Second International Meeting for
Large Neutrino Infrastructures

Fermilab, April 22nd, 2015

Neutrino mass measurements (single beta, double beta) in Europe

Andrea Giuliani

CSNSM – Orsay

Outline

- The neutrino mass scale
- Single beta decay and neutrino mass
- Double beta decay: isotope choice
- Double beta decay: experimental status in Europe
- Double beta decay: prospects towards 1 ton

The absolute neutrino mass scale

Cosmology, **single** and **double β decay** measure different combinations of the neutrino mass eigenvalues, constraining the **neutrino mass scale**

In a standard three active neutrino scenario:

$$\Sigma \equiv \sum_{i=1}^{3} M_i$$

cosmology
simple sum
pure kinematical effect

$$\langle M_\beta \rangle \equiv \left(\sum_{i=1}^{3} M_i^2 \, |U_{ei}|^2 \right)^{1/2}$$

β decay
incoherent sum
real neutrino

$$\langle M_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^{3} M_i \, |U_{ei}|^2 \, e^{i\alpha_i} \right|$$

double β decay
coherent sum
virtual neutrino
Majorana phases

$$\langle M_\beta \rangle$$

Direct ν mass measurement

use $\mathbf{E^2 = p^2c^2 + m^2c^2}$ → $m^2(\nu)$ is the observable

Use low Q-value beta-like processes and study endpoint of electron or γ spectrum

MAC-E-filter
Spectrometers
KATRIN

CRES
PROJECT 8

$^{3}H \rightarrow {}^{3}He + e^{-} + \nu_e$ Q ~ 18.6 keV

Bolometers
NUMECS
HOLMES
ECHO

~~$^{187}Re \rightarrow {}^{187}Os + e^{-} + \nu_e$~~ Q ~ 2.5 keV

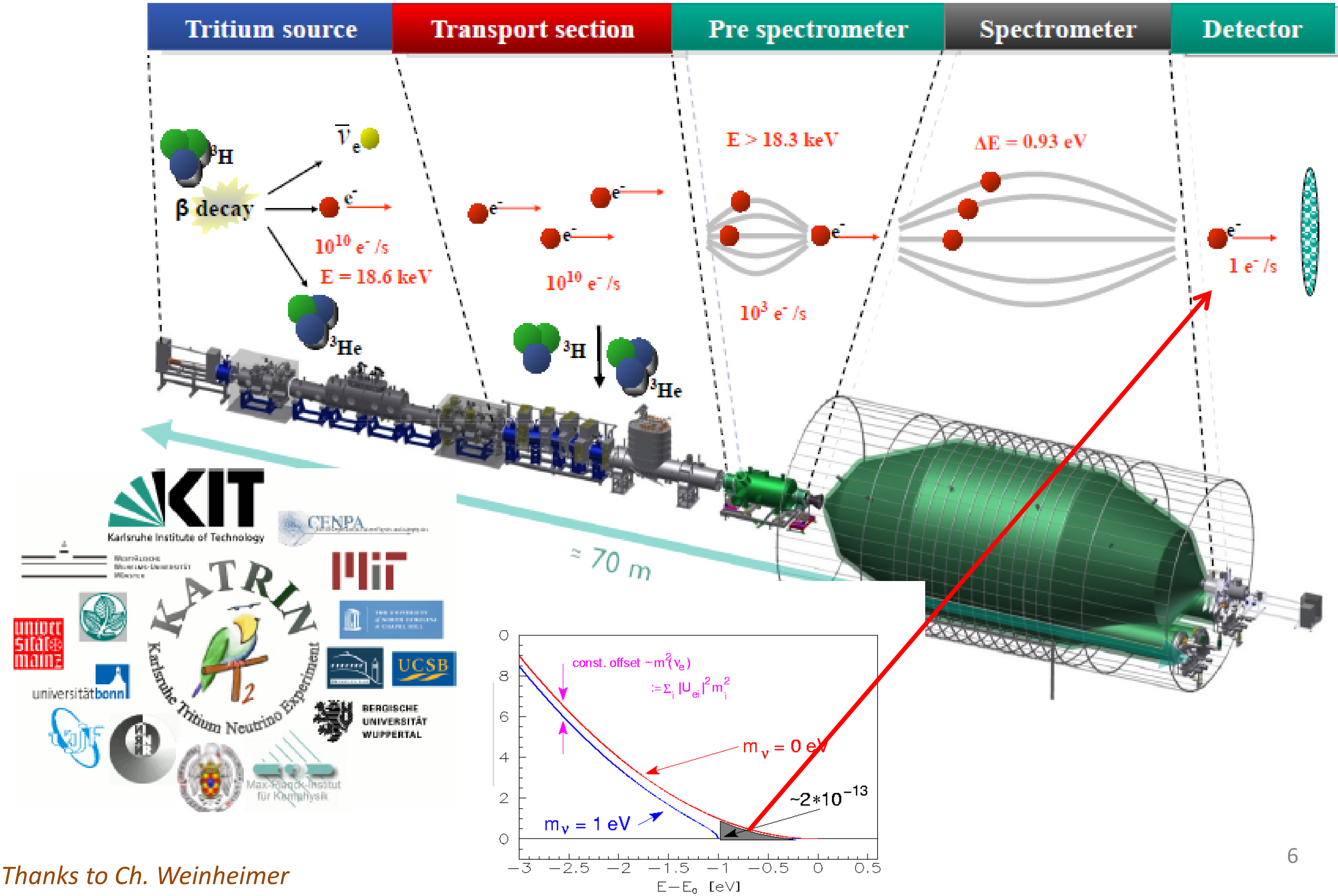
$^{163}Ho + e^{-} \rightarrow {}^{163}Dy^{*} + \nu_e$ Q ~ 2.8 keV

($^{163}Dy^{*}$ → γ)

In Nigel Smith's talk

In red, projects located in EU

KATRIN



Thanks to Ch. Weinheimer

KATRIN

Schedule and open issues

- Main spectrometer & detector successfully commissioned, still a bit too high background, but that is not the end of the story
- Tritium source and electron transport/tritium retention system on a good way
- Start regular data taking in 2016 !

- **Cosmic rays – natural radioactivity** on spectrometer walls
- **Radon** background in spectrometer volume

Both are now under control

Unknown origin of the **residual background**, which is 40 times higher than the objective (However, sensitivity to neutrino mass depends only on power 1/6 of the background rate)

sensitivity:

m_ν < 0.2eV (90%CL)

discovery potential:

m_ν = 0.3eV (3σ)

m_ν = 0.35eV (5σ)

In addition sensitive to eV and keV sterile neutrinos !

$$\langle M_{\beta\beta} \rangle$$

Decay modes for Double Beta Decay

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$

2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \sim 10^{18} - 10^{21}$ y

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$

neutrinoless Double Beta Decay (0ν-DBD)
never observed (except a discussed claim)
$\tau > 10^{25}$ y

③ $(A,Z) \rightarrow (A,Z+2) + 2e^- + \chi$

Double Beta Decay
with Majoron (light neutral boson)
never observed – $\tau > 10^{22}$ y

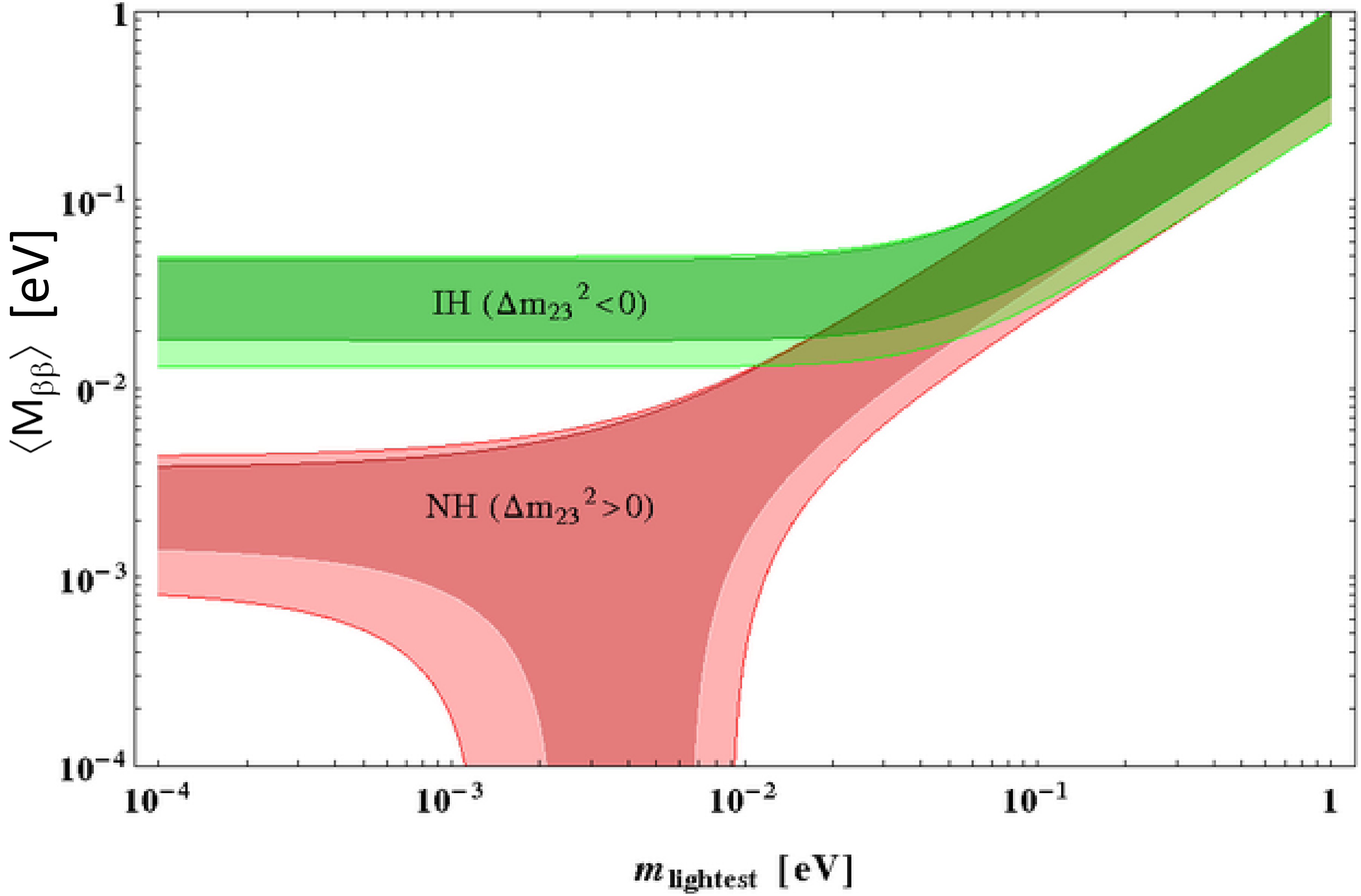
Processes ② and ③ would imply new physics beyond the Standard Model

violation of total lepton number conservation

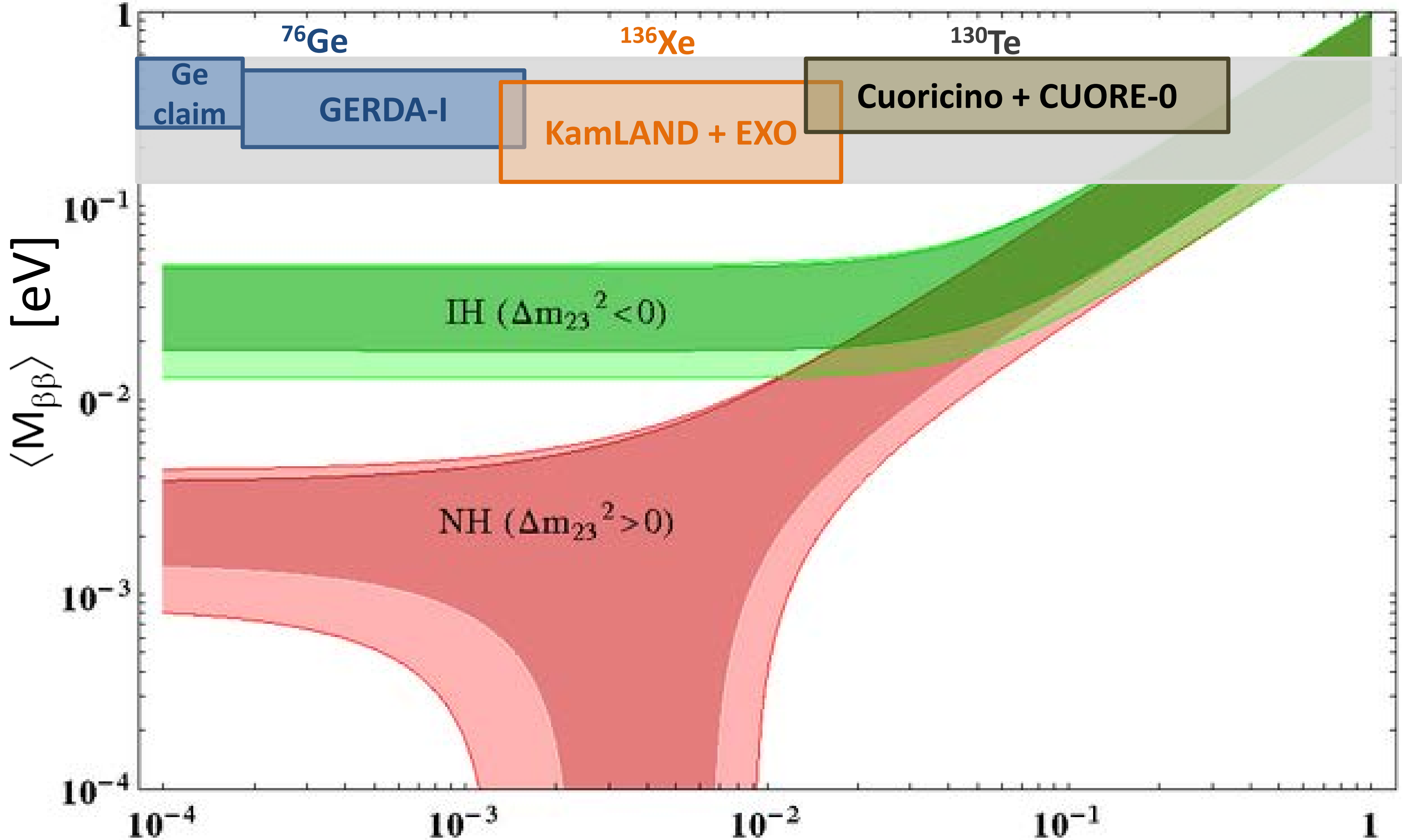
Why is neutrinoless Double Beta Decay important

- Majorana mass term
- See-saw mechanism $\Rightarrow$ naturalness of small neutrino masses
- Leptogenesis and matter-antimatter asymmetry in the Universe

Status


1
10⁻¹
0⁻²
10⁻³
10⁻⁴
⟨M_ββ⟩ [eV]
IH (Δm₂₃² < 0)
NH (Δm₂₃² > 0)
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
m_lightest [eV]

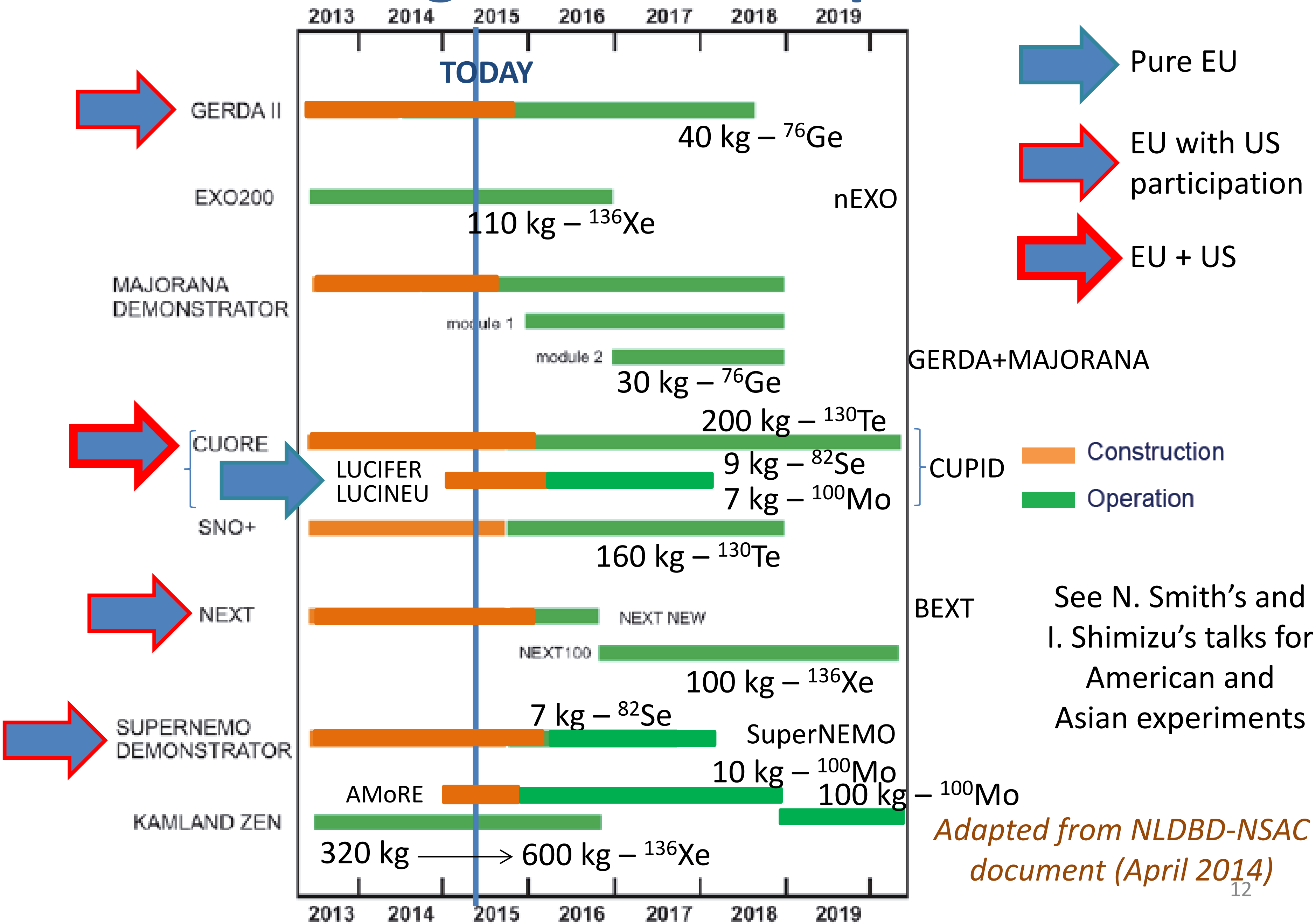
Status



Here and afterwards see F. Iachello's talk

g_A = 1.25 (no quenching)

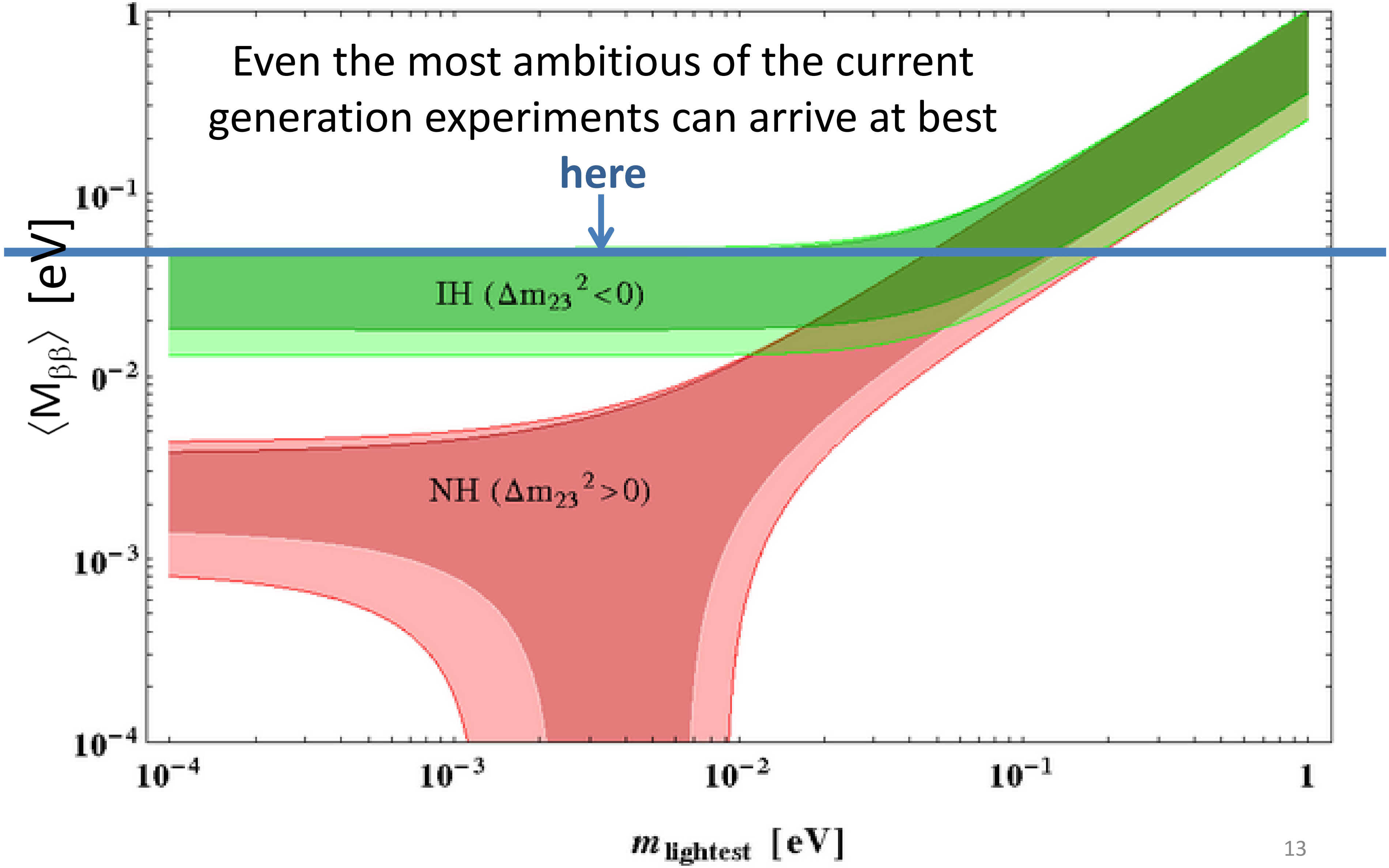
Current-generation experiments



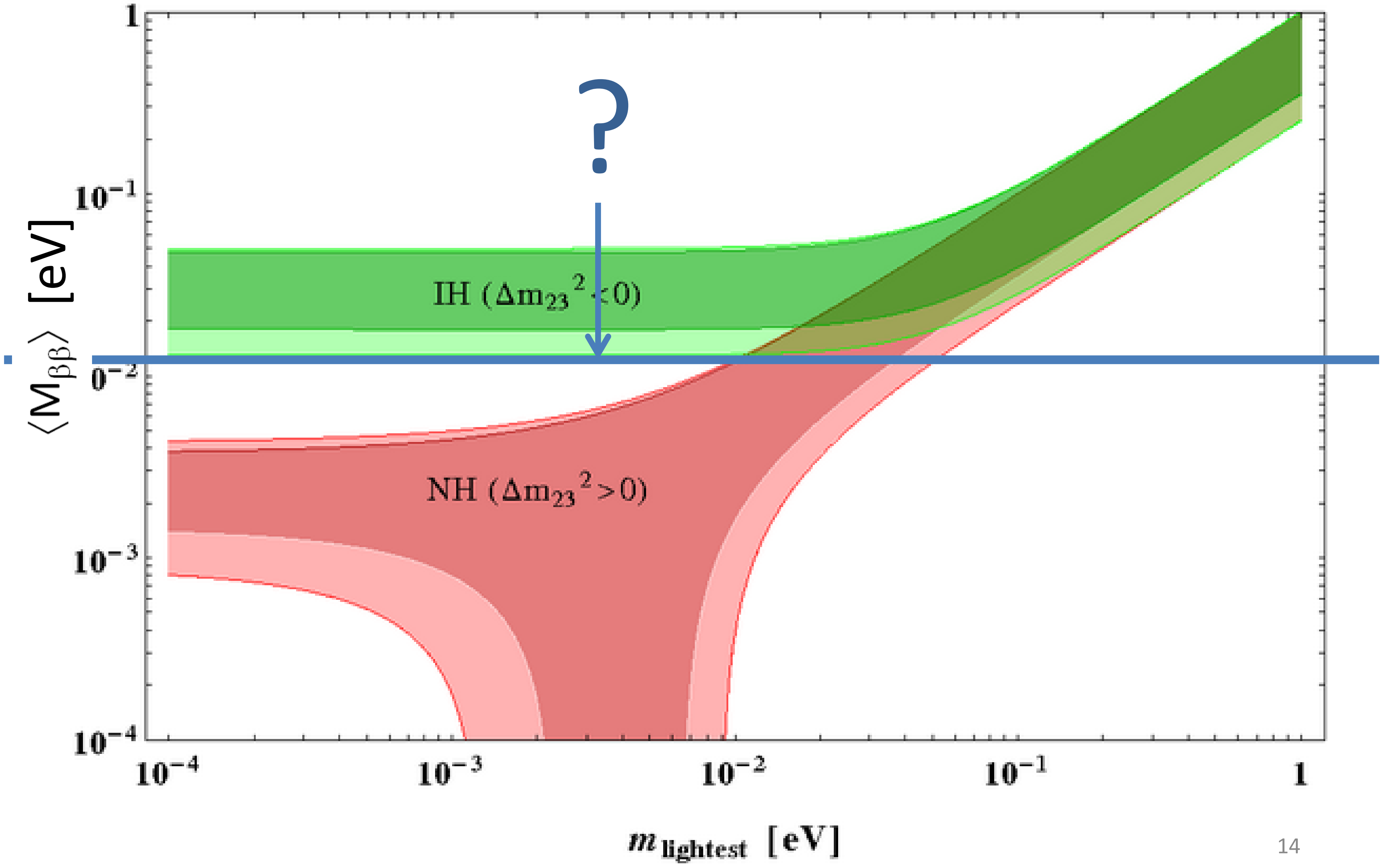
See N. Smith's and I. Shimizu's talks for American and Asian experiments

Adapted from NLDBD-NSAC document (April 2014)

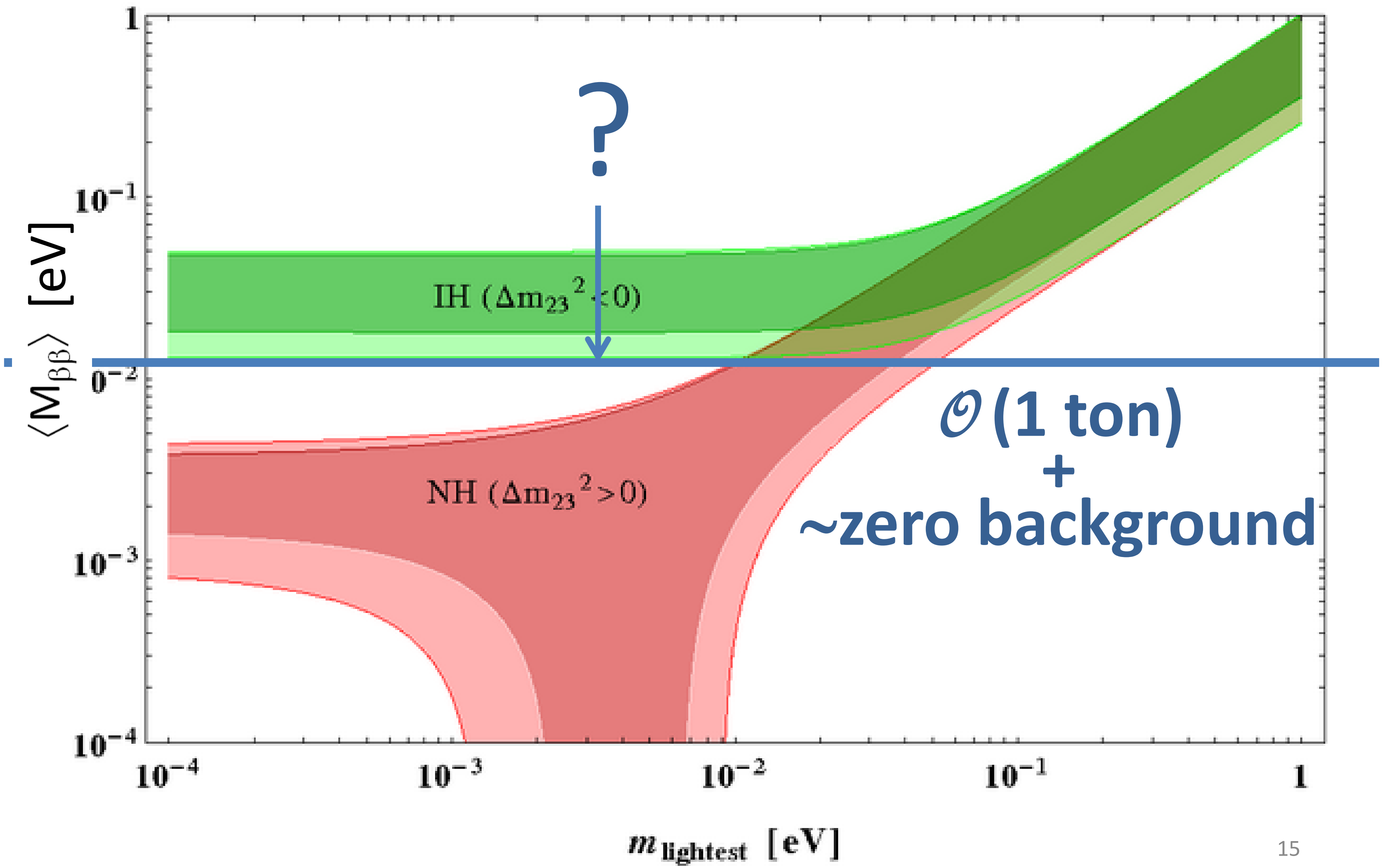
Current-generation experiments



Strategic milestone

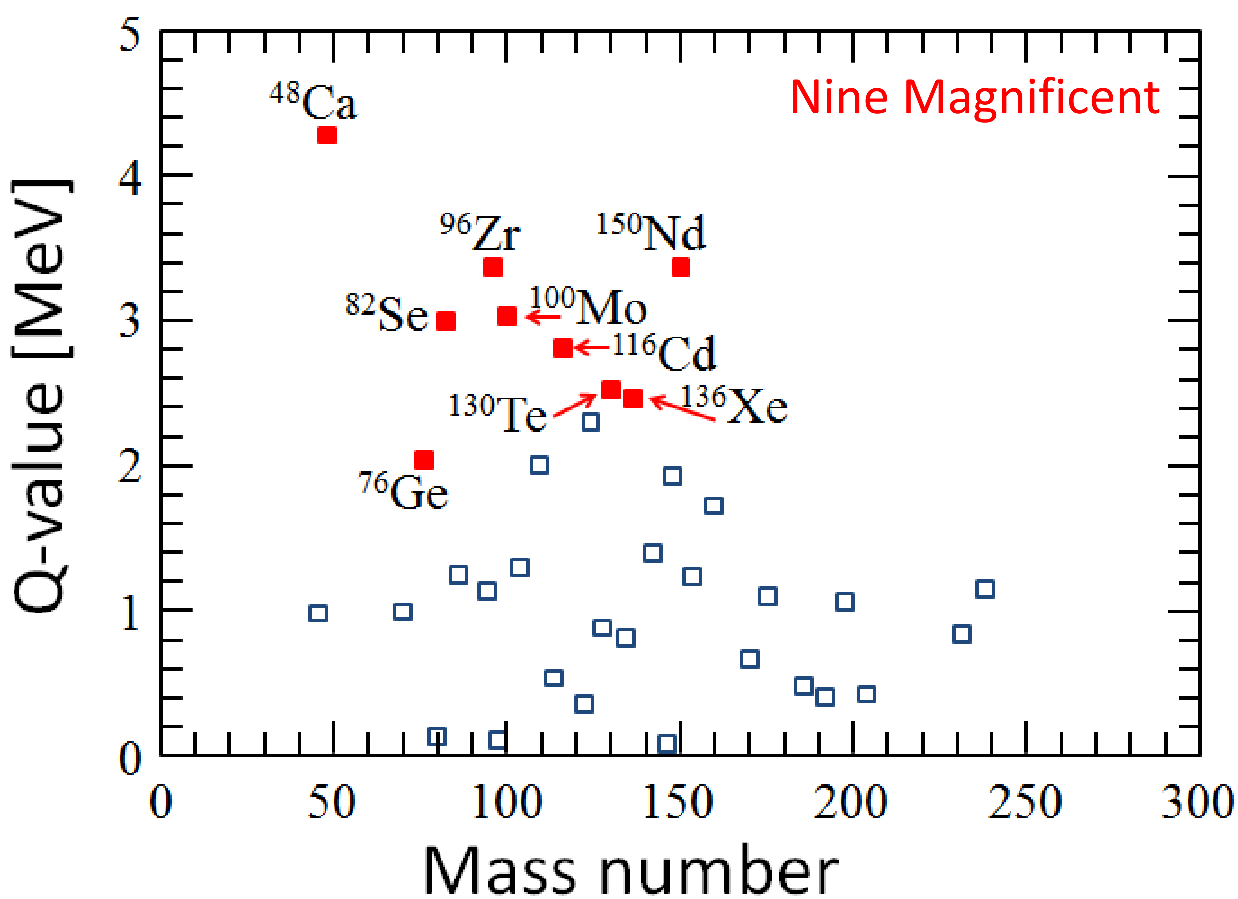


Strategic milestone

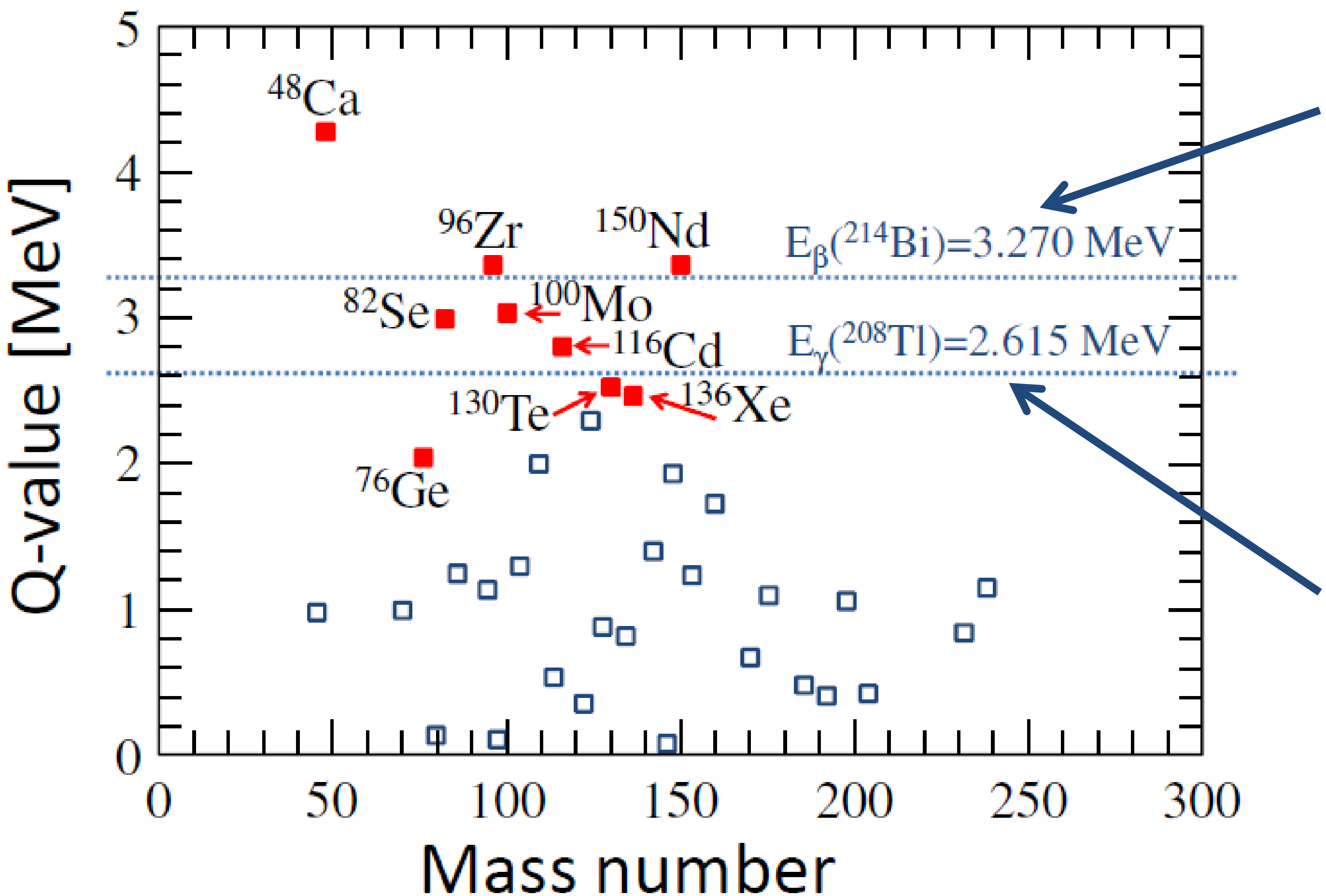


Factors guiding isotope selection

Q is the crucial factor → Phase space: $G(Q,Z) \propto Q^5$
→ Background



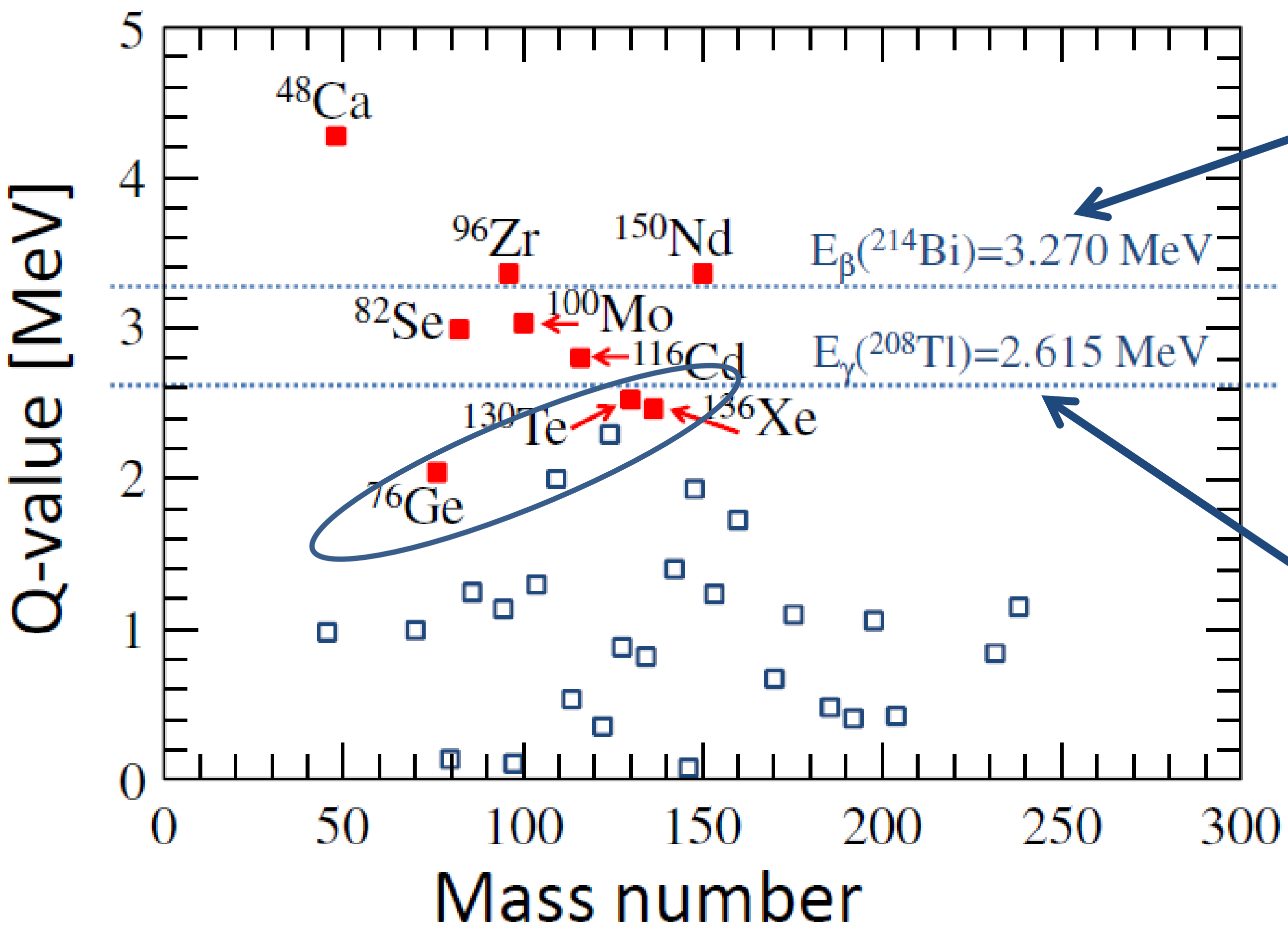
Isotope, enrichment and technique



End-point of ^{222}Rn-induced radioactivity

End-point of natural γ radioactivity

Isotope, enrichment and technique



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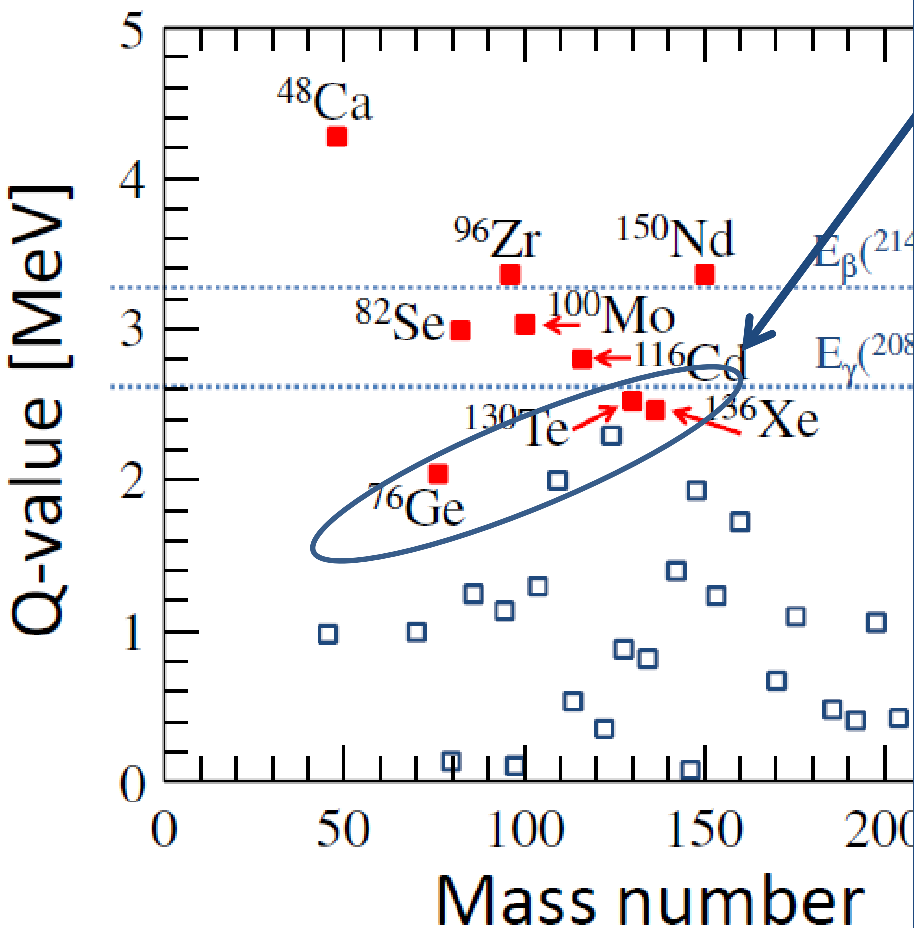
Isotope, enrichment and technique



Excellent technologies are available in the source=detector approach:

- **Ge diodes ⇒ ^{76}Ge (GERDA, MAJORANA)** - ΔE<<1%
- **Bolometers ⇒ ^{130}Te (TeO_2 crystals) (CUORE)** - ΔE<<1%
- **Dissolving the element** (**Te**) in a large liquid scintillator volume **(SNO+)**
- **TPCs (EXO, NEXT), inclusion in large volume of liquid scintillator (KamLAND-Zen) ⇒ ^{136}Xe**

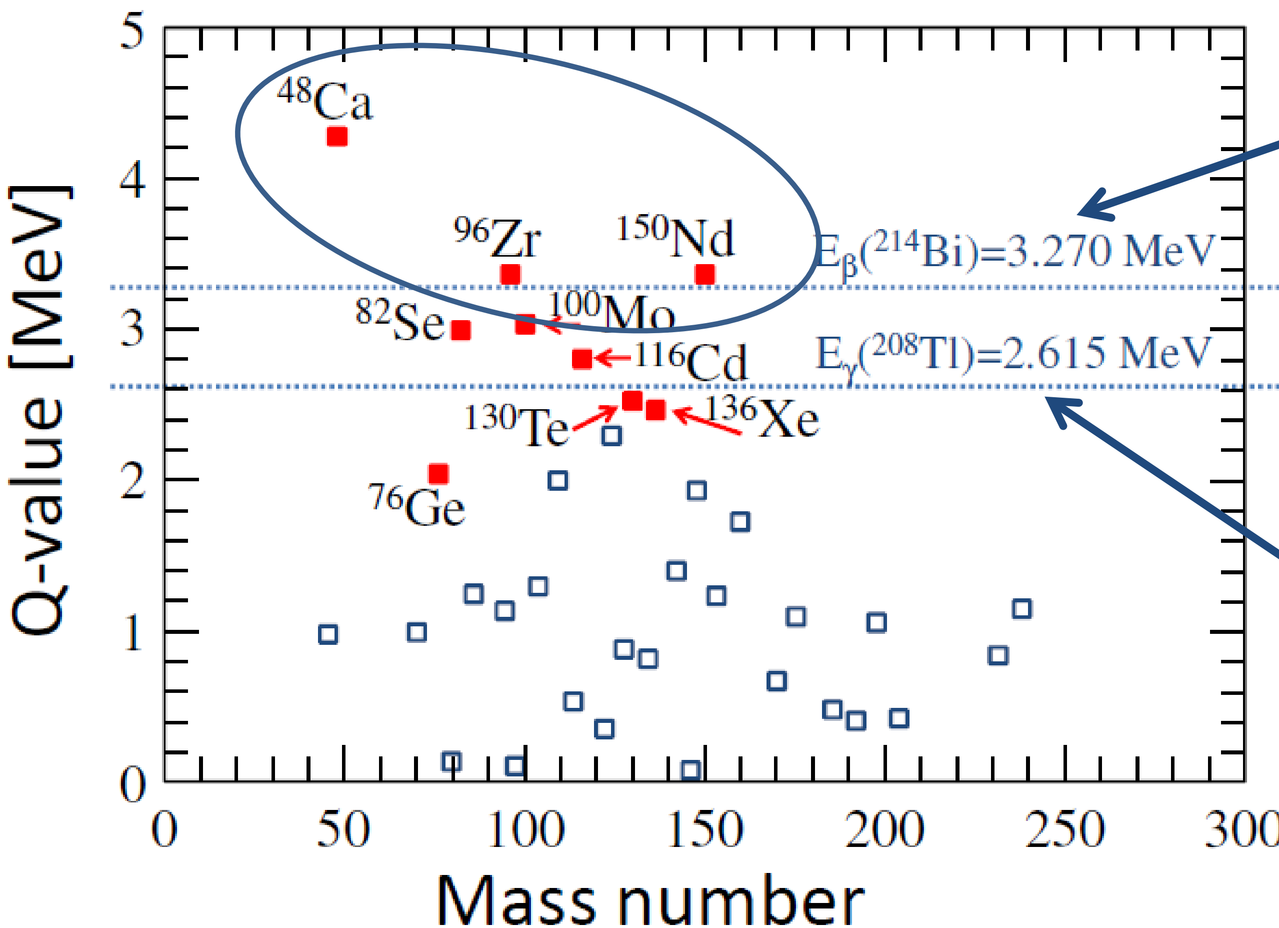
Enrichment is “easy” and for ^{130}Te not necessary at the present level

BUT

Less favorable in terms of background!

In red, projects located in EU

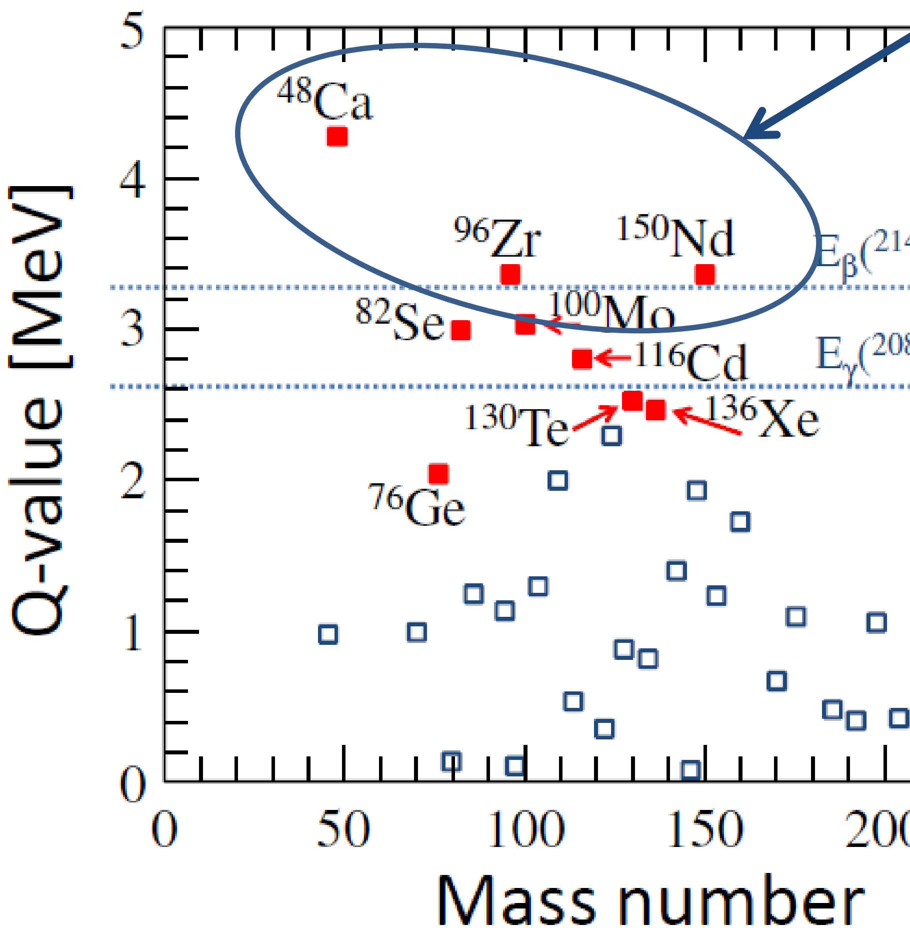
Isotope, enrichment and technique



End-point of ^{222}Rn-induced radioactivity

End-point of natural γ radioactivity

Isotope, enrichment and technique



Almost background free isotopes!

BUT

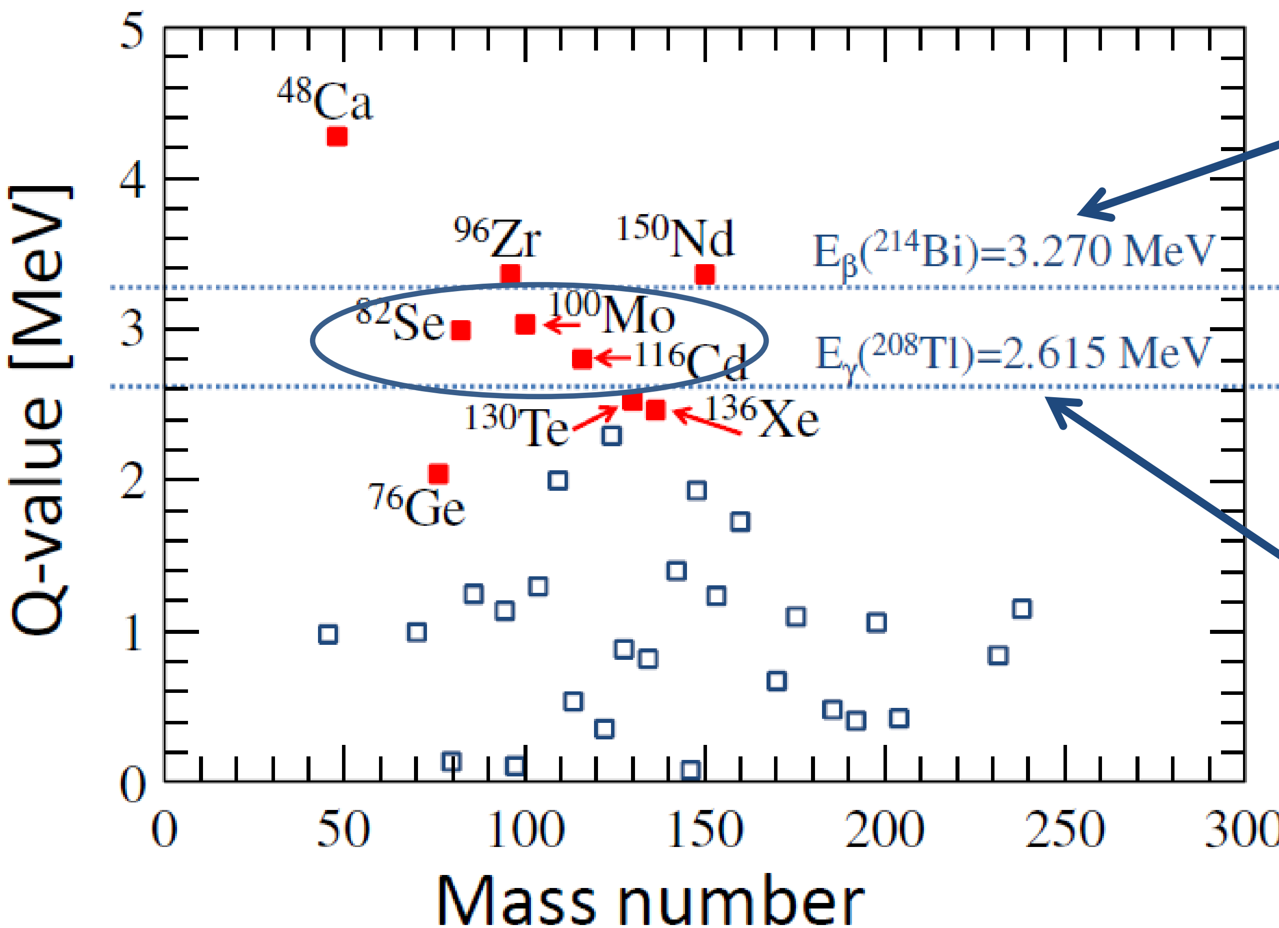
Low isotopic abundance and problematic enrichment (good news about Nd)

Better studied with source≠detector (**tracko-calo approach**) **(SuperNEMO)**

CaF_2 scintillators (and in principle bolometers) are interesting for **^{48}Ca (CANDLES)**

In red, projects located in EU

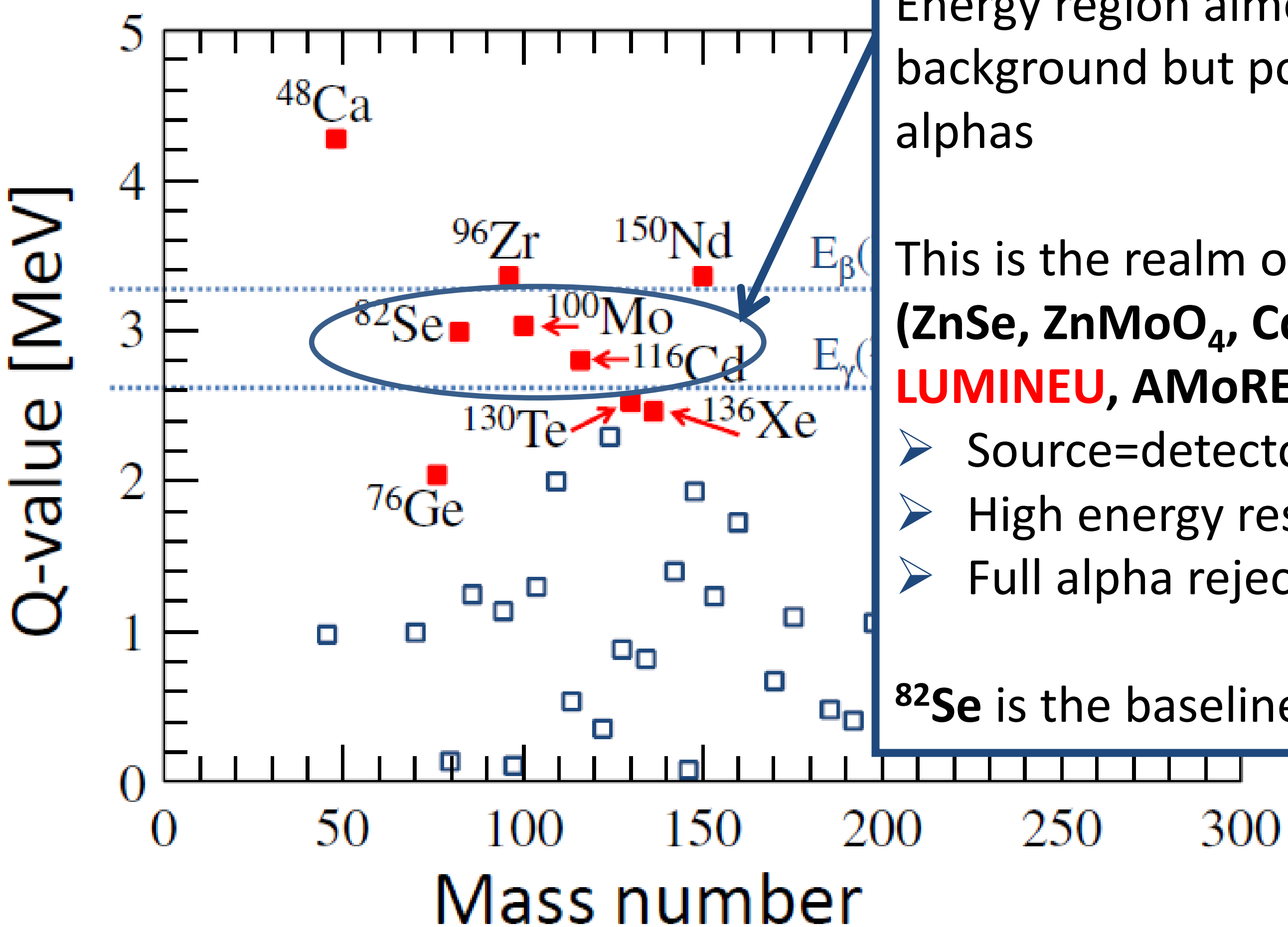
Isotope, enrichment and technique



End-point of ^{222}Rn-induced radioactivity

End-point of natural γ radioactivity

Isotope, enrichment and technique



Energy region almost free from natural γ background but populated by degraded alphas

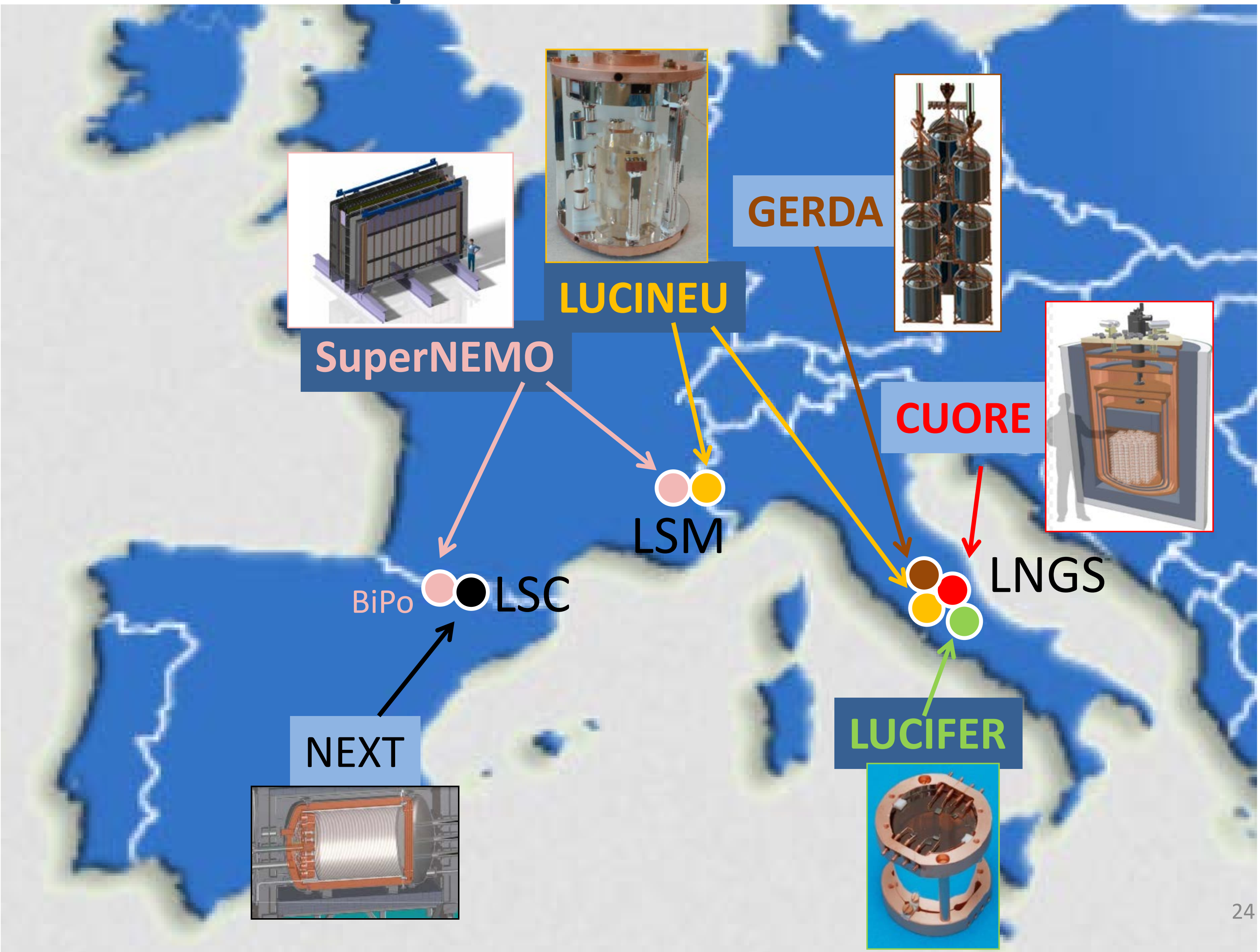
This is the realm of **scintillating bolometers** **(ZnSe, $ZnMoO_4$, $CdWO_4$) (LUCIFER, LUMINEU, AMoRE)** , which offer:

- Source=detector
- High energy resolution - ΔE<<1%
- Full alpha rejection

^{82}Se is the baseline option for **SuperNEMO**

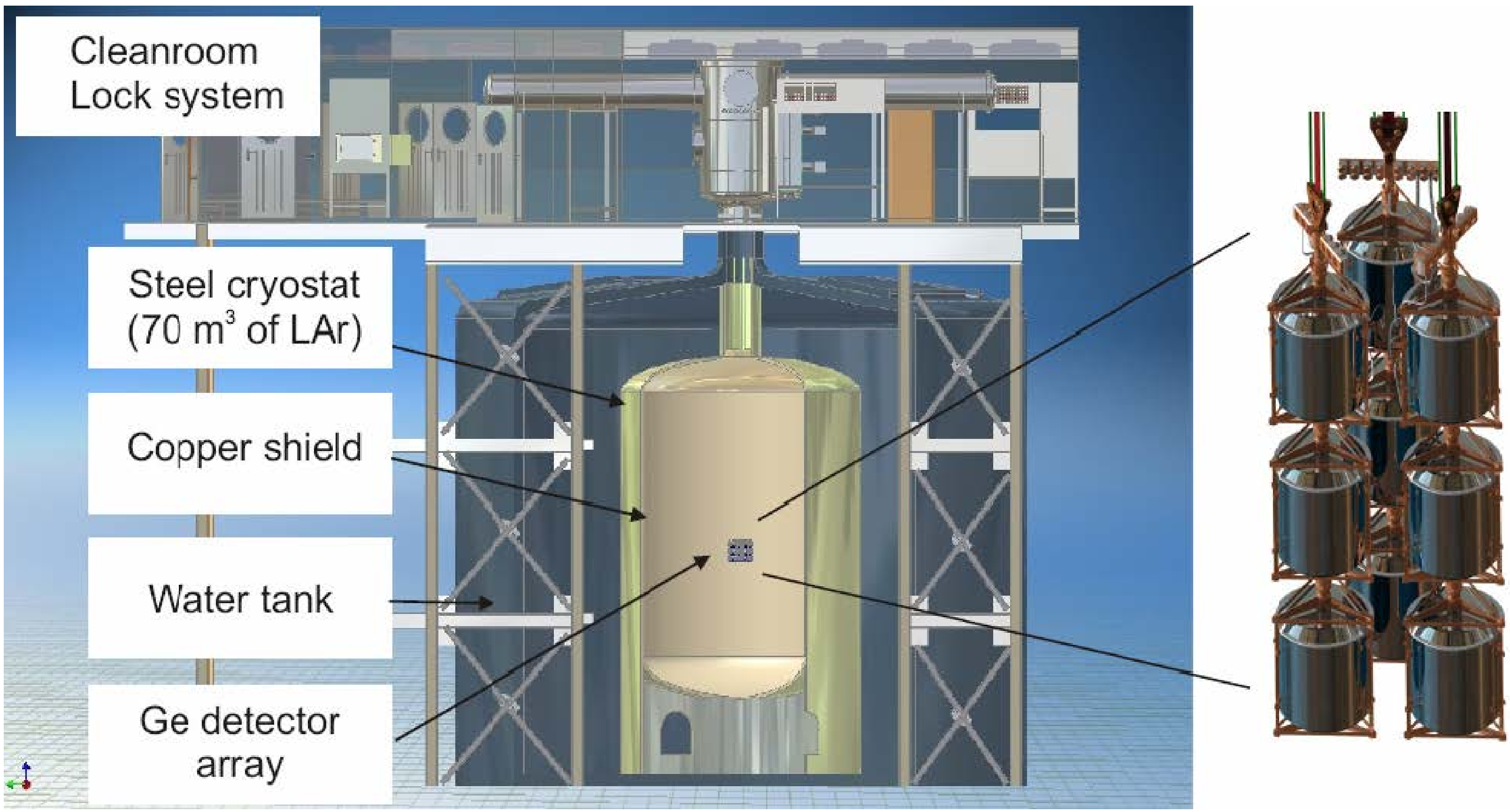
In red, projects located in EU

Experiment location



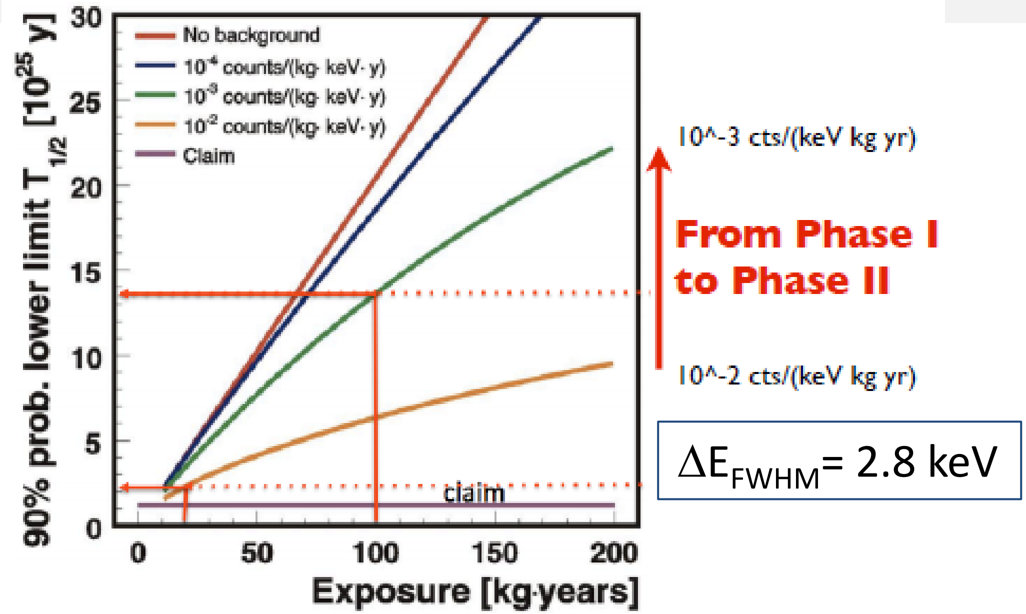
GERDA

Technique/location: bare enriched Ge diodes in liquid argon – LNGS (Italy)
Source: phase 1: Ge - 14.6 kg (coax) + 3 kg (BEGe) – ^{76}Ge enriched at 86% → **1.2x10^{26} nuclides**
phase 2: additional 20 kg → **2.6x10^{26} nuclides**
Sensitivity: phase 1: Klapdor's claim strongly disfavored; phase 2: **80 – 150 meV**
Timeline: GERDA phase 1 is over; GERDA phase 2 is in preparation (data taking in fall 2015)



Mainly from C. Macolino's talk at NEUTEL2015 – Thanks also to B. Schwingenheuer and S. Schoenert

GERDA – phase 2



Scale up to 1 ton

GERDA – MAJORANA common effort

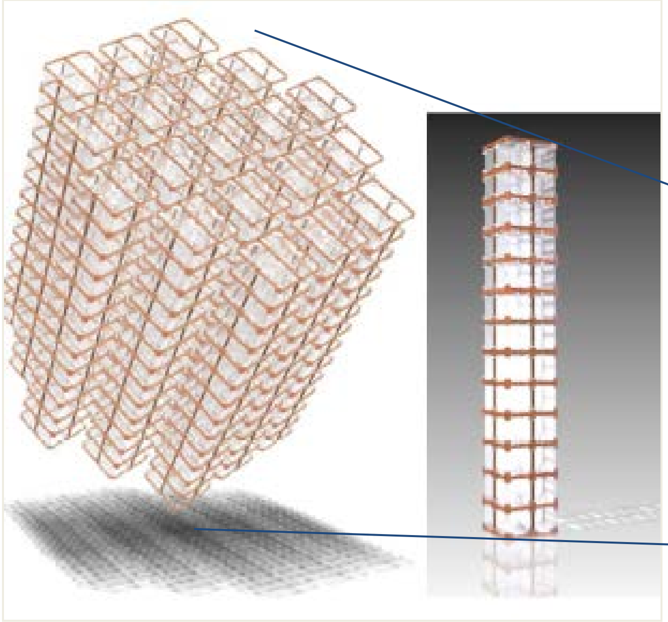
How to get a higher sensitivity for the Phase II:

- Phase II transition currently ongoing at LNGS
- increase mass: additional 30 enriched BEGe detectors (about 20 kg)
- **reduce background** by a factor of 10 w.r.t. GERDA Phase I:
  1. by Pulse Shape Analysis (BEGe improved performance)
  2. by LAr scintillation light for background recognition and rejection

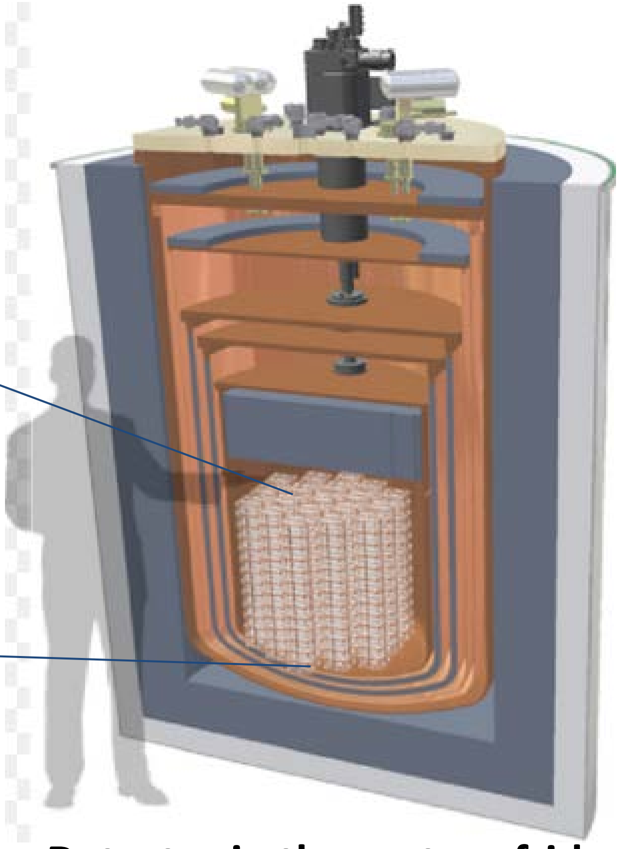
First commissioning data from Phase II in these days!

CUORE

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 in 2015 – **all 19 towers completed** – **cryostat under test**



Structure of the detector



Detector in the custom fridge

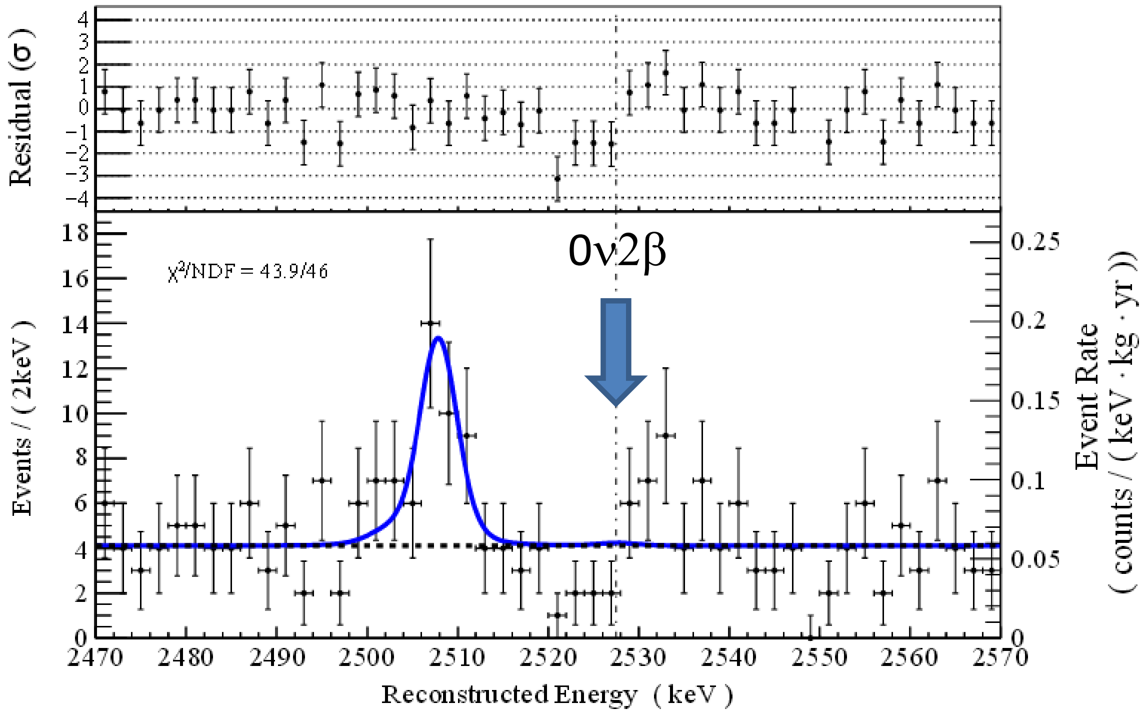
CUORE-0

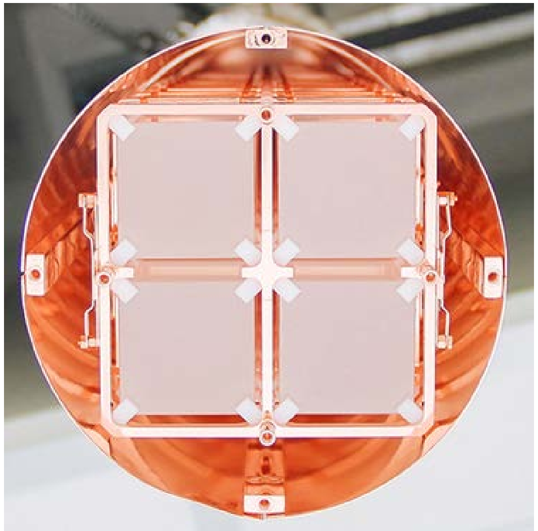
- First CUORE tower now operating in the former Cuoricino cryostat
- Excellent detector and background results
- Background substantially reduced with respect to Cuoricino

Confirmation of the CUORE background target: **10^{-2} counts/(keV kg y)**

$\Delta E_{FWHM} = 4.8$ keV

arXiv:1504.02454





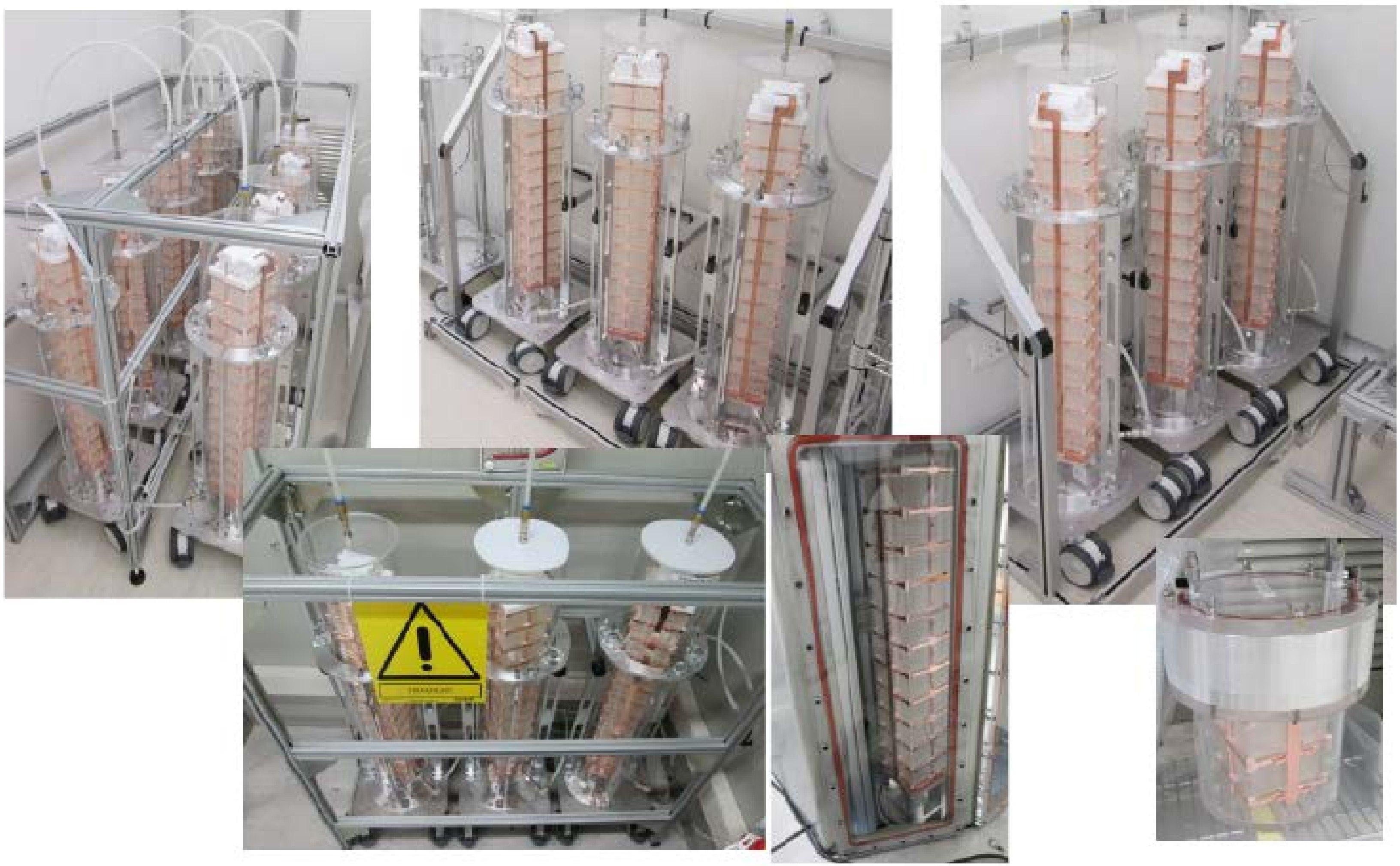
Combining results with Cuoricino

$$T_{1/2} > 4 \times 10^{24}\ \mathrm{y}$$

$$\langle M_{\beta\beta} \rangle < 270 - 650\ \mathrm{meV}$$

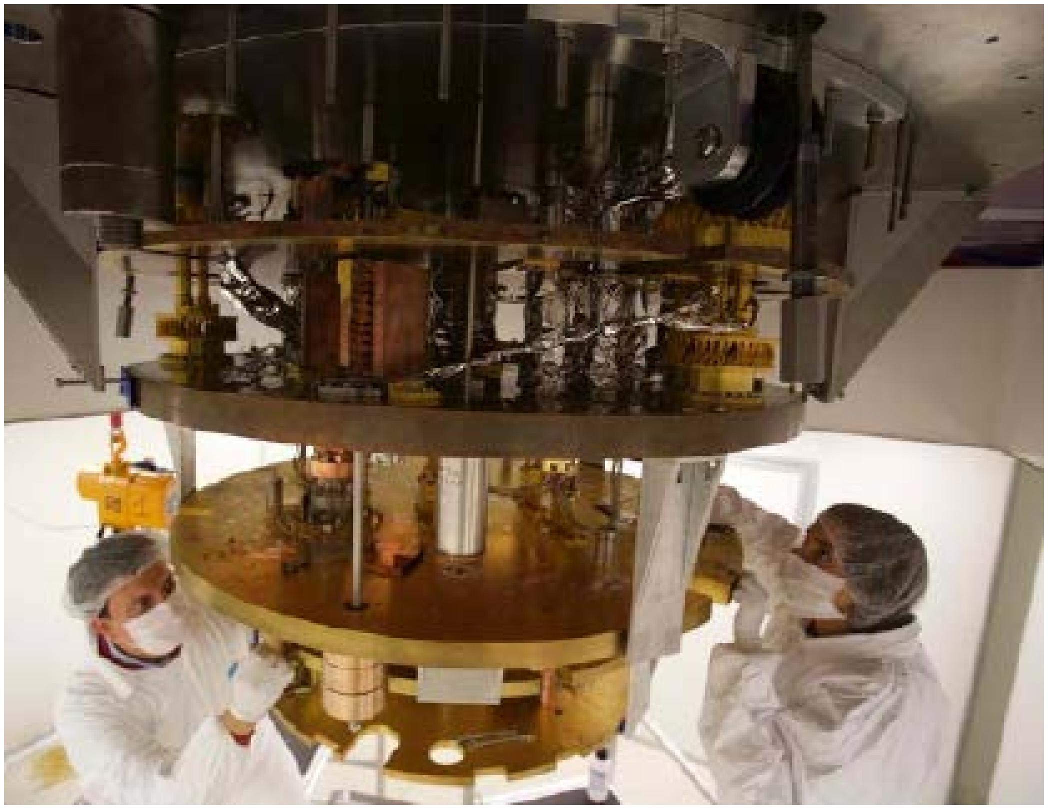
CUORE

The 19 towers



CUORE

CUORE cryostat – 6 mK achieved over ~400 kg of Cu and ~1 m^3 volume
→ The coldest contiguous cubic meter in the Universe!



CUORE operation: end 2015

$T_{1/2} > 9.5\text{x}10^{26}$ → $\langle M_{\beta\beta} \rangle < 51 – 133$ meV

CUPID

CUORE Upgrade with Particle IDentification

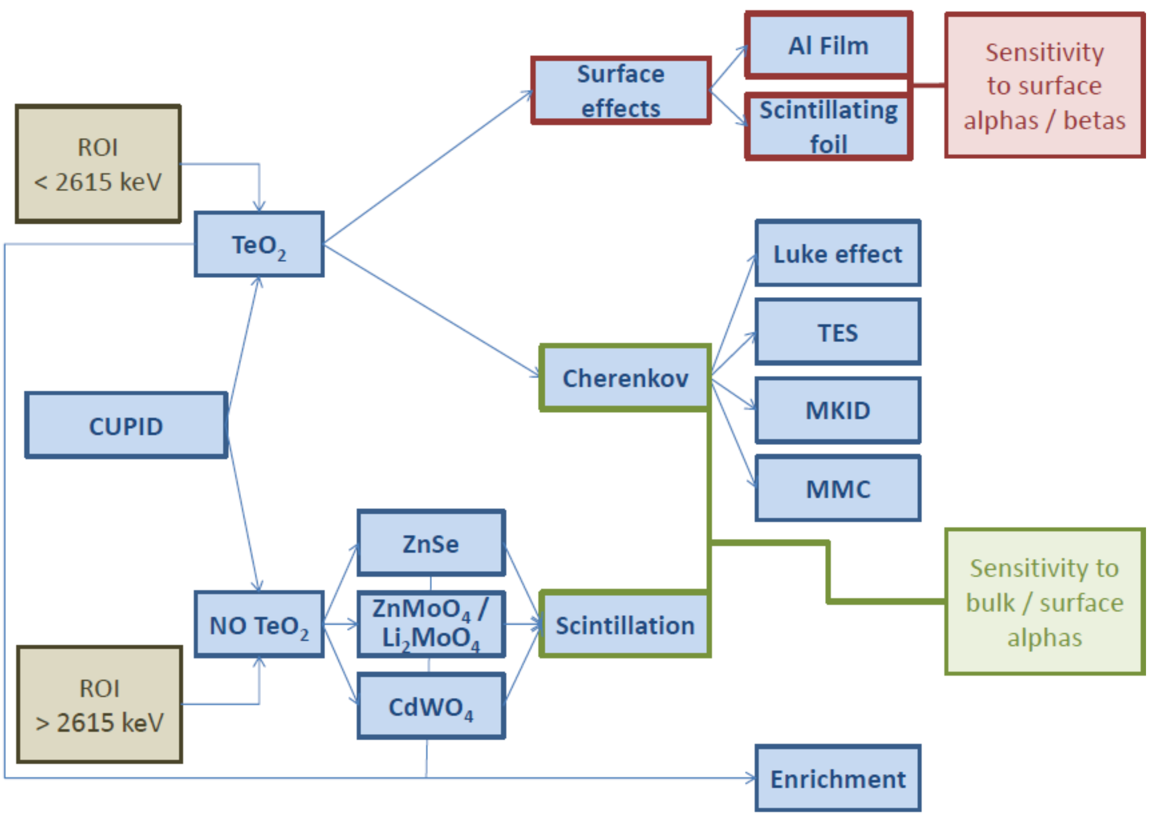
Basic idea: CDR in ~two years

Scale up to 1 ton

Use CUORE infrastructure with

- **enriched crystals**
- upgraded technology to get **0 background at ton × y scale** (10-15 meV sensitivity)

In particular, get rid of the dominant alpha background



CUPID group of interest
(in formation)
100 persons from CUORE
30 persons from outside

arXiv:1504.03612v1

CUPID

CUORE Upgrade with Particle IDentification

CDR in ~two years

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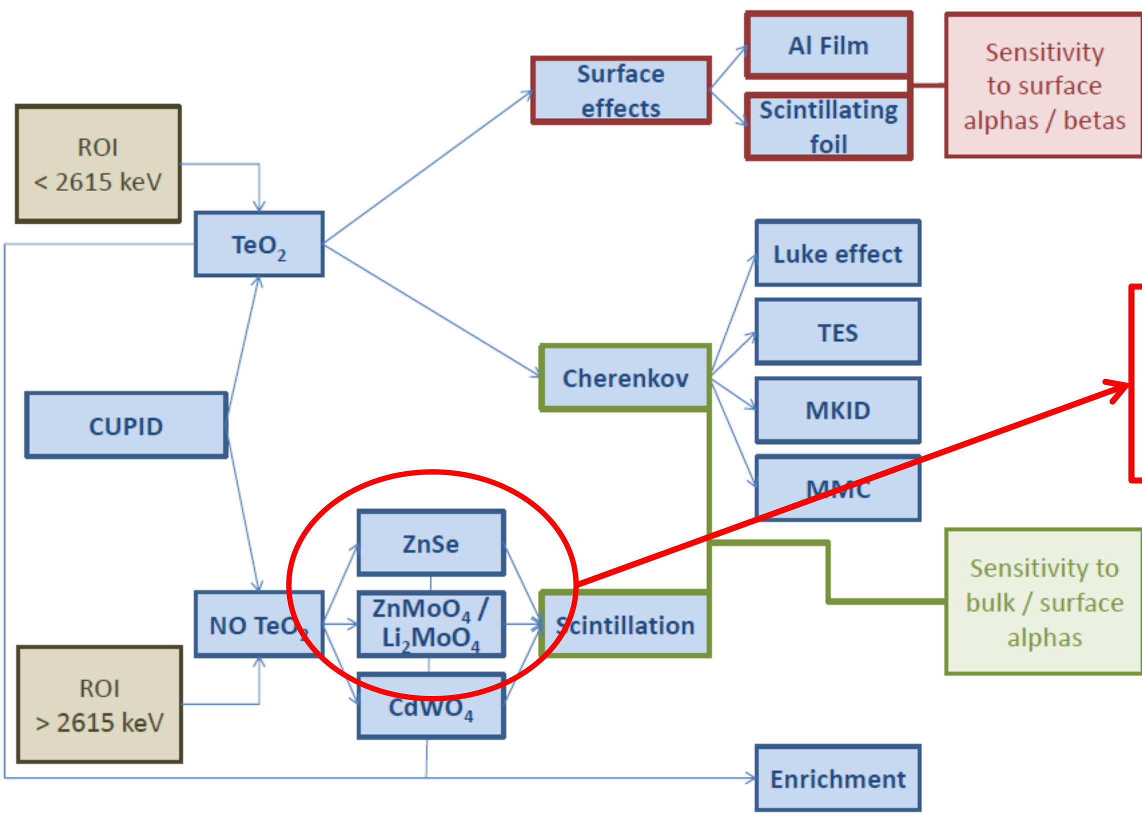


LUCIFER – ZnSe

LUMINEU, **LUCINEU** – $ZnMoO_4$

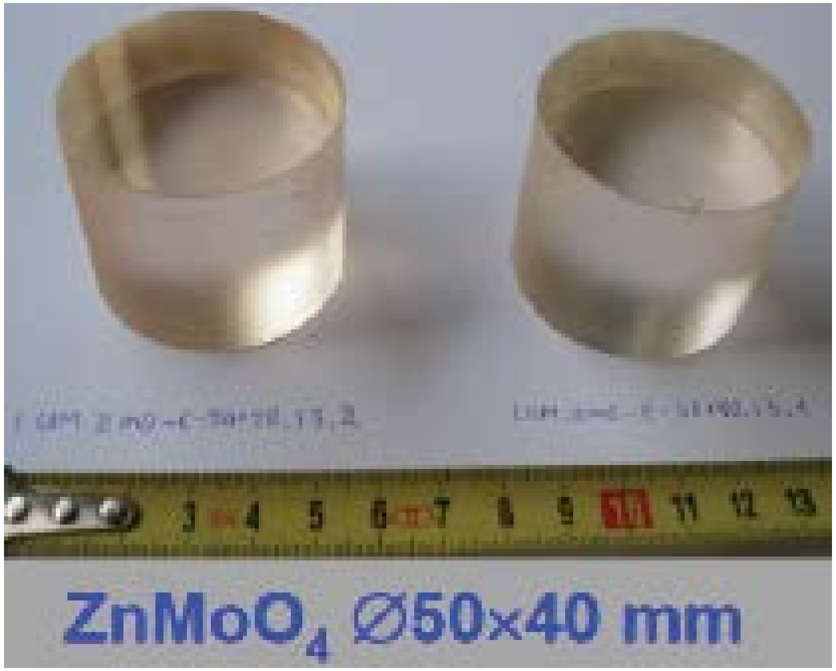
Pilot experiments in the framework of CUPID

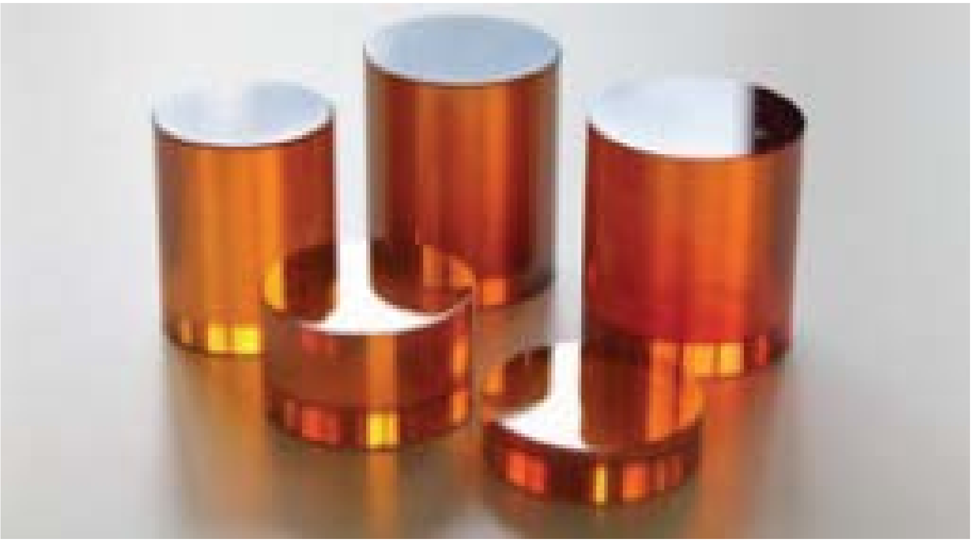
arXiv:1504.03612v1

CUPID

LUCIFER, LUCINEU

Basic idea:
Use scintillating bolometers for full alpha/beta separation





ZnSe

Phys. Lett. B 710 (2012) 318–323

JINST 9 (2014) P06004

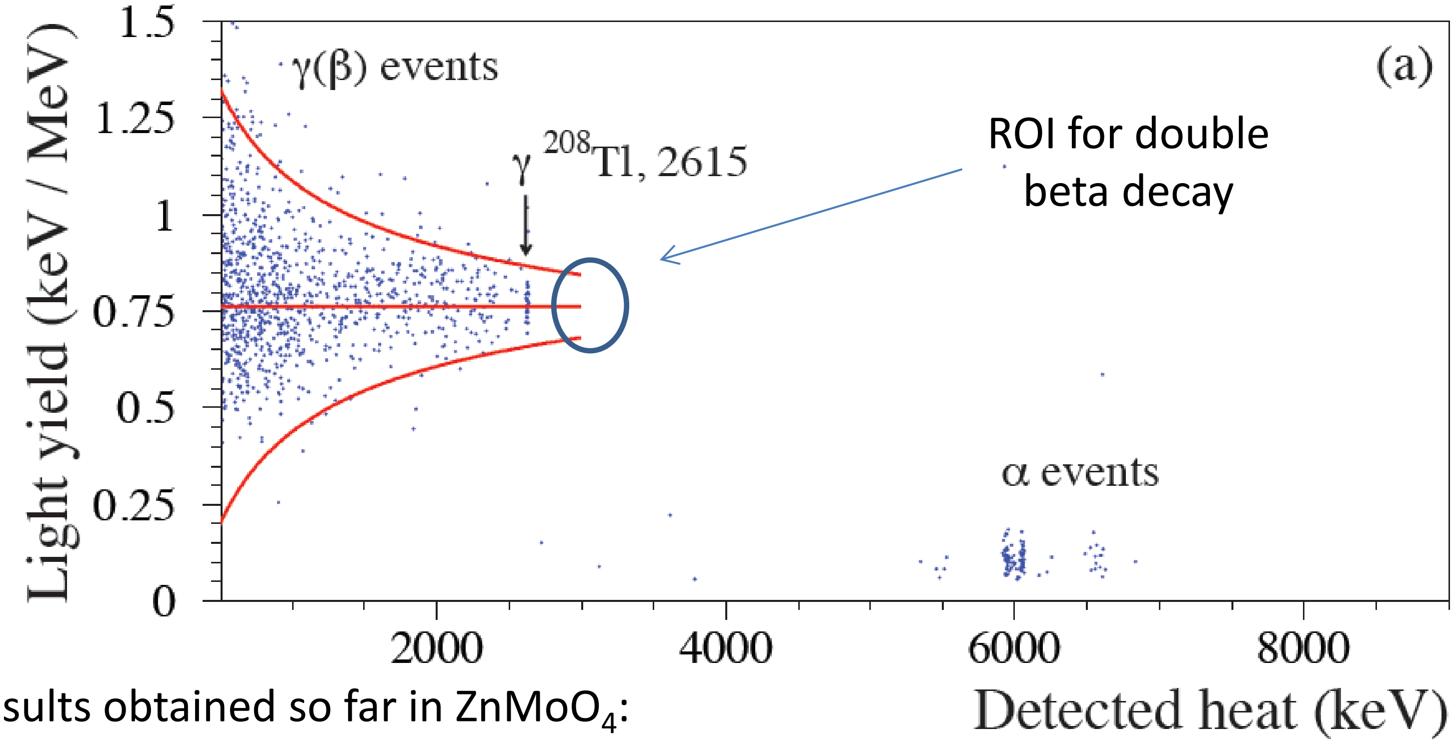
JINST 8 (2013) P05021

Adv. High En. Phys. 2013 (2013) 237973

CUPID

LUCIFER, LUCINEU

Example of α background rejection: 313 g $ZnMoO_4$ crystal in Modane



Results obtained so far in $ZnMoO_4$:

extreme radiopurity < 4 μBq/kg U, Th

α **rejection factor** > 99.9 %

+ high energy resolution (5 keV FWHM),

Q-value > 2615 keV

Eur. Phys. J. C 72 (2012) 72

arXiv :1502.01161

Background ~ 10^{-4} counts/(keV kg y)

Eur. Phys. J. C 74(2014)3096

Background < 0.5 counts (y x ton)

CUPID

LUCIFER, LUCINEU

Enriched crystal growth in progress

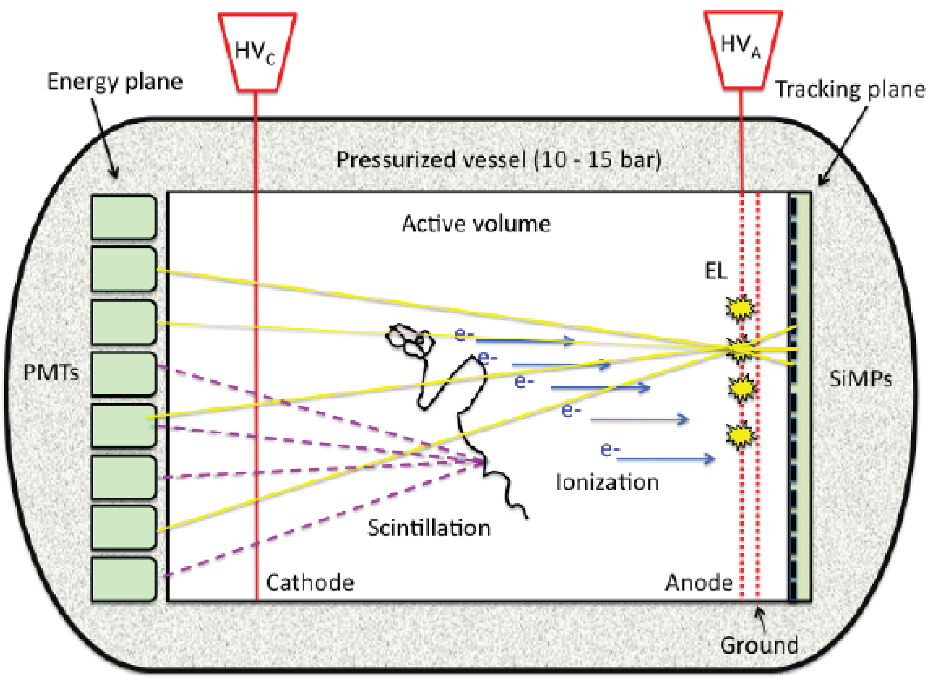
Eur. Phys. J. C 74 (2014) 3133

	LUCIFER	LUCINEU
Crystal	ZnSe	Li_2MoO_4/$ZnMoO_4$
$0\nu\beta\beta$ isotope	^{82}Se	^{100}Mo
Enrichment	95%	95%
Total mass	17 kg	16 kg
Isotope mass	~9 kg	~7 kg
Laboratory	LNGS	Modane+LNGS
$\tau_{1/2}$	~2.4x10^{25} y(6)	~1.2x10^{25} y(2)
Sensitivity	~100-300 meV	90-300 meV

Start data taking in 2016

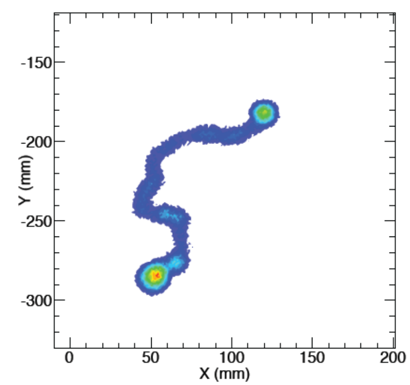
NEXT

Technique/location: High pressure (10-15 bar) enriched Xe gas TPC – Canfranc (Spain)
Source: ^{136}Xe enriched at 90% - 89 kg → **3.9x10^{26} nuclides**
Sensitivity: **67 - 187 meV** in 300 kg × y
Timeline: small scale (~1 kg) prototypes extensively tested
intermediate scale prototype (~10 kg) – NEW – under commissioning in Canfranc
NEW physics run in 2016 – 2ν detection and background model validation
full **NEXT-100** – start physics run beginning 2018



Energy: both electroluminescence and direct scintillation are recorded in the photosensor plane behind the transparent cathode
Tracking: exploit electroluminescence light generated at the anode and recorded in the photosensor plane behind it

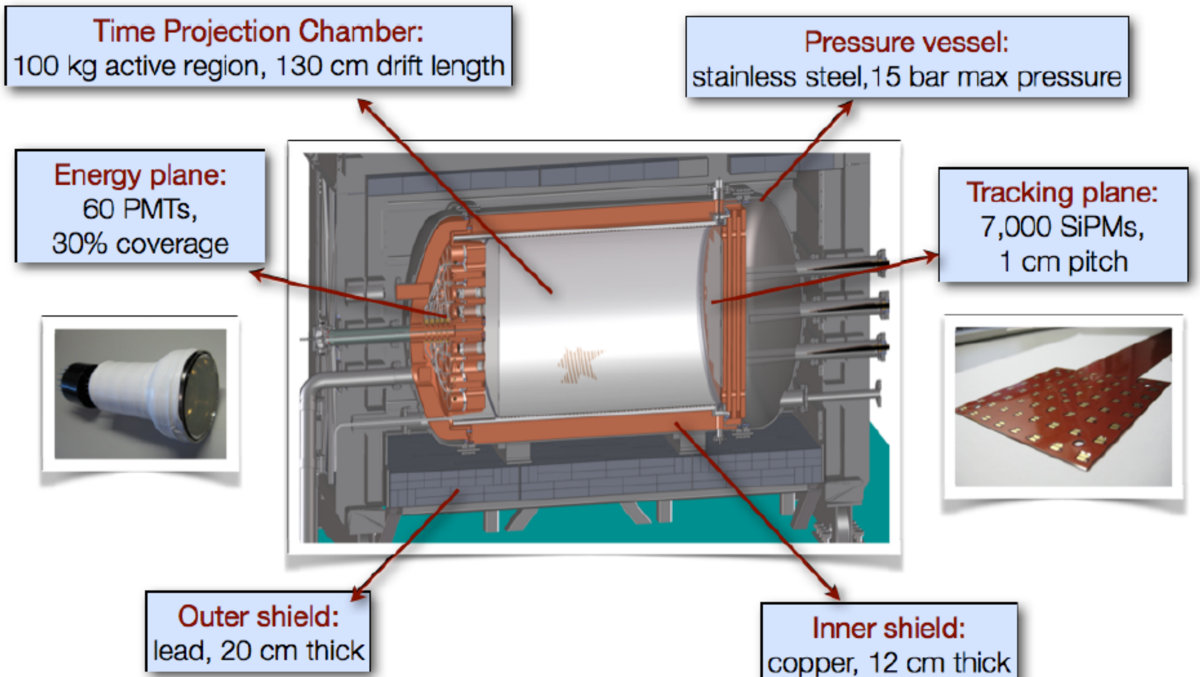
Double beta decay event (MC)



Thanks to J.J. Gomez-Cadenas

NEXT

Scheme of NEXT100



The merit of this technology is to combine

- Reasonable energy resolution (use of electroluminescence)
- Topology of the event (use of gaseous target)

ΔE_{FWHM}= 20 keV (expected)

Expected background (simulation): 5×10^{-4} counts/(keV kg y)

$T_{1/2} > 7\text{x}10^{25}$ y

in 300 kg $\times$ y

$\rightarrow$ $\langle M_{\beta\beta} \rangle$ < 67 – 187 meV

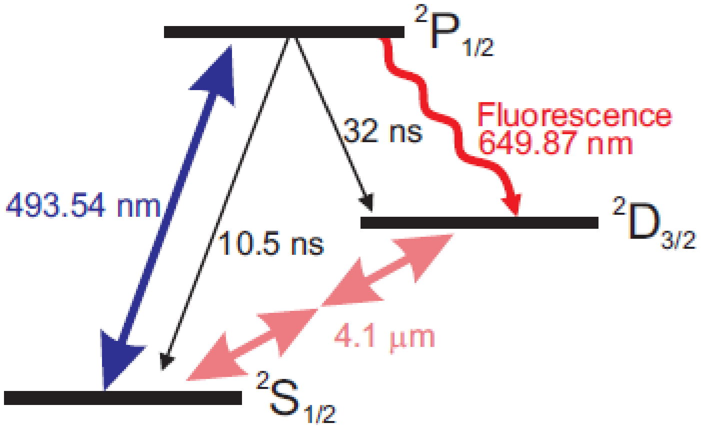
NEXT → BEXT

Scale up to 1 ton

NEXT-like 1-3 ton ^{136}Xe TPC with major upgrades with respect to NEXT

Objectives:

- ΔE_{FWHM} = 0.5% → 12 keV
- Better radiopurity of the critical materials
- Magnetic field (improvement of multi-site – single-site event ejection)
- Ba (daughter nucleus) tagging (as proposed in EXO – easier in gas)
  → investigation of Ba tagging using a fluorescent organic molecule



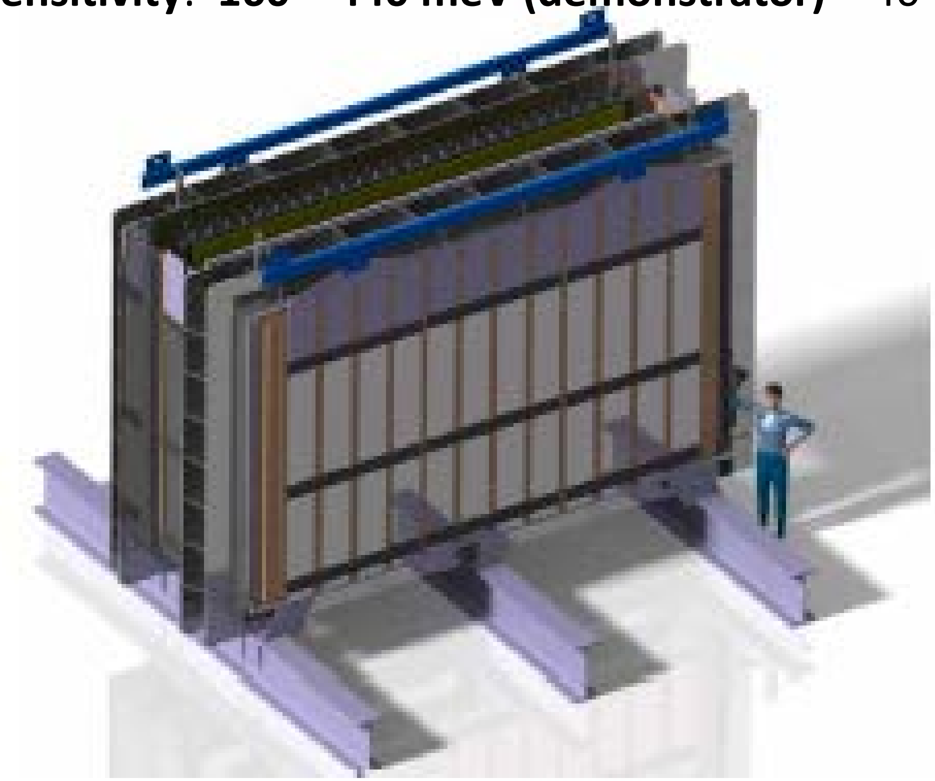
SuperNEMO

Technique/location: tracking Geiger cells + plastic scintillator – Modane (France) and possibly other laboratories – evolution of NEMO-3 – **Source ≠ Detector**

Source: baseline: ^{82}Se – ^{150}Nd under consideration (it depends on enrichment possibility) assuming 100 kg of materials : **7x10^{26} ^{82}Se nuclides - 2.5x10^{26} ^{150}Nd nuclides**

Timeline: demonstrator module (~7 kg) operational in 2016
end 2017 → decision on full scale SuperNEMO (100 kg – 20 modules)

Sensitivity: **160 – 440 meV (demonstrator)** – 40 -100 meV (full SuperNEMO)



Unique feature: precise tracking
Full reconstruction of 2 beta events

- Single electron energy spectrum
- Angular correlation

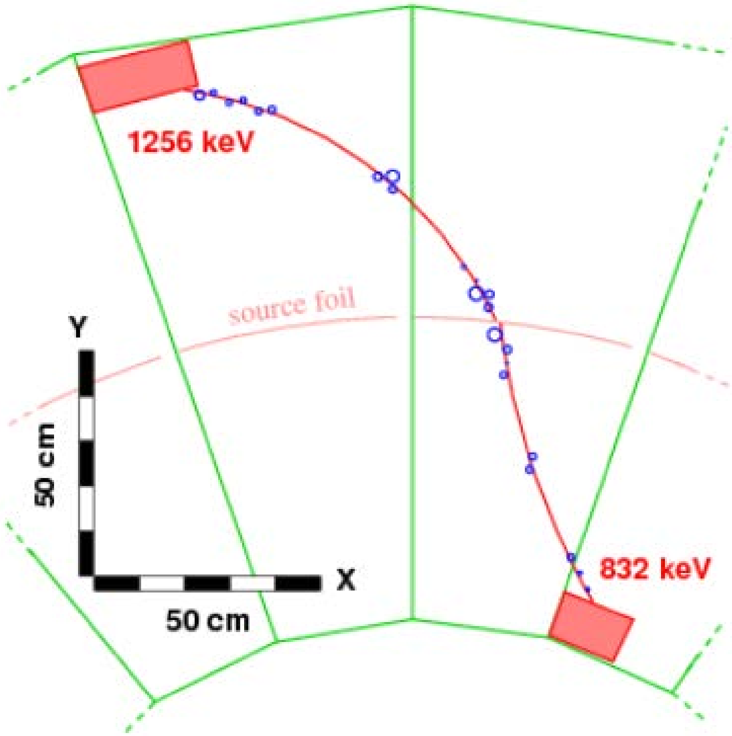
↓

- Possible identification of the mechanism
- Excellent background discrimination (except 2ν background)

ΔE_{FWHM}= 120 keV

Thanks to F. Piquemal and X. Sarazin

SuperNEMO



Accurate full reconstruction of double beta decay event (NEMO-3)

Unfavorable surface/volume ratio

↓

scale-up to 1 ton is difficult

However, if **large-scale Nd enrichment** is feasible, the potential of the experiment will increase substantially:

- Phase space (^{150}Nd) = 4 × Phase space (^{82}Se)
- Zero background achievable

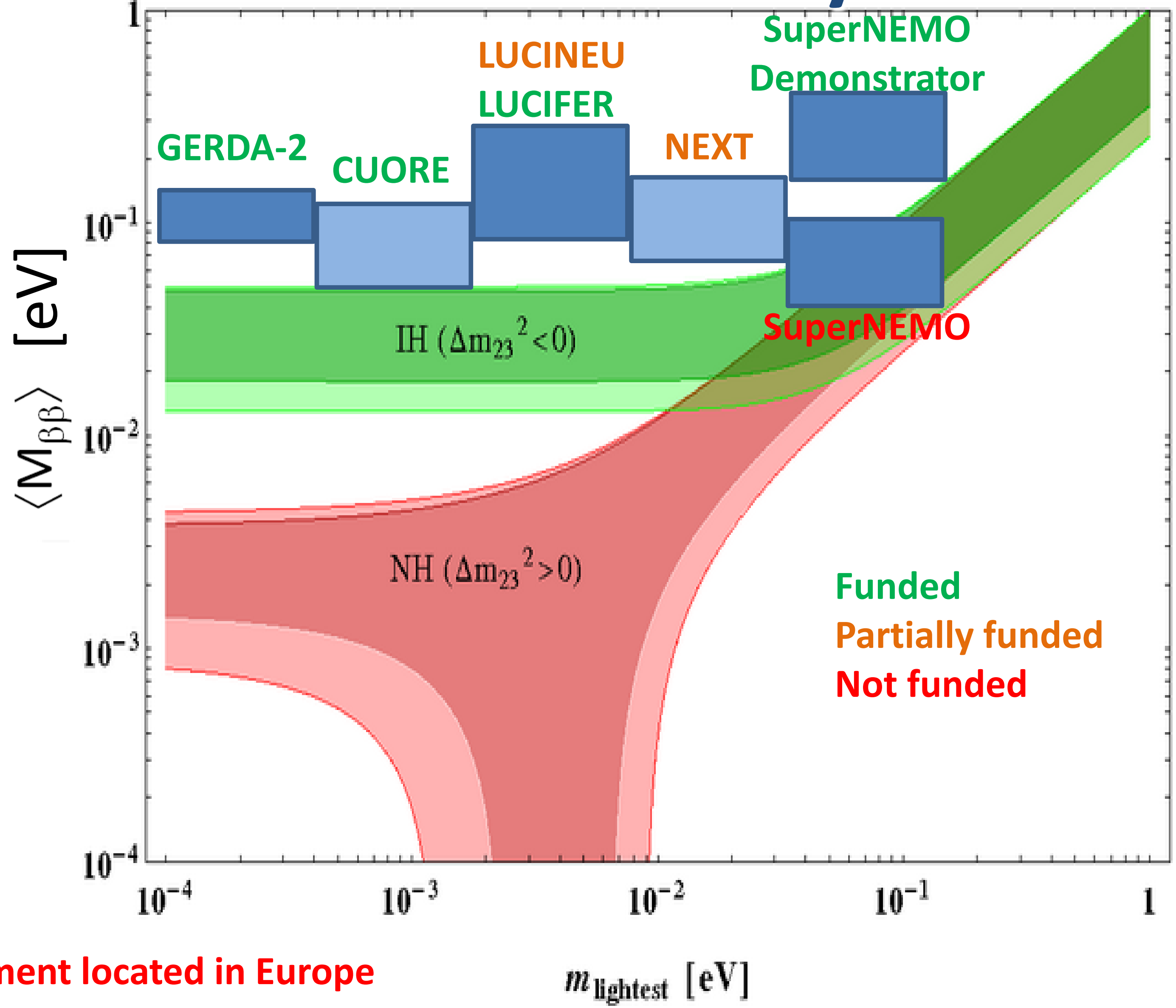
(in case of ^{82}Se
2 bkg-counts/(y 100kg)
are expected)

Good news

^{150}Nd ~ 500 g recently delivered

(gaseous Nd compound at high temperature)

Current-generation experiments: sensitivity



Experiment located in Europe

Summary of energy resolution and background levels

ISOTOPE/ EXPERIMENT	ΔE_{FWHM} [keV]	b [counts/(keV kg y)]	BKG in ROI [counts/(ton y)]
^{76}Ge / GERDA-2	2.8	10^{-3}	2.8
^{130}Te / CUORE	4.8	10^{-2}	48
^{136}Xe / NEXT	20	5×10^{-4}	10
^{82}Se / SuperNEMO	120	1.5×10^{-4}	18
^{100}Mo / LUCINEU	5	3×10^{-4}	1.5
^{82}Se / LUCIFER	15	3×10^{-4}	4.5

$b \times \Delta E_{FWHM}$

Possible routes to 1 ton

Collaborations are already thinking to improve/upgrade their technology in view of 1 ton set-up

In order to select the best(s) technology(ies) for 1 ton, it is necessary to get the complete scenario of the current generation experiments and demonstrators

Wait 2-3 years for a sensible decision

Possible routes to 1 ton

❶ Fluid-embedded source way

- SNO+ (^{130}**Te** 200 kg) – SNO+ (^{130}**Te** 800 kg)
- KamLAND-Zen → KamLAND2-Zen
  (1 ton ^{136}**Xe**, higher energy resolution, pressurized Xe)
- EXO-200 → nEXO (5 ton liquid ^{136}**Xe** TPC)
- **NEXT-100 → BEXT** (1-3 ton high pressure ^{136}**Xe** TPC)

Low energy resolution
250 keV FWHM
80 keV FWHM

^{214}Bi line not resolved from $0\nu2\beta$ ^{136}Xe signal

Wait for NEXT-100

❷ Crystal source way

Extreme background demand
(10^{-4} counts/keV/kg/y at 2 MeV)

- **GERDA 2 → GERDA+MAJORANA** → 1 ton ^{76}Ge (Ge diodes)
- **CUORE** ⟶ **CUPID** (1 ton ^{130}**Te** or ^{100}**Mo** or ^{82}**Se**) (bolometers)
  LUCIFER, LUMINEU, LUCINEU
  AMoRE (^{100}**Mo** 10 kg) AMoRE (^{100}**Mo** 200 kg)

Cryogenics
Crystallization
Enrichment

Impact of enrichment cost

Isotope	Abundance	Price/ton [M$]
^{76}Ge	7.61	~ 80
^{82}Se	8.73	~ 80
^{100}Mo	9.63	~ 80
^{116}Cd	7.49	~ 180
^{130}Te	34.08	~ 20
^{136}Xe	8.87	~ 5-10
^{150}Nd (?)	5.6	> 200

Adapted from A. Barabash J. Phys. G: Nucl. Part. Phys. 39 (2012) 085103

Conclusions

$\langle M_\beta \rangle$

- KATRIN will take date in 2016, with sensitivity 0.2 eV
- R&D in progress with low temperature calorimeters

$\langle M_{\beta\beta} \rangle$

- Klapdor's claim strongly disfavored by GERDA - 1
- Present sensitivity in the 150-400 meV range:
  GERDA–1, EXO, KamLAND-Zen, CUORE-0
- New experiments located in Europe will approach the inverted hierarchy region:
  CUORE, GERDA - 2
- ~10 kg demonstrators will aim to validate new technologies in Europe:
  SuperNEMO demonstrator, NEW (NEXT-10), LUCIFER+LUCINEU
- Two routes towards the 1 ton scale - in Europe (with important US contributions):
  CUPID, BEXT, GERDA+MAJORANA
- No complete elements for down-selection of technologies before 2-3 years