GDR Neutrino meeting May 29-30 2017

May 29th, 2017

CUPID

Advanced bolometric technologies for double beta decay search in France

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CSNSM

Outline

- The challenging quest for neutrinoless double beta decay
- The bolometric approach: from CUORE to CUPID
- The ^{100}Mo way: LUMINEU → CUPID-Mo
- The ^{130}Te way: detection of Cherenkov light
- Development of new ideas: CROSS

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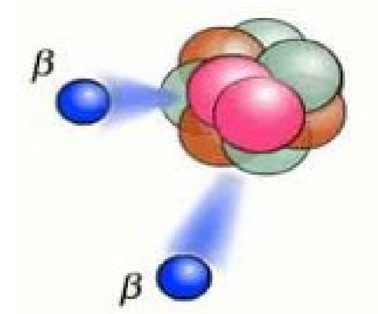
Neutrinoless double beta decay (0ν2β): standard and non-standard mechanisms

0ν2β is a test for « creation of leptons »: **2n → 2p + 2e⁻ ⇒ LNV**

This test is implemented in the nuclear matter:
(A,Z) → (A,Z+2) + 2e⁻



Energetically possible for **35 nuclei**
Only a few are experimentally relevant

0ν2β →

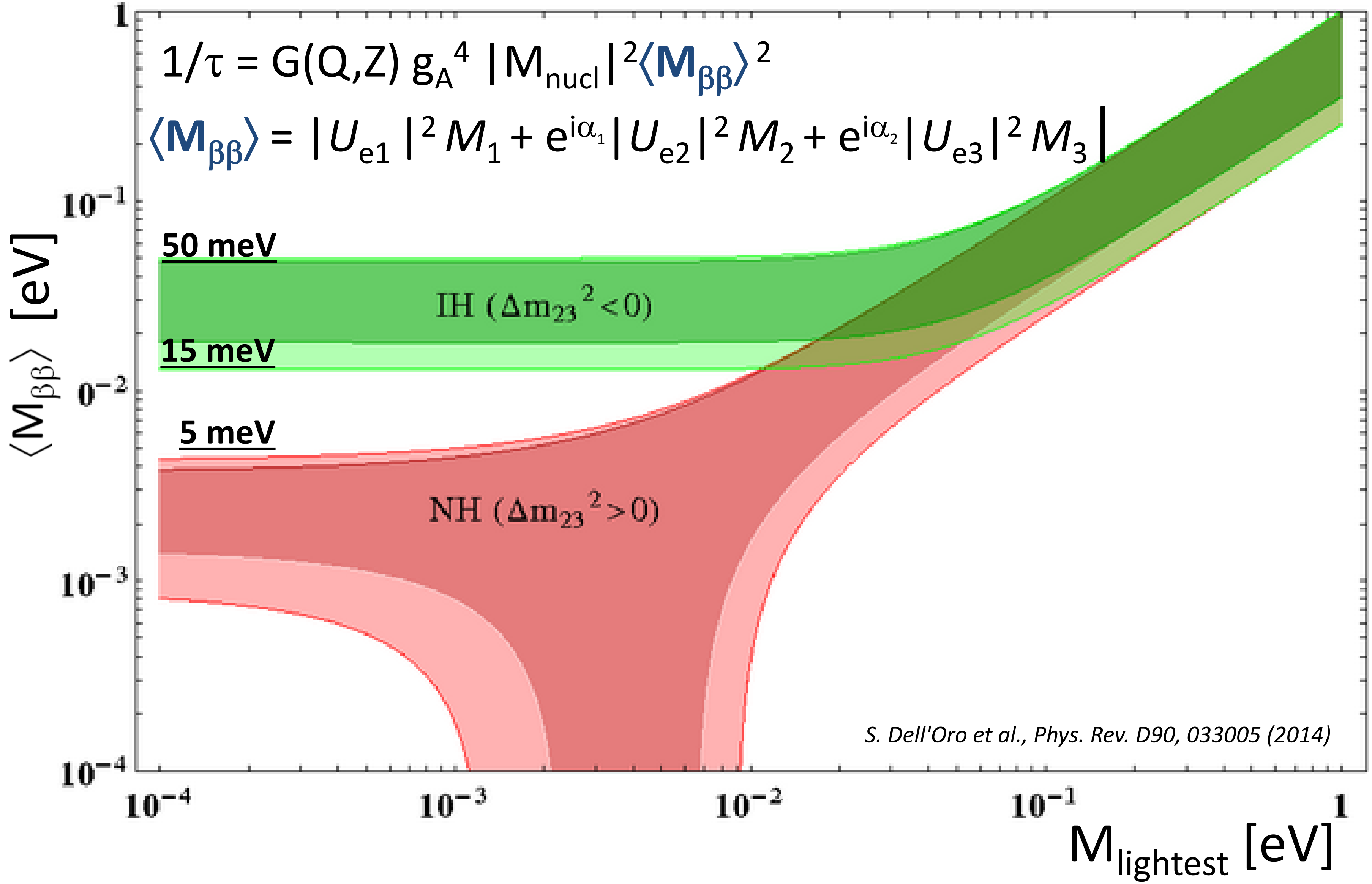
Standard mechanism: **neutrino physics**

0ν2β is mediated by **light massive Majorana neutrinos** (exactly those which oscillate)

Non-standard mechanism: **BSM, LNV**

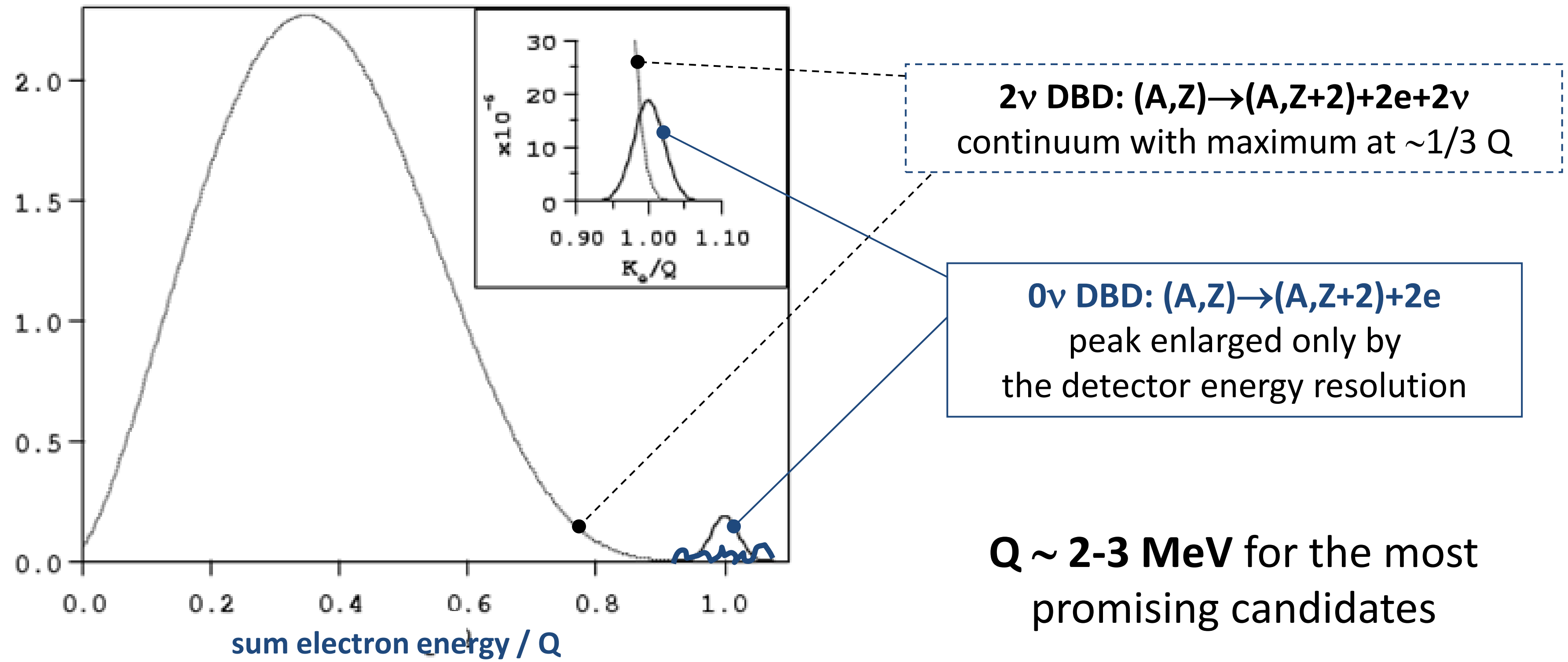
Not necessarily neutrino physics

$\langle M_{\beta\beta} \rangle$ vs. lightest ν mass



What we are looking for

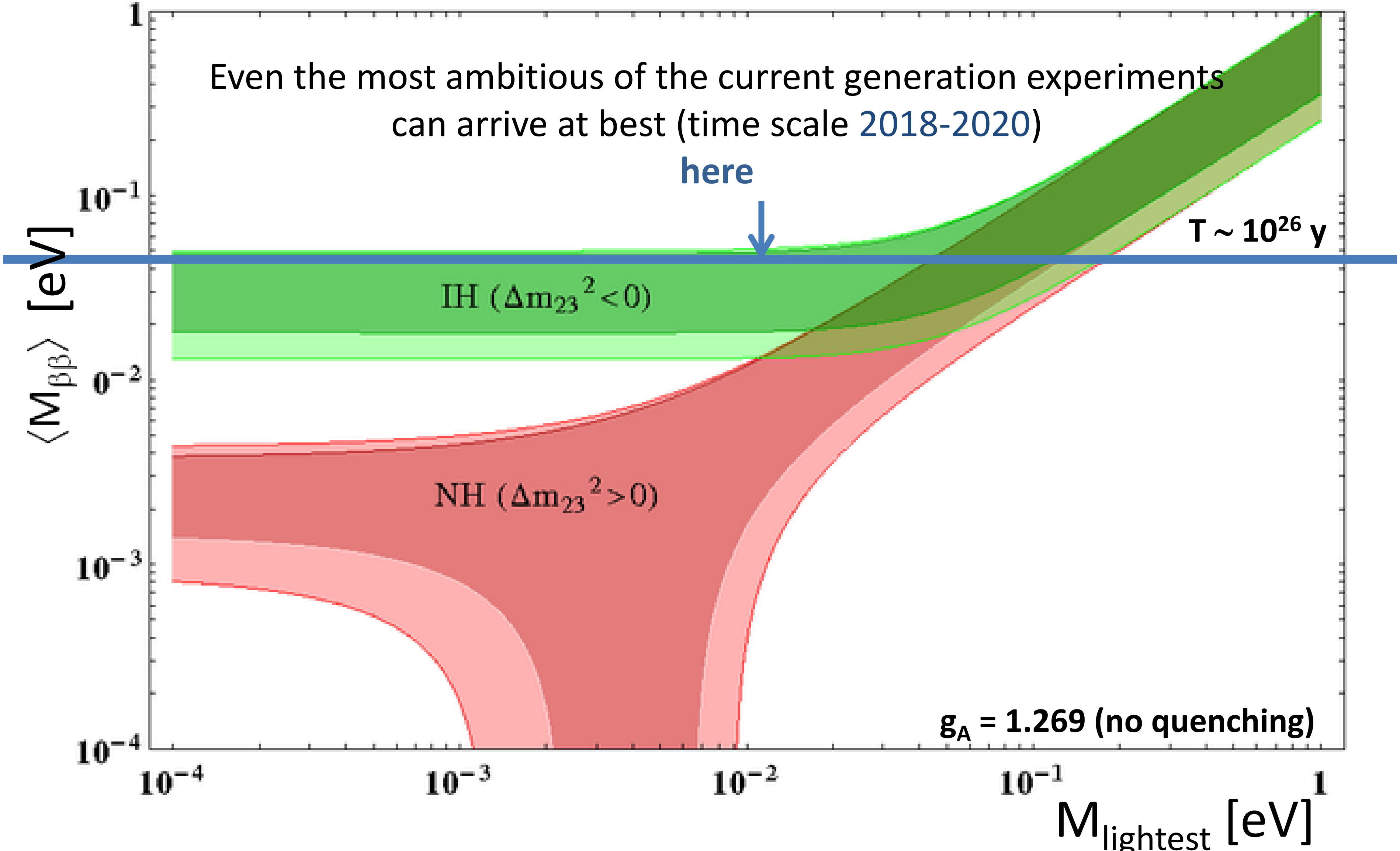
The shape of the two-electron sum-energy spectrum enables to distinguish between the **0ν** (new physics) and the **2ν** decay modes



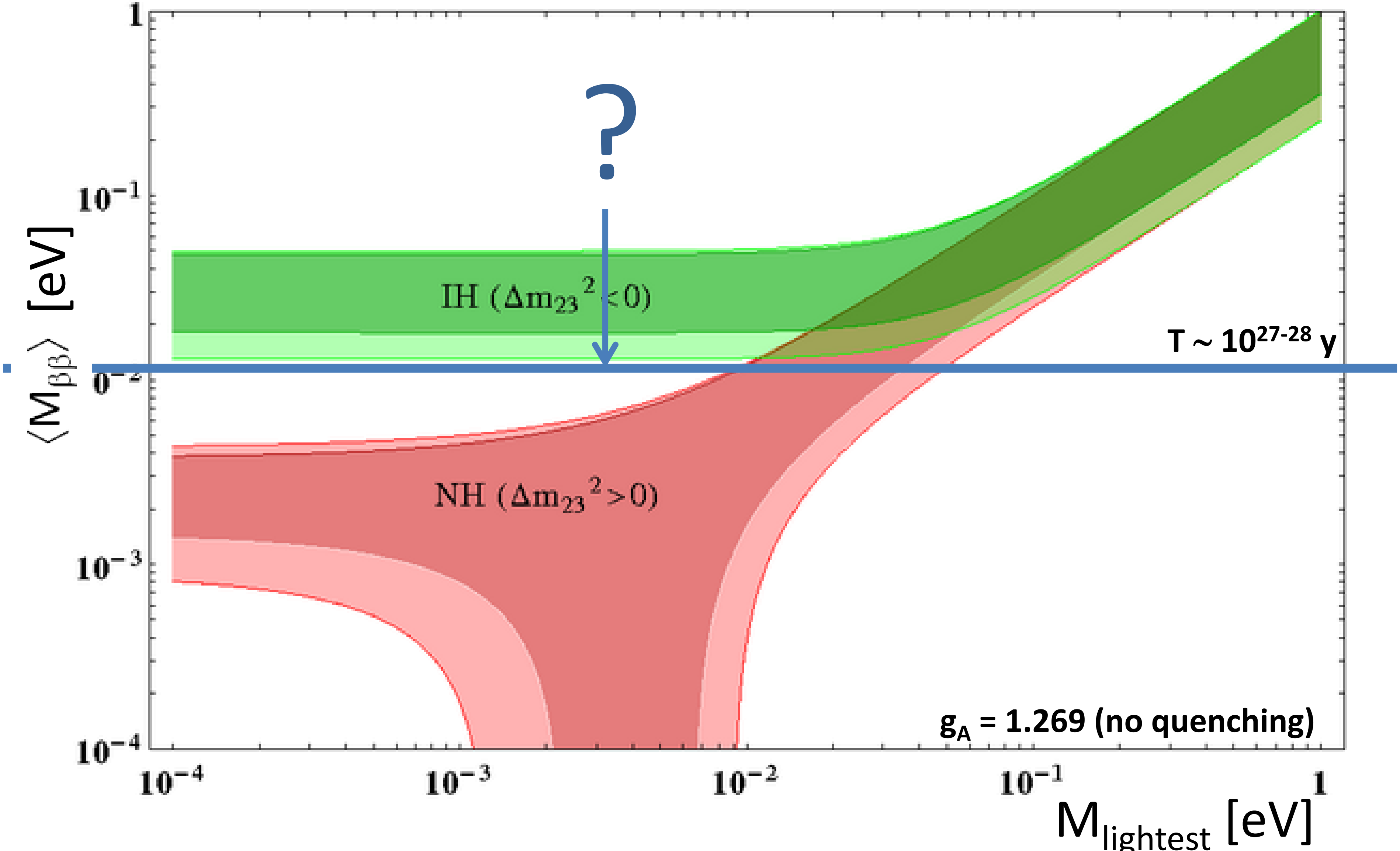
Q ~ 2-3 MeV for the most promising candidates

The signal is a **peak (at the Q-value)** over an almost **flat background**

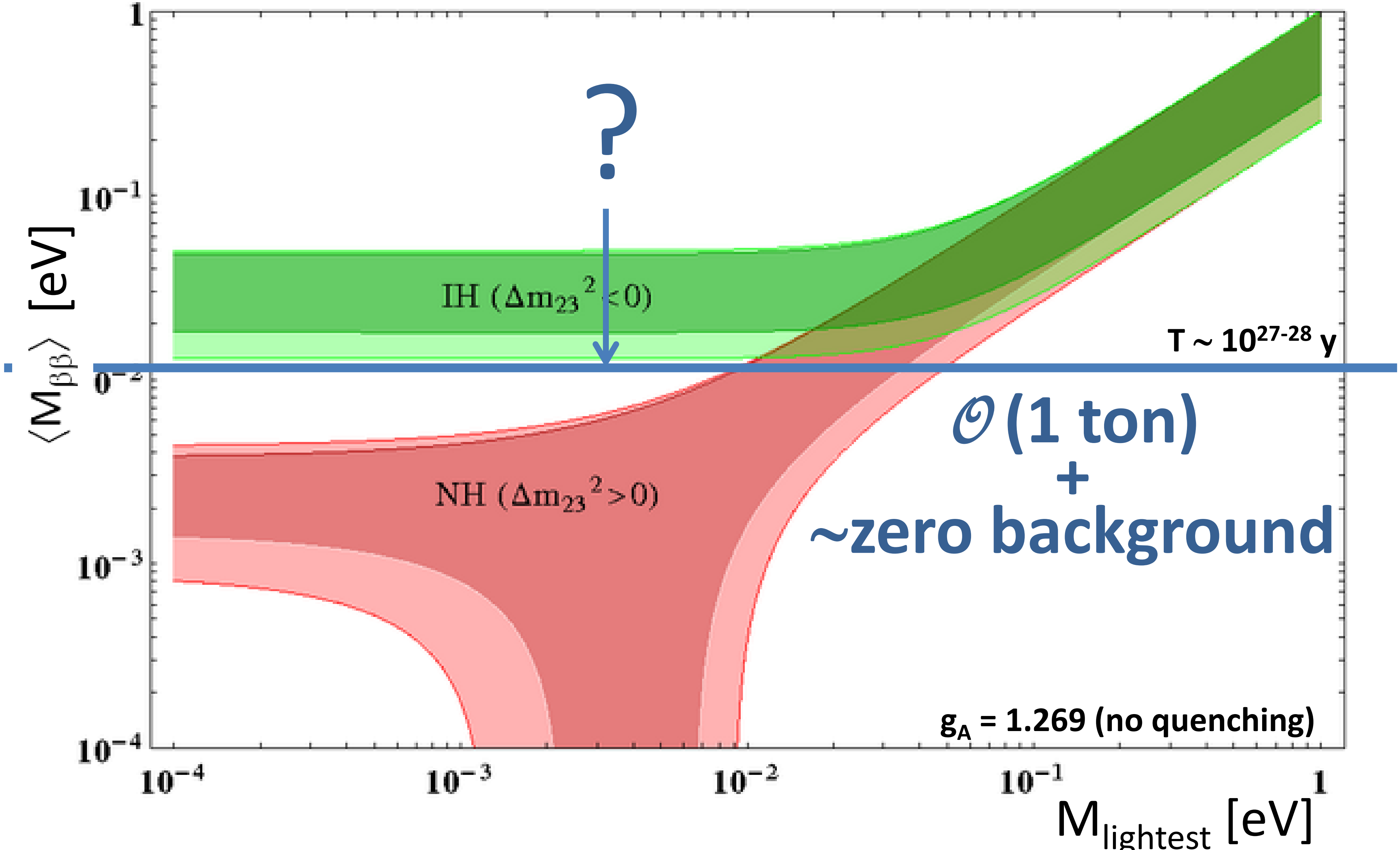
Current-generation experiments



Strategic milestone



Strategic milestone



Request for the background index

Background index

***b* [counts/(keV kg y)]**

defined as

$$b = \frac{\textbf{number of background counts}}{\textbf{detector (isotope) mass} \times \textbf{live time} \times \textbf{energy interval}}$$

around the region of interest

In the source=detector approach with high energy resolution technique ($\Delta E_{FWHM} < 10$ keV) zero background at the tonne scale means

$b \leq 10^{-4}$ [counts/(keV kg y)]

Present record: GERDA (^{76}Ge) – b~ 7 x 10^{-4} counts/(keV kg y) – $\Delta E_{FWHM} \sim 3$ keV

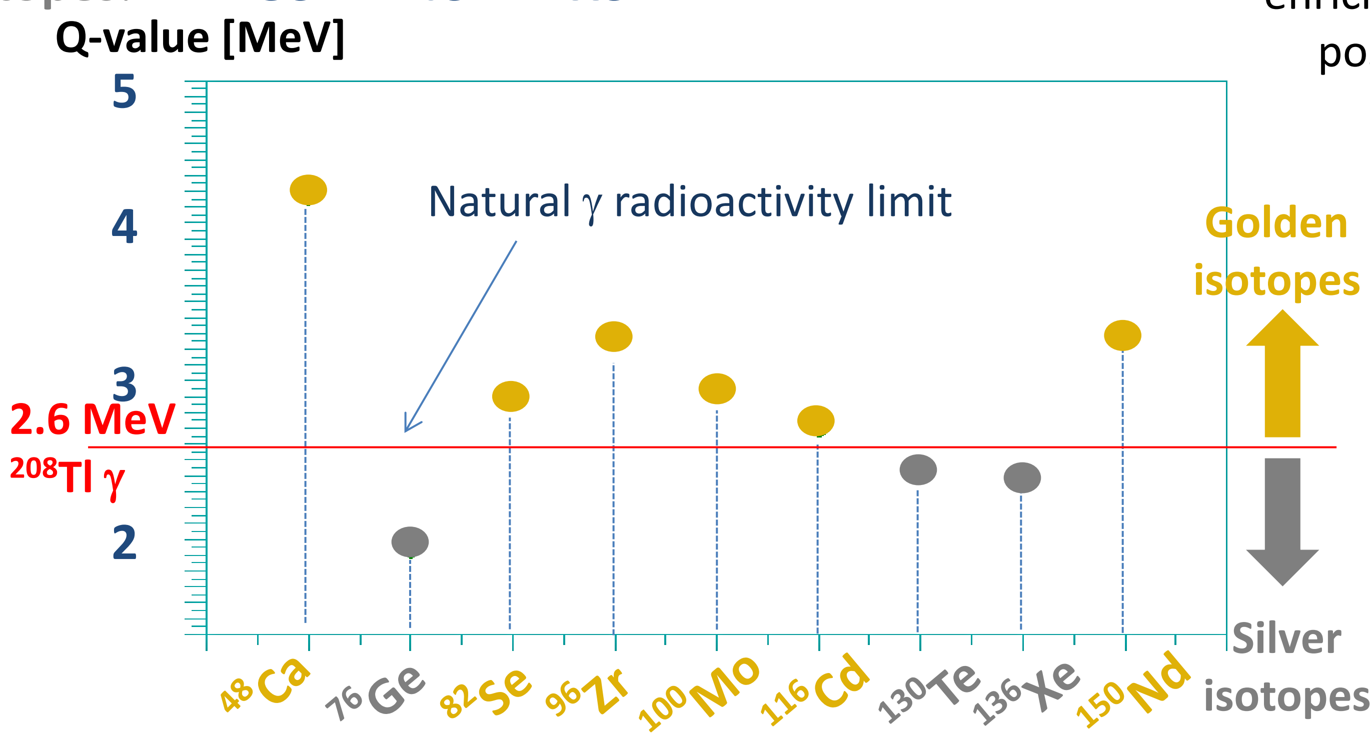
Silver and golden isotopes

Q is the crucial factor → Phase space: $G(Q,Z) \propto Q^5$ / Background ⇒ **Magnificent Nine candidates**

Golden isotopes: ^{48}Ca – ^{150}Nd – ^{96}Zr – ^{100}Mo – ^{82}Se – ^{116}Cd

Silver isotopes: ^{76}Ge – ^{130}Te – ^{136}Xe

Large-scale enrichment is possible (^{100}Mo – ^{82}Se – ^{116}Cd)



^{130}Te is almost golden: Q-value (**2530 keV**) in a clean window between **2615 keV** γ and its Compton edge (**2382 keV**)

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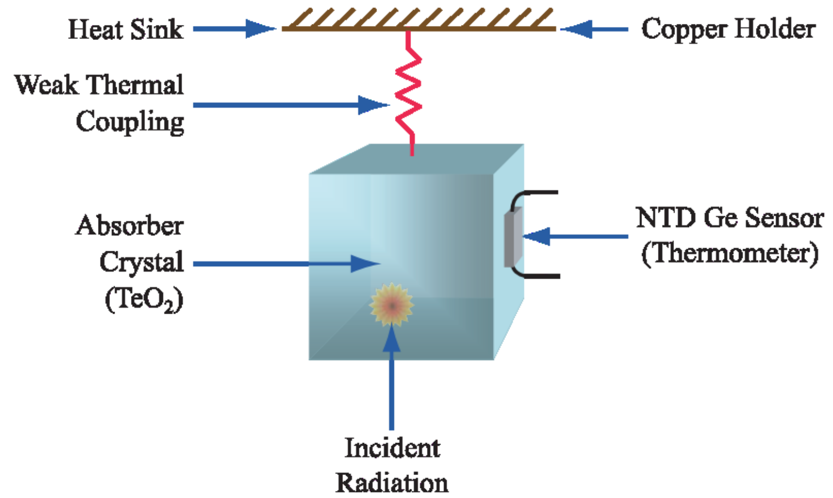
Bolometers in nutshell

Bolometric approach: the source is embedded in a crystal, which is cooled down to 10-20 mK and works as a **perfect calorimeter**

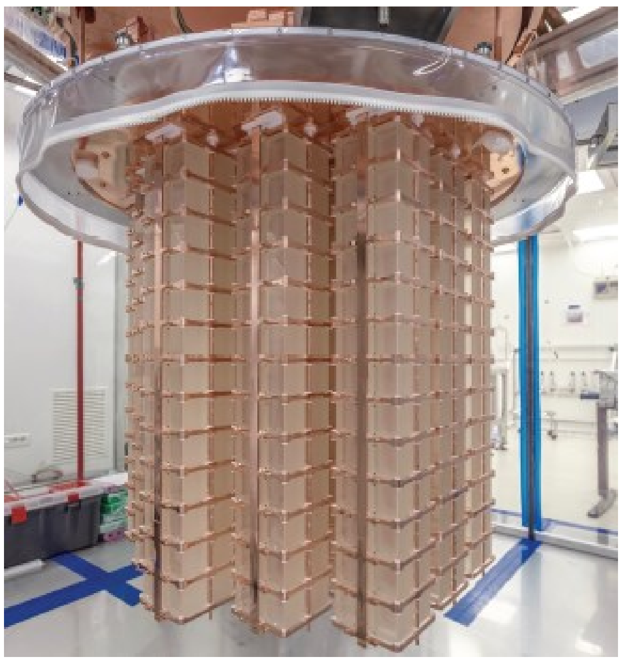


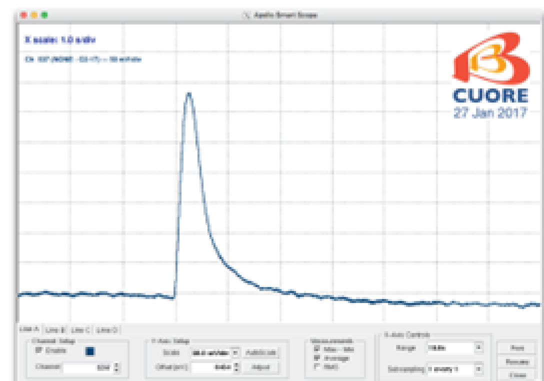
$$\Delta T = E/C$$

- High energy resolution (~ **5 keV FWHM**)
- **~ 0.1 - 0.5 kg** source in each crystal → arrays
- High efficiency **(~ 80 – 90 %)**
- **Cuoricino – CUORE** experiments → crystals of **TeO_2** (isotope **^{130}Te**)
- **Large flexibility in the detector material choice:** ^{130}Te, and **three golden isotopes (^{82}Se, ^{100}Mo, ^{116}Cd) can be studied**

CUORE: the largest bolometric search

Technique/location: natural 988 TeO_2 bolometers at 10-15 mK– LNGS (Italy)
→ evolution of Cuoricino
Source: TeO_2 – 741 kg with natural tellurium - **9.5×10^{26} nuclides of ^{130}Te**
Sensitivity: **51 – 133 meV** (5 years) – approach closely inverted hierarchy region
Timeline: first CUORE tower (CUORE-0) has completed successfully its physics run
Full apparatus operational at end 2016 – **all 19 towers are now taking data**



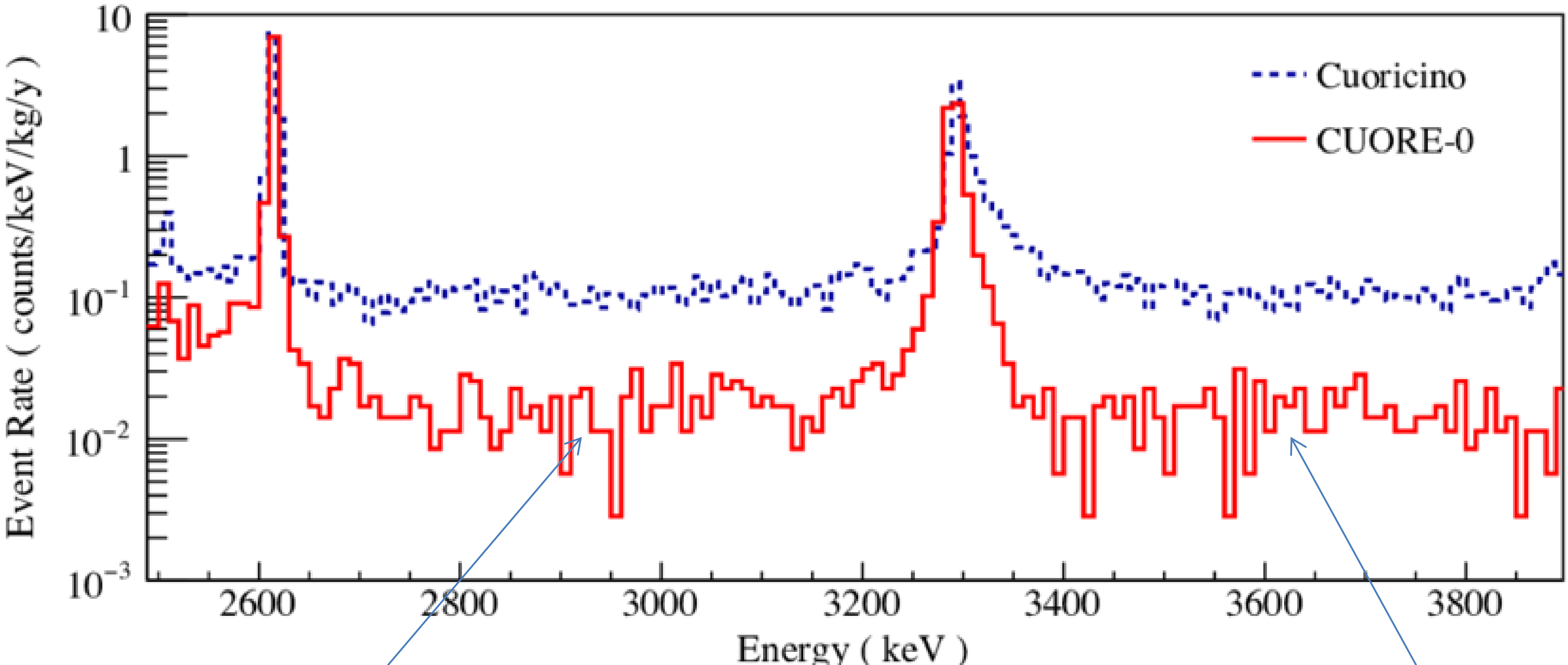


First CUORE pulse

Very high natural abundance of ^{130}Te: 34% ⇒ competitive experiment without enrichment

Background beyond 2.6 MeV

Lessons learned from TeO_2 bolometric experiments



Irreducible background due to **alpha particles**, emitted at the **surfaces** and energy-degraded

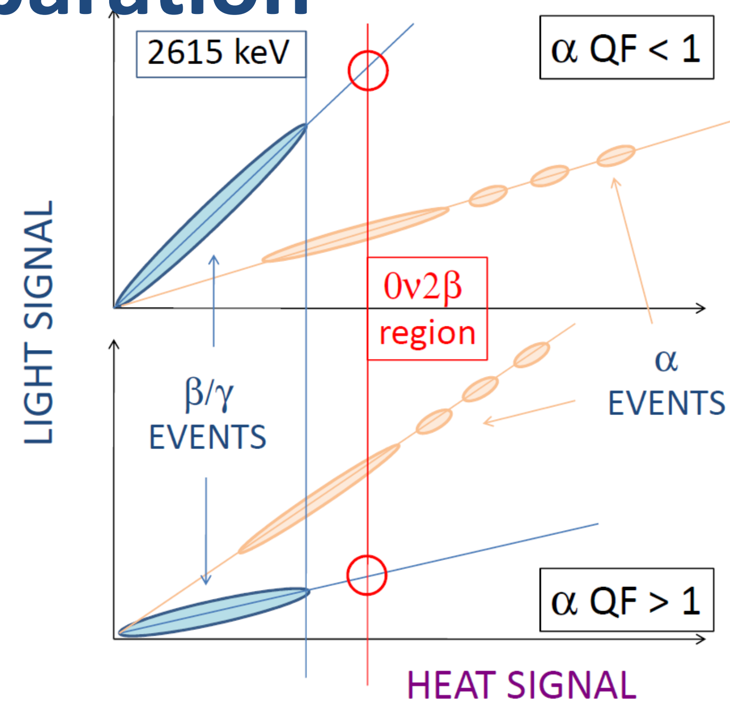
$b \sim 10^{-2}$ [counts/(keV kg y)] ← CUORE target

CUORE will not be background free

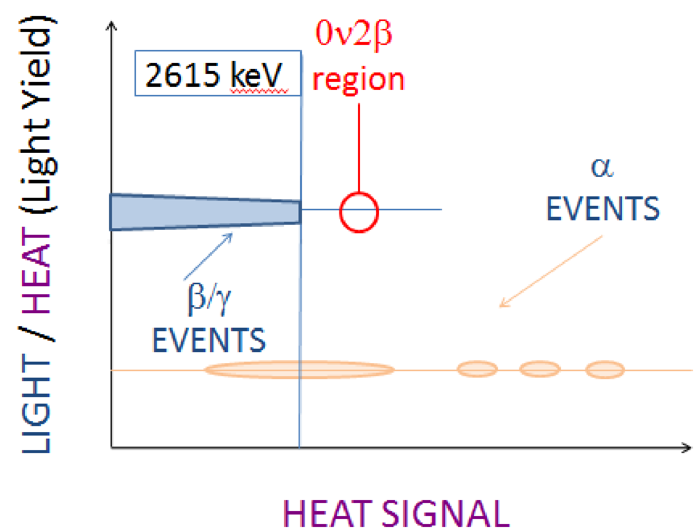
Current solution: scintillating / Cherenkov bolometers

Alpha / beta separation

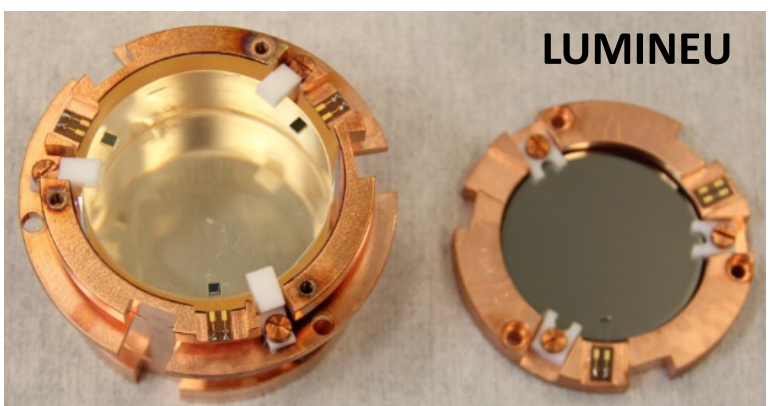
Alphas emit a different amount of light with respect to beta/gamma of the same energy (normally lower → **α QF < 1, but not in all cases – ZnSe is an exception**).



A **scatter plot light vs. heat** or a **plot light-yield vs. heat)** separates alphas from betas / gammas.



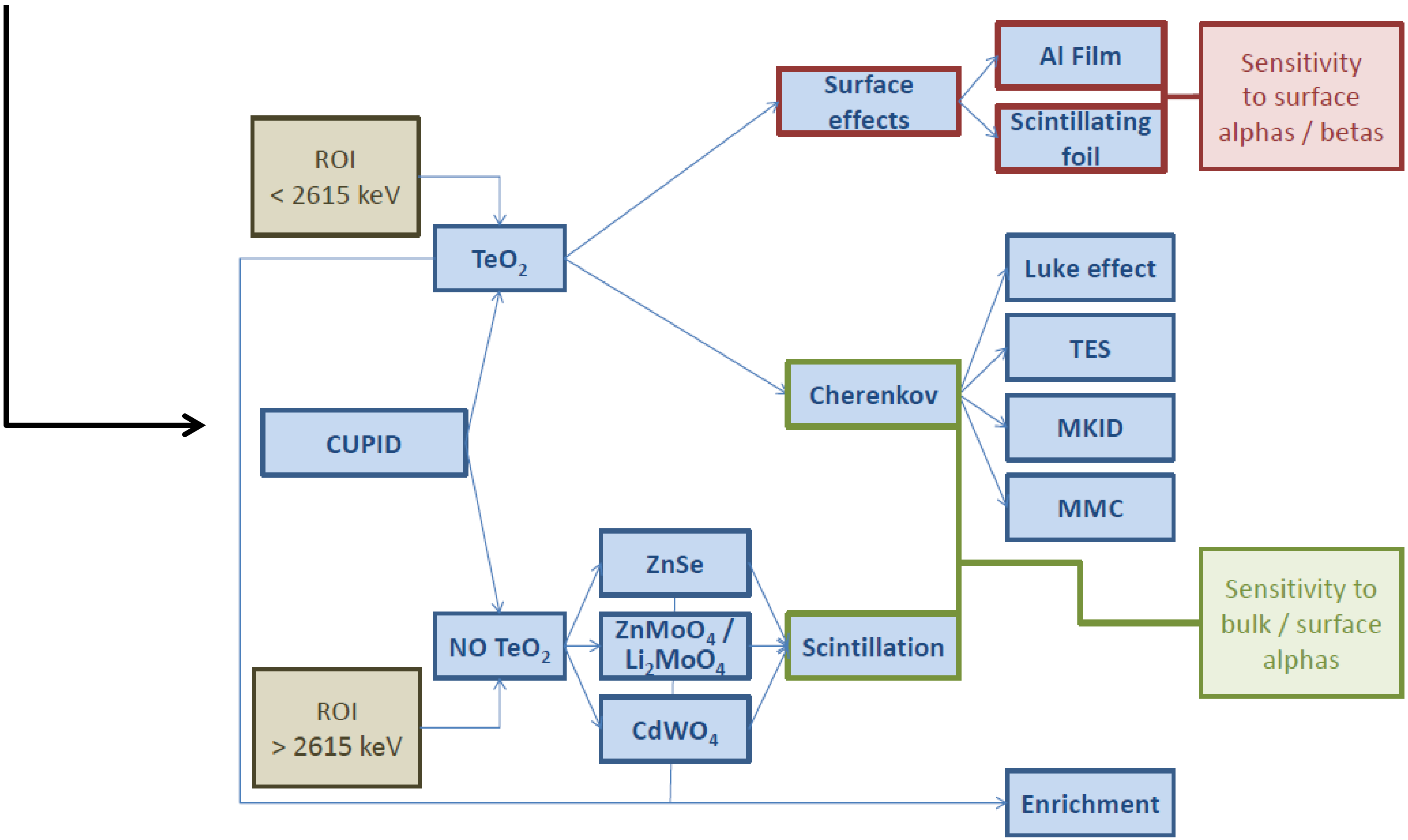
Of course, a bolometric light detector is needed, facing the main crystal



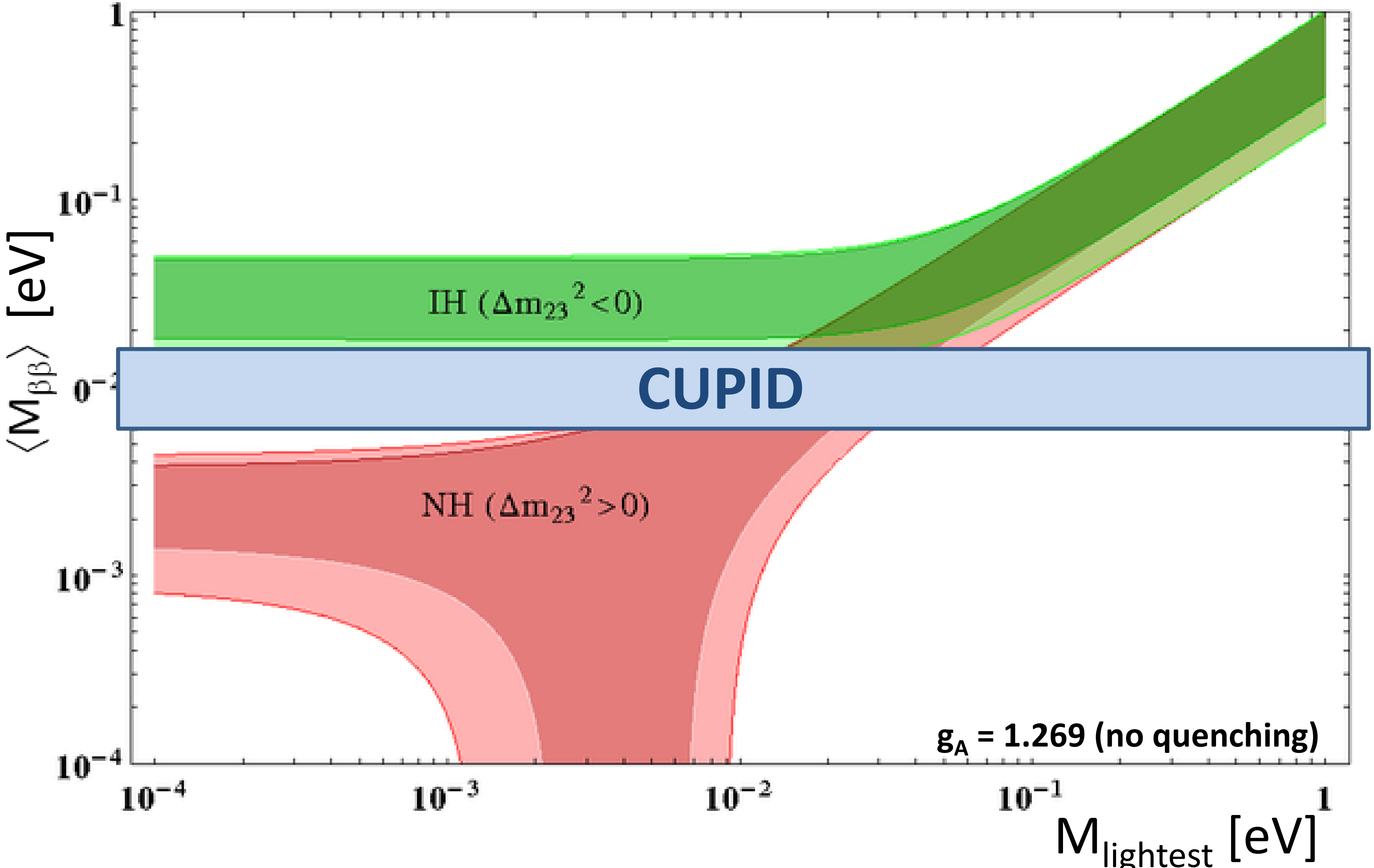
CUPID

Follow-up to CUORE with background improved by a factor 100

- Reduce / control background from materials and from muon /neutrons
- Optimize the enrichment-purification-crystallization chain
- **Improve detector technology to get rid of α / surface background**



CUPID goal



1
10^{-1}
10^{-3}
10^{-4}
$\langle M_{\beta\beta} \rangle$ [eV]
IH ($\Delta m_{23}{}^2 < 0$)
CUPID
NH ($\Delta m_{23}{}^2 > 0$)
g_A = 1.269 (no quenching)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$M_{lightest}$ [eV]

CUPID – pilot experiments

Follow-up to CUORE with background improved by a factor 100

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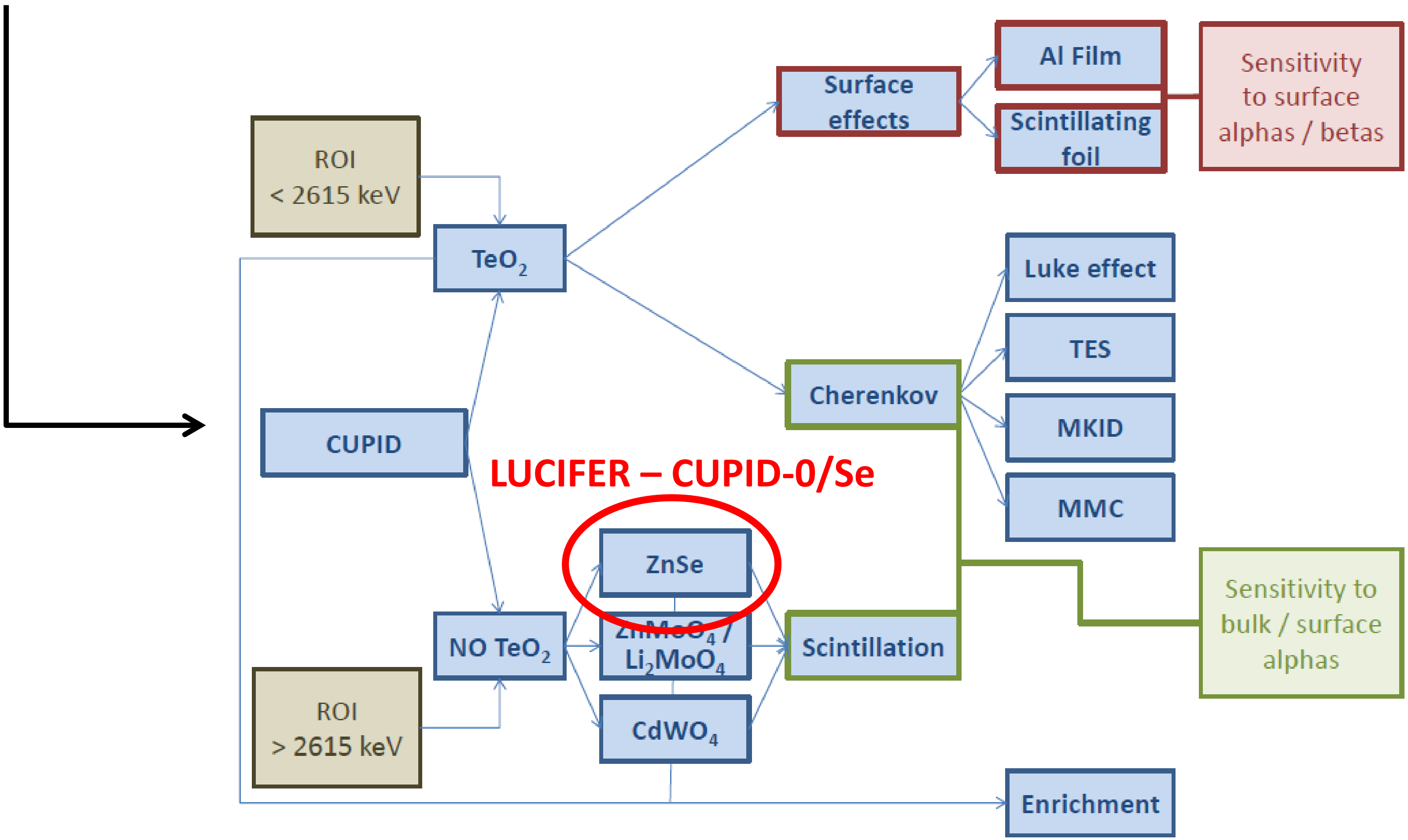

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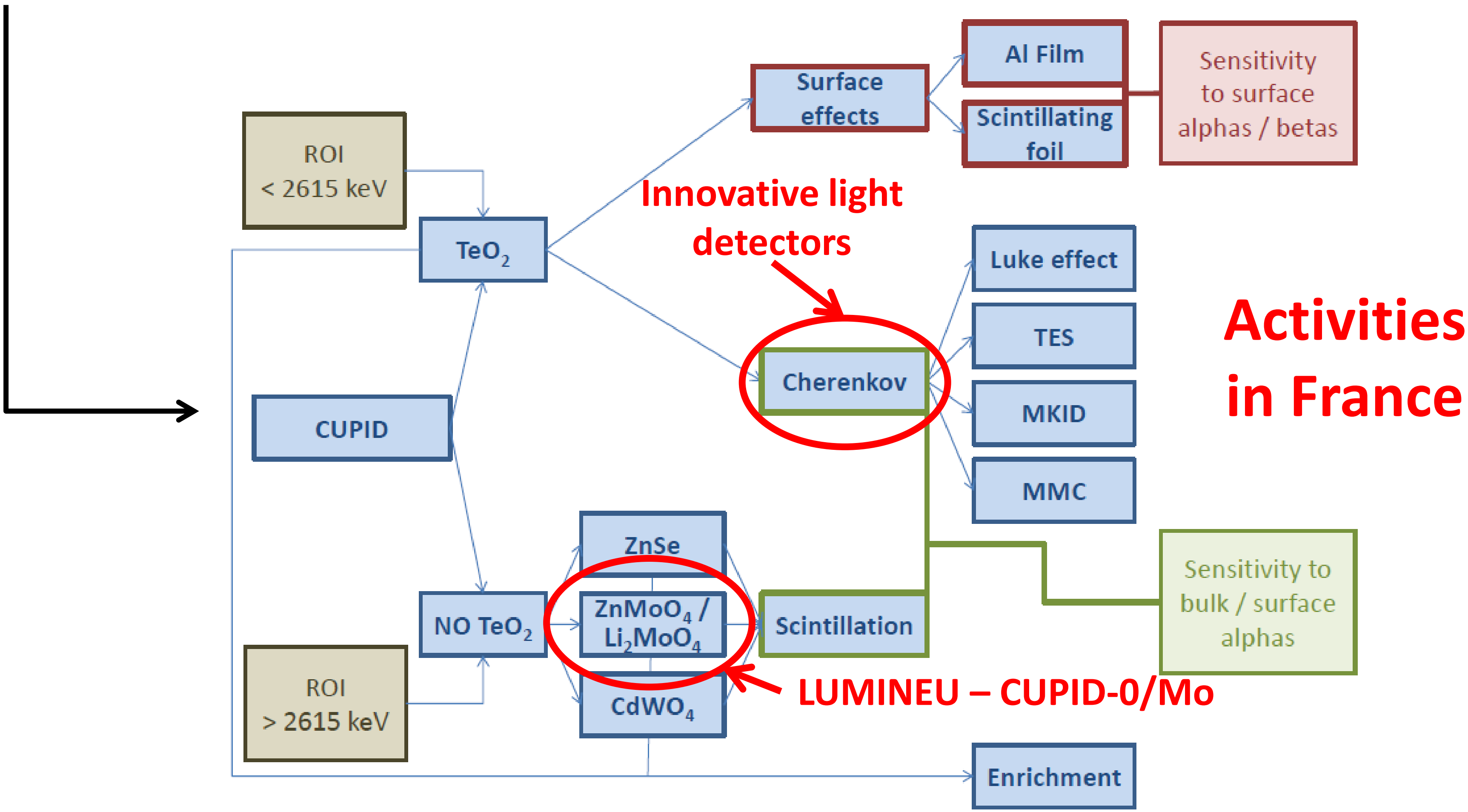

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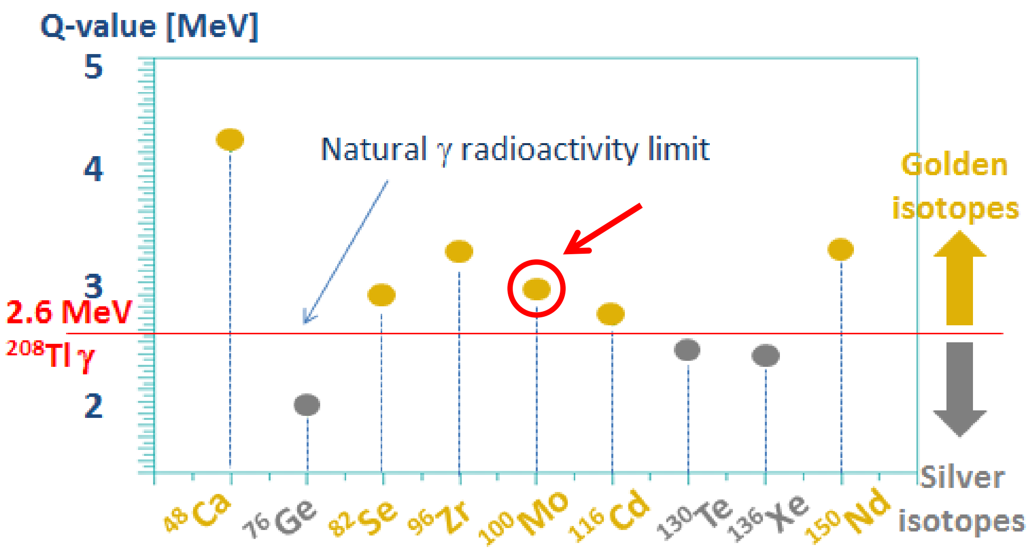
Some properties of ^{100}Mo



- $^{100}Mo \rightarrow {}^{100}Ru + 2e^-$
- $Q_{\beta\beta}$ = **3034 keV**
- I.A.(100) = 9.7 %
- enrichable by gas centrifugation

Caveats

- $T_{1/2}(2\nu) = 7.1 \times 10^{18}$ y – the fastest one in all $0\nu2\beta$ candidates
- ^{214}Bi line at 3054 keV – B.R. 0.021 % - Compton edge 2818 keV

Useful Mo-based crystals

Crystals succesfully tested so far as scintillating bolometers:

$CdMoO_4$
$PbMoO_4$
$SrMoO_4$
$CaMoO_4$
$ZnMoO_4$
Li_2MoO_4

AMoRE
Drawbacks:
- Necessity of ^{48}Ca depletion
- Radiopurity (difficult to purify Ca from U, Th, Ra)

LUMINEU
Initial choice (2012): $ZnMoO_4$
First tests on large Li_2MoO_4 crystals: spring 2014

Astropart. Phys. 72, 38 (2016)

Selection of Li_2MoO_4 for a pilot experiment (March 2016)

- Better bolometric performance
- Easy crystallization / excellent quality
- Outstanding radiopurity

Caveats

- Hygroscopic material
- ^{40}K is natural contaminant
- Lower light yield (~0.8 keV/MeV)

Preparing a ^{100}Mo experiment

Funding / resources from

- **ANR (France) – main fund provider (LUMINEU: 2012-2017)**
- CEA-Saclay – substantial funds / PhD
- CSNSM direction – funds for crystals (« AP interne »)
- EDELWEISS – underground facility, electronics & DAQ
- IN2P3 – dedicated personnel
- KINR Kiev – radiopure scintillator know-how, simulation, – enriched ^{100}Mo
- ITEP Moscow – enriched ^{100}Mo
- NIIC Novosibirsk - crystals
- INFN / LUCIFER (LNGS / Rome) – underground facility and manpower for R&D

Extension of the Mo collaboration: CUPID-Mo

New participants

LAL – Orsay

MIT
UCB and LBL
UCLA
} USA

Fudan Shanghai
USTC Hefei
} China

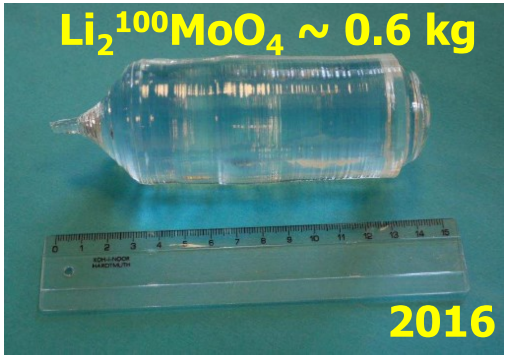
Strong interest in China – large CUPID group in formation
Project for a "parallel CUPID" at JinPing laboratory
International workshop on neutrinoless double beta decay physics
June 28-30, 2017, Fudan University, Shanghai, China.
http://www.physics-conference.xyz/

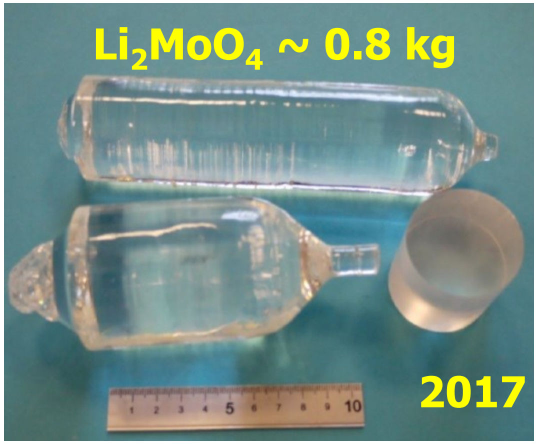
Li_2MoO_4: purification and crystallization

From 2013 to 2016, a series of important milestones were achieved:

- **Mo purification / crystallization protocol** (**NIIC, Novosibirsk**, Russia) (**Mo irrecoverable losses < 4%**)
- Selection of the **appropriate Li_2CO_3 powder** for compound formation
- Successful program to **control internal content of ^{40}K** (from ~60 mBq/kg to < 5 mBq/kg)
  → Random coincidences: $2\nu2\beta$ + ^{40}K << $2\nu2\beta$ + $2\nu2\beta$
- Efficient use of existing **~10 kg of ^{100}Mo** (~9 kg to ITEP-Moscow and ~1 kg to KINR-Kiev) (MoU among IN2P3 / INFN / ITEP – February 2015)
  → Natural isotopic abundance: **9.7%**

NIM A 729, 856 (2013)
JINST 9, P06004 (2014)
EPJC 74, 3133 (2014)
JINST 10, P05007 (2015)
http://arxiv.org/abs/1704.01758 (submitted to EPJC)



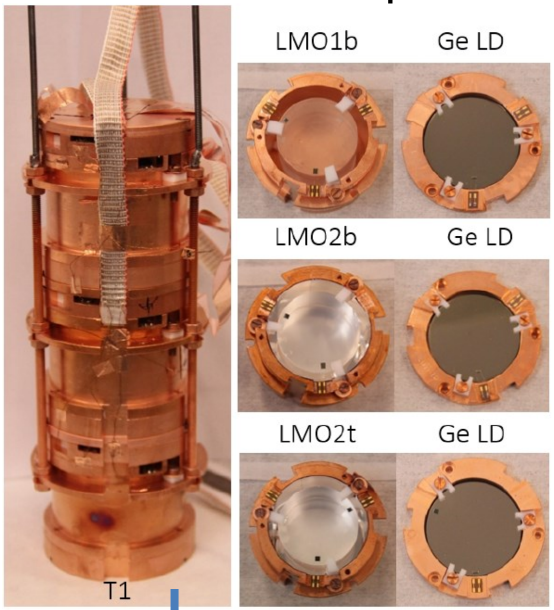


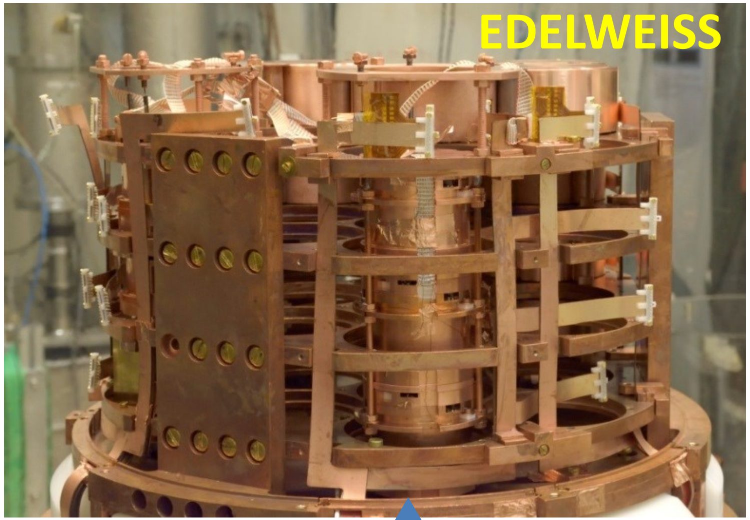
$Li_2{}^{100}MoO_4$ scintillating bolometers: a mature technology

Multiple tests with **natural and enriched crystals** (2014-2017) in LSM and LNGS with outstanding results in terms of: *http://arxiv.org/abs/1704.01758*

Reproducibility	→	excellent performance uniformity
Energy resolution	→	~ **4-5 keV FWHM** in RoI
α/β separation power	→	**> 99.9 %**
Internal radiopurity	→	**< 5 μBq/kg in ^{232}Th, ^{238}U**; **< 5 mBq/kg in ^{40}K**

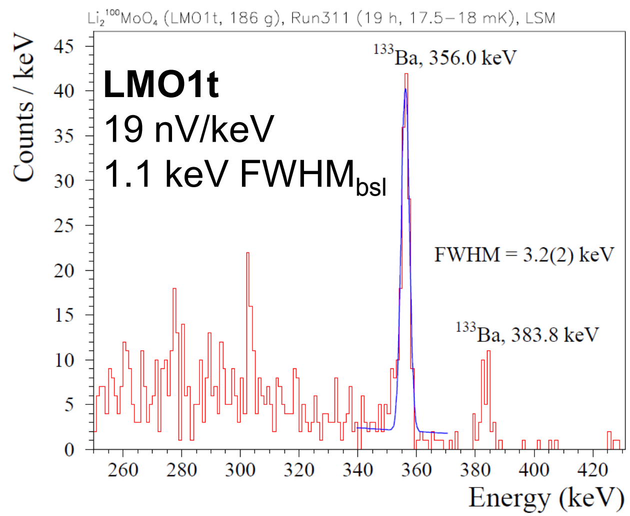
→ Compatible with $b \leq 10^{-4}$ **[counts/(keV kg y)]**

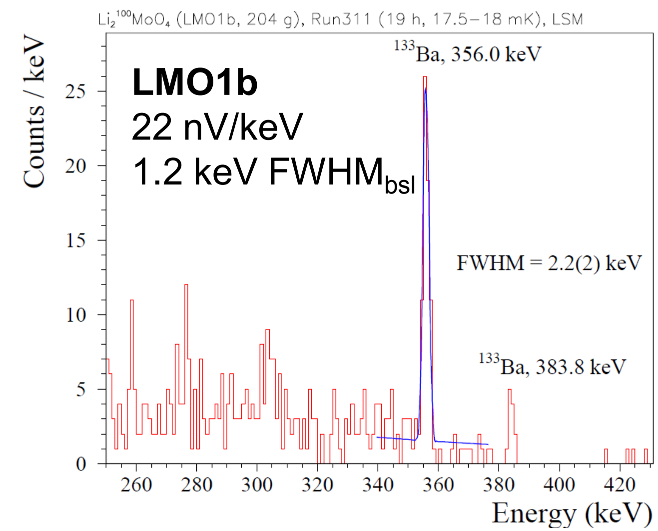


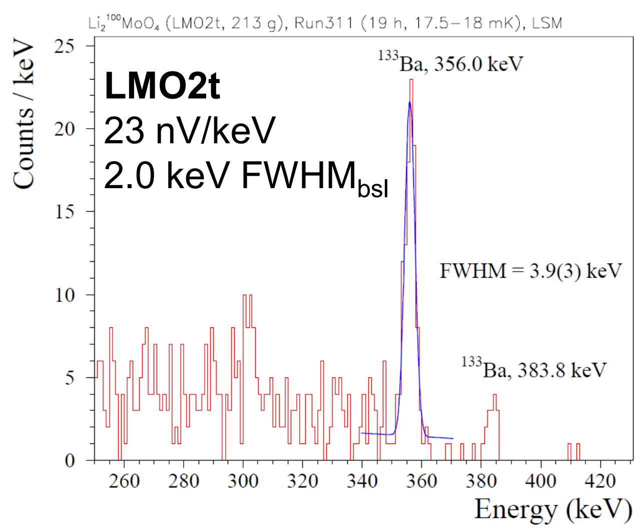


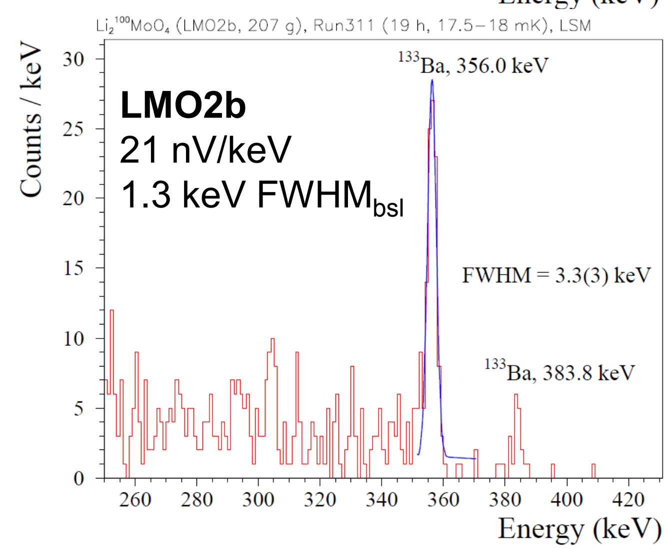
Reproducibility

Array of **four** enriched detectors, **M ~ 210 g**, **LSM** (EDELWEISS setup)



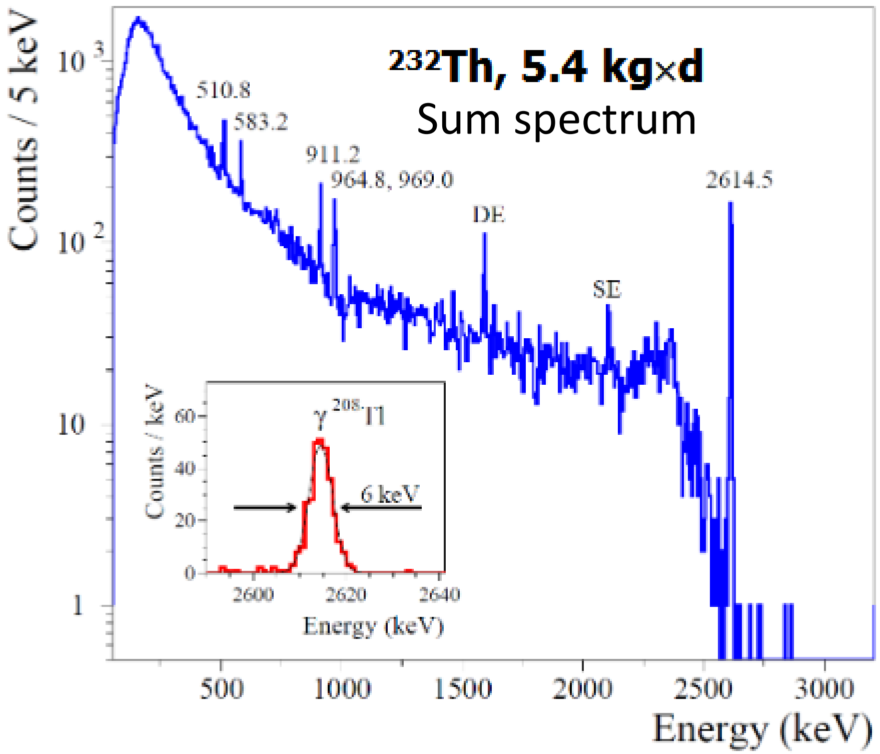


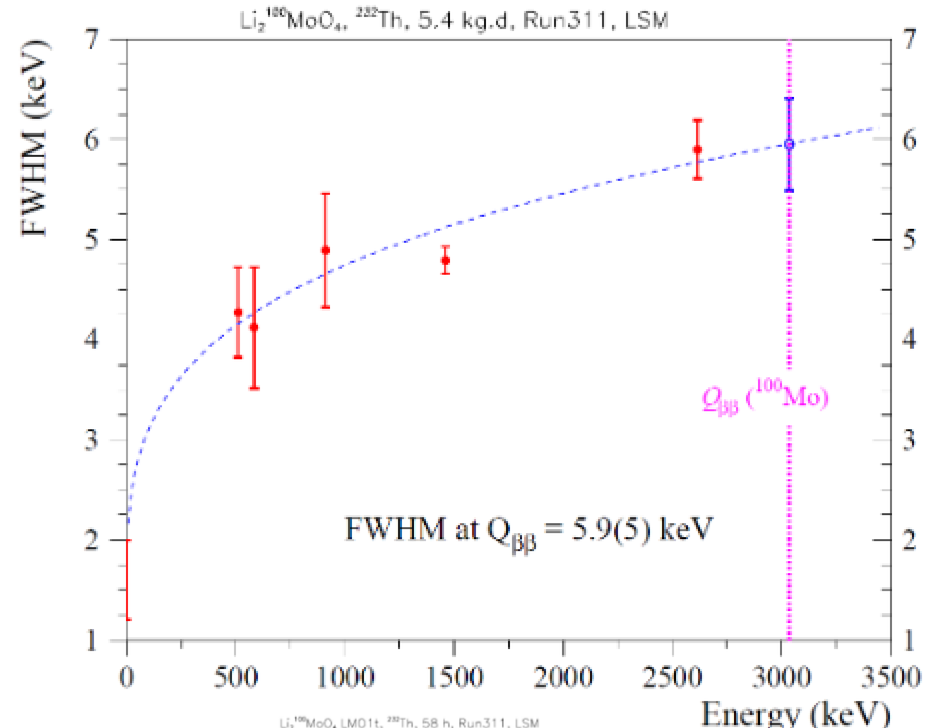




Energy resolution

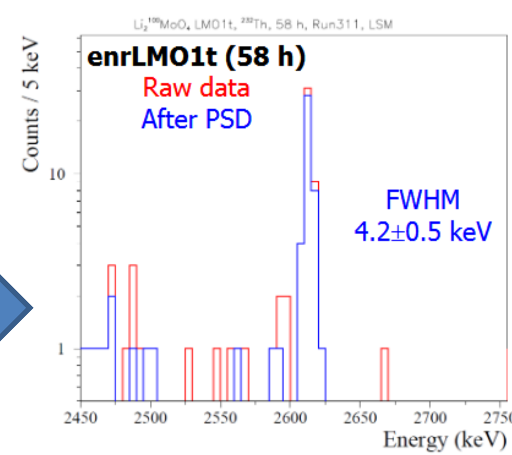
Array of **four** enriched detectors, **M ~ 210 g**, **LSM** (EDELWEISS setup)





Non-optimal calibration condition:
high pile-up effect

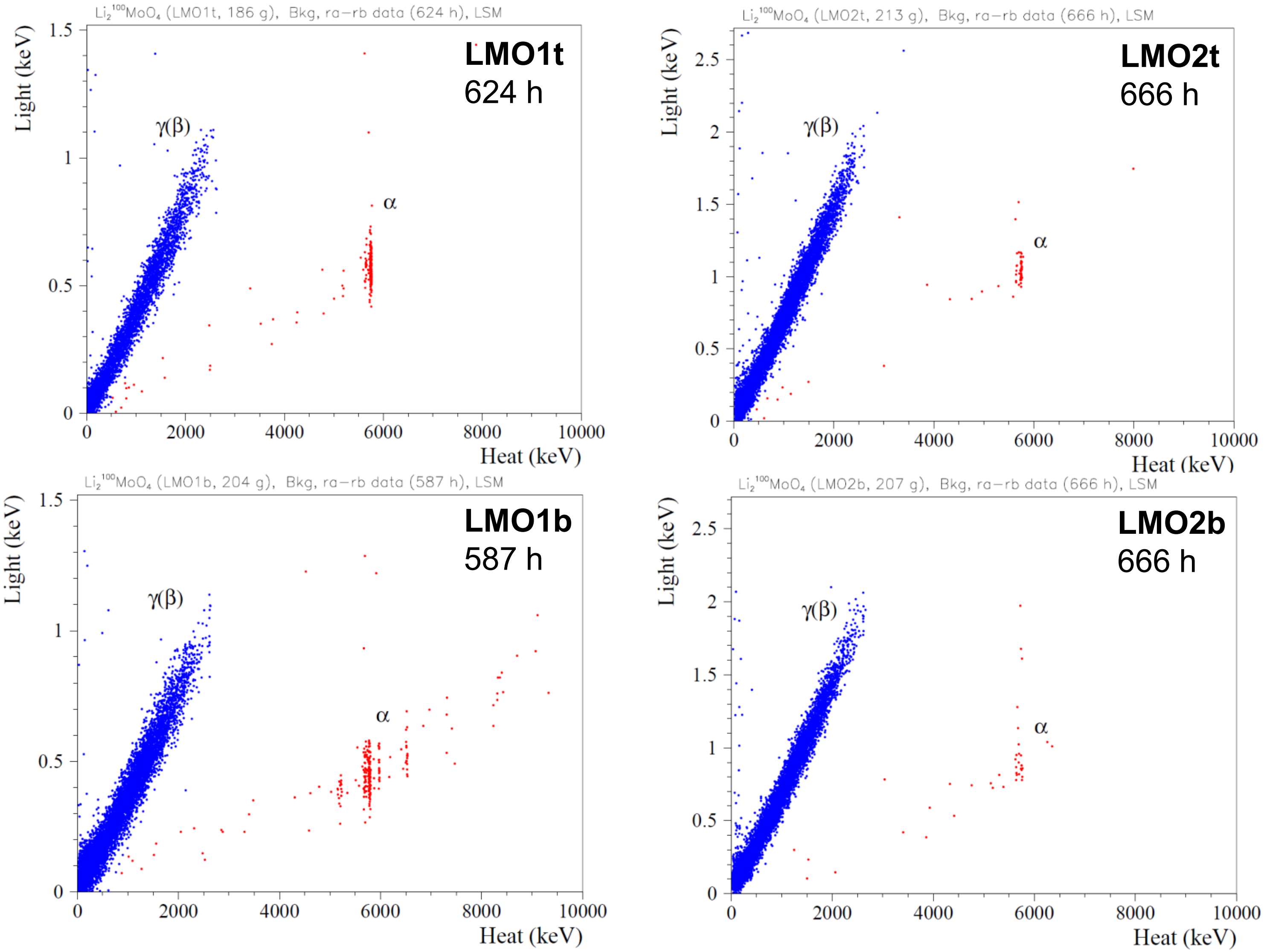
For the detector farther from the source
(low pile-up effect)
better energy resolution (**~4keV FWHM**)



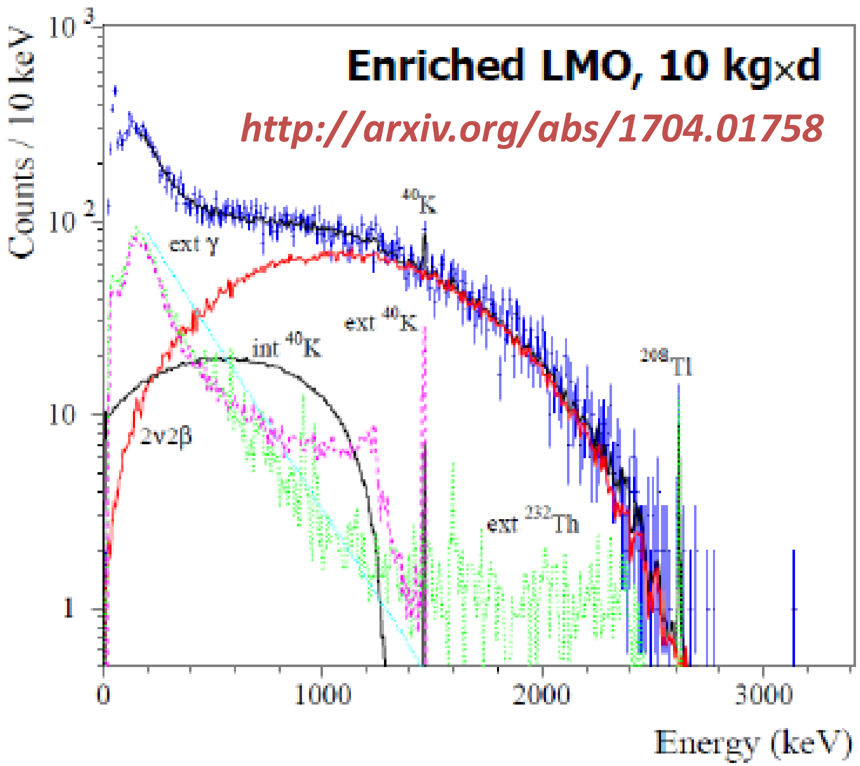
α rejection and internal purity

Using light yield and a detector with a smeared α source:

99.9% α rejection with **99.7 % β acceptance**



Two-neutrino double beta decay



$T_{1/2}$, yr	S/B	Ref., year
$11.5^{+3.0}_{-2.0} \cdot 10^{18}$	1/7	[49], 1991
$11.6^{+3.4}_{-0.8} \cdot 10^{18}$	7	[50], 1991
$[7.3 \pm 0.35(\text{stat}) \pm 0.8(\text{syst})] \cdot 10^{18}$ [b]	3	[51], 1995
$7.6^{+2.2}_{-1.4} \cdot 10^{18}$	1/2	[52], 1997
$[6.75^{+0.37}_{-0.42}(\text{stat}) \pm 0.68(\text{syst})] \cdot 10^{18}$	10	[53], 1997
$[7.2 \pm 1.1(\text{stat}) \pm 1.8(\text{syst})] \cdot 10^{18}$	1/9	[54], 2001
$[7.11 \pm 0.02(\text{stat}) \pm 0.54(\text{syst})] \cdot 10^{18}$ [c]	40	[1], 2005
$[7.15 \pm 0.37(\text{stat}) \pm 0.66(\text{syst})] \cdot 10^{18}$	~5 [d]	[19], 2014
$(2.1 \pm 0.3) \cdot 10^{18}$ (geochem.)		[55], 2004
Average value: $(7.1 \pm 0.4) \cdot 10^{18}$		

Nucl. Phys. A 935 (2015) 52

$$T_{1/2} = [6.90 \pm 0.15(\text{stat.}) \pm 0.42(\text{syst.})] \times 10^{18} \text{ yr}$$ **LUMINEU, 0.03 kg×yr**

$$[7.11 \pm 0.02(\text{stat.}) \pm 0.54(\text{syst.})] \times 10^{18} \text{ yr}$$ **NEMO-3, 7.37 kg×yr**

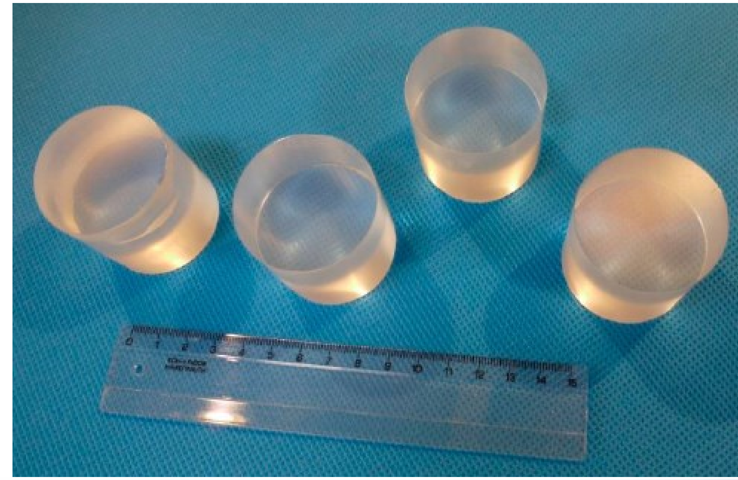
Good physics results can be achieved even with one LUMINEU detector

Next pilot experiments

CUPID-0/Mo Phase I (20 crystals):

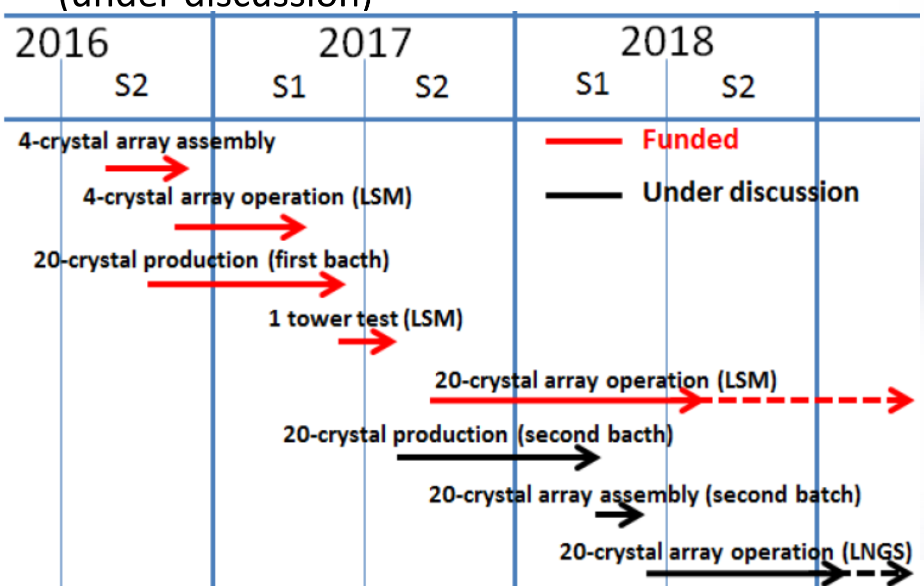
- **20 ^{100}Mo-enriched (97%) Li_2MoO_4**
  (∅44×45 mm, 0.21 kg each; 4.18 kg total)
  ⇒ 2.34 kg of ^{100}Mo (1.37×10^{25} ^{100}Mo nuclei)
- **20 Ge light detectors** (∅44×0.175 mm)+SiO
- **EDELWEISS set-up** @ LSM (France)

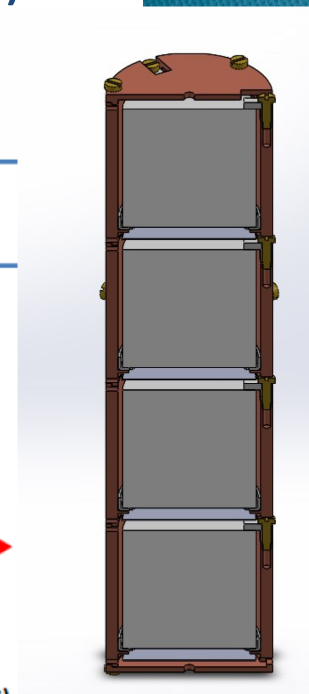
START DATA TAKING: December 2017

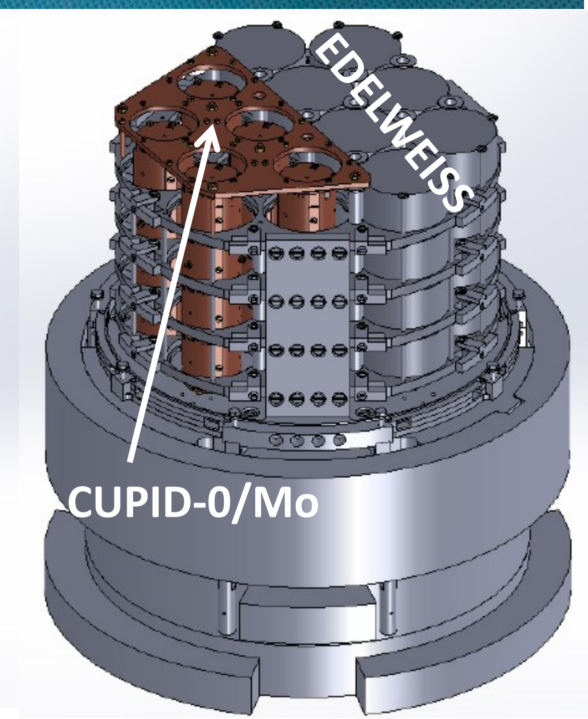


CUPID-0/Mo Phase II (20+20 - or more - crystals):

- At least additional **20 $Li_2{}^{100}MoO_4$**
- **CUPID-0 set-up** @ LNGS (Italy)
  (under discussion)







Sensitivity of CUPID-Mo

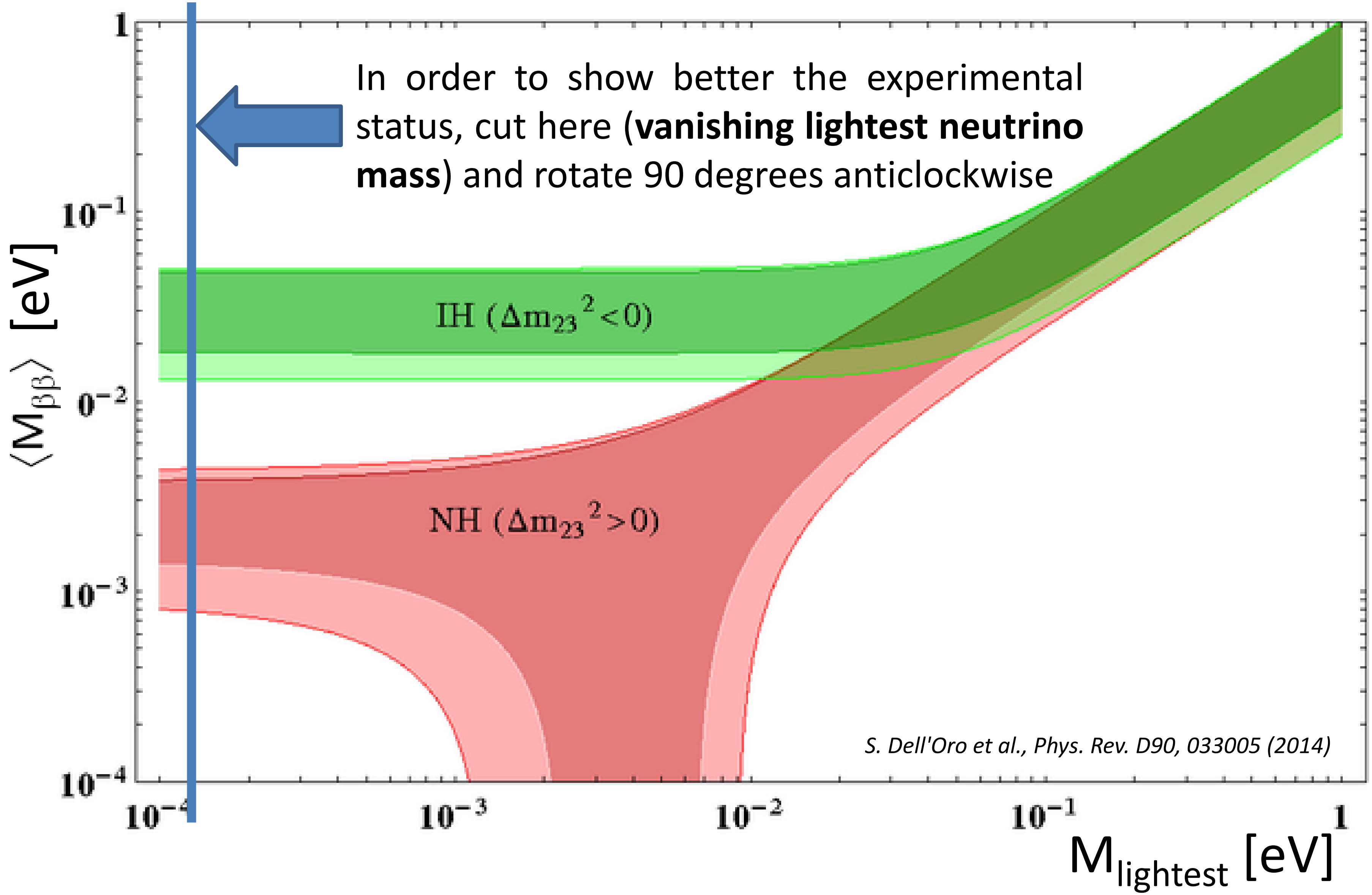
In calculating the sensitivity (90% C.L.), we will assume:

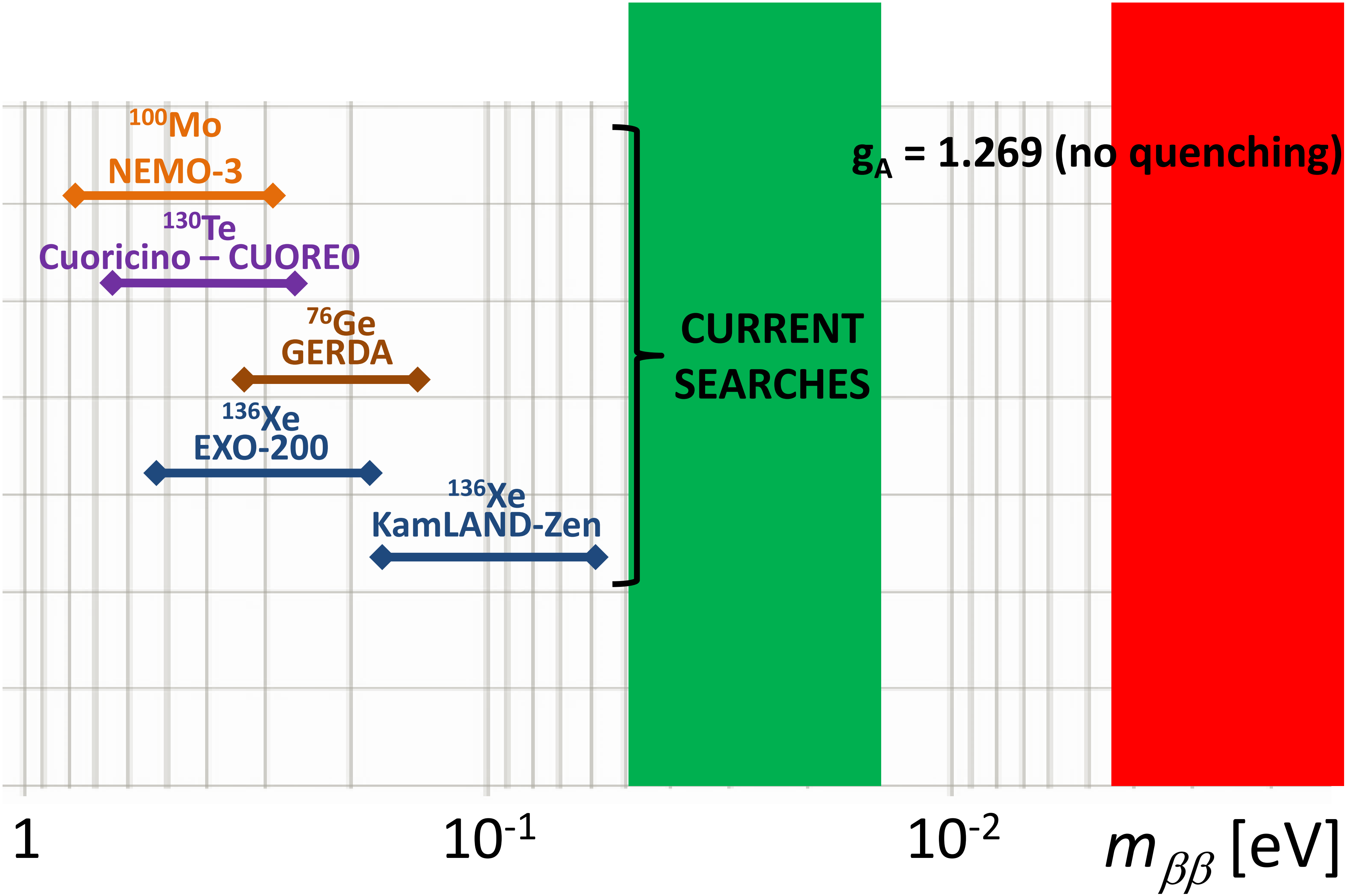
- **b = 1 × 10^{-3} counts/(keV kg y)**
- **8 keV** energy window
- **78%** efficiency

Configuration	Half life limit [90% c.l.]	$M_{\beta\beta}$ [meV]
(1) 20 crystal [20×0.5 cr.×y]	1.4×10^{24}	240 – 670
(2) 20 crystal [20×1.5 cr.×y]	4.2×10^{24}	140 – 390
(3) 40 crystal [40×3 cr.×y]	1.7×10^{25}	70 – 200

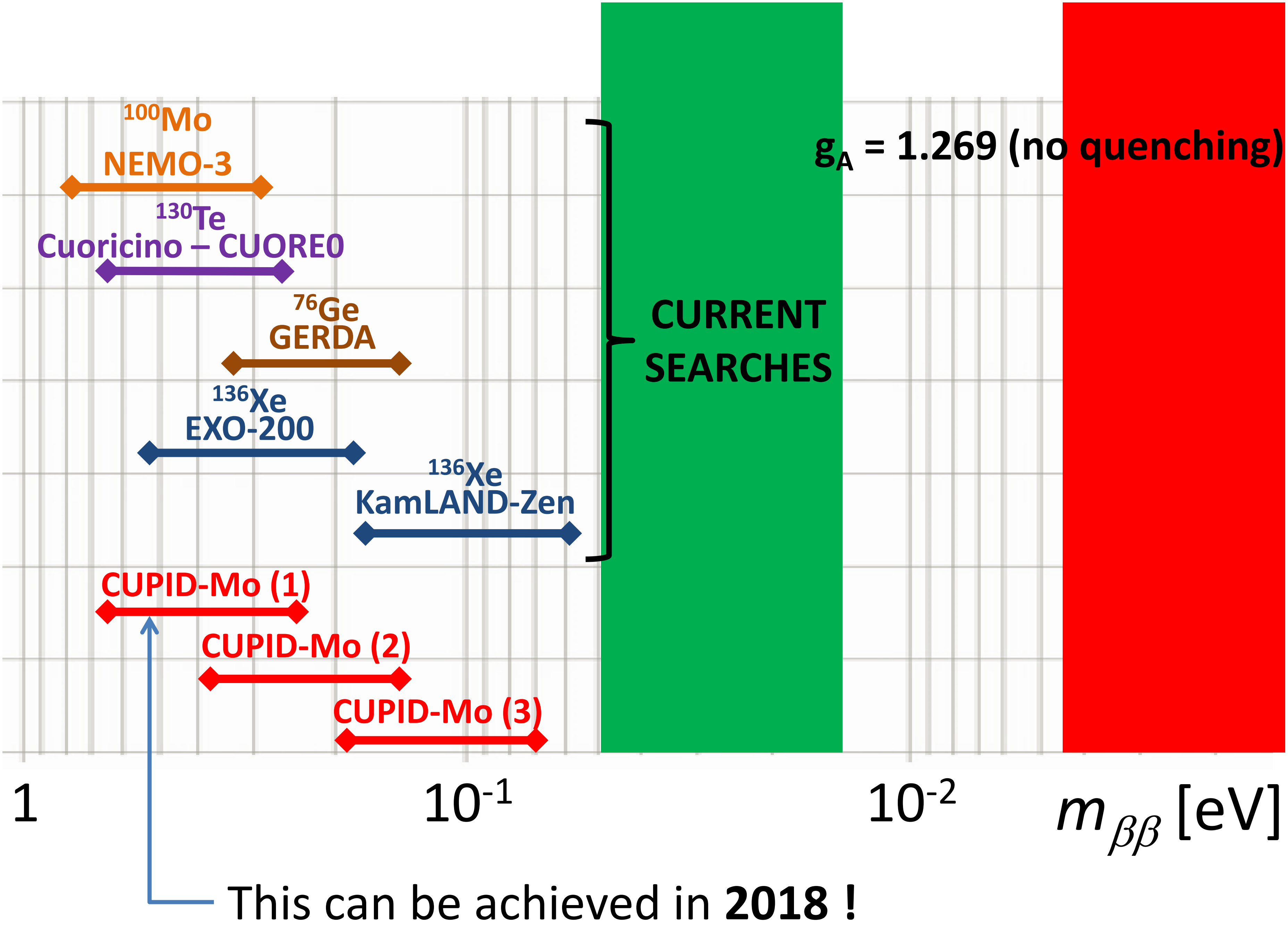
First two options sensitivities substantially unchanged by
b = 1 × 10^{-2} counts/(keV kg y)

⟨$M_{\beta\beta}$⟩ vs. lightest ν mass





^{100}Mo
NEMO-3
^{130}Te
Cuoricino – CUORE0
^{76}Ge
GERDA
^{136}Xe
EXO-200
^{136}Xe
KamLAND-Zen
CURRENT SEARCHES
g_A = 1.269 (no quenching)
1
10^{-1}
10^{-2}
$m_{\beta\beta}$ [eV]



100Mo
NEMO-3
130Te
Cuoricino – CUORE0
76Ge
GERDA
136Xe
EXO-200
136Xe
KamLAND-Zen
CUPID-Mo (1)
CUPID-Mo (2)
CUPID-Mo (3)
CURRENT
SEARCHES
gA = 1.269 (no quenching)
1
10-1
10-2
mββ [eV]
This can be achieved in 2018 !

Outline

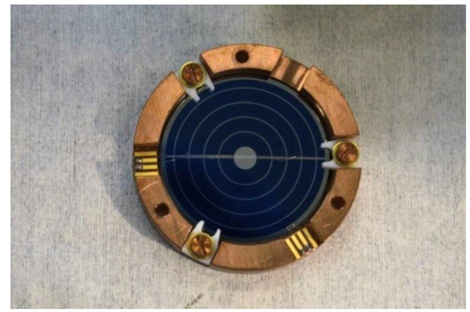
- The challenging quest for neutrinoless double beta decay
- The bolometric approach: from CUORE to CUPID
- The ^{100}Mo way: LUMINEU → CUPID-Mo
- The ^{130}Te way: detection of Cherenkov light
- Development of new ideas: CROSS

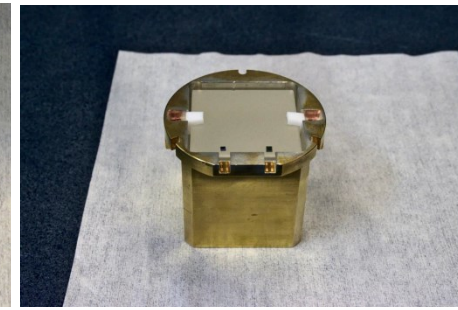
α/β separation in TeO_2

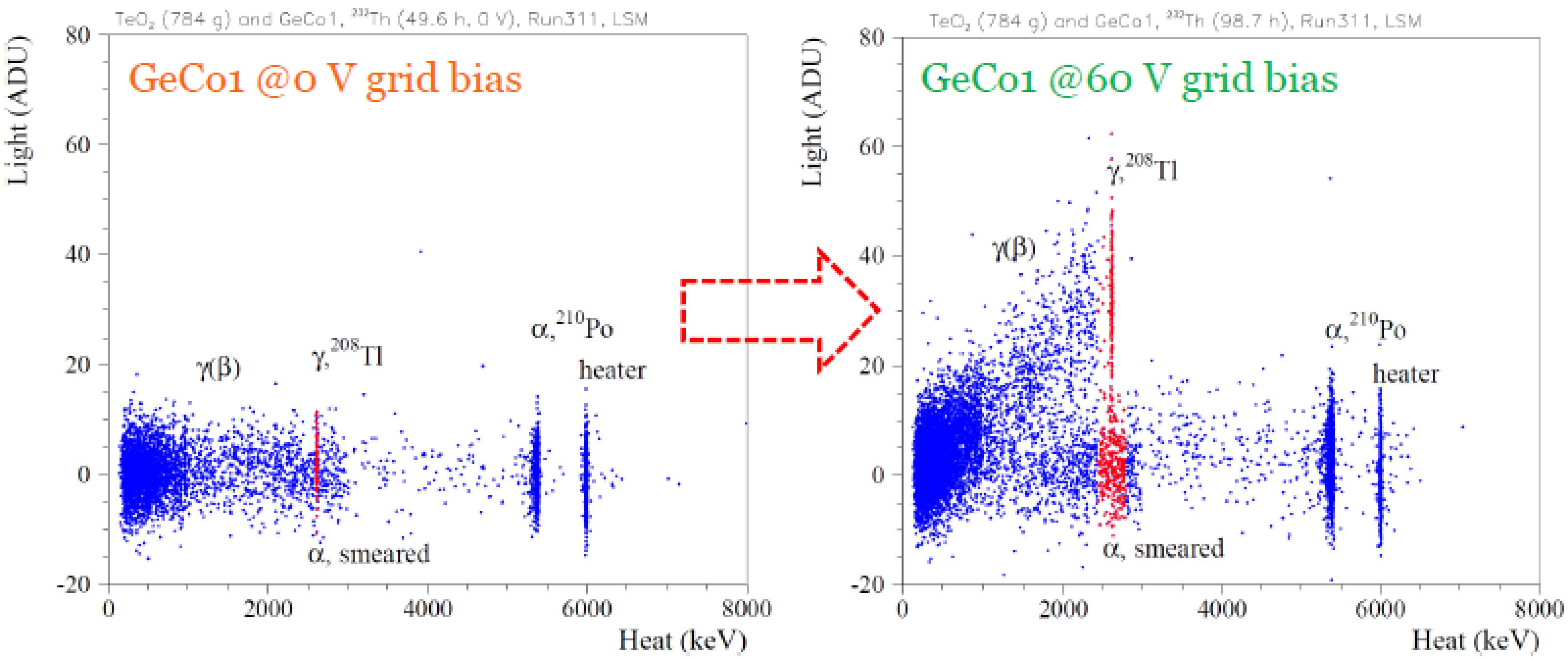
TeO_2 is a very weak scintillator → Detection of **Cherenkov light** is needed to achieve α rejection

Development of a special light detector at CSNSM based on **EDELWEISS Al electrode technology → Neganov-Luke effect**

The application of an electric field boosts the phonon signal.







99.9% α rejection with **96.3 % β acceptance**

The best result ever obtained with a CUORE-size crystal, compliant with CUPID goal

Outline

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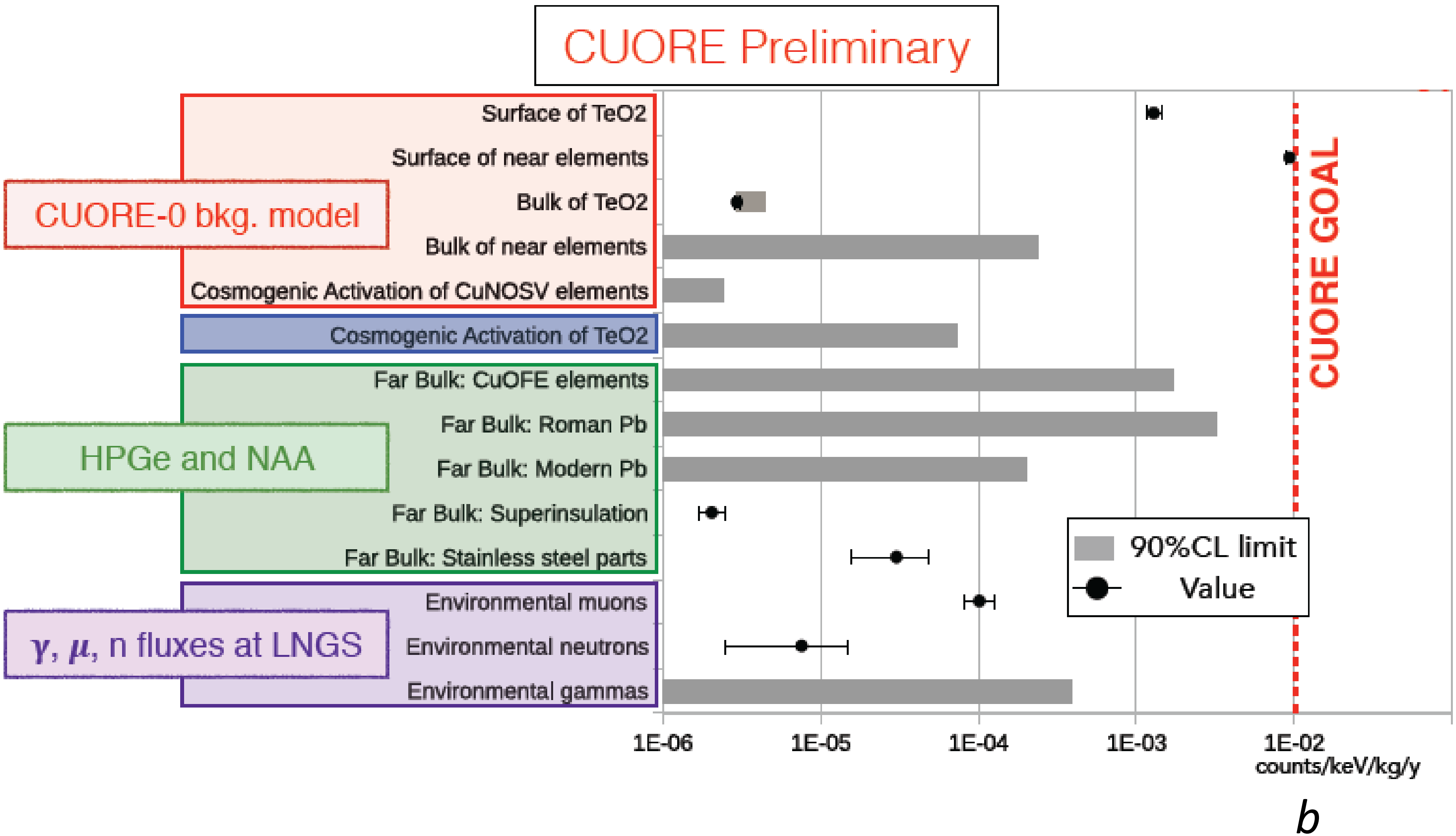
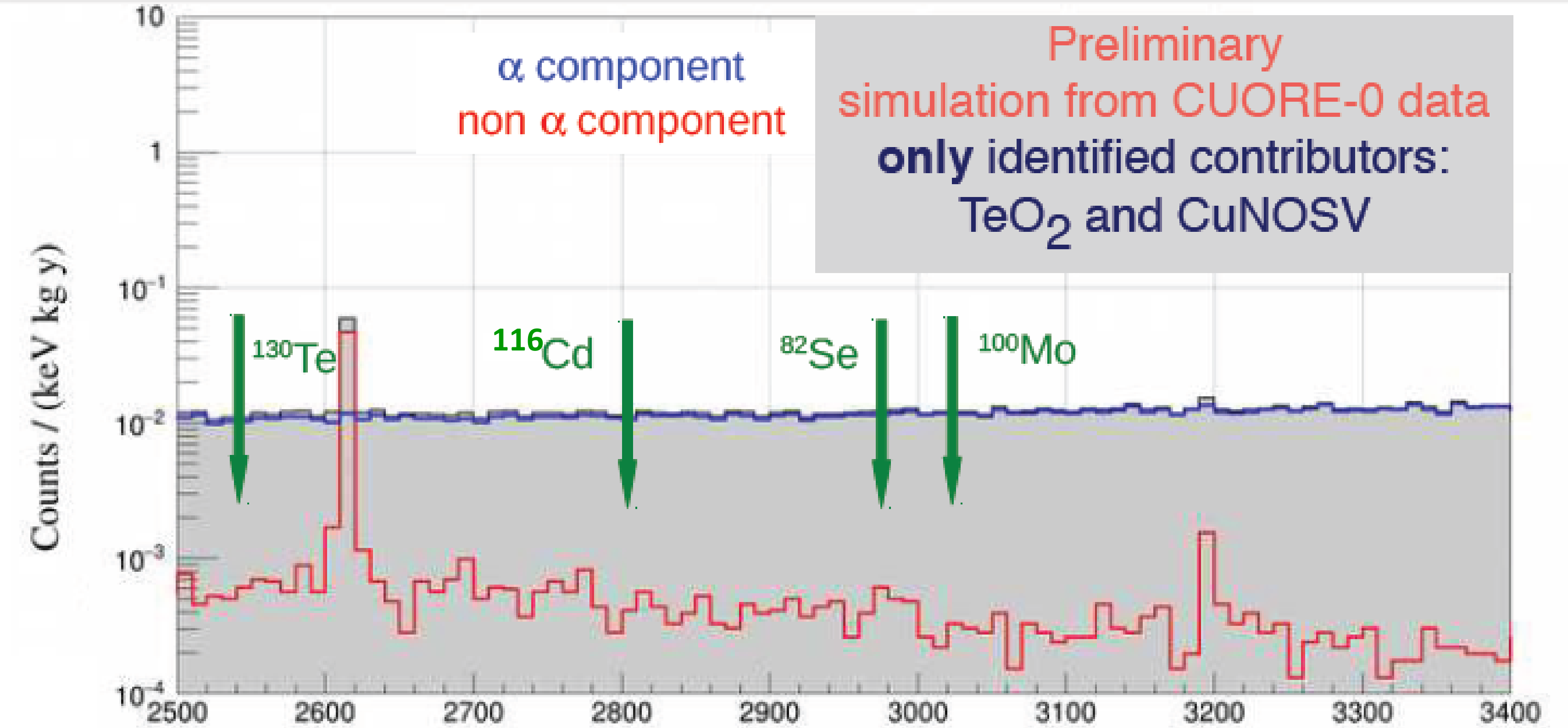
Current role of surface radioactivity

CUORE background model



Eliminating surface α's is enough?

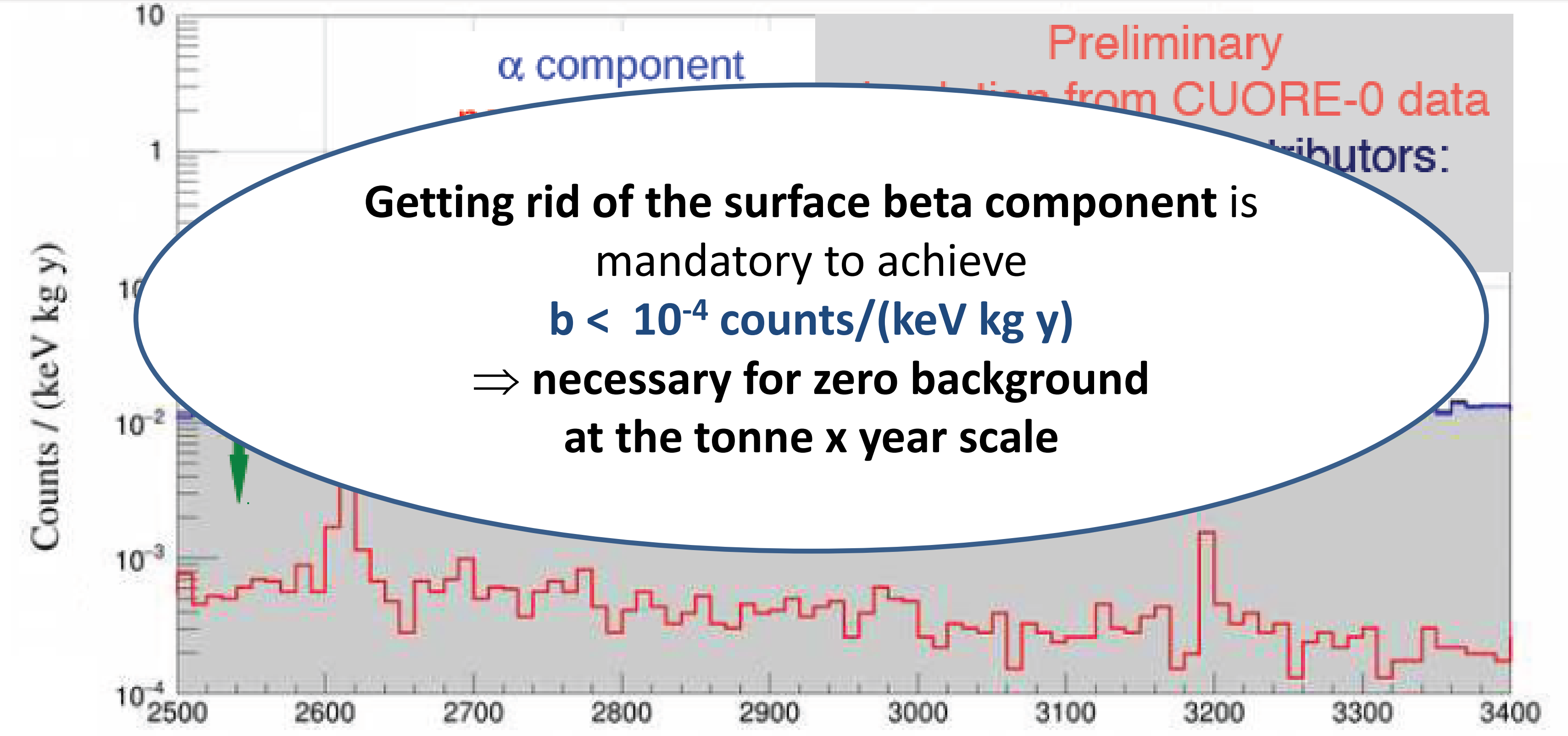


The residual background after alpha rejection comes mainly from **high Q-value beta emitters from surface contamination**

^{226}Ra – generates **^{214}Bi** – 3.27 MeV endpoint

^{228}Th – generates **^{208}Tl** – 5.00 MeV endpoint

Eliminating surface α's is enough?



Getting rid of the surface beta component is mandatory to achieve

b < 10^{-4} counts/(keV kg y)

$\Rightarrow$ **necessary for zero background at the tonne x year scale**

The residual background after alpha rejection comes mainly from **high Q-value beta emitters from surface contamination**

^{226}Ra – generates **^{214}Bi** – 3.27 MeV endpoint

^{228}Th – generates **^{208}Tl** – 5.00 MeV endpoint

CROSS: new advancement opportunity

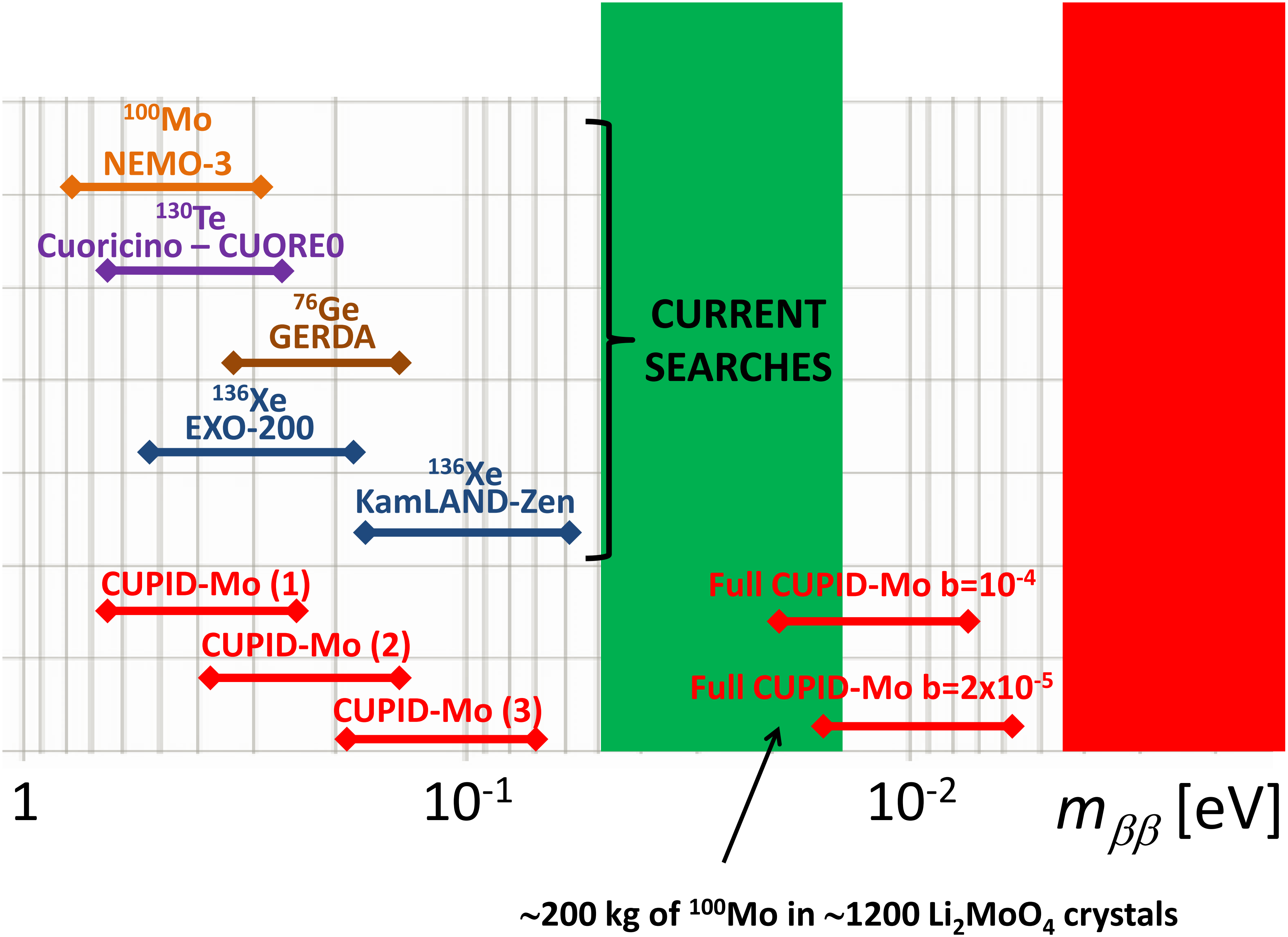
ERC advanced grant CROSS

Cryogenic **R**are-event **O**bservatory with **S**urface **S**ensitivity

CROSS is a bolometric experiment to search for 0ν-DBD

- **Core of the project** (high risk / high gain)
  Background rejection through **pulse shape discrimination**
  - **Surface sensitivity** through **superconductive Al film coating**
  - **Fast NbSi high-impedance TES** to replace / complement NTDs

  → **get rid of light detectors**
- Complete crystallization of available **^{100}Mo (10 kg)** in Li_2MoO_4 elements
- Purchase / crystallize **^{130}Te (up to 17 kg)** in TeO_2 elements
- Run demonstrator in a dedicated cryostat (LSC – Spain)



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136Xe
KamLAND-Zen
CURRENT
SEARCHES
CUPID-Mo (1)
CUPID-Mo (2)
CUPID-Mo (3)
Full CUPID-Mo b=10-4
Full CUPID-Mo b=2x10-5
1
10-1
10-2
mββ [eV]
~200 kg of 100Mo in ~1200 Li2MoO4 crystals

The struggle against background

$b = 10^{-2}$ counts/(keV kg y)

Pure bolometers ⇒ **CUORE-0, CUORE**

Scintillating bolometers,
$Q > 2615$ keV
alpha/beta separation

$b = 10^{-3}$ counts/(keV kg y)

LUCIFER, LUMINEU
(**CUPID-0/Se, CUPID-Mo**)

Surface sensitivity

$b = 10^{-4}$ counts/(keV kg y)

CROSS

CUPID

CUPID projects with French leadership

CLYMENE ANR

Li_2MoO_4 crystals in France

CUPID-Mo → Scintillating bolometers

- Favored isotope: ^{100}**Mo**
- Keep technology ready for ^{116}**Cd**

CYGNUS

Paris Sud chair

EPJ C 76, 487(2016)

CUPID-TeO_2 → High-performance light detectors

- Luke effect *Phys. Lett. B 767, 321 (2017)*
- MKIDs

CUPID-CROSS → Surface sensitivity

CUPID projects with Frenc… dership

…NE

ANR

…crystals in France

CUPID-M…

…YGNUS

…is Sud chair

CU…

CUPID…

…nsitivity

Fully open to new collaborators:

- Data analysis for large arrays
- Background model
- Extraction of physics results
- Pulse-shape discrimination algorithms
- Support the new challenging R&D's
- ….

Conclusions

- Neutrinoless double beta decay is a key process in particle physics, neutrino physics and cosmology: innovation is mandatory to fully explore the inverted ordering region of neutrino masses and go beyond

- The bolometric approach is extremely competitive (CUORE), and its sensitivity can be substantially improved with new technologies → CUPID

- CUPID-Mo, an evolution of LUMINEU, is a competitive project at the international level, in excellent position for the CUPID technology selection

- TeO_2, the compound of CUORE, is still in the game for CUPID thanks to ultrasensitive large-surface light detectors developed in France

- The project CROSS develops new ideas for background rejection, based on pulse shape discrimination, capable of providing a decisive step forward of the bolometric technology