Neutrinoless double beta decay with CUPID-Mo

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LINÉAIRE

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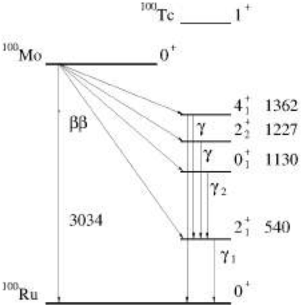
Two neutrino double beta decay

Certain isotopes are forbidden from decaying through standard beta decay because m(Z,A) $<$ m(Z+1,A)

$2\beta2\nu$

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

- Allowed in the **Standard Model**
- Observed for 12 isotopes
- **$T_{1/2}^{2\beta2\nu} \sim 10^{19-21}$ ys**
- Important constraint for nuclear matrix elements calculation



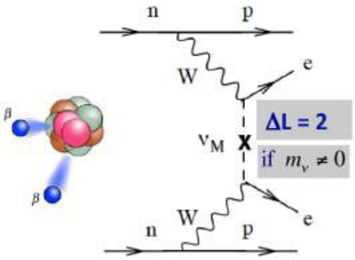
Neutrinoless Double Beta decay

$2\beta0\nu$

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

If the neutrino is a **Majorana particle**, then the process of zero-neutrino double beta decay should be observable

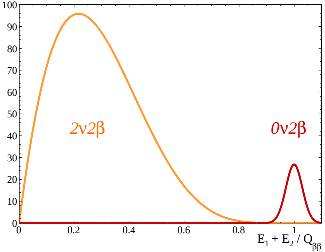
- Experimentally not observed
- **Implies lepton number violation**
- Offers strong support for the explanation of baryon asymmetry via leptogenesis
- Current bounds $T_{1/2}^{2\beta0\nu} > 10^{24-26}$ ys

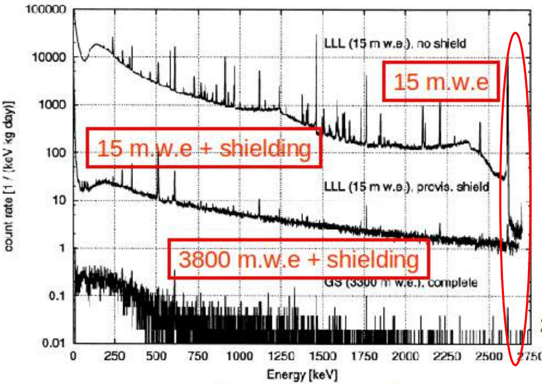


Experimental signature for $2\beta0\nu$ decay

Background

Signal





(Applied Rad and Isotopes 53 (2000) 191)

- The signal is a peak at the $Q_{\beta\beta}$ value
- The most energetic γ line from natural radioactivity is at 2615 keV → $Q_{\beta\beta} > 2$ - 3 MeV for most promising isotopes

$2\beta0\nu$ experiments measure decay rates, $T_{1/2}^{2\beta0\nu}$

How $T_{1/2}^{2\beta0\nu}$ is connected to neutrino masses?

Phase space

Nuclear matrix elements

$$\frac{1}{T_{1/2}^{2\beta0\nu}} = G(Q,Z)g_A^4|M_{0\nu}|^2 m_{\beta\beta}^2$$

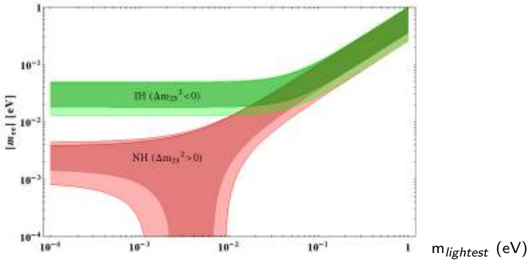
Axial vector coupling constant

Effective Majorana mass

$2\beta0\nu$ **rate**

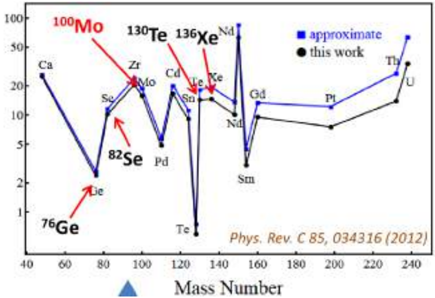
(In case of process induced by light ν exchange, mass mechanism)

$$m_{\beta\beta} = m_1|U_{e1}|^2 + m_2|U_{e2}|^2 e^{i\alpha} + m_3|U_{e3}|^2 e^{2i\beta}$$



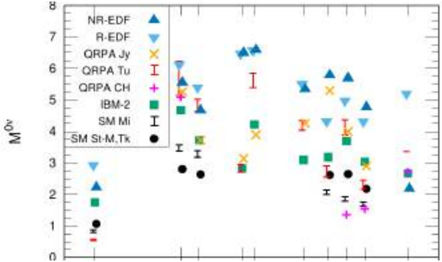
Theoretical ingredients

Phase space, exactly calculable:



Phys. Rev. C 85, 034316 (2012)

Nuclear matrix elements, several models



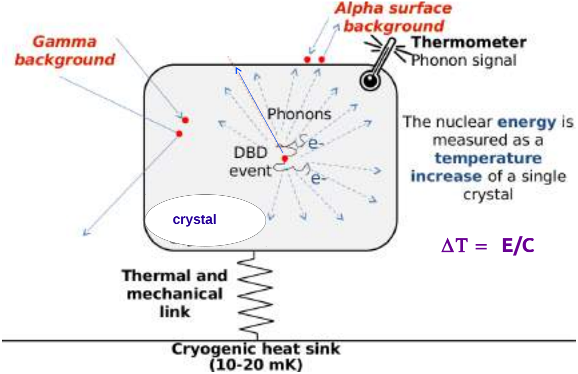
J. Engel and J. Menéndez, Rep. Prog. Phys. 80, 046301

g_A is quenched in $2\beta2\nu$ decay. Is the renormalization the same for $2\beta0\nu$?

- $g_A = 1.269$ free nucleon (no quenching)
- g_A, *eff* ~ 0.6 - 0.8

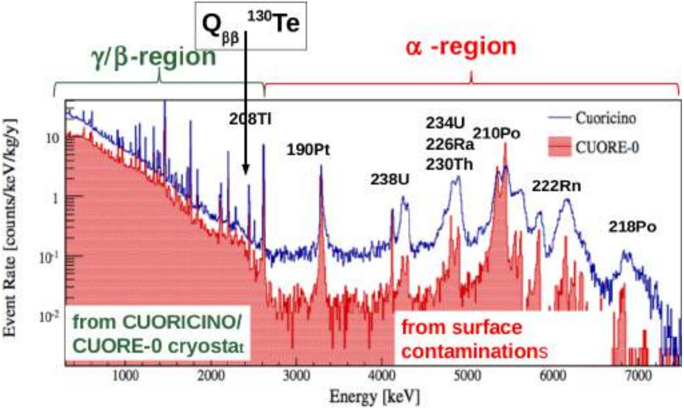
If quenching exists, the sensitivity to $m_{\beta\beta}$ will descrease

Bolometers



- **High energy resolution (5 keV FWHM, $\sim$ 0.2 %, at $2\beta0\nu$ ROI)**
- 0.2 - 0.5 kg each crystal → scalability to a ton scale array
- **High efficiency($\sim$ 70 - 90 %)**

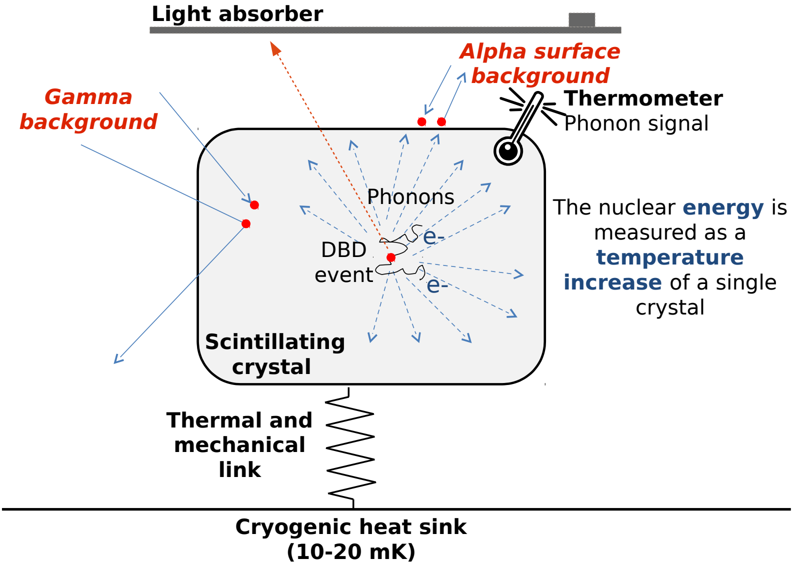
Lessons learnt from CUORE



Irreducible background due to α particles emitted at the surfaces and degraded in energy **b $\sim 10^{-2}$ counts/kev kg y**

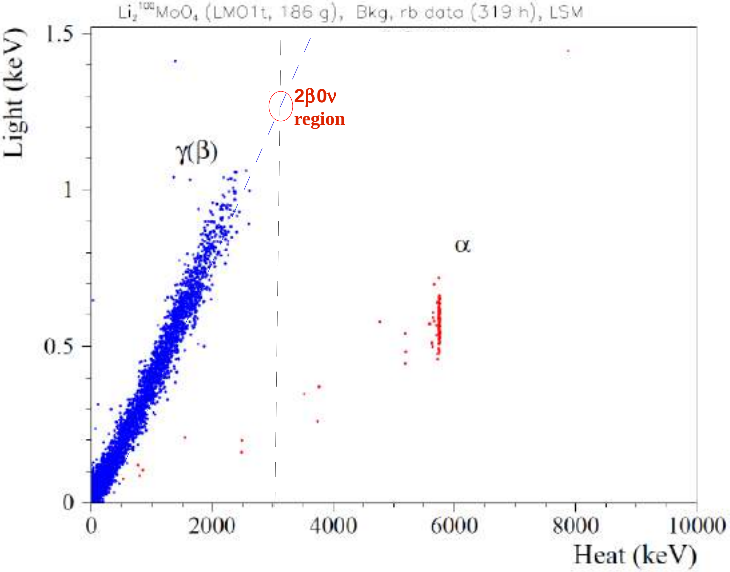
Current solution: scintillating bolometers

Scintillating bolometers



The nuclear **energy** is measured as a **temperature increase** of a single crystal

α discrimination in a scintillating bolometer



EDELWEISS-III cryogenic facility at LSM (France)

Laboratoire Souterrain de Modane

1.7 km rock overburden (~4.8 km w.e.)
5 μ/day/m^2; 10^{-6} n/day/cm^2 (>1 MeV)
Deradonized air flow (~30 mBq/m^3)

EDELWEISS set-up

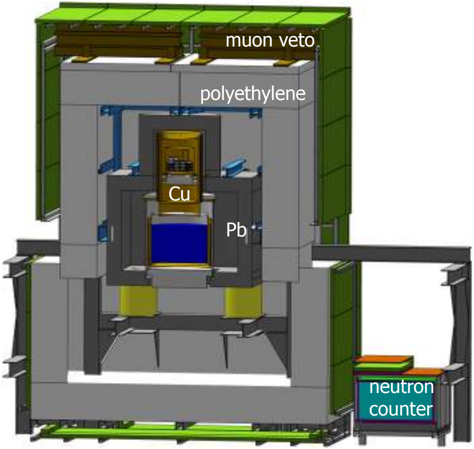
Clean room (ISO Class 4)

^{3}He/^{4}He inverted wet cryostat

Passive shield
Modern lead (18 cm)
Roman lead (2 cm; 14 cm at 1 K plate)
Polyethylene (external ~ 50+5 cm and 10 cm at 1 K plate)

Background monitors
Muon veto (98.5% covering)
Neutron counter
Radon counter

Electronics, DAQ (Samba)
Low noise cold electronics
AC bias, modulation (100 kHz)
→ demodulation (up to 1 kHz)
16-bit or 14-bit ADC
Trigger and/or Stream data



PLB 702 (2011) 329; JINST 12 (2017) P08010; EPJC 77 (2017) 785

From D. Poda

Tests of $Li_2^{100}MoO_4$ scintillating bolometers

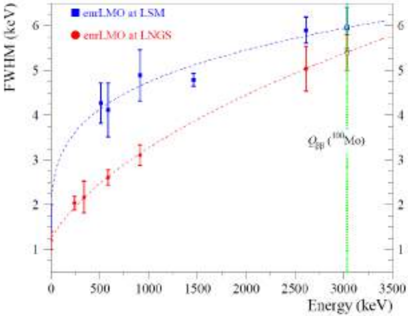
- Multiple tests with natural and enriched crystals in LSM and LNGS
- Longest run with 4 LMO crystals in the Edelweiss cryostat using Edelweiss electronics and DAQ (November 2016 - April 2017) [*AIP Conf. Proc. 1894, 020017 (2017)*]

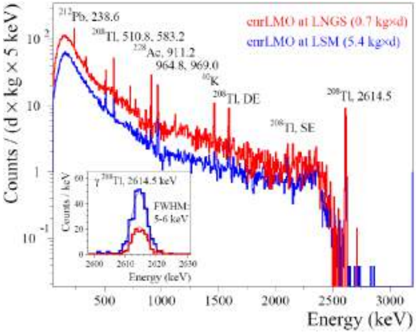
CUPID-Mo

From D. Poda

Energy resolution

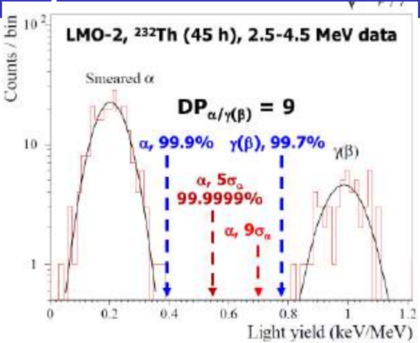
Measured with a Th source (mixed ^{232}Th and ^{238}U) which allows to have several points for energy calibration





- **The energy resolution (5 keV FWHM at $Q_{\beta\beta}$) required to build a next generation $2\beta0\nu$ experiment is achieved**

α rejection



AIP Conf. Proc. 1894, 020017 (2017)

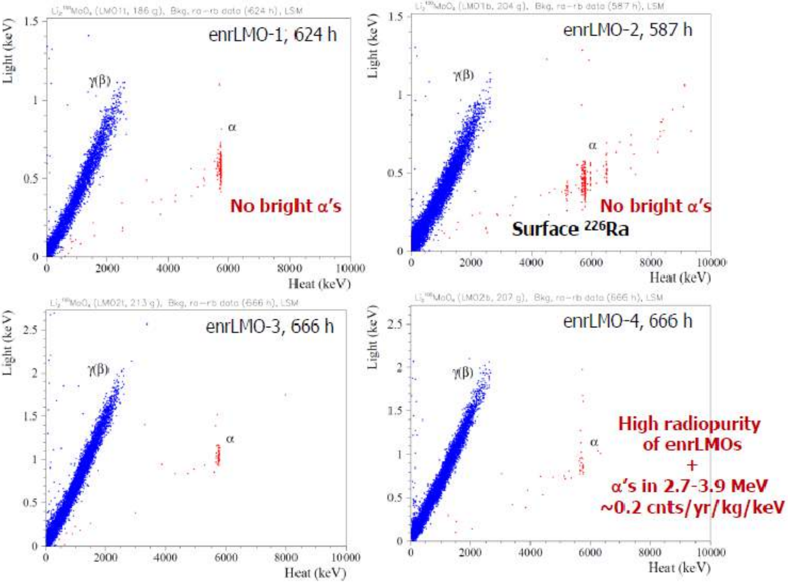
$$DP = \frac{|\mu_{\beta/\gamma} - \mu_\alpha|}{\sqrt{\sigma^2_{\beta/\gamma} + \sigma^2_\alpha}}$$

Detector	**FWHM (keV) at 2615 keV**	**Light Yield$_{\gamma/(\beta)}$ (keV/MeV)**	**$\alpha/\gamma/(\beta)$ separation above 2.5 MeV**
enrLMO-1	5.8(6)	0.41	9σ
enrLMO-2	5.7(6)	0.38	9σ
enrLMO-3	5.5(5)	0.73*	14σ*
enrLMO-4	5.7(6)	0.74*	14σ*

* with reflecting foil

Rejection of α's at the level of 9σ

First measurements with 4 bolometers



No bright α's

No bright α's

Surface ^{226}Ra

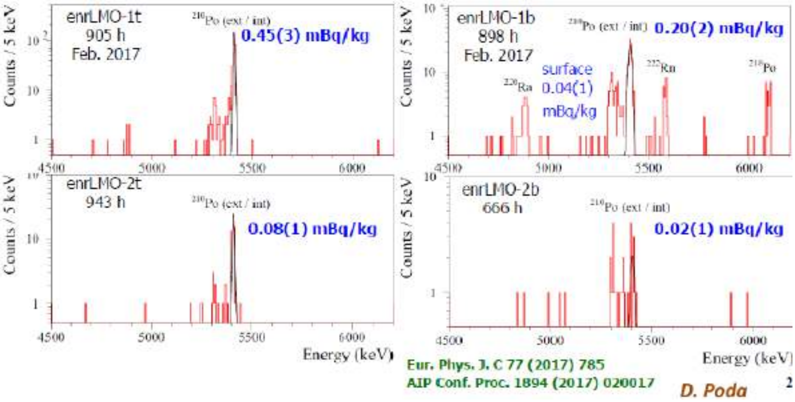
High radiopurity of enrLMOs

+

α's in 2.7-3.9 MeV ~0.2 cnts/yr/kg/keV

From D. Poda

Crystal radiopurity



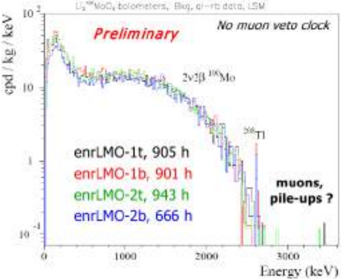
Eur. Phys. J. C 77 (2017) 785
AIP Conf. Proc. 1894 (2017) 020017

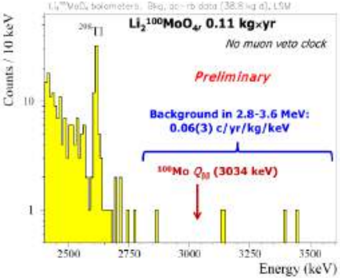
D. Poda

- ^{228}Th < 3 μBq/kg
- ^{226}Ra < 3 μBq/kg
- ^{210}Po : [20 - 450] μBq/kg

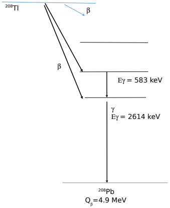
High radiopurity of $Li_2^{100}MoO_4$ crystals → no background in $2\beta0\nu$ region from internal contamination

Gamma/Beta background

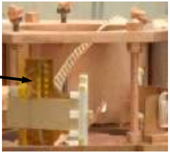




Pile-ups from



Background above 2.8 MeV :
0.06 ± 0.03 cts/(keV kg y)
compatible with Th contamination
from connectors close to the detector

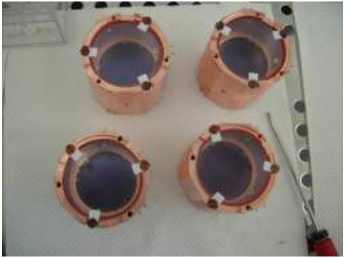


Connectors and cabling were changed for CUPID-Mo
Full estimation of background in progress
Reasonable expectation : b $\sim 10^{-2}$ - 10^{-3} cts/kev kg y

CUPID-Mo demonstrators

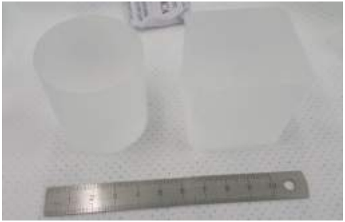
Phase I:

- 20 cylindrical $Li_2^{100}MoO_4$ crystals
  $\rightarrow \sim$ **2.5 kg of ^{100}Mo**
- Edelweiss set up at LSM
- **Start physics data taking end July 2018**



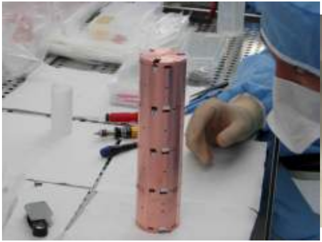
Phase II:

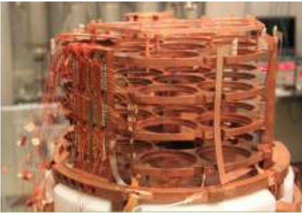
- Additional 26 cubic crystals (20 + 26 cryst.)→ $\sim$ **5 kg of ^{100}Mo**
- CUPID-0 set up at LNGS
- **Planned start data taking mid-2019**



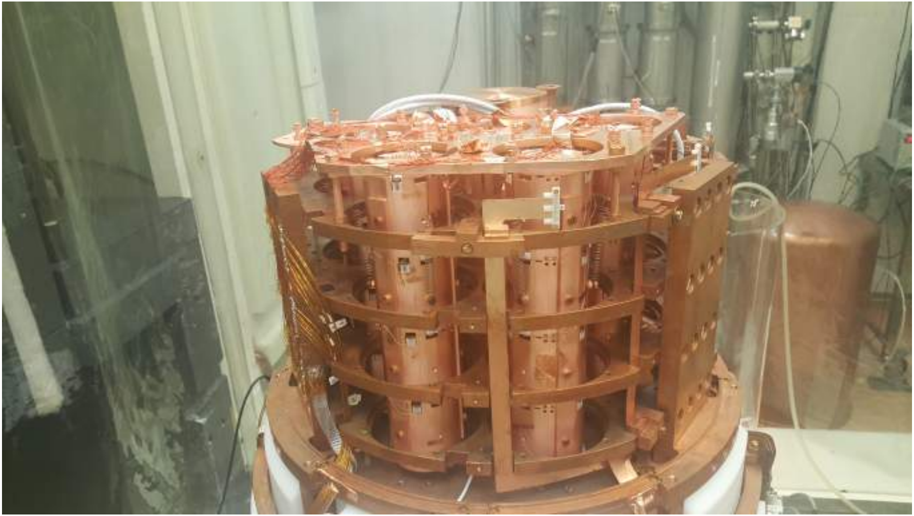
CUPID-Mo Phase I

- $Li_2^{100}MoO_4$ crystals diam 44 x 45 mm
- Light detectors Ge wafer, diam 44.5 mm x 70 μm
- NTD temperature sensors
- Copper holders radiopure NOSV copper
- Spacers PTFE
- Ball bonding, 25 μm gold wires



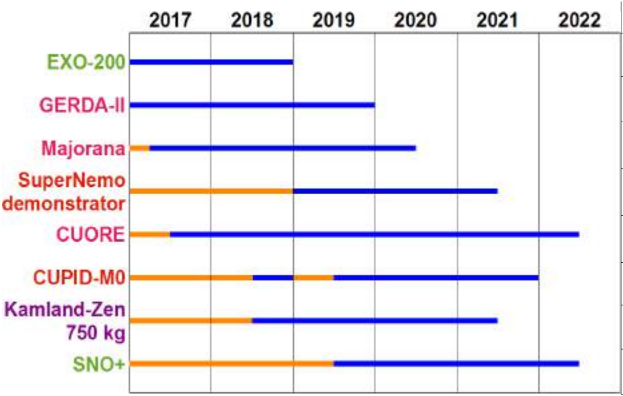


CUPID-Mo in Edelweiss set-up



What's the near future? A possible scenario

M, kg
200
35
30
7
200
5
750
800



$T_{1/2}$, y	$<m_\nu>$ meV
4. 10^{25}	100 - 270
2. 10^{26}	80 – 200
1. 10^{26}	110 - 280
5.5. 10^{24}	260 - 620
9. 10^{25}	50 – 200
1.5. 10^{25}	90 – 170
2. 10^{26}	45 - 120
1. 10^{26}	45 - 190

🟧 construction
🟦 data

+ NEXT, AMORE, PandaX-III

CUPID-Mo : Competitive results with only 5 kg of ^{100}Mo
($b=10^{-3}$ cts/keV kg y, 10 keV ROI, 70 % eff)

Adapted from A. Barabash 'Brief review on double beta decay experiments', arXiv:1702.06340

- **$g_A = 1.27$**
- **Phase-space factors from :**

[12] Kotila J and Iachello F 2012 *Phys. Rev.* C **85** 034316.
[13] Mirea M Pahomi T and Stoica S 2015 *Rom. Rep. Phys.* **67** 872

- **NME from :**

[3] Hyvarinen J and Suhonen J 2015 *Phys. Rev.* C **91** 024613.
[4] Simkovic F Rodin V Faessler A and Vogel P 2013 *Phys. Rev.* C **87** 045501.
[5] Barea J Kotila J and Iachello F 2015 *Phys. Rev.* C **91** 034304.
[6] Rath P K *et al.* 2013 *Phys. Rev.* C **88** 064322.
[7] Rodriguez T R and Martinez-Pinedo G 2010 *Phys. Rev. Lett.* **105** 252503.
[8] Menendez J Poves A Caurier E and Nowacki F 2009 *Nucl. Phys.* A **818** 139.
[9] Neacsu A and Horoi M *et al.* 2015 *Phys. Rev.* C **91** 024309.
[10] Mustonen M and Engel J 2013 *Phys. Rev.* C **87** 064302.
[11] Song L S *et al.* 2017 *Phys. Rev.* C **95** 024305.

CUPID: Cuore Upgrade with Particle IDentification

Follow-up of CUORE, towards a **ton scale bolometric experiment** with a factor 100 background reduction.

R&D efforts in three axis:

1. $Li_2^{100}MoO_4$ scintillating bolometers
2. $^{130}TeO_2$ Cherenkov bolometers
3. $Zn^{82}Se$ scintillation bolometers

Based on the result of on-going R&D and demonstrator experiments, **$Li_2^{100}MoO_4$ is identified as a promising baseline** and $^{130}TeO_2$ Cherenkov as a mature viable alternative.

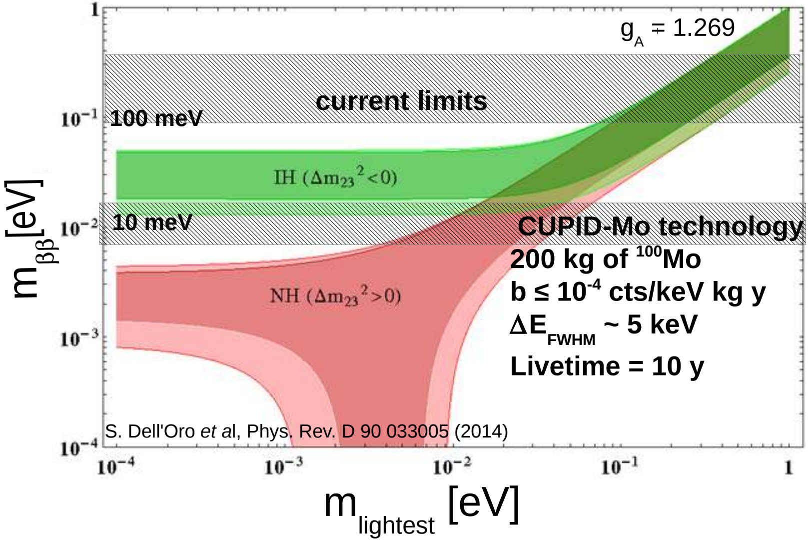
Purpose: fully explore the $m_{\beta\beta}$ Inverse Hierarchy region

- **$b \sim 10^{-4}$ counts/kev kg y**
- $T_{1/2} > 10^{27}$ y

CUPID collaboration will be formed in the near future

CUPID kick-off meeting planned fall 2018

Next generation experiments



CUPID-Mo technology

200 kg of ^{100}Mo

$b \leq 10^{-4}$ cts/keV kg y

ΔE_{FWHM} ~ 5 keV

Livetime = 10 y

S. Dell'Oro *et* al, Phys. Rev. D 90 033005 (2014)

Summary

- Study of neutrinoless double beta decay is one of the most urgent topics in particle physics and cosmology
- The bolometric approach is a viable technique confirmed at large scale by the CUORE results
- A promising technology based on enriched $Li_2^{100}MoO_4$ scintillating bolometers was developed and is now applied to the CUPID-Mo demonstrator
- CUPID (Cuore Upgrade with Particle IDentification) is one of the most promising next-generation searches

CUPID-Mo collaboration

Follow up of LUMINEU collaboration (ANR-French funding, 2012-2017)

http://cupid-mo.mit.edu

7 countries, 15 institutions, ~110 scientists

- CSNSM Orsay, CEA/DRF Gif-sur-Yvette, IPNL Lyon, LAL Orsay, FRANCE
- KIT Karlsruhe, GERMANY
- INFN Bicocca and Roma, LNGS INFN L'Aquila, ITALY
- KINR Kyiv, UKRAINE
- JINR Dubna, ITEP Moscow, NIC Novosibirsk, RUSSIA
- MIT Boston, UCB/LBNL Berkeley, US
- CUPID-China: Fudan Shangai, USTC Hefei, CHINA

EXTRA SLIDES

Prospect for next generation experiments

Experiment	**Mass (kg)**	**t (y)**	**Sensitivity $T_{1/2}$ (y)**	**Sensitivity $<m_{\nu}>$ meV**
CUPID	200	10 (2022? - 2032)	$2.2 .10^{27}$	6 - 17
nEXO	5000	10 (2025? - 2035)	10^{27} 10^{28}	6 - 53
LEGEND	200	4 (2022? - 2026)	$1.0 . 10^{27}$	34 - 91
KamLAND-Zen	1000	3 (2020? - 2023)	$6.0 . 10^{26}$	26 – 69
SNO+	8000	5 (2020?- 2025)	$7 . 10^{26}$	20-73
SuperNEMO	100	?	$1.0 . 10^{26}$	40-140

For CUPID-Mo:

Assuming $b=10^{-4}$counts /keV kg y, 10 year running, 8 keV energy window, 78% efficiency