CUPID:
CUORE Upgrade with Particle ID

CUPID

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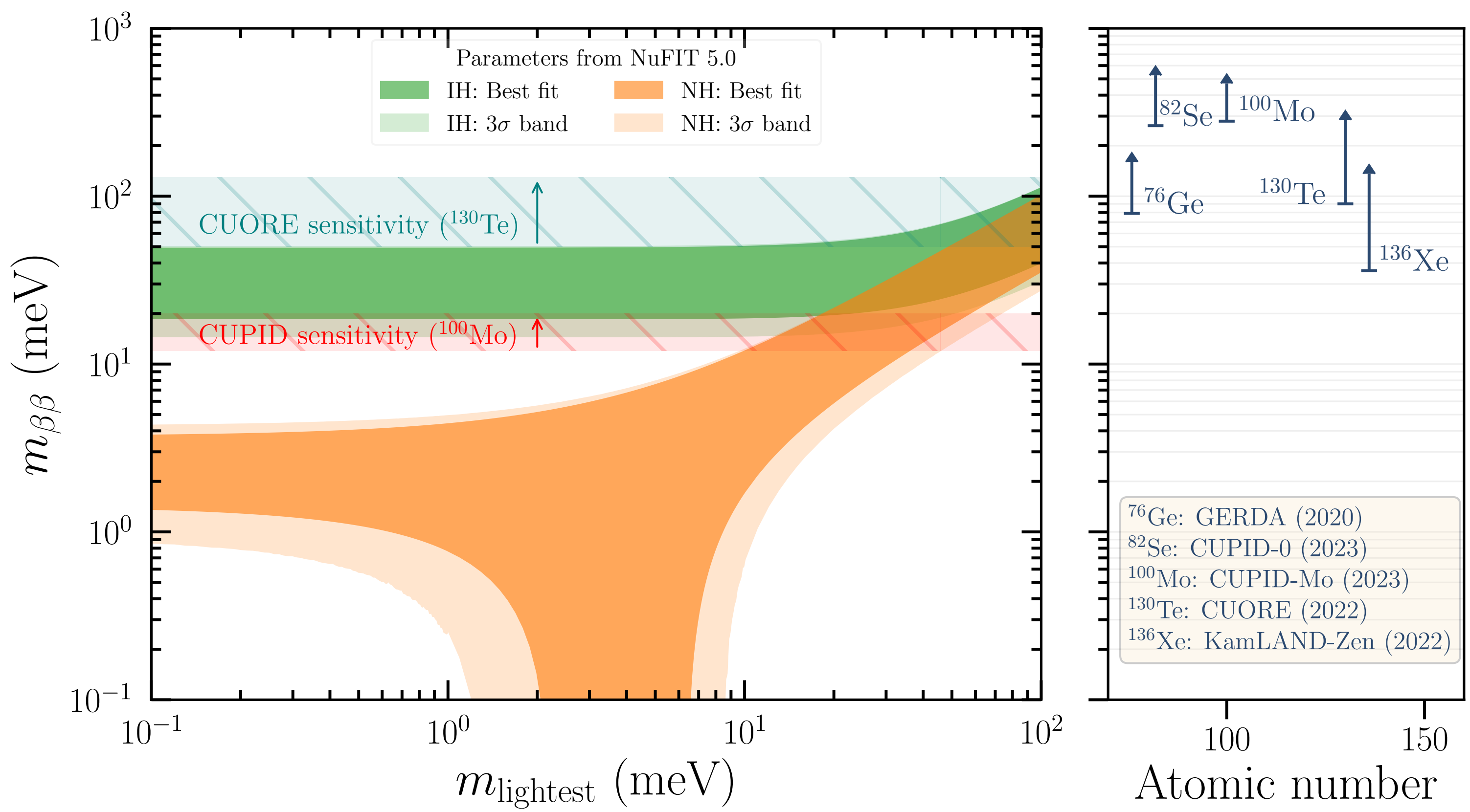
GOAL

Cover the Inverted Hierarchy and a fraction of Normal Hierarchy

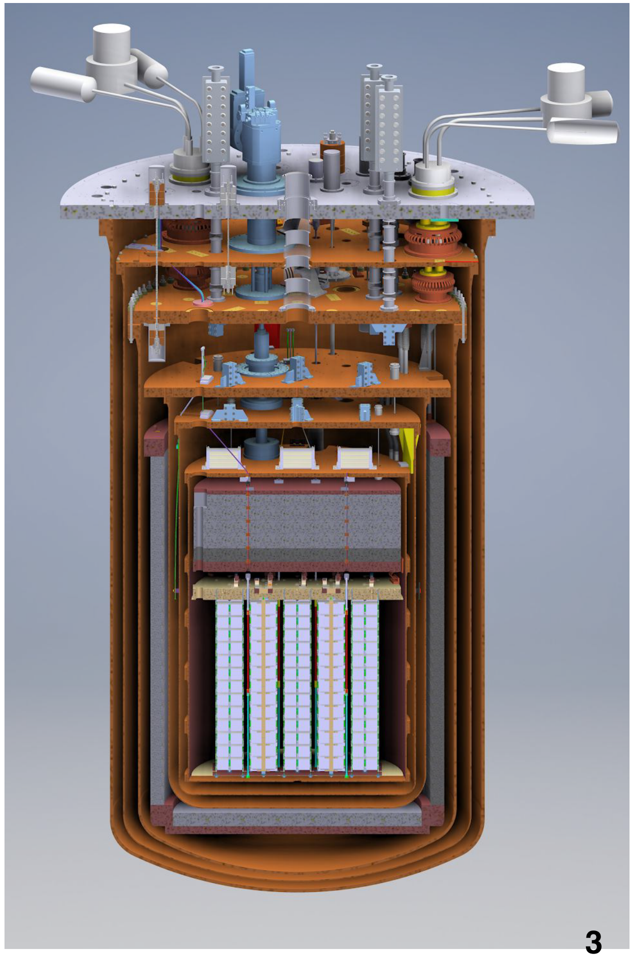
- 3σ discovery sensitivity $m_{\beta\beta}$: [13-21] meV
- 3σ discovery sensitivity $T^{0\nu}_{1/2} > 10^{27}$ yr



CUPID Strategy

A ton scale high-resolution detector array for the search of $0\nu\beta\beta$

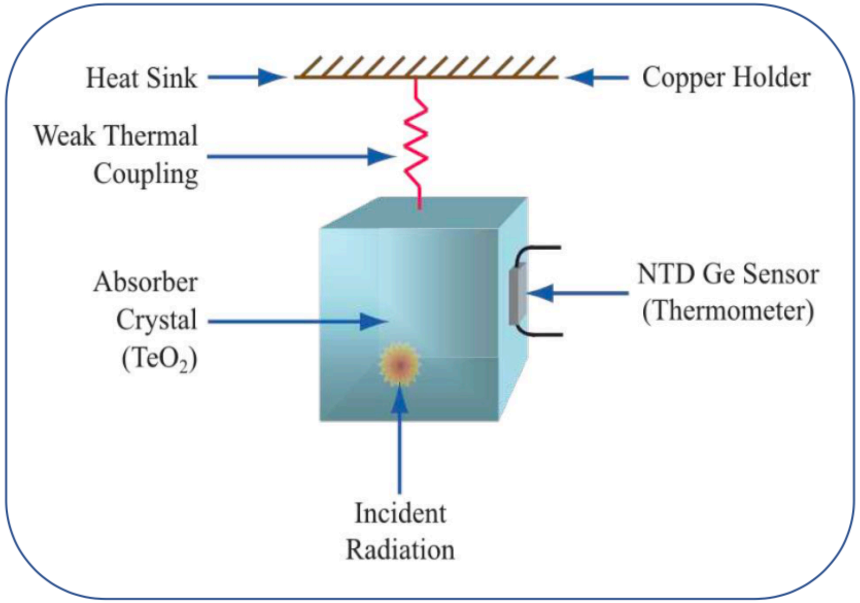
- Re-use CUORE Infrastructure
- Replace CUORE ${}^{nat}TeO_2$ detectors with an array of 95% enriched $Li_2{}^{100}MoO_4$



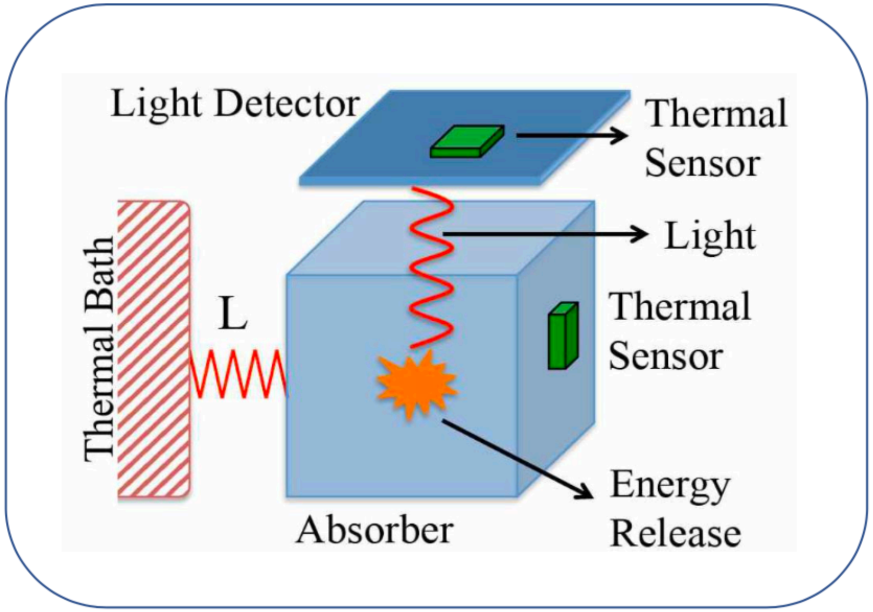
- Enough to take a leap forward in sensitivity because background reduces dramatically (~x100):
  - ${}^{100}Mo$ has higher $Q_{\beta\beta}$ (3037 keV) than ${}^{130}Te$ (2527 keV): lower γ-induced background, more favourable phase space and matrix element
  - new detector with very efficient α particle rejection: remove the dominant background in CUORE

Concept

CUORE ^{130}Te
pure thermal detector
(bolometer)

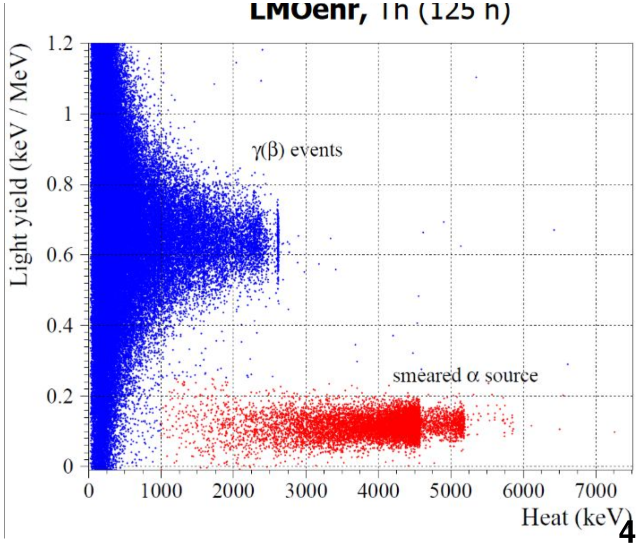


CUPID ^{100}Mo
heat + light
(scintillating bolometer)



No PID
Q = 2527 keV **< 2615 keV**

~~α background~~
PID



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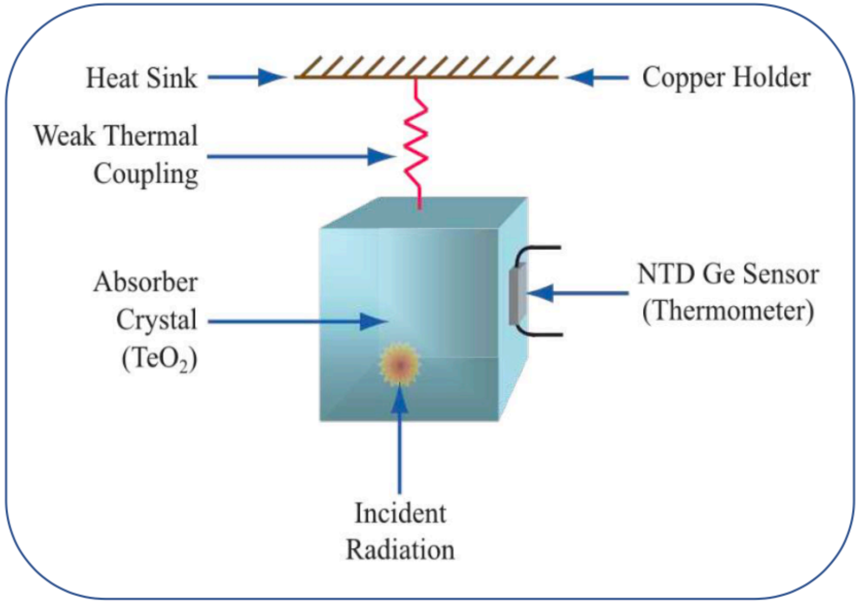

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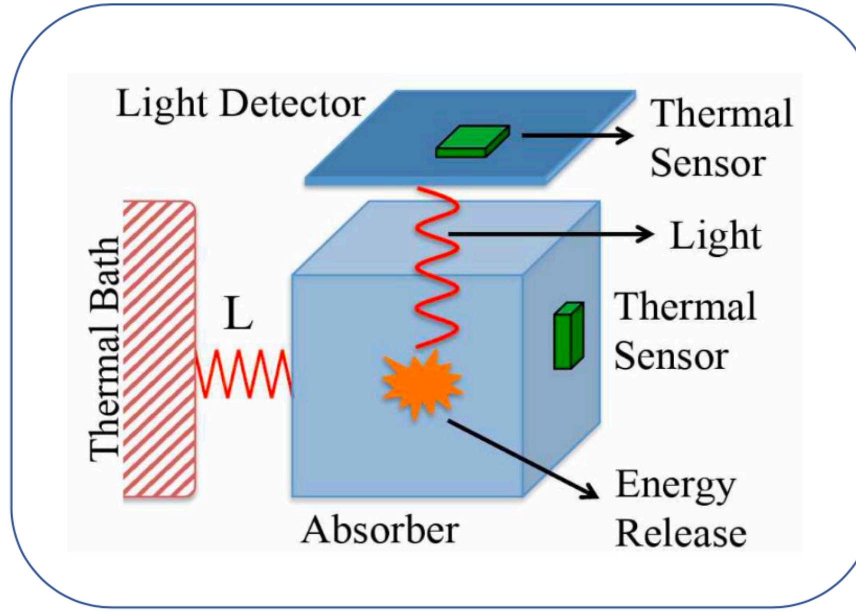
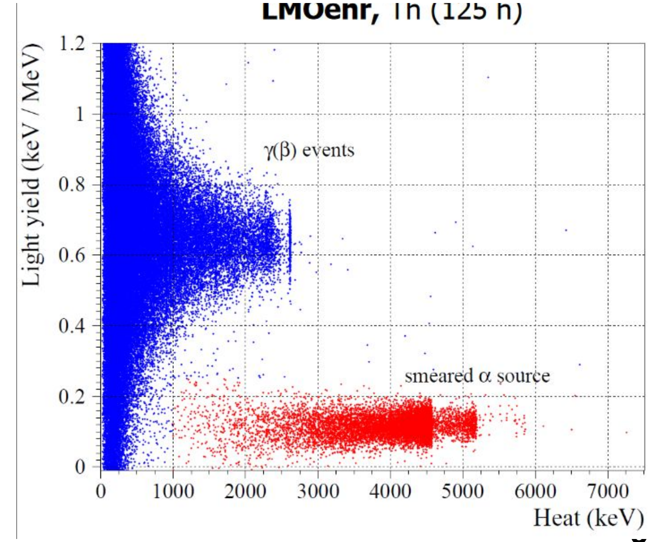


No PID
Q = 2527 keV **< 2615 keV**

~~α background~~
~~γ background~~
PID

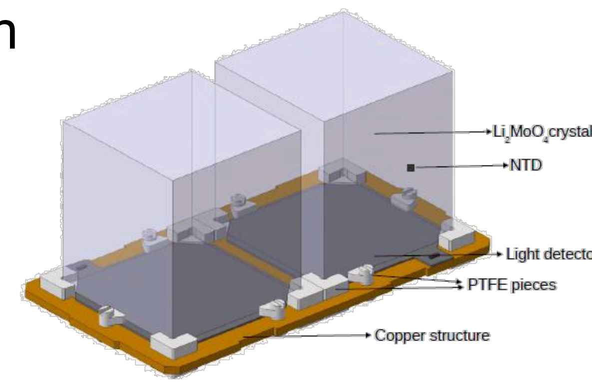
Q = 3034 keV **> 2615 keV**



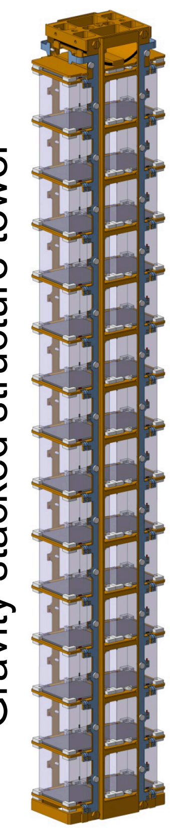
CUPID

- Single module: $Li_2{}^{100}MoO_4$, 45x45x45 mm, 280 g
- Detector: 1596 crystals in 57 towers,14 floors, 2 crystals each
  - ~240 kg of ^{100}Mo ~$1.6.10^{27}$ ^{100}Mo atoms
- 1710 Ge Light Detector (LD) with SiO antireflective coating + Al electrodes for Neganov-Trofimov-Luke (NTL) effect
  - NTD Ge thermistor readout for both LD and $Li_2{}^{100}MoO_4$
- CUPID performance goal
  - Energy resolution: 5 keV FWHM
  - LY: 0.3 keV/MeV
  - LD: $\sigma_{baseline}$ ~100 eV for PID
  - Background: 10^{-4} ckky (cts/keV·kg·yr)
  - 3σ discovery sensitivity $T^{0\nu}_{1/2} > 10^{27}$ yr, $m_{\beta\beta}$: [13-21] meV

Detector Module



Gravity stacked structure tower



Collaboration

International collaboration: ~140 collaborators across 7 countries

Leverage previous collaborative experiences

https://cupid.lngs.infn.it

CUORE

Built on the success of the CUORE Collaboration in building the only project of comparable scale

Integrate the experience from CUPID-0 and CUPID-Mo in operating detectors with Particle Identification technology

CUPID-0

CUPID-Mo

Major participants: Italy (~60 authors), US (~40 authors), France (~25 authors)
Other participants: Ukraine, Russia, China, Spain

Collaboration

International collaboration: ~140 collaborators across 7 countries

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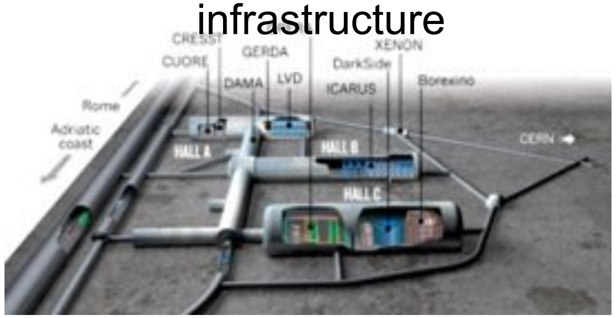
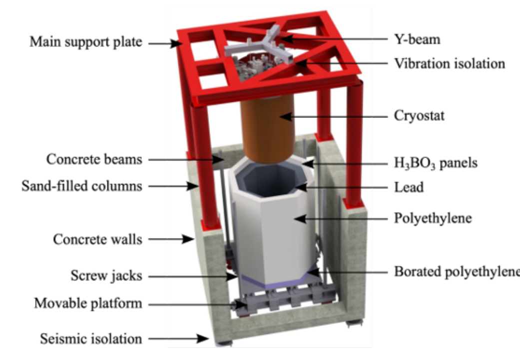
Leverage previous technical experiences

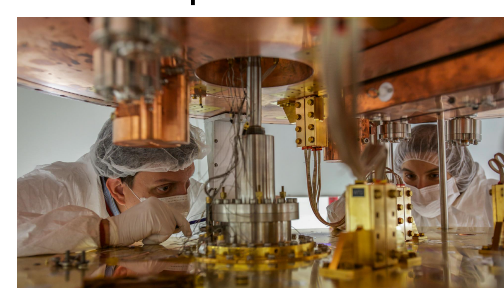
Long-lasting and well developed interaction with LNGS services and infrastructure





Cost and time-effective reuse of the CUORE underground infrastructure

Fully leverages the CUORE cryogenic infrastructure, experience and expertise in its operation



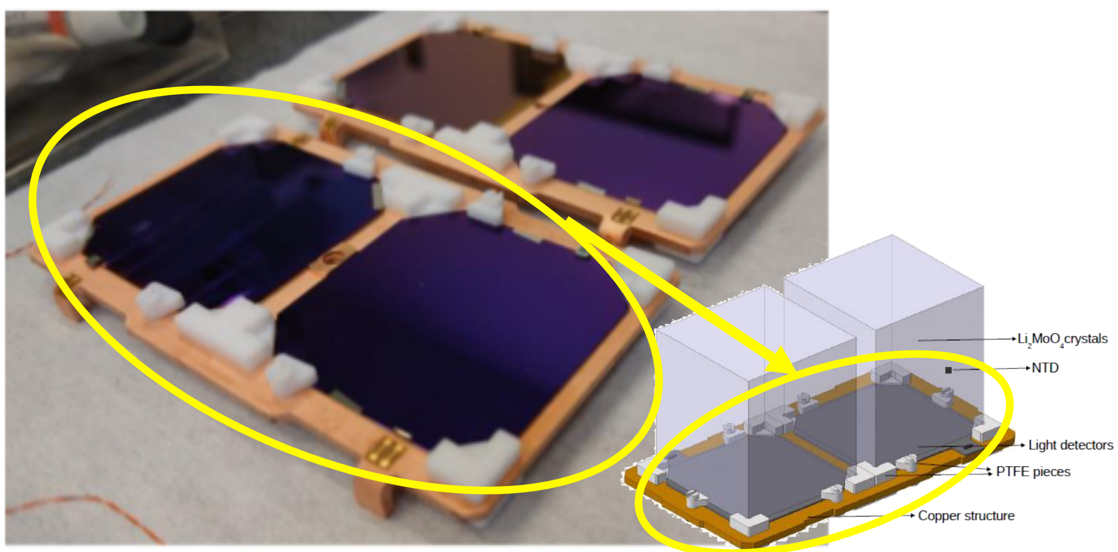
Re-use a unique existing infrastructure

CUPID leverages many years of work and investment

Light Detectors

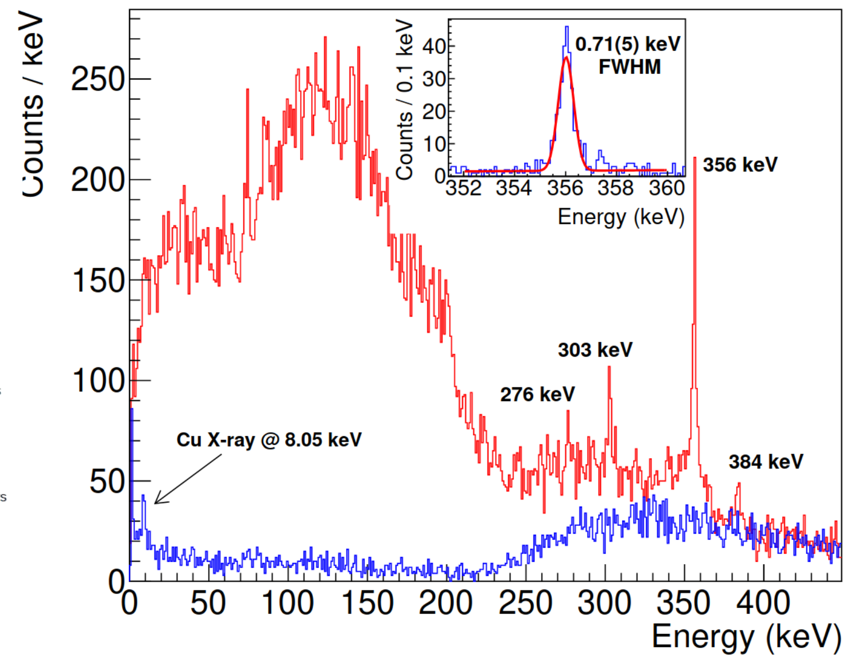
- High-purity Ge wafer with anti-reflective SiO coating and NTD readout: a robust technology from predecessors
    - Performances extensively studied in 2022 JINST 18 P06033

Assembled light detectors for test in **Pulse Tube** cryostat at IJCLAB



σ_{base}~70-90 eV

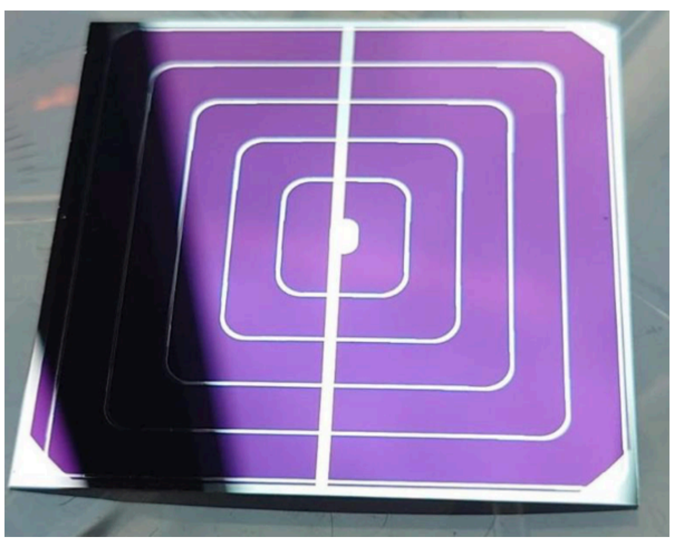
Excellent energy resolution 0.7 keV FWHM at 356 keV (^{133}Ba source)

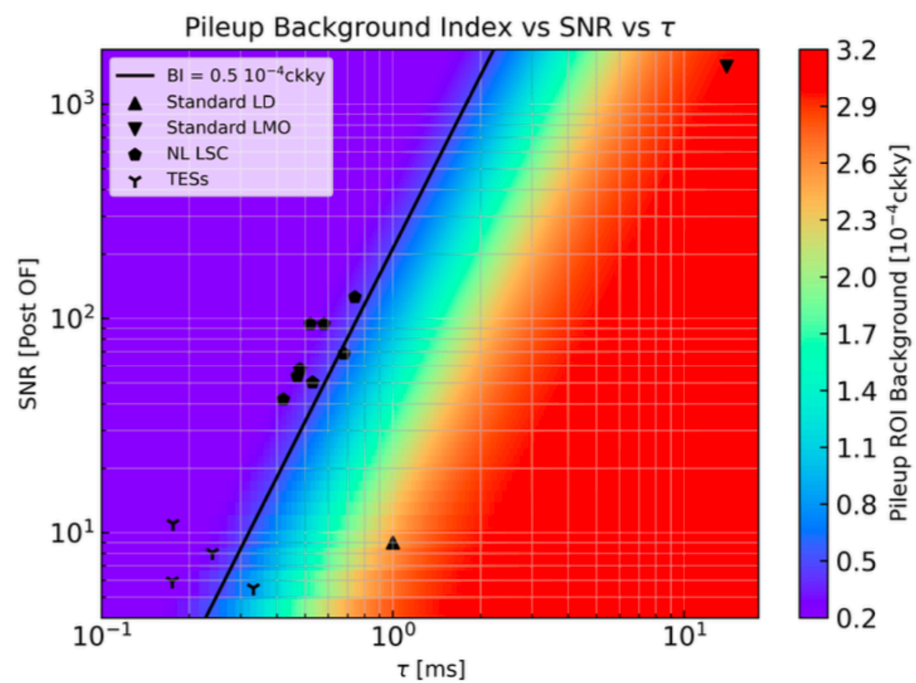


- Performances meet CUPID requirements but at limit for pile-up rejection

Pile up rejection

- Relatively fast ^{100}Mo $T^{2\nu}_{1/2} = 7.1 \times 10^{18}$ yr leads to the possibility of 2 $2\nu\beta\beta$ decays events piling up & reconstructing in ROI
- Rejection depends on: SNR after Optimum Filter, rise time (τ), algorithms
- Goal for pile up background contribution: 5×10^{-5} ckky
- Use LD: faster than Li_2MoO_4
    - NTL effect to increase SNR (x10)
    - reduce LD NTD size, tune working point to reduce τ

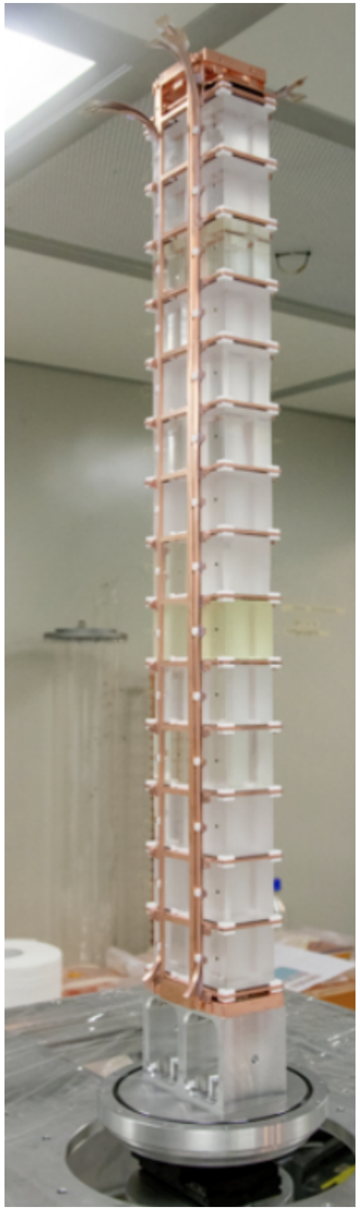




- Alternative to baseline: TES sensors→ require major change in readout

Detector Structure

- The challenge:
  - integrate LD without adding complexity
  - address weak points in CUORE design
  - reduce Cu amount
  - increase cryostat filling factor



- The solution: "gravity assisted" tower
  - no vertical constraint, stack of crystals and light detectors sitting one on top of the other (vs. rigid, fixed height structure in CUORE)
  - easier & faster assembly - no screws, self-aligning structure
  - loose tolerances - easy to produce (laser cut of Cu sheets), easy to clean (with no special care for threads and abutment surfaces)
  - better wiring integration
  - same materials used in CUORE (Cu, PTFE, CuPEN wiring)

Tower Test

- Goal:
  - validate assembly procedure, mechanical structure and thermalization
  - performances studies, test of glue, LD coating

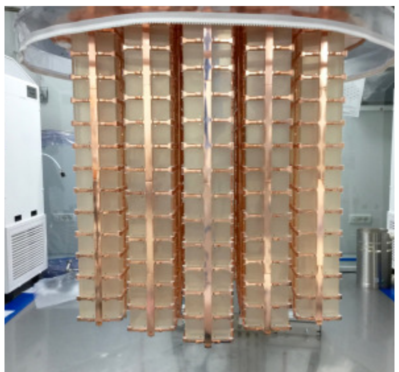
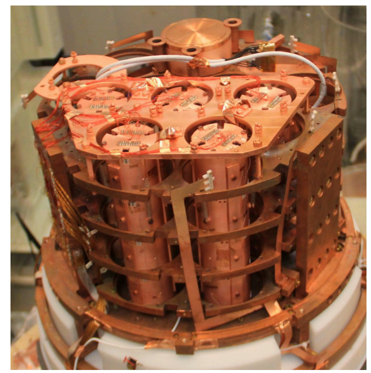
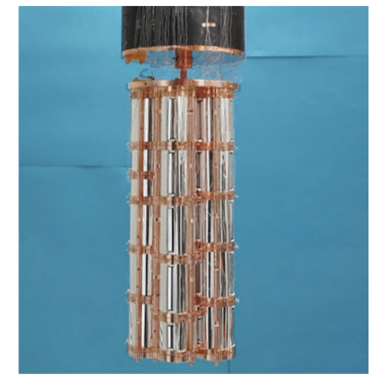
- 14 floors, 28 crystals, 30 LD in 2 different runs
  - Fast and uniform cool down→thermal and mechanical scheme validated
  - Same performance for spattered/evaporated SiO coating
  - New UV glue type proved better noise resolution & faster signal
  - Good LMO performances (σ~6.5 keV),
  - excess noise in LD: ascribed to Cu spine hosting the CuPEN in contact (by mistake) with Cu frames and double bonding
  - 72 channels of new DAQ installed and successfully tested

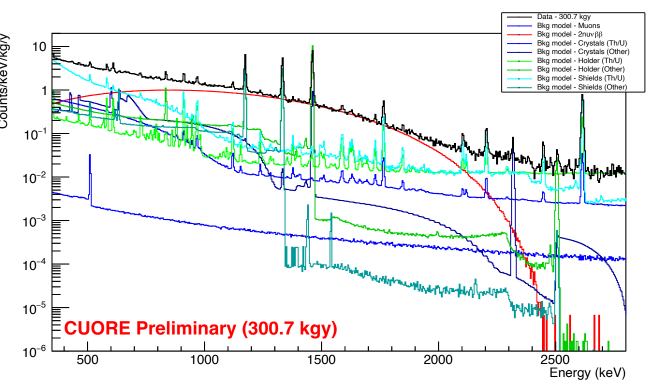
- 2024: test with NTL LD, Cu reduction, optimised LD anchoring on frame

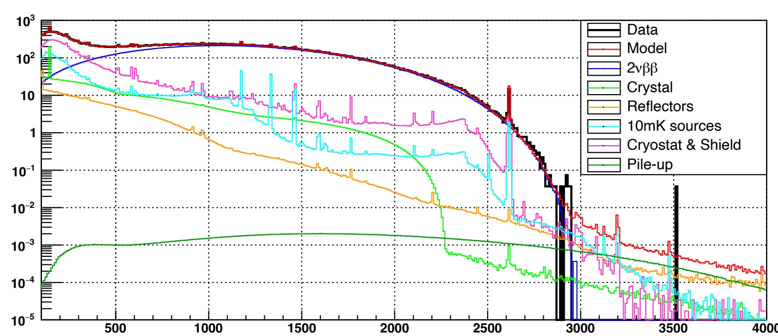
CUPID Background model

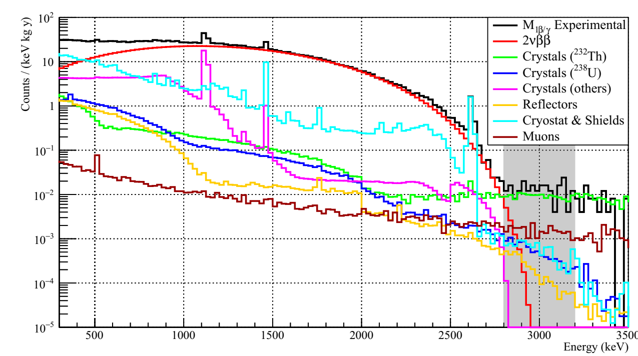
Our background model reconstruction approach is well validated in multiple experiments.

All the materials for CUPID have been directly measured in bolometric setups.

CUORE	**CUPID-Mo**	**CUPID-0**
		
TeO_2	$Li_2{}^{100}MoO_4$	$Zn^{82}Se$







Characterize β/γ bgkd from cryogenic system and detector holders in the ^{100}Mo ROI ($Q_{\beta\beta}$= 3034 keV)

Confirms:

- α tagging performance
- Radiopurity of crystals
- Energy resolution

Alpha-rejection
Confirms the β/γ background from detector holders in 3 MeV ROI

Background budget

Our background model reconstruction approach is well validated in multiple experiments.

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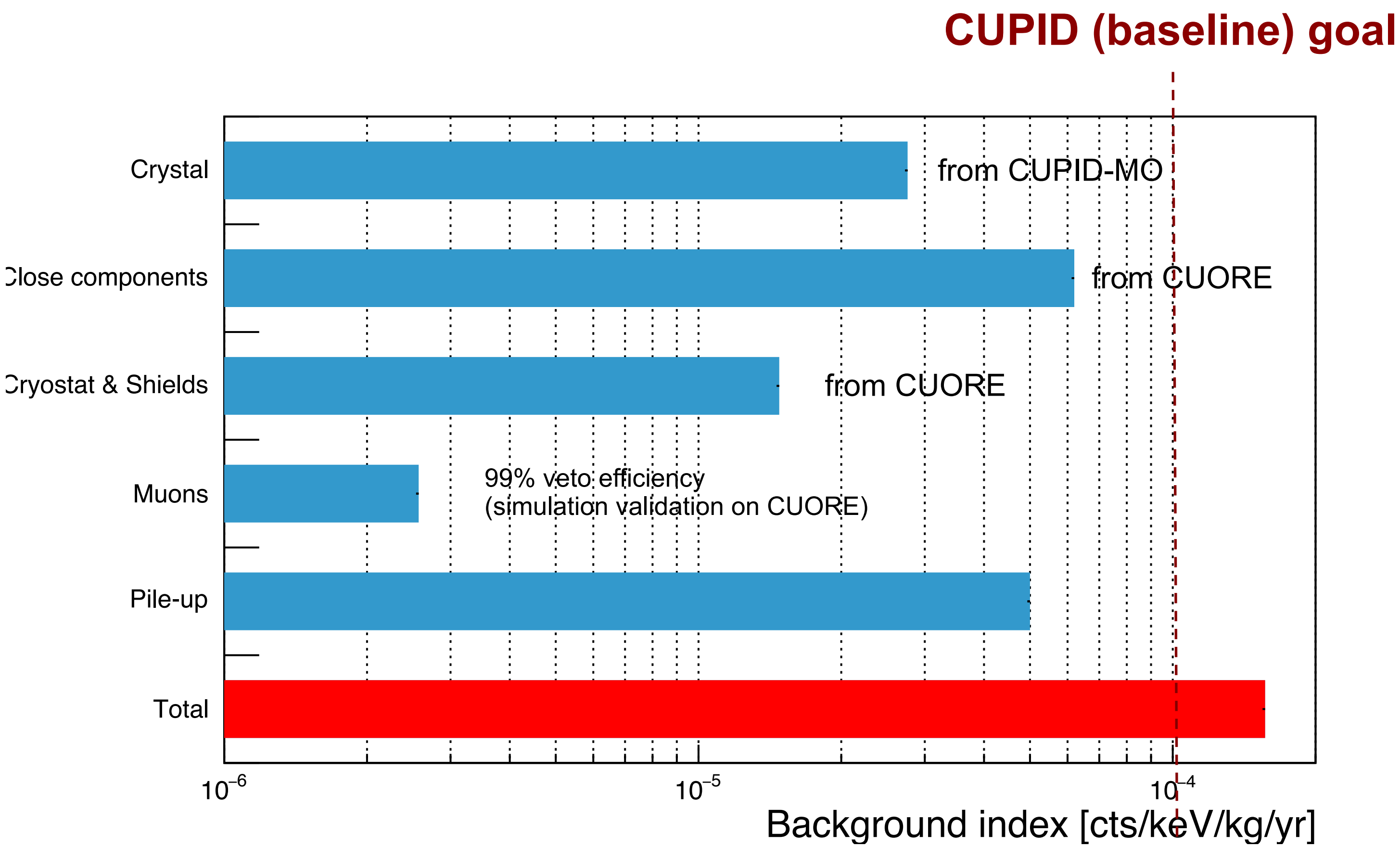
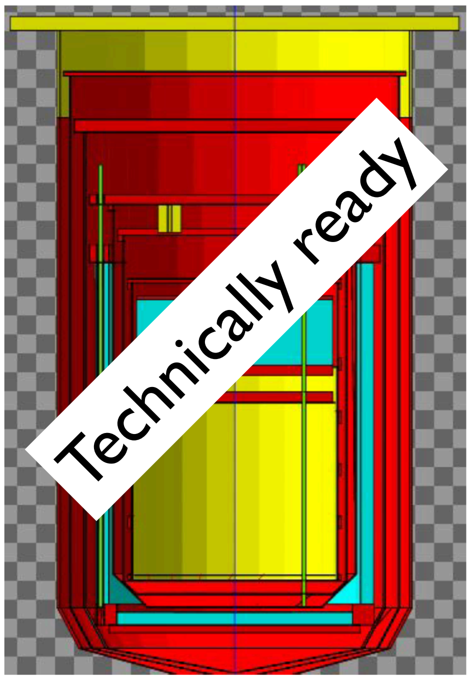


Well-defined path to reduce the CUORE backgrounds to the levels required for CUPID

CUPID scenarios

CUPID Baseline

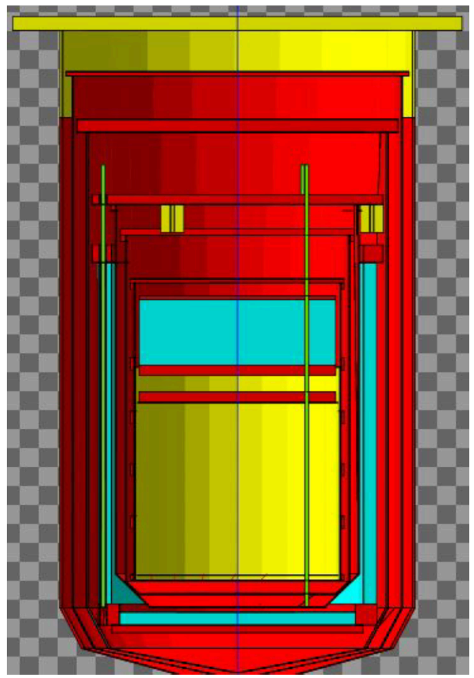


240 Kg ^{100}Mo
CUORE Cryostat
Bkgd: 10^{-4} ckky

$T_{1/2} > 1\times10^{27}$ yr

$M_{\beta\beta}$:[13-21] meV

CUPID Reach

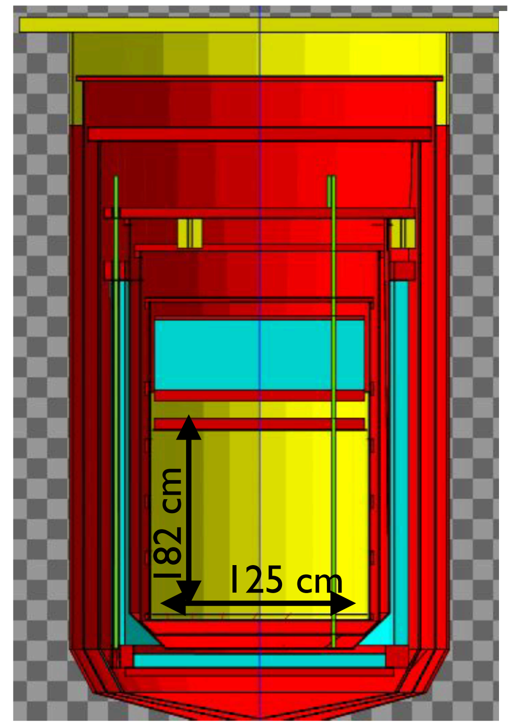


240 Kg ^{100}Mo
CUORE Cryostat
Bkgd: 2 10^{-5} ckky

$T_{1/2} > 2\times10^{27}$ yr

$M_{\beta\beta}$ > [9-15] meV

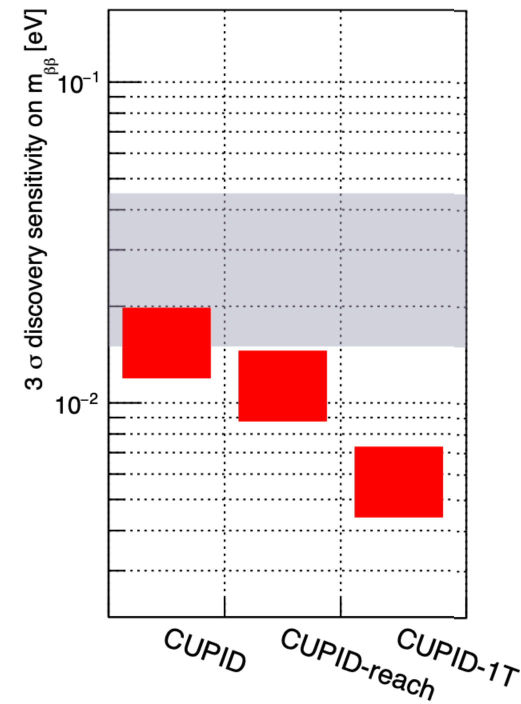
CUPID 1Ton



1000 Kg ^{100}Mo
New Cryostat
Bkgd: 5 10^{-6} ckky

$T_{1/2} > 9\times10^{27}$ yr

$M_{\beta\beta}$ > [4-7] meV

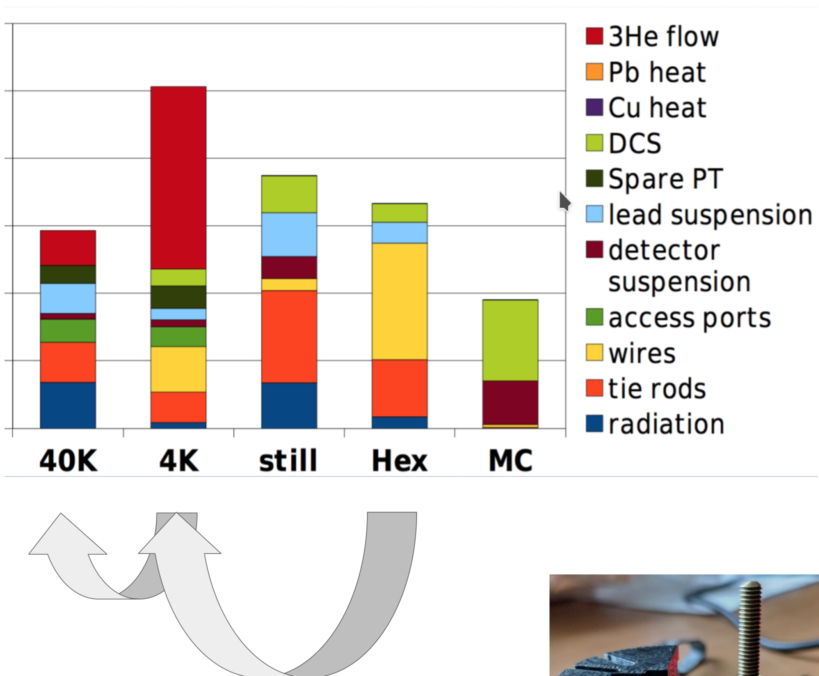


Conclusions

- CUPID builds on an existing and well-functioning international collaboration
- Collaboration has operational experience at LNGS for ton-scale bolometric experiment and uses an existing infrastructure (CUORE cryostat and experimental site)
- Exceptional opportunity: cost effective, leverages international investments
- Crystallisation and enrichment at large scale are possibile and demonstrated
- Data-driven background model indicates bkgd~10^{-4} ckky.
- CUPID will the Inverted Hierarchy region
- Possibility of mass scaling and multi-isotopes deployment in case of discovery
- Collaboration is working on getting ready for CUPID.

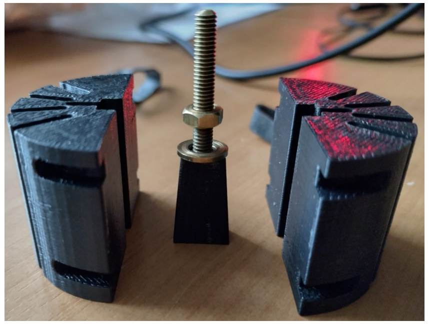
Backup

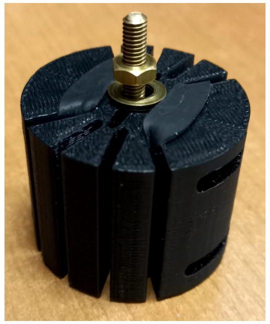
Cryostat upgrade

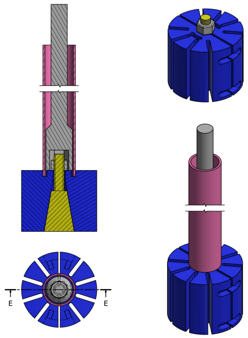


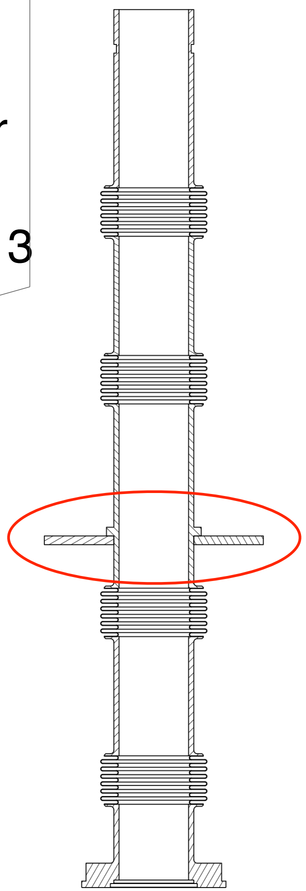
- CUORE Cryostat thermal budget extremely well known and understood
- Relevant contribution on colder stages comes from wiring
- Wiring will increase by a factor 3

Improve the thermalization at 40K where extra cooling power is available









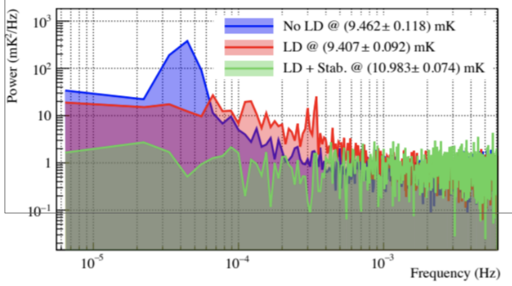
Cryostat upgrade

Pulse Tubes system is an important source of vibrational noise

Three interlinked tactics to further reduce it

New linear drives for motor head control:

- improve current stability
- improve control on stepper motors
- enable new algorithms for PT phase scan and optimization

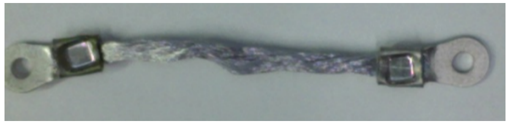


New Pulse Tubes:

- more cooling power
- less PTs required
- easier and more effective active noise cancellation

New termalizations

- high purity 6N Al
- increase thermal link while reducing mechanical coupling
- thermal switches to isolate unused PTs



Reduce input vibration power and improve active noise cancellation efficiency

Data readout: FEE and DAQ

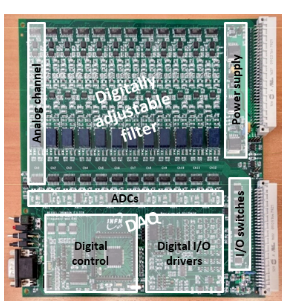
CUORE: custom-designed room-temperature front end electronics. Raw data is stored for offline processing

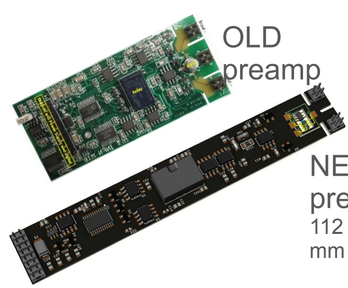
- Very stable and reliable operation for 5 years → Readout scheme proven on the field

CUPID will add several challenges

- More channels (x3), hence more power, more space, more data, etc.
- Faster signals on light detectors, required for pile-up rejection

New filter+DAQ board





OLD preamp

NEW preamp 112 mm x 17 mm

Main upgrades

- New frontend will save a factor of 2 in space
- Keep same power budget, optimizing preamps for light channels (same power, lower noise) & heat channels (lower power, same noise)
- Reduce wiring capacitance to reduce input RC time constant
- New board merges DAQ (24-bit ADCs, 25ksps sampling rate for channels) + anti-aliasing filters (with 10-bit tunable cut-off up to 2.5 kHz)
- Update DAQ software and storage infrastructure to cope with increased data rate

Small scale prototypes already deployed in multiple facilities for R&D

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