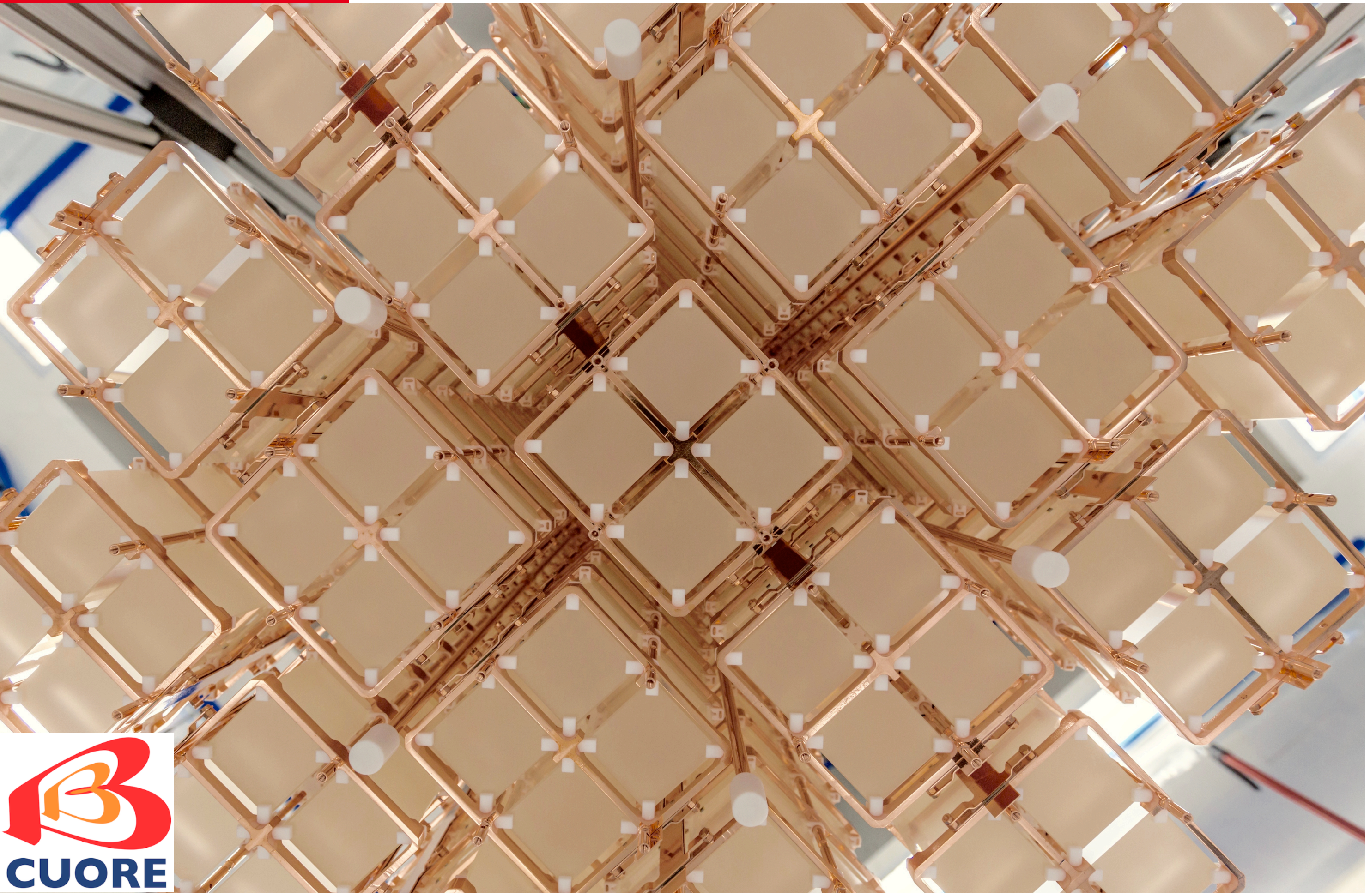
Results and status of the CUORE & CUPID neutrinoless double beta decay search



BORMIO'24, Benjamin Schmidt for the CUORE & CUPID collaborations

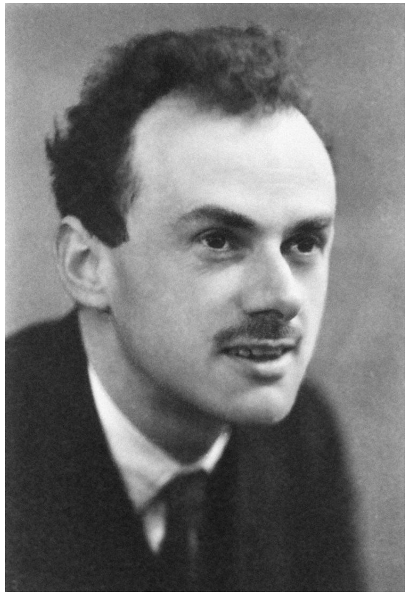
Neutrino - Majorana/Dirac particle?

Neutrino mass scale

- Neutrinos are massive
- Mass scale is 6 orders below the mass of other leptons

Two theories - Majorana versus Dirac

- Majorana - Allows Lepton Number Violation
  Allows neutral leptons to be their own anti-particle
  - Potential to explain Baryogenesis through Leptogenesis matter generation
  - Potential to explain smallness of neutrino mass scale



"Teoria simmetrica dell'elettrone e del positrone". Il Nuovo Cimento. **14 (1937)**

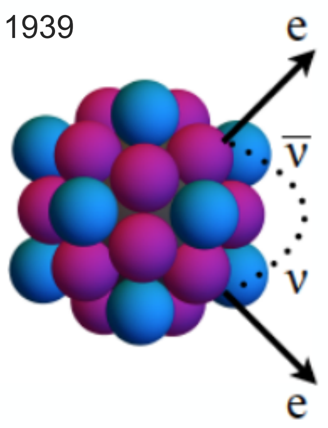
Majorana neutrino phenomenology - Pontercorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

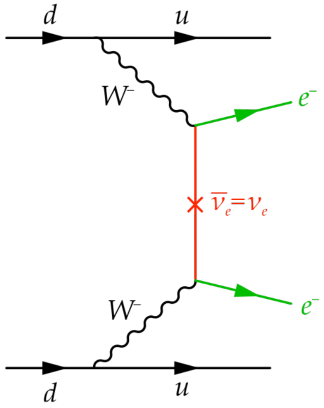
Majorana phases

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrinoless double beta decay
Light Majorana neutrino exchange

Furry 1939





See also Heiko's talk

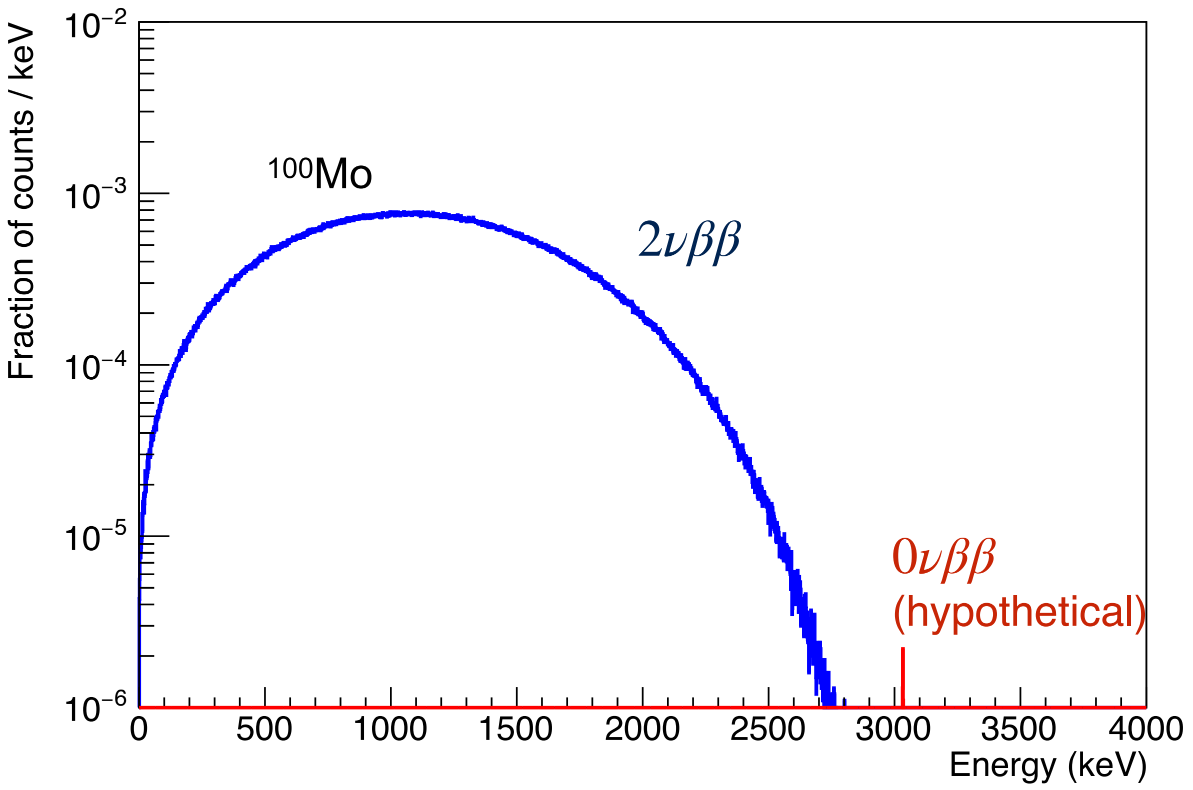
$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} \sim g_A^4 \cdot G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

Effective Majorana mass:

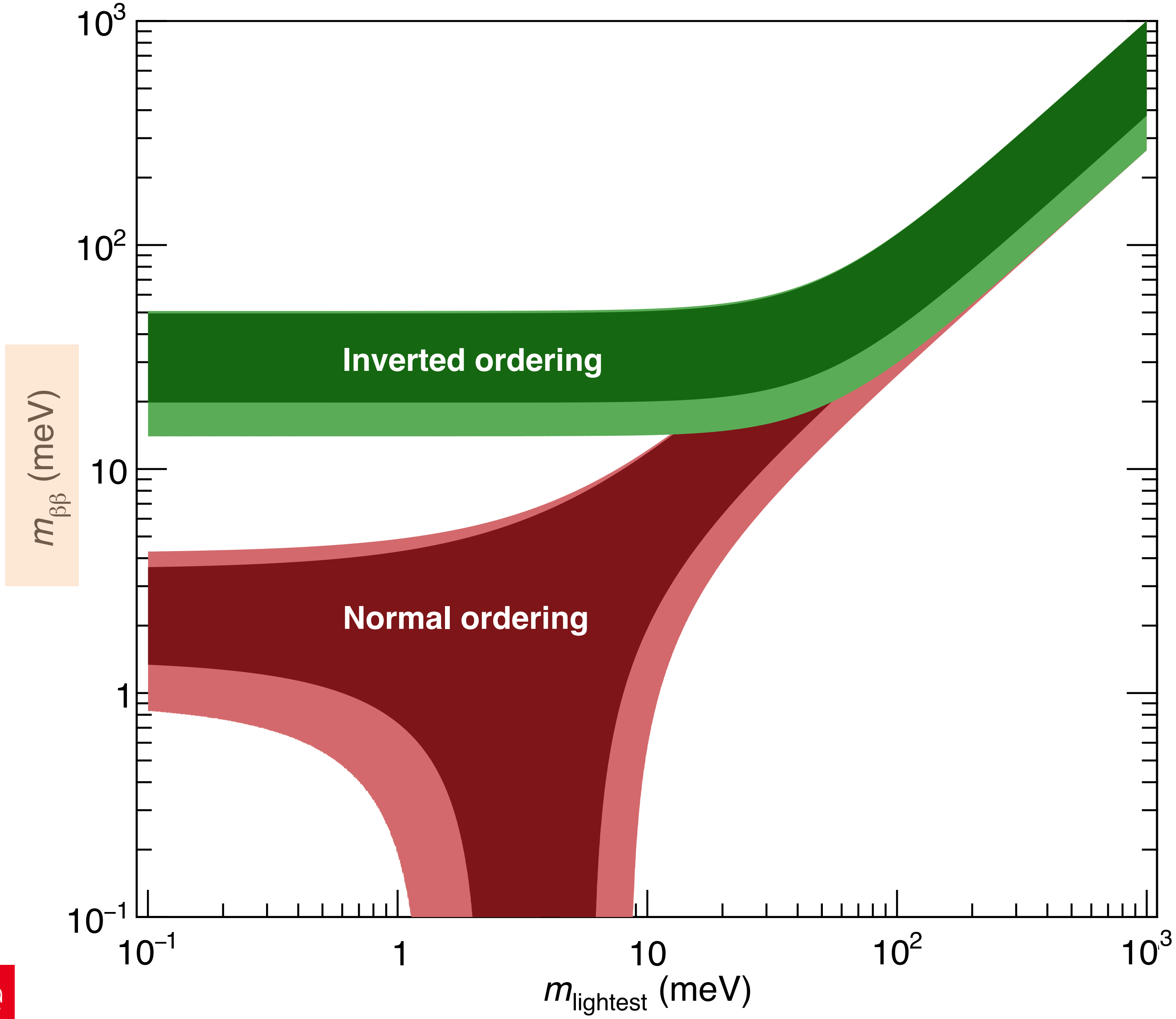
$$\langle m_{\beta\beta}\rangle = |\sum_{i=1,2,3} U_{e,i}^2 m_i|$$

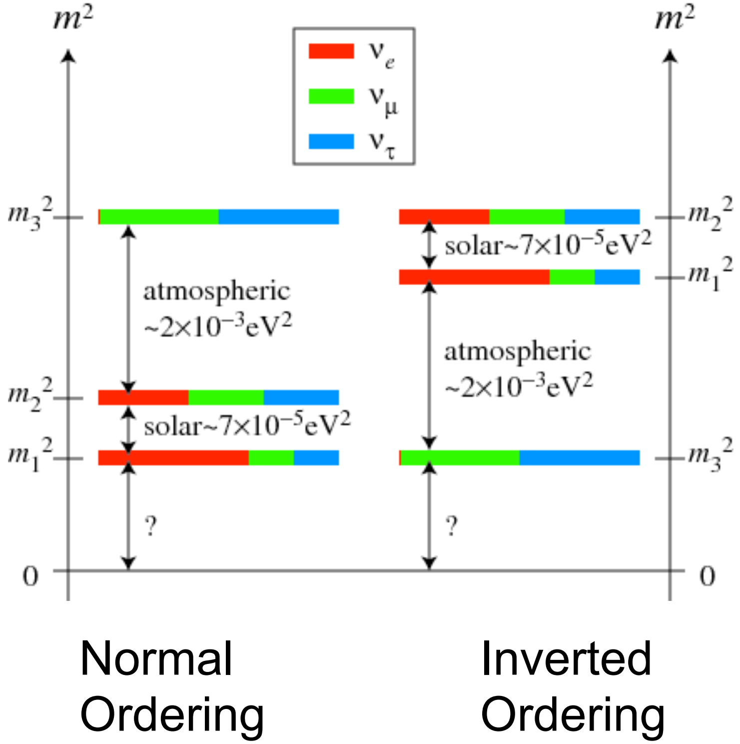
Observables

- $\Delta L = 2$, lepton number violation
- Majorana nature of neutrino?



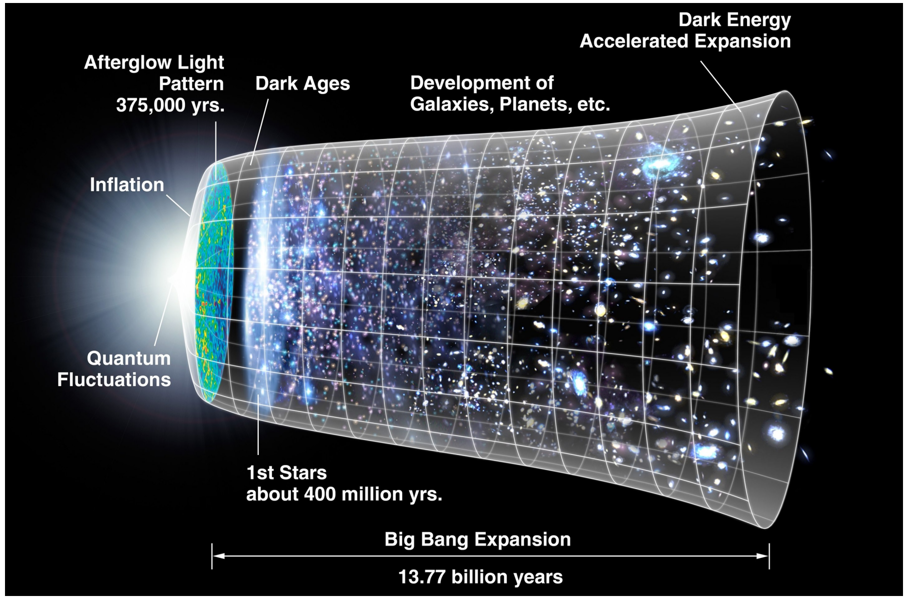
$0\nu\beta\beta$ The parameter space



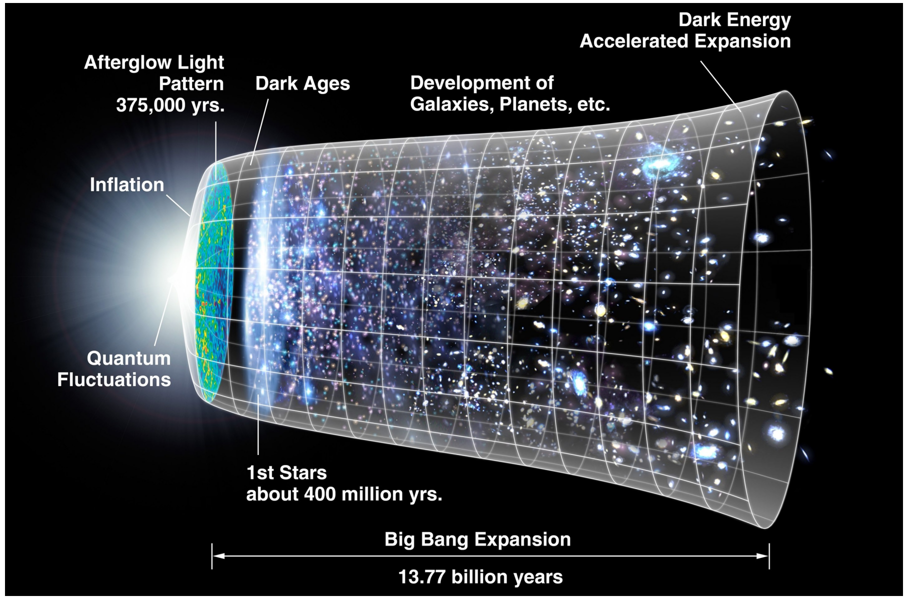


The experimental challenge

Probe a process with a half-life larger > 10^{25} yr - 10^{26} yr



x



x 10^5 yr

15 Bq / banana

Next generation experiments:

Need to find single events in a ton of isotope x year(s) of exposure!
Or search for an activity at the level of 3 x 10^{-14} Bq/g

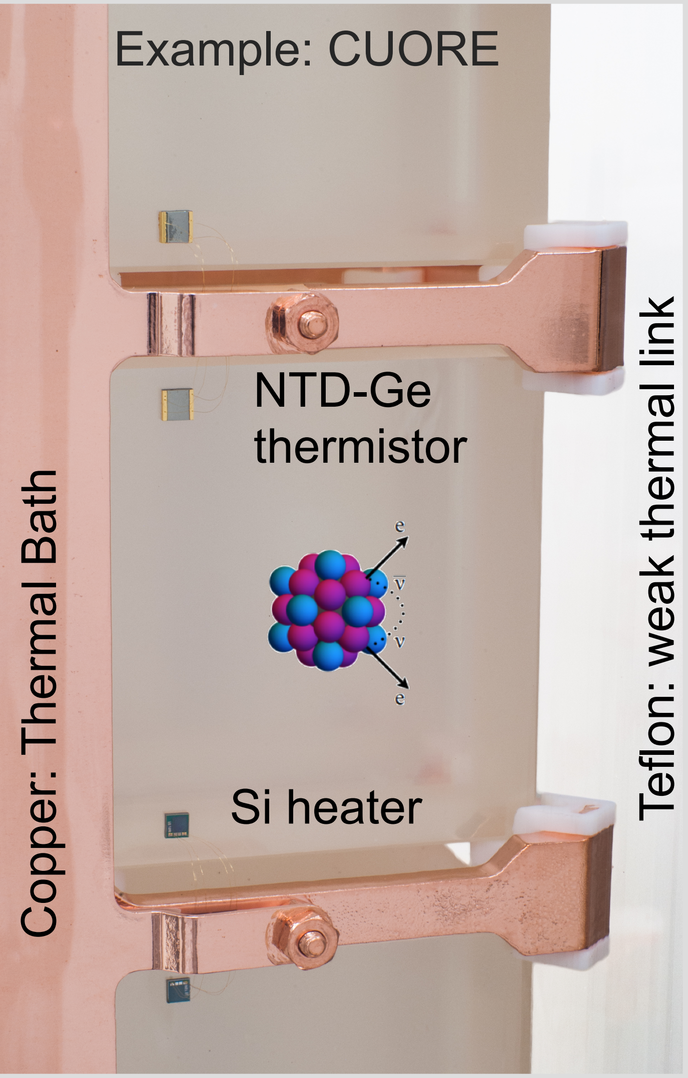
We go to extreme length to limit ubiquitous radioactivity

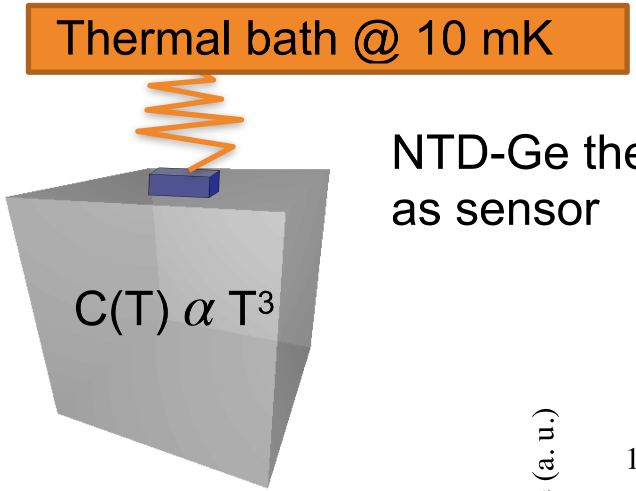
Cryogenic Underground Observatory for Rare Events
CUORE collaboration

https://cuore.lngs.infn.it/

27 institutions from 4 different countries (Italy, US, France, China)

Cryogenic calorimeters in a nutshell



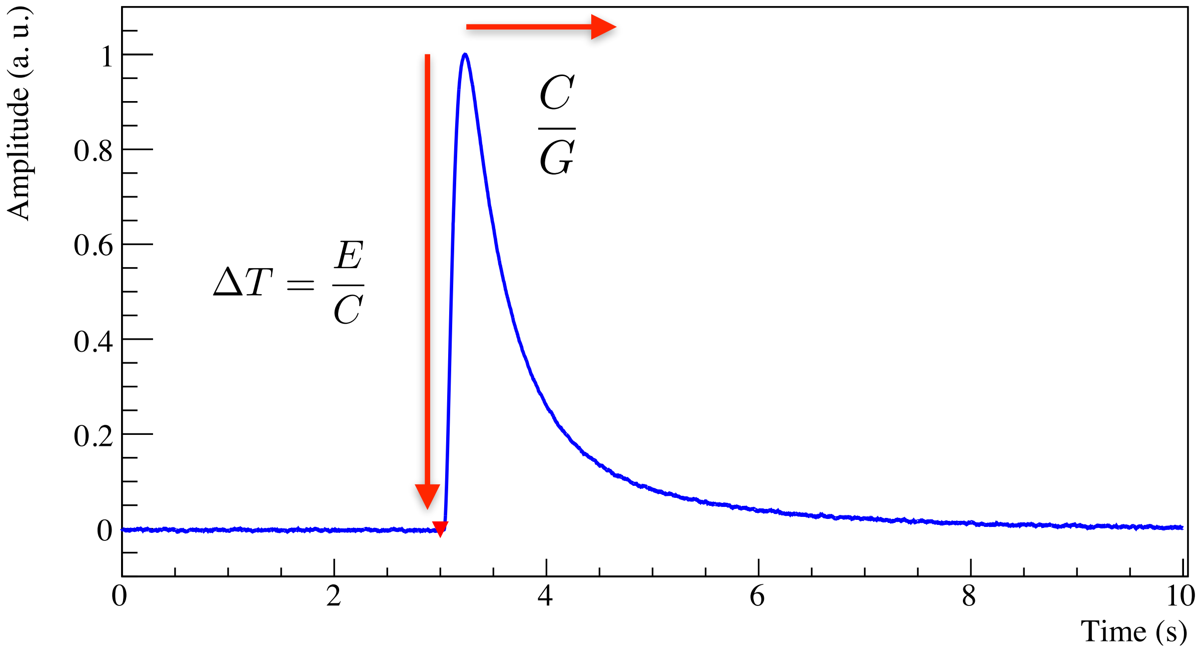


NTD-Ge thermistor as sensor

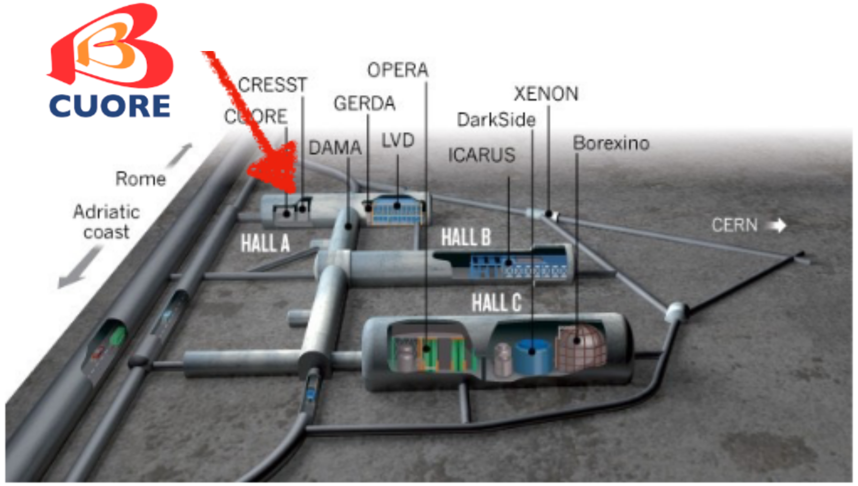
$$R(T) = R_0 e^{\sqrt{T_0/T}}$$

$$\Delta T \approx 0.1 \text{ mK/MeV}$$

Source = Detector
—> high efficiency



Current cryogenic flagship experiment CUORE

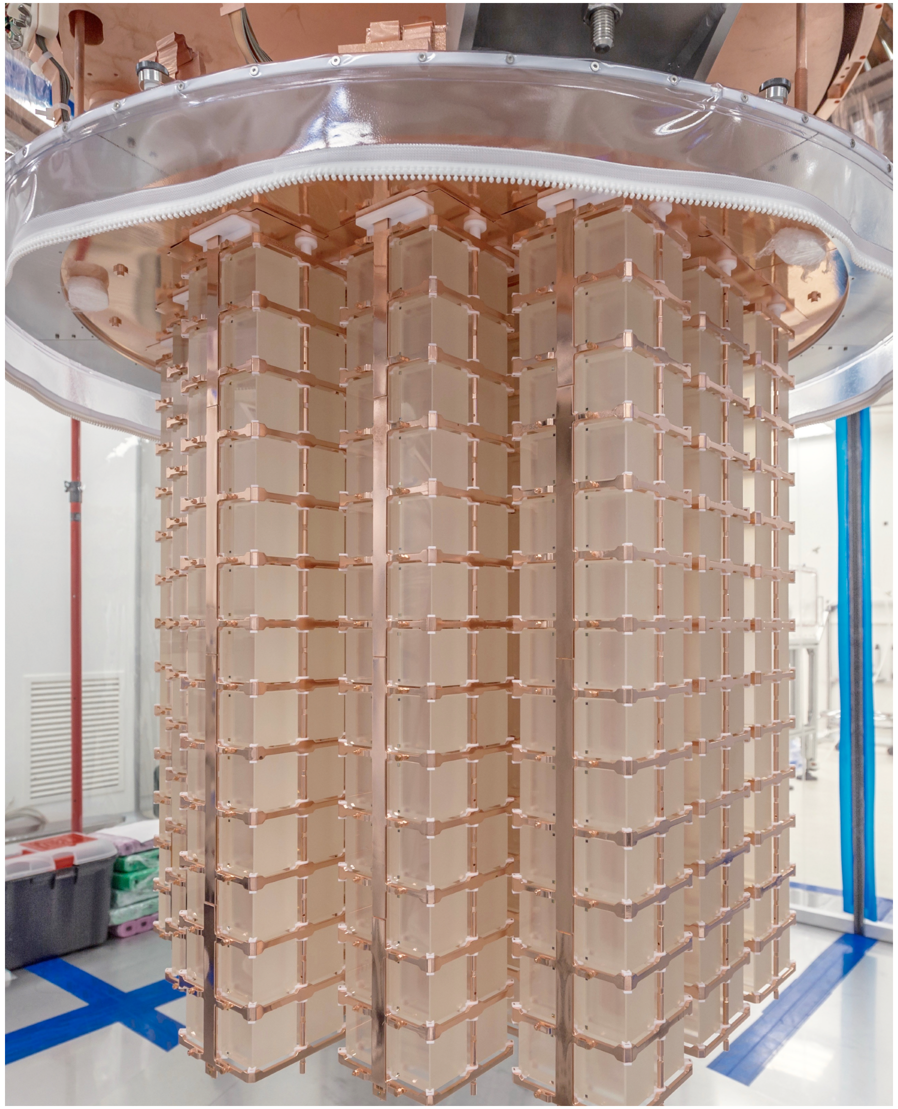


At LNGS ~ 3600 m.w.e.

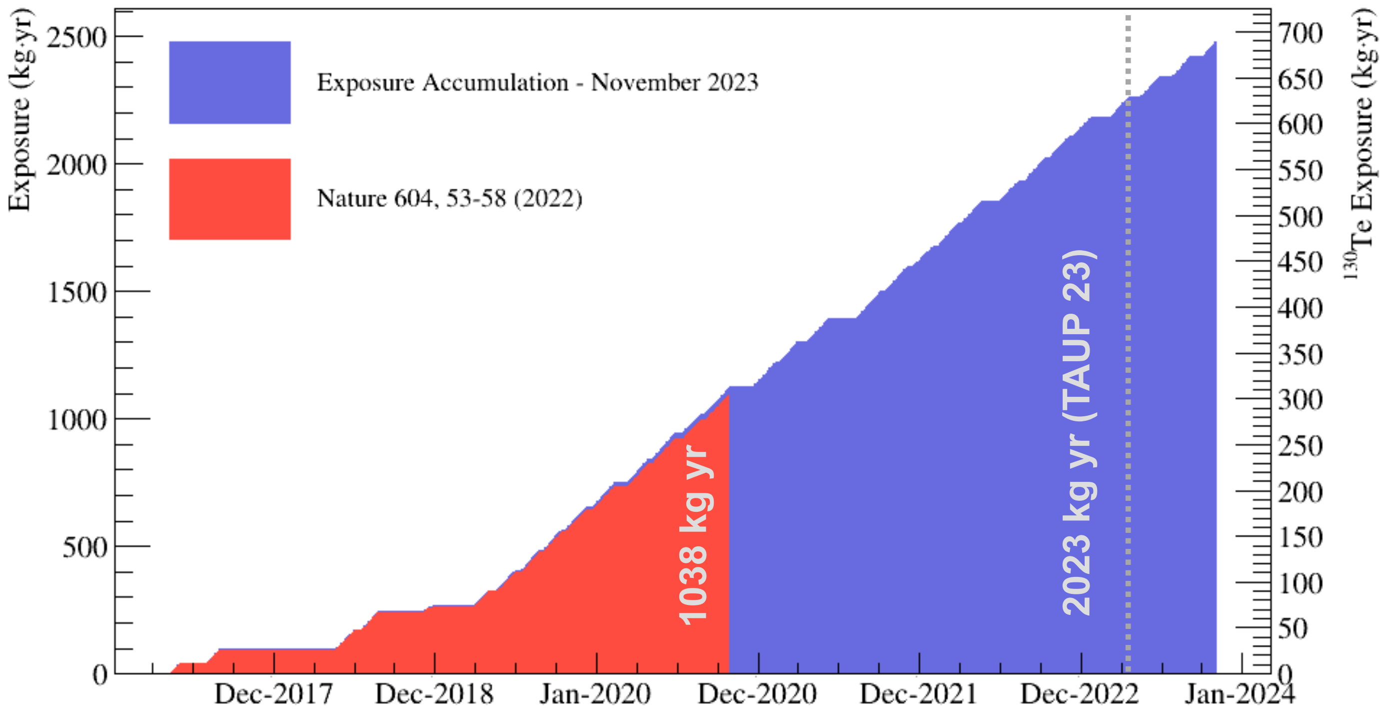
External shielding:
25 cm Pb,
18 cm PET + 2 cm H_3BO_3

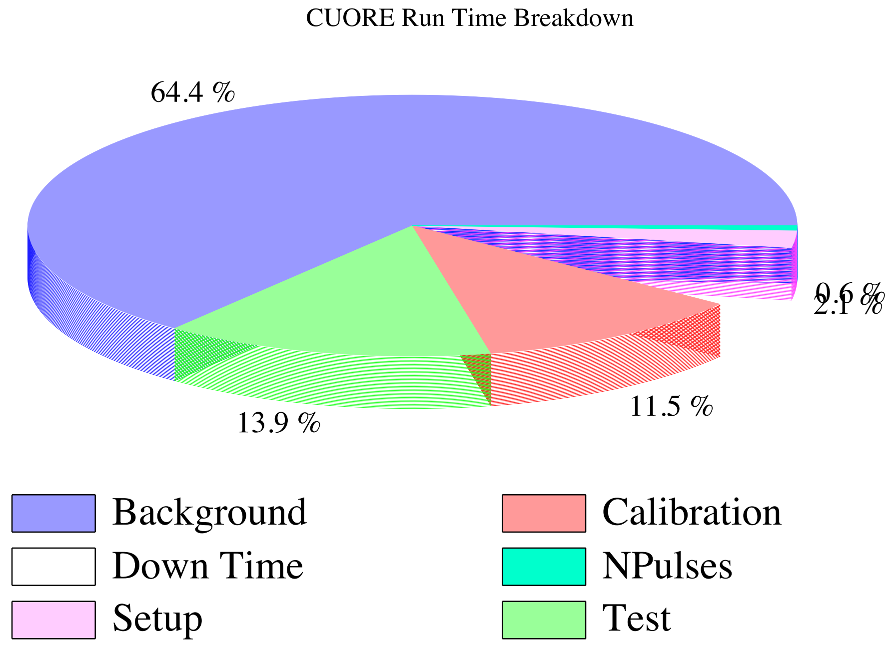
Internal shields:
6 tons of lead < 4 K

Detector
988 TeO_2 crystals:
742 kg of TeO_2,
206 kg of ^{130}Te,



CUORE - Operations & Data taking



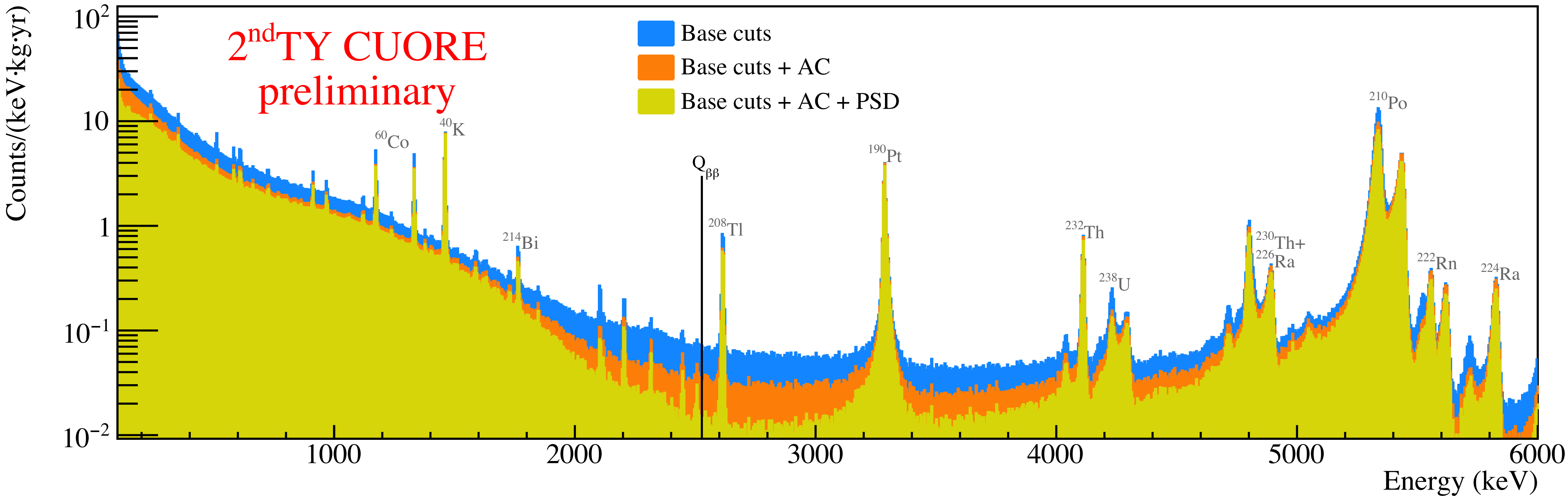


Operational performance
Analysis selection:
On avg. 934 / 984 channels (95) % (1TY analysis)
Exposure accumulation: ~ 50 kg yr / month
Goal: 3000 kg yr

Highly efficient:
~80% science operation,
~14% optimisation (noise - environmental monitoring)
~6% maintenance/down time

CUORE - Data

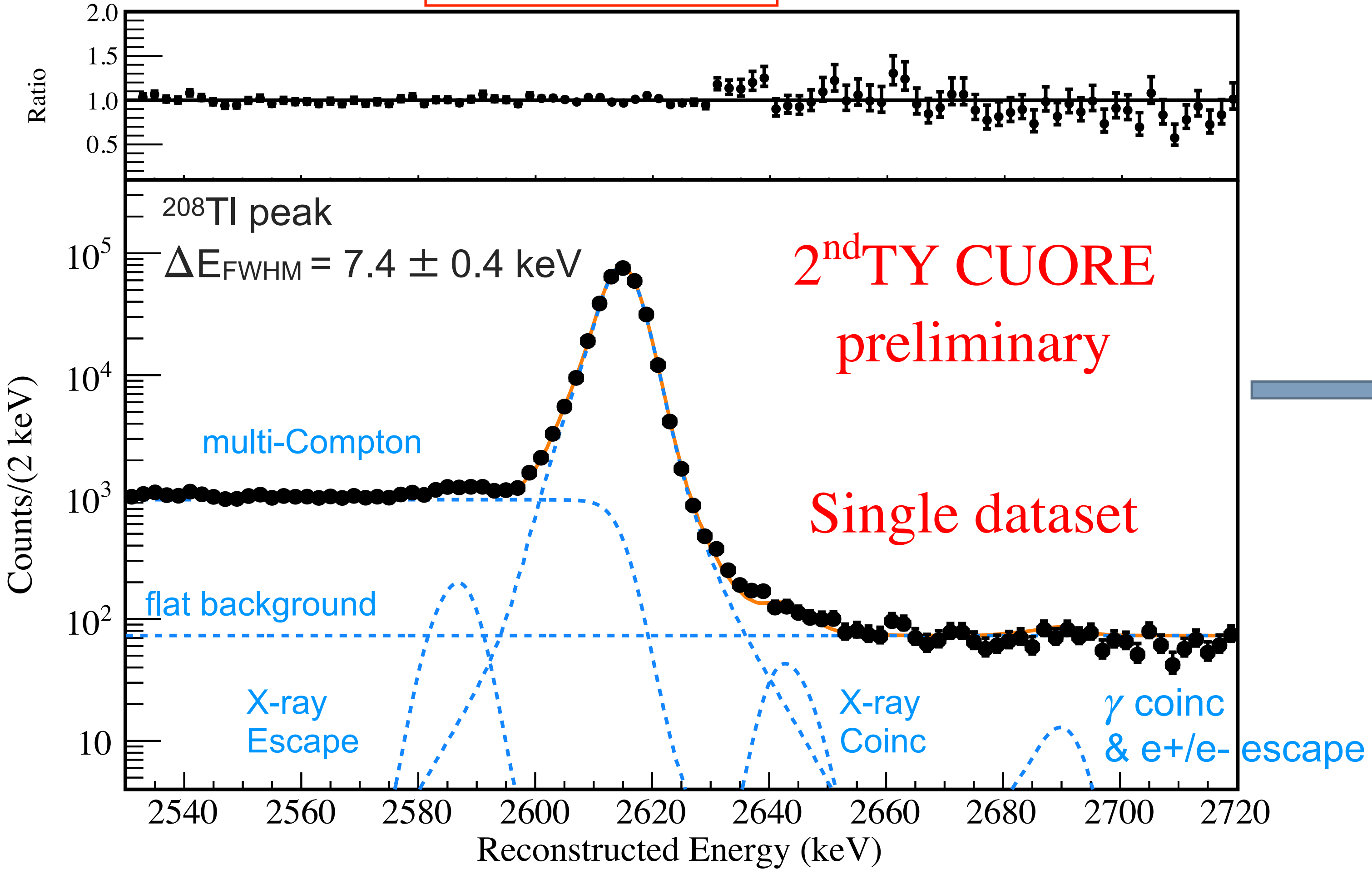
New: Denoising in signal processing arXiv:2311.01131



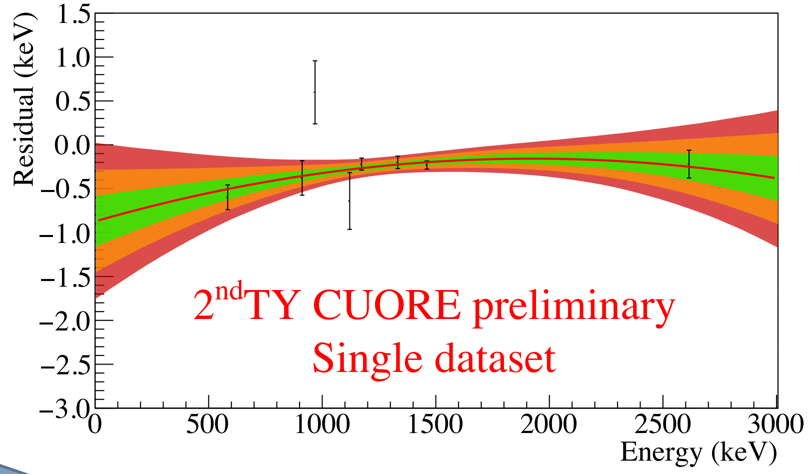
Overall analysis efficiency 93.2%

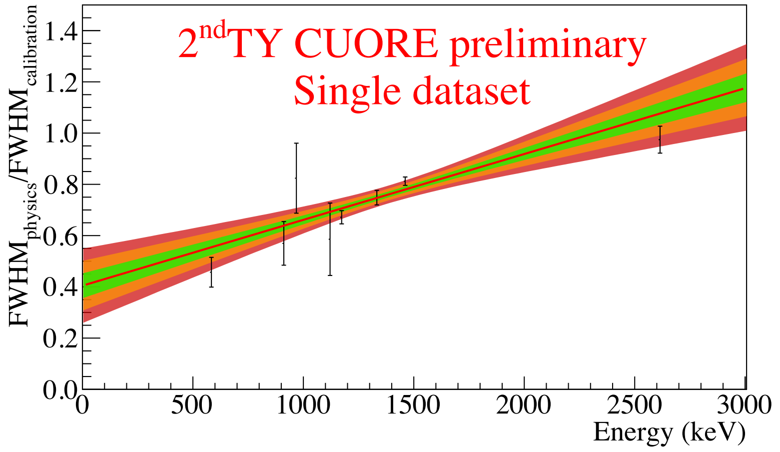
CUORE - Detector response

Calibration data



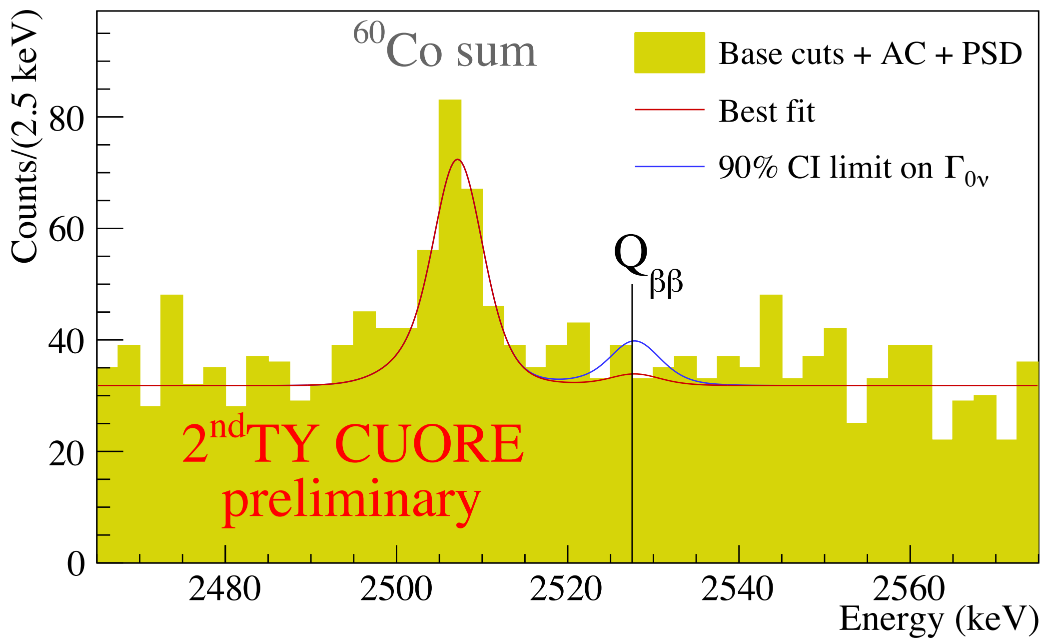
Physics data





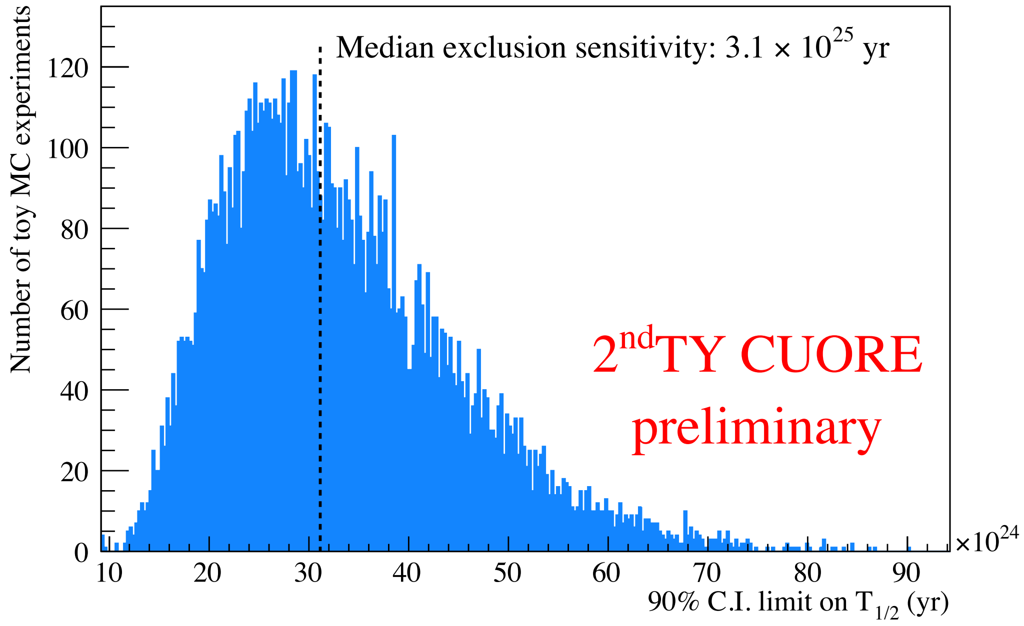
$\Delta E_{Q_{\beta\beta}} = 7.3^{+0.4}_{-0.5}$ keV

$0\nu\beta\beta$ result - 2nd TY



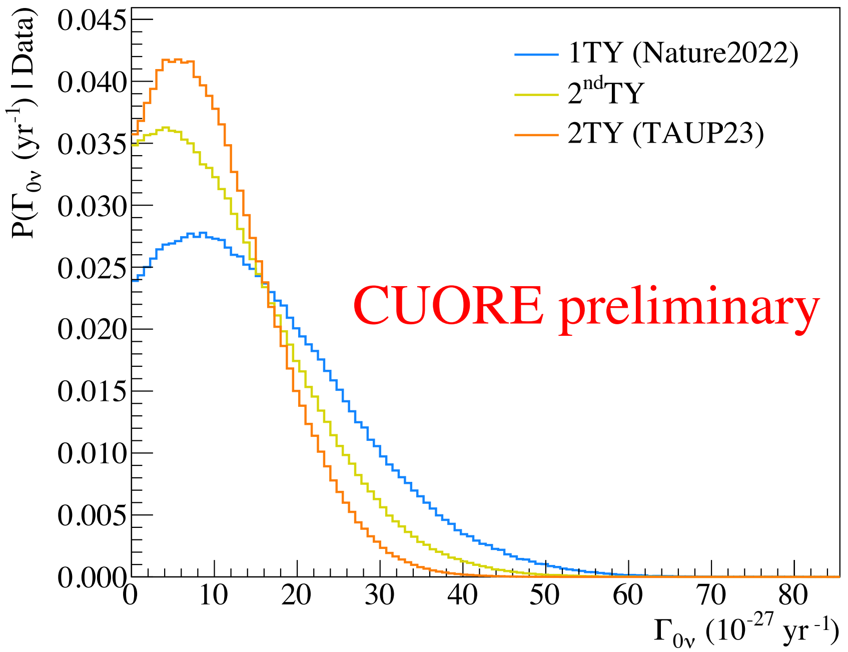
$$T^{0\nu\beta\beta}_{1/2} > 2.7 \cdot 10^{25}\, yr \qquad 90\,\%\ \mathrm{C.I.}$$

Avg. $BI = (1.30 \pm 0.03) \cdot 10^{-2}$ counts/keV/kg/yr



Systematics incl. as nuisance parameters	Dependence	Prior
Analysis efficiency	Dataset	Gauss
Energy bias	Dataset	From Bias fit Bg data
Resolution	Dataset	From ratio fit Bg/Cal
Q-value	Global	Gauss
Isotopic abundance	Global	Gauss

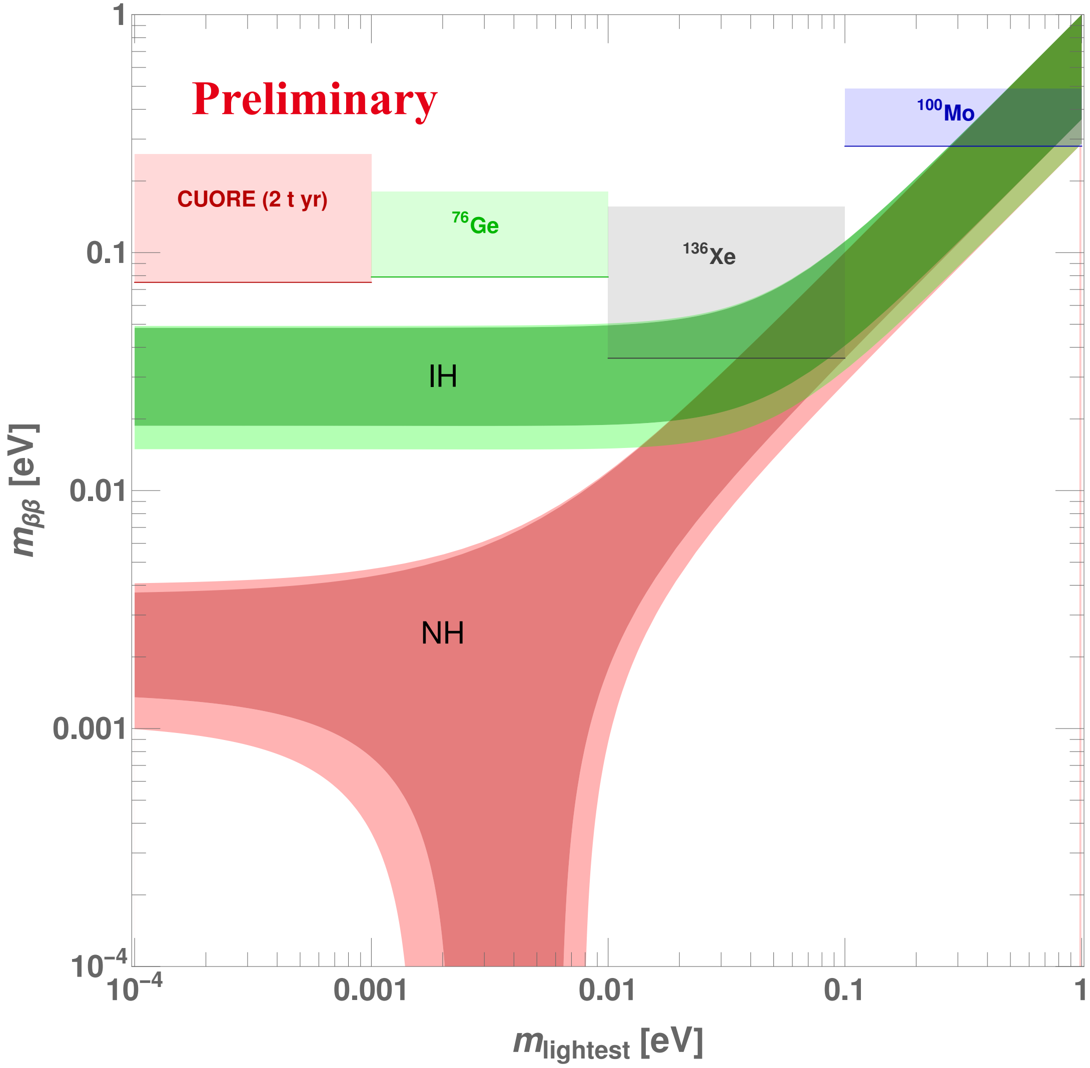
$0\nu\beta\beta$ result - 1st + 2nd TY



TAUP23: 2023 kg yr total
Combination of posteriors:

$$T_{1/2}^{0\nu\beta\beta} > 3.3 \cdot 10^{25}\, yr \qquad 90\,\%\ \mathrm{C.I.}$$

$$m_{\beta\beta} < (75 - 255)\ \mathrm{meV}$$



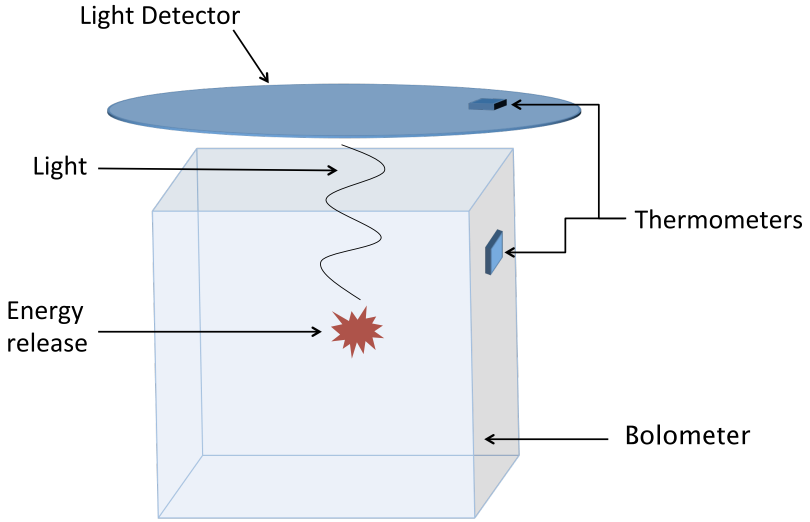
Outlook/Ongoing: Fully reprocess 1st TY with denoising to provide improved analysis of full exposure

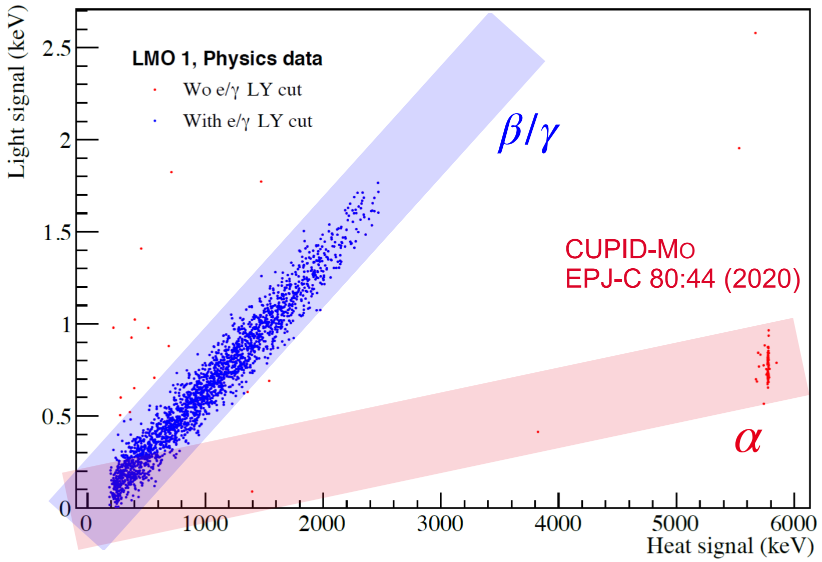
CUPID collaboration

140 collaborators from 7 countries

https://cupid.lngs.infn.it/

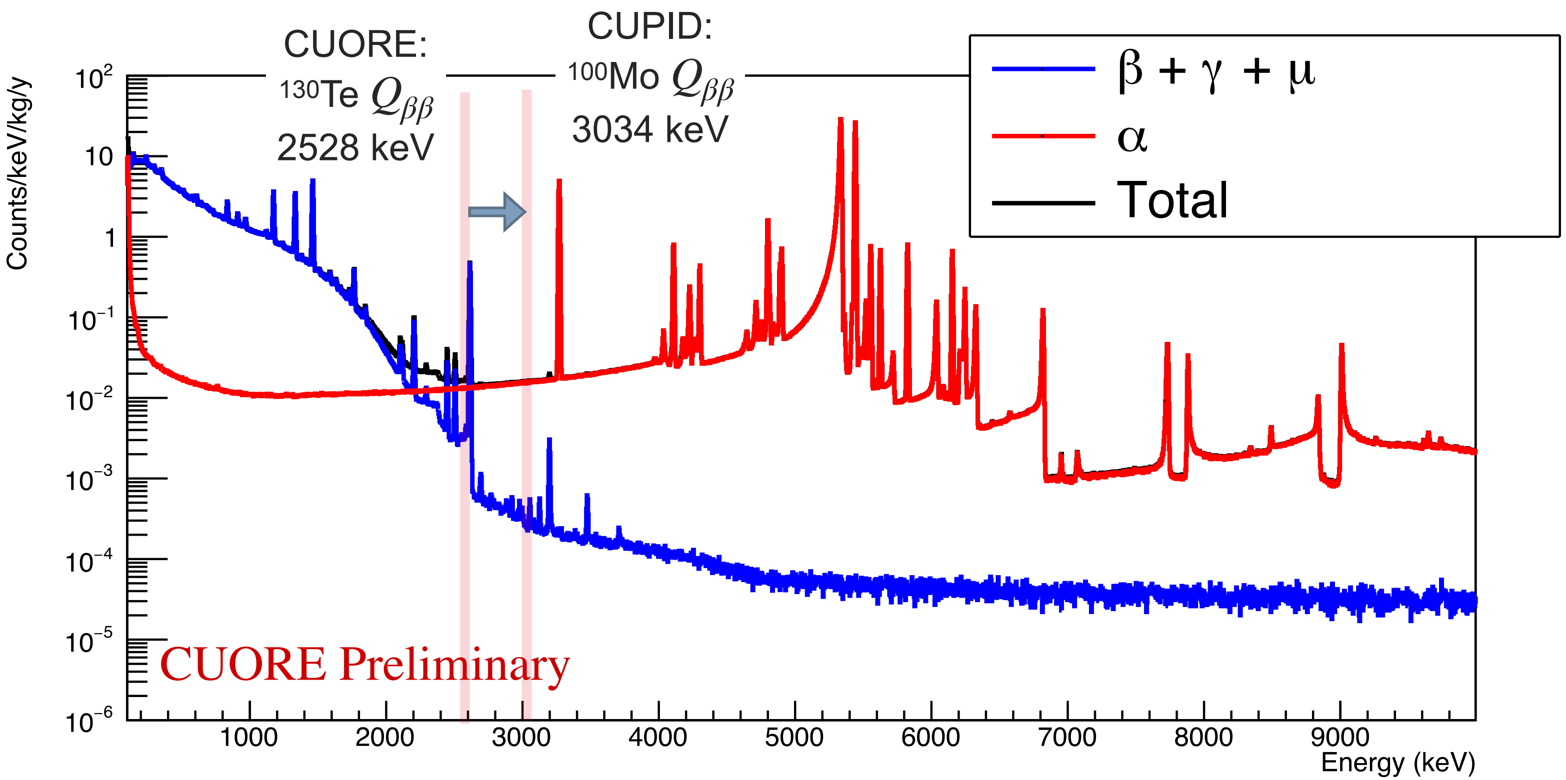
CUPID - CUORE upgrade with particle identification





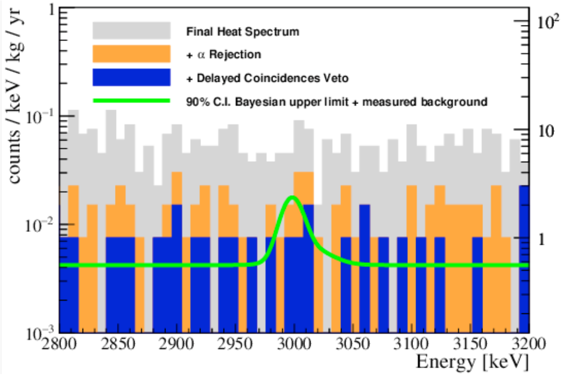
α discrimination through dual readout: heat & light

Higher Q-value target ^{100}Mo reduces γ background



CUPID-0 | CUPID-Mo two demonstrators for CUPID

Phys. Rev. Lett. 129, 111801 (2022)



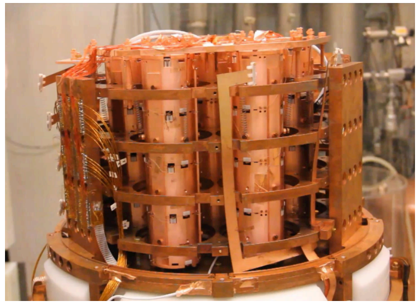
ZnSe dual heat+light readout

1st quantitative results for α identification & rejection

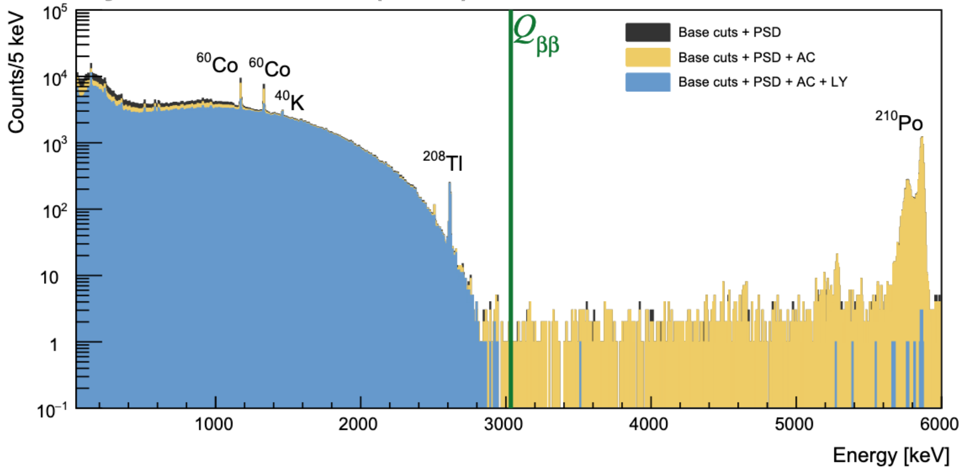
> 99.9 % α rejection

ΔE = 21.8 keV @$Q_{\beta\beta}$ (2998 keV)

Background: 4 x 10^{-3} counts/keV/kg/yr
(Muons, Crystals, Shields)



Eur. Phys. J. C 82:1033 (2022)



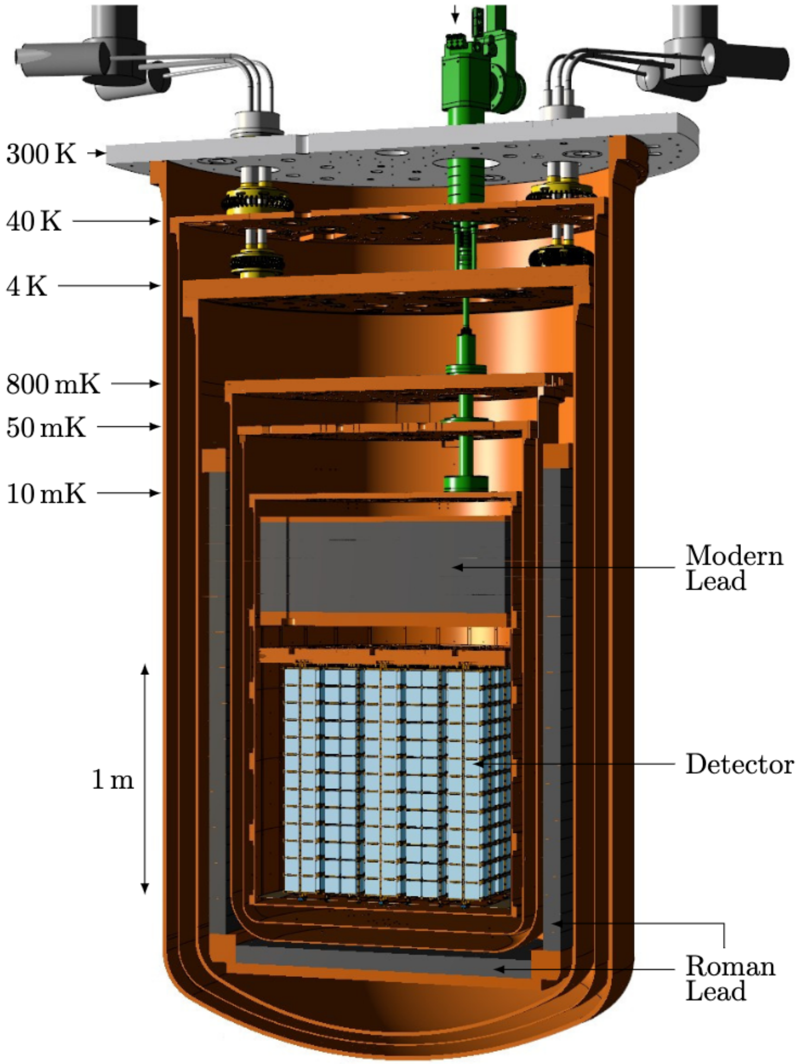
Li_2MoO_4 dual heat+light readout

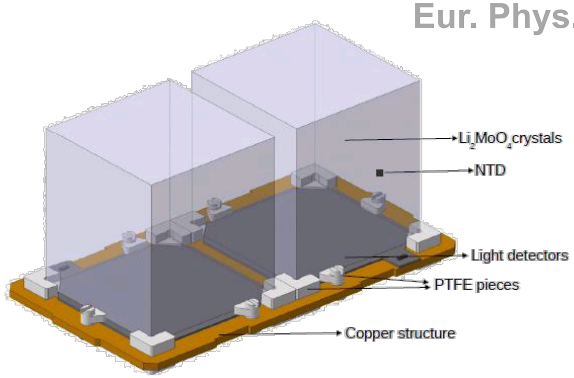
> 99.9 % α rejection

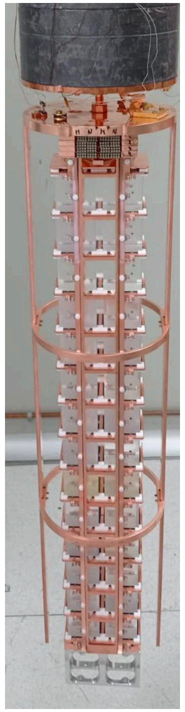
ΔE = 7.4 keV @$Q_{\beta\beta}$ (3034 keV)

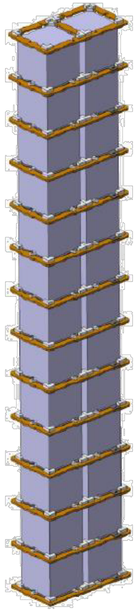
Background: 2.7 x 10^{-3} counts/keV/kg/yr
(Cryostat & close components, reflectors)

CUPID in a nutshell









Step-wise validations:
JINST 18 P06033 (2023)
Eur. Phys. J C82, 810 (2022)
Eur. Phys. J. C81, 104 (2021)

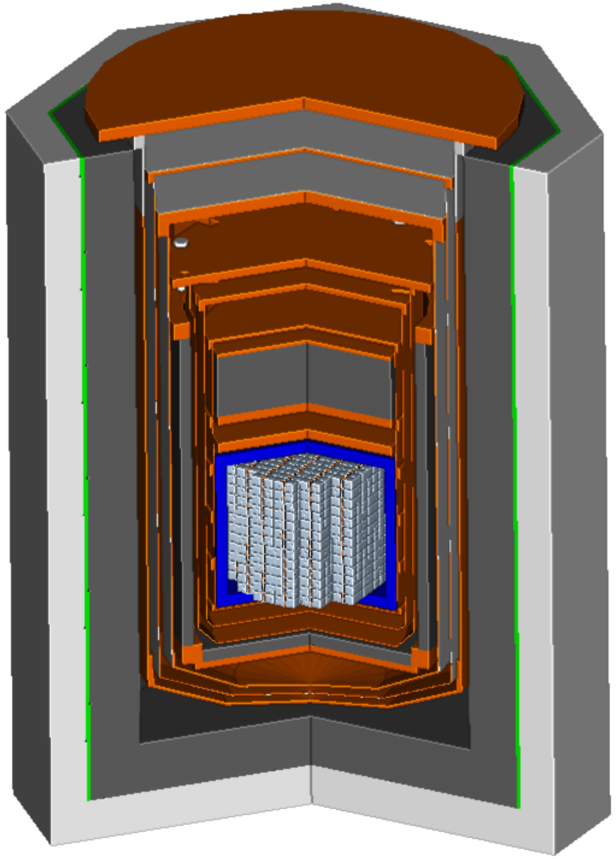
Design:

- CUORE cryostat & shielding,
- 1596 $Li_2{}^{100}MoO_4$ detector modules (light & heat)
- 240 kg of ^{100}Mo (>95% enrichment)
- Additional muon-veto system & neutron shields

Objectives:

- Energy resolution 5 keV FWHM at 3034 keV
- Bg index: 10^{-4} counts/keV/kg/yr
- $0\nu\beta\beta$ exclusion sensitivity after 10 years: 1.4 x 10^{27} yr

CUPID BG projection



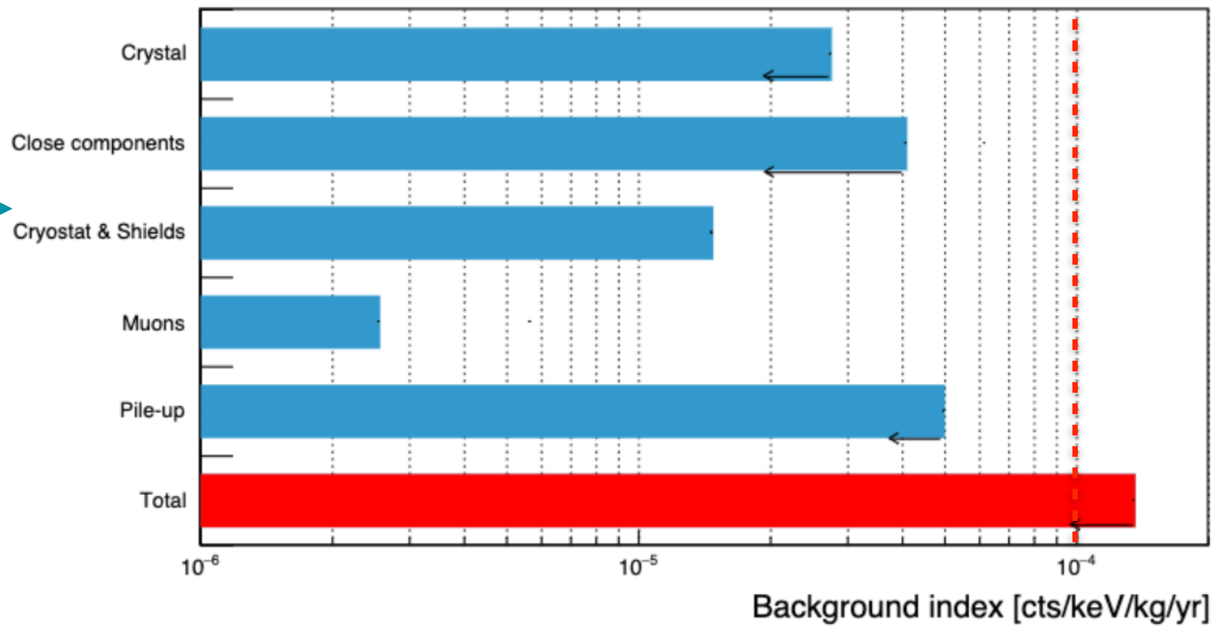
CUORE
Phys. Rev. Lett. 126, 171801 (2021)
Work in progress (2024)

GEANT4

EPJ-C 83, 675 (2023)
Phys. Rev. Lett. 131, 162501 (2023)

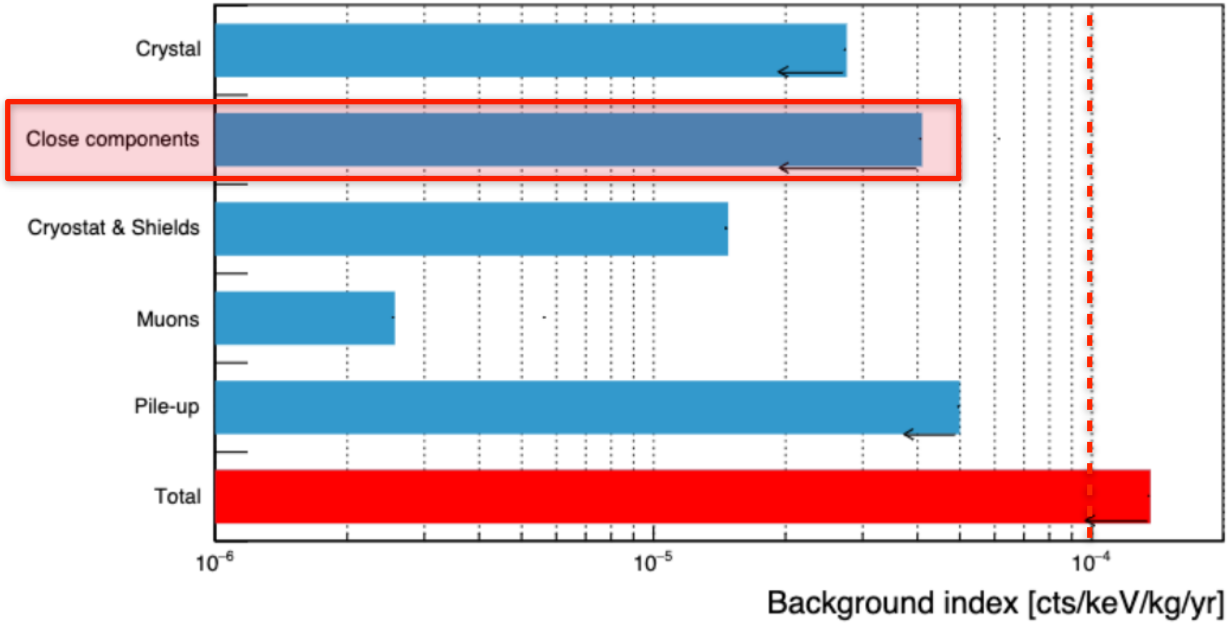
CUPID-0
EPJ-C 79, 583 (2019)
Phys. Rev. Lett. 131, 222501 (2023)

CUPID BG simulation

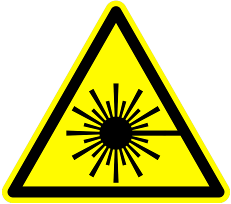


CUPID BG projection - Improvements

CUPID BG simulation



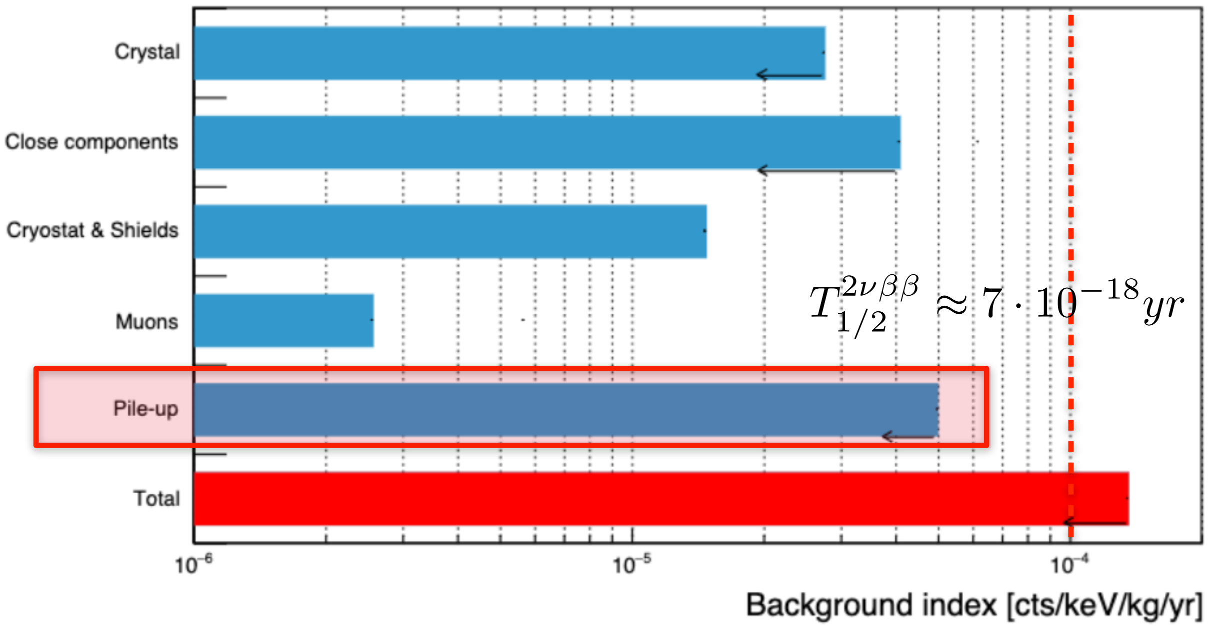
Improvements to be evaluated:



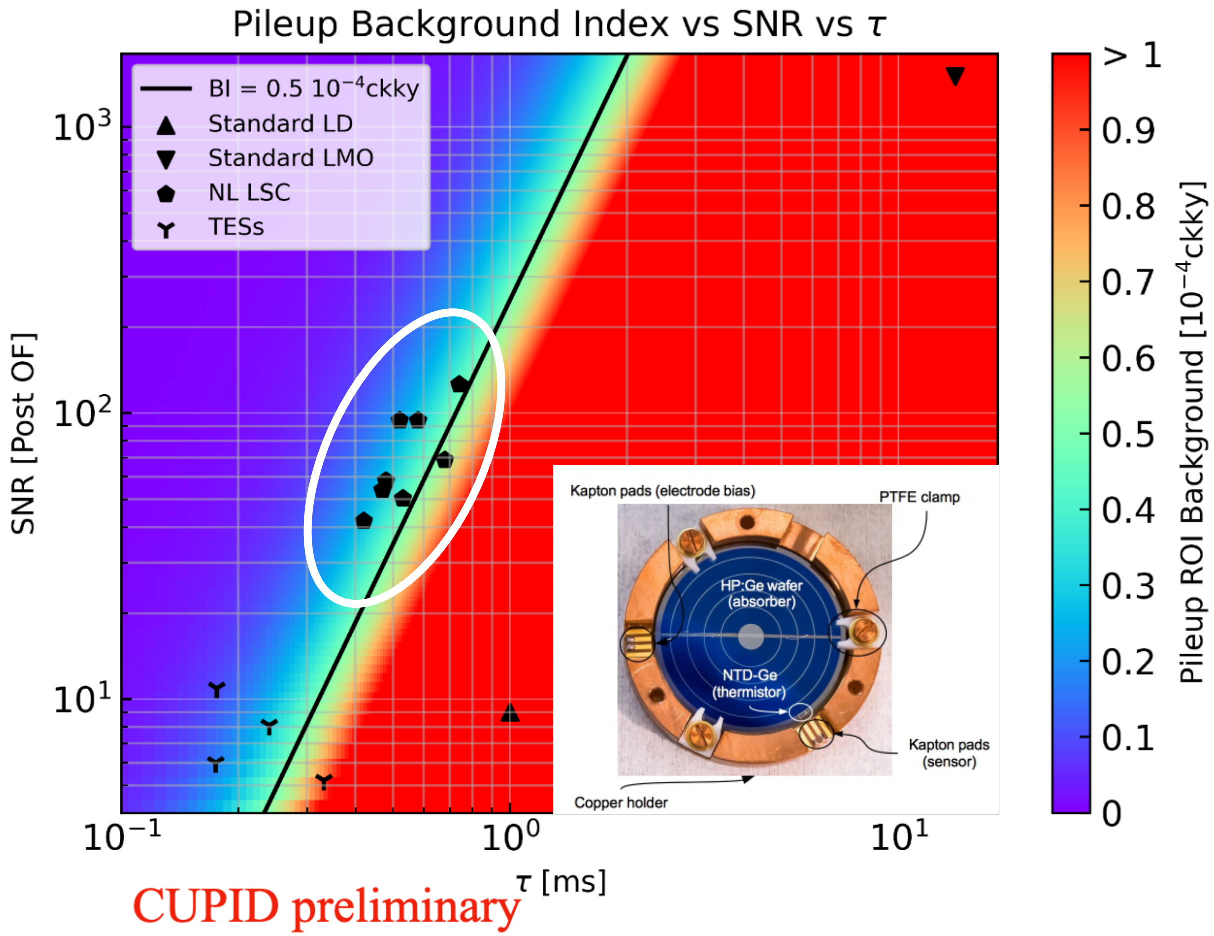
- New simplified mechanical tower design
- —> Less machining & handling
  - Contact-less production with laser cutting
- —> Improved radiopurity during construction & storage

CUPID - Improvements: NTL light detectors

CUPID BG simulation

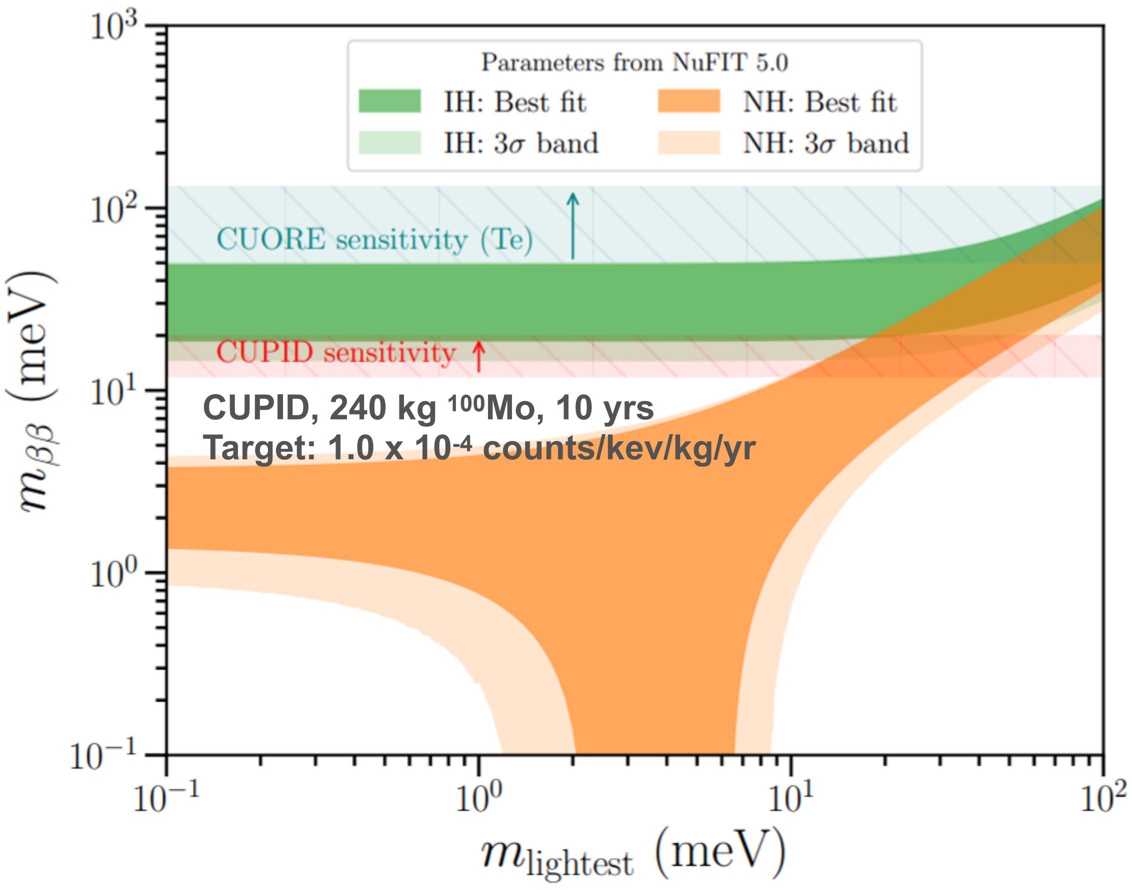


NIM A 940, 320 (2019)

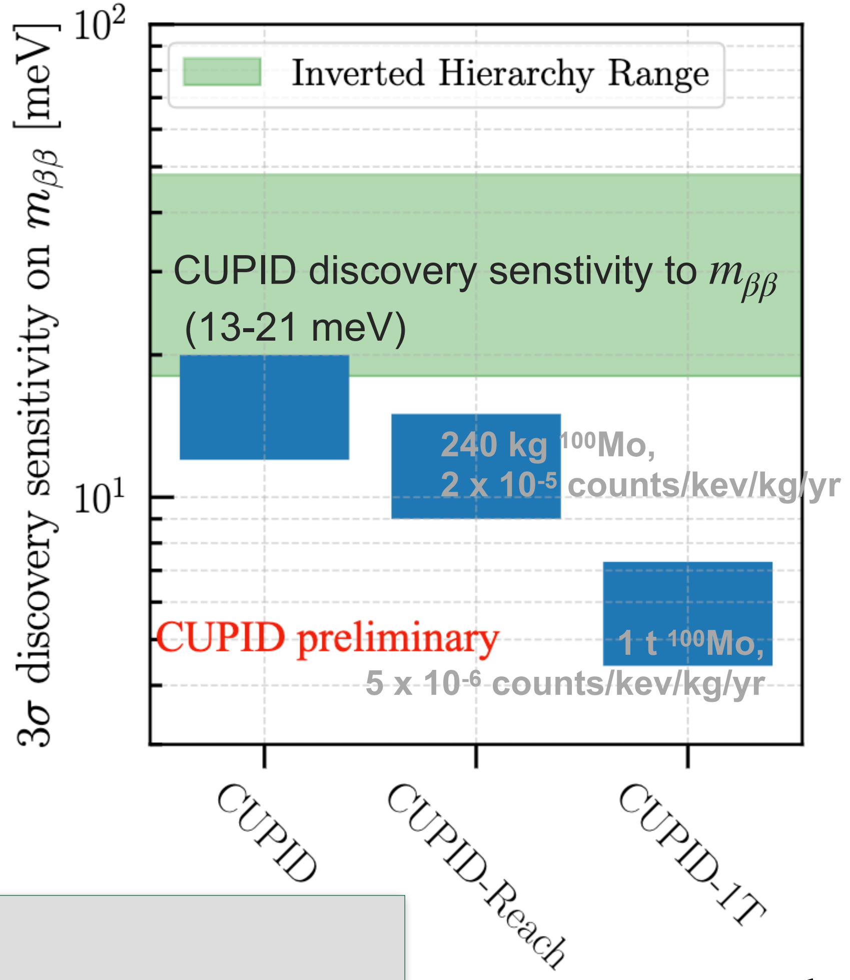


Newly adopted NTL light detectors ->Pile-up can be reduced to less than 5 x 10^{-5} counts/keV/kg/yr

Conclusions & Outlook



CUPID



Single modules & technologies validated
Full tower tests in preparation at LNGS
Enriched Li_2MoO_4 crystal pre-production is ongoing & scalable
Bg model indicates sensitivity to fully cover inverted hierarchy for favourable NME!

Stay tuned!