Searching for $0\nu\beta\beta$ decay with CUPID

Jorge Torres✉, for the CUPID collaboration
Feb 22, 2024 (Lake Louise Winter Institute)

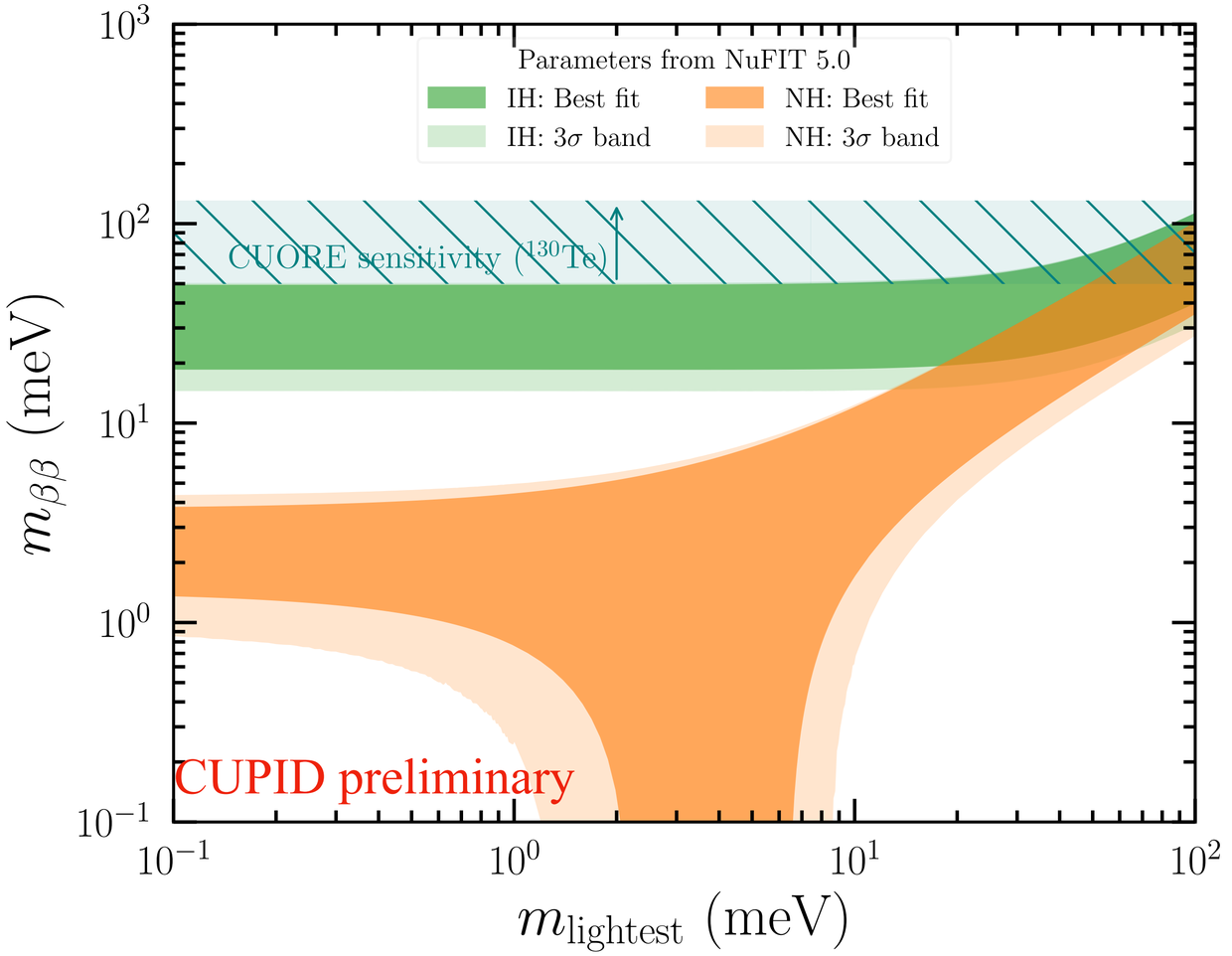
Wright Laboratory

Yale

CUPID

The case for CUPID (**C**UORE **U**pgrade with **P**article **ID**)

- CUPID is an upgrade to the **successful** CUORE experiment.
- Discovery sensitivity (3σ):
  - $T^{0\nu}_{1/2} > 1.0 \times 10^{27}$ yrs
  - $m_{\beta\beta} = (13 - 21)$ meV
- CUPID can probe the IH region.
- New technology to **decrease** backgrounds and **increase** sensitivity.



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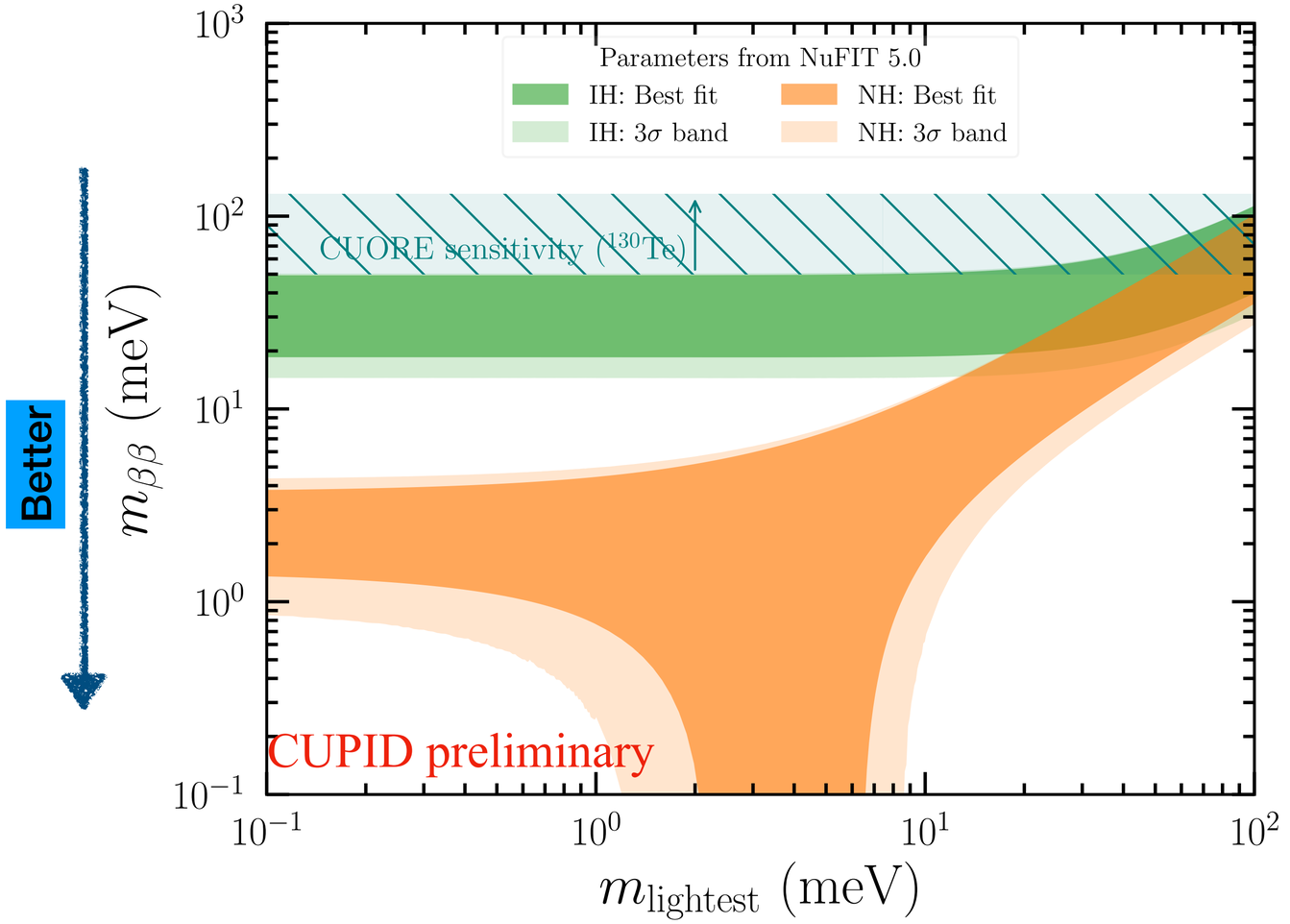

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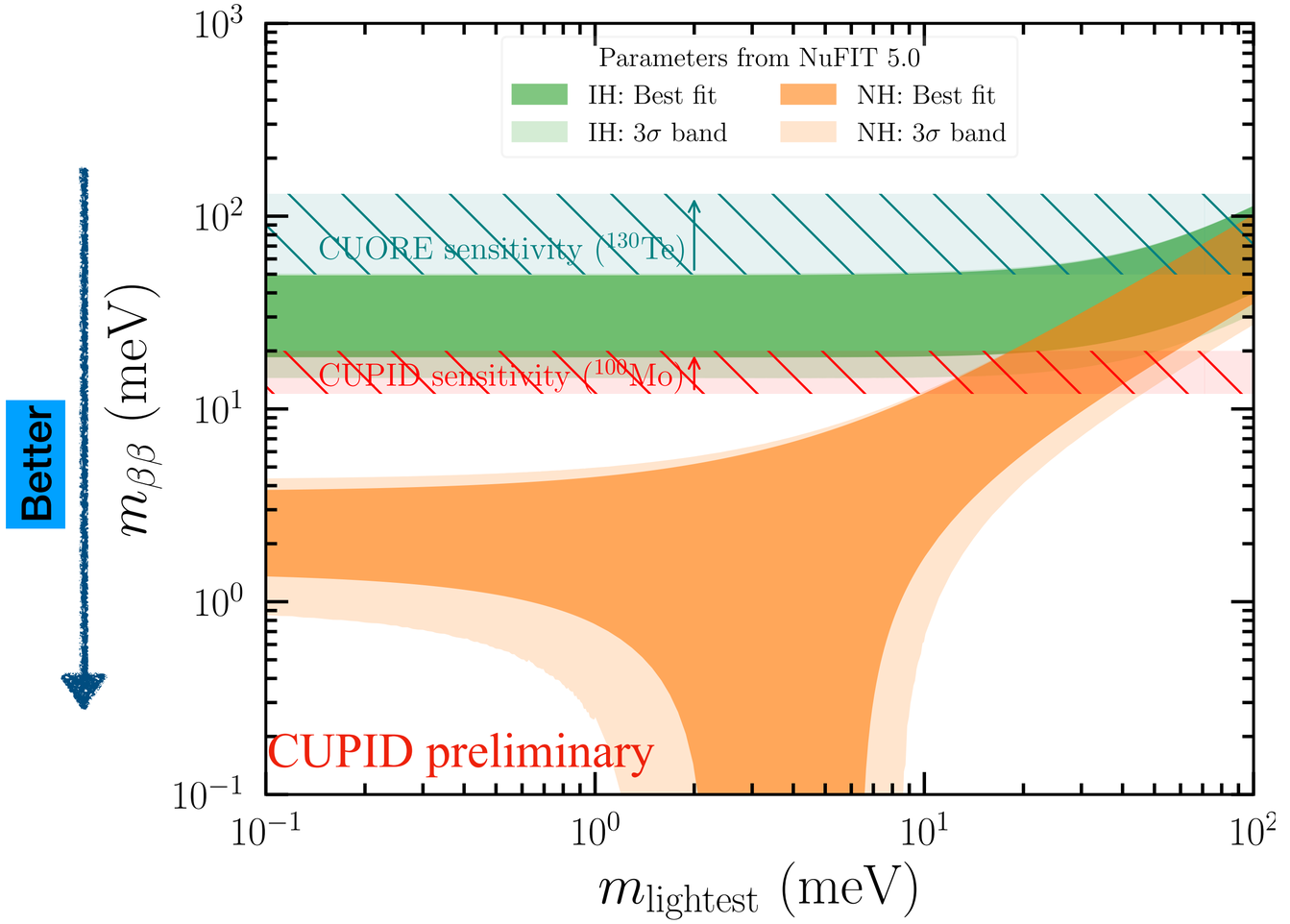

The CUPID Collaboration

Experience from 3 collaborations:

- CUORE
- CUPID-0
- CUPID-Mo

CUPID builds on CUORE's success

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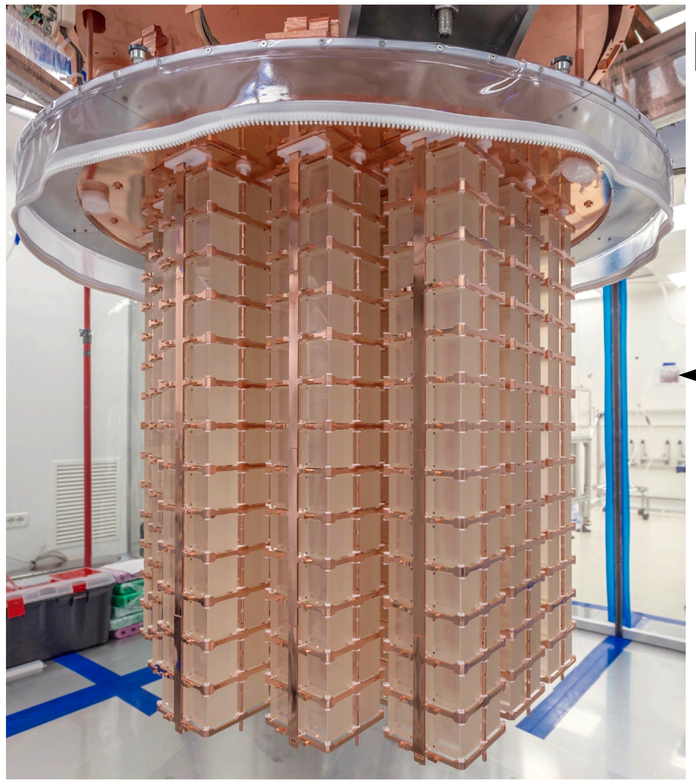

Nature 604 ,53 (2022)

First tonne-scale experiment using the bolometric technique.

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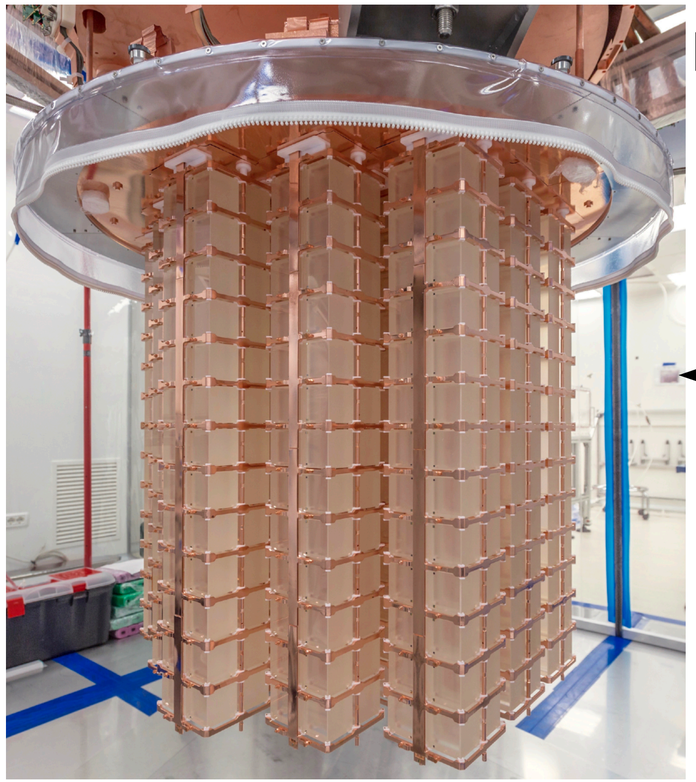

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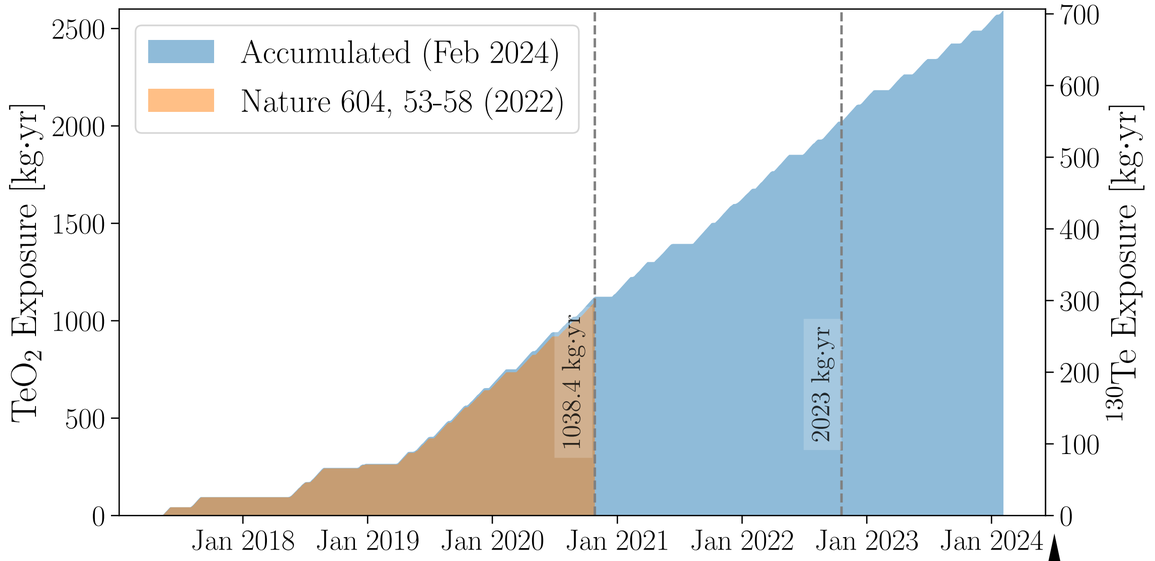

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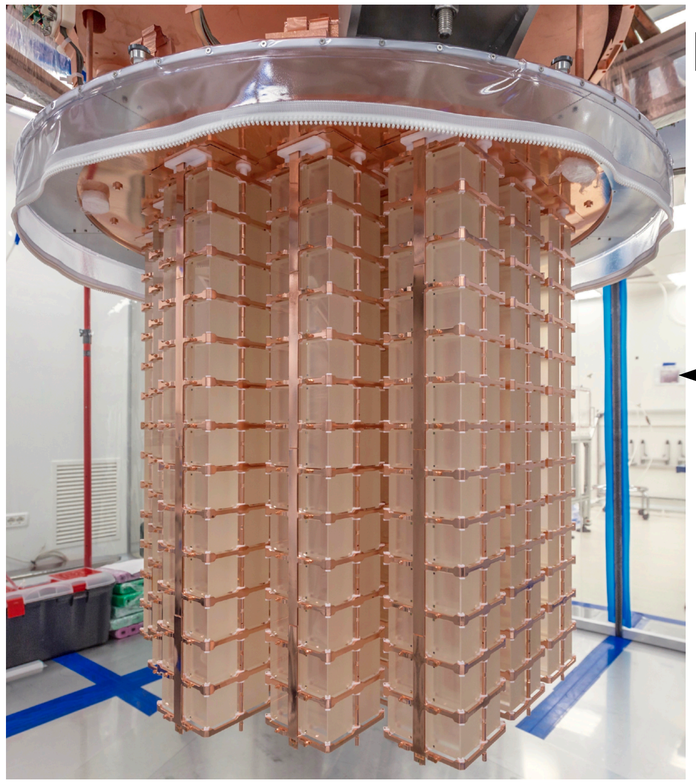

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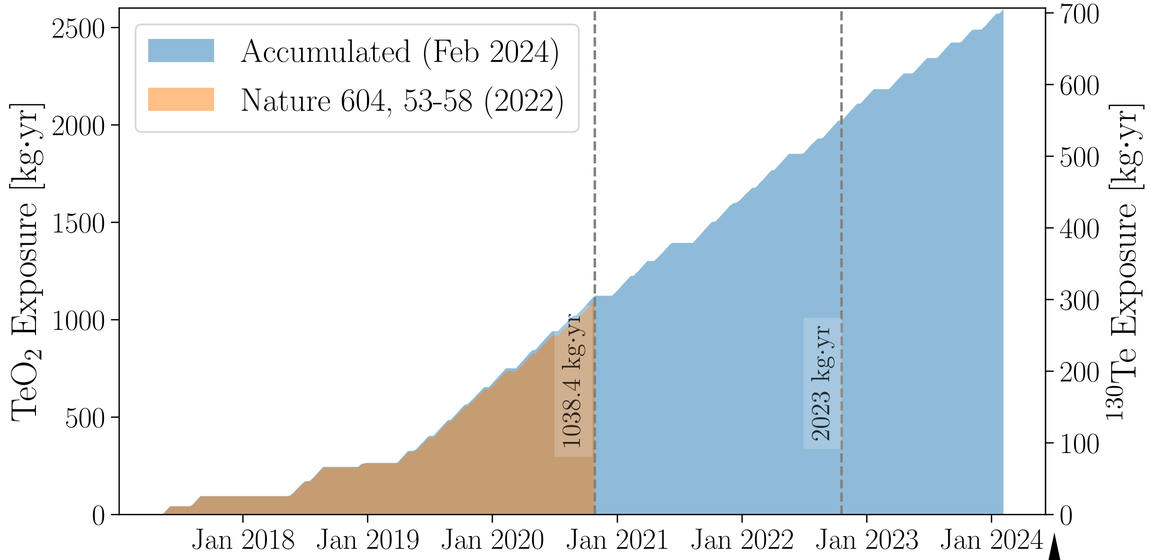

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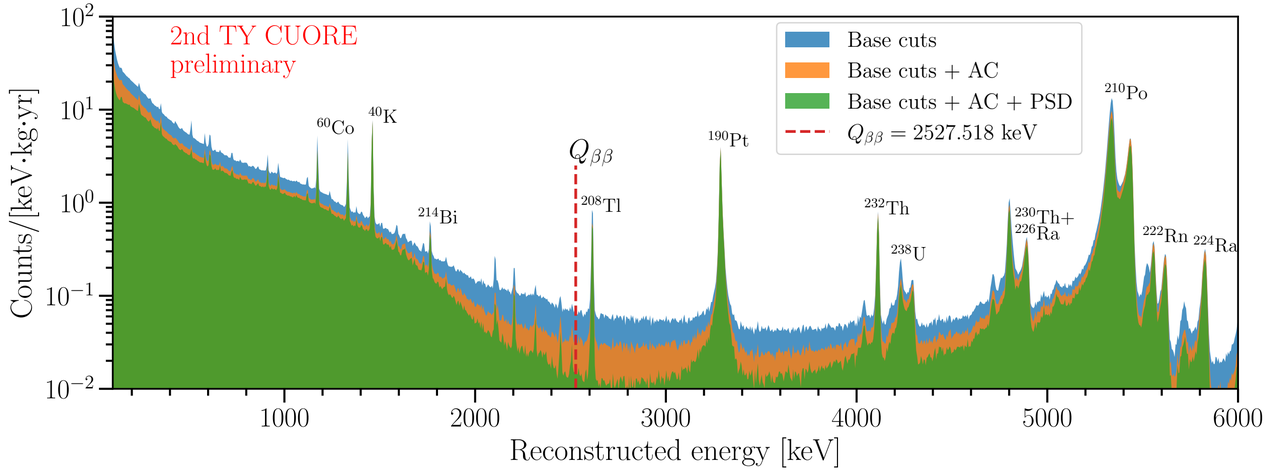
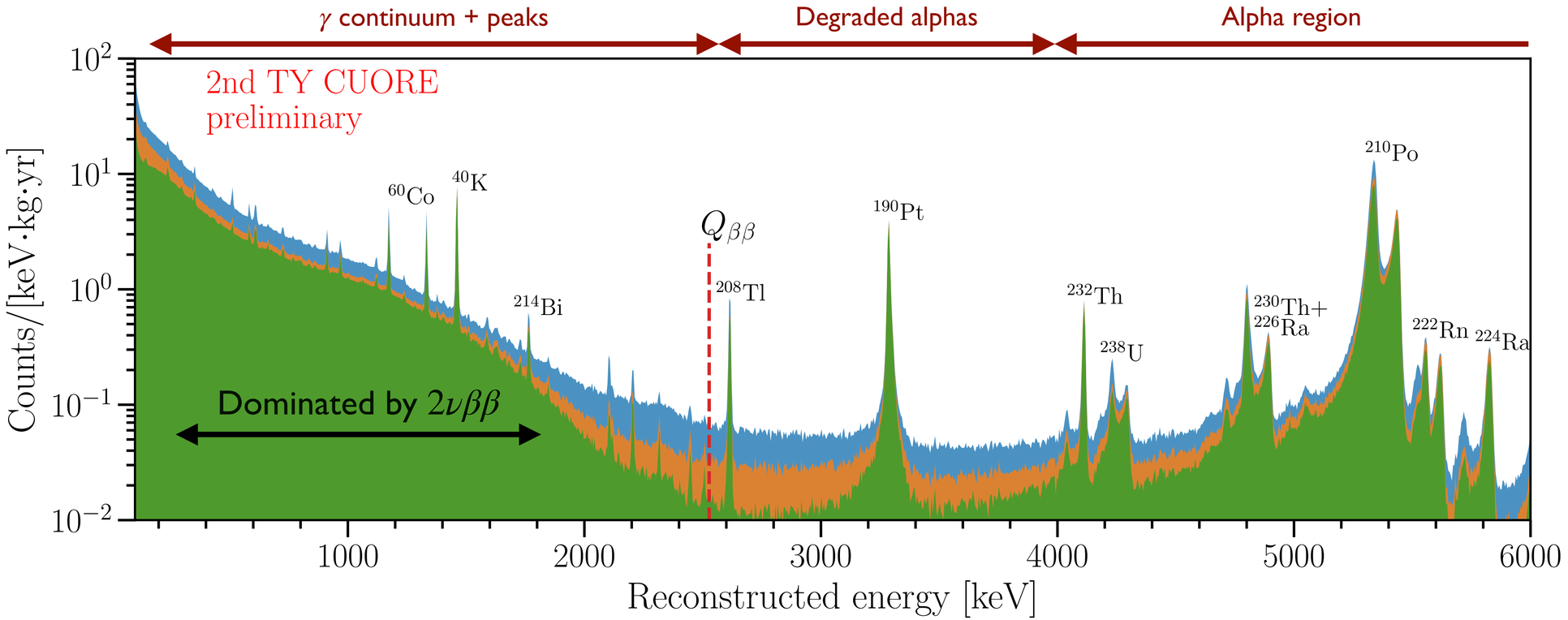
Background model from CUORE.



Demonstrated low background for Mo-100



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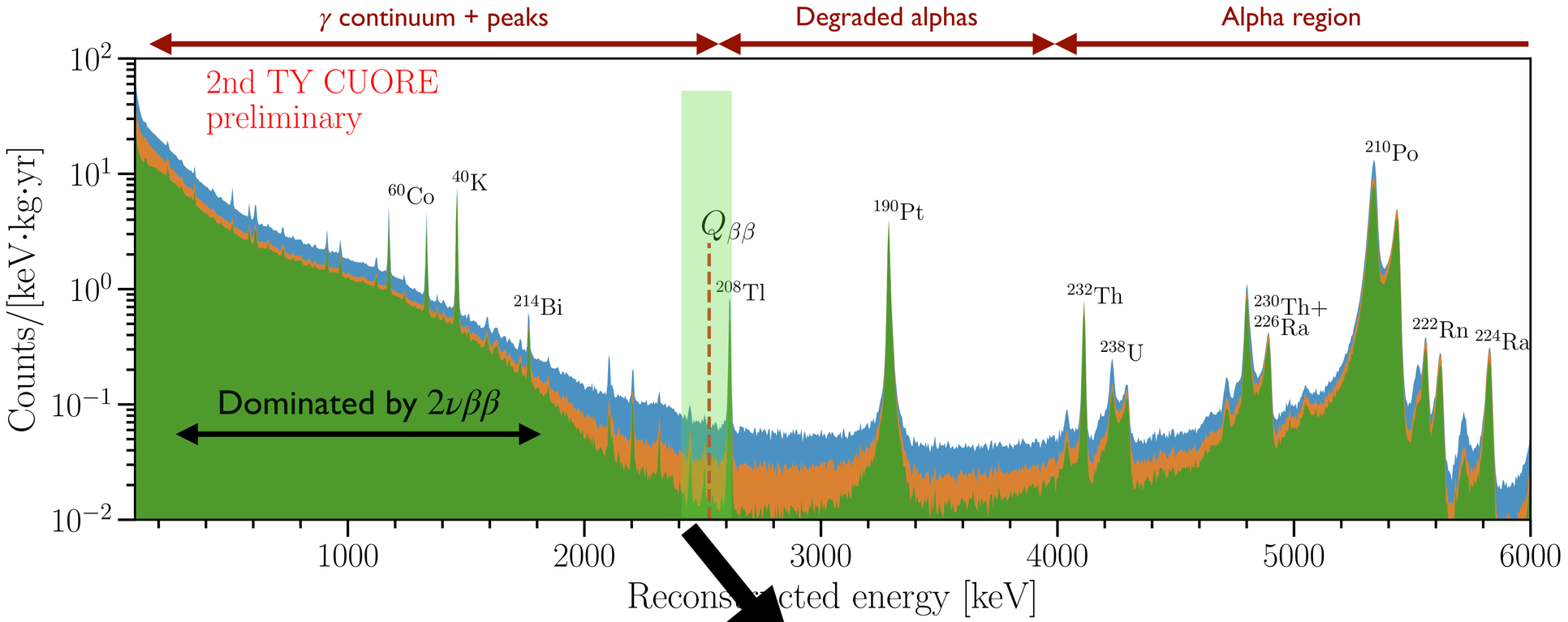

Residual backgrounds in the ROI

β/γ

~10% β/γ radioactivity

α

~90% degraded alphas (U/Th)

μ

$\lesssim$1% muons

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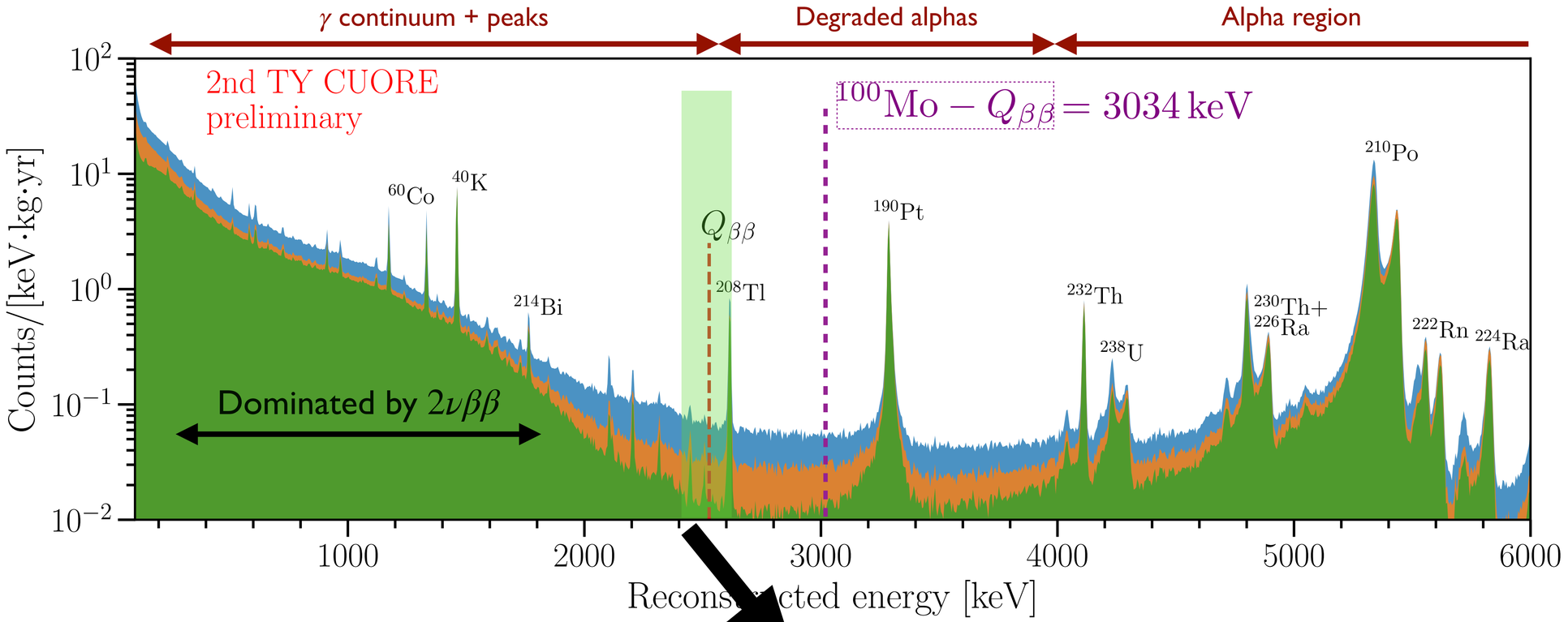

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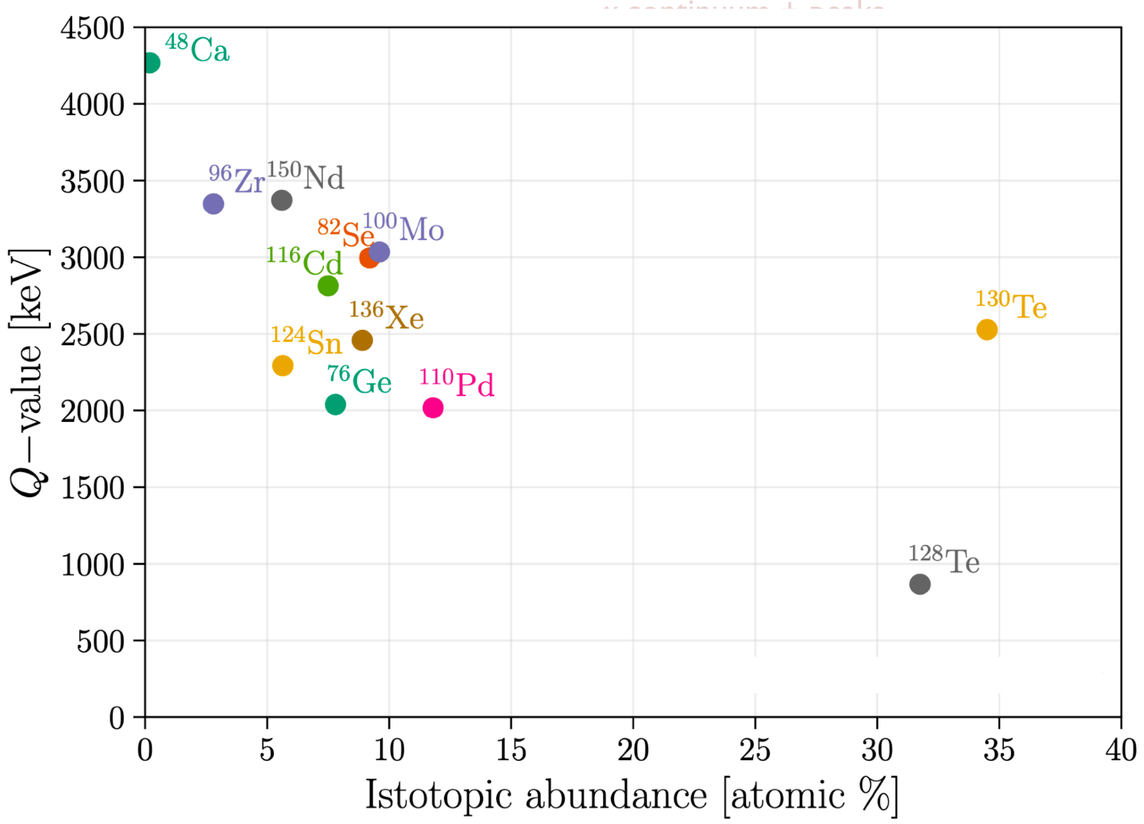

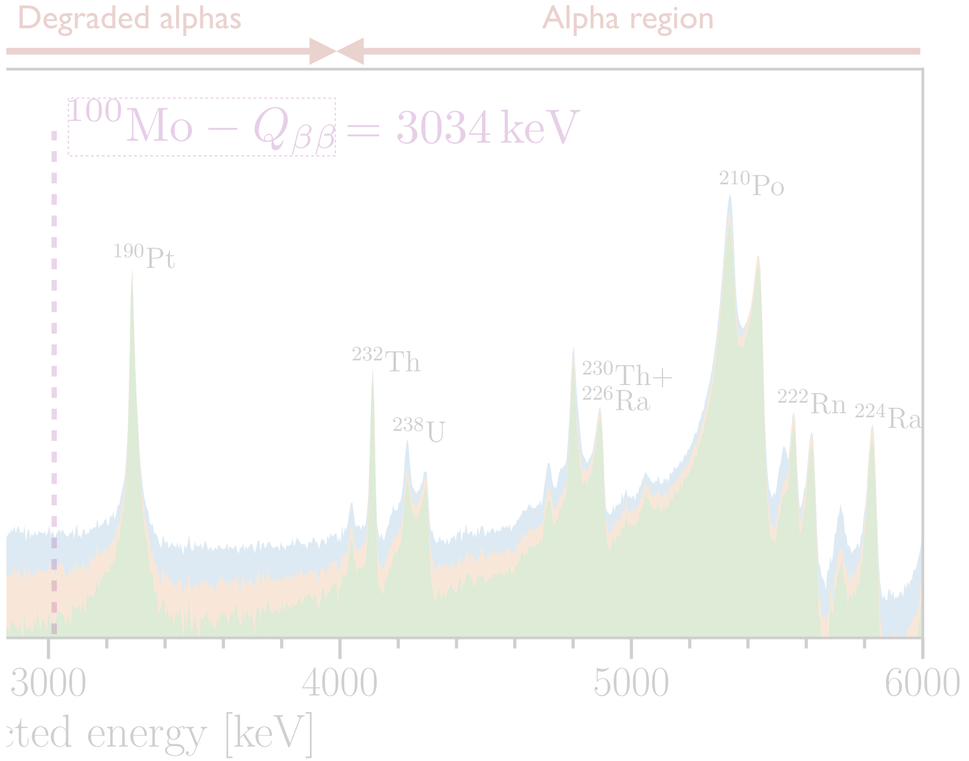

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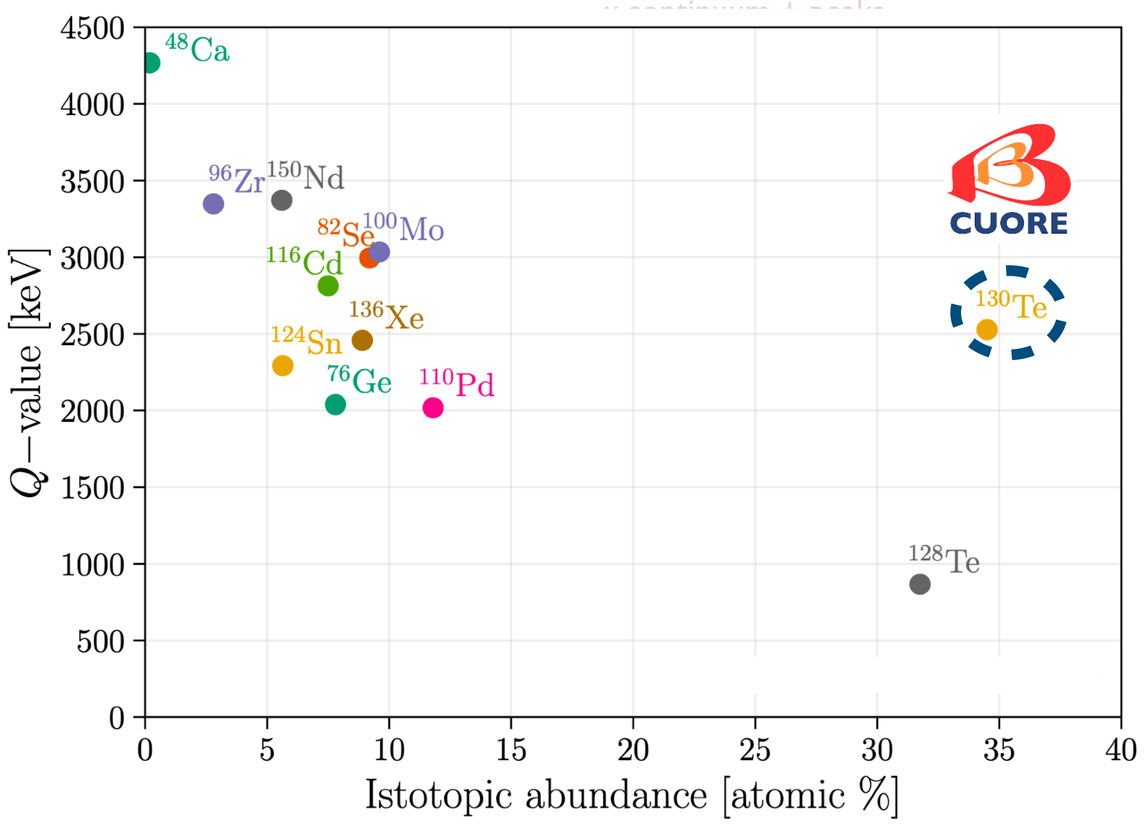

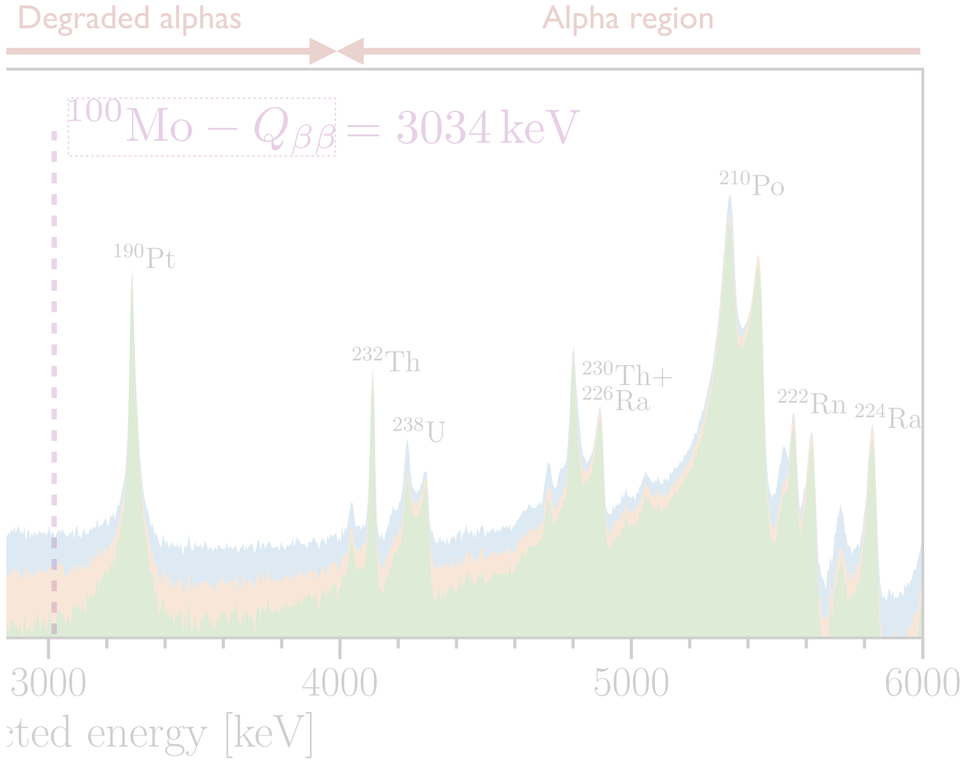

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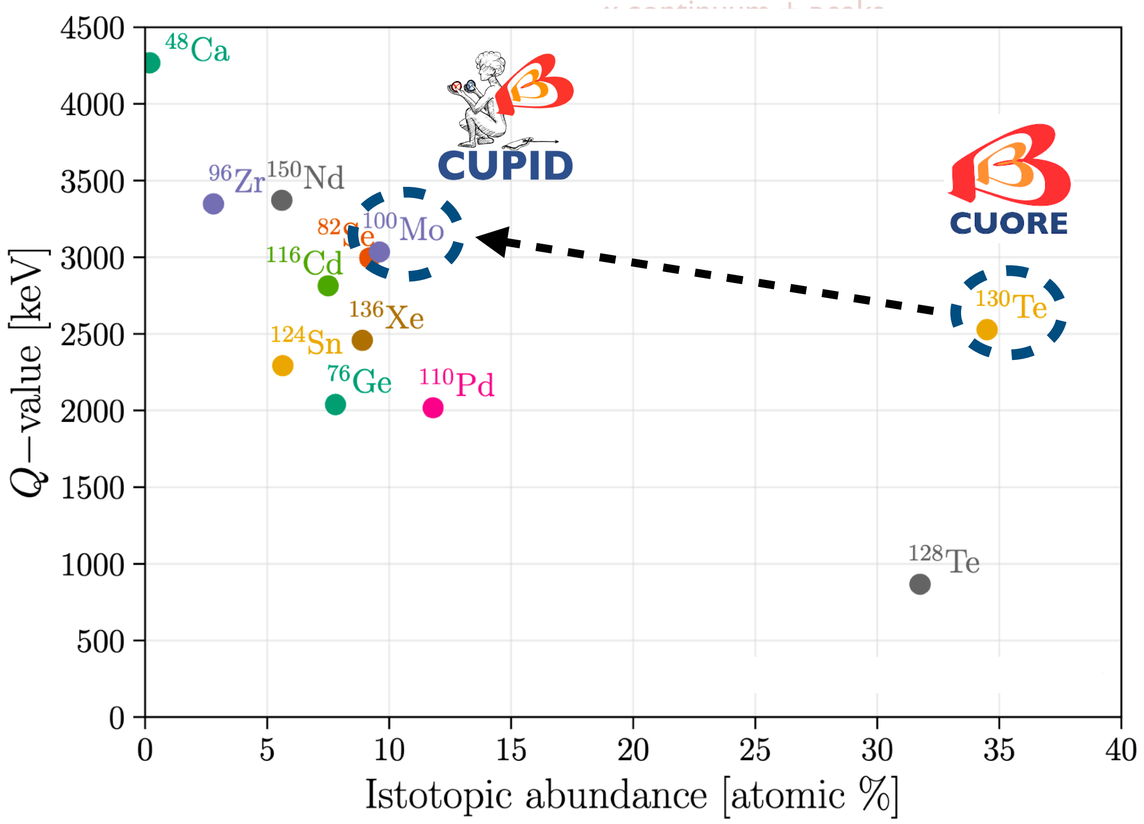

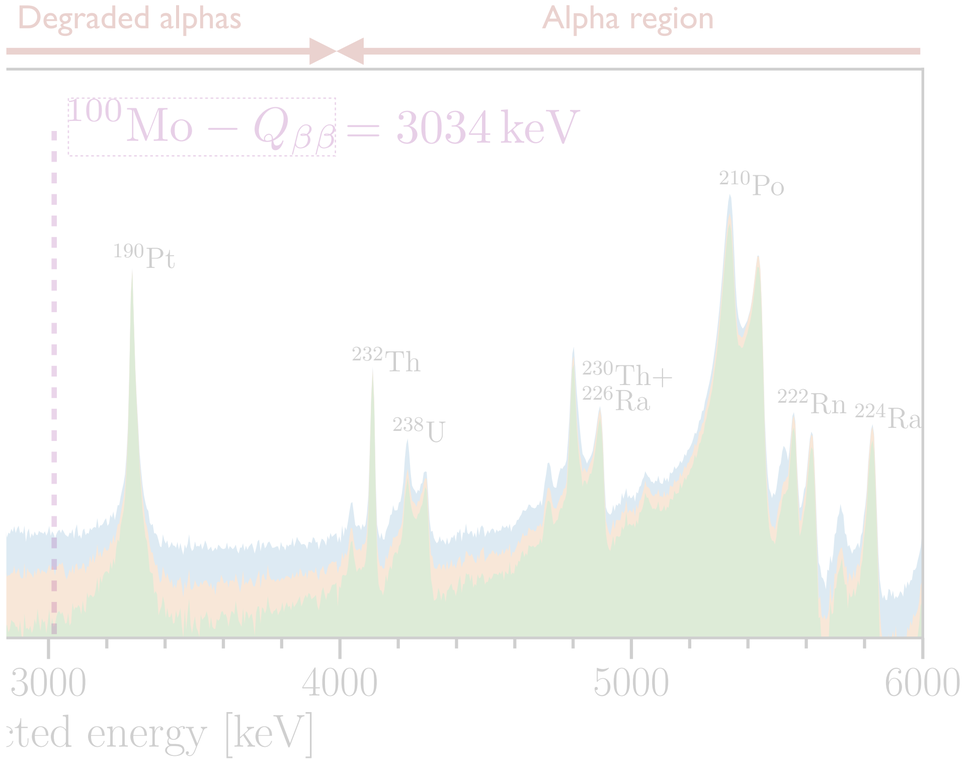

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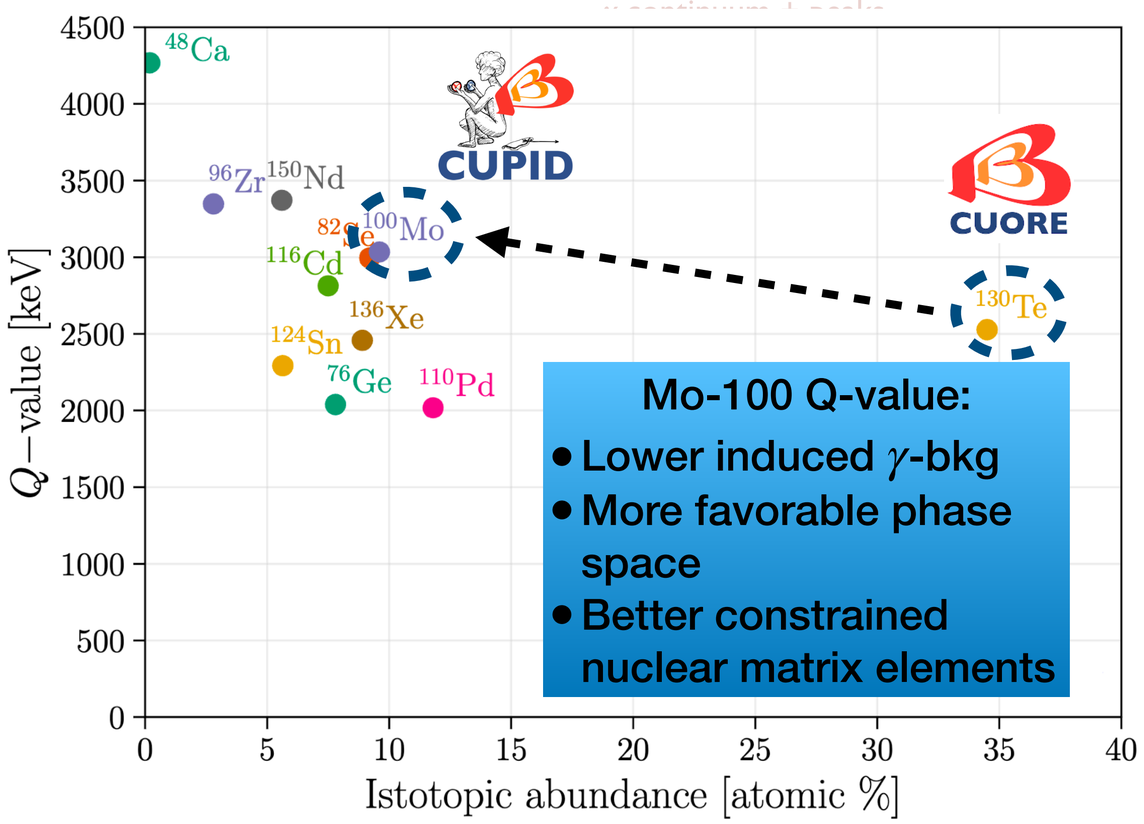

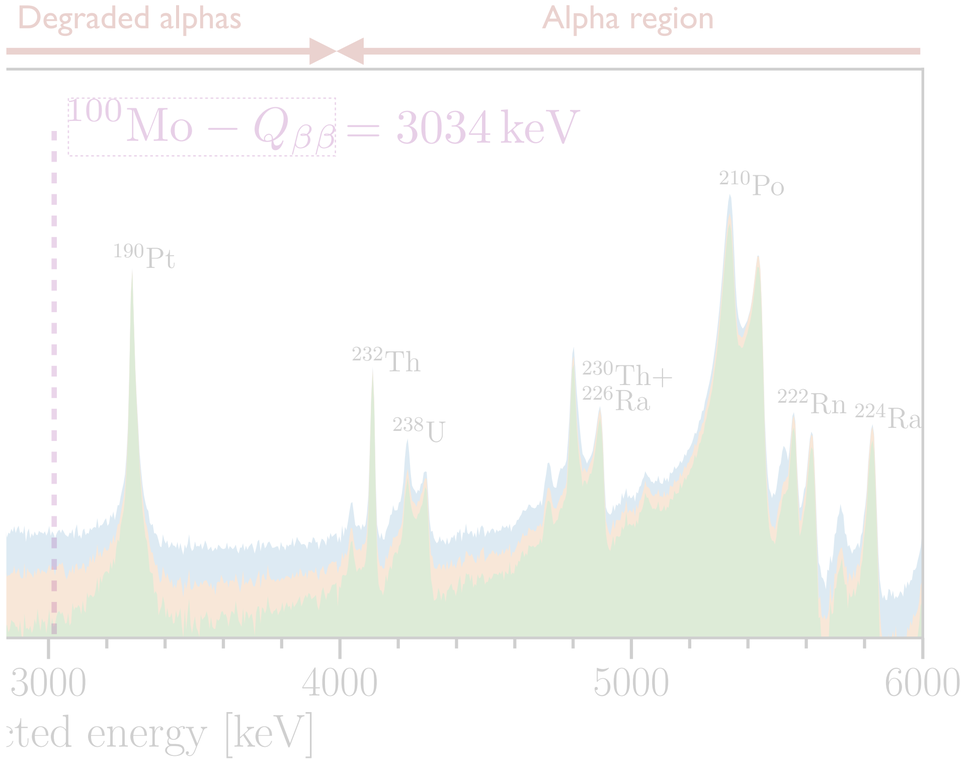

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Mitigating alpha backgrounds

- Exploit the scintillating nature of crystals.
- Exploration of dual readout for heat and light signals:
  - Bolometer coupled to light detector (Ge wafer linked to thermometer)
  - Different light-yield for alphas and betas
- Discrimination based on bivariate cut on light and heat signals.
- Build demonstrators to validate new technology.

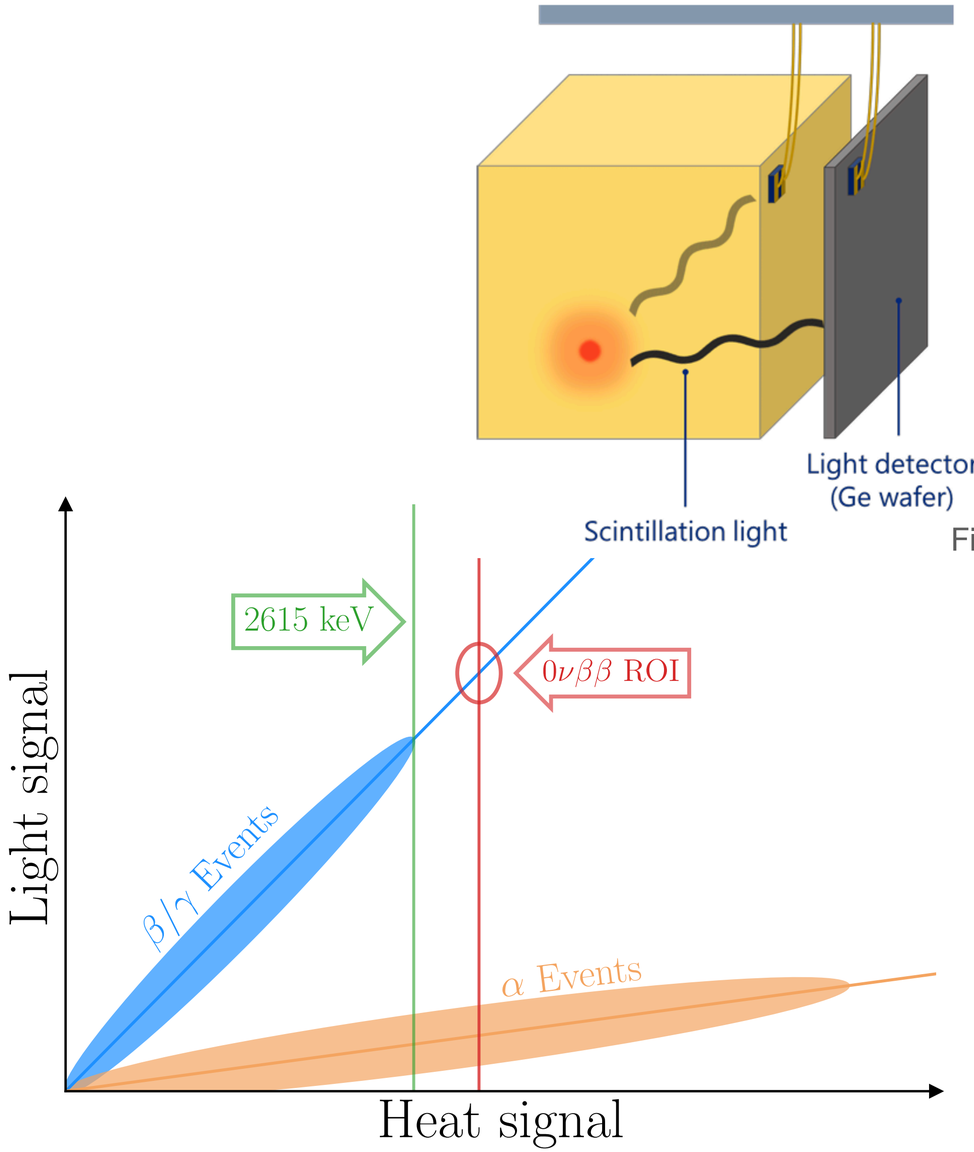


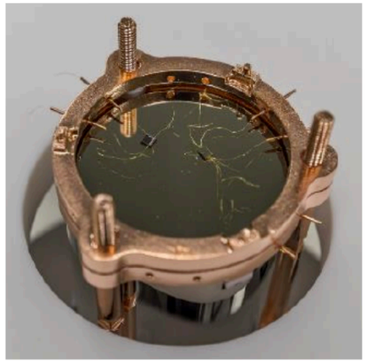
Figure: H. Khalife

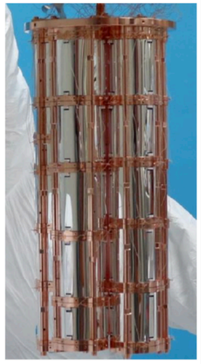
Successful 10 kg-scale demonstrators

CUPID-0

- $Zn^{82}Se$ crystals, 95% enrichment ^{82}Se (5.17 kg) at LNGS (Italy)
- α-rejection efficiency > 99.9%
- Background index: 3.5×10^{-3} ckky*
- $\Delta E = 21.8$ keV @ $Q_{\beta\beta}$ (2998 keV)
- Physics results
- Bkg studies

PRL **129**, 111801 (2022)





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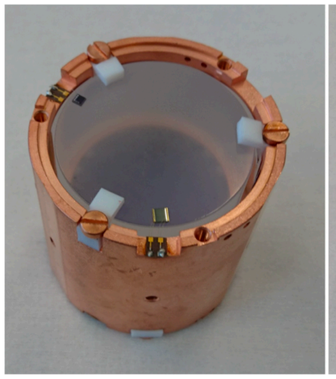
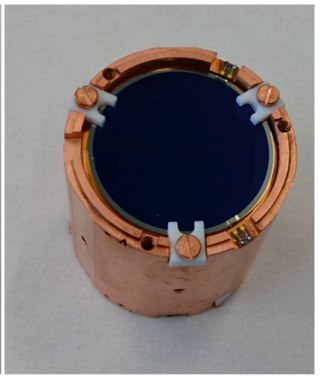
Eur. Phys. J. C (2022) **82**, 1033





* Cts/keV kg yr

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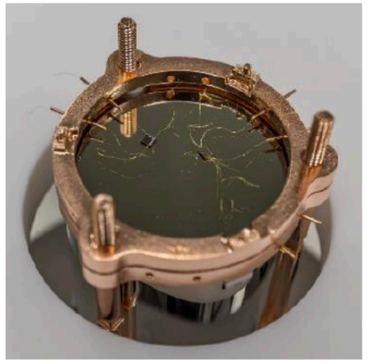

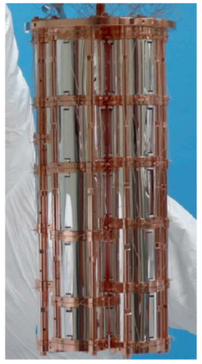

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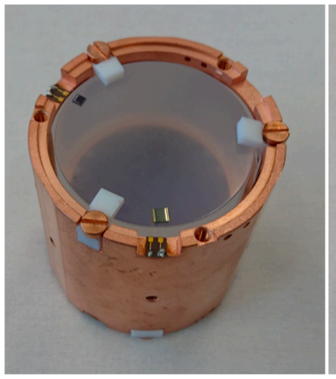
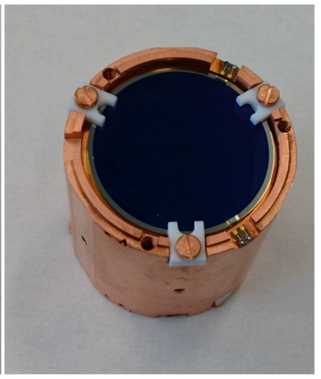
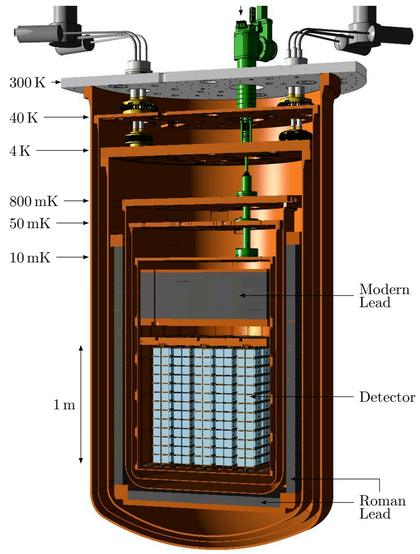


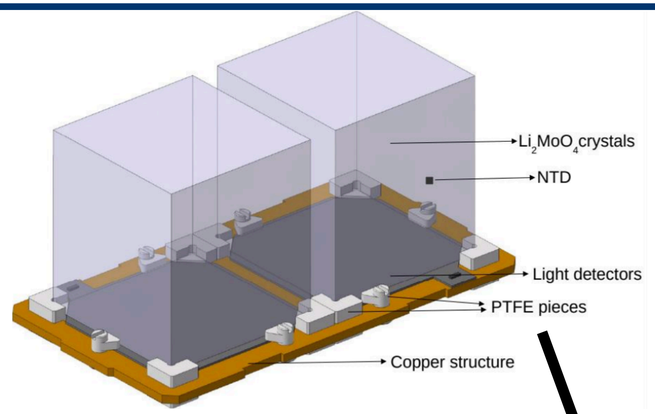


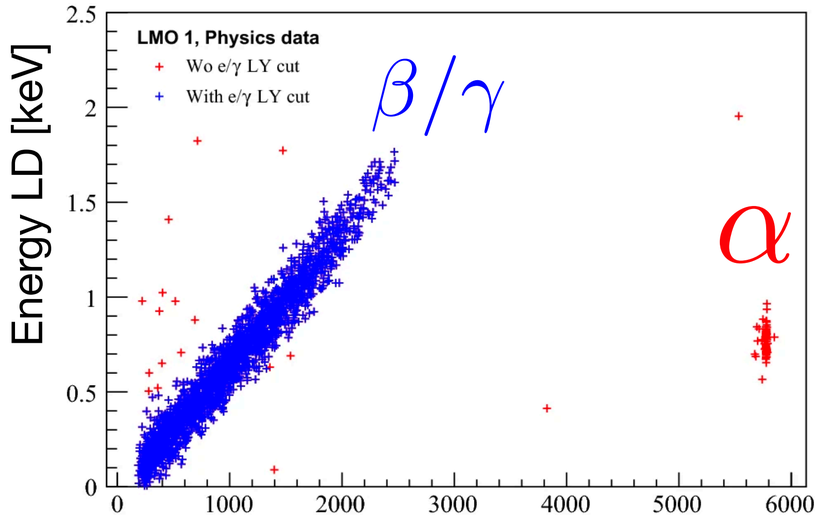
* Cts/keV kg yr

The CUPID baseline: what we can build now.

- Use CUORE's infrastructure
- 1596 $Li_2^{100}MoO_4$ crystals (45x45x45 mm^3)
- 240 kg of ^{100}Mo (enrichment > 95%)
- 1710 Ge wafer light detectors
- α–rejection efficiency demonstrated to be > 99.9%
- Energy resolution: FWHM < 5 keV at $Q_{\beta\beta}$
- LD baseline resolution < 100 eV RMS
- Light yield: 0.3 keV/MeV



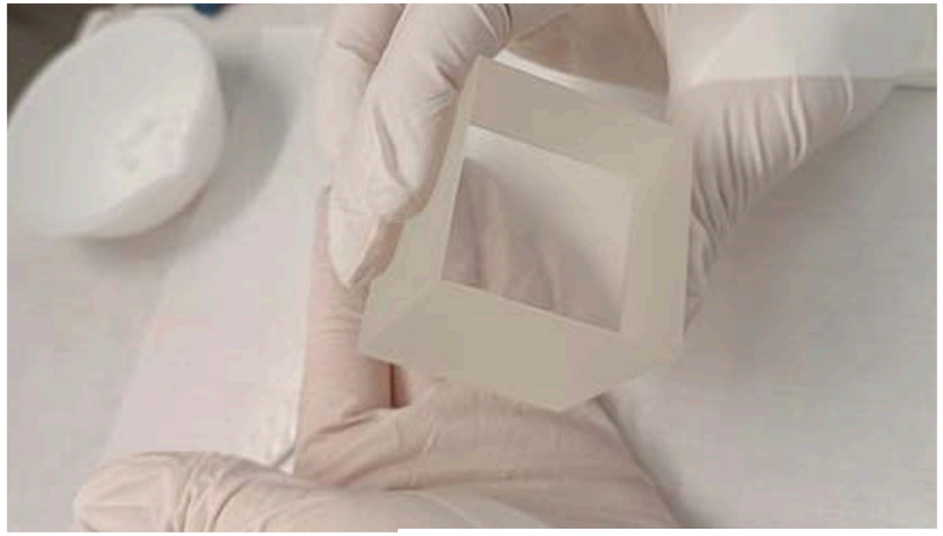


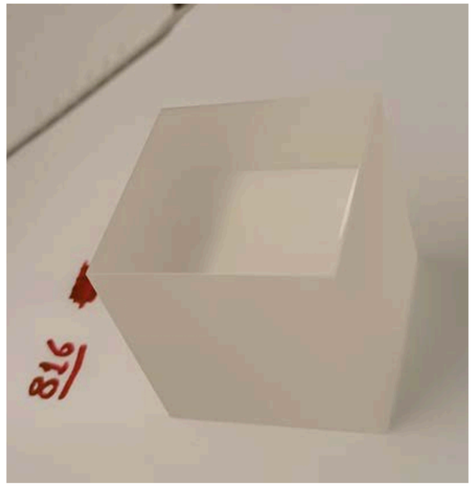


Eur. Phys. J. C (2020) 80:44

Production of enriched LMO crystals is feasible

- Ongoing pre-production in China (SICCAS)
- Enriched MoO_3 powder to be produced in China.
- Tests at Gran Sasso to validate performance/ radio purity and assess contamination.
- Strategies to improve crystal surface cleaning, and thus reach CUPID's bkg goal, being developed.
- Full production at **large scale** for CUPID is **viable** and currently under negotiation.

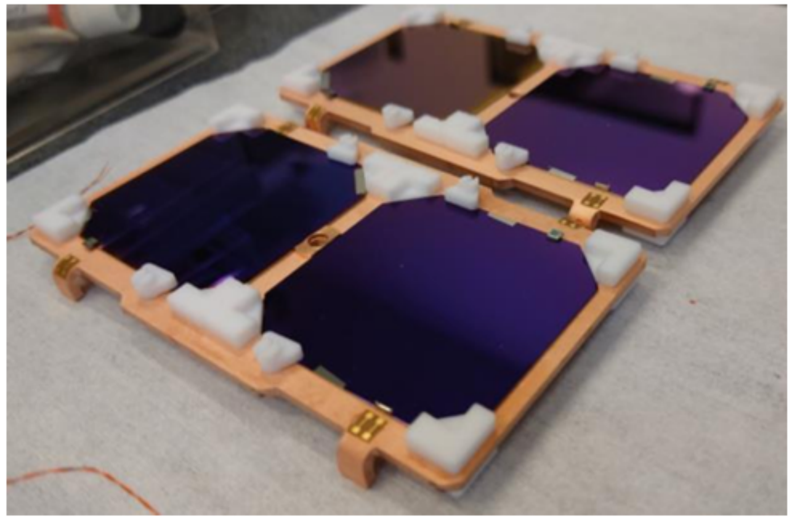




LMO crystals by SICCAS

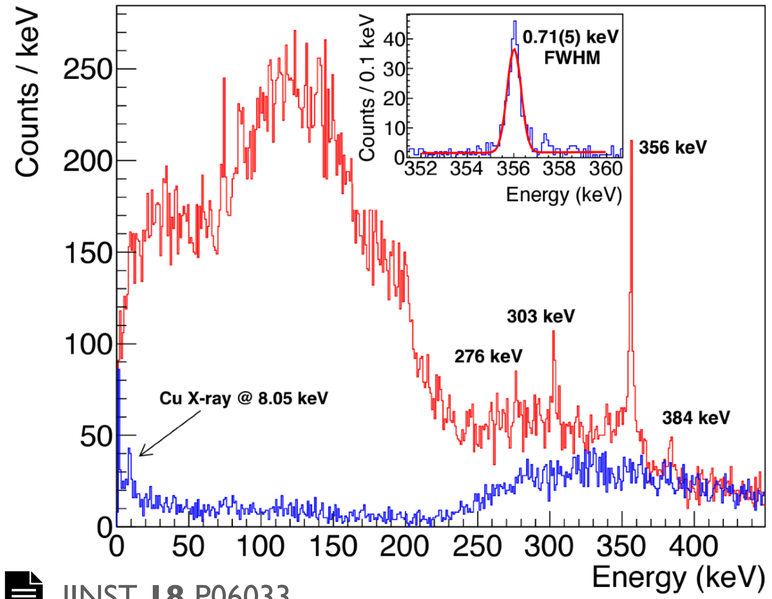
Light collection optimization and detector validation

- Performed studies with Ge wafer with anti-reflective SiO coating and NTD readout for CUPID baseline.
- Performed in a pulsetube cryostat at IJCLab.
- Baseline energy resolution 70-90 eV RMS.
- Also studies on reflecting foil and light detector position optimization.
- Results show that CUPID baseline **meets necessary α-rejection capabilities**, but saturates pile-up bkg constraint.



Eur. Phys. J. C (2022) 81:104

Eur. Phys. J. C (2022) 82:810

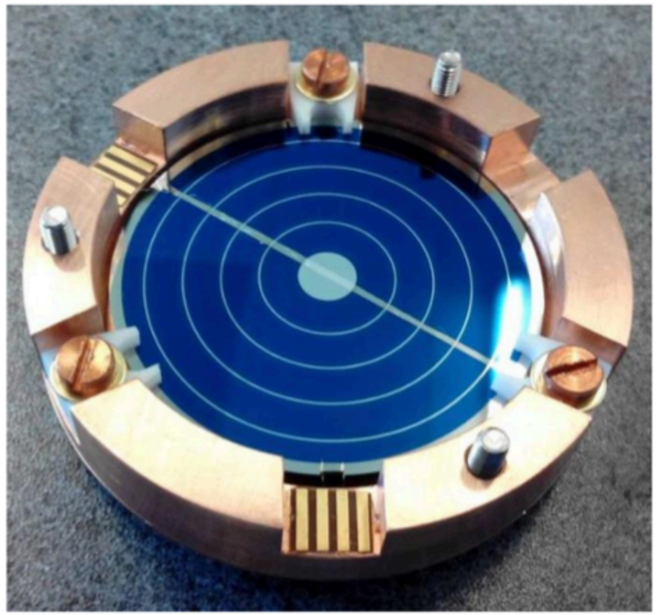


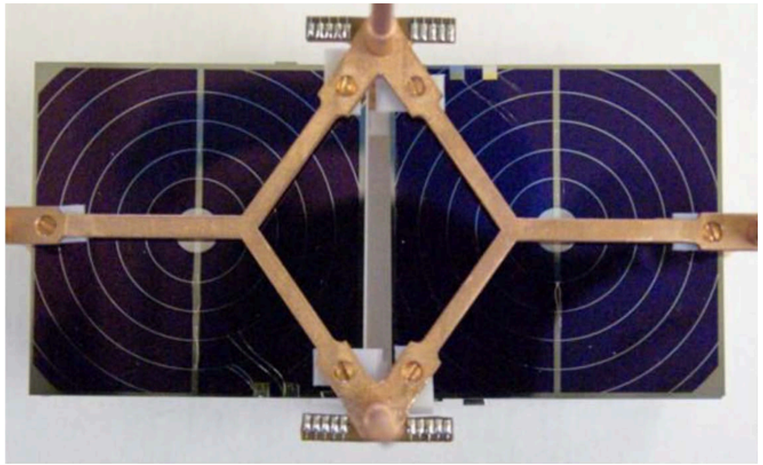
JINST **18** P06033

- ^{133}Ba source calibration.
- $\Delta E = 0.71$ keV FWHM @ 356 keV.

Improved light-detectors

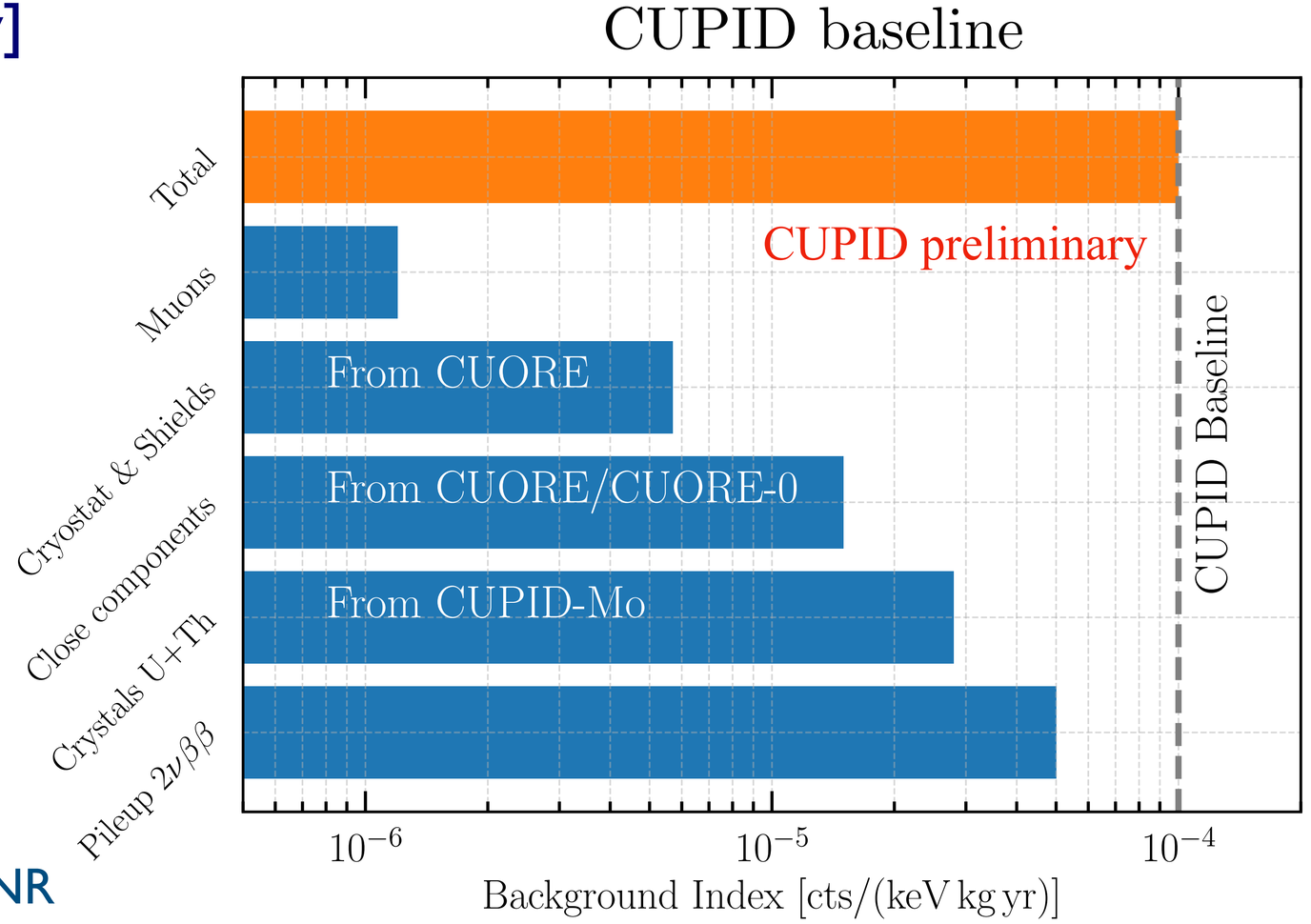
- Relatively fast $2\nu\beta\beta$ decay of ^{100}Mo: $T^{2\nu}_{1/2} = 7.1 \times 10^{18}$ yr
- Slow pulses from heat readout cause random bkg coincidences in ROI.
- Goal: 0.5×10^{-4} ckky, rely on light detectors
- Ways to address this issue:
  - Increase SNR: NTDs with Neganov-Trofimov-Luke (NTL) effect. (**Baseline**)
  - Shorten rise-time: Transition edge sensors (TES)
- New technologies **demonstrate to reach** needed B.I. level goals.



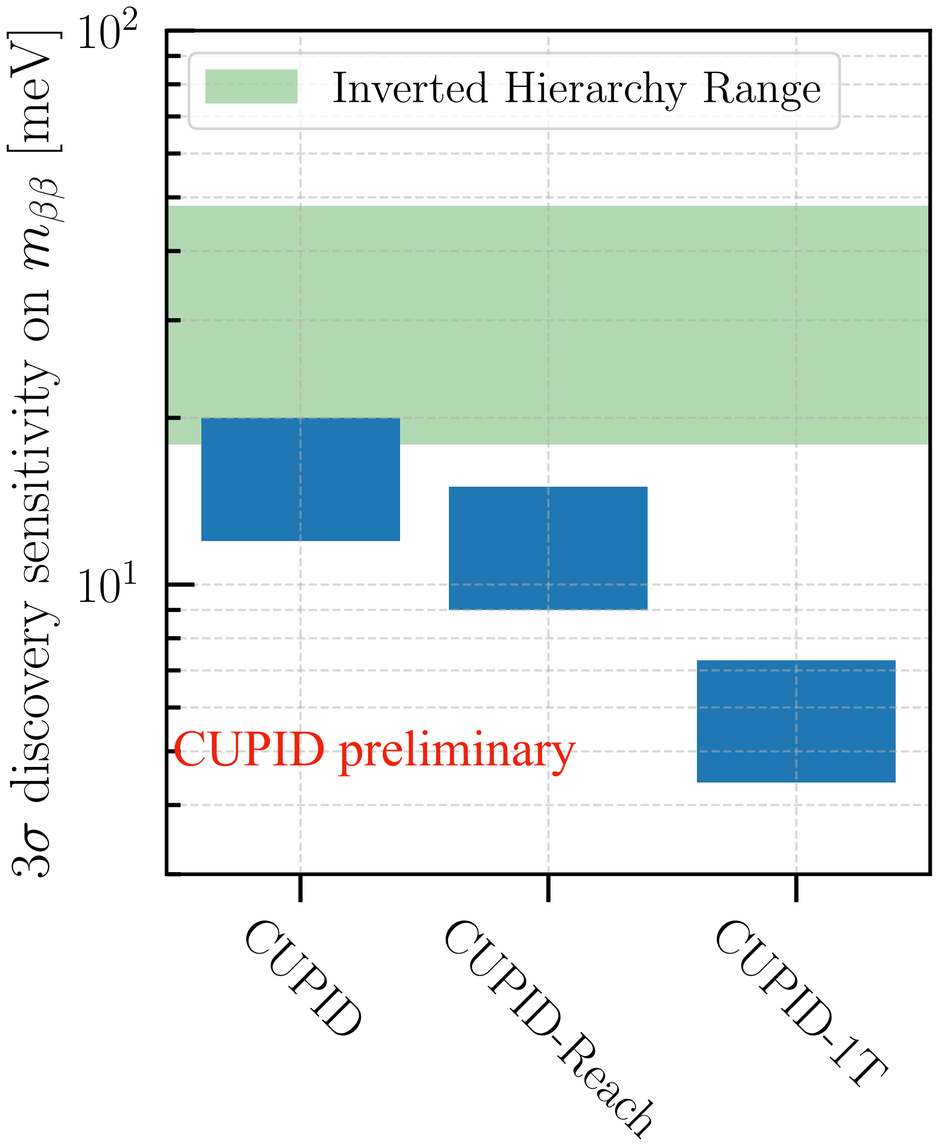


Validated CUPID's projected background index

- ROI Background Index (B.I.) goal: $\sim 10^{-4}$ cts/(keV kg yr) [vs. CUORE's 10^{-2} ckky]
- Upper limits and measurements from predecessor experiments.
- **Well-defined** mitigation strategies:
  - Muon veto.
  - Material selection, cleaning, shielding.
  - Delayed coincidence cuts (U/Th chains).
  - Lower noise, higher bandwidth electronics.
  - Improved light-detector timing resolution/SNR

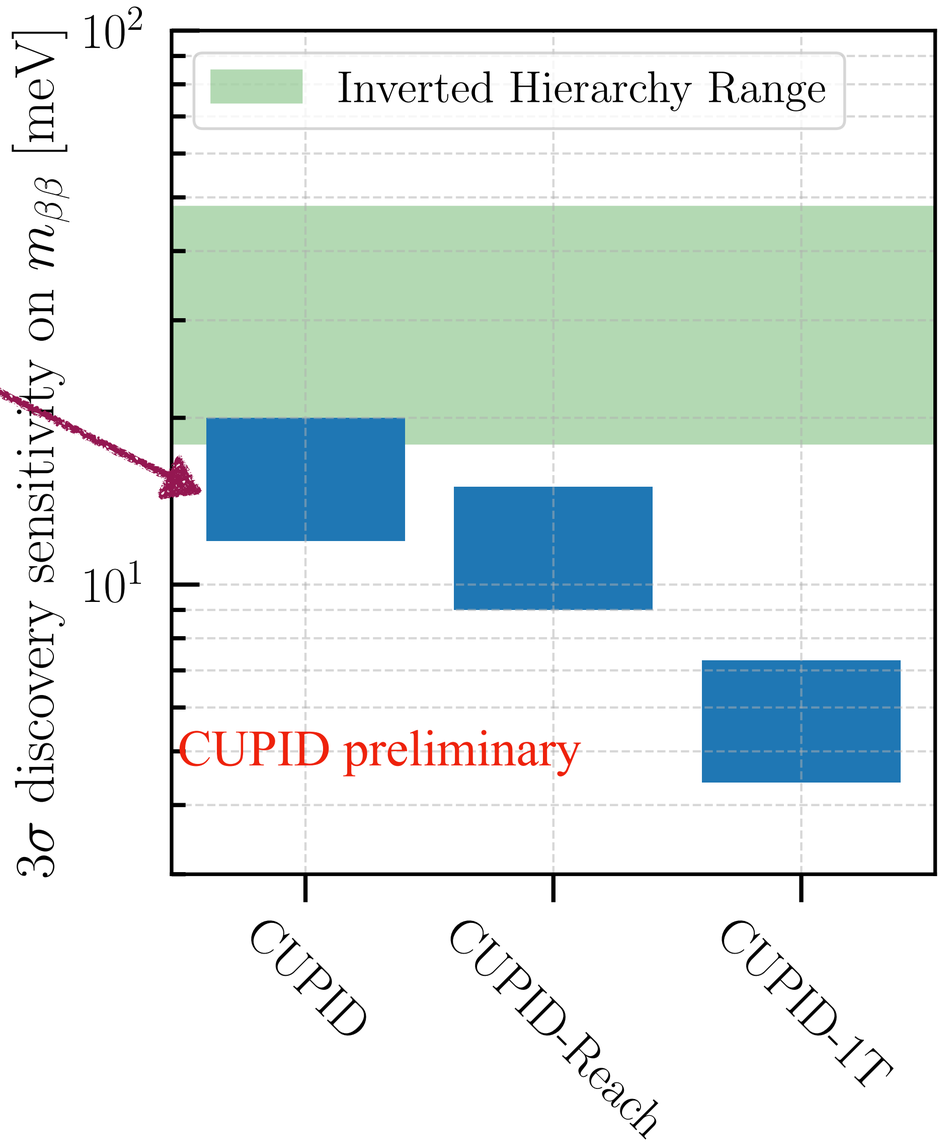


CUPID and beyond



CUPID and beyond

CUPID = baseline, what we know we can build now



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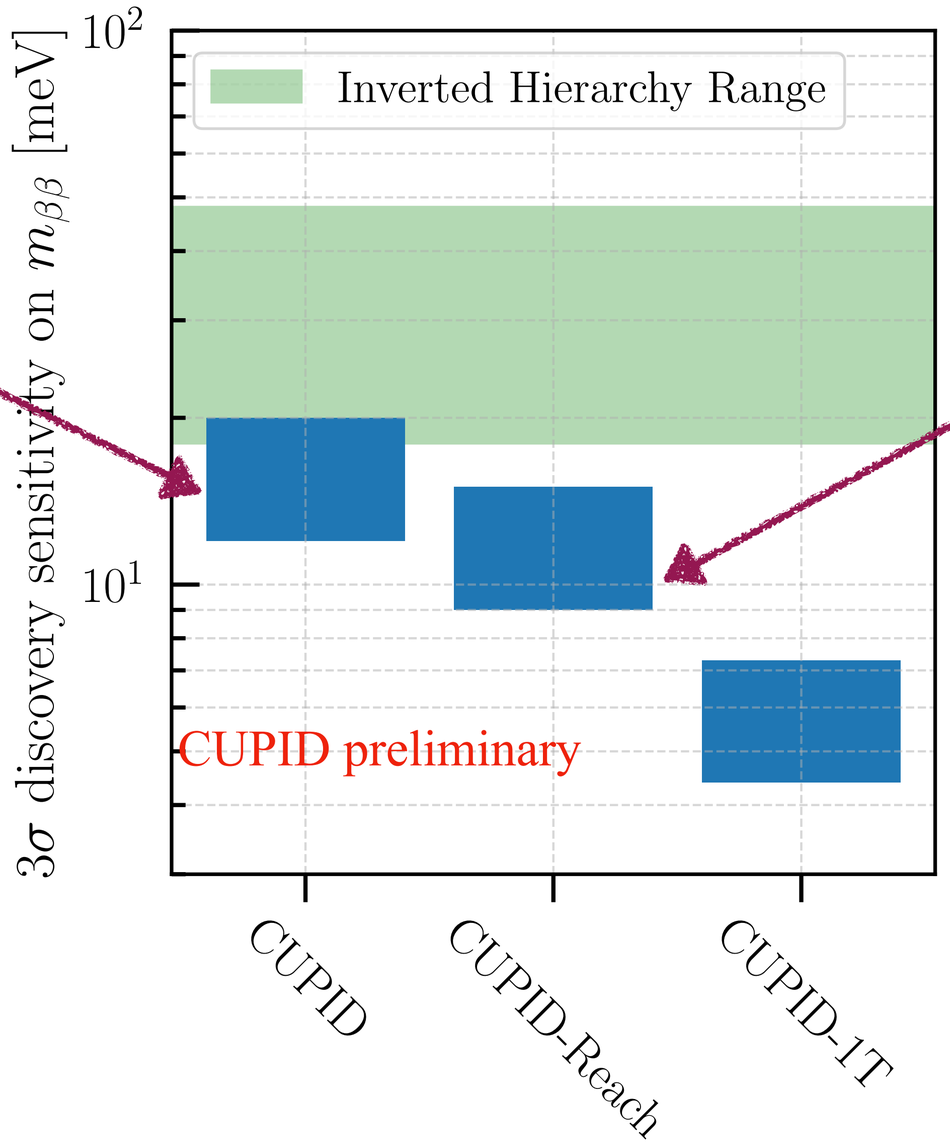

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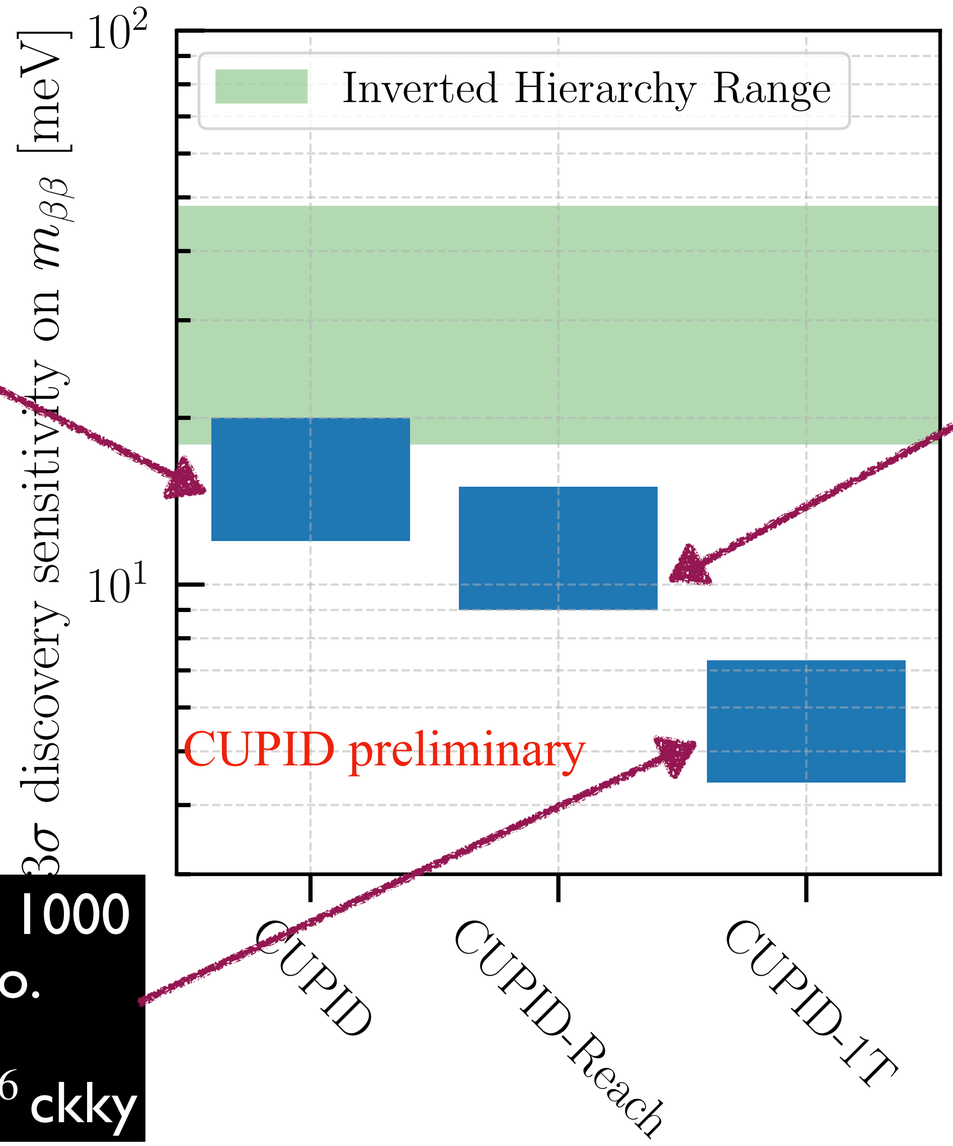
CUPID 1-Ton: 1000 kg of ^{100}Mo.

B.I. $\sim 5 \times 10^{-6}$ ckky



Summary

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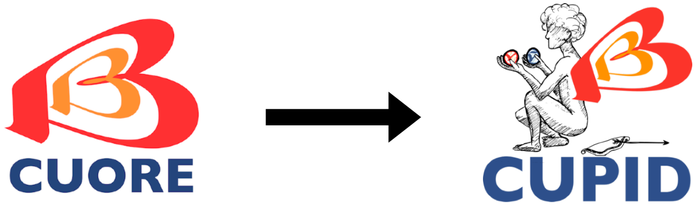
- CUPID will be an upgrade to the successful CUORE experiment.



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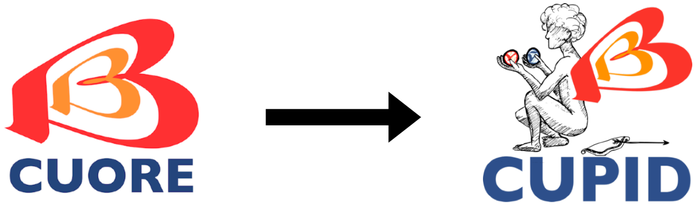
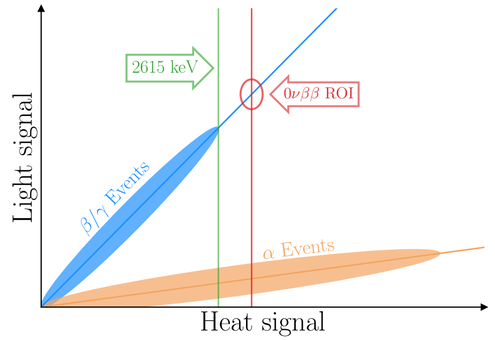


- CUPID will build upon previous experiments knowledge/ infrastructure.
- Adding particle ID + other techniques to reduce B.I.



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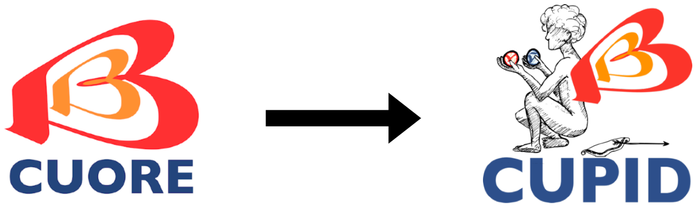

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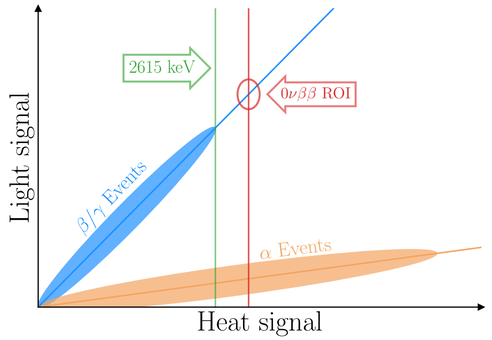
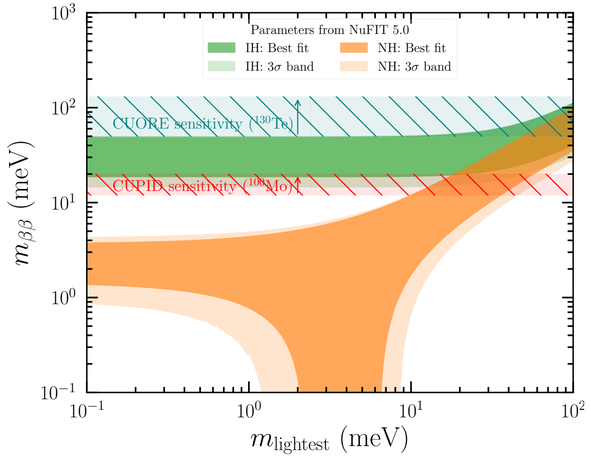


- Experiment moving forward.
- Planning to take data by end of decade.
- CUPID will be among the world-wide suite of $0\nu\beta\beta$ decay experiments with discovery potential.



Thanks!

CUPID

U.S. DEPARTMENT OF ENERGY

NSF

More questions?/Want to hear more?

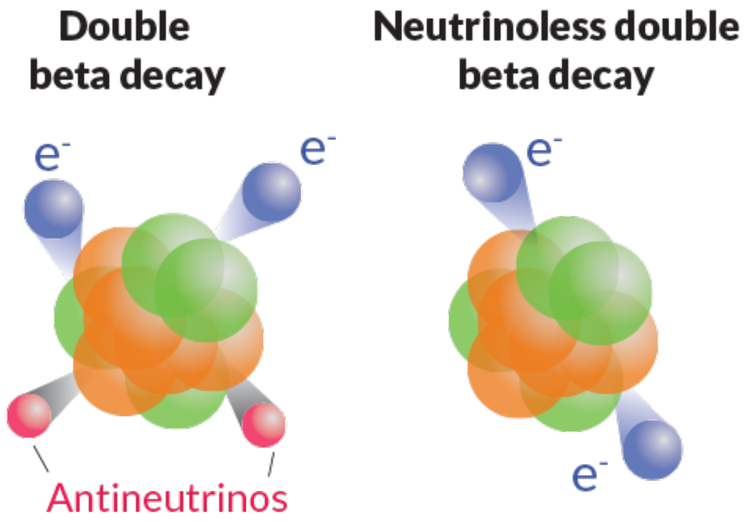
Backup slides

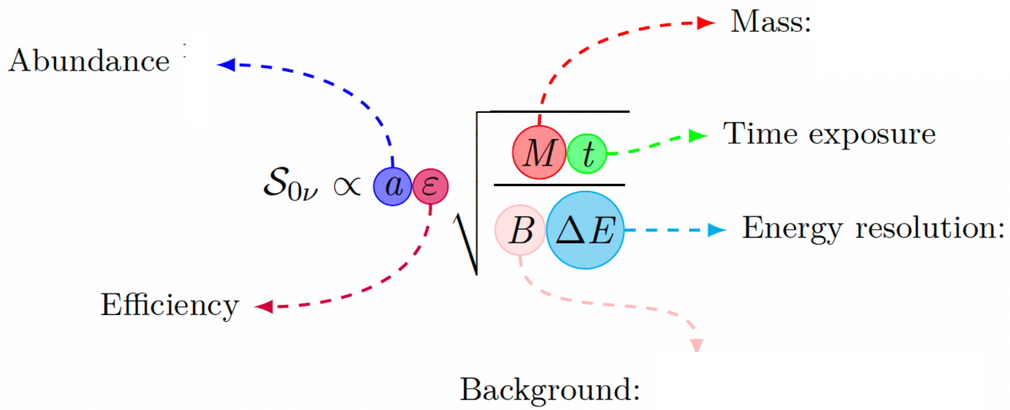
Tower optimization/validation

- Goals:
  - Validate assembly procedure, thermalization, and mechanical structure
  - Study of glue type effects on NTD thermistor
  - Validate performance of LMOs and light-detectors
  - Tests on vibrations
- 14 floors, 28 crystals, 30 LDs, 2 runs so far.
- Future tests in 2024:
  - Tests with NTL LDs
  - Reduction of copper

Neutrinoless double beta ($0\nu\beta\beta$) decay

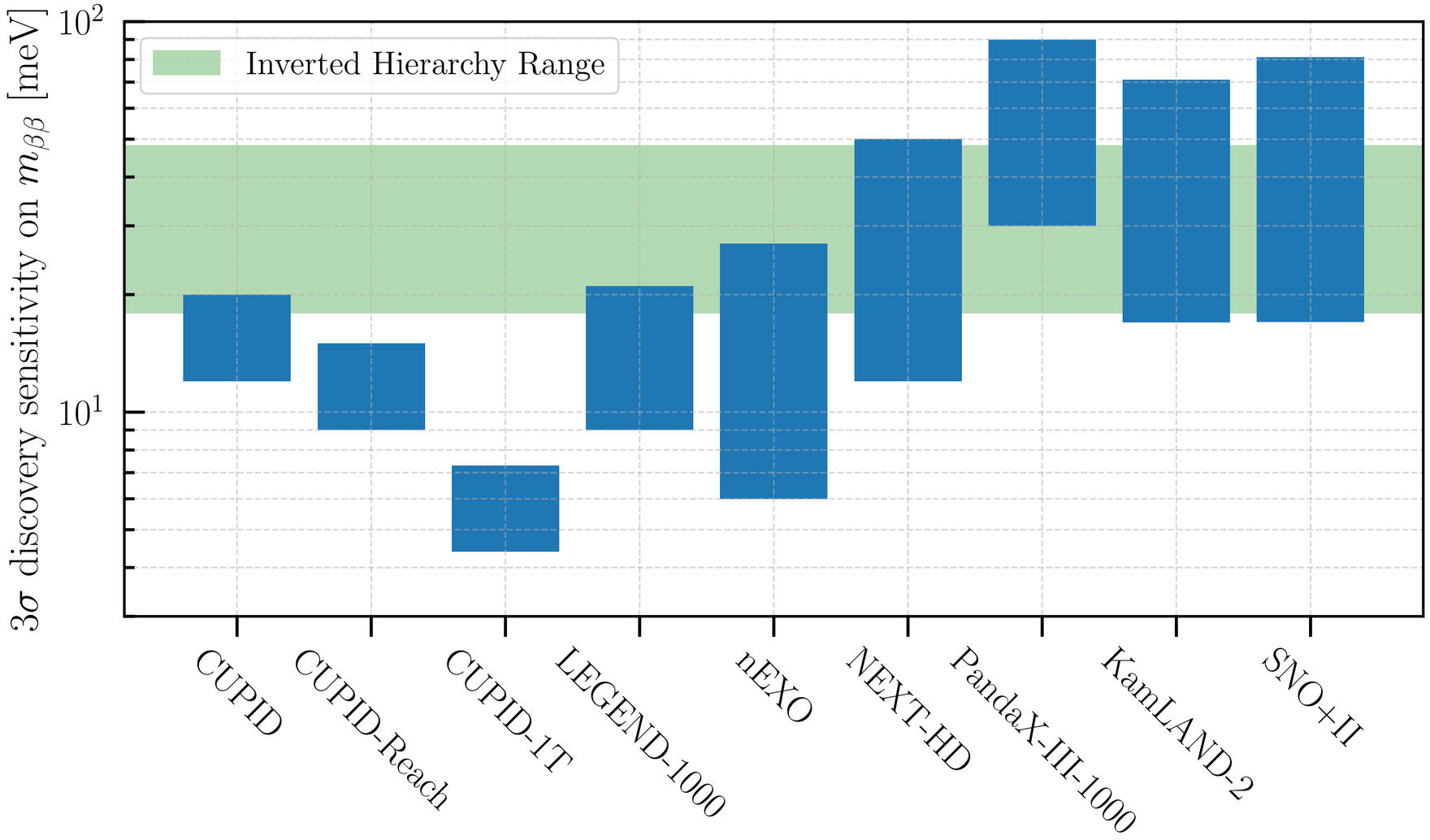
- Observation of $0\nu\beta\beta$ decay implies that neutrinos are Majorana.
- Decay rate proportional to effective Majorana mass
- $0\nu\beta\beta$ signal is a peak at Q-value.
- Sensitivity limited by backgrounds (inverse square root).
- Experiments currently taking data, next generation being planned



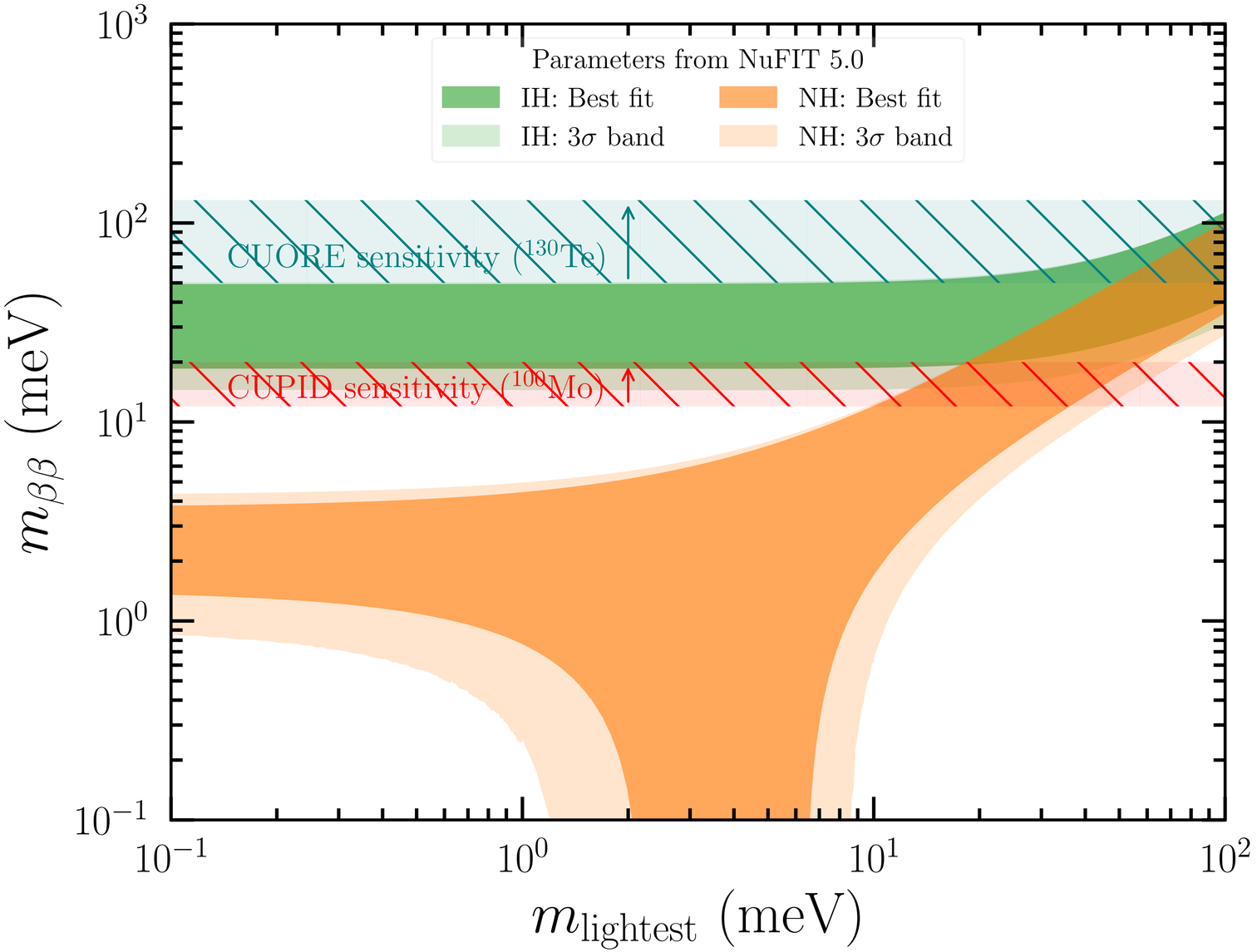


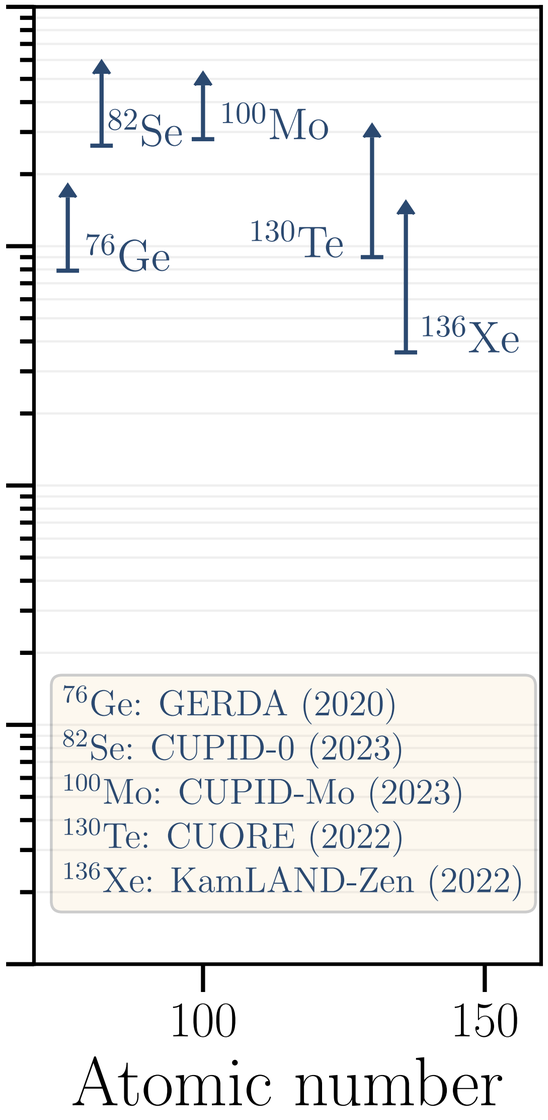
Projected Sensitivity

CUPID will be among the world-wide suit of $0\nu\beta\beta$ decay experiments with discovery potential

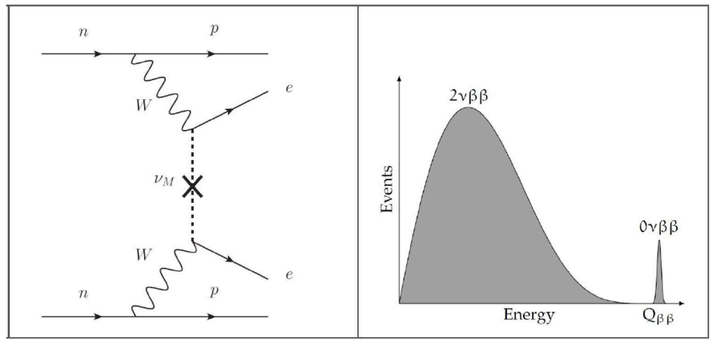


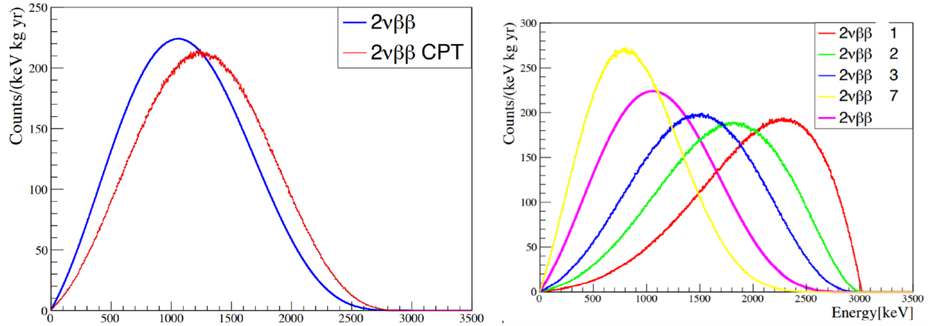
Current limits

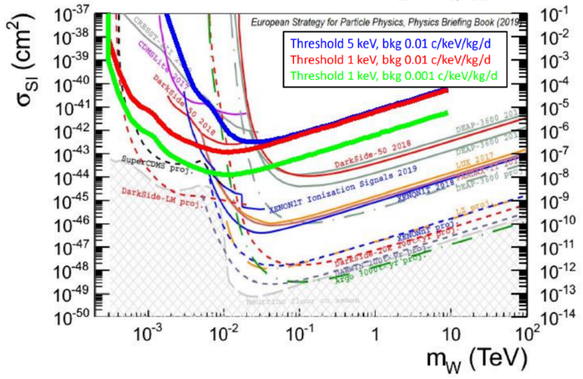


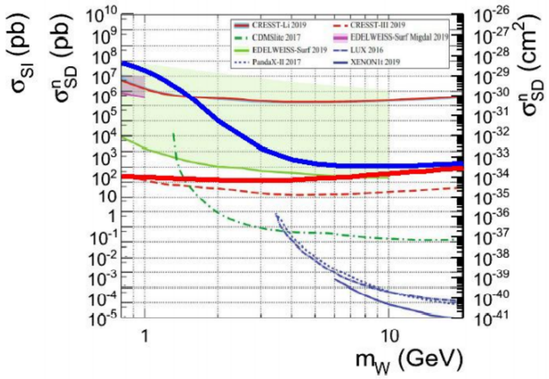


CUPID science program









Search for 0νββ decay

Precision two-neutrino double beta decay

$2\nu\beta\beta$ and $0\nu\beta\beta$ decays to excited states

Majoron-emitting decays

Tests of Lorentz invariance and CPT violation

Tests of fundamental principles

- Electric charge conservation
- Verification of the Pauli exclusion principles

Tri-nucleon decay and baryon number conservation

Light dark matter searches

Supernova neutrino searches

Solar axion searches

Millicharged particles

Neutrinos as backgrounds

- Neutrino Charged Current Interaction

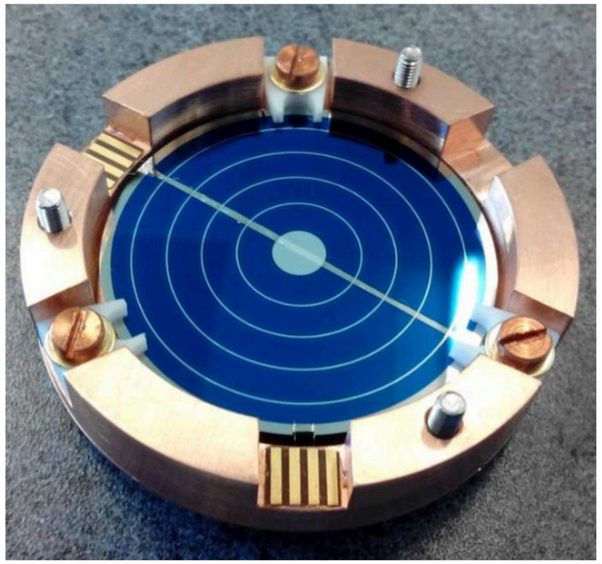
$$\nu + {}^{100}\mathrm{Mo} \rightarrow {}^{100}\mathrm{Tc} + e^- + \gamma(\mathrm{s}) \quad (1)$$

$$ {}^{100}\mathrm{Tc} \rightarrow {}^{100}\mathrm{Ru} + e^- + \bar{\nu} \quad (Q = 3.2\,\mathrm{MeV}, t_{1/2} = 15s) \quad (2)$$

  - Ejiri and Elliott (2017) use a similar procedure as de Barros & Zuber to estimate the rates for all solar ν sources:
    - Backgrounds from (2) contribute ~1×10^{-6} counts/(keV · kg · yr)
    - Backgrounds from (1) are 2-3 orders of magnitude below (2)
  - Delayed coincidence cuts to reduce this further

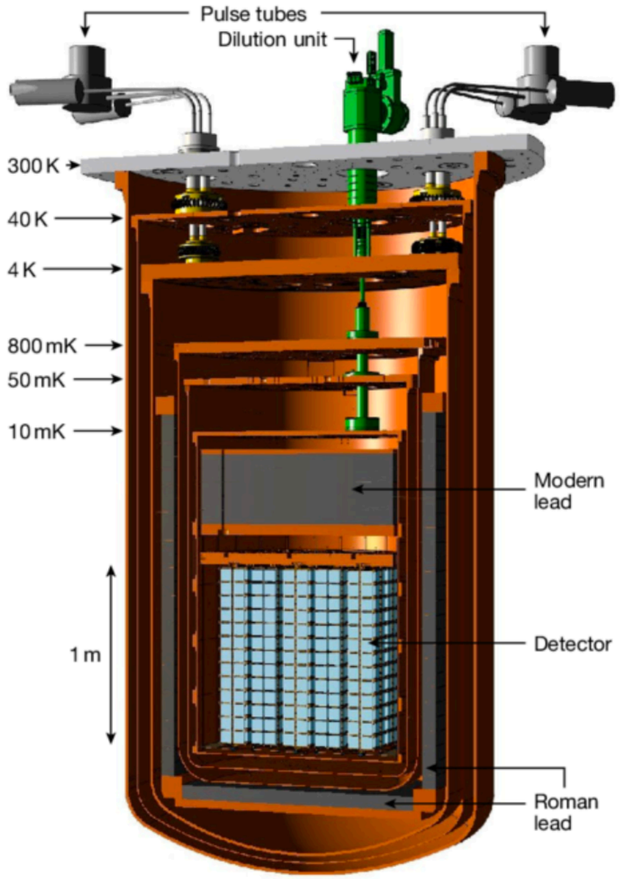
Neganov-Trofimov-Luke LD

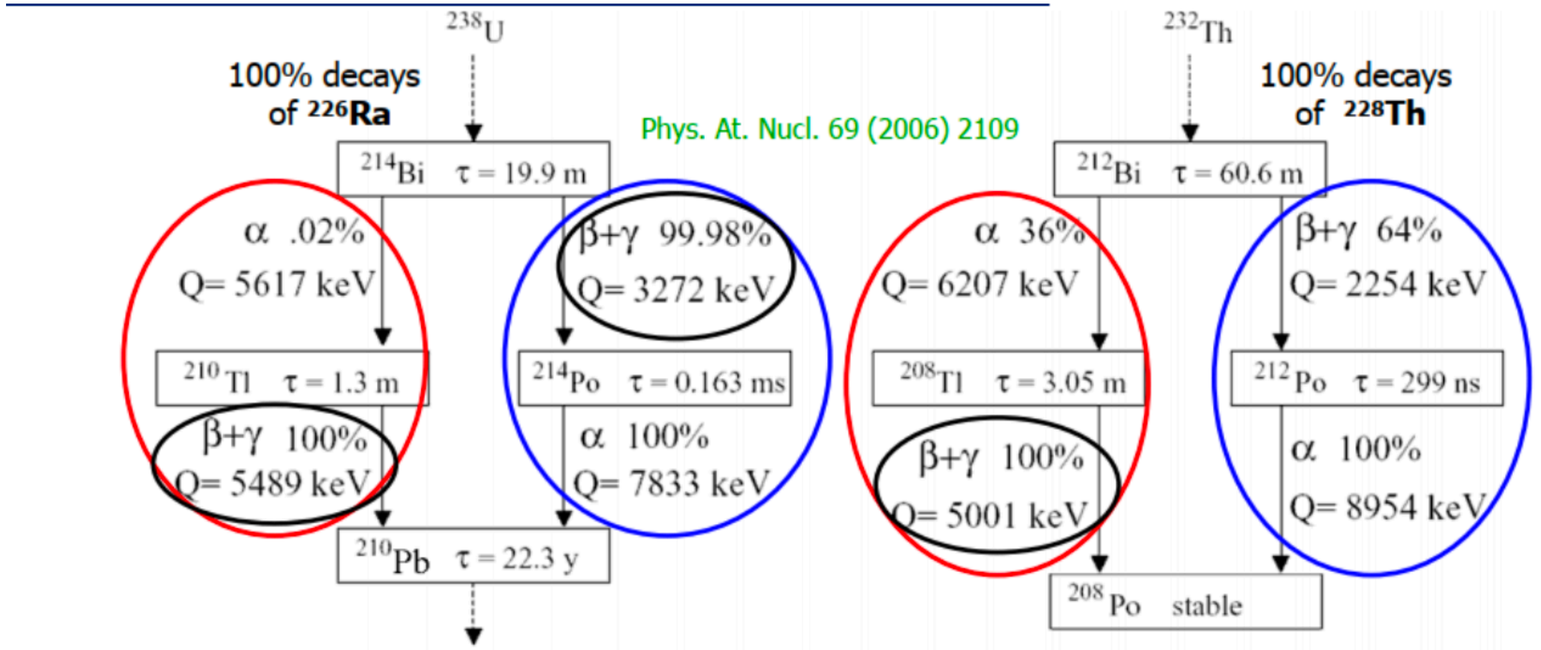
- Ge wafer provided with Al electrodes on its surface
- When applying voltage across these electrodes an electric field is establish
- The absorption of photons produces electron-hole pairs
- The electric field drifts the charges and it prevents their recombination
- Carriers collide with the lattice during the drift, increasing the temperature
- This means signal amplification that is read by a thermistor (NTD)



Cryostat

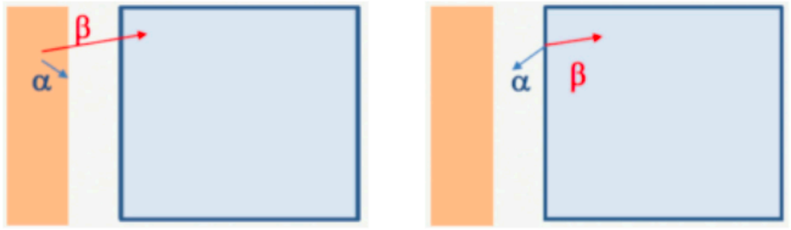
- Cryogen-free cryostat
- Cools down ~1 ton detector to ~10 mK
- Mechanically decoupled for extremely low vibrations
- PT to cool down to ~4K
- Dilution refrigerator down to operating temperature ~10 mK
- Nominal cooling power: 4 μW @ 10mK
- Cryostat total mass ~30 tons
- Mass at T < 4K: ~15 tons
- Mass at T < 50 mK: ~3 tons (Pb, Cu and TeO2)

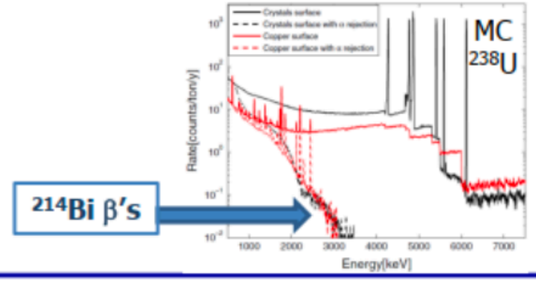


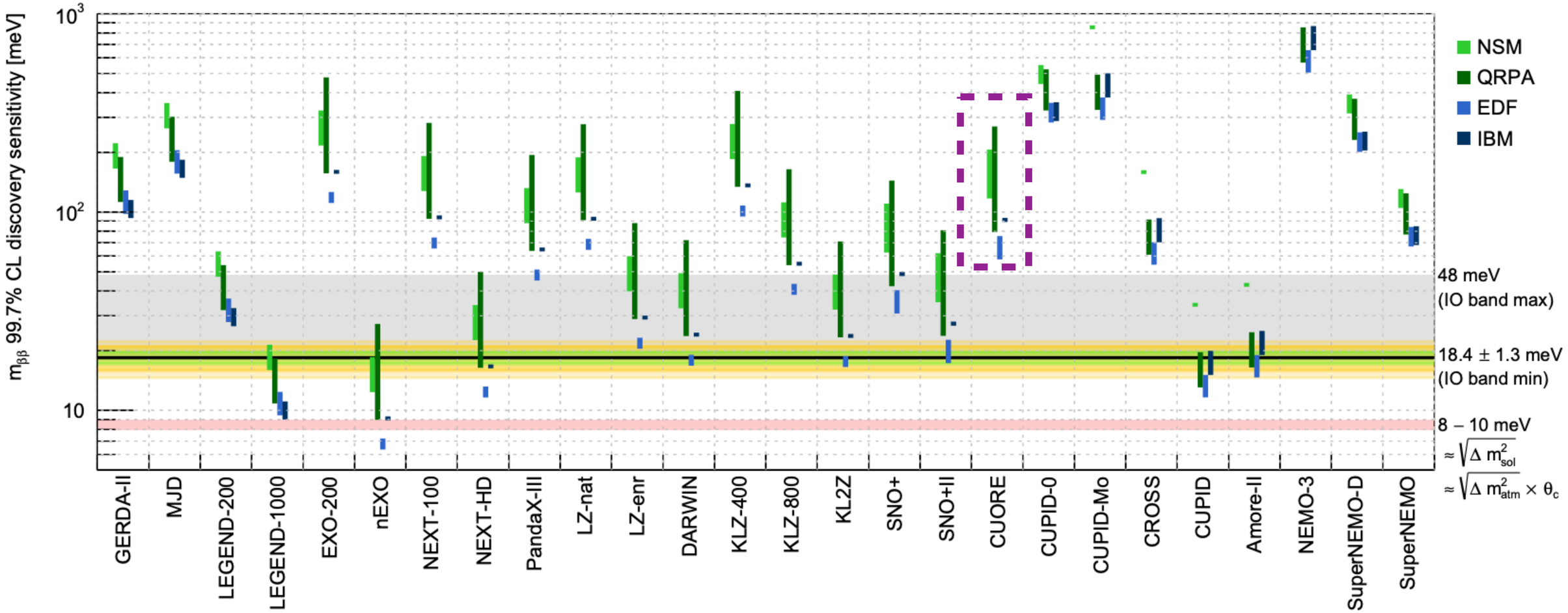


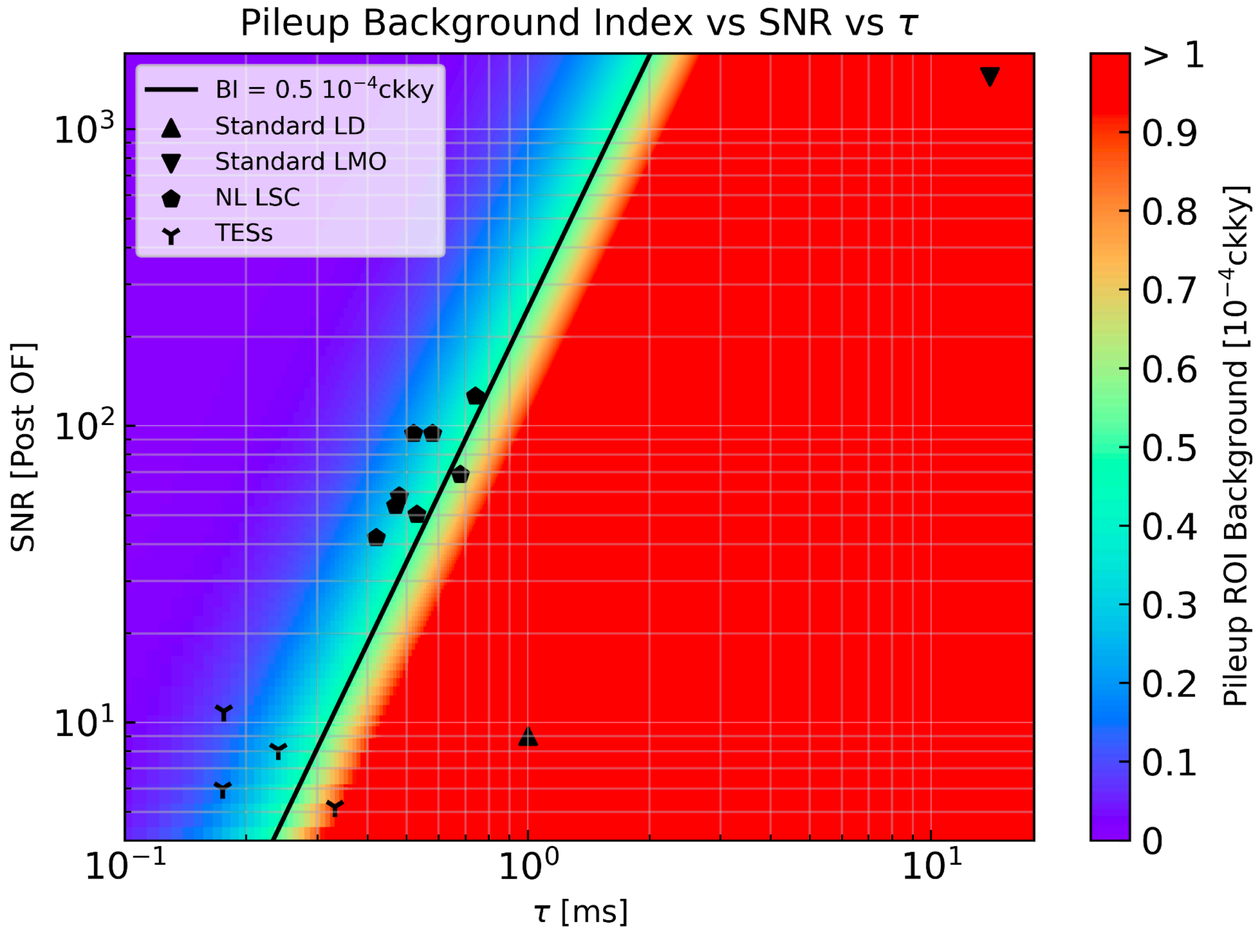
For DBD bolometers with particle ID:

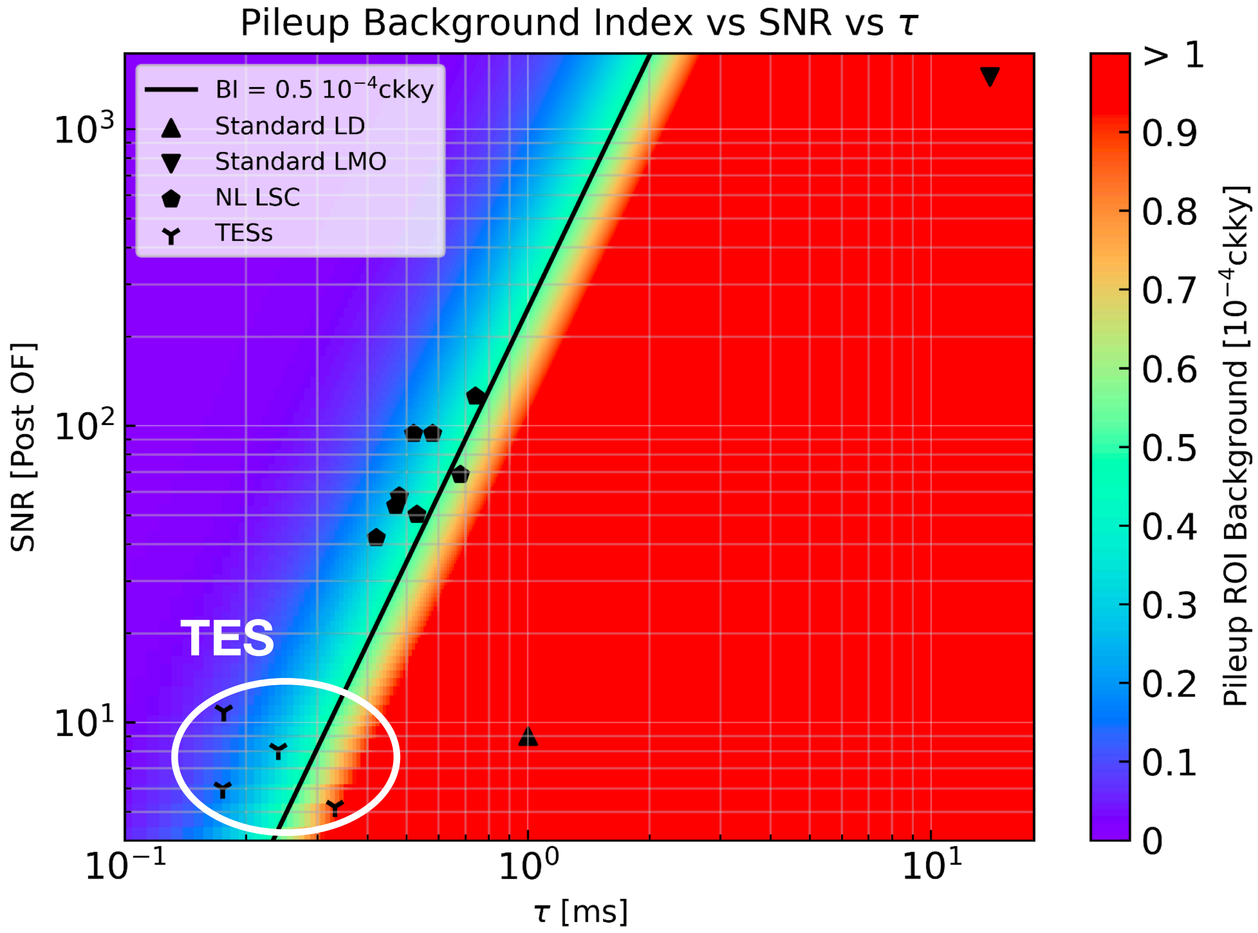
- **BiPo events** (mixed β+α decays with a total E > ~8 MeV) **negligible contribute to ROI**
- **Delayed events of ^{210,208}Tl β's can be rejected by an off-line gate after ^{214,212}Bi α's**
- **β's of ^{212,214}Bi subchains ($Q_\beta > Q_{\beta\beta}$) detected without α's contribute significantly to ROI**






10^3
10^2
10
$m_{\beta\beta}$ 99.7% CL discovery sensitivity [meV]
NSM
QRPA
EDF
IBM
48 meV
(IO band max)
18.4 ± 1.3 meV
(IO band min)
8 – 10 meV
$\approx \sqrt{\Delta m^2_{sol}}$
$\approx \sqrt{\Delta m^2_{atm}} \times \theta_c$
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
PandaX-III
LZ-nat
LZ-enr
DARWIN
KLZ-400
KLZ-800
KL2Z
SNO+
SNO+II
CUORE
CUPID-0
CUPID-Mo
CROSS
CUPID
Amore-II
NEMO-3
SuperNEMO-D
SuperNEMO


Pileup Background Index vs SNR vs τ
BI = 0.5 10⁻⁴ckky
Standard LD
Standard LMO
NL LSC
TESs
SNR [Post OF]
10³
10²
10¹
10⁻¹
10⁰
10¹
τ [ms]
> 1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Pileup ROI Background [10⁻⁴ckky]


Pileup Background Index vs SNR vs τ
BI = 0.5 10⁻⁴ckky
Standard LD
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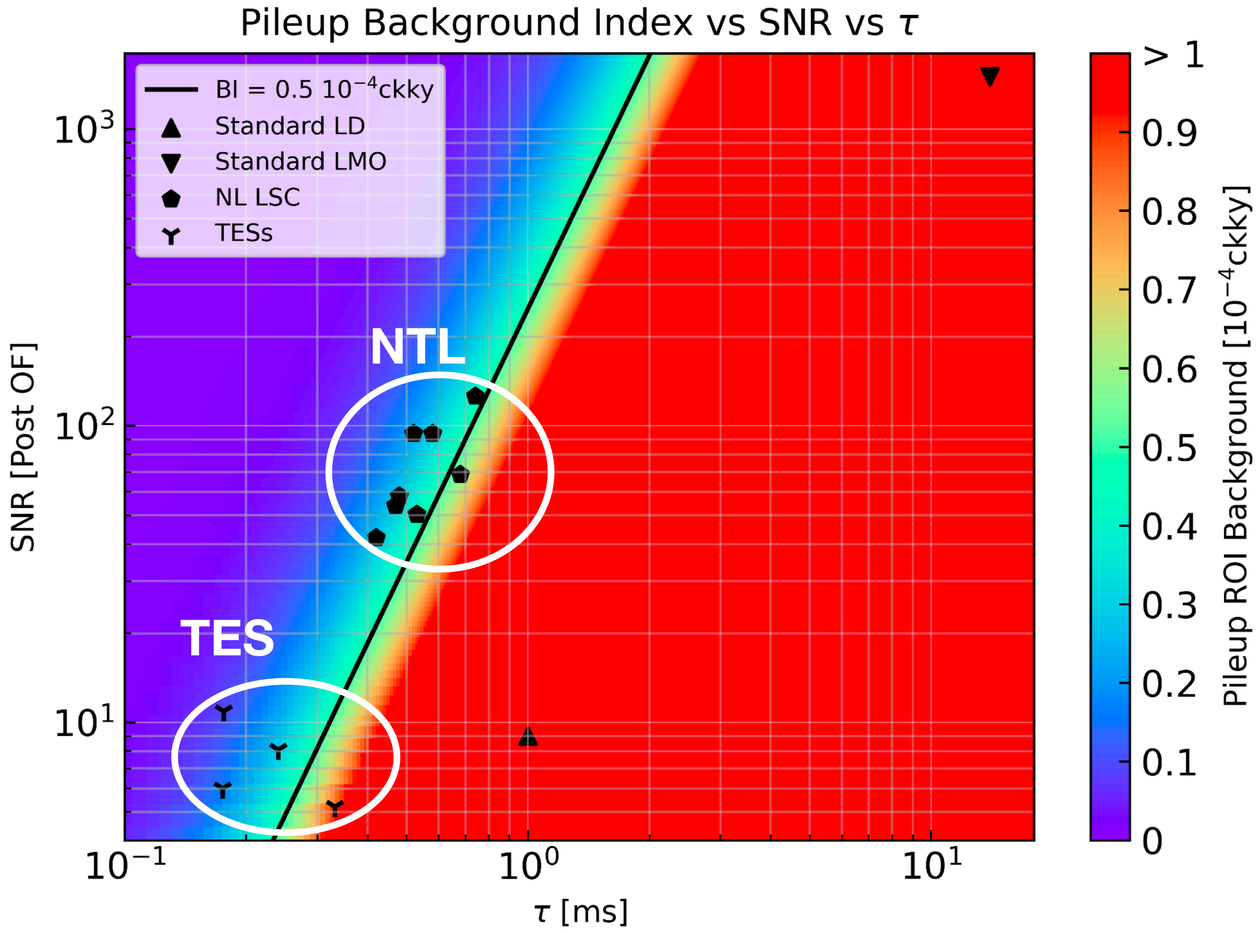
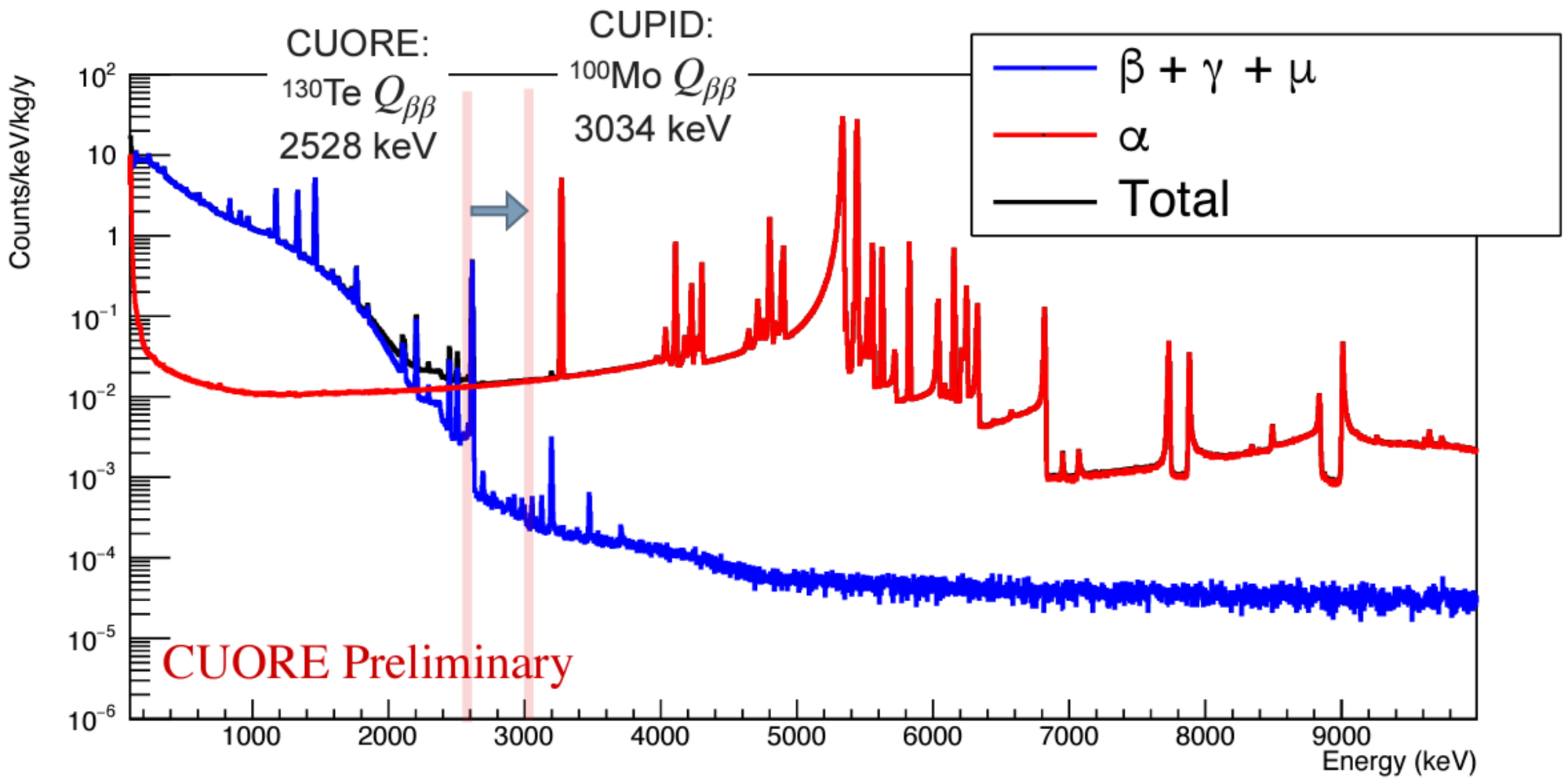
TESs
TES
SNR [Post OF]
τ [ms]
Pileup ROI Background [10⁻⁴ckky]
> 1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

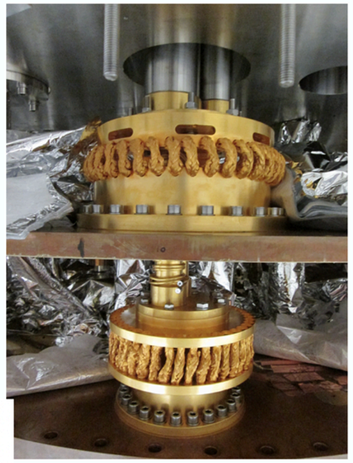

Pileup Background Index vs SNR vs τ
BI = 0.5 10⁻⁴ckky
Standard LD
Standard LMO
NL LSC
TESs
NTL
TES
SNR [Post OF]
τ [ms]
Pileup ROI Background [10⁻⁴ckky]
> 1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

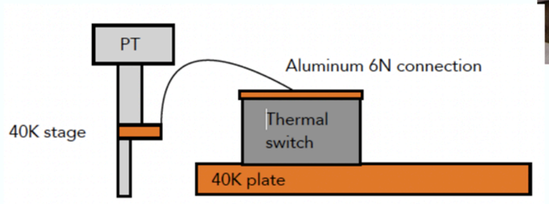

CUORE:
^{130}Te $Q_{\beta\beta}$
2528 keV
CUPID:
^{100}Mo $Q_{\beta\beta}$
3034 keV
β + γ + μ
α
Total
Counts/keV/kg/y
Energy (keV)
CUORE Preliminary

CUORE infrastructure beyond 2025

Planned upgrades in view of CUPID

Cryogenic upgrades
- new pulse tubes
- new thermalisation





Muon tagger system