Neutrinoless Double Beta Decay

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DISCRETE 2010, 9th December 2010, Rome

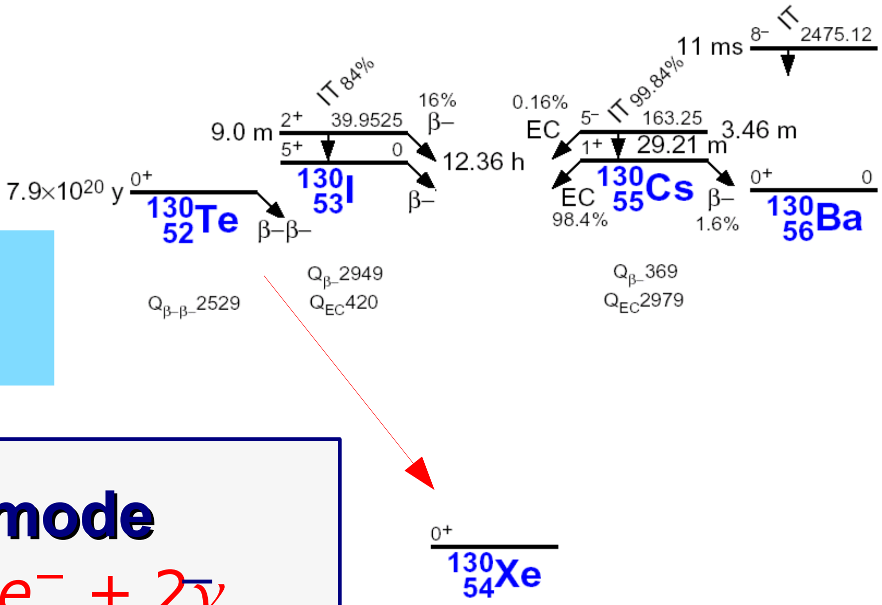
Outline

- Introduction
- Why Neutrinoless Double beta Decay?
- Experimental Approaches
- Sensitivity
- Present Status
- Challenges/Perspectives
- Conclusions

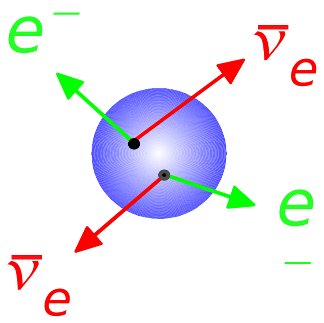
Nuclear Double Beta Decay

Rare Nuclear Decay

$(A,Z) \rightarrow (A,Z+2) + 2e^{-} + [\ldots]$



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



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

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

allowed in Standard Model

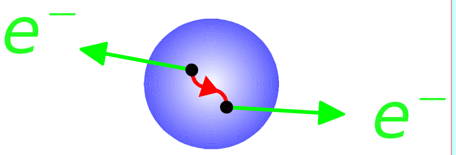
second order weak transition

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

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

not allowed in Standard Model

Neutrino nature and mass scale



If observed:

$\Delta L=2$

$\nu = \nu^{c}$

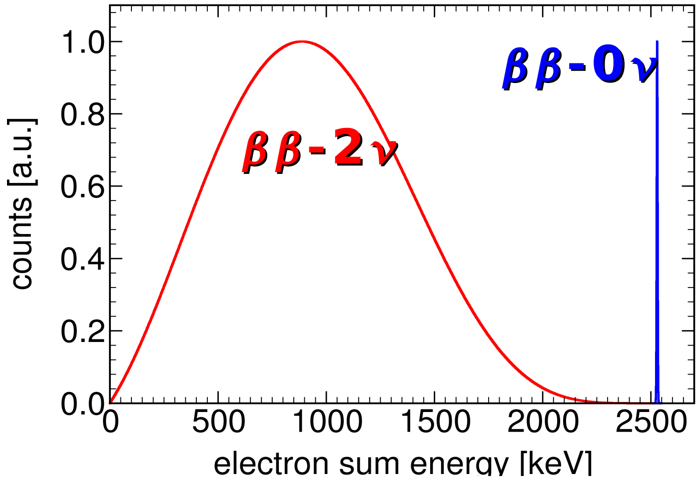
$m_{\nu} > 0$

Unique process to measure mass and nature of the neutrino

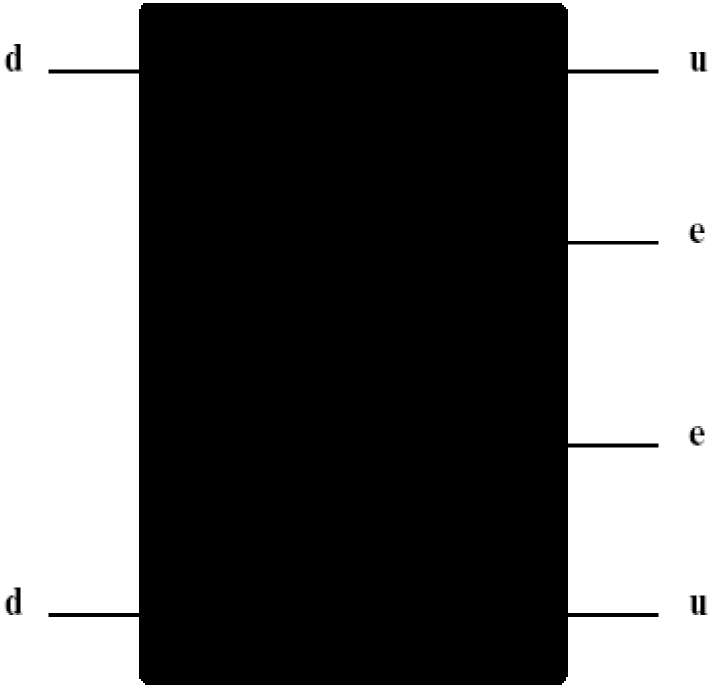
Neutrinoless Double Beta Decay

Observables:

- Electron Sum Energy
- Single Electron Energies
- Decay rate
- Angular correlation



DBD black box



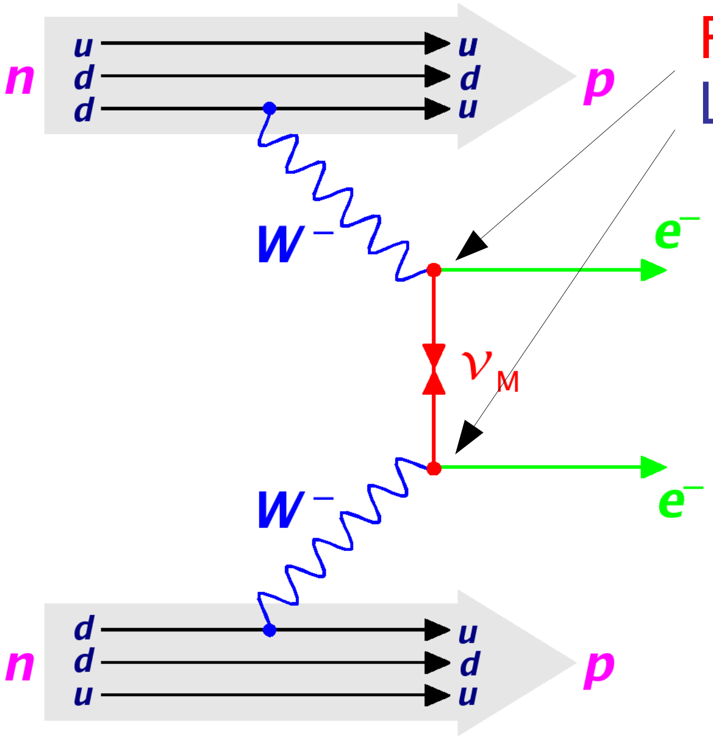
Many models beyond SM with lepton number violation can contribute!

Constraints on the model parameters

- **Left-right symmetric models**
- **R-parity violating ...**
- **R-parity conserving supersymmetric models**
- **[...]**
- **Light neutrinos**

Neutrinoless Double Beta Decay and neutrino Physics

Mass Mechanism: exchange of a light neutrino



RH antineutrino (L=1) is emitted at one vertex
LH neutrino (L=-1) is absorbed at the other vertex

- **Majorana particle**
- Helicity flip

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

$$\langle m_\nu \rangle = \sum_k U_{ek}^2 m_k$$

$$= c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

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 measuremets needed!

Neutrinoless Double Beta Decay

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:

cosmology
simple sum
pure kinematical effect

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

single β decay
incoherent sum
real neutrino

$$\langle m_\beta \rangle = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 M_i^2}$$

double β decay
coherent sum
virtual neutrino
Majorana phases

$$\langle m_{\beta\beta} \rangle = |\sum_{i=1}^{3} e^{i\alpha_i} |U_{ei}|^2 M_i|$$

Present bounds

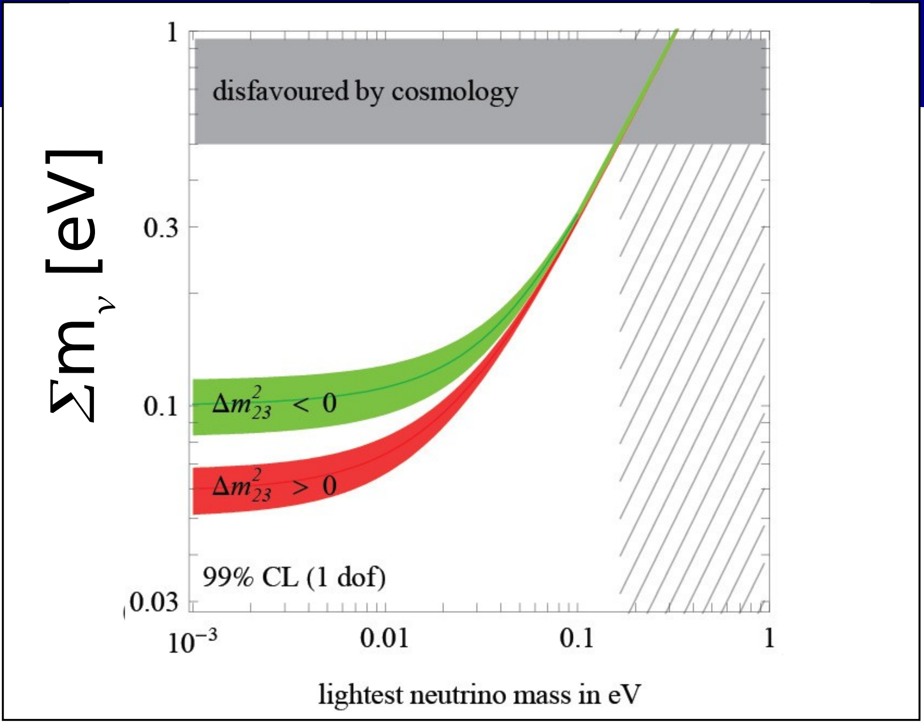
The three constrained parameters can be plot as a function of the lightest neutrino mass

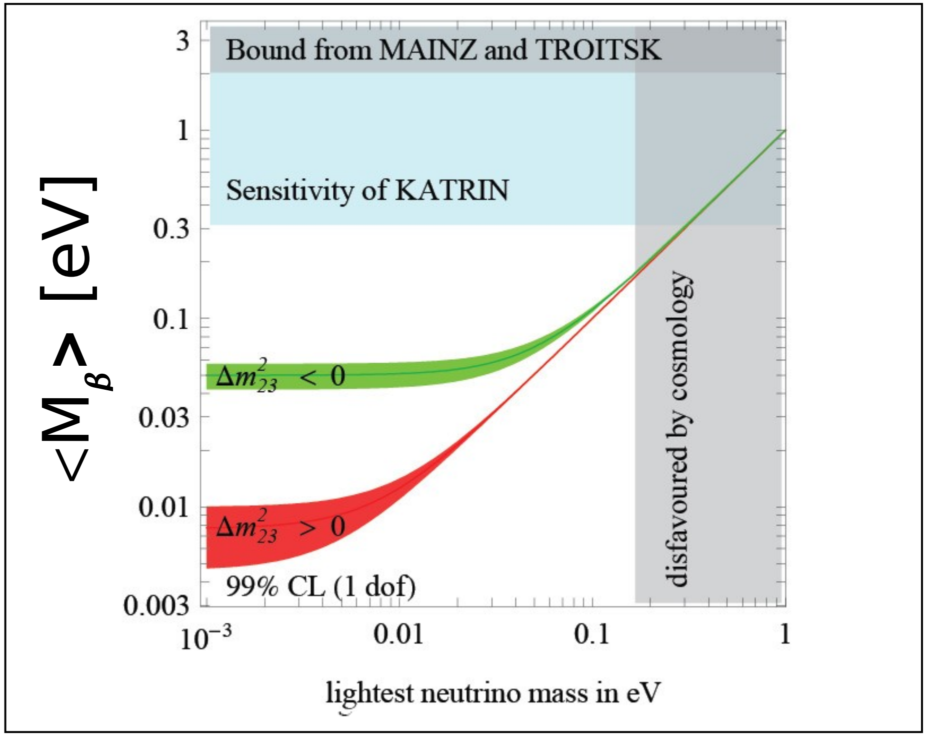
Two bands appear in each plot, corresponding to inverted and direct hierarchy

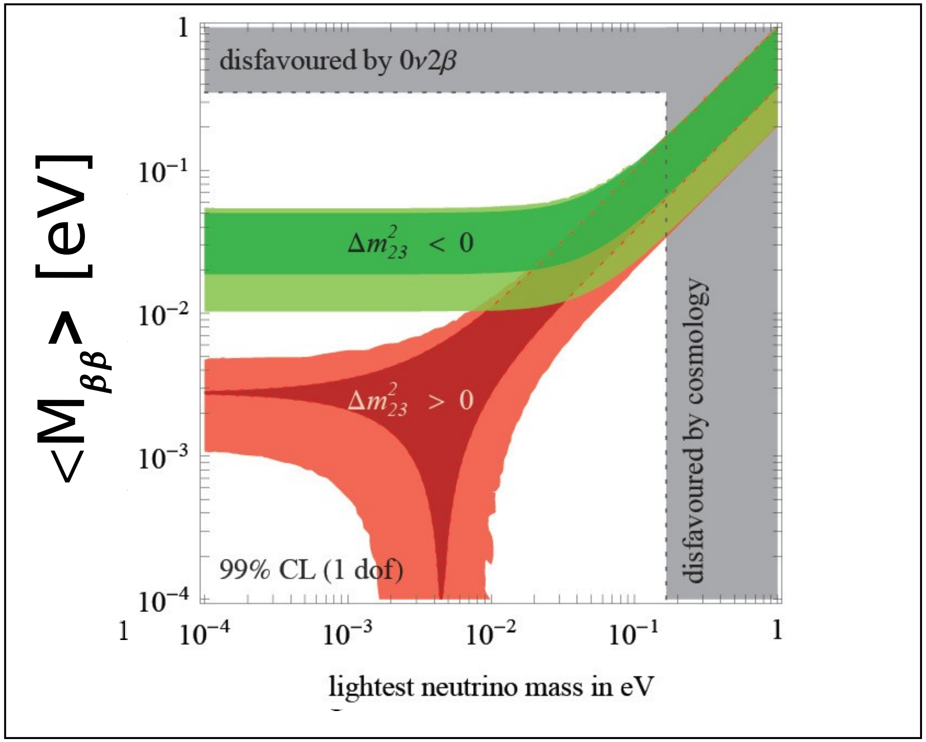
Sensitivity (eV)

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

Strumia-Vissani hep-ph/0503246



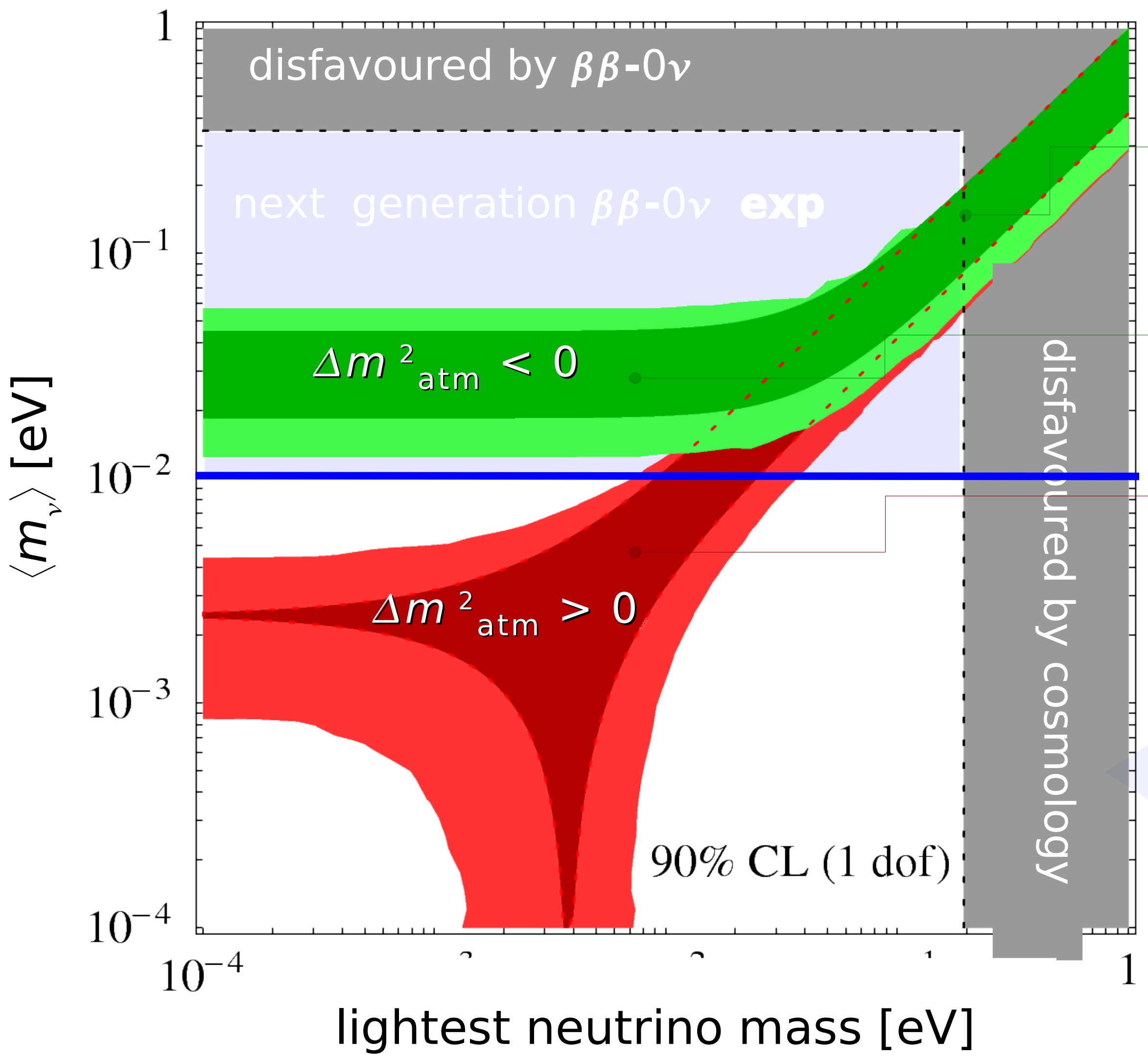




What oscillations don't say: ν mass hierarchies

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

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



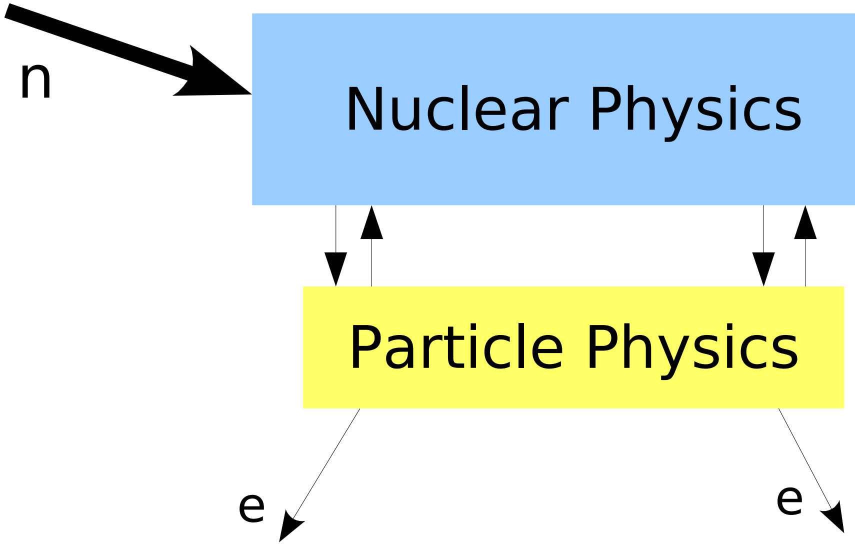
degeneration: $m_1 \approx m_2 \approx m_3$

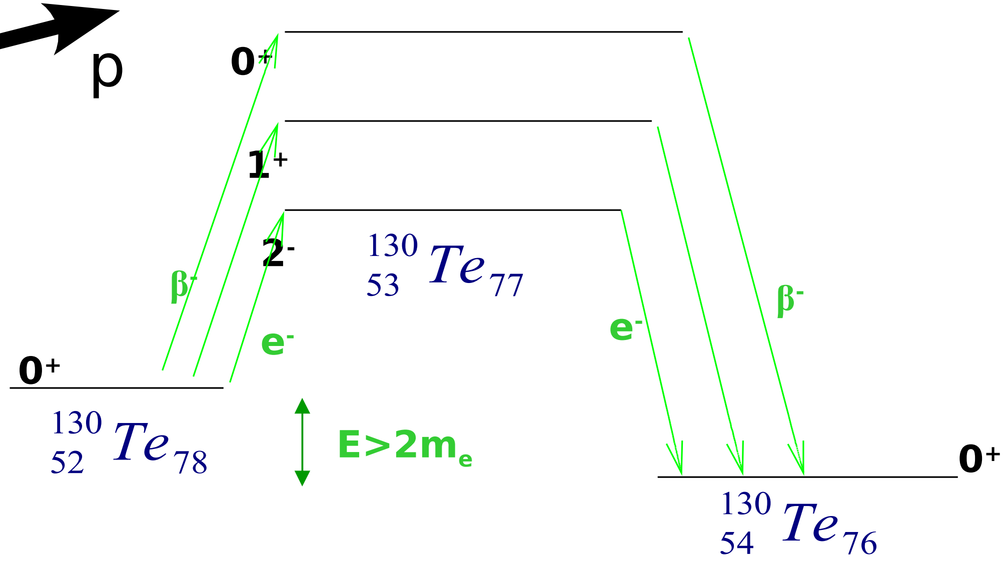
inverse hierarchy: $m_3 \ll m_1 \approx m_2$

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

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

Decay rate





Phase space factor

Nuclear Matrix Element

uncertainties

$$\tau^{-1} = G_{0\nu}\cdot\left|M^{0\nu}\right|^{2}\cdot\left|\langle m_{\nu}\rangle\right|^{2} = F_{N}\cdot\frac{\left|\langle m_{\nu}\rangle\right|^{2}}{m_{e}^{2}}$$

Effective Neutrino Mass

Nuclear Factor of Merit

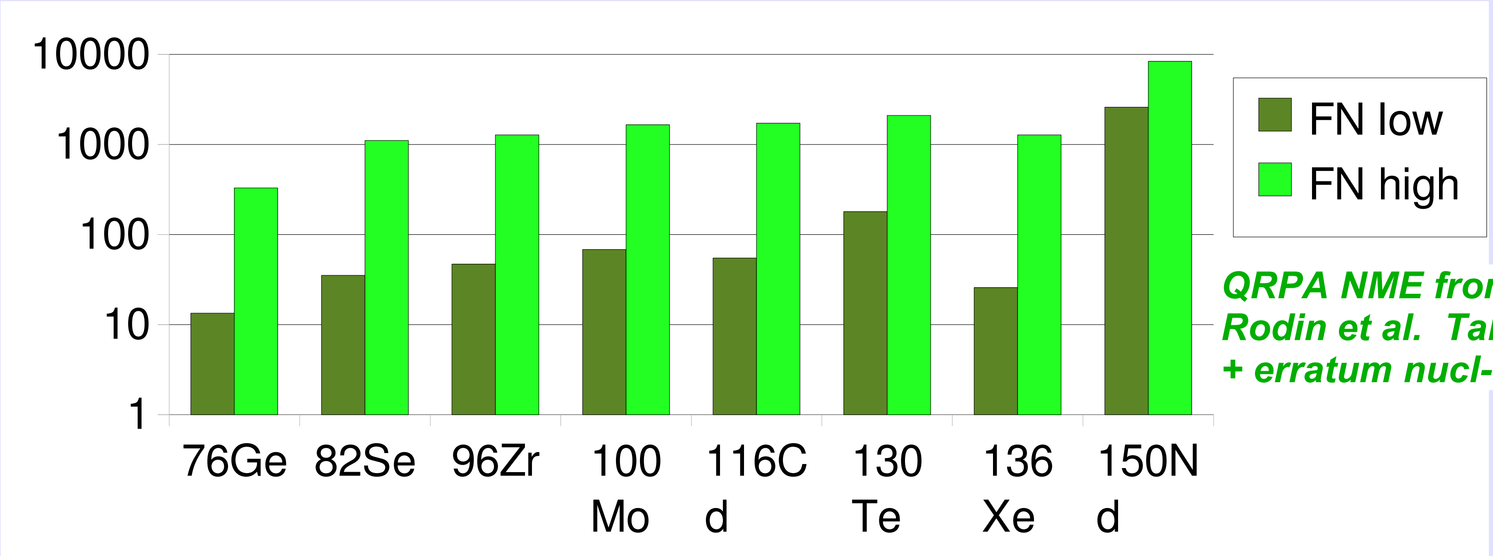
Extracting m_ν from $T_{1/2}$

0νββ half-life (measurement or lower bound)

F_N nuclear factor of merit

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

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



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

m_ν range: $$\left(\frac{1}{T_{1/2}^{0\nu\beta\beta} \, F_{Nhigh}} \; ; \; \frac{1}{T_{1/2}^{0\nu\beta\beta} \, F_{Nlow}} \right)$$

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

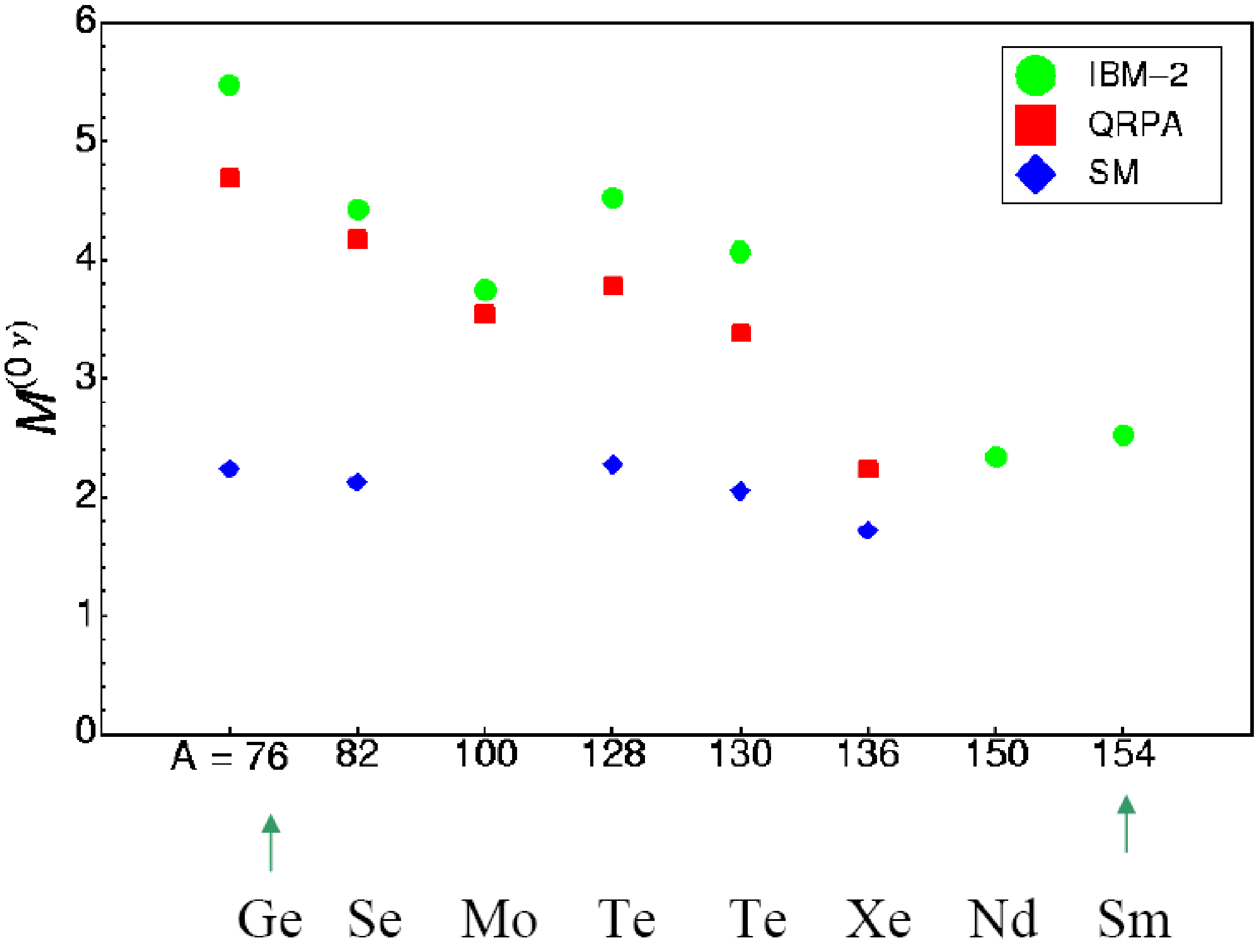
- ▸ *does not take into account the improvements of the Models*
- ▸ *does not help in the choice of the best candidate for an experiment*

exchanges between groups to

- **understand discrepencies and evaluate errors**
- **use of β and 2νββ 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

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

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

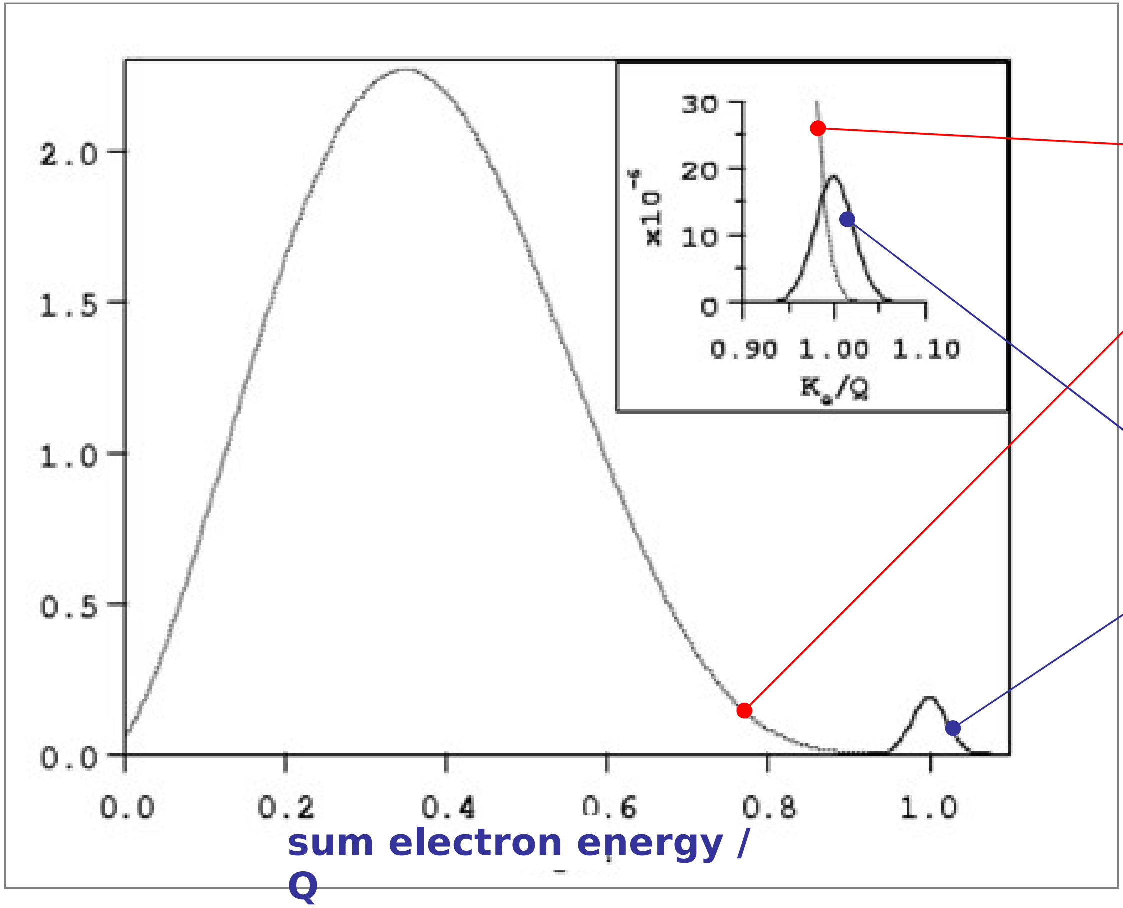
Daughter ion (A,Z+2)

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 ~1/3 Q

neutrinoless DBD
peak enlarged only by the detector energy resolution

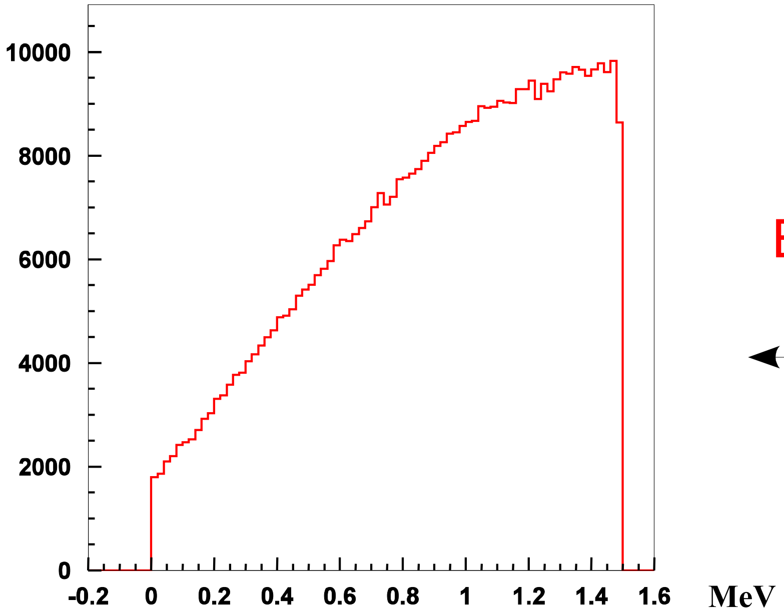
additional signatures:
- single electron energy distribution
- angular distribution

Most promising nuclides
Q ~ 2-3 MeV

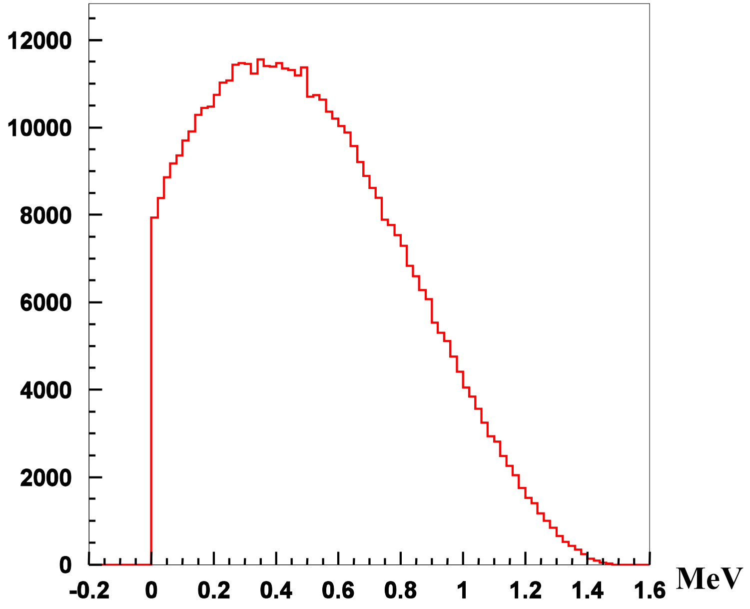
DBD: single electron energy

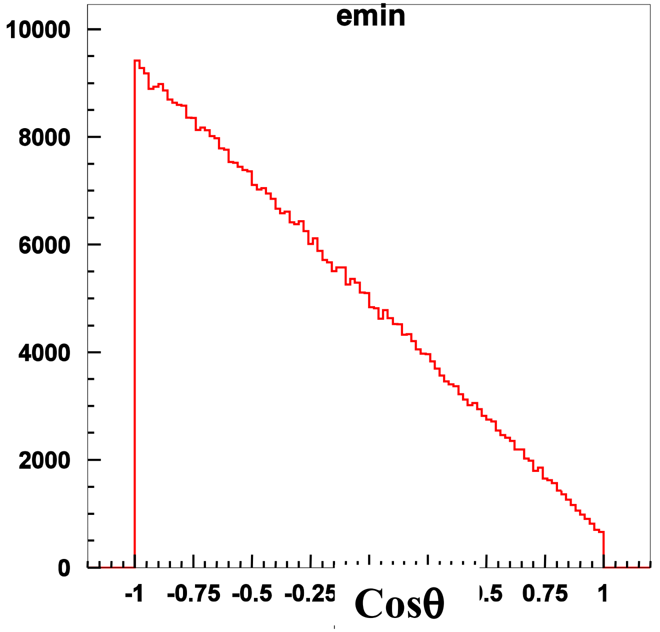
Light neutrino exchange

V+A current

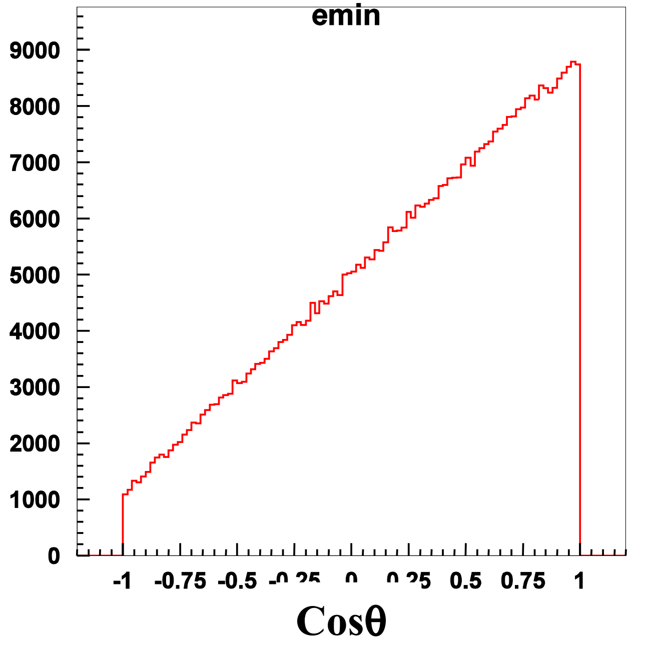


Electron minimum energy spectrum





Angular distribution between the 2 electrons



Experimental rate and sensitivity

Experimental $\beta\beta$-0ν rate

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

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

Experimental sensitivity

lifetime corresponding to the minimum detectable numberof events over background at a given confidence level

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

1. N_B >> 1

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

2. “zero background”: $N_B \leqslant O(1)$

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

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]

N_B=bkg M ΔE t_{meas}

number of background events expected along the experiment lifetime

Crucial parameters:
- **Isotopical abundance**
- **Mass**
- **Energy resolution**
- **Background level**

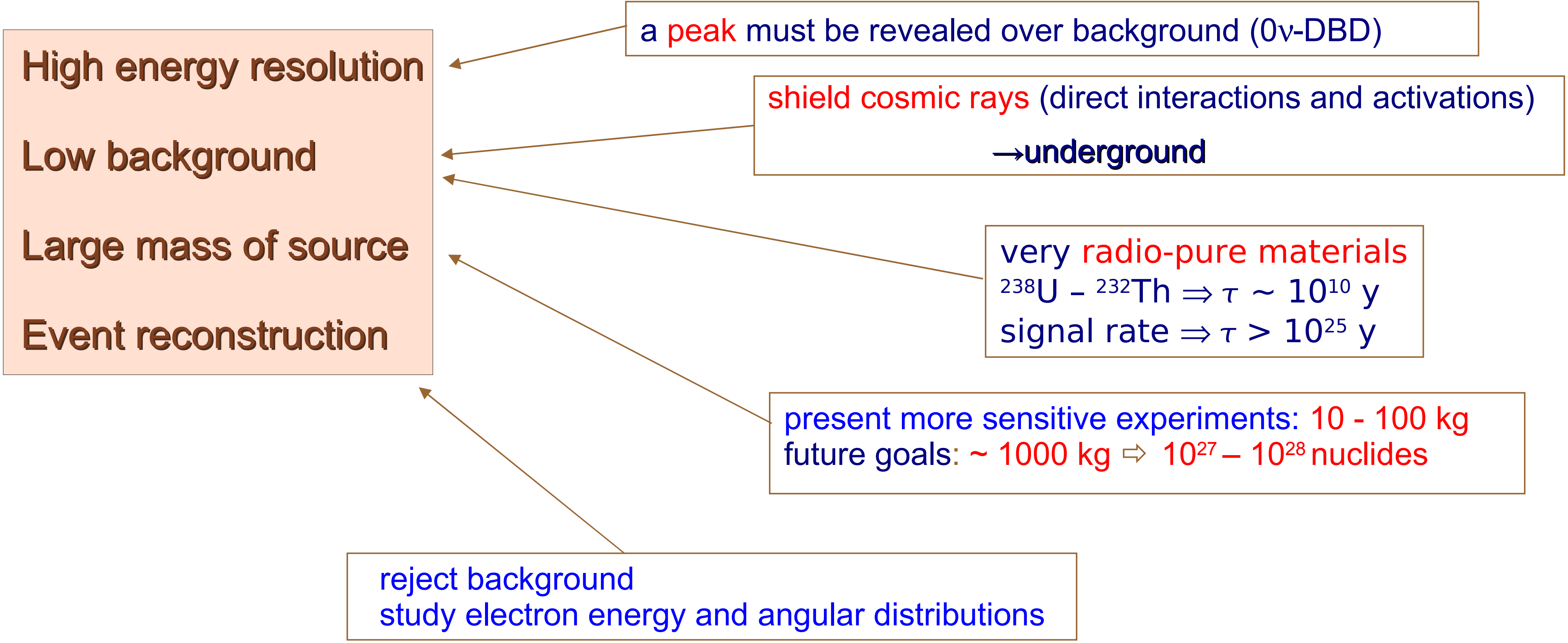
Experimental strategies

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

Real-time 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)

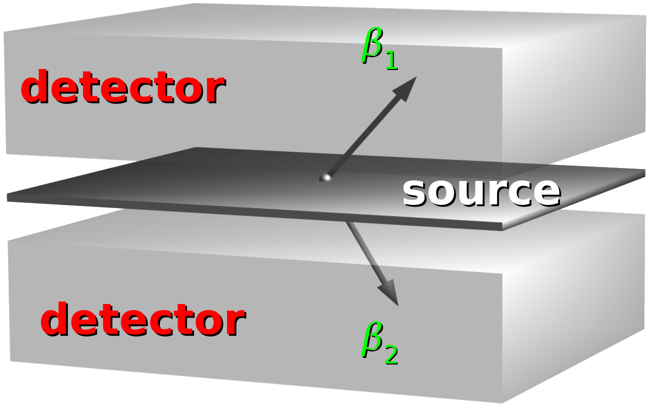
→**underground**

very radio-pure materials
^{238}U – ^{232}Th $\Rightarrow \tau \sim 10^{10}$ y
signal rate $\Rightarrow \tau > 10^{25}$ y

present more sensitive experiments: 10 - 100 kg
future goals: ~ 1000 kg ⇨ $10^{27} – 10^{28}$ nuclides

reject background
study electron energy and angular distributions

Inhomogeneous approach



Source ≠ Detector

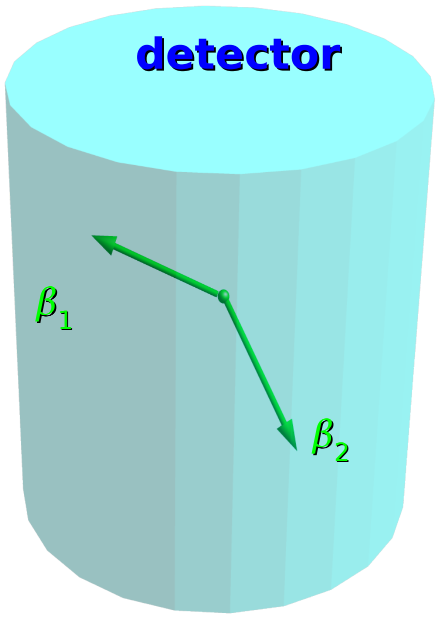
- scintillation
- gaseous TPC
- gaseous drift chamber
- magnetic field and TOF

☺ 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 ≡ 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

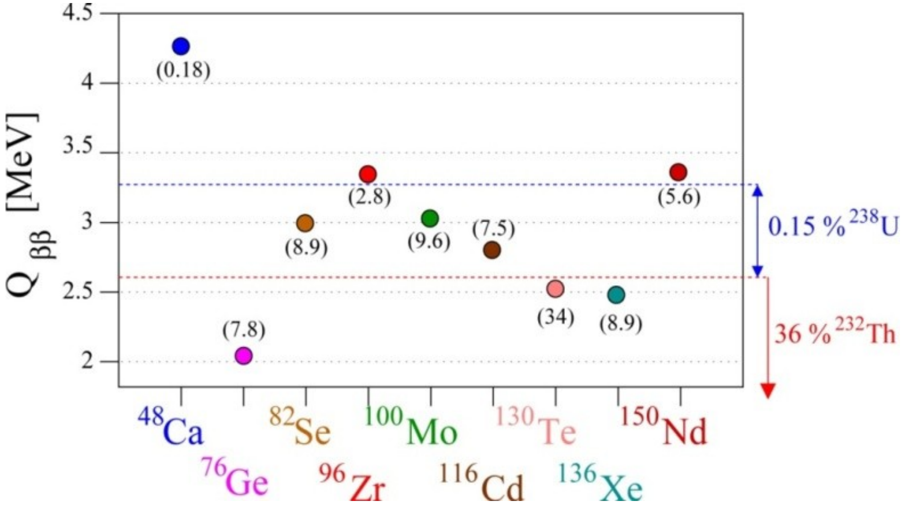
☹ often contrasting requests

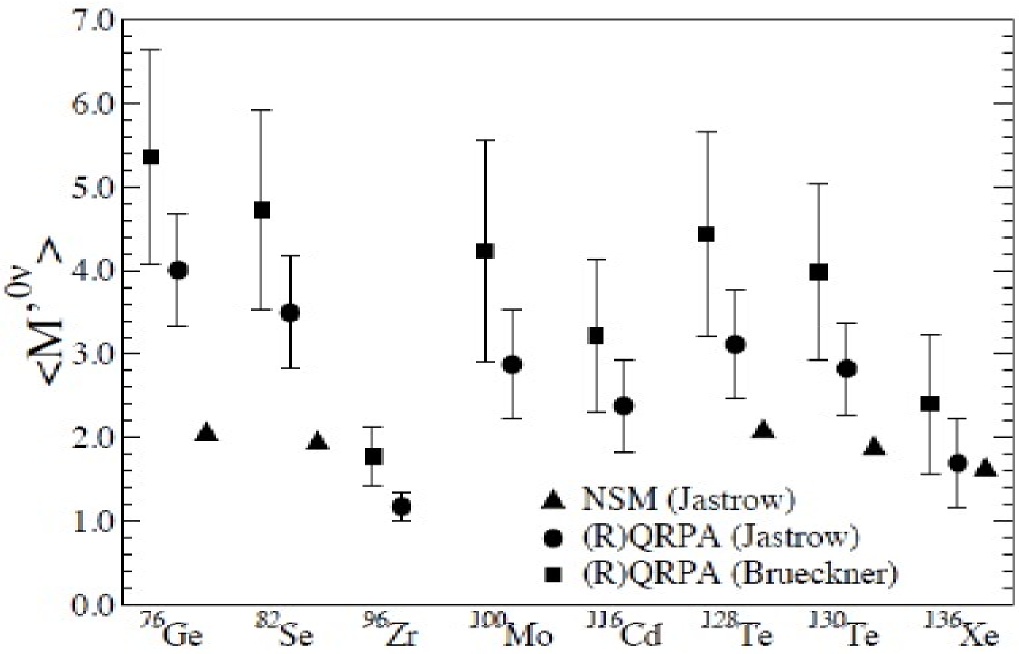
Choice of the isotope

	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

Q Influences also $G_{\beta\beta}$, the Phase Space factor





Experiments: 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)

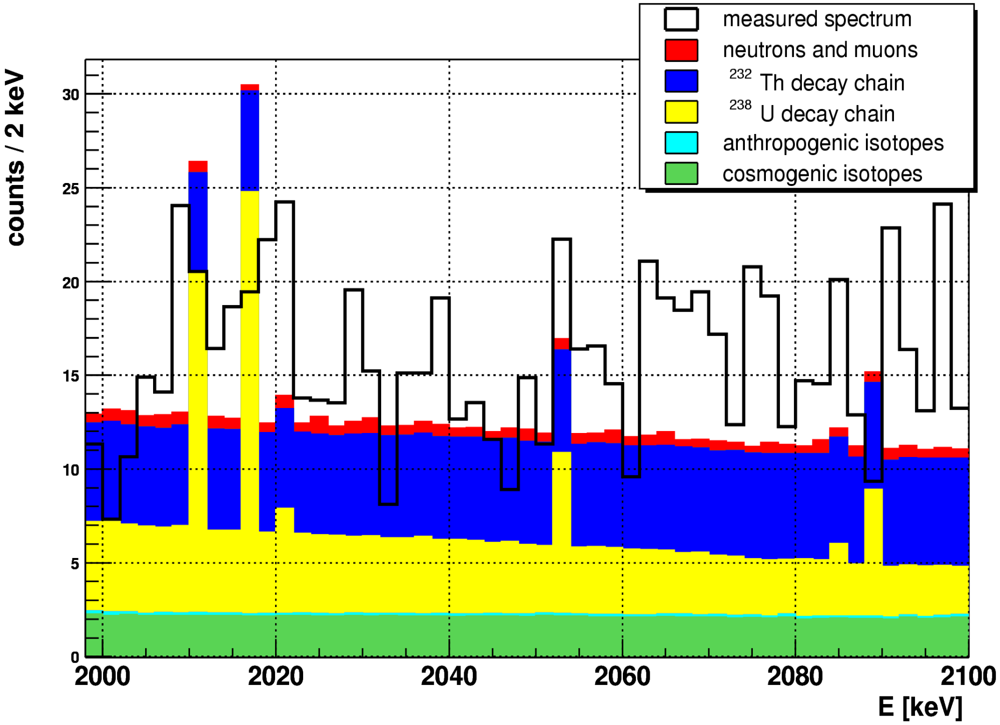
intermediate generation experiment based on the bolometric technique.
Demonstator of CUORE

Nucleus	Detector	EXP	Material	kg y	$\tau_{1/2}$ Limit (y) (90% CL)
^{76}Ge	Ge diode	IGEX/HDM*	Ge	~ 47.7	> 1.6-1.9 x 10^{25}
^{82}Se	Tracking	NEMO3	Se	**4.5**	> 3.2 x 10^{23}
^{100}Mo	Tracking	NEMO3	Mo	**31.5**	> 1.0 x 10^{24}
^{96}Zr	Tracking	NEMO3	Zr	0.03	> 9.2 x 10^{21}
^{150}Nd	Tracking	NEMO3	Nd	0.1	> 1.8 x 10^{21}
^{128}Te	Bolometer	Cuoricino	TeO_2		> 1.1 x 10^{23}
^{130}Te	Bolometer	Cuoricino	TeO_2	**19.75**	> 2.8 x 10^{24}
^{136}Xe	Xe scint	DAMA	L Xe	~ 4.5	> 1.2 x 10^{24}
^{116}Cd		Solotvina			> 1.7 x 10^{23}
^{48}Ca					> 1.4 x 10^{22}
^{160}Gd					> 1.3 x 10^{21}

* 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 ⇒ 125.5 moles of ^{76}Ge
- run from 1990 to 2003 in Gran Sasso Underground Laboratory
- total statistics 71.7 kg×y
    - 820 moles×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 ofthe detector
- digital Pulse ShapeAnalysis(PSA)



1990 – 2001 data

exposure = 35.5 kg×y SSD

$\tau_{1/2}^{0\nu} > 1.9\times10^{25}$ years

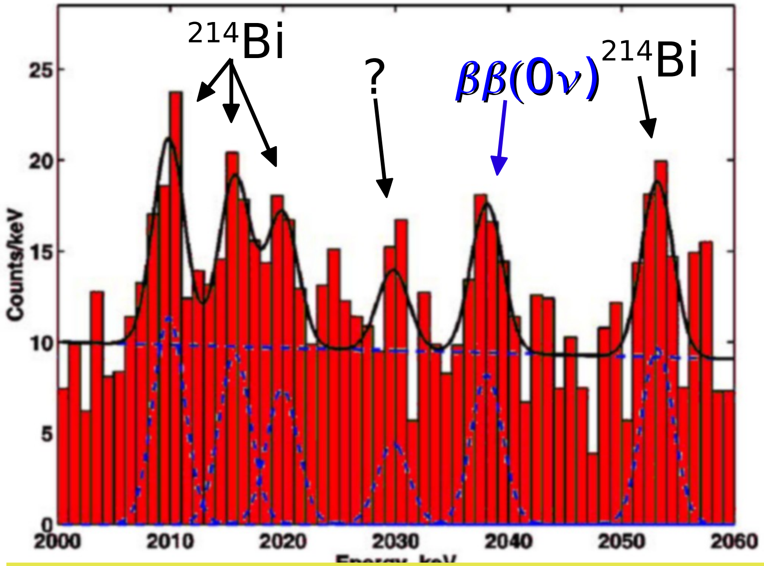
$\langle m_\nu \rangle < 0.35$ eV (0.3 – 1.24 eV)

H.V.Klapdor-Kleingrothaus *et al.*, Eur. Phys. J. A12 (2001

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 (~1/4) new statistics and improved in the following years



1990 – 2003 data, all 5 detectors

exposure = 71.7 kg×y

$\tau_{1/2}$ = 1.2×10^{25} years

$\langle m \rangle$ = 0.44 eV

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

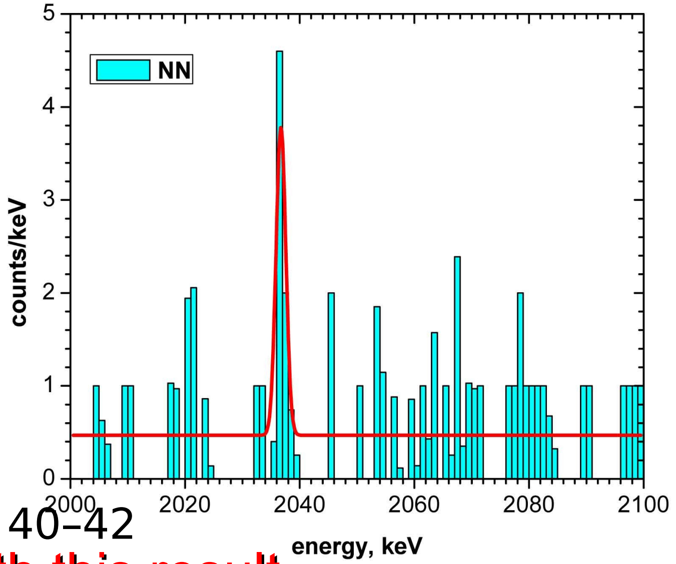
1995-2003 data new re-analysis:

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

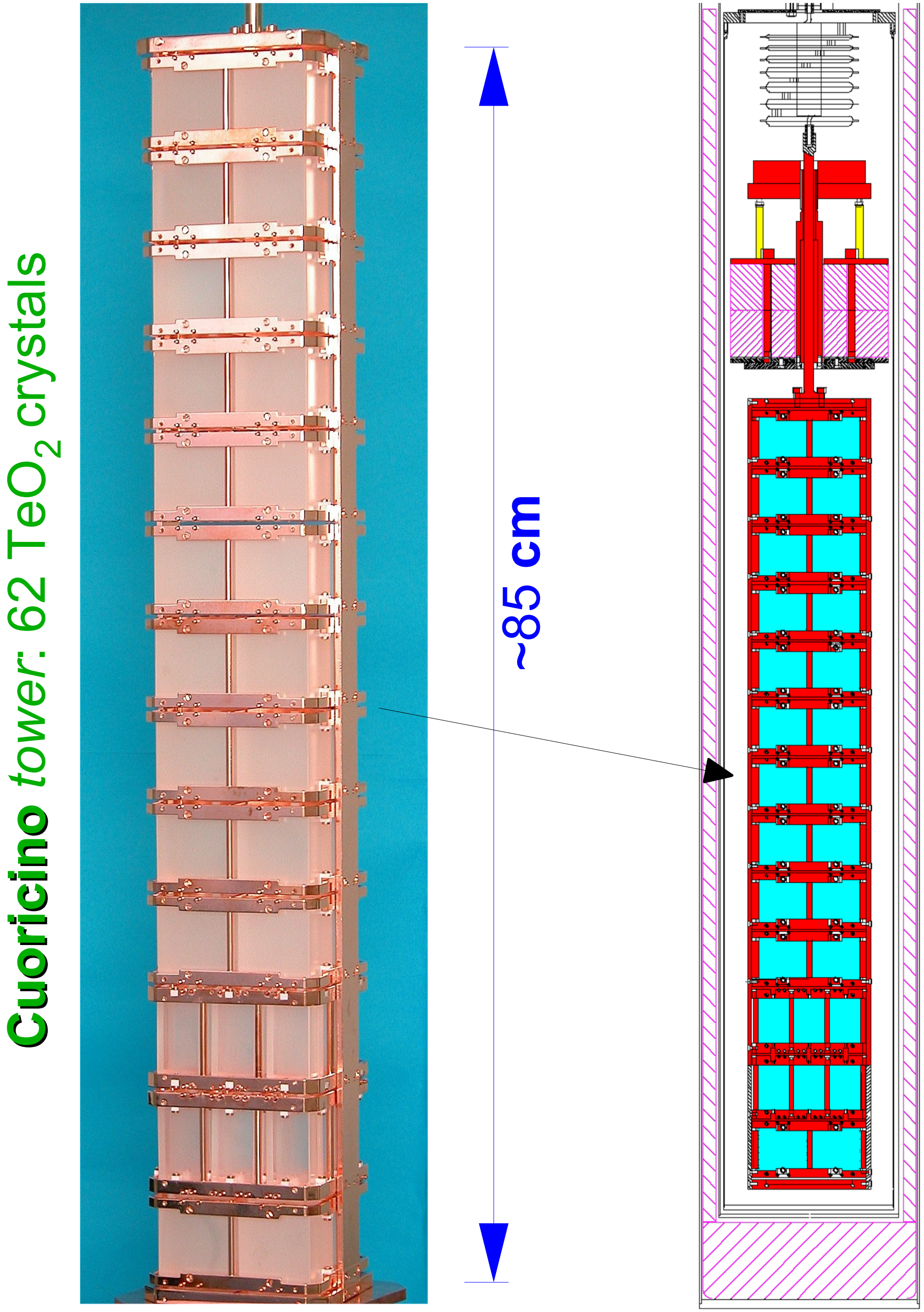


H.V.Klapdor-Kleingrothaus *et al.*, Phys. Scr. T127 (2006) 40–42

all future experiment will certainly have to cope with this result

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

CUORICINO



TeO_2 thermal calorimeters

Active isotope ^{130}Te

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 TeO_2

low heat capacity

large crystals available

radiopure

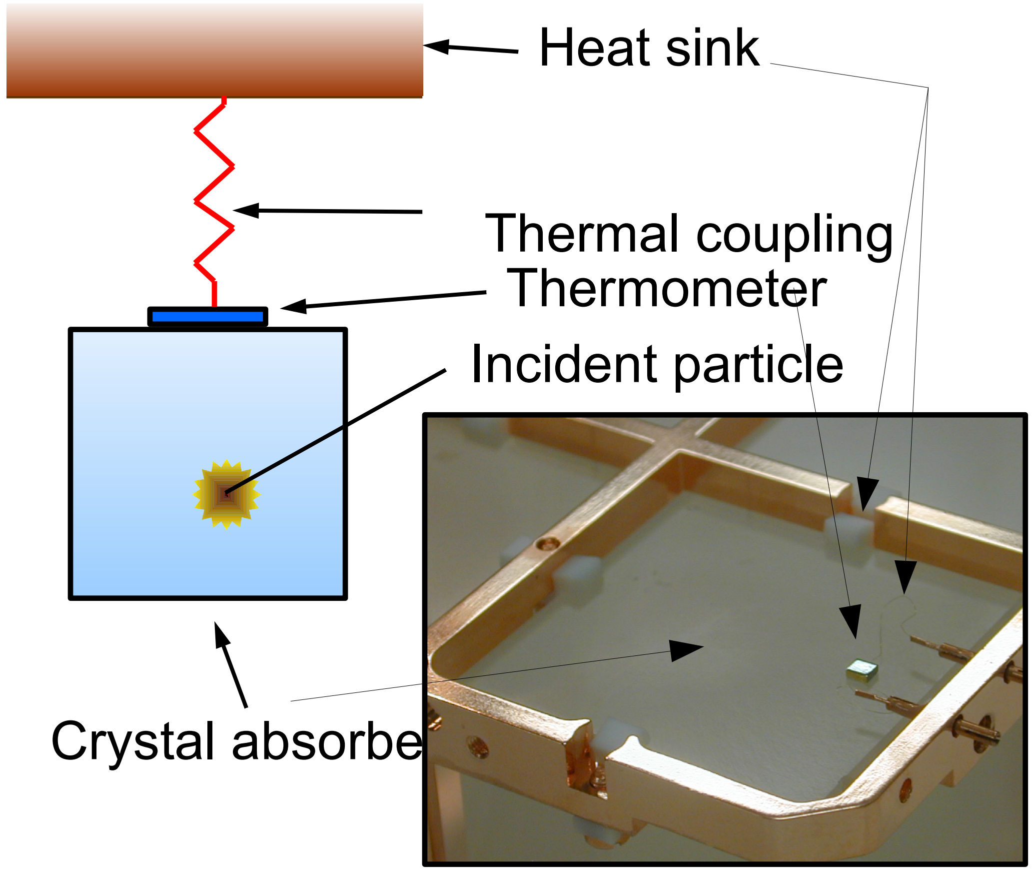
intermediate size $\beta\beta$ experiment

important test for

radioactivity

performance of large LTD arrays

Low Temperature Detectors (LTD)



Heat sink

Thermal coupling

Thermometer

Incident particle

Crystal absorbe

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

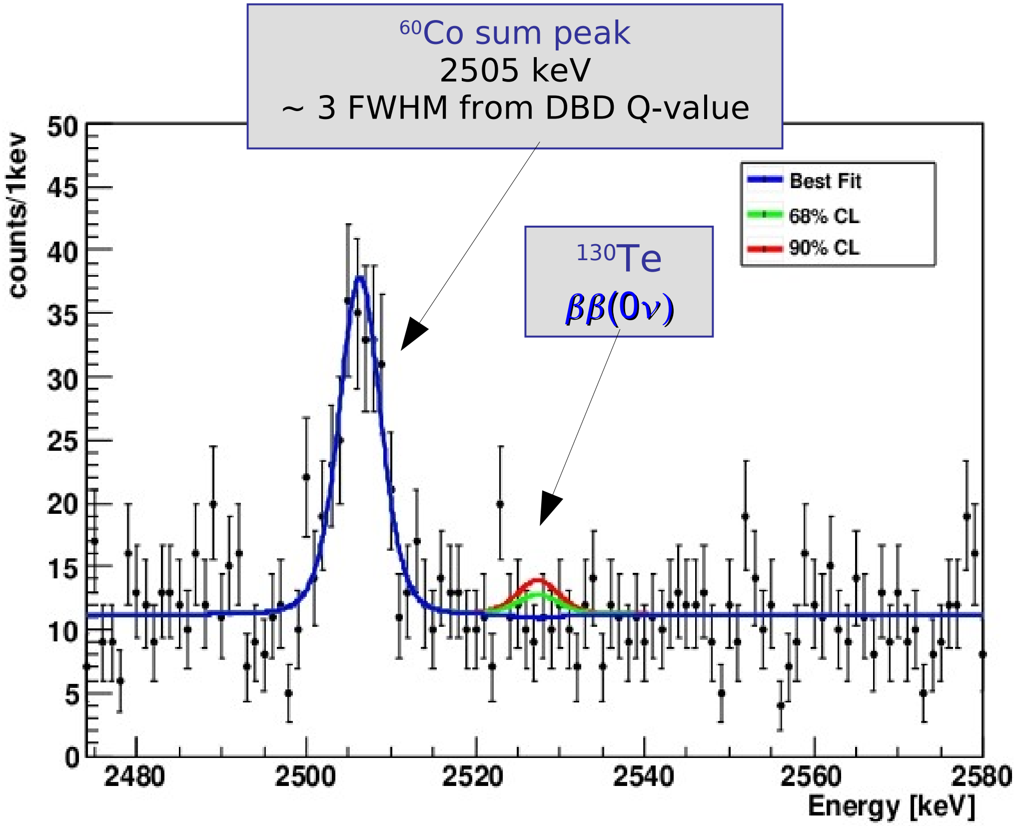
slow $\tau = C/G \sim 1 \div 10^3$ ms

CUORICINO results

- total statistics 19.75 kg×y
- average energy resolution FWHM ΔE = 7.5 keV at $Q_{\beta\beta}$ (σ_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% ± 10%	**^{208}Tl (cryostat contamination)**
20% ± 10%	**TeO_2 surfaces (α contaminations)**
50% ± 10%	**Cu surfaces (β contaminations)**

stopped in June 2008 and disassembled


^{60}Co sum peak
2505 keV
~ 3 FWHM from DBD Q-value

^{130}Te
$\beta\beta(0\nu)$

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

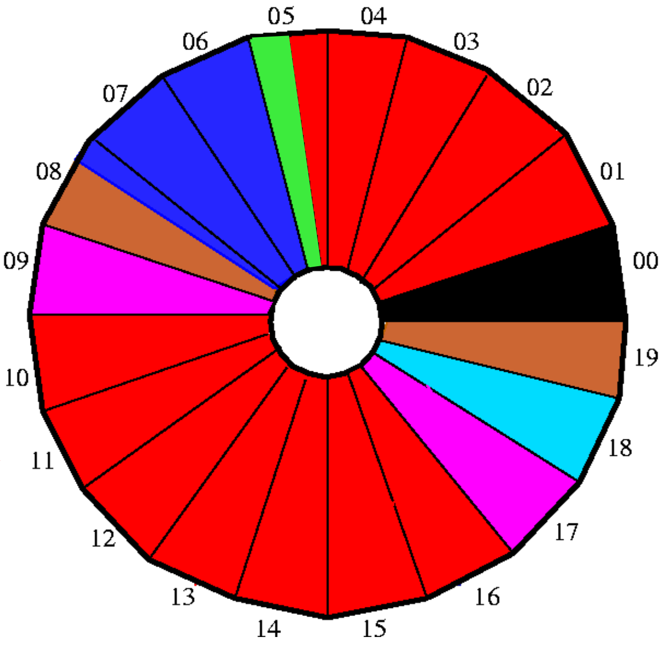
@ 90% C.L.
$\tau_{1/2} > 2.8\ 10^{24}$ [yr]
$m_{ee} < 0.3 \div 0.7^{1\text{-}4}$ eV

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

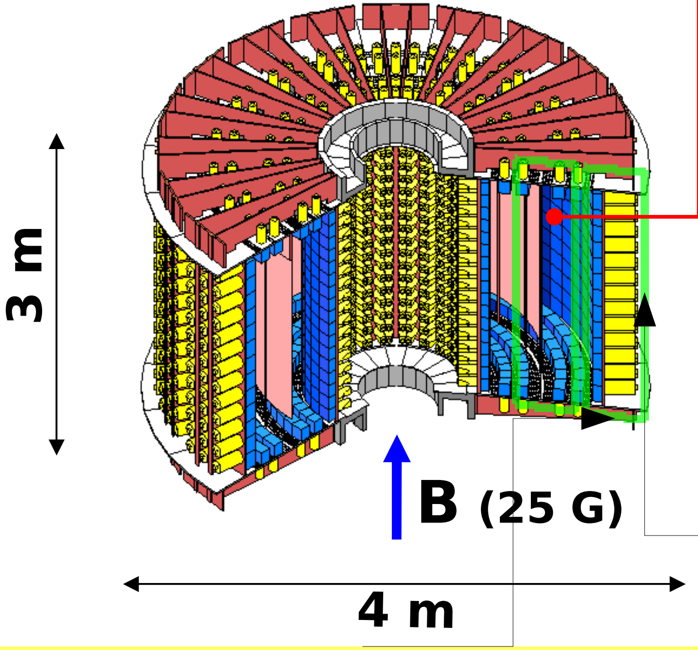
NEMO-3

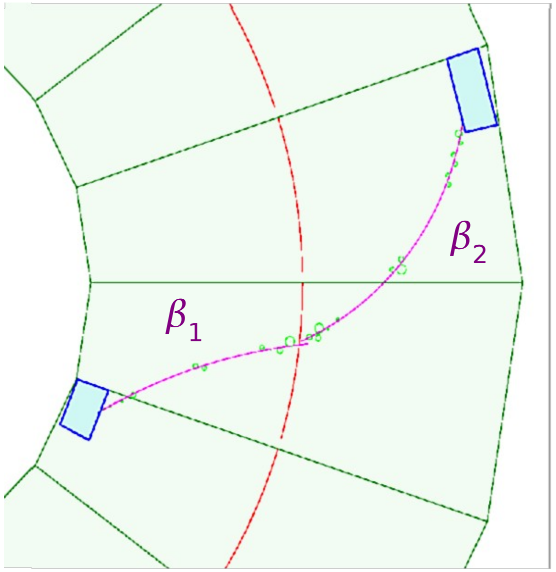
Tracking detector for $\beta\beta$-2ν and $\beta\beta$-0ν
at Frejus (4800 m.w.e.)

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



sources in foils



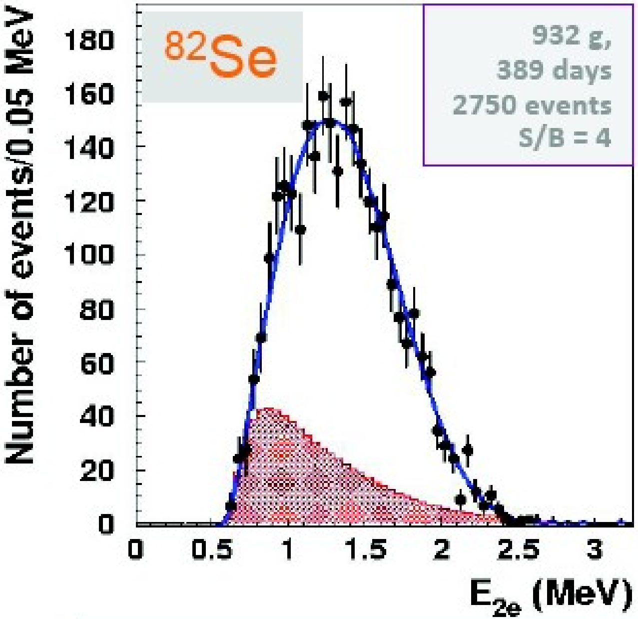


^{100}Mo	(6.9 kg)	➨ $\beta\beta$-0ν
^{82}Se	(0.9 kg)	
^{130}Te	(0.45 kg)	
^{116}Cd	(0.4 kg)	
^{150}Nd	(37g)	
^{96}Zr	(9.4 g)	
^{48}Ca	(7.0g)	
^{nat}Te	(0.5 kg)	
Cu	(0.6 kg)	

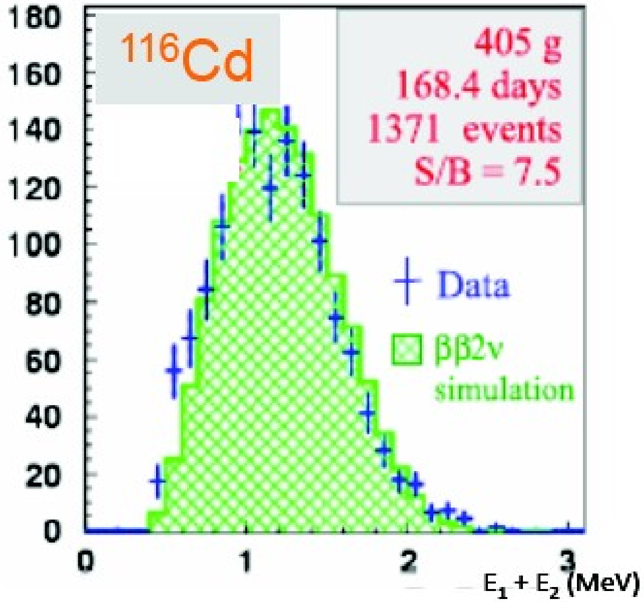
tracking volume (drit wire chamber)

calorimeter (scintillators)

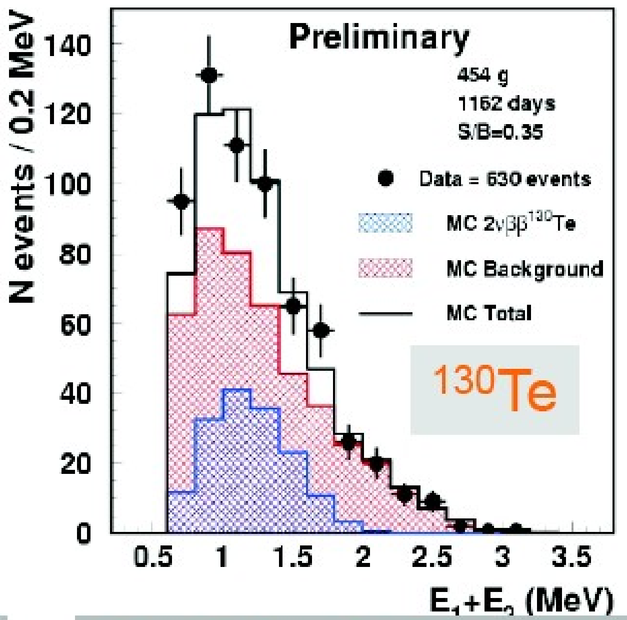
NEMO-3: a unique tool to study ββ(2ν)



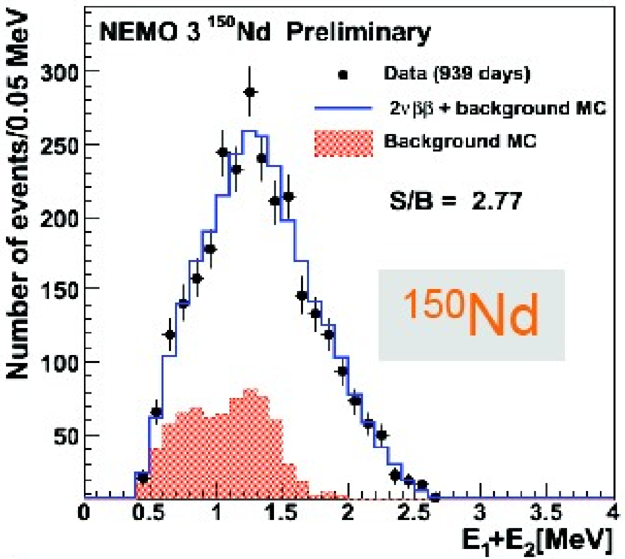
9.6 ± 0.3 (stat) ± 1.0 (sys) 10^{19} y



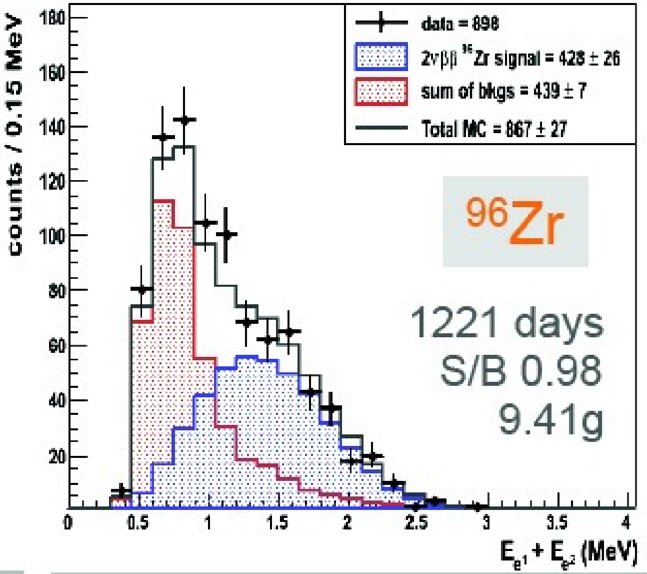
2.8 ± 0.1 (stat) ± 0.3 (sys) 10^{19} y



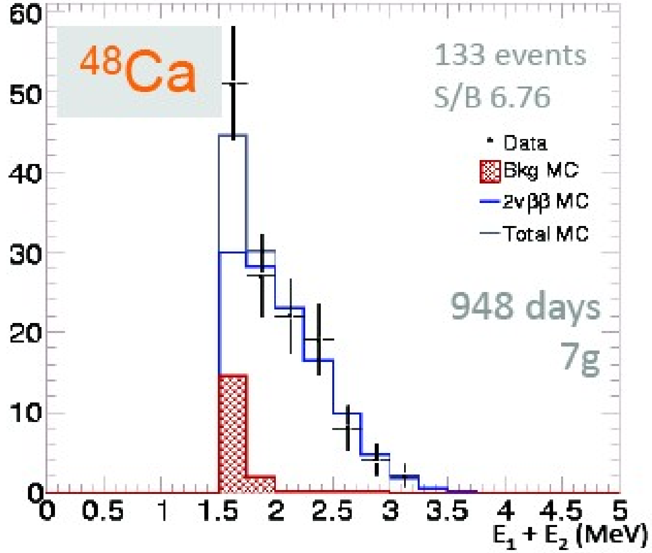
6.9 ± 0.9 (stat) ± 1.0 (sys) 10^{20} y



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

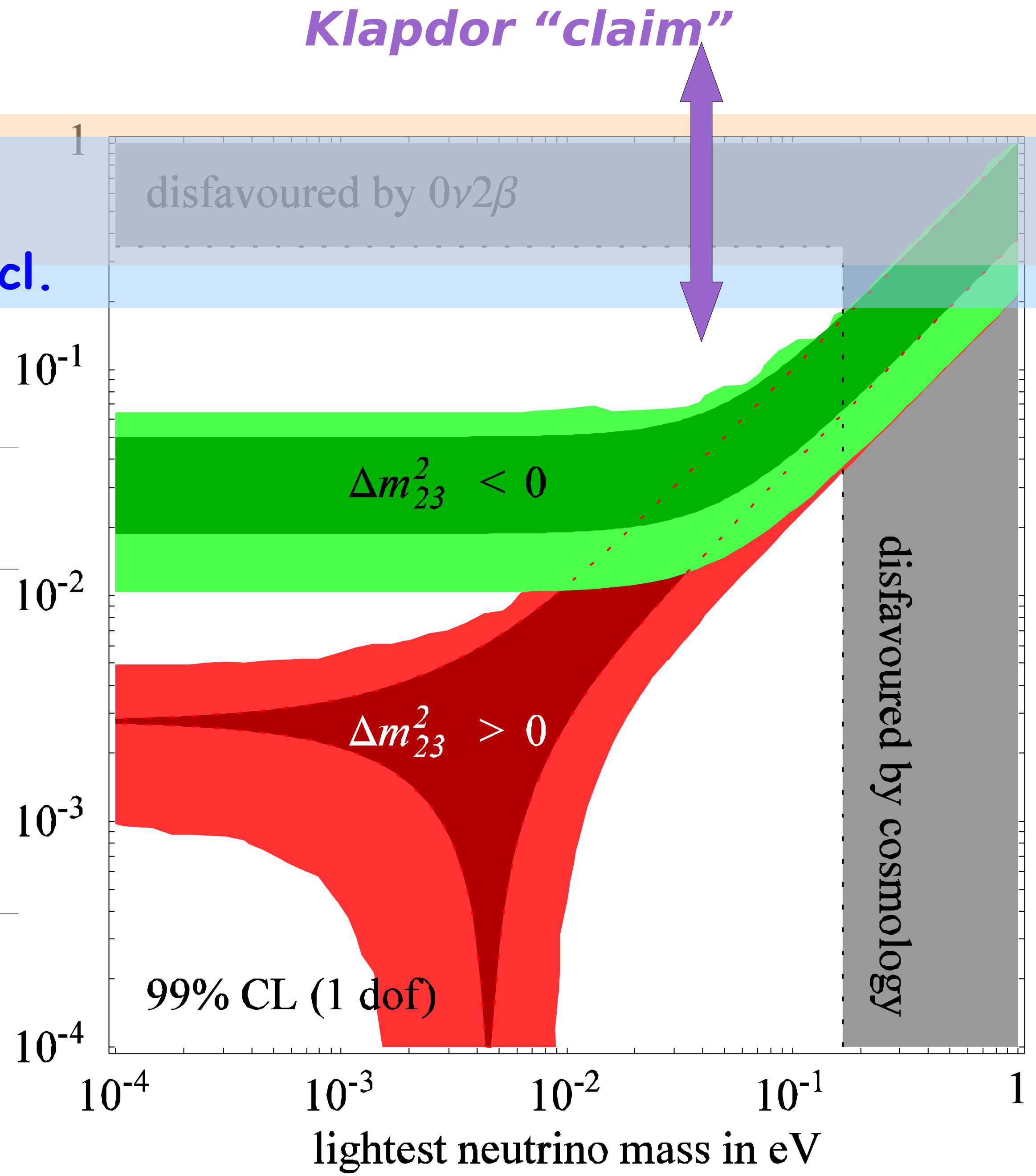


2.35 ± 0.14 (stat) ± 0.16 (sys) 10^{19} y



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

Present situation



Isotope	τ 90% limit [y]	Experiment	High [eV]	Low [eV]
^{76}Ge	1.9E+25	HM	1.0	0.2
^{82}Se	3.2E+23	NEMO3	3.6	0.6
^{100}Mo	1.1E+24	NEMO3	1.9	0.4
^{130}Te	2.8E+24	Cuoricino	0.7	0.2
^{136}Xe	1.2E+24	Dama '03	2.9	0.4
^{150}Nd	1.8E+22	NEMO3	4.1	1.3

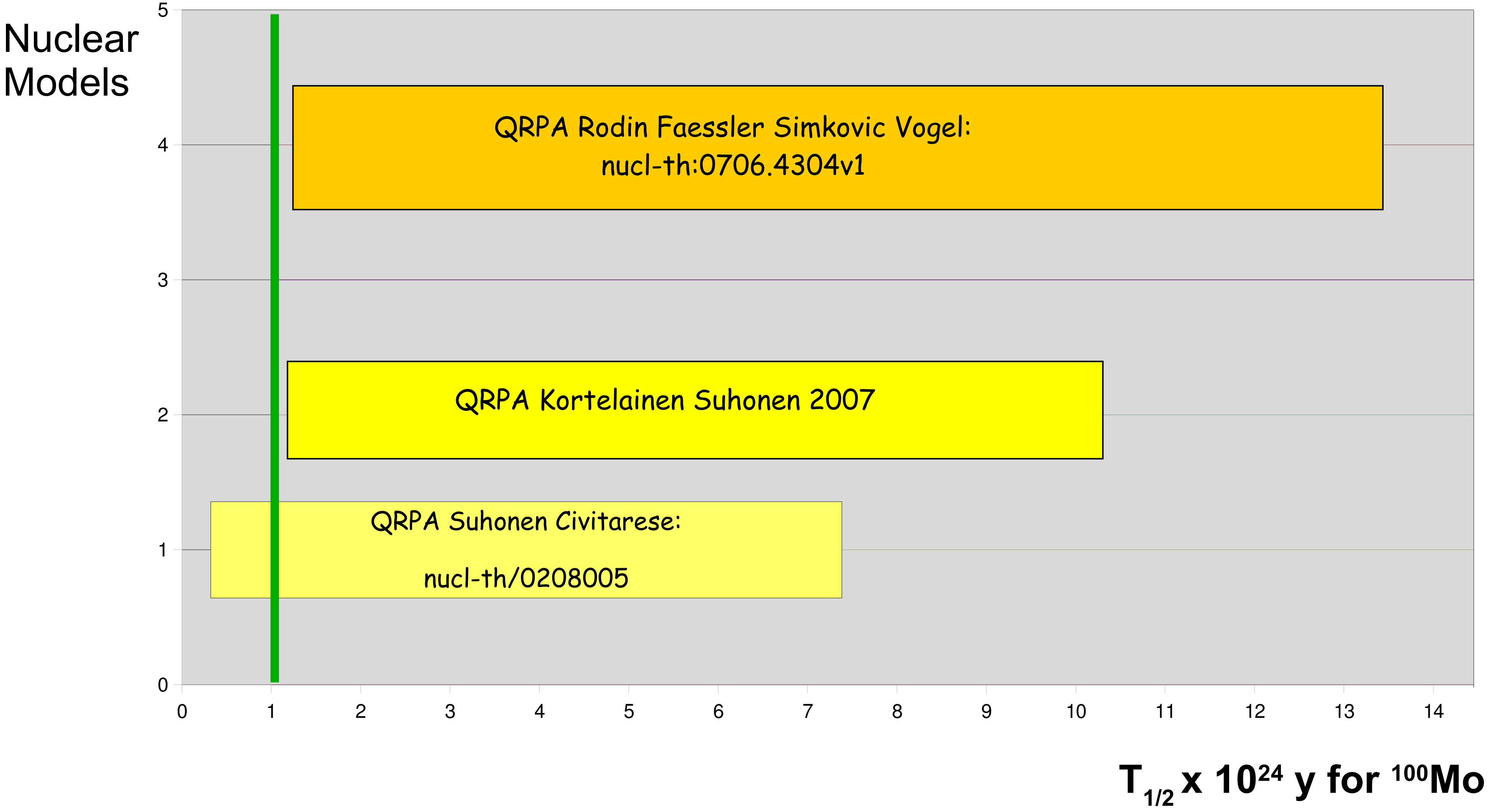
QRPA NME from:
Rodin et al. Table 3 Nucl. Phys. A 2006
+ erratum nucl-th:0706.4304v1

HM claim: NEMO3 90%CL

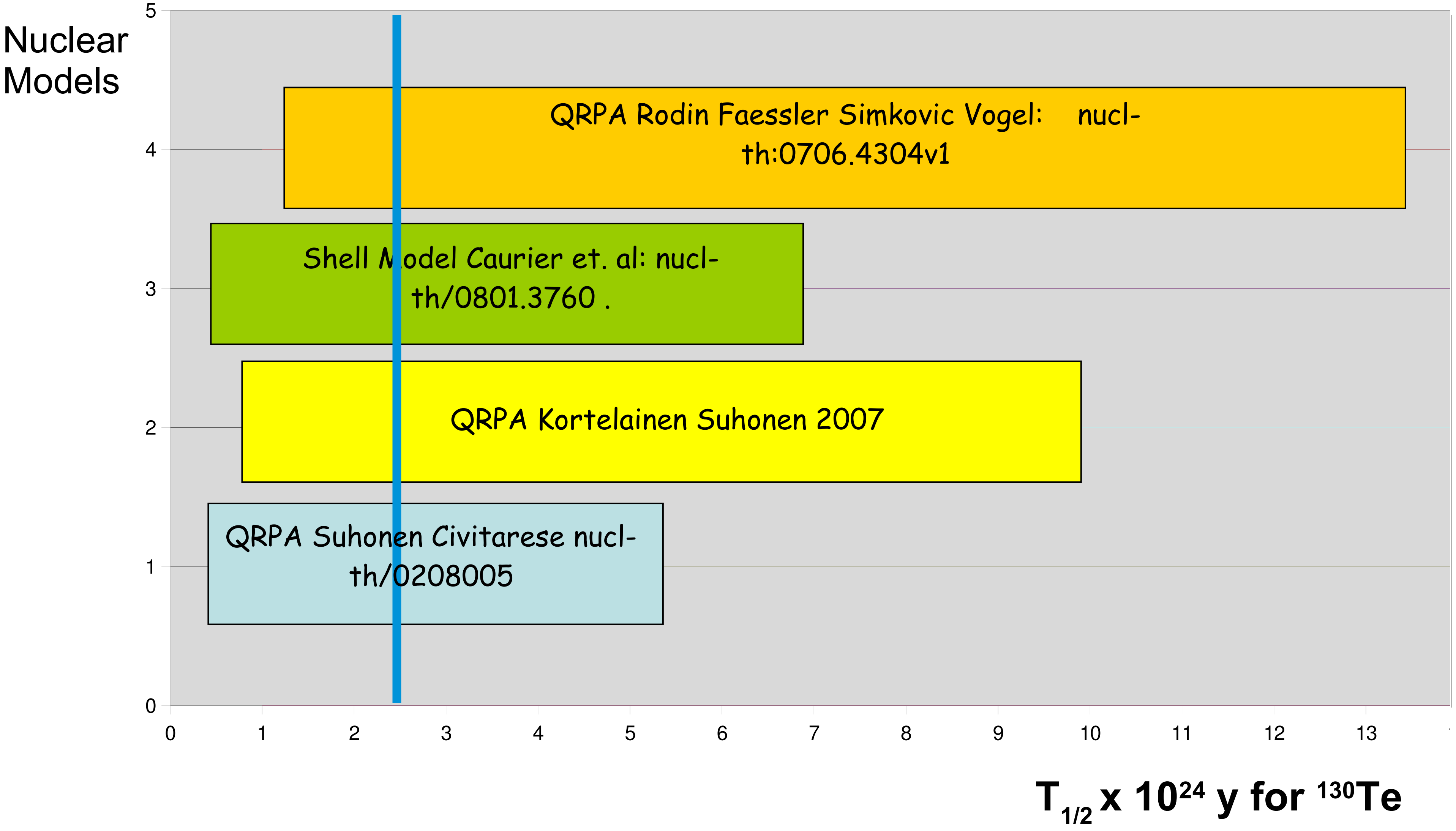
HM claim of evidence:
$T_{1/2}^{0\nu}$ (y) = (0.69-4.18) × 10^{25} (3σ range)

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

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



HM claim: CUORICINO 3σ



Goals of next generation 0ν-DBD experiments

- **sensitivities down to few 0.01 eV on $\langle m_\nu \rangle$ or better**
- 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

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

increase experimental mass

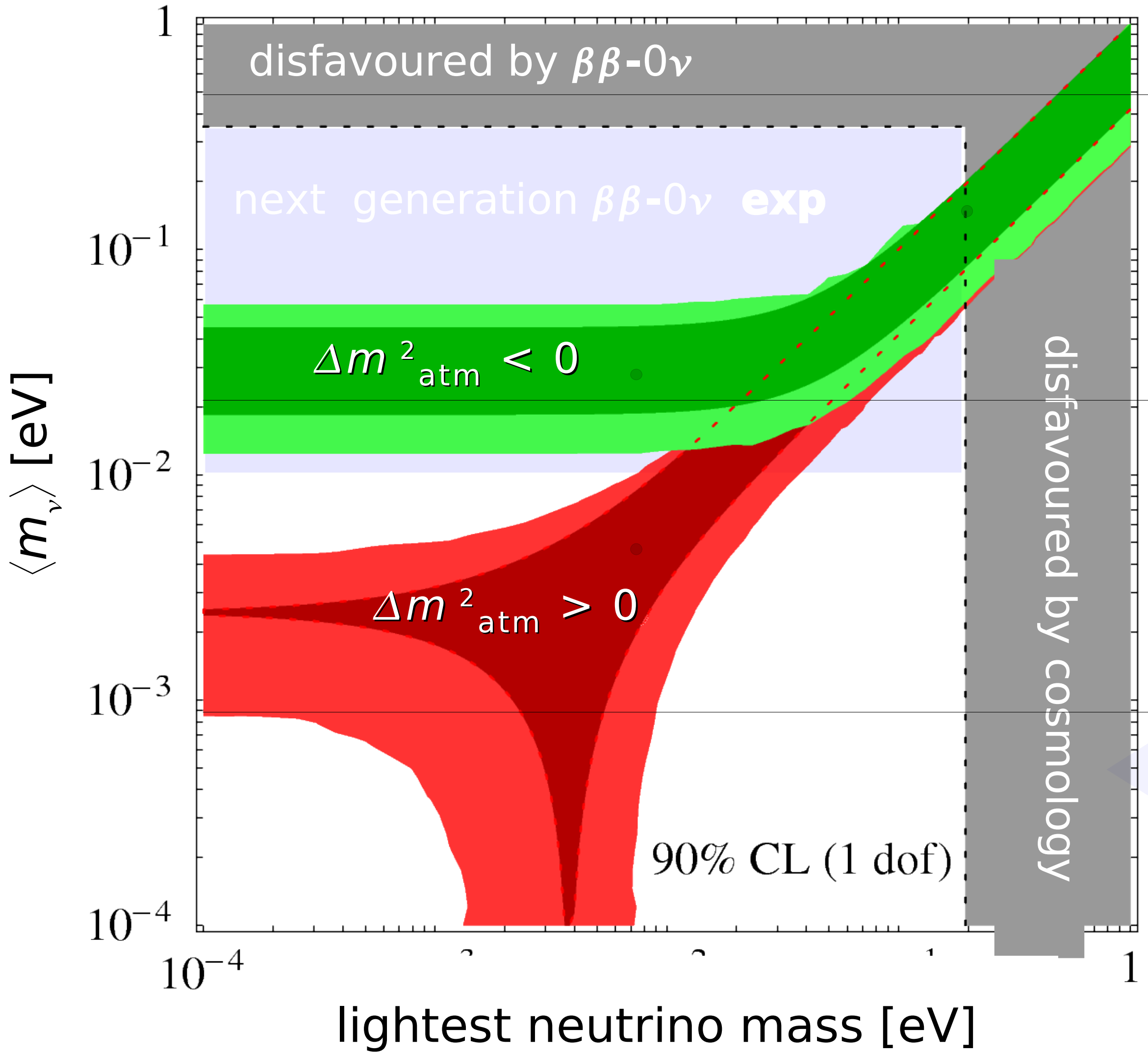
reduce background by:
material selection and proper handling
choosing proper technique
using signatures
improving energy resolution

The challenge: -Background +Mass

$N_B = B\,\Delta M\,T$ is the crucial parameter

Goal: $N_B \sim O(1)$ i.e. $B\,M \sim$ const

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



Background level B ...

100-1000 counts/y/ton

0.5-5 counts/y/ton

0.1-1 counts/y/(100 ton)

... subject to B M ~ const constraint

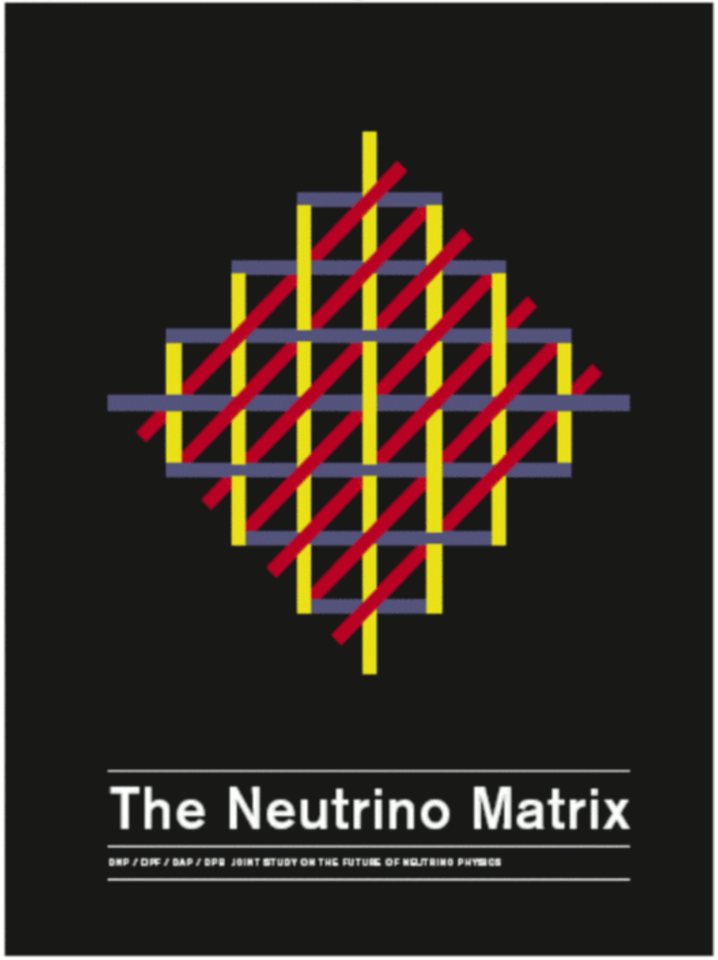
The international strategy

APS neutrino study

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

neutrinoless nuclear double beta decay (0νββ)

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.

The international strategy: ASPERA roadmap

PHASED PROGRAM

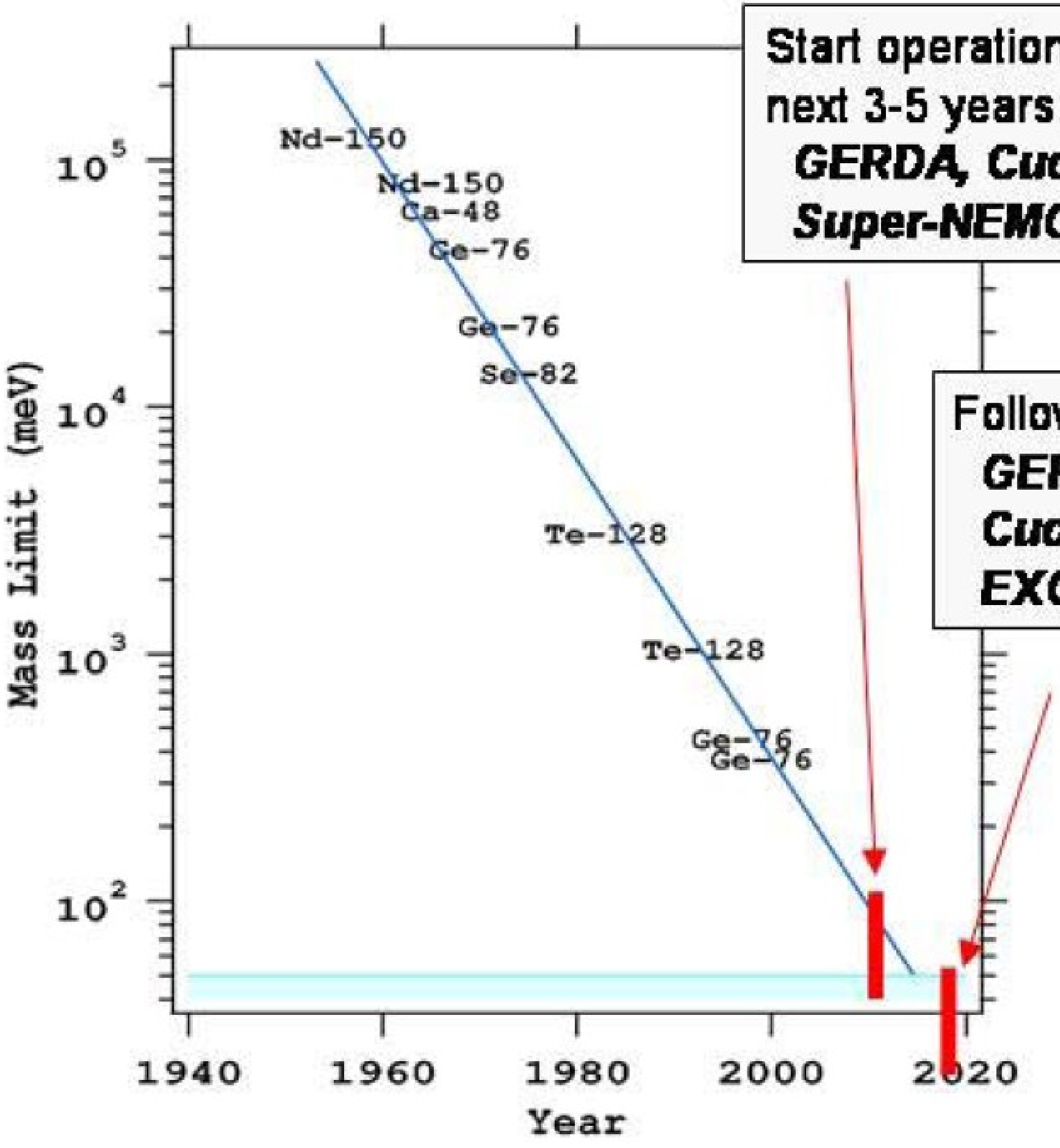
Present:	10-50 kg
Next Future:	200-500 kg
Long range:	tons

KAMLAND (Xe)
SNO+ (Nd)

LS @ LNGS (Nd)

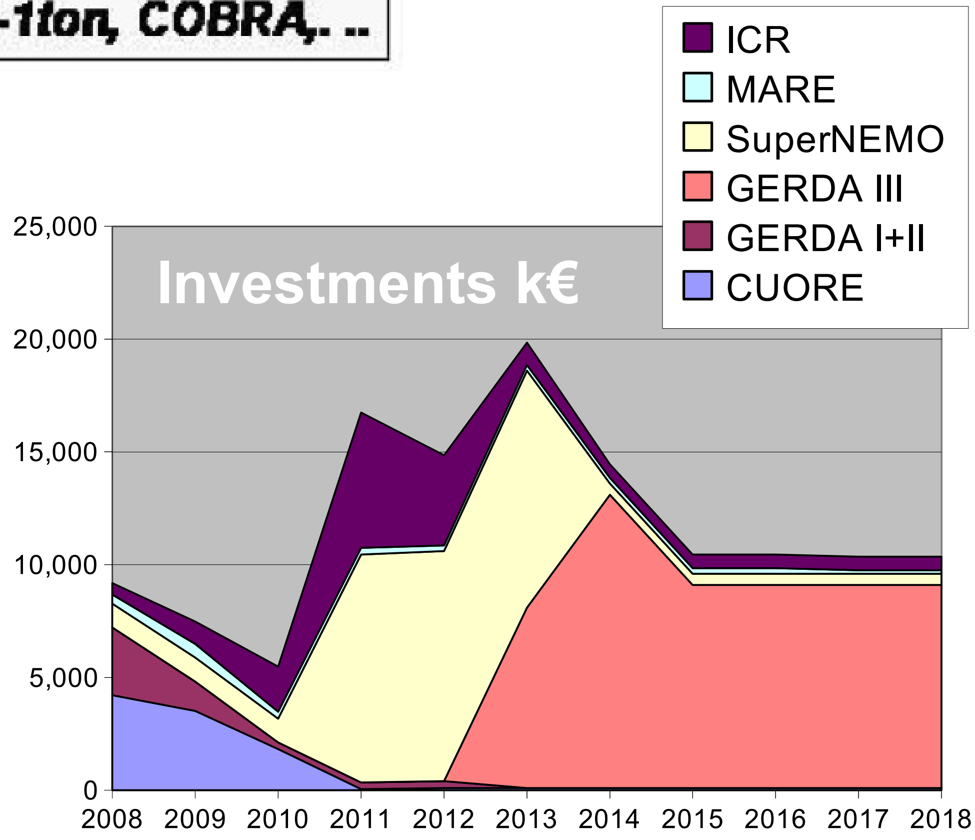
Name	Nucleus	Method	Location	European Members	Others
Running experiments					
CUORICINO	^{130}Te	bolometric	LNGS	IT, NL, ES	US
NEMO-3	^{100}Mo ^{82}Se	tracko-calo	LSM	FR, CZ, UK ES, FIN	US, RU, JP
Construction funding					
CUORE	^{130}Te	bolometric	LNGS	IT, NL, ES	US
GERDA	^{76}Ge	ionization	LNGS	DE,BE,IT,PO	RU
Substantial R&D funding					
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
R&D and/or conceptual design					
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 + ...
other decay modes					
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

^{76}Ge 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

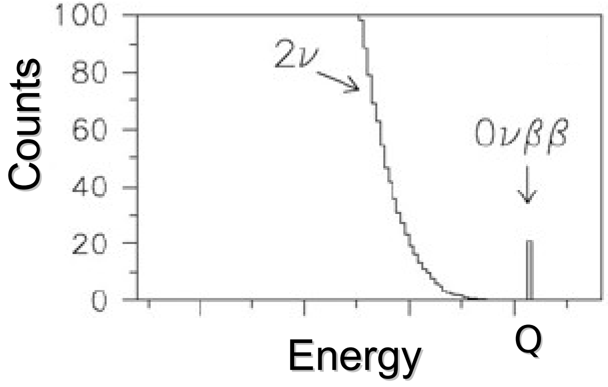
and of course
- Proper isotope
- Low background

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



Energy resolution

A

CUORE
GERDA
MAJORANA
LUCIFER

B

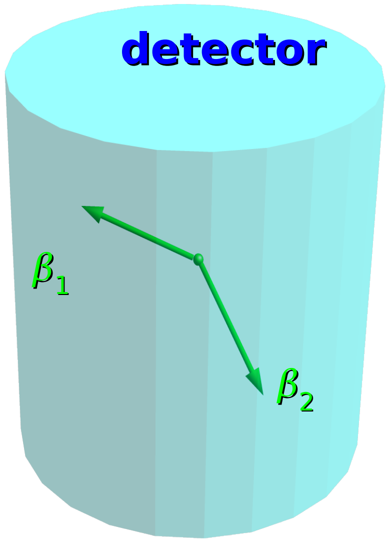
KAMLAND-Zen
SNO+
XMASS
CANDLES

C

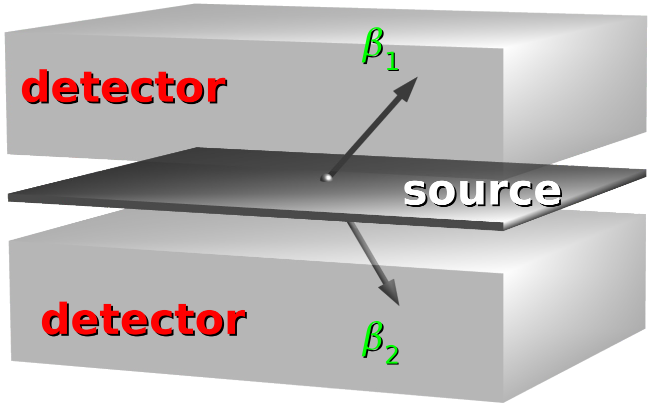
EXO
NEXT
COBRA

D

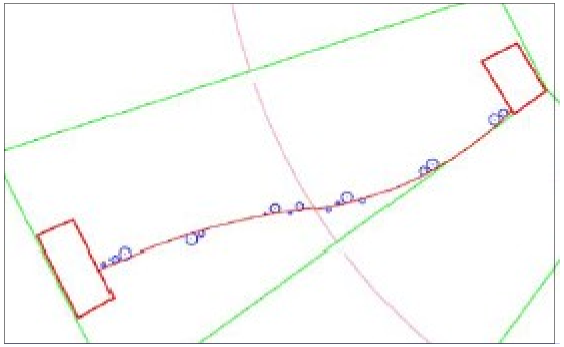
SUPERNEMO
MOON
DCBA



Source ≡ Detector



Source ≠ Detector



Tracking/Topology

Group A: high resolution homogeneous detectors

CUORE – ^{130}Te

- Array of low temperature natural TeO_2 calorimeters operated at ~10 mK - LNGS
- First step: 200 Kg (2013)
- It can take advantage from previous experience with Cuoricino
- Proved energy resolution: 0.2 % FWHM

GERDA – ^{76}Ge

- Array of enriched Ge diodes operated in liquid argon - LNGS
- First phase: 18 Kg (HDM+IGEX); second phase: 40 Kg (freshly produced)
- Proved energy resolution: 0.16 % FWHM

MAJORANA – ^{76}Ge

- Array of enriched Ge diodes operated in conventional Cu cryostats
- Based on modules; first step (demonstrator): 2x20 Kg modules
- Proved energy resolution: 0.16 % FWHM

LUCIFER – ^{82}Se – ^{116}Cd – ^{100}Mo

- Array of scintillating bolometers operated at ~10 mK (ZnSe or $CdWO_4$ or $ZnMoO_4$)
- ~ 10 Kg (2014) – LNGS
- Essentially R&D project to fully test the principle (background reach)
- Proved energy resolution: 0.3 - 1 % FWHM

Group A: high resolution homogeneous detectors

Although these experiments do not have tracking capability they can rely on some space information and other tools for the background reduction:

GRANULARITY

- CUORE: 988 closed packed individual bolometers
- COBRA: 64,000 closed packed individual detectors
- MAJORANA: 57 closed packed individual diodes per module

PULSE SHAPE DISCRIMINATION

- GERDA / MAJORANA can separate single / multi site events

SEGMENTATION/PIXELLIZATION

- Granularity can be achieved through electrodes segmentation
- R&D in progress for GERDA, MAJORANA, COBRA

ACTIVE SHIELDING

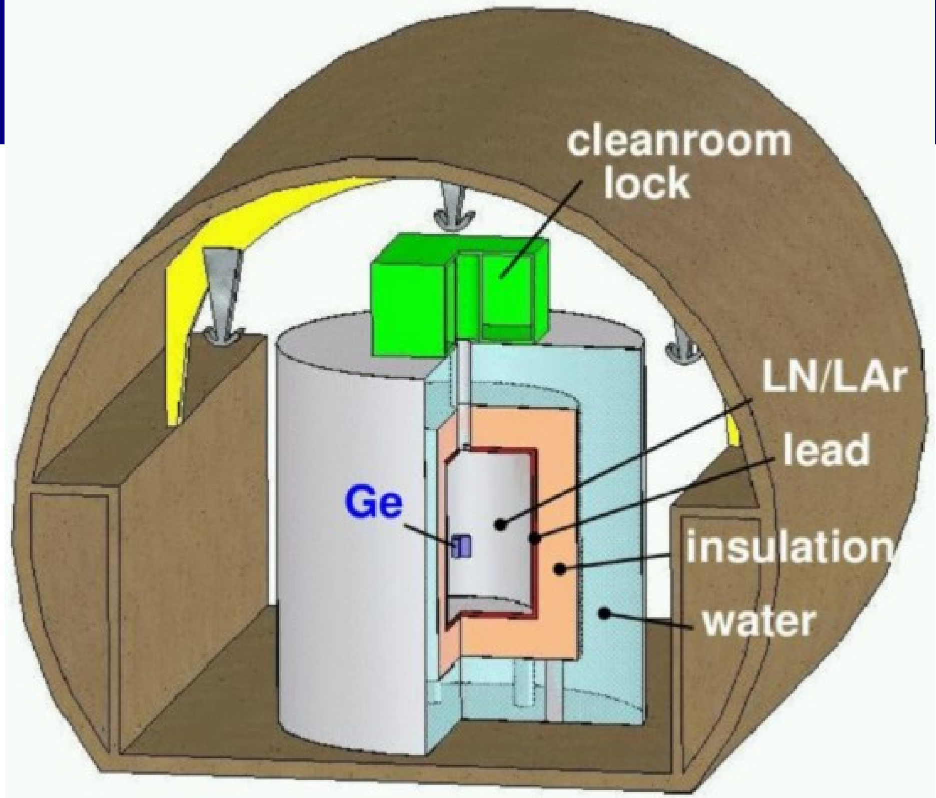
- GERDA: Ge diodes operated in active LAr

Simultaneous LIGHT and PHONON detection in bolometers

- Excellent results on a/b rejection already obtained in R&D studies for various scintillating materials

LNGS

GERDA



Germany, Italy, Belgium, Russia

Goal: analise 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)

- Undergriound commissioning
- Background: 0.01 counts/ keV kg y
- Scrutinize ^{76}Ge claim with the same nuclide (5s exclusion/confirmation)
- Half life sensitivity: 3×10^{25} 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): 2×10^{26} y ($\langle m_\nu < 90 - 290$ meV)

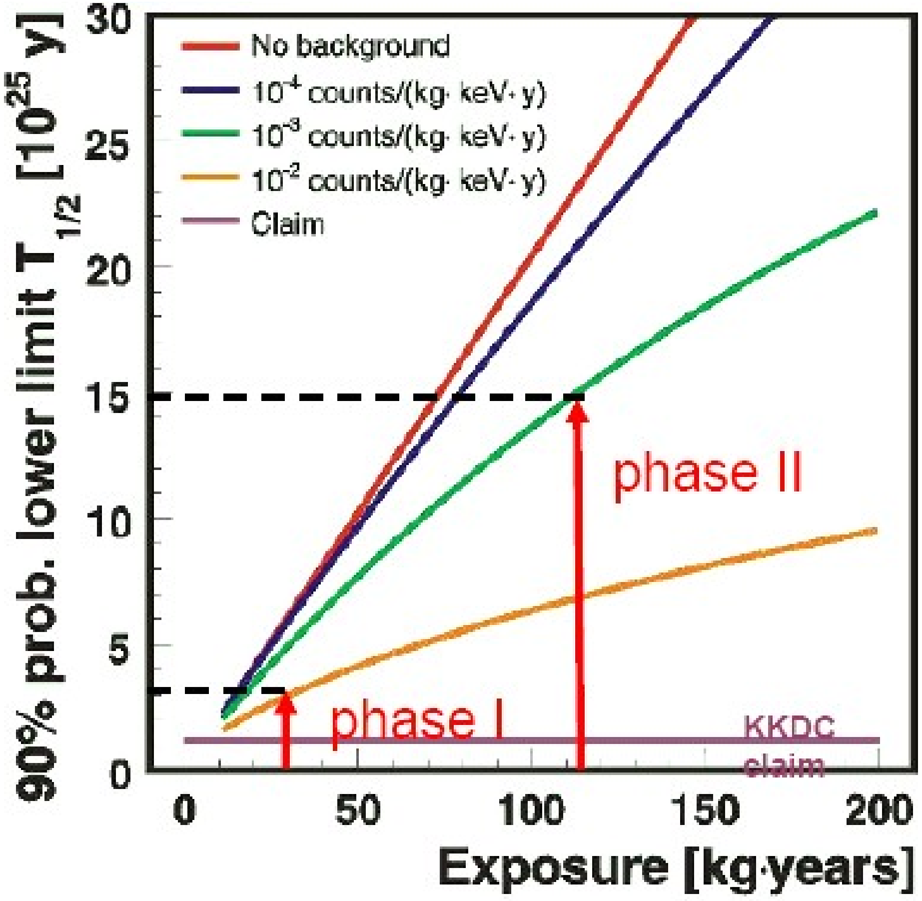
Phase III: depending on physics results of Phase I/I

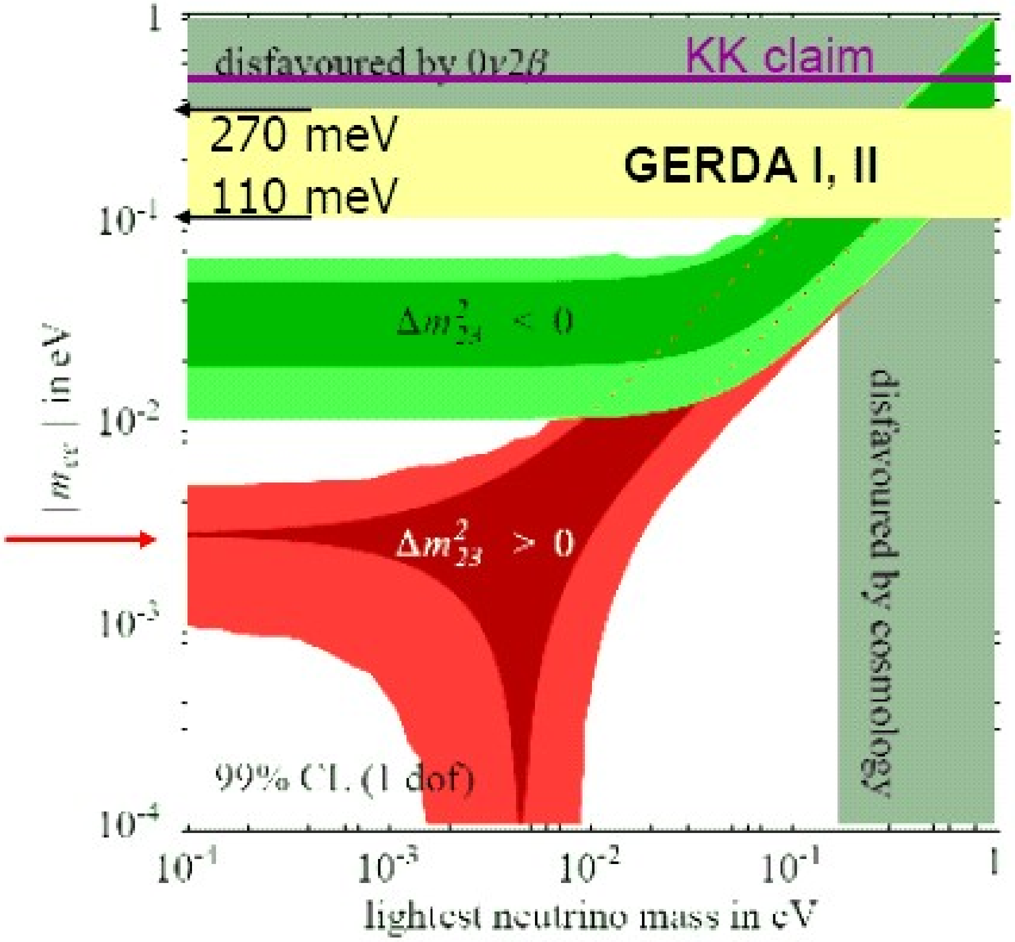
~ 1 ton experiment in world wide collaboration with MAJORANA

$\langle m_\nu \rangle < 20 - 50$ meV

2010:
Setup complete
Started with Natural Ge

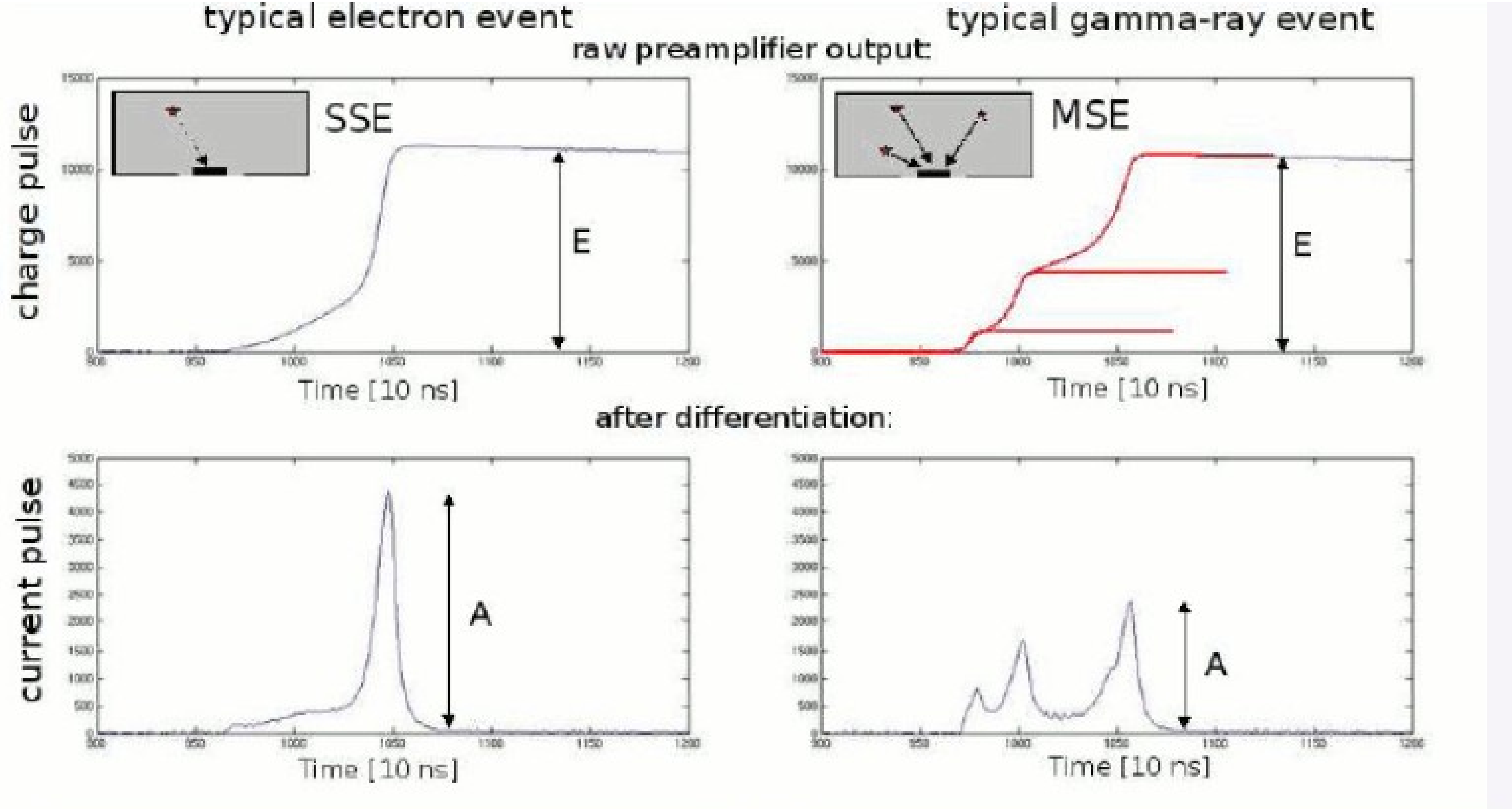
GERDA sensitivity





→ if signal found in HM by KK is true ββ 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 ~ 10^{-5}

GERDA II: pulse shape discrimination (A/E)



$A_{SSE} \propto q_{tot}$ $E_{SSE} \propto q_{tot}$

$\Rightarrow (A/E)_{SSE} = k$, constant

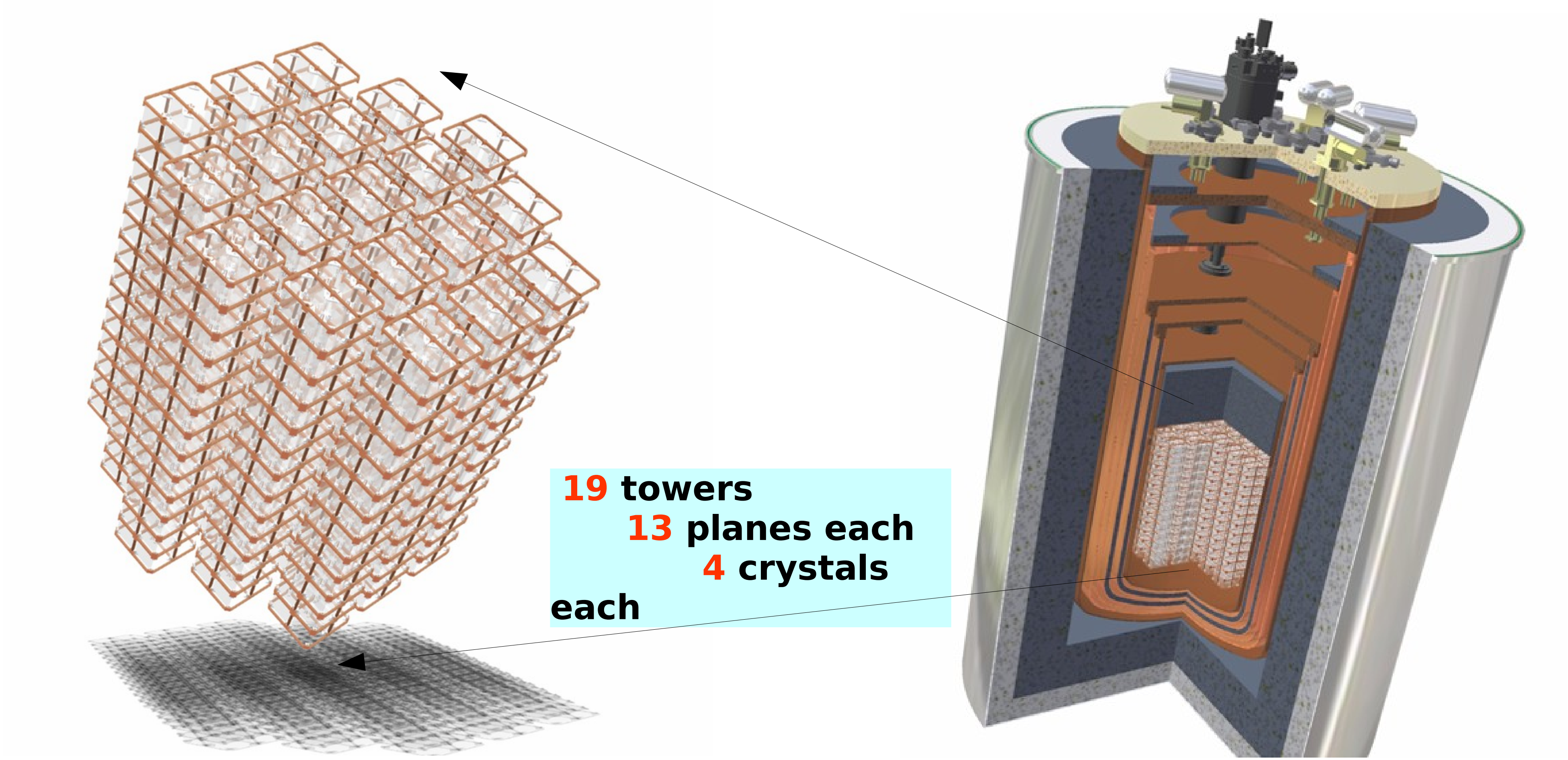
$A_{MSE} \propto q_{SSE_{max}}$ $E_{MSE} \propto q_{tot}$

$\Rightarrow (A/E)_{MSE} < (A/E)_{SSE} = k$

CUORE

Cryogenic Underground Observatory for Rare Events

- Closely packed array of 988 TeO_2 crystals $5\times5\times5$ cm^3 (750 g)
  - 741 kg TeO_2 granular calorimeter
  - 600 kg Te = 203 kg ^{130}Te
- Single high granularity detector



19 towers
13 planes each
4 crystals each

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	ΔE_{FWHM}	$\tau_{1/2}^{0\nu}$	m_{ee} [meV]			
[c/keV/kg/y]	[keV]	[y] @ 68%C.L.	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 costruction since 2005

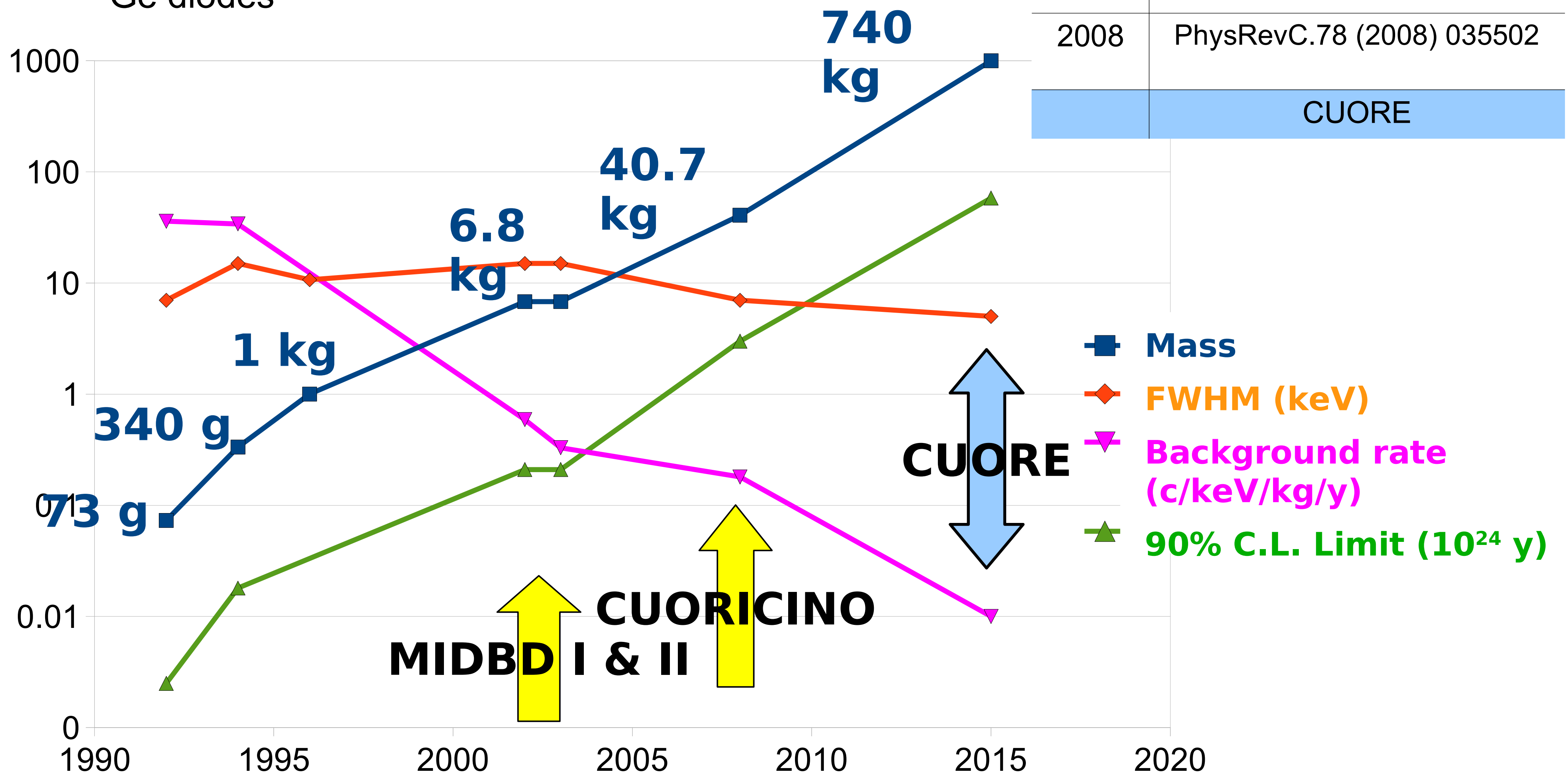
Detector completion: 2013

TeO$_2$ @ LNGS

1992	PhysLettB.285(1992)176
1994	PhysLettB.335(1994)519
1996	NIMA.370(1996)241
2002	PhysLettB.557(2003)167
2003	PhysLettB.557(2003)167
2008	PhysRevC.78 (2008) 035502
	CUORE

TeO$_2$ 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

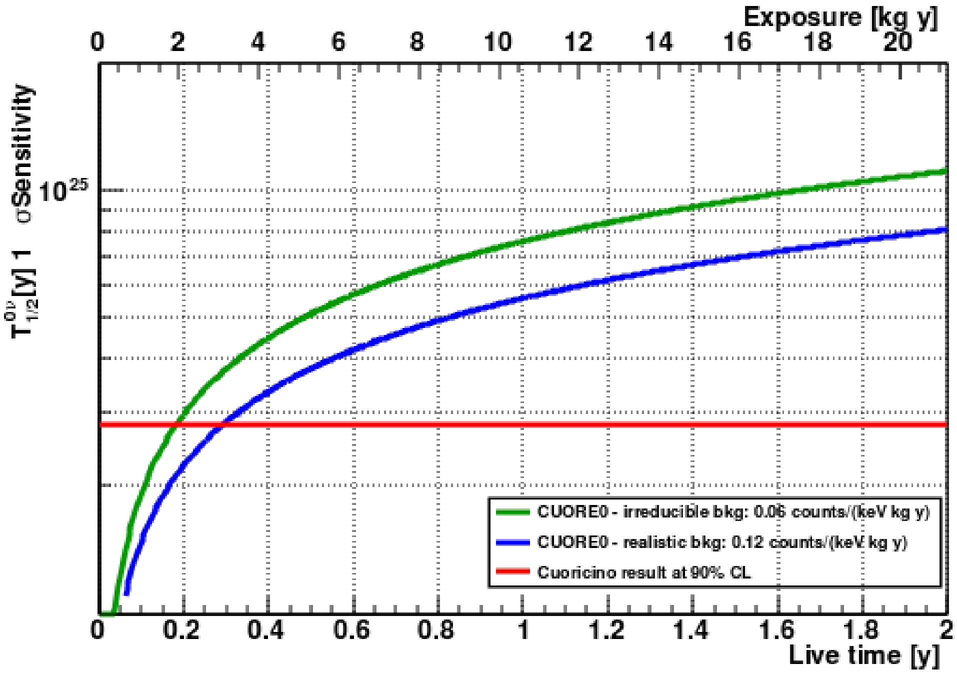
High statistics test of the many improvements/changes developped for the CUORE assembly procedure:

- gluing
- holder
- zero-contact approach
- Wires
- …

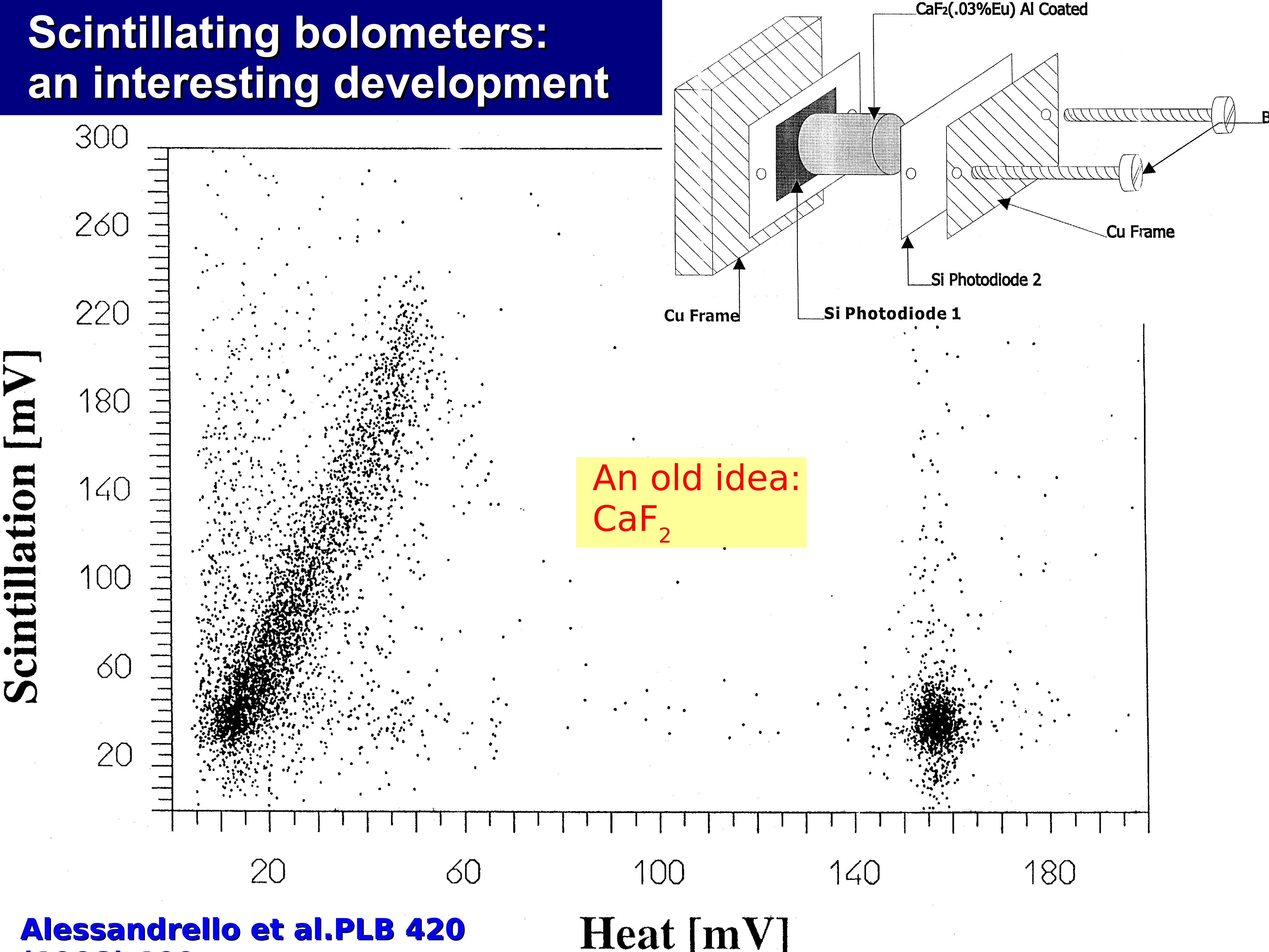
CUORE demonstrator: expected background in the DBD and alpha energy regions reduced by a factor 3 with respect ro CUORICINO

Powerful experiment: it will overtake soon CUORICINO sensitivity

Data taking: start fall 2011



Scintillating bolometers: an interesting development



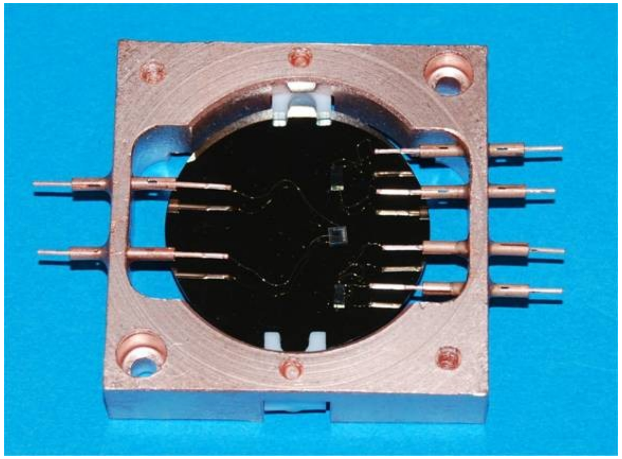
An old idea: CaF$_2$

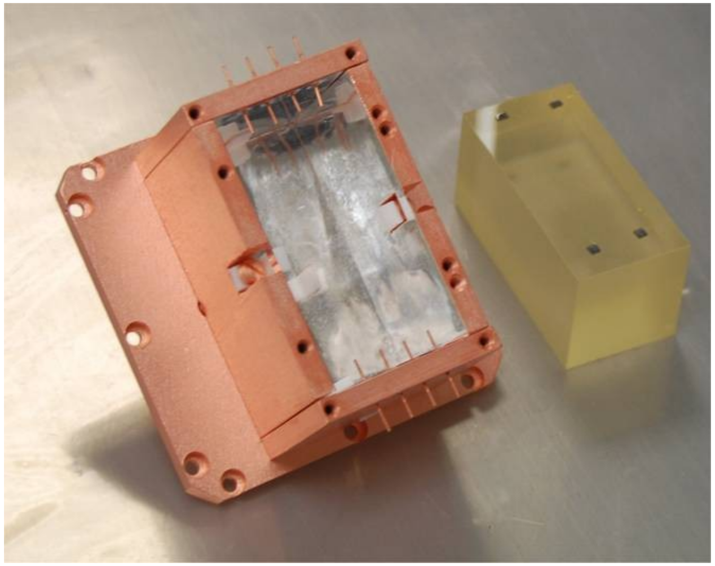
Alessandrello et al.PLB 420

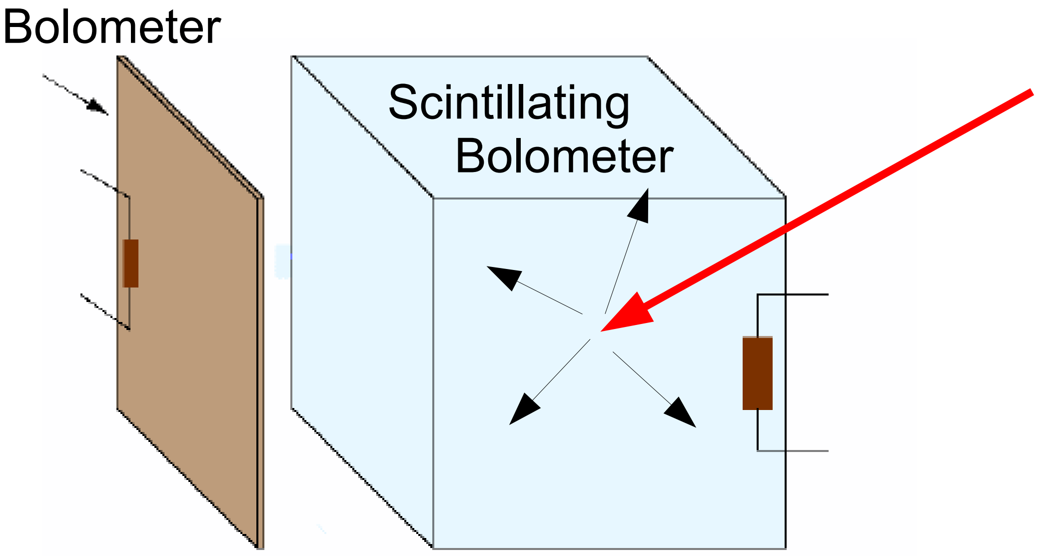
Scintillating bolometers @ LNGS

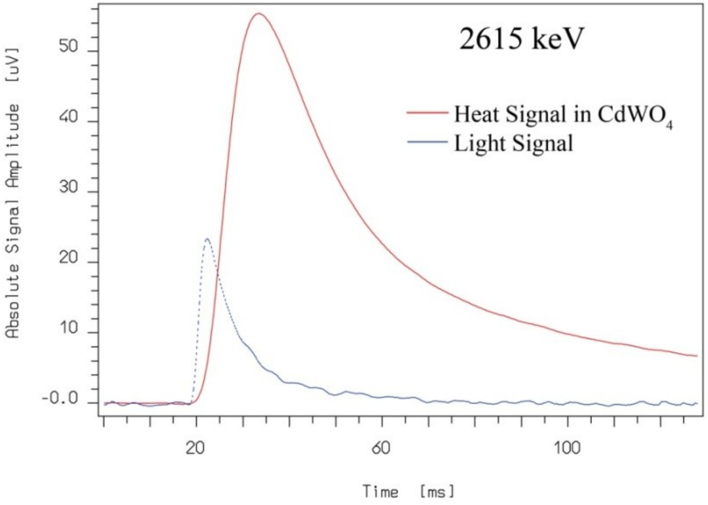
A very promising technique for background reduction

Concept: separate the dangerous alpha background exploiting different scintillating properties







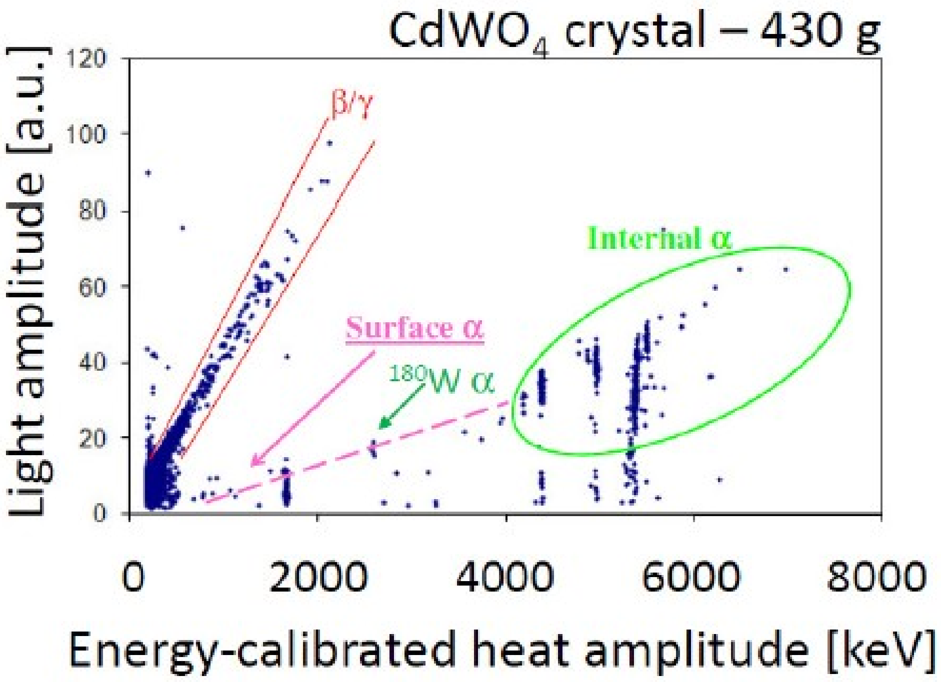


Not viable for TeO2 ... but ... PSA could be a surprise (arxiv 1011.5415)

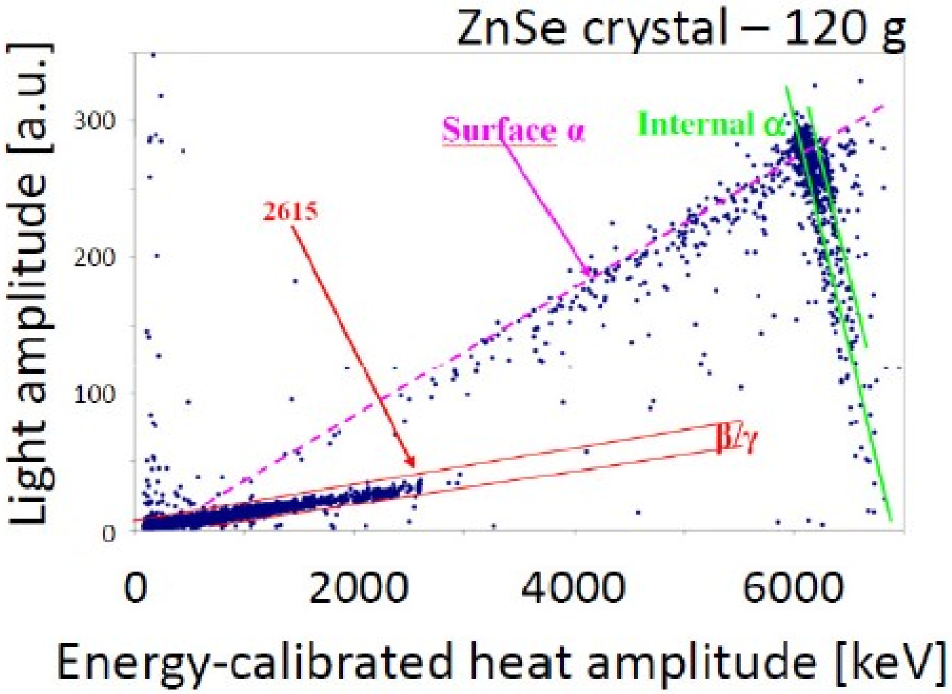
Scintillating bolometers: discriminating power

Scatter plot of light signals vs. heat signal

Alpha light yield < beta light yield



CdWO$_4$ crystal – 430 g



ZnSe crystal – 120 g

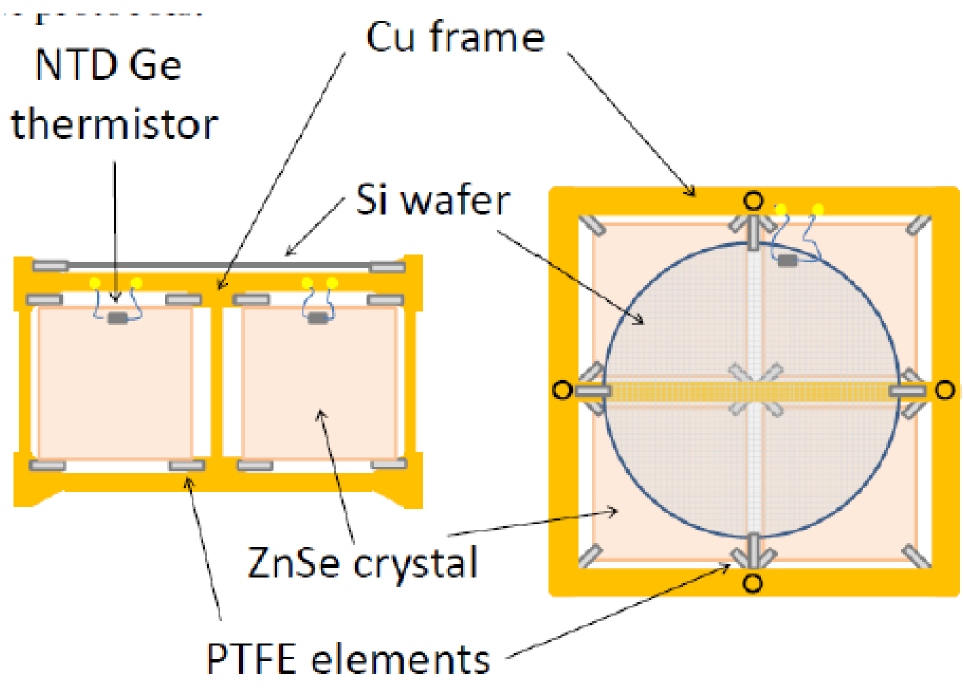
Alpha light yield > beta light yield

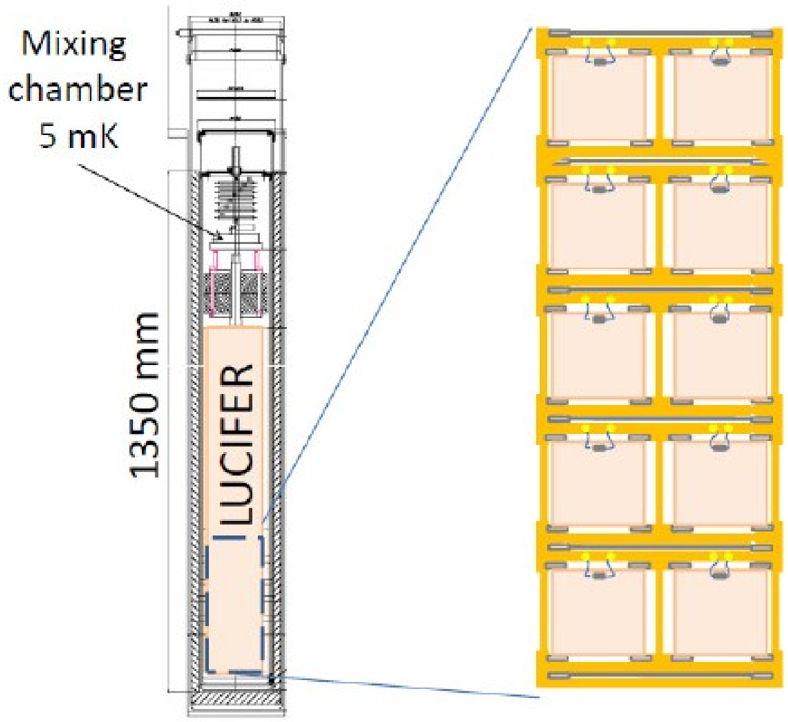
Arxiv [Nucl-ex]: 1006.2721
Arxiv: 1005.1239 and Astroparticle

LUCIFER

ERC call: funded march 2010

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





Single module: CUORE0-like structure

Group B: large mass homogeneous detectors

KamLAND-ZEN – ^{136}Xe

- Dissolve Xe gas in KAMLAND liquid scintillator – feasable at 3% wt
- Use a dedicated balloon immersed in the main bessel
- Increase number of PM and change scintillator – 400 kg of enriched Xe in the first phase

SNO+ – ^{150}Nd

- SNO detector filled with Nd-loaded liquid scintillator
- 0.1% loading with natural Nd 1000 Kg Nd in 1000 tons scintillators 56 Kg of isotope
- Crucial points: Nd enrichment and purity; ^{150}Nd nuclear matrix elements

XMASS – ^{136}Xe

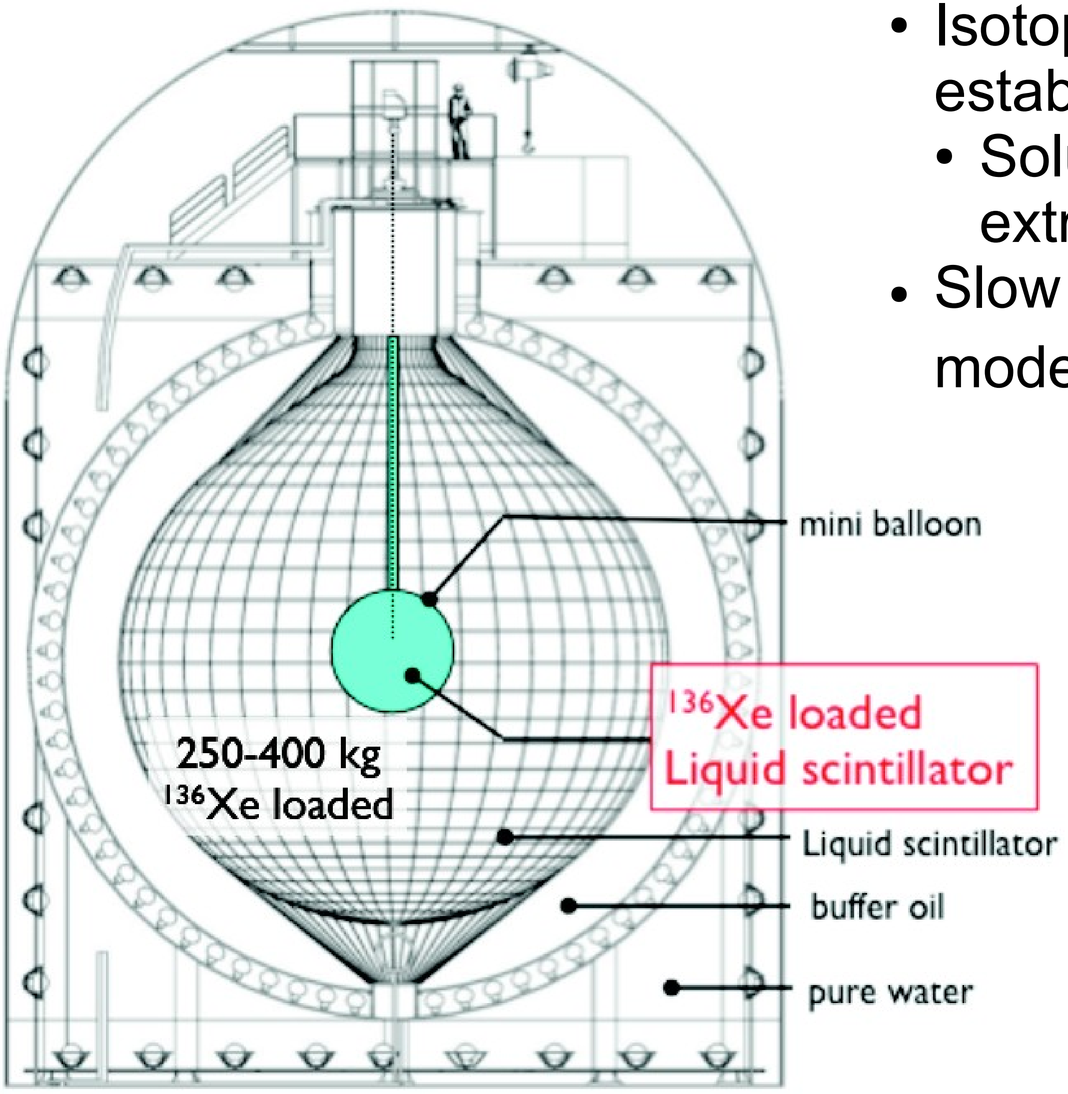
- Multipurpose scintillating liquid Xe detector (Dark Matter, Double Beta Decay, solar neutrinos)
- Three development stages: 3 Kg (prototype) 1 ton 10 ton
- DBD option: low background in the MeV region
- Special development with an elliptic water tank to shield high energy gamma rays
- High light yield and collection efficiency energy resolution down to 1.4% control $2\nu\beta\beta$ background
- Target: to cover inverted hierarchy with 10 ton natural or 1 ton enriched

CANDLES – ^{48}Ca

- Array of natural pure (not Eu doped) CaF_2 scintillators
- Prove of principle completed (CANDLES I and II)
- Proved energy resolution: 3.4 % FWHM (extrapolated from 9.1 % at 662 keV)
- The good point of this search is the high Q-value of ^{48}Ca: 4.27 MeV out of gamma (2.6 MeV end point), beta (3.3 MeV end point) and alpha (max 2.5 MeV with quench) regions
- Other background cuts come from PSD and space-time correlation for Bi-Po and Bi-Tl

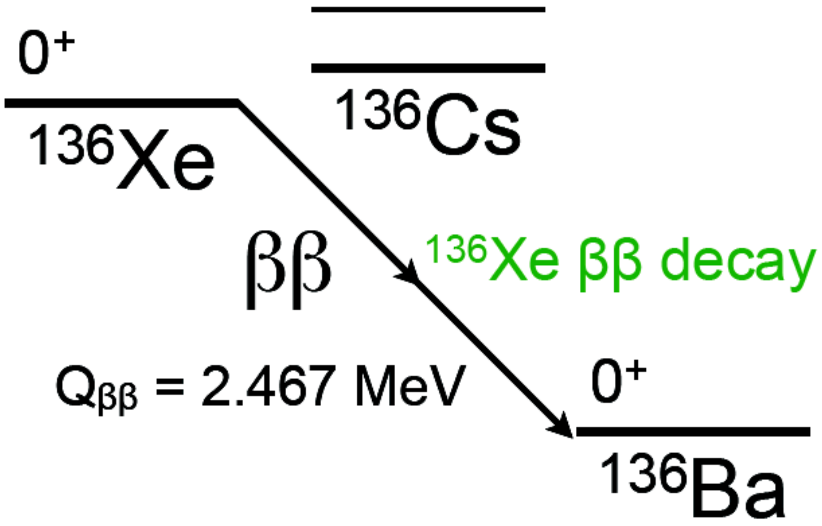
KamLAND-Zen

^{136}Xe loaded LS



Phase I concept

- 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



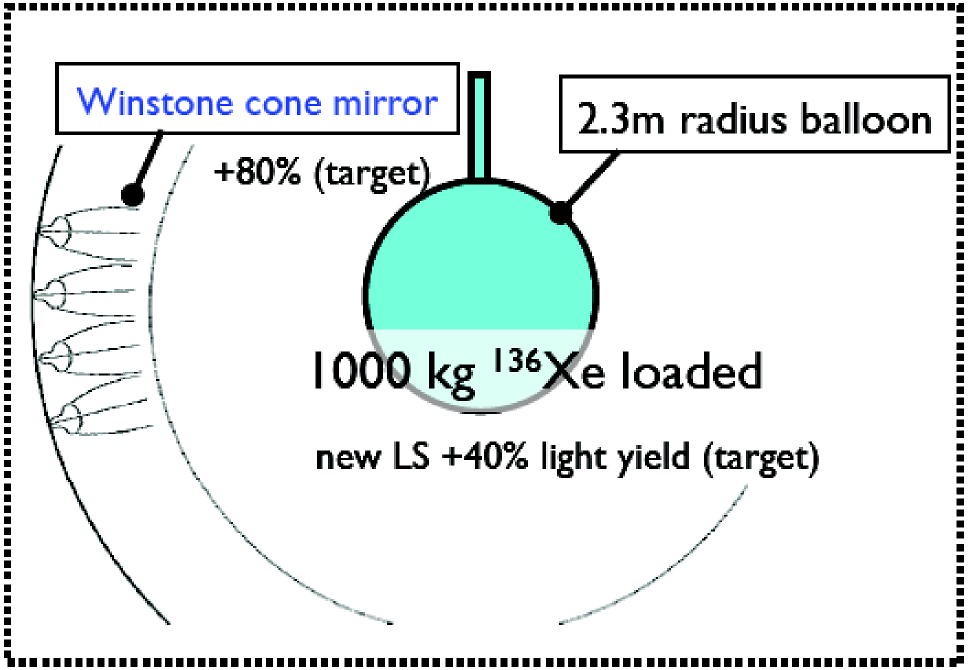
KAMLAND merits

- Ultra low radioactivity environment based on ultra pure LS and
- 9m radius active shield: $^{38}U < 3.5\ 10^{-18}$ g/g $^{232}Th < 5.2\ 10^{-17}$ 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 136Xe, improvement of energy resolution with light concentrators and brighter LS (~30M$)

25 meV in 5 years



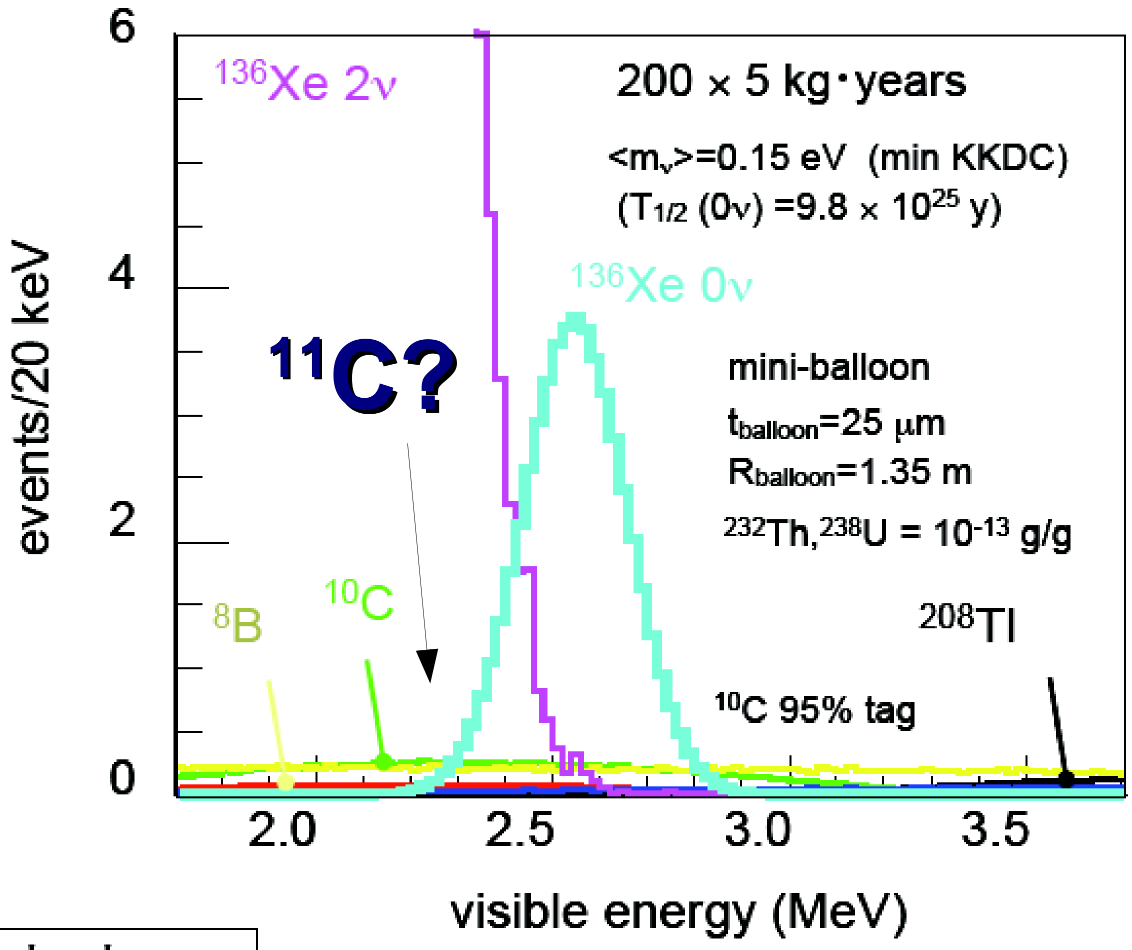
R&D items

- 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

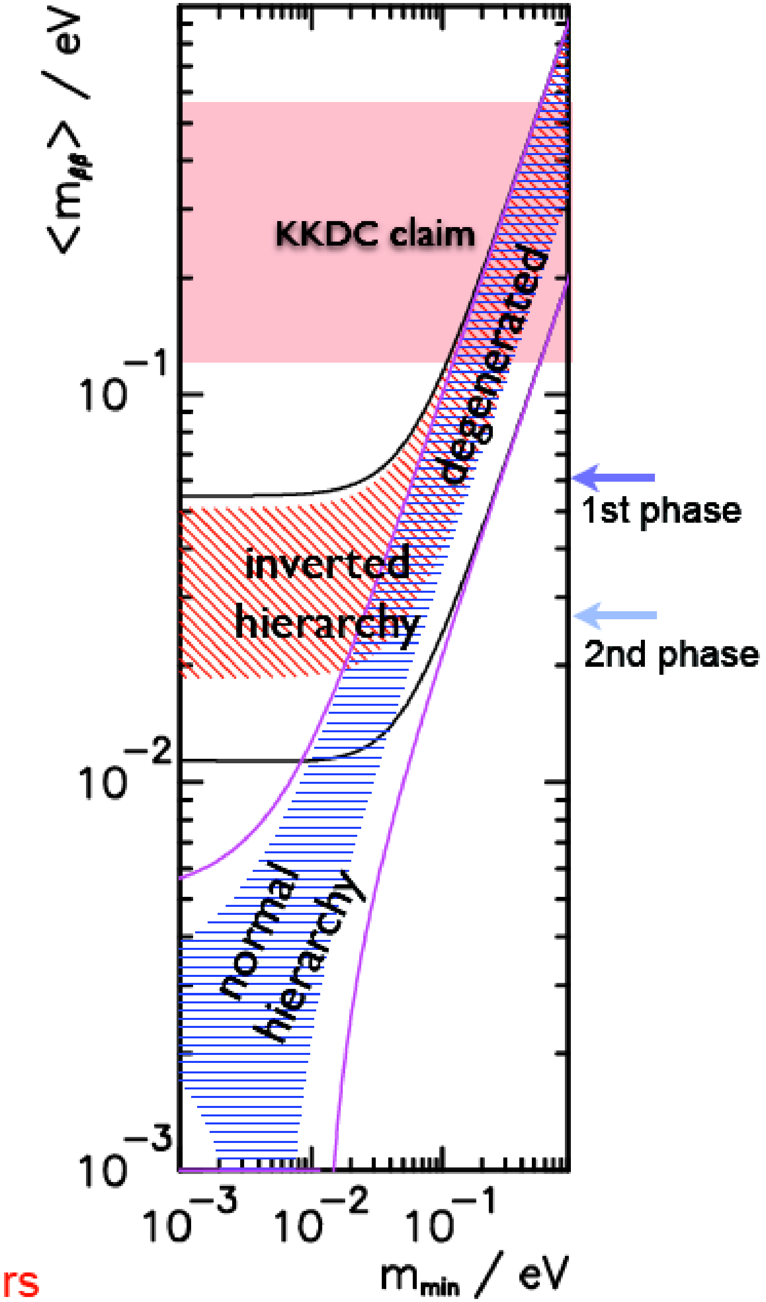
KKDC claim, degenerated hierarchy test



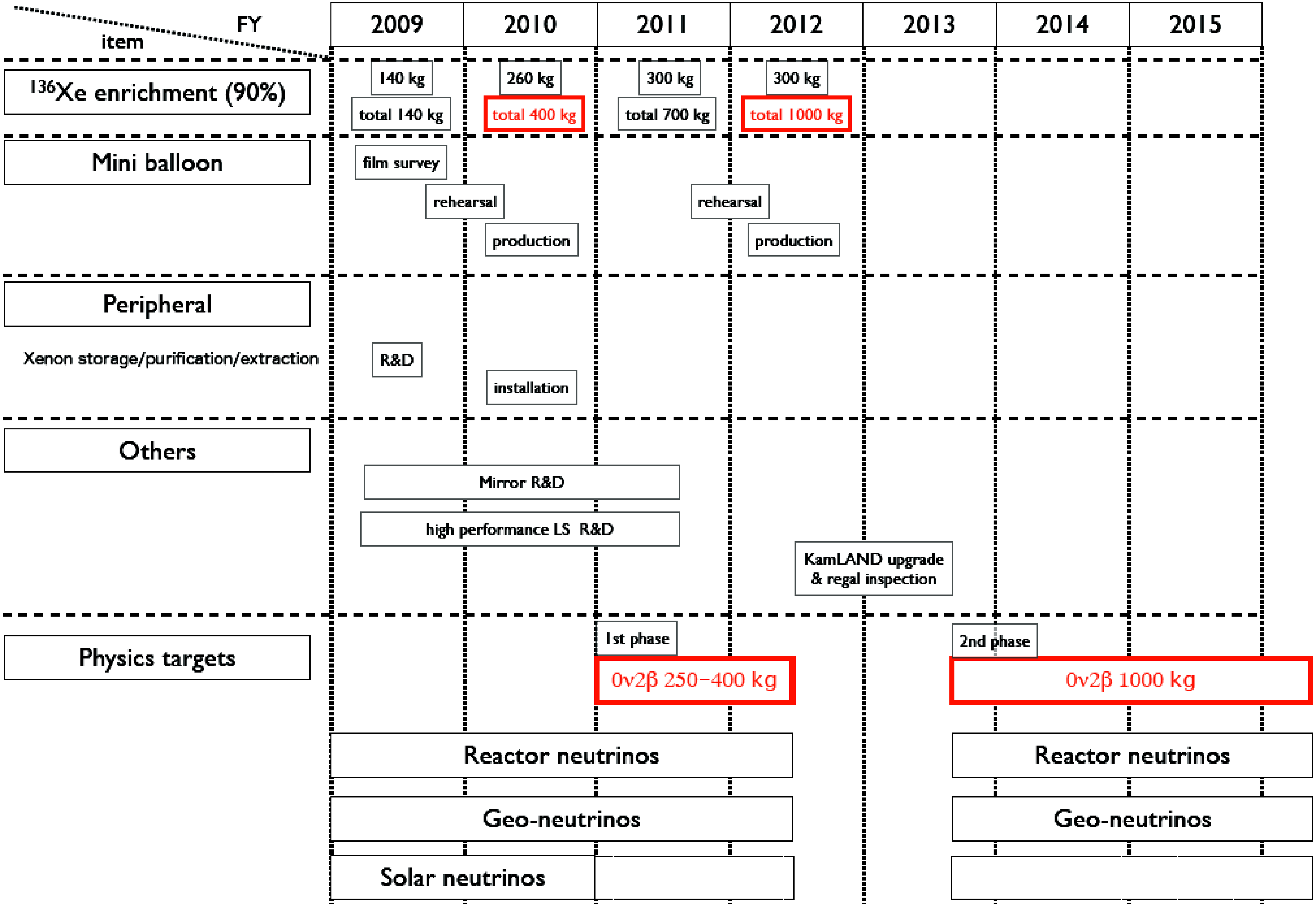
2nd phase

inverted hierarchy test

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



KAMLAND-Zen timeline



item \ FY	2009	2010	2011	2012	2013	2014	2015
^{136}Xe enrichment (90%)	140 kg total 140 kg	260 kg total 400 kg	300 kg total 700 kg	300 kg total 1000 kg			
Mini balloon	film survey rehearsal	production	rehearsal	production			
Peripheral							
Xenon storage/purification/extraction	R&D	installation					
Others	Mirror R&D high performance LS R&D			KamLAND upgrade & regal inspection			
Physics targets			1st phase 0ν2β 250–400 kg			2nd phase 0ν2β 1000 kg	
	Reactor neutrinos					Reactor neutrinos	
	Geo-neutrinos					Geo-neutrinos	
	Solar neutrinos						

Group C: tracking homogeneous detectors

EXO – ^{136}Xe

- TPC of enriched liquid (first phase) and gaseous (second phase) Xenon
- Event position and topology; in prospect, tagging of Ba single ion (DBD daughter) through optical spectroscopy only 2n DBD background
- Next step (EXO-200: funded, under commissioning): 200 kg – WIPP facility – sensitivity: 270-380 meV
- Further steps: 1-10 ton
- Proved energy resolution: 3.3 % FWHM (inproved thanks to simultaneous measurement of ionization and light)
- In parallel with the EXO-200 development, R&D for Ba ion grabbing and tagging

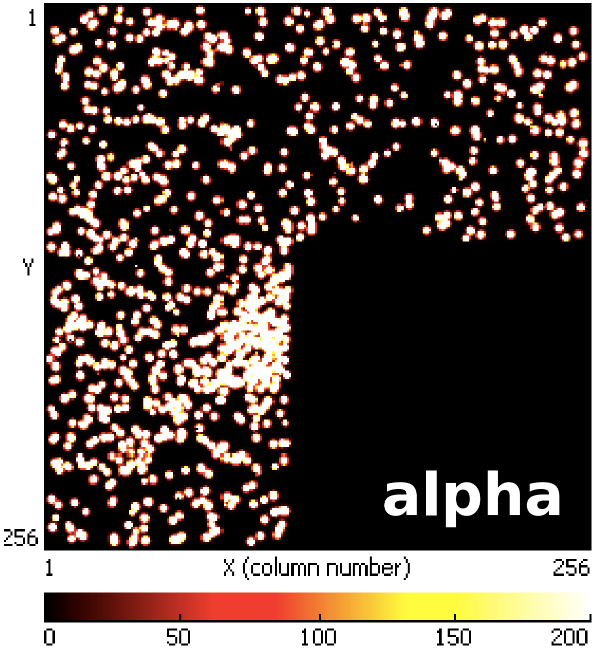
NEXT – ^{136}Xe

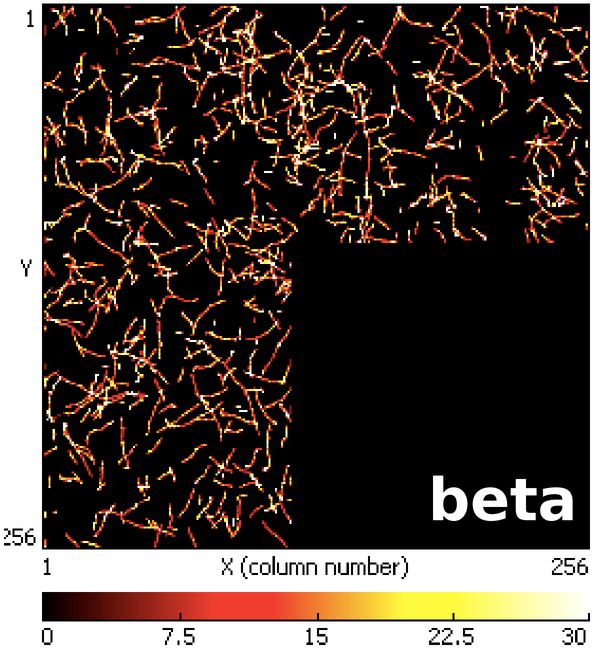
- High pressure gas TPC
- Total mass: 100 kg
- Aims at energy resolution down to 1% FWHM exploiting electroluminesce in high field region
- NEXT-10, a 10kg prototype, should provide data in CANFRANC in 2013

COBRA - ^{116}Cd competing candidate – 9 ββ isotopes

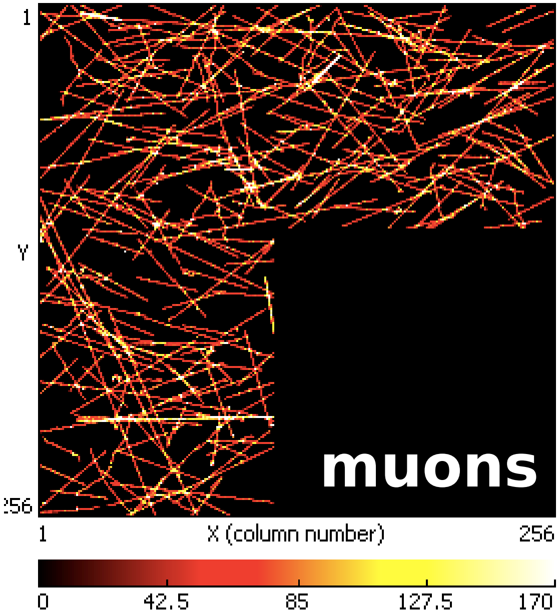
- Array of 116Cd enriched CdZnTe of semiconductor detectors at room temperatures
- Small scale prototype at LNGS
- Proved energy resolution: 1.9% FWHM
- Pixellization can provide tracking capability

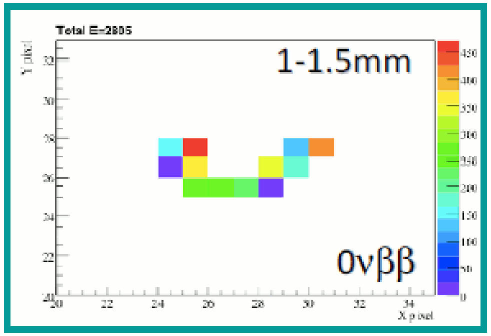
TPC's: Topology reconstruction

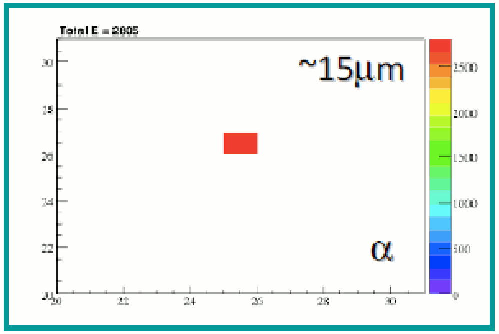




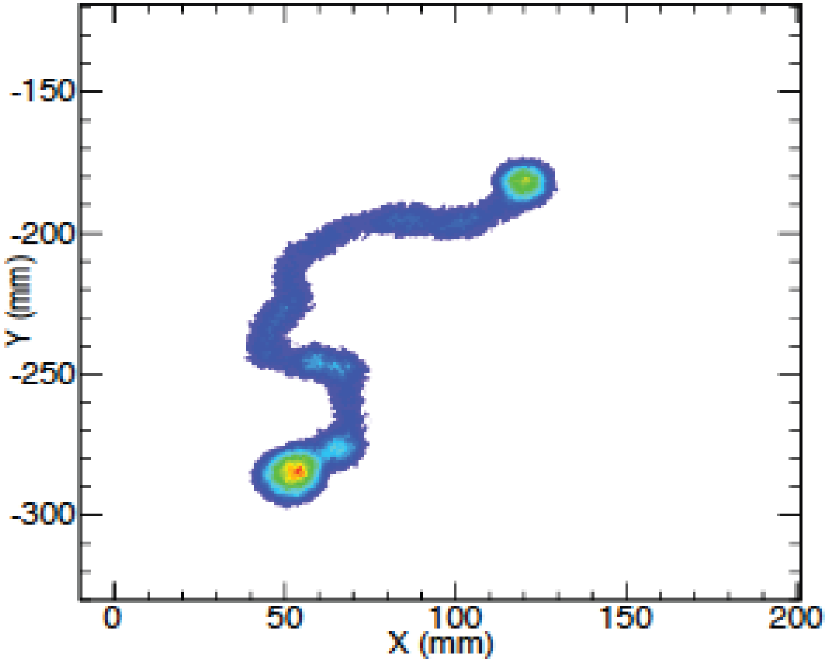
COBRA: a solid state TPC for alpha/beta discrimination (250µm pixels)







NEXT: a gas (Xe) TPC for conventional double track reconstruction



Group D: tracking inhomogeneous detectors

SUPERNEMO - ^{82}Se or ^{150}Nd

- Modules with source foils, tracking (drift chamber in Geiger mode) and calorimetric (low Z scintillator) sections. Magnetic field for charge sign
- Possible configuration: 20 modules with 5 kg source for each module 100 Kg in Modane extension.
- Energy resolution: 4 % FWHM
- It can take advantage of NEMO3 experience

MOON - ^{100}Mo or ^{82}Se or ^{150}Nd

- Multilayer plastic scintillators interleaved with source foils + tracking section (PL fibers or MWPC)
  - MOON-1 prototype without tracking section (2006)
  - MOON-2 prototype with tracking section
- Proved energy resolution: 6.8 % FWHM
- Final target: collect 5 y x ton

DCBA - ^{150}Nd

- Momentum analyzer for beta particles consisting of source foils inserted in a drift chamber with magnetic field
- Realized test prototype DCBA-T2: space resolution ~ 0.5 mm; energy resolution 11% FWHM at 1 MeV
- 6 % FWHM at 3 MeV
- Test prototype DCBA-T3 under construction: aims at improved energy resolution thanks to higher magnetic field (2kG) and higher space resolution
- Final target: 10 modules with 84 m2 source foil for module (126 through 330 Kg total mass)

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)**

Planar geometry

- **source (40 mg/cm^2): 12m^2**
- **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 σ_E = 2.6% @ 3 MeV

efficiency: 40%

Canfranc/LSM

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

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

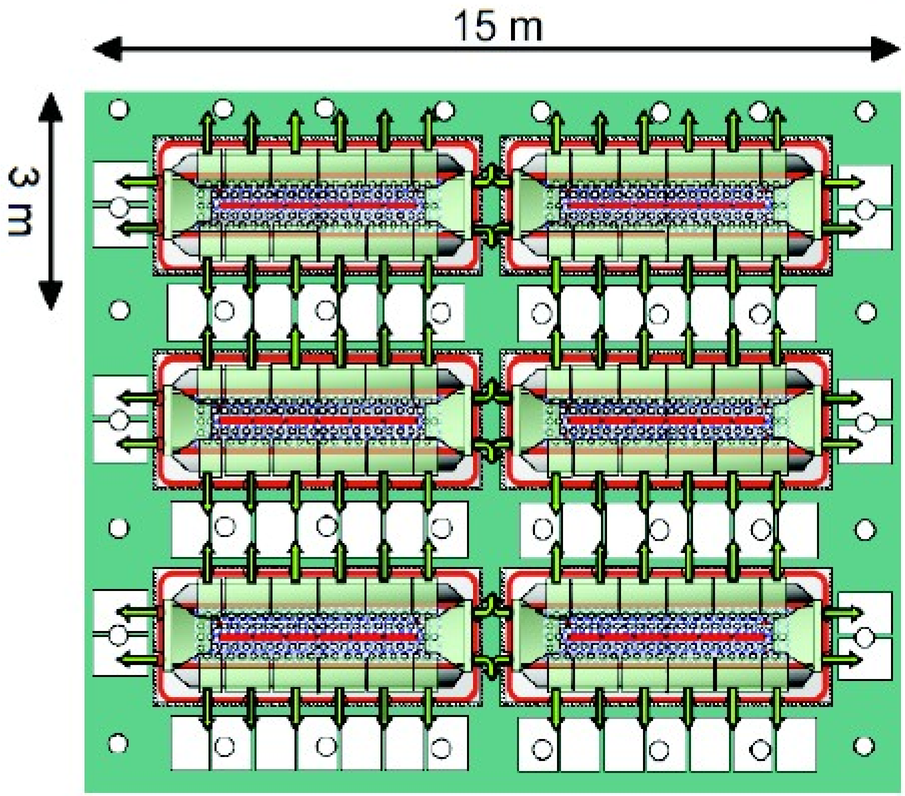
funded by France, UK and Spain

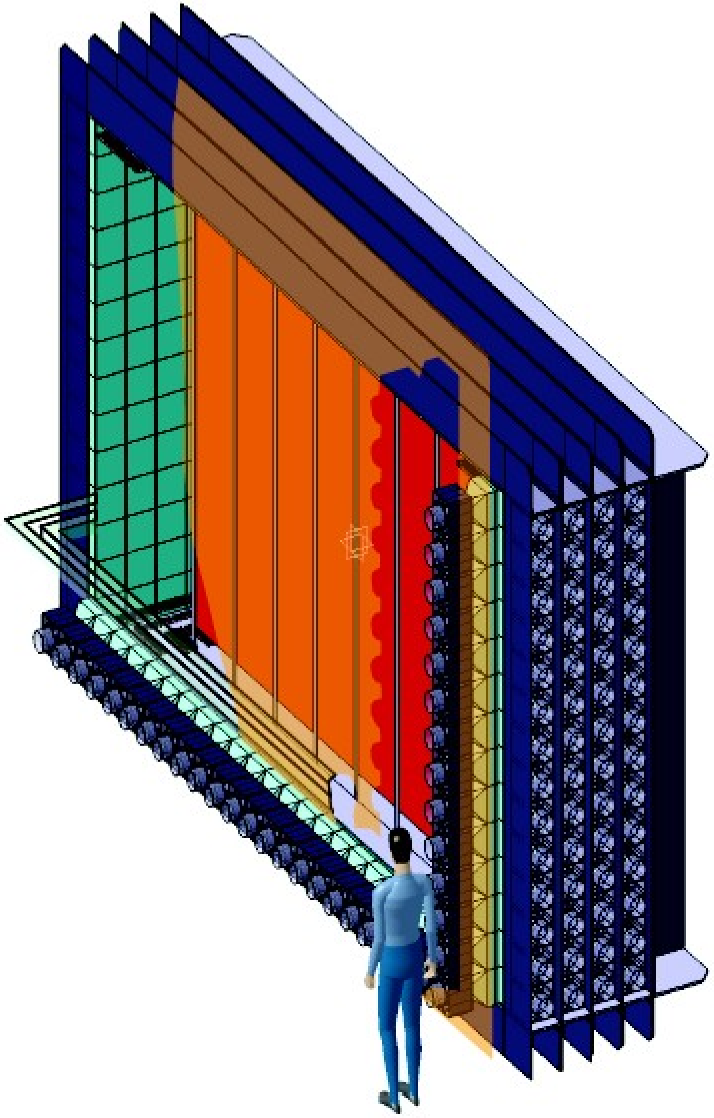
- **2009: TDR**
- **2011: commissioning and data taking of first modules in Canfranc (Spain)**
- **2013: Full detector running**

SuperNEMO

20 modules for 100 kg

Source: ~ 5kg (4 0 mg/cm², 12m²)
Tracking: ~2,100 drift cells).
Calorimeter: ~600 blocks

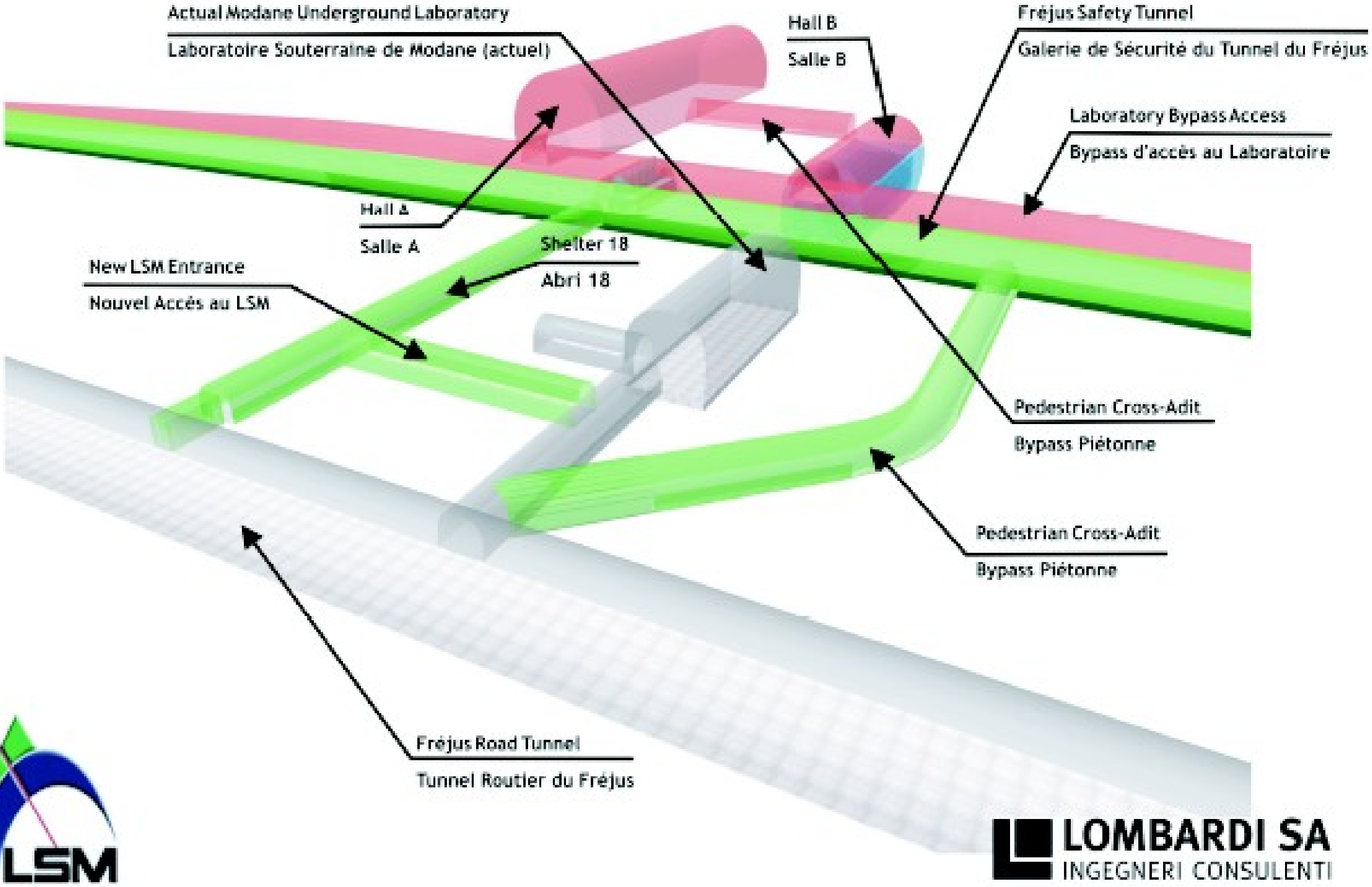




ULISSE project

MODANE UNDERGROUND LABORATORY 60'000 m^3 EXTENSION

LABORATOIRE SOUTERRAINE DE MODANE AGRANDISSEMENT 60'000 m^3



Actual Modane Underground Laboratory
Laboratoire Souterraine de Modane (actuel)

Hall B
Salle B

Fréjus Safety Tunnel
Galerie de Sécurité du Tunnel du Fréjus

Laboratory Bypass Access
Bypass d'accès au Laboratoire

Hall A
Salle A

Shelter 18
Abri 18

New LSM Entrance
Nouvel Accés au LSM

Pedestrian Cross-Adit
Bypass Piétonne

Pedestrian Cross-Adit
Bypass Piétonne

Fréjus Road Tunnel
Tunnel Routier du Fréjus

LOMBARDI SA
INGEGNERI CONSULENTI

Status and near future projects

Experiment	Isotope	Isotope mass (kg)	$T_{1/2}$ (y)	Data taking Start	$\langle m_\nu \rangle$ QRPA	Status
CUORE	^{130}Te	203	2.1×10^{26}	2013	70	Construction
CUORE0	^{130}Te	10.7	1.5×10^{25}	2011	190	Construction
GERDA I	^{76}Ge	17.9	3×10^{25}	2011	190	Construction
GERDA II	^{76}Ge	40	2.0×10^{26}	2013	90	Funded
EXO-200	^{136}Xe	200	6.4×10^{25}	2011	110	Construction
KamLAND-Zen	^{136}Xe	400		2011	40	Preparation
Majorana	^{76}Ge	30-60	1.1×10^{26}	2011	120	Funded R&D
Lucifer	^{82}Se	15-30	2.5×10^{26}	2014	70	Funded R&D
SuperNEMO	^{82}Se	100	2.1×10^{26}	2011	70	R&D
SuperNEMO	^{150}Nd	100	1.0×10^{26}	2011		R&D
CANDLES	^{48}Ca	0.35		2010		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

Conclusions

3 different likely scenarios

Scenario	<m> (meV)	Region	Detector mass (y)	Time scale (y)
A	100-500	degenerate	100-200	1-5
B	15-50	inverted	1000	5-10
C	2-5	direct	100000	?

Scenario A (^{76}Ge claim) – The HOPE:

- GERDA phase I / II will see $\beta\beta(0\nu)$ in ^{76}Ge
- CUORE will see it in ^{130}Te and may do
- SuperNEMO will investigate the mechanism (^{82}Se or ^{150}Nd)
- EXO-200 and KAMLAND-Zen will see it in ^{136}Xe
- SNO+ could see it in ^{150}Nd

multi-isotope searches (^{130}Te - ^{116}Cd - ^{100}Mo)

- Large scale enrichment required
- reduction of uncertainties in NME

Scenario B – The CHALLENGE:

- CUORE could marginally(but cleanly) see it in ^{130}Te clearly
- EXO and KAMLAND-Zen could see it in ^{136}Xe
- SNO++ could see it in ^{150}Nd
- GERDA phase III could see it in ^{76}Ge
- SuperNEMO could marginally see it in ^{82}Se or ^{150}Nd

discovery in more than one (at least 3 or 4) isotopes is needed in orderto confirm the observation and to improve $\langle m_{\beta\beta} \rangle$ estimate

Scenario C – The DREAM:

- new strategies must be developed
- Maybe it is worth to throww the seeds now
- upcoming experiments are the key elements to select future approaches
- large investment are mandatory

Born 75 years ago (M.Goeppert-Mayer 1935) DBD is still alive and in good shape.

End