Supernova neutrinos with CUORE and CUPID

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SNνD 2023 - International Conference on Supernova Neutrino Detection

LNGS, L'Aquila, Italy

May 29th - June 1st, 2023

Rare events Observatories

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

C U O R E — **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

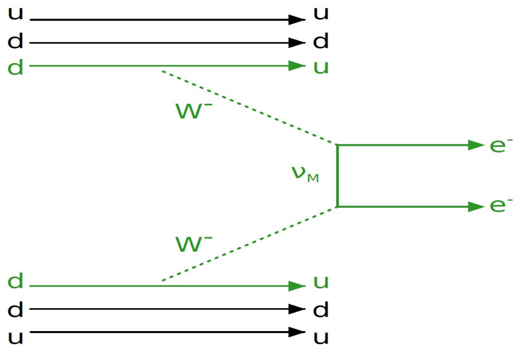
Neutrino-less double beta decay

Double beta decay: 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

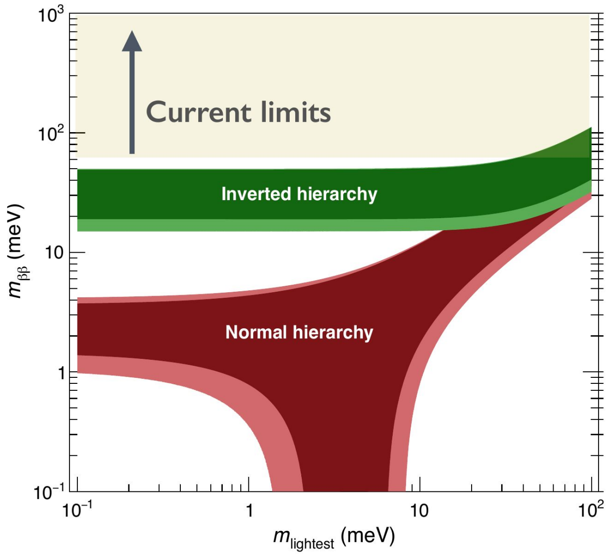
$$(A,Z) \rightarrow (A,Z+2) + 2e^-$$



- 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 $m_{\beta\beta}$:

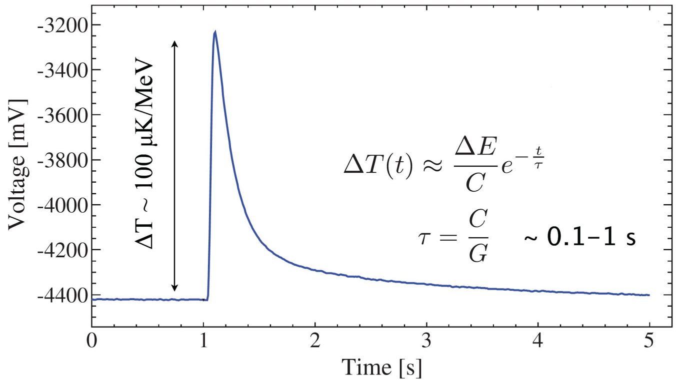
- measures the intensity of the new-physics involved in the process
- compares different isotopes

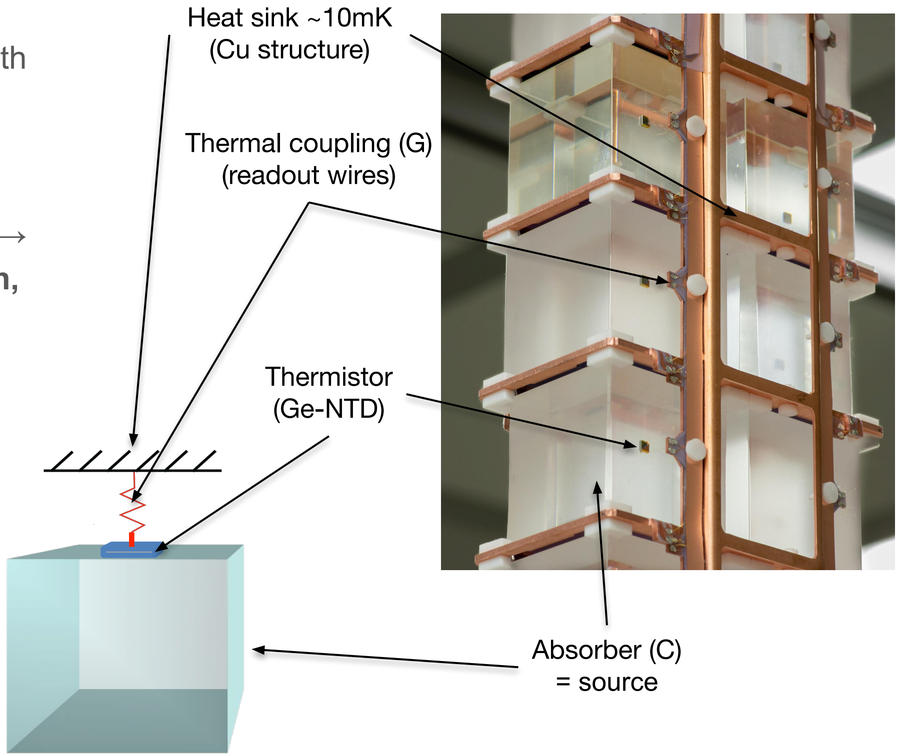


Experimental technique: low temperature detectors

Low temperature detectors:

- macroscopic (hundreds of grams) crystals instrumented with thermistors operated @10 mK → low thermal capacity
- energy deposition detected as temperature variation
- **large active mass** and **efficiency** per unit cost
- fully active sensitive volume (= source), no dead-layer → simple response function → **high energy resolution, model-independent signature**





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CUORE CUPID

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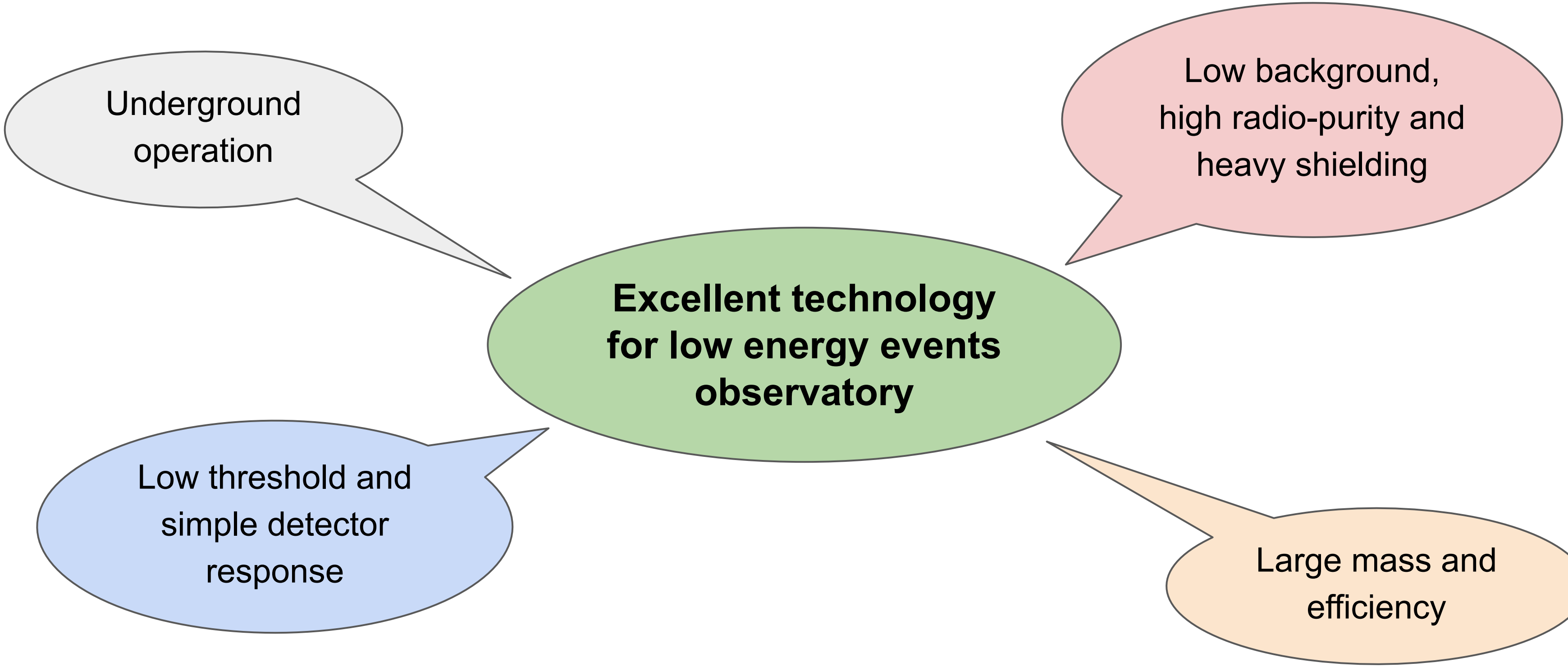
Compounds containing large fractions of heavy materials available as absorber

Intrinsically multi-isotope technique: many available compounds containing candidate nuclei

- $^{130}TeO_2$ (CUORE)
- $Li_2{}^{100}MoO_4$ (CUPID, AMORE)
- $Zn^{82}Se$ (CUPID-0)
- $^{48depl}Ca^{100}MoO_4$
- $Na_2{}^{100}MoO_7$
- $^{48}CaF_2$
- $^{116}CdWO_4$

Unique feature: test simultaneously multiple candidates to **cross check discovery** and perform precision nuclear matrix measurements!

Experimental technique: low temperature detectors



Experimental technique: low temperature detectors

Excellent technology for low energy events observatory

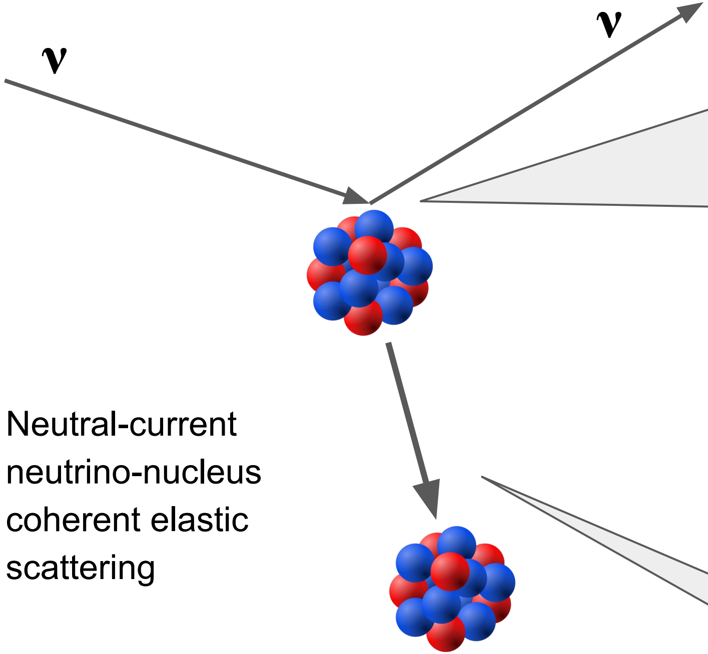
Signatures of rare decays and exotic processes

Solar axions search

Nuclear recoils from neutrino coherent scattering

WIMP direct detection

Detection mechanism



Neutral-current neutrino-nucleus coherent elastic scattering

Cross section* depends on:

*spin independent

- weak charge

$$Q_w = N - \left(1 - 4\sin^2\theta_W\right) Z$$

- nuclear form factor (accounts for the coherence of the interaction as a function of transferred momentum Q)

$$F(Q^2) = \frac{3\left(\frac{\sin(QR_0)}{(QR_0)^2} - \frac{cos(QR_0)}{QR_0}\right)}{QR_0} \times \exp\left(-\frac{(Qs)^2}{2}\right)$$

$$R_0^2 = R^2 - 5s^2$$

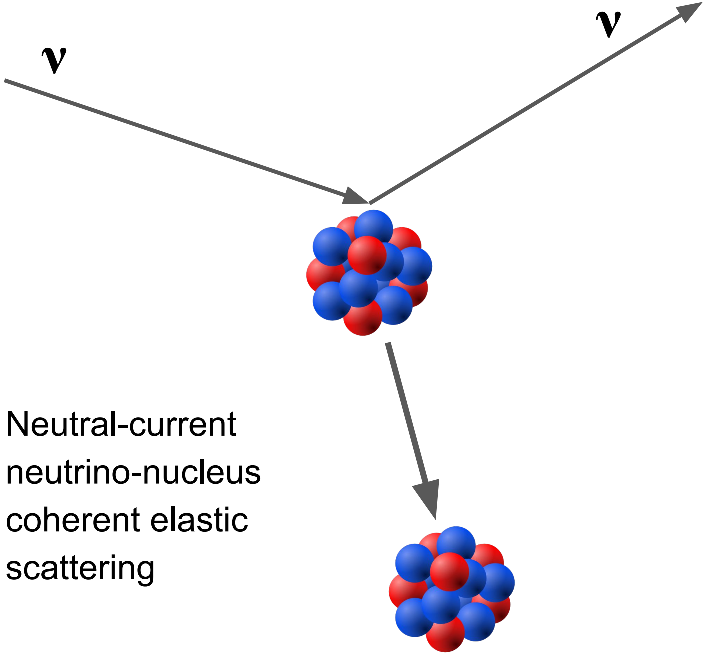
$$R = (1.2 \times A^{1/3})\mathrm{fm}$$

$$s = 0.5\mathrm{fm}$$

Nucleus recoil energy depends on:

- momentum transfer
- nucleus mass

What neutrinos?



Neutral-current neutrino-nucleus coherent elastic scattering

Core-collapse supernovae cooling phase:

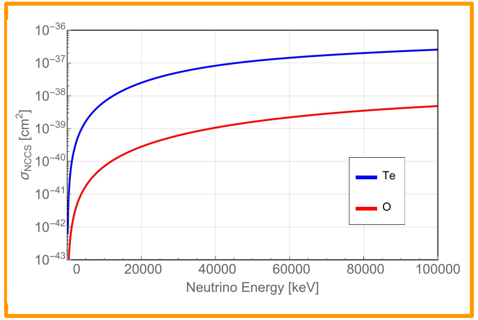
- detection via neutral current interaction → cross section is flavor independent
- sensitive to total neutrino flux
- assumptions on neutrino spectra:
  - only cooling phase emission is considered as it dominates total flux
  - thermal spectra with temperature fixed by neutrino-sphere radius ($T_e < T_{anti\text{-}e} < T_X$)
  - time profile exponential with 3.5 s decay time
  - SN distance 8.5 kPc (if not specified)

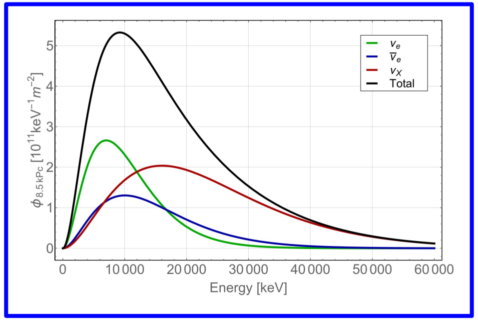
Detection mechanism

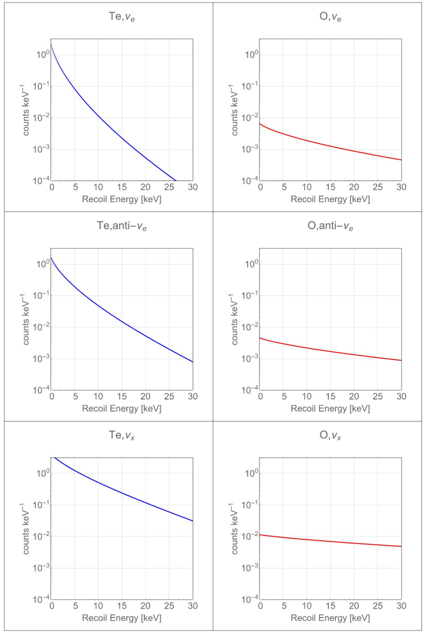
We measure the kinetic energy of the recoiling nucleus as an increase in the crystal temperature

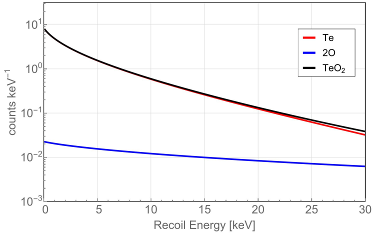
$$Y(T)=\frac{\mathrm{d}N}{\mathrm{d}T}=\sum_{\alpha=\mathrm{Te,O}}\sum_{i}N_{\alpha}^{\mathrm{targ}}\iint \mathrm{d}\Omega\,\mathrm{d}E\,\boxed{\frac{\mathrm{d}\sigma_\alpha}{\mathrm{d}\Omega}(Q^2,F(Q^2),Q_W^2,A)}\,\boxed{\phi_i(E)}\,\delta\left(T-\frac{Q^2}{2M_\alpha}\right)$$

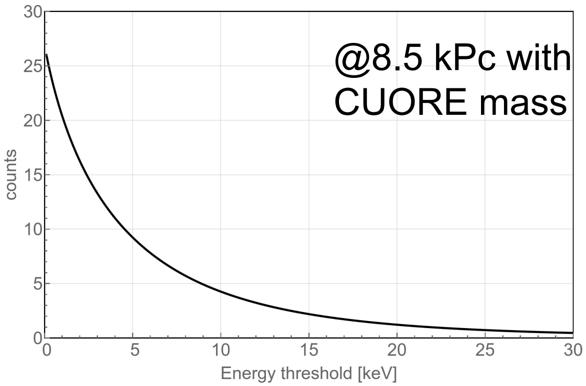
https://doi.org/10.1016/j.astropartphys.2012.05.009











CUORE detector

Cryogenic Underground Observatory for Rare Events

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

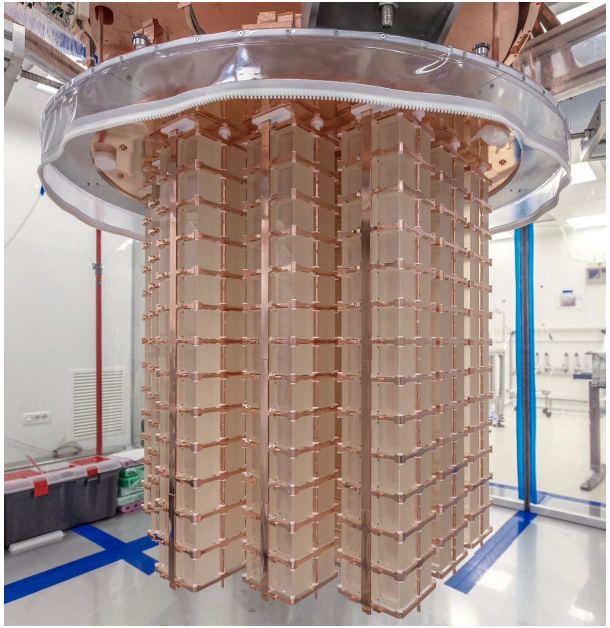
Design principle: closely packed modular array of 988 natural crystals

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:

$$\mathbf{T_{0\nu}^{1/2} > 9.0 \times 10^{25}\ yr}$$
$$\mathbf{m_{\beta\beta} < 50\text{-}130\ meV}$$



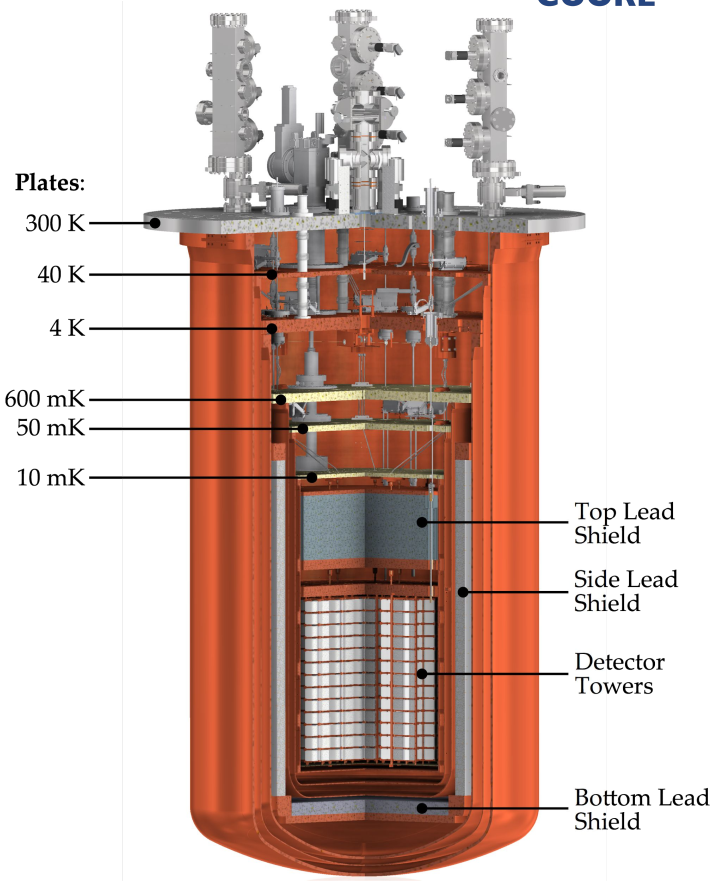
CUORE cryostat

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

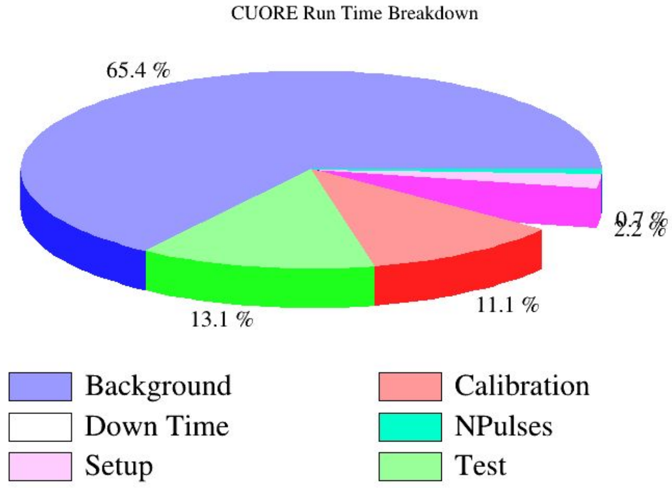


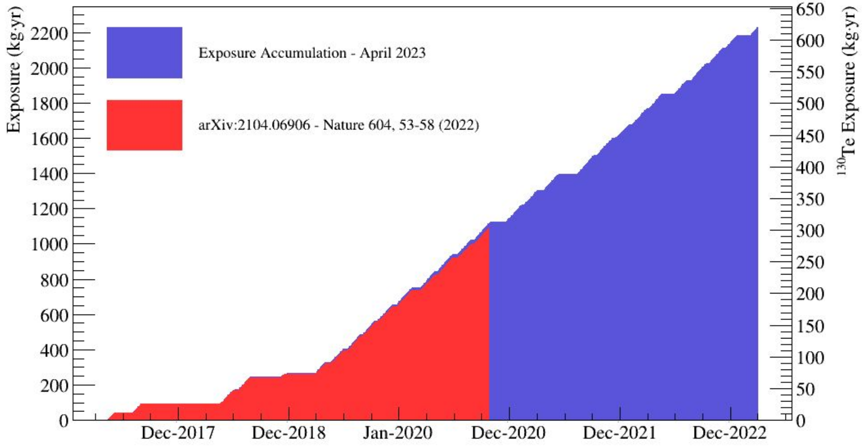
https://doi.org/10.1016/j.cryogenics.2019.06.011

Data taking

Timeline:

- Jan 2017: data taking started
- 2017-2019: low duty cycle detector optimization and upgrades
- 2019-today: low downtime (~90% duty cycle)
- ~1 ton*yr last official data release
- > 2 ton*yr collected and data release in preparation

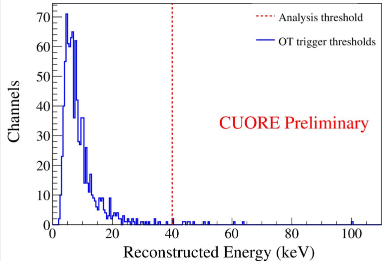




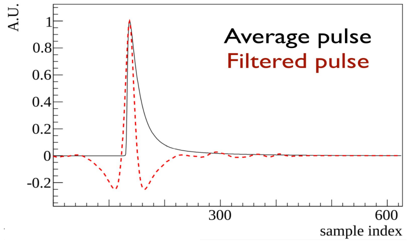
~ 90% data available for SN search: stability of operation for ton-scale cryogenic detector is a fundamental also for SN detection!

Event reconstruction

1. Trigger of continuous data stream

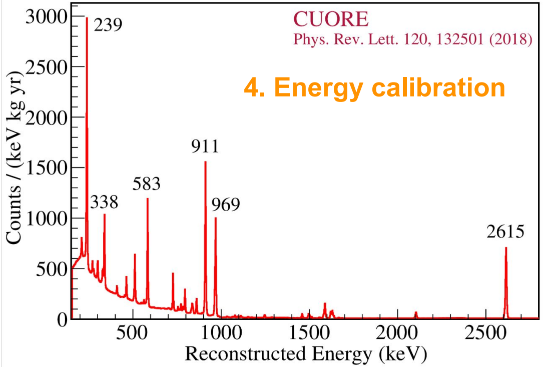


2. Amplitude evaluation with Optimum Filter

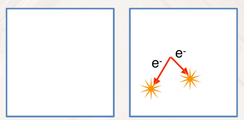


3. Thermal gain stabilization vs. baseline temperature

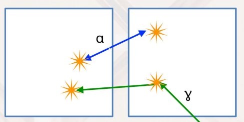
4. Energy calibration



5. Event multiplicity selection

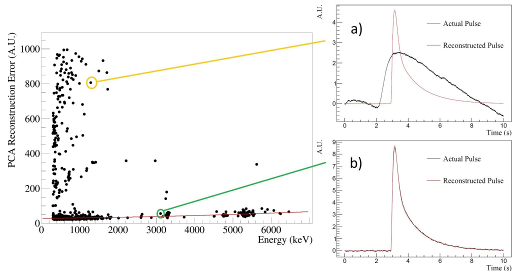


M1 - 0νββ/2νββ signal like

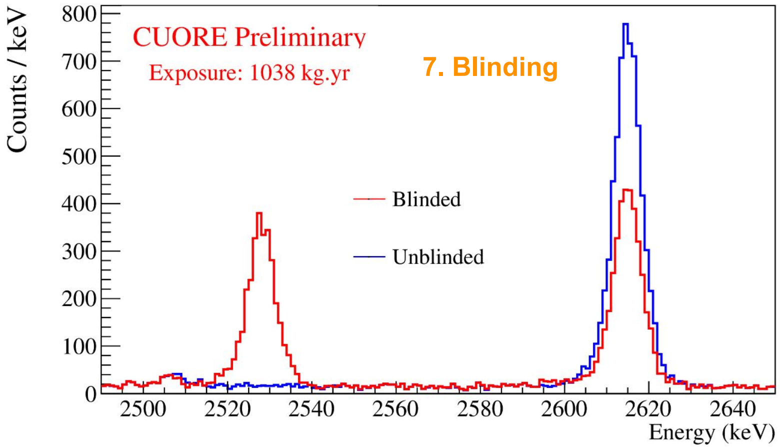


M2 - rejected background and important information for bkg studies

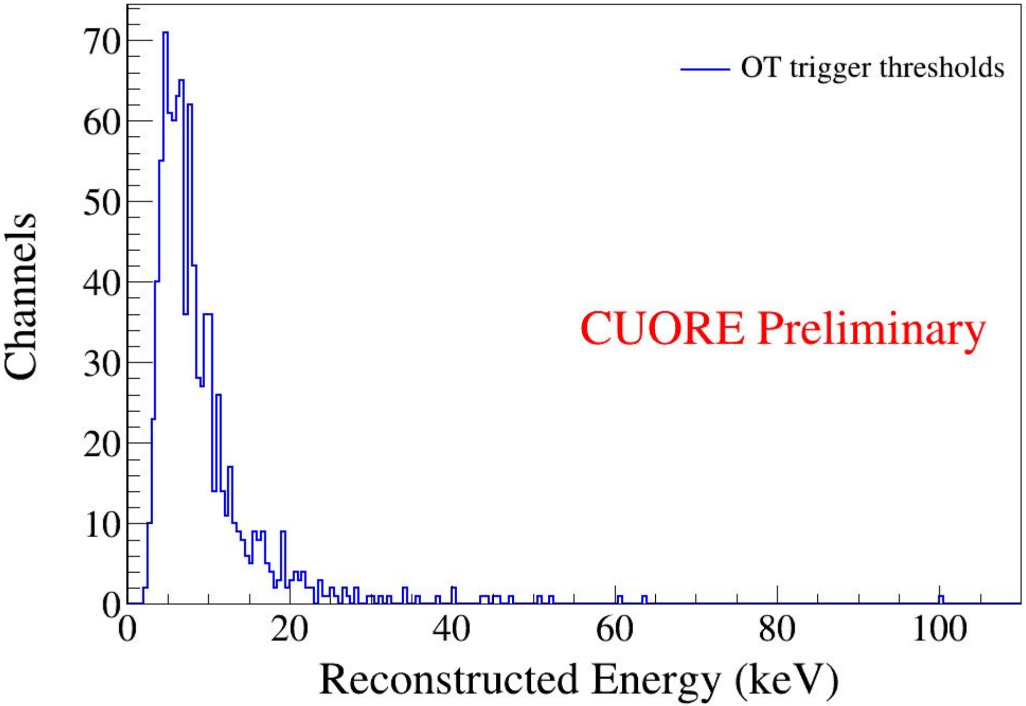
6. Pulse shape cut



7. Blinding



Event reconstruction at low energy



Energy threshold:

- most important factor
- OT trigger: triggers filtered waveform to maximize S/N ratio
- very sensitive to knowledge of noise features
- very sensitive to noise stability
- currently the best performing algorithms
- threshold defined as 90% trigger probability
- median ~7 keV

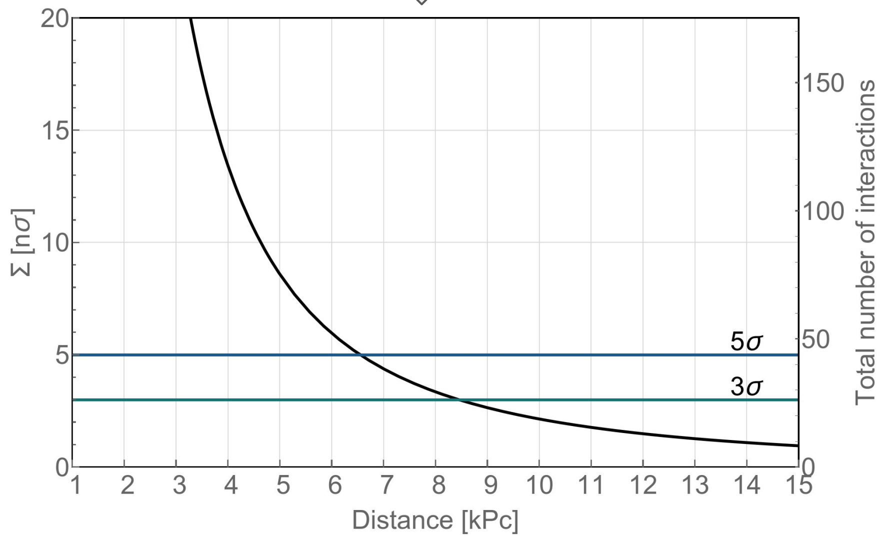
https://doi.org/10.48550/arXiv.1708.07809

Event reconstruction at low energy

Low energy background:

- not published yet
- assuming (conservative) background from CUORE radioactivity validation runs (CCVR)
- ~exponentially shaped with ~1 cps integral rate

https://doi.org/10.48550/arXiv.1708.07809



Time correlation analysis

- SN events expected with exponential time distribution
- background events flat distribution
- S/N is maximized within the first ~ 4 seconds
- time resolution of CUORE detectors ~10 ms
- high multiplicity coincidence can be searched for in a few seconds time window around explosion time
- pileup in same crystal very unlikely

Future improvements in CUORE

Main factors currently limiting energy threshold

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

Future improvements in CUORE

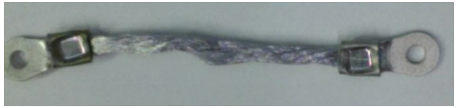
Main factors currently limiting energy threshold

Vibrational noise

10.1016/j.cryogenics.2018.05.001

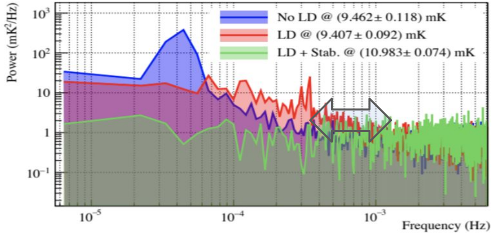
Reduce power and improve active suppression

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



New Pulse Tubes:
- more cooling power
- less PTs required
- 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



Future improvements in CUORE

Main factors currently limiting energy threshold

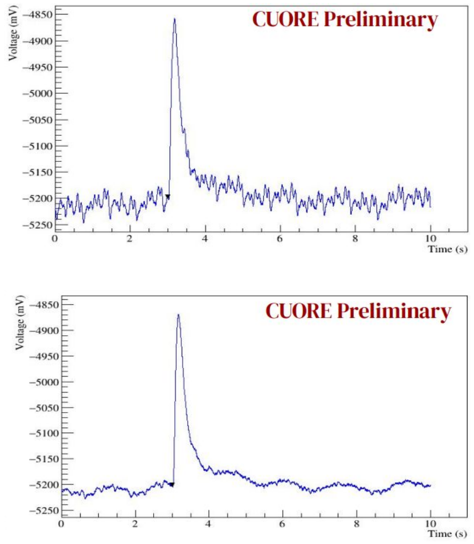
Noise instabilities

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



Future improvements in CUORE

Main factors currently limiting energy threshold

Vibrational noise

Noise instabilities

All upgrades to be implemented in 2025 and tested in the following years of CUORE science run before CUPID is ready for installation

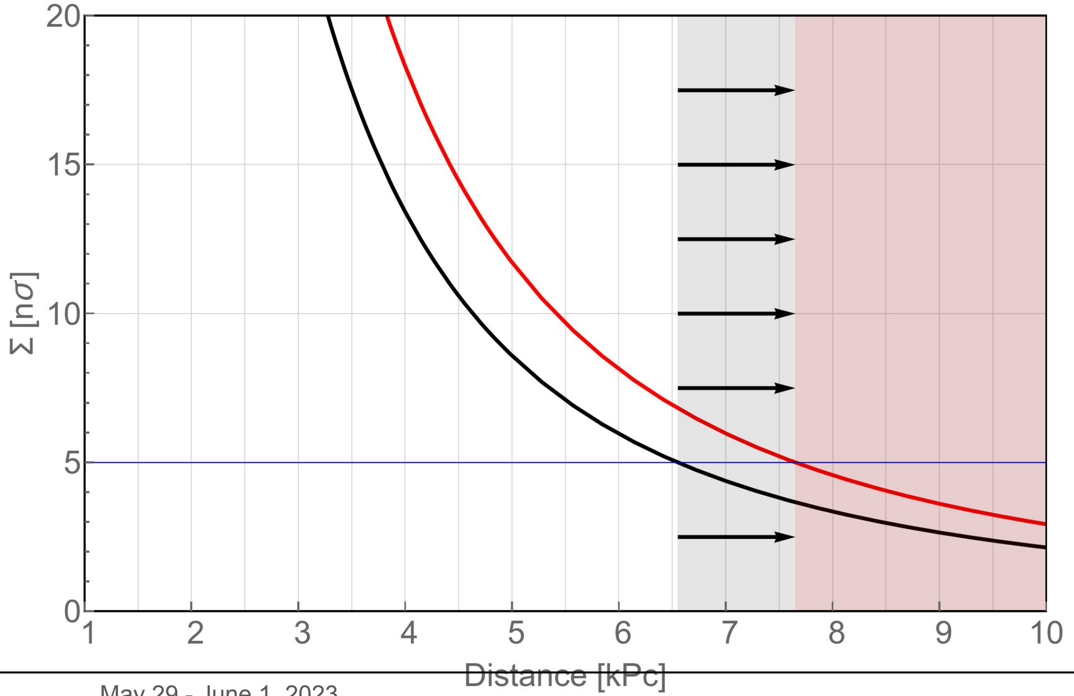
After ~1 year stop, CUORE will be online with increased SN sensitivity for years to come

Future improvements in CUORE

After ~1 year stop, CUORE will be online with increased SN sensitivity for years to come

Factor 2 improvement in energy threshold expected

Extend by more then 1 kPc sensitivity to SN detection

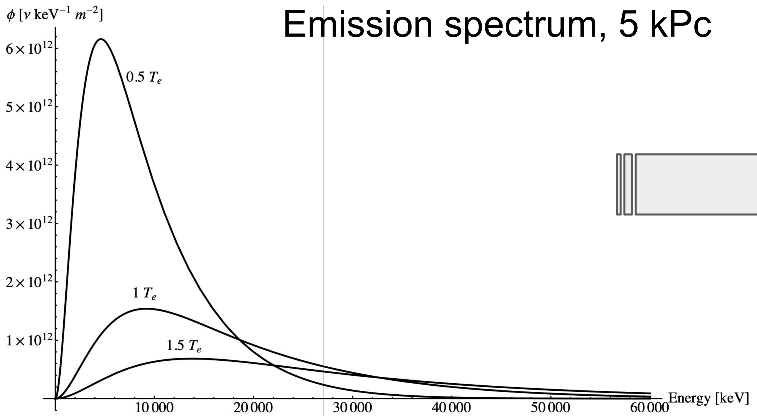


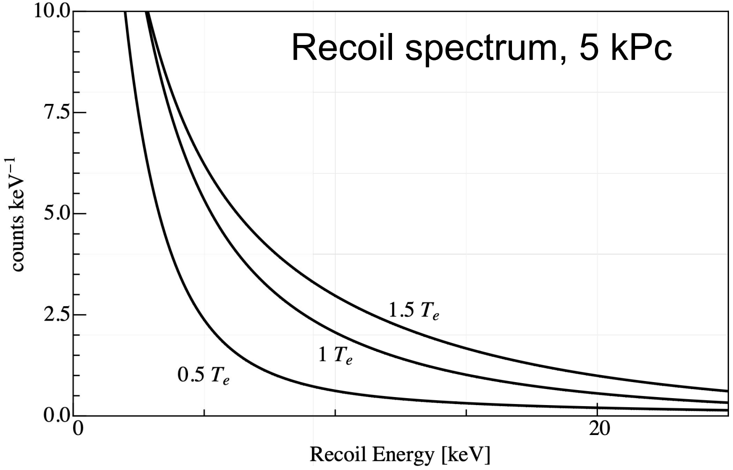
SN parameters with observation

Uncertainty in the parameter T_e (characteristic temperature or neutrino-sphere radius) translates into different spectral shapes:

- larger $T_e \rightarrow$ smaller flux, higher energy
- smaller $T_e \rightarrow$ larger flux, softer spectrum

Recoil energy spectrum depends on original spectrum → for known distance, overall normalization and flux “temperature” can be measured to some extent





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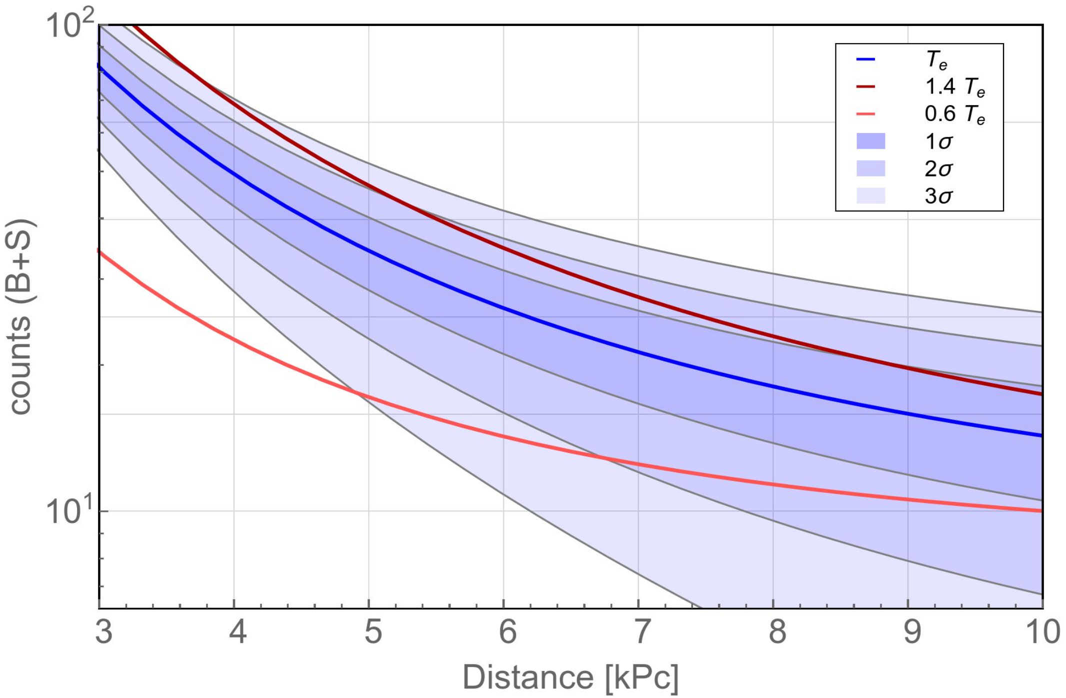
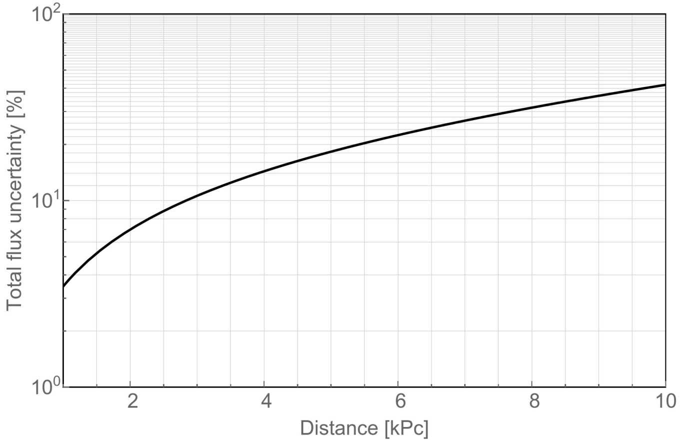


@5 kPc:

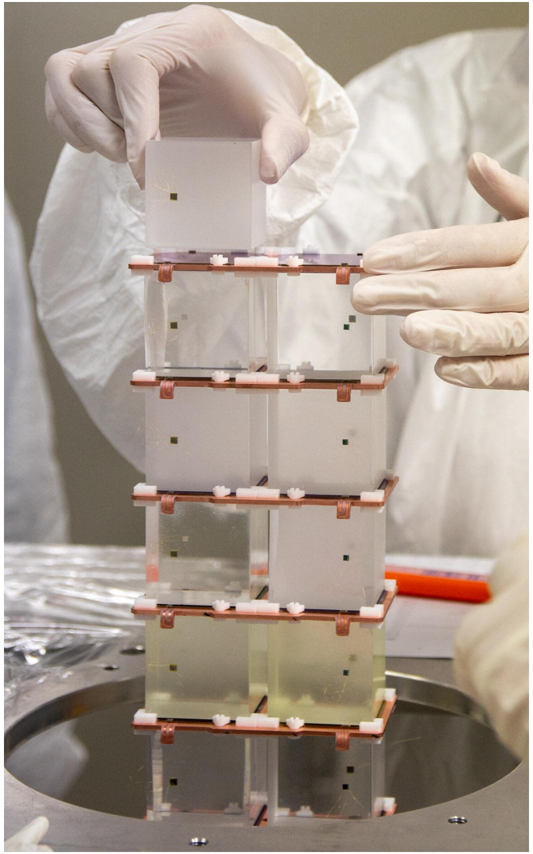
- a 40% variation of T_e can be measured at 3σ level
- total flux with <20% uncertainty



CUPID concept: Cuore Upgrade with Particle IDentification

Large scale array of high-resolution cryogenic calorimeters for the search for $0\nu\beta\beta$ and other other rare events

- replace CUORE (TeO_2) detector with new one based on $Li_2{}^{100}MoO_4$ crystals
- same mass 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
  - pile-up rejection with fast light-detectors
  - increased number of channels (x3)



Isotope choice

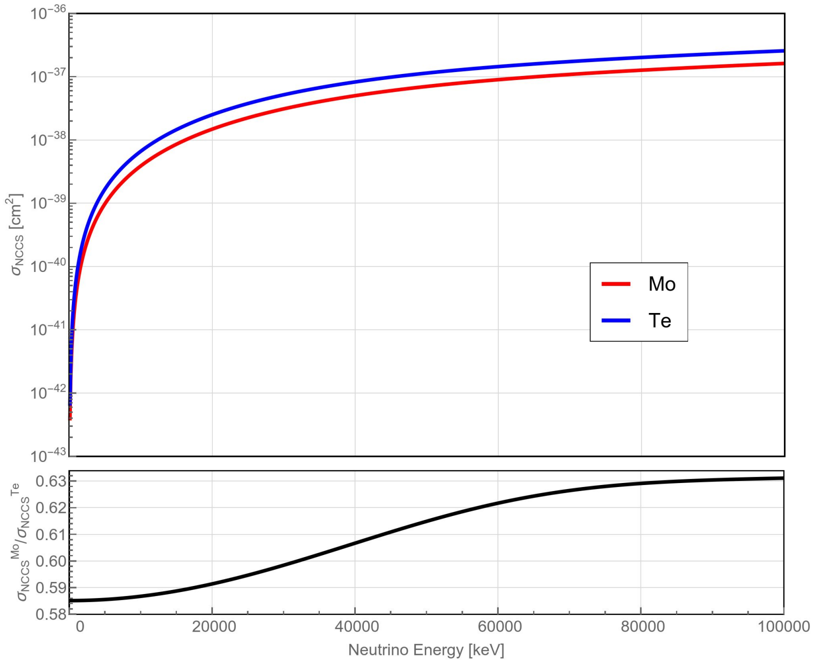
CUORE CUPID

Balance between **performance** (background reduction, NME, detector performance) and **cost** (isotope enrichment, crystal growth). **Higher Q-value translates into smaller background → very convenient for NDBD search**

Competing effects for SN detection

- Mo coherent cross section significantly smaller than Te (~ 60%)
- total Mo mass significantly smaller (~40%)
- larger recoil energy for same momentum transfer

Number of total expected interactions reduced compared to CUORE



Total signal

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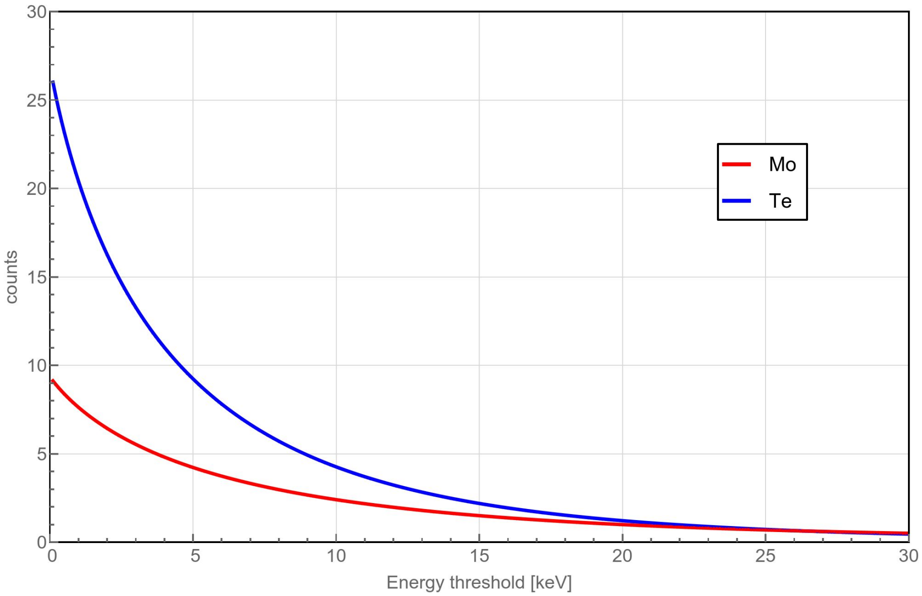
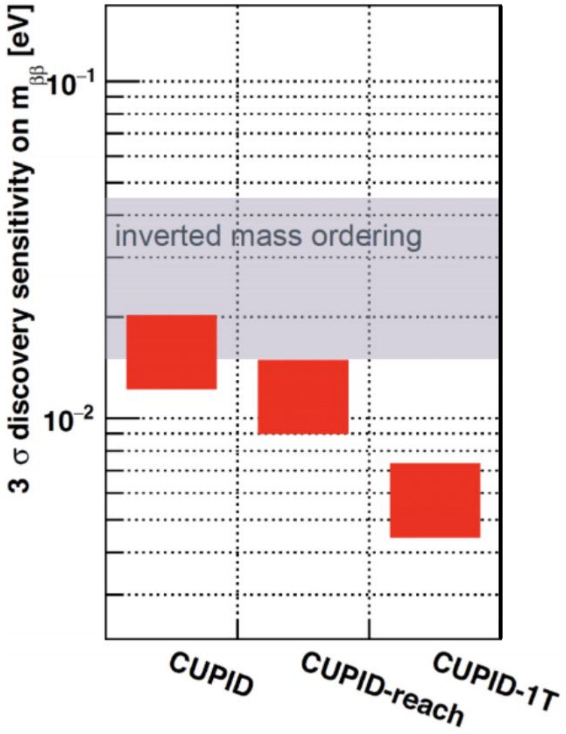


From CUPID to CUPID-1ton

CUPID is the first step in a phased program to increase the sensitivity on $m_{\beta\beta}$ towards the direct ordering.

CUPID-1T is the final goal, with:

- 1000 kg of ^{100}Mo deployed in the form of scintillating crystals, possibly multi-isotope deployment
- new cryogenic infrastructure with improved passive and active background suppression
- next generation readout based on quantum sensors to increase energy and time resolution
- improved scintillation with materials R&D to increase particle discrimination capabilities at low energy

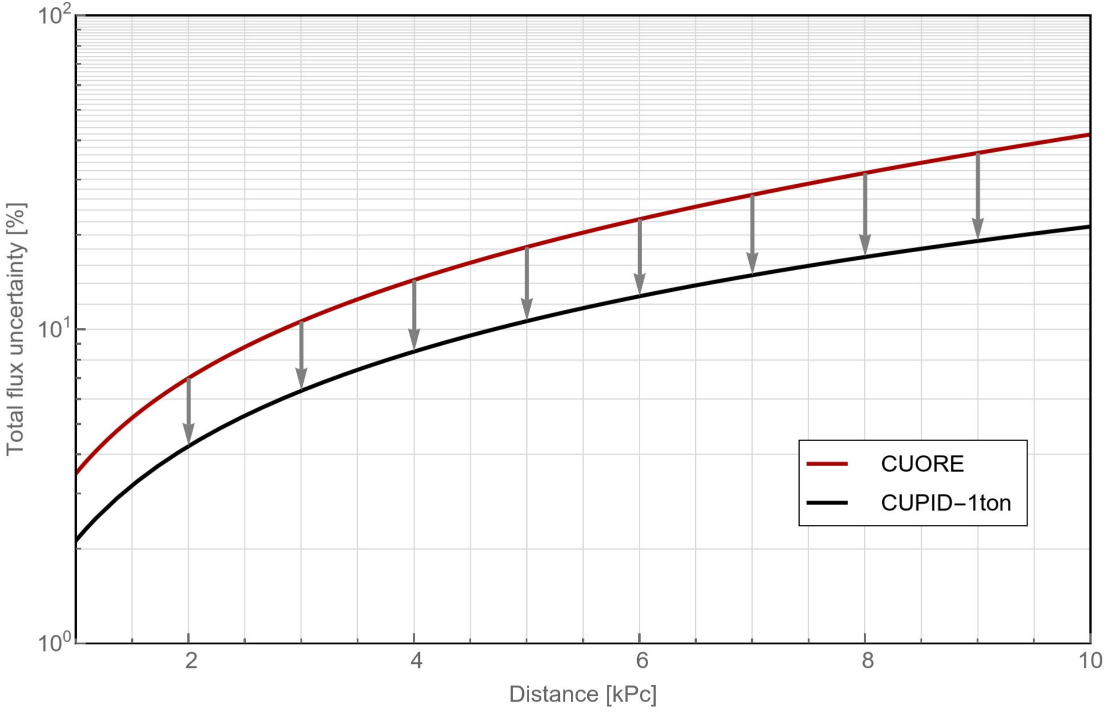


From CUPID to CUPID-1ton

CUPID 1-ton tentative design:

- 1000 kg ^{100}Mo with 1800 kg total active mass
- 1 keV energy threshold with quantum sensors readout
- factor 10 reduction of low energy background counting rate w.r.t. CUORE (basically zero background events in 10 s window)

Factor ~2 improvement in total flux uncertainty w.r.t. CUORE



Conclusions

- Flavor-independent neutral current coherent scattering is a powerful tool to measure absolute flux of neutrinos from core-collapse supernovae
- Thanks to large enhancement of cross section compared to other detection mechanisms relatively small detectors are sensitive to galactic explosions
- Low temperature detectors are best candidates to exploit this mechanism: large active mass, low threshold, large atomic mass compounds
- CUORE is online and ready to detect a galactic event for the coming years with high duty cycle
- Following generations will have comparable or better sensitivities, depending on isotope/multi-isotope choice