 cm thick)



All the details in poster # 143 By E. Martinenghi



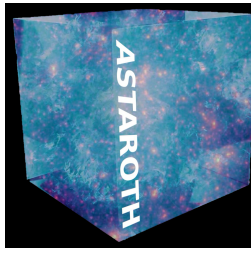
INTEGRATING A LIQUID ARGON ACTIVE VETO IN ASTAROTH: A CRYOGENIC SiPM BASED EXPERIMENT FOR LOW-THRESHOLD NAI(TL) DARK MATTER SEARCHES

Edoardo Martinenghi¹, for the ASTAROTH collaboration

¹Istituto Nazionale di Fisica Nucleare (INFN) sezione di Milano, Via Celoria 16, 20133 Milano (Italy)

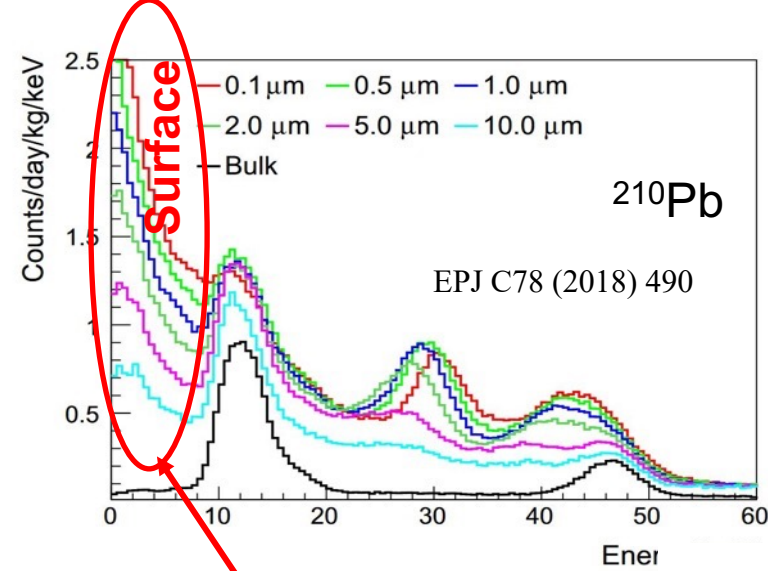
16th International Workshop on the Identification of Dark Matter, 1 - 5 JUNE 2026, Zaragoza (Spain)

ASTAROTH

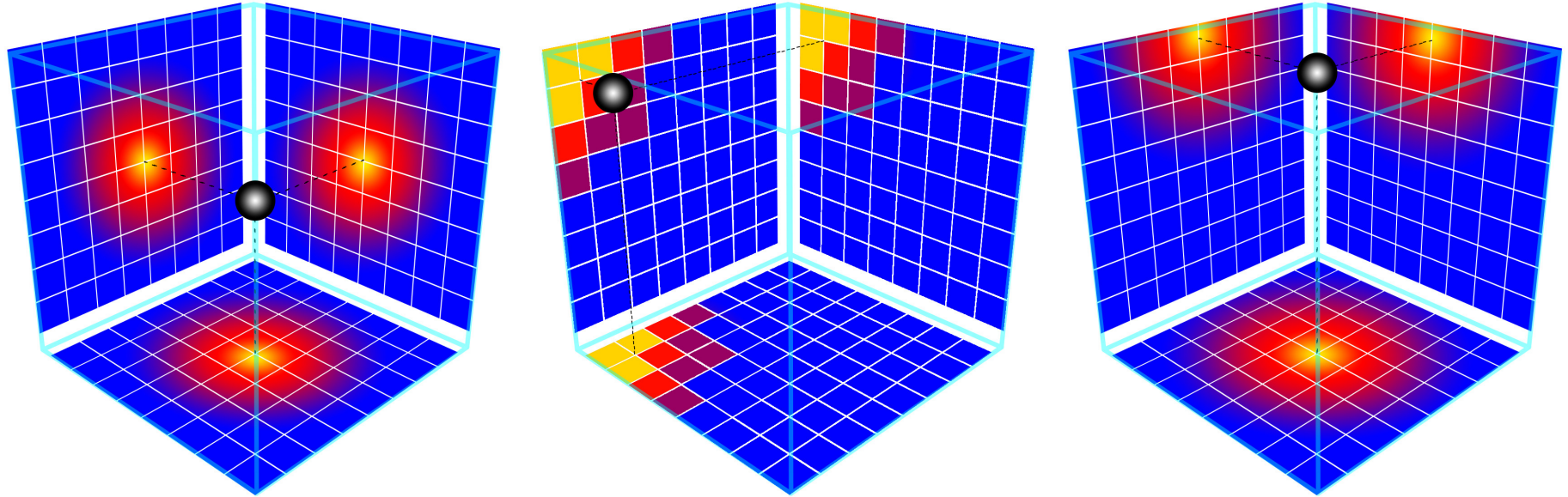


Reject surface background by light map?

Low radioactivity ASIC-based electronics



^{210}Pb (radon daughter) can be implanted on the surfaces (observed by COSINE, SABRE) and impact the ROI more than bulk

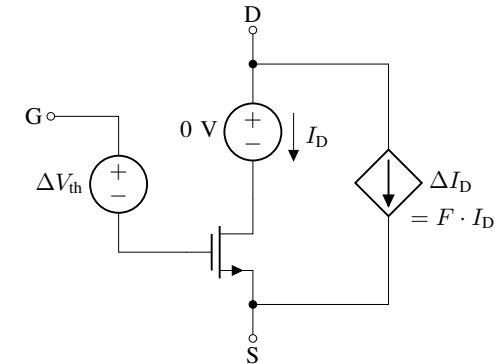
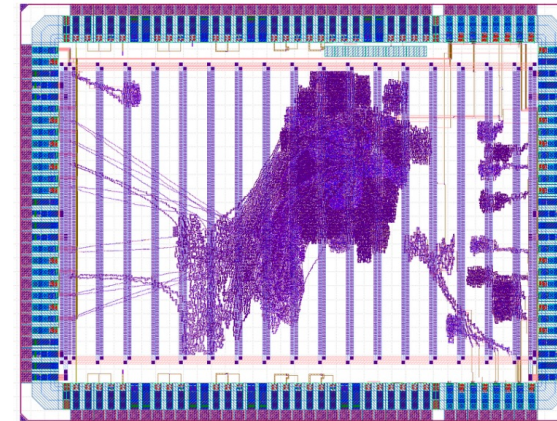
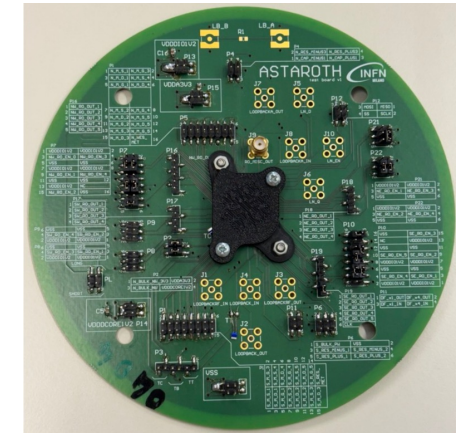
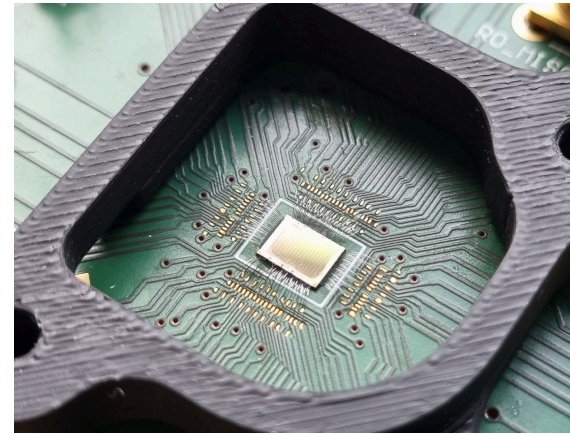


A machine learning algorithm fed with the charge map from (at least) three sides could discriminate surface from bulk events.

A readout with this capability working at cryogenic temperature has an appeal that goes beyond ASTAROTH

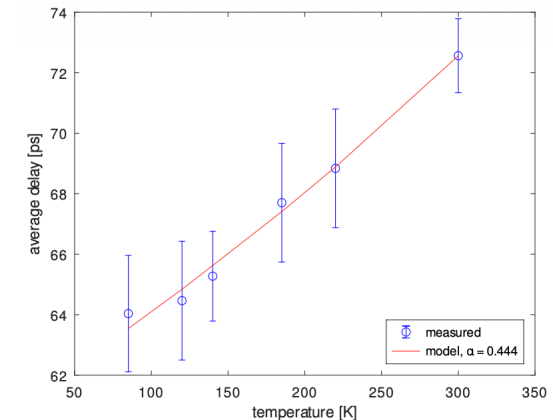
ASIC technology test at cold

- Test chip based on CMOS 110 nm with:
 1. Transistors
 2. R, C passive elements
 3. ring oscillatorsmade of (INV, NAND, BUFF, NOR, XOR) logic ports.
- Simulations with Synopsys Custom Compiler and HSPICE
 - Introducing a temperature dependent model
- Tested in ASTAROTH cryostat at LASA Oct 2023
 - Temperature range 300 K -> 80 K
- OUTCOME: technology is suitable for circuits operating at cryogenic temperatures.
 - Port delay decrease by $\sim 10\%$ at cold.
 - Our temperature dependent model reproduces data.
- Of general interest for the IC community

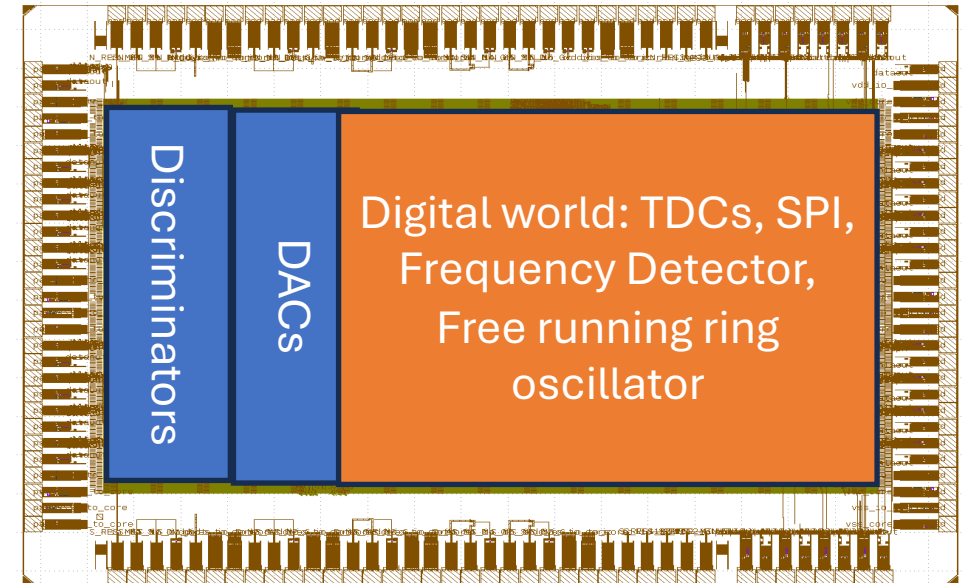
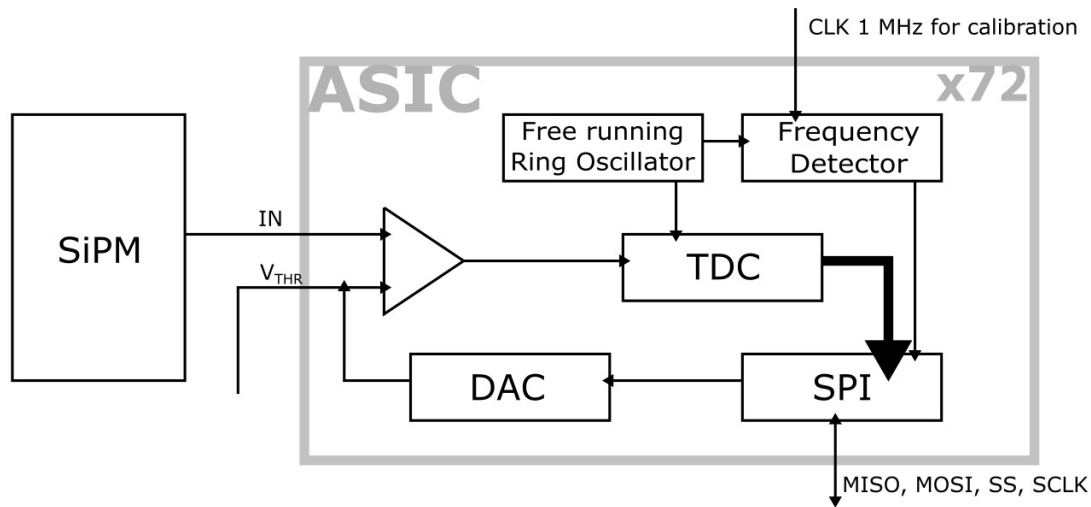
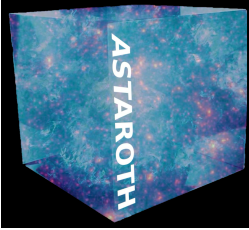


preliminary

[paper in preparation]

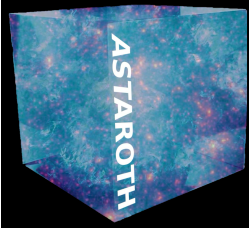


Designing ASIC-based front-end

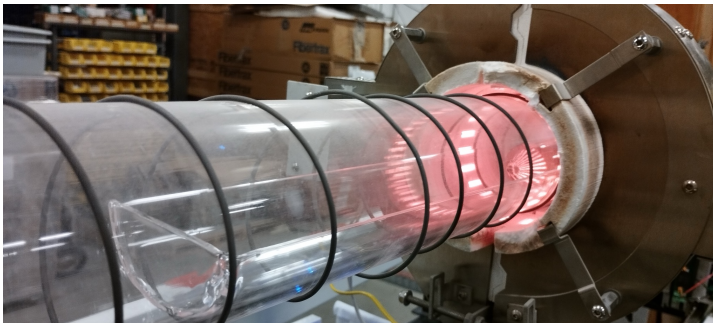
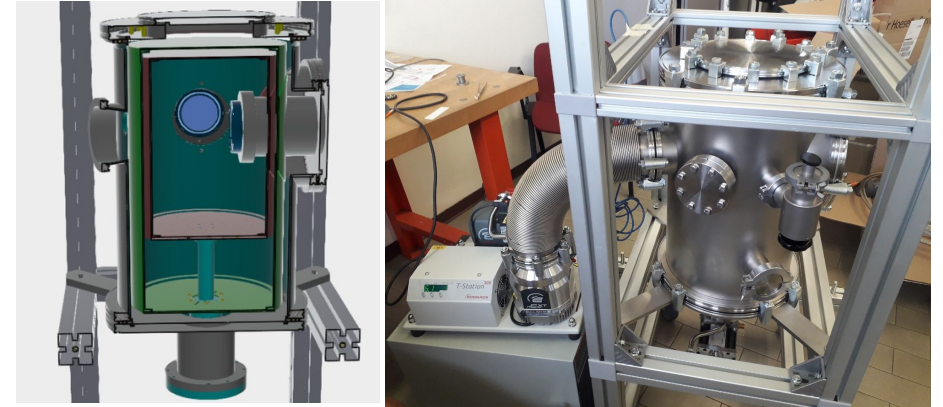


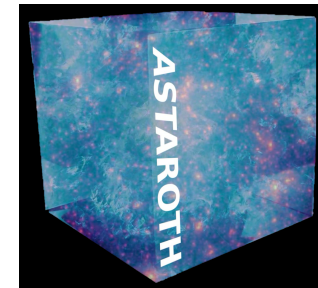
- Tricky part is the analog one:
 - Design based on *current conveyor*
- Work started a year ago
 - submission in MPW July or Sept 2026

More on the to-do list



- **Optical coupling** of SiPM with silicon pads or Si-gel
- Try *undoped* crystal (just delivered)
- Study crystal response (LY, tau) vs doping and T
- Move to **underground** location (LNGS?)
- Switch to **high-purity crystal** from SABRE-North producer RMD (Boston)





Thank you for your attention !

First use of large area SiPM matrices coupled with NaI(Tl) scintillating crystal for low energy dark matter search

**Edoardo Martinenghi^{a,1}, Valerio Toso^{1,2}, Fabrizio Bruno Armani^{1,2}, Andrea Castoldi^{1,3},
Giuseppe Di Carlo⁴, Luca Frontini¹, Niccolò Gallice^{1,2,5}, Chiara Guazzoni^{1,3}, Valentino
Liberali^{1,2}, Alberto Stabile^{1,2}, Valeria Trabattoni^{1,2}, Andrea Zani¹, Davide D'Angelo^{b,1,2}**

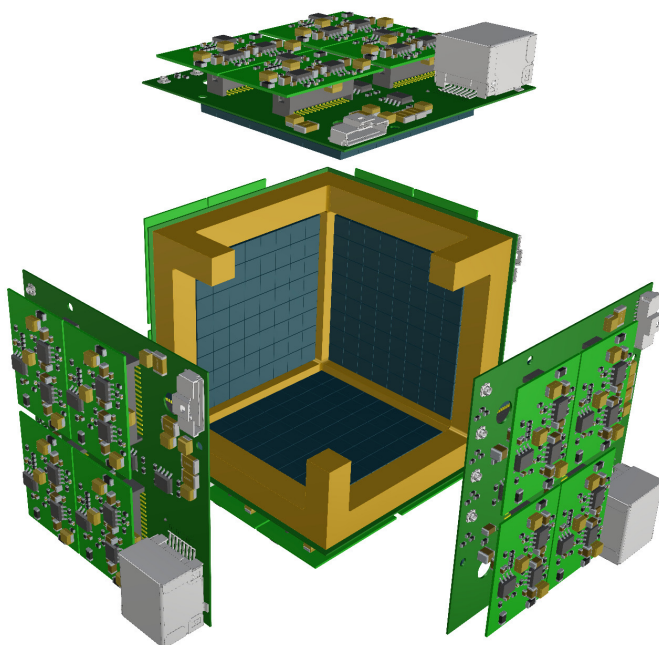
¹INFN - Sezione di Milano, via Celoria 16, 20133 Milano, Italy

²Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy

³Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB), Politecnico di Milano, piazza Leonardo da Vinci 32, 20133 Milano, Italy

⁴INFN - Laboratori Nazionali del Gran Sasso (LNGS), via G. Acitelli 22, 67100 Assergi, Italy

⁵Brookhaven National Laboratory, PO 5000, Upton, NY 11973, USA



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Stay for the ANAIS+ talk!