First cryogenic SiPM readout of a NaI(Tl)-based dark matter detector with the ASTAROTH project

Davide D'Angelo

Università degli Studi di Milano and INFN

TAUP 2025
24-30 Aug 2025
Xichang (China)

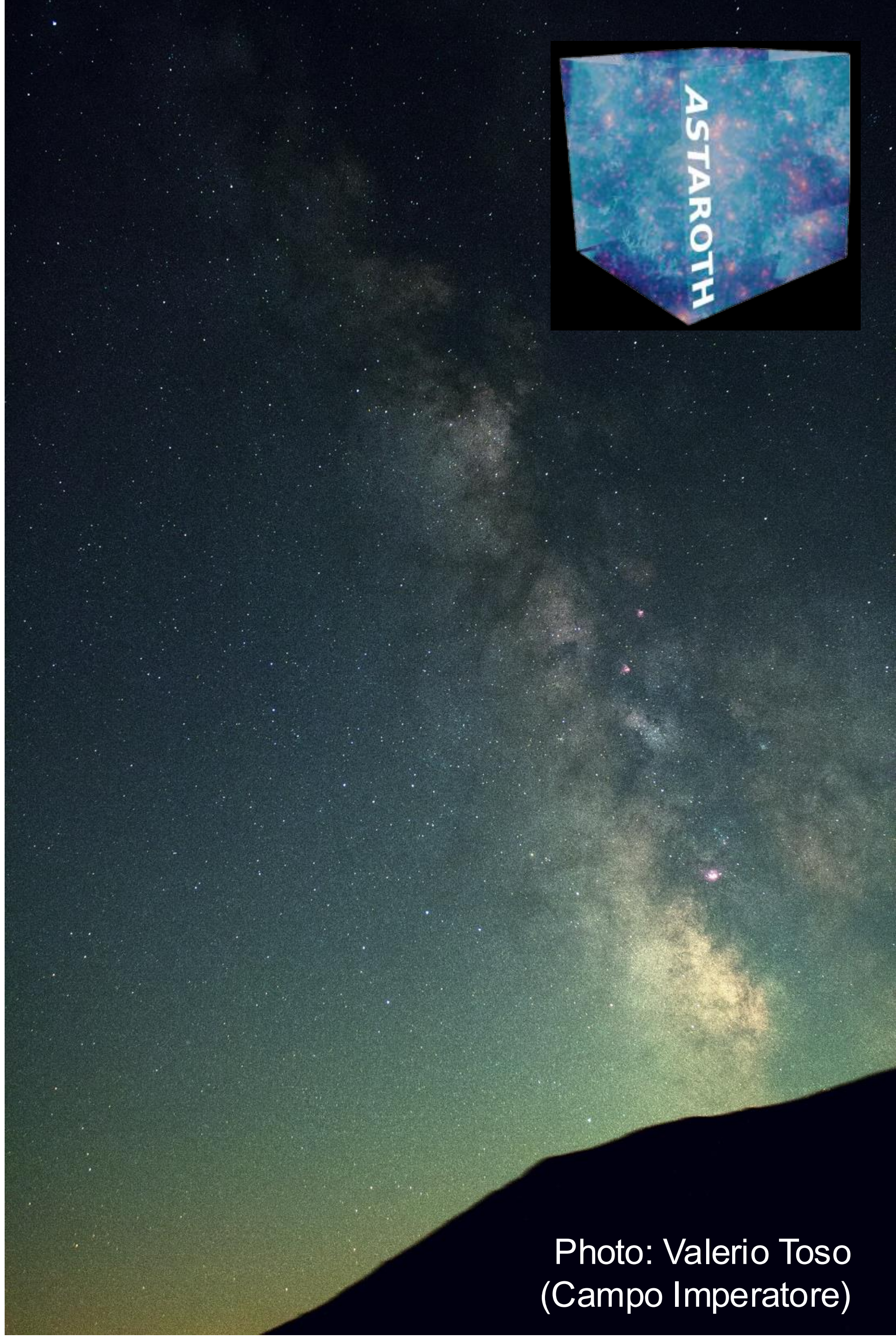
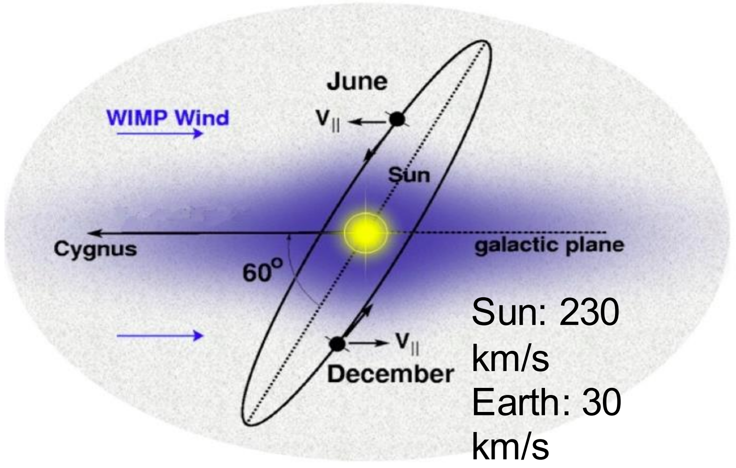


Photo: Valerio Toso
(Campo Imperatore)

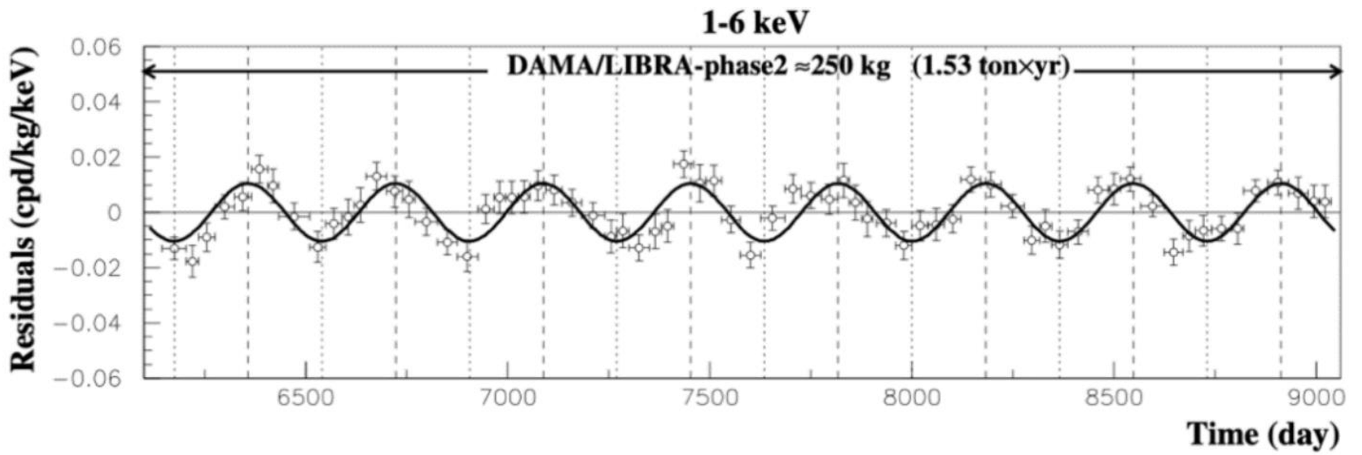
Physics Case



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)

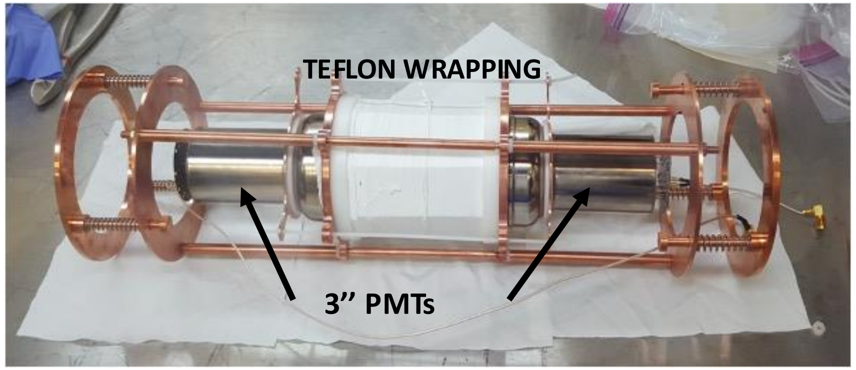


[Nucl. Phys. At. Energy 2021, vol. 22, iss. 4, p 329-342]

- 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

Current technological scenario

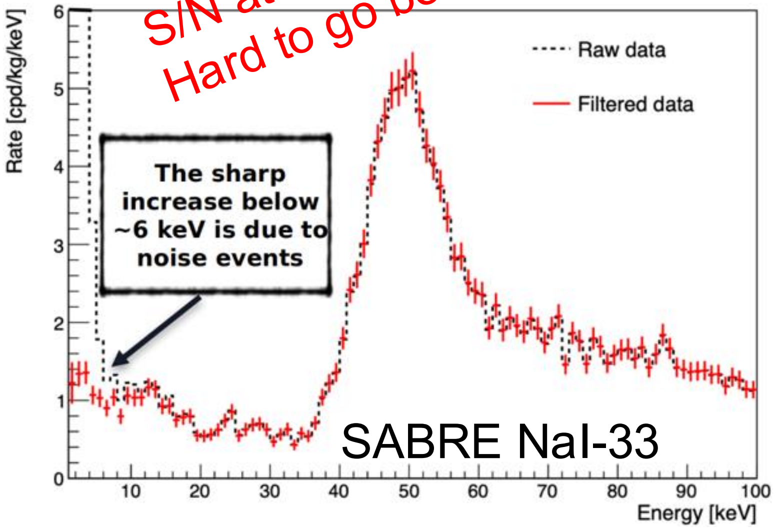
Existing **NaI(Tl)-based detectors:** DAMA, SABRE, ANAIS and COSINE



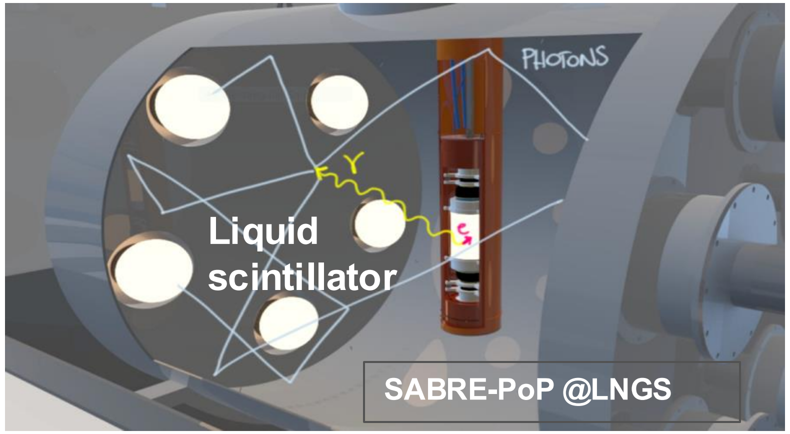
Elongated crystals, wrapped in reflector and coupled with PMTs.

1. Mass of crystals ~ 5-12 kg: hard to achieve with very high purity.
2. Light collection limited to 7-15 ph.e./keV.
   ↪ Out of 40-42 ph./keV
3. Reflector can be a source of surface contamination.
4. PMTs feature intrinsic **high noise** and radioactivity.

S/N at 1 keV ~ 0.01
Hard to go below!



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.



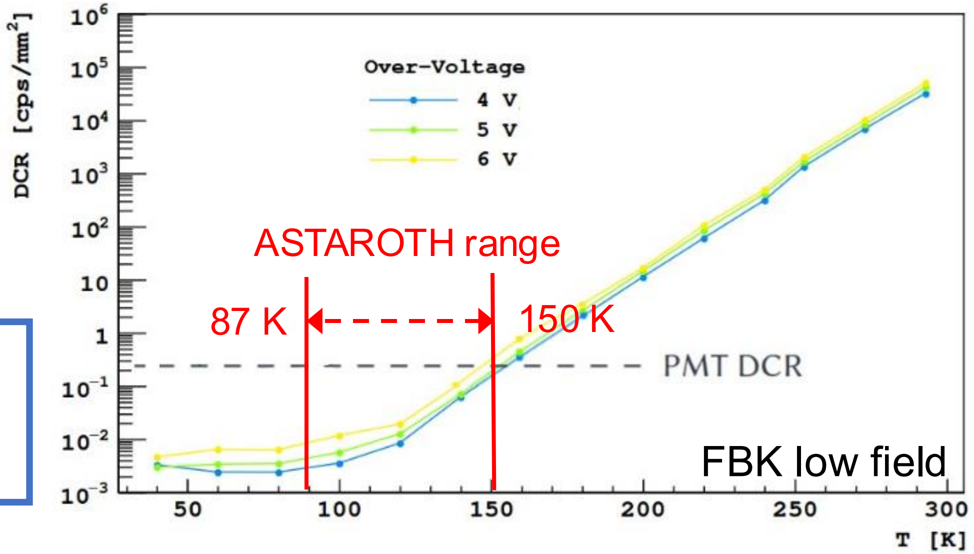
ASTAROTH surpasses all 5 limitations!

Overcoming limitations with SiPMs

Silicon PhotoMultipliers (SiPMs) advantages over PMTs:

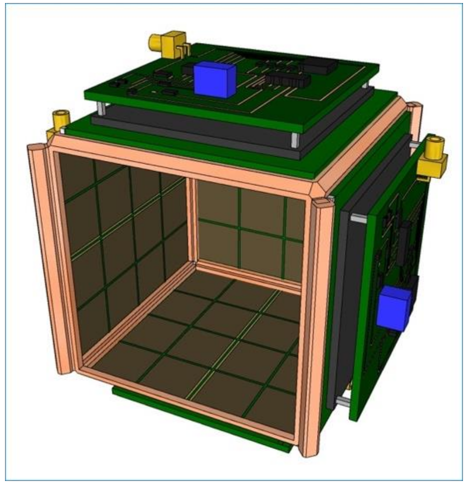
- ✓ higher PDE (55%), w.r.t. ~30-35% max QE of PMTs
  at 420 nm (peak NaI(Tl) emission)
- ✓ smaller transverse dimensions: compactness
- ✓ lower intrinsic radioactivity
- ✓ Lower noise than PMTs at **T<150 K**

Require cryogenic environment



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

ASTAROTH



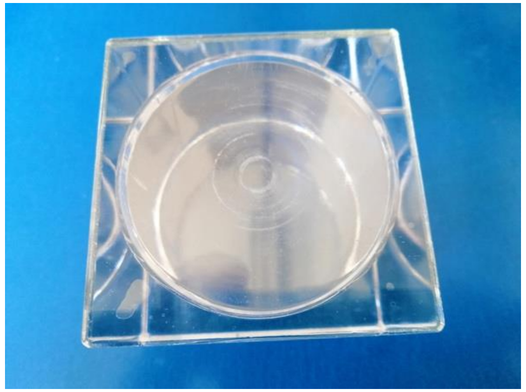
- ➢ **Small cubic** crystals (5x5x5 cm^3)
- ➢ read on **all six surfaces** by SiPM matrices (w/o reflector)
- ➢ At *tunable* temperature: optimal for crystal response and SiPM noise
- ➢ **Liquid Argon** provides cooling power and can double as VETO detector

→ Improve S/N to ~1 at 1 keV

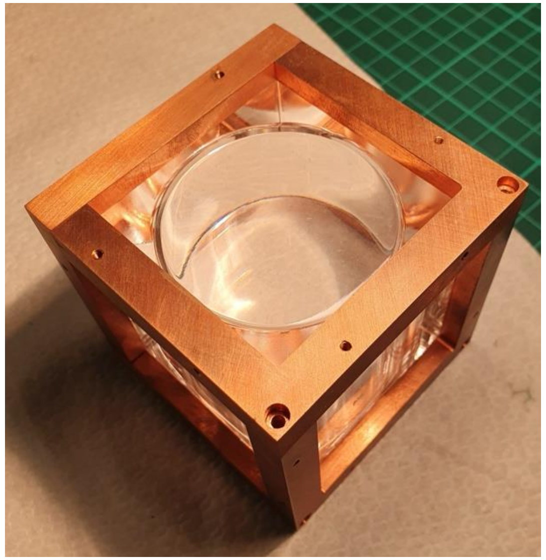
→ Access to sub-keV recoil energies

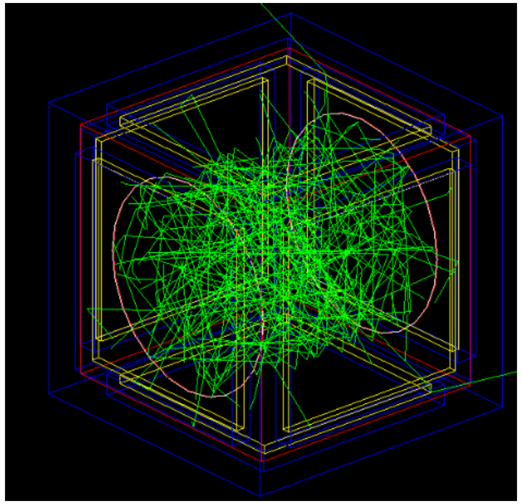
Crystal detector design

- NaI is hygroscopic
- ASTAROTH operates in a cryostat, need a case with several requirements:
  - 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 ≠ quartz)
  - 50x50 mm cylinder-in-a-cube temporary solution
  - Problem: only ~50% of light exits



Hilger Crystals, UK





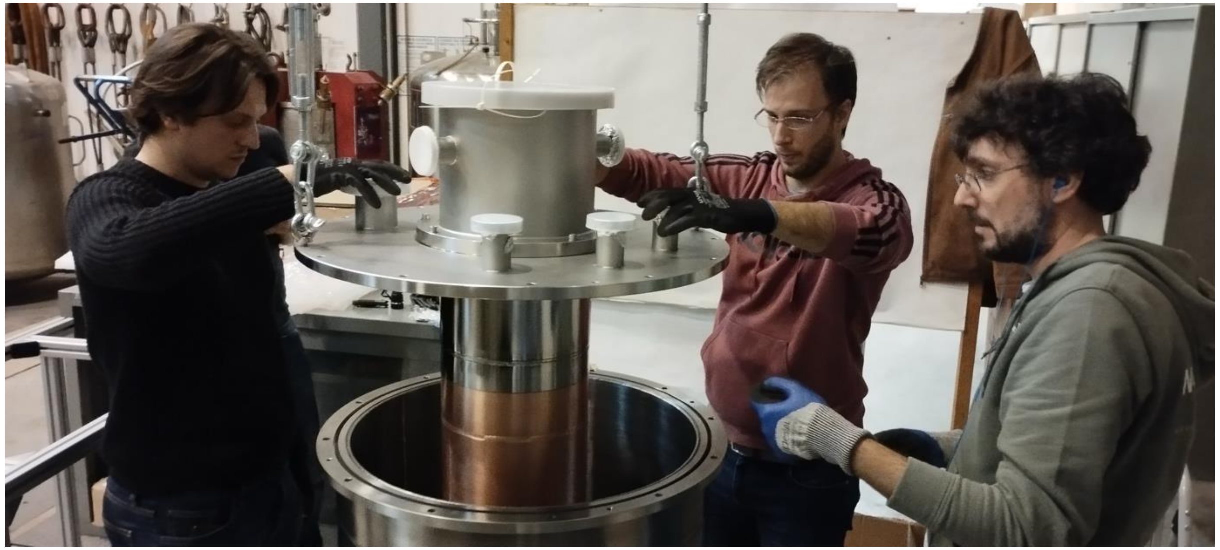
Recently steered into a new direction

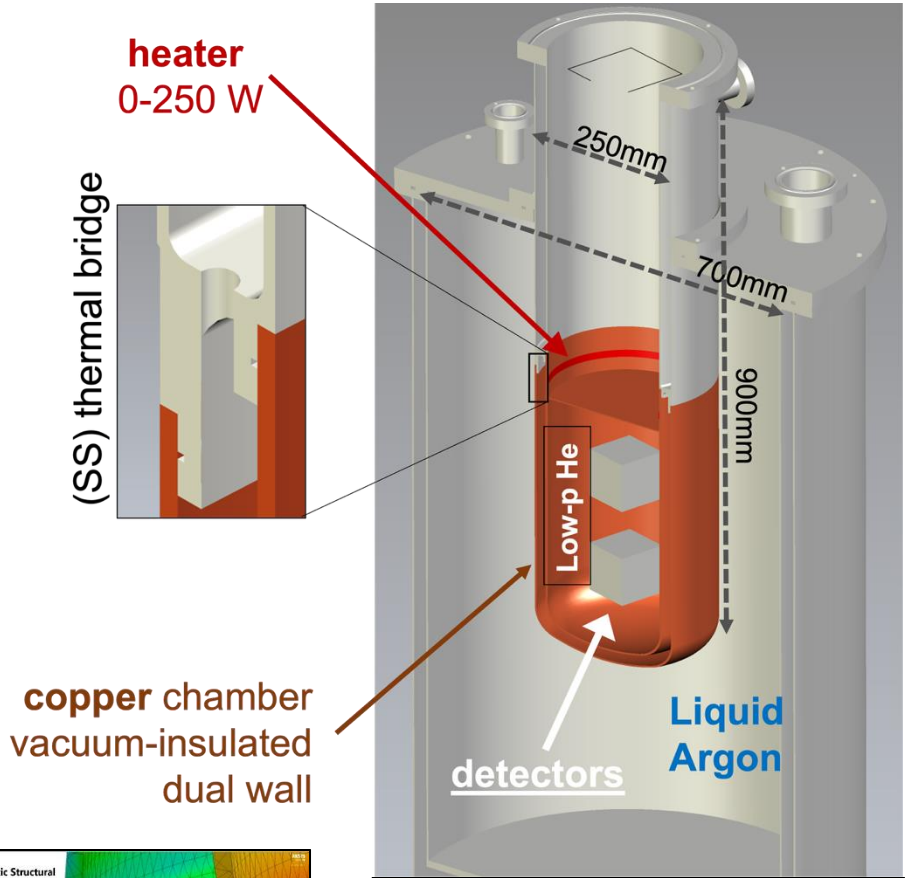
→

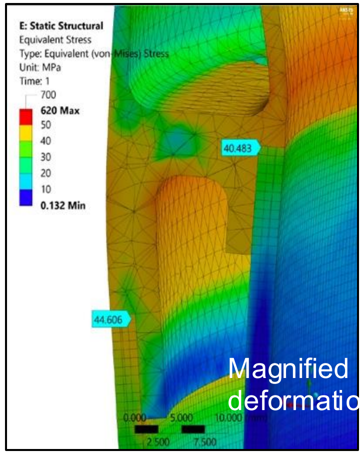
(slide 14)

ASTAROTH cryostat

- **Dual-wall,** vacuum-insulated radio-pure copper chamber, immersed in a **cryogenic bath.**
- **Cooling power** through a specially designed **stainless steel 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.
- Installed and commissioned in 2023 **in LN_2**





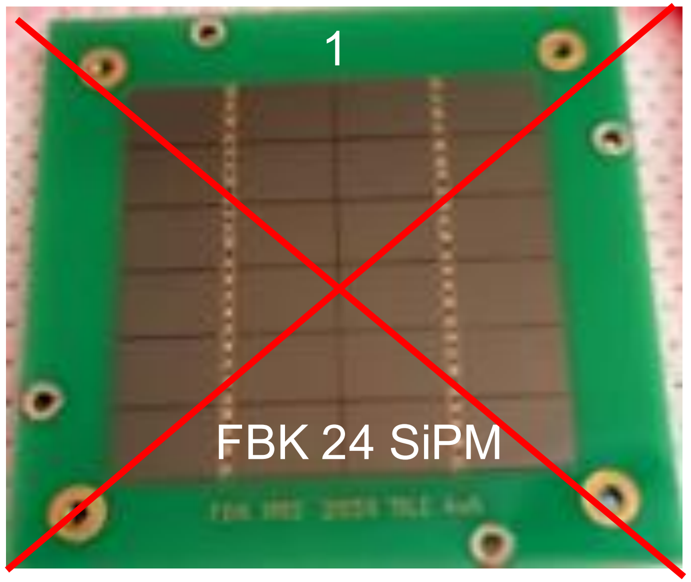


- Thermomechanical ANSYS simulations at Milano and LNGS
- Cryogenic deformation and rupture tests of copper
- Eng. paper in preparation

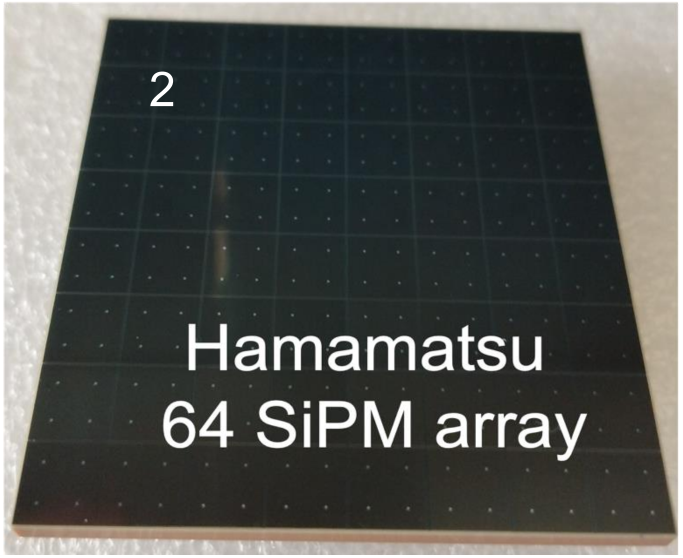
SiPM arrays

	Vendor	Technology	Model	Tile size (mm^2)	Devices	Area (mm^2)	Also used	Pitch (mm)	Route	Ganging	Ch	Resin
1	FBK	NUV-HD-Cryo	custom	50x50	24	8x12	DS-20k	35	Wire bond	2s3p	4	epoxy
2	HPK	S13361	6050AS-08	50x50	64	6x6	Dune	50	TSV	no	64	silicon
3	FBK	NUV-HD-Cryo	custom	50x50	64	6x6	Dune	30	Wire bond	no	64	epoxy

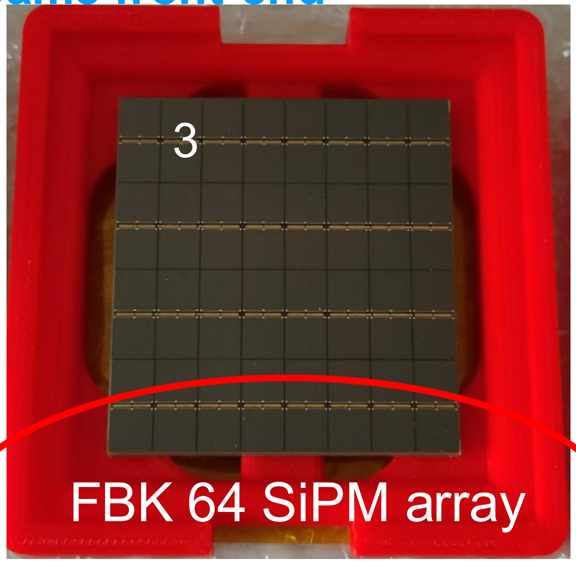
Same connectors = same front-end



mech. broken, to be replaced



Analysis just started

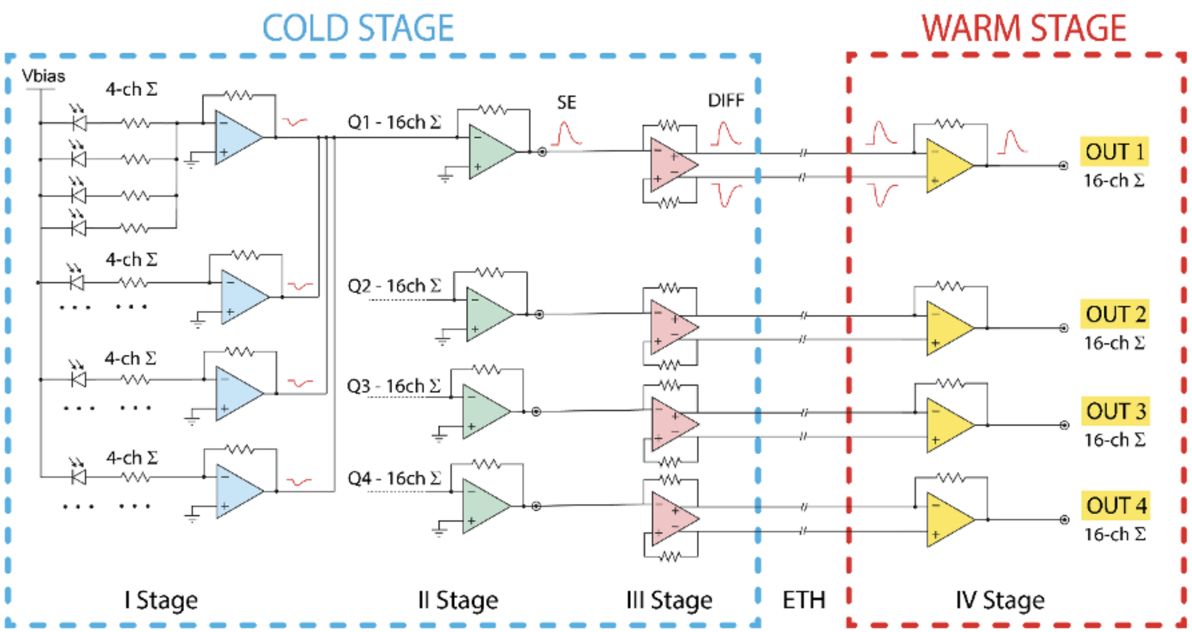


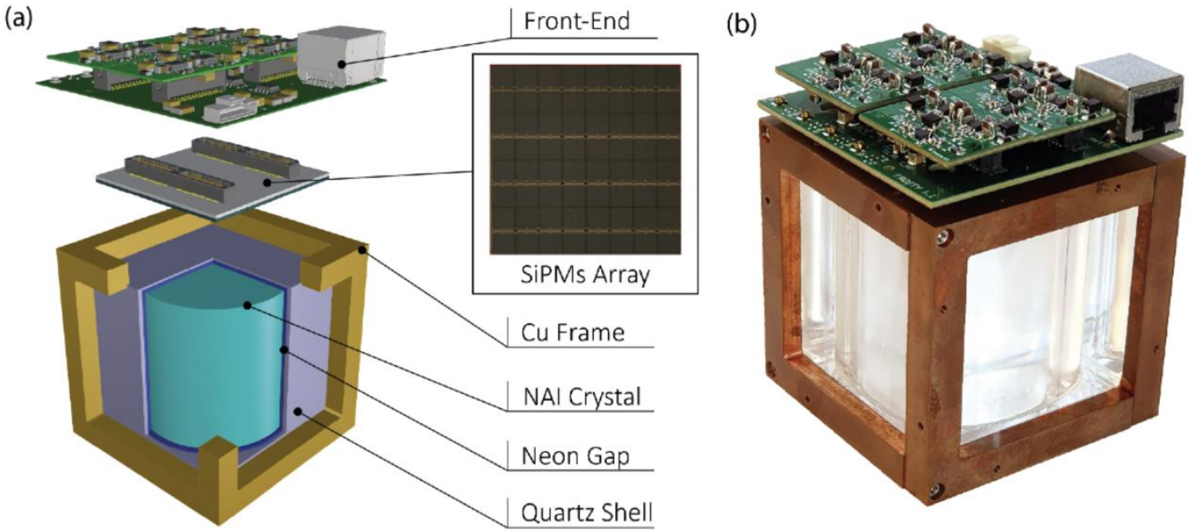
Results here

SiPM readout for FBK & HPK arrays

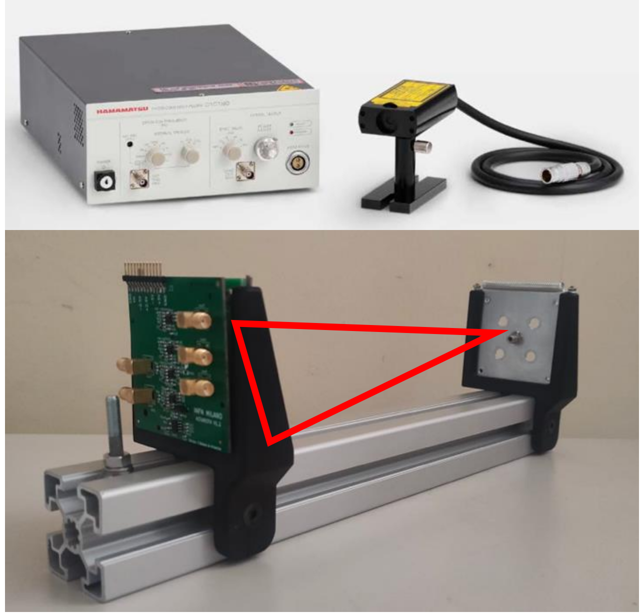
Developed a single custom cryogenic front-end to read out 64-SiPM arrays, both HPK & FBK

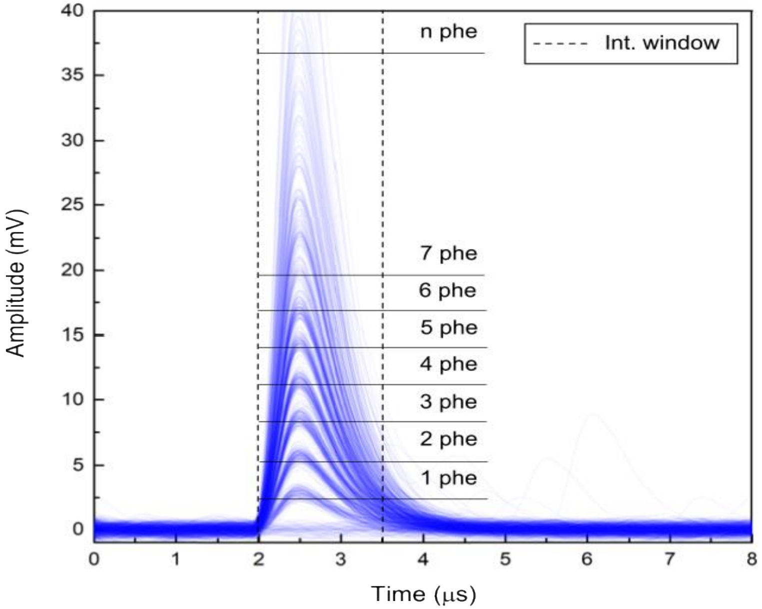
- Selection of components after cryogenic test for some SiGe Op-amp
- Cold section: Motherboard + 4 piggy boards: 3-stage amplifer
- Directly coupled to SiPM array
- **4 channels out:** differential signals on CAT7 ethernet cable.
- Warm board to convert back to single-ended
- DAQ with a commercial 14-bit,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

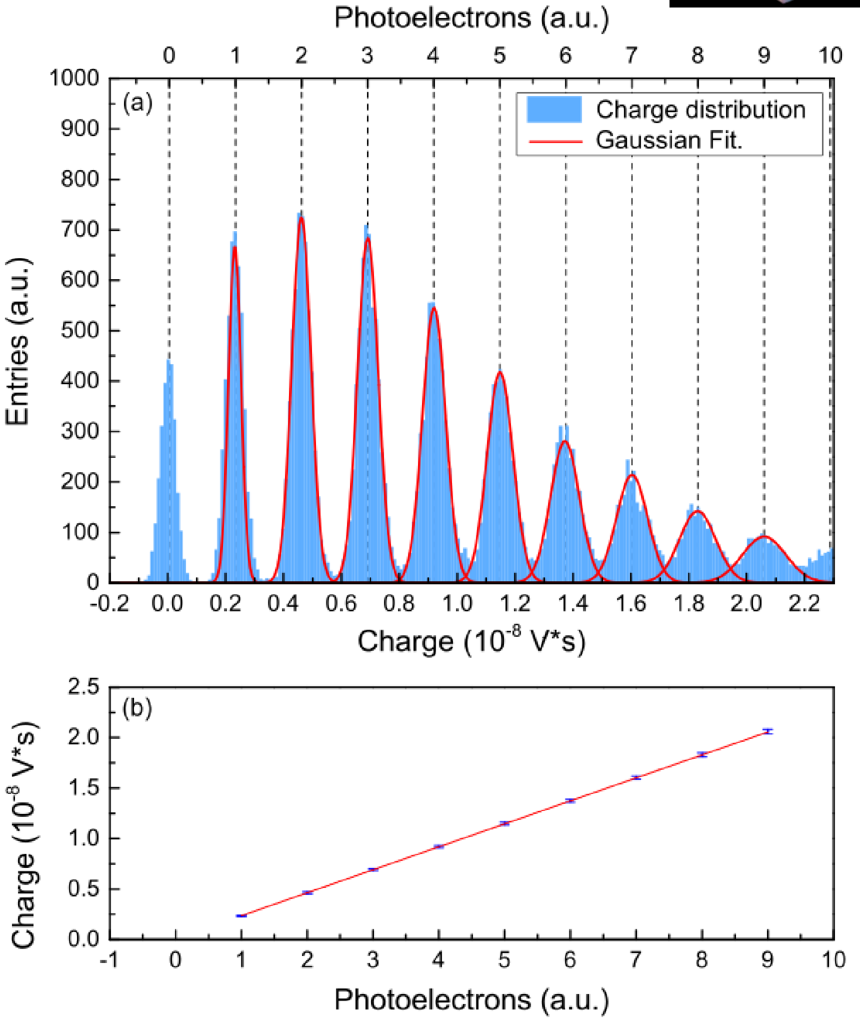




Laser calibration (@ 77 K)





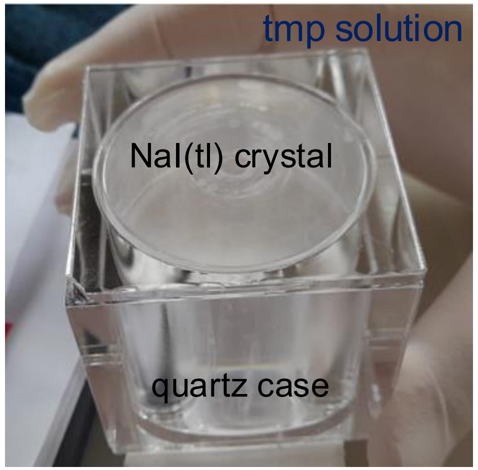


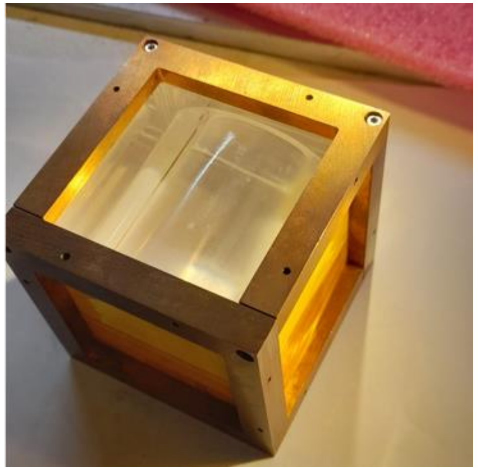
- 405 nm ps-pulsed laser (Hamamatsu C10196)
- 200 μm multimodal fiber
- PTFE diffuser (not shown)
- In liquid nitrogen
- In Faraday cage

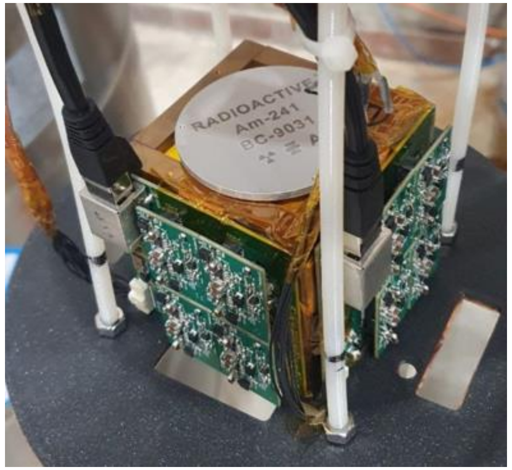
Excellent performance of FBK SiPM + custom electronics

ASTAROTH ^{241}Am cryogenic source runs

INFN LASA
Istituto Nazionale di Fisica Nucleare
Laboratorio Acceleratori e Superconduttività Applicata

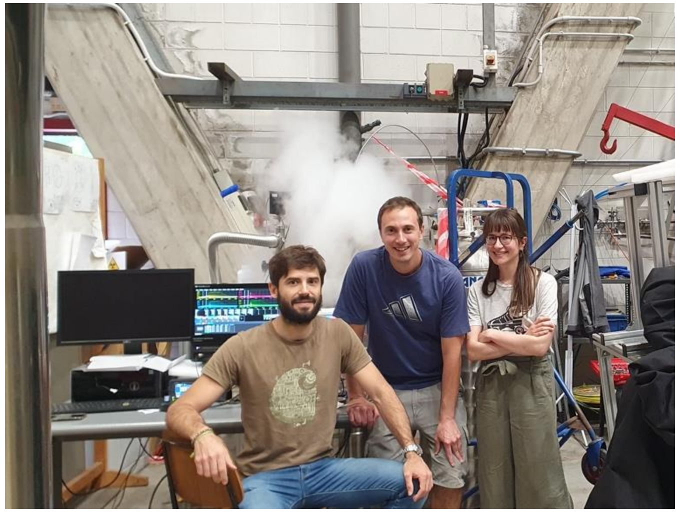


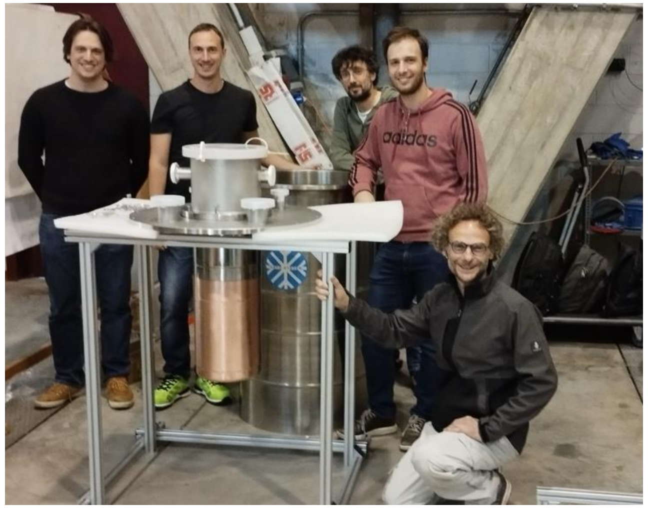




1. Mar 24: old FBK array + FE
2. Jun 24: new FBK array, tmp DAQ
3. Mar 25: new FBK array and DAQ
4. Jul 25: HPK array + epoxy-cased crystal

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

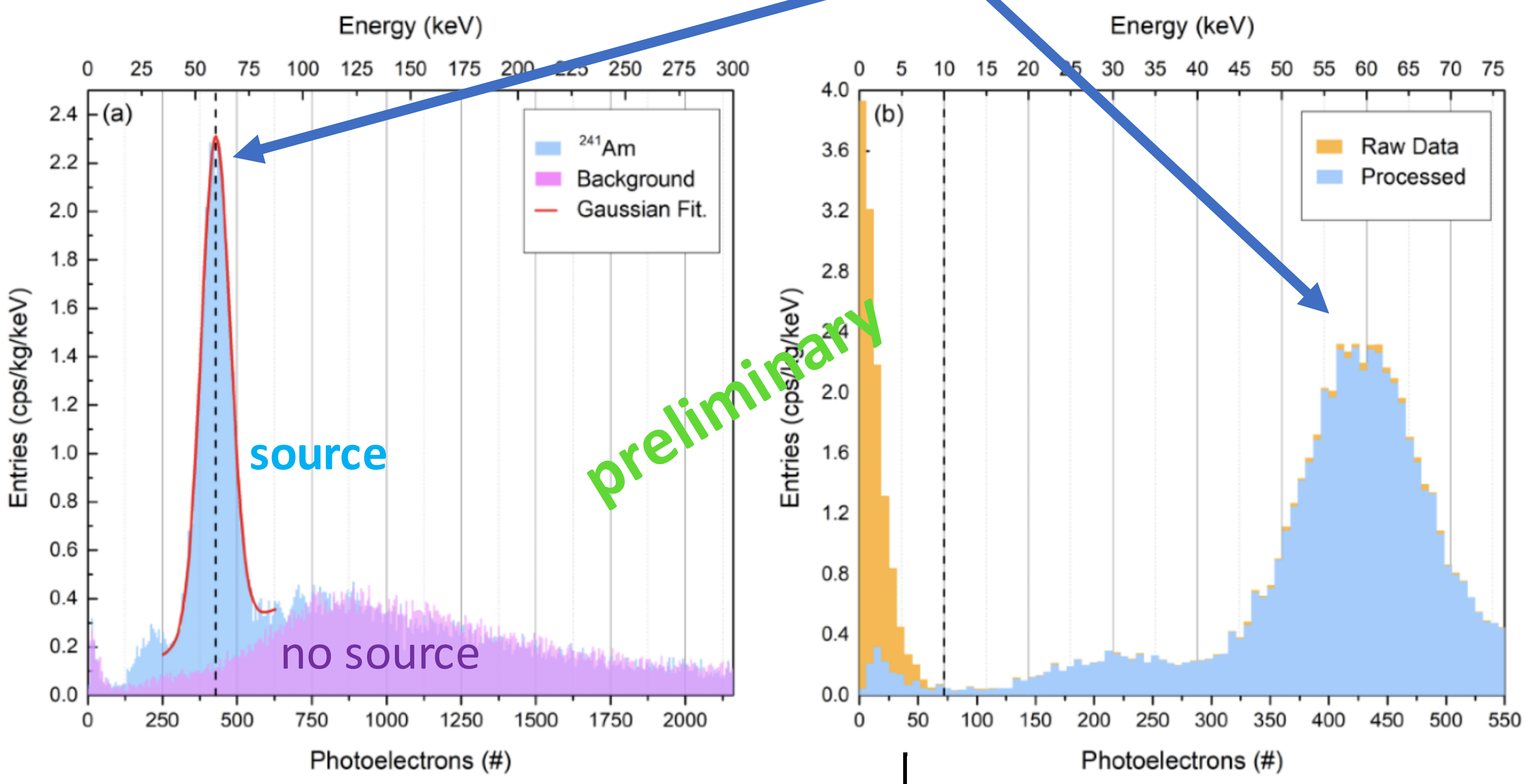




Energy spectrum

arXiv:2507.21612, subm. to EPJ C

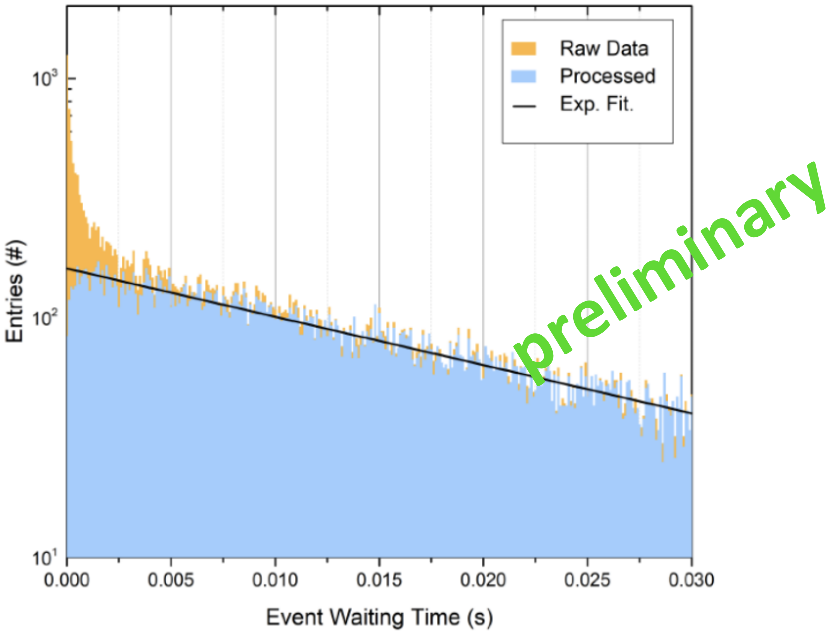
59.5 keV gamma from ^{241}Am Source



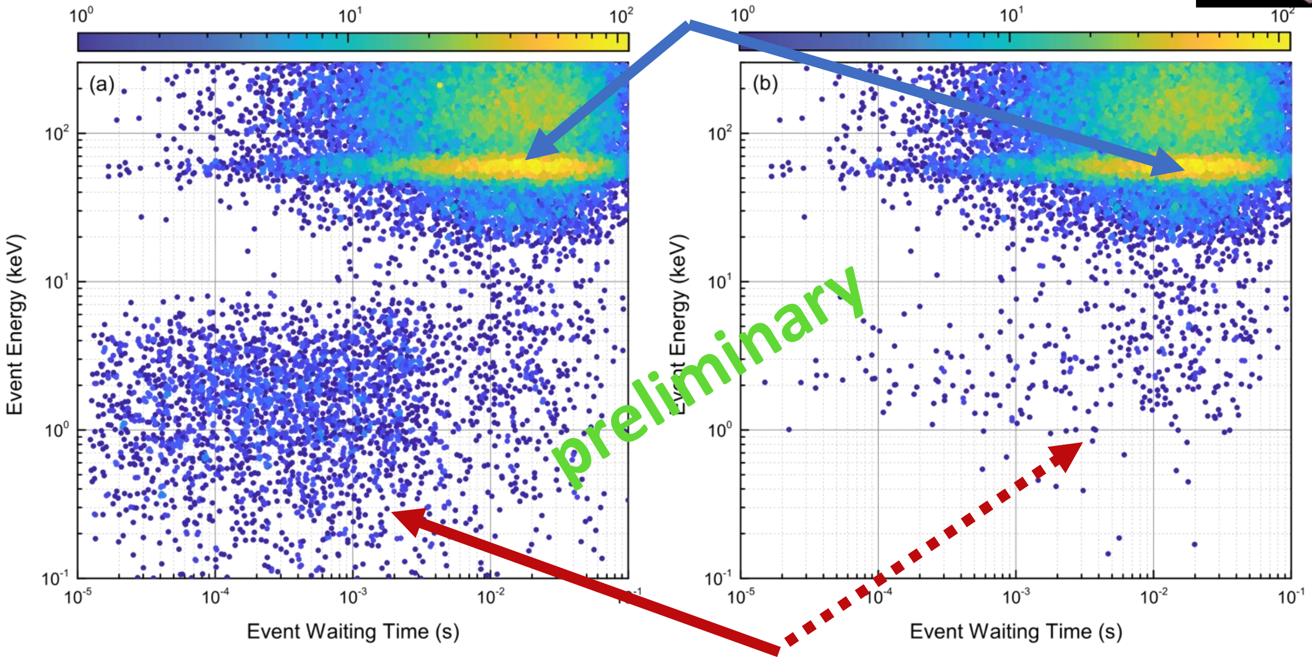
quality cuts to remove artifact triggers

- 64 SiPMs FBK array
- Ph.e. yield:
  ~ 7.2 ph.e./keV
- Remarkably better then expected!
  Considering:
  - only 1 array
  - case with gas gap
  - no optical coupling case/SiPM
- **Several ways to improve!**
- FWHM: 37 %
- Trigger thresh: 0.5 keV

Data quality selection



59.5 keV gamma from ^{241}Am Source



“fake” triggers

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

ASTAROTH phase-1 (2020-24) **completed,** demonstrating the **viability of the technology**

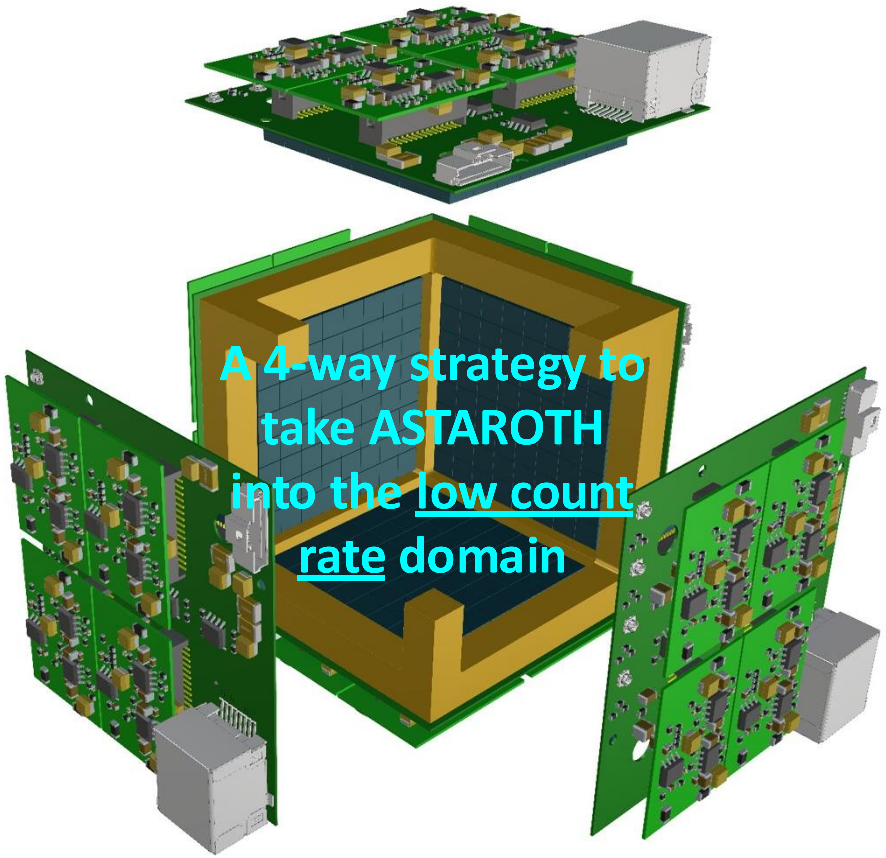
ASTAROTH_BEYOND

APPROVED

by INFN
2025-27

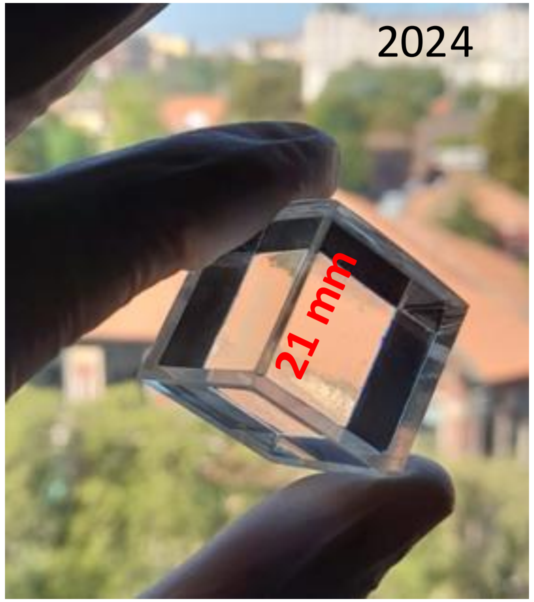
1. Maximize light collection

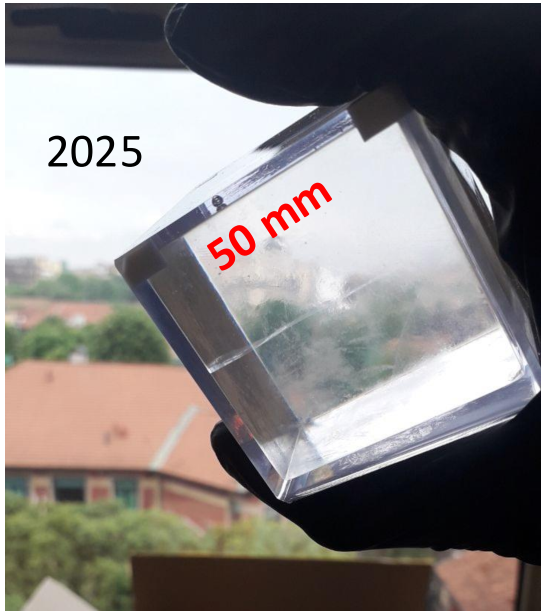
2. ASIC-based electronics



3. Veto detector

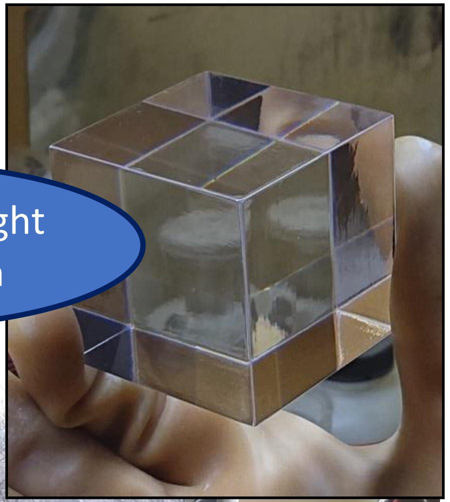
4. Run underground



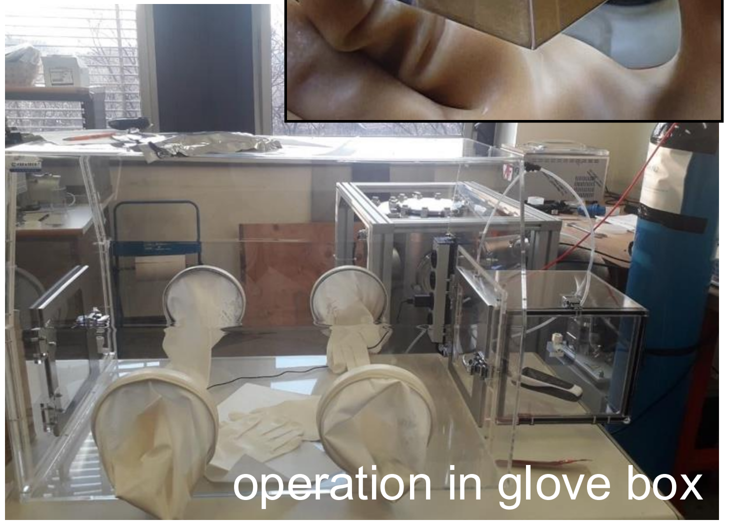


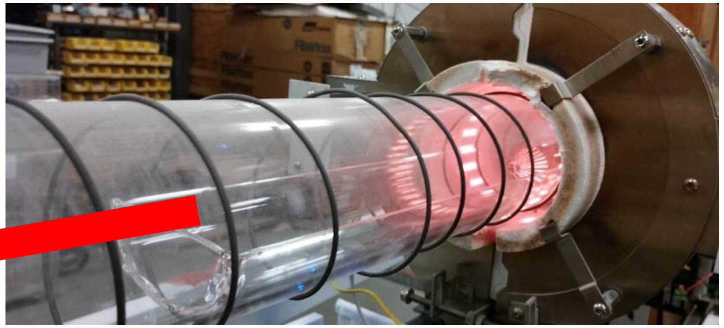
First epoxy-coated NaI(Tl)

- A <u>revolution</u> in handling of hygroscopic crystals
- Method developed with 21 mm NaI(Tl) crystals and <u>two</u> resins (Epo-tek, Stycast)
- First *fully transparent cold-compliant* epoxy-coated crystal in 2024
- **Succefully scaled to 50 mm in 2025**
- *Operated with SiPMs* in July 2025
  - Analysis in progress
- To be done:
  - **Optical coupling**
    - with silicon pads or Si-gel
  - Switch to **high-purity crystal**
    - from SABRE-North producer RMD (Boston)

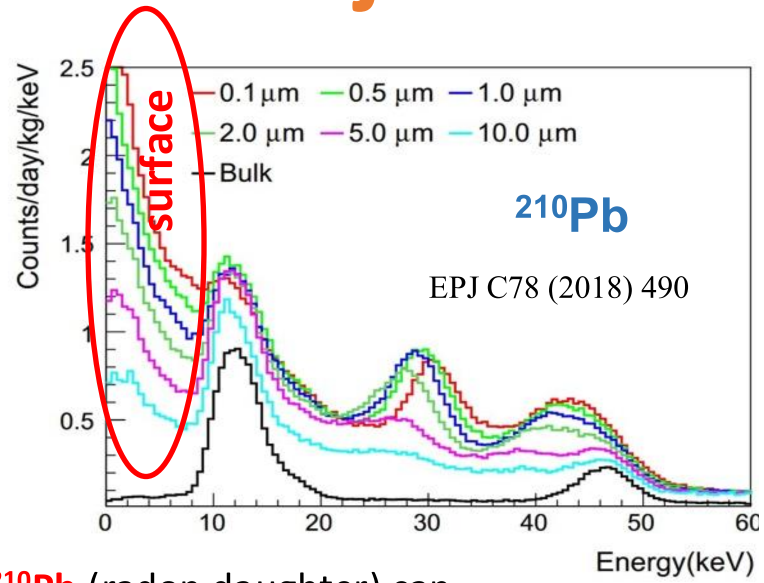


1. Maximize light collection

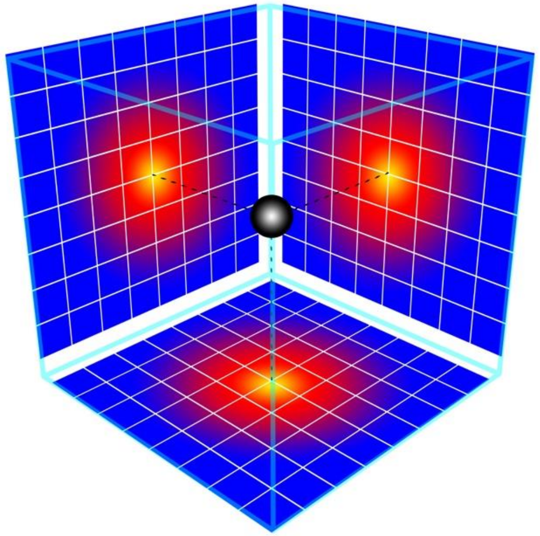




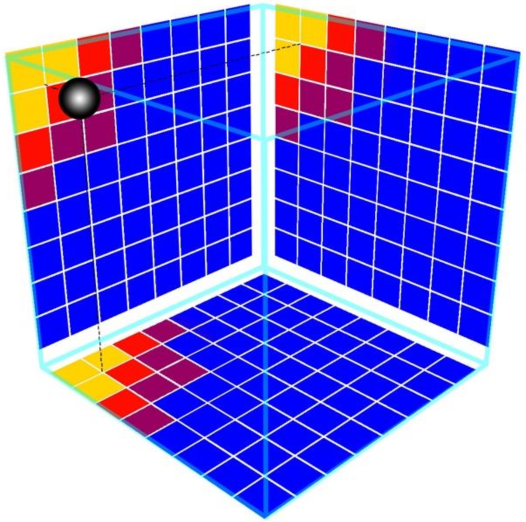
Reject surface background by light map



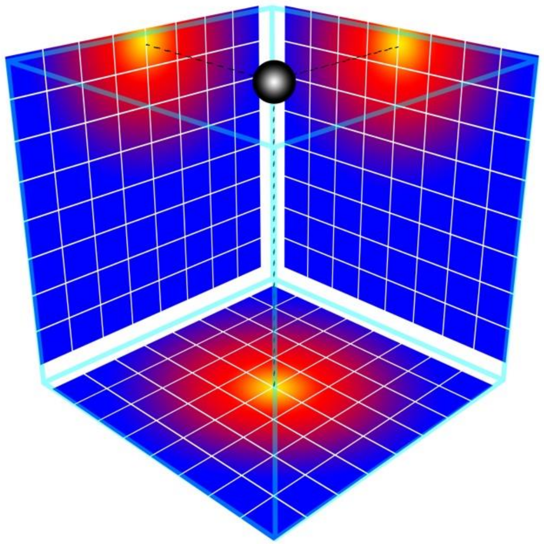
^{210}Pb (radon daughter) can be implanted on the surfaces (observed by COSINE, SABRE) and impact the ROI more than bulk



2. ASIC-based electronics

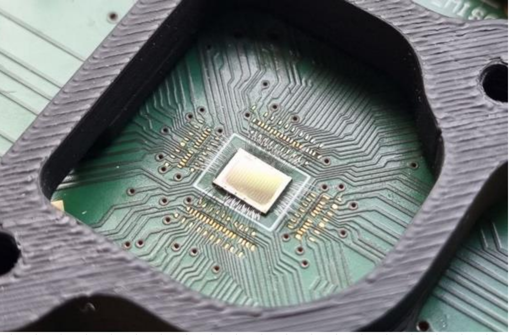


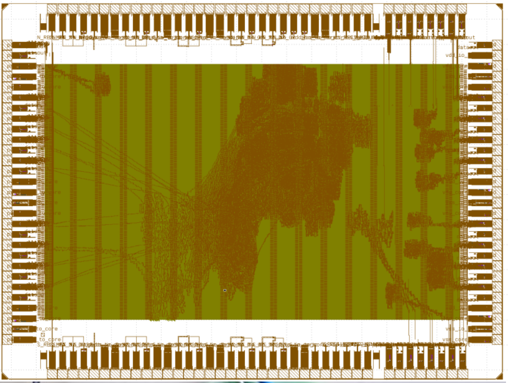
1. radiopure
2. compact
3. low power

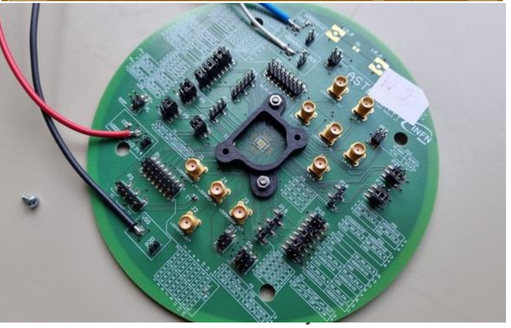


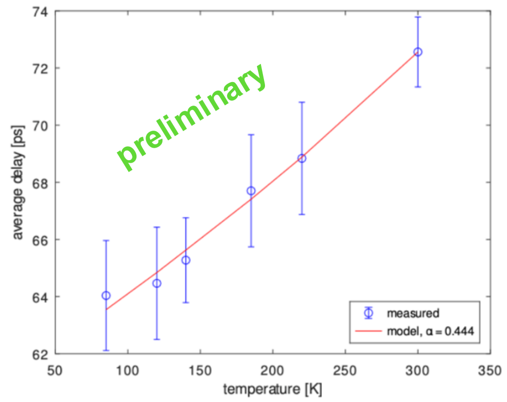
A machine learning algorithm fed with the charge map from (at least) three sides could **discriminate surface from bulk events**.

A readout with this capabily working at crygenic temperature has an appeal that goes beyond ASTAROTH









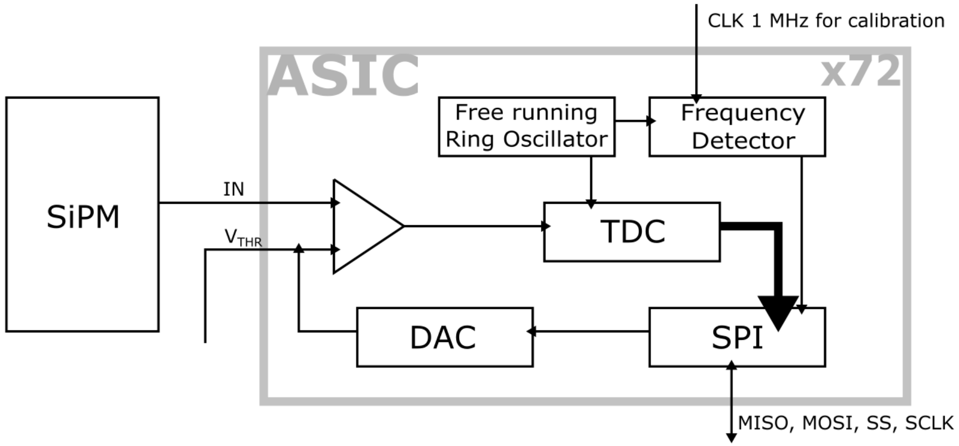
ASIC front end

What we did

- Test chip in **CMOS 110 nm** with p-/n-mos, R, C and ring oscillators made of most common logic ports.
- Simulation model upgraded with temperature dependency.
- 4 tested in ASTAROTH cryostat Oct 2023 in 85-295 K.
- **Technology works!** for analog and digital circuits at cryogenic temperatures.
- Port delay decrease by ~10% at cold.
- *Our temperature dependent model reproduces data.*
- Of general interest for the IC community

Andreani A., et al, MOCAST 2023

+ paper in preparation



What we need to do

- Final chip design *started*, to be submitted in 2026
- Mixed analog/digital chip
- Pick up SiPM signal with a current conveyor
- DAC-programmed discrimination threshold
- **Time-over-threshold charge estimate**
- SPI interface
- <1 ns resolution <-> **spe sensitivity**

Veto detector

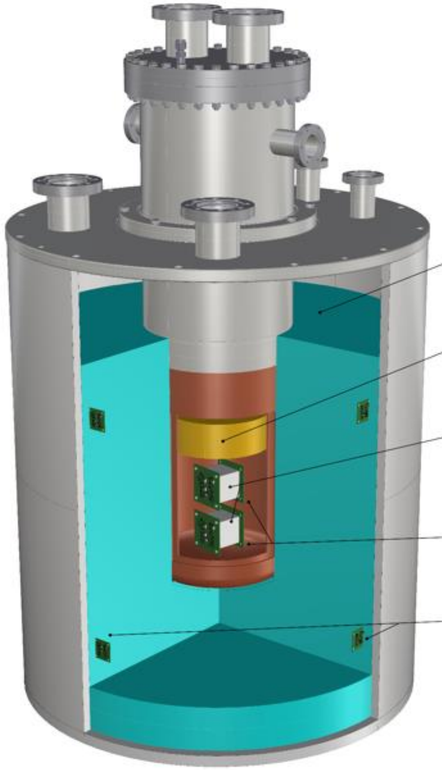
ASTAROTH accomplished:

cryostat operated multiple times

Temperature stable < 0.1K !!!

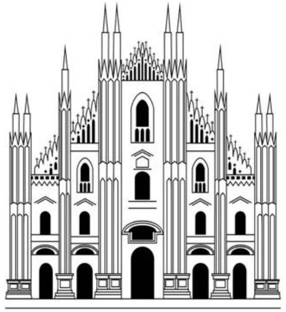
3. Veto detector
(and shielding)

- Switch from LN_2 to LAr
- Instrument outer volume with SiPM
  - Independent Geant4 and Fluka simulations in progress to understand coverage and disposition
- Surround with a lead castle (~10 cm thick)
  - Acquired ~ 600 lead bricks



Final underground run (2027)

Muon disruptive interactions in the crystal can last a few minutes (!)
Final year: plan to go to an **underground lab.**
At LNGS (10^6 less muons) there is interest of the SABRE-North collaboration and lab director.



4. Go underground
(last year)

arXiv:2507.21612, subm. to EPJ C

The team

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 Carlo[4], Luca Frontini[1], Niccolò Gallice[1,2,5], Chiara Guazzoni[1,3], Valentino Liberali[1,2], Alberto Stabile[1,2], Valeria Trabattoni[1,2], Andrea Zani[1], Davide D'Angelo[b,1,2]

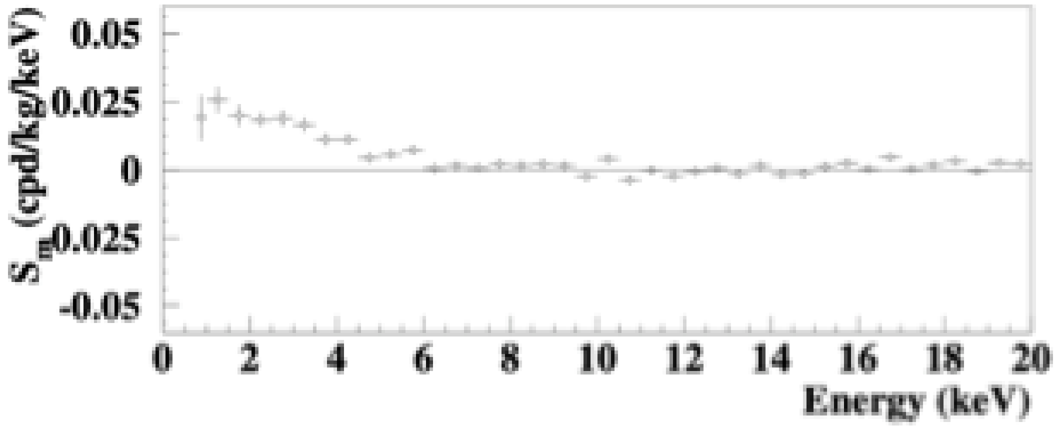
[1]INFN - Sezione di Milano, via Celoria 16, 20133 Milano, Italy
[2]Dipartimento di Fisica, Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy
[3]Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB), Politecnico di Milano, piazza Leonardo da Vinci 32, 20133 Milano, Italy
[4]INFN - Laboratori Nazionali del Gran Sasso (LNGS), via G. Acitelli 22, 67100 Assergi, Italy
[5]Brookhaven National Laboratory, PO 5000, Upton, NY 11973, USA

Thank you for your attention !

☞ The ANAIS+ project is developing a similar technology, see talk of M. Martinez in this session

Back Up

Why low energy ?



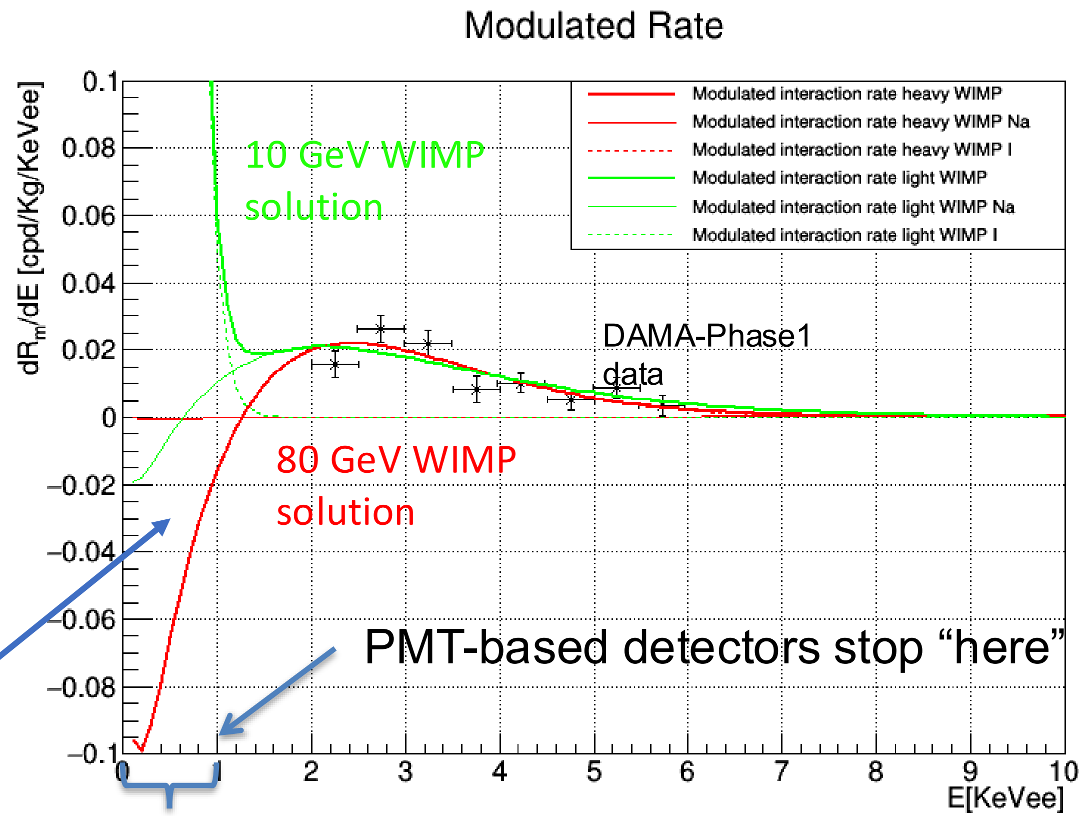
[Nucl. Phys. At. Energy 2021, vol. 22, iss. 4, p 329-342]

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

DAMA/LIBRA phase-2

- The signal seems to be larger at lower energies.
- DAMA (2022) & COSINE (2024) report for the first time a 0.75 keV threshold.

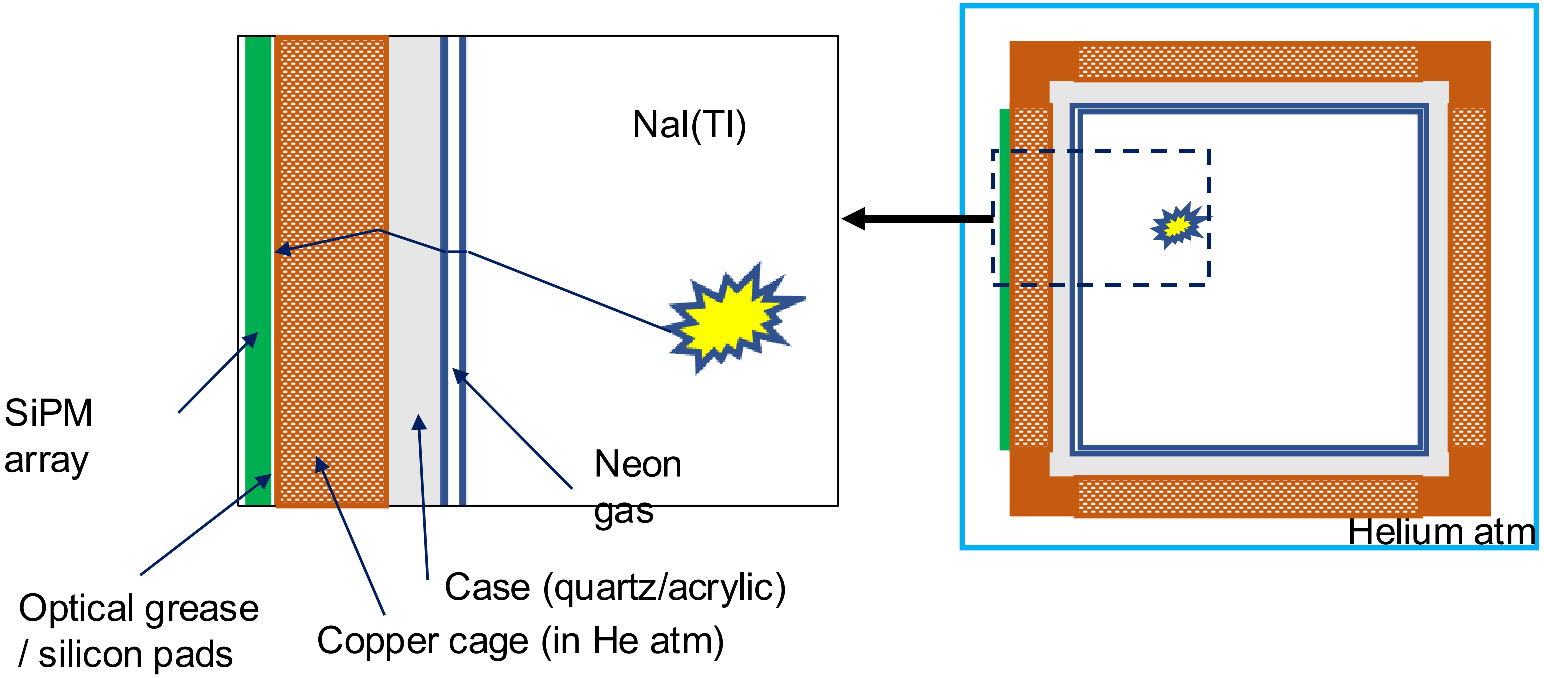


Old simplified excercise - basic hypotheses on DM interaction (standard Halo distribution, spin-independent coupling).

Setup simulation

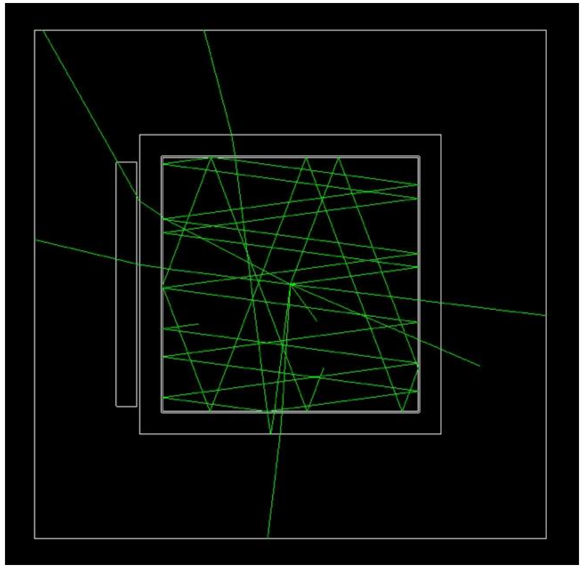
ASTAROTH can operate 2 encapsulated 5x5x5 cm^3 NaI(Tl) crystals (0.46 kg each).

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



Performed GEANT4 simulations of optical photons in the fused silica cased crystal

- 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. Neon layer induces several total reflections -> 50% light absorbed on the crystal
4. Importanto to keep SiPM close to case

Toward epoxy-coated crystals

NaI
CTE: 47.5
Ref ind.: 1.84

- Three products identified and procured:

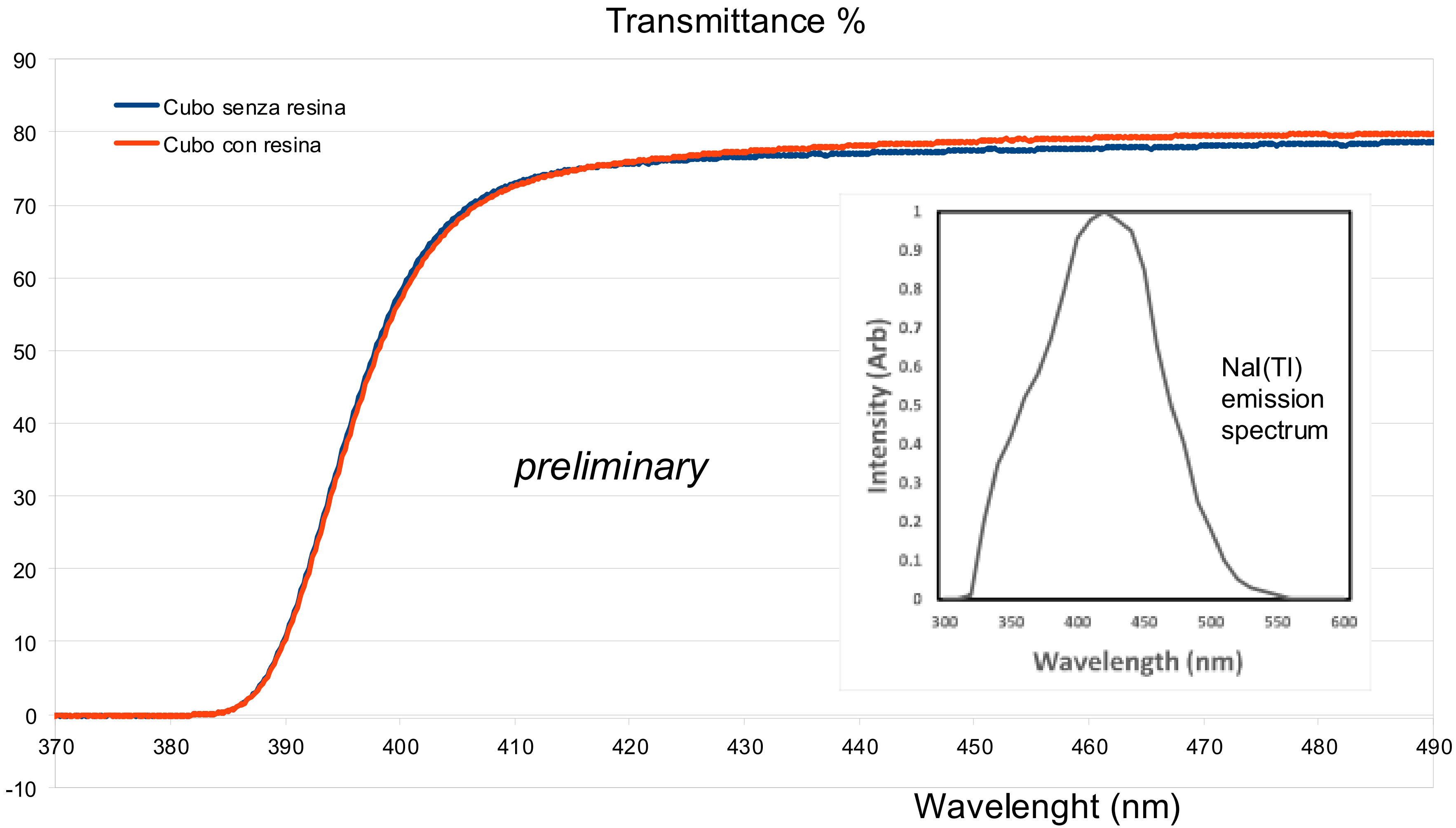
Firm	Name	Price	Quantity (l)	T range	CTE (µm/m)	R index	Transparency @ 420nm	Viscosity @ 23C (cps)	Work t	Cure t	Shelf life (yr)	Note
Masterbond	EP29LPSP	1200 $	0.473	4-400 K				500-1500	4-5h	8-10h @50C	0.5	NASA rated
Epo-tek	NDA	170 €	0.227		61	1.53	99%	225-425	8h	16h @45C	1	used by FBK
Stycast	1266	240 €	1	-65+105 C				650	30m	1-2h @65C	1	used by Dune

- Goal thickness: ~1.5 mm on each side
- Casts:
  - Optical glass cuvette: they break when cooled -> one shot -> expensive (~250 € / trial)
  - Silicon:
    - Either commercial ones in standard sizes
    - Self made with raw silicon
- Procedure developed first with PMMA cubes:
  - Bottom layer -> vacuum degassing -> oven curing -> cube insertion -> resin fills cast -> vacuum degassing -> oven curing

Epoxy trasmittance

Tested by spectrophotometer.

20 mm PMMA cube with and w/o a 1.5 mm *Stycast* epoxy coating on all sides

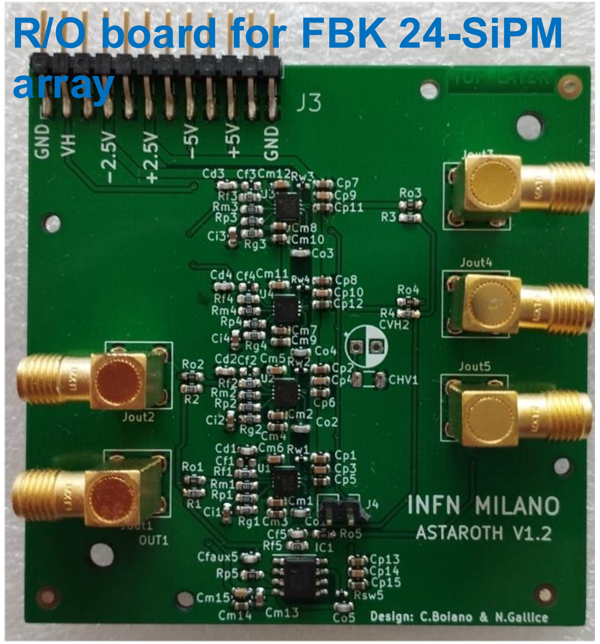


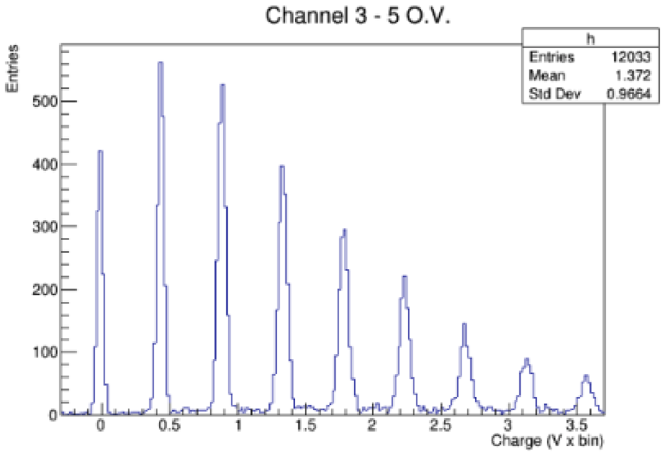
SiPM readout for FBK-1 array

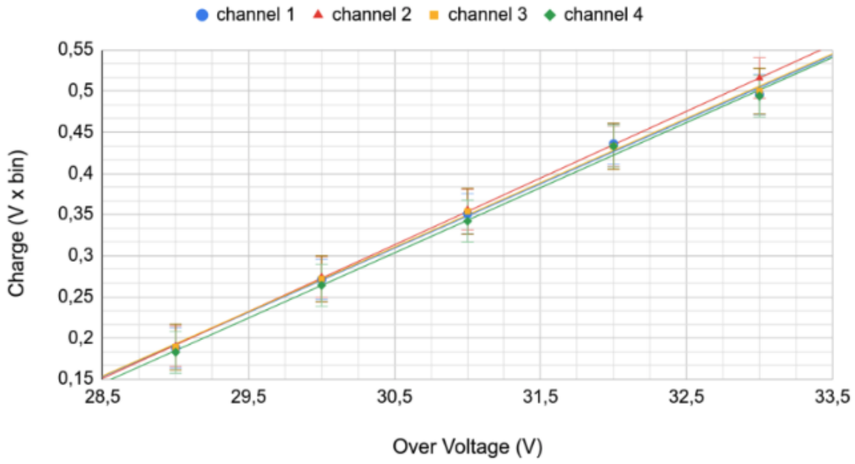
Frontend board for FBK-1 24-SiPM array (Internal design):

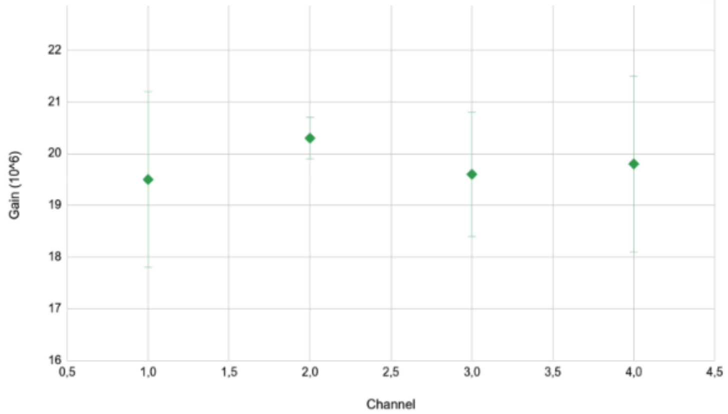
- 4 channels + SUM.
- Designed internally (N. Gallice), based on design of DS-20k.
- Solved issue on mounting of components and leakage current
- Characterized (M. Galli) at room and LN2 temperature with laser.

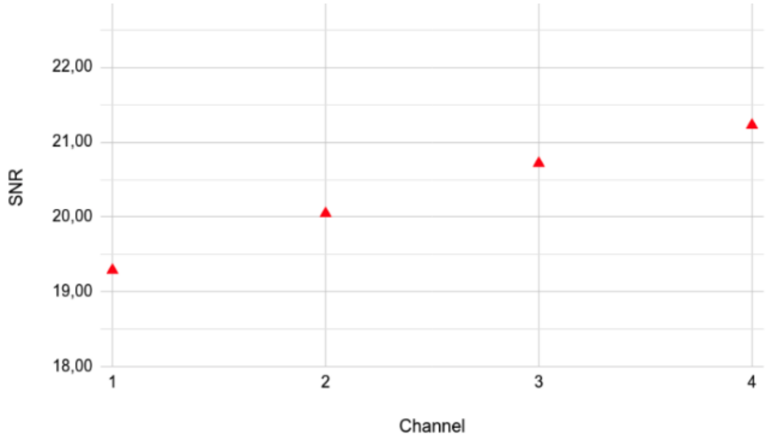
R/O board for FBK 24-SiPM array



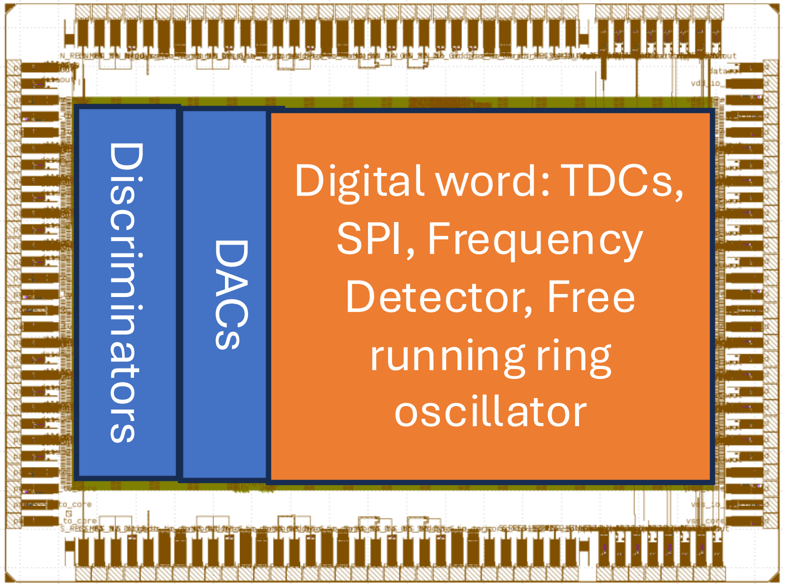


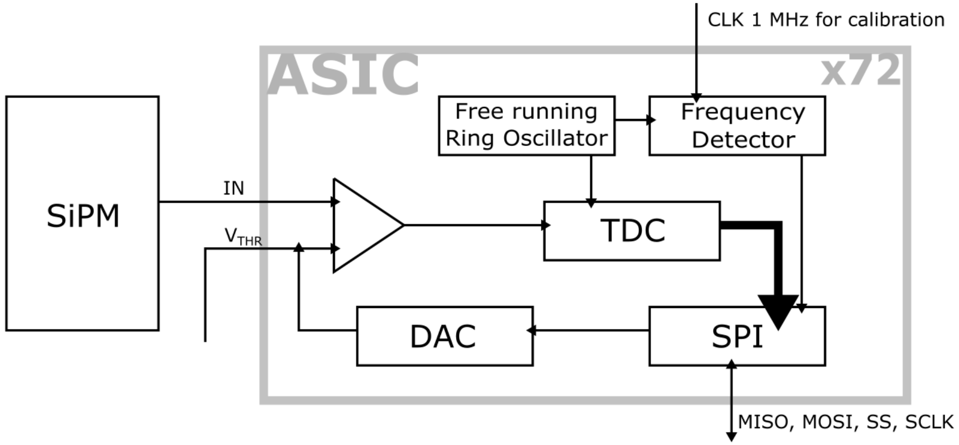






Chip ASTAROTH_BEYOND





Up to 72 channels

Discriminator:

1. Programmable threshold tunable externally or internally (DAC)
2. Receives scintillation charge signals from a Silicon Photomultiplier (SiPM)

Clock Generation:

1. High-frequency clock for the TDC generated by a Digital Ring Oscillator (DRO)
2. DRO calibration managed by an internal frequency detector

Mixed-Signal Design:

1. Combines digital (SPI, DRO, counters) and analog/mixed components (discriminators, DAC)
2. Digital parts are implemented using standard cells and EDA software
3. Automatic placement and routing (Place & Route)

Silicon-proof:

1. SPI interface, Digital Ring Oscillator (DRO), and simple counters are silicon-proven from the previous Astaroth chip

Control and Data Management:

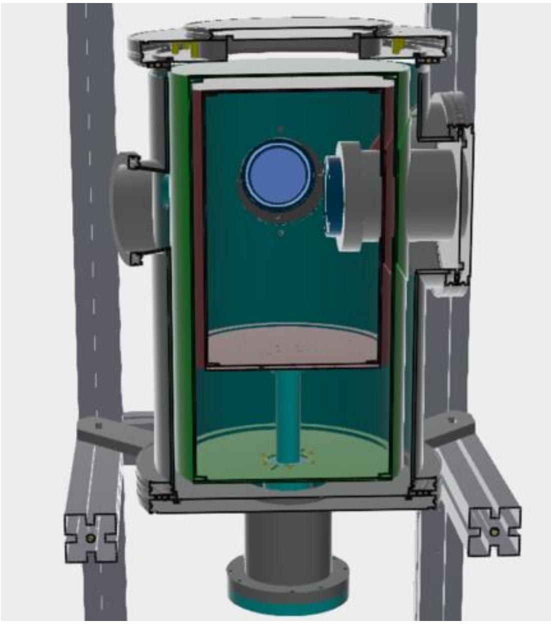
1. SPI interface
2. Due to low event frequency (<< 1 kHz), output data will be stored in SPI registers to obtain a charge map

Raw resolution

1. To discriminate for 1 to 2 photons a minimum resolution of ns is needed

Understanding crystal response

- Light yield and pulse shape of NaI(Tl) vary significantly with temperature. Physics is not well understood and the literature is confused.
- ASTAROTH performed three different campaigns at LNGS in a COSINUS cryostat.
- Several problems with crystals and setup, results inconclusive.
  Solution:



- crystals with 3 doping levels procured
- 250, 750, 1500 ppm.
- New cryocooler with two optical windows

Just commissioned!

New facility in Milano!

Where do we stand?

ASTAROTH phase-1 completed: 2020-24

- Demonstrated the viability of the technology
- Preliminary outcomes:

A. Ph.e. yield **~ 7.2 ph.e./keV** (1 array)
   already better then expected!
   -> with several ways to improve

B. Blank run (no crystal):
   instrumental noise < 1 Hz

C. Residual low energy events must be addressed:
   1. External background
   2. Electronics radioactivity
   3. Crystal bulk and surface radioactivity
   4. Muon disruptive interactions

This shows that the goal of ASTAROTH of demonstrating a S/N ~ 1 at 1keV and a sub-keV threshold is at hand

Very busy to-do list

+ maximize light collection

+ shielding + LAr veto

+ low radioactivity

crystal + electronics

+ ASIC to reject surface backgr.

+ underground site (final year)