

Neutrinoless Double Beta Decay Searches

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Outline

Introduction

- Goal
- NME
- Experimental Approaches
- Sensitivity
- Experimental Techniques

Present Status

Short term Experiments

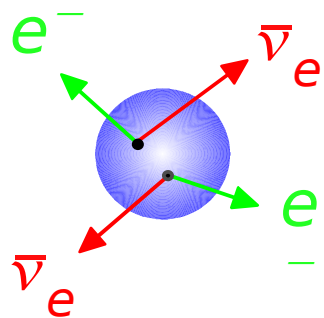
Conclusions

Nuclear Double Beta Decay

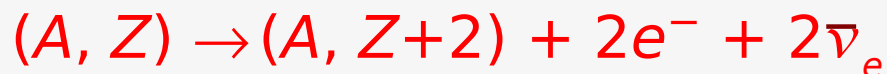
Rare Nuclear Decay



occurs in a number of even-even nuclei in A even multiplets



$\beta\beta(2\nu)$: two neutrino mode



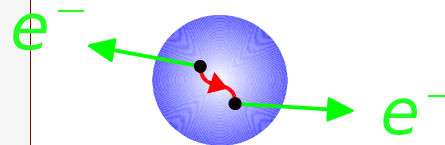
allowed in Standard Model
second order weak transition

$\beta\beta(0\nu)$: neutrinoless mode



not allowed in Standard Model

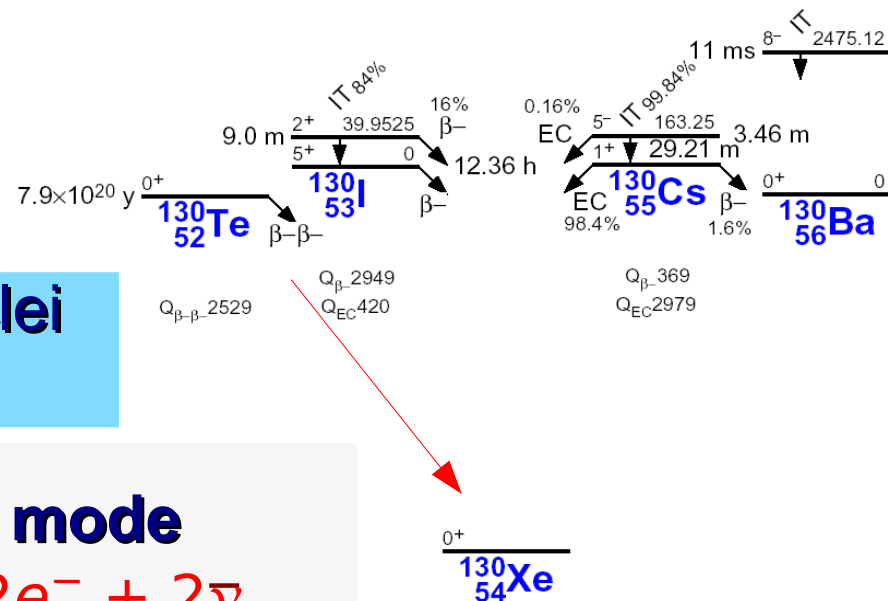
Neutrino nature and mass scale



$$\Delta L=2$$

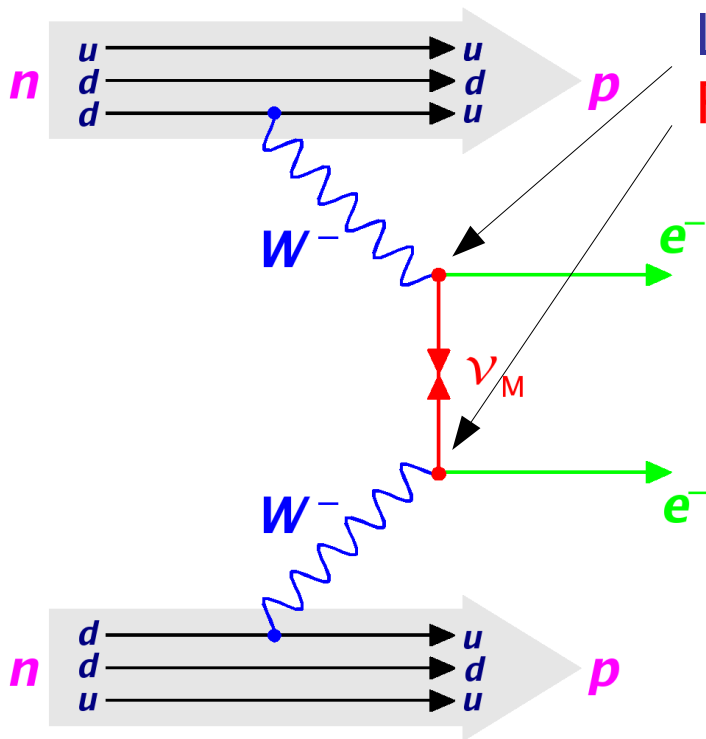
$$\nu = \nu^c$$

$$m_\nu > 0$$



Unique process to measure mass and nature of the neutrino

Mass Mechanism: exchange of a light neutrino



LH neutrino ($L=-1$) is absorbed at one vertex

RH antineutrino ($L=1$) is emitted at the other vertex

• Majorana particle

• Helicity flip

In the limit of small neutrino masses, the amplitude is proportional to (**effective neutrino mass**)

$$\begin{aligned}\langle m_\nu \rangle &= \sum_k U_{ek}^2 m_k \\ &= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3\end{aligned}$$

Seven unknown quantities:

- 3 masses: m_k
- 2 angles: θ_{12} and θ_{13}
- 2 CP violating phases: α and β

Only one experimental
constraint

More complementary
measurements needed!

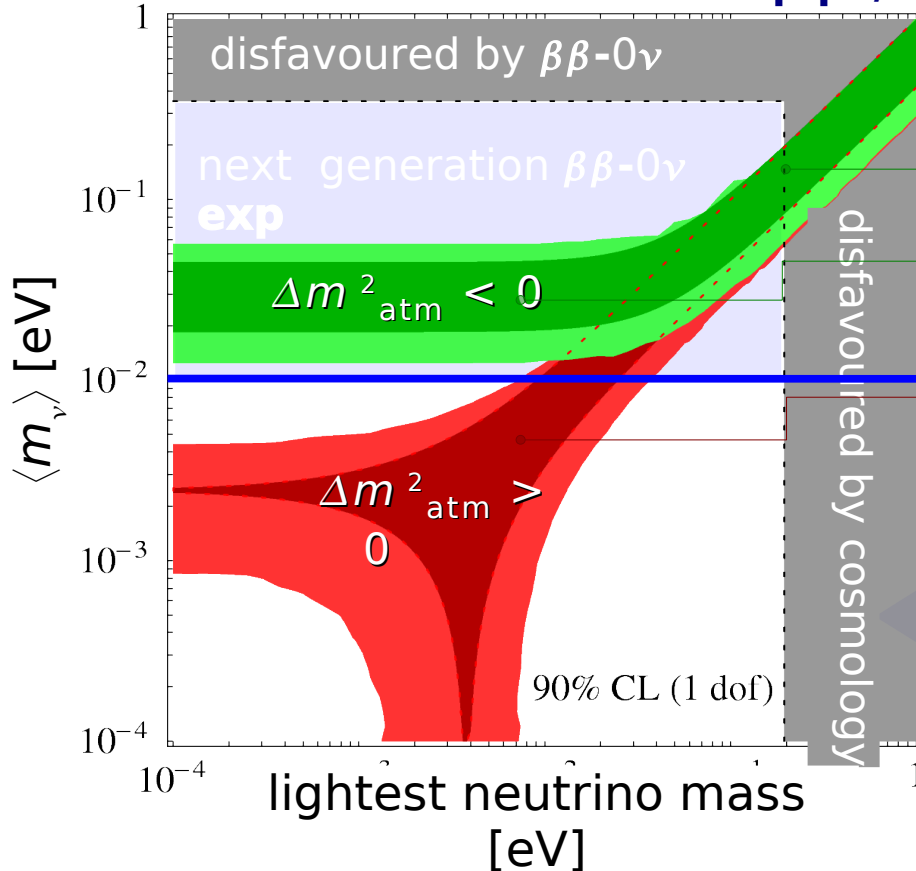
Neutrino mass hierarchies

Hierarchies: neutrino mass ordering scenarios compatible with results of neutrino oscillation experiments

The three constrained parameters can be plot as a function of the **lightest neutrino mass**

Two bands appear in each plot, corresponding to **inverted** and **direct** hierarchy
The two bands merge in the **degenerate** case (the only one presently probed)

A.Strumia and F.Vissani.: hep-ph/0503246



degeneration: $m_1 \approx m_2 \approx m_3$

inverse hierarchy: $m_3 \ll m_1 \approx m_2$

normal hierarchy: $m_1 \approx m_2 \gg m_3$

$$\langle m_\nu \rangle = f(m_{\text{low}}, U_{ek})$$

Present bounds

Combined informations:

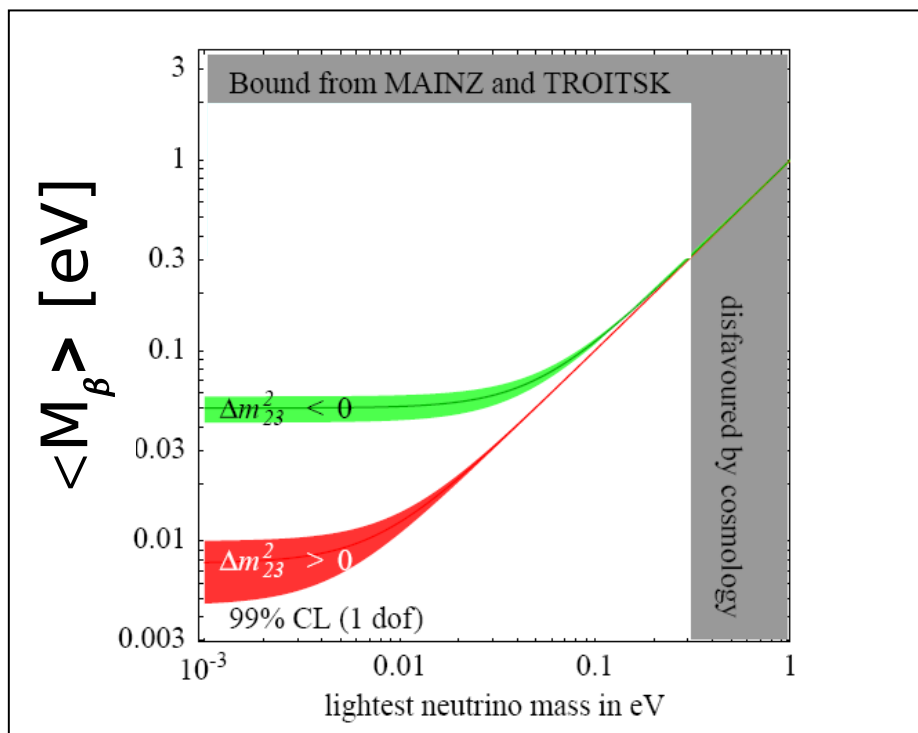
cosmology

single β -decay

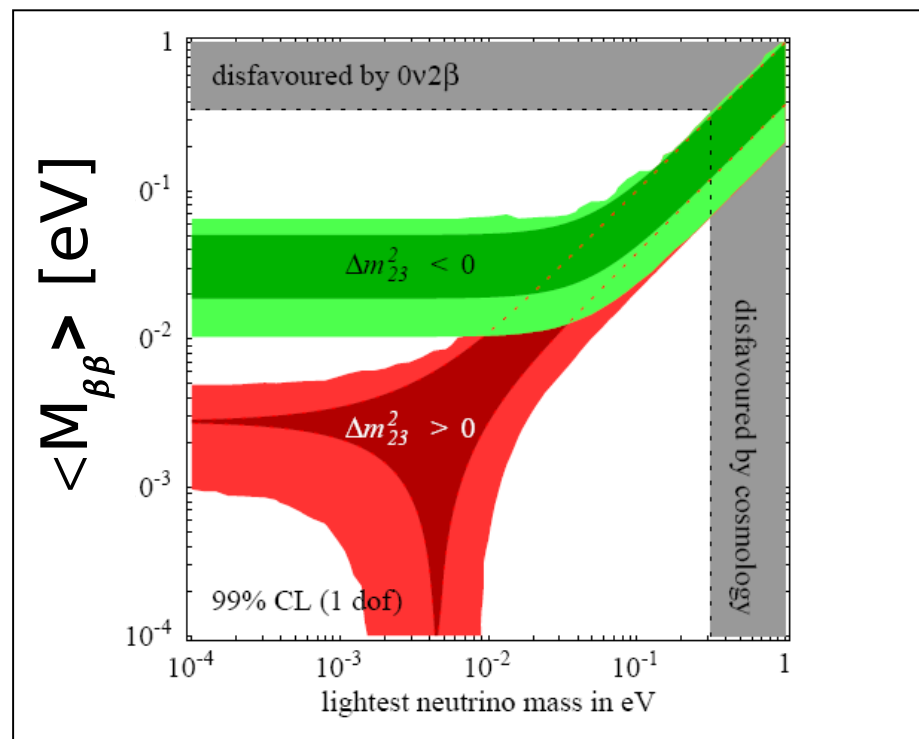
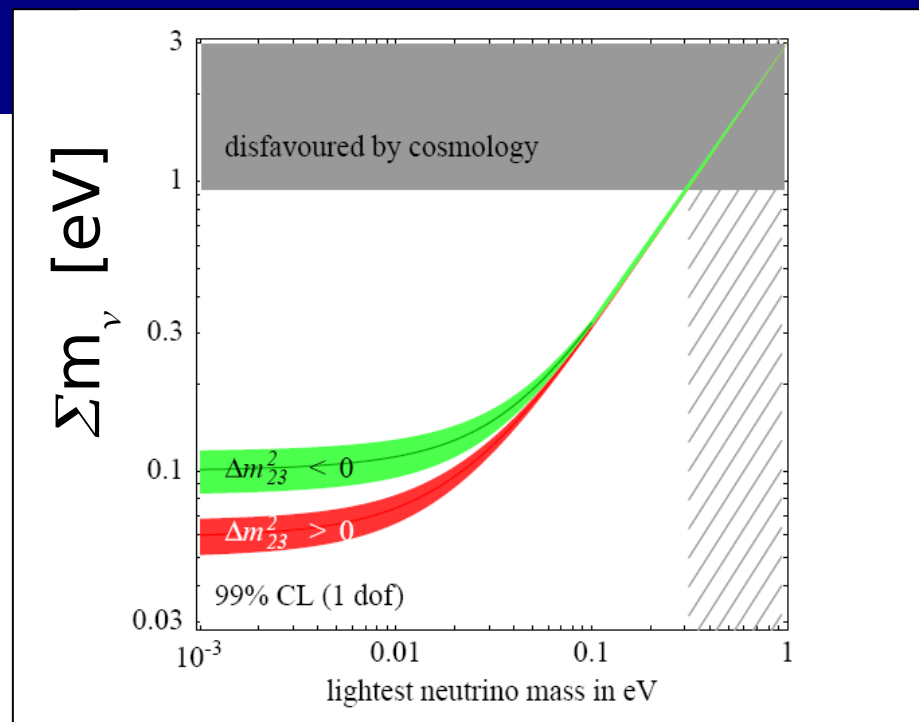
double β -decay

Sensitivity (eV)

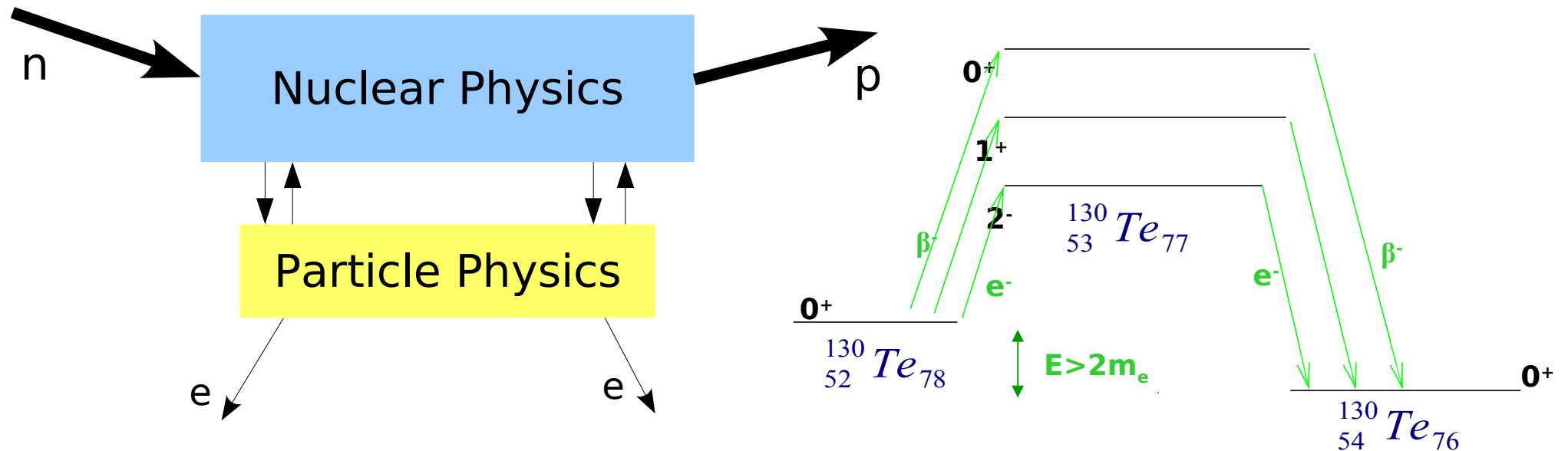
Method	Present	Future
Cosmology	0.7-1.0	0.1
$\beta\beta(0\nu)$ decay	0.5	0.05
B-decay	2.2	0.2



Strumia-Vissani hep-ph/0503246



Decay rate



Phase space factor

Nuclear Matrix Element

uncertainties

$$\tau^{-1} = G_{0\nu} \cdot |M^{0\nu}|^2 \cdot |\langle m_\nu \rangle|^2 = F_N \cdot \frac{|\langle m_\nu \rangle|^2}{m_e^2}$$

Effective Neutrino Mass

Nuclear Factor of Merit

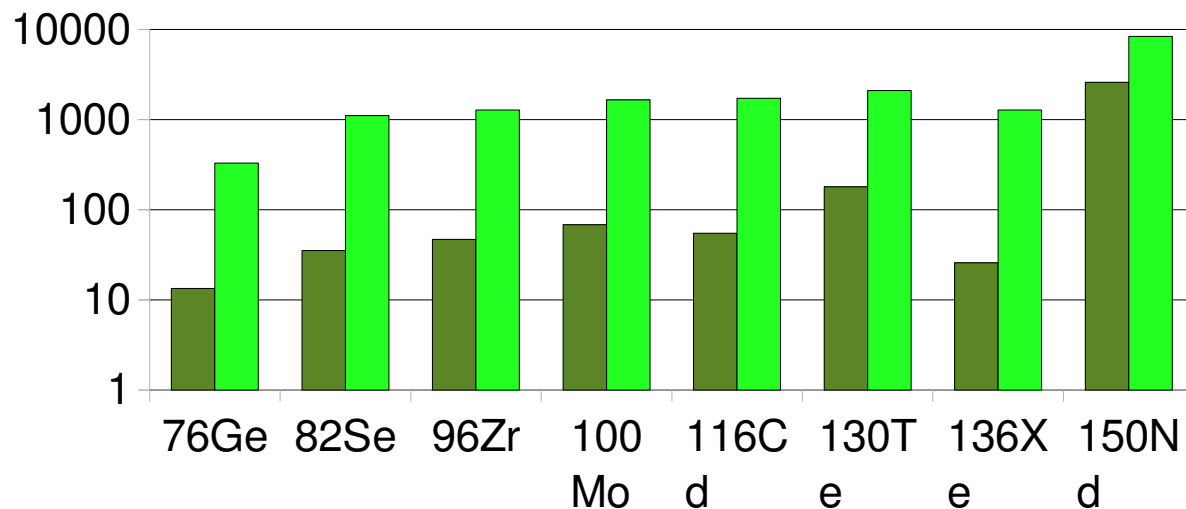
Extracting m_ν from $T_{1/2}$

$$\langle m_\nu \rangle^2 = \frac{1}{T_{1/2} F(Q_{\beta\beta}, Z)}$$

$0\nu\beta\beta$ half-life (measurement or lower bound)

F_N nuclear factor of merit

$$\tau'_i = \tau'_j \frac{F_N^j}{F_N^i}$$



QRPA NME from:
Rodin et al. Table 3 Nucl. Phys. A 2006
+ erratum nucl-th:0706.4304v1

→ m_ν range:

$$\left(\frac{1}{T_{1/2}^{0\nu\beta\beta} F_{N\text{high}}} ; \frac{1}{T_{1/2}^{0\nu\beta\beta} F_{N\text{low}}} \right)$$

But ...

which selection of NME values should be used?

Nuclear Matrix Elements

Nuclear matrix elements are calculated according to various models:

QRPA (RQRPA, SQRPA,), **Shell model** ...

with sometimes (particularly in the past) quite different results

suggestion from Bahcall et al.

use the nuclear matrix range as an uncertainty: « Democratic approach »

BUT

- ▶ *does not take into account the improvements of the Models*
- ▶ *does not help in the choice of the best candidate for an experiment*

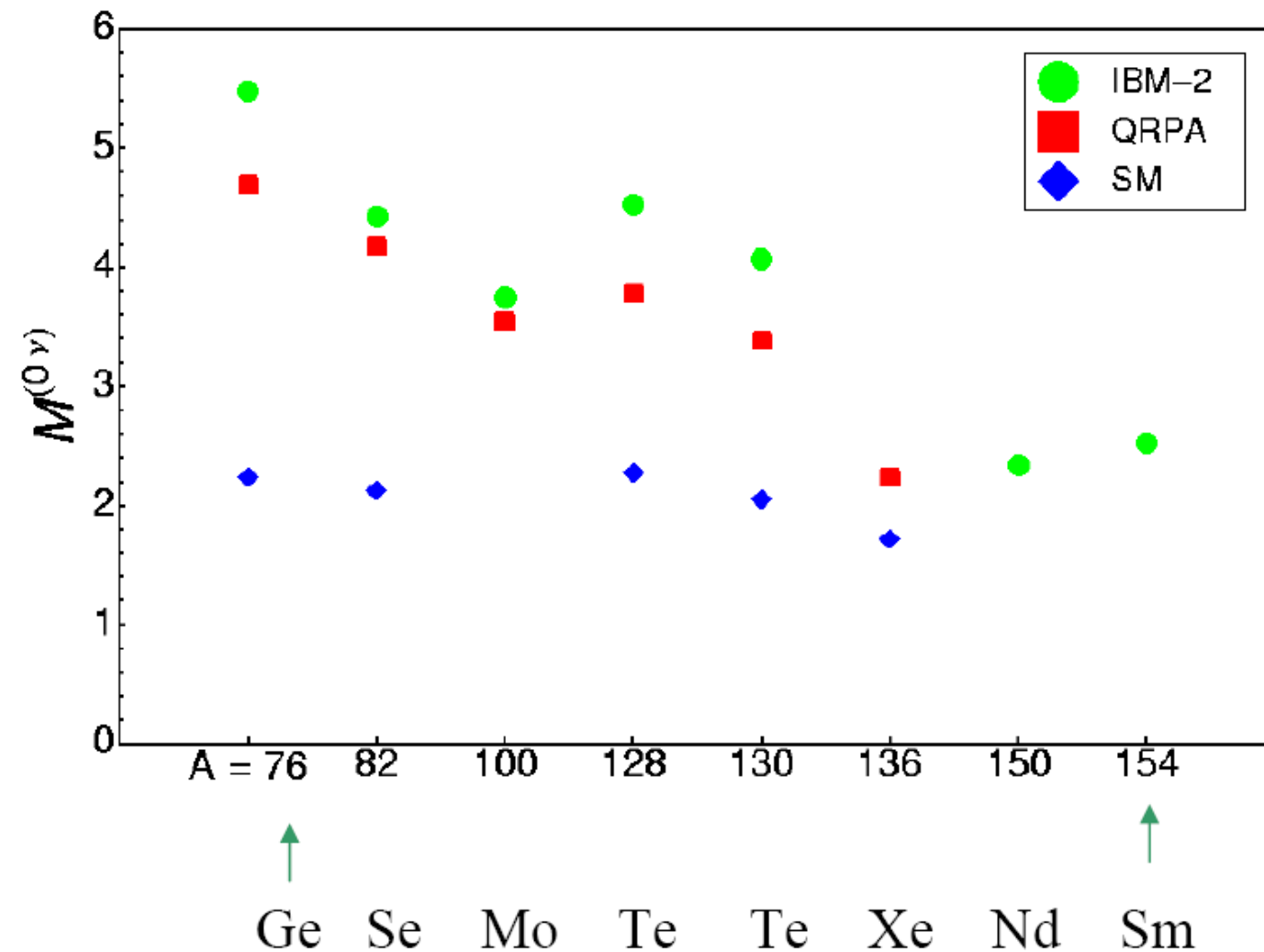
Recently ...

exchanges between groups to

- **understand discrepancies and evaluate errors**
- **use of β and $2\nu\beta\beta$ decay data to fix parameters in QRPA**
- **new efforts (SM)**
- **new methods (IBM)**

new results are much more similar than in the past !!!

Nuclear Matrix Elements Status



Only average values are plotted while

Model variation intervals are not shown.

Errors are of the order **25-30%**

- QRPA from F. Šimkovic, A Faessler, V. Rodin, P. Vogel, and J. Engel, Phys. Rev. C77, 045503 (2008), with $gA=1.25$, Jastrow SRC.
- ◆ SM from E. Caurier, J. Menendez, F. Nowacki, and A. Poves, Phys. Rev. Lett. 100, 052503 (2008).
- IBM-2 from J.Barea and F.Iachello, Phys. Rev. C79, 044301 (2009), $gA=1.25$, Jastrow SRC.

Signal information



Signal:

- One new isotope (ionised)
- Two electrons

In principle we can therefore obtain:

Spectroscopic information

- Single electron energies
- Angle between electrons
- **Sum energy of both electrons**

Often only available information

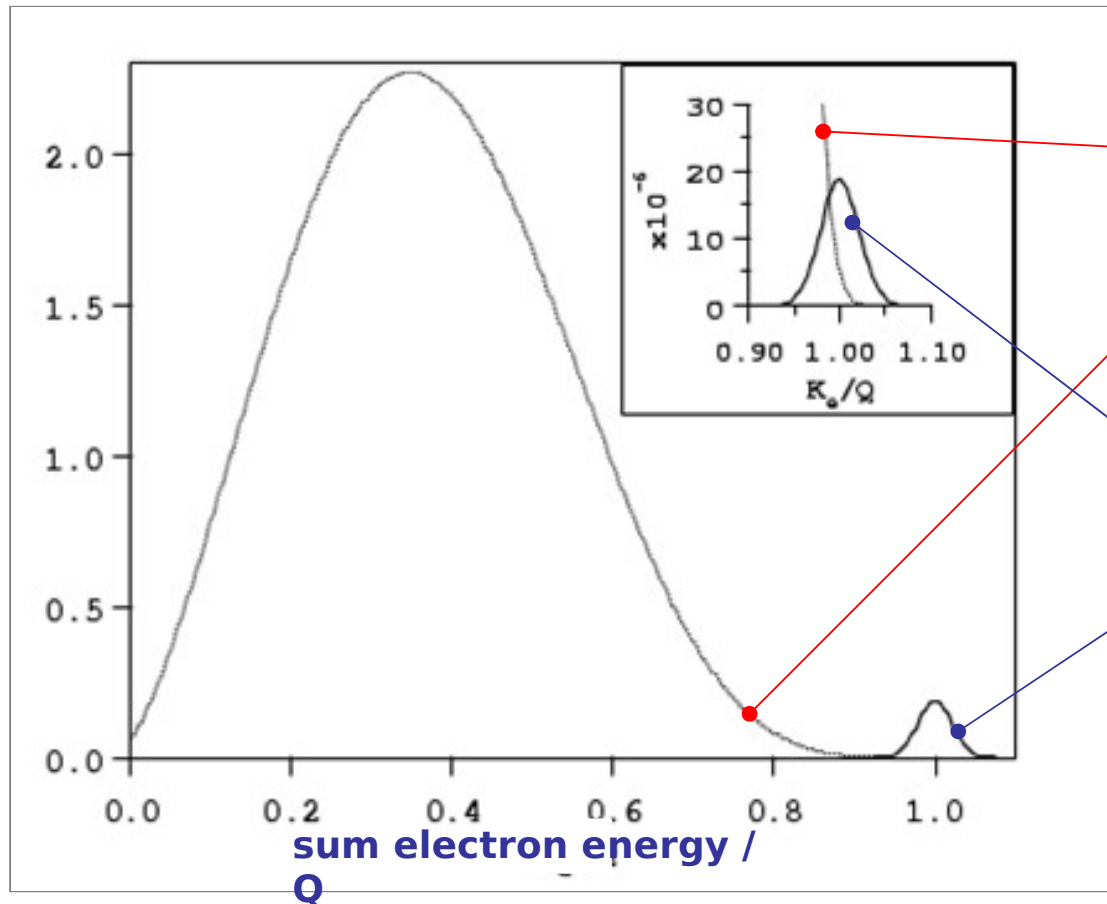
Daughter ion (A,Z+2)

Gamma rays

- decays on excited states
- 511 keV photons in β^+ involving decays

DBD: electron sum energy

The **shape** of the **two electron sum energy spectrum** enables to distinguish among the most relevant decay modes



two neutrino DBD
continuum with maximum at $\sim 1/3$
 Q

neutrinoless DBD
peak enlarged only by
the detector energy
resolution

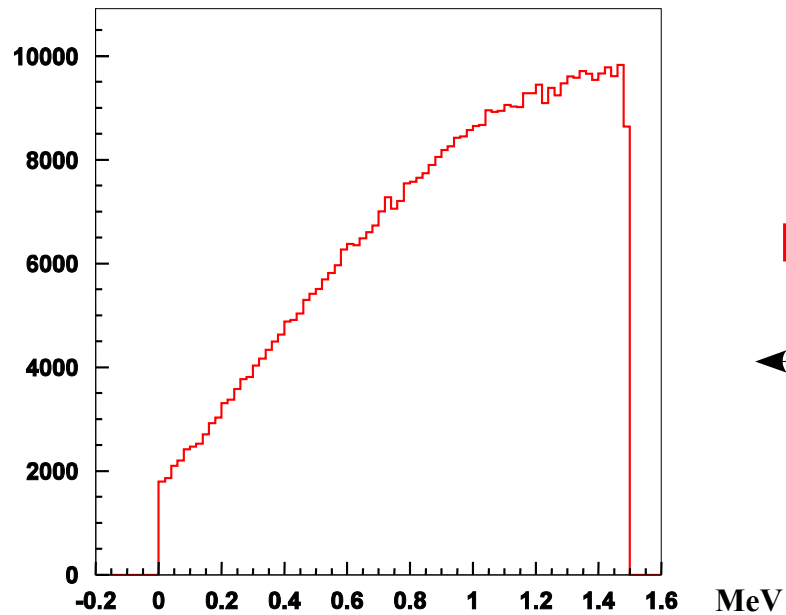
additional signatures:

- single electron energy distribution
- angular distribution

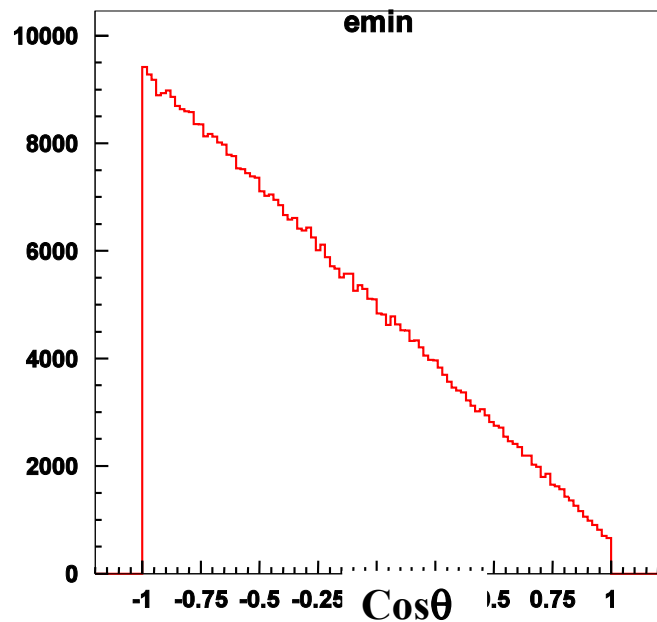
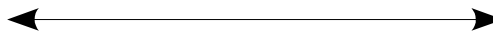
Most promising nuclides
 $Q \sim 2-3 \text{ MeV}$

DBD: single electron energy

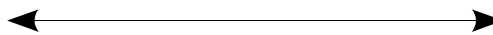
Light neutrino exchange



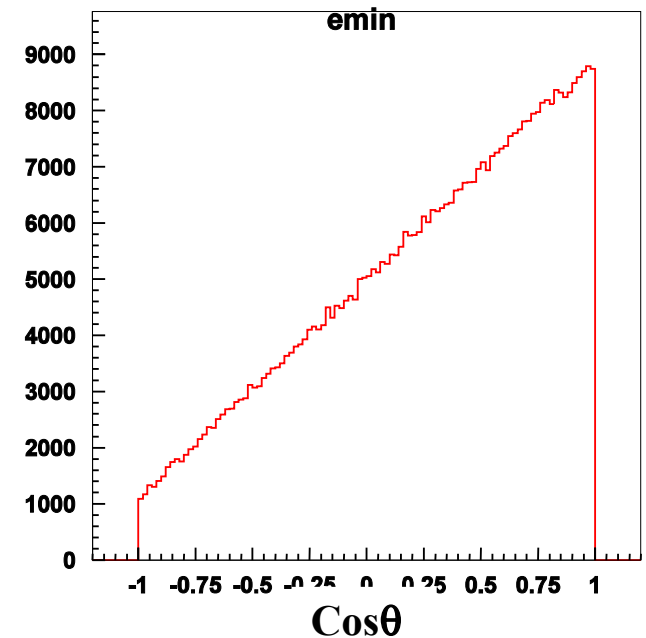
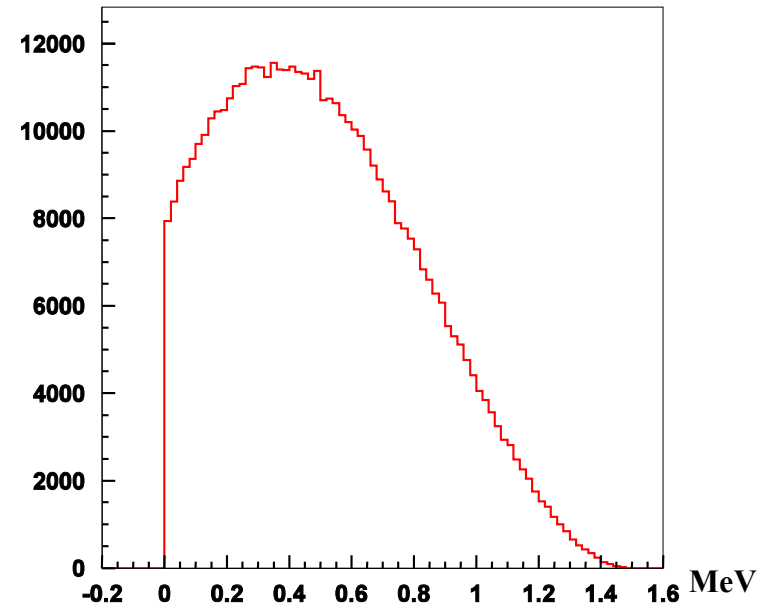
Electron minimum
energy spectrum



Angular distribution
between the 2 electrons



V+A current



Experimental rate and sensitivity

Experimental $\beta\beta$ - 0ν rate

with $N_{\beta\beta}$ $\beta\beta$ - 0ν decays observed

$$\tau_{1/2}^{0\nu} = \ln 2 \frac{\epsilon N_{nuclei} t_{meas}}{N_{\beta\beta}}$$

Experimental sensitivity to $\tau_{1/2}^{0\nu}$

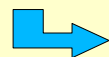
with no $\beta\beta$ - 0ν decay observed

$$N_{\beta\beta} \leq (bkg \cdot \Delta E \cdot M \cdot t_{meas})^{1/2} \text{ at } 1\sigma$$

$$\sum \left(\tau_{1/2}^{0\nu} \right) \propto \epsilon \cdot \frac{i.a.}{A} \sqrt{\frac{M t_{meas}}{\Delta E \cdot bkg}}$$

for $bkg = 0$, at 1σ (“**zero background**”)

$$\sum \tau_{1/2}^{0\nu} \propto \frac{\epsilon i.a.}{A} M t_{meas}$$



$$N_{TOT} = B \Delta T \\ \sim O(1)$$

N_{nuclei}

number of active nuclei in the experiment

t_{meas}

measuring time [y]

M

detector mass [kg]

ϵ

detector efficiency

i.a.

isotopic abundance

A

atomic number

ΔE

energy resolution [keV]

bkg

background [c/keV/y/kg]

Crucial parameters:

- Isotopical abundance
- Mass
- Energy resolution
- Background level

Experimental strategies

Detection & Identification of daughter nuclei (**indirect searches**)

- impossible to distinguish the decay channel
- important in the 70s-80s – no more pursued now

geochemical experiments
radiochemical experiments

Detection of the 2 electrons with a proper detector (**direct searches**)

High energy resolution

Low background

Large mass of source

Event reconstruction

a **peak** must be revealed over background (0ν-DBD)

shield cosmic rays (direct interactions and activations)

→underground

very **radio-pure materials**

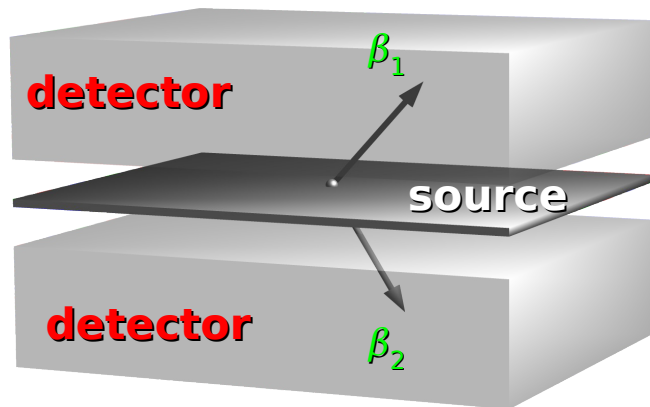
$^{238}\text{U} - ^{232}\text{Th} \Rightarrow \tau \sim 10^{10} \text{ y}$

signal rate $\Rightarrow \tau > 10^{25} \text{ y}$

present more sensitive experiments: 10 - 100 kg
future goals: $\sim 1000 \text{ kg} \Rightarrow 10^{27} - 10^{28} \text{ nuclides}$

reject background
study electron energy and angular distributions

Inhomogeneous approach

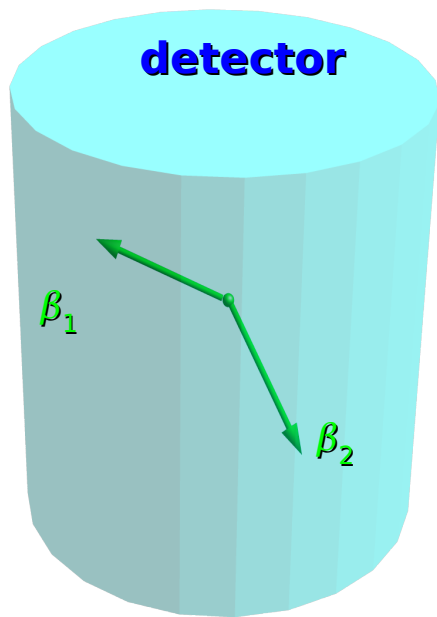


Source $\neq$ Detector

- scintillation
- gaseous TPC
- gaseous drift chamber
- magnetic field and TOF

- 😊 neat reconstruction of **event topology**
- ☹ it is **difficult** to get large source mass
- 😊 **several candidates** can be studied with the same detector

Homogeneous approach



Source $\equiv$ Detector
(calorimetric technique)

scintillation
phonon-mediated detection
solid-state devices
gaseous detectors

☹ constraints on **detector materials**

😊 very **large masses** are possible
demonstrated: up to ~ 50 kg
proposed: up to ~ 1000 kg

😊 with proper choice of the detector,
very **high energy resolution**

Ge-diodes
Bolometers

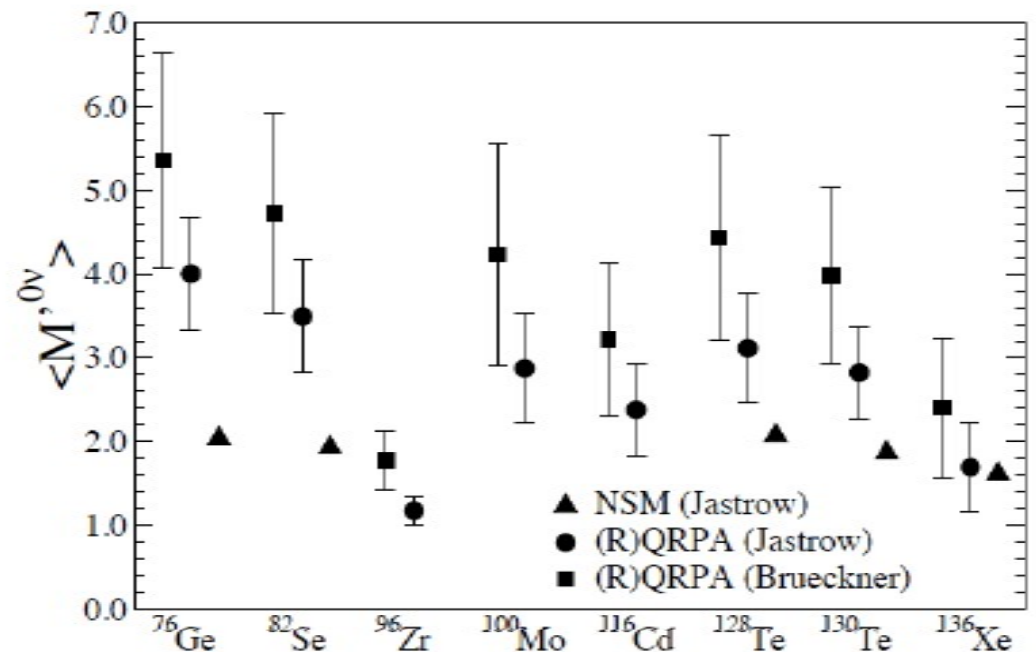
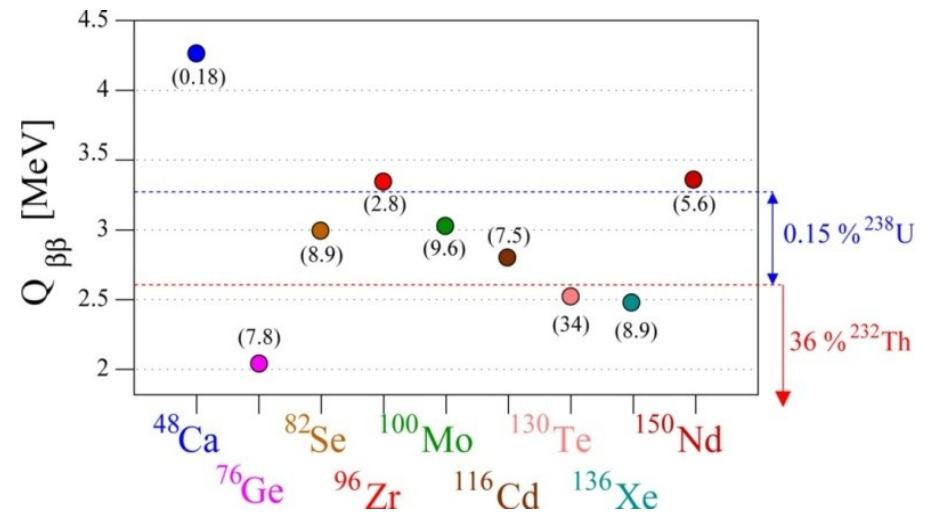
😊 in gaseous/liquid xenon detector,
indication of **event topology**

☹ often contrasting
requests

Choice of the isotope

	Q	i.a.
$^{48}\text{Ca} \rightarrow ^{48}\text{Ti}$	4.271	0.19
$^{136}\text{Xe} \rightarrow ^{136}\text{Ba}$	2.479	8.9
$^{130}\text{Te} \rightarrow ^{130}\text{Xe}$	2.533	34.5
$^{124}\text{Sn} \rightarrow ^{124}\text{Te}$	2.228	5.64
$^{116}\text{Cd} \rightarrow ^{116}\text{Sn}$	2.802	7.5
$^{110}\text{Pd} \rightarrow ^{110}\text{Cd}$	2.013	11.8
$^{100}\text{Mo} \rightarrow ^{100}\text{Ru}$	3.034	9.6
$^{96}\text{Zr} \rightarrow ^{96}\text{Mo}$	3.350	2.8
$^{82}\text{Se} \rightarrow ^{82}\text{Kr}$	2.995	9.2
$^{76}\text{Ge} \rightarrow ^{76}\text{Se}$	2.040	7.8
$^{150}\text{Nd} \rightarrow ^{150}\text{Sm}$	3.367	5.6

- Transition Energy
- Isotopic Abundance
- Nuclear Matrix Elements



EXPERIMENTAL STATUS

Present near and past

Heidelberg –Moscow (HM) (stopped in May 2003)

dominated DBD scenario over a decade. **claim of evidence!!**

NEMO3 (running)

intermediate generation experiment capable to study different isotopes

CUORICINO (stopped in june 2008)

intermediate generation experiment based on the bolometric technique.

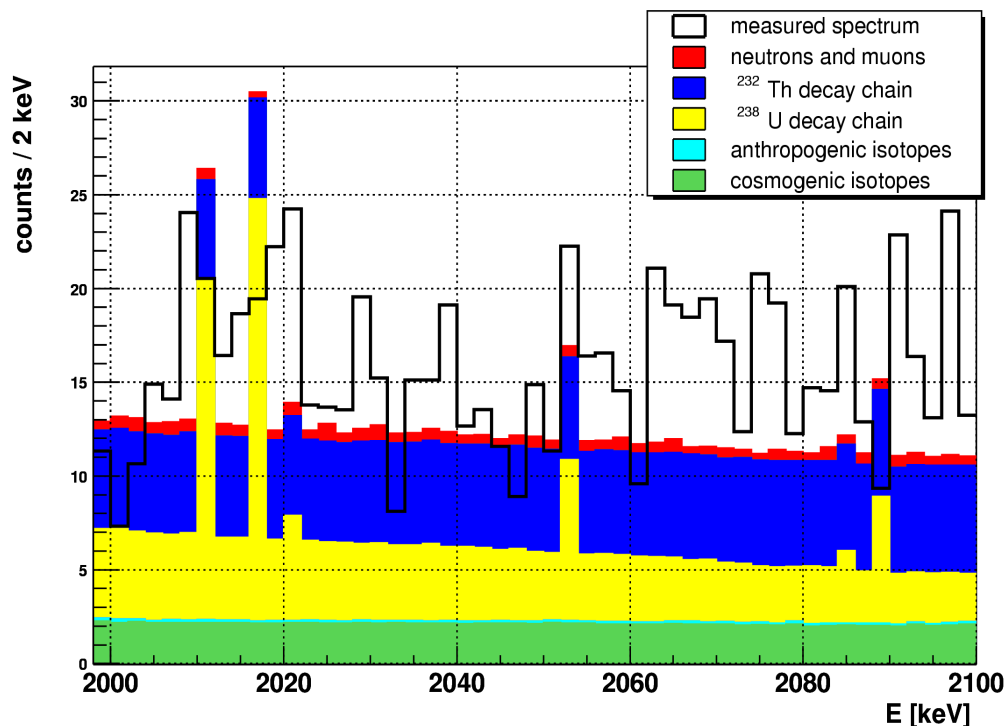
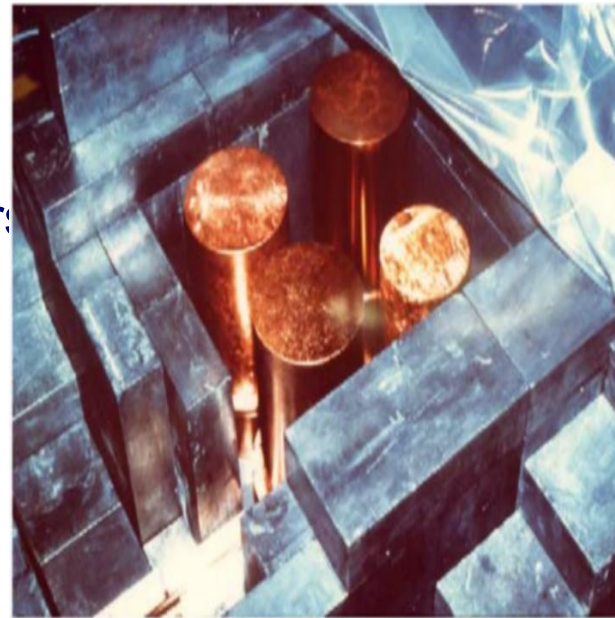
Demonstator of **CUORE**

Nucleus	Detector	EXP	Material	kg y	$\tau_{1/2}$ Limit (y) (90% CL)
⁷⁶Ge	Ge diode	IGEX/HDM*	Ge	~ 47.7	> 1.6-1.9 x 10²⁵
⁸²Se	Tracking	NEMO3	Se	4.5	> 3.2 x 10²³
¹⁰⁰Mo	Tracking	NEMO3	Mo	31.5	> 1.0 x 10²⁴
⁹⁶Zr	Tracking	NEMO3	Zr	0.03	> 9.2 x 10²¹
¹⁵⁰Nd	Tracking	NEMO3	Nd	0.1	> 1.8 x 10²¹
¹²⁸Te	Bolometer	Cuoricino	TeO ₂		> 1.1 x 10²³
¹³⁰Te	Bolometer	Cuoricino	TeO ₂	19.75	> 2.8 x 10²⁴
¹³⁶Xe	Xe scint	DAMA	L Xe	~ 4.5	> 1.2 x 10²⁴
¹¹⁶Cd		Solotvina			> 1.7 x 10²³
⁴⁸Ca					> 1.4 x 10²²
¹⁶⁰Gd					> 1.3 x 10²¹

* Existing claim for a **positive result** by part of the same group

Heidelberg-Moscow: ^{76}Ge

- 5 HP-Ge crystals, enriched to 87% in ^{76}Ge
total active mass of 10.96 kg $\Rightarrow$ 125.5 moles of ^{76}Ge
- run from 1990 to 2003 in Gran Sasso Underground Laboratory
- total statistics 71.7 kg $\times$ y
820 moles $\times$ y
- main background from U/Th in the set-up
 $b \approx 0.11$ c/keV/kg/y at $Q_{\beta\beta}$
- lead box and nitrogen flushing of the detector
- digital Pulse Shape Analysis (PSA)



1990 - 2001 data

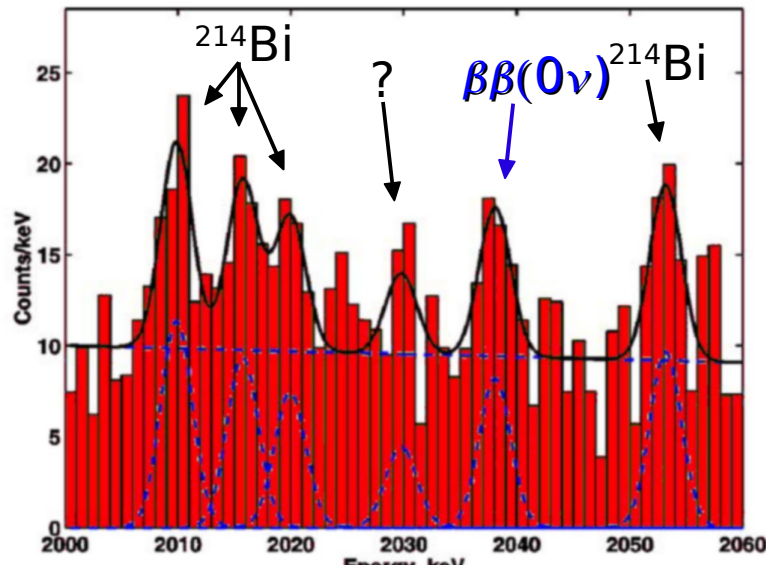
exposure = 35.5 kg $\times$ y SSD

$\tau_{1/2}^{0\nu} > 1.9 \times 10^{25}$ years

$\langle m_\nu \rangle < 0.35$ eV (0.3 - 1.24 eV)

H.V.Klapdor et al.: ^{76}Ge 0ν -DBD evidence

First claim in January 2002 (Klapdor-Kleingrothaus HV et al. hep-ph/0201231) with a statistics of 55 kg y and a 2.2-3.1 statistical significance → **strong criticism**
claim confirmed in 2004 with the addition of a significant ($\sim 1/4$) new statistics and improved in the following years



1990 - 2003 data, all 5 detectors

exposure = 71.7 kg×y

$\tau_{1/2} = 1.2 \times 10^{25}$ years

$\langle m \rangle = 0.44$ eV

H.V.Klapdor-Kleingrothaus et al., Phys. Lett. B 586 (2004) 198

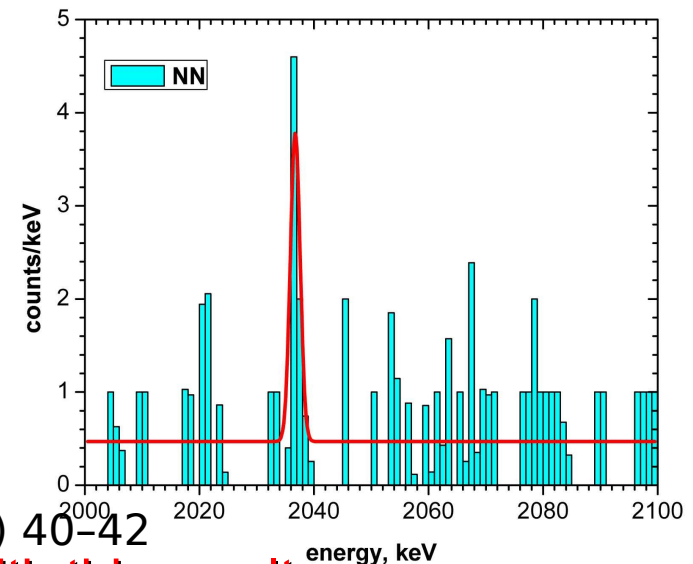
1995-2003 data new re-analysis:

SSE selection by MC & ANN

6.4σ signal

7.05 ± 1.11 events

$2.23^{+0.44}_{-0.31} 10^{25}$ years / 0.32 ± 0.03 eV



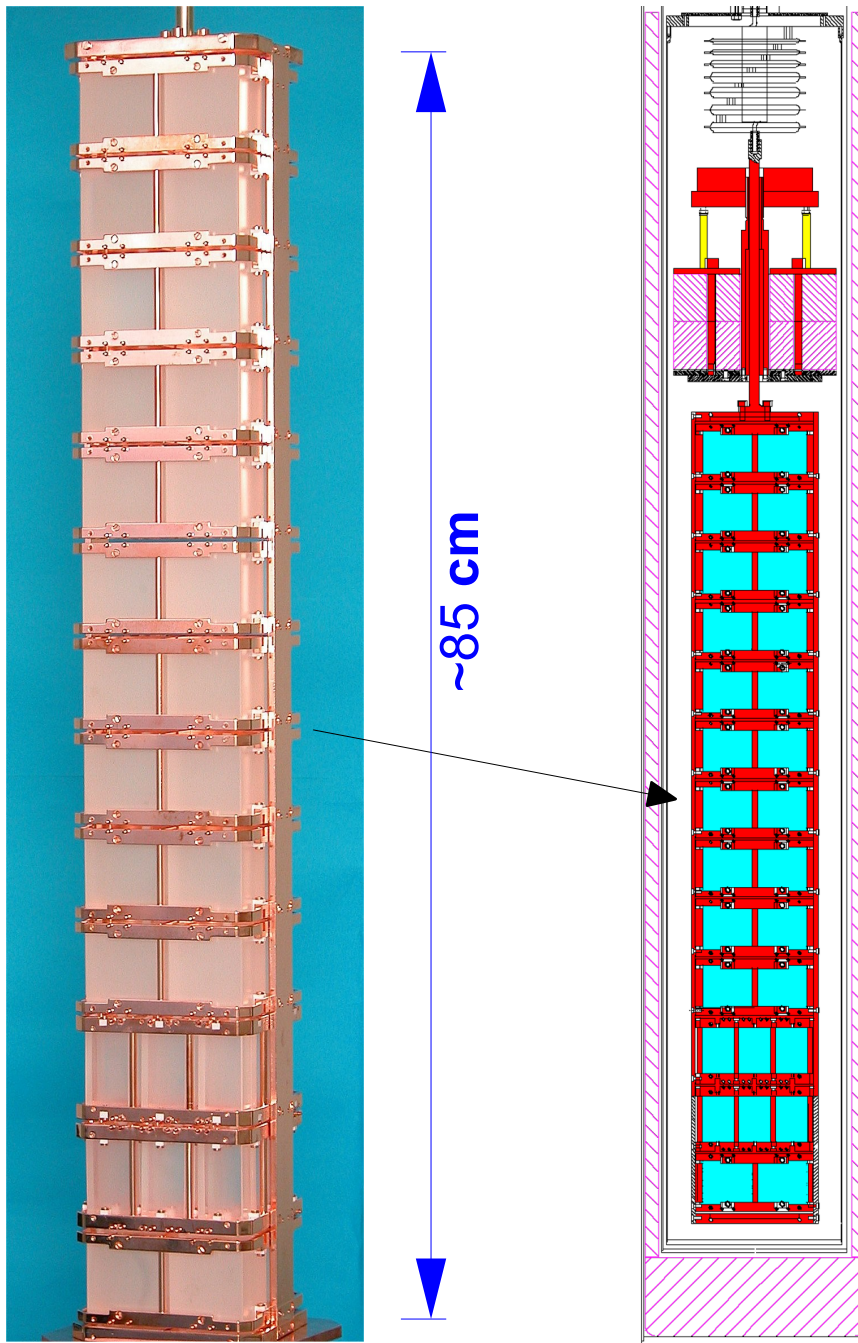
H.V.Klapdor-Kleingrothaus et al., Phys. Scr. T127 (2006) 40-42

all future experiment will certainly have to cope with this result

arXiv:1006.2025v1 [hep-ph]: Kirpichnikov alternate interpretation of 2039 keV line

CUORICINO

Cuoricino tower: 62 TeO₂ crystals



TeO₂ thermal calorimeters

Active isotope ¹³⁰Te

natural abundance: a.i. = 33.9%

transition energy: $Q_{\beta\beta} = 2529$ keV

encouraging predicted half life

$\langle m_{\nu} \rangle \approx 0.3$ eV $\Leftrightarrow \tau_{1/2}^{0\nu} \approx 10^{25}$ years

Absorber material TeO₂

low heat capacity

large crystals available

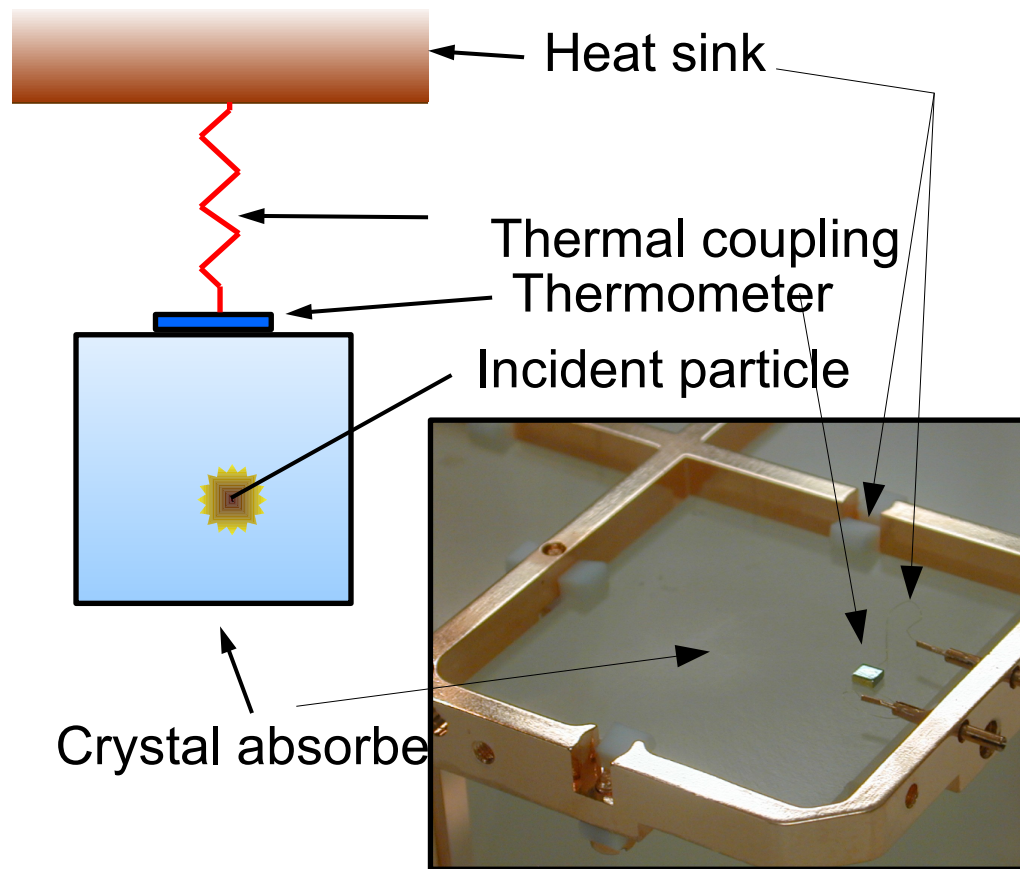
radiopure

intermediate size $\beta\beta$ experiment
important test for

radioactivity

performance of large LTD arrays

Low Temperature Detectors (LTD)



Detection Principle

$$\Delta T = E/C$$

C : thermal capacity

low C

low T (i.e. $T \ll 1\text{K}$)

dielectrics, superconductors

ultimate limit to E resolution:
statistical fluctuation of internal
energy U

$$\langle \Delta U^2 \rangle = k_B T^2 C$$

Thermal Detectors Properties

good energy resolution

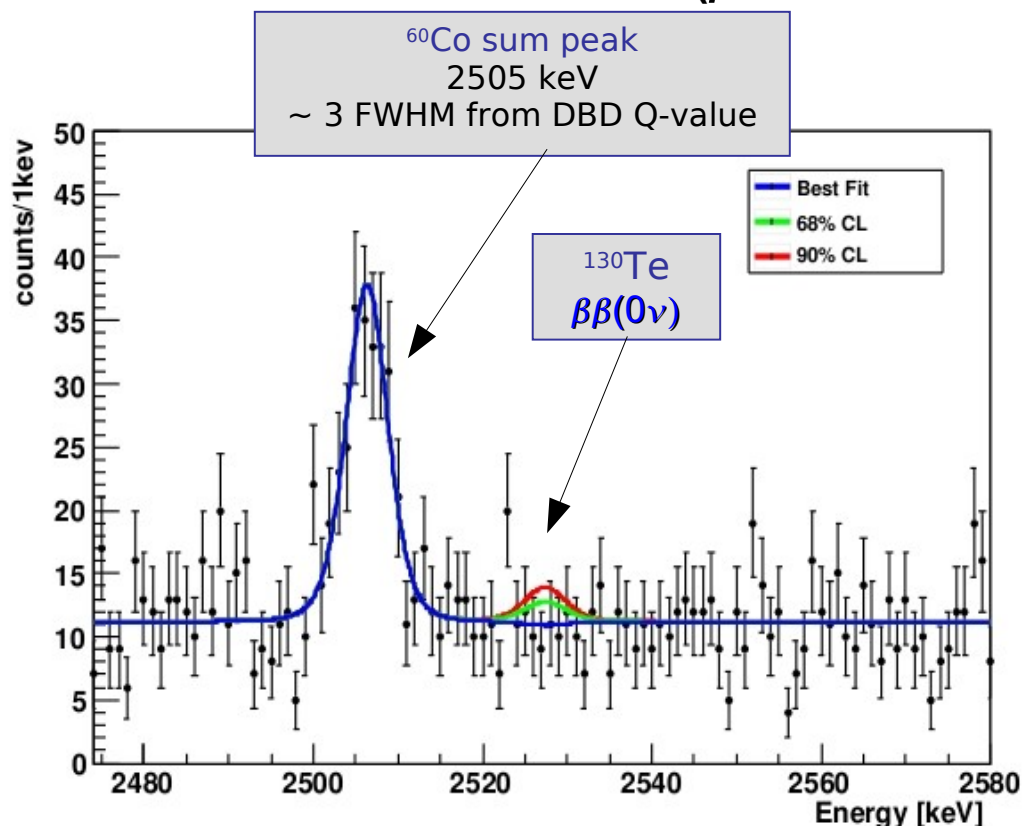
wide choice of absorber materials

true calorimeters

slow $\tau = C/G \sim 1 \div 10^3$ ms

CUORICINO results

- total statistics 19.75 kg×y
- average energy resolution FWHM $\Delta E = 7.5$ keV at $Q_{\beta\beta}$ ($\sigma_E = 1.3\%$)
- anticoincidence applied to reduce surface U/Th background and external γ 's
- background level: $b \approx 0.18 \pm 0.01$ c/keV/kg/y @ $Q_{\beta\beta}$
 - 30% $\pm$ 10% ^{208}Tl (cryostat contamination)
 - 20% $\pm$ 10% TeO_2 surfaces (α contaminations)
 - 50% $\pm$ 10% Cu surfaces (β contaminations)



stopped in June 2008
and disassembled

TOTAL EXPOSURE
19.75 [kg(^{130}Te) yr]

@ 90% C.L.

$\tau_{1/2} > 2.8 \cdot 10^{24}$ [yr]

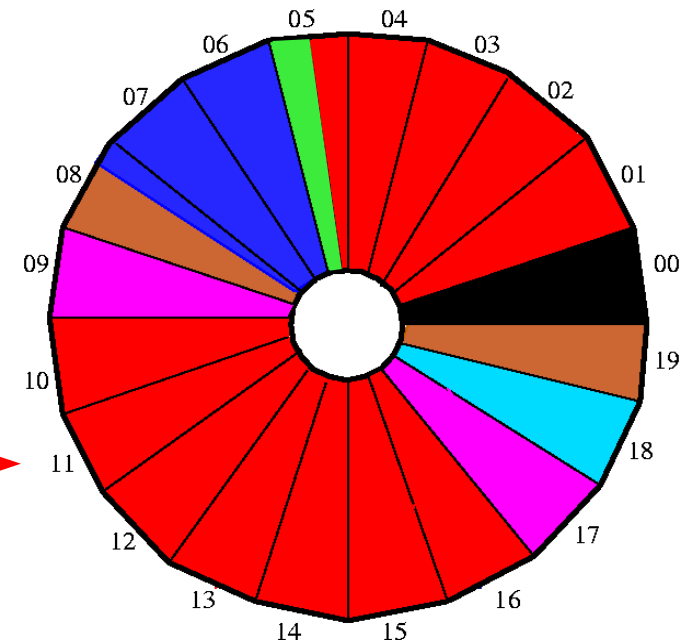
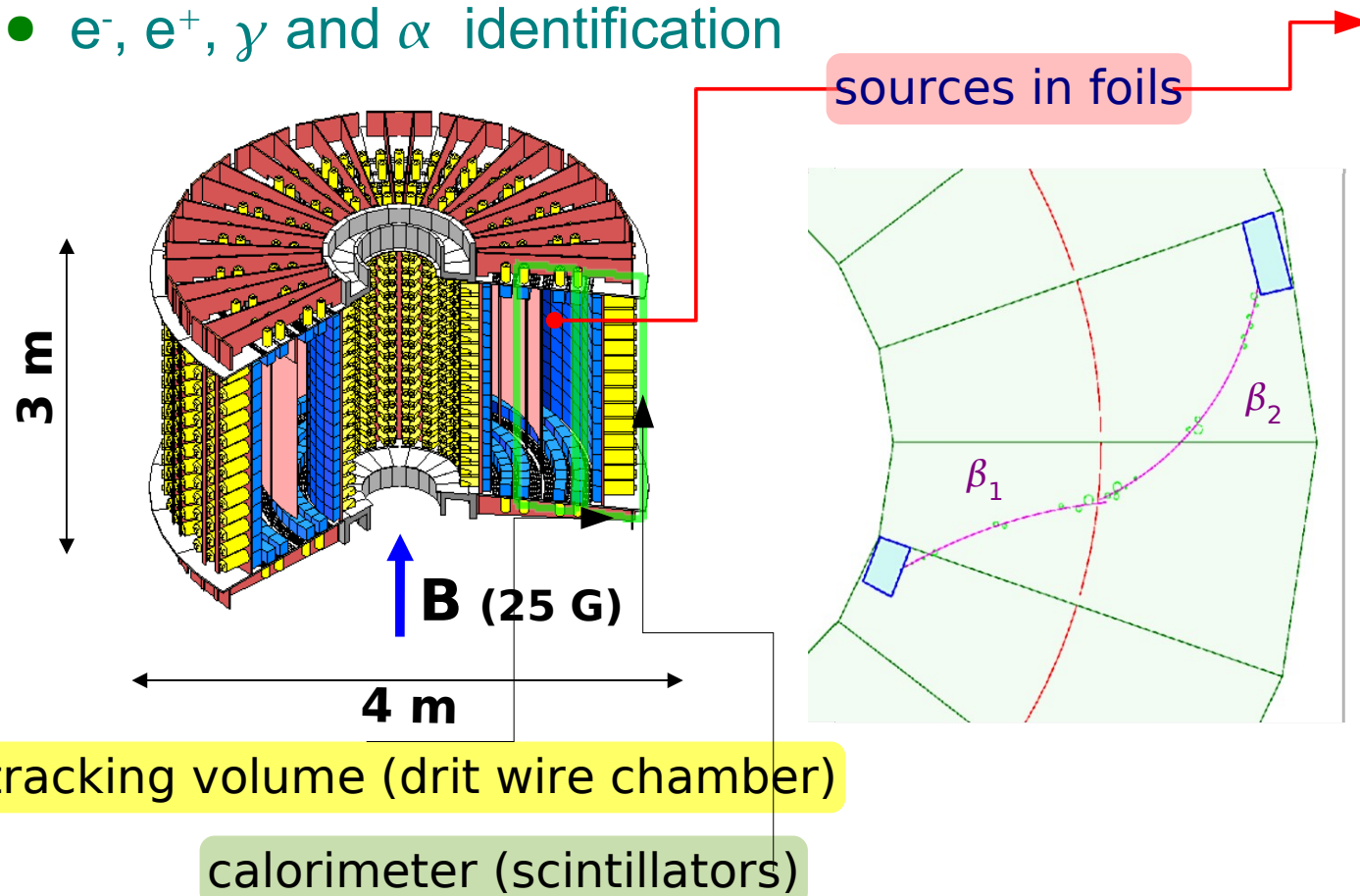
$m_{ee} < 0.3 \div 0.7^{1-4}$ eV

- 1 Šimkovic et al., PRC 77 (2008) 045503
- 2 Civitarese et al., JoP:Conference series 173 (2009) 012012
- 3 Menéndez et al., NPA 818 (2009) 139
- 4 Barea and Iachello, PRC 79 (2009) 044301

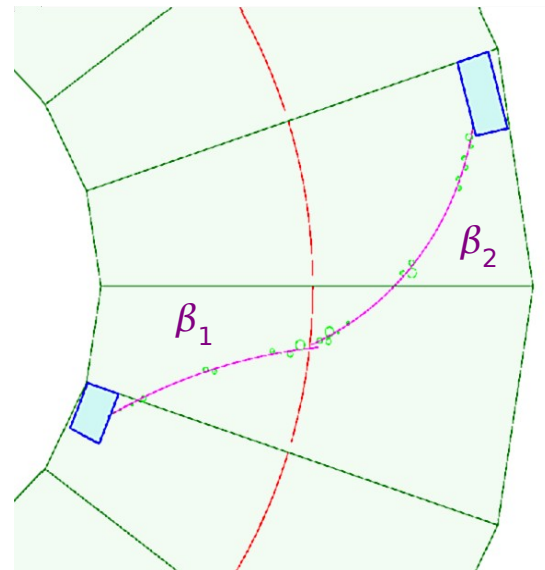
NEMO-3

Tracking detector for $\beta\beta\text{-}2\nu$ and $\beta\beta\text{-}0\nu$ at Frejus (4800 m.w.e.)

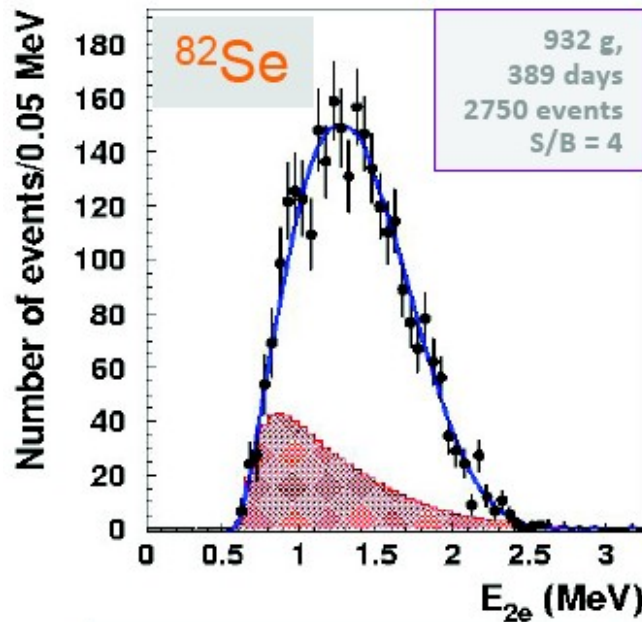
- 10 kg of enriched material in foils
- 6180 geiger cells $\Rightarrow$ drift wire chamber
- 1940 plastic scintillators + PMTs
- iron (γ) + water with B (n) shielding + anti-Rn box
- e^- , e^+ , γ and α identification



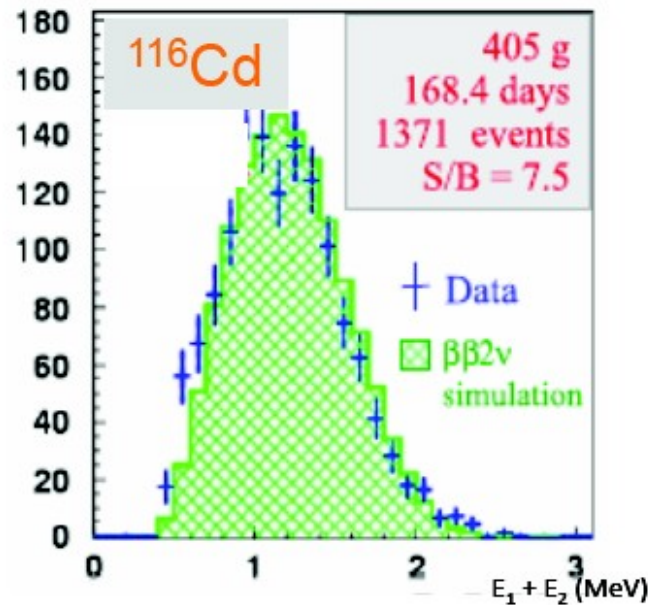
^{100}Mo	(6.9 kg)	$\rightarrow \beta\beta\text{-}0\nu$
^{82}Se	(0.9 kg)	
^{130}Te	(0.45 kg)	
^{116}Cd	(0.4 kg)	
^{150}Nd	(37g)	
^{96}Zr	(9.4 g)	
^{48}Ca	(7.0g)	
$^{\text{nat}}\text{Te}$	(0.5 kg)	
Cu	(0.6 kg)	



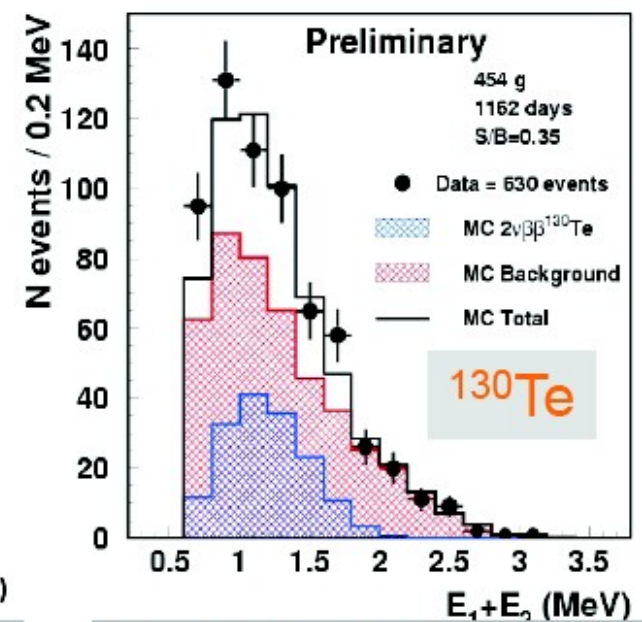
NEMO-3: a unique tool to study $\beta\beta(2\nu)$



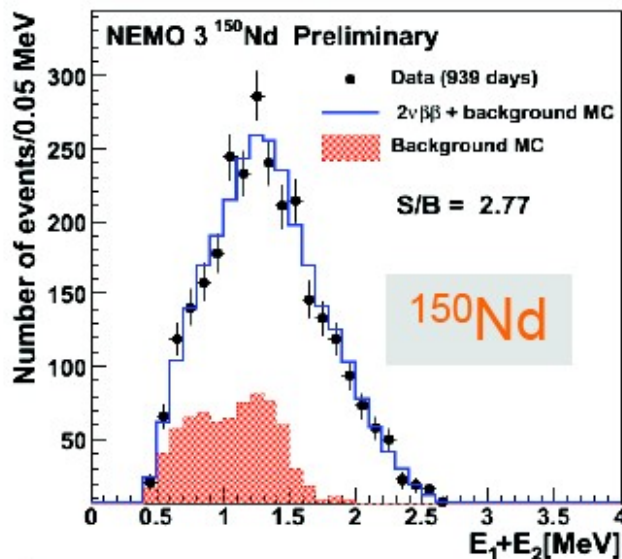
9.6 ± 0.3 (stat) ± 1.0 (sys) 10^{19} y



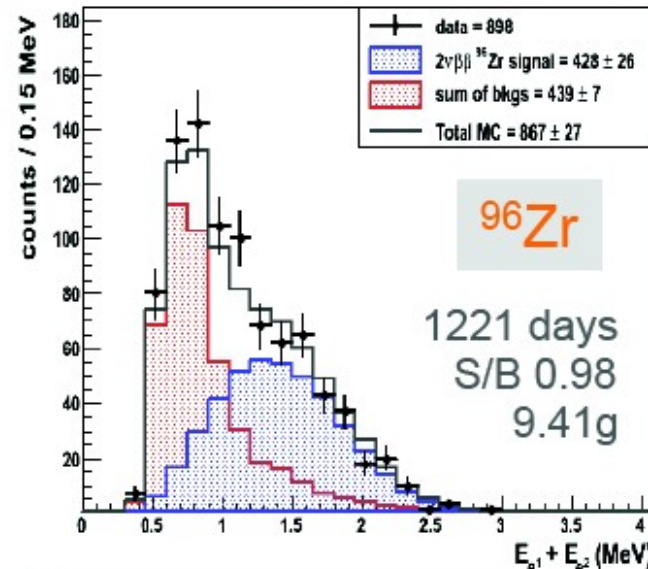
2.8 ± 0.1 (stat) ± 0.3 (sys) 10^{19} y



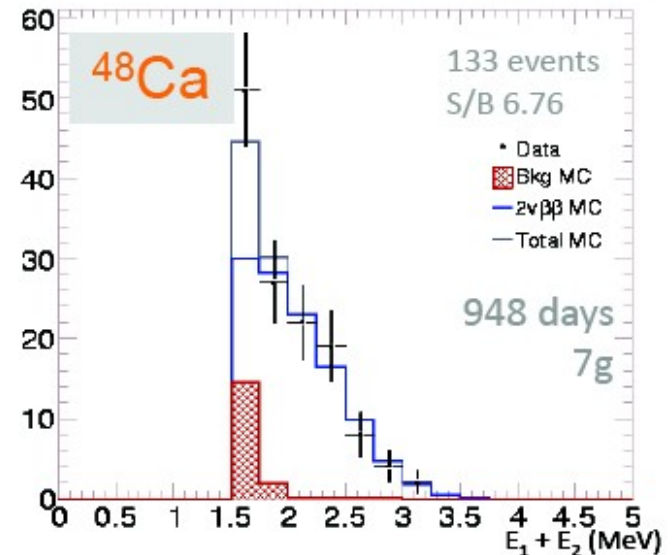
6.9 ± 0.9 (stat) ± 1.0 (sys) 10^{20} y



$9.11^{+0.25}_{-0.22}$ (stat) ± 0.63 (sys) 10^{18} y



2.35 ± 0.14 (stat) ± 0.16 (sys) 10^{19} y



$4.4^{+0.5}_{-0.4}$ (stat) ± 0.4 (sys) 10^{19} y

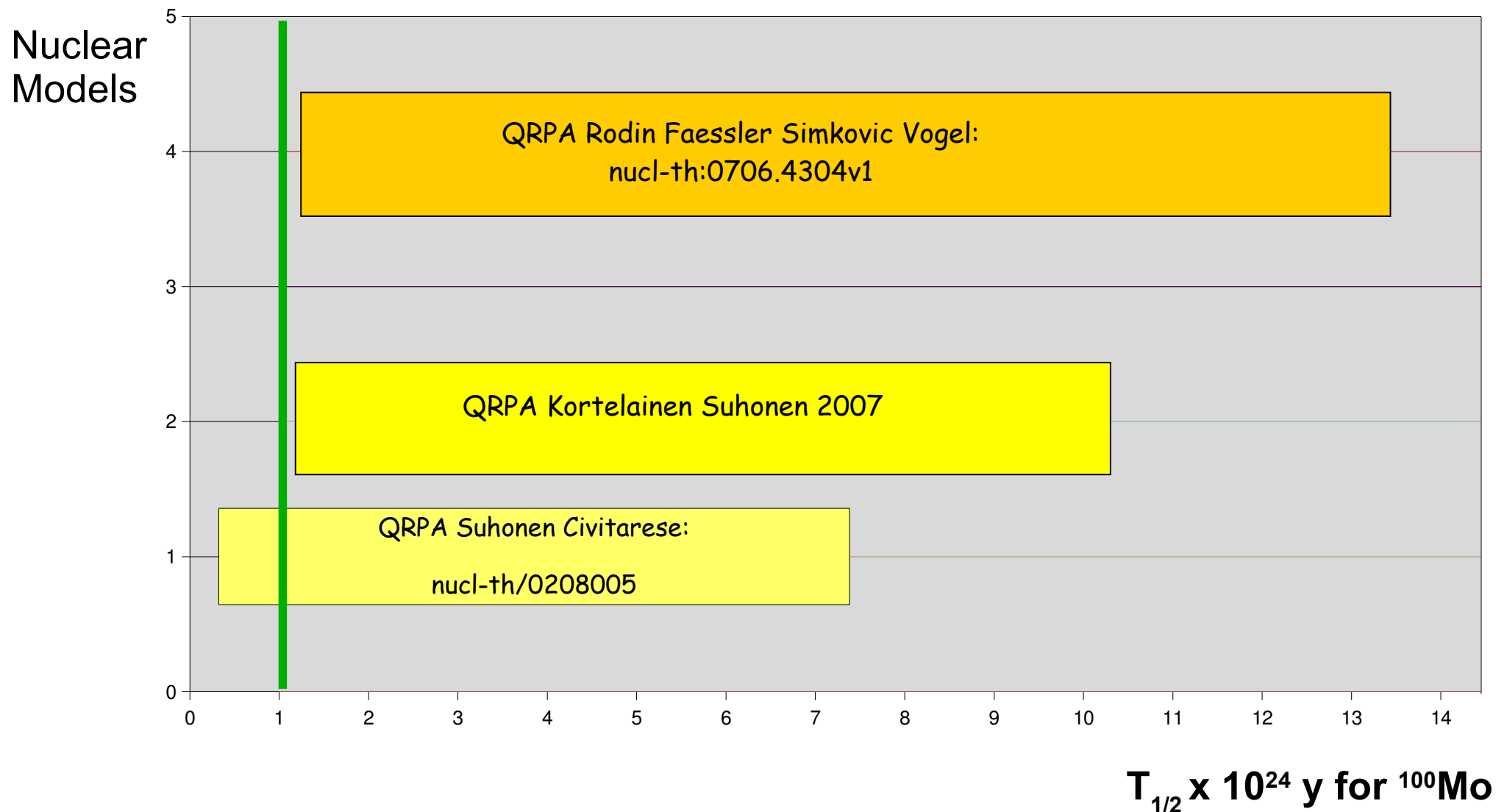
HM claim: NEMO3 90%CL

HM claim of evidence: $T_{1/2}^{0\nu}(\text{y}) = (0.69-4.18) \times 10^{25} \text{ (3}\sigma \text{ range)}$

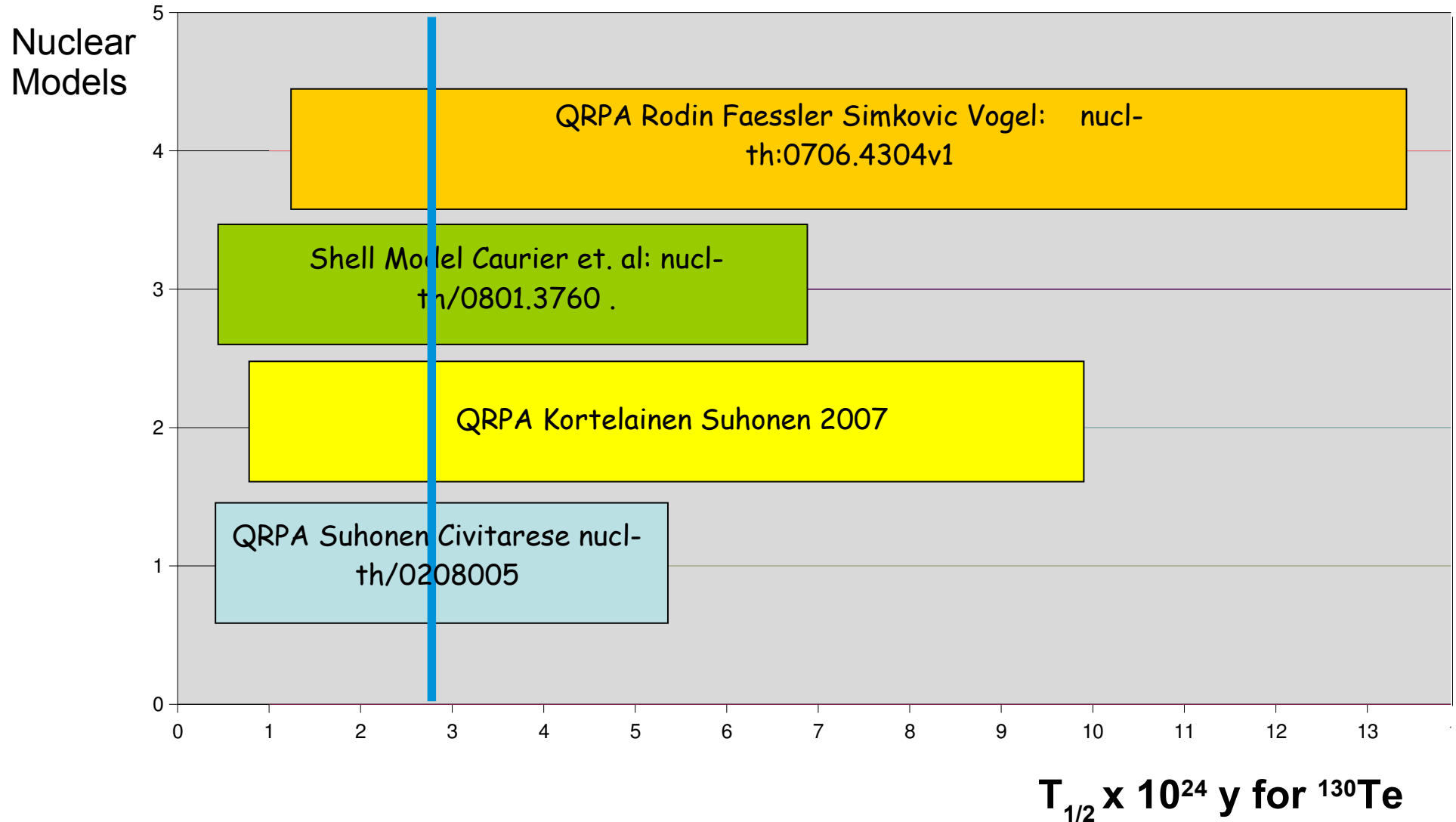
$$T_{1/2}^{-1} = F(Q_{\beta\beta}, Z) |M|^2 \langle m_\nu \rangle^2$$

$\longrightarrow$

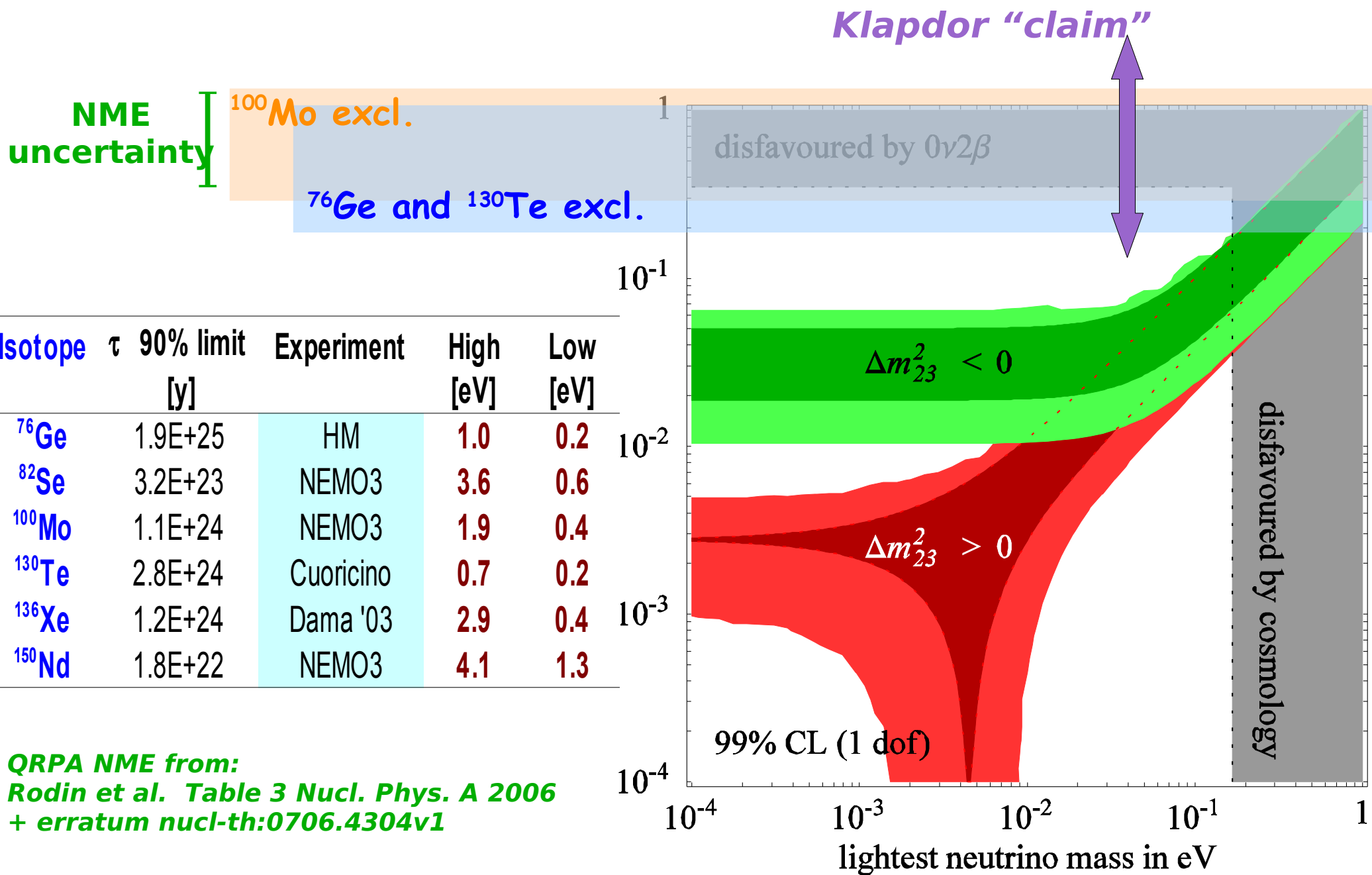
$^{100}\text{Mo}/^{130}\text{Te}$
predicted
 $T_{1/2}^{0\nu}(\text{y})$ range



HM claim: CUORICINO 3σ



Present situation



Goals of next generation 0ν -DBD experiments

- sensitivities of few 0.01 eV on $\langle m_\nu \rangle$
- hierarchy problem solution
- good chances to observe $\beta\beta(0\nu)$ (LNV, Majorana ν 's)
- **confirmation/rejection of the ^{76}Ge result**
 - confirmation:** sensitivities of few 100 meV on $\langle m_\nu \rangle$ are enough
check different isotopes
 - rejection:** much better sensitivities on $\langle m_\nu \rangle$ must be achieved

How?

- promote as many as possible experiments on different isotopes
- reduce uncertainties in nuclear matrix F_N
- Improve all parameters determining sensitivity

increase isotopic abundance by enrichment

$$\sum (\tau_{1/2}^{0\nu}) \propto \epsilon \cdot \frac{a.i.}{A} \sqrt{\frac{M t_{meas}}{\Delta E \cdot bkg}}$$

increase experimental mass

reduce background by:
material selection and proper handling
choosing proper technique
using signatures
improving energy resolution

THE INTERNATIONAL 0v-DBD STRATEGY

APS neutrino study

We recommend, as a high priority,
that a **phased program** of
increasingly sensitive searches for

**neutrinoless nuclear double beta
decay ($0\nu\beta\beta$)**

be initiated as soon as possible.



Range	Covered spectrum	Required mass	Status
100 – 500	Quasi-degenerate	200 kg	close
20 – 50	Inverted	1 ton	proposed
2 – 5	Any	100 tons	future technology

In the first two stages, more than one experiment is desirable,
worldwide, both to permit confirmation and to explore the underlying
physics.

ASPERA roadmap

PHASED PROGRAM

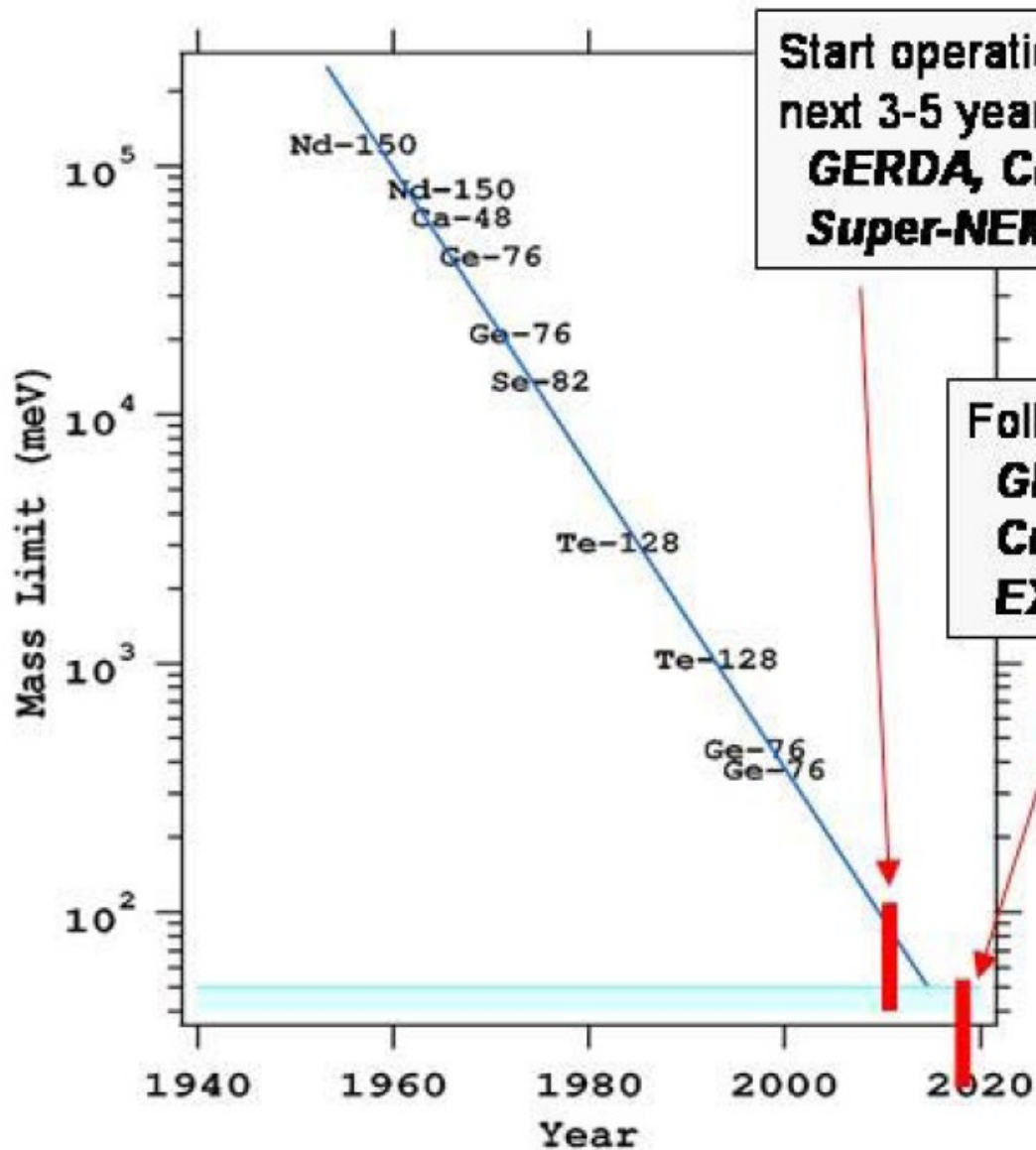
Present: 10-50 kg
 Next Future: 200-500 kg
 Long range: tons

KAMLAND
 (Xe)
 SNO+ (Nd)

LS @ LNGS (Nd)

Name	Nucleus	Method	Location	European Members	Others
<i>Running experiments</i>					
CUORICINO	^{130}Te	bolometric	LNGS	IT, NL, ES	US
NEMO-3	^{100}Mo ^{82}Se	tracko-calo	LSM	FR, CZ, UK ES, FIN	US, RU, JP
<i>Construction funding</i>					
CUORE	^{130}Te	bolometric	LNGS	IT, NL, ES	US
GERDA	^{76}Ge	ionization	LNGS	DE, BE, IT, PO	RU
<i>Substantial R&D funding</i>					
EXO	^{136}Xe	tracking	WIPP	CH	US, RU, CAN
SuperNEMO	^{150}Nd or ^{82}Se	tracko-calo	LSC or LSM	FR, CZ, UK, SK, PL, ES, FIN	US, RU, JP UKR
<i>R&D and/or conceptual design</i>					
CANDLES	^{48}Ca	scintillation	Oto Lab	-	JP
CARVEL	^{48}Ca	scintillation	Solotvina	-	UKR, RU, US
COBRA	^{116}Cd , ^{130}Te	ionization	LNGS	UK, DE, IT, PO, SK	US
DCBA	^{150}Nd	tracking	t.b.d.	-	JP
MAJORANA	^{76}Ge	ionization	SNOLAB or DUSEL	-	US
MOON	^{100}Mo	tracking	t.b.d.	-	JP
SNO++	^{150}Nd	scintillation	SNOLAB	-	CAN, US + ...
<i>other decay modes</i>					
TGV	^{106}Cd	el. capture, running	LSM	FR, CZ	RU

ASPERA roadmap

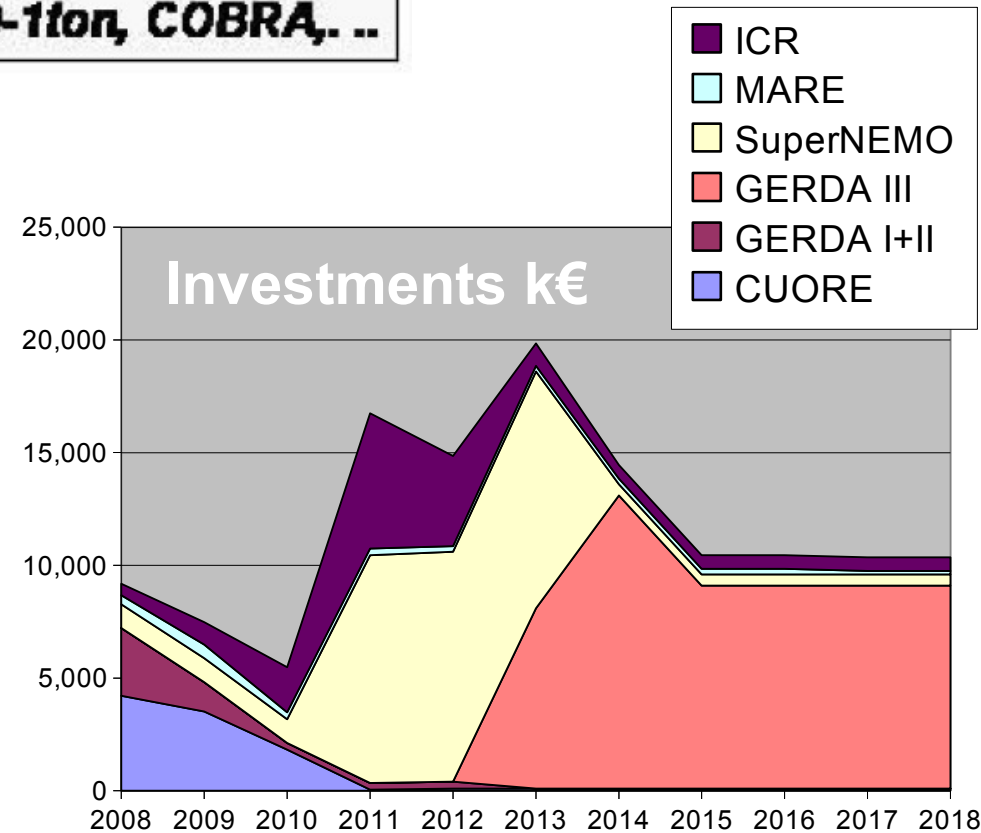


Start operation within next 3-5 years:

GERDA, Cuore, Super-NEMO, EXO-200, ..

Following generation:

GERDA+Majorana, Cuore-enhanced EXO-1ton, COBRA, ..



ASPERA recommendations

Isotopical enrichment

Isotope enrichment will have a large impact on the cost of future Experiments. The production of a large amount of isotopes is possible though ultra-centrifugation, laser separation (AVLIS) or Ion Cyclotron Resonance (ICR) techniques. [...]

A Design Study should be done for a large production (100kg) with the ICR technique.

Nuclear Matrix Elements

We finally reiterate the importance of assessing and reducing the uncertainty in our knowledge of the corresponding nuclear matrix elements, experimentally and theoretically as well as the importance of studying alternative interpretations of neutrino-less double beta decay such as those offered by super-symmetry. This requires a program as vigorous, although not as expensive, as construction of the double beta detectors itself.

The challenge

⁷⁶Ge controversy: why?

- Low statistics of claimed signal - hard to repeat measurement
- Background level and model uncertainty
- Unidentified lines
- Insufficient auxiliary handles

Hierarchy problem: background reduction

- To start exploring the inverted hierarchy region: 1-10 counts / y ton
- To cover the inverted hierarchy region: 0.1 -1 counts / y ton

Goal: 1 count/ton/y

- $\beta\beta(2\nu)$
- natural occurring radioactive materials
- neutrons
- long-lived cosmogenics

A phased approach

Present experiments have masses **~10 kg (isotope)**

To reject inverted hierarchy mass scenario

- **Mass (isotope): 1 ton**

and of course

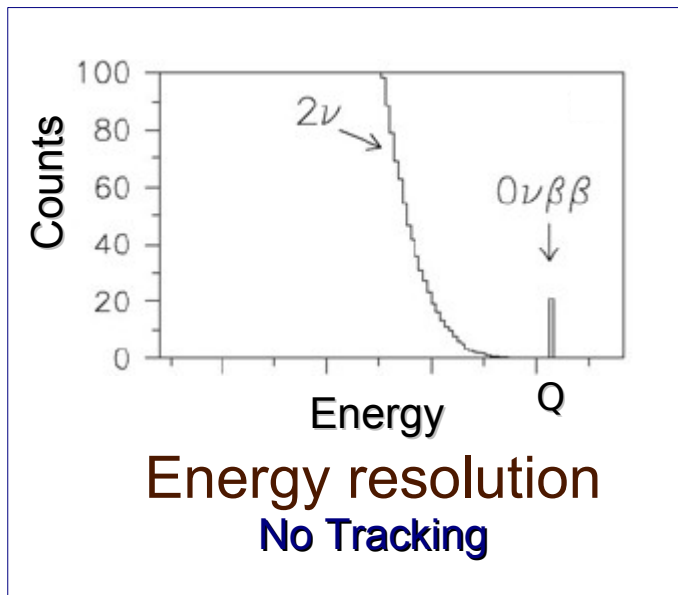
- Proper isotope
- Low background

It is unrealistic to plan to go directly from 10 kg to 1 ton scale

Intermediate steps at **100 kg** scale are needed ...

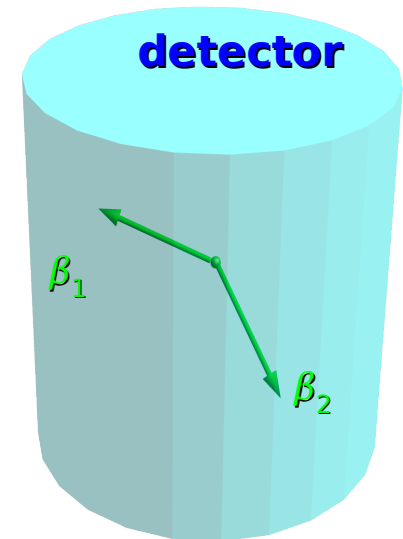
... with full understanding and control of the background

Experiments and techniques



CANDLES
CAMEO
XMASS
SNO++

Calorimeters:
CUORE
GERDA
MAJORANA
COBRA*

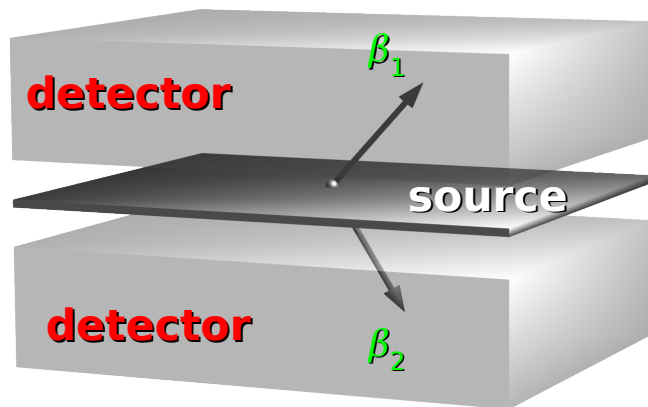


Source $\equiv$ Detector
Large mass (ton scale)

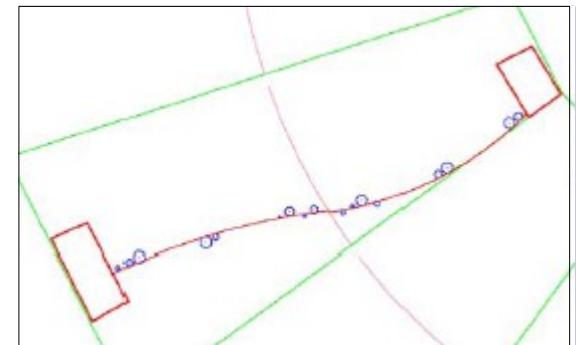
TAG

EXO

SUPERNEMO
MOON*
DCBA



Source $\neq$ Detector
Tracking capability



(*) Dedicated talks @MEDEX09

Status and near future projects

Experiment	Isotope	Isotope mass (kg)	$T_{1/2}$ (y)	Data taking Start	Status
CUORE	^{130}Te	203	2.1×10^{26}	2012	Construction
GERDA I	^{76}Ge	17.9	3×10^{25}	2009	Construction
GERDA II	^{76}Ge	40	2.0×10^{26}	2011	Funded
EXO-200	^{136}Xe	200	6.4×10^{25}	2009	Construction
Majorana	^{76}Ge	30-60	1.1×10^{26}	2011	Funded R&D
SuperNEMO	^{82}Se	100	2.1×10^{26}	2011	R&D
SuperNEMO	^{150}Nd	100	1.0×10^{26}	2011	R&D
CANDLES	^{48}Ca	0.35		2009	Funded R&D
MOON II	^{100}Mo	120			R&D
DCBA	^{150}Nd	20			R&D
SNO+	^{150}Nd	50-500			R&D
COBRA	^{116}Cd	420			R&D
COBRA	^{130}Te	420			R&D
KamLAND-Zen	^{136}Xe	250-400			Preparation

IN EUROPE

LNGS



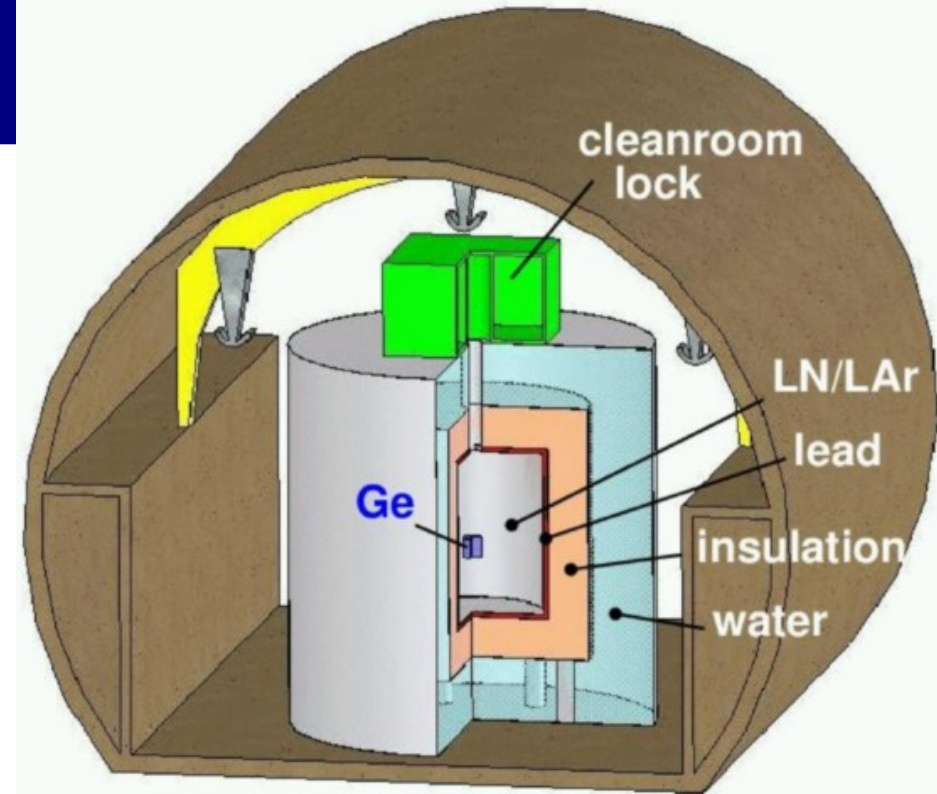
GERDA

Germany, Italy, Belgium, Russia

Goal: analyse HM evidence in a short time using existing ^{76}Ge enriched detectors (HM, Igex)

Concept: naked Ge crystals in LAr

- 1.5 m (LAr) + 10 cm Pb + 2 m water
- 2-3 orders of magnitude better bkg than present Status-of-the-Art
- active shielding with LAr scintillation



3 phases experiment

Phase I: operate refurbished HM & IGEX enriched detectors (~20 kg)

- Underground commissioning
- Background: 0.01 counts/ keV kg y
- Scrutinize ^{76}Ge claim with the same nuclide (5s exclusion/confirmation)
- Half life sensitivity: $3 \times 10^{25} \text{ y}$
- Start data taking: 2009

Phase II: additional ~20 kg ^{76}Ge diodes (segmented detectors)

- Background: 0.001 counts / keV kg y
- Sensitivity after 100 kg y (~3 years): $2 \times 10^{26} \text{ y}$ ($\langle m_\nu \rangle < 90 - 290 \text{ meV}$)

Phase III: depending on physics results of Phase I/I

~ 1 ton experiment in world wide collaboration with MAJORANA

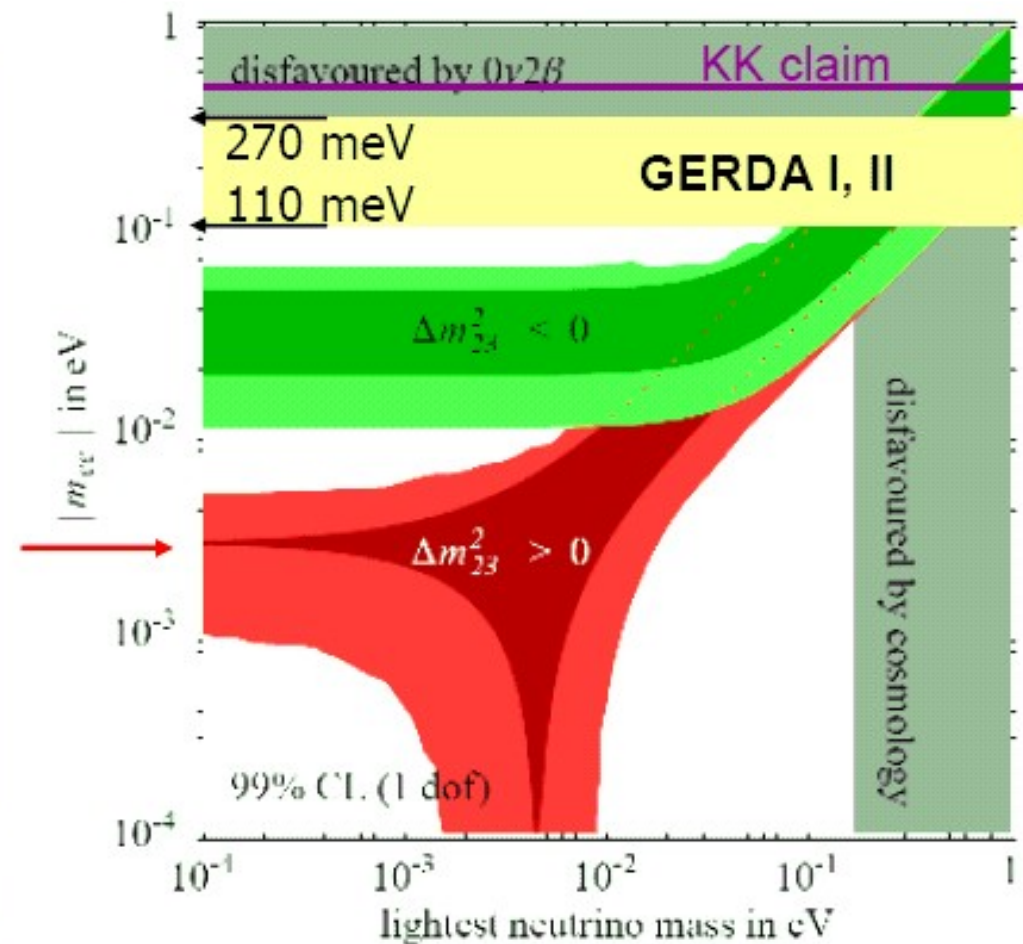
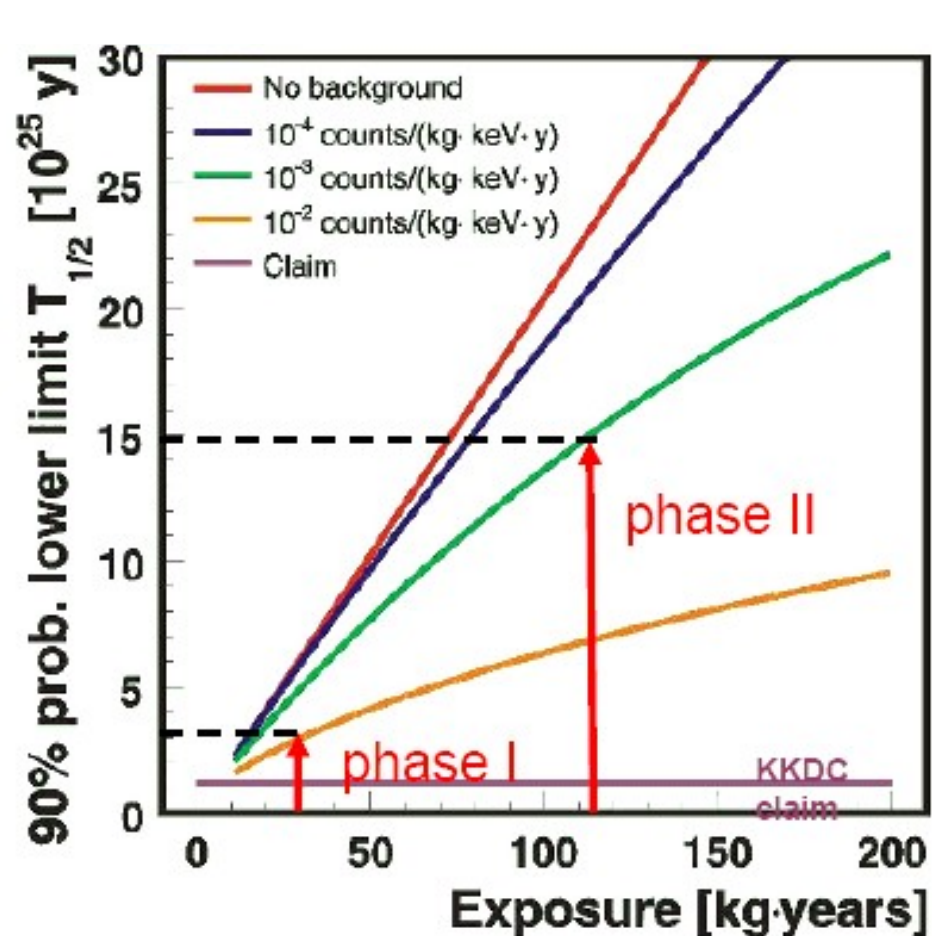
$\langle m_\nu \rangle < 20 - 50 \text{ meV}$

2010:

Setup complete

Started with Natural Ge

GERDA sensitivity

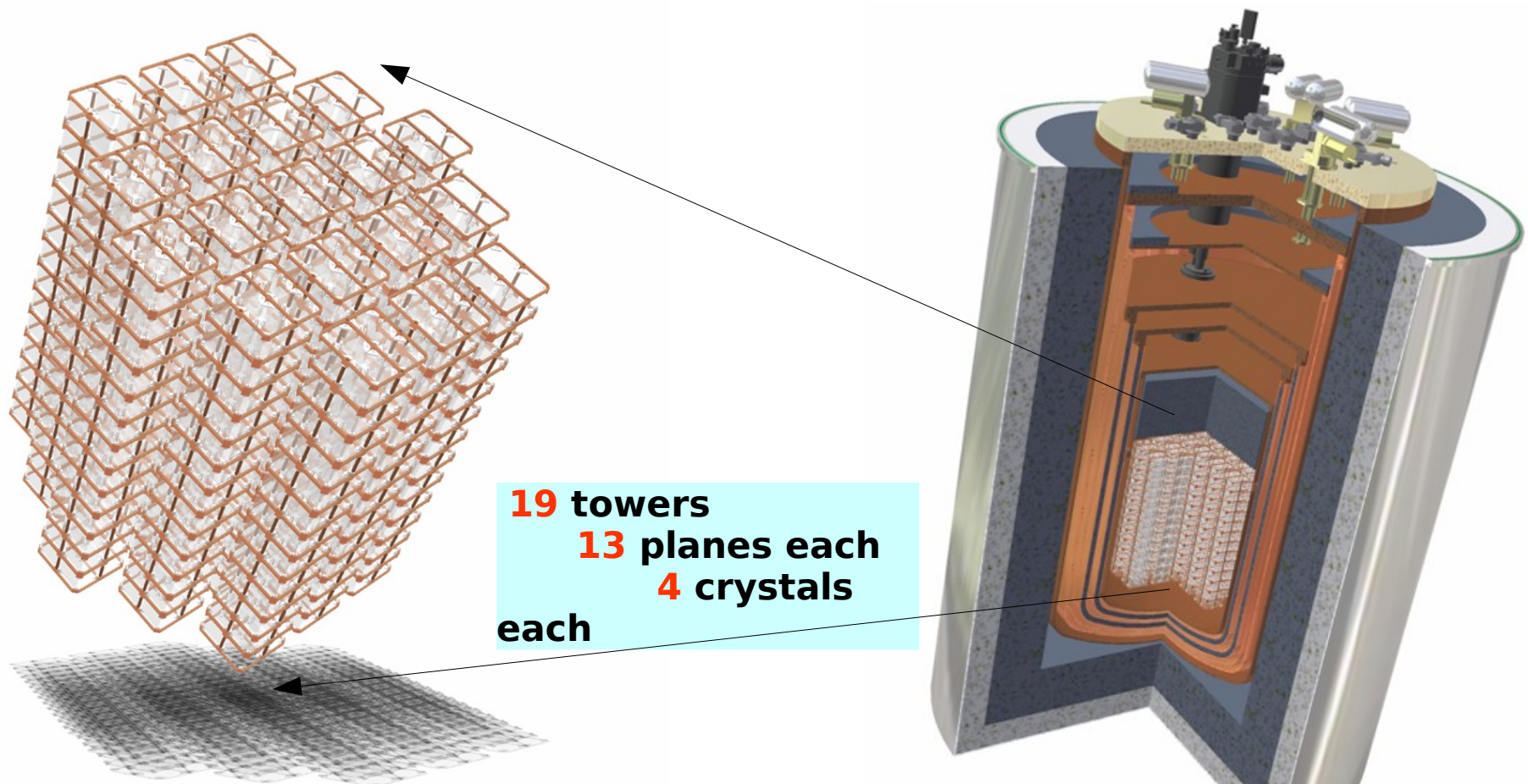


→ if signal found in HM by KK is true $\beta\beta$ decay, this would produce in ~ 1 year GERDA I data taking (assuming 18 kg y exposure) 7 cts, above bckg of 0.5 cts → probability that bckg simulate signal $\sim 10^{-5}$

CUORE

Cryogenic Underground Observatory for Rare Events

- Closely packed array of 988 TeO_2 crystals $5 \times 5 \times 5 \text{ cm}^3$ (750 g)
741 kg TeO_2 granular calorimeter
600 kg Te = 203 kg ^{130}Te
- Single high granularity detector



CUORE (2)



Large international Collaboration

I NL GB - US- CHINA

Good control of the background

- Dedicated underground setup
- CUORICINO

Still work in progress to reduce surface radioactivity contribution

Operated @ LNGS

- Special cryostat built with selected Materials
- Cryogen-free dilution refrigerator
- Shielded by several lead and PET layers

Approved in fall 2004

- 1000 TeO_2 crystals funded by INFN and DoE: delivery started end 2008
- The first CUORE tower (CUORE-0) will be assembled and operated in 2009

5 y sensitivity

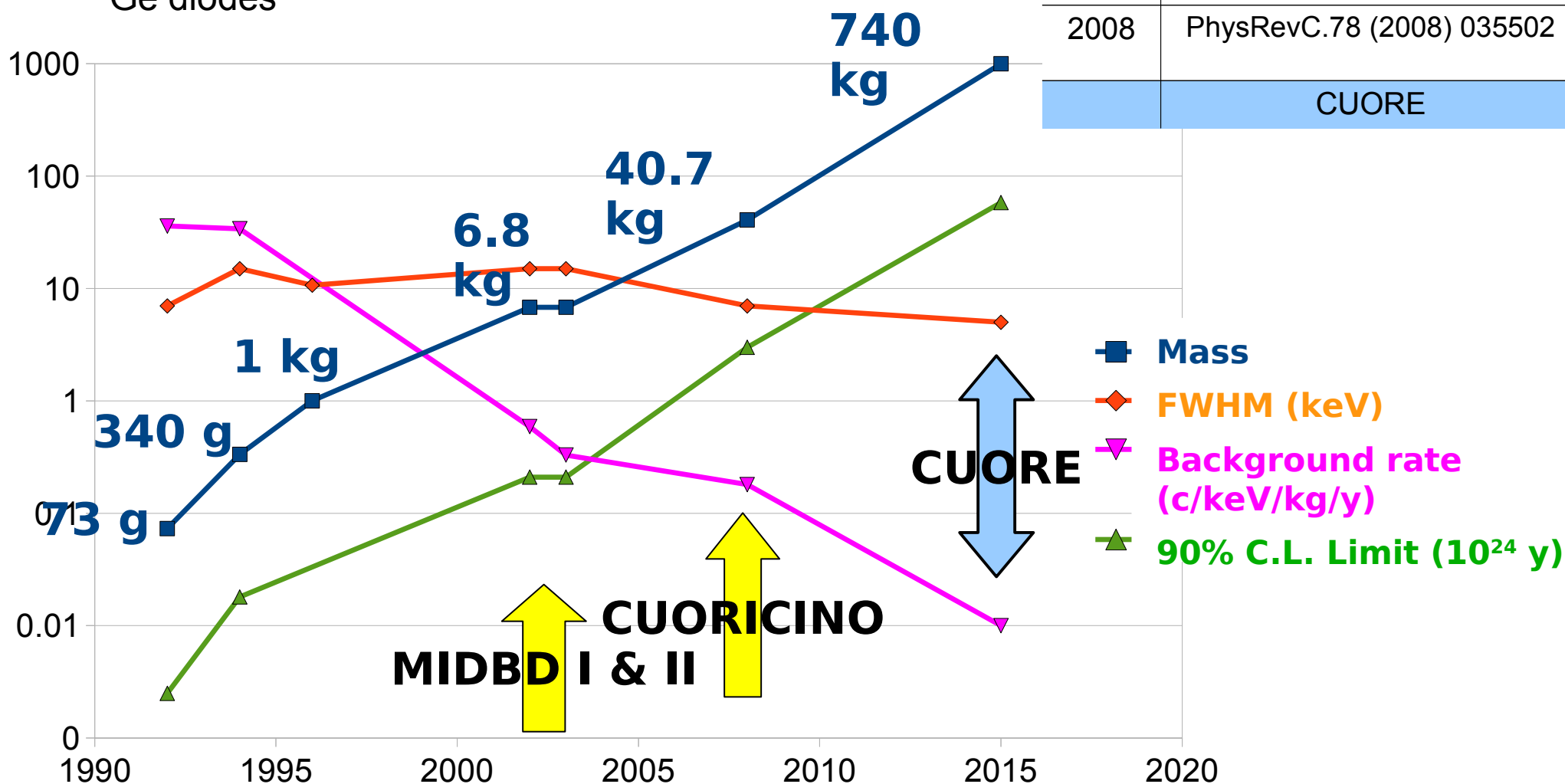
Background [c/keV/kg/y]	ΔE_{FWHM} [keV]	$\tau_{1/2}^{0\nu}$ [y] @ 68% C.L.	m_{ee} [meV]			
			R(QRPA) ¹	pn(QRPA) ²	ISM ³	IBM-2 ⁴
0.01	5	2.1×10^{26}	35 ÷ 66	41 ÷ 67	65 ÷ 82	41
0.001	5	6.5×10^{26}	20 ÷ 38	23 ÷ 38	37 ÷ 47	23

Under construction since 2005
Start data taking 2013

TeO₂ @ LNGS

TeO₂ bolometers:

- Technique suggested in 1985 by E. Fiorini and T.O. Niinikoski
- energy resolution comparable with Ge diodes



CUORE-0

CUORE-0 = first CUORE tower to be installed in the CUORICINO dilution refrigerator (hall A @ LNGS)

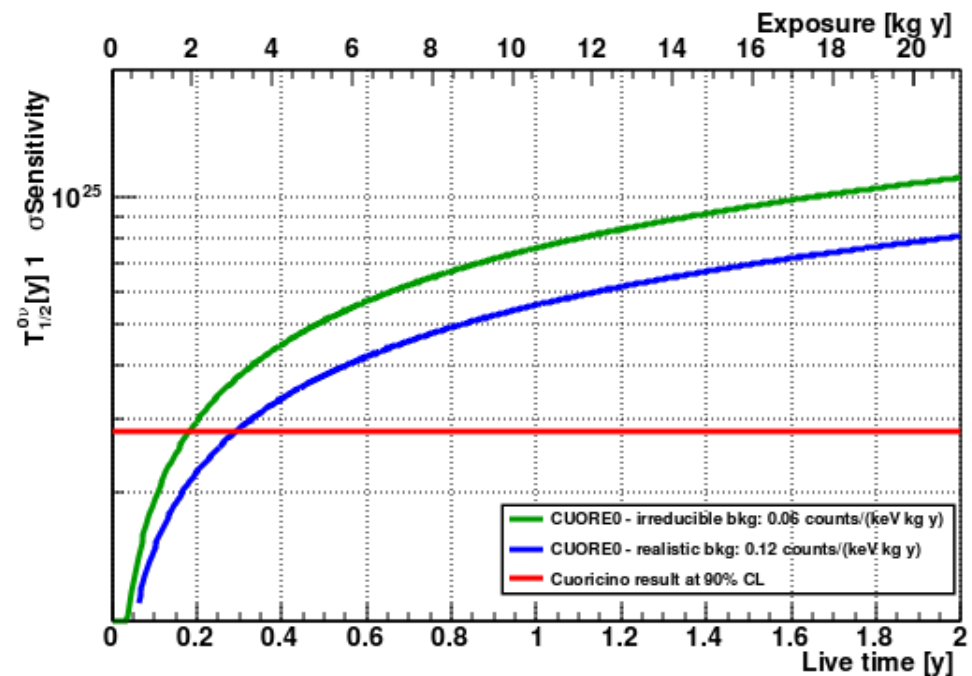
Motivations

High statistics test of the many improvements/changes developed for the CUORE assembly procedure:

- gluing
- holder
- zero-contact approach
- Wires
- ...

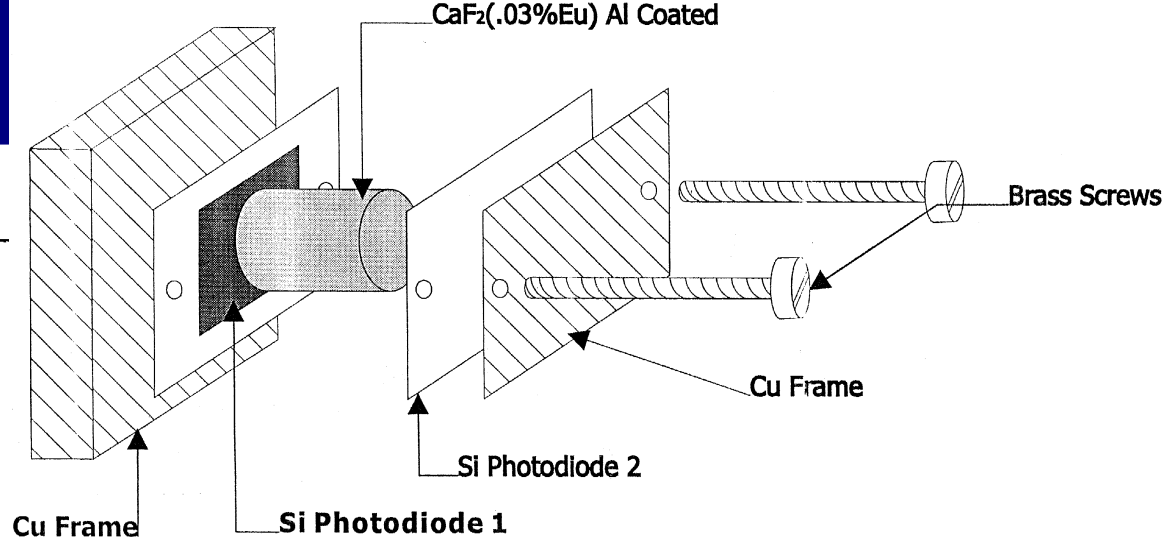
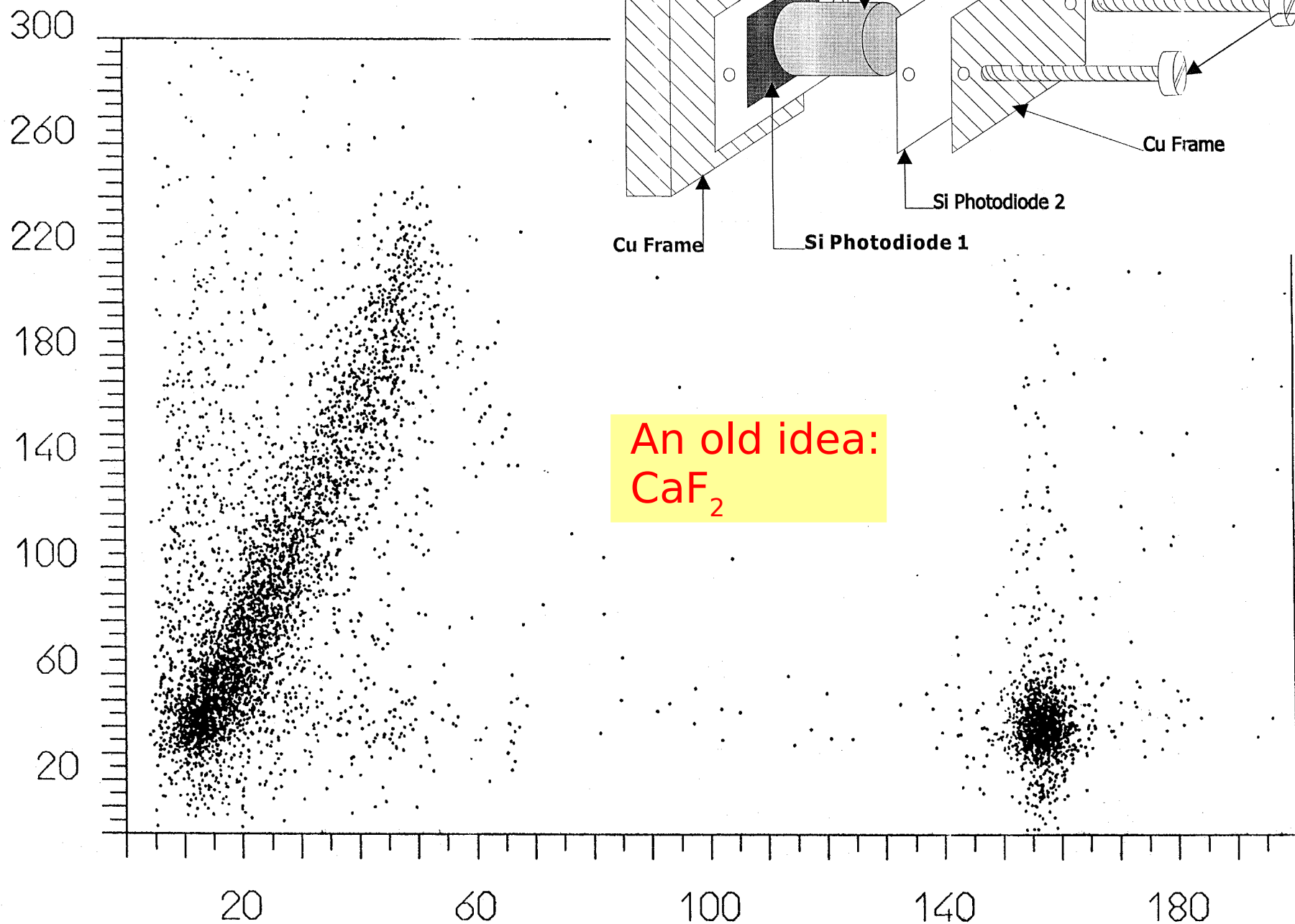
CUORE demonstrator: expected background in the DBD and alpha energy regions reduced by a factor 3 with respect to CUORICINO

Powerful experiment: it will overtake soon CUORICINO sensitivity



Scintillating bolometers

Scintillation [mV]

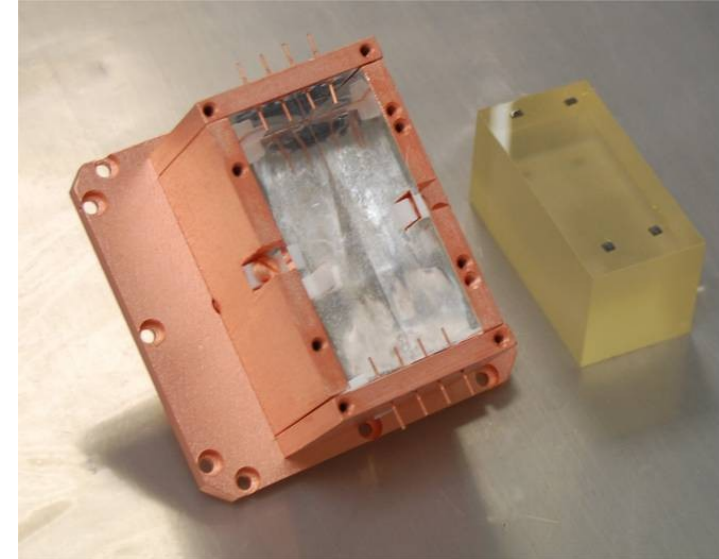
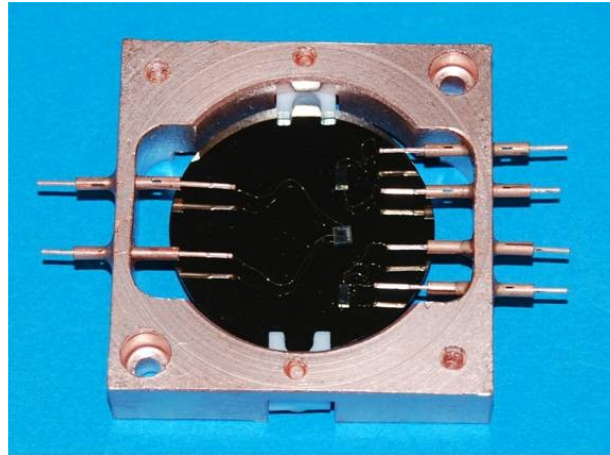


An old idea:
CaF₂

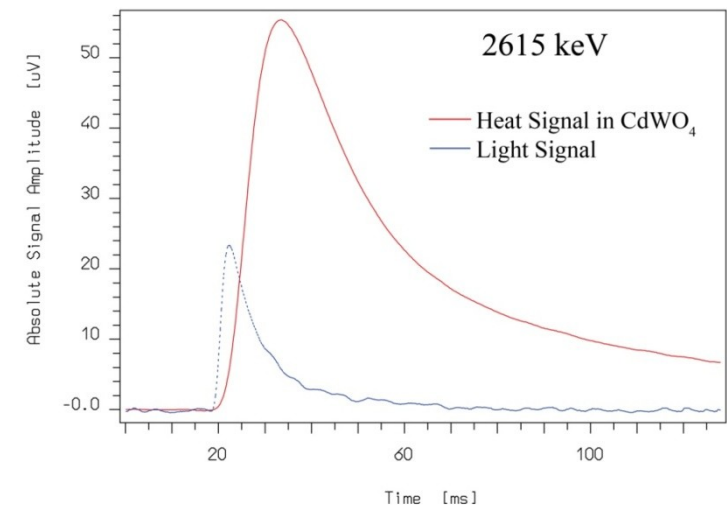
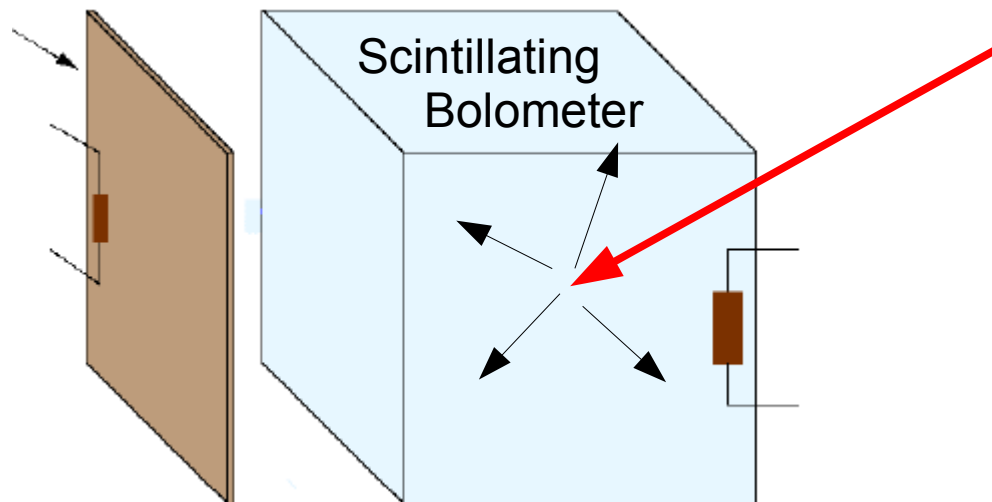
Scintillating bolometers: BOLUX

A very promising technique for background reduction

Concept: separate the dangerous alpha background exploiting different scintillating properties



Bolometer

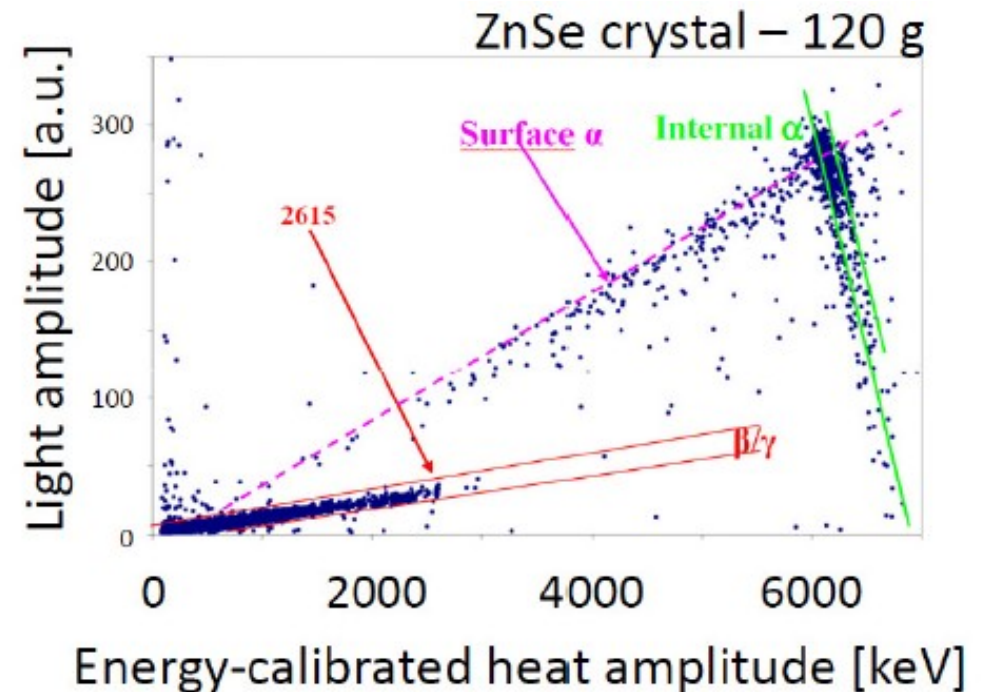
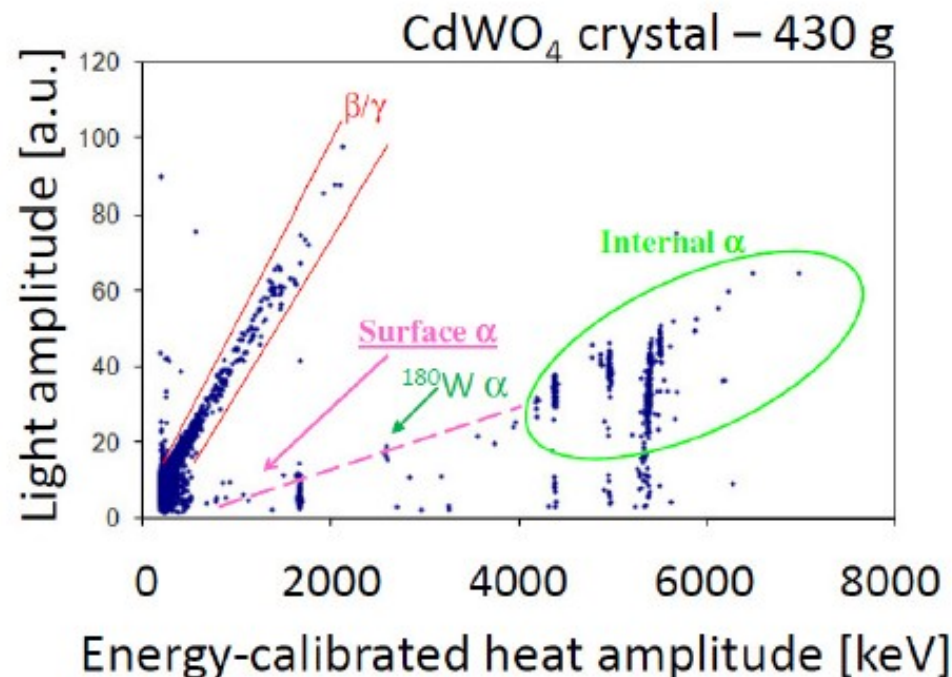


Not viable for TeO_2 ... but ...

Scintillating bolometers: discriminating power

Scatter plot of light signals vs. heat signal

Alpha light yield < beta light yield



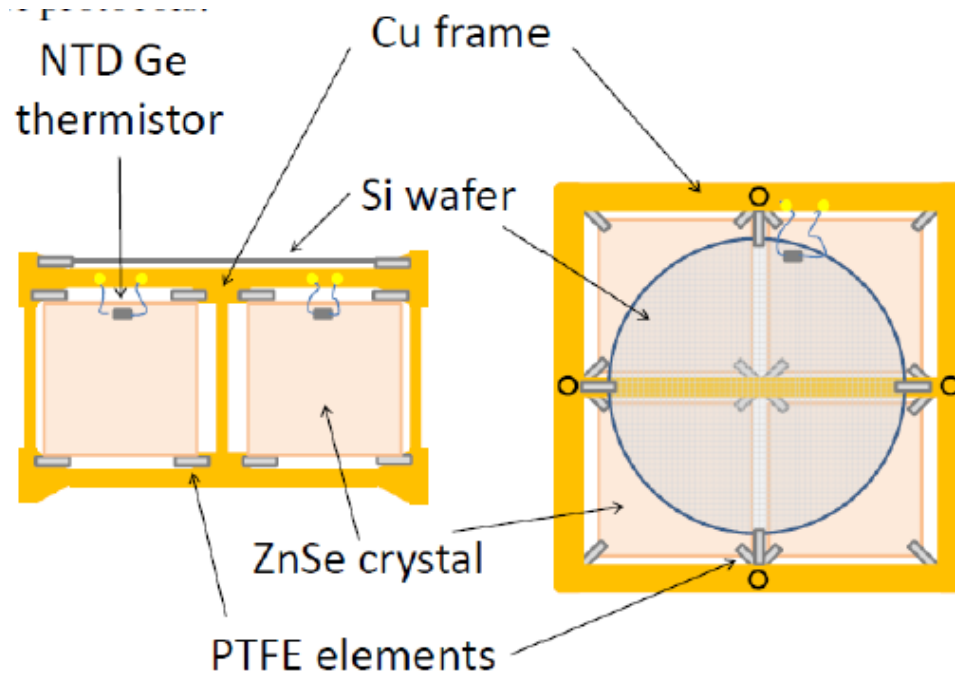
Arxiv [Nucl-ex]: 1006.2721
Arxiv: 1005.1239 and Astroparticle

Alpha light yield > beta light yield

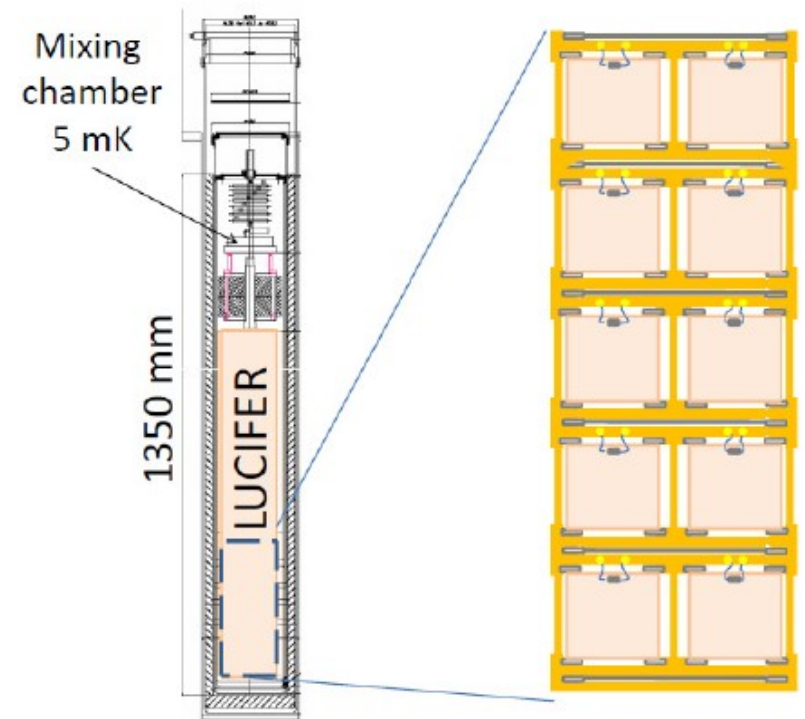
LUCIFER

ERC call: funded march 2010

Goal: demonstrate feasibility of 10^{-3} c/keV/kg background



Single module



SuperNEMO

France, UK, Russia, Spain, USA, Japan, Czech Republic, Ukraine, Finland

- **concept:** scale NEMO3 setup
100 kg of ^{82}Se or ^{150}Nd
- possibility to produce ^{150}Nd with the French AVLIS facility
- tracking calorimeter
- already tested technology (NEMO3)
- **event topology (Detection of the 2 electrons)**
- **single and sum energy + angular correlation**
- **particle identification**
-
- **Background control**
- **source purification**
- **background level measurement**
- **external background reduction (Rn)**

3 years R&D aiming at a 50-90 meV
 $\langle m_n \rangle$ sensitivity: $T_{1/2} > 2 \cdot 10^{26} \text{ yr}$

- improvement of energy resolution
- increase of efficiency
- background reduction

funded by France, UK and Spain

Planar geometry

- **source (40 mg/cm²): 12m²**
- **tracking volume: ~3000 channels**
- **calorimeter: ~1000 PMT**

Modular:

- **~5 kg of enriched isotope/module**
- **100 kg: 20 modules**

~ 60 000 channels for drift chamber
~ 20 000 PMT

energy resolution $\sigma_E = 2.6\% @ 3 \text{ MeV}$
efficiency: 40%

Canfranc/LSM

- **2009: TDR**
- **2011: commissioning and data taking of first modules in Canfranc (Spain)**
- **2013: Full detector running**

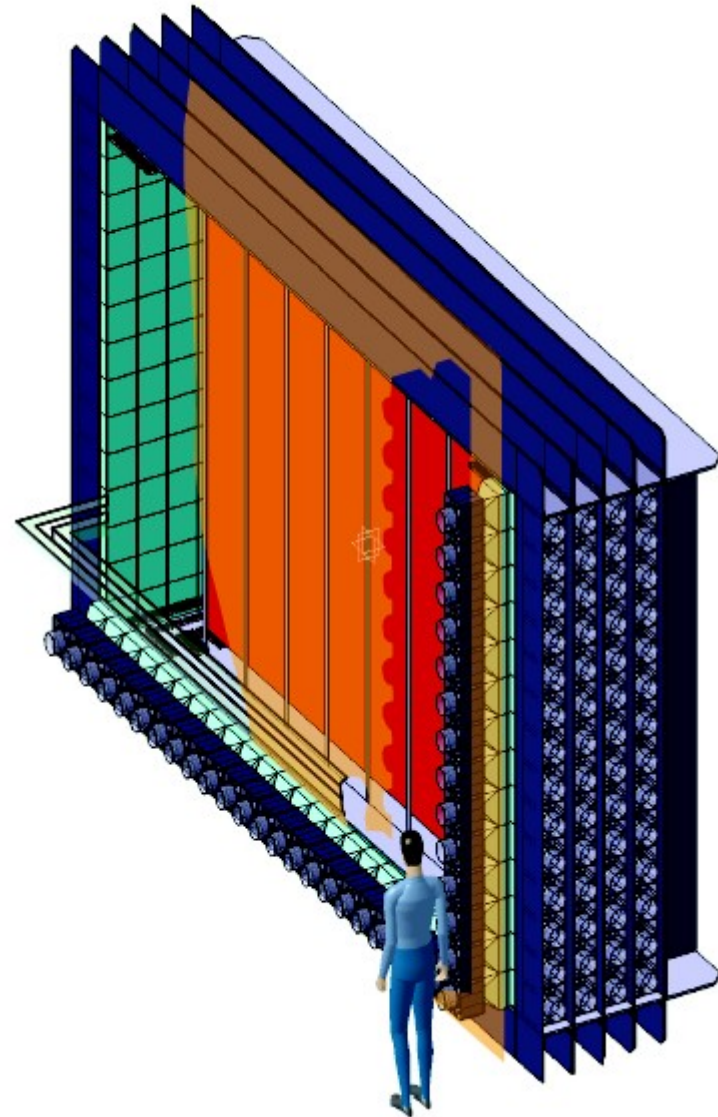
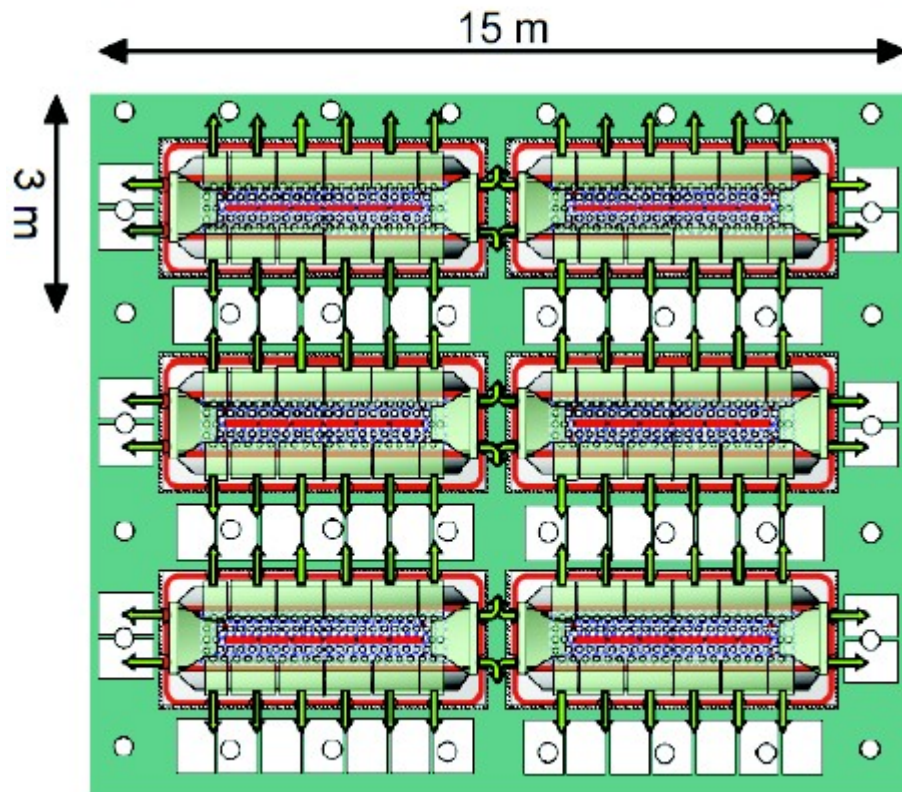
SuperNEMO

20 modules for 100 kg

Source: $\sim 5\text{ kg}$ (4.0 mg/cm^2 , 12 m^2)

Tracking: $\sim 2,100$ drift cells).

Calorimeter: ~ 600 blocks

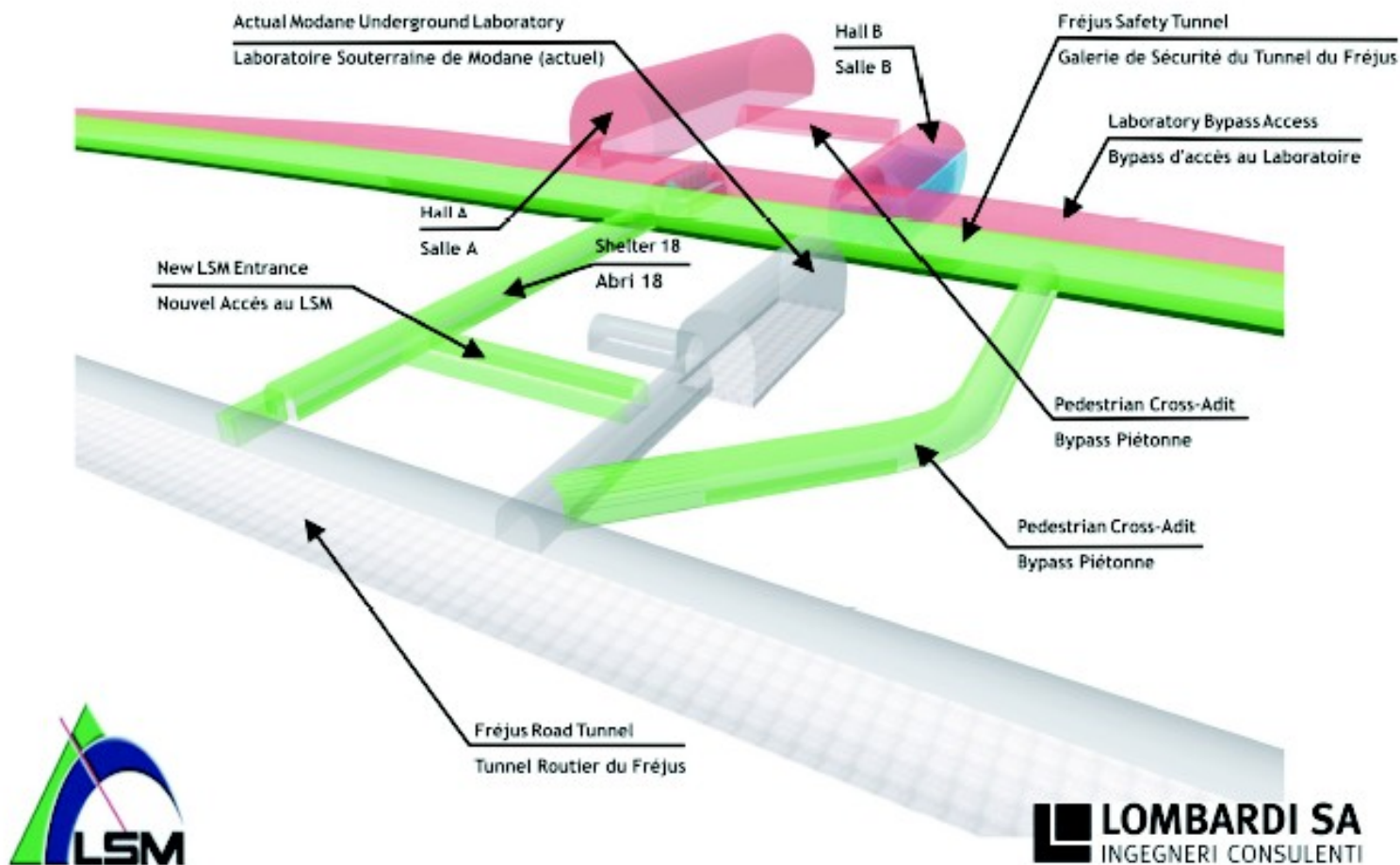




ULISSE project

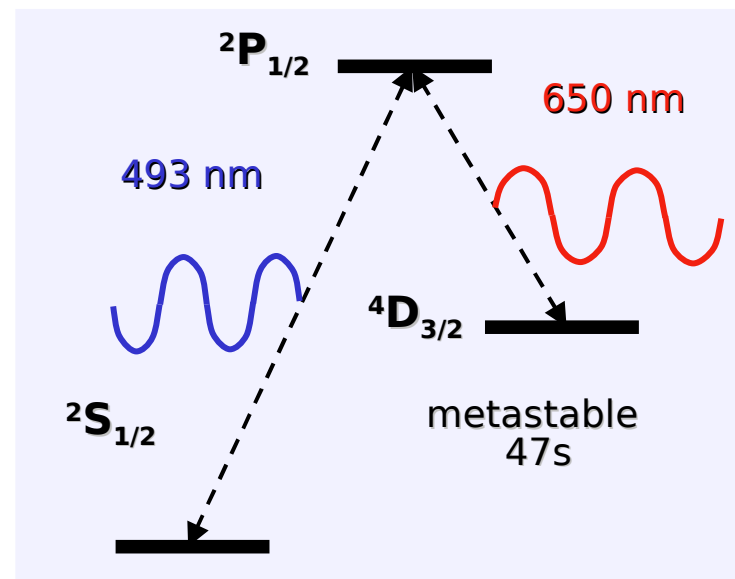
MODANE UNDERGROUND LABORATORY 60'000 m³ EXTENSION

LABORATOIRE SOUTERRAIN DE MODANE AGRANDISSEMENT 60'000 m³



IN THE WORLD

- **concept:** scale Gotthard experiment adding **Ba tagging** to suppress background ($^{136}\text{Xe} \rightarrow ^{136}\text{Ba}^{++} + 2e$)
- **calorimetry + tracking**
- single Ba^+ detected by optical spectroscopy
- ^{136}Xe enrichment easier and safer
- **LXe TPC + scintillation**
- energy resolution $\sigma_E = 2\%$
- expected bkg only by $\beta\beta - 2\nu$



Goal: 5y sensitivity (1 ton 80% i.e. Xe): $T_{1/2} > 2 \cdot 10^{27} \text{ y}$ ($\langle m \rangle \sim 25\text{-}30 \text{ meV}$)

Parallel activities:

EXO-200:

a LXe detector without Ba tagging using 200 kg of Xe enriched to 80% in ^{136}Xe with $\sim 150 \text{ meV}$ sensitivity to Majorana masses

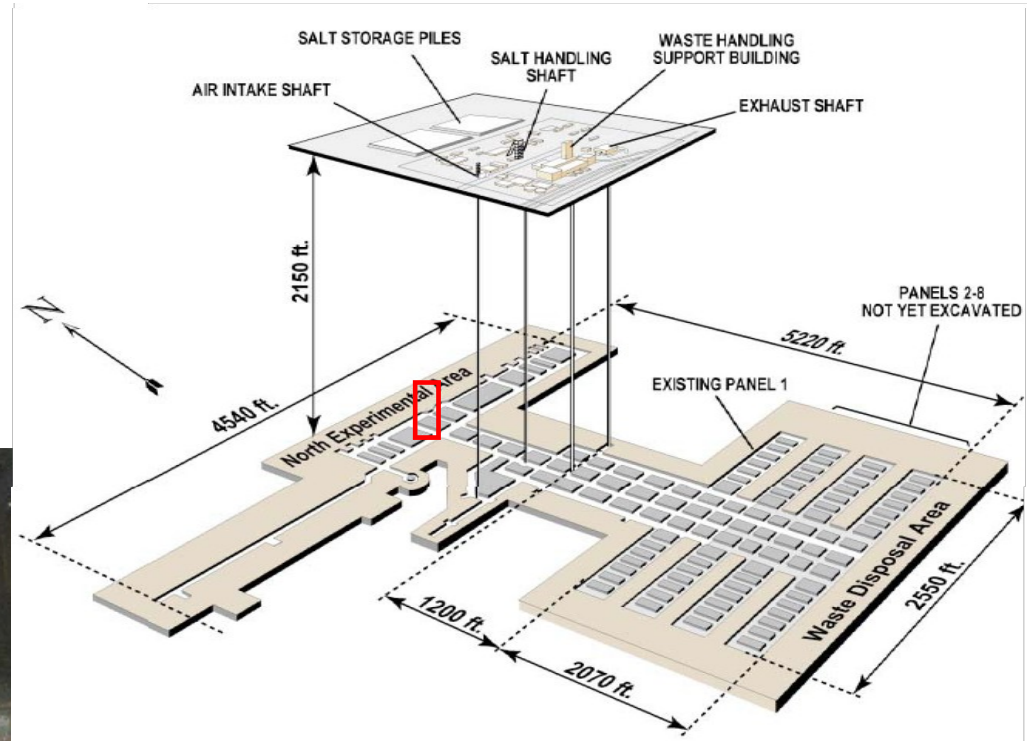
Ba-tagging R&D:

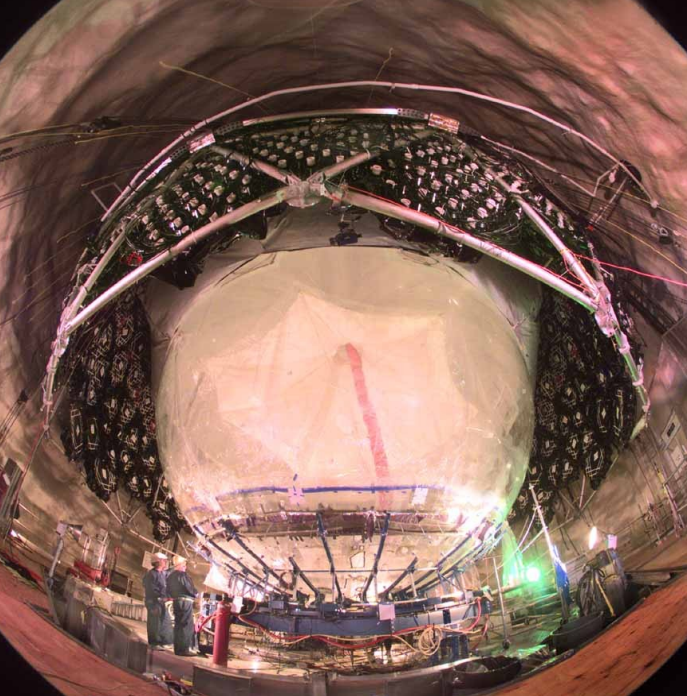
- Transfer from LXe to ion trap
- Directly tag in LXe volume

High pressure GXe detector R&D:

- Energy resolution and readout scheme
- Tracking: pressure and light gas mixes
- Ba tagging in gas

EXO-200 @ WIPP





SNO: One million pieces transported down in the 9 ft x 12 ft x 9 ft mine cage and re-assembled under ultra-clean conditions. Every worker takes a shower and wears clean, lint-free clothing.

SNO



**Over 70,000
Showers
to date and
counting**



SNO: main engineering changes

The organic liquid is lighter than water so the Acrylic Vessel must be held down.

Existing
AV Support
Ropes

AV Hold Down
Ropes

nt. Purification, AV Hold Down
erwise, the existing detector, electronics etc. are unchanged

SNO+: SNO filled with liquid scintillator

A liquid scintillator detector has poor energy resolution

Huge quantities of isotope (high statistics) and low backgrounds however help compensate

- source in–source out capability
- large, homogeneous liquid detector leads to well-defined background model
- possibly source in–source out capability
- using the technique that was developed originally for LENS and now also used for Gd-loaded scintillator
- SNO+ collaboration managed to load Nd into pseudocumene and in linear alkylbenzene (>1% concentration)
- with 1% Nd loading (natural Nd) a very good neutrinoless double beta decay sensitivity is predicted, but...

Nd loaded scintillator:

1% loading (Natural Nd) large light absorption by Nd

47 ± 6 pe/MeV (Monte Carlo)

0.1% loading (Isotopically enriched to 56% Nd) acceptable

400 ± 21 pe/MeV (Monte Carlo)

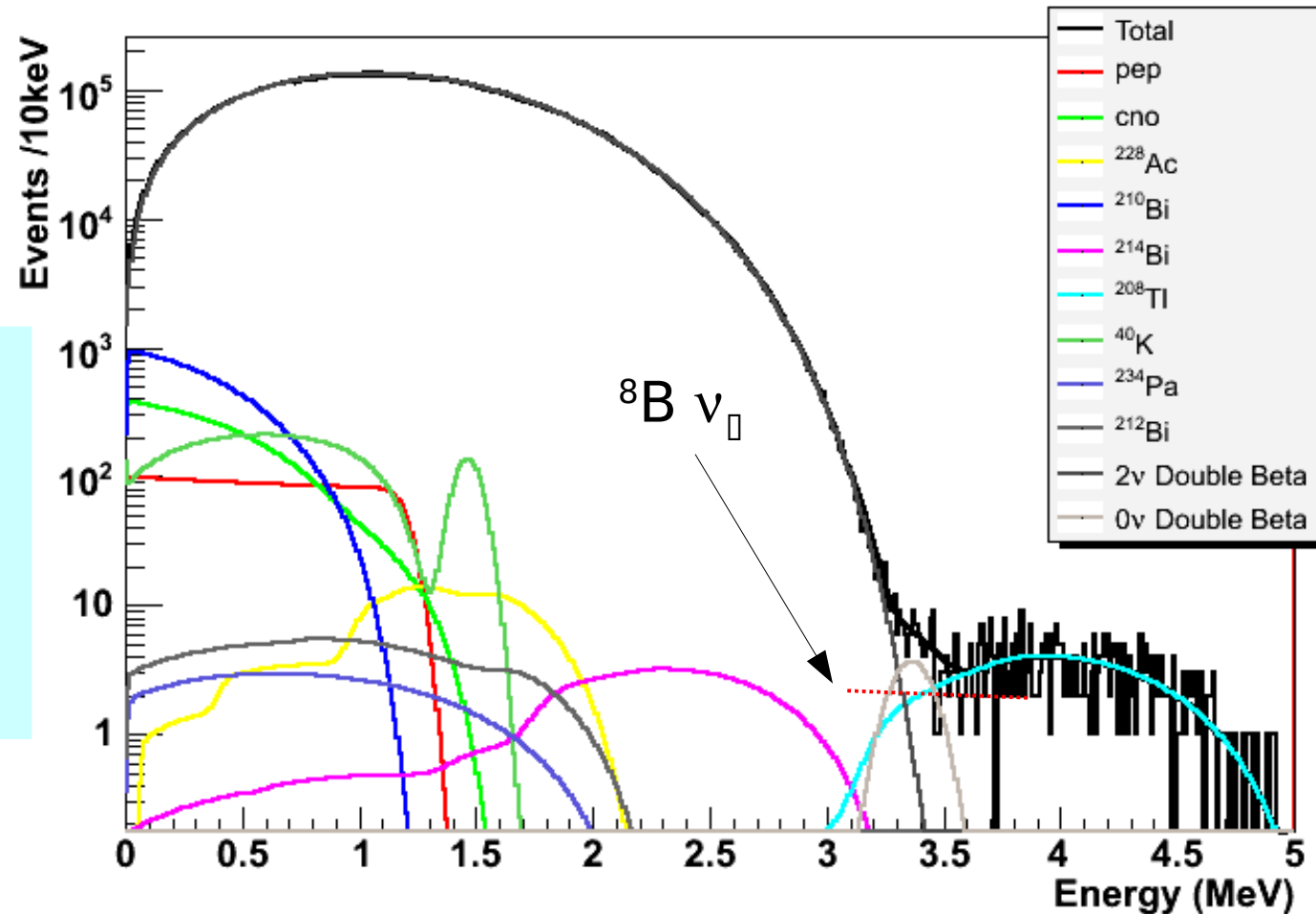
SNO+

- Using existing SNO infrastructure
- Well understood detector

1057 events per year with 500 kg ^{150}Nd -loaded liquid scintillator in SNO+.

Simulation assuming light output and background similar to Kamland.

Simulated SNO+ Energy Spectrum



Sensitivity Limits (3 yrs):

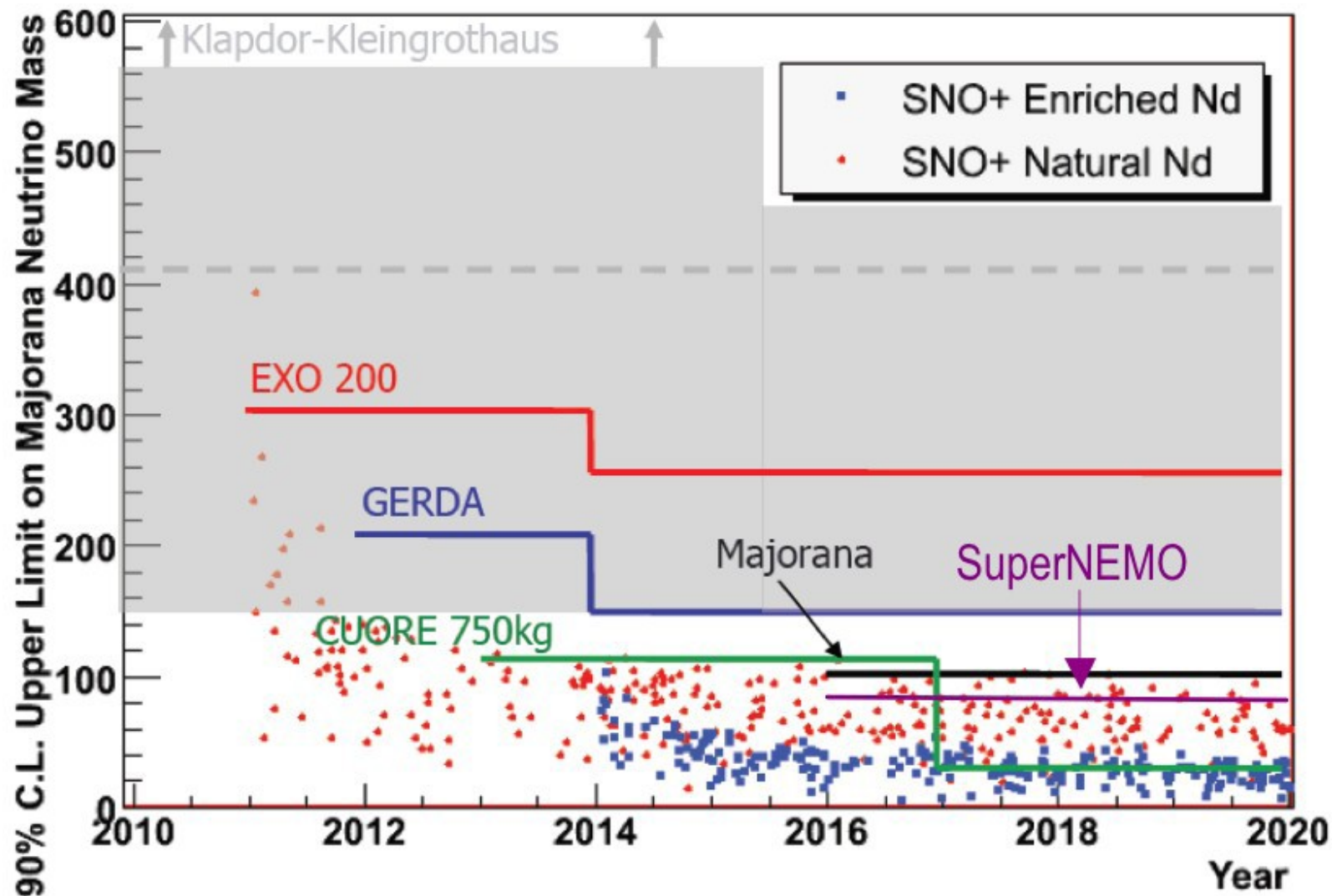
- Natural Nd (56 kg isotope):
 $m_{\beta\beta} \sim 0.1 \text{ eV}$
- 500 kg enriched ^{150}Nd
 $m_{\beta\beta} \sim 0.04 \text{ eV}$

Funded by NSERC for final design/engineering and initial construction 2008-2010

End of 2010 → ready for scintillator filling

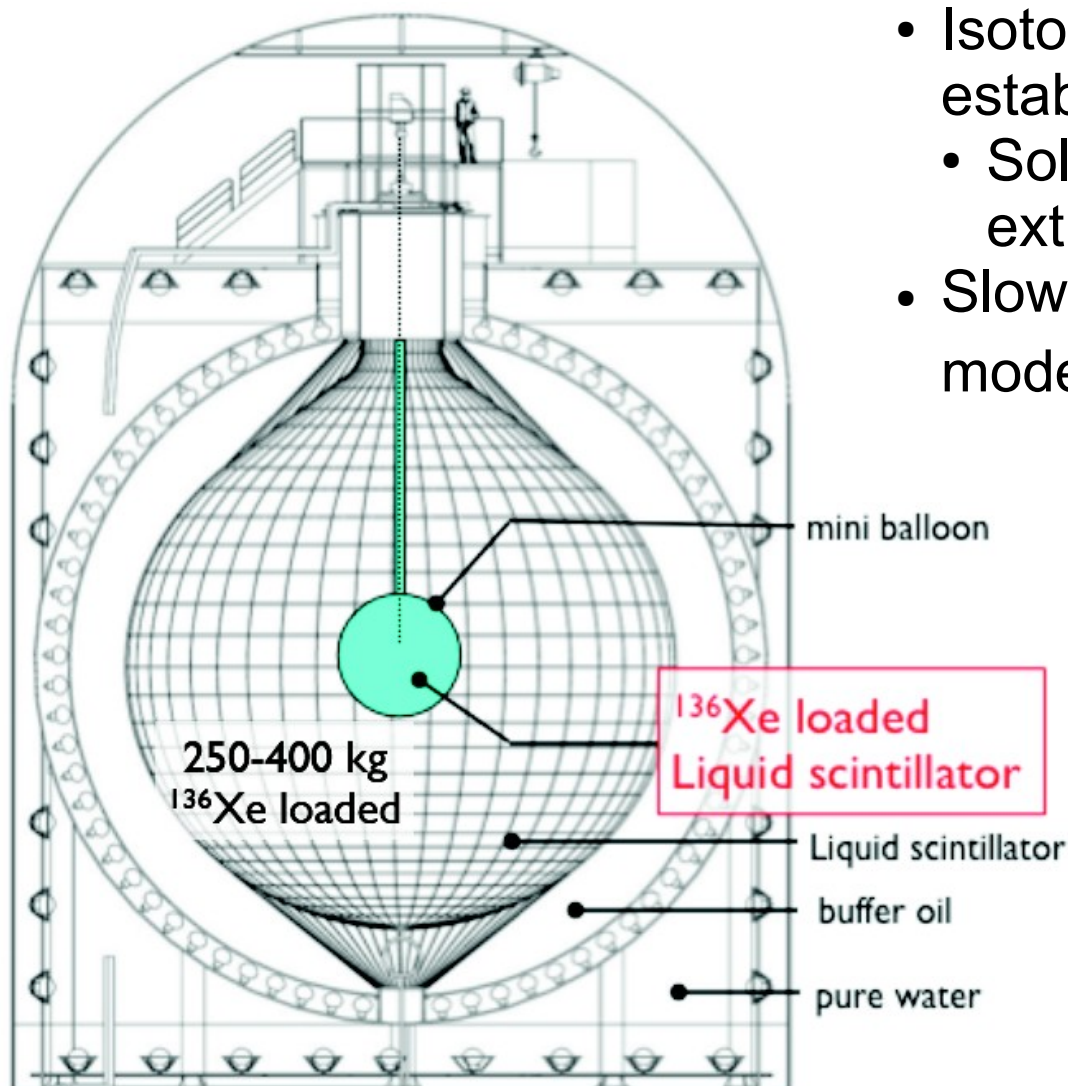
SNO+ sensitivity

The D.B.D. Limit as a Function of Livetime

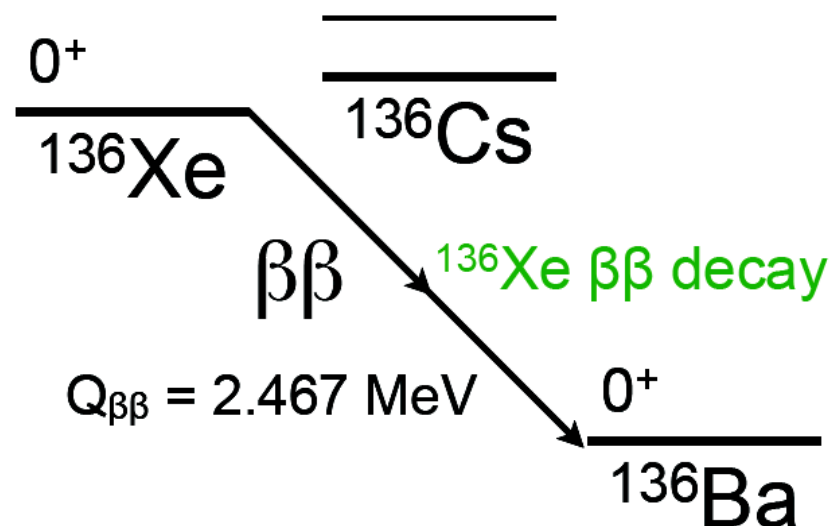


- Each SNO+ point represents a different MC “experiment” so as to reflect the statistical spread of derived limits.
- Ultimately, the ability to achieve such sensitivities in practise may rest on securing sufficient control of backgrounds

^{136}Xe loaded LS



- Isotopic enrichment, purification established
 - Soluble to LS more than 3 wt%, easily extracted
- Slow $2\nu\beta\beta$ ($T_{1/2} > 10^{22}$ years) requires modest energy resolution



Phase I concept

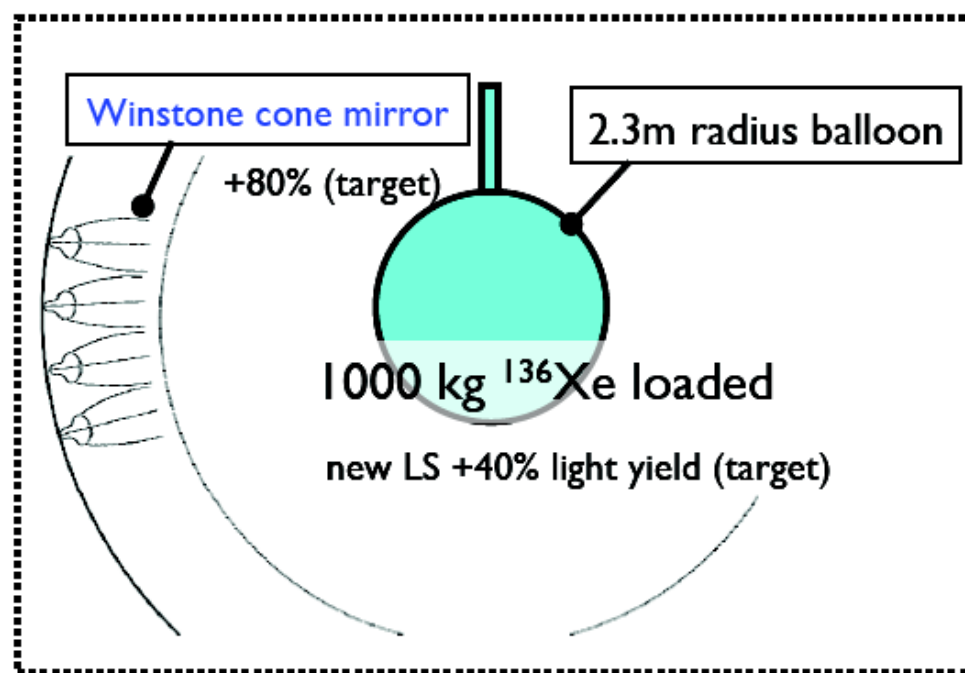
KAMLAND merits

- Ultra low radioactivity environment based on ultra pure LS and
- 9m radius active shield: $^{38}\text{U} < 3.5 \cdot 10^{-18} \text{ g/g}$ $^{232}\text{Th} < 5.2 \cdot 10^{-17} \text{ g/g}$
- No modification to the detector is necessary to accommodate DBD nuclei
- High sensitivity with low cost (~6M\$, budget secured) **60 meV in 1.5 years**
- Reactor and geo- antineutrino observations continue
- High scalability (2nd phase)

Phase II

1000 kg ^{136}Xe , improvement of energy resolution with light concentrators and brighter LS (~30M\$)

25 meV in 5 years



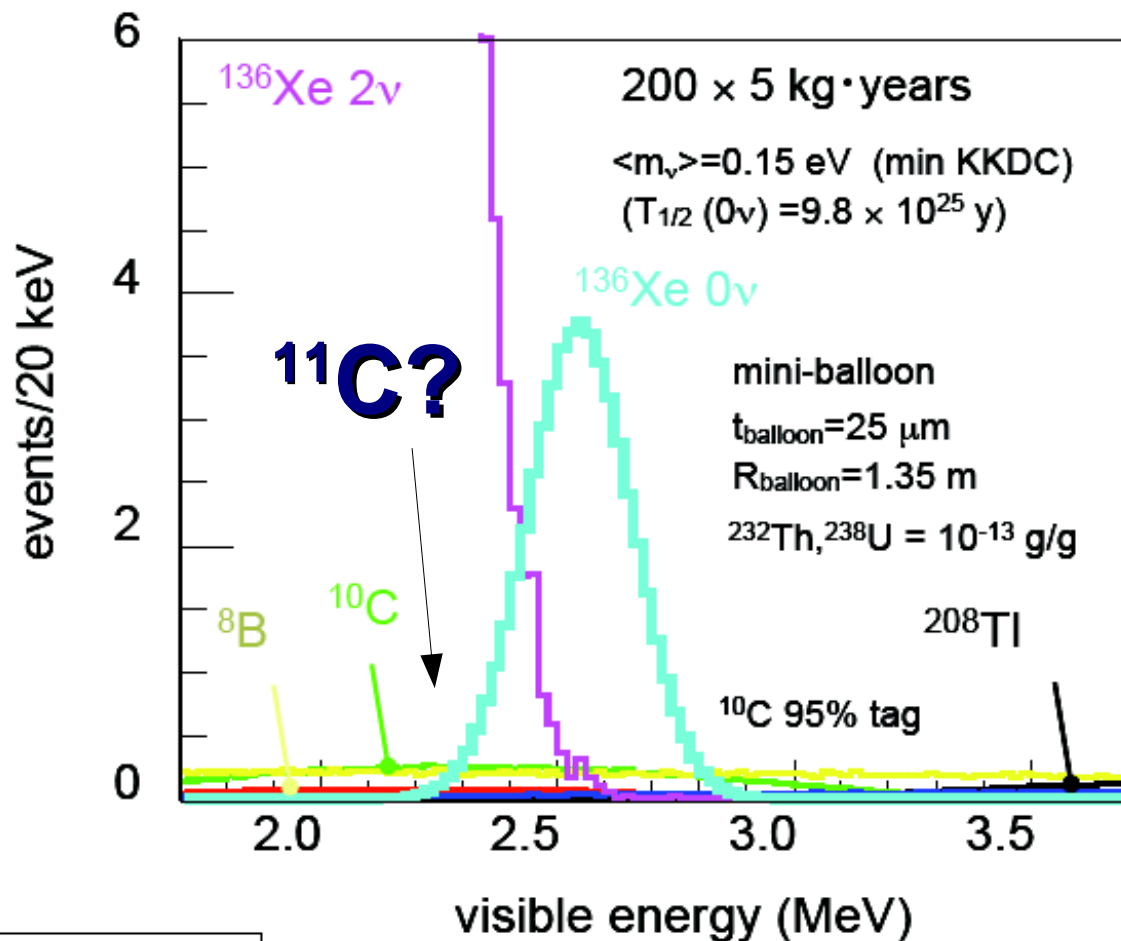
R&D items

- Xenon loaded LS with the same density, luminosity, transparency
- 2.7~4 m ϕ Mini-balloon
- Xenon purification, storage, extraction etc
- Cosmogenic background rejection with dead-time free electronics

KAMLAND sensitivity

1st phase

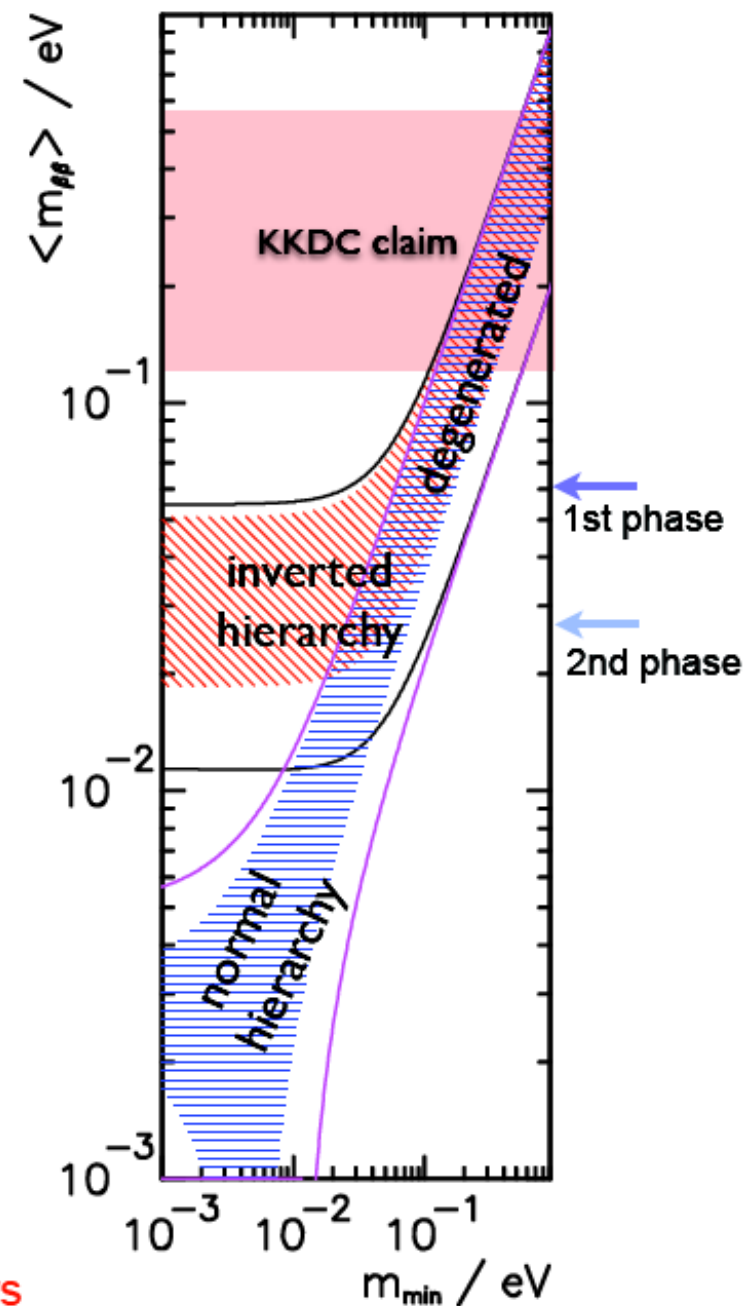
KKDC claim, degenerated hierarchy test



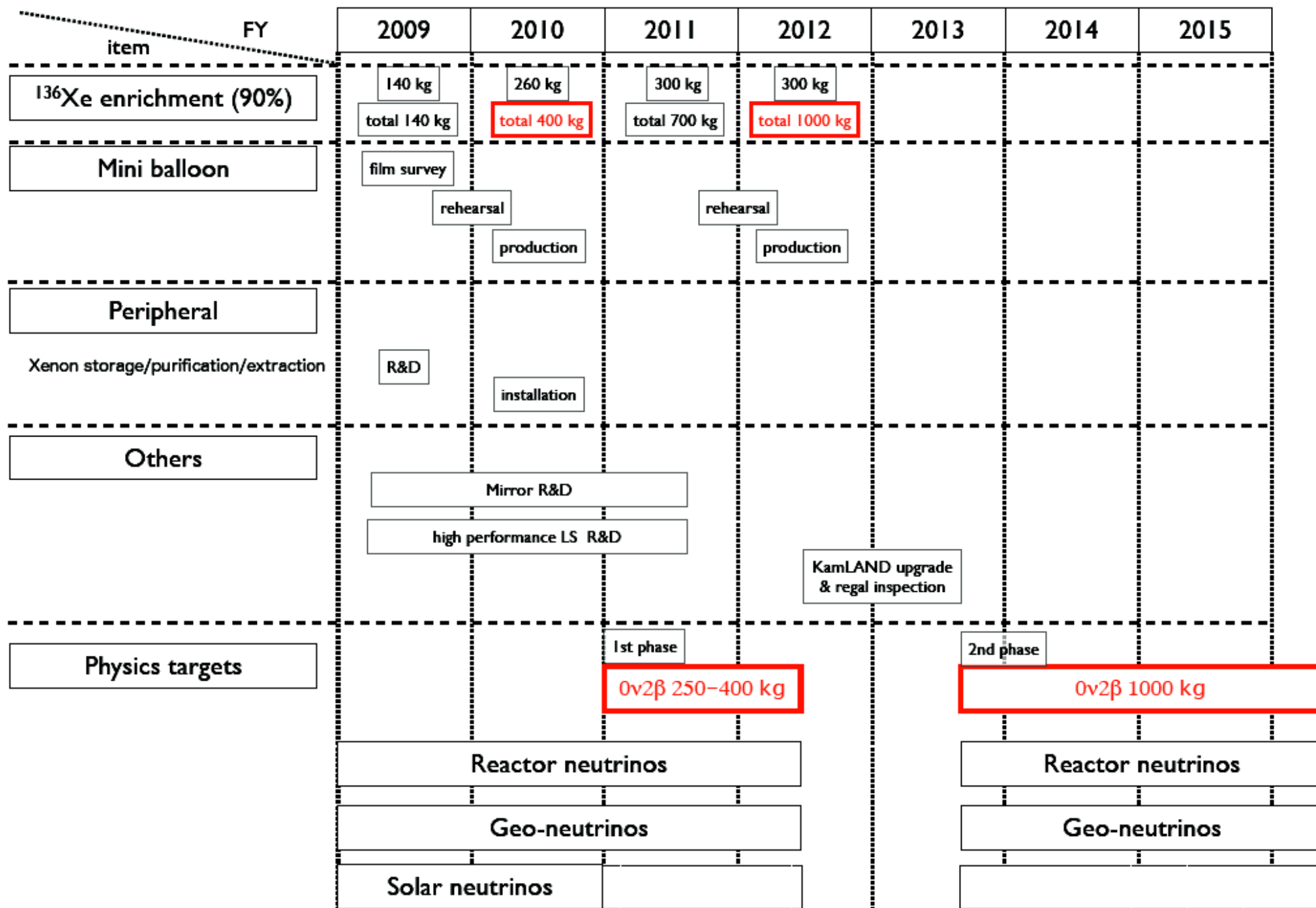
2nd phase

inverted hierarchy test

Target sensitivity of the 2nd phase is ~25 meV with 5 years



KAMLAND timeline



MAJORANA

Array of enriched Ge diodes operated in conventional Cu cryostats

Based on 60 Kg modules

First step: Actively pursue the development of R&D aimed at a ~ 1 ton scale ^{76}Ge $\beta\beta(0\nu)$ -decay experiment.

Proved energy resolution: 0.16 % FWHM

Technical goal: Demonstrate background low enough to justify building a tonne scale Ge experiment.

Science goal: build a prototype module (60kg) to test the recent claim of an observation of $\beta\beta(0\nu)$. This goal is a litmus test of any proposed technology.

Work cooperatively with GERDA Collaboration to prepare for a single international tonne-scale Ge experiment that combines the best technical features of MAJORANA and GERDA.

Pursue longer term R&D to minimize costs and optimize the schedule for a 1-tonne experiment.

MAJORANA: demonstrator module

^{76}Ge offers an excellent combination of capabilities & sensitivities.

Excellent energy resolution, intrinsically clean detectors, commercial technologies, best $0 \rightarrow \nu \nu$ sensitivity to date

60-kg of Ge detectors

- 30-kg of 86% enriched ^{76}Ge crystals required for science goal; 60-kg for background sensitivity
- Examine detector technology options
focus on point-contact detectors for DEMONSTRATOR

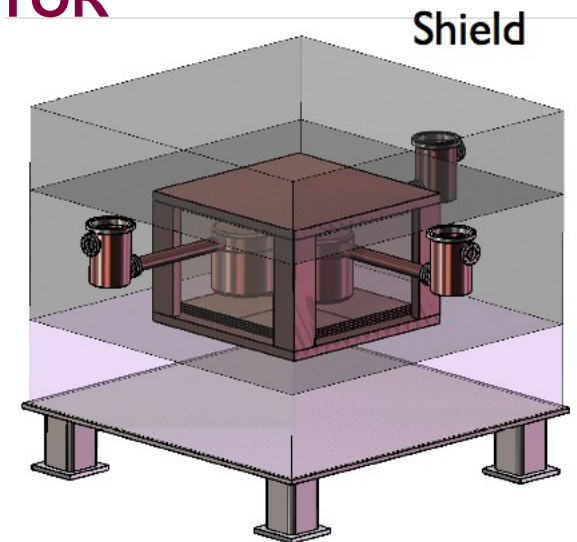
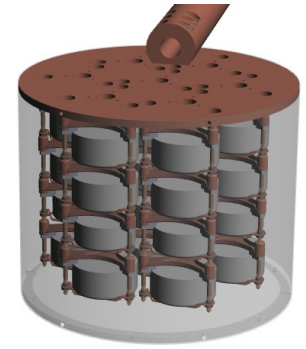
Low-background Cryostats & Shield

- ultra-clean, electroformed Cu
- naturally scalable
- Compact low-background passive Cu and Pb shield with active muon veto

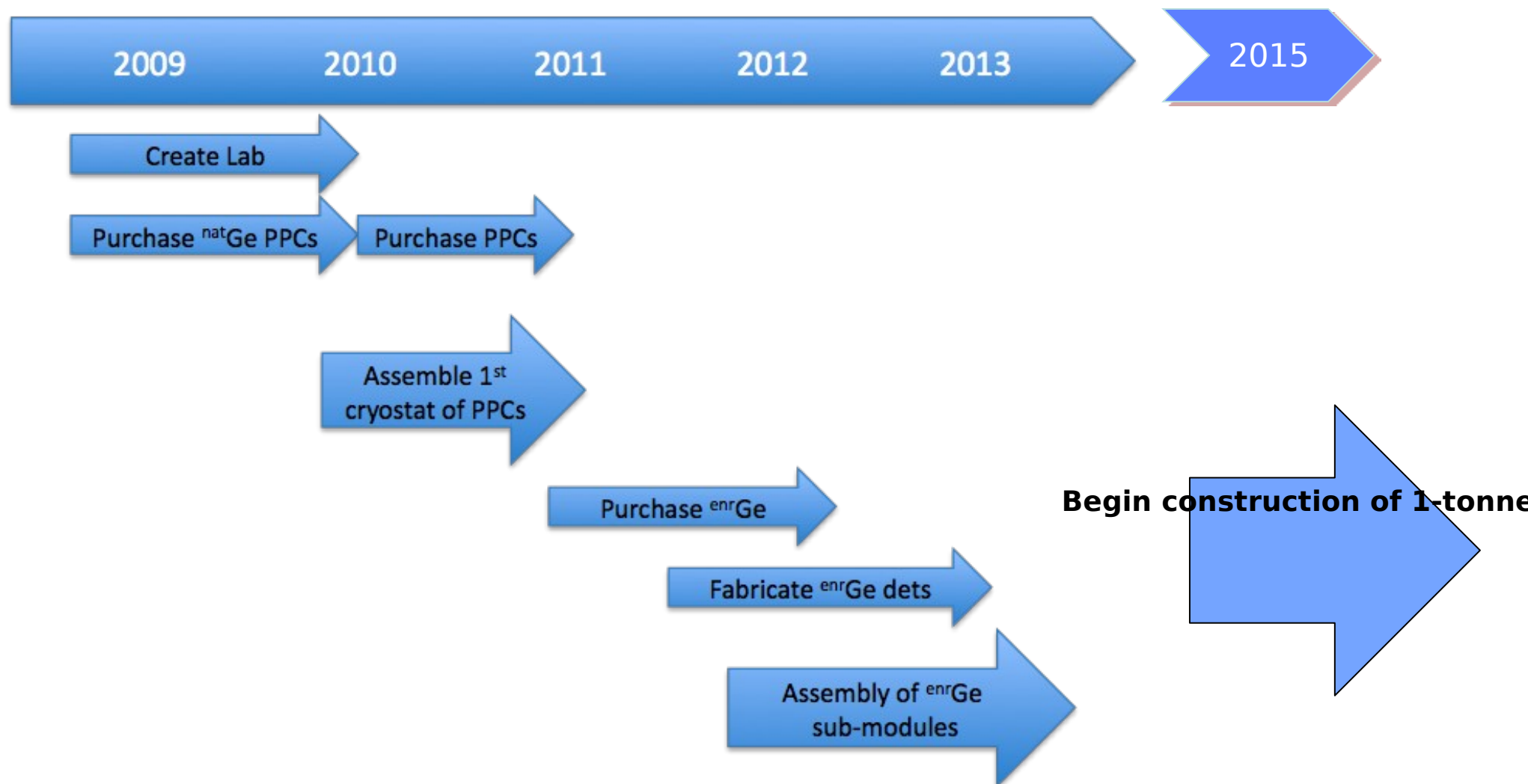
Agreement to locate at 4850' level at Sanford Lab

Background Goal in the $\beta\beta(0\nu)$ peak ROI (4 keV at 2039 keV)

- **~ 1 count/ROI/t-y (after analysis cuts)**



MAJORANA: demonstrator schedule



CONCLUSIONS

Neutrinoless Double Beta Decay is a unique tool to study neutrino properties:

- **Nature (Majorana/Dirac)**
 - Absolute Mass Scale
 - Lepton Number Violation
 - CP Violation

NME calculations

Experimental situation:

- one claim of evidence for $\beta\beta(0\nu)$ of ^{76}Ge
- new 2nd generation experiments (200 kg) under construction
- a number of proposals and R&D for the future

Exploit /compare results from different research fields (e.g. cosmology)

Ultimate goal: $\langle m_\nu \rangle \sim 10 \text{ meV}$

- many proposals with different techniques and isotopes
- promote as many as possible experiments on different isotopes
- reduce uncertainties in nuclear matrix F_N

CONCLUSIONS (2)

Exciting period for neutrino masses:

degeneracy is going to be probed

discovery potential in case of
inverted hierarchy

