Prospectives Nationales 2020:
Physique Nucléaire, des Particules et Astroparticules

Séminaire Thématique "Physique des neutrinos et matière noire"

Depuis 80 ans, nos connaissances bâtissent de nouveaux mondes

28 October 2019
L'Agora du Haut-Carré - Université de Bordeaux

# Neutrino physics: La double désintégration bêta

**Andrea Giuliani** CSNSM

**Five presented documents:**

1. Expérience SuperNEMO → F. Mauger
2. CUPID: a next-generation $0\nu2\beta$ experiment → A. Giuliani
3. Multi-ton Double-Beta Decay with LiquidO → A. Cabrera
4. R2D2: Rare Decays with Radial Detector → C. Jollet
5. Proposal for a national double-beta decay strategy → A. Giuliani, C. Marquet

# Importance of neutrinoless double beta decay

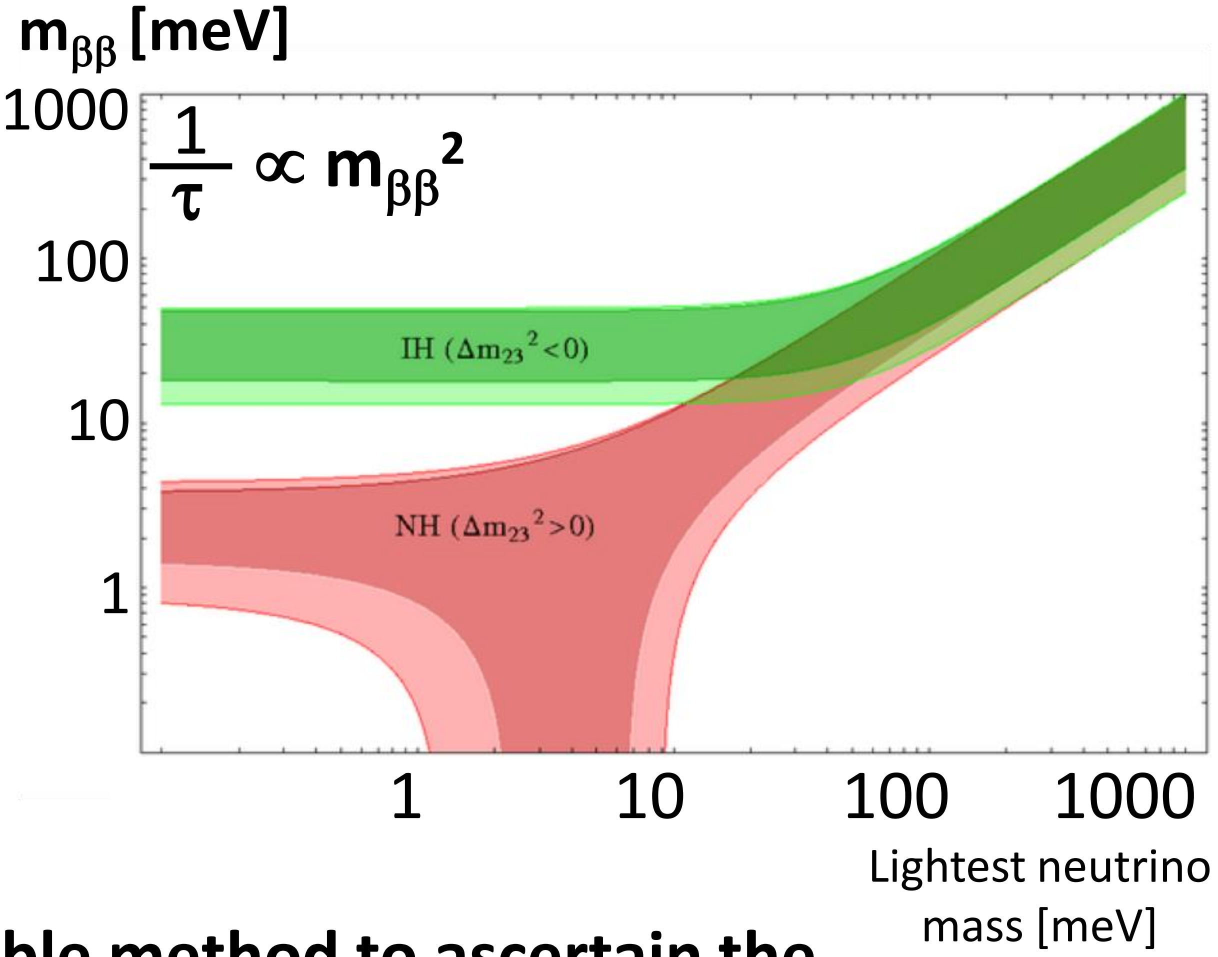
$(A,Z) \rightarrow (A,Z+2) + 2e^-$ $\tau > 10^{26}$ y

**Creation of matter without antimatter partners**

**Never observed.**

Its detection would:

- establish that neutrino is a **Majorana particle**
- fix the **neutrino mass scale,** provided by the **effective Majorana neutrino mass $m_{\beta\beta}$**
- prove **Lepton Number Violation (not only neutrino physics)**




**The only experimentally viable method to ascertain the Majorana nature of neutrino**

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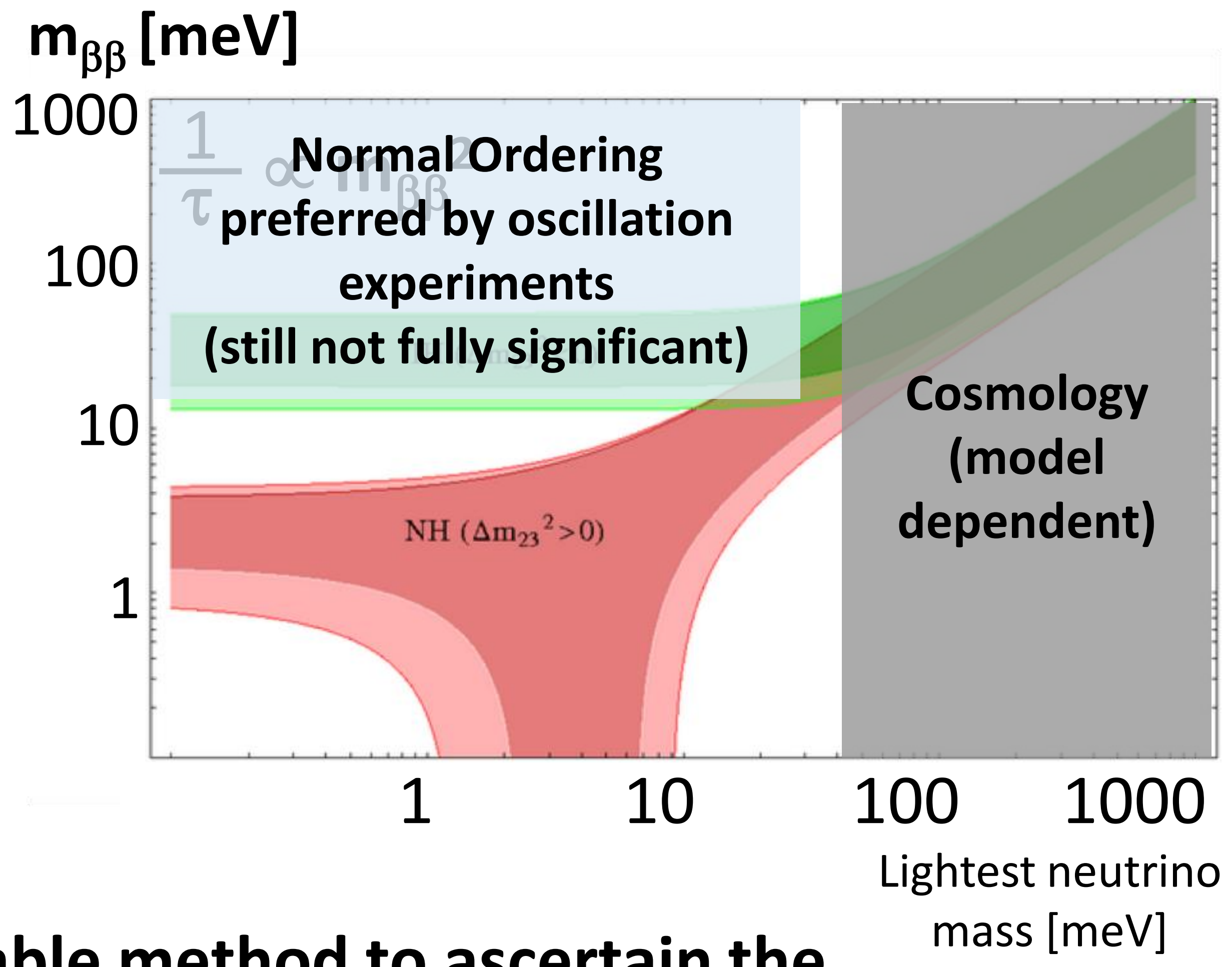
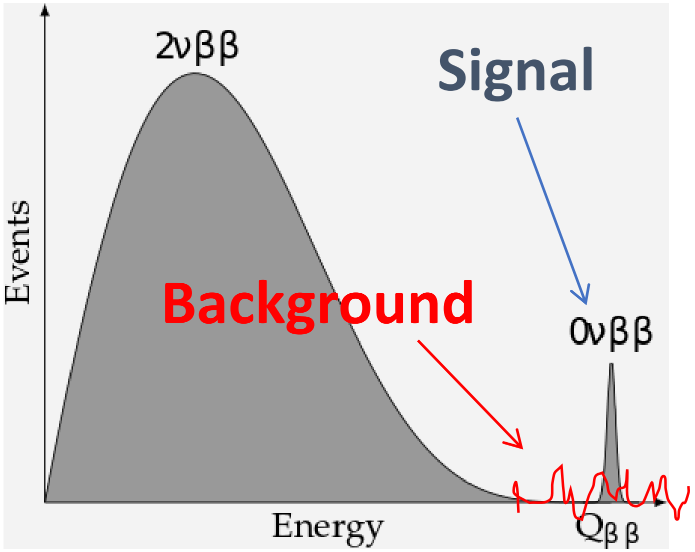
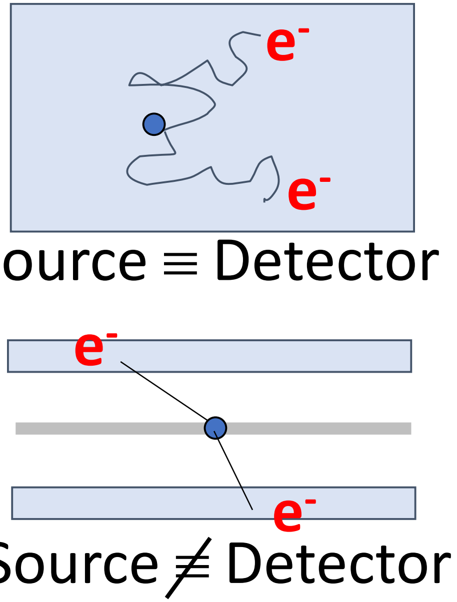



**The only experimentally viable method to ascertain the Majorana nature of neutrino**

# Background and energy resolution




**Background index**

$$b = \frac{\text{Background counts}}{M \times \Delta E \times T}$$ [counts/(keV kg y)]

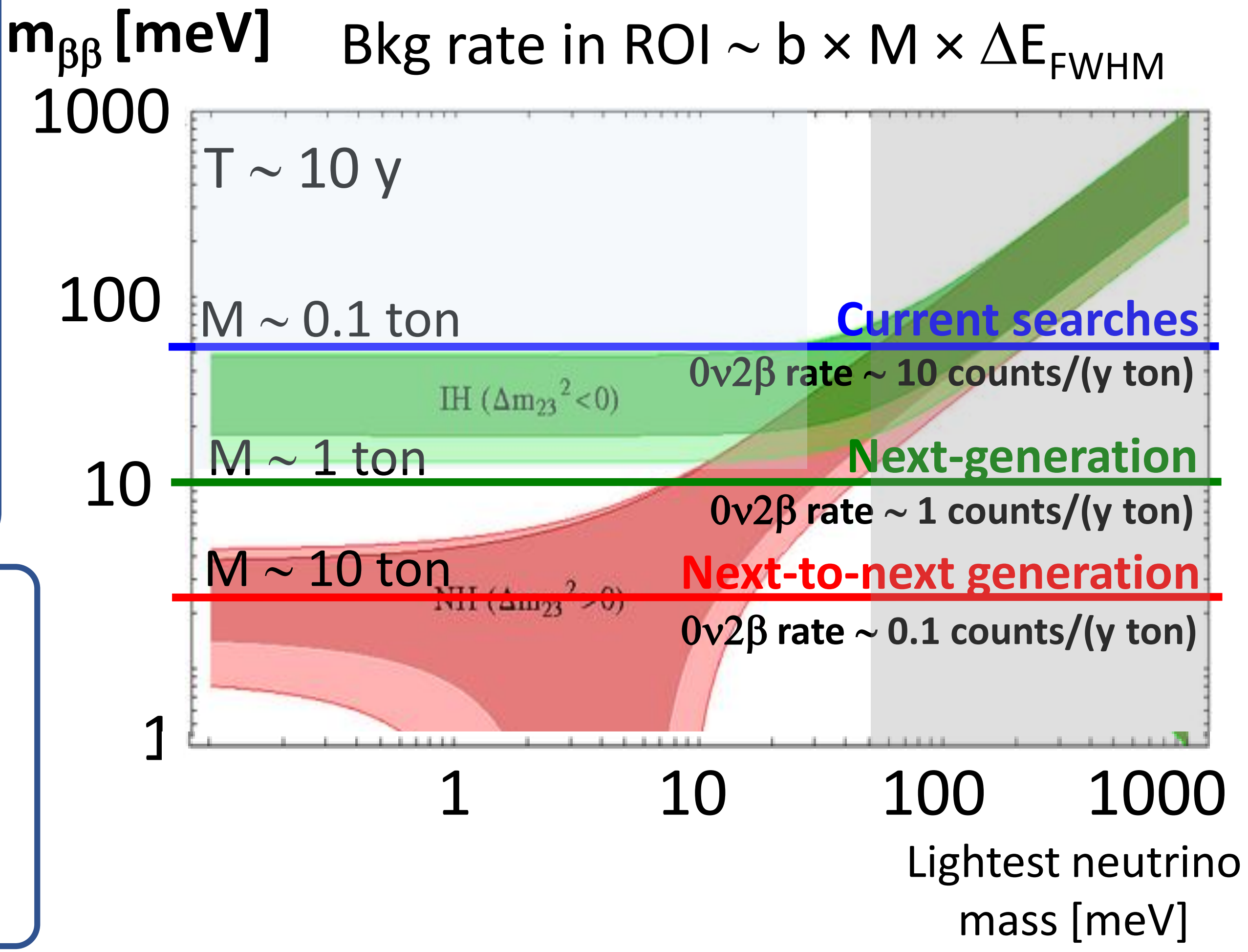
Detector/source mass

Energy interval

Measurement time

**Key parameters: $\Delta E_{FWHM}$ , b**

Bkg rate in ROI ~ b × M × $\Delta E_{FWHM}$




**35 candidate isotopes**

A few interesting: $^{76}$Ge, $^{82}$Se, $^{96}$,Zr $^{100}$Mo, $^{116}$Cd, $^{130}$Te, $^{136}$Xe, $^{150}$Nd

**High $Q_{\beta\beta}$ value** → > 2MeV, better if >2.6 MeV

Low background, high decay probability

# The situation in France in a nutshell

(Documents presented for the Prospectives)

**Key parameters: $\Delta E_{FWHM}$ , b**

Bkg rate in ROI ~ b × M × $\Delta E_{FWHM}$

Multi-isotopes

**Mature technology**

**SuperNEMO**

Tehcnically ready

Unique: full event reconstruction

Non-scalable to next-generation

**CUPID**

Technically ready

Cost-effective

Scalable

**R&D**

**R2D2**

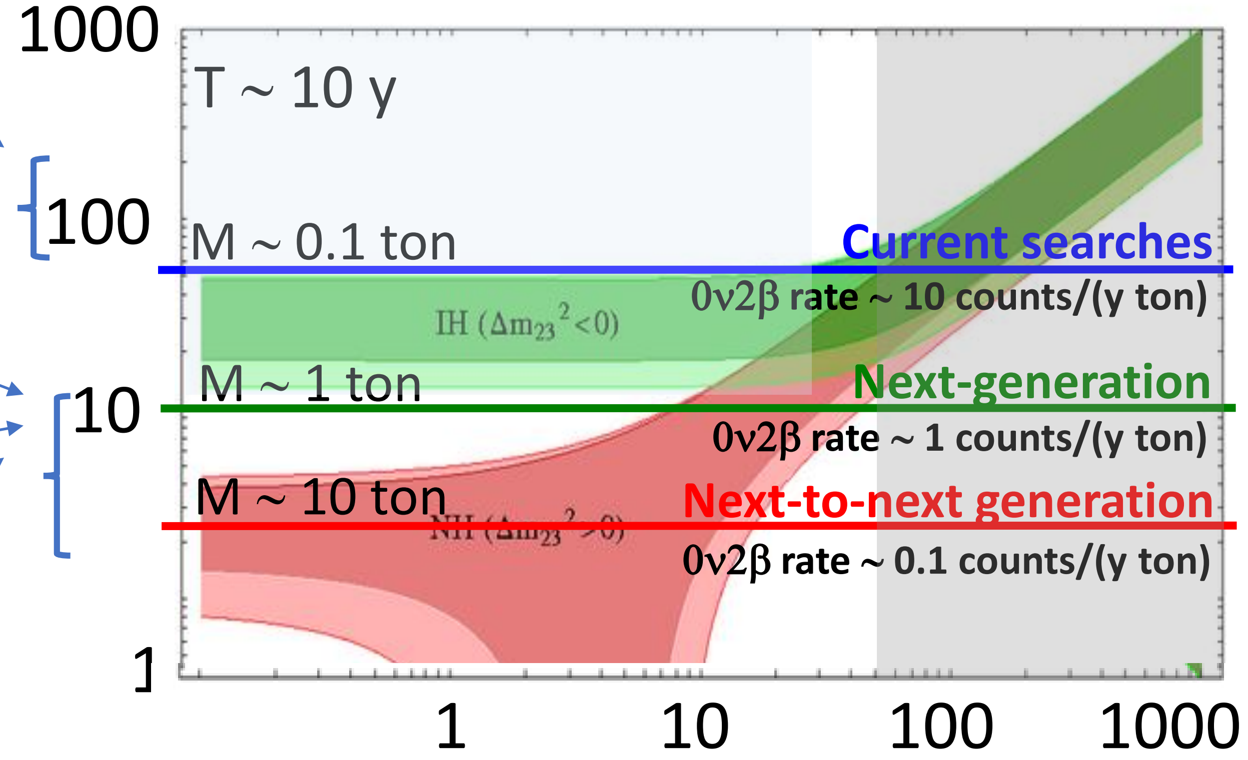
Simple → low radioactivity

Scalable

**LiquidO**

Event ID by revolutionary approach in liquid scintillators

Scalable



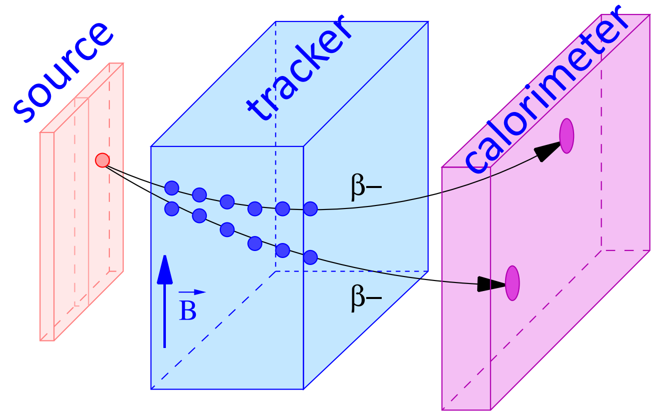
# SuperNEMO

supernemo collaboration

**9 countries**
**21 Laboratories**

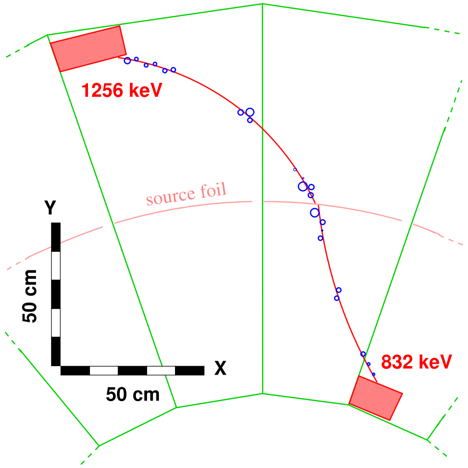
## Main objectives:

- Build on the experience of the successful **NEMO-3 experiment**
- **Tracking-calorimeter approach**
  $\rightarrow$ identification and suppression of background.
- **Zero-background experiment** in the **SuperNEMO demonstrator** at LSM
- In case of a discovery by current or future experiments, provide a unique technology to **identify the mechanism inducing $0\nu2\beta$ decay**



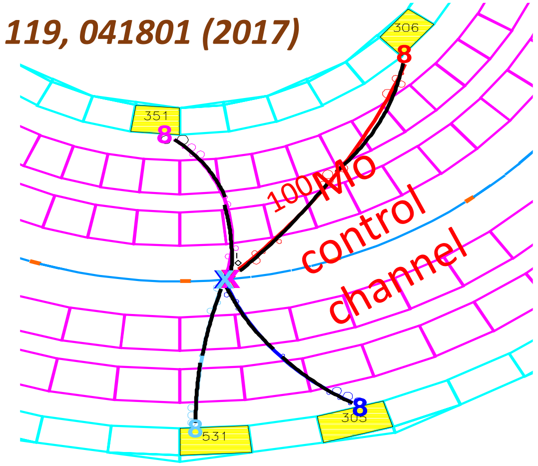

**$T_{1/2}$ > 1.1 × $10^{24}$ y at** 90% C.L. ($^{100}$Mo)

*PRD 92, 072011 (2015)*



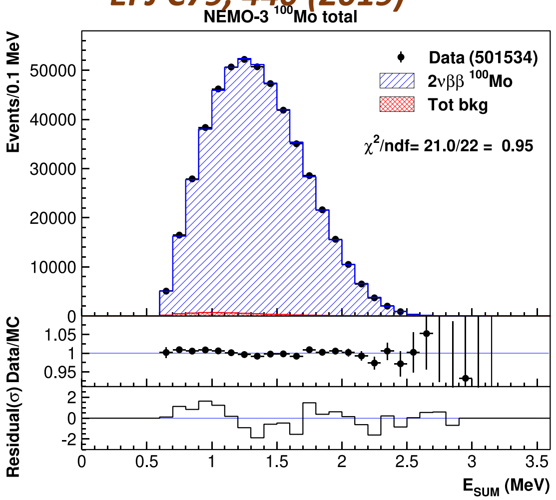

Access tp **unique signatures**
e.g. $0\nu4\beta$

*PRL 119, 041801 (2017)*

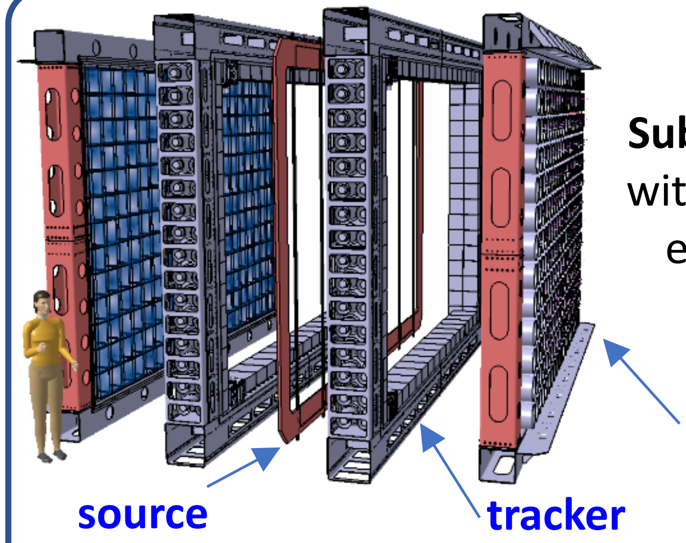



Kinematic probes of $2\nu2\beta$ **mechanism** (SSD/HSD)

*EPJ C79, 440 (2019)*



# SuperNEMO demonstrator




**Substantial improvement** with respect to **NEMO3** in energy resolution and source radiopurity

- **6 kg of $^{82}$Se**
- Background rate in ROI: **0.043 counts/(kg y)**
- Sensitivity: ~**6.5 × 10$^{24}$ y** in **3 y** → **$m_{\beta\beta}$ < 260 – 500 meV** with exposure of 18 kg × y → 3 y data-taking
- **Full event reconstruction of $2\nu2\beta$ of $^{82}$Se**
  → **unique precision measurements** (limits on right currents, Majoron emission, supersymmetric modes, excited states)
  → access to nuclear physics: **$g_A$ analysis**

**SuperNEMO Demonstrator Module**: final commissioning in progress at LSM

## Lessons and perspectives

- Experience from the Demonstrator Module
  → lessons about how **scaling up to 20 modules, 100 kg** (**~10$^{26}$ y** in **5 y** → **$m_{\beta\beta}$ < 82 – 160 meV**)
- Implement the tracko-calorimeter technology for more promising **high Q-value isotopes** ($^{150}$**Nd**, $^{96}$**Zr**), **now enrichable by centrifugation**
- Can the technique be extended to **confirm a signal anywhere in the IH region ?**

  → **R&D and isotope developments** can point the way.

# SuperNEMO prospects

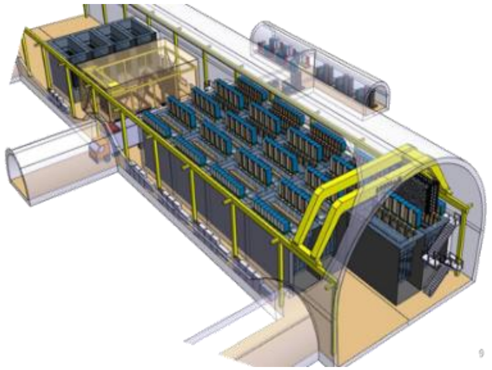
**Quoting from the SuperNEMO document**

**Problems of mechanical assembly and difficult interfaces in the current conception** ☹

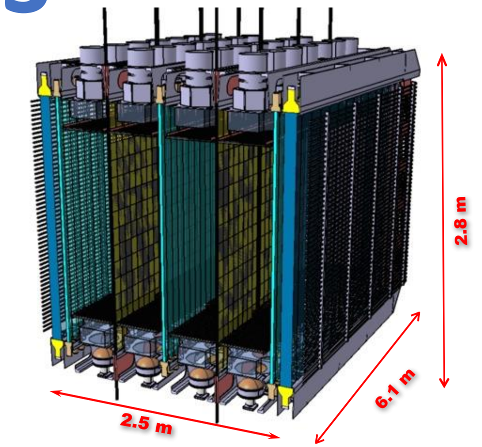
> « Il semble donc pratiquement **impossible d'envisager une mise a l’echelle du design actuel** et donc un avenir pour cette technologie en l'etat. »

**Difficulty in competing with other techniques** ☹

> « En termes de prospectives physiques, meme si le demonstrateur remplit correctement son cahier de charge […], **le passage a l'echelle avec par exemple 20 modules pour une exposition de 500 kg.an dans le futur (vers 2030) ne permet pas d'envisager de concourir aupres des experiences double beta de nouvelle generation** qui ont pris une serieuse avance en terme de sensibilite. »



**20 modules**




**Alternative design**

**Inevitable approach for safe determination of the $0\nu 2\beta$ mechanism** ☺

> « Toutefois, dans l'**hypothese ou un signal ββ0ν serait detecte** dans un futur proche par l'une des experiences actuellement en fonctionnement, la communaute devrait considerer **l'approche de SuperNEMO pour etudier la conception d'une experience dimensionnee pour la confirmation independante d'un signal ββ0ν** et beneficiant des **caracteristiques remarquables d'identification de la technologie ≪ tracko-calo ≫**. »

# CUPID

**CUPID** (**C**UORE **U**pgrade with **P**article **ID**) is a proposed $0\nu2\beta$ bolometric experiment exploiting the **CUORE infrastructure** with a **background 100 times lower than CUORE at the ROI**

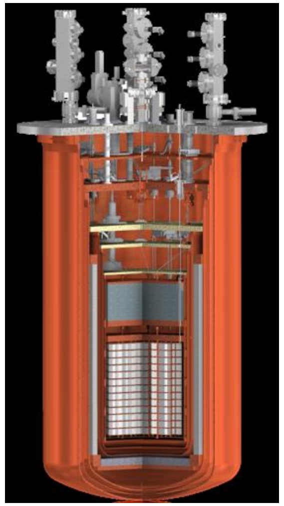
**CUORE** is an array of ~**1000 natural $TeO_2$ bolometers** searching for $0\nu2\beta$ decay of the **isotope $^{130}$Te ($Q_{\beta\beta}$=2527 keV)** and taking data in LNGS (Italy)

One of the most sensitive $0\nu2\beta$ experiments of the current generation

The largest bolometric experiment ever

- Exposure: 369.9 kg × y
- **$T_{1/2}$ > 2.3×10$^{25}$ y**
- **$m_{\beta\beta}$ < 90 – 420 meV**

After 1.5 years' optimization of cryogenics, now regular data taking and **high duty cycle**

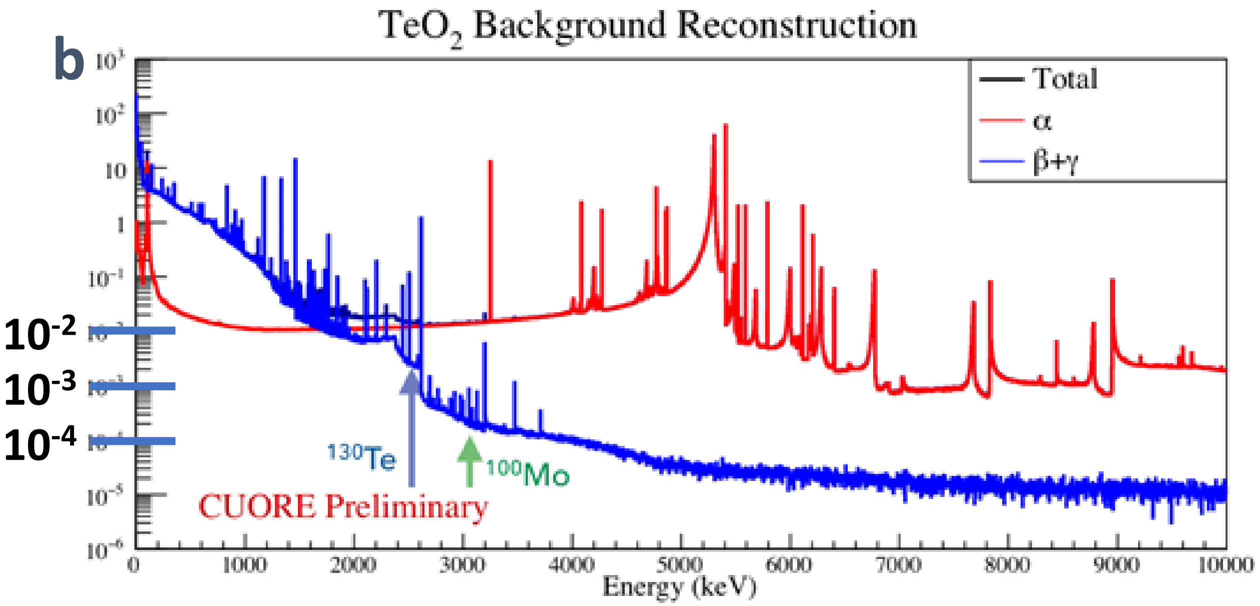


**CUORE is not background free**

**~50 counts/y in the ROI**

dominated by **surface alpha-particle background**

**b=1.4×10$^{-2}$** (according to expectations)




## CUORE → CUPID

- Reject $\alpha$ background with **scintillating bolometers**
- Abate $\gamma$ background by **moving to $^{100}$Mo**
  - $Q_{\beta\beta}$: 2527 keV ($^{130}$Te) → 3034 keV ($^{100}$Mo)
- Increase isotope mass by **enrichment**

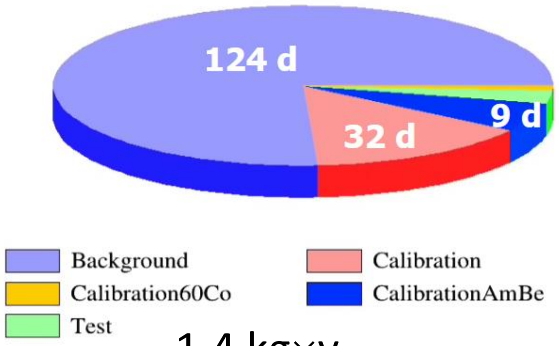
# CUPID-Mo ≡ CUPID demonstrator

**LUMINEU** (from 2013) has succesfully developed the scintillating-bolometer **$Li_2{}^{100}MoO_4$ technology**

## CUPID-Mo

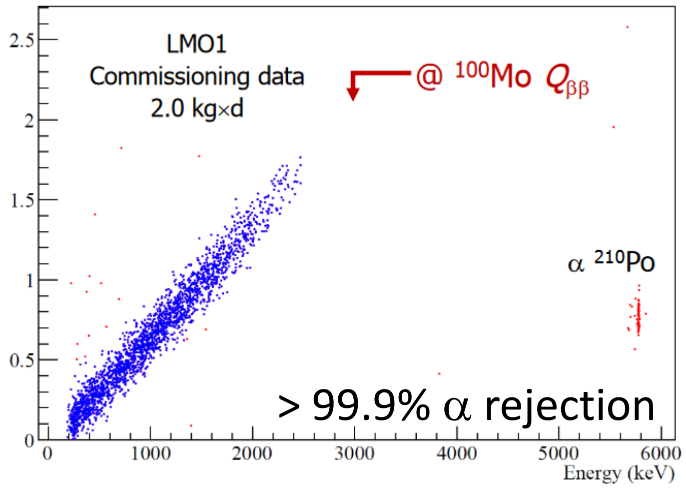
- 20 $^{100}$Mo-enriched (97%) $Li_2MoO_4$ crystals
  ⇒ **~2.3 kg of $^{100}$Mo**
- 20 Ge light detectors
- 5 towers with 4 detectors each
- **EDELWEISS set-up @ LSM (France)**

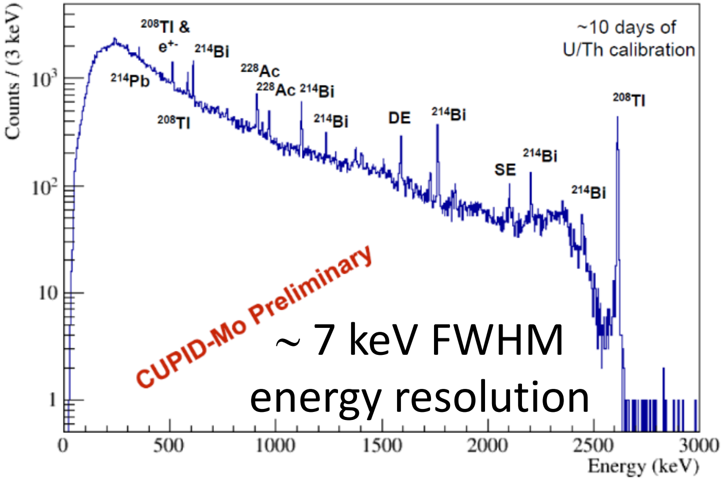
Regular data taking started in April 2019
It will go on until February 2020




1.4 kg×y

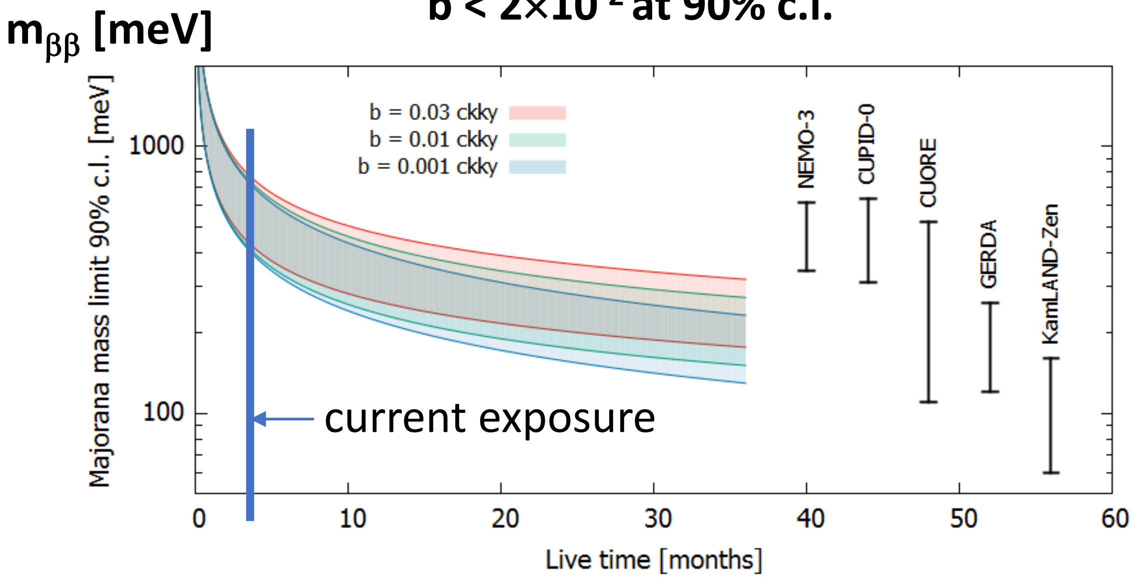
*arXiv:1909.02994 – accepted by EPJC*




In the statistics analyzed up to now (0.5 kg×y) , 0 counts in the β band above 3 MeV

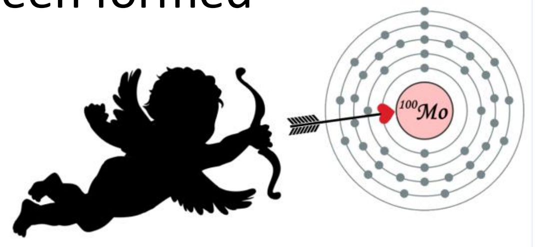
**b < 2×10$^{-2}$ at 90% c.l.**



# CUPID: prospects and sensitivity

The CUORE collaboration has selected the **$Li_2MoO_4$ technology for CUPID**

CUPID collaboration has been formed




Experiment described in CUPID CDR
***arXiv:1907.09376***

7 countries, 33 institutions, 160 physicists

Selected at the **CD0 level** in the US

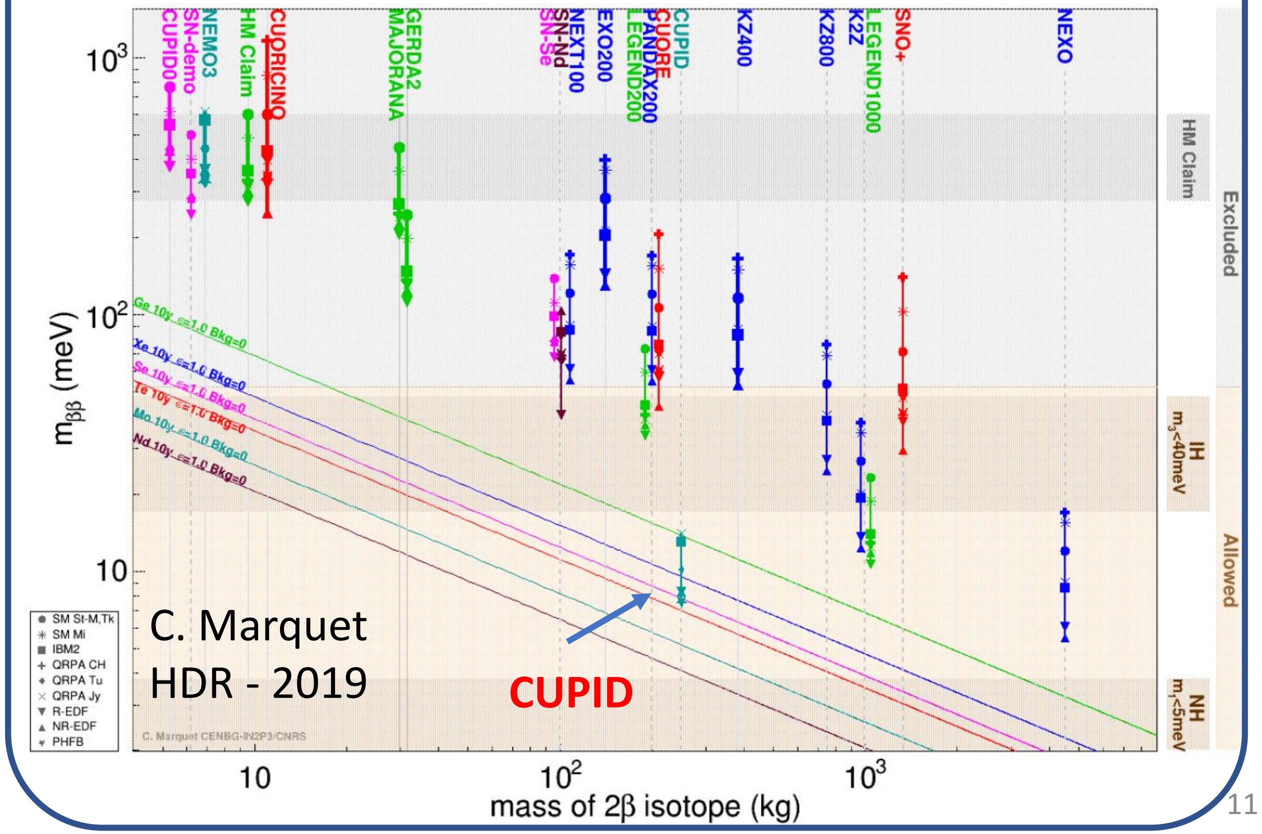
- Single module: $Li_2{}^{100}MoO_4$ **Ø50×50 mm**
- 118 towers of 13 floors each - **1534 crystals**
- **~250 kg of $^{100}$Mo** for >95% enrichment
- **$1.6\times10^{27}$** $^{100}$Mo atoms
- **b ~ $10^{-4}$**

If funded, start data taking in **6 years from now**

**CUPID =**
**CUORE cryostat (LNGS) + CUPID-Mo technology**

- Technology achieved
- Data driven
- Reliable background mode
- Existing infrastructure
- Costs dominated by isotope and crystals (~20 M€)

1/3 – 1/2 of the cost of competing experiment



# R2D2

J. Busto,[a] C. Cerna,[b] A. Dastgheibi-Fard,[c] C. Jollet,[b] S. Jullian,[f] I. Katsioulas,[d] I. Giomataris,[d] M. Gros,[d] P. Lautridou,[e] A. Meregaglia,[b] X. F. Navick,[d] F. Perrot,[b] F. Piquemal,[b,c] M. Zampaolo[c]

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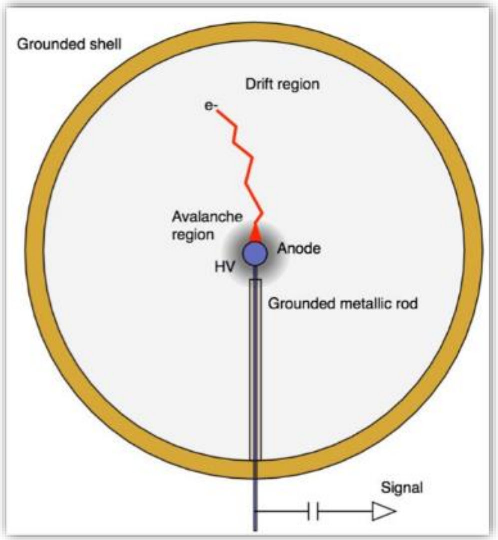
**R&D program** aiming at the development of a **zero background ton scale detector**

**Spherical Xenon gas TPC at high pressure** (i.e. 40 bars)
→ 1 ton ~ 1 m radius

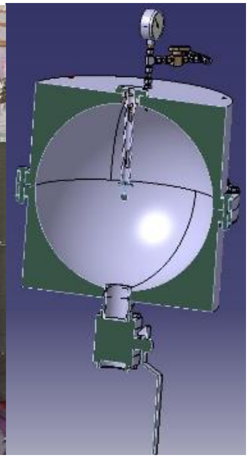
Multichannel central anode for **PID** and **coarse tracking** (common R&D with **NEWS-G**)




**R2D2 aims at meeting the most important requirements for next-generation experiment**

- **Good energy resolution** → To be validated
  **(0.3 - 1 % FWHM at 2458 keV)**
- **Low background** → Low material budget → High radiopurity of Cu
- **Large masses of isotopes** → Easy scalability
  - increase radius
  - multiple elements

# R2D2: Prototypes and roadmap

① Up to **7.9 kg (40 bars) Xenon prototype** - no low radioactivity demonstrate detector performance, in particular **energy resolution**

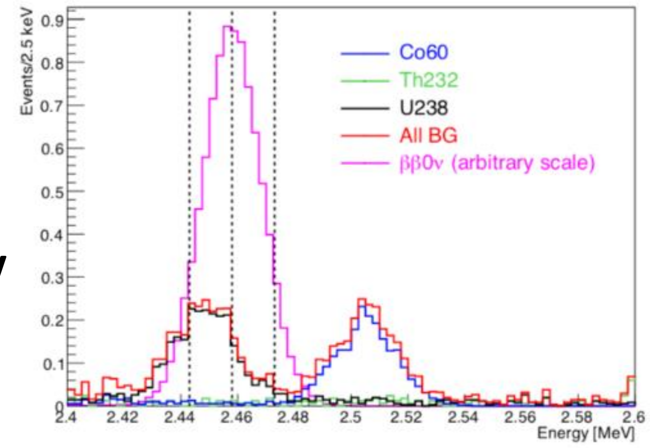
- **Existing prototype at CENBG** (20 cm radius) made of Aluminium
- Currently operated with **Ar (98%) + $CH_4$ (2%)** at **low pressure**
- Data taking with **Xenon and high pressure foreseen in 2020**

→ If ① successful and ② funded

② **50 kg enriched Xenon Cu detector**, 40 bars, 37 cm radius

- Ultra-pure copper
- Active veto (liquid scintillator + passive layers)
- **Radial position reconstruction** to reject background
  → multi-site vs. single-site events
- **Zero background** and **physics results**

**~$10^{26}$ y** in **3 y**
**$m_{\beta\beta}$ < 70 – 150 meV**




*JINST 13 (2018) no.01, P01009*

→ Depending on results and funds

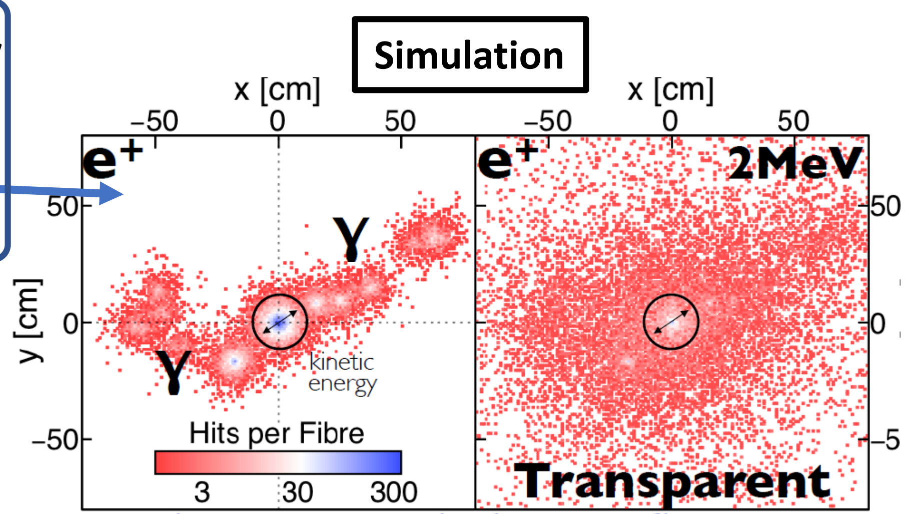
③ **1 ton background free detector**
→ Inverted ordering region

→ Exploit the detector with **other gases** to cross check the background and possibly obtain interesting results selecting **higher $Q_{\beta\beta}$ candidates**, as well as the possibility to do tracking

# LiquidO

**R&D activity** based on the **well-known liquid scintillator technology**
**Opaque scintillator** + **tight array of fibres**

- conventional paradigm of transparency is abandoned
- scintillation light is confined and collected near its creation point




**opacity↔ stochastic light confinement**
**⟹ sharp sub-atomic images (particle ID)**

**High isotopic mass** → Target loading fractions: **5-30 %** (vs. current 1-3 %)
Transparency constraint is relaxed

**Non-enriched multi-isotope loading** → Loading compensates enrichement
Every isotope with I.A. > 5% interesting
Special interest in $^{130}$**Te (I.A. = 34%)**
High $Q_{\beta\beta}$ isotopes ($^{82}$**Se**, $^{100}$**Mo**, $^{150}$**Nd**)
Build on KamLAND-Zen, SNO+ experiences

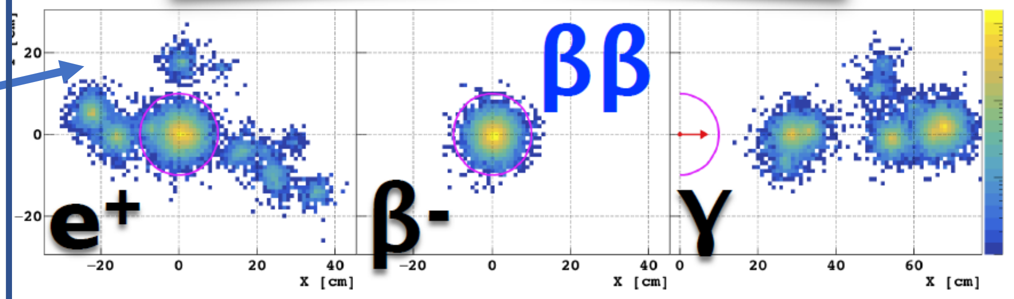
**10 ton isotope**

**Active background rejection** → **Multi-site** ($\gamma$ and other backgrounds) vs. **single site** (double-beta decay signal)

**Radiopurity** → Build on Borexino experience for liquid purification
GERDA experience for fibre radiopurity (improvable)

**Energy resolution** → **Main LiquidO weekness**
conservatively 7-13 % (FWHM at 1 MeV)
R&D pointing at non convential high light-yield opaque scintillator

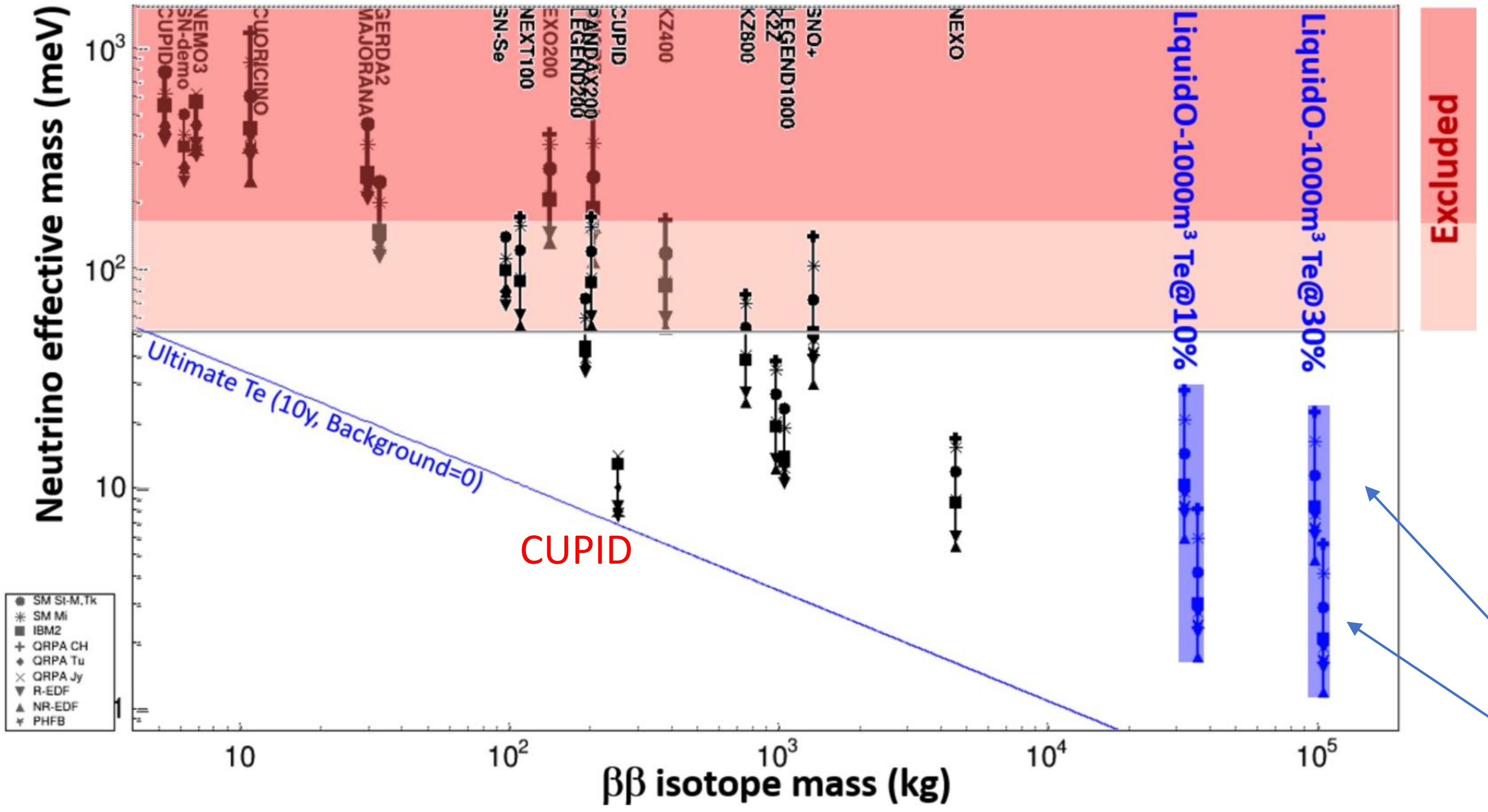
**2MeV particles in LiquidO (simulation)**

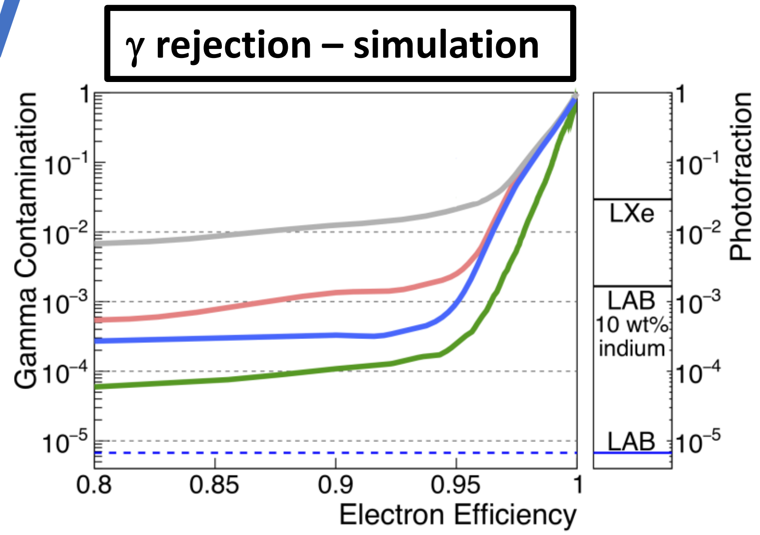



*Preprint at arXiv:1909.02859*

**Collaborators⊕Cooperators**
(Brasil, Canada, Chile, France, Germany, Italy, Japan, Spain, UK, USA)
contact: anatael@in2p3.fr & suekane@awa.tohoku.ac.jp

# LiquidO sensitivity




- **10 ton** Te natural
- **10 y** livetime
- 2 different loading factors (10% - 30%)
- **b=$10^{-4}$** – ΔE = 13 % (FWHM a t 1 MeV) [KamLAND-Zen-like]
- **b=$10^{-6}$** – ΔE = 7 % (FWHM at 1 MeV)

**R&D**


opaque scintillator | new readout | experimental validation prototype | mechanical design & prototype

# Proposal for a national strategy

current — next — next-to-next

**2020**

**$m_{\beta\beta}$ ~ 50 – 500 meV**

Explored by several world-wide searches (KamLAND-Zen, CUORE, GERDA,…)

**SuperNEMO demonstrator**

**CUPID-Mo**

In case of discovery in this range, SuperNEMO technology can indentify the mechanism

**Keep SuperNEMO technology ready**

**2025**

**$m_{\beta\beta}$ ~ 10 – 50 meV**

Few advanced projects (CUPID, LEGEND, nEXO, NEXT, SNO+)

**CUPID is very well positioned**

- Technologically ready
- Data-driven
- Cost effective
- Technology developed in France

**Naturally part of the national strategy**

**2030**

**$m_{\beta\beta}$ < 10 meV**

1 -10 ton isotope scale

1. Major update of existing technologies
2. New technological breakthroughs

- Evolutions of CUPID (>1 ton, $TeO_2$) → CROSS technology
- LiquidO technology (10 ton)
- R2D2 multi-ton
- $0\nu2\beta$ in JUNO (> 2030)

**Support R&Ds and new ideas**

**Promising R&Ds ongoing**

**R2D2 - LiquidO**

**Dark matter / $0\nu2\beta$ synergy: DARWIN**

- Built on XENON experience
- 50 LXe tons → 3.5 tons of $^{136}Xe$

**Synergies**

**DULP GDR**

(Deep Underground Laboratory Physics)

- The main research lines in France (SuperNEMO, CUPID and others) can benefit one from the other
  (BiPo detector – Rn control – low radioactivity in general radiopure databases – nuclear physics etc.)
- Expertise in scintillation (SuperNEMO, LiquidO, CUPID)
- CUPID-LiquidO: exploit Te and Mo compounds

# Proposal for a national strategy

current | next | next-to-next

2

$m_{\beta\beta}$ ~ 50

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Promising

R2D2

Dark matter / 0

- Built on XEN
- 50 LXe tons -

**France can play a leadership role in $0\nu2\beta$ decay in the next decade**

**All the pieces of the puzzle are on the table**

meV

ope scale

existing technologies

al breakthroughs

CUPID (>1 ton, $TeO_2$)

nnology

ology (10 ton)

n

(> 2030)

nd new ideas

(SuperNEMO, CUPID

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MO, LiquidO, CUPID)

compounds

# BACK UP