

CUORE towards CUPID: the scaling-up of a ton-scale millikelvin crystal array

Low Temperature Detectors 20

Antonio D'Addabbo
for the CUPID collaboration

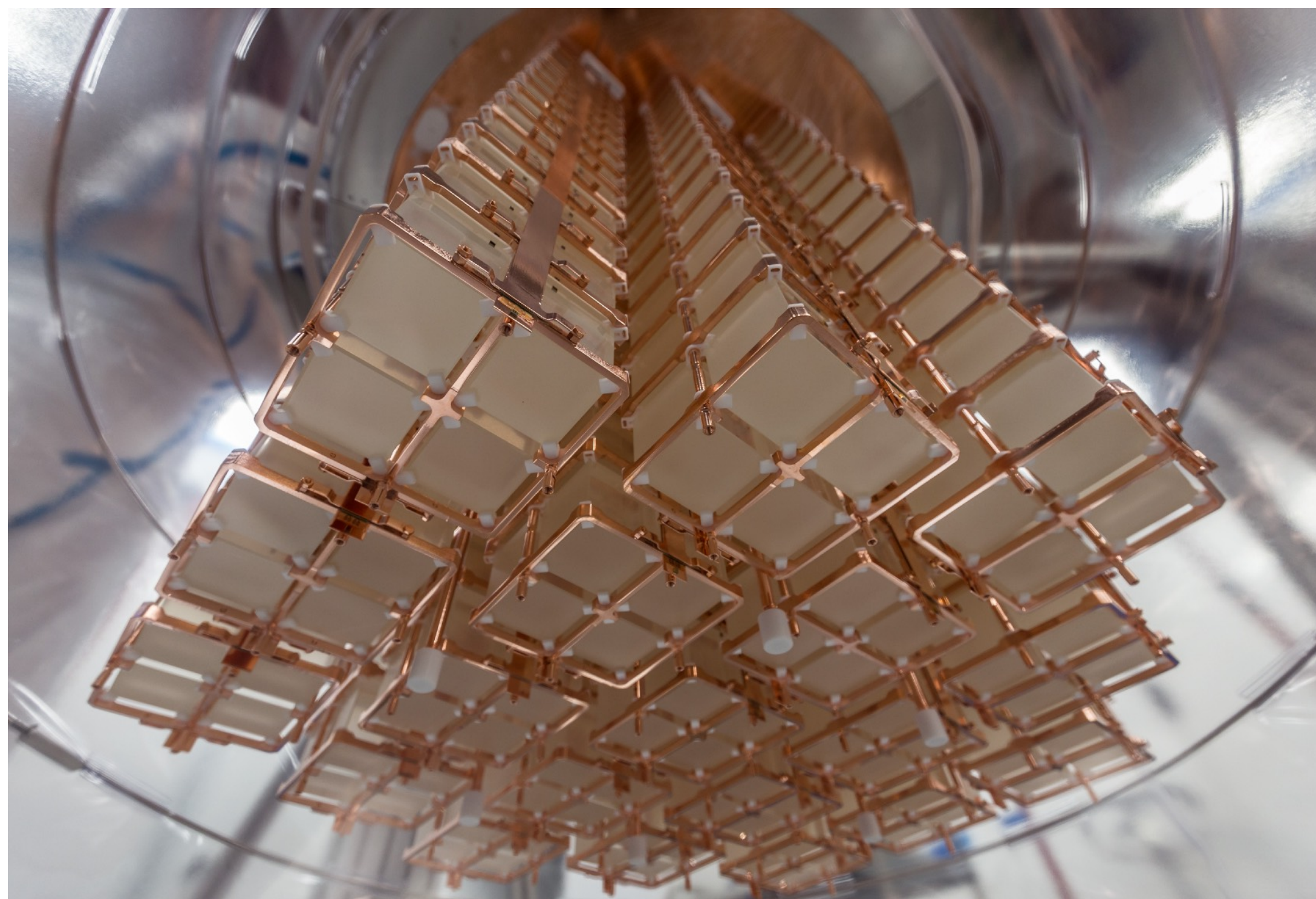
CUPID

CUORE in a nutshell



The largest cryogenic macro-calorimeters array

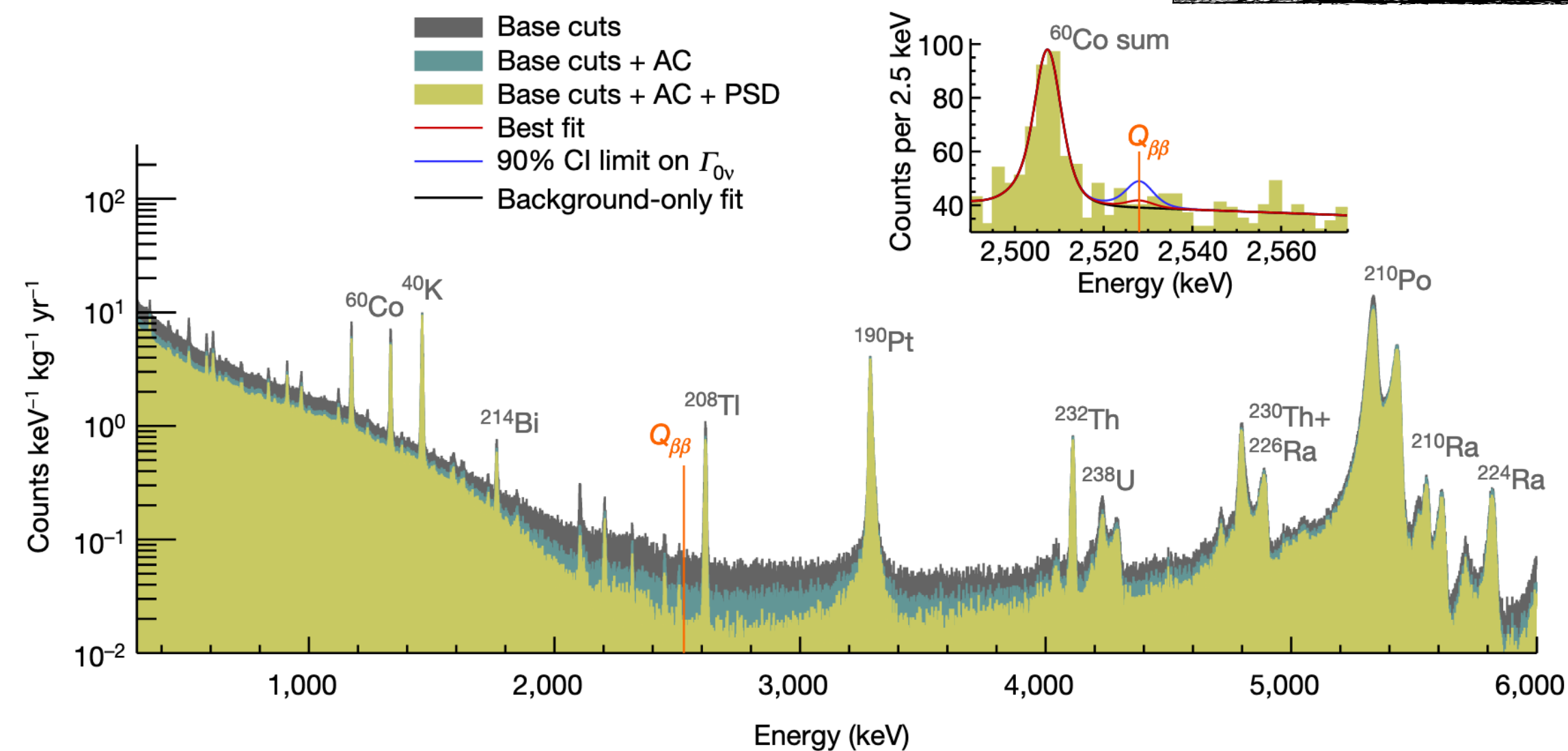
- 988 5x5x5 cm³ crystals of TeO₂
- 19 towers of 13 floors each
- Total mass : 742 kg (206 kg of ¹³⁰Te)



One of the most sensitive current generation 0ν2β experiments

- 0ν2β isotope : ¹³⁰Te ($Q_{\beta\beta}=2527$ keV)
- 1 ton.yr exposure (288 kg.yr ¹³⁰Te)
- ¹³⁰Te half life: $T_{1/2} > 2.2 \times 10^{25}$ yr
- $m_{\beta\beta} < 90-305$ meV

L. Marini poster
code: MP 072



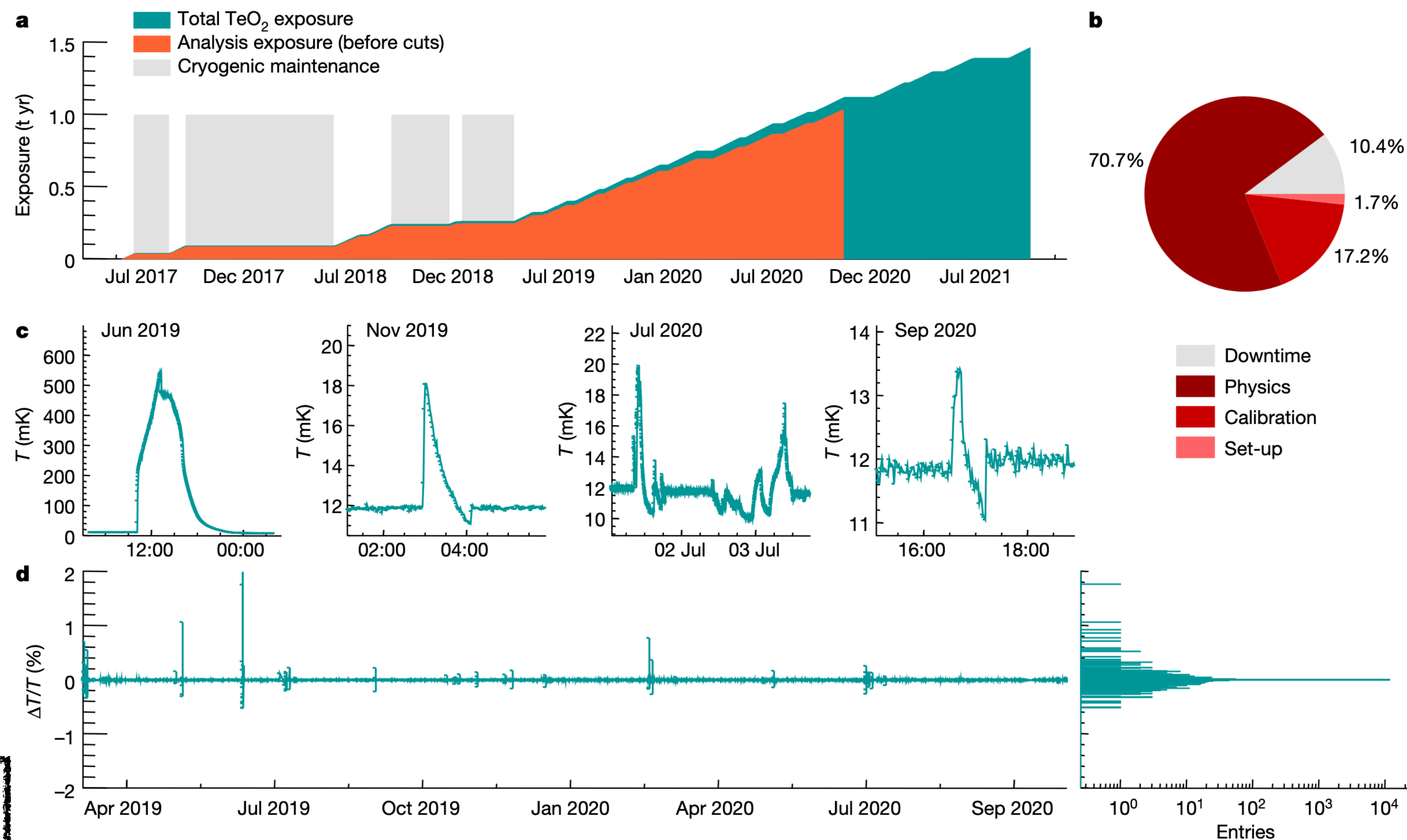
The CUORE and CUPID challenges

Ton-scale array operated at 10 mK on a time scale of a decade

CUORE paved the way to CUPID:

- CUORE and CUPID same mass scale: feasibility already demonstrated with 4 years of stable data-taking
- Cryogenic macro-calorimeters are a robust technology
- Existing cryogenic infrastructure: cost effective, low risk

The CUORE collaboration,
Nature 604 (2023), 53-58

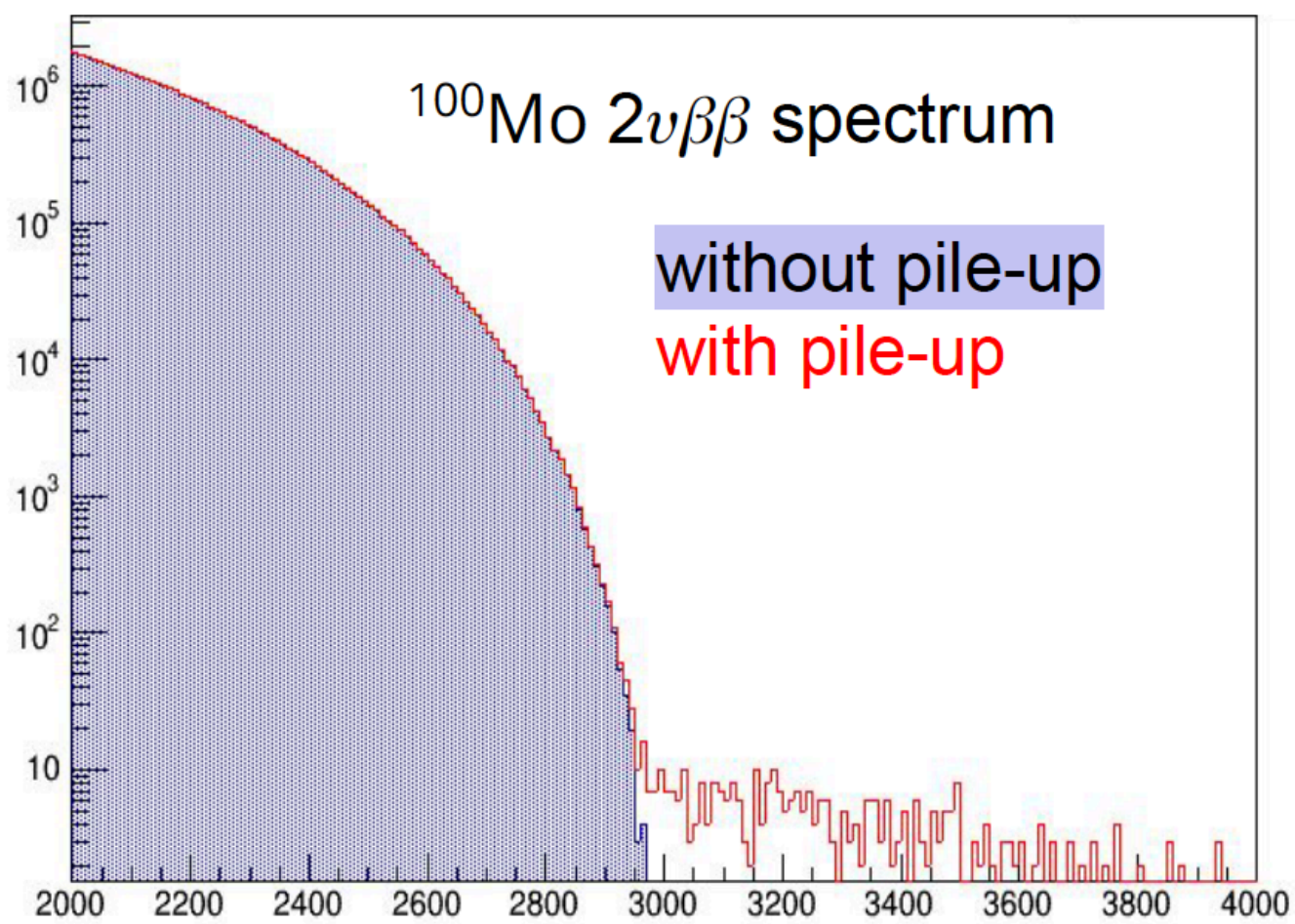


CUORE and CUPID project parameters

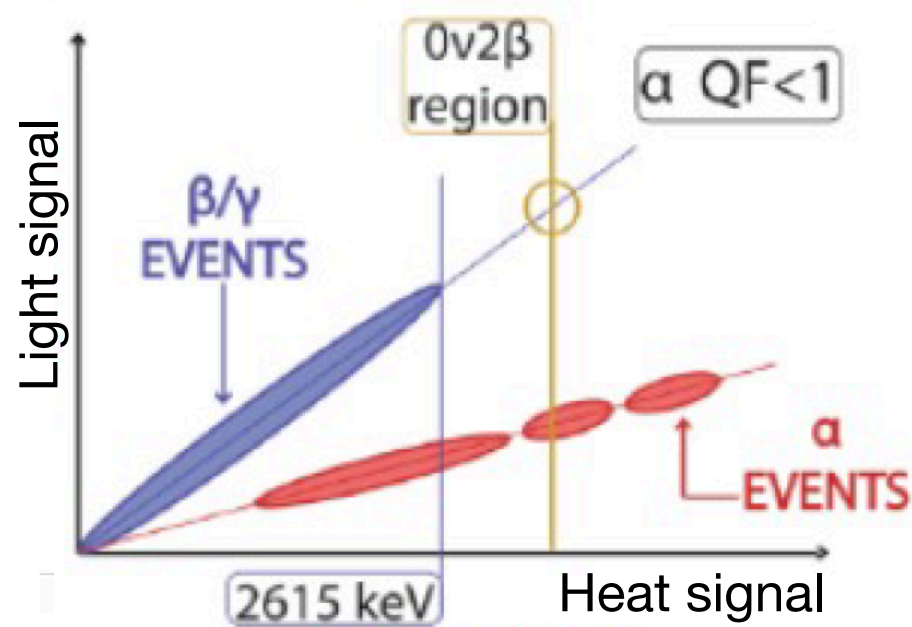
Parameter	(CUORE reference)	Value
Crystal	(TeO ₂)	Li ₂ ¹⁰⁰ MoO ₄
Size	(50x50x50 mm ³)	45x45x45 mm ³
Number of crystals	(988)	1596
Number of light detectors		1710
Detector mass	(742 kg)	450 kg
Enrichment	(nat. 34.1%)	95%
¹⁰⁰ Mo mass	(206 kg)	240 kg
Energy resolution	(7.8 keV)	5 keV
Light yield (β)		0.3 keV/MeV
Background index	(1.5 10 ⁻²)	10 ⁻⁴ counts/(kg*keV*year)
Selection Efficiency		90%

Parameter	Value
LD light absorption	>90%
LD energy resolution	<100 eV RMS
LD pileup resolution	<0.17 ms
LD risetime*resolution	<1 msec*80 eV-FWHM
Muon detector efficiency	>90%
Crystal radiopurity	CUPID-Mo
Surface radiopurity	CUORE
Cu, PTFE radiopurity	CUORE
DAQ bandwidth, storage	~10xCUORE
Calibration system	External (CUORE)
Cryogenics	CUORE

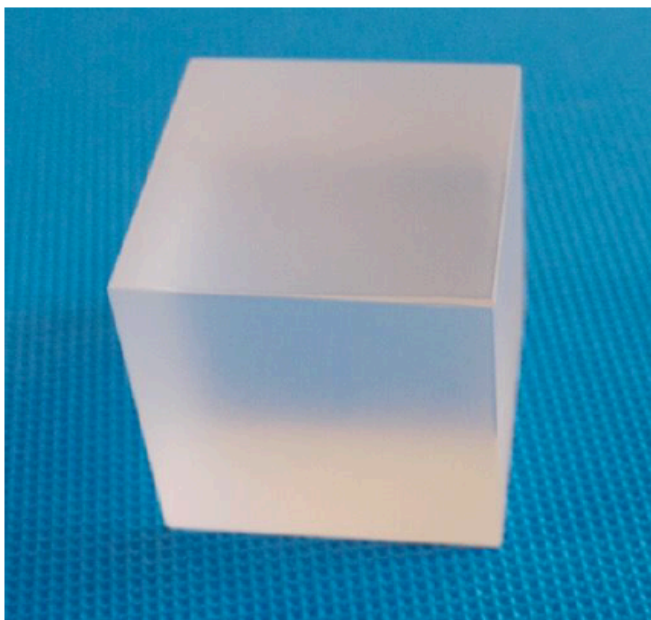
LD performance - pileup rejection



LMO performance



LMO crystals mass & i.a.



Background control and reduction

CUPID: CUORE Upgrade with Particle Identification

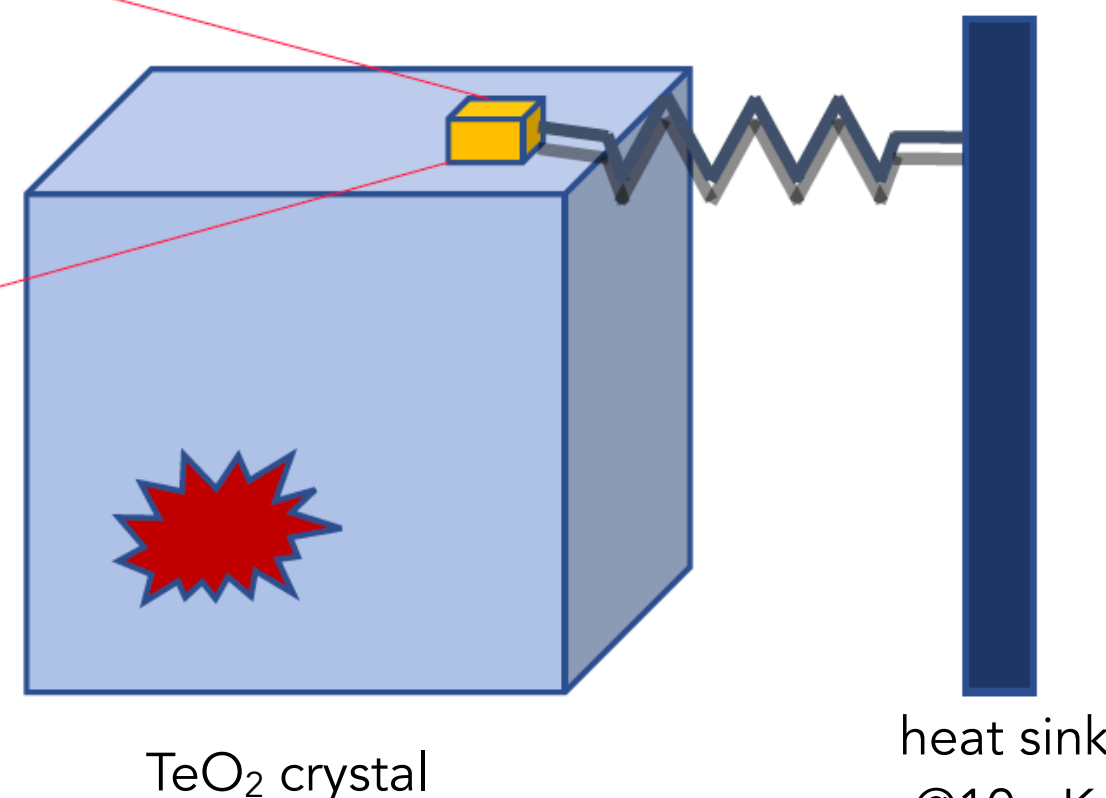
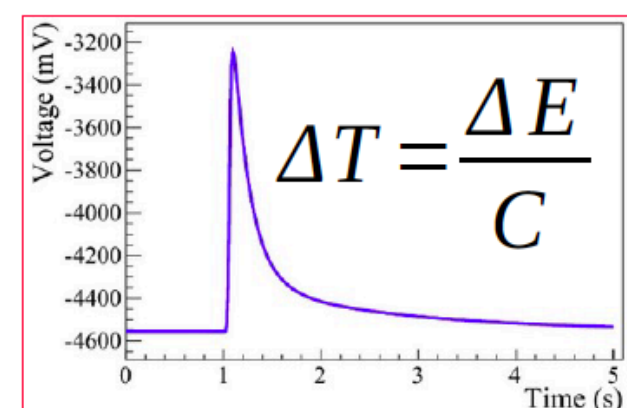
High-resolution cryogenic macro-calorimeters for the search for $0\nu\beta\beta$ and other rare events

- replace CUORE TeO_2 detector with new one based on $\text{Li}_2^{100}\text{MoO}_4$ crystals
- use Ge light detectors for background suppression

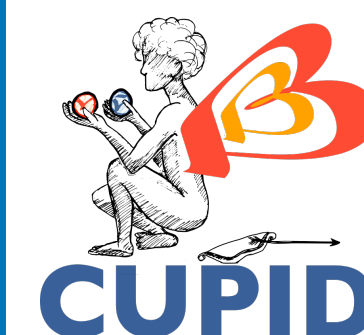


CUORE ^{130}Te

"Bolometer" = heat signal

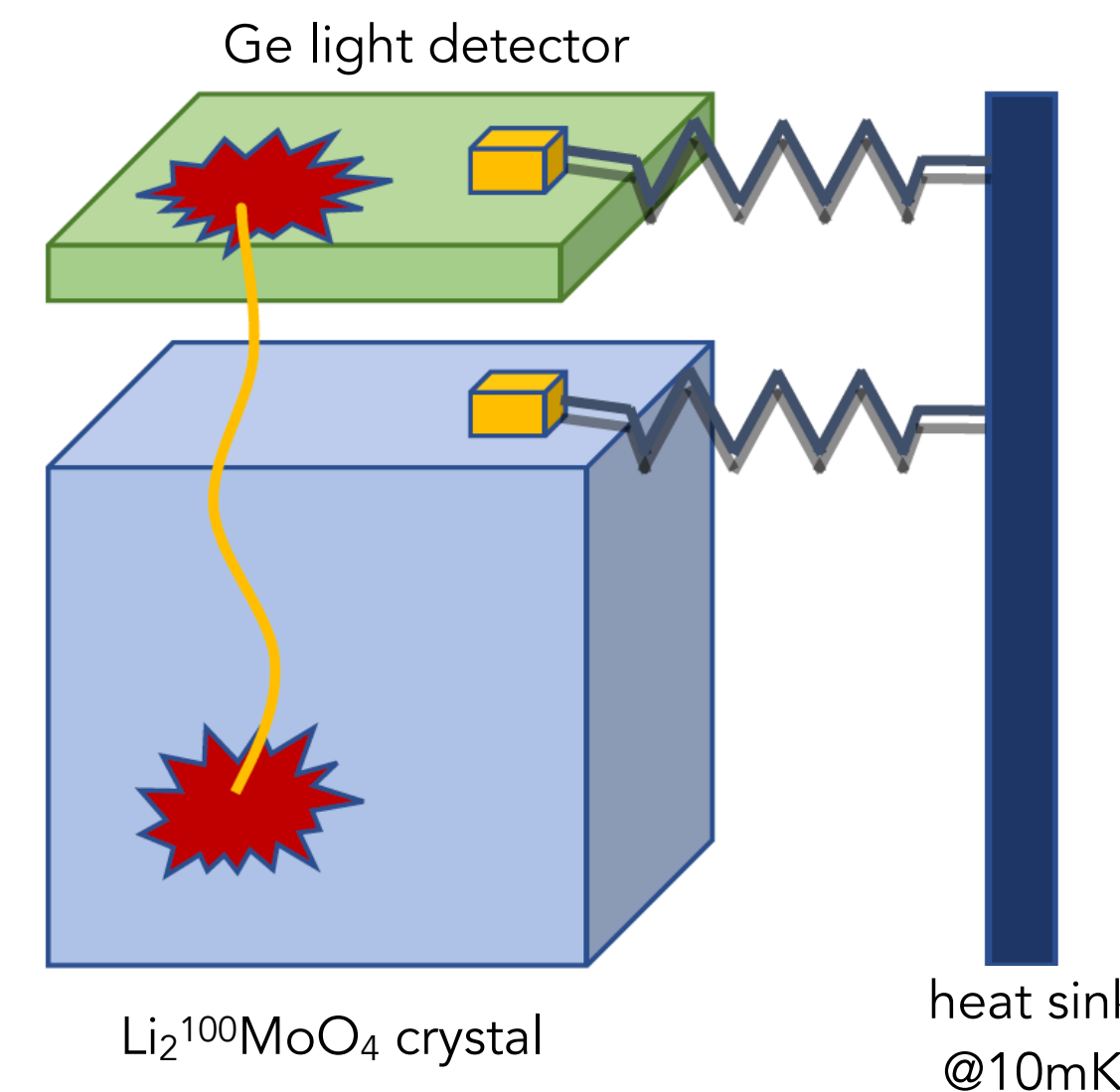
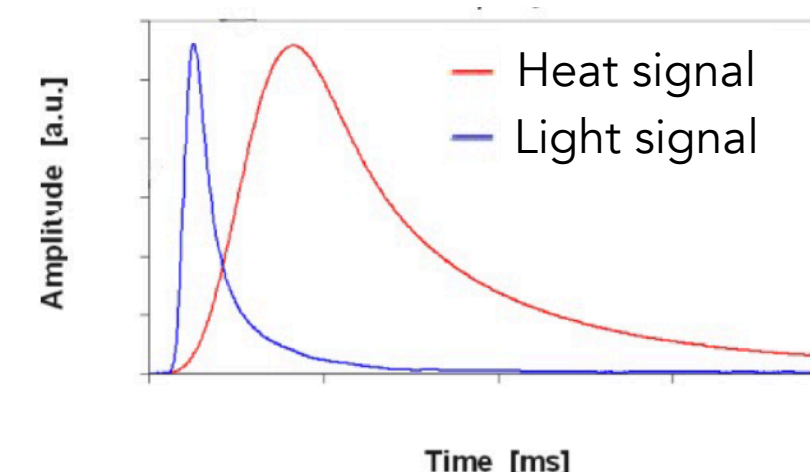


- Pure thermal detector
- Heat capacity $C \sim T^3$
- NTD-based readout
- Q-value 2527 keV



CUPID ^{100}Mo

Scintillating "bolometer" = heat + light signals



- Particle Identification (PID):
 - α -discrimination
 - $2\nu 2\beta$ pile-up rejection
- Higher Q-value (3034 keV)

Detector performance

2 mini-towers

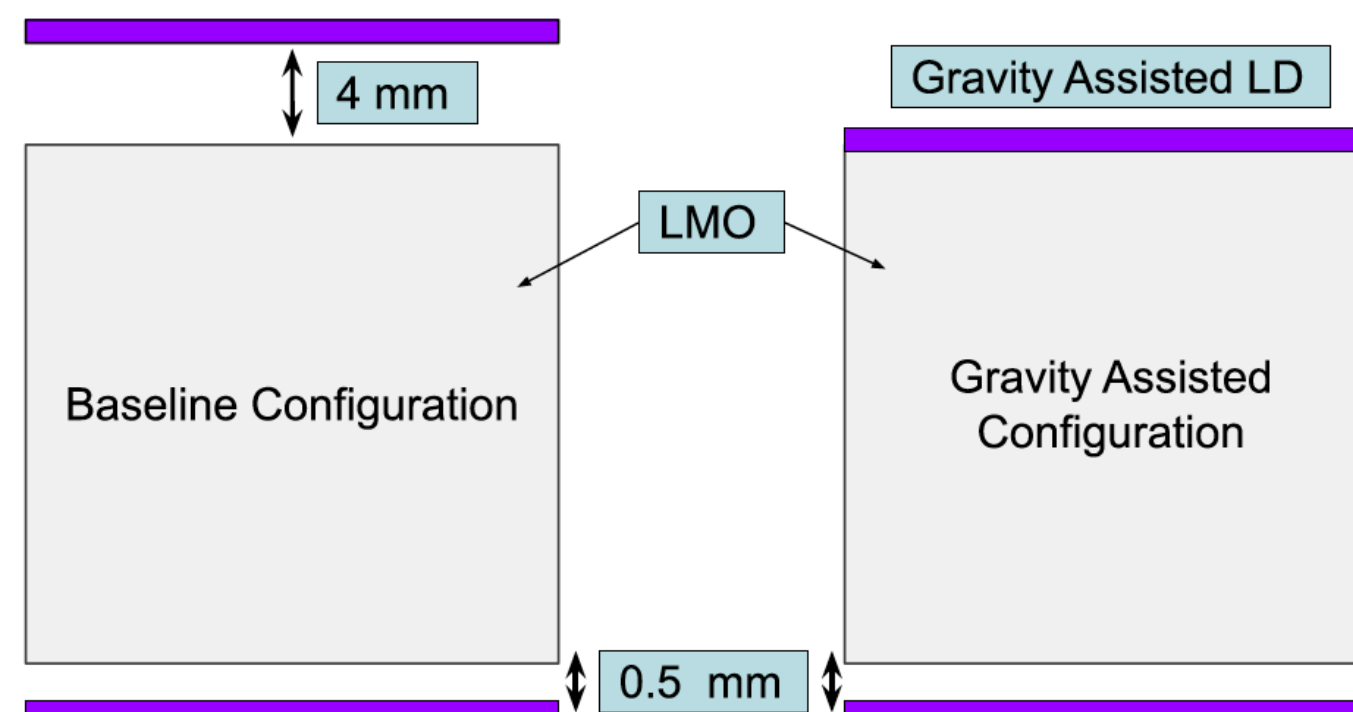
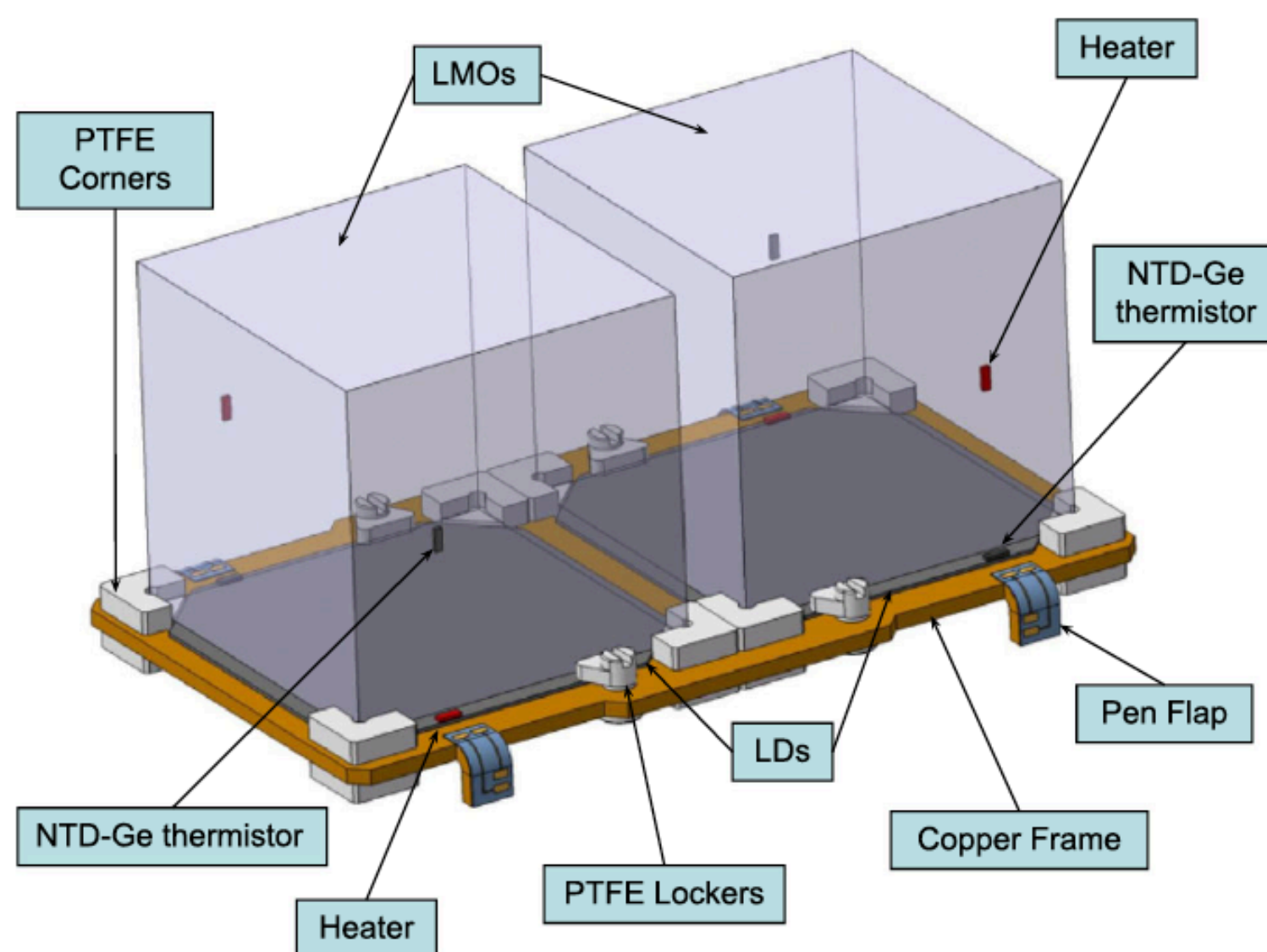
(CUPID-like proof-of-principle on small scale)

8 Li_2MoO_4 crystals (LMO)

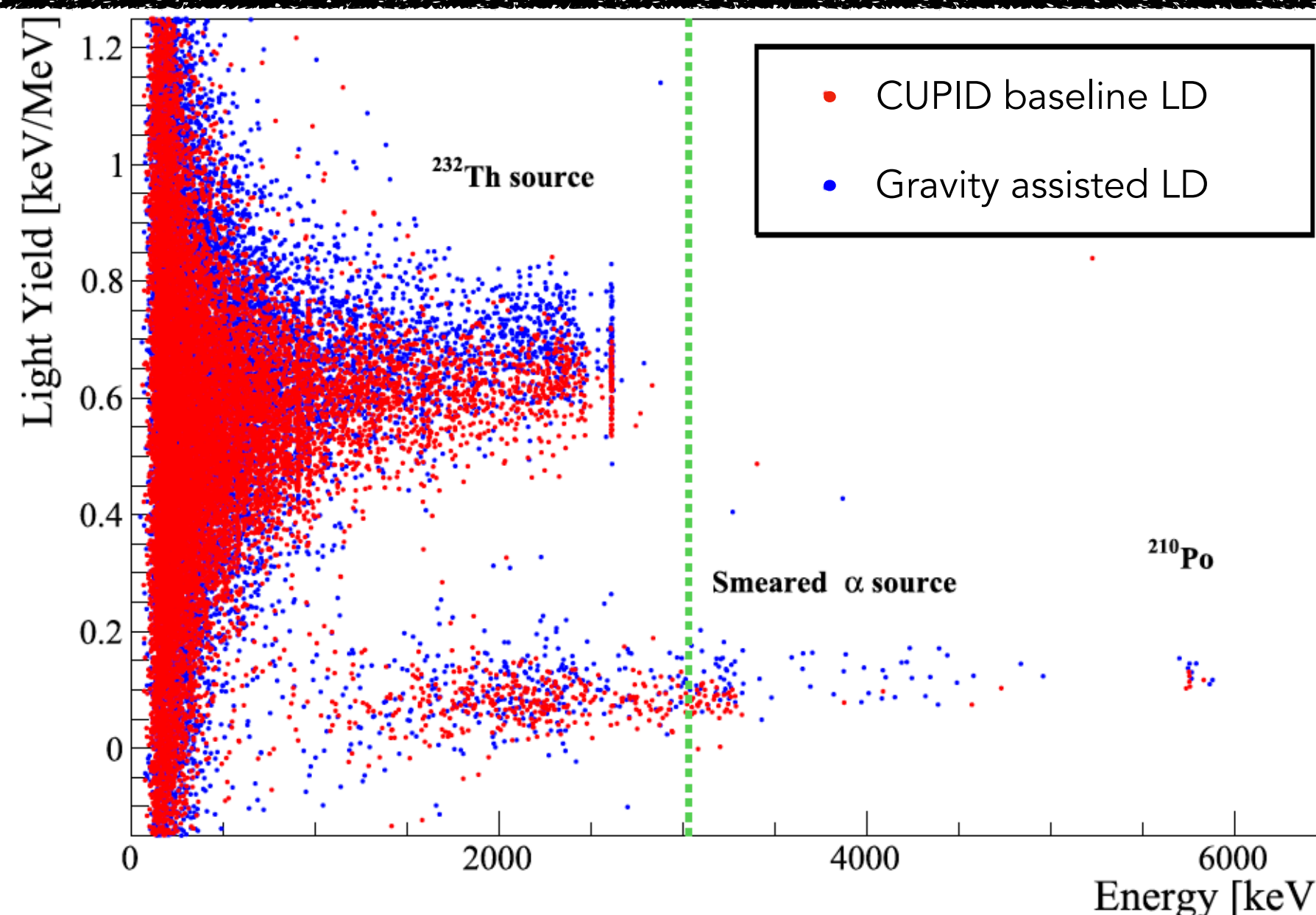
- natural Mo, cubic ($45 \times 45 \times 45 \text{ mm}^3$), 280 g
- NTD readout
- Si heaters

12 Ge light detectors (LD)

- SiO_2 antireflective coating, quasi-square
- NTD readout
- CUPID baseline LD vs Gravity assisted LD



CUPID collaboration, Eur. Phys. J. C 82 (2022), 810



Results

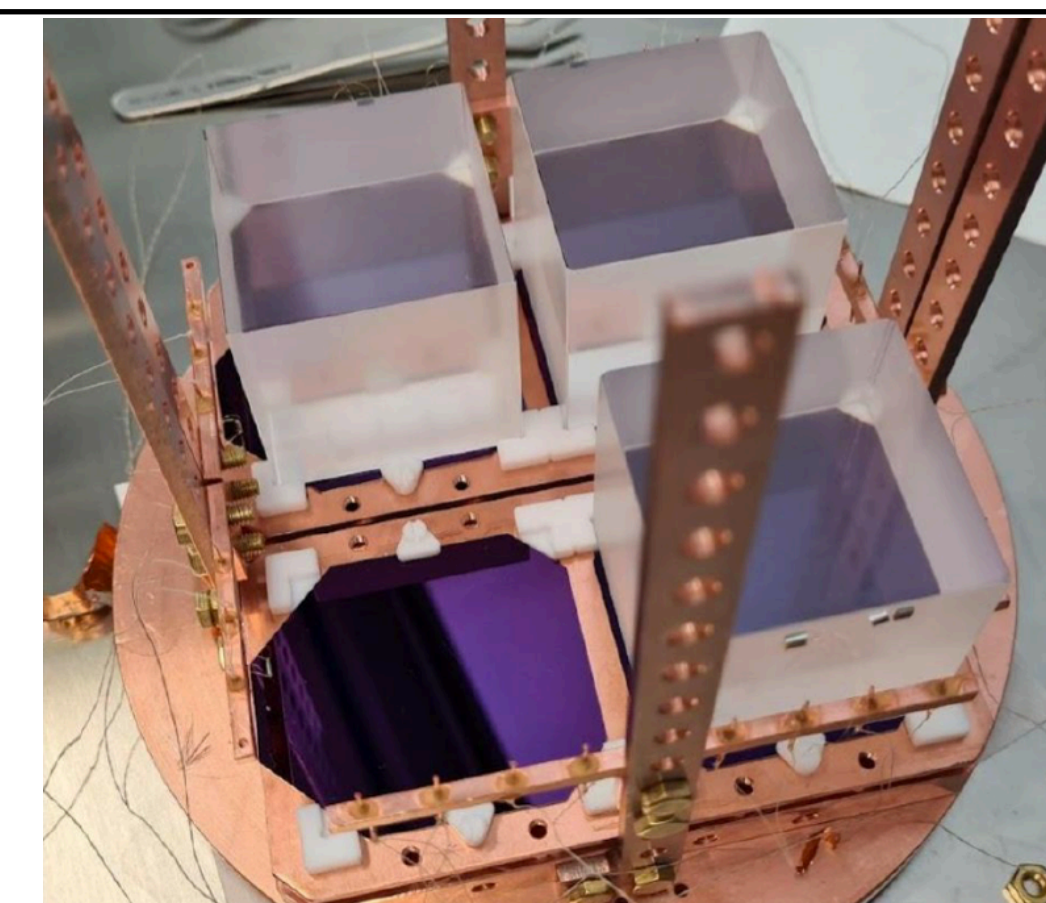
(in a LHe-based cryostat)

LMO crystals (energy resolution)

- $(0.69 \pm 0.06) \text{ keV RMS}$ on the baseline
- $(5.9 \pm 0.2) \text{ keV}$ at 3034 keV (^{100}Mo Q-value)

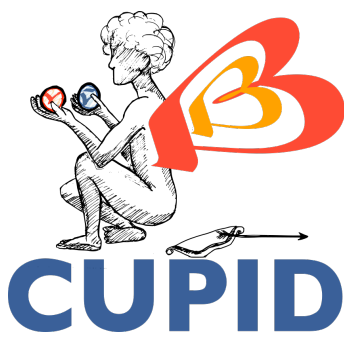
Ge Light Detectors

- energy resolution: 35-70 eV on the baseline
- LY: $(0.28 \pm 0.02) \text{ keV/MeV}$ for 4 mm-spaced, $(0.33 \pm 0.03) \text{ keV/MeV}$ 0.5 mm-spaced



α -particle rejection
> 99.9 % demonstrated

Light detector performance

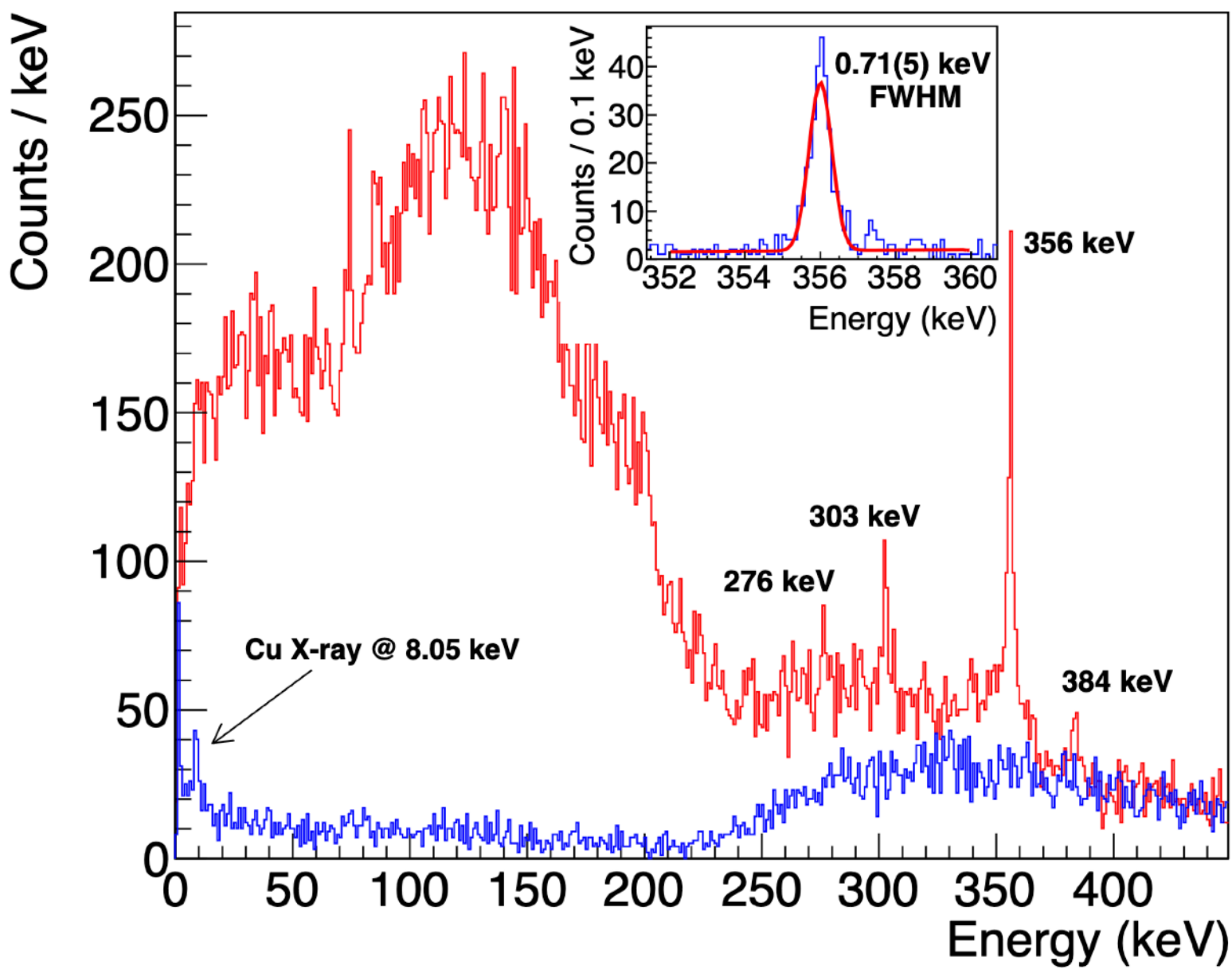
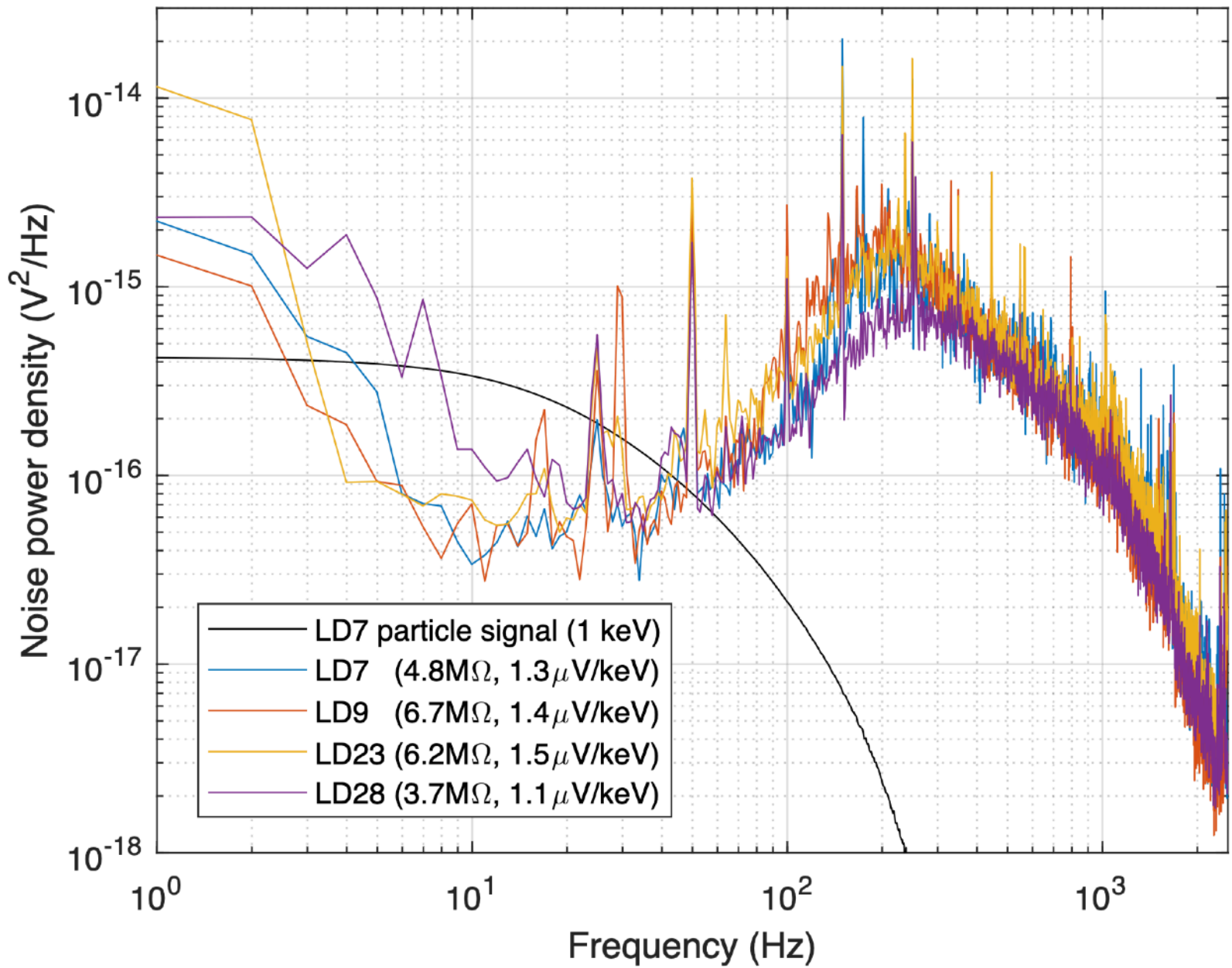
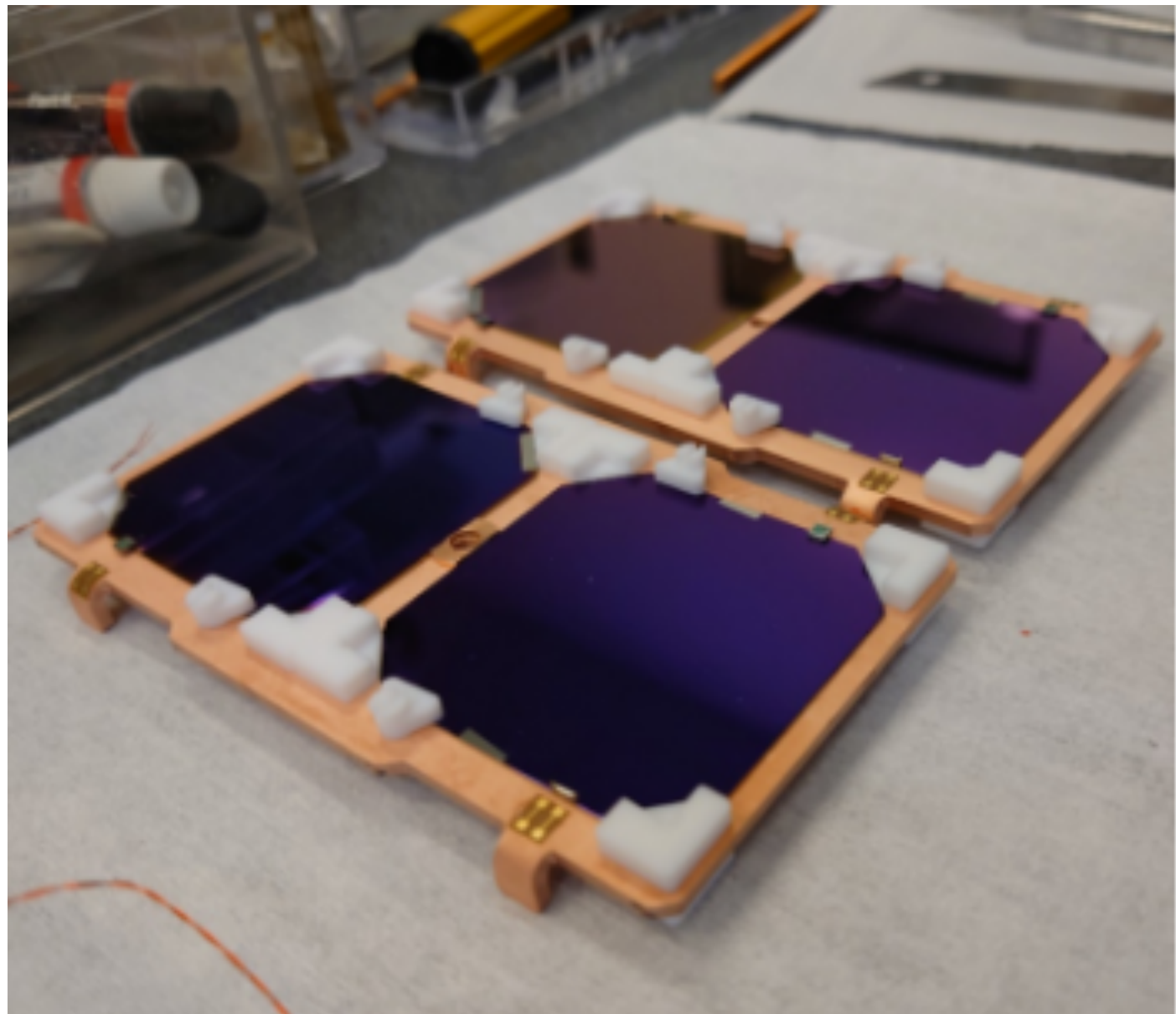


Results (in a PT-based cryostat)

- best energy resolution: 0.71 keV @ 356 keV
- average baseline resolution: 76 eV
- average rise time: 1.8 ms
- average sensitivity: 1.2 $\mu\text{V}/\text{keV}$

LD#	R_{NTD} (M Ω)	I_{NTD} (nA)	τ_r (ms)	τ_d (ms)	A_s ($\mu\text{V}/\text{keV}$)	RMS_{bsln} (eV)	FWHM_{356} (keV)
LD7	4.8	2.1	1.7	6.4	1.3	73(1)	1.84 ± 0.16
LD9	6.7	1.8	2.0	6.5	1.4	70(1)	0.71 ± 0.05
LD23	6.2	1.7	1.7	6.2	1.5	73(1)	–
LD28	3.7	2.1	1.8	9.8	1.1	89(1)	0.91 ± 0.08
Mean	5.1	1.9	1.8	7.0	1.2	76	

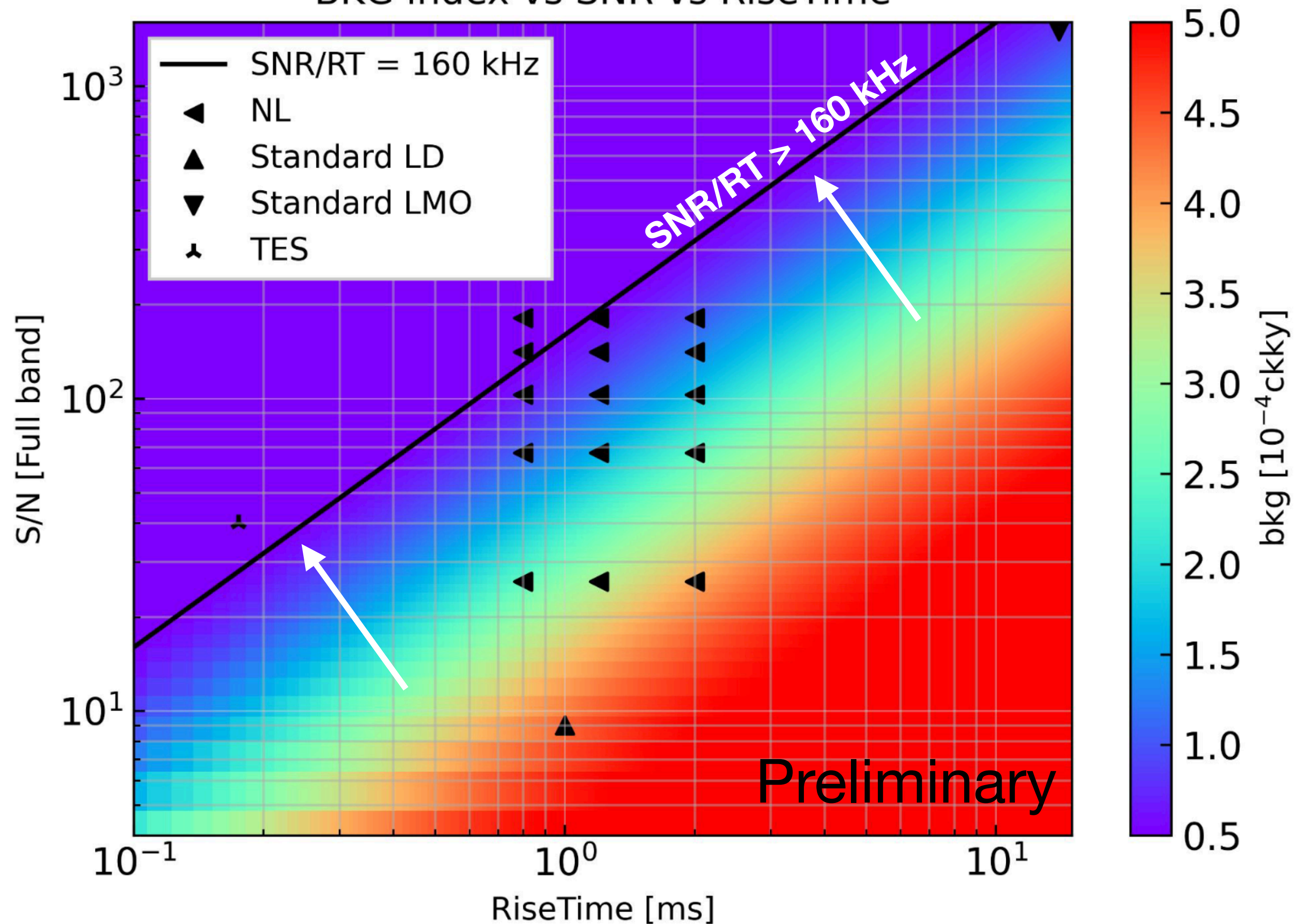
α -particle rejection
> 99.9 % confirmed
in a PT cryostat



K. Alfonso et al., JINST 18 P06033, Jun 2023

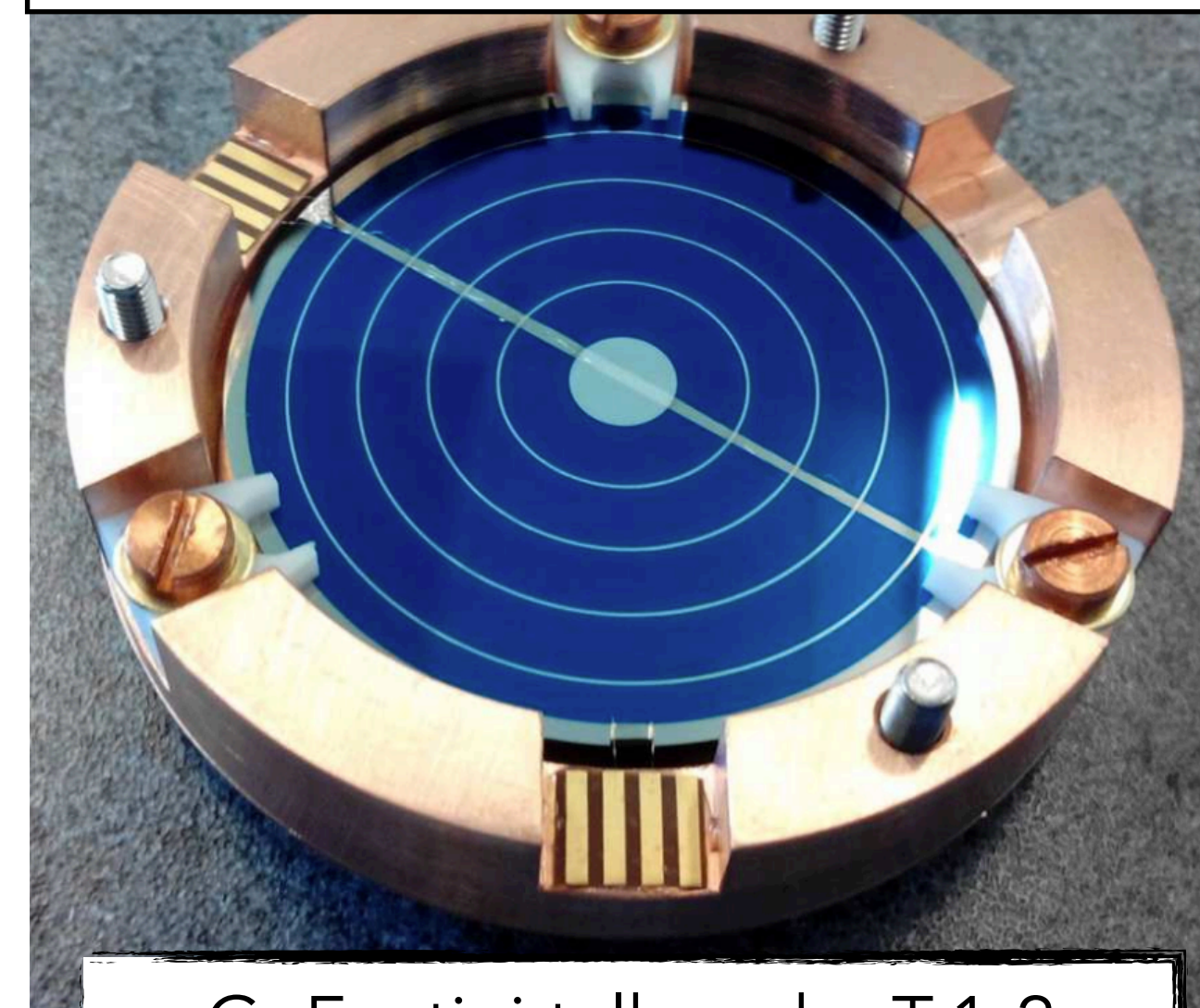
Requirement for pile-up rejection

BKG index vs SNR vs RiseTime



Shorten rise time or increase SNR
to achieve **$2v2\beta$ pile-up rejection**

NL increase SNR by factor ~ 25
 $2v2\beta$ pile-up rejection in reach



G. Fantini talk code: T-1-2

Detector Structure - from CUORE to CUPID

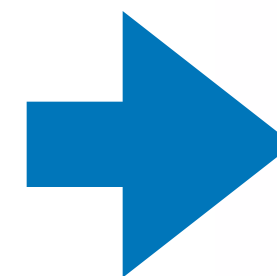
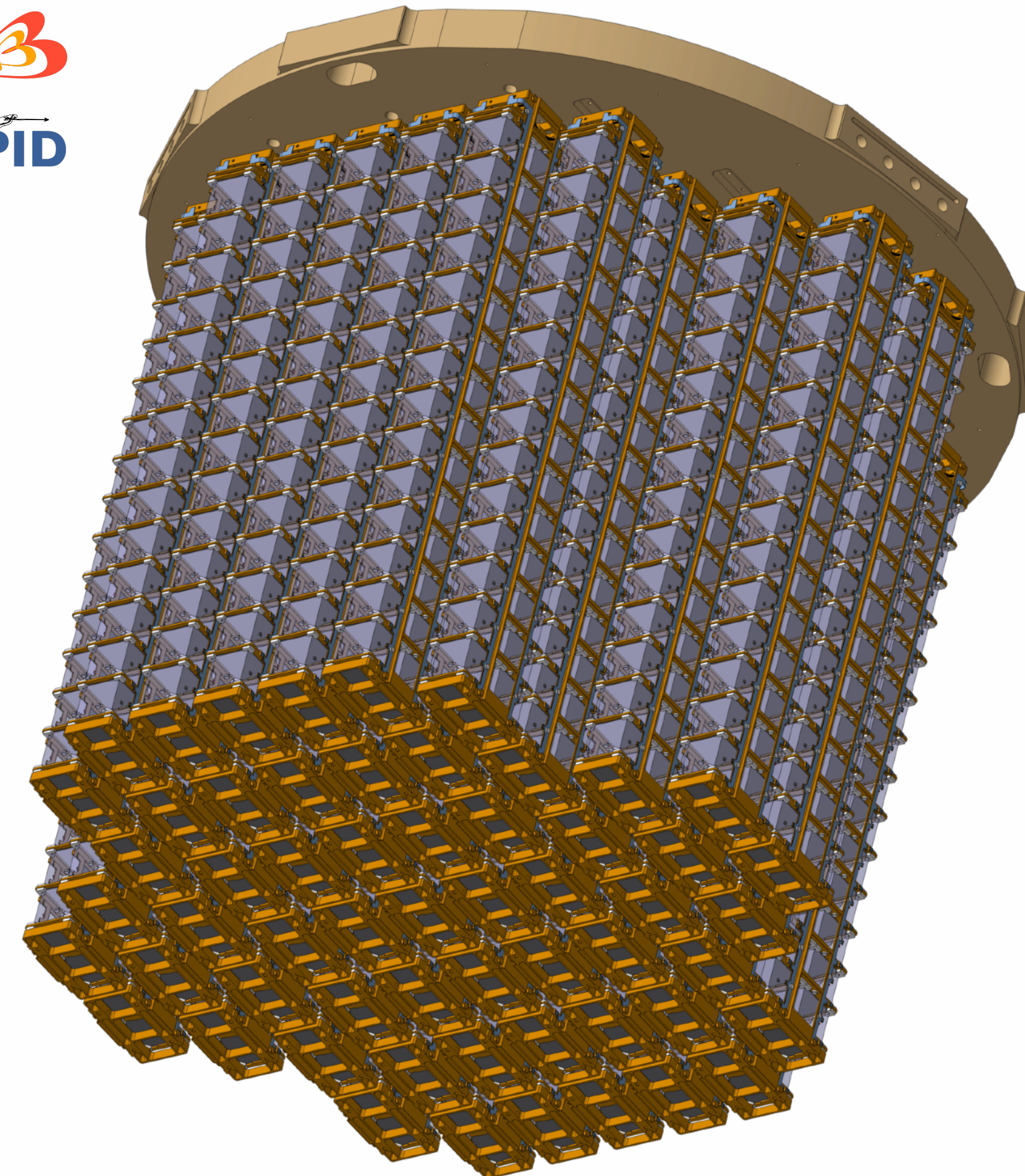
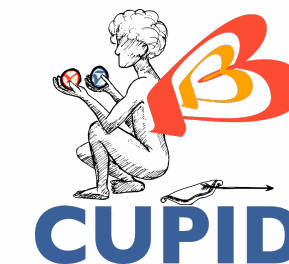
CUORE detector

19 towers, 988 TeO_2 crystals, ~2200 wires



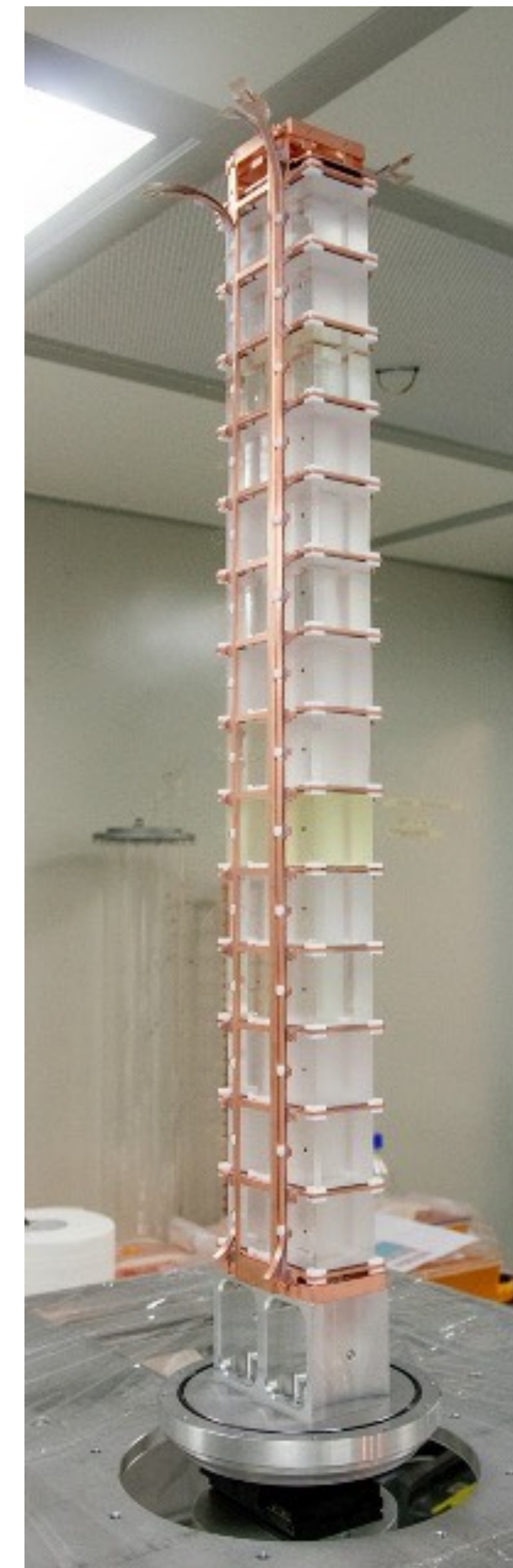
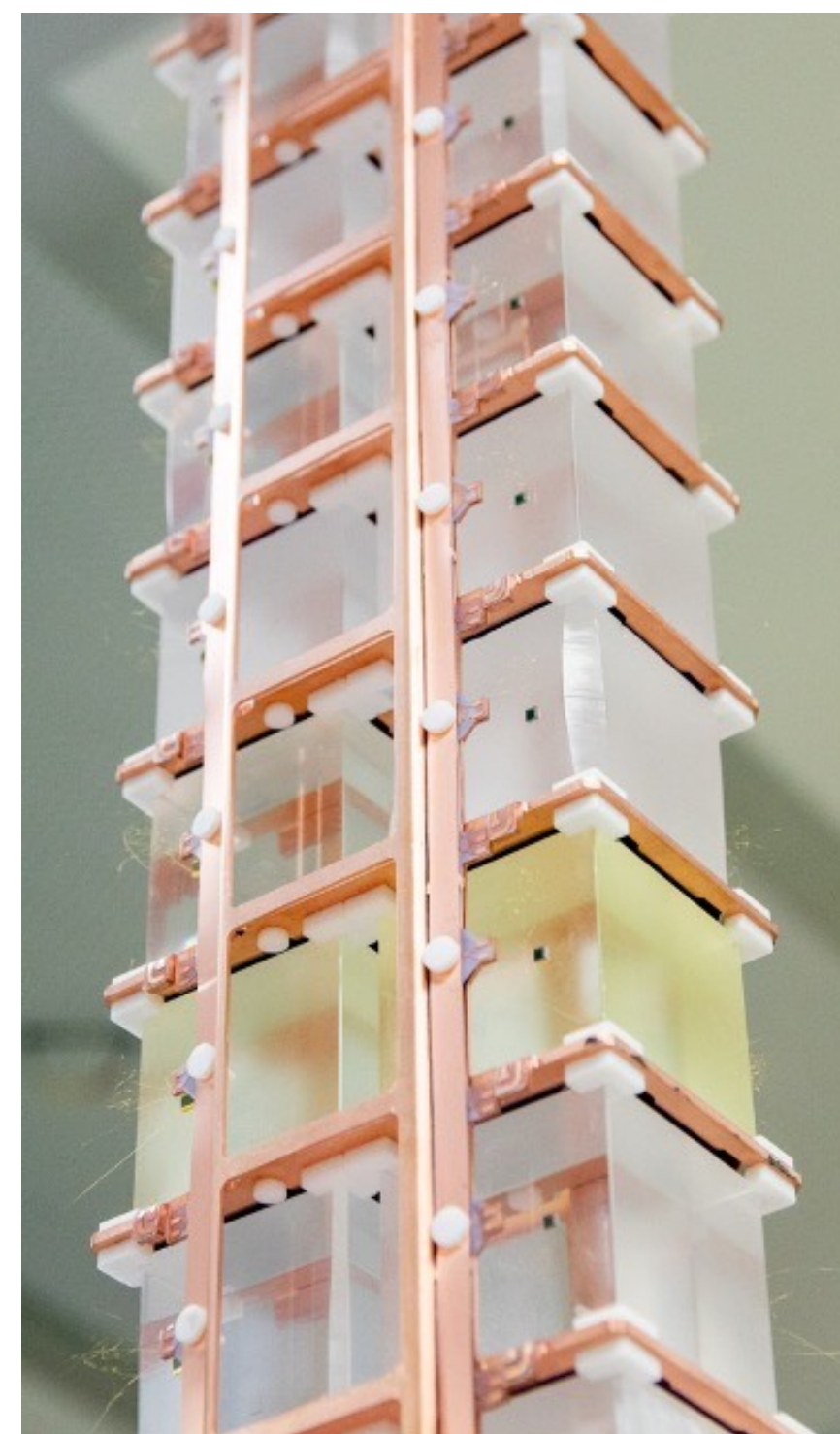
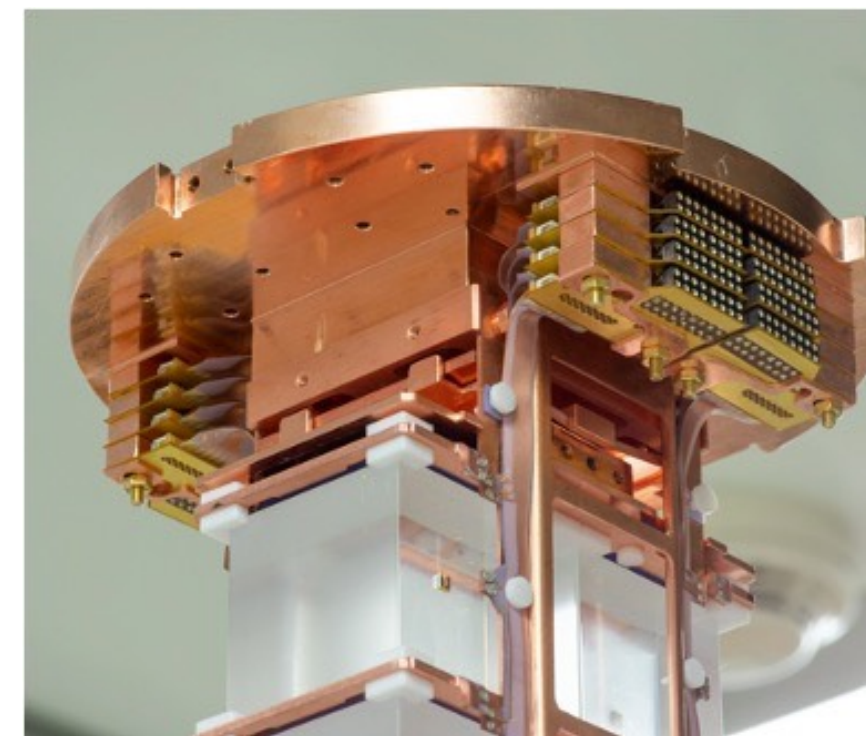
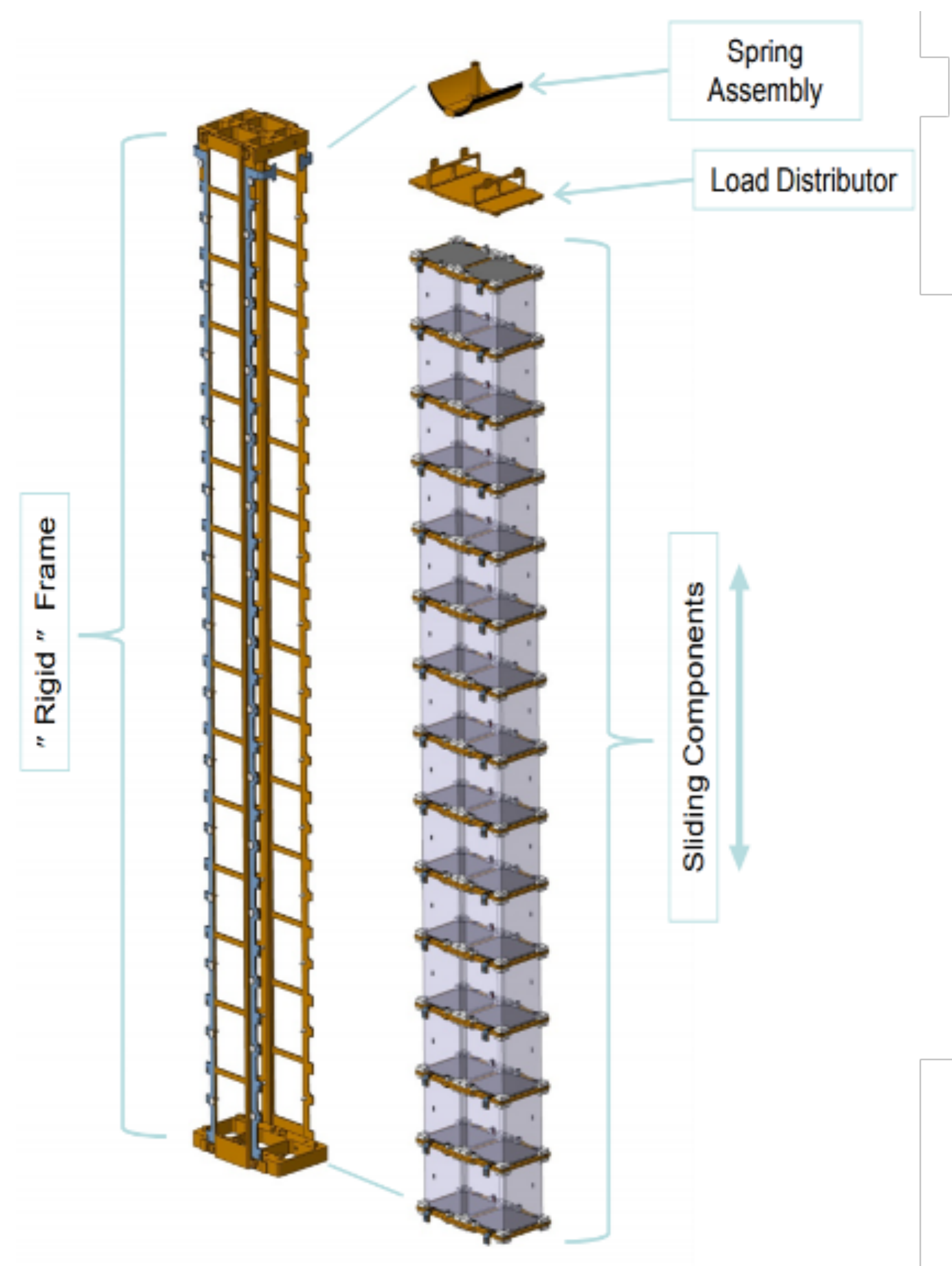
CUPID detector

57 towers, 1596 $\text{Li}_2^{100}\text{MoO}_4$ crystals, 1710 LD, ~7300 wires



Baseline Detector Prototype Tower (BDPT)

- “gravity assisted” - no vertical constraint, stack of crystals and light detectors sitting one on top of the other (vs. rigid, fixed height structure in CUORE)
- tunable spring at the top for vibration damping and extra rigidity during transport
- smaller Cu mass compared to CUORE
- easy and safe assembly - no screws, self-aligning structure
- loose tolerances - cost effective, easy cleaning



BDPT validation

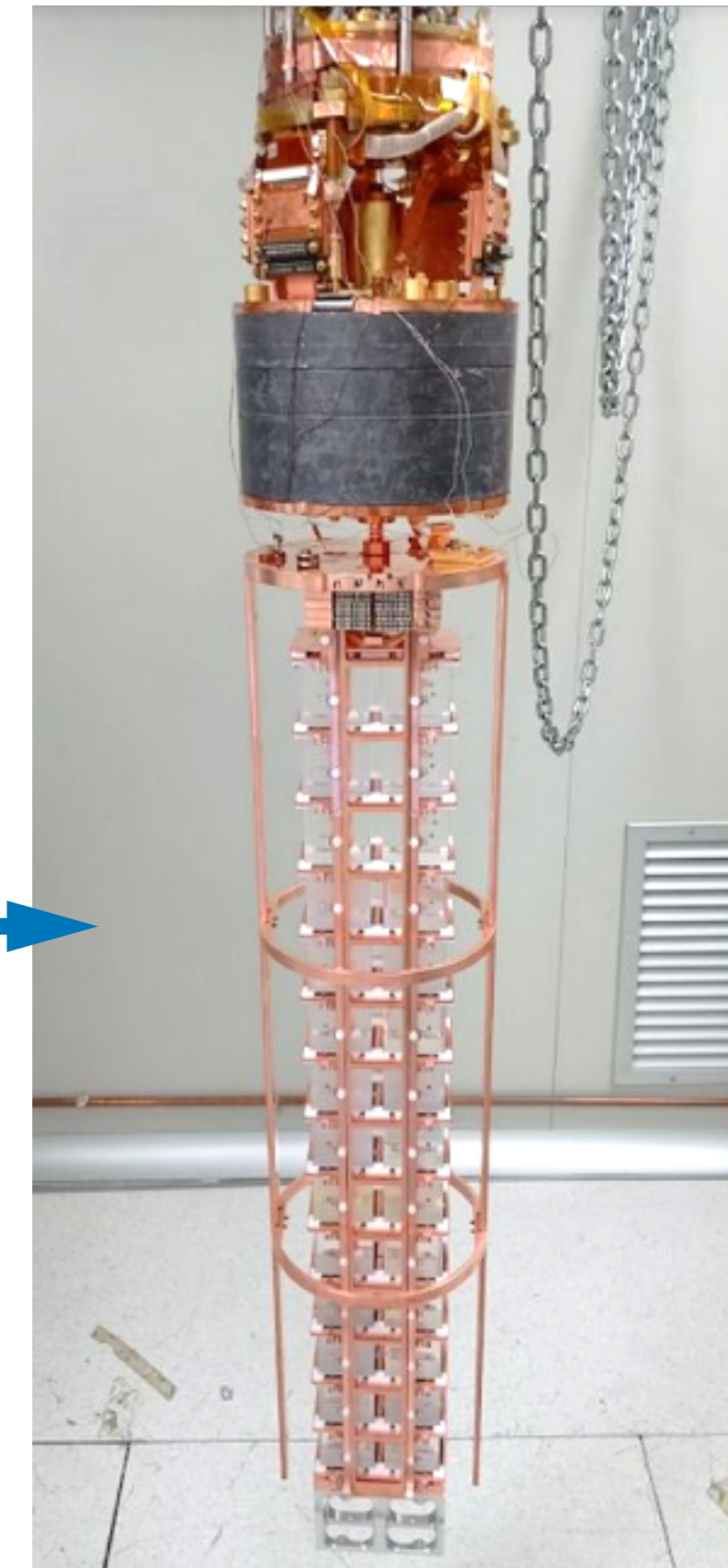
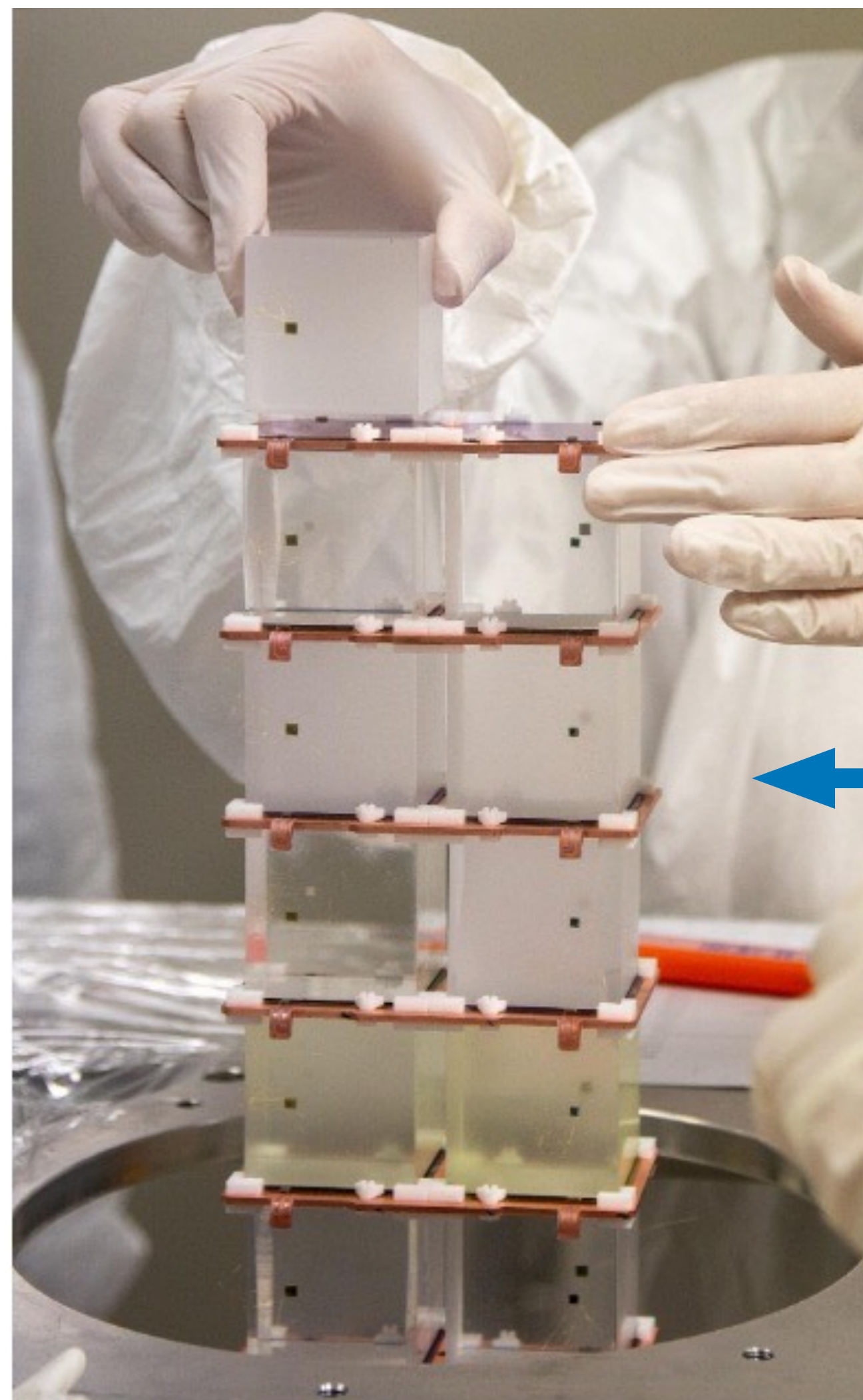
First test of the BDPT at LNGS

- 14 CUPID tower baseline modules
- 28 LMO crystals from different origins
- 30 Ge light detectors

Studies pursued

- Vibrational properties
- Thermalization on each floor
- Validation of the tower assembly procedure
- Tower installed at LNGS
- LMO and LD performance with spring loaded vs unloaded (Run1 vs Run 2)
- Further test on vibrations and thermalisation (Run 3) - ongoing

**First results : good detector performance,
still some study to make**



Cryostat status and upgrade

CUORE

Cryogen-free cryostat able to guarantee
 $T_{\text{base}} < 10 \text{ mK}$ for a ton-scale detector
over a 5 years live-time

- Cryogen-free cryostat:
 - 4 (5) Pulse Tubes (PT) each 1.2 W @ 4.2 K
 - Joule-Thomson expansion instead of 1K-pot
- Dilution refrigerator
 - no heater on Still
 - 4 μW @ 10 mK
 - Base temperature $\sim 7 \text{ mK}$
 - two independent condensing lines
- Fast cooling system:
 - precooling by cold gHe circulation
 - 1800 W at 77 K

A. Alduino, et al.,
Cryogenics, 102 9-21 (2019)

UPGRADE

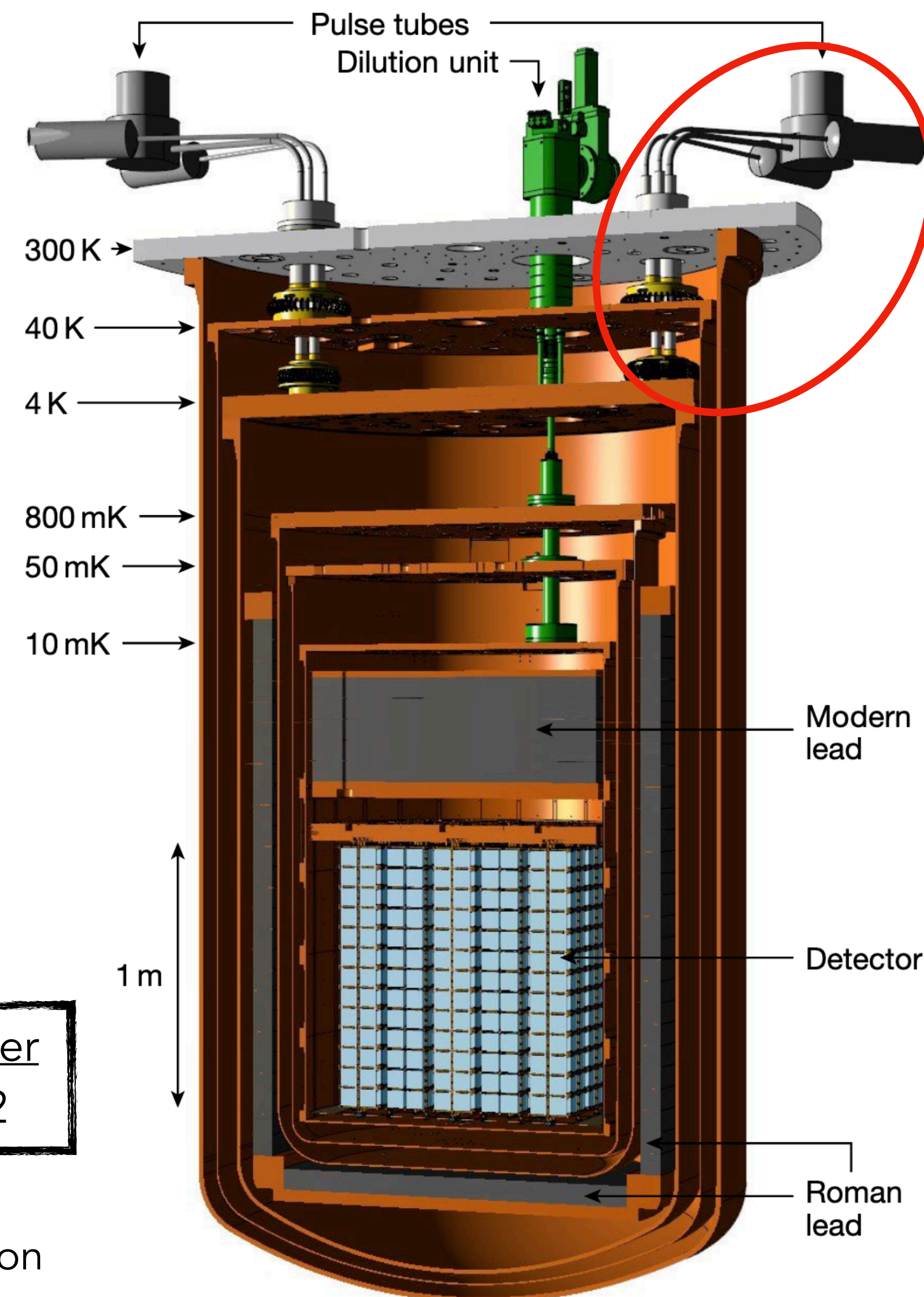
- 3 (4) Pulse Tubes (PT) each 2.2 W @ 4.2 K
- more effective mechanical decoupling
- 6 μW @ 10 mK with 10 mW on Still
- DCS removal

Masses

- 40 K: $\sim 0.98 \text{ ton}$
- 4 K: $\sim 7.4 \text{ ton}$
- 800 mK: $\sim 0.84 \text{ ton}$
- 50 mK: $\sim 3.0 \text{ ton}$
- 10 mK: $\sim 1.5 \text{ ton}$

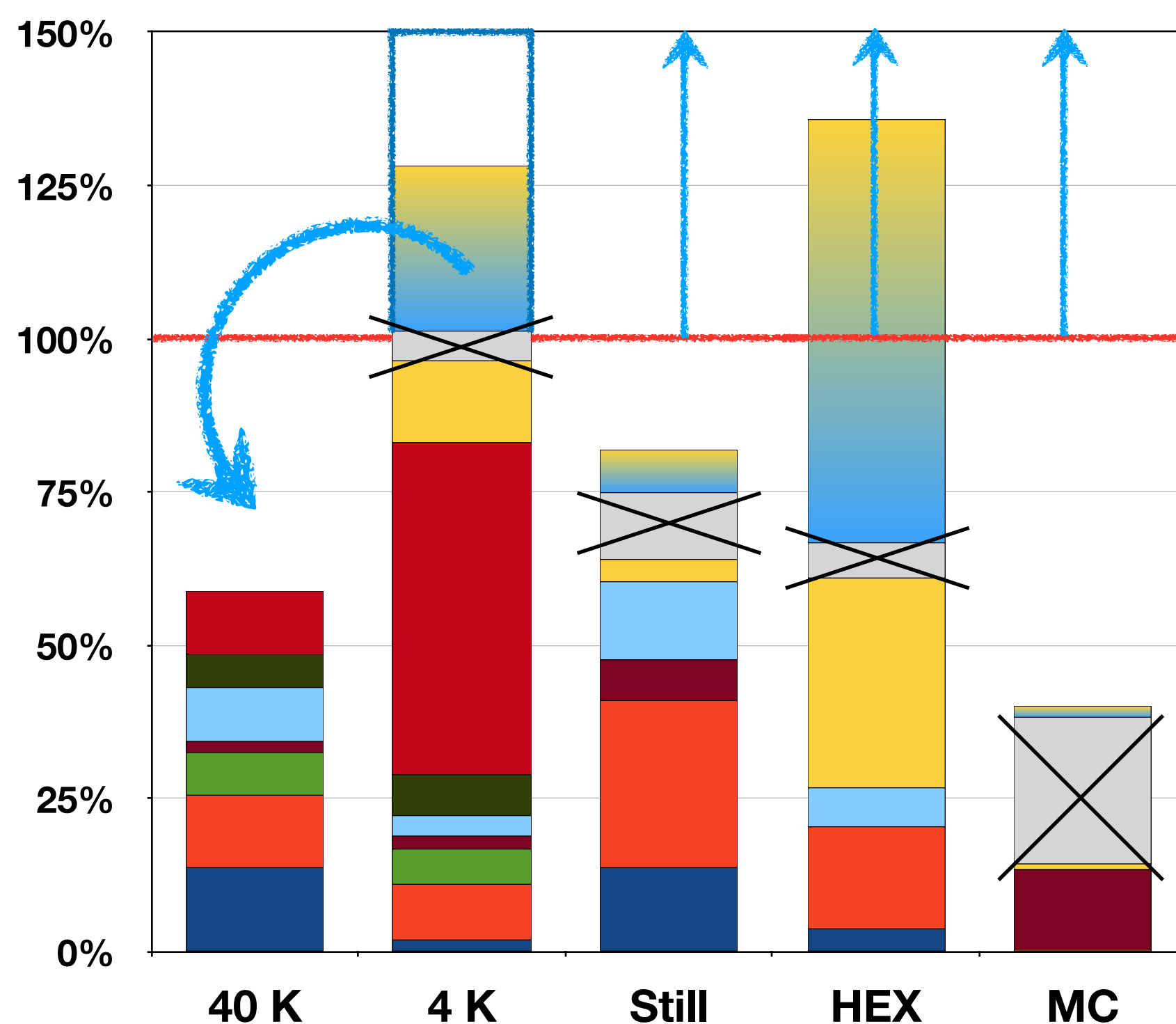
See S. Fu poster
code: RP-032

- 10 mK: $\sim 1.2 \text{ ton}$



Cryostat upgrades

CUORE cryostat thermal budget well known and understood



Preliminary CUPID thermal budget

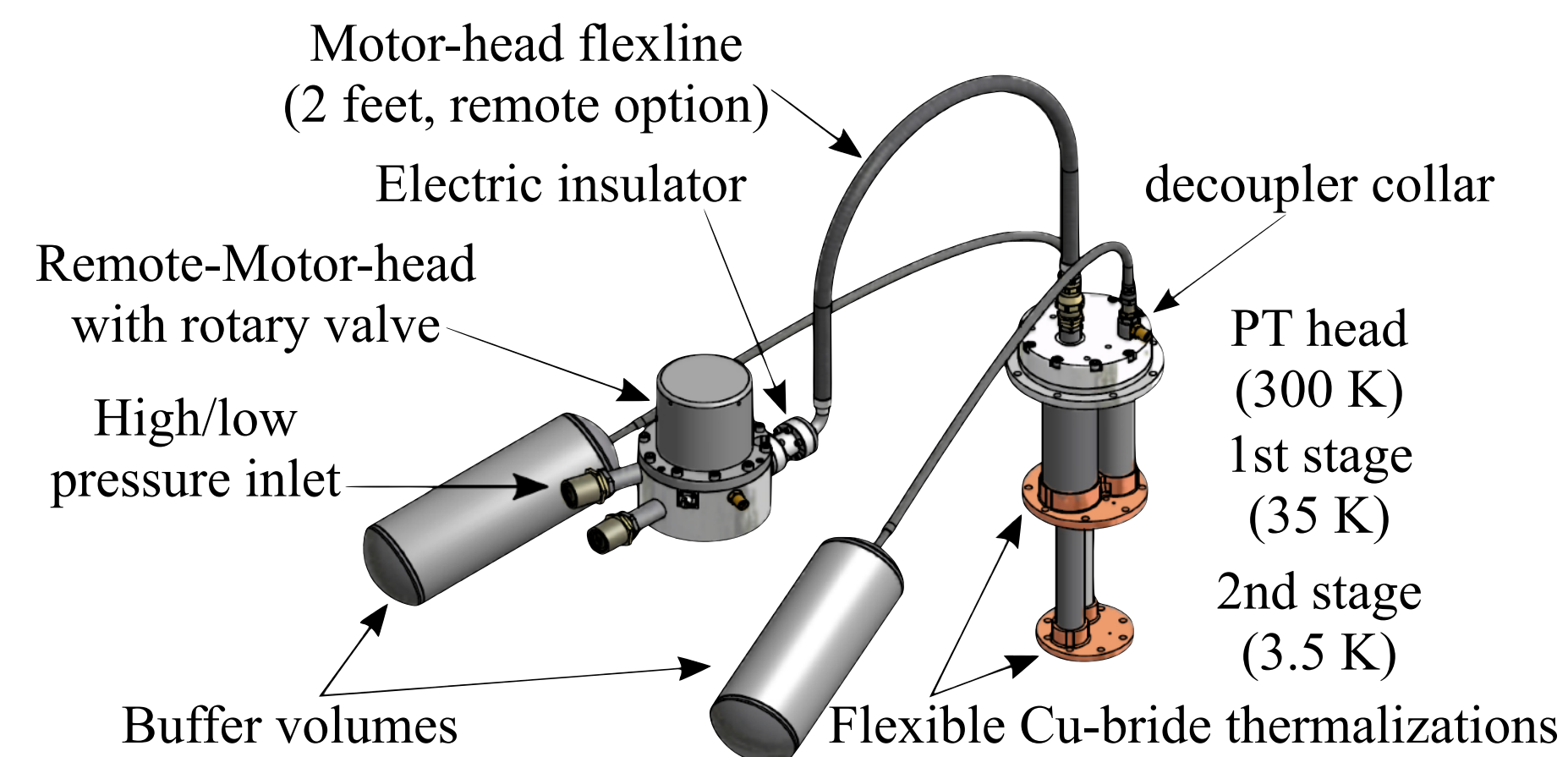
- Wires from CUPID
- ~~DCS~~
- Wires
- 3He flow
- Pb heat
- Cu heat
- Spare PT
- Lead suspension
- Detector suspension
- Access ports
- Tie rods
- Radiation

CUORE thermal load limit

CUPID thermal load limit

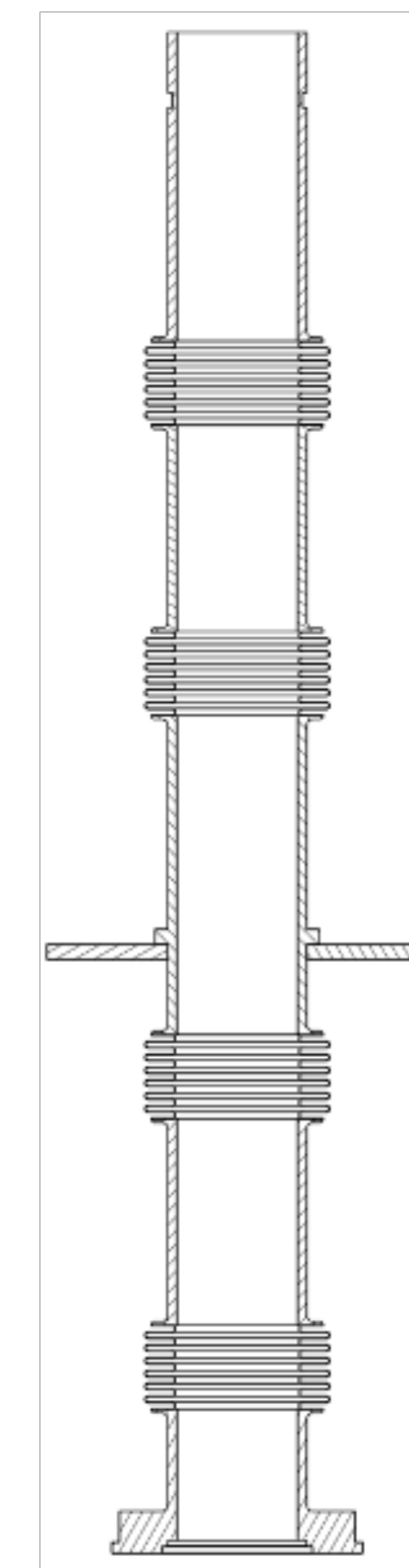
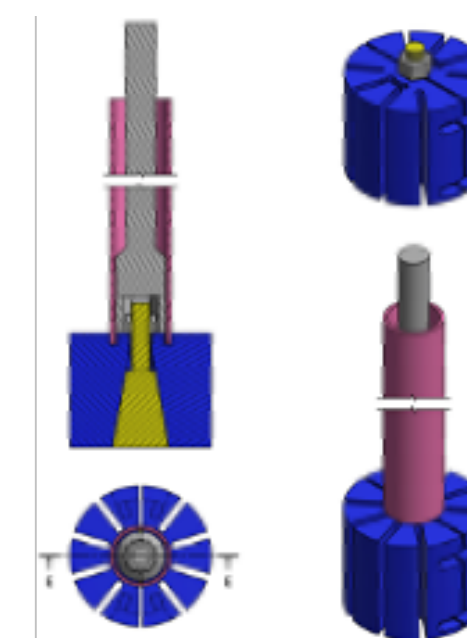
Strategies against higher heat load

Increase available cooling power at 4 K and 40 K



Parallel strategy: move wiring heat load from 4 K to 40 K

- wires increase by a factor 3
- new thermalization at 40 K



Vibration abatement

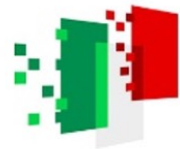
Based on CUORE experience we see a strong correlation between the noise of the detectors and the vibration level

L. Marini
talk code F-2-2

1.4 Hz working frequency and related harmonics from PTs give the strongest contribution

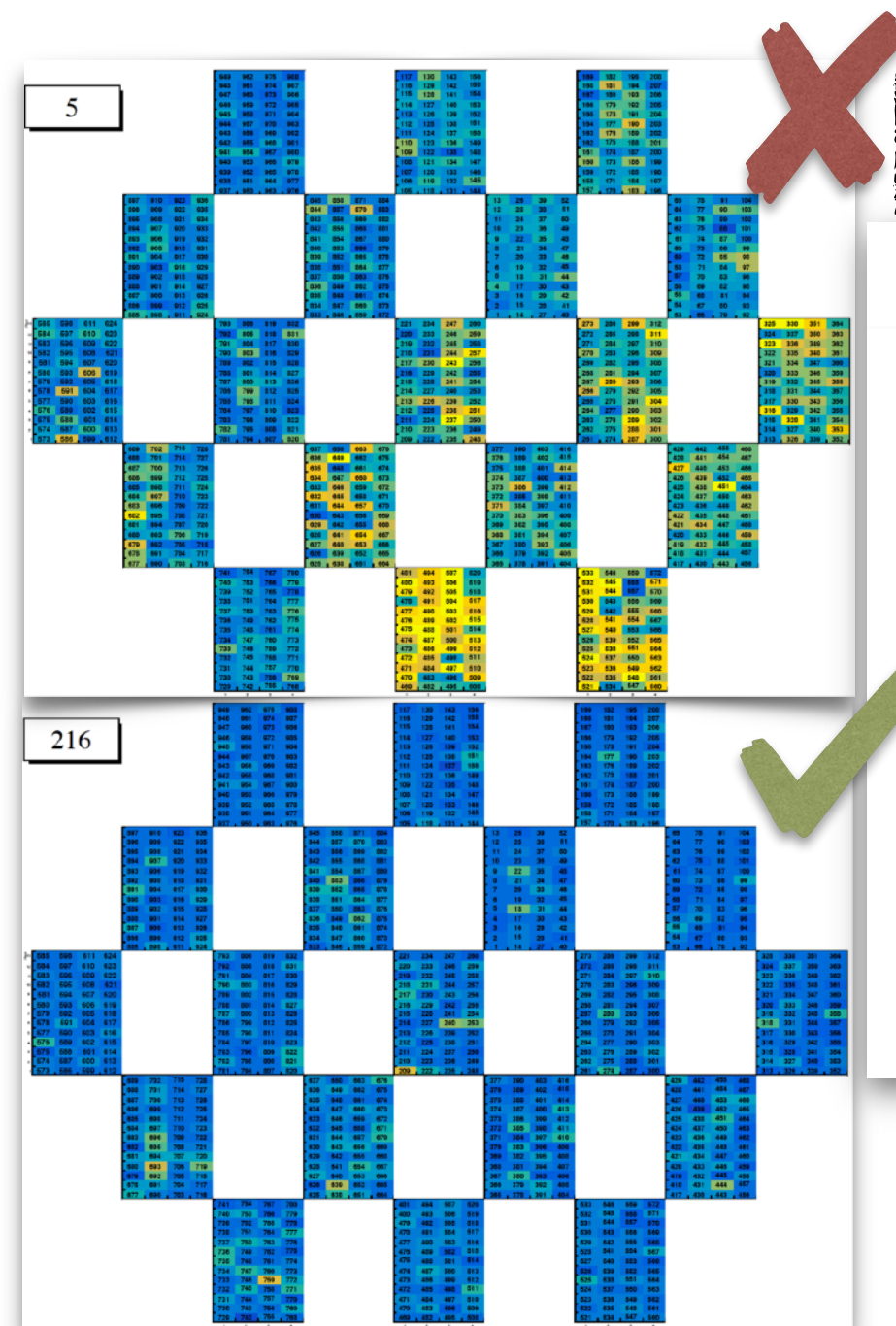
- Upgrade of the Pulse Tube cryocooler system:

- from 4 PT415-RM (1.2 W@ 4.2 K each) to 3 PT425-RM (2.35 W@ 4.2 K each)

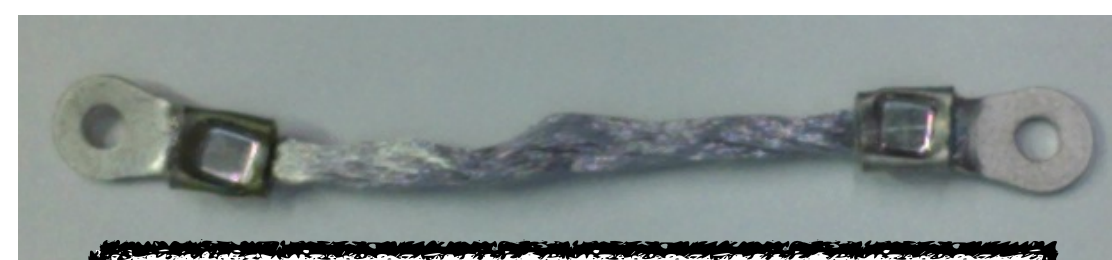
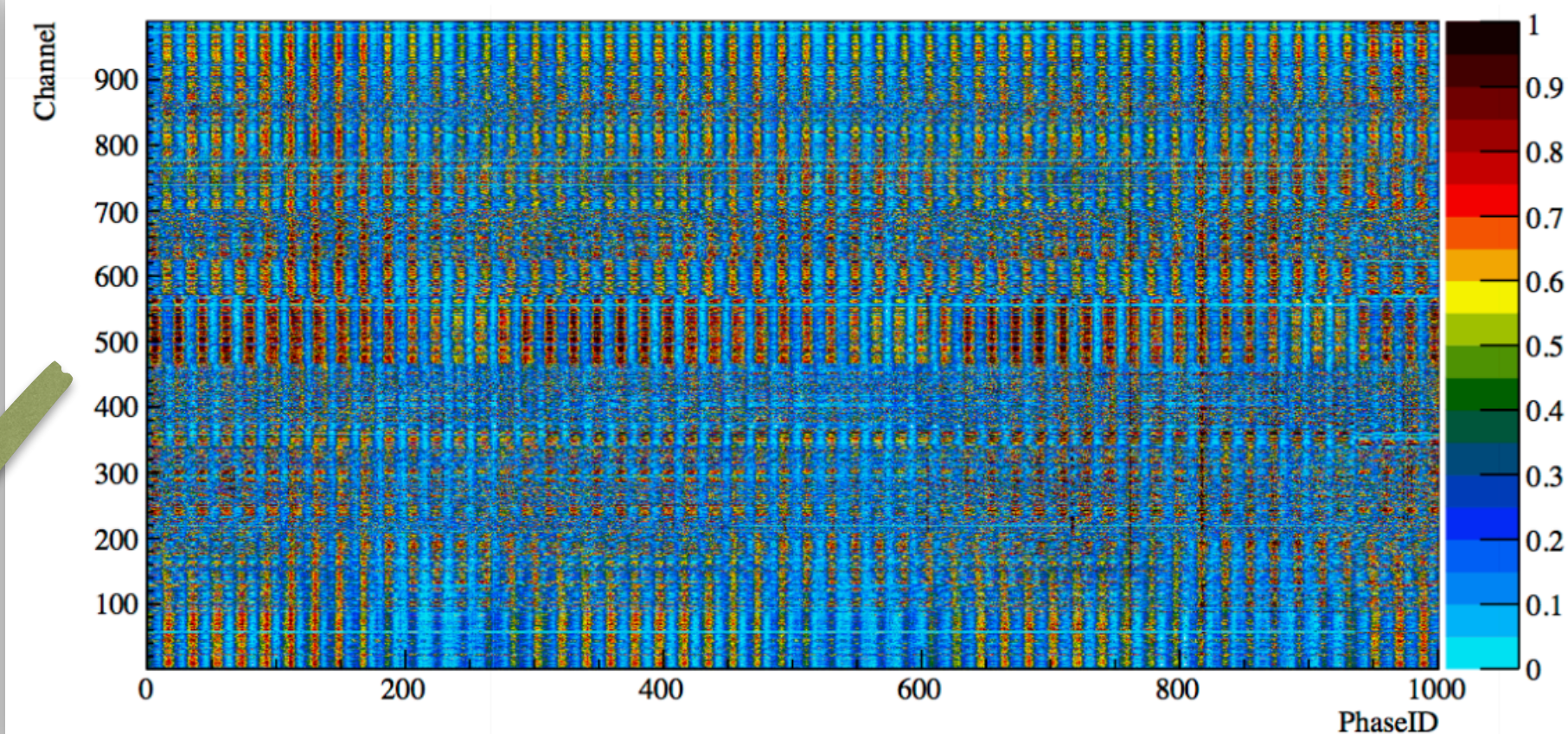


- high purity Al thermal links (e.g. KAGRA)
- upgrade of the active noise cancellation system

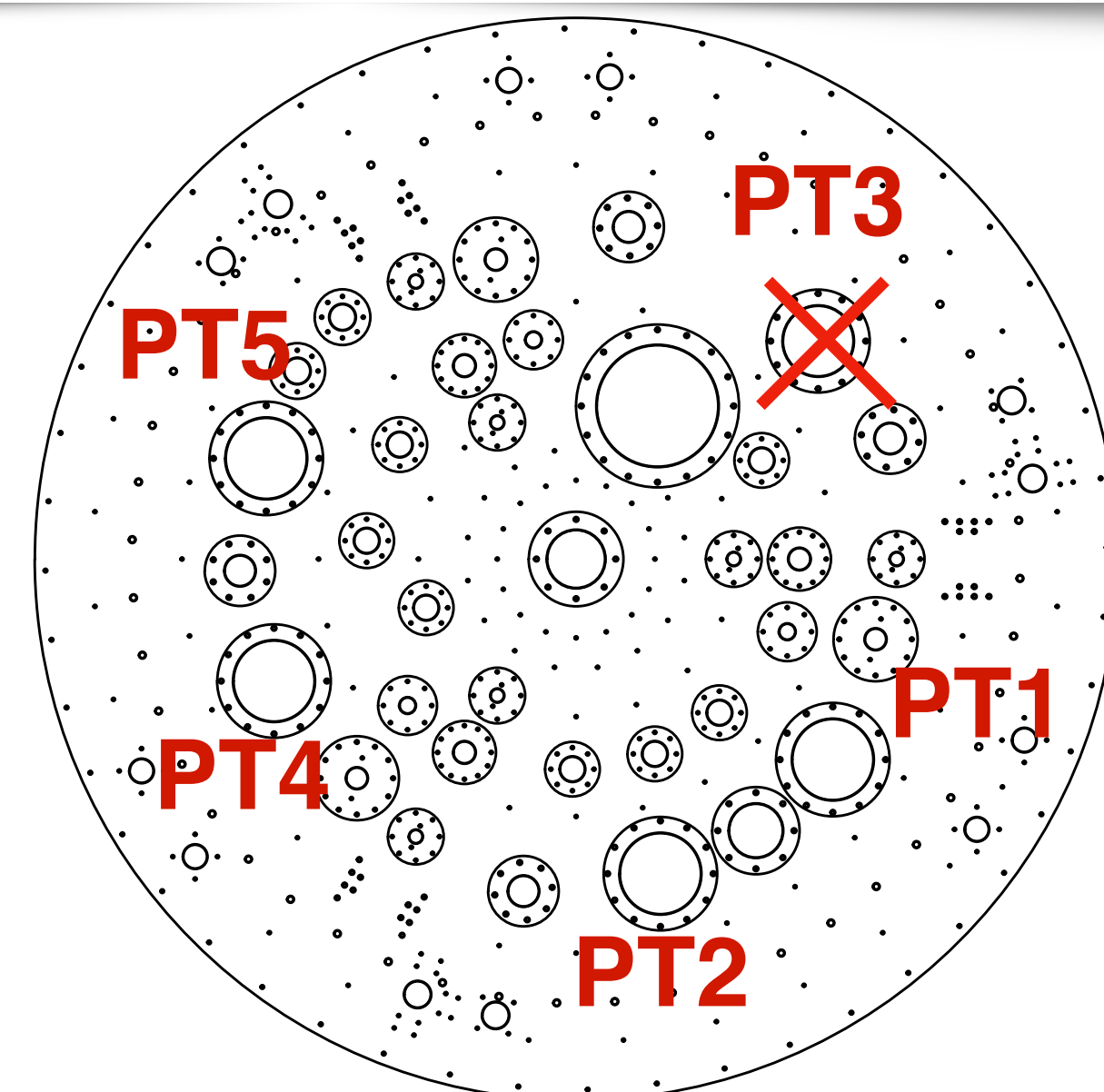
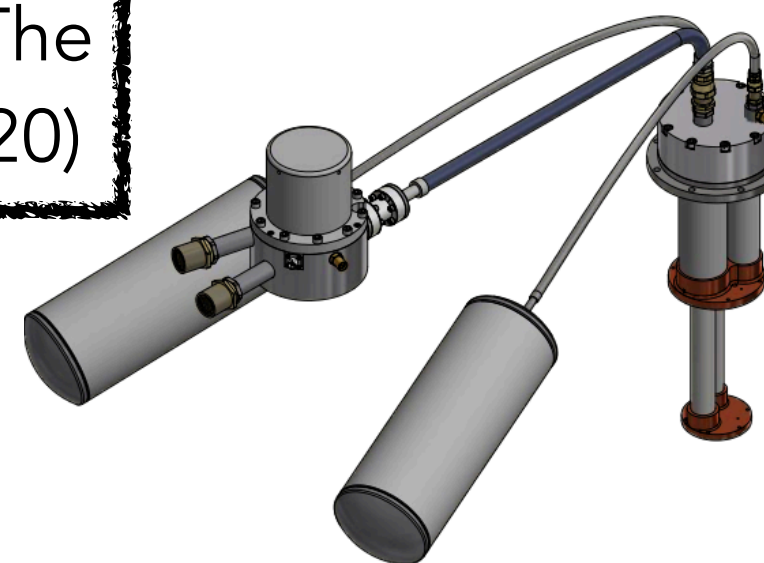
- Validation with the CUORE detector at the end of CUORE science program: critical test of the impact of the upgrades in terms of vibration decoupling and thermal performance



A. D'Addabbo et al., Cryogenics 93 (2018), 56-65



T. Yamada, PhD thesis, The University of Tokyo, (2020)



Conclusions

- CUPID will operate a **ton-scale array at 10 mK on a time scale of a decade**
- Collaboration has **operational experience at LNGS for ton-scale, macro-calorimeters experiment** and utilizes **existing infrastructure** (CUORE cryostat, experimental site)
- **CUPID detector towers design and assembly successfully validated**
- **CUPID detector α -particle rejection capability demonstrated**
- **Limited technology verification remaining to achieve $2\nu 2\beta$ pile-up rejection**
- Scheduled a **cryostat upgrade** to allow the handling of ~ 7300 wires down to 10 mK and to reduce vibration noise

Thanks for your attention

