The search for neutrino-less double beta decay ($0\nu\beta\beta$)

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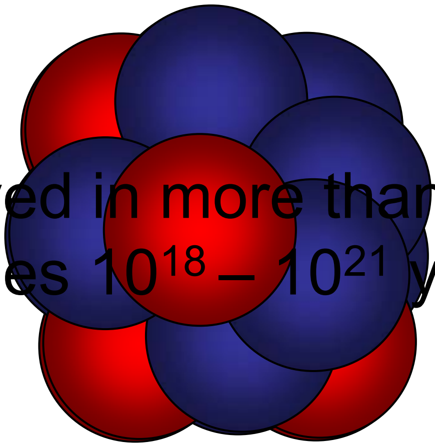
Outline

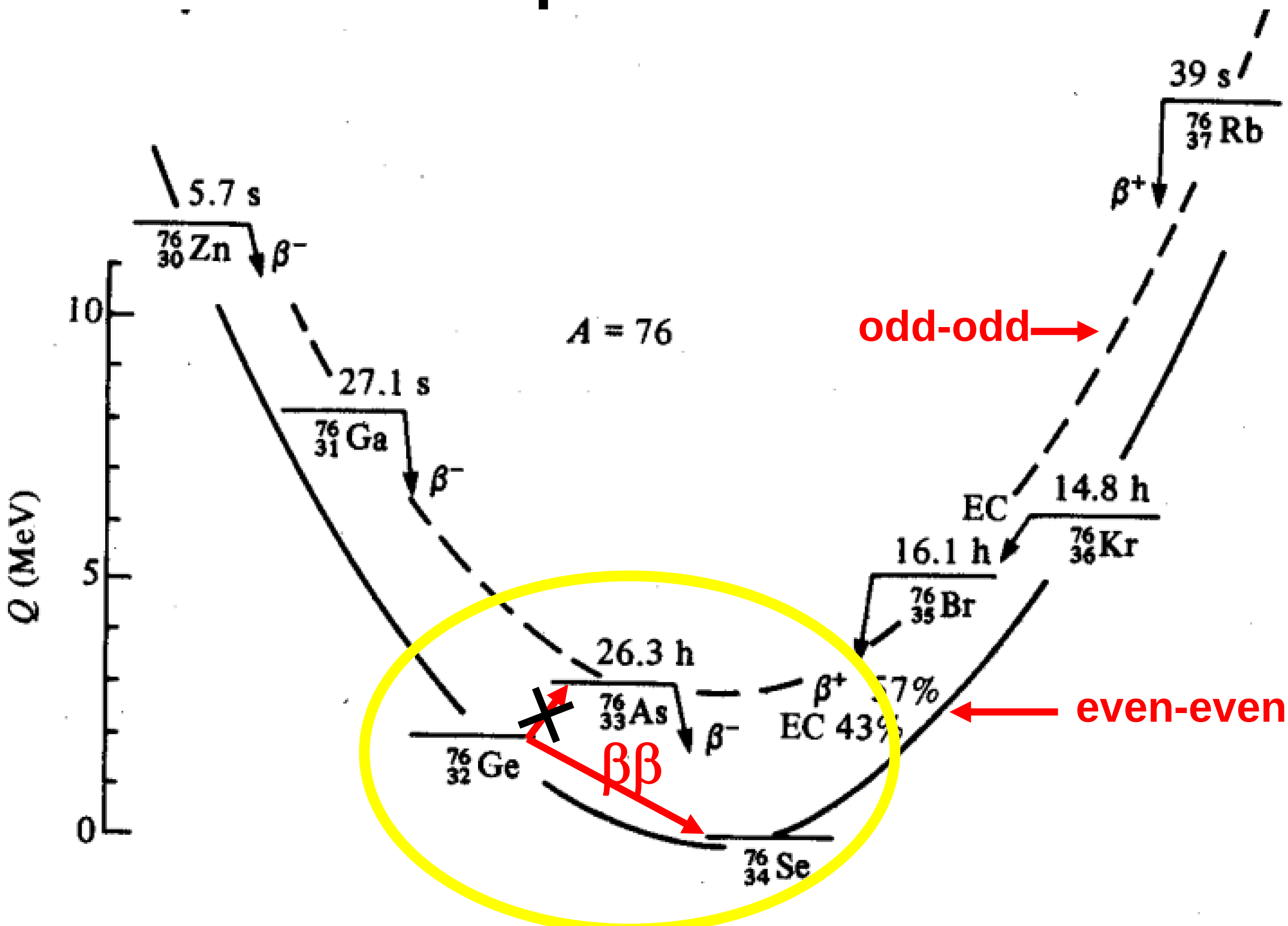
- $0\nu\beta\beta$ decay and predictions from oscillation experiments
- Comparison of DBD isotopes
- Challenges & experimental approaches
- Overview experimental projects
- Outlook

$2\nu\beta\beta$ Decay



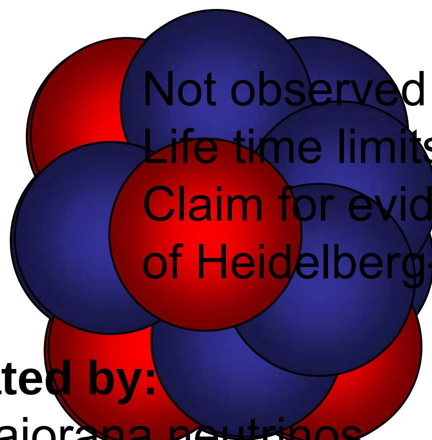
Observed in more than 10 isotopes
Life times $10^{18} - 10^{21}$ years

Mass parabolas



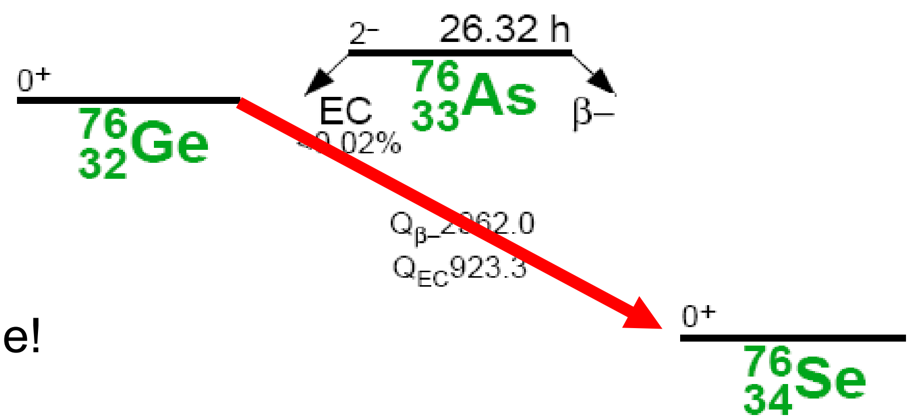
Ground states of even-even nuclei: 0^+

$0\nu\beta\beta$ Decay



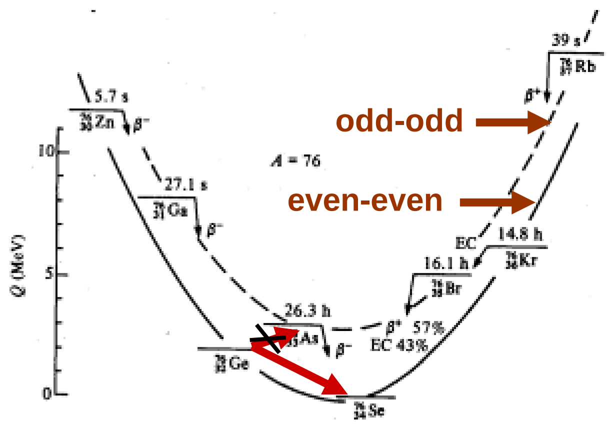
Not observed yet;
Life time limits > $10^{24} - 10^{25}$ y;
Claim for evidence in Ge-76 by part of Heidelberg-Moscow Collab.

$0\nu\beta\beta$ can be generated by:
- exchange of light Majorana neutrinos
- SUSY
- LR
- …..



Schechter & Valle:
if $0\nu\beta\beta$ observed $\Rightarrow$ ν is Majorana particle!

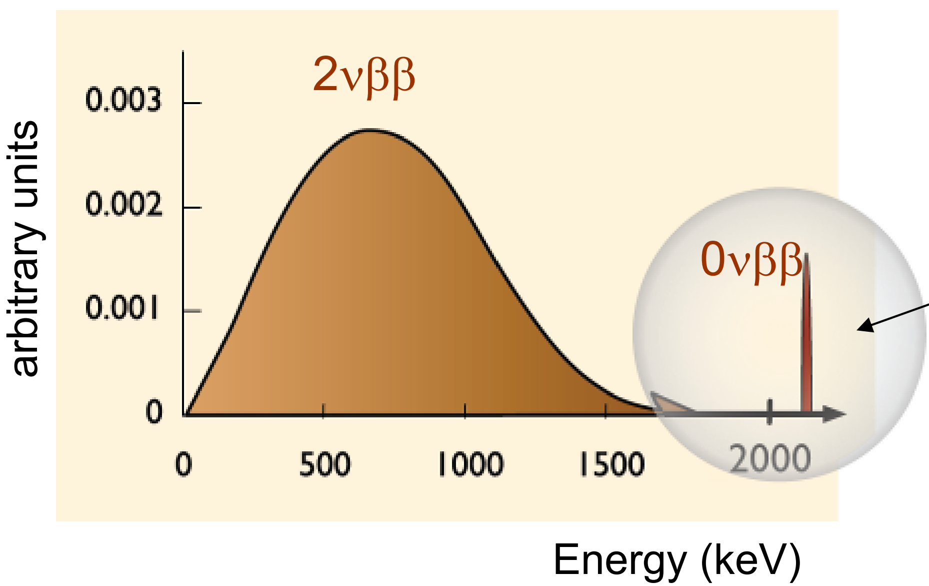
Phenomenology of 0ν- and 2νββ decay



2νββ: $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\,\bar{\nu}_e$ **ΔL=0**

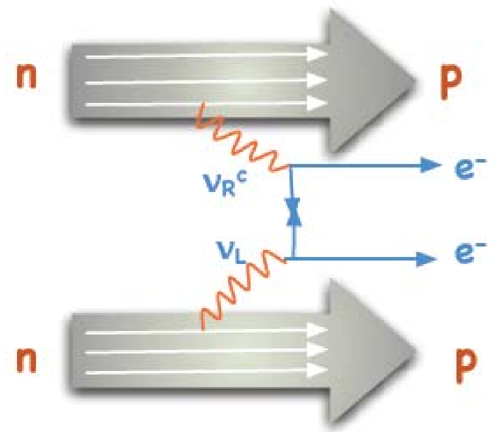
$$T_{1/2}^{2\nu} = (10^{18}\text{-}10^{21})\,\mathrm{y}$$

0νββ: $(A,Z) \rightarrow (A,Z+2) + 2e^-$ **ΔL=2**



Experimental signatures:
- peak at $Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e$
- two electrons from vertex
- production of grand-daughter isotope

Decay rate and effective neutrino mass



Assume leading term is exchange of light Majorana neutrinos

Expected decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \,\langle m_{ee}\rangle^2$$

Phase space integral

HK 9.7 P.Grabmayr

Nuclear matrix element

$$Q = E_{e1} + E_{e2} - 2m_e$$ Q-value of decay

$$\langle m_{ee}\rangle = \left|\sum_i U_{ei}^2\, m_i\right|$$ Effective neutrino mass

U_{ei} (complex) neutrino mixing matrix

0νββ: physics implications

T.Schwetz-Mangold

1) Dirac vs. Majorana particle: (i.e. its own anti-particle)?

- 0νββ ⇒ Majorana nature
- Majorana ⇒ See-Saw mechanism $m_\nu = \frac{m_D^2}{M_R} << m_D$

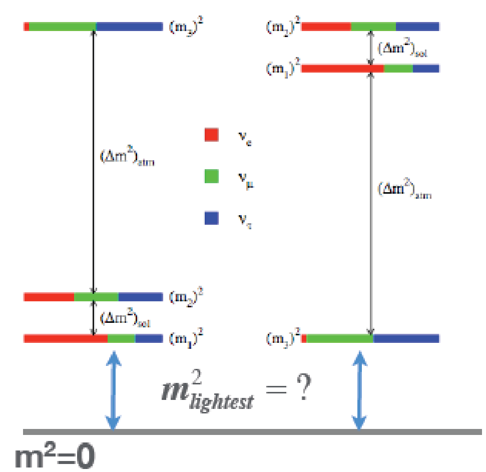
$$m_3 \sim \left(\Delta m^2_{atm}\right)^{1/2}, \;\; m_D \sim m_t \Rightarrow M_R \sim 10^{15}\,GeV$$

- Majorana ⇒ CP violation in M_R → higgs + lepton

  ⇒ Leptogenesis ⇒ B asymmetry

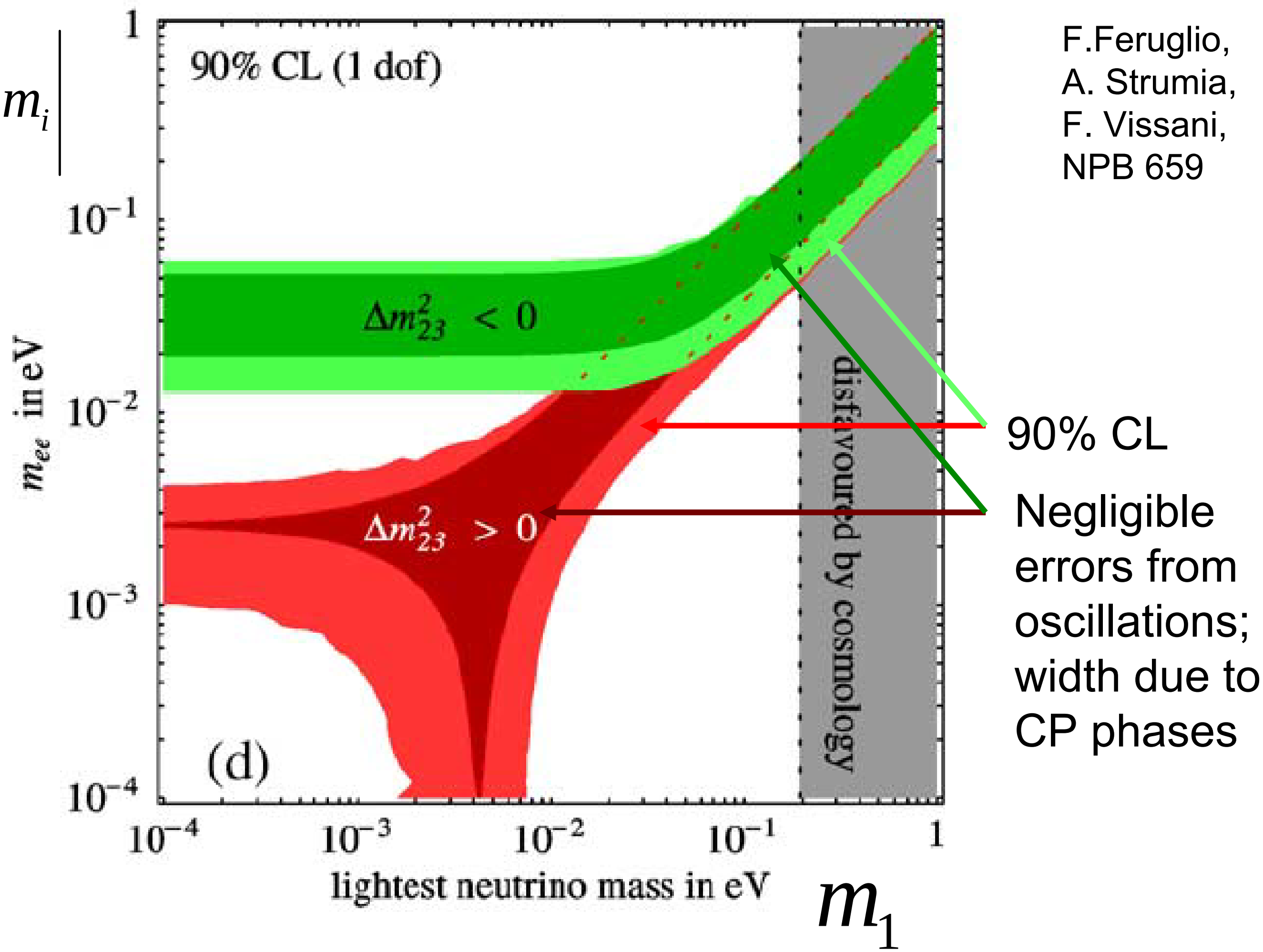
2) Absolute mass scale:

- Hierarchy: degenerate, inverted or normal
- (effective) neutrino mass



Predictions from oscillation experiments

$$\langle m_{ee} \rangle = \left| \sum_i U_{ei}^2 \, m_i \right|$$

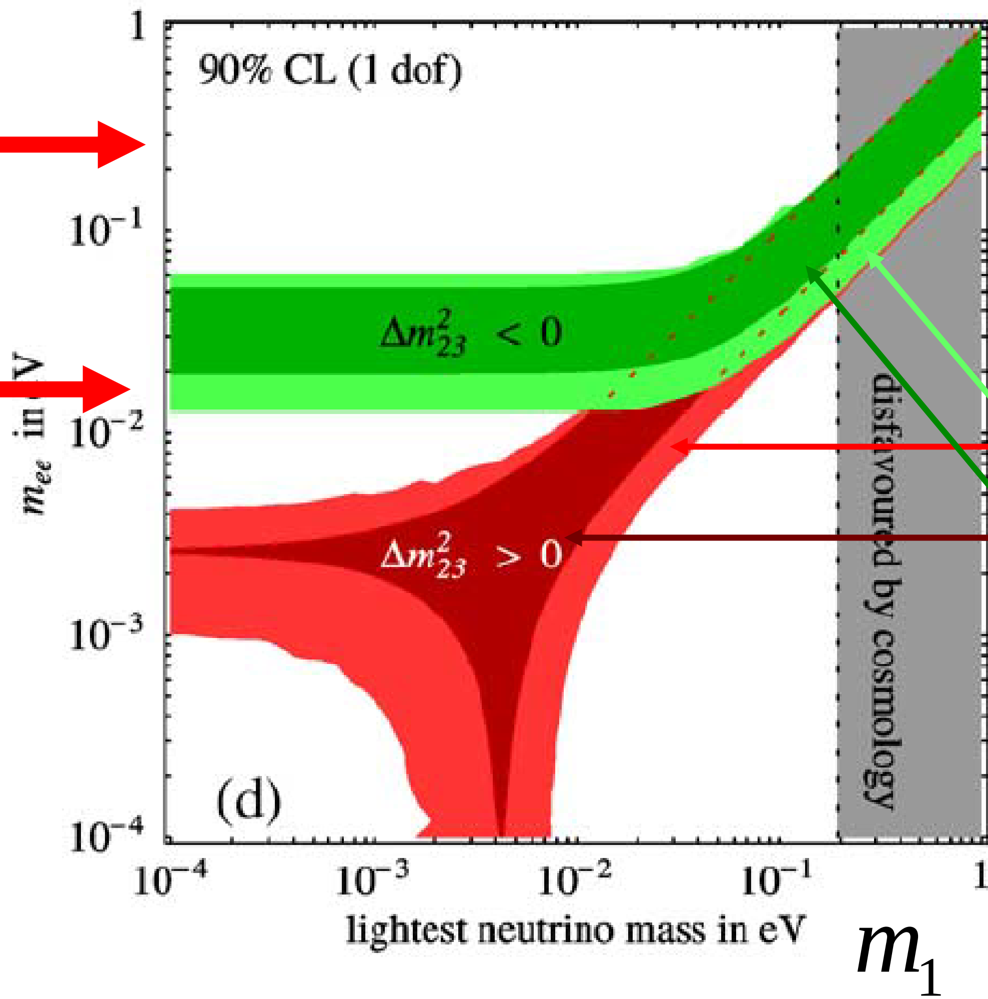


F.Feruglio,
A. Strumia,
F. Vissani,
NPB 659

Predictions from oscillation experiments

KDKC claim:
[0.17-0.45] eV
(PRD79)

Goal of next generation experiments:
~10 meV



F.Feruglio,
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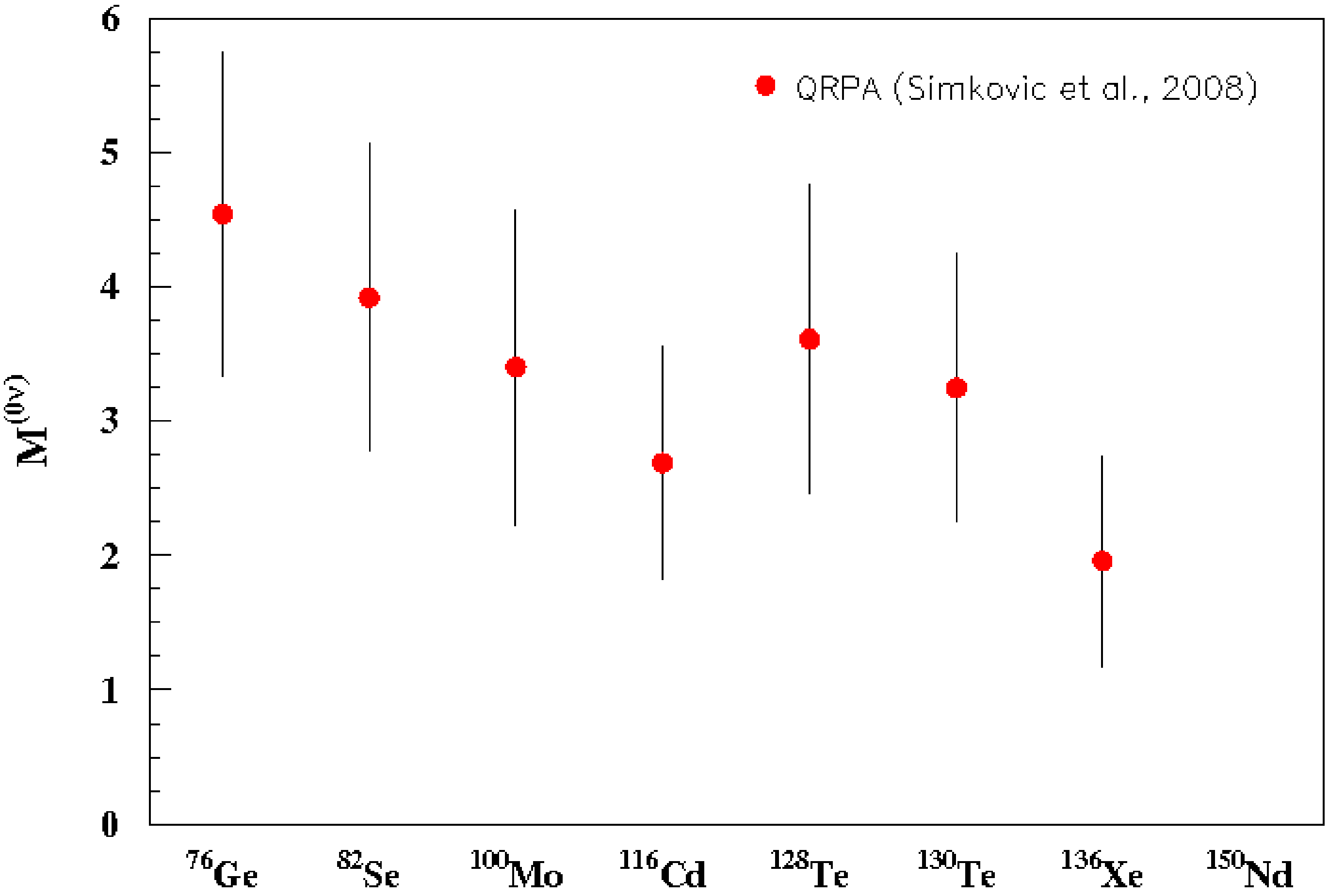
NPB 659

90% CL

Negligible errors from oscillations; width due to CP phases

Comparison of DBD isotopes: Recent calculations of nuclear matrix elements



QRPA calculations from other groups give similar results

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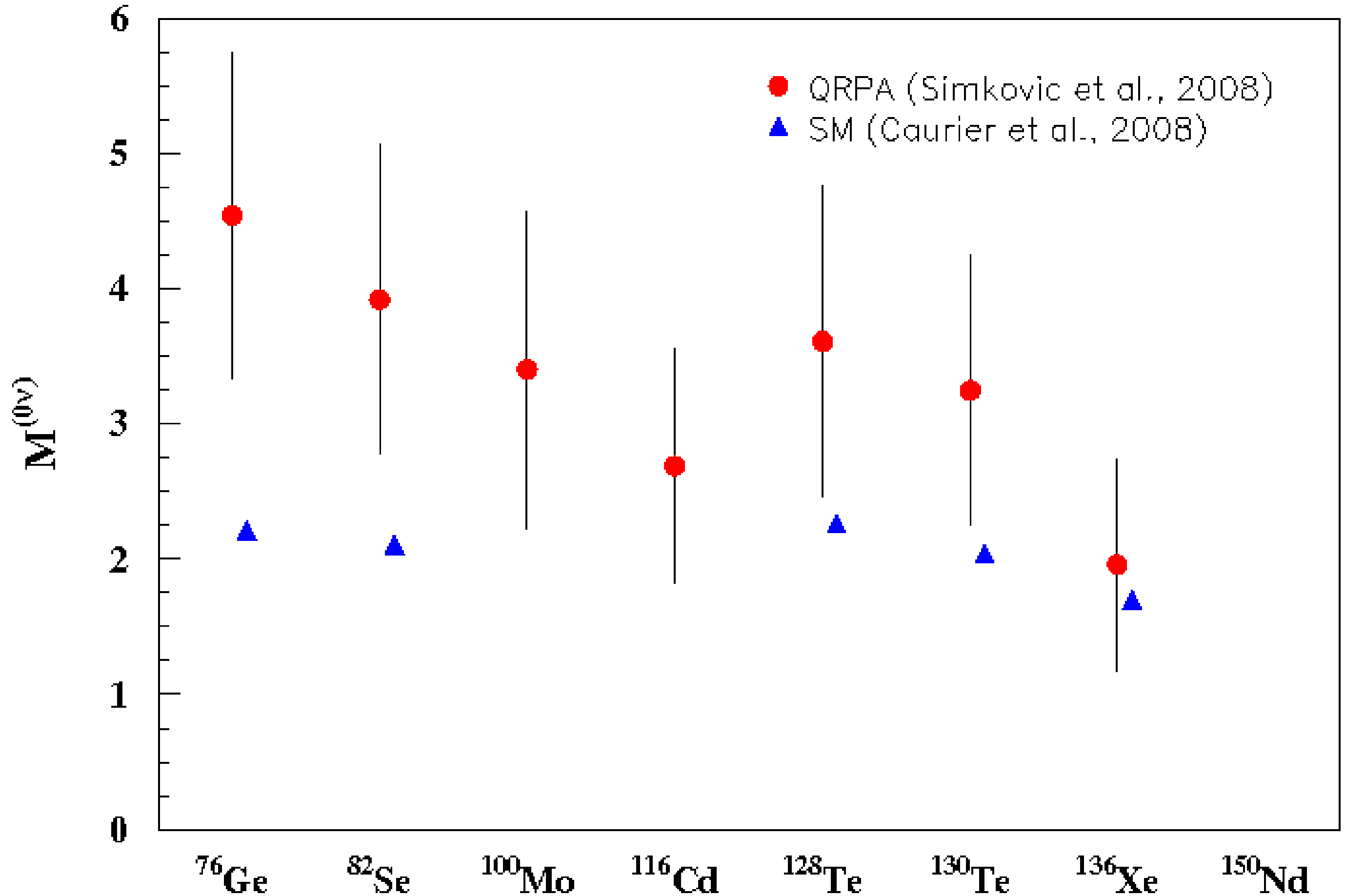
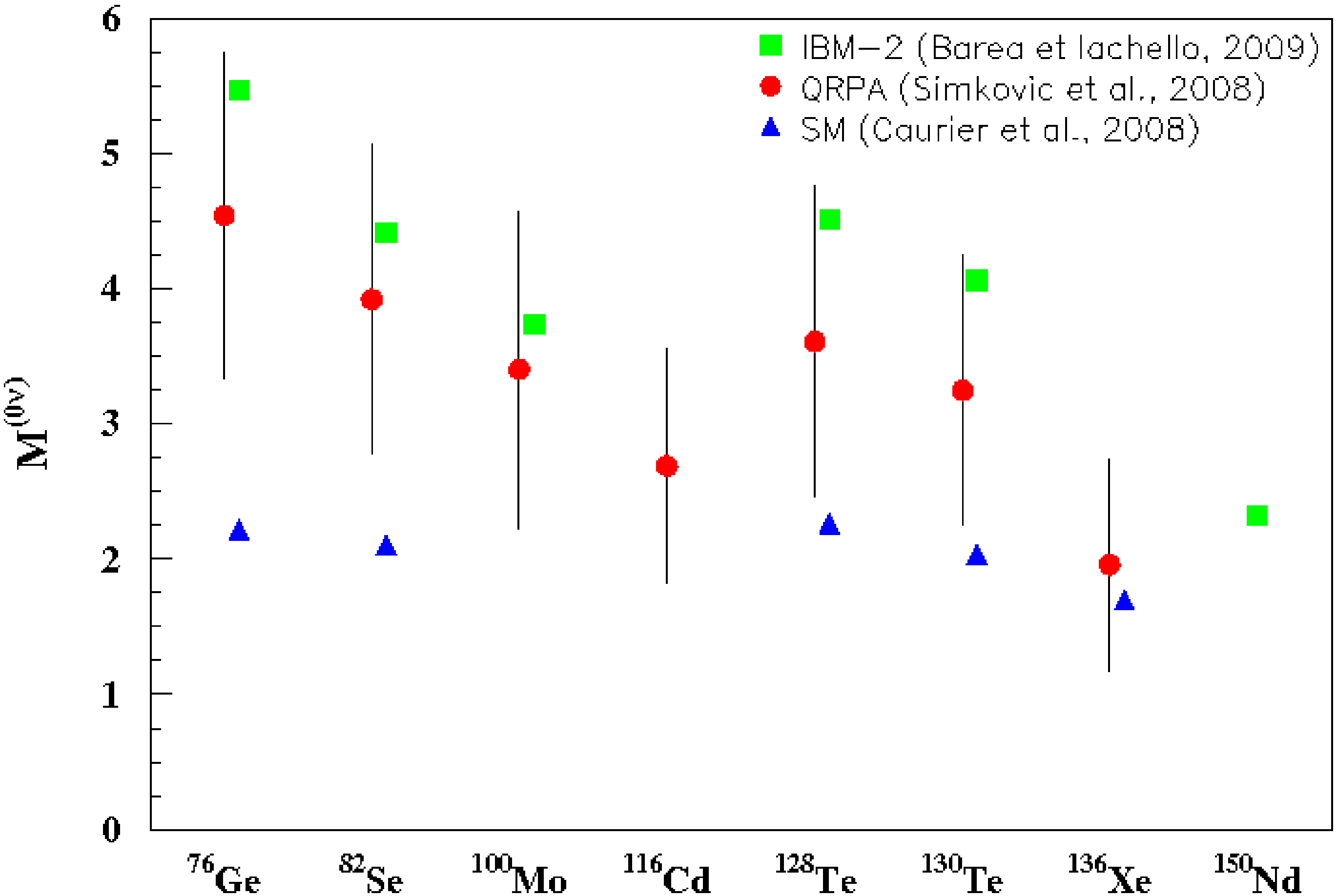


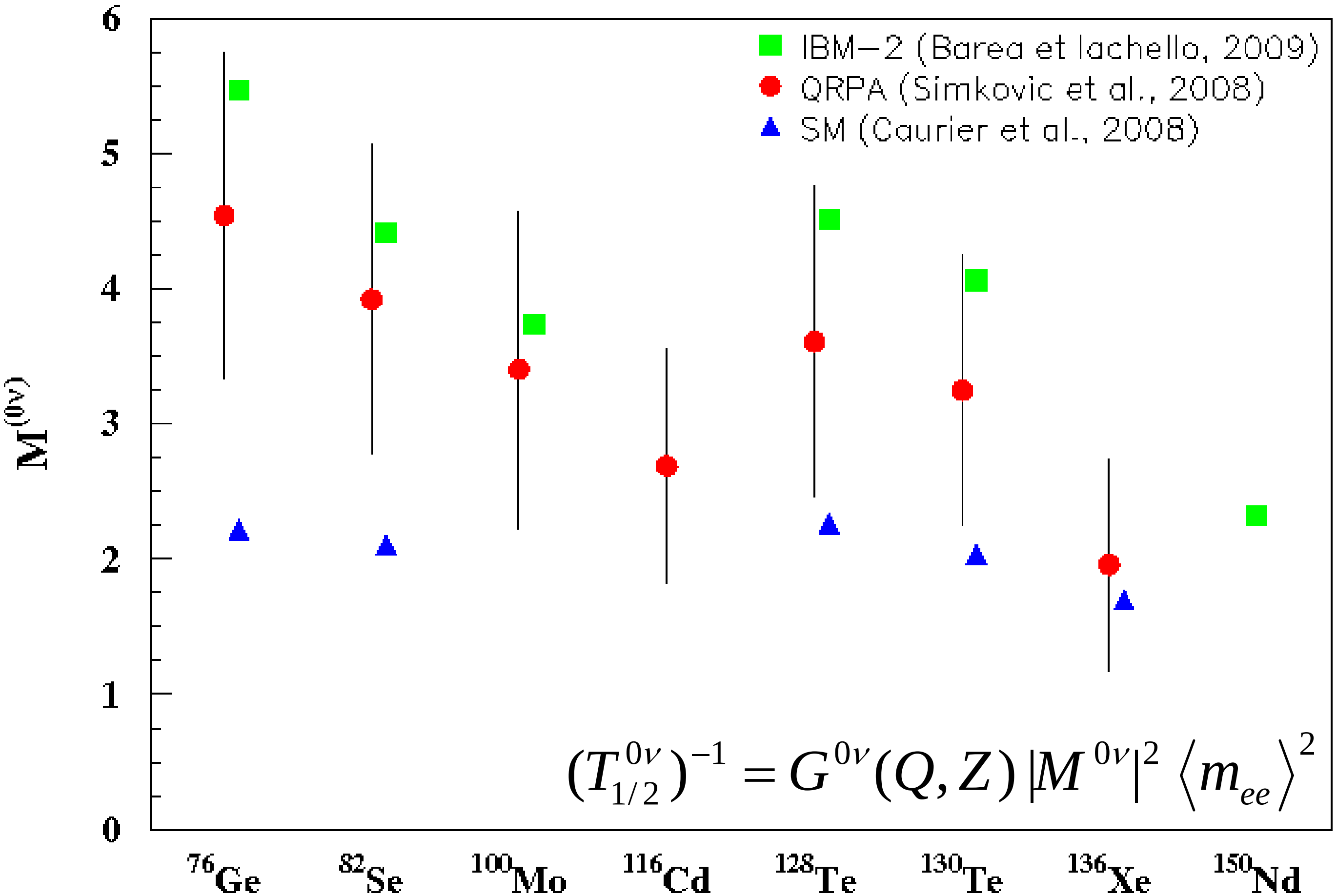
But shell model and QRPA calculations still disagree up to a factor 2 for lighter nuclei

Comparison of DBD isotopes: Recent calculations of nuclear matrix elements



New IBM-2 calculations agree (coincide?) with QRPA values! Score 2:1 ?
IBM-2 includes deformations for ^{150}Nd

Comparison of DBD isotopes: Recent calculations of nuclear matrix elements

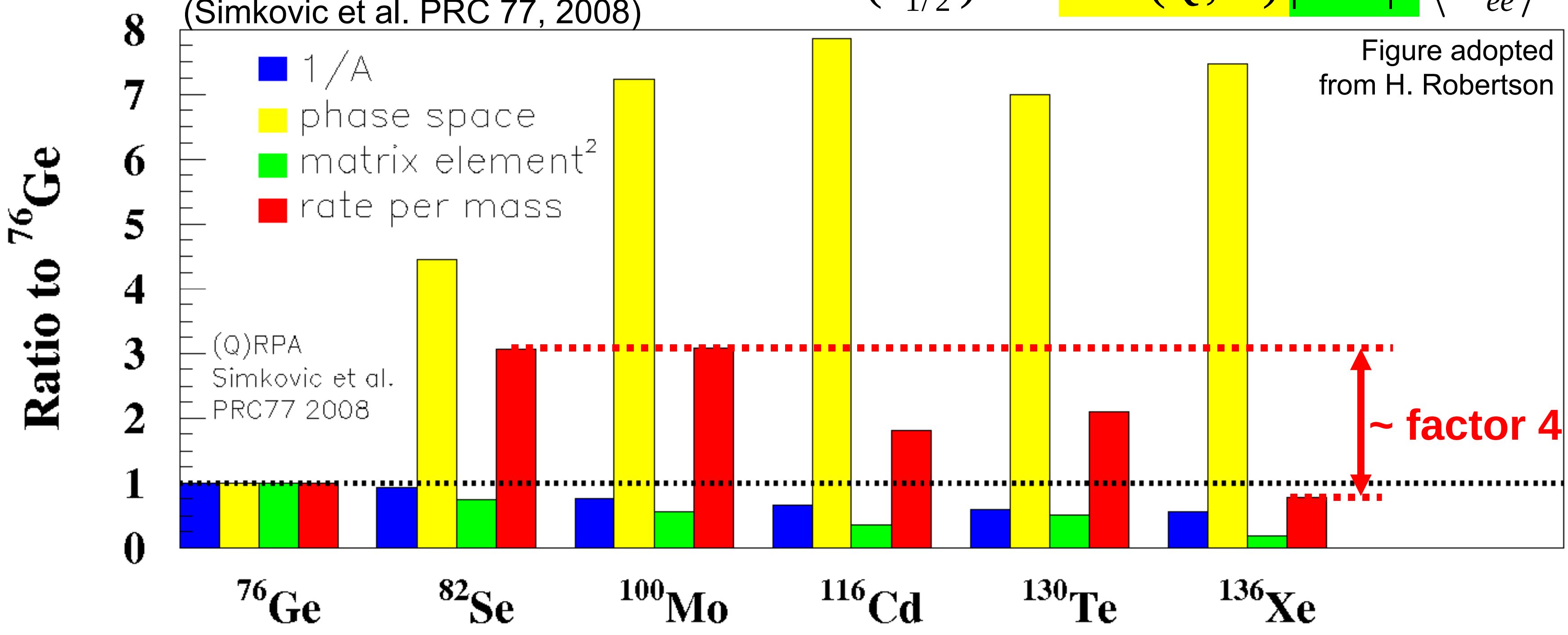


Is M decreasing with $A^{-2/3}$ (IBM-2, QRPA) or constant with A (SM) ?

Comparison of isotopes:
Is there a *super-DBD-isotope* ?

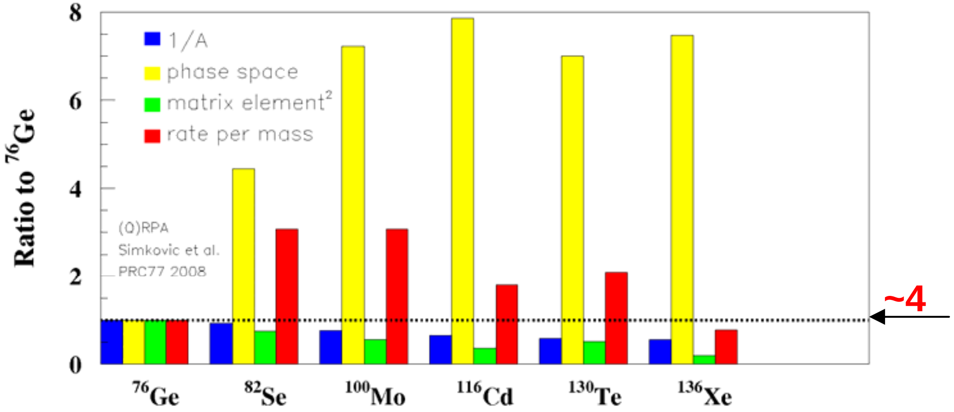
QRPA
(Simkovic et al. PRC 77, 2008)

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2 \langle m_{ee} \rangle^2$$



Expected 0νββ **rates per mass** vary within a factor ~ 4 !

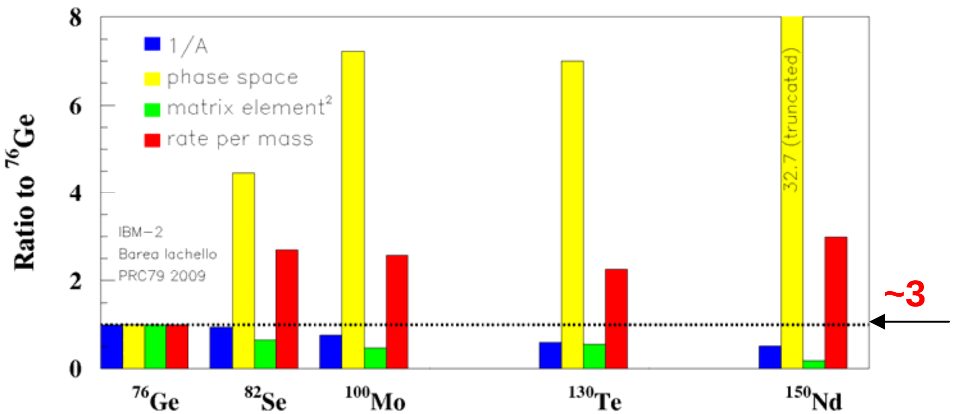
QRPA
(Simkovic et al. PRC 77, 2008)



for $\langle m \rangle = 50\,\text{meV}$:

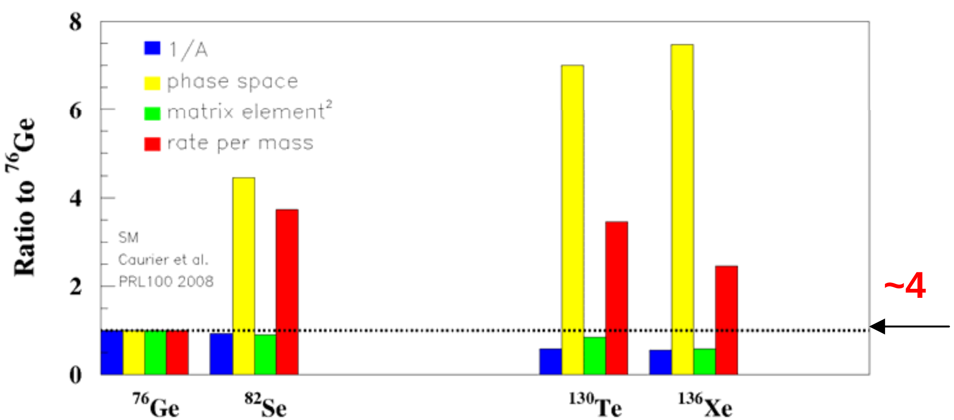
9.1 cts/(ton year)

IBM2
(Barea and Iachello, PRC 79, 2009)



13.2 cts/(ton year)

SM
(Caurier et al., PRL 100, 2008)



2.2 cts/(ton year)

Experimental sensitivity

Without bkgd: $\langle m \rangle \leq \frac{const}{(M\,T)^{1/2}}$

With bkgd: $\langle m \rangle \leq const \left(\frac{b\,\Delta E}{M\,T} \right)^{1/4}$

$M\,T$: exposure [kg y]

b : background rate at $Q_{\beta\beta}$ [cts/kg/keV/year]

ΔE : energy resolution

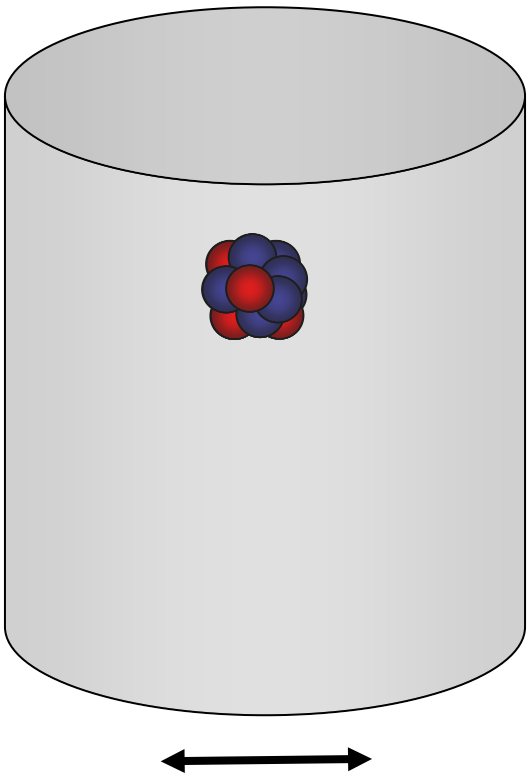
⇒ Maximize number of nuclei under observation

⇒ Minimize background (radioactivity, cosmics) in energy window at $Q_{\beta\beta}$ ("background free")

⇒ 1 ton of isotopes **AND** $b \cdot \Delta E < 10^{-3}$ / kg y for 10 meV scale

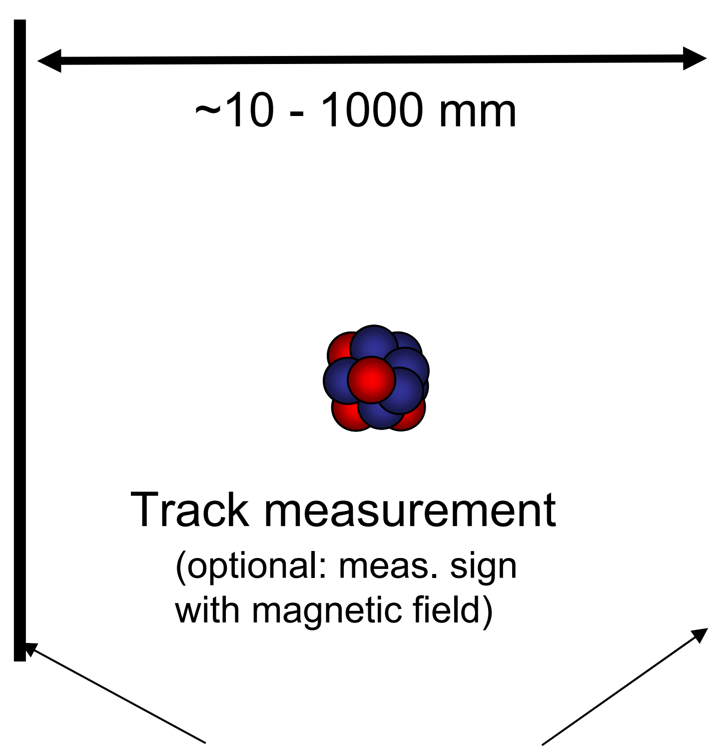
Two ways to measure $0\nu\beta\beta$ decay

Source = Detector

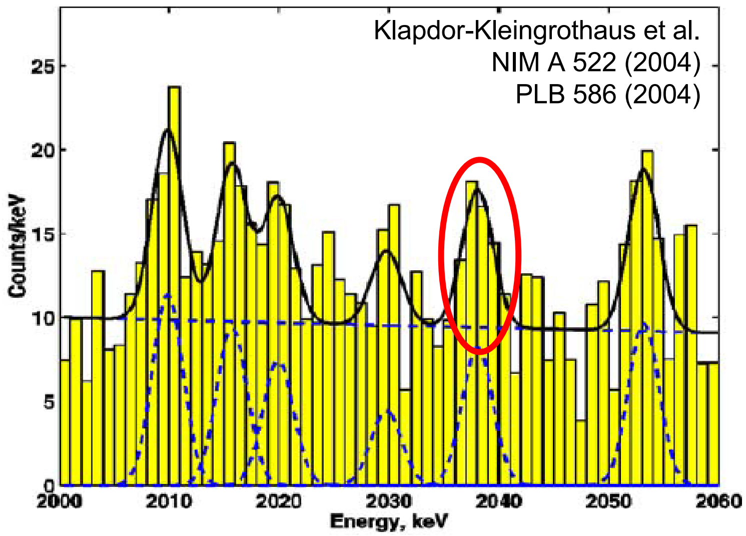


Calorimetry
&
tracking

Source ≠ Detector

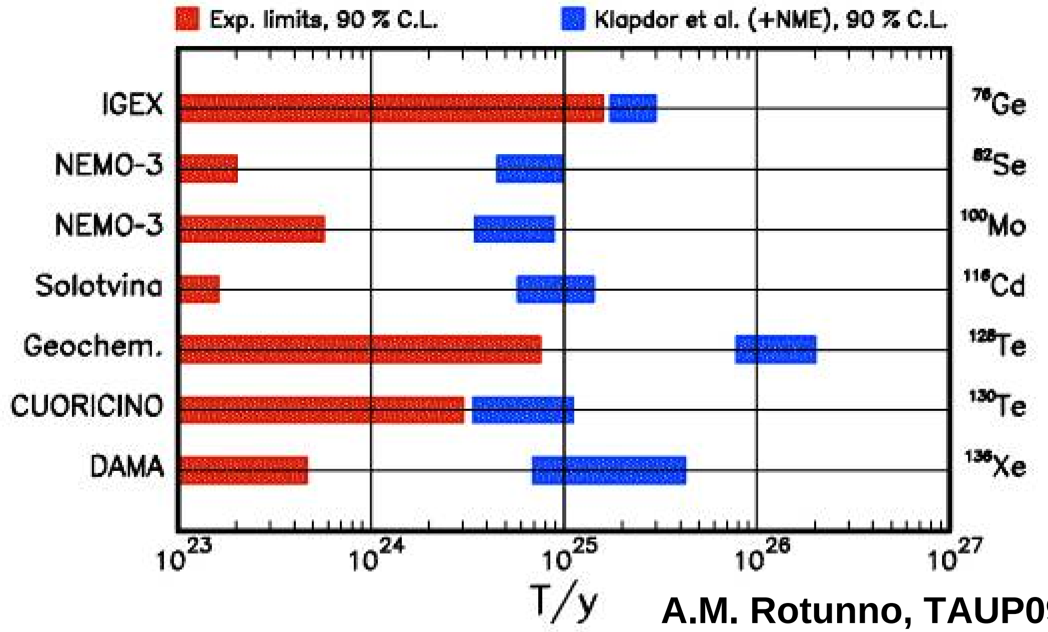


State-of-the-art: limits & claim



Significance and $T_{1/2}$ depend on bgd discription:
- Strumia & Vissani Nucl.Phys. B726 (2005)
- Chkvorets, PhD dissertation Univ. HD, (2008): using realistic background model
  - ⇒ peak significance: 1.3σ,
  - ⇒$T_{1/2} = 2.2 \times 10^{25}$ y

- 71.7 kg year - Bgd 0.11 / (kg y keV)
- 28.75 ± 6.87 events (bgd:~60)
- Claim:4.2σ evidence for $0\nu\beta\beta$
- (0.69–4.18) $\times 10^{25}$ y (3σ)
- Best fit: 1.19 $\times 10^{25}$ y (NIMA 522/PLB 586)
- PSA analysis (Mod. Phys. Lett. A21): (2.23 + 0.44 – 0.31)$\times 10^{25}$ y (6σ)
- Tuebingen/Bari group (PRD79): m_{ee} /eV = 0.28 [0.17-0.45] 90%CL



A.M. Rotunno, TAUP09 (PRD 79)

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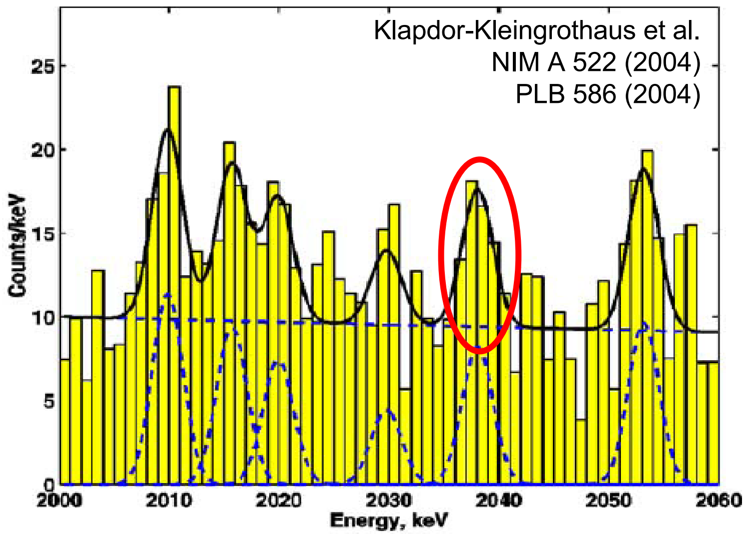

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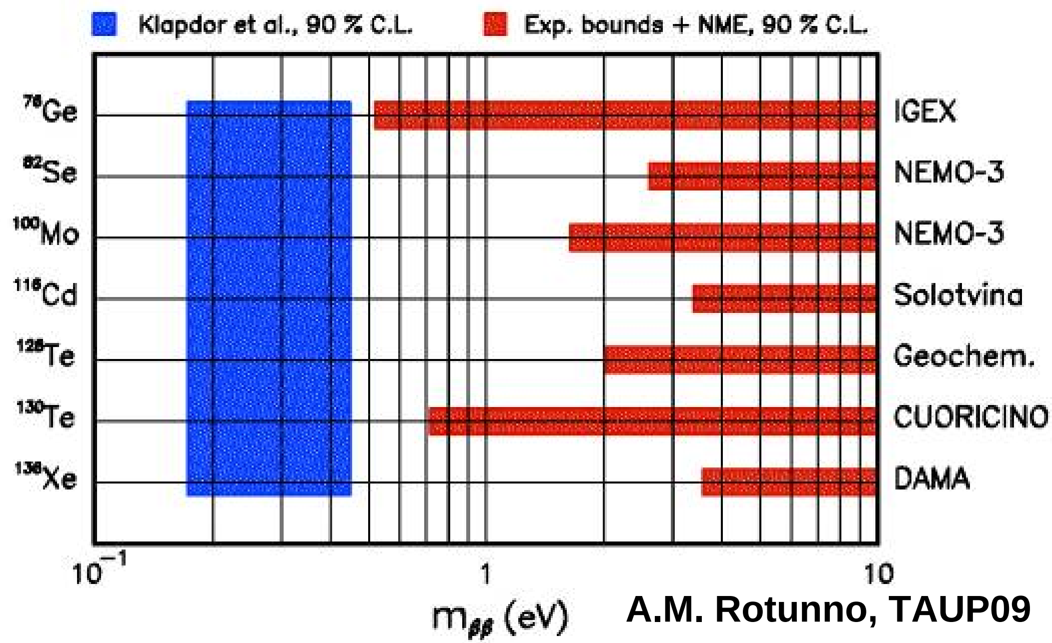
  $\Rightarrow$ peak significance reduced to 1.3σ,
  $\Rightarrow T_{1/2} = 2.2\times 10^{25}$ y



A.M. Rotunno, TAUP09

$\Rightarrow$ Claim must be scrutinized with ^{76}Ge AND other isotopes

Overview of Experiments

Name	Nucleus	Mass*	Method	Location	Time line
Running & recently completed experiments					
CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2010 (commis.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (commis.)
LUCIFER	Se-82 (Mo-100)	18 (11) kg	bolom./scint.	LNGS	2013 (commis.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
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SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48		scintillation	Solotvina	
COBRA	Cd-116, Te-130		ionization	LNGS	
DCBA	Nd-150		drift chamber	Kamioka	
EXO gas	Xe-136		gas TPC	SNOlab	
MOON	Mo-100		tracking	Oto	
Other decay modes					
TGV	Cd-106		ionization	LSM	operational

***: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%**

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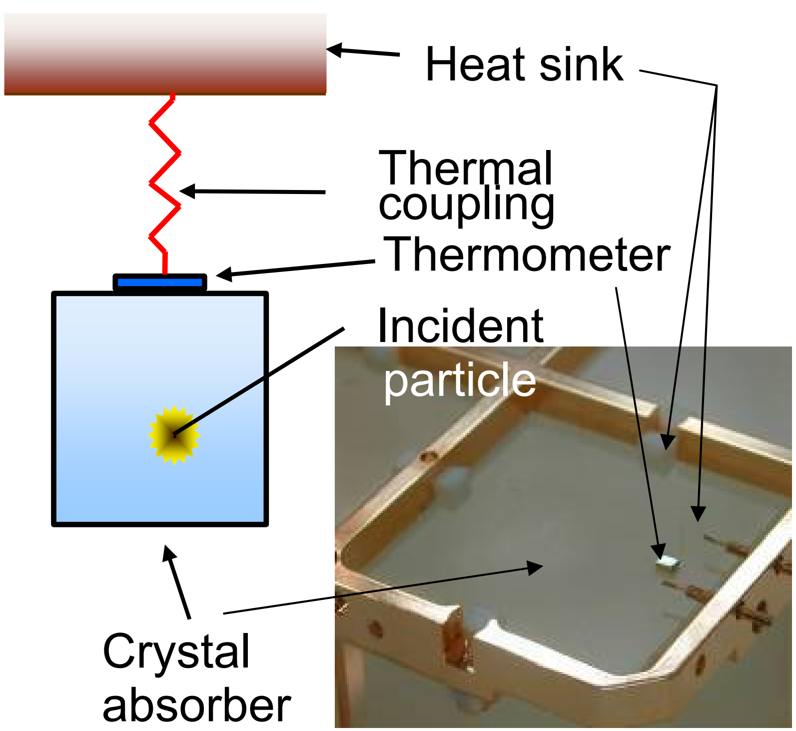
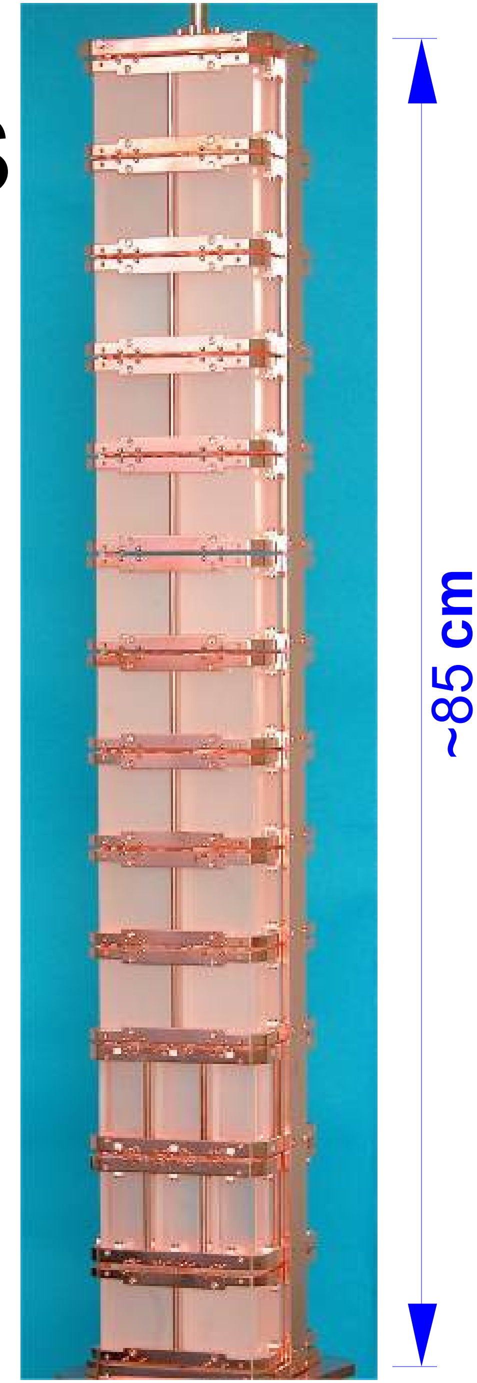
^{130}Te: Cuoricino @ LNGS

Cryogenic detector

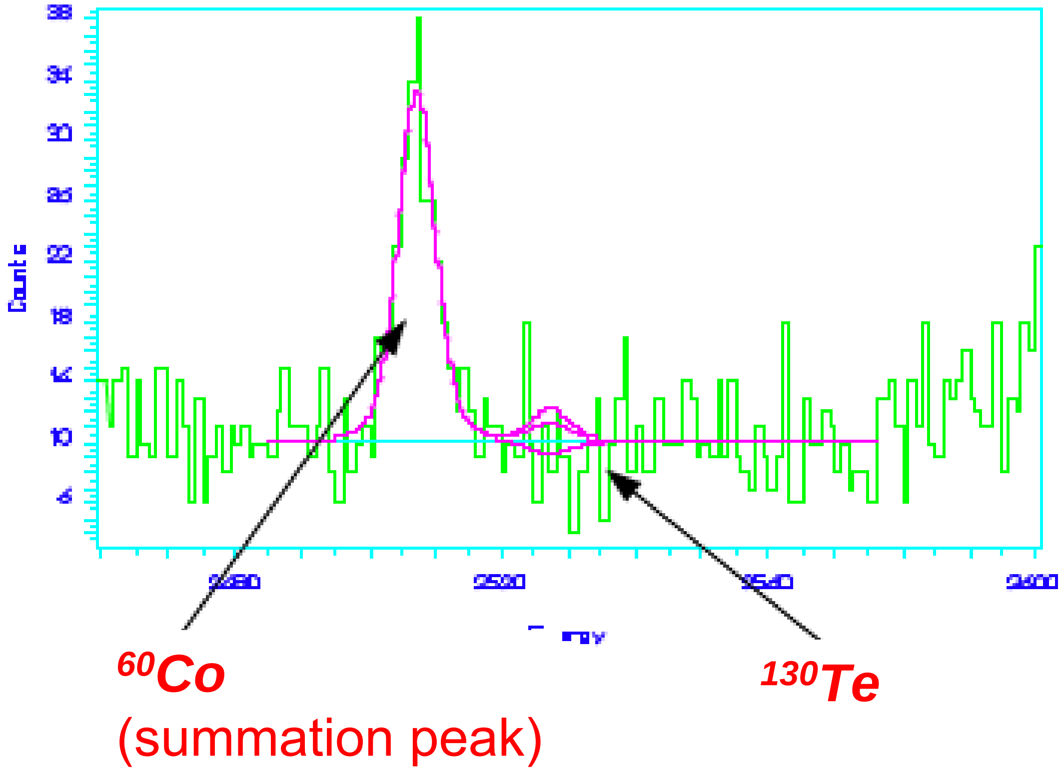


Measurement of $\Delta T = E/C$

- 41 kg TeO_2
- nat. abundance of ^{130}Te: 34%
- active mass: 11 kg of ^{130}Te
- New $Q_{\beta\beta}$:
  2527.518 ± 0.013 keV
  (F. Avignone et al 2008)
  2527.01± 0.32 keV
  (R. Norman et al 2008)
  ΔE: -3 keV



Cuoricino data taking completed,….



- Cuoricino data taking successfully completed in 2008

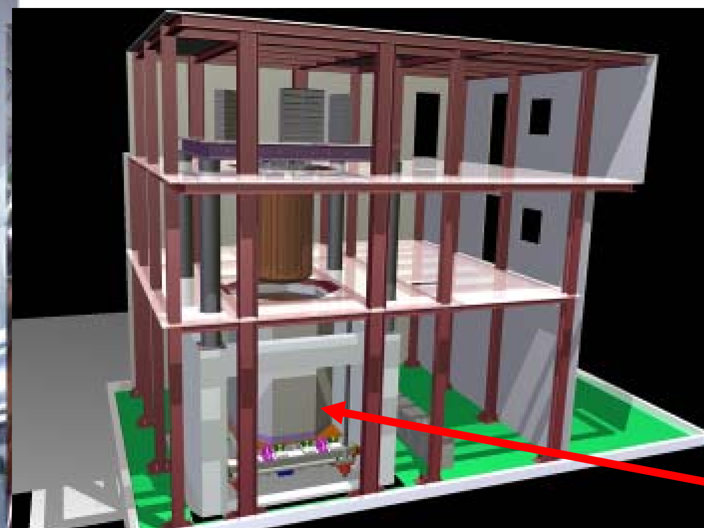
- Full statistics statistics:
  18 kg x year of ^{130}Te

- Background at $0\nu\beta\beta$:
  0.18 ± 0.02 cts/(keV kg y)
  degraded α's (60%)
  ext. ^{208}Tl γ's (40%)

- Limit on ^{130}Te $0\nu\beta\beta$ decay:
  $T_{1/2}$ > 2.94x10^{24} y (90% C.L.)
  m_{ee}< 0.2 – 0.98 eV

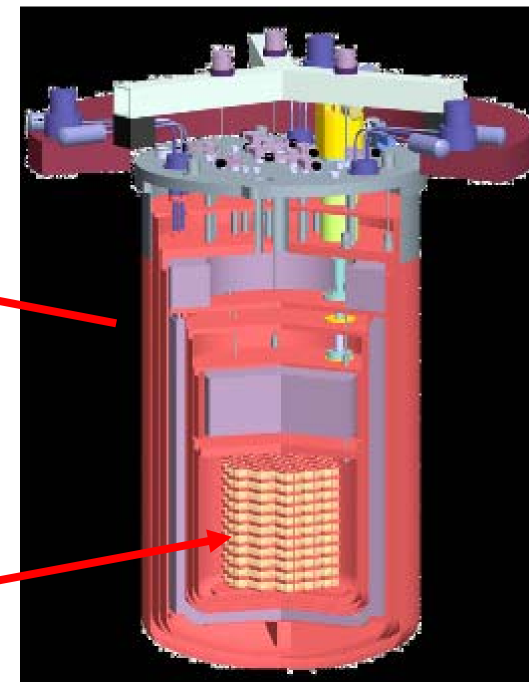
(M. Sisti, Taup 09)

…CUORE construction started..

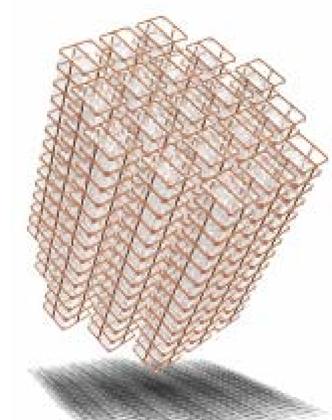


The COURE building in hall A of LNGS

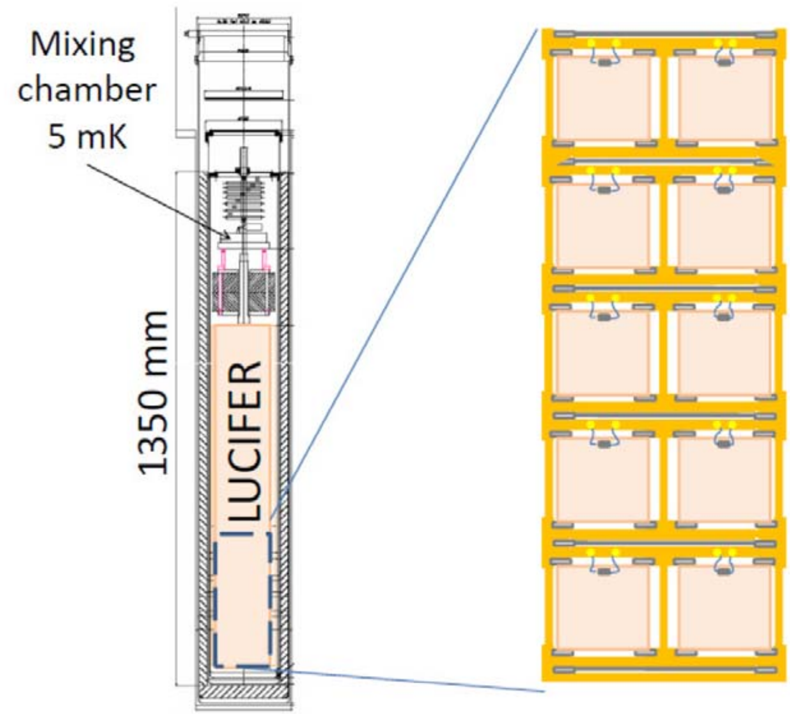
Cryostat order placed

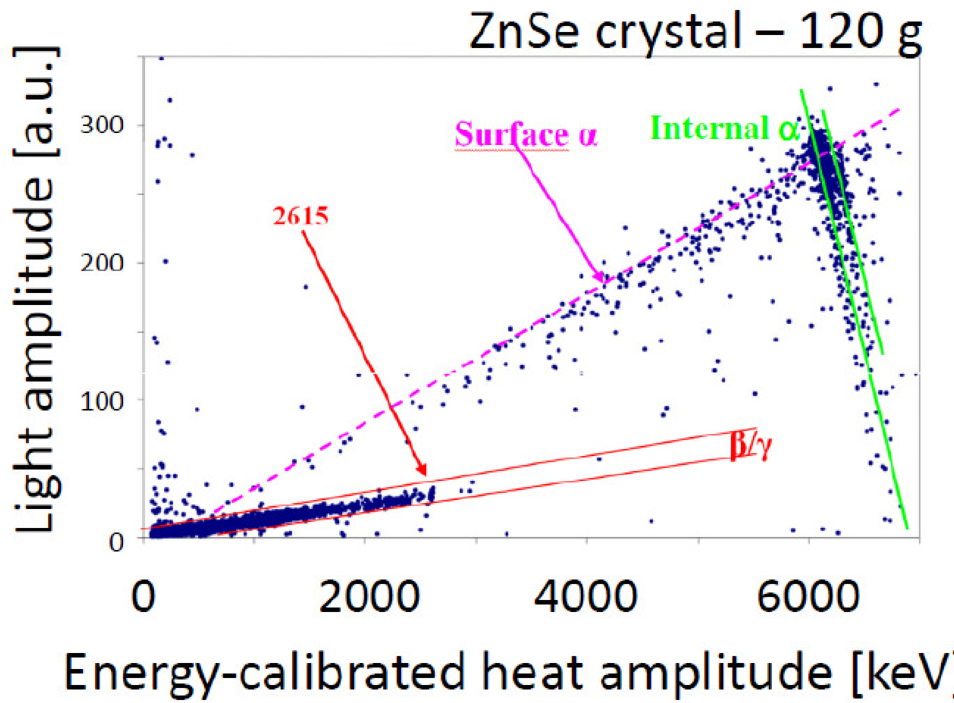


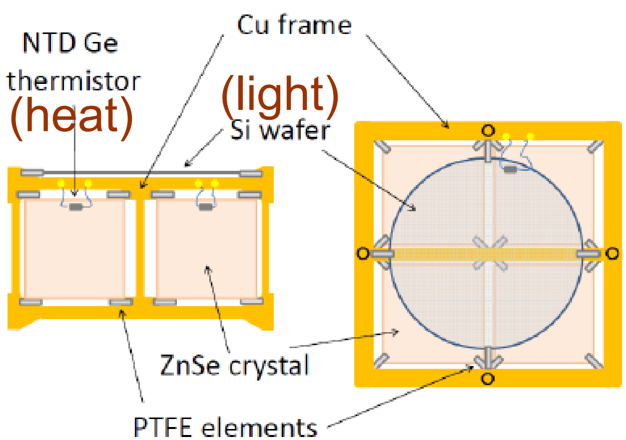
988 TeO_2 5x5x5 cm3 crystals => 741 kg TeO_2 => 204 kg ^{130}Te



…. and LUCIFER is funded!







Suppression of surface alphas by simultaneous read-out of heat & light

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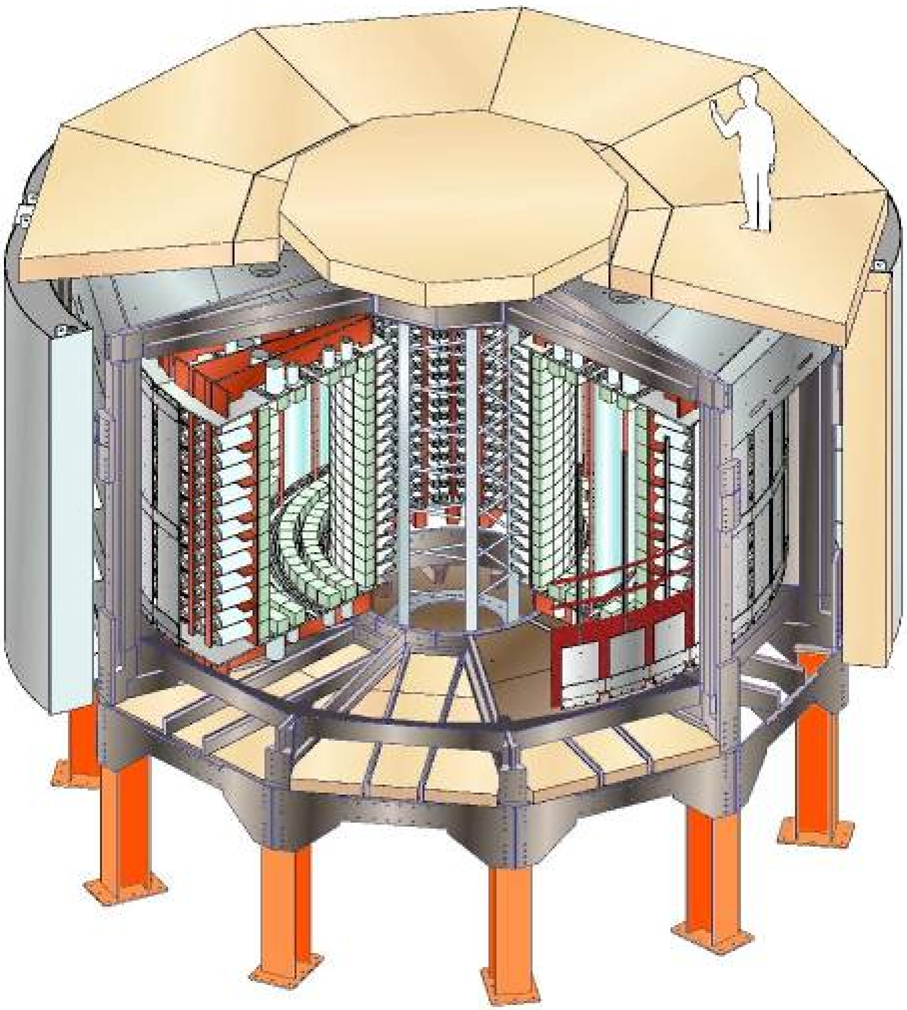
NEMO 3 @ LSM: The '2νββ factory'…



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m^2, 60 mg/cm^2

Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water
+ Wood

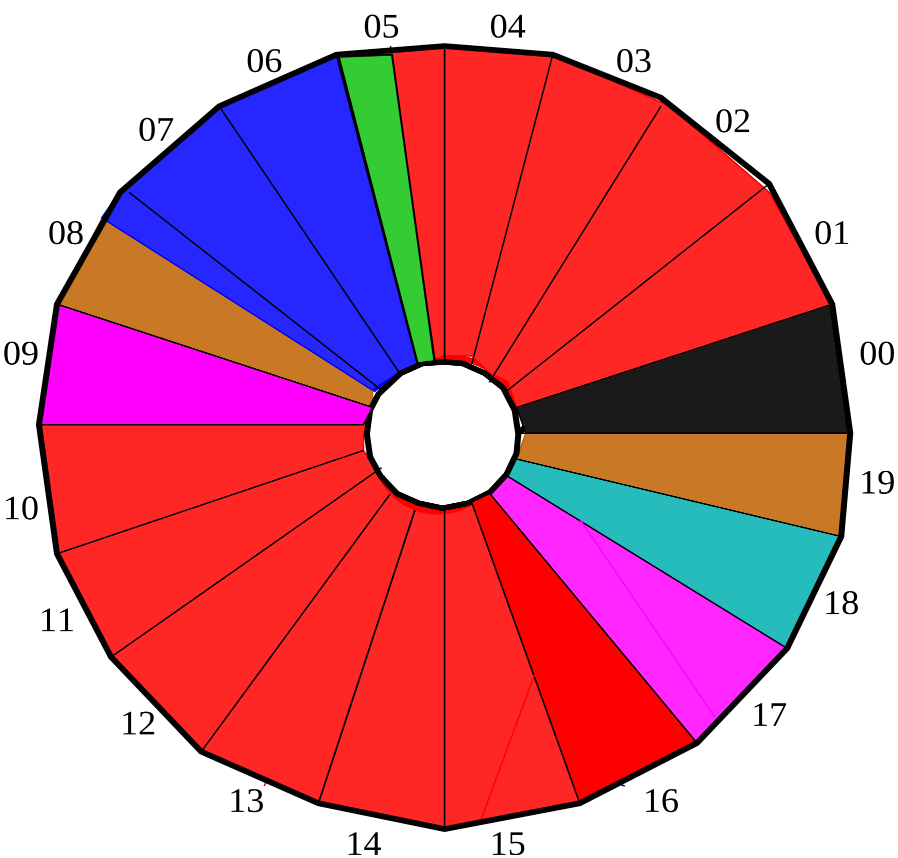
….and its sources

^{100}Mo 6.914 kg $Q_{\beta\beta}$ = 3034 keV

&

^{82}Se 0.932 kg $Q_{\beta\beta}$ = 2995 keV

→ **0νββ decay search**



^{116}Cd 405 g $Q_{\beta\beta}$ = 2805 keV

^{96}Zr 9.4 g $Q_{\beta\beta}$ = 3350 keV

^{150}Nd 37.0 g $Q_{\beta\beta}$ = 3367 keV

^{48}Ca 7.0 g $Q_{\beta\beta}$ = 4272 keV

^{130}Te 454 g $Q_{\beta\beta}$ = 2529 keV

} **2νββ decay measurement**

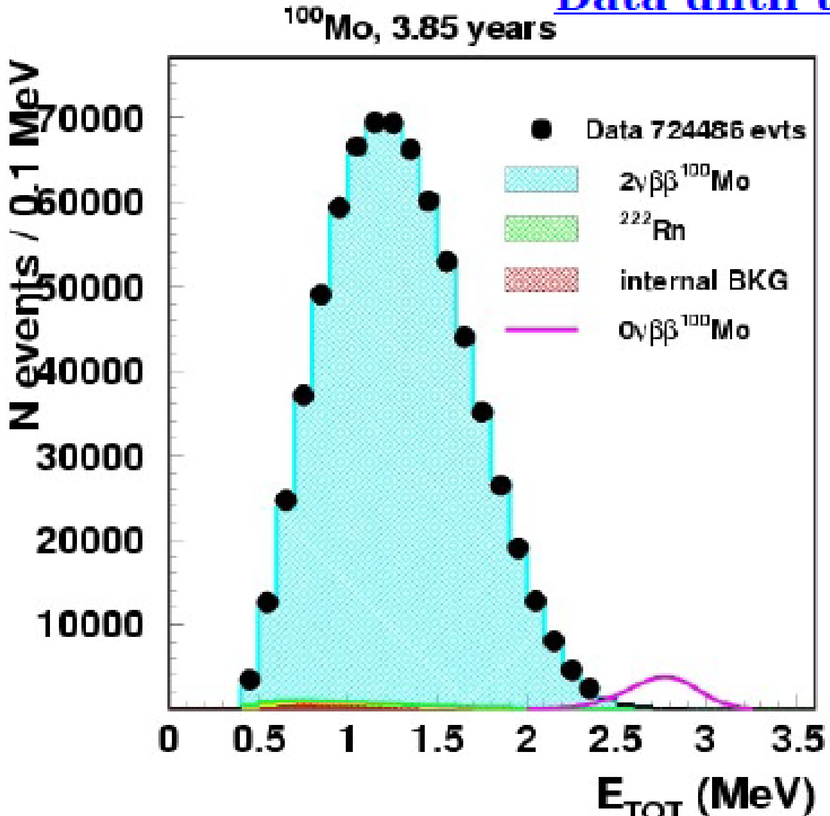
^{nat}Te 491 g

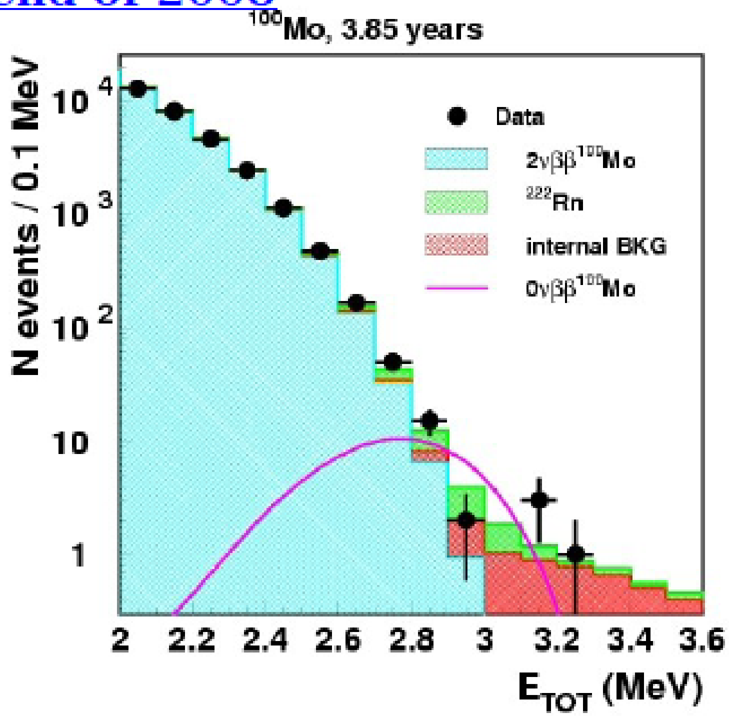
Cu 621 g

} **External background measurement**

Results from NEMO3's strongest source: ^{100}Mo

Data until the end of 2008





[2.8 , 3.2] MeV:
Data: 20 events, Expected: 18.6 events
Excluded at 90% C.L. 9.6 events
Efficiency ε= 0.0726

MCLIMIT : [2.0, 3.2] MeV
18 events excluded
Total mean 0ν efficiency ε = 0.174

$T_{1/2}$ (0ν) > 1.1 · 10^{24} y @90% C.L.

<mν> < 0.45 – 0.93 eV

V. Tretyak (Medex'09), also F. Mauger (Taup09)

From NEMO3 to SuperNEMO

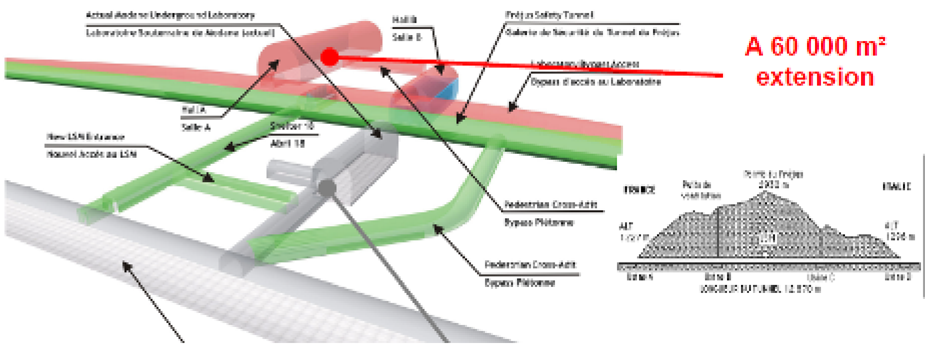
NEMO3		SuperNEMO
$T_{1/2}$ > 1.4 x 10^{24} y <m> < 390 – 810 meV	EXPECTED SENSITIVITY	$T_{1/2}$ > 1 – 1.5 x 10^{26} y <m> < 43 – 145 meV *
7 kg	Mass of Isotopes	100 – 200 kg
8 % FWHM @ 3 MeV	Calorimeter Resolution	4 % FWHM @ 3 MeV
18 %	Efficiency	30 %
^{208}Tl < 20 µBq / kg ^{214}Bi < 300 µBq / kg	Foils Radiopurity	^{208}Tl < 2 µBq / kg ^{214}Bi < 10 µBq / kg

NME : E. Caurier et. al., Phys. Rev. Lett. 100 (2008) 052503
Tübingen Simkovic et al., Phys. Rev. C 77 (2008) 045503
Jyvaskyla Suhonen et al. Int. J. Mod. Phys. E 17 (2008) 1

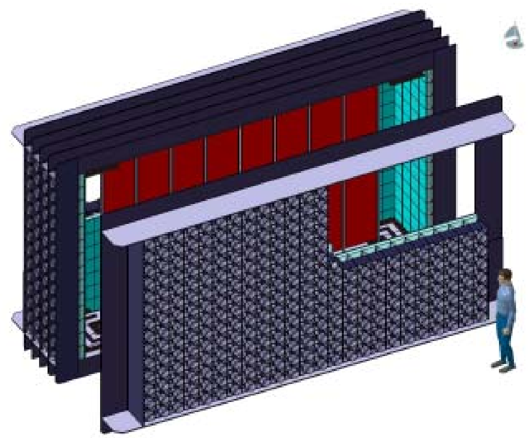
* : for ^{82}Se

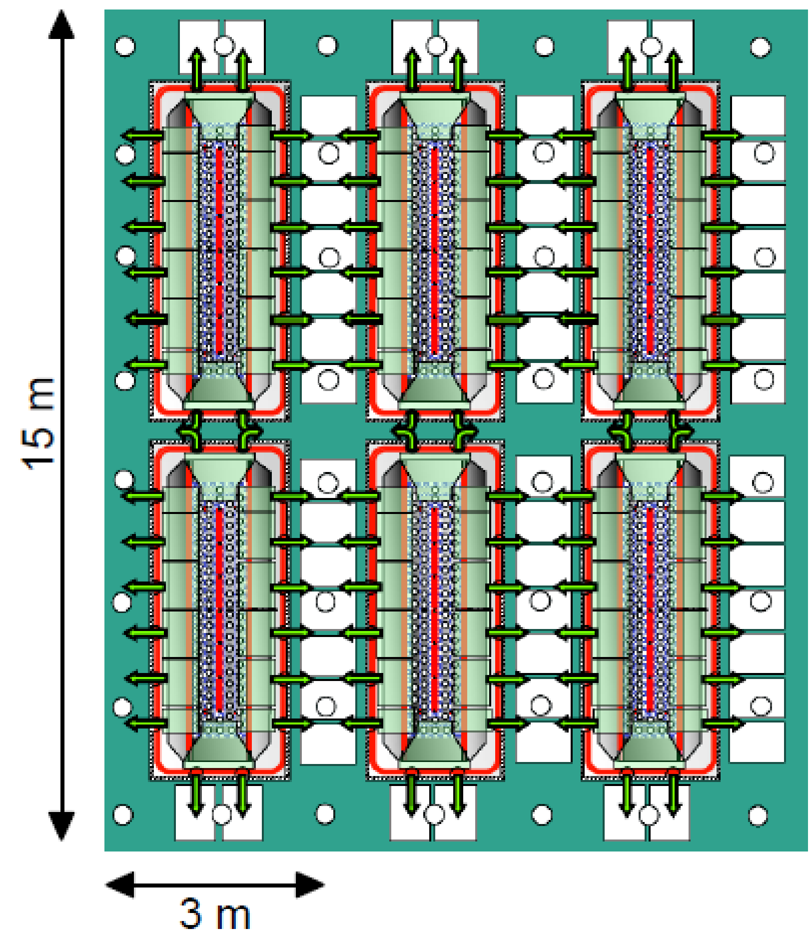
Baseline: ^{82}Se
Alternatives: ^{150}Nd, ^{48}Ca

SuperNEMO at the new LSM



- 5 - 7 kg of ββ isotope per module
- 20 - 22 modules for the full detector
  for 100 – 150 kg of isotope in total
- modules surrounded by water shielding
- Location: LSM (France)
- demonstrator operational 2011





Name	Nucleus	Mass*	Method	Location	Time line
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CUORICINO	Te-130	11 kg	bolometric	LNGS	2003-2008
NEMO-3	Mo-100/Se-82	6.9/0.9 kg	tracko-calo	LSM	until 2010
Construction funding					
CUORE	Te-130	200 kg	bolometric	LNGS	2012
EXO-200	Xe-136	160 kg	liquid TPC	WIPP	2010 (commis.)
GERDA I/II	Ge-76	35 kg	ionization	LNGS	2009 (commis.)
LUCIFER	Se-82 (Mo-100)	18 (11) kg	bolom./scint.	LNGS	2013 (commis.)
SNO+	Nd-150	56 kg	scintillation	SNOlab	2011
Substantial R&D funding / prototyping					
CANDLES	Ca-48	0.35 kg	scintillation	Kamioka	2009
Majorana	Ge-76	26 kg	ionization	SUSL	2012
NEXT	Xe-136	80 kg	gas TPC	Canfranc	2013
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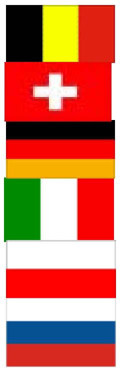
R&D and/or conceptual design					
CARVEL	Ca-48		scintillation	Solotvina	
COBRA	Cd-116, Te-130		ionization	LNGS	
DCBA	Nd-150		drift chamber	Kamioka	
EXO gas	Xe-136		gas TPC	SNOlab	
MOON	Mo-100		tracking	Oto	
Other decay modes					
TGV	Cd-106		ionization	LSM	operational

***: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%**

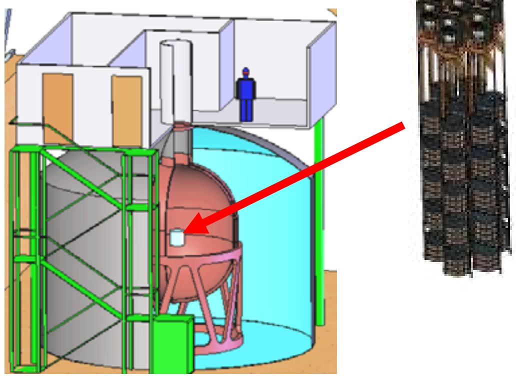
HK 9.2 A.Vauth
HK 9.3 G. Meierhofer
HK 9.6 D. Budjáš
HK 9.7 P.Grabmayr
HK 9.9 M. Agostini
HK 69.8 M. Tarka
T 109.5 K. Freund
T 109.6 H.Khozani
T 110.5 M.Barnabé Heider
T 110.6 S.Hemmer
T 110.7 F.Froborg
T 113.8 M.Heisel

2010

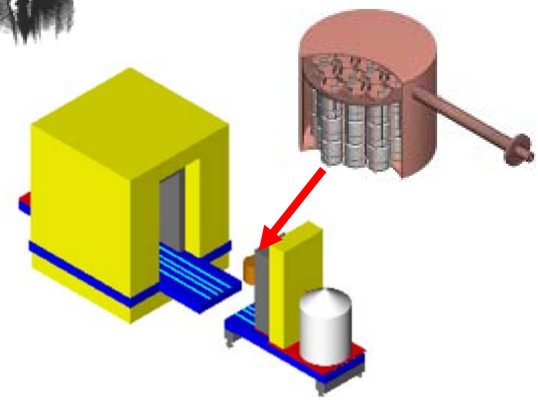
Two new ^{76}Ge Projects:

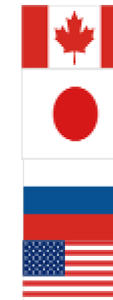


GERDA



Majorana





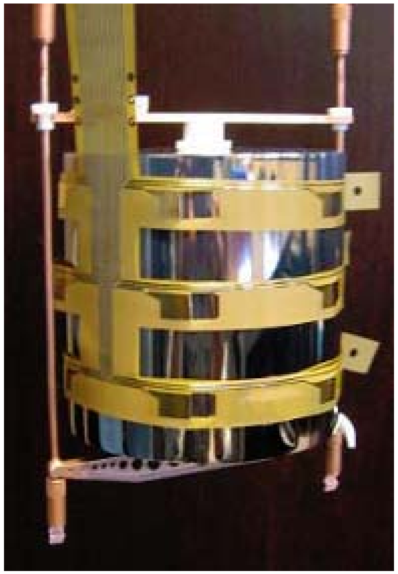
- 'Bare' ^{enr}Ge array in liquid argon
- Shield: high-purity liquid Argon / H_2O
- Phase I: 18 kg (HdM/IGEX) / 15 kg nat.
- Phase II: add ~20 kg new enr. Detectors; total ~40 kg

- Array(s) of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total ~60 kg (30 kg enr.)

Physics goals: degenerate mass range
Technology: study of bgds. and exp. techniques

LoI
- open exchange of knowledge & technologies (e.g. MaGe MC)
- intention to merge for O(1 ton) exp. (inv. Hierarchy) selecting the best technologies tested in GERDA and Majorana

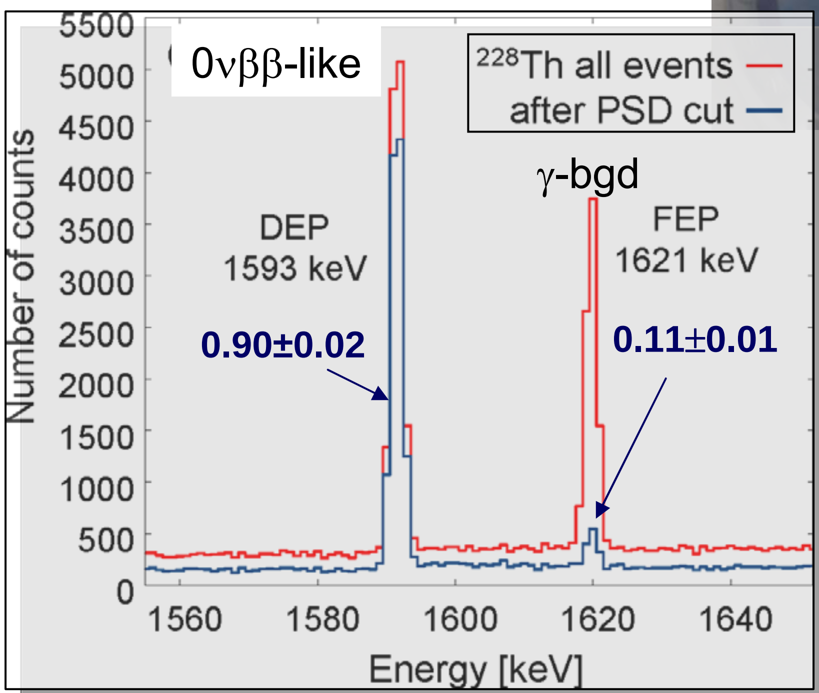
Novel Ge-detectors with advanced 0νββ-signal recognition & background suppression

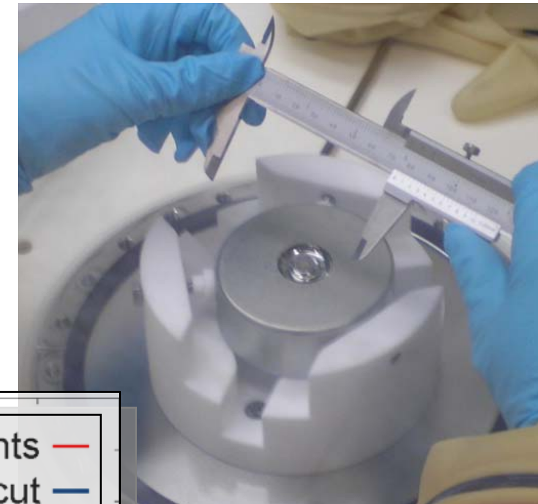


n-type detectors with 18-fold segmented electrodes

HK 9.2 A.Vauth
T 110.6 S.Hemmer

- **0νββ:** point-like events
- **Bgd:** multi-site or partial energy deposition outside crystal



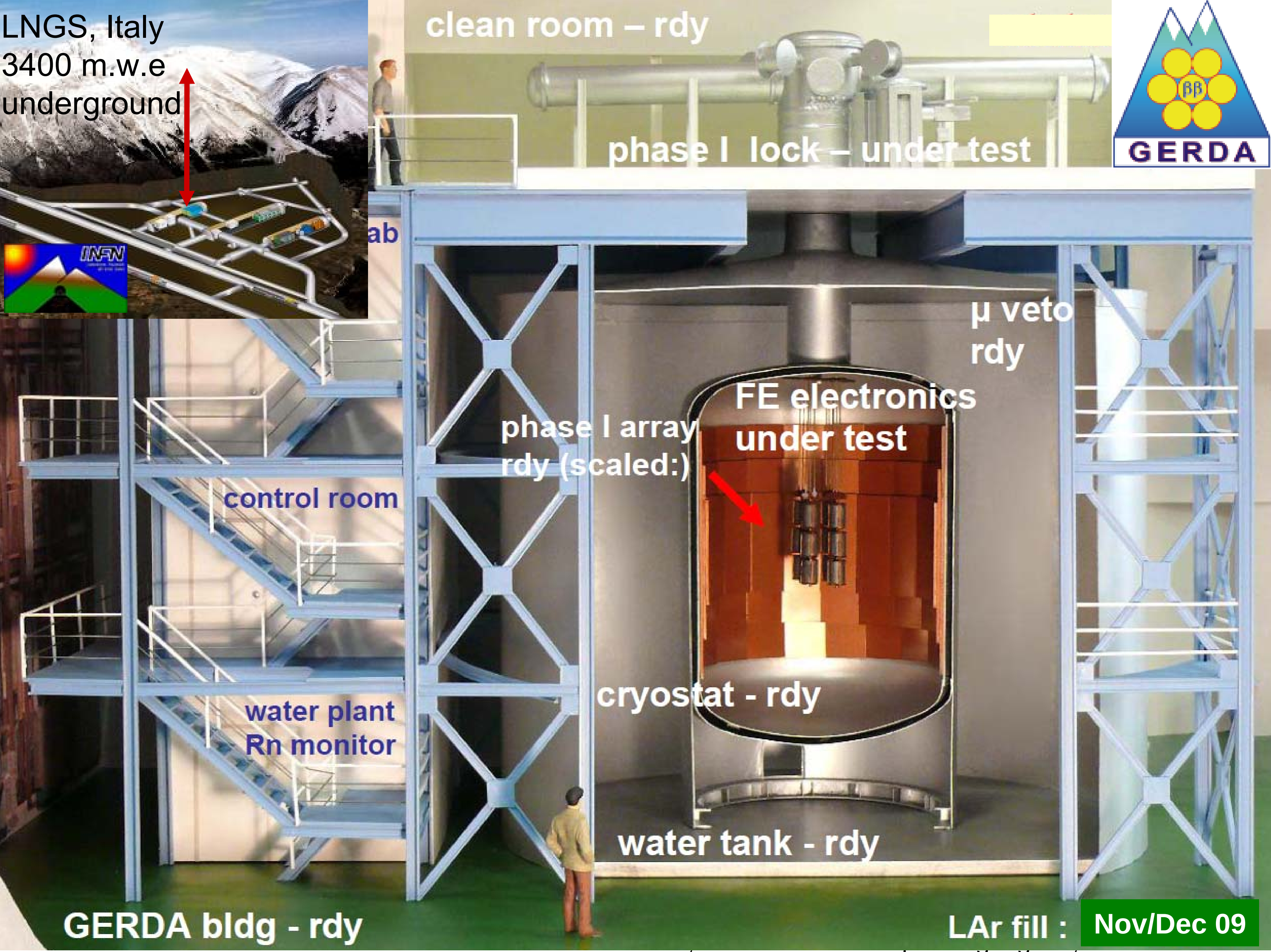


p-type with small signal electrode (thick-window BEGe detector)

HK 9.6 D.Budjáš
HK 9.9 M.Agostini

R&D: LAr scintillation read out

T 109.6 H.A.Khozani
T 113.8 M.Heisel,


LNGS, Italy
3400 m.w.e
underground
INFN
clean room – rdy
phase I lock – under test
GERDA
ab
μ veto
rdy
FE electronics
under test
phase I array
rdy (scaled:)
control room
cryostat - rdy
water plant
Rn monitor
water tank - rdy
GERDA bldg - rdy
LAr fill : Nov/Dec 09


Unloading of vacuum cryostat
(6 March 08)
Produced from selected
low-background austenitic steel

Construction of water tank

∅ 10 m

H = 9.5 m

V = 650 m^3

Designed for
external γ,n,μ
background
~10^{-4} cts/(keV kg y)

construction of clean room

clean room, active cooling device getting prepared for installation


Water tank and cryostat prior muon veto installations


WT and cryostat with muon veto installed


“Pill box”

Glove-box for Ge-detector handling and mounting into commissioning lock under N_2 atmosphere installed in clean room

- Liquid argon filled in Dec.'09
- Successful commissioning of cryogenic system
- Water tank partially filled
- Installation c-lock in March
- Ready for commissioning run with ^{nat}Ge detector string in April '10
- Subsequently, start Phase I physics data taking

Phases and physics reach

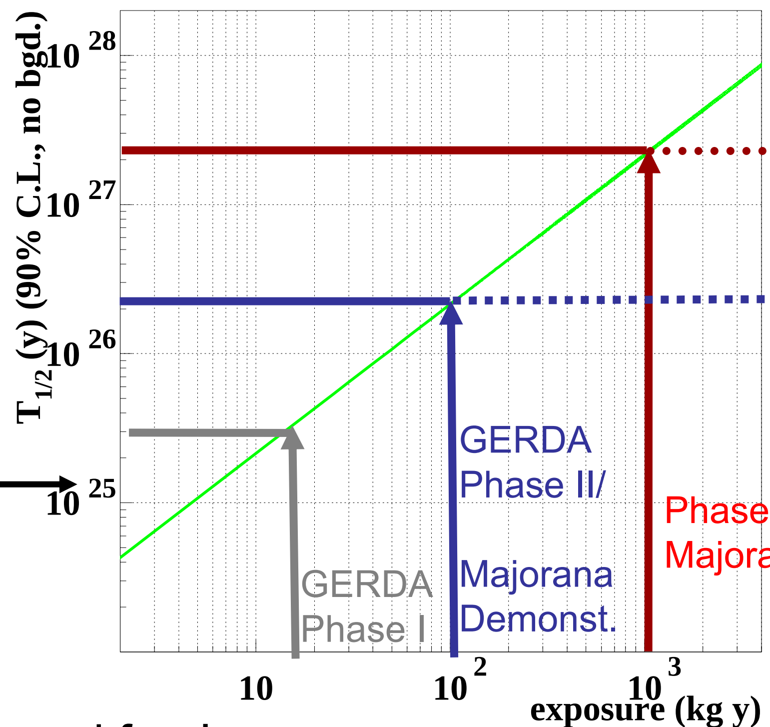
2·10^27 (90 % CL) *

2·10^26 (90 % CL) *

3·10^25 (90 % CL)*

KK

*: no event in ROI



<24 - 41 meV

<75 - 129 meV

assuming
$|M^{0\nu}|$=2.99-8.99
[Smol&Grab PRC'10]
and 89% enrichment

required for 'background free'
exp. with ΔE~3.3 keV (FWHM): **O(10^{-3})** **O(10^{-4})** counts/(kg·y·keV)

Background requirement for GERDA/Majorana:

⇒Background reduction by factor **10^2 - 10^3** required w.r.t. to precursor exps.

⇒Degenerate mass scale **O(10^2 kg·y)** ⇒ Inverted mass scale **O(10^3 kg·y)**

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Other decay modes					
TGV	Cd-106		ionization	LSM	operational

T 110.4 M. Ball

***: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%**

2010

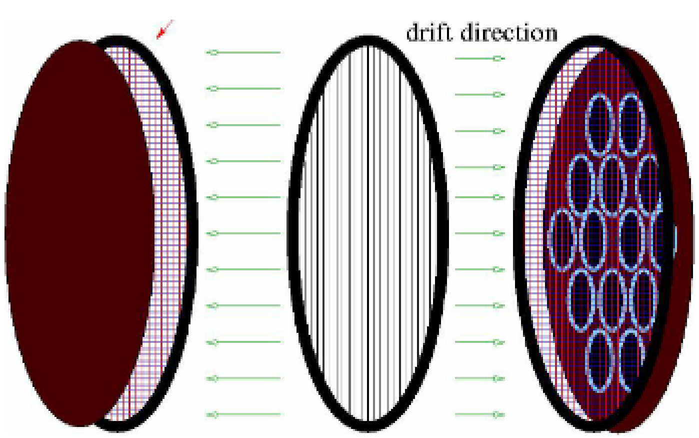
EXO-200: a liquid ^{136}Xe TPC

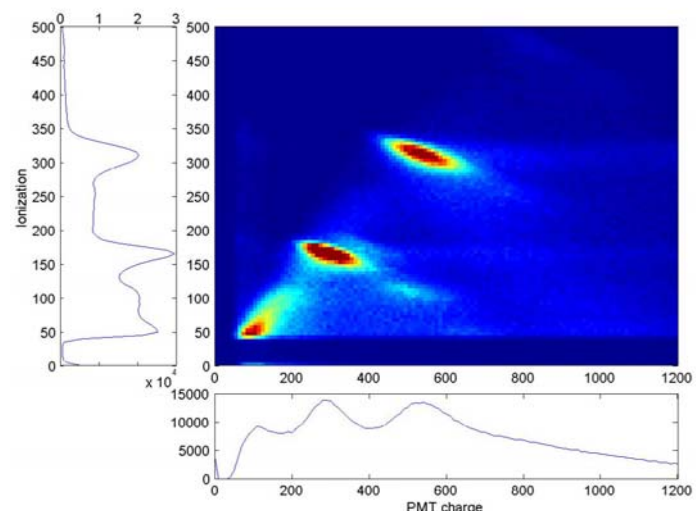
(without ^{136}Ba grand-daughter tagging)

Case	Mass (ton)	Eff. (%)	Run Time (yr)	σ_E/E @ 2.5MeV (%)	Radioactive Background (events)	$T_{1/2}^{0\nu}$ (yr, 90%CL)	Majorana mass (eV) QRPA	NSM
EXO-200	0.2	70	2	1.6	40	6.4 x 10^{25}	0.133[1]	0.186[2]

~110 kg ^{136}Xe active mass

46 -170 events on top of bgd for KK claim





L. Kaufmann, Taup09

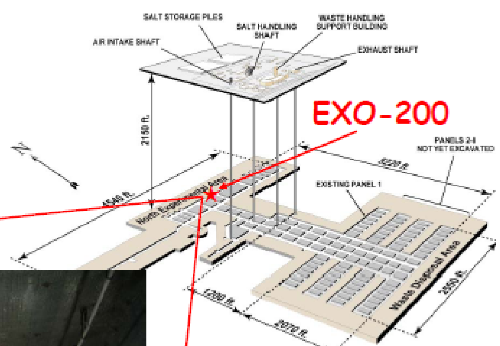
Ionization & Scintillation:

$\sigma(E)/E$ = 3.0% @ 570 keV or 1.4% @ Q($\beta\beta$)

EXO-200 goes underground…

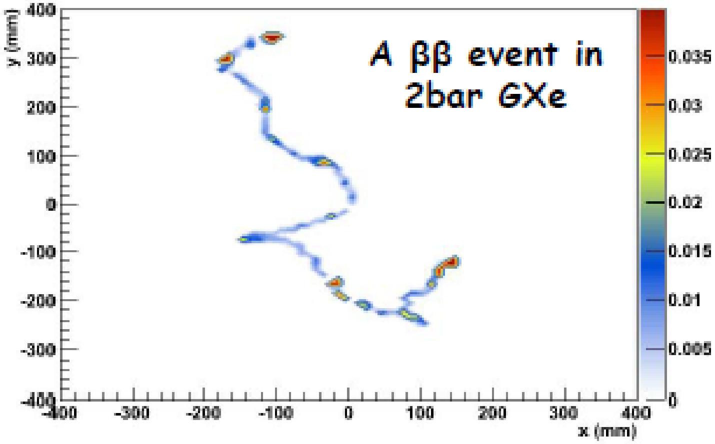
…and commissioning will start early 2010

EXO-200 at WIPP



Part of the EXO-200 infrastructure at WIPP, NM

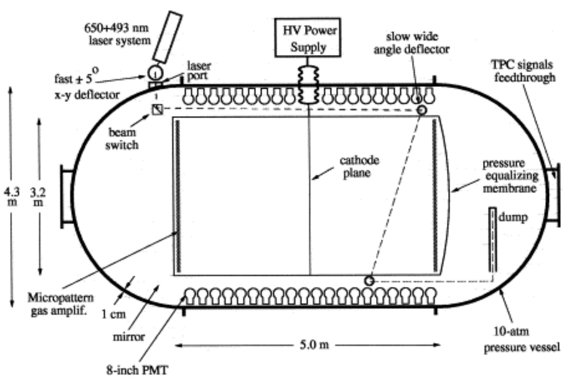
Gaseous ^{136}Xe TPC R&D



<u>Advantage:</u> Gas Xe has the potential of providing event topology information along with very good energy resolution

<u>Challenge:</u> low density provides limited self shielding

<u>EXO-gas</u> with Ba-tagging

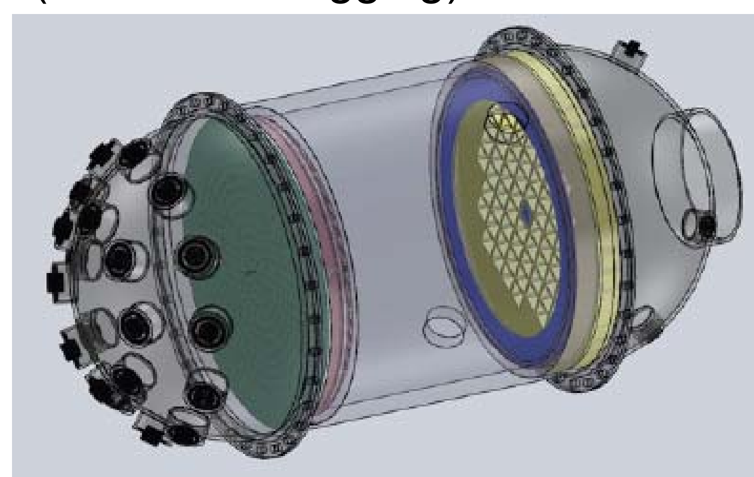


Initial concept: in-situ tagging
New concept: Ba++ extraction

(D. Sinclair, Taup 2009)

<u>NEXT</u> high pressure TPC (without Ba-tagging) in Canfranc

T 110.4 M. Ball



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MOON	Mo-100		tracking	Oto	
Other decay modes					
TGV	Cd-106		ionization	LSM	operational

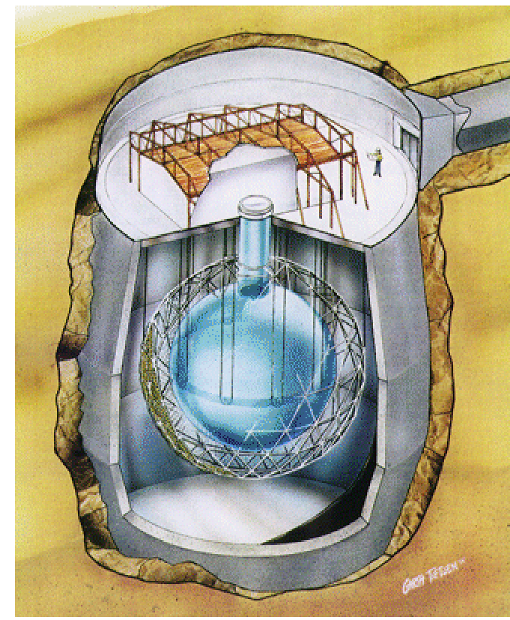
HK 9.4 P.Schrock

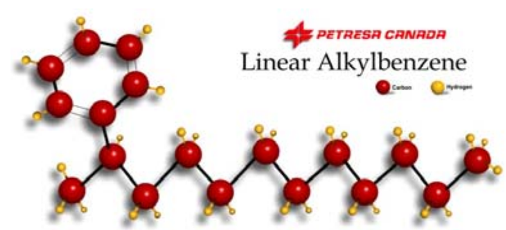
***: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%**

2010

SNO+

- $300M of heavy water removed and returned to Atomic Energy of Canada Limited (every last drop)
- SNO detector to be filled with liquid scintillator
  - 50-100 times more light than Cherenkov
- linear alkylbenzene (LAB)
  - compatible with acrylic, undiluted
  - high light yield, long attenuation length
  - safe: high flash point, low toxicity
  - cheaper than other scintillators
- physics goals: *pep* and *CNO* solar neutrinos, geo neutrinos, reactor neutrino oscillations, supernova neutrinos, double beta decay with Nd

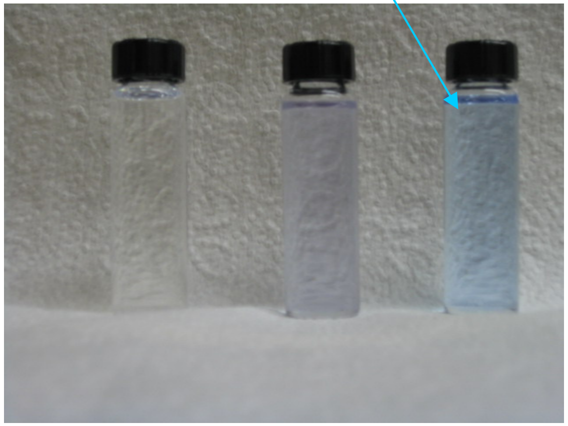


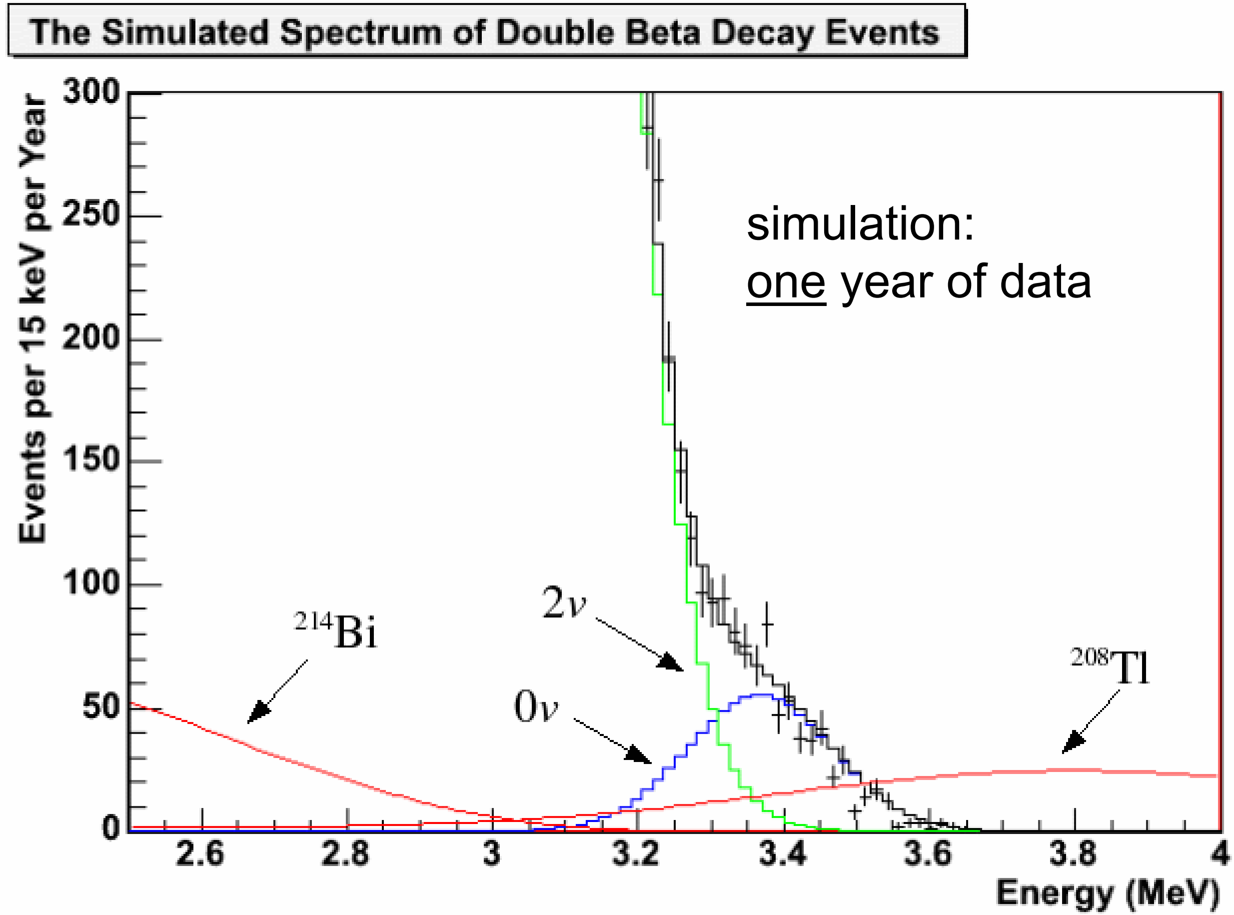


(C. Krauss, Taup 09)

$0\nu\beta\beta$ Signal for $<m_\nu> = 0.150$ eV

1000 events per year (assuming QRPA with spherical nucleus!) with 1% natural Nd-loaded liquid scintillator in SNO++





- 0.1% natural Nd-loaded liquid scintillator in SNO+ ⇒ 56 kg of ^{150}Nd
- Future: use of enriched ^{150}Nd ?

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Other decay modes					
TGV	Cd-106		ionization	LSM	operational

HK 9.1 B. Janutta
T 109.7 F. Lück
T 109.8 C. Oldorf
T 109.9 T. Koettig
T 110.1 O. Schulz
T 110.2 N. Heidrich
T 110.3 T. Neddermann

***: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%**

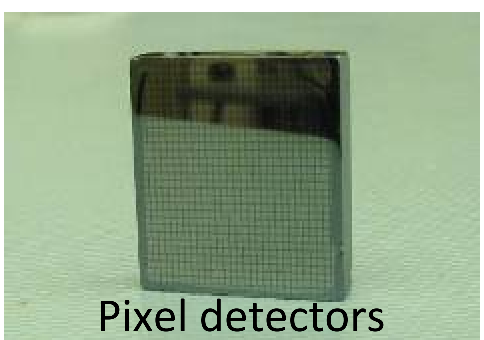
2010

COBRA: CdZnTe Semiconductor Detectors

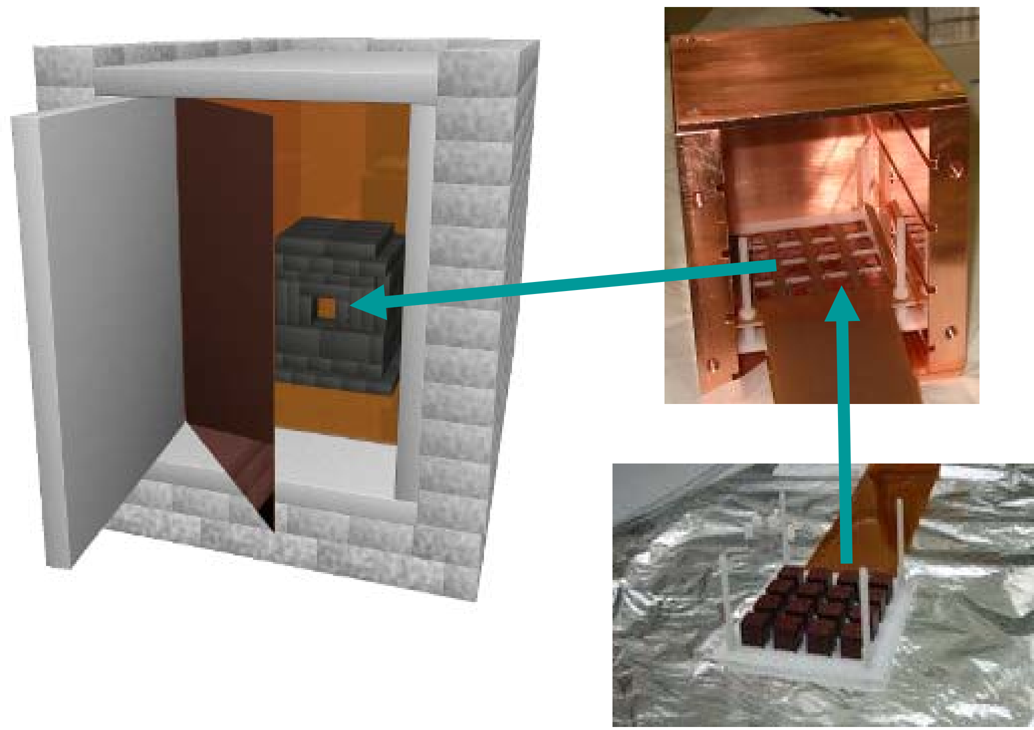
Focus on ^{116}Cd, Q-value: 2809 keV

Energy measurement only

Energy measurement and tracking



Underground setup at LNGS

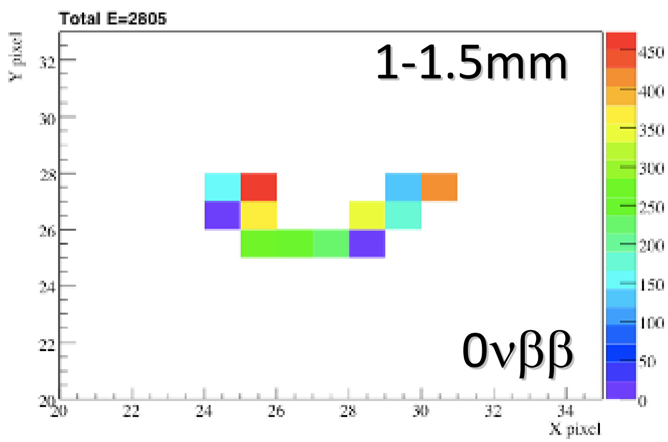


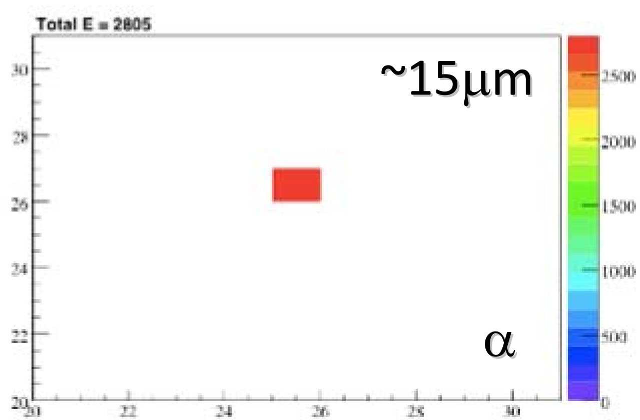
(K. Zuber, Taup 2009)

COBRA as solid-state TPC:

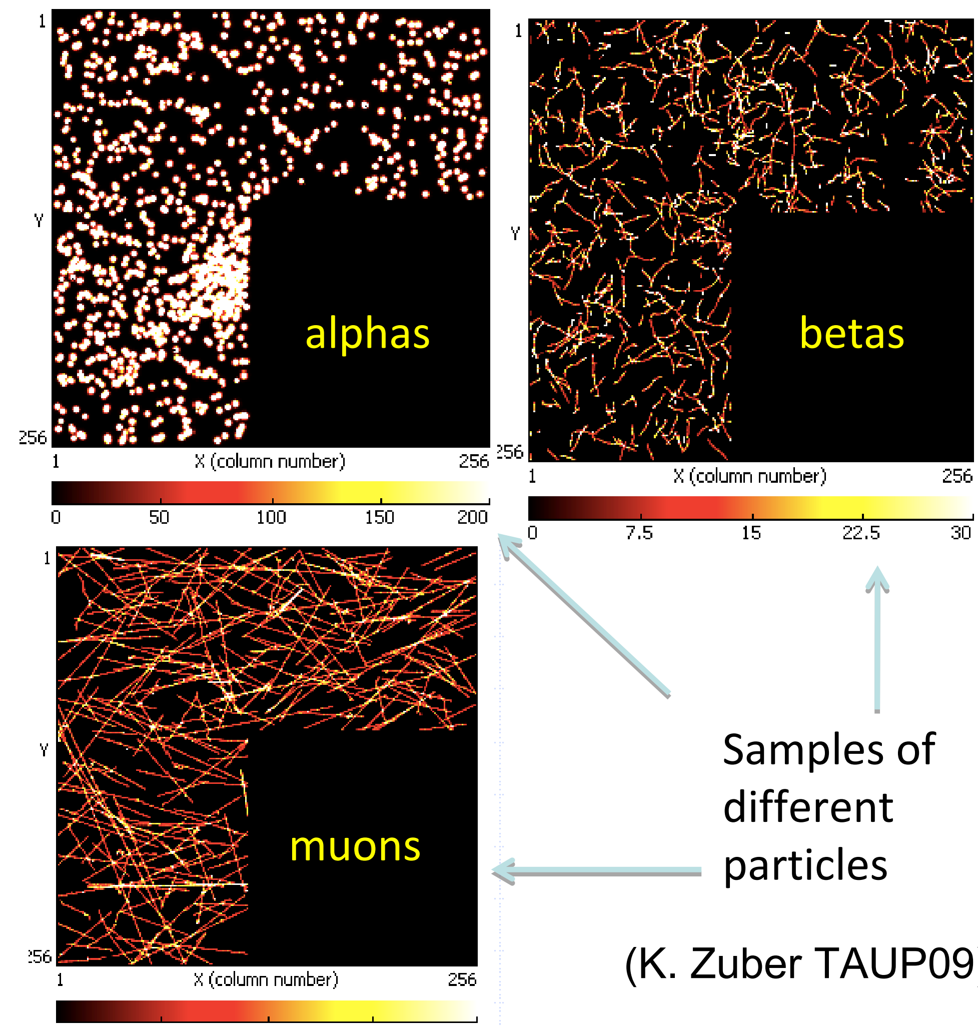
Pixelisation can be used for background reduction by particle identification

Monte Carlo: 200 μm pixel size





Real data: 55 μm pixel size

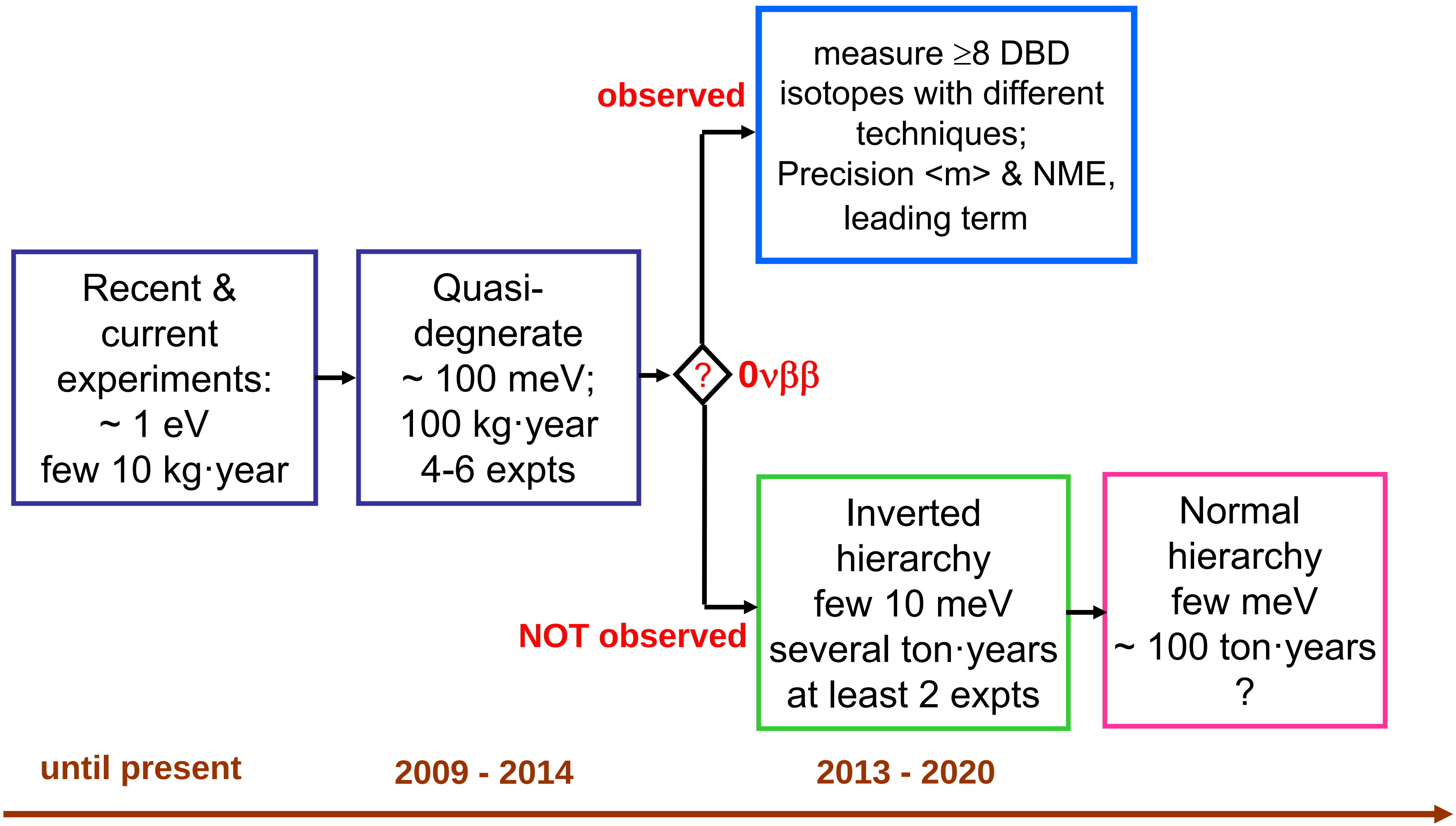


Samples of different particles

(K. Zuber TAUP09)

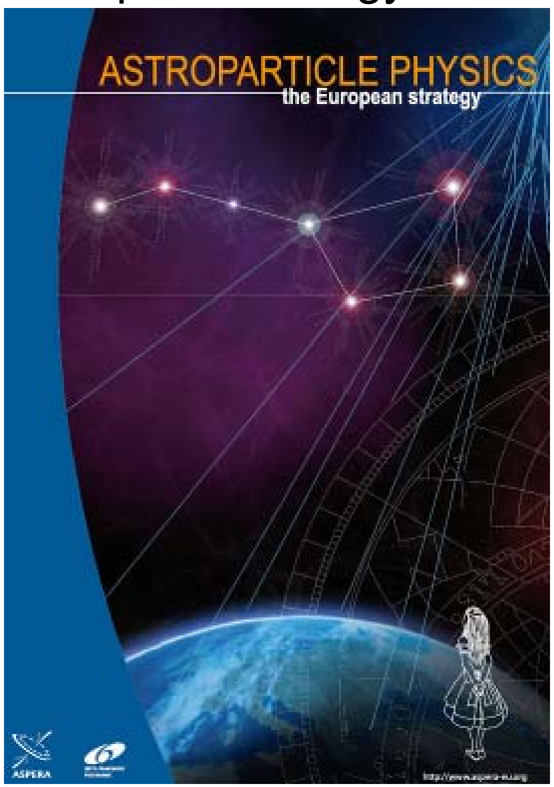
Summary & Outlook

0νββ experimental strategy during the next decade



Outlook

ASPERA
European strategy



ASPERA recommendation for Neutrino Mass:
Depending on the outcome of the present generation of double beta decay experiments being prepared, we recommend the eventual construction and operation of **one or two double beta decay experiments** on the **ton-scale**, capable of exploring the inverted-mass region, with a **European lead role or shared equally with non-European partners**. A decision on the construction could be taken around 2013.

NuPECC

LRP 2010

Similar financial efforts from North America & Japan required to realize ton scale experiments !

Extra slides

Many thanks to all colleagues & friends for providing up to date material!

Apologies to those whose projects could not be covered in this talk!

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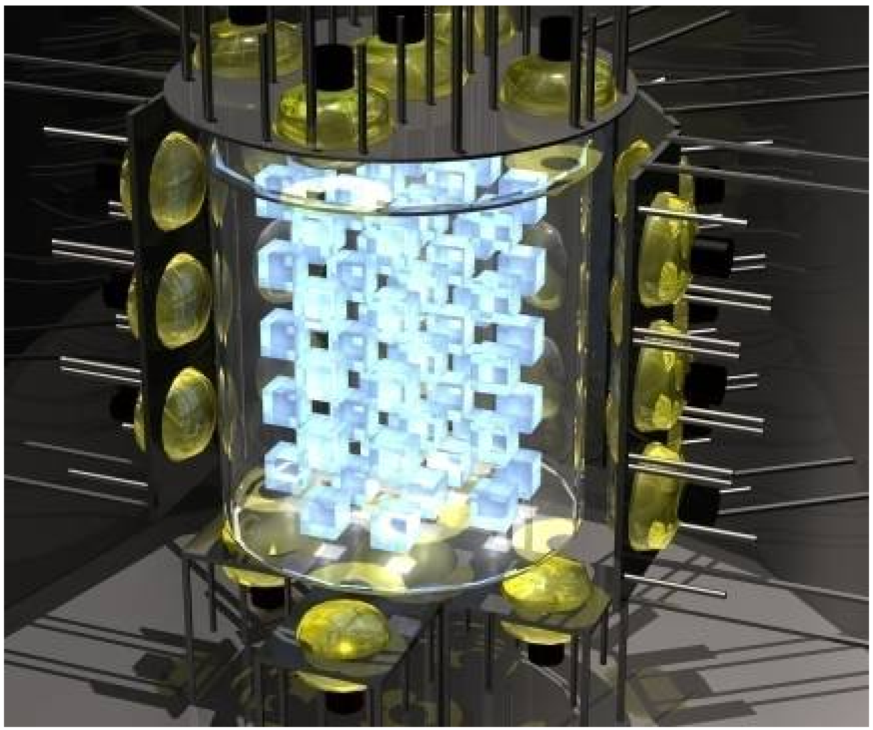
SuperNEMO	Se-82 or Nd-150	100 kg	tracko-calo	LSM	2012 (first mod.)
R&D and/or conceptual design					
CARVEL	Ca-48		scintillation	Solotvina	
COBRA	Cd-116, Te-130		ionization	LNGS	
DCBA	Nd-150		drift chamber	Kamioka	
EXO gas	Xe-136		gas TPC	SNOlab	
MOON	Mo-100		tracking	Oto	
Other decay modes					
TGV	Cd-106		ionization	LSM	operational

***: mass of DBD-isotopes; detector & analysis inefficiencies NOT included! Range: 18% to ~90%**

^{48}Ca CANDLES…..

CAlcium fluoride for studies of Neutrino and Dark matters by Low Energy Spectrometer

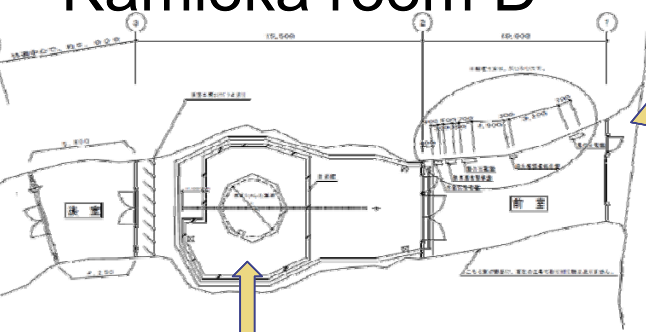


- undoped CaF_2 (CaF_2(pure))
  - ^{48}Ca ($Q_{\beta\beta}$=4.27 MeV)
  - Attenuation length > 10 m
  - Low radioactive impurities
- Low background detector
  - 4π active shield (LS)
  - Passive shield (Water, LS)
  - Pulse shape information
- Good energy resolution
  - large photo-coverage
  - Two phase LS system

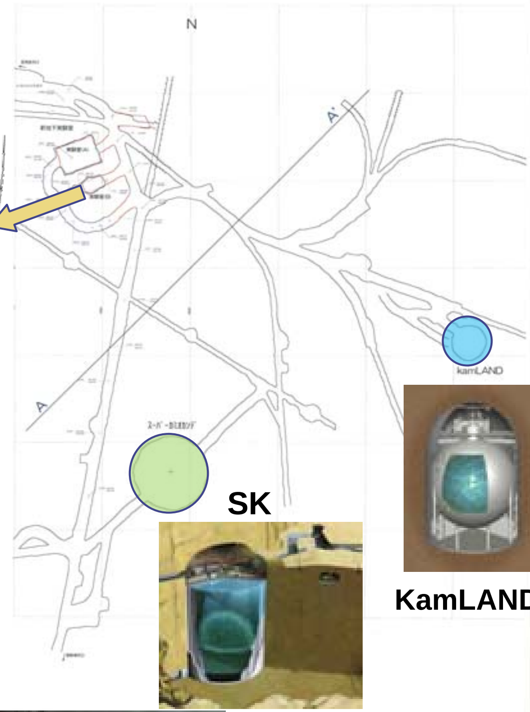
(I. Ogawa, Taup 2009)

….will illuminate Kamioka

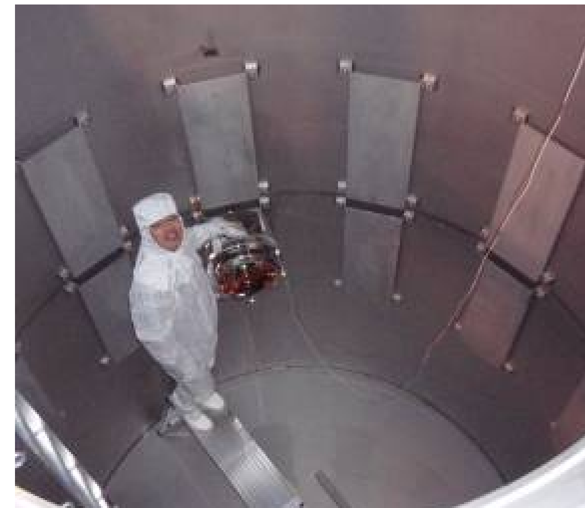
Kamioka room D



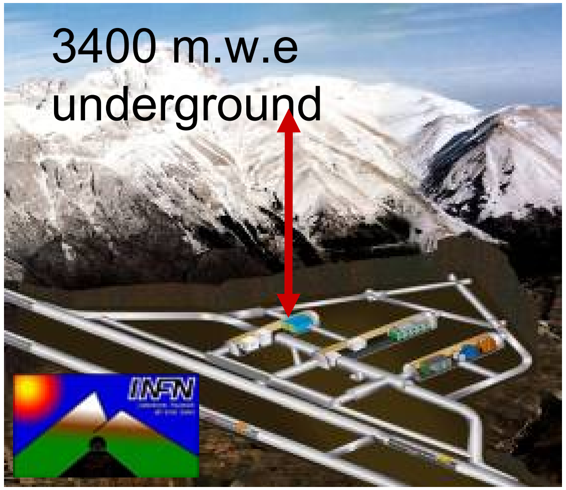
San-chika



305 kg (96 x 10^3 cm^3 crystals) of natural-CaF_2
$\Rightarrow$350 g of Ca-48



First PMT was installed at 24 June, 2009.



GERDA @ LNGS

Commissioning started in autumn 2009

Detector string
Glove box & lock
Clean room
Cryostat & μ-veto
Heat exchanger & pipes