0νDBD: Status and expectations over the next ~5 years

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European Strategy for Future Neutrino Physics, 1 Oct 2009, CERN

Outline

Introduction to $\beta\beta(0\nu)$

- Goal
- NME
- Experimental Approaches
- Sensitivity

Present Status

Short term program

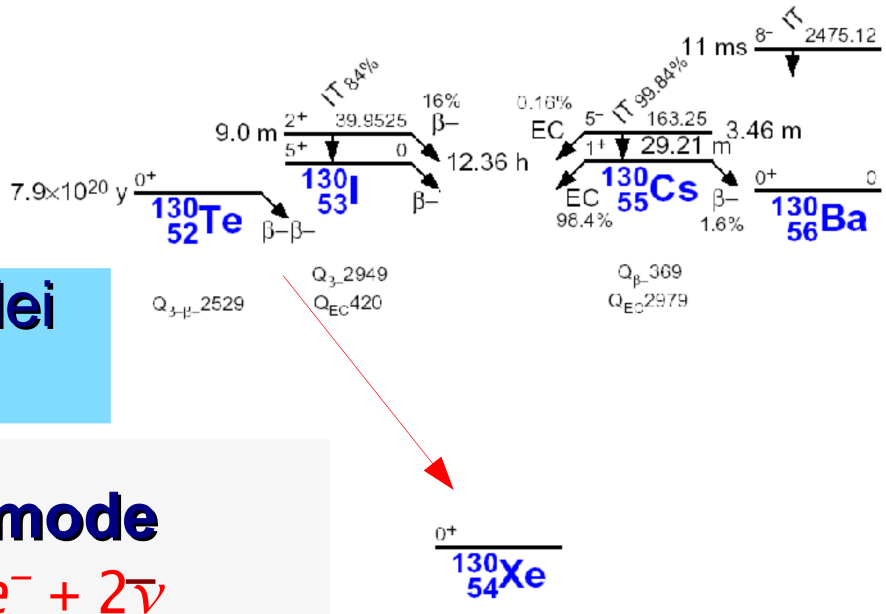
Conclusions

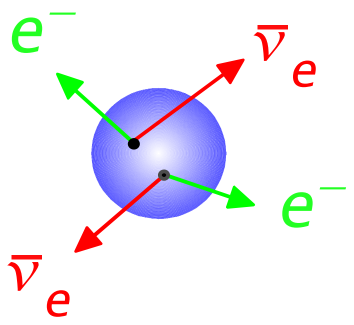
Nuclear Double Beta Decay

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

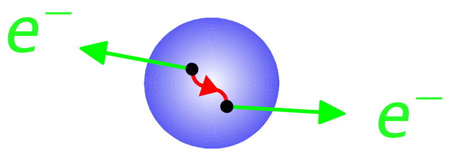
second order weak transition

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

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

not allowed in Standard Model

Neutrino nature (and mass scale)



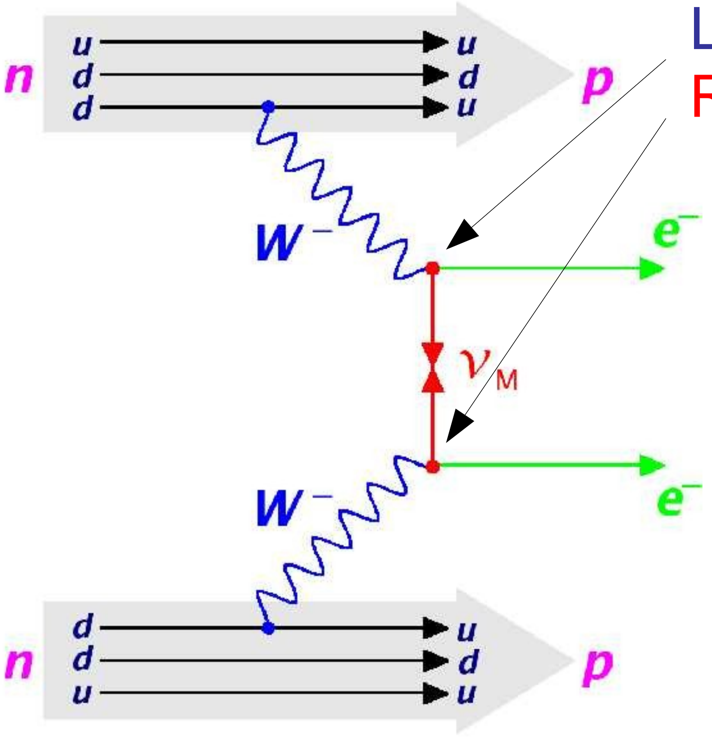
$\Delta L=2$

$$\nu = \nu^C$$

$m_\nu > 0$

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**)

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

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

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!

Neutrino mass hierarchies

Hierarchies: neutrino mass ordering scenarios compatible with neutrino oscillation experiments

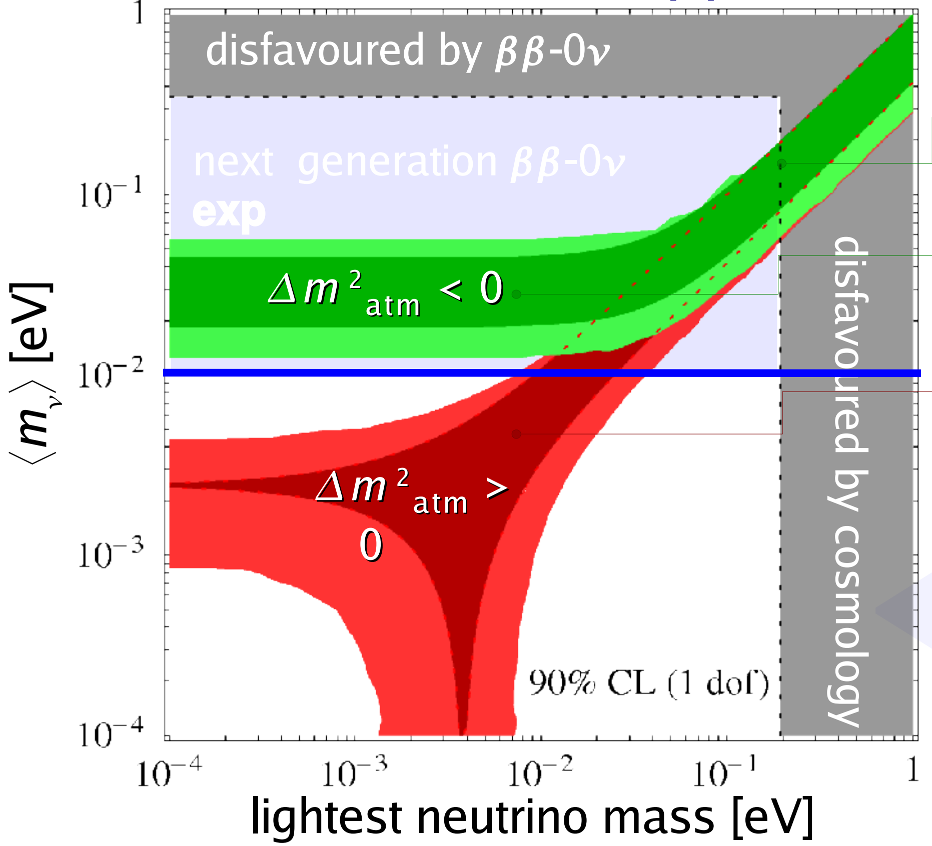
$$\langle m_\nu \rangle = f(m_{low}, U_{ek})$$

$\langle m_\nu \rangle$ can be plotted 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: $m_1 \approx m_2 \gg m_3$

Present bounds

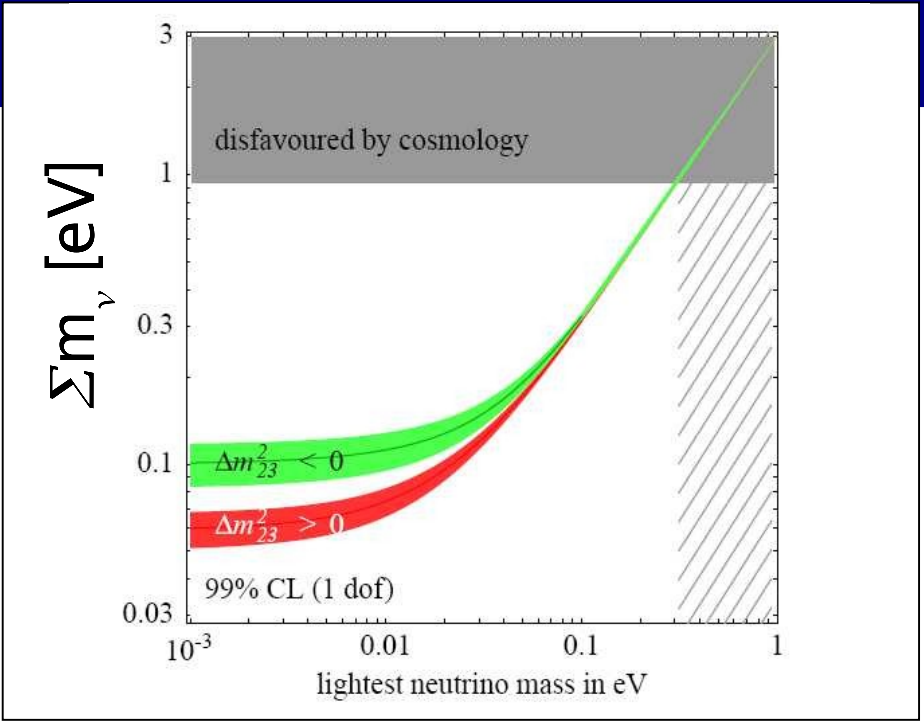
Combined informations:

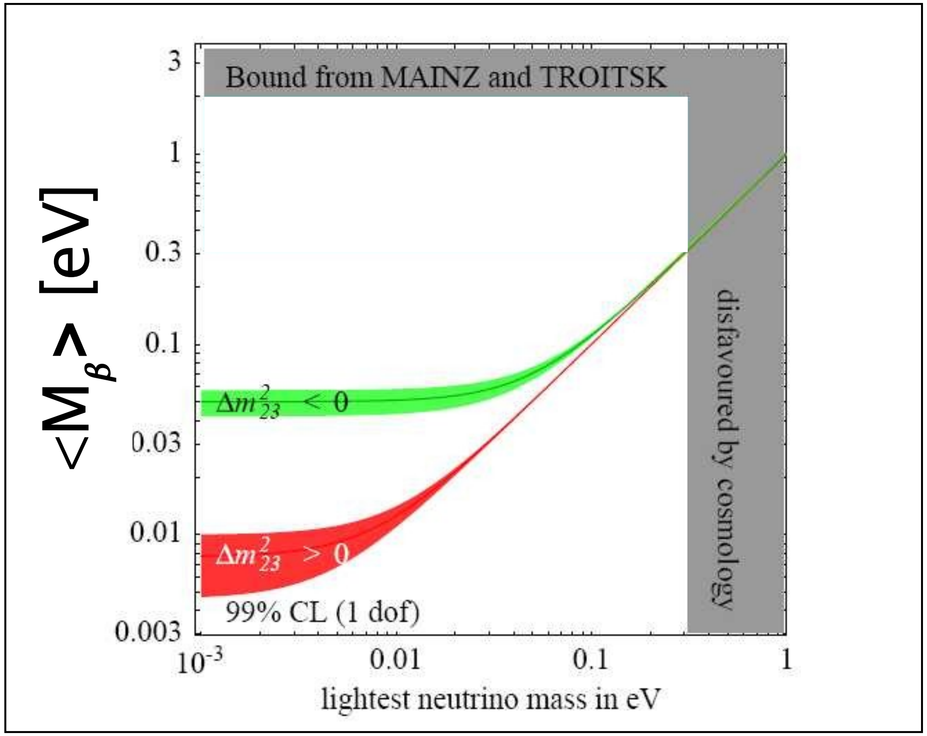
- **cosmology**
- **single β-decay**
- **double β-decay**

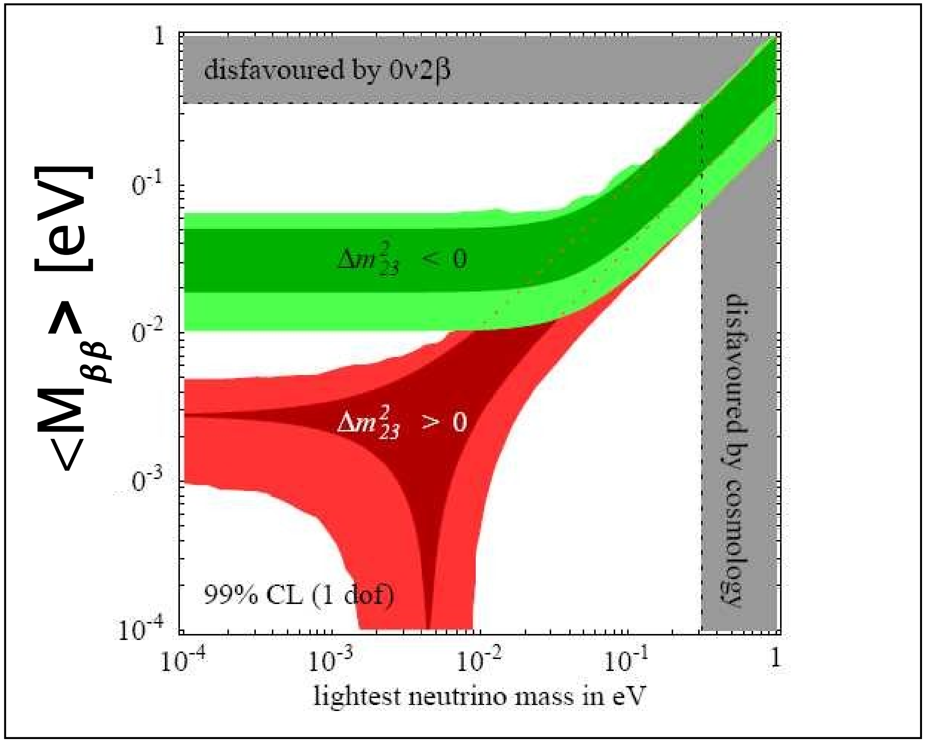
Sensitivity (eV)

Method	Present	Future
Cosmology	0.7-1.0	0.1
ββ(0ν) decay	0.5	0.05
Β-decay	2.2	0.2

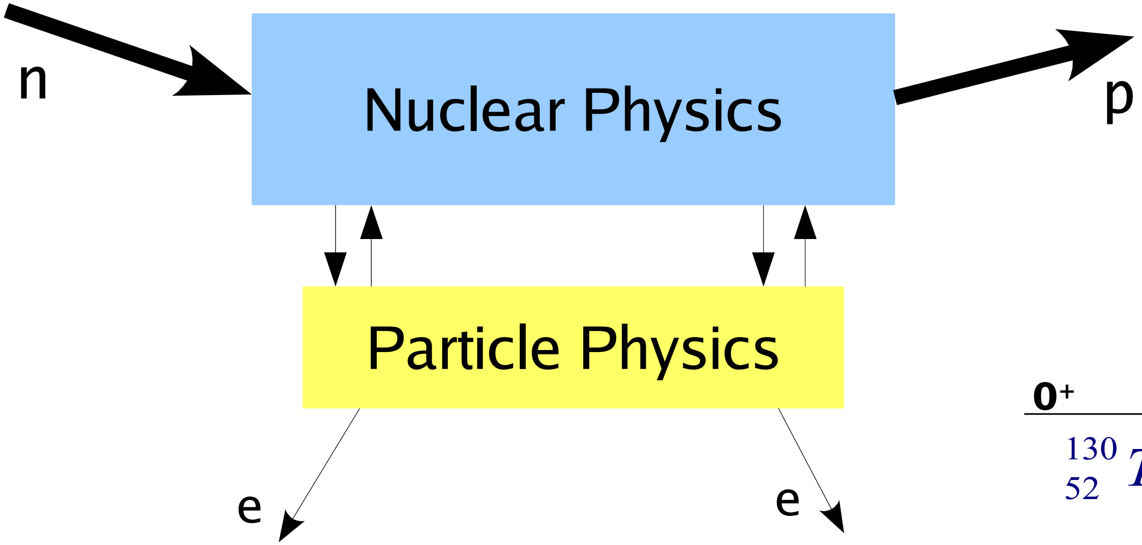
Strumia-Vissani hep-ph/0503246





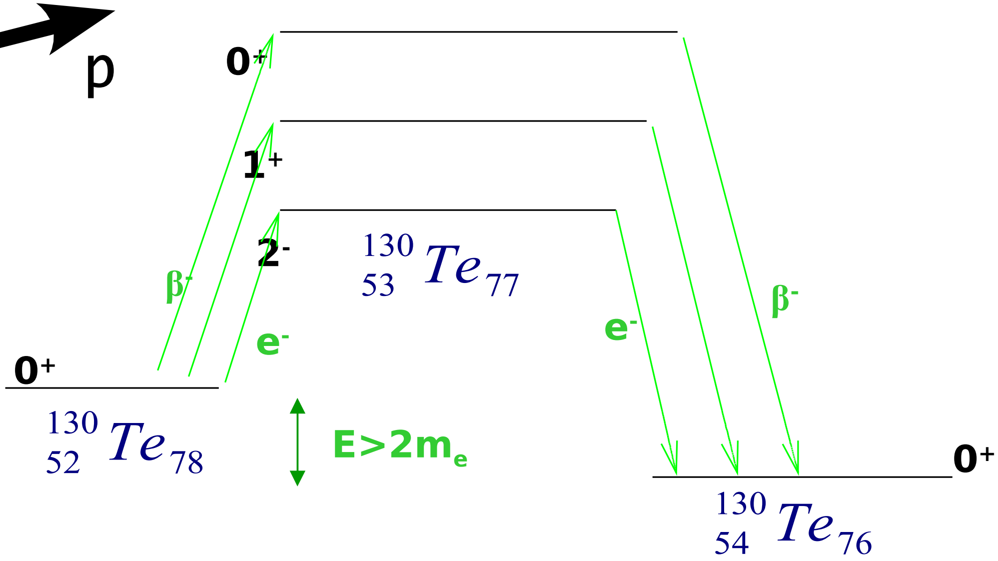


Decay rate



Nuclear Physics

Particle Physics



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

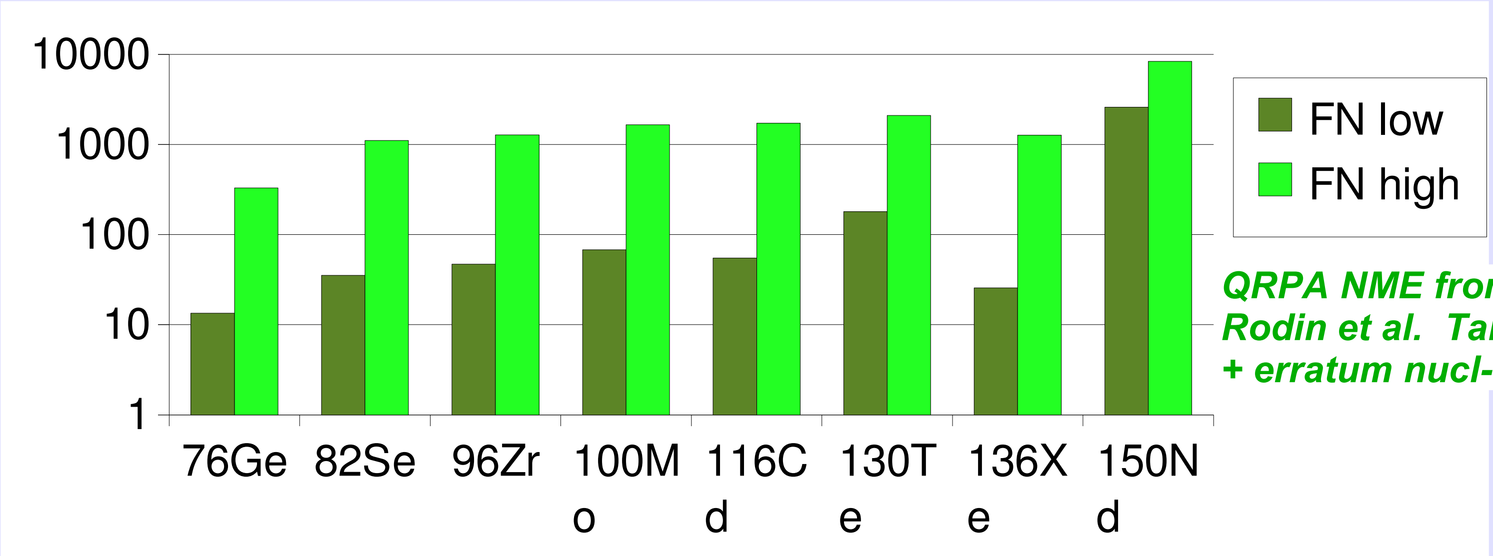
Extracting m_ν from $T_{1/2}$

$0\nu\beta\beta$ 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*

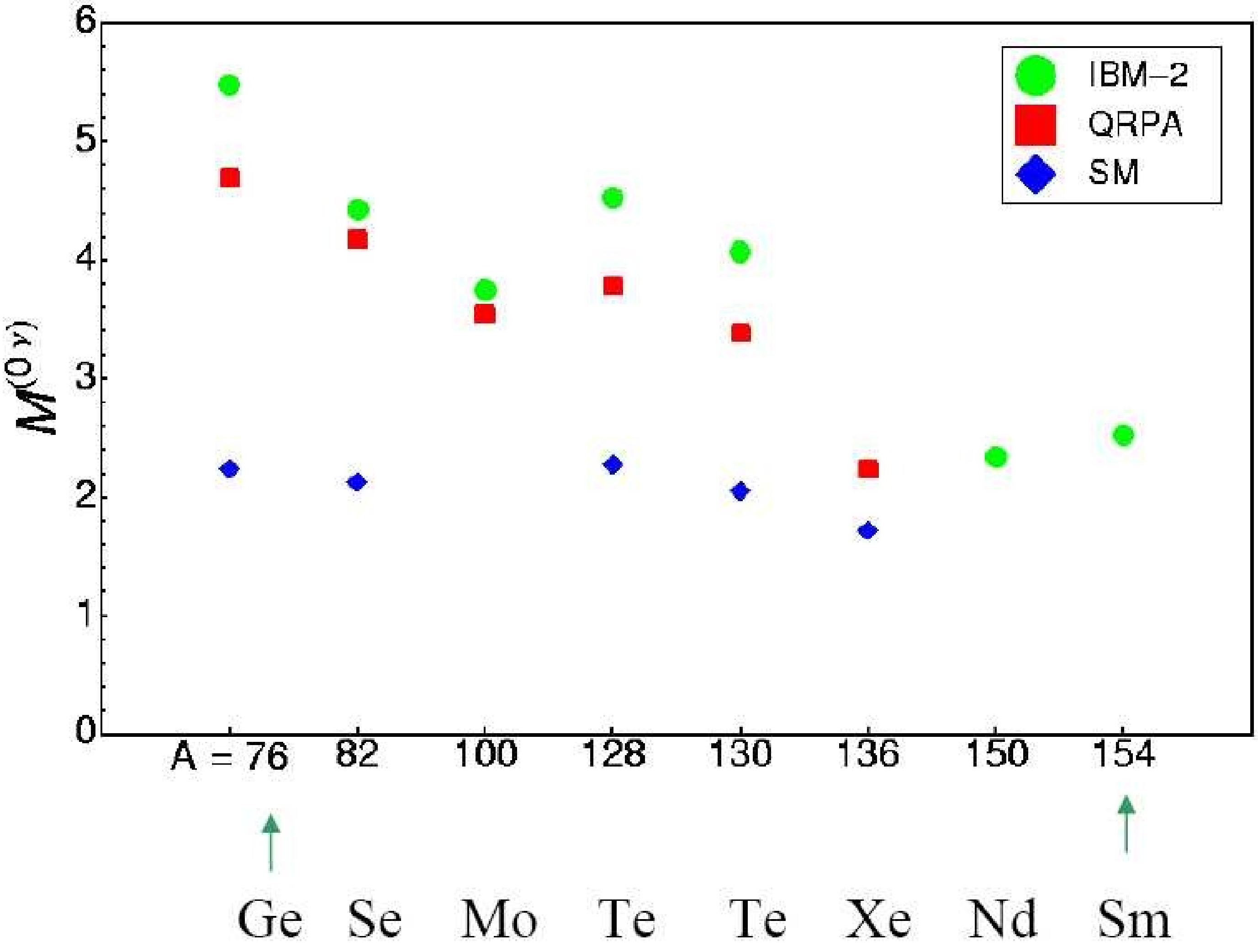
Recently …

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: MEDEX09



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.**

Nuclear Matrix Elements ... “Roadmap”

F.Iachello proposal @ MEDEX09

HOMEWORK

Goal: All model calculations within 25% (estimated error).

All methods: do a test calculation of MGT , MF , MT for ^{76}Ge-^{76}Se (GERDA) and ^{130}Te-^{130}Xe (CUORE)

- with the same assumptions for model space and for single-particle energies
- with the same values of g_A =1.25, g_V =1.00
- most importantly, with the same transition operator.

Check on the wave functions: All methods should produce spectra of initial and final nuclei and their comparison with experiment.
HOMEWORK

Check on radial integrals: Make sure that both methods, configuration space and momentum space, give the same result.

Alessandro Bettini (Padova) and Peter Grabmayr (Tübingen) will hold a joint theory-experiment workshop at the Gran Sasso Laboratory (LNGS) in March 2010 to discuss the results of this homework.

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

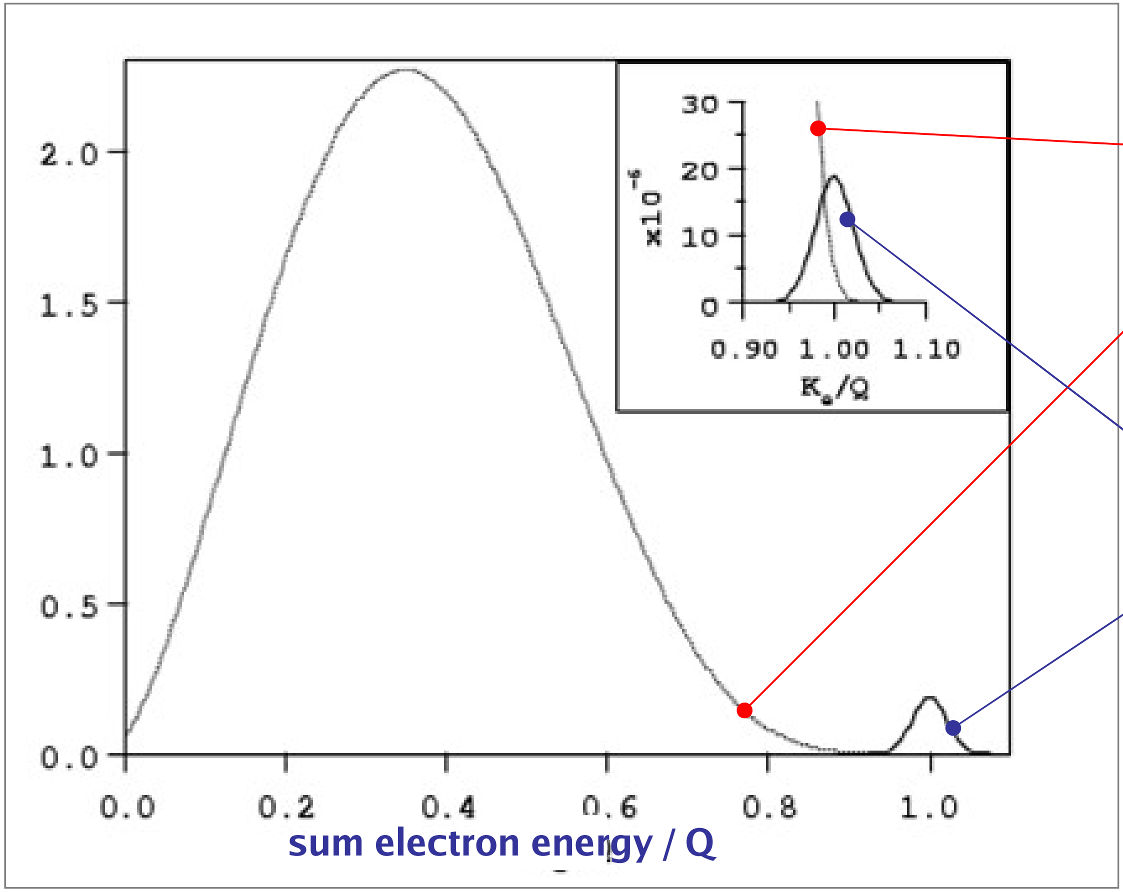
Daughter ion (A,Z+2)

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

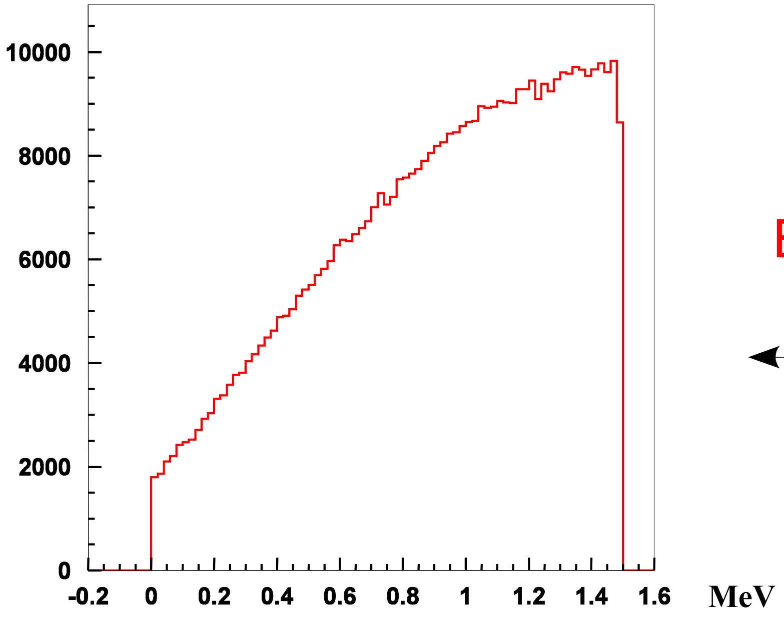
neutrinoless DBD
peak enlarged only by
the detector energy resolution

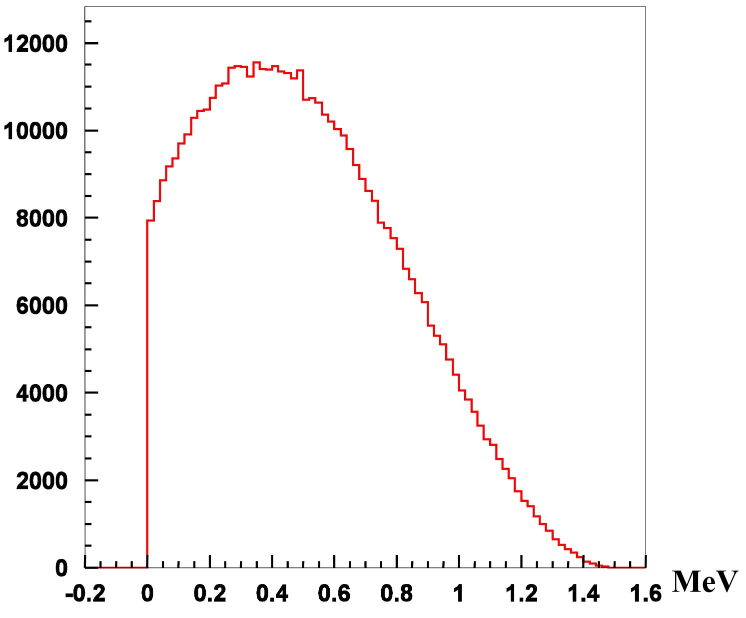
Most promising nuclides
Q ~ 2-3 MeV

DBD: single electron distributions

Light neutrino exchange

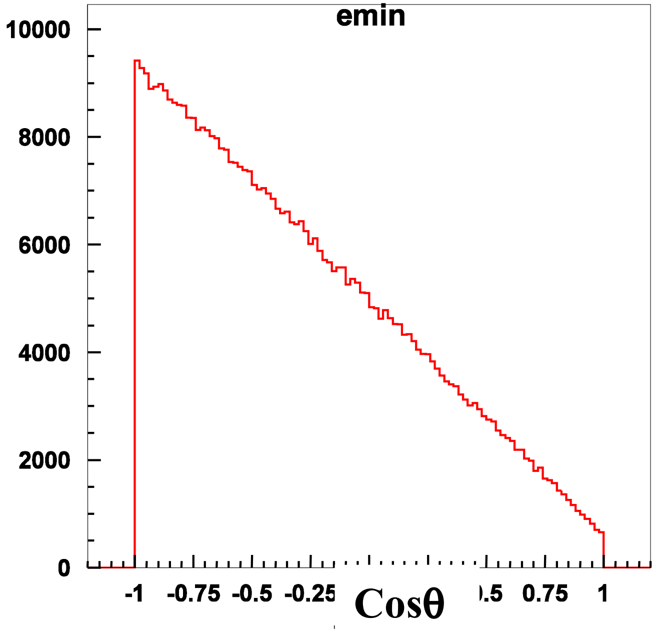
V+A current

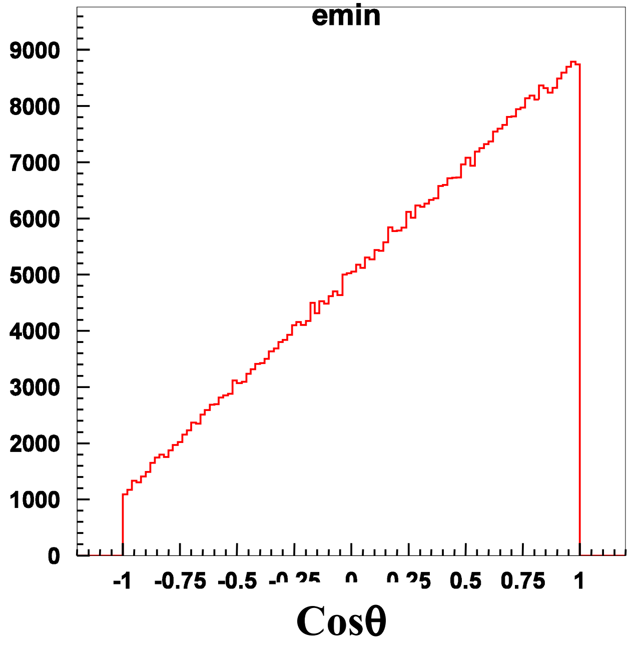




Electron minimum energy spectrum

↔





Angular distribution between the 2 electrons

↔

Experimental rate and sensitivity

Experimental $\beta\beta$-0ν rate

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

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

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]

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

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

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

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

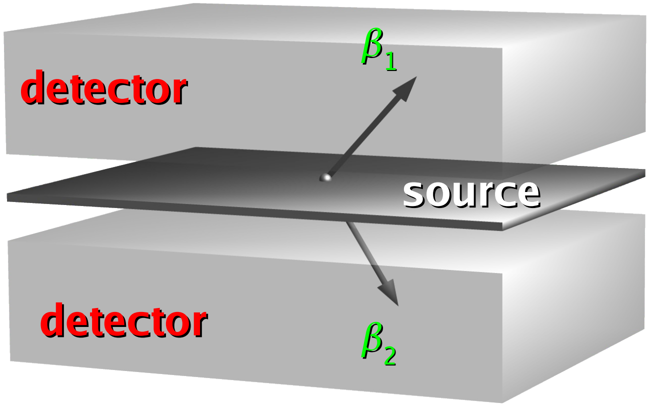
for $bkg = 0$, at 1σ

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

Crucial parameters:

- ○ **Isotopical abundance**
- ○ **Mass**
- ○ **Energy resolution**
- ○ **Background level**

Inhomogeneous approach



Source ≠ Detector

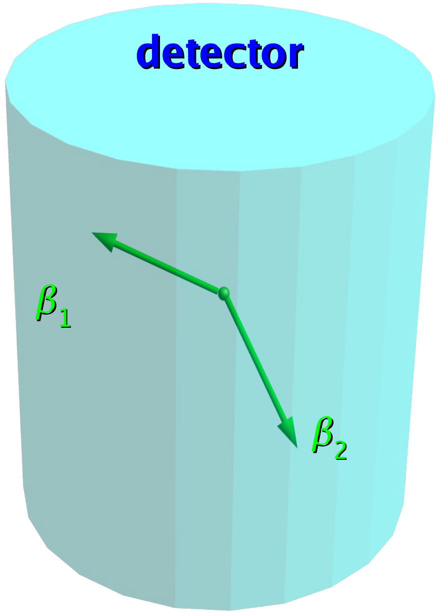
- scintillation
- gaseous TPC
- gaseous drift chamber
- magnetic field and TOF

☺ 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**

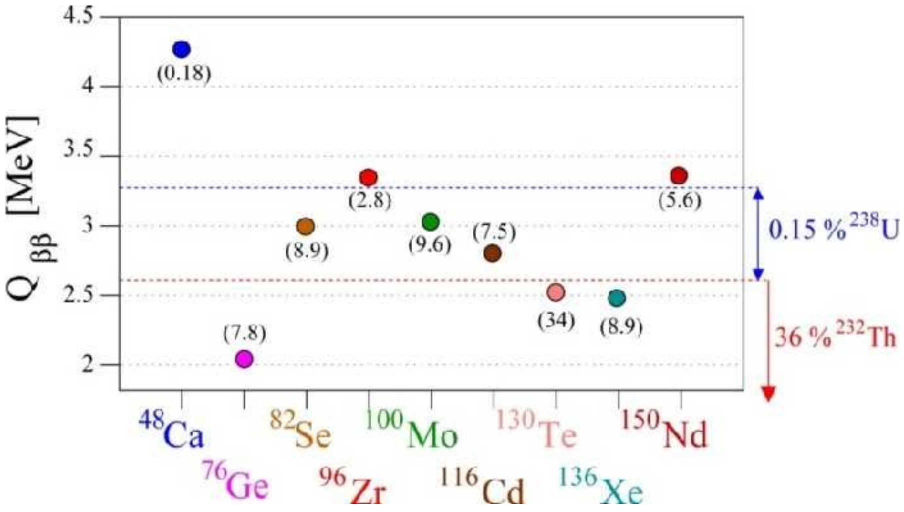
Ge-diodes
Bolometers

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

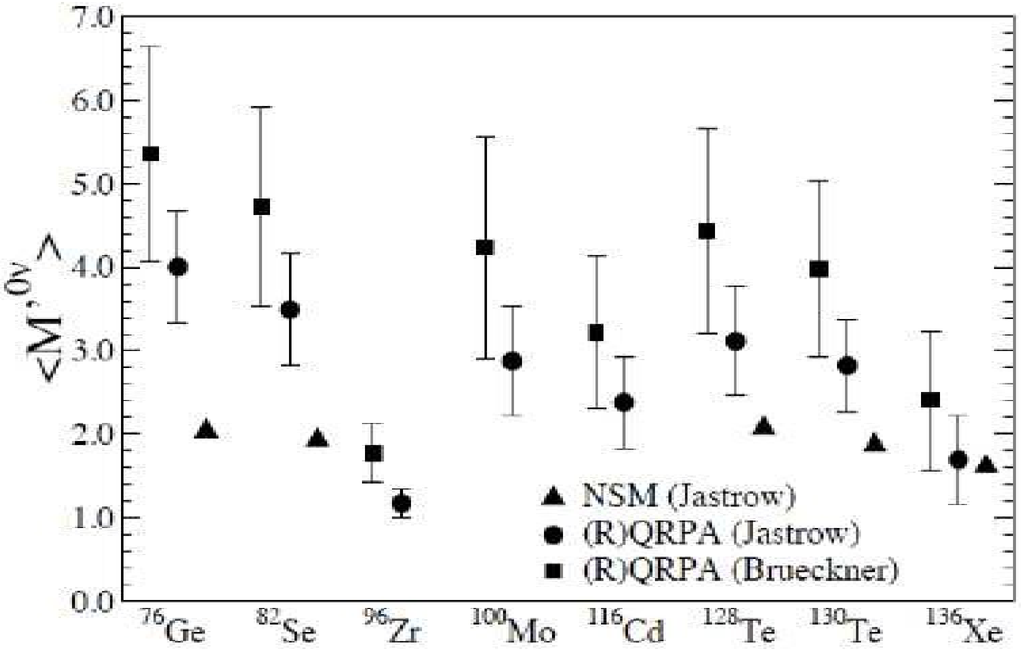
☹ often contrasting requests

Choice of the isotope

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

NEMO3 (running)

intermediate generation experiment capable to study different isotopes

CUORICINO (stopped in june 2008)

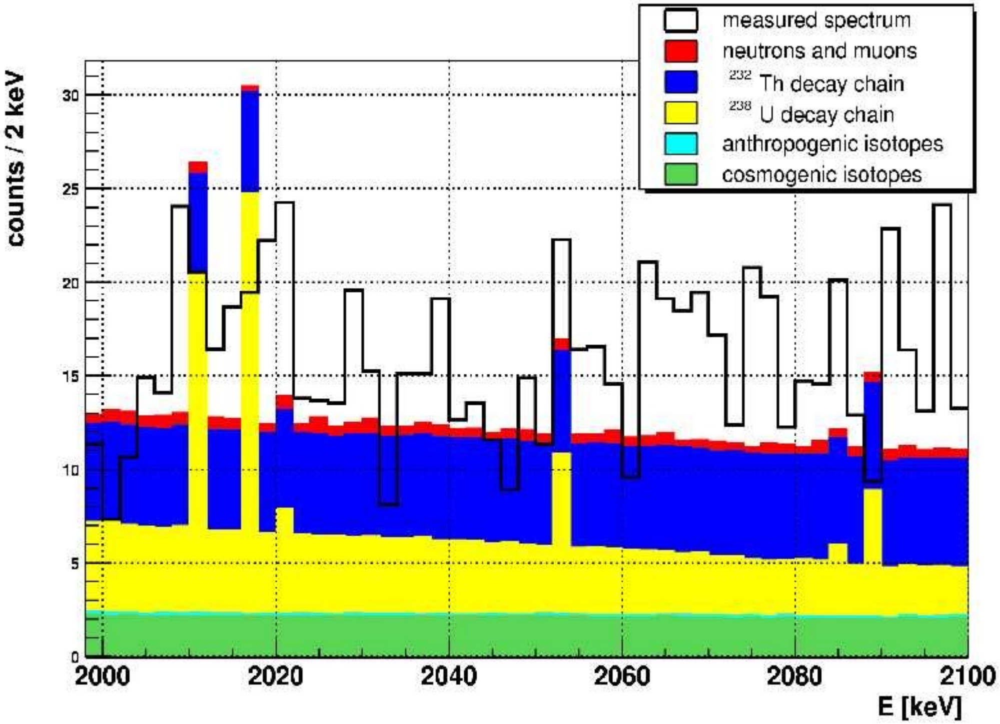
intermediate generation experiment based on the bolometric technique.
Demonstator of CUORE

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	3.6	> 3.6 x 10^{23}
^{100}Mo	Tracking	NEMO3	Mo	26.6	> 1.1 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	18	> 2.94 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 detectors
- digital Pulse ShapeAnalysis(PSA)



1990 – 2001 data

exposure = 35.5 kg×y SSD

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

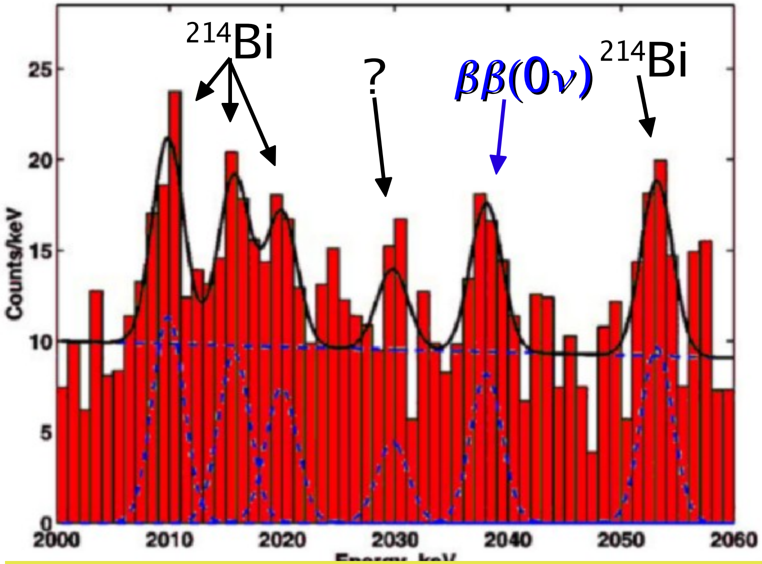
$\langle m_\nu \rangle < 0.35$ eV (0.3 – 1.24 eV)

H.V.Klapdor-Kleingrothaus *et al.*, Eur. Phys. J. A12 (2001) 147

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

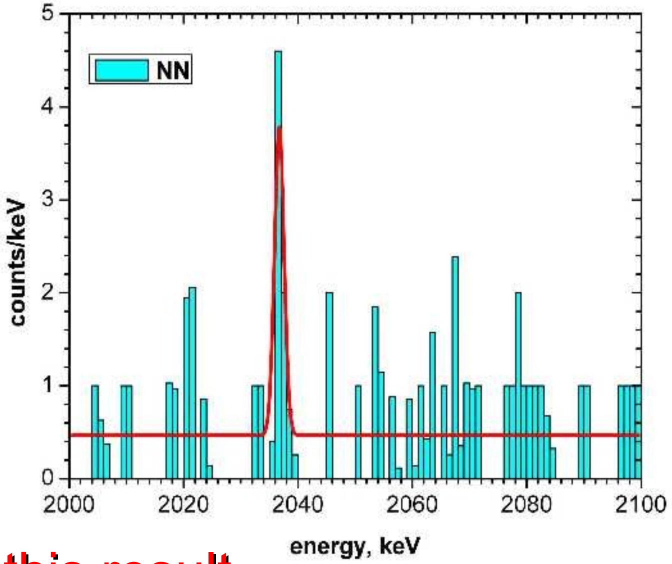
1995-2003 data new re-analysis:

SSE selection by MC & ANN

6.4σ signal

7.05 ± 1.11 events

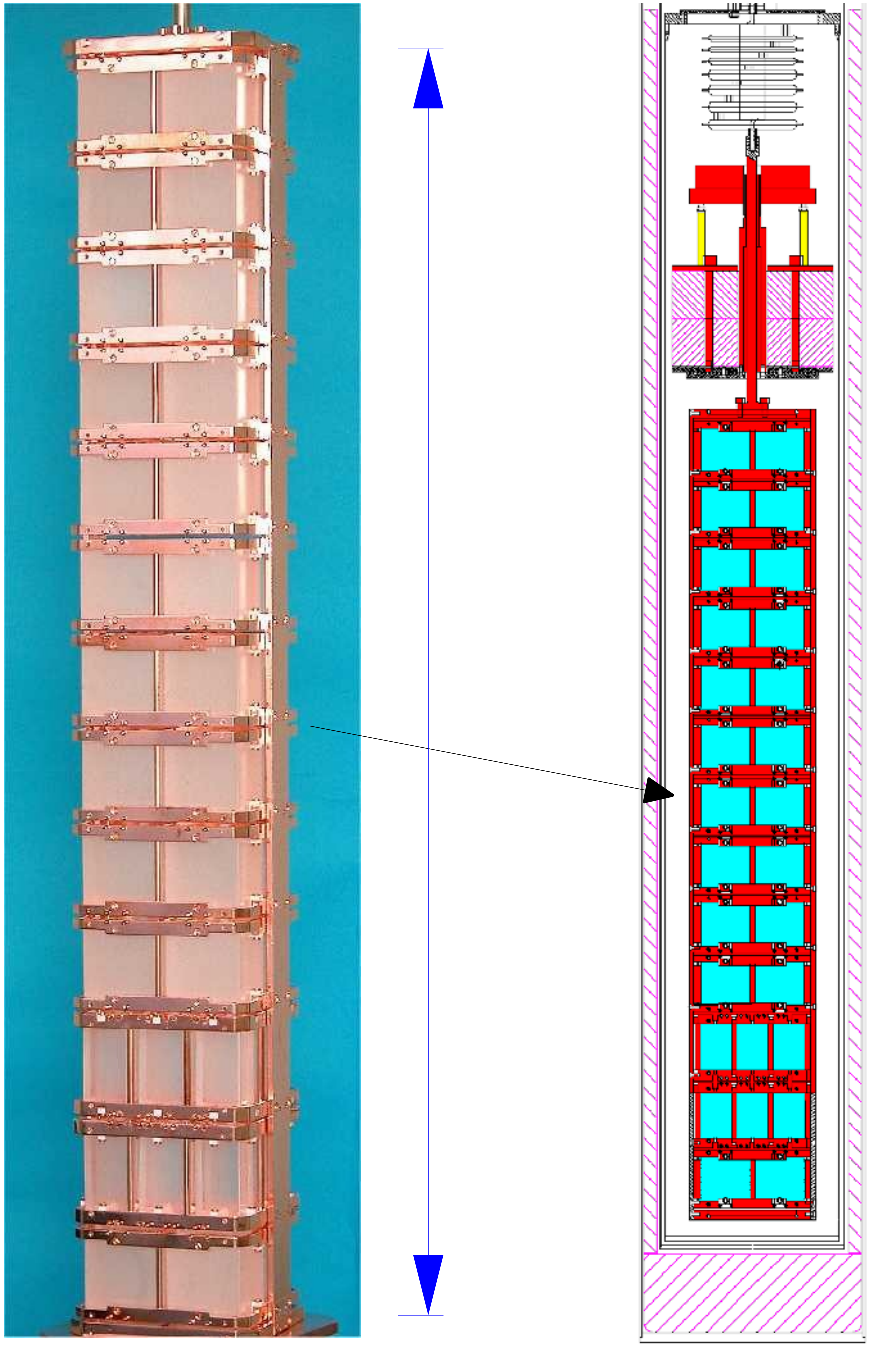
$2.23^{+0.44}_{-0.31}$ 10^{25} years / 0.32±0.03 eV



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

all future experiment will certainly have to cope with this result

CUORICINO



Cuoricino *tower*: 62 TeO_2 crystals

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

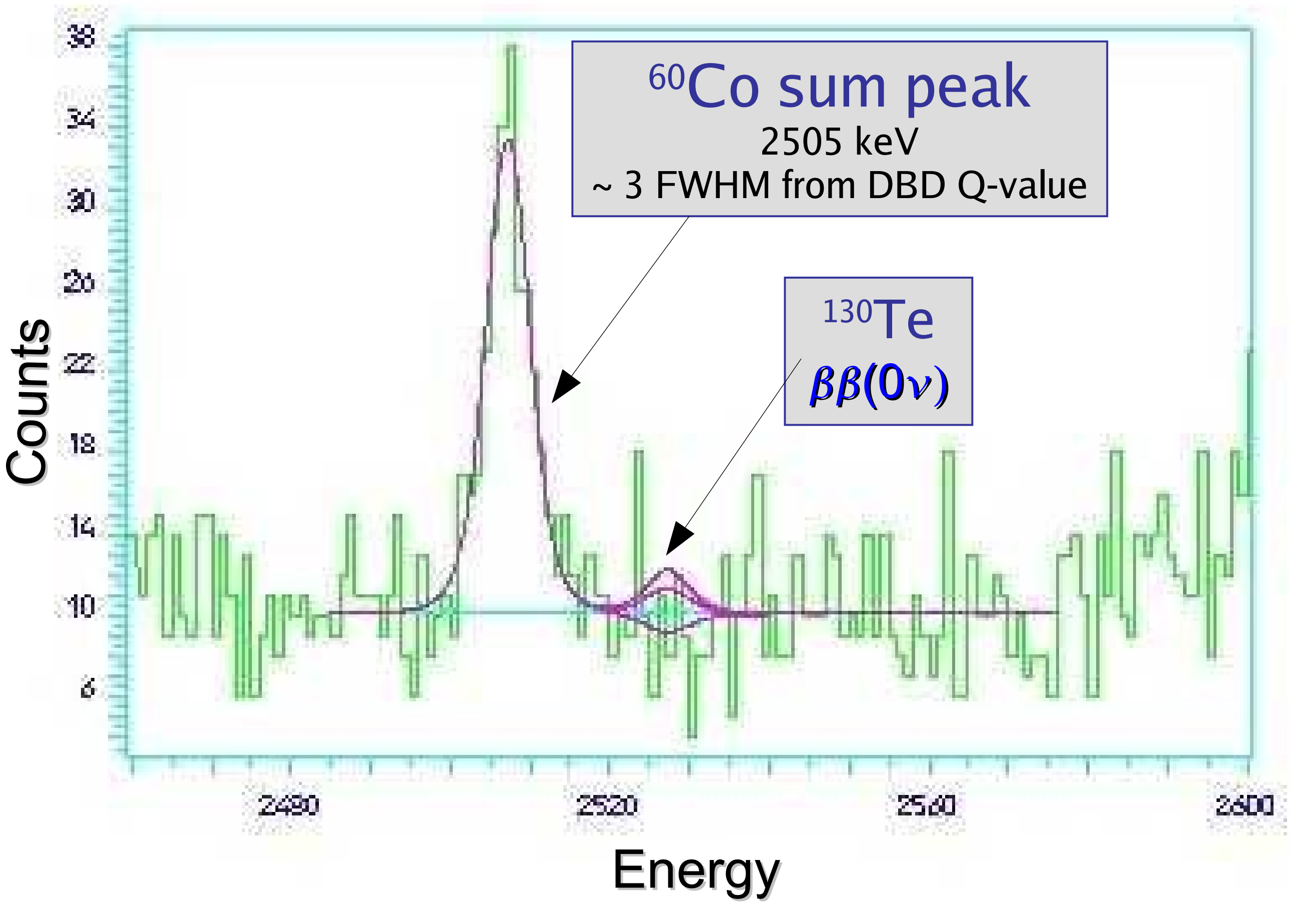
- low heat capacity
- large crystals available
- radiopure

- **intermediate size $\beta\beta$ experiment**
- **important test for**
- **radioactivity**
- **performance of large LTD arrays**

CUORICINO results

- total statistics 18 kg×y
- average energy resolution FWHM $\Delta E = 7.5$ 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)**



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

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

Statistics [yr * kg^{130}Te]	**Q value [keV]**	**Limit [yr] 90% C.L.**
18	2527.2	**2.94 10^{24}**

$\langle m_\nu \rangle \leqslant 0.20 \div 0.68$ eV

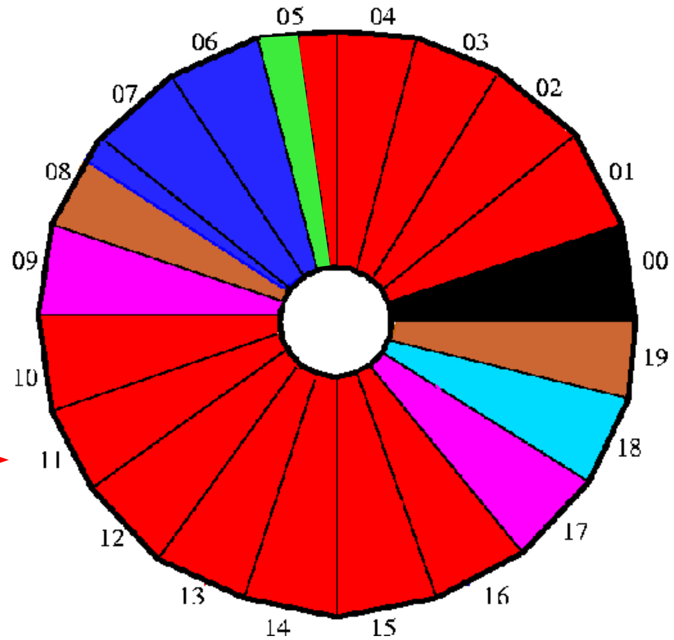
NME from the review table of QRPA calculation in Rodin et al Nucl. Phys. A 766,107 (2006) and nucl-th:0706.4304v1

stopped in June 2008
and disassembled

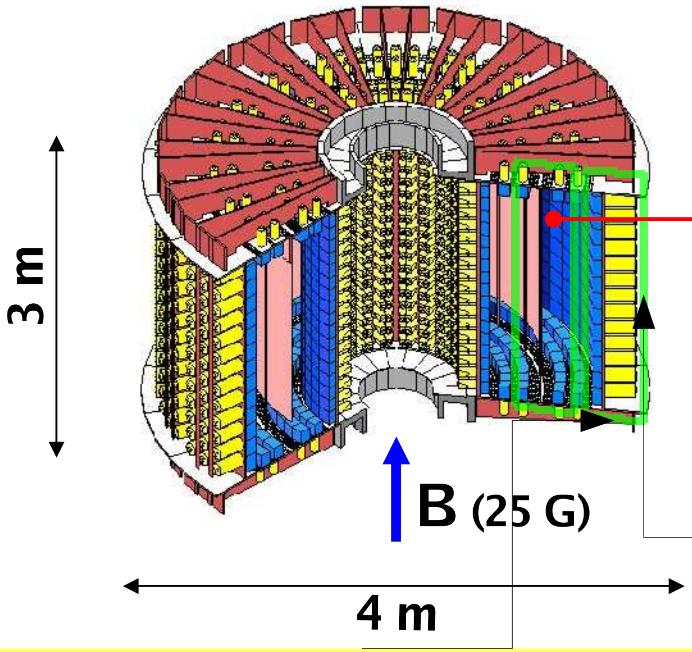
NEMO-3

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

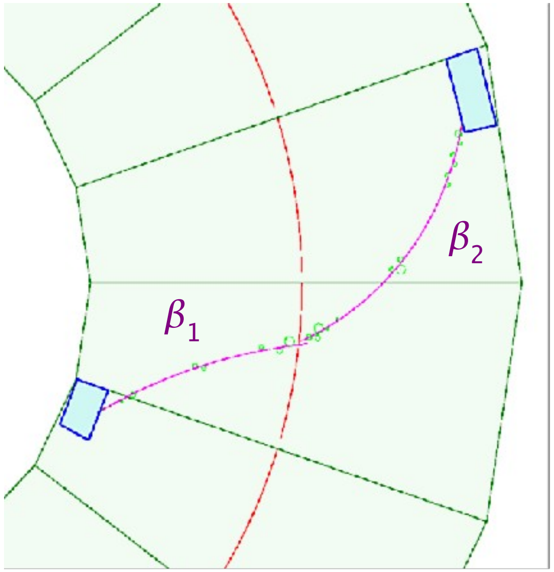


sources in foils



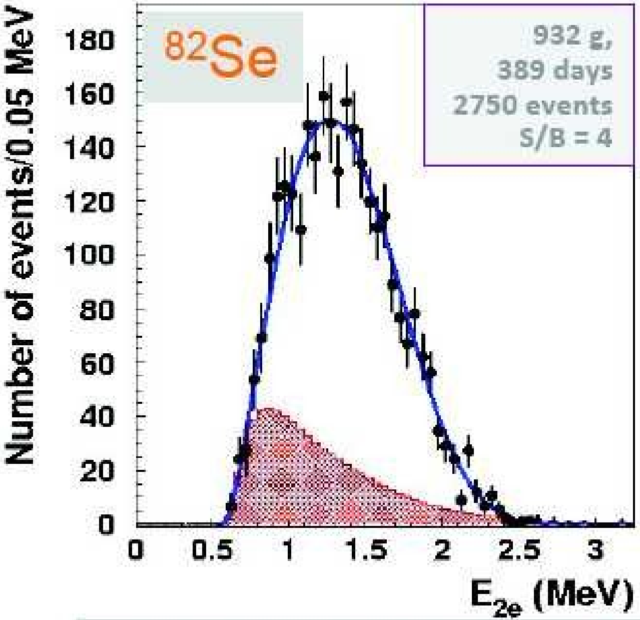
tracking volume (drit wire chamber)

calorimeter (scintillators)

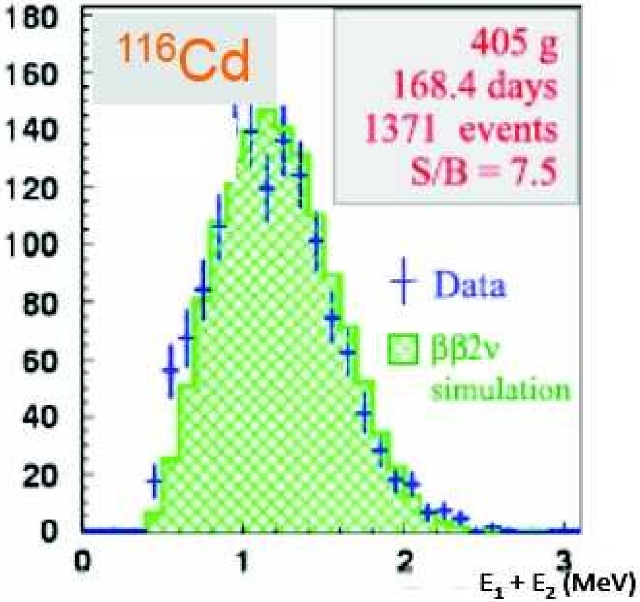


^{100}Mo	(6.9 kg)	➡ $\beta\beta$-0ν
^{82}Se	(0.9 kg)	
^{130}Te	(0.45 kg)	
^{116}Cd	(0.4 kg)	
^{150}Nd	(37g)	
^{96}Zr	(9.4 g)	
^{48}Ca	(7.0g)	
^{nat}Te	(0.5 kg)	
Cu	(0.6 kg)	

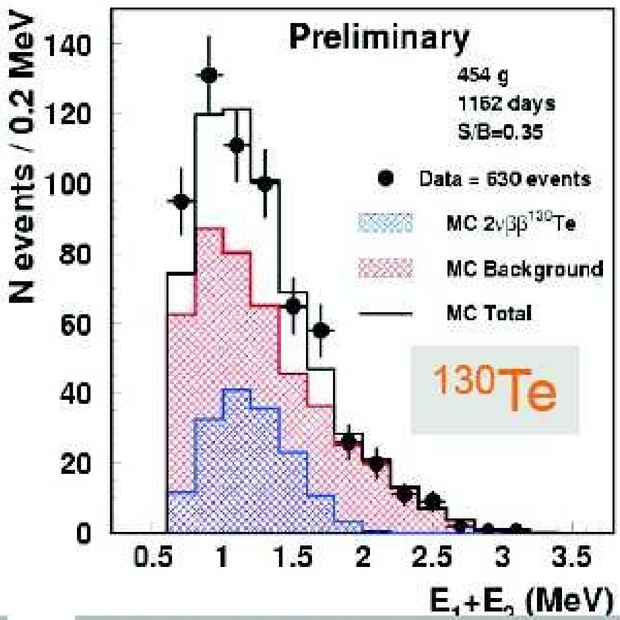
NEMO-3: a unique tool to study ββ(2ν)



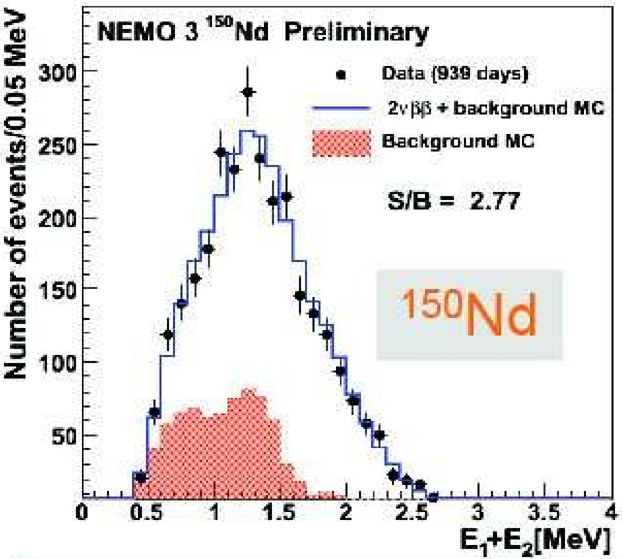
9.6 ± 0.3 (stat) ± 1.0 (sys) 10^{19} y



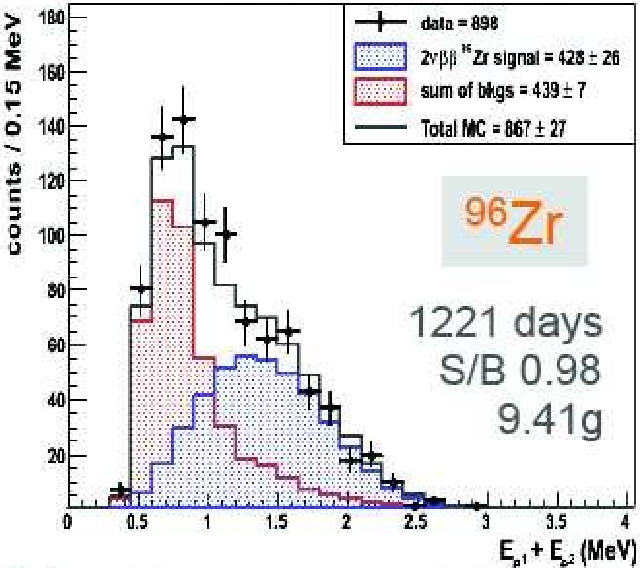
2.8 ± 0.1 (stat) ± 0.3 (sys) 10^{19} y



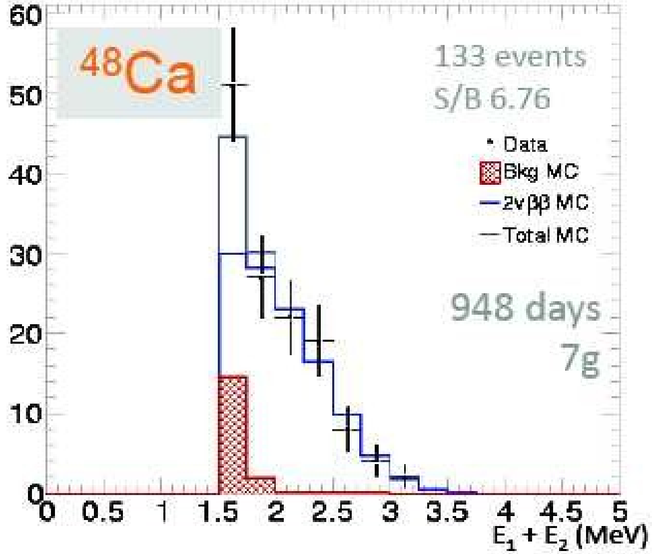
6.9 ± 0.9 (stat) ± 1.0 (sys) 10^{20} y



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

NEMO-3 $\beta\beta(0\nu)$ results

Isotope	Exposure (kg·y)	$T_{1/2}(0\nu\beta\beta)$ [years]	$\langle m_\nu \rangle$ [eV]	NME reference
^{100}Mo	26.6	$> 1.1 \cdot 10^{24}$	**< 0.45 – 0.93**	1-3
^{82}Se	3.6	$> 3.6 \cdot 10^{23}$	**< 0.9 – 1.6** **< 2.3**	1-3 7
^{150}Nd	0.095	$> 1.8 \cdot 10^{22}$	**< 1.5 – 2.5** **< 4.0 – 6.8**	4,5 6
^{130}Te	1.4	$> 9.8 \cdot 10^{22}$	**< 1.6 – 3.1**	2,3
^{96}Zr	0.031	$> 9.2 \cdot 10^{21}$	**< 7.2 – 19.5**	2,3
^{48}Ca	0.017	$> 1.3 \cdot 10^{22}$	**< 29.6**	7

Nuclear Matrix Elements references:

[1] M.Kortelainen and J.Suhonen, Phys.Rev. C 75 (2007) 051303(R)

[2] M.Kortelainen and J.Suhonen, Phys.Rev. C 76 (2007) 024315

[3] F.Simkovic, et al. Phys.Rev. C 77 (2008) 045503

[4] V.A. Rodin et al. Nucl.Phys. A 793 (2007) 213

[5] V.A. Rodin et al. Nucl.Phys. A 766(2006) 107

[6] J.H.Hirsh et al. Nucl.Phys. A 582(1995) 124

[7] E.Caurrier et al. Phys.Rev.Lett 100 (2008) 052503

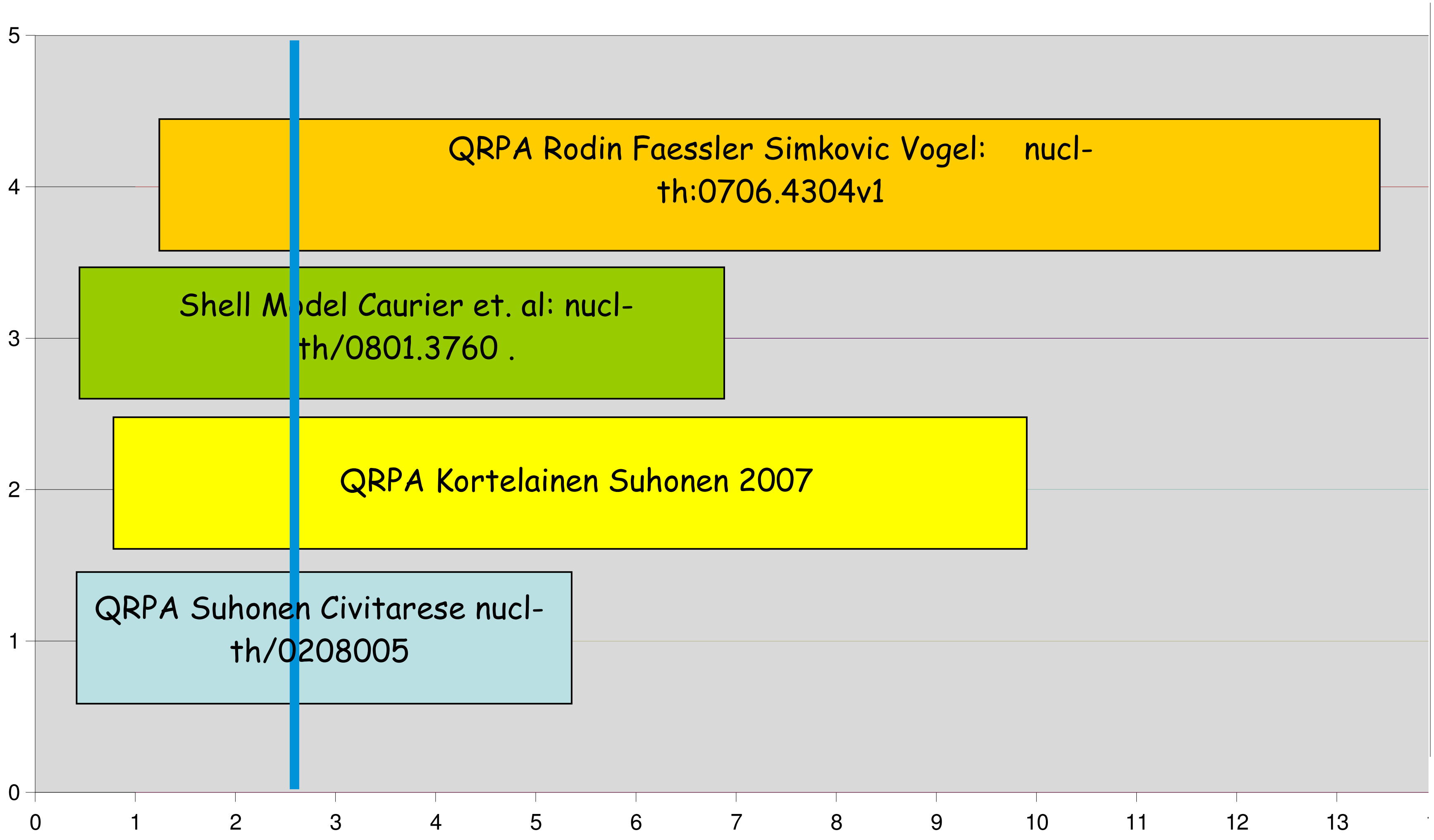
HM claim: CUORICINO 3σ

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

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

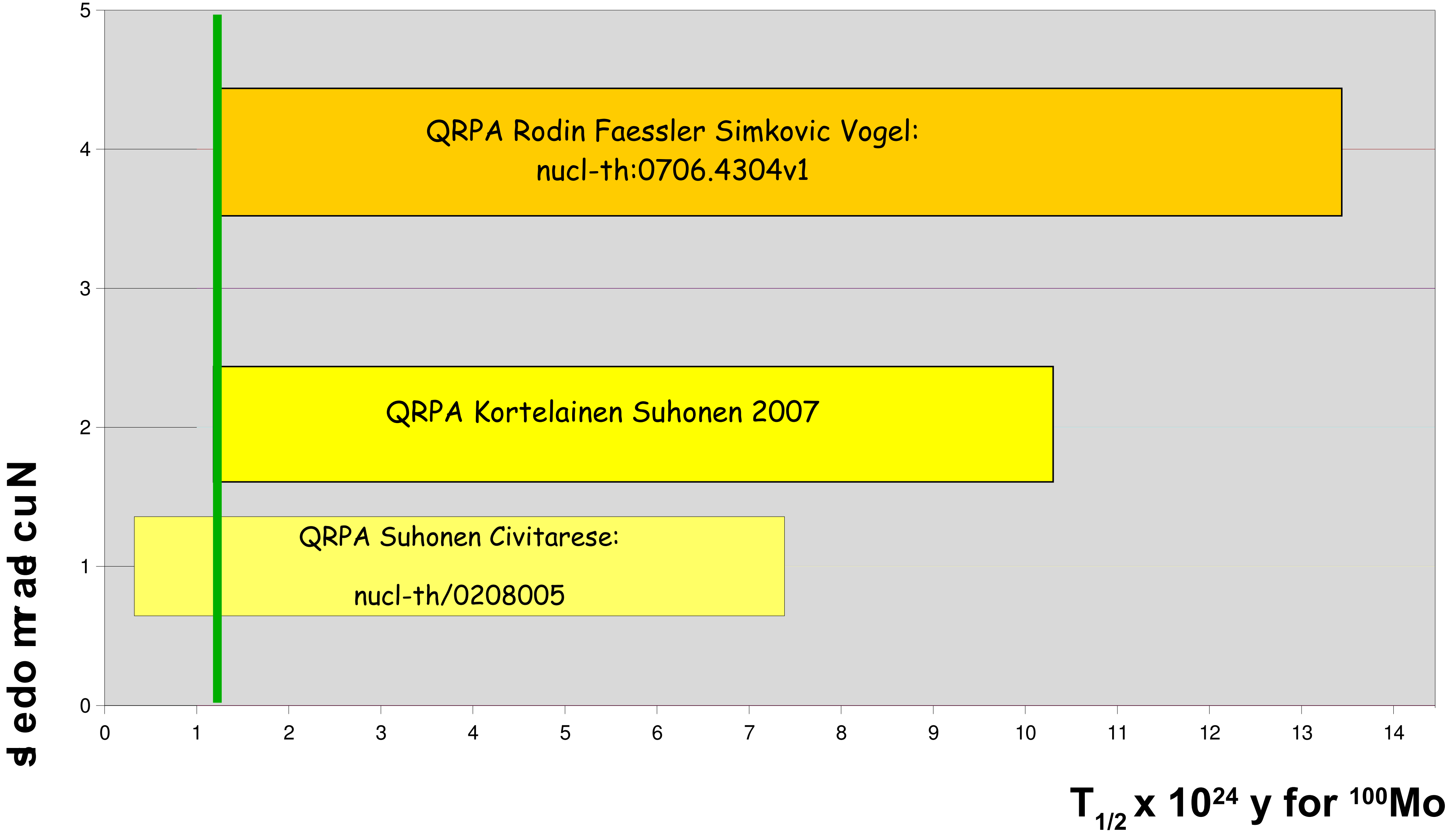
→

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



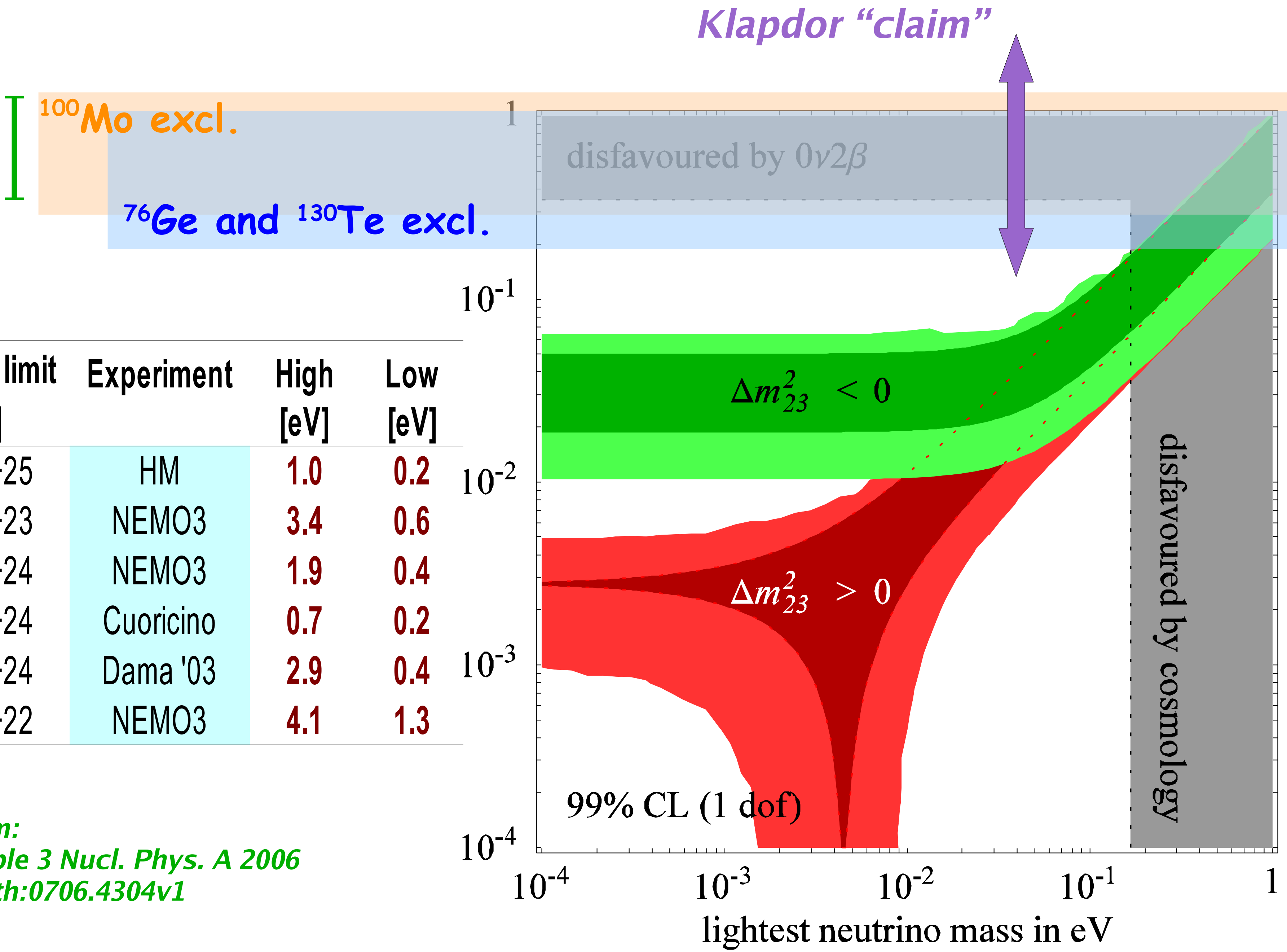
$T_{1/2}$ x 10^{24} y for ^{130}Te

HM claim: NEMO3 90%CL



Present situation

NME uncertainty



Isotope	τ 90% limit [y]	Experiment	High [eV]	Low [eV]
^{76}Ge	1.9E+25	HM	1.0	0.2
^{82}Se	3.6E+23	NEMO3	3.4	0.6
^{100}Mo	1.1E+24	NEMO3	1.9	0.4
^{130}Te	2.9E+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

Goals of next generation 0ν-DBD experiments

- **sensitivities of few 0.01 eV on $\langle m_\nu \rangle$**
  - hierarchy problem solution
  - 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**

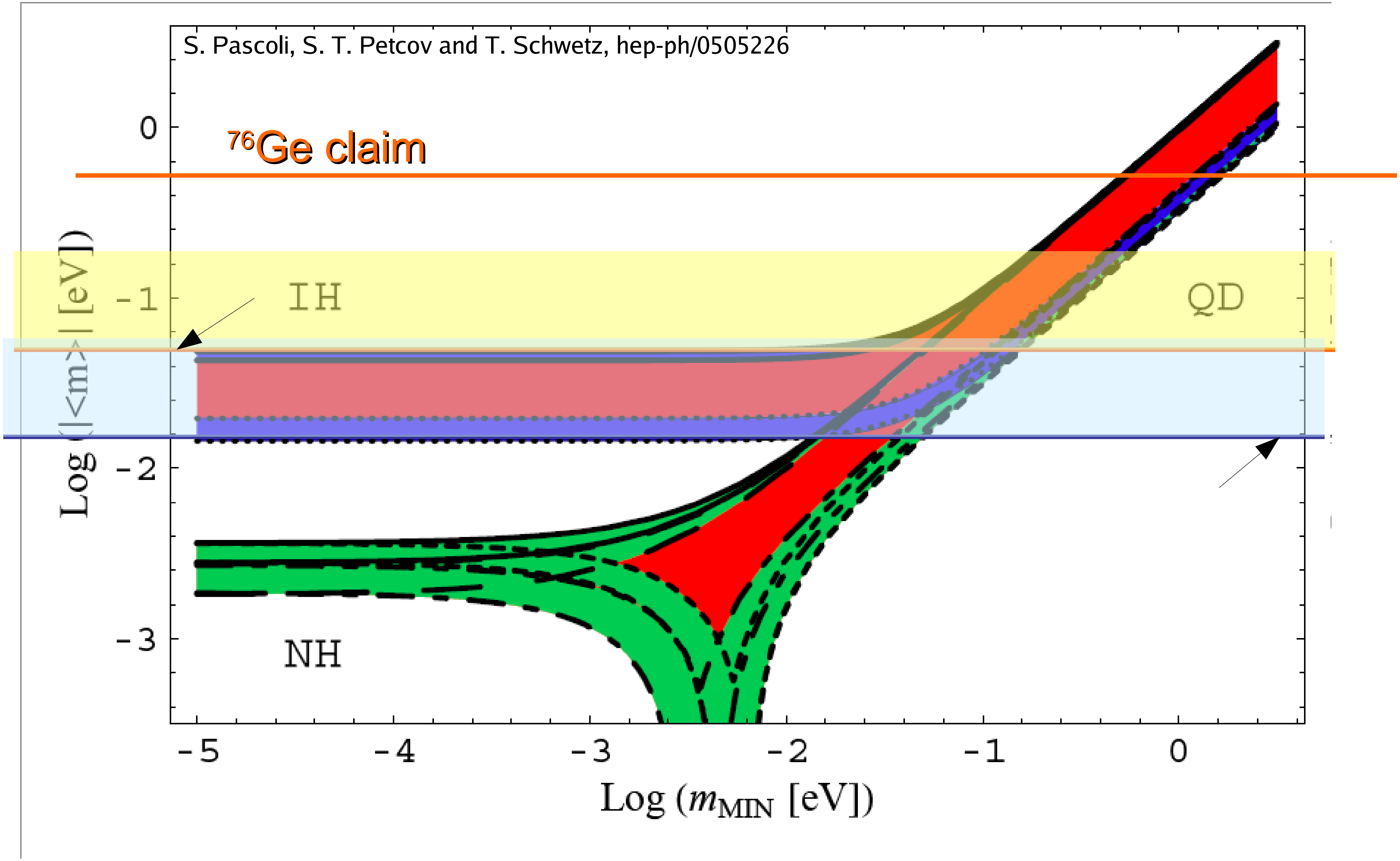
increase isotopic abundance by enrichment

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

increase experimental mass

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

Expectations



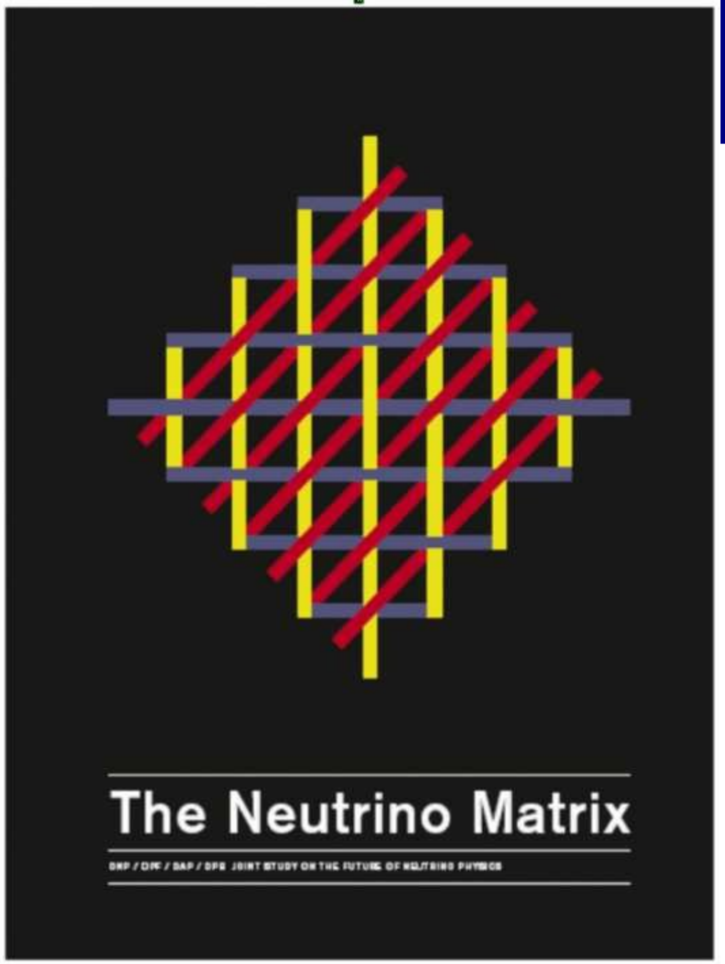
THE INTERNATIONAL 0ν-DBD STRATEGY

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.



The Neutrino Matrix

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.

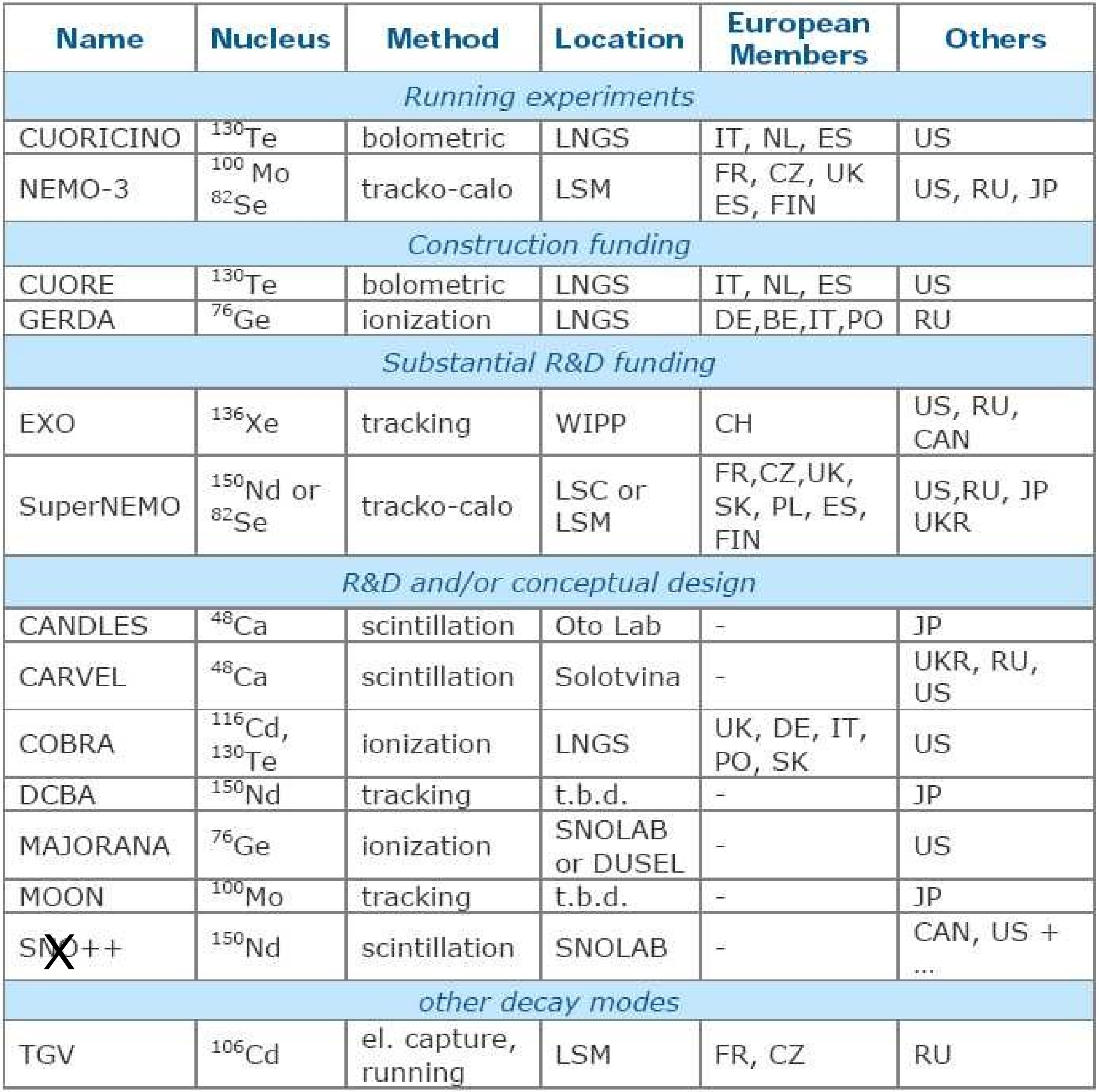
ASPERA roadmap

PHASED PROGRAM

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

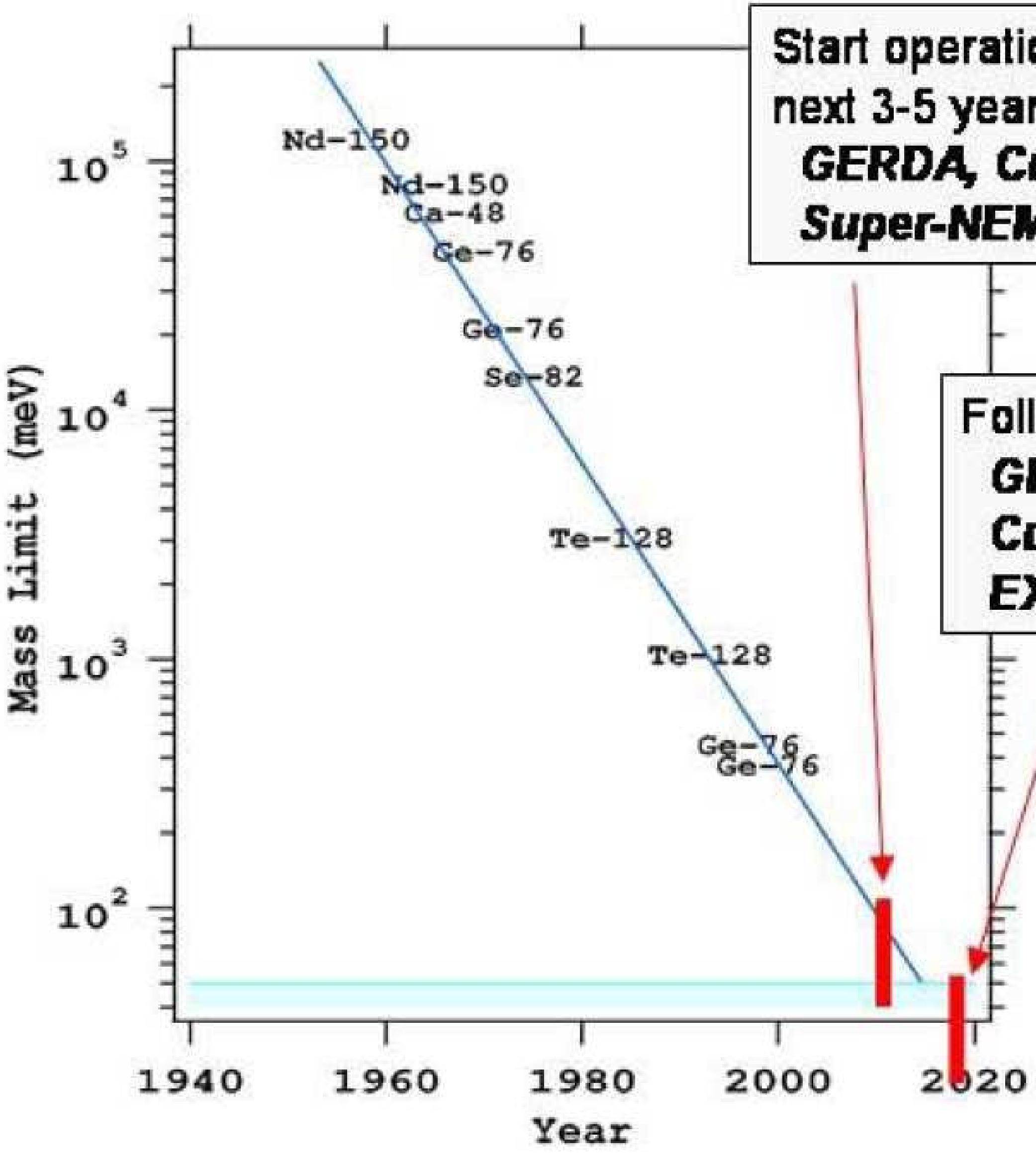
KAMLAND (Xe)
SNO+ (Nd)

LS @ LNGS (Nd)



Name	Nucleus	Method	Location	European Members	Others
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
SN~~O~~X++	^{150}Nd	scintillation	SNOLAB	-	CAN, US + …
other decay modes					
TGV	^{106}Cd	el. capture, running	LSM	FR, CZ	RU

ASPERA roadmap

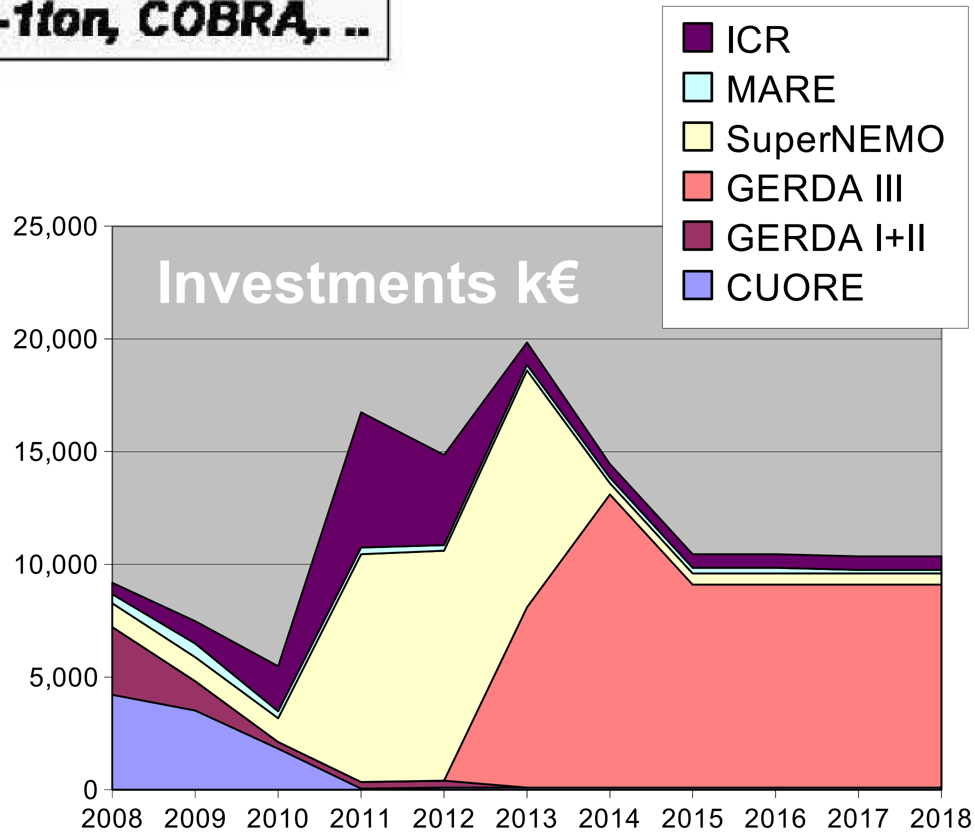


Start operation within next 3-5 years:

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.

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

IN EUROPE

LNGS

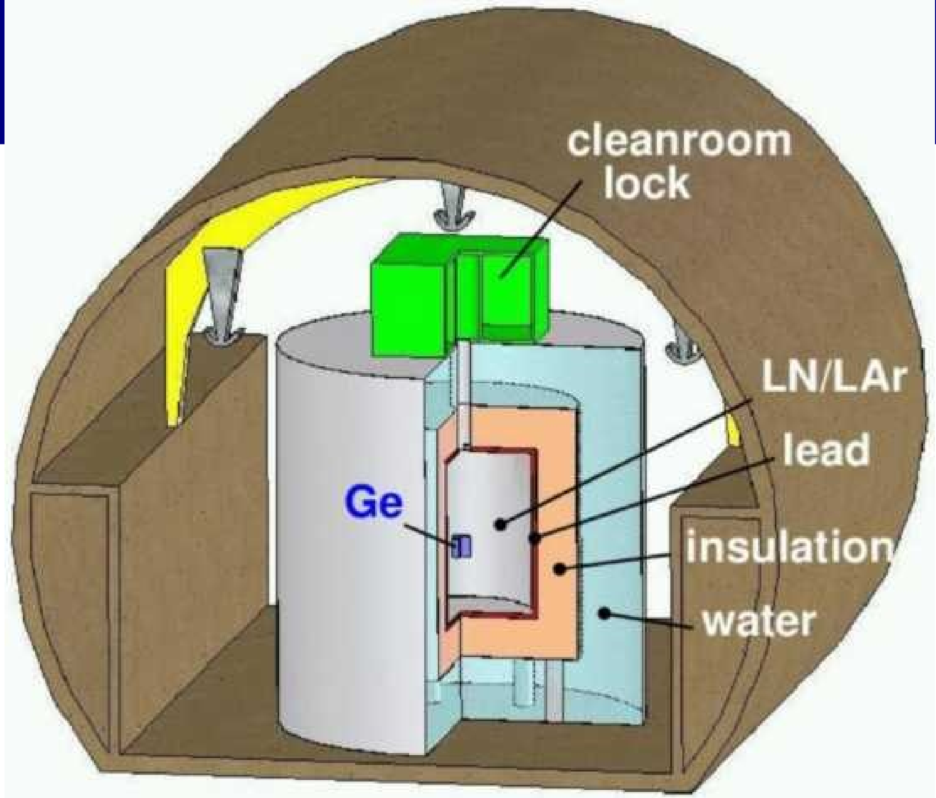
GERDA

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)

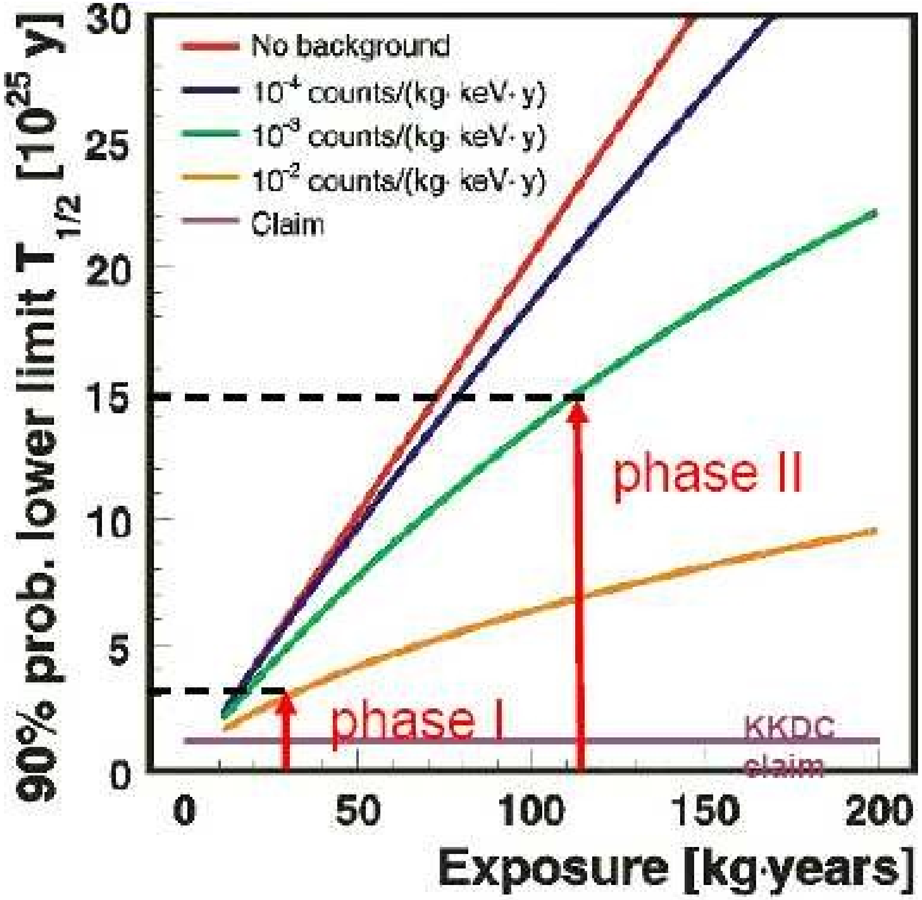
- Background: 0.001 counts / keV kg y
- Sensitivity after 100 kg y (~3 years): 2×10^{26} y ($\langle m_\nu < 90 - 290$ meV)

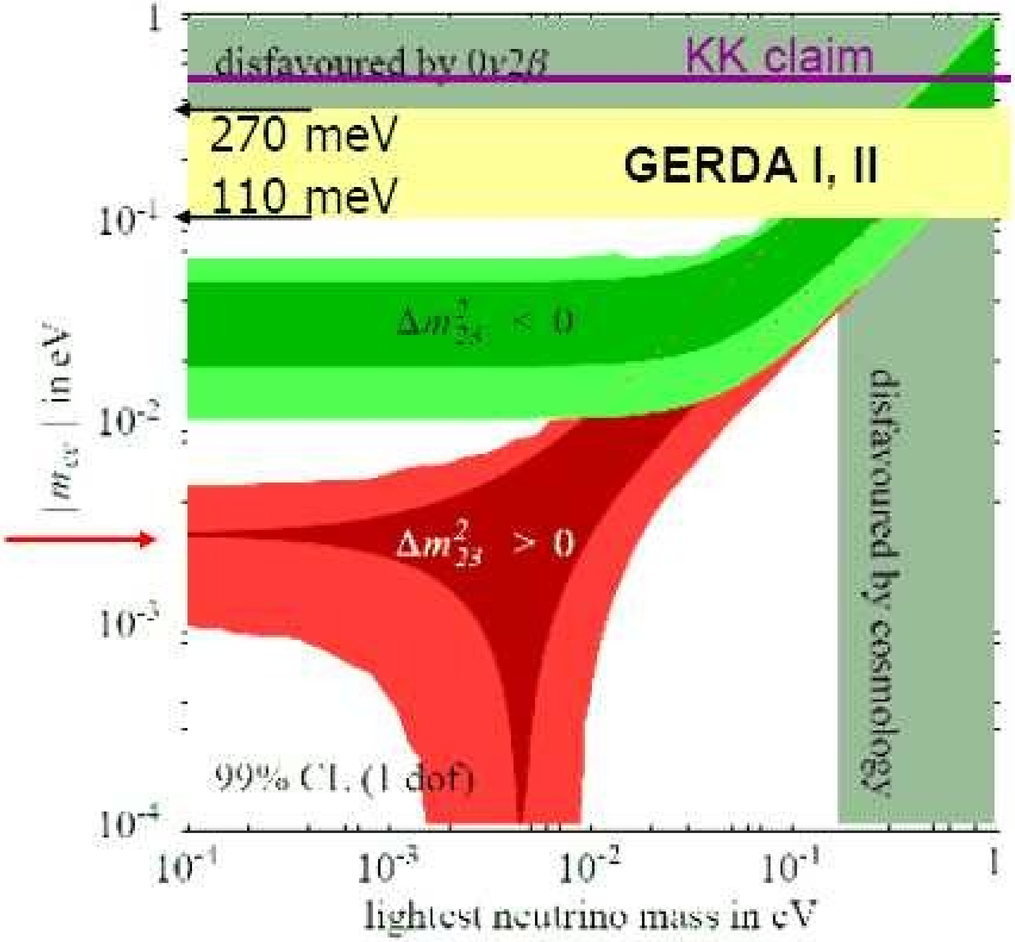
Phase III: depending on physics results of Phase I/I

~ 1 ton experiment in world wide collaboration with MAJORANA

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

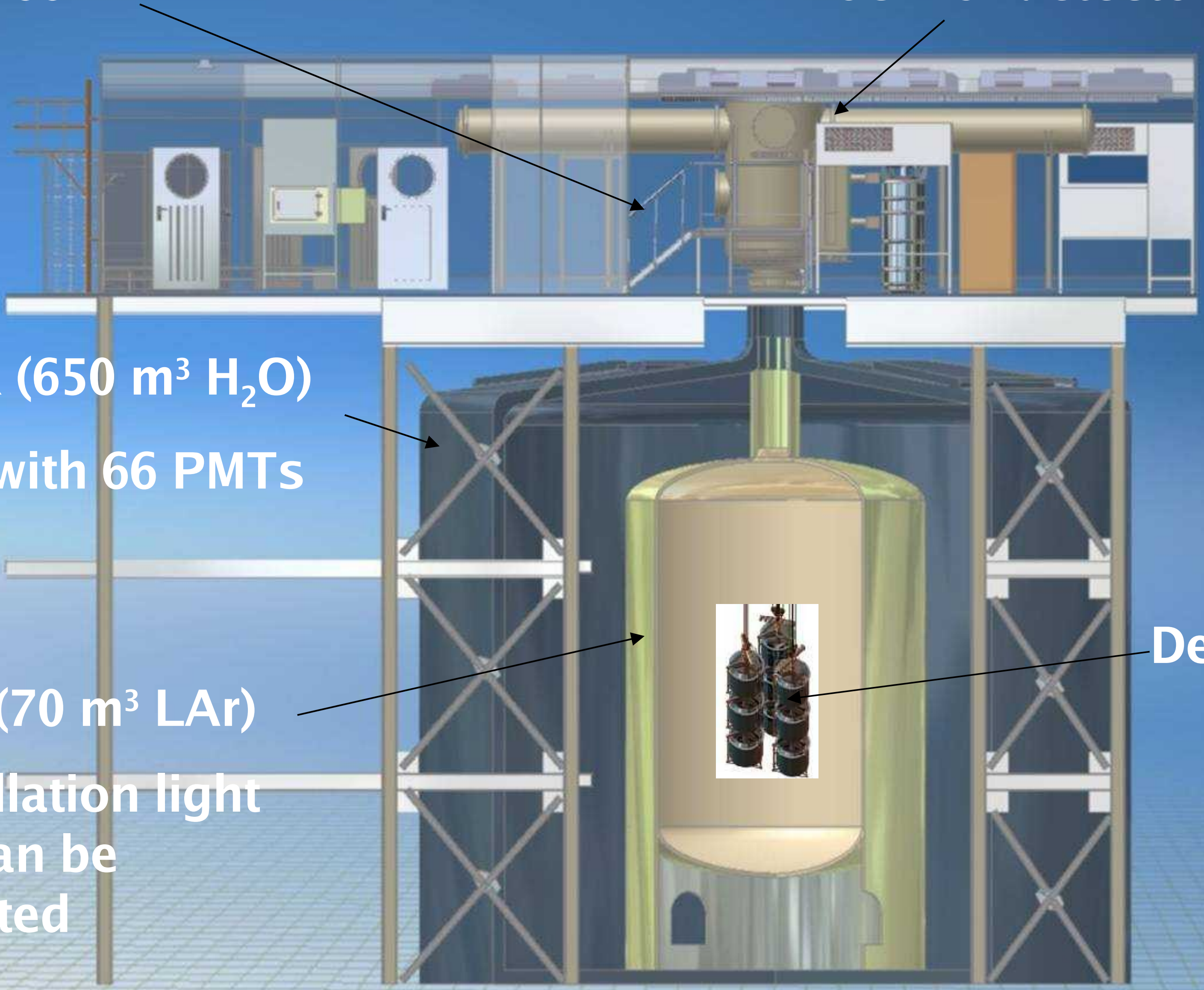
GERDA sensitivity





→ 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 design



Cleanroom

Lock for detector insertion

Water tank (650 m^3 H_2O)

Equipped with 66 PMTs for μ-veto

Detector Array

Cryostat (70 m^3 LAr)

LAr scintillation light readout can be implemented

GERDA cryostat

6 march 2008

Built with low activity steel

1-5 mBq/kg

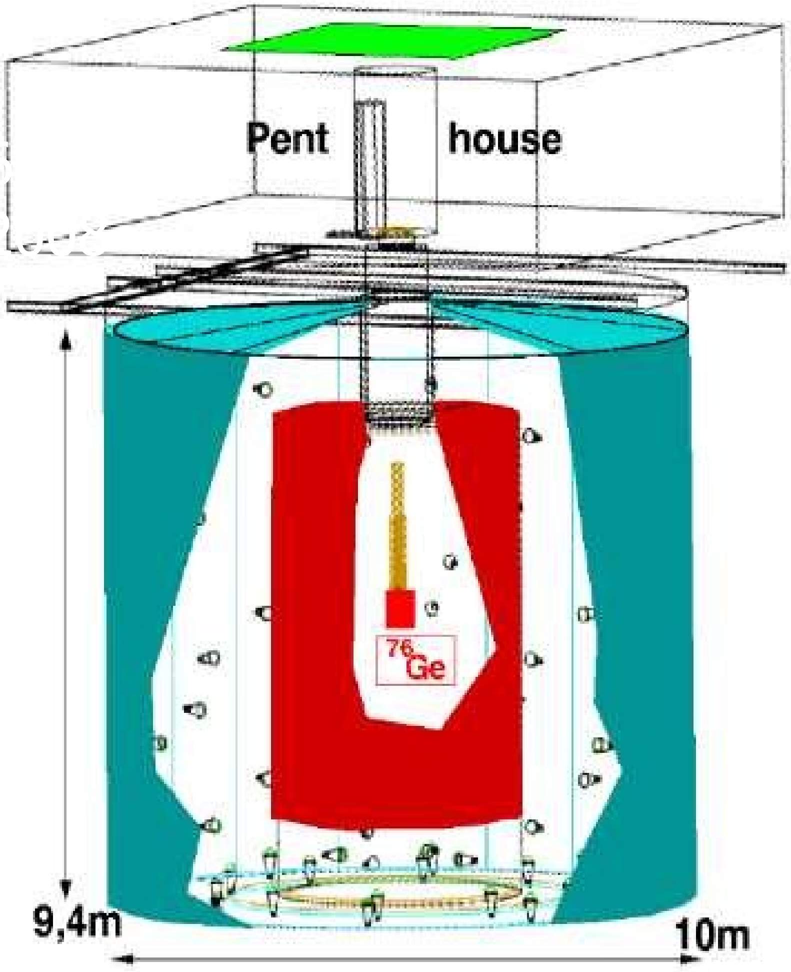
Cu plate being lifted at top of cryostat

A view inside the cryostat with Cu lining already in place

- Wipe cleaning to reduce Rn emanation ~30 mBq (need 15 mBq)
- Mounting of inner Cu shielding plates (thickness 3/6 cm) completed
- LAr evaporation rate tested (< 2% day^{-1})
- LAr scintillation light readout to reduce external bckg in detectors can be implemented

GERDA water tank and muon veto

- Active shield
- Filled with ultra-pure water from Borexino plant
- 66 PMTs: Cherenkov detector
- Plastic scintillator on top of cleanroom



GERDA I: detector testing

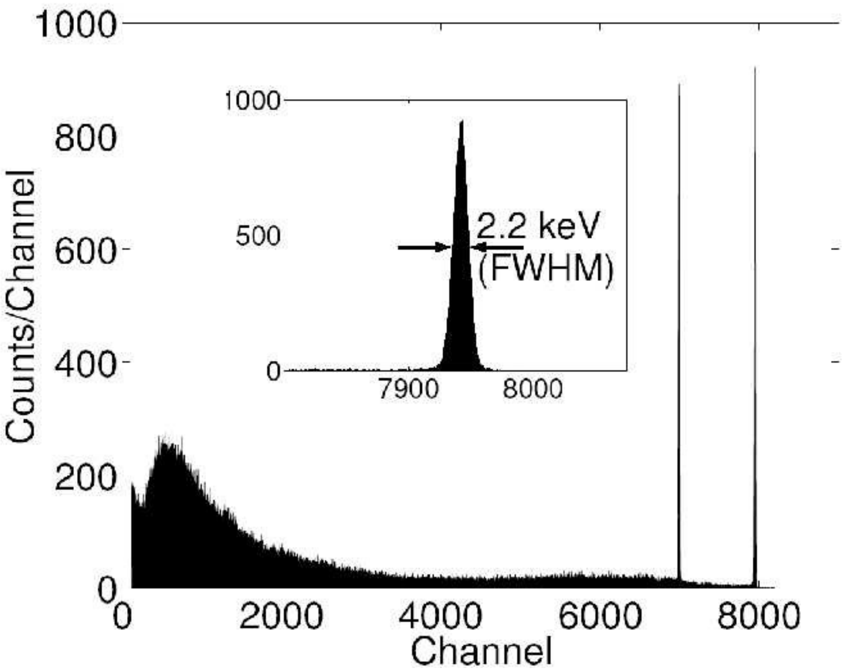
Low mass detector holder: developed and tested

- Definition of detector handling protocol
- Optimization of thermal cyclings

Bare Ge Crystals in L Ar

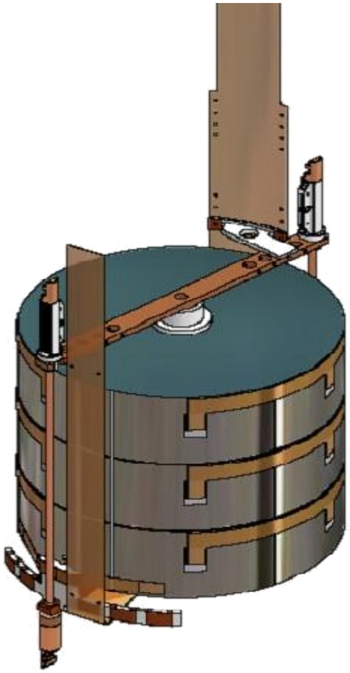
- detector parameters are not deteriorated
- >40 warming and cooling cycles carried out
- More than 1 year of operation at low leakage

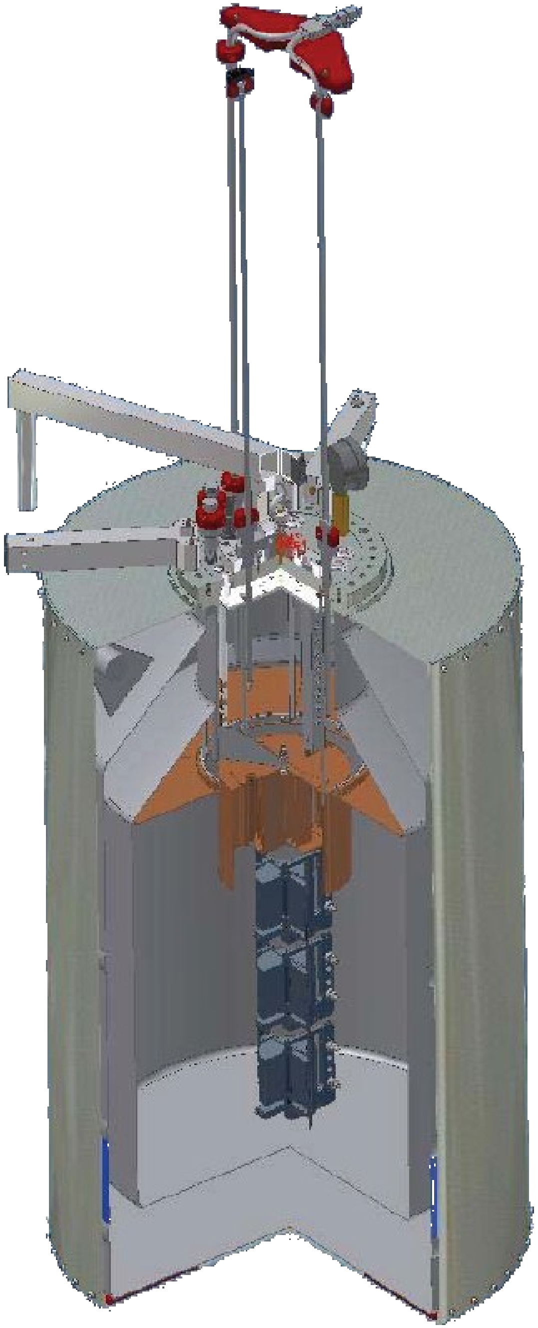
Same performance in LN_2/LAr



GERDA II: detetctors R&D

- test three 18-fold segmented detectors immersed directly in LN (full GERDA string)
- test 18-segment p-type detector
- detector response to IR & UV light

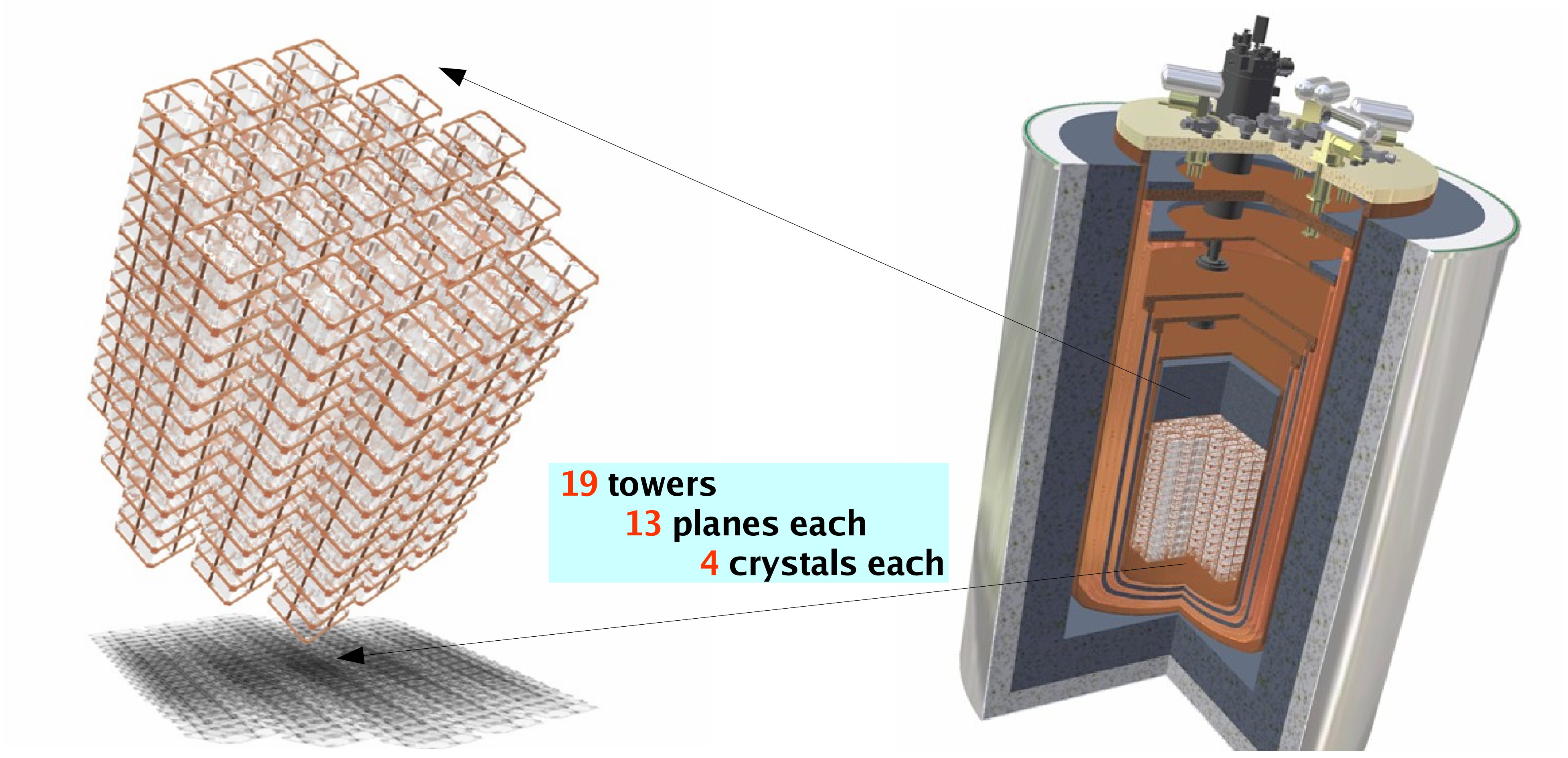




CUORE

Cryogenic Underground Observatory for Rare Events

- Closely packed array of 988 TeO_2 crystals 5×5×5 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 control 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

Under costruction since 2005

- 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

B c/keV/ton/y	**D** keV	**$T_{1/2}$** 10^{26} y	**$\|<m_\nu>\|$** meV
10	5	2.1	19-100

CUORE: hut

CUORE Hut is under construction at LNGS

- Walls
- Doors (& windows) underway
- MSP Installation
- Utilities Tender (published 6th February)
- Clean Room Tender (to be published)
- Lead for the External Shielding
- Floors covering
- Shielding Lift (to be completed)
- Shielding horizontal movement
- Columns filling
- Nitrogen supply
- Precise leveling (Lift, MSP)
- Utilities installation
- Clean Room installation
- Small cranes installation
- Nitrogen distribution

CUORE: schedule

2008:
- Hut construction
- Crystals production

2009:
- Utilities
- Clean room
- External Shielding
- Cryogenics

2009-2012:
- TeO_2 crystals
- Cu production & cleaning

2010-2012:
- CUORE0
- Detector assembly
- Faraday Cage
- Front-end & DAQ

2012:
- Detector complete

CUORE-0

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

Motivations

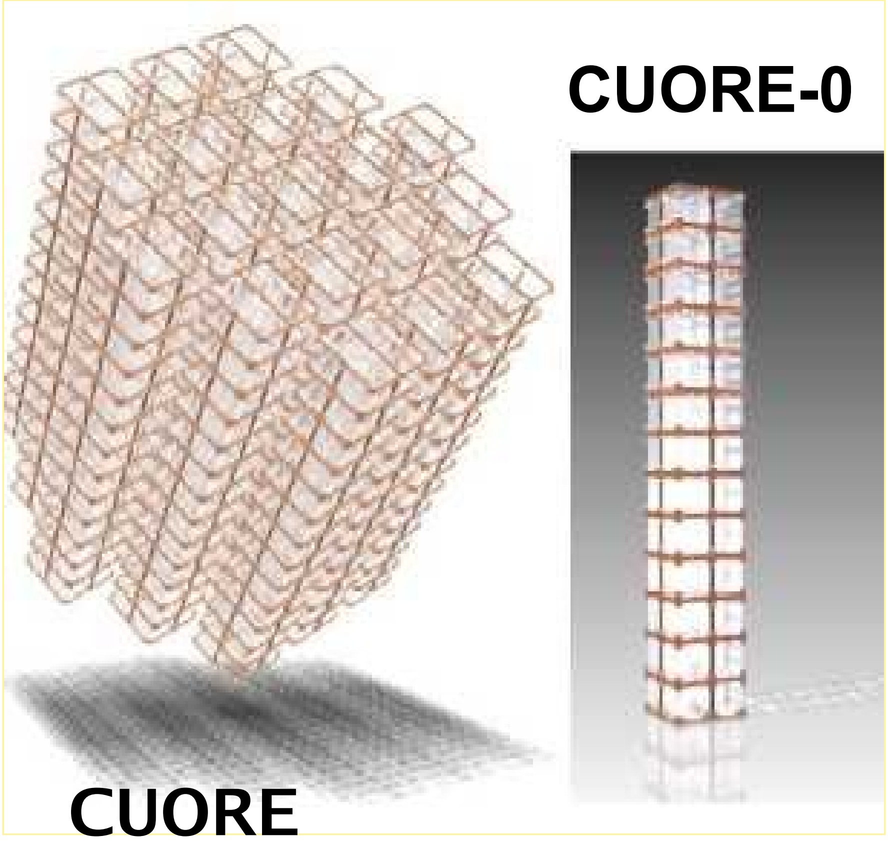
High statistics test of the many improvements/changes developped for the CUORE assembly procedure:

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

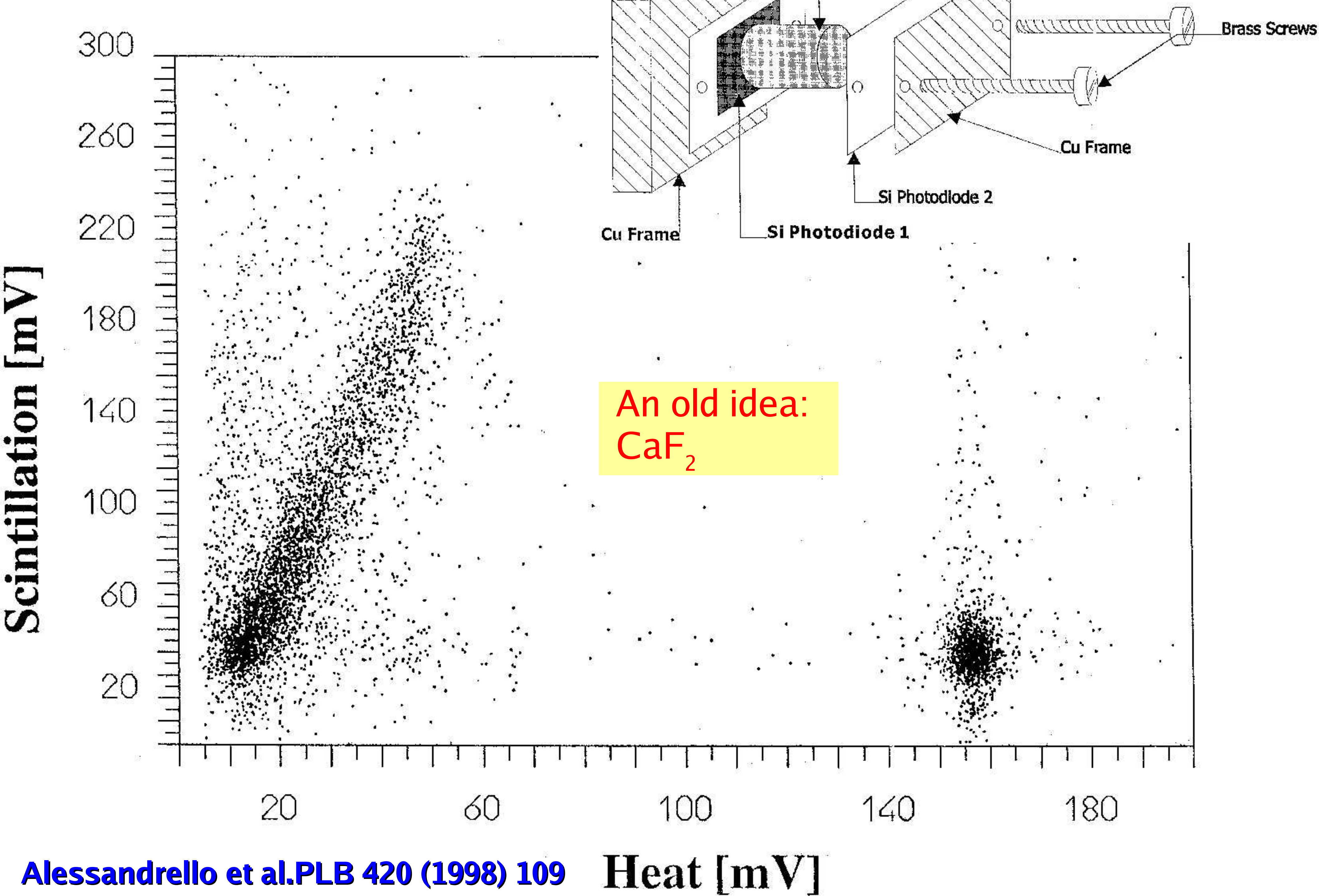
CUORE demonstrator: expected background in the DBD and alpha energy regions reduced by a factor 3 with respect ro CUORICINO

0.07 counts/keV/kg/y

Powerful experiment: it will overtake soon CUORICINO sensitivity



Scintillating bolometers



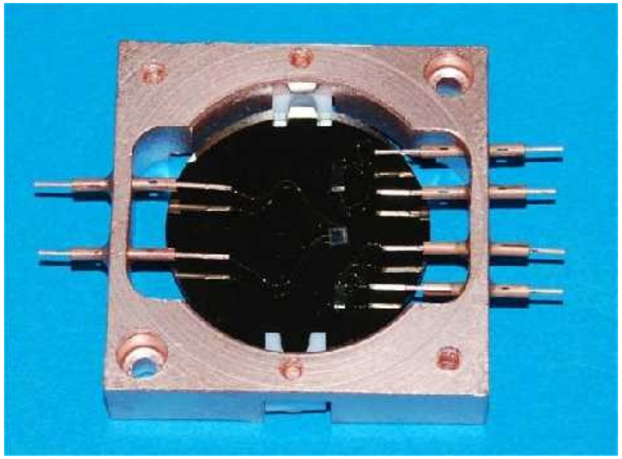
An old idea: CaF_2

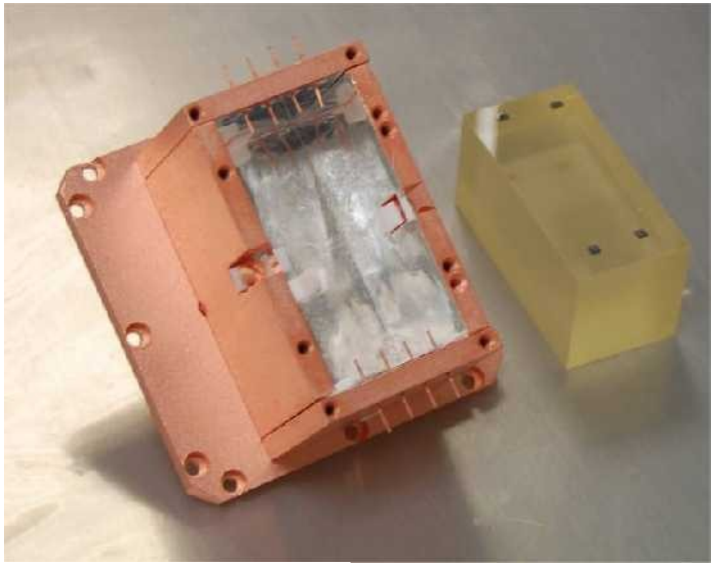
Alessandrello et al.PLB 420 (1998) 109

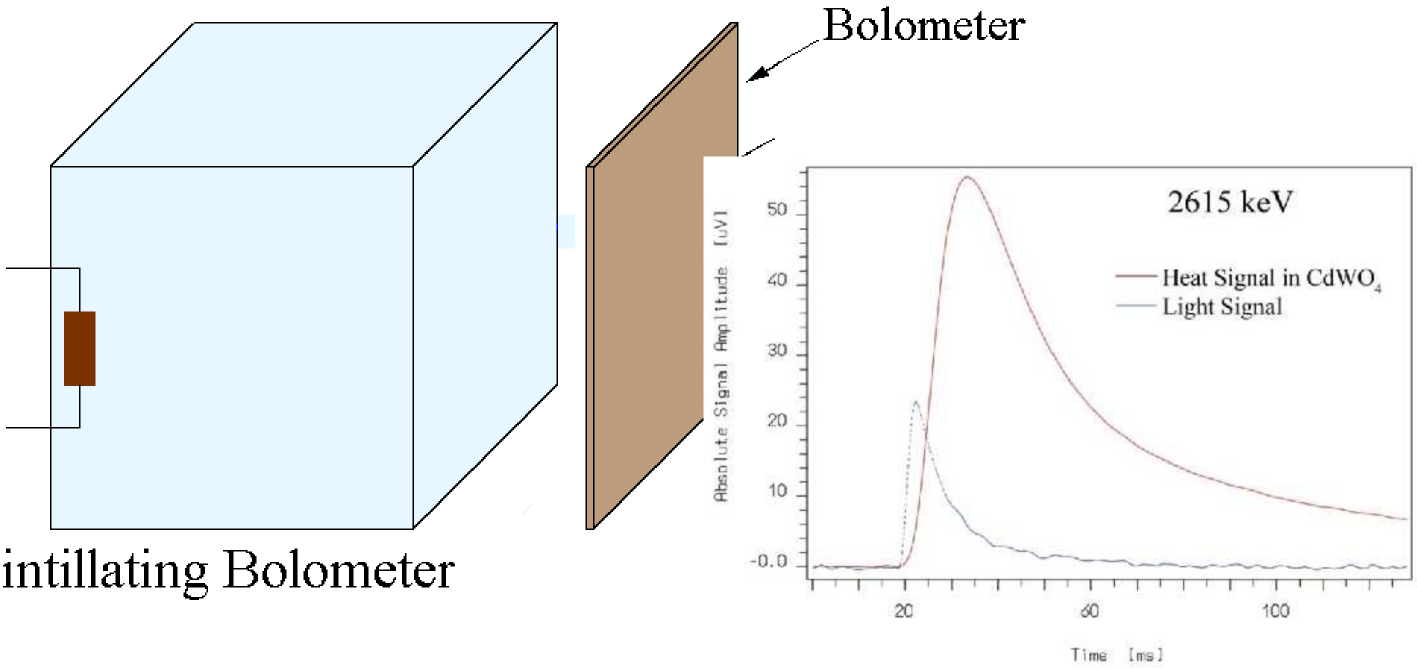
Scintillating bolometers: BOLUX

A very promising technique for background reduction

Concept: separate the dangerous alpha background exploiting different scintillating properties







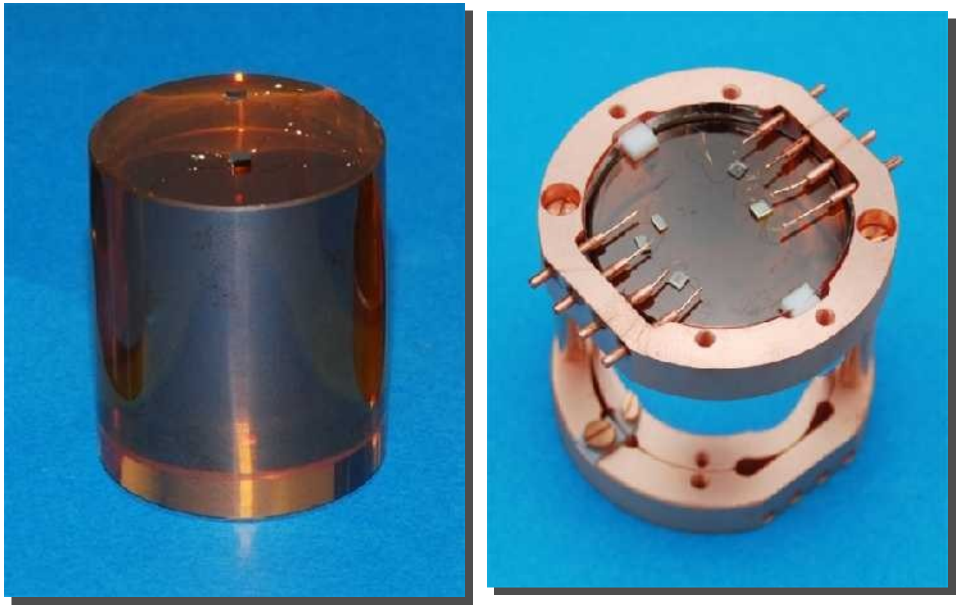
Not viable for TeO2 ... but ...

Scintillating bolometers: BOLUX

$CdWO_4$: 508g

- Already tested different scintillating crystals ($CdWO_4$, CaF_2, $CaMoO_4$, $SrMoO_4$, $PbMoO_4$, ZnSe, …).
- With some of them we have obtained excellent results (for example $CdWO_4$, $CaMoO_4$ and ZnSe).

ZnSe:337 g

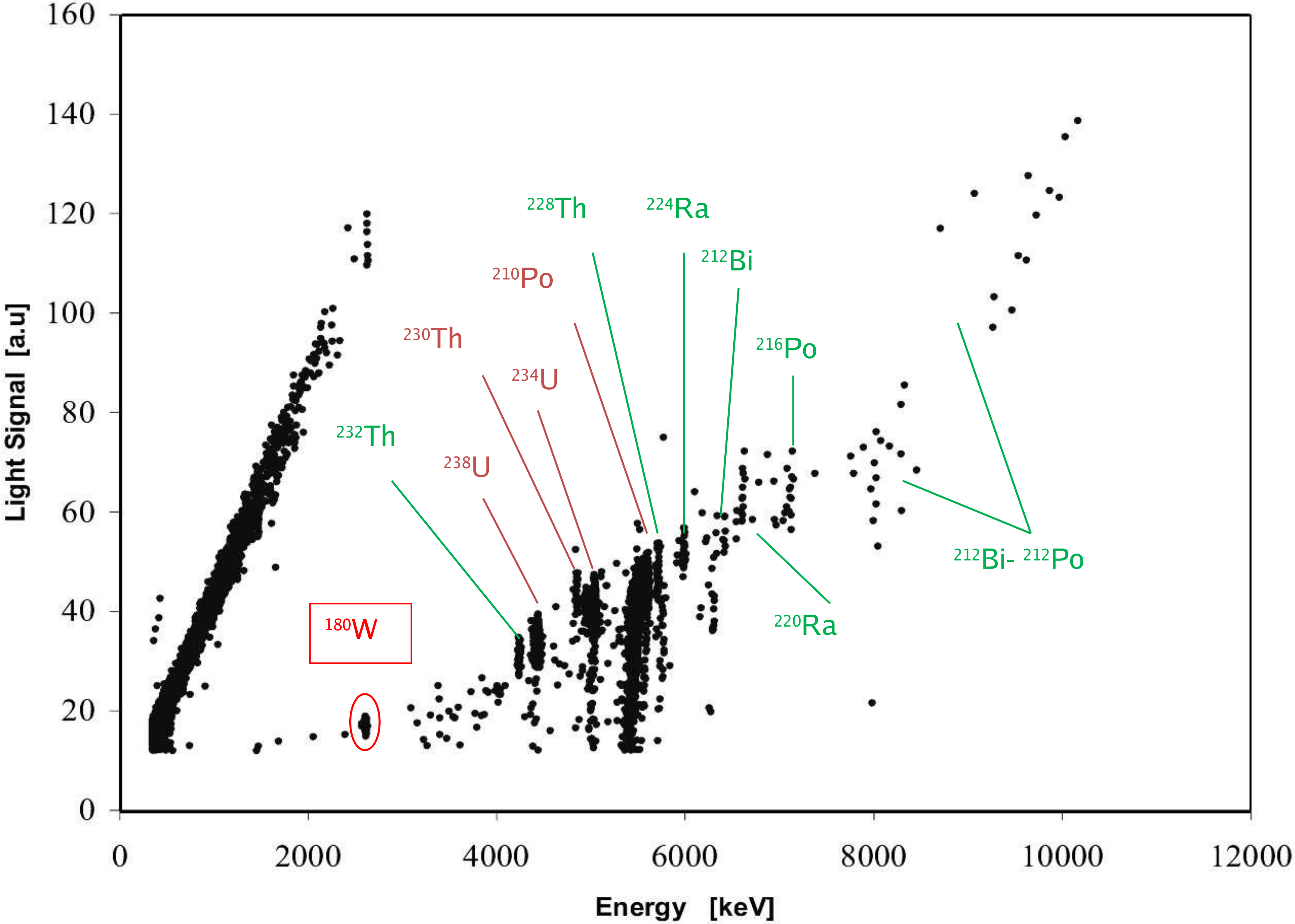


$CaMoO_4$: 157g

BOLUX: $CdWO_4$

Background $CdWO_4$ 3x3x6 (426 g) – Scatter Plot

724 hours



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

$<m_\nu>$ sensitivity: $T_{1/2} > 2.\ 10^{26}$ yr

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

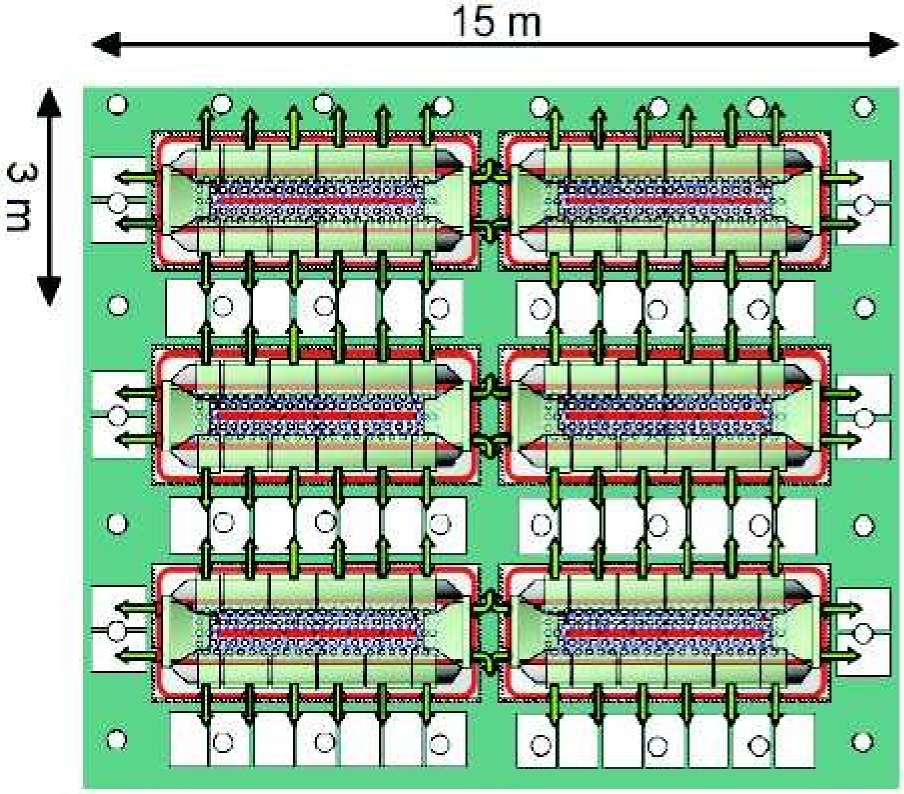
funded by France, UK and Spain

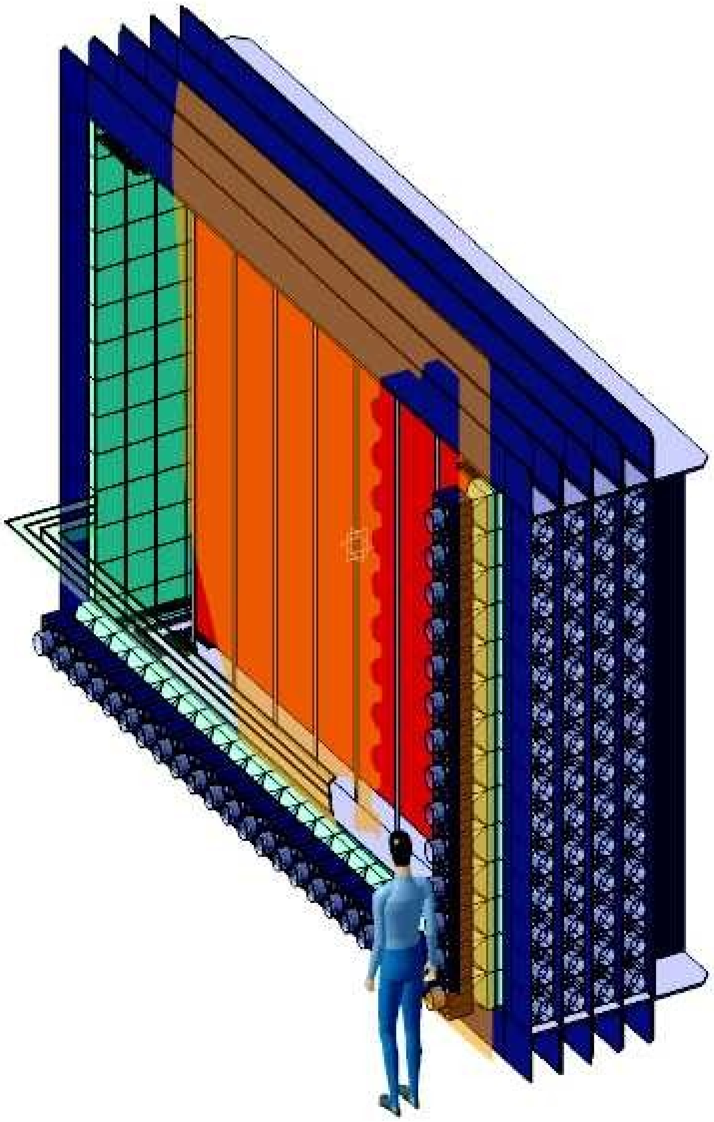
- **2009: TDR**
- **2011: commissioning and data taking of first modules in Canfranc (Spain)**
- **2013: Full detector running**

SuperNEMO

20 modules for 100 kg

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

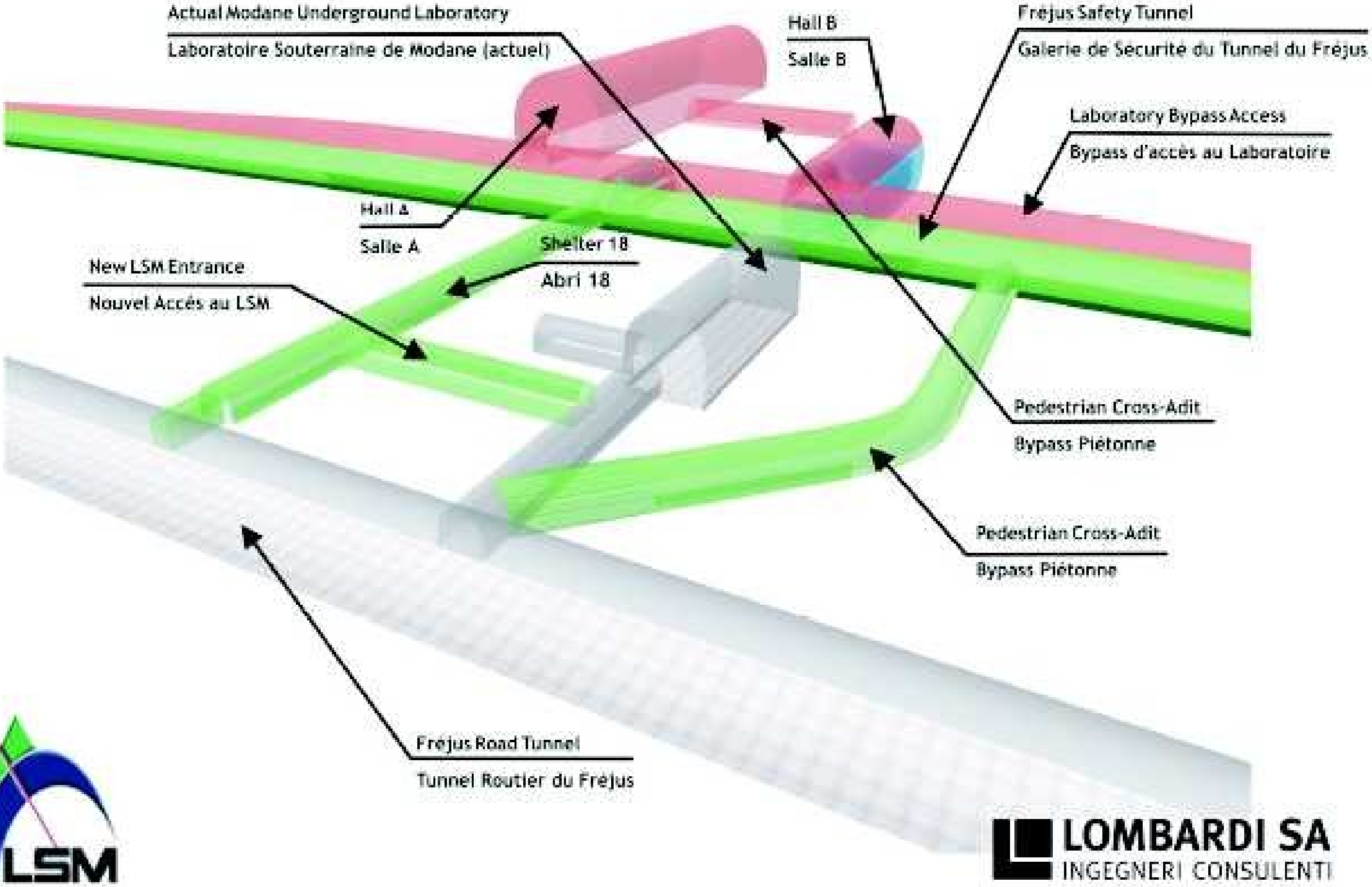




ULISSE project

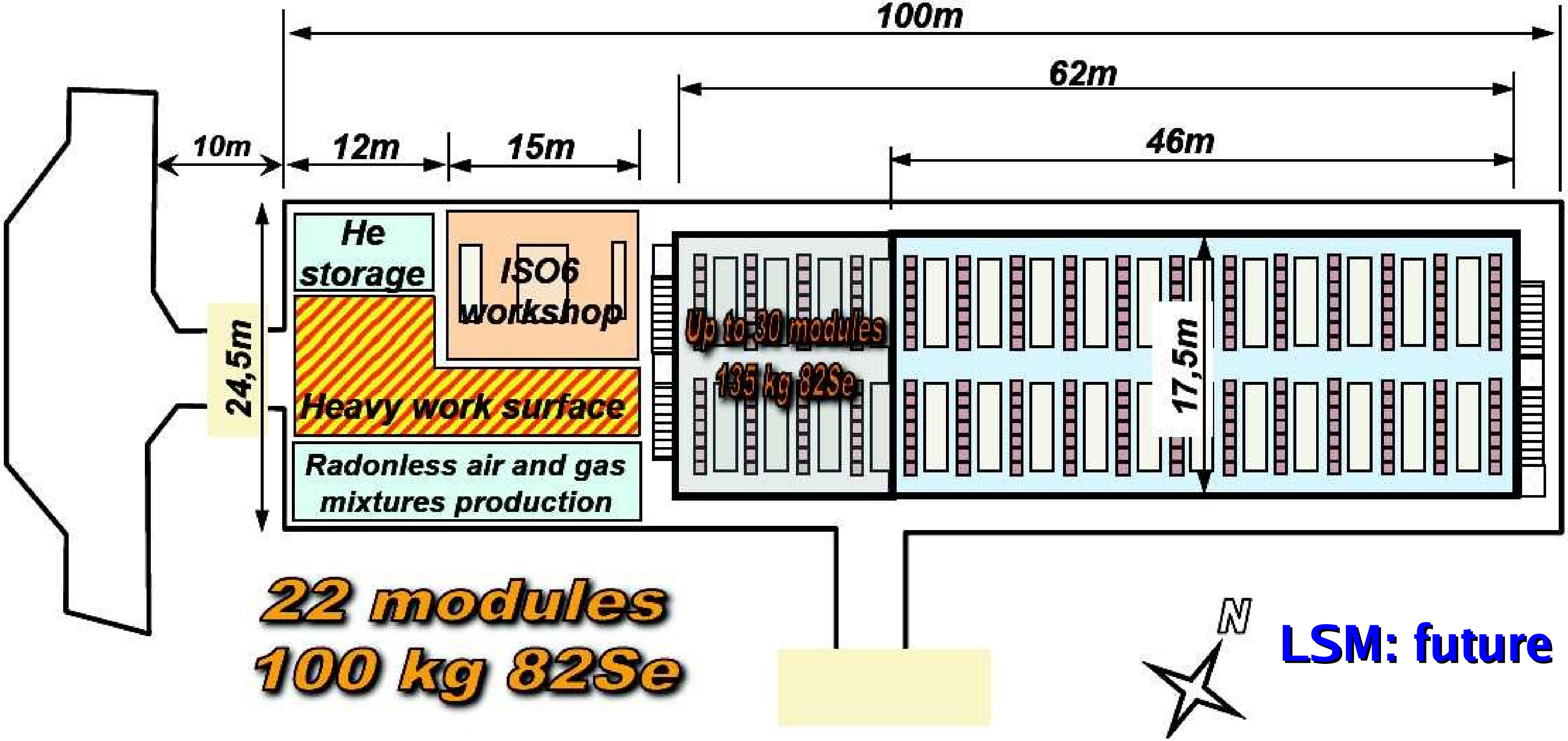
MODANE UNDERGROUND LABORATORY 60'000 m^3 EXTENSION

LABORATOIRE SOUTERRAINE DE MODANE AGRANDISSEMENT 60'000 m^3



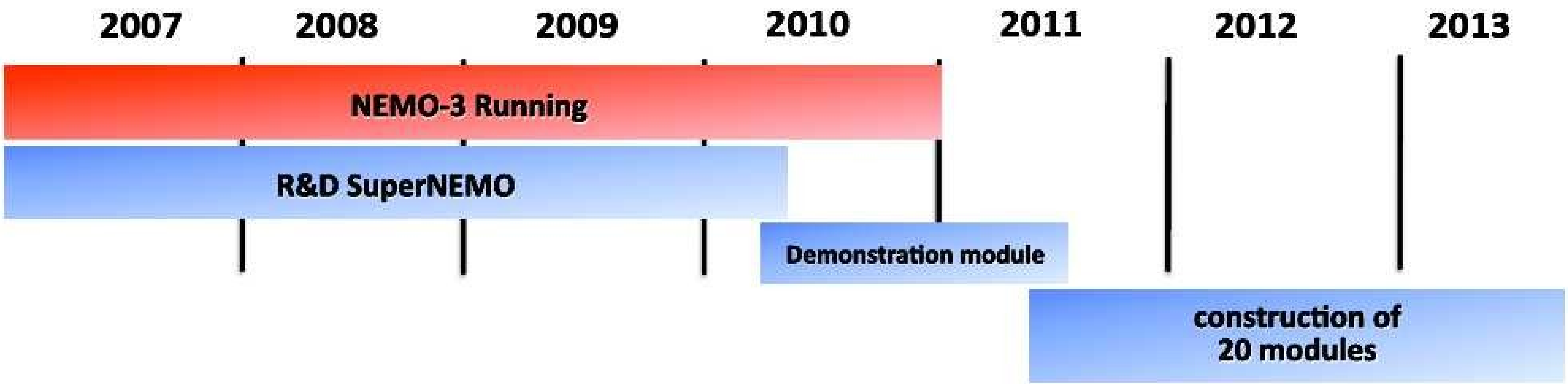
LOMBARDI SA
INGEGNERI CONSULENTI

SuperNEMO



22 modules
100 kg 82Se

LSM: future hall A



NEMO-3 Running

R&D SuperNEMO

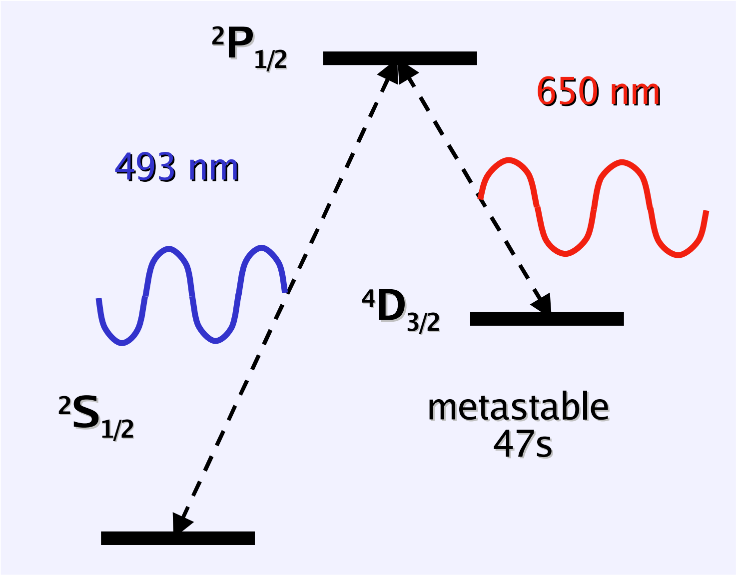
Demonstration module

construction of
20 modules

IN THE WORLD

EXO

- **concept**: scale Gotthard experiment adding **Ba tagging** to suppress background (^{136}Xe→^{136}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 $\beta\beta$-2ν



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

Parallel activities:

EXO-200:

a LXe detector without Ba tagging using 200 kg of Xe enriched to 80% in 136Xe with ~150 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

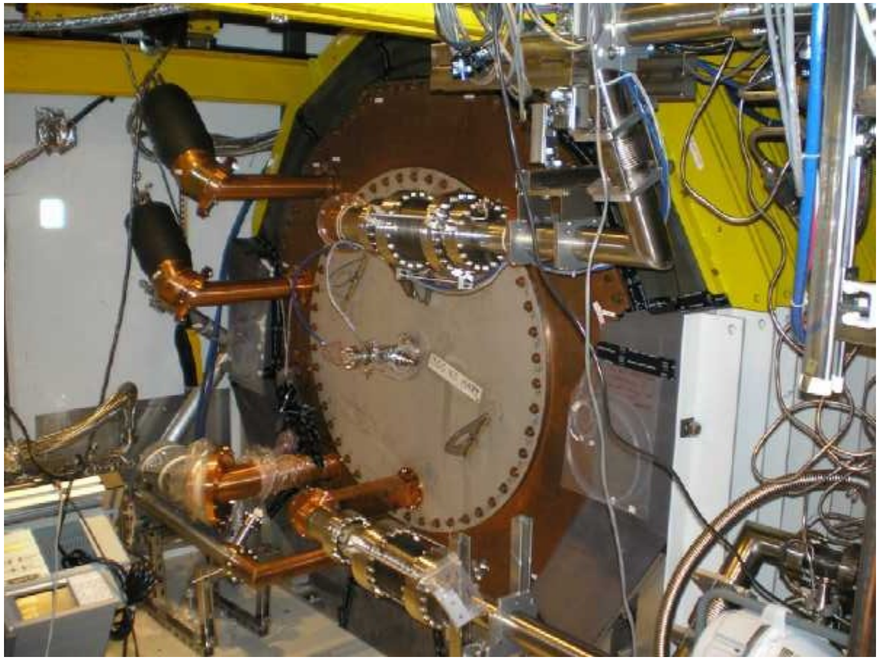
EXO-200

Intermediate Prototype without Barium Tagging

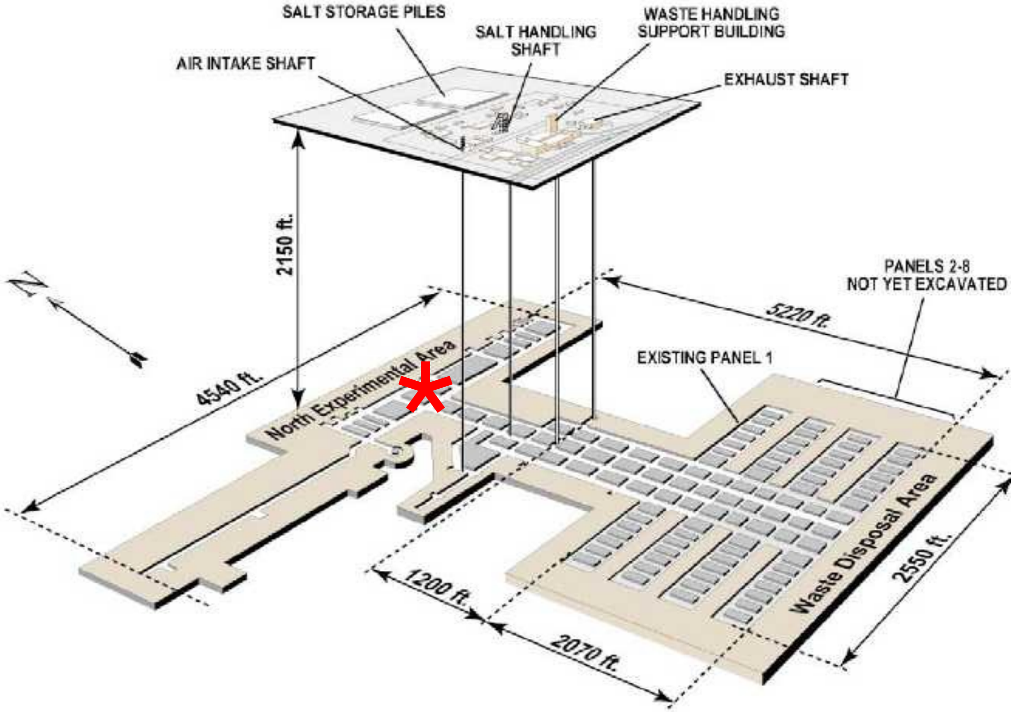
- TPC Vessel fully machined at Stanford under 7 m.w.e shielding; E-beam welding used for all but final weld to minimize introduction of radioactive background
- 200 kg enr. Xe (80% in 136Xe)
- Vessel complete, welded to door
- Half detectors almost complete
- (APDs, cables under assembly)
- Detector at WIPP: lead shielding, Xe plumbing almost complete, cryogenics tests in progress

Schedule:

- engineering run Summer 09
- physics run Fall 09
- First 2nu measurement 2010
- 0nu 3–5 years



EXO-200 @ WIPP


SALT STORAGE PILES
SALT HANDLING SHAFT
WASTE HANDLING SUPPORT BUILDING
AIR INTAKE SHAFT
EXHAUST SHAFT
2150 ft.
N
PANELS 2-8 NOT YET EXCAVATED
5220 ft.
EXISTING PANEL 1
4540 ft.
North Experimental Area
*
Waste Disposal Area
2550 ft.
1200 ft.
2070 ft.

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+

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 sintillator:

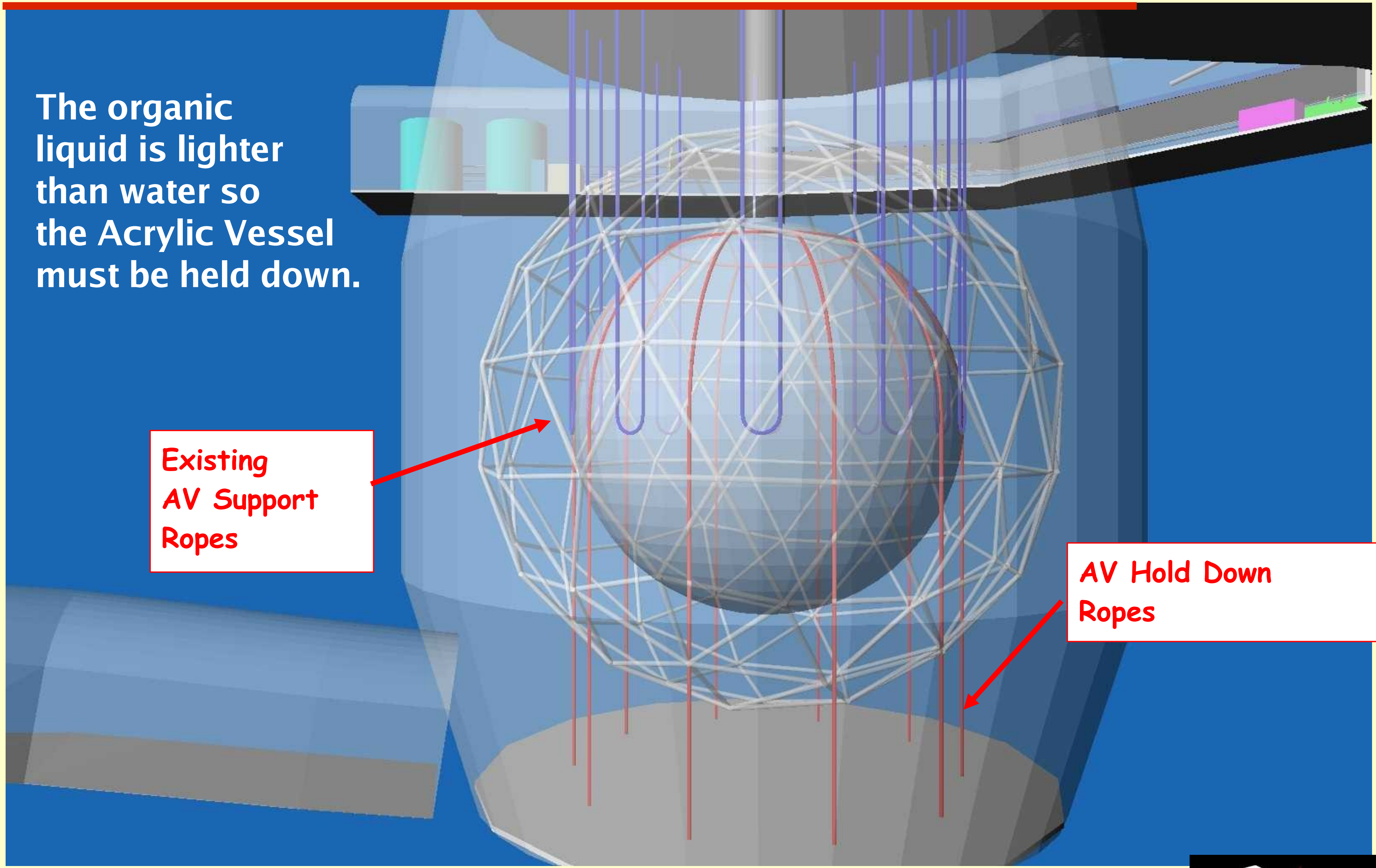
1% loading (Natural Nd) large light absorption by Nd

47 ± 6 pe/MeV (Monte Carlo)

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

400 ± 21 pe/MeV (Monte Carlo)

SNO+: 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

Scint. Purification, AV Hold Down

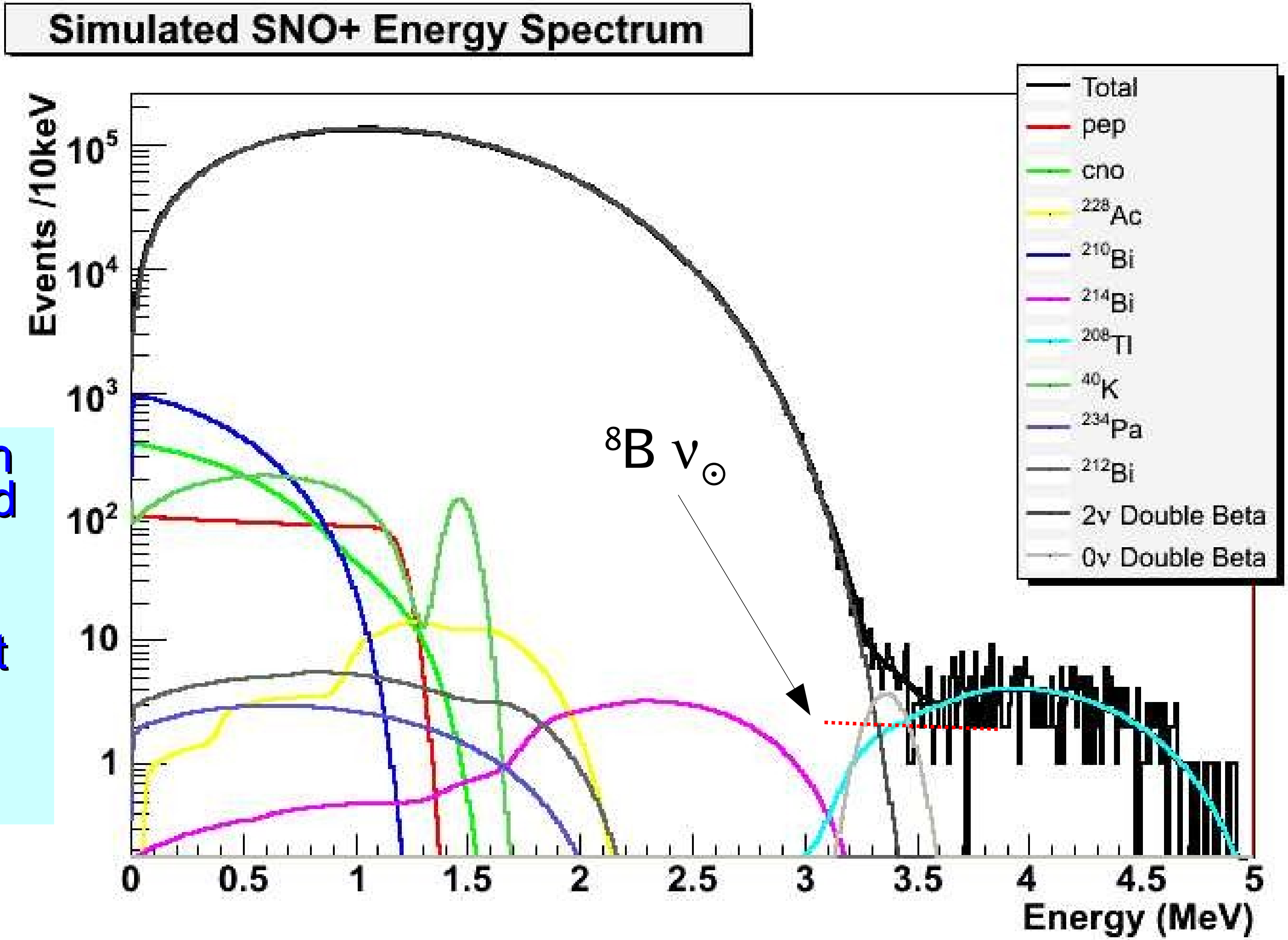
Otherwise, the existing detector, electronics etc. are unchanged.

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.



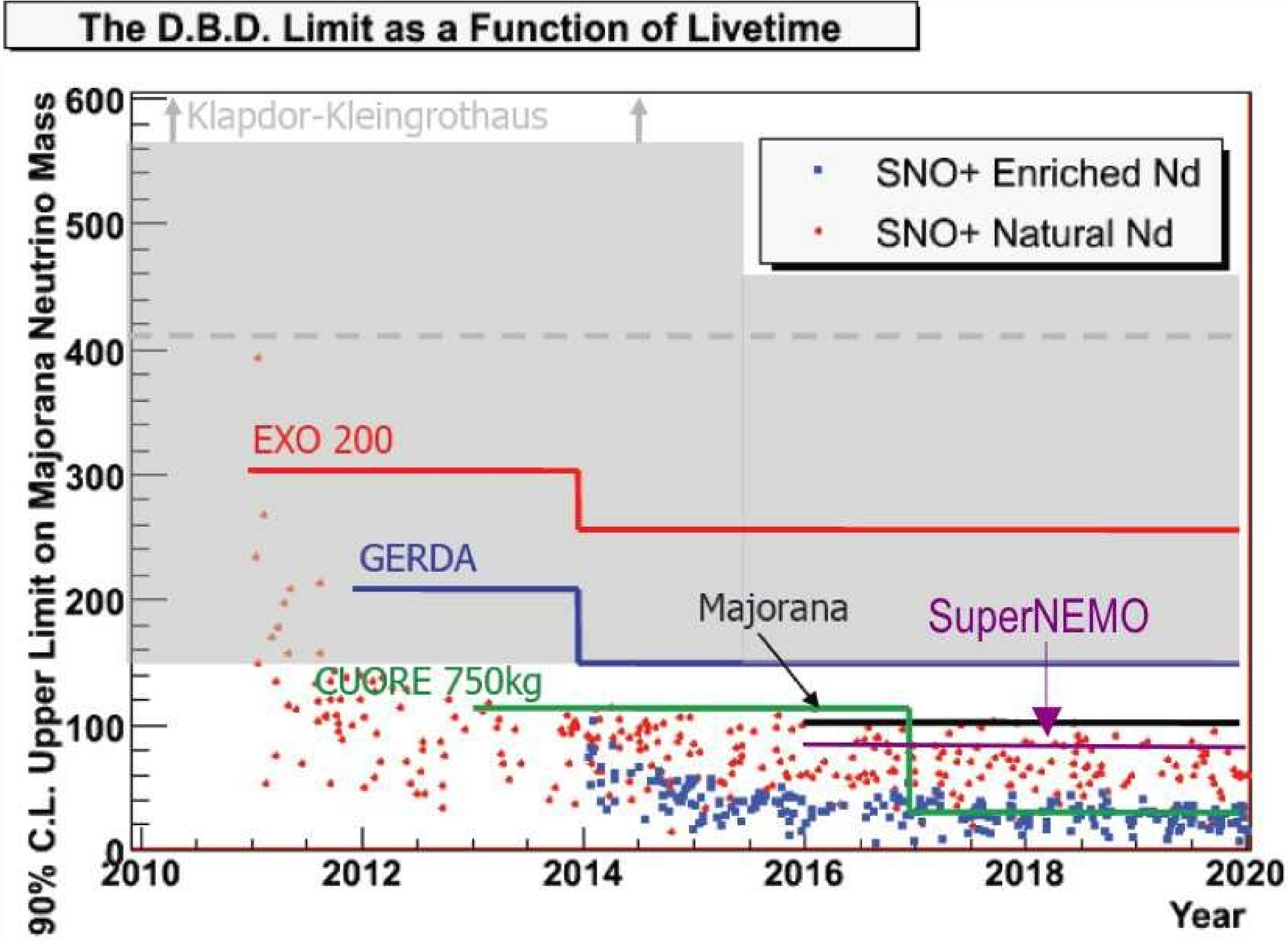
Sensitivity Limits (3 yrs):

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

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

End of 2010 → ready for scintillator filling

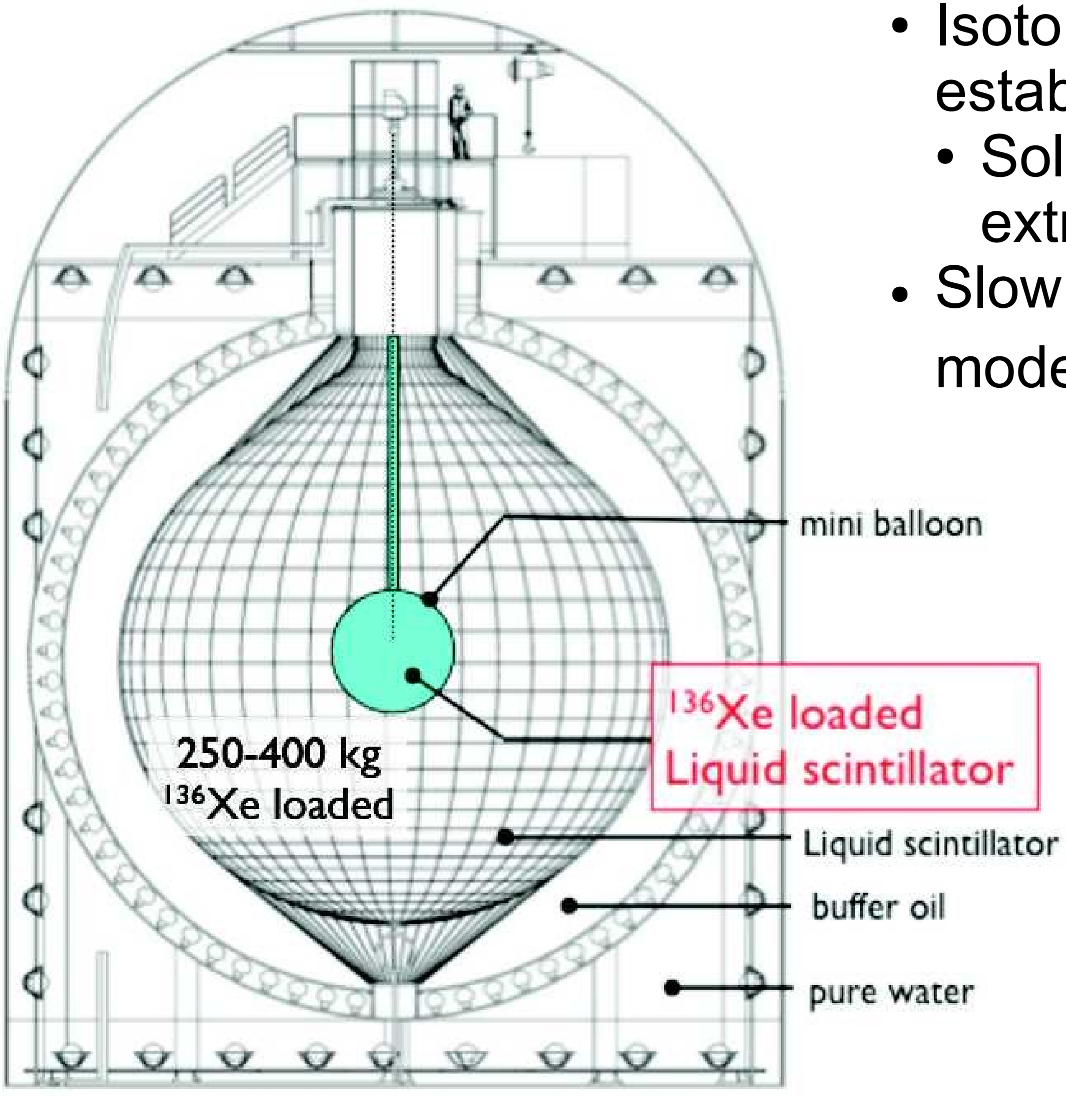
SNO+ sensitivity



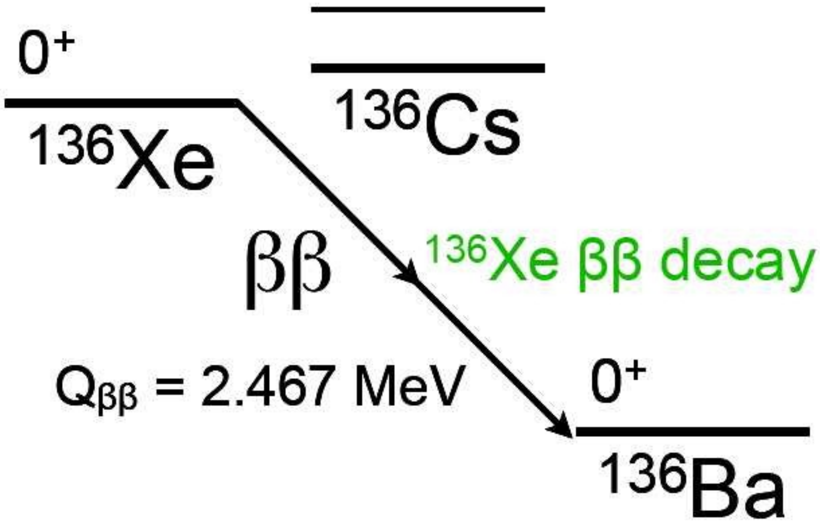
- Each SNO+ point represents a different MC “experiment” so as to reflect the statistical spread of derived limits.
- Ultimately, the ability to achieve such sensitivities in practise may rest on securing sufficient control of backgrounds

KAMLAND

^{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

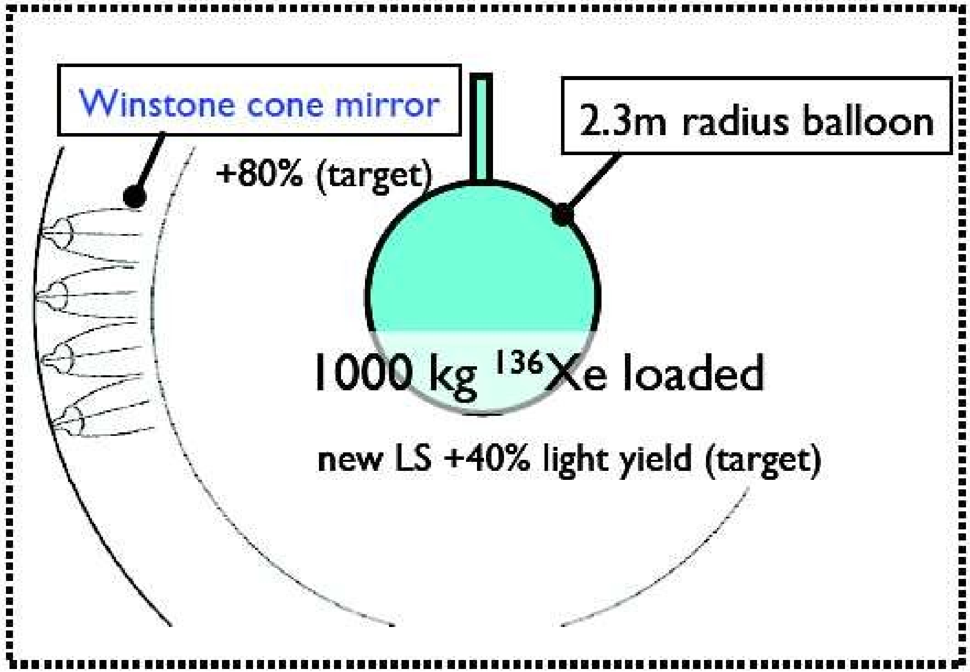
KAMLAND merits

- Ultra low radioactivity environment based on ultra pure LS and
- 9m radius active shield: ^{38}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 ^{136}Xe, improvement of energy resolution with light concentrators and brighter LS (~30M$)

25 meV in 5 years



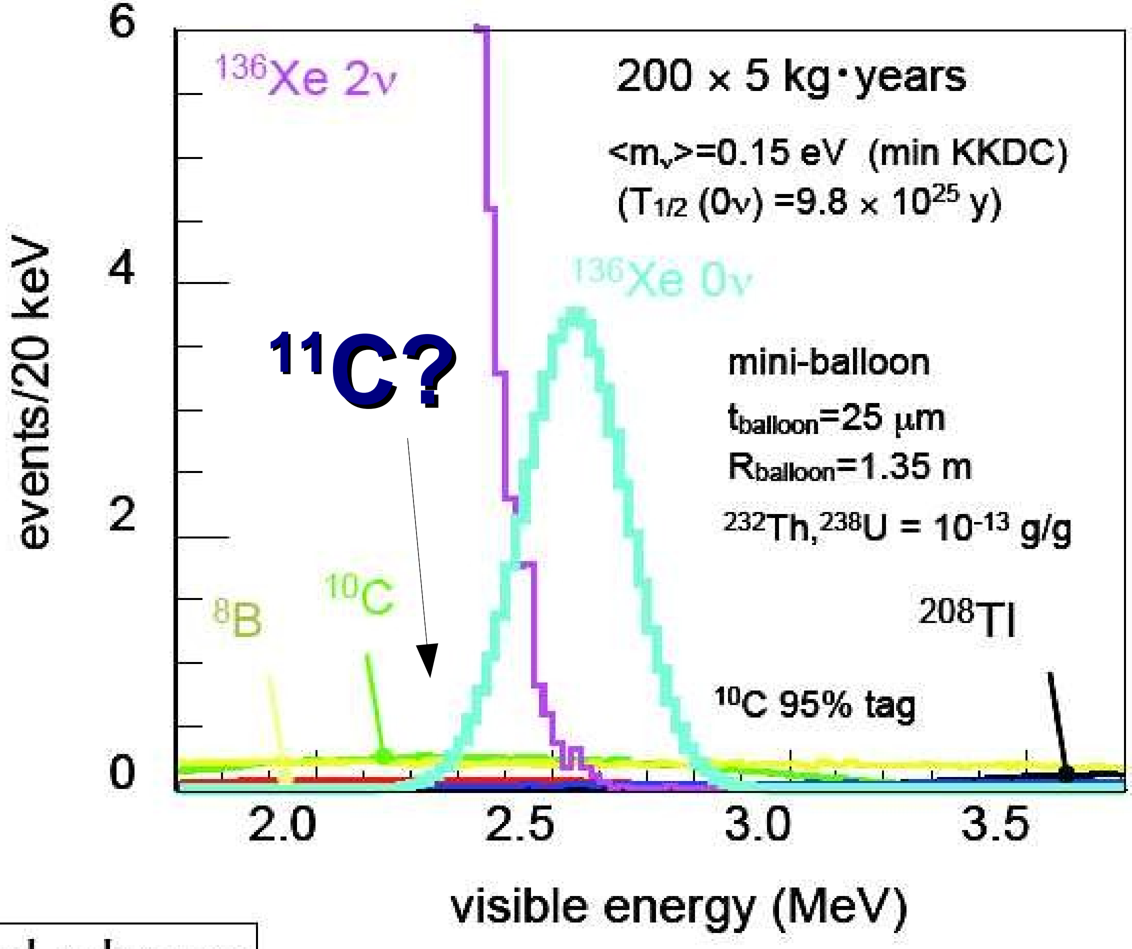
R&D items

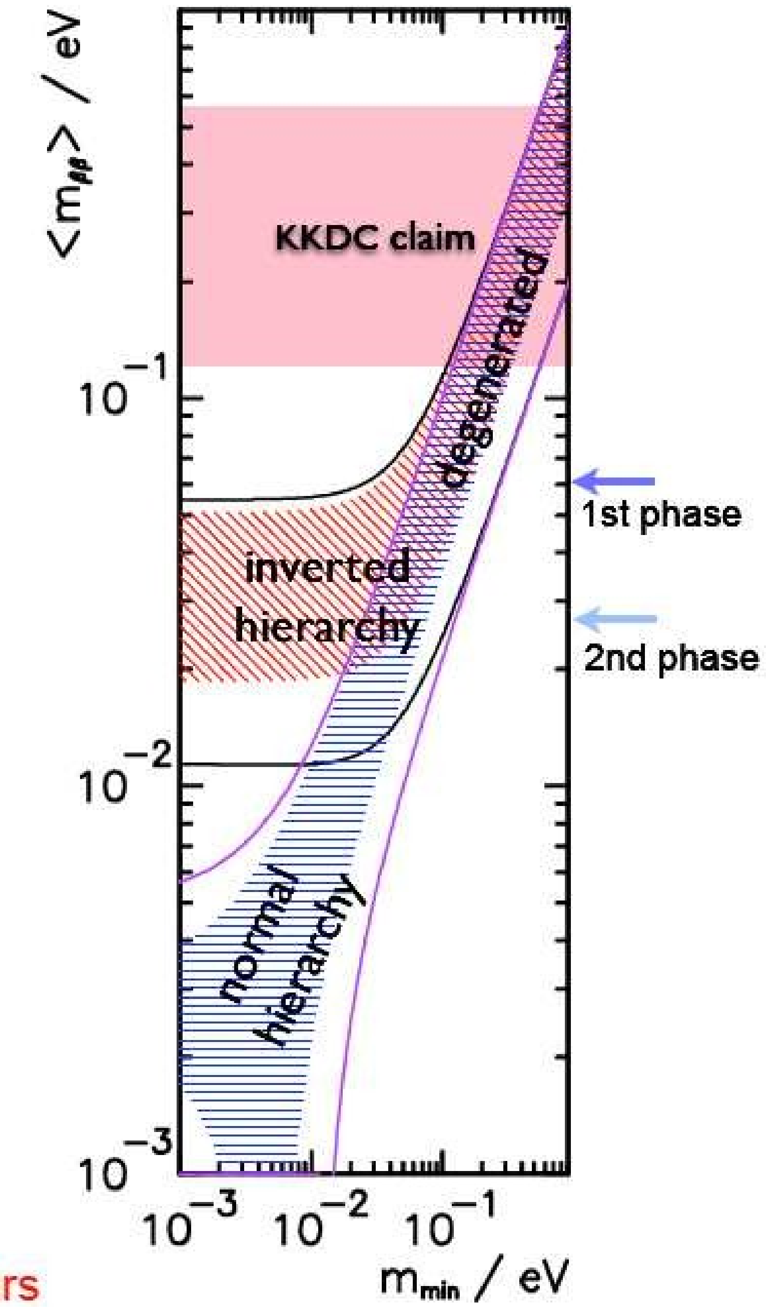
- Xenon loaded LS with the same density, luminosity, transparency
- 2.7~4 m φ Mini-balloon
- Xenon purification, storage, extraction etc
- Cosmogenic background rejection with dead-time free electronics

KAMLAND sensitivity

1st phase

KKDC claim, degenerated hierarchy test



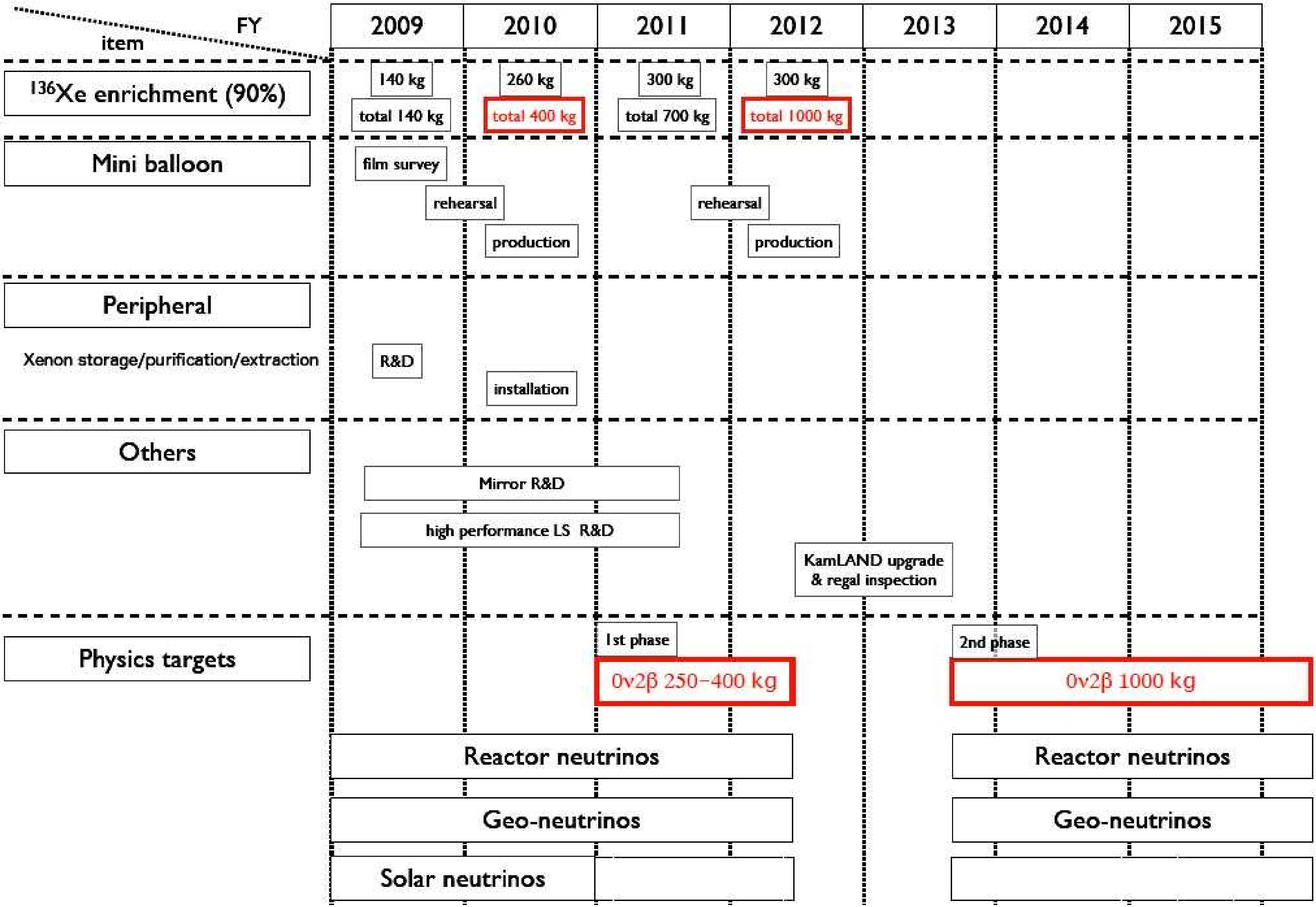


2nd phase

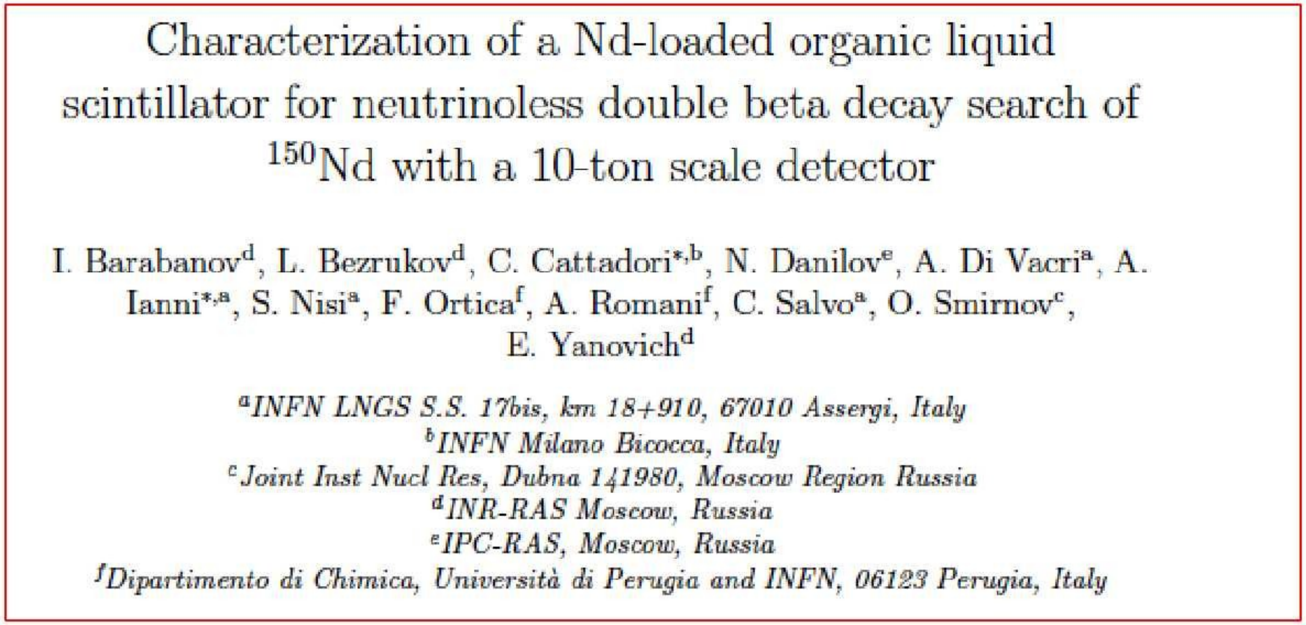
inverted hierarchy test

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

KAMLAND timeline



FY / item	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						



Characterization of a Nd-loaded organic liquid scintillator for neutrinoless double beta decay search of ^{150}Nd with a 10-ton scale detector

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[e]IPC-RAS, Moscow, Russia
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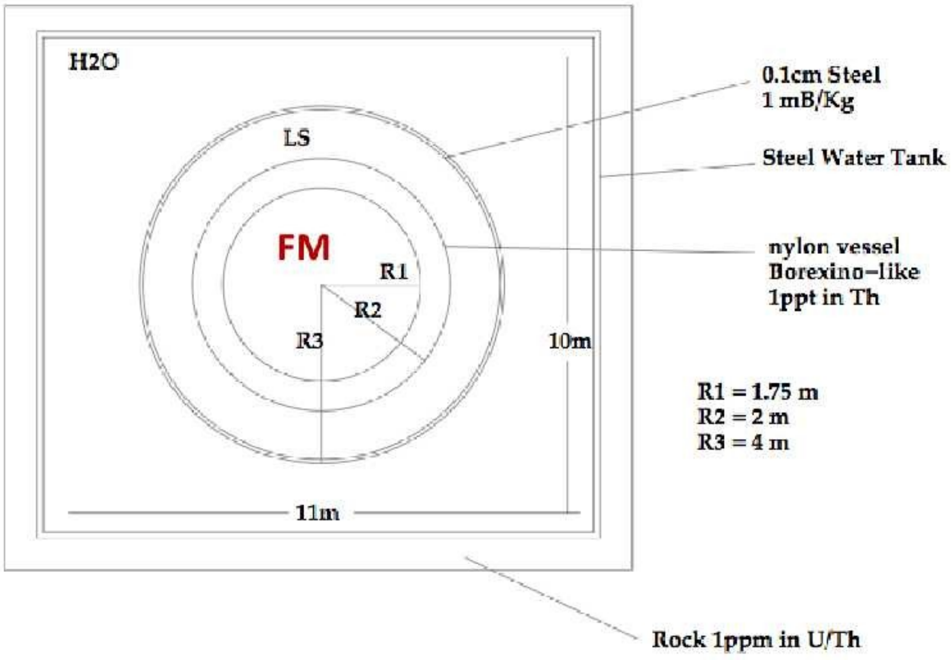
The Detector: basic idea



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 76Ge
- new 2nd generation experiments (200 kg) under construction
- a number of well-established R&D for the near future program

Ultimate goal: $<m_\nu>$ ~ 10 meV

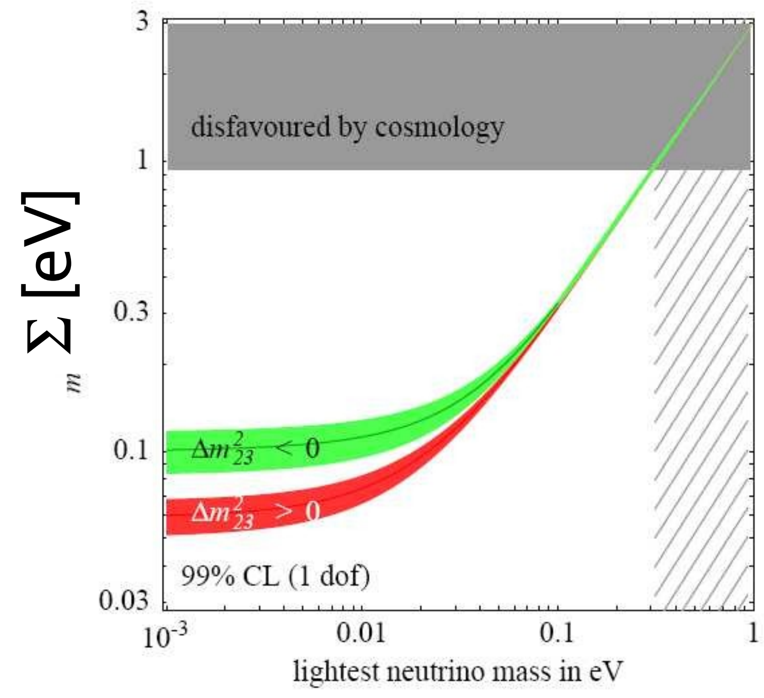
- many proposals with different techniques and isotopes
- promote as many as possible experiments on different isotopes
- reduce uncertainties in nuclear matrix F_N

CONCLUSIONS (2)

Exciting period for neutrino masses:

degeneracy is going to be probed

potential for excluding inverted hierarchy



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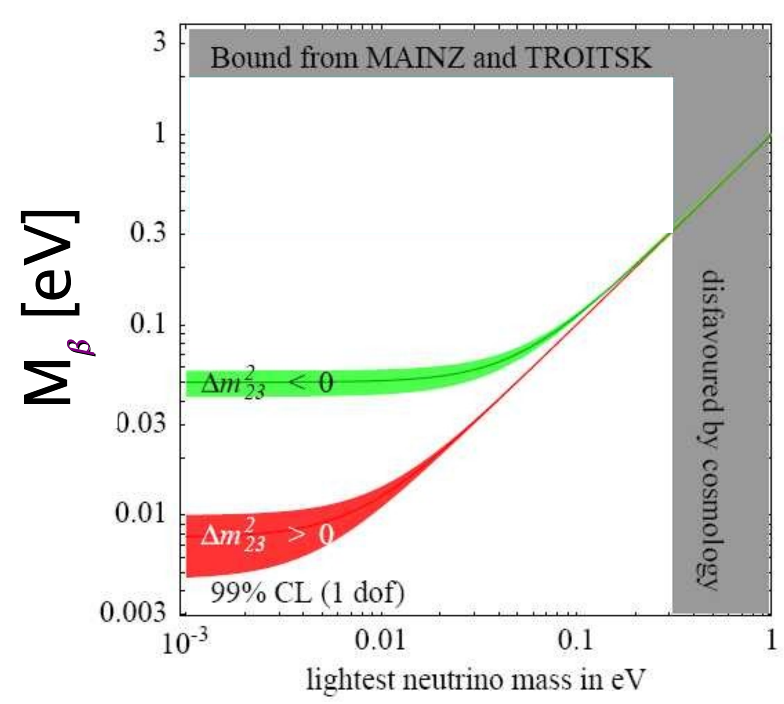

S
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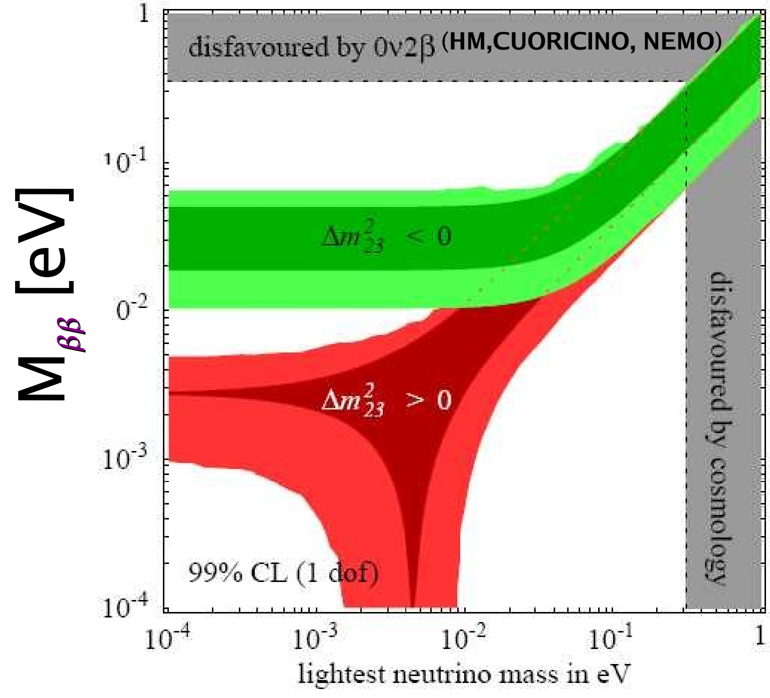
β



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