The CUORE cryostat, an infrastructure for rare-event searches at 10mK

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Rare events Observatories

Cryogenic **U**nderground **O**bservatory for **R**are **E**vents

CUORE **U**pgrade **P**article **ID**entification

Multi-generation high sensitivity search for rare events:

- main focus: Neutrino-less Double Beta Decay
- secondary goal: any rare physics with signature in the keV to MeV energy range with high resolution energy spectroscopy

CUORICINO

CUORE-0

CUPID-0

CUPID-Mo

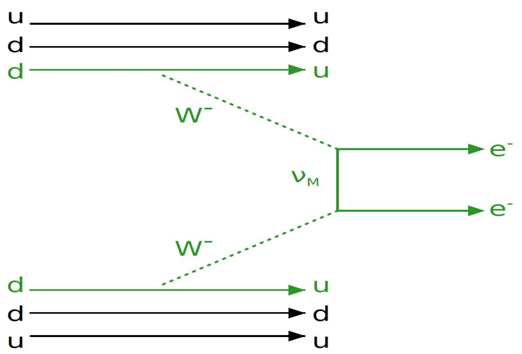
Neutrino-less double beta decay

Double beta decay - DBD: second order nuclear process, alternative to beta decay when forbidden by negative mass difference for some even-even nuclei

$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$$

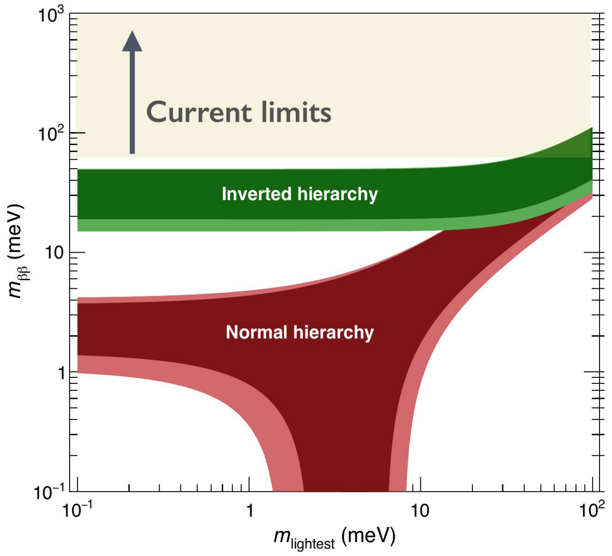
2nd order SM process, observed on nuclei with $T_{1/2}$ ~ $10^{18\text{-}24}$ years

$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$



- SM forbidden, lepton number violation → **MATTER CREATION!**
- **if** observed, **then** neutrino is a Majorana particle
- underlying mechanism can give insight into BSM physics:
  - light neutrino mass scale and hierarchy
  - heavy, sterile neutrinos

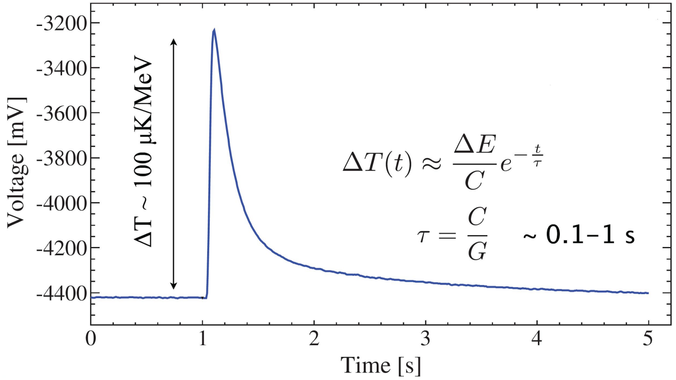
Effective neutrino mass $m_{\beta\beta}$:
- measures the intensity of the new-physics involved in the process
- compares different isotopes

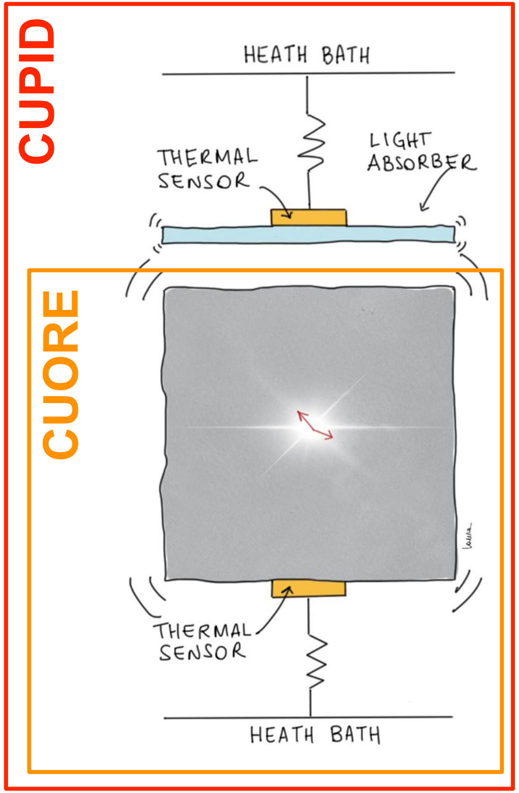


Experimental technique: low temperature detectors

Low temperature detectors:

- DBD isotope crystals instrumented with thermistors operated @10 mK → low thermal capacity
- energy deposition detected as temperature variation
- scintillation light (if any) also detected as temperature variation in dedicated sensor
- **large active mass** and **efficiency** per unit cost
- fully active homogeneous sensitive volume → **high energy resolution, model-independent signature**





CUORE detector

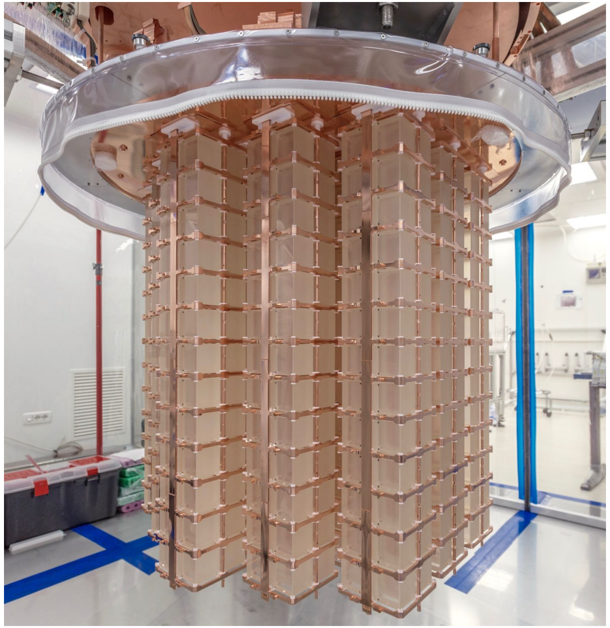
Cryogenic Underground Observatory for Rare Events

Primary goal: search for NLDBD in ^{130}Te

Design principle: closely packed modular array of 988 natural crystals

Design parameters:

- active mass: 742 kg (206 kg ^{130}Te)
- energy resolution: 5 keV FWHM in the ROI
- low background: 10^{-2} ckky
  - high granularity
  - deep underground location (LNGS, Italy) @3600 mwe
  - strict radio-purity controls on materials and assembly
  - passive shielding



Target sensitivity (5 years, 90% C.L.) on 0ν inverse decay rate:

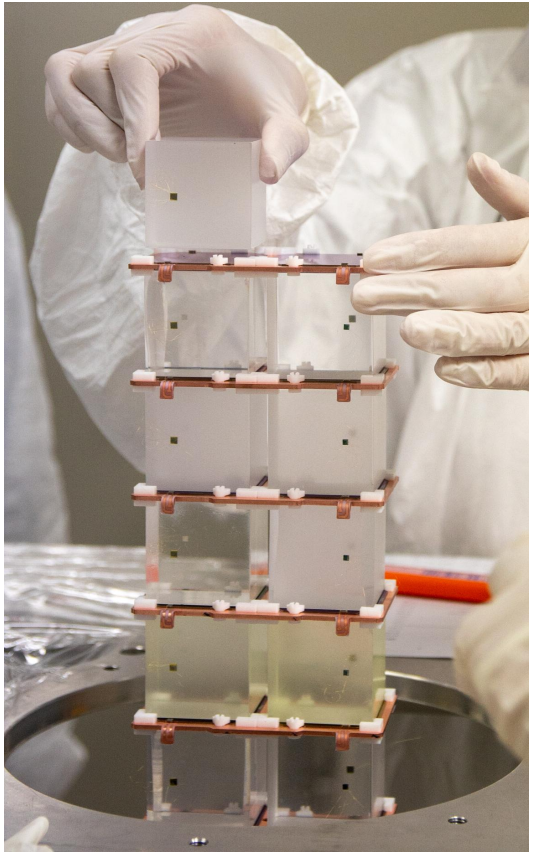
$$T_{0\nu}^{1/2} > 9.0 \times 10^{25} \text{ yr } (4.4 \times 10^{25} \text{ yr current limit})$$

$$m_{\beta\beta} < 50\text{-}130 \text{ meV } (70\text{-}240 \text{ meV current limit})$$

CUPID concept: Cuore Upgrade with Particle IDentification

Conceived to overcome CUORE limitations and push the technology towards the future generations, **sharing cryogenic facility:**

- replace CUORE (TeO_2) detector with new one based on $Li_2{}^{100}MoO_4$ crystals **implementing particle identification**
- 450 kg detector mass, same scale as CUORE: feasibility already demonstrated with 3 years of stable data-taking
- existing cryogenic infrastructure with upgrades tested with CUORE extension run: cost effective, low risk
- additional detector functionality:
  - particle identification with scintillating crystals and Ge light sensors
  - pile-up rejection with fast light-detectors
  - increased number of channels (1596 heat + 1710 light)
  - improved mechanical structure design
  - improved materials handling and cleaning

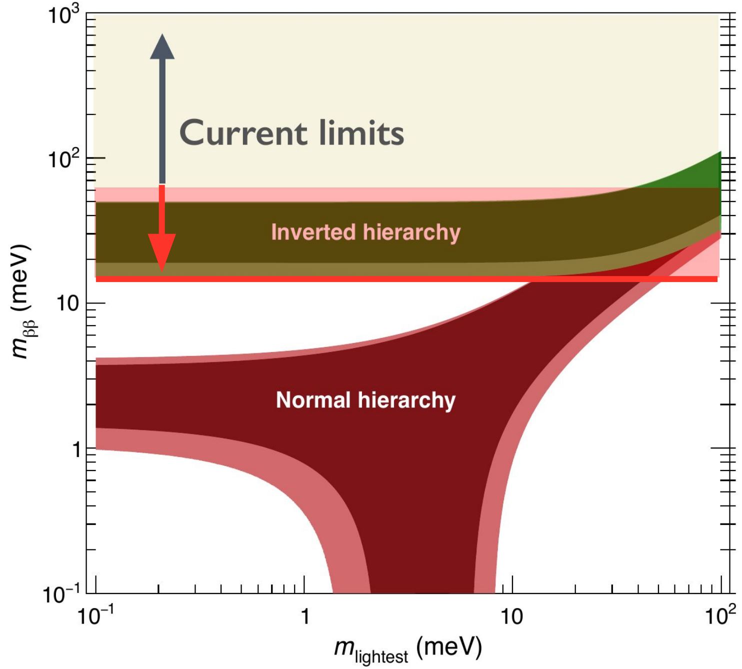


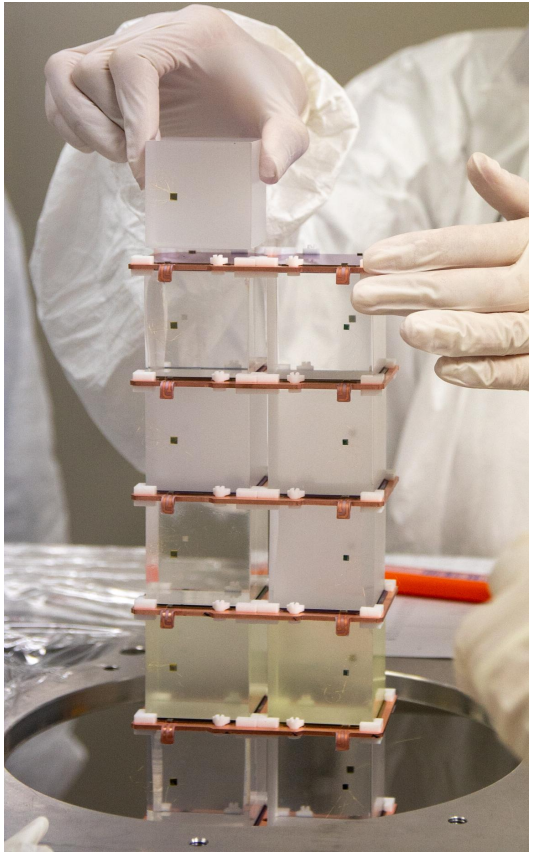
CUPID concept: Cuore Upgrade with Particle IDentification

Conceived to overcome CUORE limitations and push the technology towards the future generations, **sharing cryogenic facility:**

Factor 100 background reduction

Explore neutrinos inverted mass hierarchy





The Cryogenic Infrastructure

CUORE CUPID

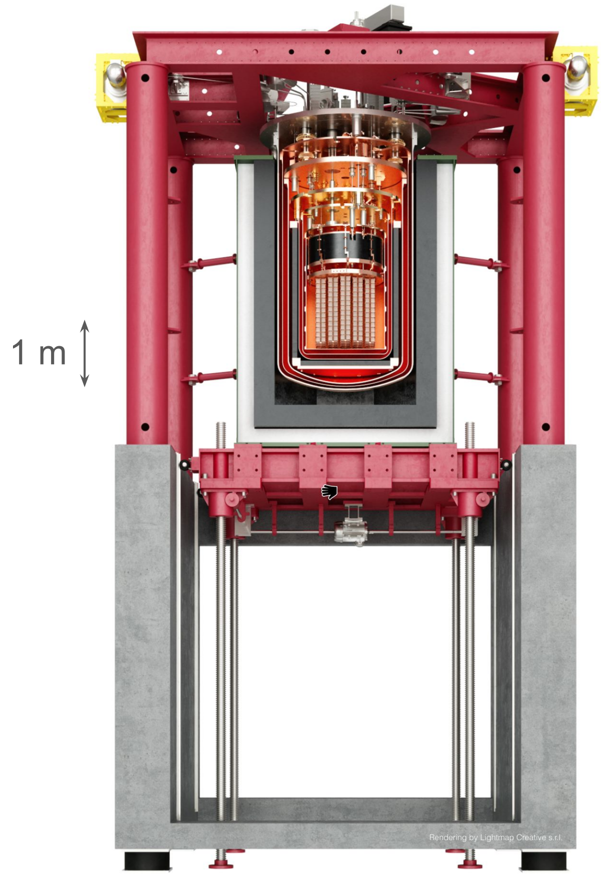
Technological challenge and outstanding achievement

Primary goal: cool down ~1 ton of material @10 mK and keep it stable in low noise environment for 5-10 years

Design parameters:

- cryogen-free cryostat
- 5 pulse tubes cryocooler to 4 K
- dilution refrigerator to operating temperature ~10 mK
- nominal cooling power: 3 muW @10 mK
- system total mass including room temperature lead shield ~100 tons
- mass to be cooled < 4 K: ~15 tons
- mass to be cooled < 50 mK: ~3 tons (Pb, Cu and TeO_2)
- mechanical decoupling for low vibrations
- low background materials

https://doi.org/10.1016/j.cryogenics.2019.06.011



The Cryogenic Infrastructure

Technological challenge and outstanding achievement

Cryogen-free cryostat:

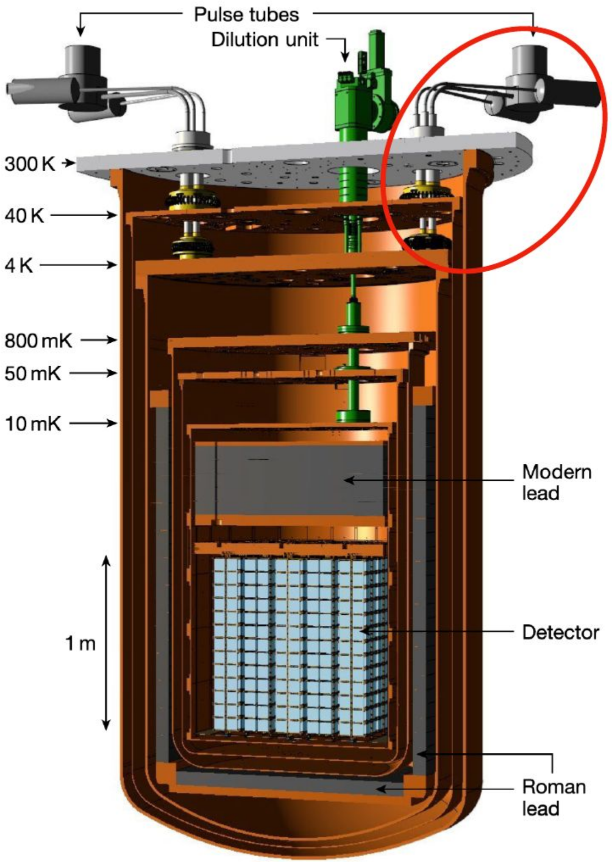
- mostly custom-made (design, shields, thermalizations)
- detector suspension @300K completely independent from cryostat plates
- 4 (+1) Cryomech P415 1.2 W @ 4.2 K each
- ~1000 high-impedance superconducting NiTi readout twisted pairs

Dilution refrigerator:

- built by Leiden Cryogenics, commissioned @LNGS
- 4 μW @ 10 mK cooling power
- base temperature ~ 7 mK
- two independent condensing lines

Fast cooling system:

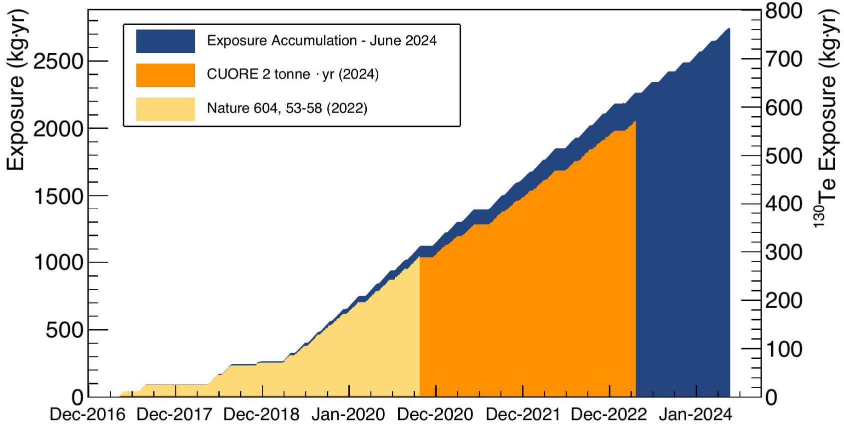
- pre-cooling of inner mass with ultra-pure gHe circulation
- 1.8 kW @ 77 K

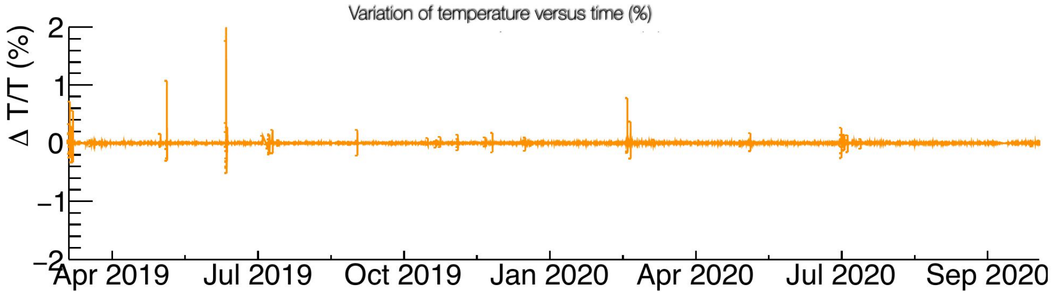


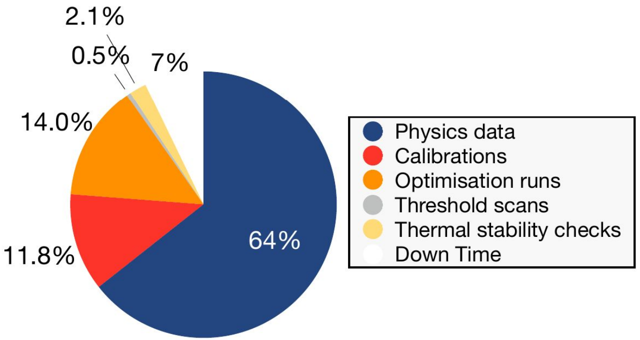
The Cryogenic Infrastructure

Achievement: long-term stable data taking

- typical experiment live time 5-10 years
- stable conditions:
  - typical temperature stability better then 10^{-3}
  - residual temperature variations easily stabilized with analysis tools
- high duty cycle:
  - uptime > 90%
  - accumulated exposure ~50 kg*y/month



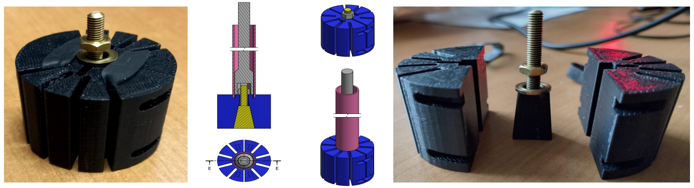


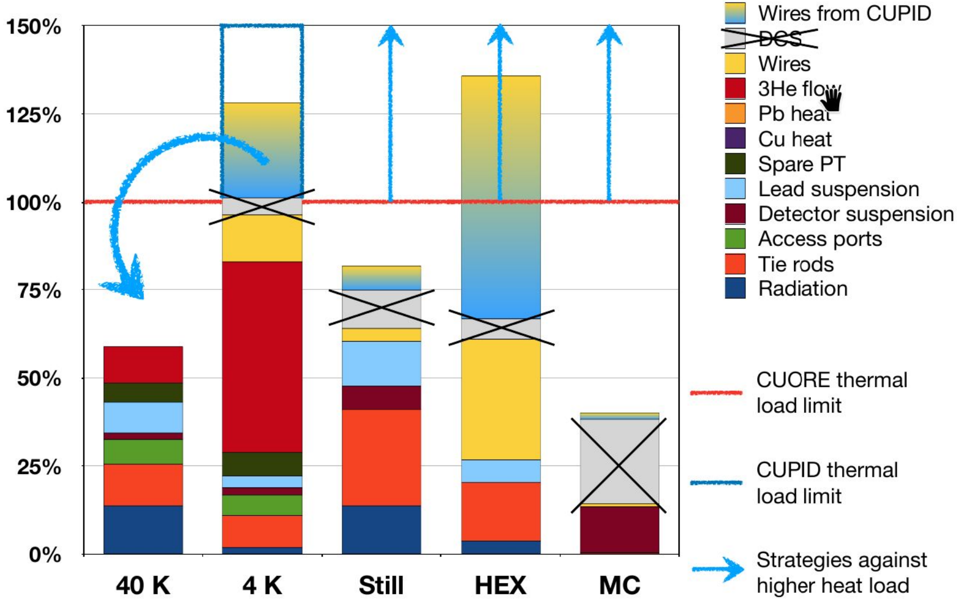


Cryostat upgrades towards CUPID

Upgrade: increase available cooling power to handle 3-fold increase in readout wiring

- replace PTs with more powerful model PT425
- implement variable conductance devices to reduce heat load from spare PT
- move most of the wiring heat load from 4 to 40 K stage with new thermalization system
- upgrade detector and cryostat suspensions





Preliminary CUPID thermal budget

Cryostat upgrades towards CUPID

Challenge: cryogenic calorimeters are sensitive to energy deposited via vibrations

Vibrational noise

- significant components in the signal frequency band
- naively: generates detector heating with features similar to low energy particles
- only partially mitigated with active phase cancelling due to PTs configuration

Noise instabilities

- some noise inputs are non-stationary (anthropic, seismic, tidal origin…)
- the cryogenic and suspension system response can vary over time
- noise predictability strongly affects trigger performance

After years of data taking and detailed studies new solutions are available

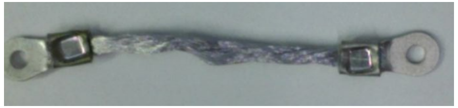
Cryostat upgrades towards CUPID

Vibrational noise

10.1016/j.cryogenics.2018.05.001

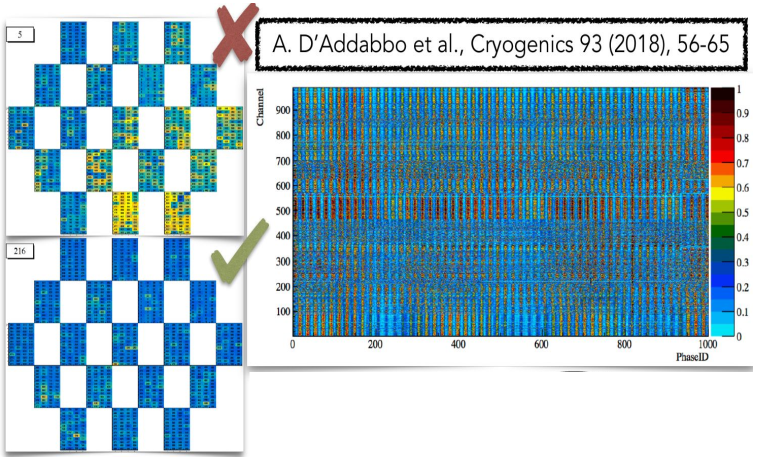
Reduce power and improve active suppression

New termalizations
- high purity 6N Al
- increase thermal link while reducing mechanical coupling



New Pulse Tubes:
- more cooling power
- less PTs required (3 → 4)
- easier and more effective active noise cancellation

New linear drives for motor head control:
- improve current stability
- improve control on stepper motors
- enable new algorithms for PT phase scan and optimization



Cryostat upgrades towards CUPID

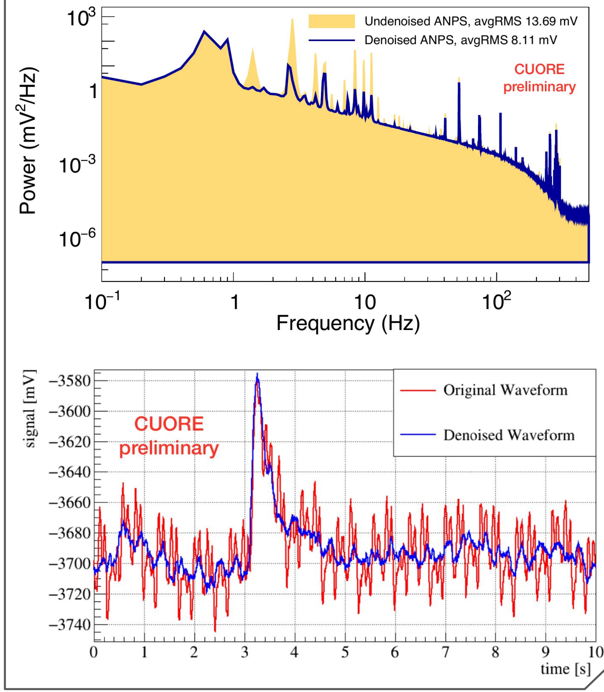
Install diagnostic devices at strategic locations inside the cryostat. Multiple devices to cover full frequency band:

- seismometers
- accelerometers
- microphones
- antennas

Denoising algorithms:

1. Measure time dependent noise sources with auxiliary device
2. Decorrelate from detector signal with corresponding transfer function
3. Apply OT to filter remaining stationary noise

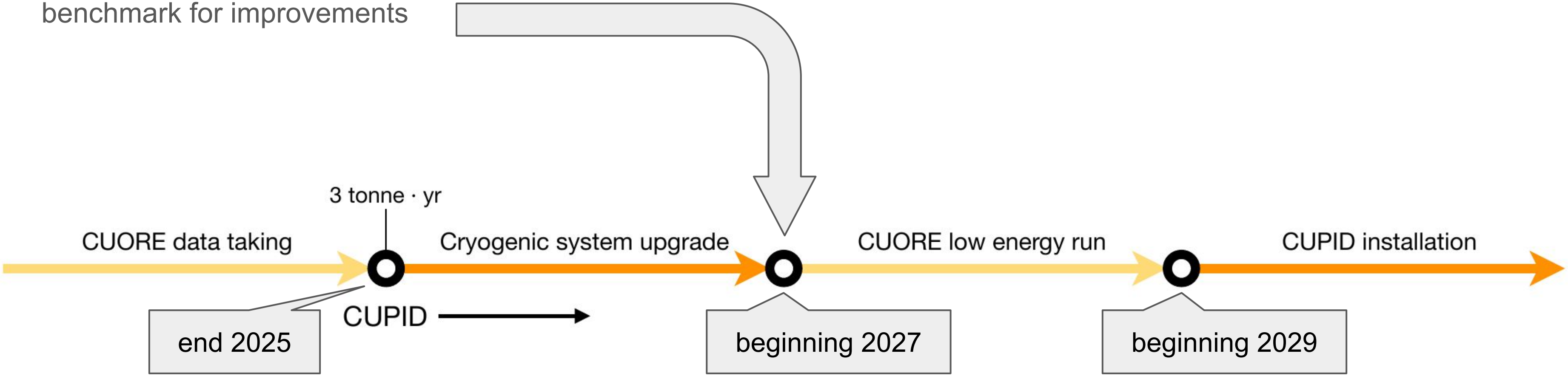
Noise instabilities



Cryostat upgrades towards CUPID

The experience with CUORE data-taking is driving the design of upgrades

All cryostat upgrades will be tested with the CUORE detector before replacing it with the CUPID detector → perfect benchmark for improvements



Conclusions

- CUORE is leading the search for neutrino-less double beta decay in ^{130}Te
- CUPID will study ^{100}Mo to explore inverted ordering
- Collaborations have operational experience at LNGS for ton-scale, bolometric experiment and utilizes existing infrastructure (CUORE cryostat, experimental site).
- CUPID will share CUORE cryogenic infrastructure resulting in a timely, highly leveraged, and cost-effective deployment
- Based on years of experience with CUORE data-taking, cryostat upgrades are planned to further improve on critical aspects, and will be validated with the CUORE detector before replacing with CUPID
- **CUORE and CUPID cryostat is a one of a kind machine, with unique and unprecedented features specifically designed and built for high sensitivity rare event physics experiments**