# Experiments in double beta decay

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1. Introduction
2. Basic facts about double beta decay
3. Detection techniques in double beta decay and main experiments
4. Future of double beta decay

# Double beta decay

- *two-neutrinos double beta decay ($2\nu\beta\beta$)*

$(Z-2,A) \longrightarrow (Z,A)+2e^-+2\nu_e$ $(2\nu\beta^-\beta^-)$ observables: $2\ e^-$

$Z+2,A) \longrightarrow (Z,A)+2e^++2\nu_e$ $(2\nu\beta^+\beta^+)$ observables: $2\ e^+$, 4x511 keV $\gamma$

$e^-+(Z+2,A) \longrightarrow (Z,A)+e^++2\nu_e$ $(2\nu\beta^+/EC)$ observables: $1\ e^+$, 2x511 keV $\gamma$, X-ray

$2e^-+(Z+2,A) \longrightarrow (Z,A)+2\nu_e+2X$ $(2\nu EC/EC)$ observables: 2 X-rays

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

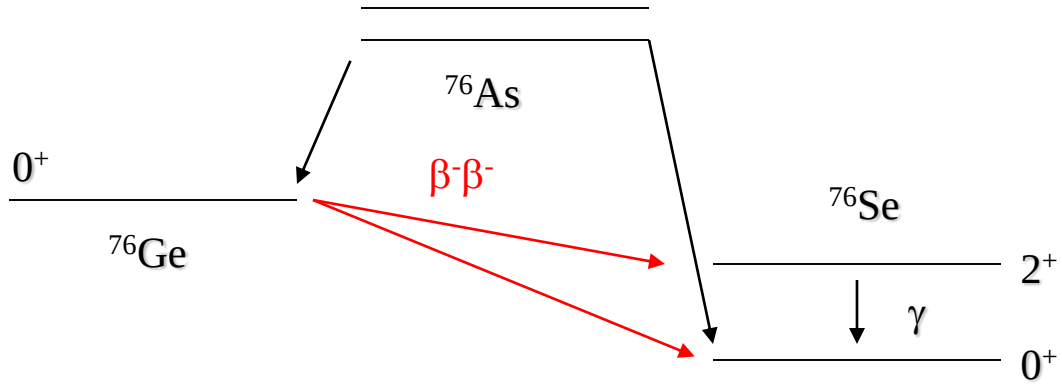
1. $(Z-2,A) \longrightarrow (Z,A)+2e^-$ $(0\nu\beta^-\beta^-)$
2. $(Z+2,A) \longrightarrow (Z,A)+2e^+$ $(0\nu\beta^+\beta^+)$
3. $e^-+(Z+2,A) \longrightarrow (Z,A)+e^+$ $(0\nu\beta^+/EC)$
4. $2e^-+(Z+2,A) \rightarrow (Z,A)^* \rightarrow (Z-2,A)+(\gamma)+2X$ $(0\nu EC/EC)$

*$2\nu\beta\beta$* - allowed process in the „Standard model“, process of the second order ($T_{1/2}= 10^{18}$-$10^{24}$ years)

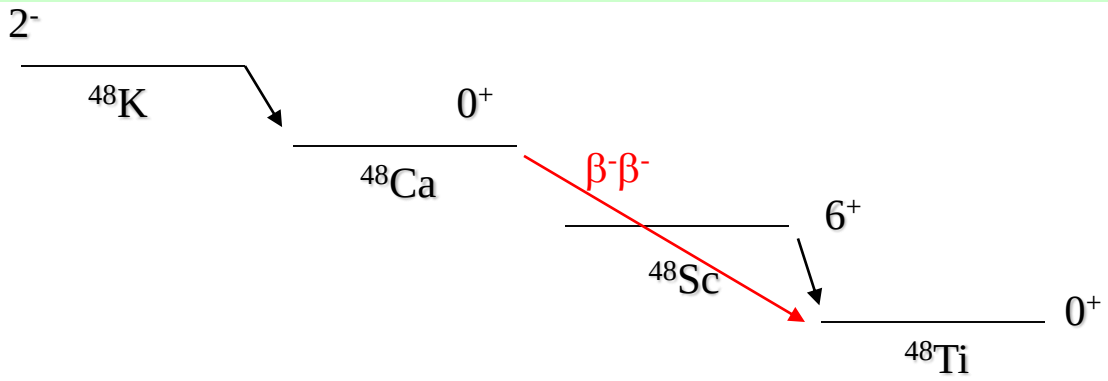
*$0\nu\beta\beta$* - forbidden process in „Standard model“, violate lepton number conservation, effective mass and type of neutrino (Majorana, Dirac), existence of right-handed currents

*2 possibilities for 2νββ:*

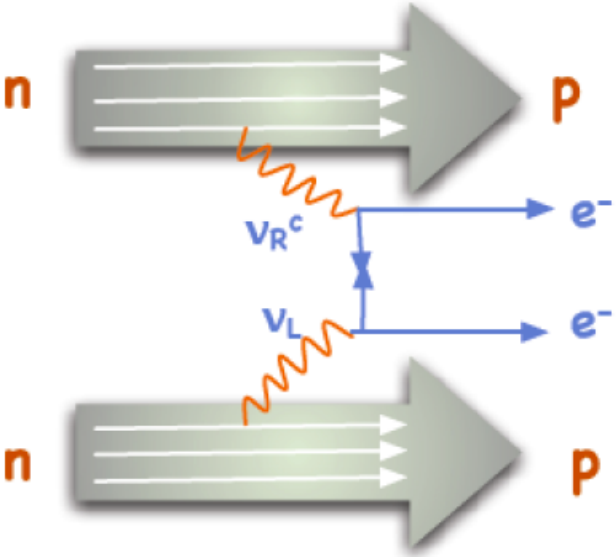
- if simple beta decay is energetically forbidden




- if "simple" beta decay is strongly suppressed by spin difference




There are 35 candidates for 2β decay, $W \sim Q^5(0\nu)$, $W \sim Q^{11}(2\nu)$




## Expected decay rate:

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

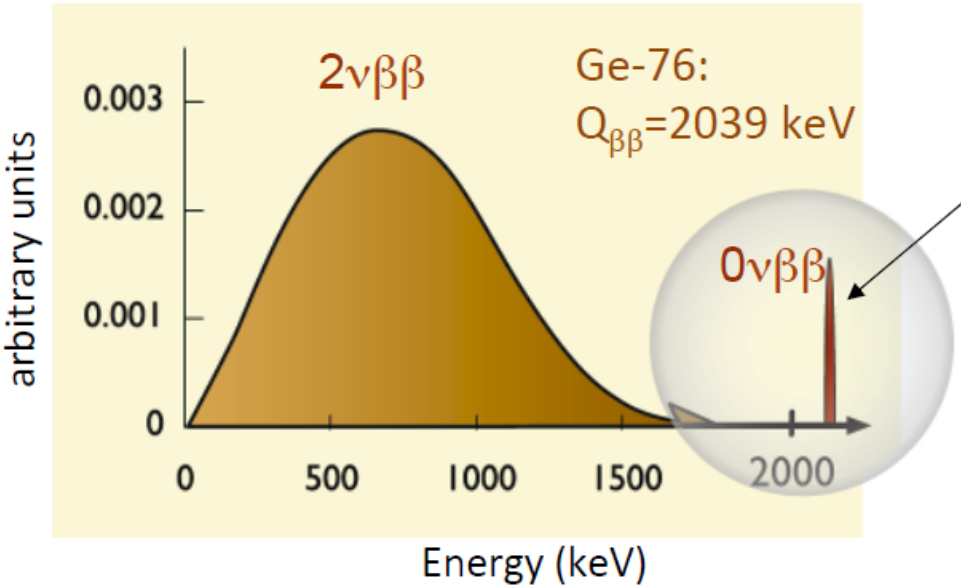
Phase space integral

Nuclear matrix element

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

Effective neutrino mass

$U_{ei}$ Elements of (complex) PMNS mixing matrix




Experimental signatures:

- peak at $Q_{\beta\beta}$ = m(A,Z)-m(A,Z+2)-2$m_e$
- two electrons from vertex

Discovery would imply:

- lepton number violation $\Delta L = 2$
- ν's have Majorana character
- mass scale & hierarchy
- physics beyond the standard model

# MEDEX workshop
## (Matrix Elements for the Double-beta-decay EXperiments)

**Organizing committee:**

Osvaldo Civitarese (University of La Plata), Jouni Suhonen (University of Jyväskylä), Ivan Štekl (Czech Technical University)

- organized from 1997 in Czech Technical University every two years
- 40-50 participants from all over the world
- last MEDEX was in 2015 **(see http://medex15.utef.cvut.cz/; published in AIP Conference Proceedings 1686, Oct 2015)**

**Basic features of MEDEX workshop:**

direct connections between theoreticians and experimentalists, free discussion during talks, round-table discussions

two working sessions:
NME for double-beta-decay,
Nuclear aspects of neutrino physics and dark matter studies.

section for young scientists and PhD students

**Two neutrino double beta decay:**

- Second order of weak interaction
- Direct measurement of NME values ⇒ nuclear theory

**Very important to measure ββ decay for many nuclei, for different processes ($2\beta^-$, $2\beta^+$, $Kb^+$, 2K, excited states)**

M. Goeppert-Mayer

## Recommended values for half-lives:

[A.S.B. Nucl. Phys. A 935 (2015) 52]

- $^{48}$Ca - $(4.4\ ^{+0.6}_{-0.5})\cdot10^{19}$ y
- $^{76}$Ge – $(1.65^{+0.14}_{-0.12})\cdot10^{21}$ y
- $^{82}$Se – $(0.92\pm 0.07)\cdot10^{20}$ y
- $^{96}$Zr – $(2.3 \pm 0.2)\cdot10^{19}$ y
- $^{100}$Mo – $(7.1 \pm 0.4)\cdot10^{18}$ y
- $^{100}$Mo – $^{100}$Ru $(0^+_1)$ – $(6.7^{+0.5}_{-0.4})\cdot10^{20}$ y
- $^{116}$Cd – $(2.87\pm 0.13)\cdot10^{19}$ y
- $^{128}$Te(geo) – $(2.0 \pm 0.3)\cdot10^{24}$ y
- $^{130}$Te – $(6.9 \pm 1.3)\cdot10^{20}$ y
- $^{136}$Xe – $(2.19 \pm 0.06)\cdot10^{21}$ y
- $^{150}$Nd - $(8.2\pm 0.9)\cdot10^{18}$ y
- $^{150}$Nd – $^{150}$Sm $(0^+_1)$ – $(1.2^{+0.3}_{-0.2})\cdot10^{20}$ y
- $^{238}$U(rad) - $(2.0 \pm 0.6)\cdot10^{21}$ y
- ECEC(2ν): $^{130}$Ba(geo) - ~ $10^{21}$ y

11 isotopes – 2νββ

2 isotopes – excited state of 2νββ

1 isotope – EC/EC decay

Neutrinoless double beta decay was not detected.

*Some obtained results:*

| Isotope | half-live [yr] | eff. neutrino mass [meV] | experiment |
|---|---|---|---|
| $^{76}$Ge | > 3,0 x $10^{25}$ | < 0,20-0,40 | GERDA I |
| $^{100}$Mo | > 1,1 x $10^{24}$ | < 0,33-0,62 | NEMO 3 |
| $^{130}$Te | > 2,8 x $10^{24}$ | < 0,31-1,10 | Cuoricino |
| $^{130}$Te | > 4,0 x $10^{24}$ | | CUORE 0 + Cuoricino |
| $^{136}$Xe | > 2,6 x $10^{25}$ | < 0,14-0,28 | KamLAND-Zen |
| $^{136}$Xe | > 1,1 x $10^{25}$ | < 0,19-0,45 | EXO-200 |

Current oscillation experiments can not tell difference between normal and inverse hierarchy. What is the expectation for $0\nu\beta\beta$?

Normal hierarchy:

$$\langle m_\nu \rangle \simeq s_{12}^2 \sqrt{\Delta m_\odot^2} \pm s_{13}^2 \sqrt{\Delta m_{\rm Atm}^2}$$
$$\simeq (1.7 - 3.9) \times 10^{-3} \text{ eV}$$

Inverse hierarchy:

$$\langle m_\nu \rangle \simeq \sqrt{\Delta m_{Atm}^2} \simeq 5 \times 10^{-2} \text{ eV}$$

## *Half-life for $0\nu\beta\beta$:*

Isotopical enrichment

Source mass

Exposure time

Detection efficiency

$$T_{1/2} = \frac{\varepsilon}{W} F_a \sqrt{\frac{M.t}{B.\Delta E}}$$

Energy resolution

Molecular weight

Background rate in c/(keV.kg.y)

- source = enriched material ($F_a$)
- big mass of the source (M)
- long time of measurement (t)
- "best" energy resolution of the detector ($\Delta E$)
- background as low as possible (B)

Candidates with $Q_{2\beta}$ > 2 MeV (natural γ rays background, E < 2,615 MeV)
There are **6 gold** and **5 silver** isotopes

| Nuclei | $Q_{2\beta}$, keV | Abundance, % |
|---|---|---|
| | | |
| 1. $^{48}$Ca | 4272 | 0.187 |
| 2. $^{150}$Nd | 3371.4 | 5.6 |
| 3. $^{96}$Zr | 3350 | 2.8 |
| 4. $^{100}$Mo | 3034.4 | 9.63 |
| 5. $^{82}$Se | 2996 | 8.73 |
| 6. $^{116}$Cd | 2805 | 7.49 |
| 7. $^{130}$Te | 2527.5 | 34.08 |
| 8. $^{136}$Xe | 2458.7 | 8.87 |
| 9. $^{124}$Sn | 2287 | 5.79 |
| 10. $^{76}$Ge | 2039.0 | 7.61 |
| 11. $^{110}$Pd | 2000 | 11.72 |

# Background Sources

- Natural radi
  (source itse

Two main sources

- Activity in the rock and in surrounding materials
  ($\alpha$, n) processes $\rightarrow$ [0,10] MeV spectrum

Choice of materials

Storage of materials underground

Partial or full detector realization underground
(Ge diodes)

$\Rightarrow$ reliable simulations
$\Rightarrow$ "Ad hoc" experiments at muon accelerators could be useful

- Neutrons

es

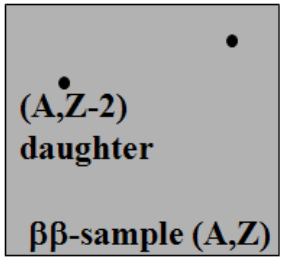
- Cosmogenic induced

- "Ad hoc" bolometers for alpha self-counting
- Full prototype used to measure contamination
  (BiPo detector)

- 2 $\nu$ Double Beta Decay

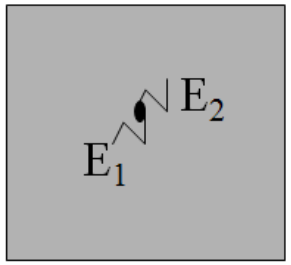
# Experimental techniques to observe ββ-decay

Geochemical & Radiochemical




**ββ-daughter rate**

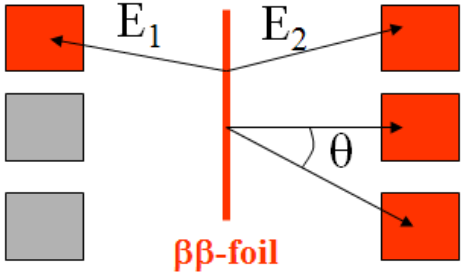
Calorimetric
Source ≡ detector



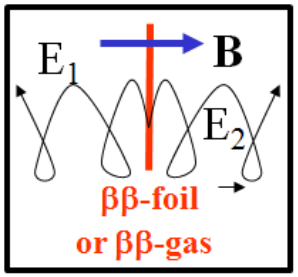

**E1+E2 spectrum**

- **Larger mass**
- **Better resolution**
- **High (~ 100%) efficiency**

Tracking
+ Calorimetric




TPC
Time Projection Chamber

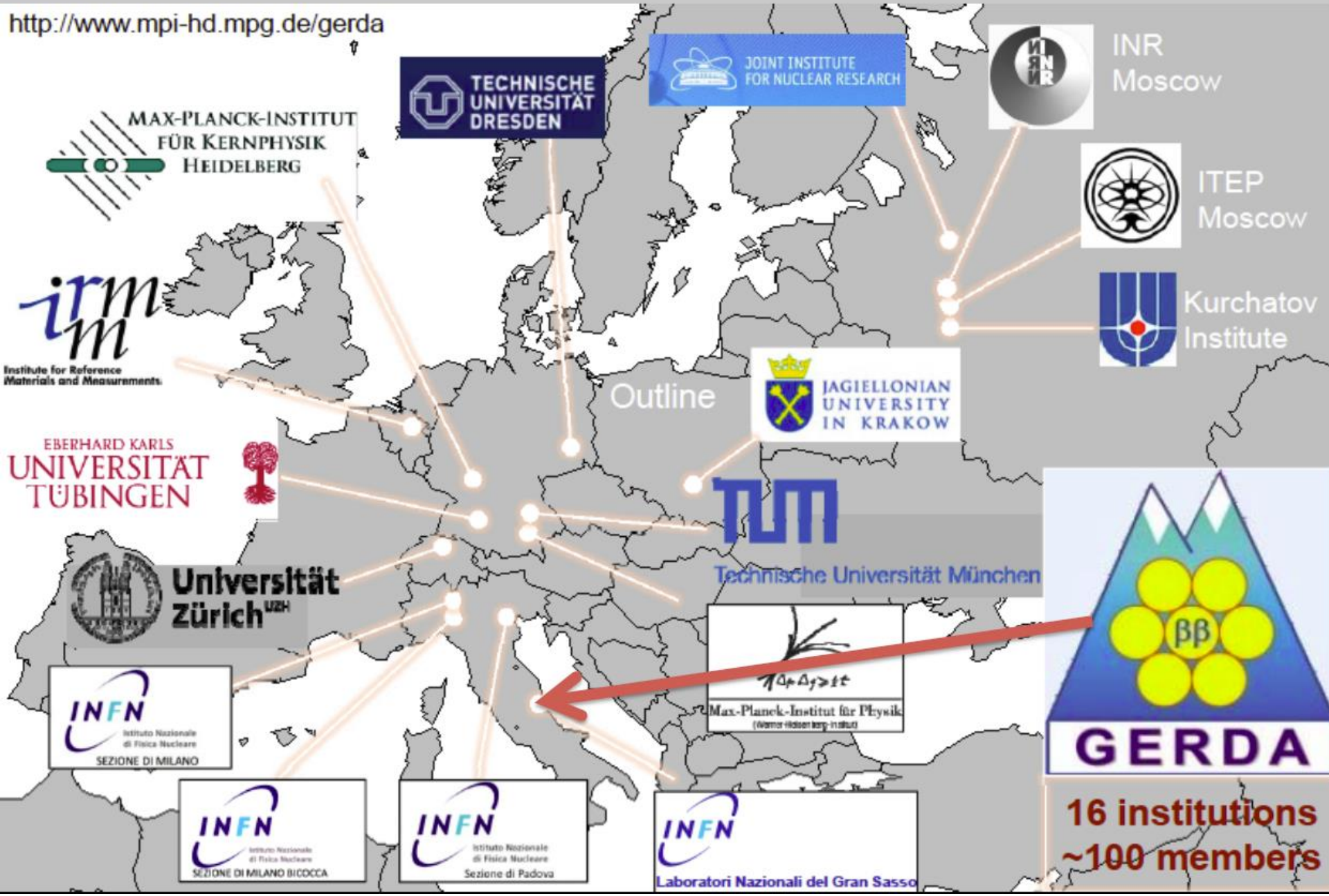



**E1, E2, θ**

- **Real ββ-observation.**
- **Any ββ-source can be measured**
- **Potentially zero-background**
- **Test of ββ0ν mechanisms**

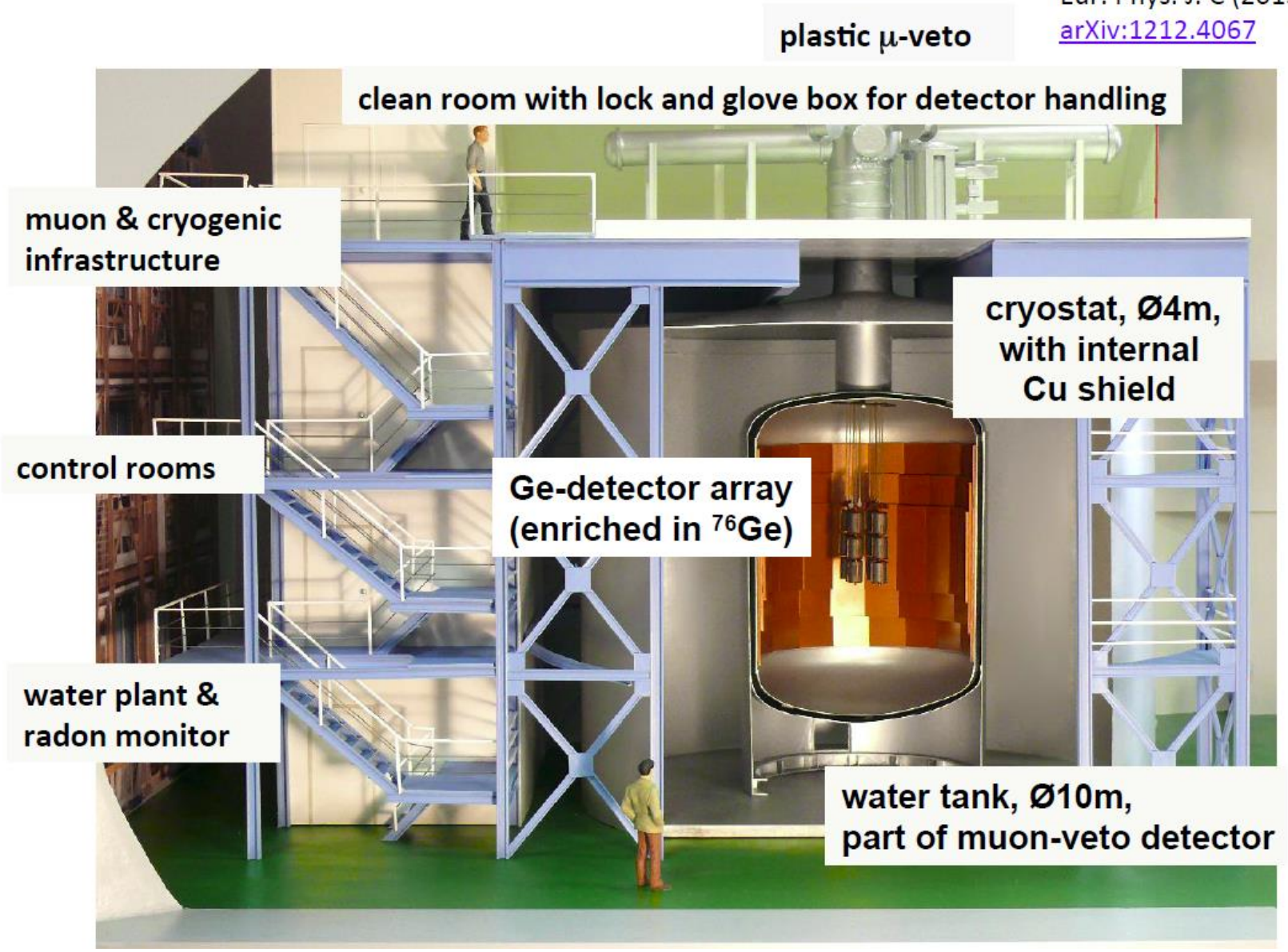
**There is no "ideal" method to meet all requirements!**

# The GERDA collaboration



# The GERDA experiment

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067



- **GERDA Phase I design goals reached:**
  - Background index after PSD: 0.01 cts / (keV kg yr)
  - Exposure 21.6 kg yr

- **No 0νββ-signal observed at $Q_{\beta\beta}$ = 2039 keV; best fit: $N^{0\nu}=0$**
  - Background-only hypothesis $H_0$ strongly favored
  - Claim strongly disfavored (independent of NME and of leading term)

- **Bayes Factor / p-value:**

  GERDA: $2.4\times10^{-2}$ / $1.0\times10^{-2}$

  GERDA+IGEX+HdM: $2 \times 10^{-4}$ / -

- **Limit on half-life:**

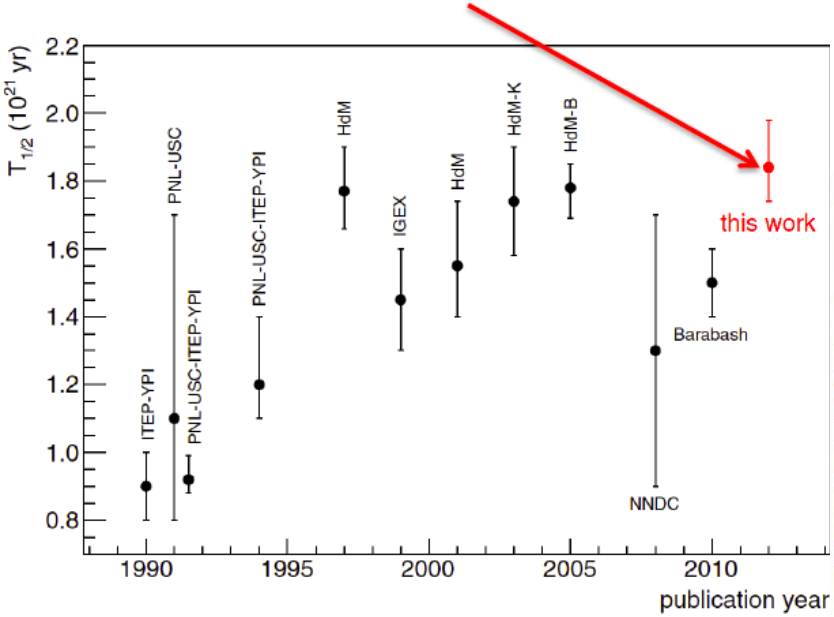
  GERDA: $T_{1/2}^{0\nu} > 2.1\times10^{25}$ yr (90% C.L.)

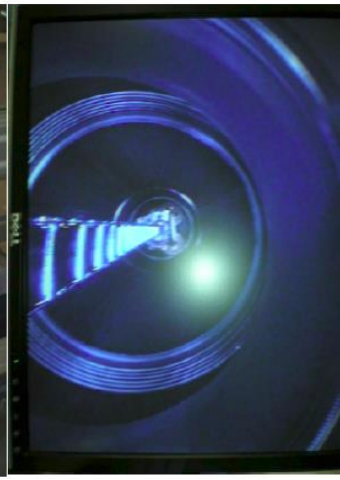
  GERDA+IGEX+HdM: $T_{1/2}^{0\nu} > 3.0\times10^{25}$ yr (90% C.L.) ($\langle m_{ee}\rangle < 0.2$-$0.4$ eV)

After only 5.04 kg yr exposure:
$T^{2\nu}_{1/2}(^{76}Ge) = (1.84^{+0.14}_{-0.10}) \cdot 10^{21}$ yr

8 refurbished enriched diodes from HdM & IGEX
- 86% isotopically enriched in Ge-76
- 17.66 kg total mass
- plus 1 natural Ge diode from GTF

2 diodes shut off because leakage current high:
- total enriched enriched detector mass 14.6 kg



# KamLAND-Zen Collaboration

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(The KamLAND-Zen Collaboration)

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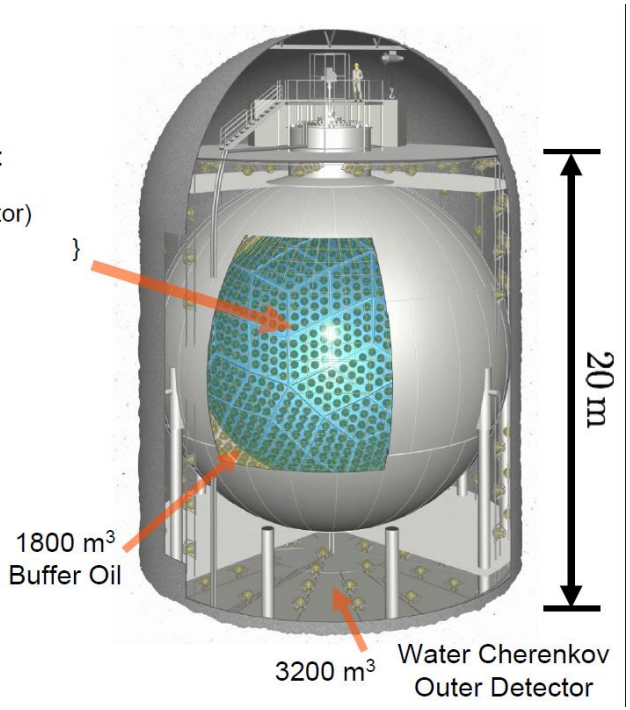
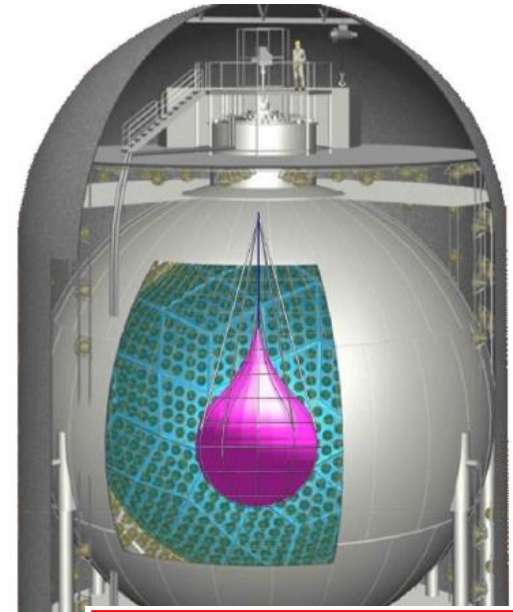
# KamLAND-Zen (Kamioka 2700 mw.e.)

$T^{2\nu}_{1/2} = 2.30 \pm 0.02\,(\text{stat}) \pm 0.12\,(\text{sys}) \times 10^{21}$ yr

Contain the Xe-loaded scintillator in a small balloon
Dissolve isotopically enriched Xe in KamLAND's ultra low background liquid scintillator.

- 1 kton Scintillation Detector
  - 6.5m radius balloon filled with:
    - 20% Pseudocumene (scintillator)
    - 80% Dodecane (oil)
    - PPO
- 34% PMT coverage
  - ~1300 17" fast PMTs
  - ~550 20" large PMTs
- Multi-hit electronics
- Water Cherenkov veto counter



+Well-understood detector

+Highly pure, self-shielding environment

+Large ββ source mass, scalable

-Relatively poor energy resolution

-No particle identification

| | |
|---|---|
| Phase 1 | $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr |
| Phase 2 | $T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr |
| Combined | $T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr |

QRPA NME model
J. Phys. G 39 124006 (2012)

$\langle m_{\beta\beta} \rangle < 0.14\text{-}0.28$ eV

Half life limit (90% CL) derived using this background subtraction:

$T_{1/2} > 1.9 \cdot 10^{25}$ yr
$\langle m_{\beta\beta} \rangle < 143\text{-}338$ meV

KamLAND-Zen combined their limit with that of EXO-200 to obtain:

$T_{1/2} > 3.4 \cdot 10^{25}$ yr

# The EXO-200 Collaboration

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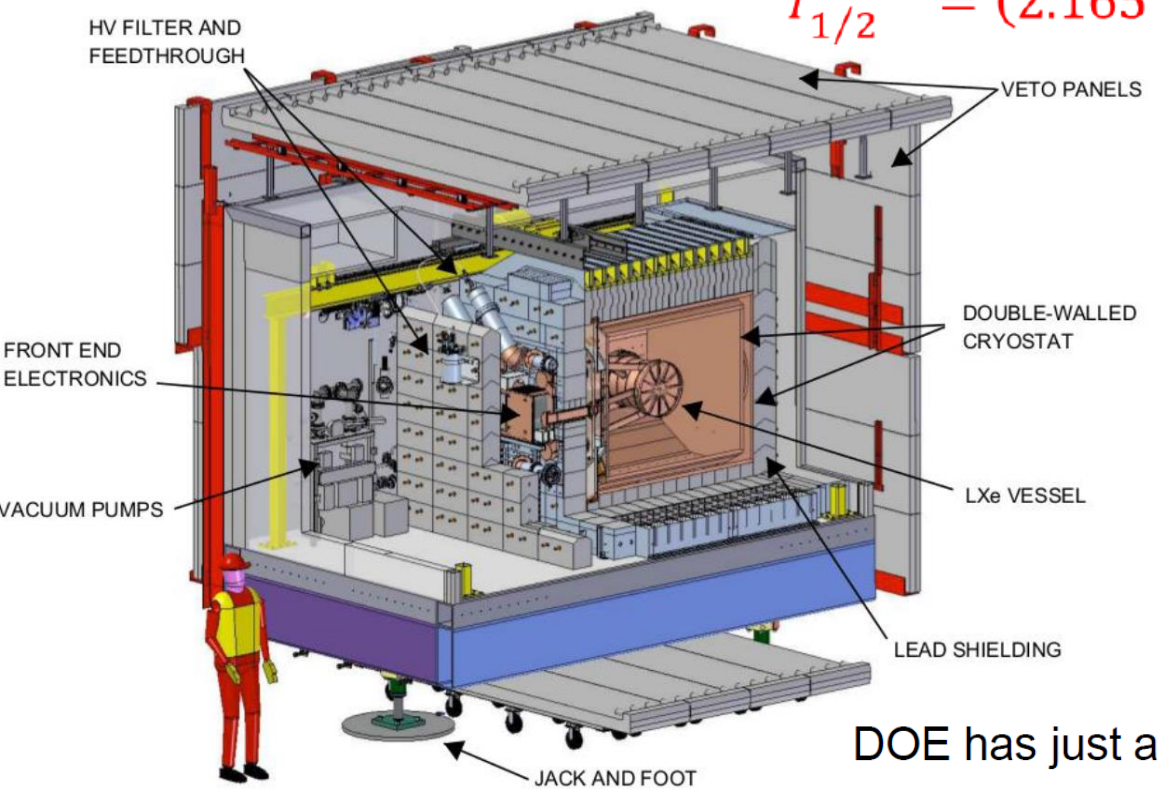
Technical University of Munich, Garching, Germany - W. Feldmeier, P. Fierlinger, M. Marino

TRIUMF, Vancouver BC, Canada – J. Dilling, R. Krücken, F. Retière, V. Strickland

# EXO-200 (WIPP 1620 mw.e.)

Large liquid (enriched) liquid Xe tracking calorimeter (TPC) with simultaneous read-out of ionization and scintillation.

$$T_{1/2}^{2\nu\beta\beta} = (2.165 \pm 0.016^{stat} \pm 0.059^{sys}) \cdot 10^{21}\ y$$




$$T_{1/2}^{0\nu\beta\beta} > 1.1 \cdot 10^{25}\ y$$

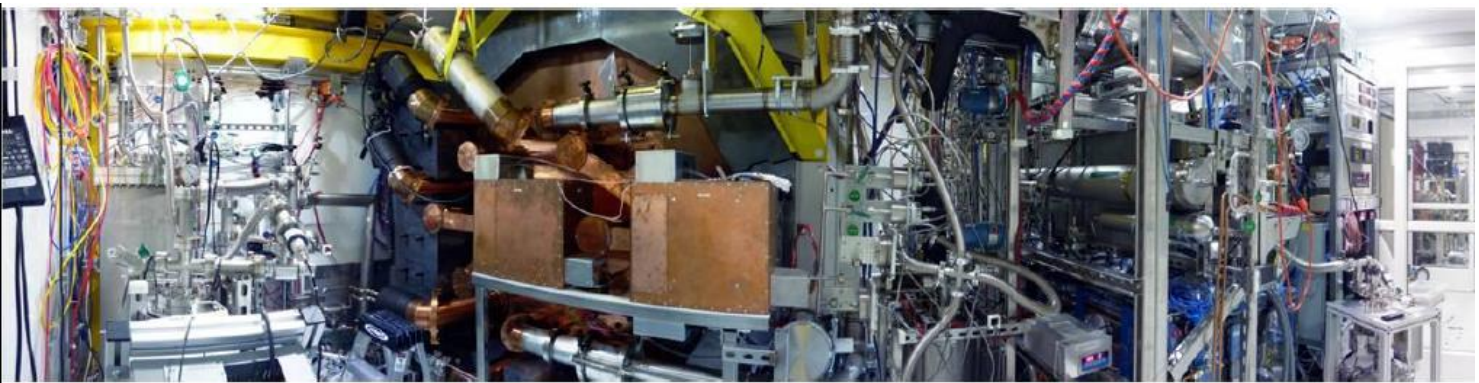
$$\langle m_{\beta\beta} \rangle < 187\ - 445\ meV$$

## Sensitivity goal

$$T_{1/2}^{0\nu\beta\beta} > 5.7 \cdot 10^{25}\ y$$

$$\langle m_{\beta\beta} \rangle < 82\ - 195\ meV$$

DOE has just approved 3 more years of data taking.



# Czech participation in double beta decay

1) Our activities are concetrated in Modane underground laboratory (France), which is included into Roadmap of large research infrastructures in Czech Republic (from 2010 – 2022)

2) Two participating institutions (Czech Technical University in Prague, Charles university in NEMO3/SuperNEMO experiment)

3) NEMO3 - provided precise results for $2\nu\beta\beta$ decay of 7 isotopes
   SuperNEMO - $0\nu\beta\beta$ decay of $^{82}Se$,
   responsibility of Czech side = radon program, improvement of energy resolution of scintillating detectors, shielding, construction of SuperNEMO frame
   TGV – double electron capture of $^{106}Cd$
   SPT – double electron capture of $^{106}Cd$ using Si pixel detectors
   OBELIX – ultra-pure HPGe detector (600 $cm^3$)
   R&D of needed technologies – removing radon from air (1 $mBq/m^3$), ultra sensitive detection techniques (detection of radon, selection of ultra-pure construction materials), theoretical calculations of NME

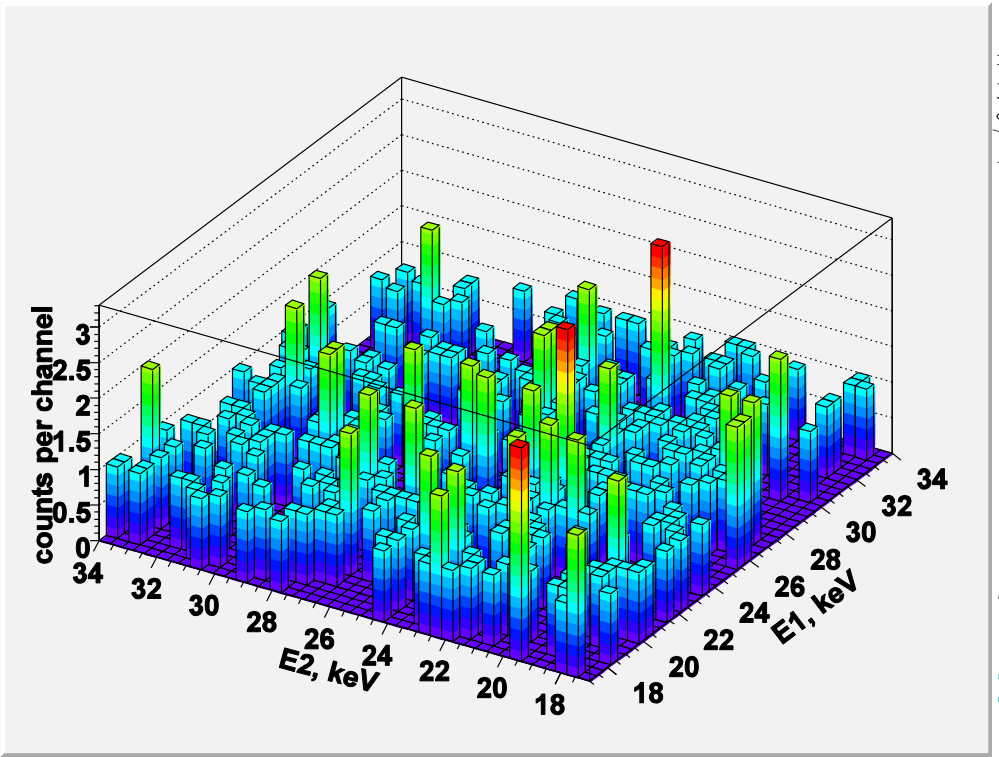
# Search for double electron capture in $^{106}$Cd (TGV collaboration)

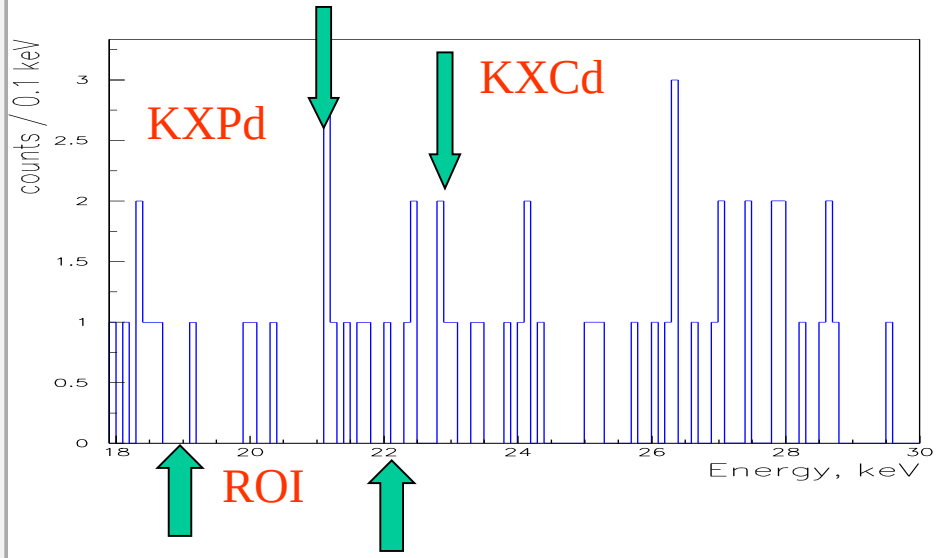
**JINR Dubna, Russia; IEAP CTU in Prague, Czech Republic**
**CSNSM Orsay, France; Comenius university, Slovakia.**

Since 2000, focus on 2nEC/EC decay of $^{106}$Cd

$$2e + {}^{106}_{48}Cd \rightarrow {}^{106}_{46}Pd + 2\nu_e + (\gamma, X-rays)$$

$$Q_{EC/EC} = 2778\,keV, \quad \text{ROI:} \quad 19\,keV \le E_X \le 23\,keV$$



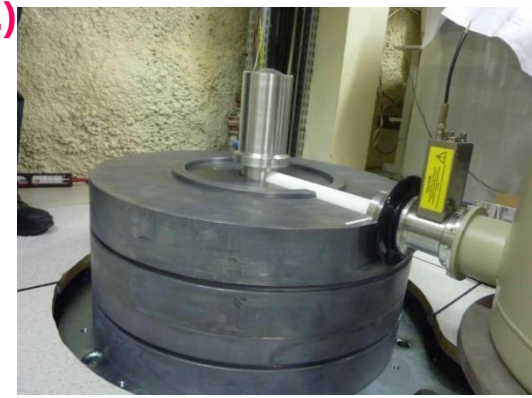




$$T_{1/2}^{2\nu EC/EC}(^{106}Cd) > 4.2 \cdot 10^{20}\ y \quad (90\%)$$

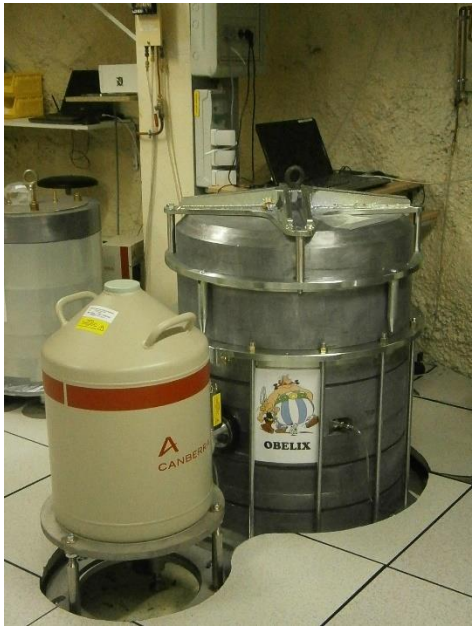
**13,6 g of $^{106}$Cd (enrichment 75%)**

# Detector “Obelix” (JINR/IEAP CTU/LSM)

**P type coaxial HPGe detector Canberra in U-type ultra low background cryostat located at LSM, France (4800 m w.e.)**



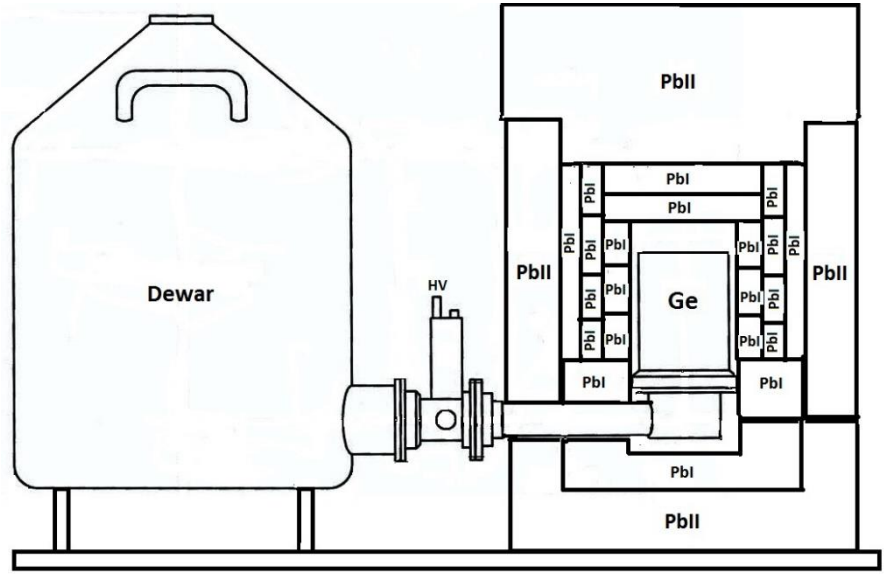
| | | | |
|---|---|---|---|
| *Sensitive volume* | 600 cm$^3$ | *Efficiency* | 162% |
| *Peak / Compton* | 83 | | |
| *Energy resolution* | ~1.2 keV at 122 keV ($^{57}$Co), ~2 keV at 1332 keV ($^{60}$Co) | | |
| *Distance from cap* | 4 mm | *Entrance window* | Al, 1.6 mm |




~12 cm arch. Pb

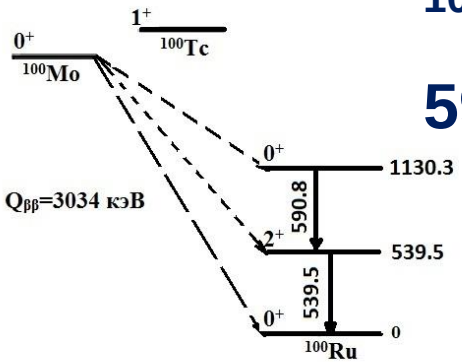
~20 cm low active Pb

Radon free air



# $^{100}Mo \rightarrow 0^+$, 1130 keV $^{100}Ru$

# 590.8+539.5 keV*

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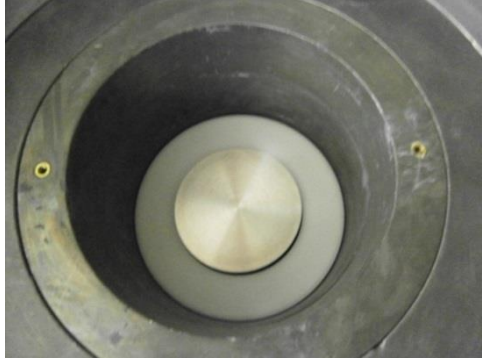
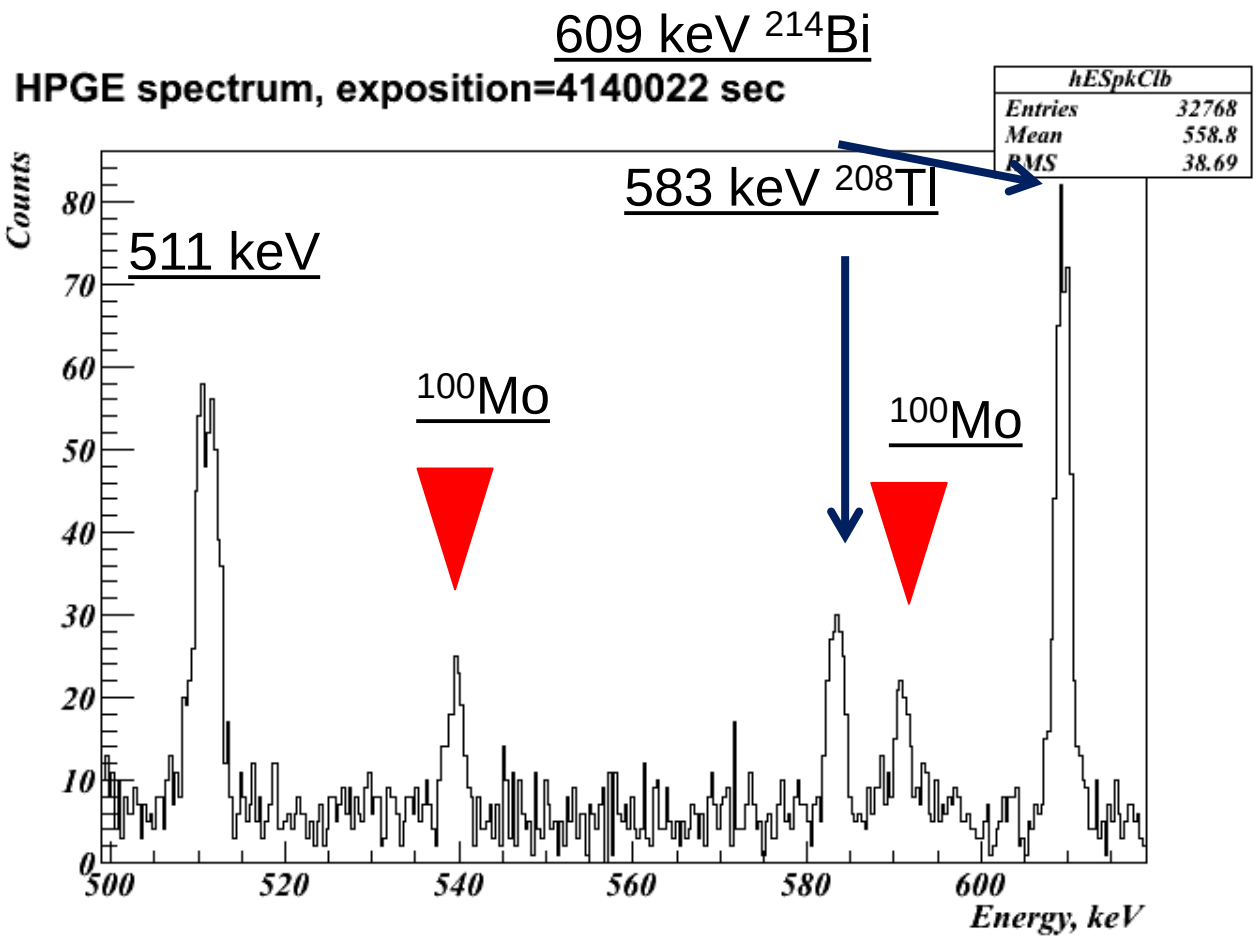





**1st run – 09.11.2011 – 02.12.2012**

**2nd run– 19.02.2012 – 02.04.2012**

- **in Marinelli bobbin**
- **Mass of foils – 2595,02 g**
- **Mass of $^{100}Mo$ – 2517,15 g**
- **Total measurement time – 2288 h**

| Process | $T_{1/2}$ [years] |
|---|---|
| $2\nu2\beta^-$ decay to $0^+_1$ [1130 keV] | $7.5 \times 10^{20}$ |
| $2\nu2\beta^-$ decay to $2^+_1$ [540 keV] | $> 2.5 \times 10^{21}$ |

# Free-Radon Air factory

A(222Rn) in LSM ~ 10-15 Bq/m$^3$

May 2004 : detector NEMO-3 in tent
A($^{222}$Rn) ~ Bq/m$^3$

Antiradon setup: starts running Oct. 2004

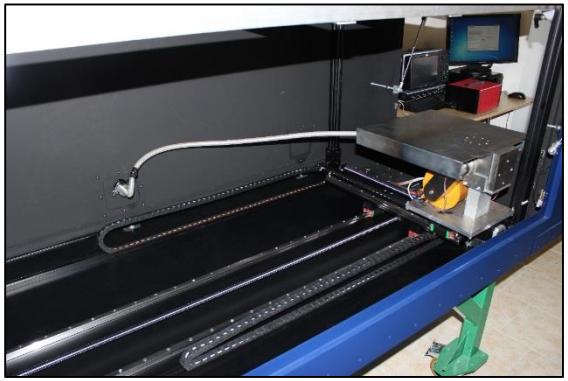
2x500 kg charcoal @ -50$^o$C, 7 bars

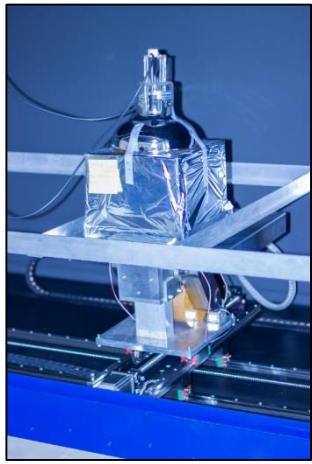
**Activity: A($^{222}$Rn) < 10 mBq/m$^3$ !!!**
**Flux: 150 m$^3$/h**
**(produced by ATEKO company, Czech rep.)**



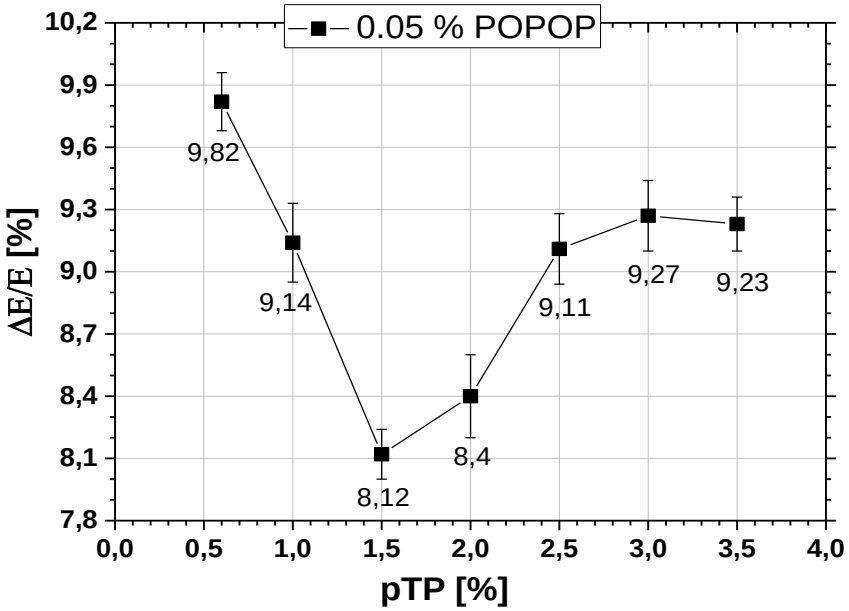
# Improvement of energy resolution of SuperNEMO detectors:

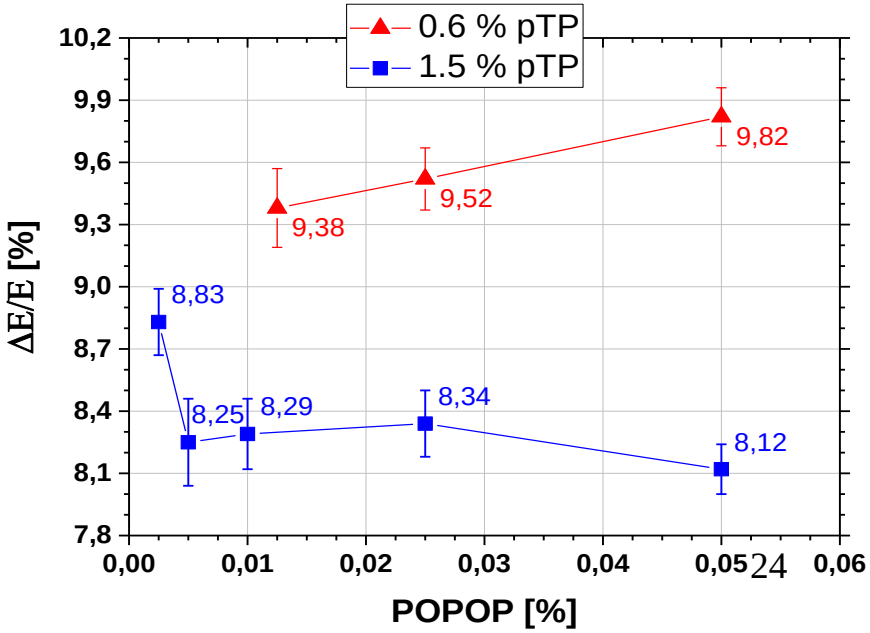
Each measurement was performed in a lightproof box, in which scintillators up to 2.2 m long and 1 m wide could be tested.





Improved ΔE/E for blocks for SuperNEMO experiment @ 1.5 % pTP and 0.05 % - 0.005 % POPOP.



# Experiment NEMO-3 and SuperNEMO

**(France, UK, Czech Rep., Russia, Spain, USA, Japan, Ukraine, Finland, Slovakia )**

| Izotope | $T_{1/2}^{\beta\beta 2\nu}$ |
|---|---|
| $^{100}$Mo | [7.16 ± 0.01 (stat) ± 0.54 (sys)] $10^{18}$ y |
| $^{82}$Se | [ 9.6 ± 0.1 (stat) ± 1.0 (sys)] $10^{19}$ y |
| $^{116}$Cd | [ 2.88 ± 0.04 (stat) ± 0.16 (sys)] $10^{19}$ y |
| $^{130}$Te | [7.0 ± 0.9 (stat) ± 0.9 (sys)] $10^{20}$ y |
| $^{150}$Nd | [9.11 + 0.25 – 0.22(stat) ± 0.63 (sys)] $10^{18}$ y |
| $^{96}$Zr | [ 2.35 ± 0.14 (stat) ± 0.16 (sys)] $10^{19}$ y |
| $^{48}$Ca | [ 4.4 + 0.5 – 0.4 (stat) ± 0.4 (sys)] $10^{19}$ y |

**700 000 $2\nu\beta\beta$ events $^{100}$Mo**

**Signal/Backgr. ratio: 76**

start of operation: 2003

end of operation: January 2011

**$^{100}$Mo $T_{1/2}$ ($\beta\beta 0\nu$) > 1.0 $10^{24}$ y $\langle m_\nu \rangle$ < 0.31 – 0.96 eV**

**$^{82}$Se $T_{1/2}$ ($\beta\beta 0\nu$) > 3.2 $10^{23}$ y**

**$\langle m_\nu \rangle$ < 0.94 – 2.6 eV**

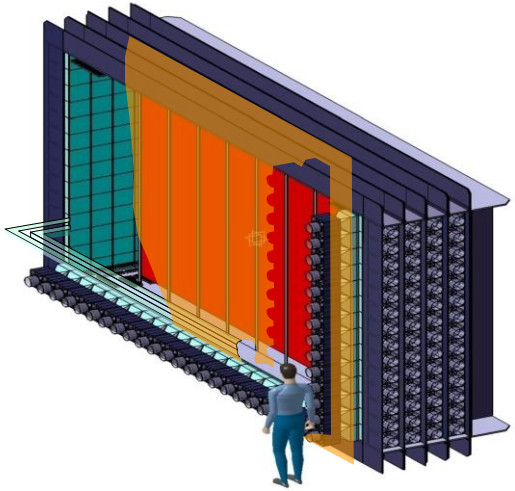
## SuperNEMO 3: $\beta\beta(0\nu)$ $T_{½}$ > 2. $10^{26}$ yr $\langle m_\nu \rangle$ < 0.04 – 0.09 eV

**Tracko-calo with 100 kg of $^{82}$Se or $^{150}$Nd**

**Background reduction: $^{214}$Bi ≤ 10 μBg/kg**

**Rn ≤ 0.15 mBg/m$^3$**

**R&D funded by France, UK, Spain, Russia, Czech Republic**

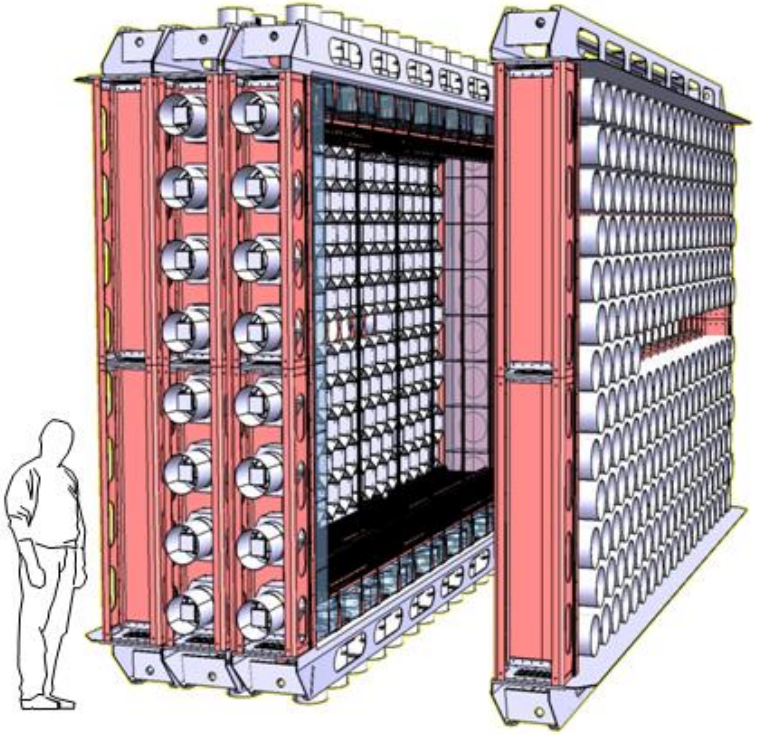


**2010-2011: TDR**

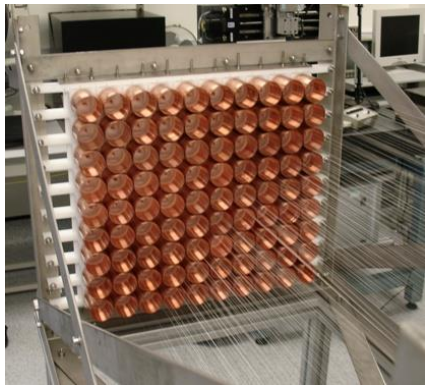
**2014-2015: commissioning of first module in LSM (France)**

**2016: Full detector running**

# SuperNEMO demonstrator

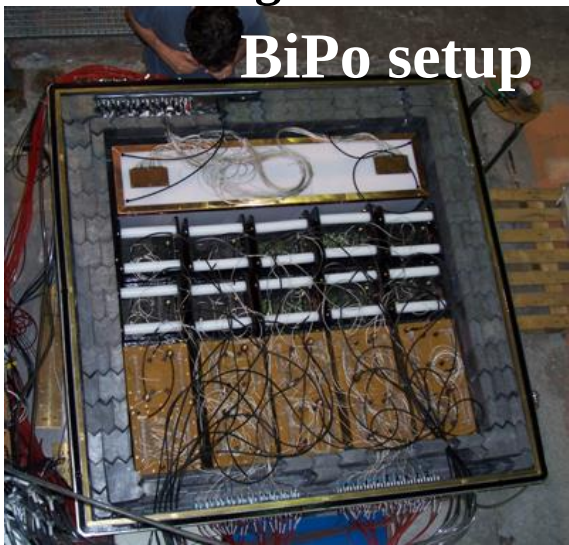


**Source:** 7 kg of $^{82}Se$
**Tracking:** 2016 drift cells
**Calorimeter:** 712 scintillator blocks
32 t, 6,2 x 2,1 x 4,1 $m^3$, 25 Gauss magnetic field
**Start:** 2016 in LSM



Tracker R&D

Low background R&D




**SuperNEMO demonstrator (first module):**

- Sensitivity of 1 module in 2.5 years, 7 kg of Se, no background – $T_{1/2}$ of $0\nu\beta\beta$ decay > 6,5 x $10^{24}$ y
- Reach sensitivity of NEMO-3 in 5 months
- $10M, operational costs 100 k€/year

**Full SuperNEMO (19 additional modules):**

- 2017-2020,
- Estimated costs $2M/module (capital)
- reach 500 kg.y exposure in 2025

# Pixel detectors in ββ decay

## $\beta^-\beta^-$ decay

- Segmented e.g. CdTe pixel detectors (enriched Cd)
- **Signature = two tracks of electrons from one pixel, final pixels of both tracks due to Bragg curve**
- Particle identification / rejection (alpha, electrons, photons)

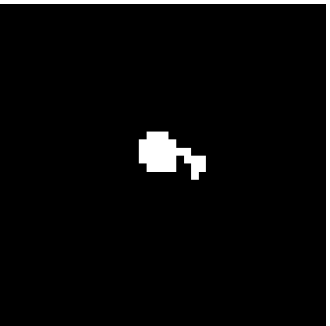
## EC/EC decay

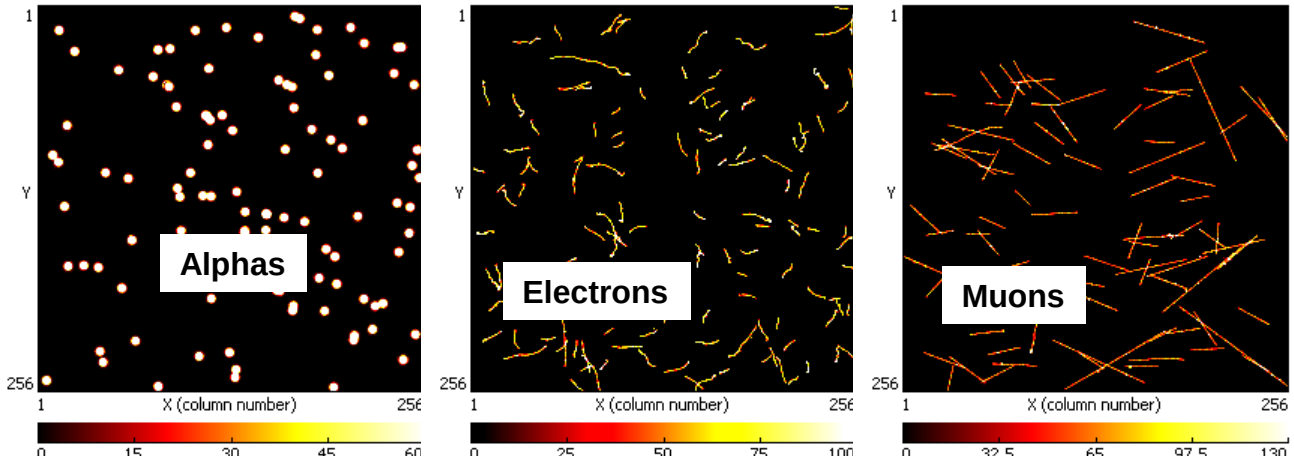
- Si pixel detectors in coincidence mode
- Thin foil of enriched isotope
- **Signature = two hitted pixels with X-rays of precise energy**
- Efficiency (factor 2x comparing with TGV II)
- Particle identification (alpha, electrons)

Semiconductor TPC

## Examples of particle type identification

$^{214}Bi \xrightarrow{\beta} {}^{214}Po \xrightarrow{\alpha} {}^{210}Pb$





# R&D of pixel telescopes in underground physics

**A) Problem of radioactivity in standard PCB (FR4)** – two solutions (CuFlon, Flexible PCB)

reduction of background (factor 4)

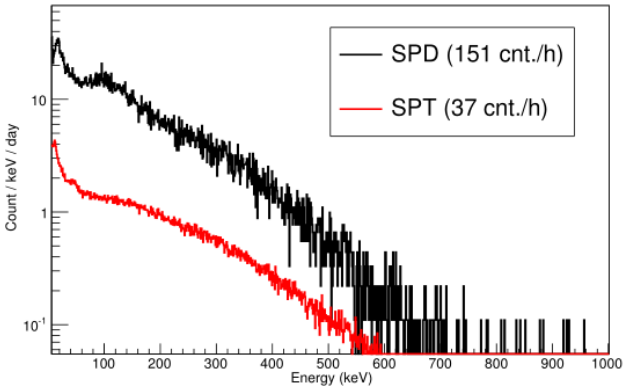


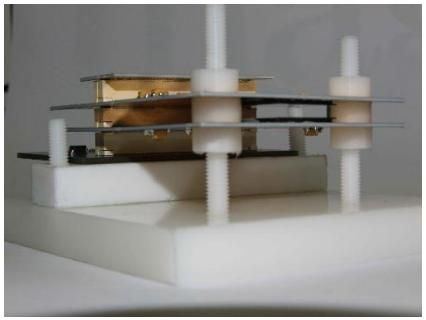

Figure 8.13: Comparison of SPT and SPD spectra from underground measurements with 5 cm of Pb shielding. Total time of measurement was 4118 hours and 219 hours for SPT and SPD, respectively. Spectrum is normalized per detector per day for both measurements.

**B) Development of hardware (CuFlon, Flexible PCB)** -

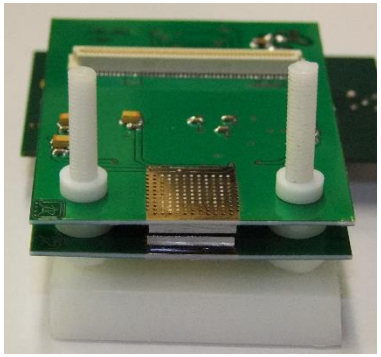
2 prototypes:

CdTe Pixel Telescope (CuFlon Version)

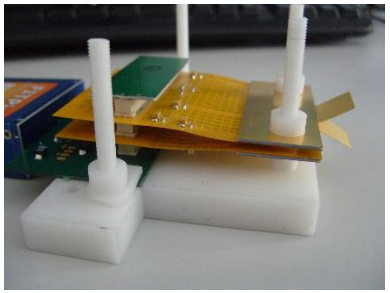
4 units of Flex-rigid Si Pixel Telescope (with 500 µm and 1000 mm Si sensors)



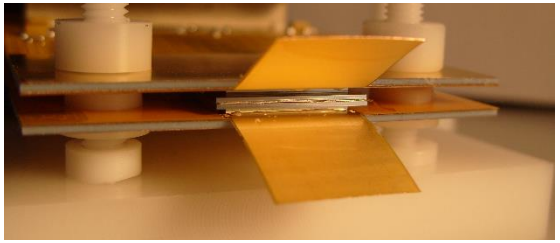
CuFlon SPT



One unit of CuFlon CdTe Pixel Telescope



Flex-rigid SPT



Close-up view of flex-rigid SPT with Cd foil

Four units of Flex-rigid SPT arranged with Delrin support structure

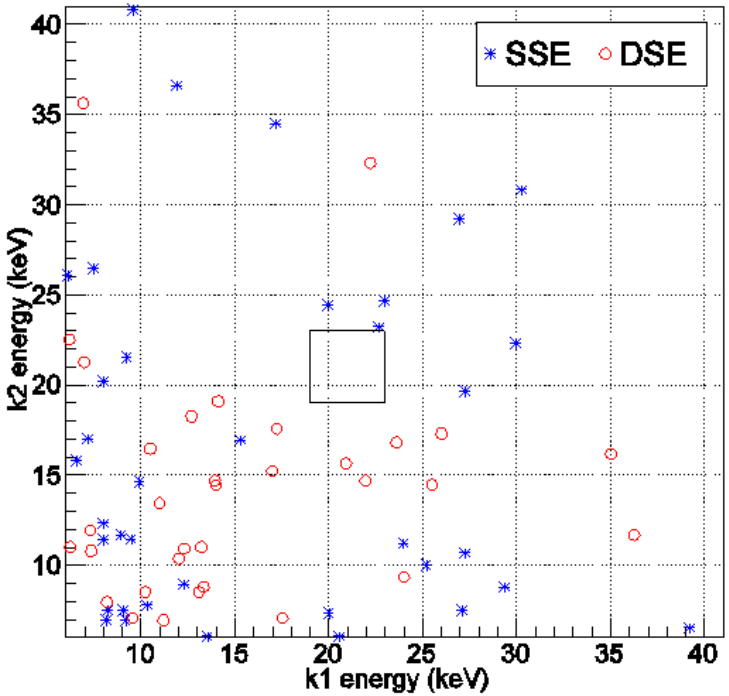
# SPT background (full shielding) vs with TGV II background

- No background events in ROI for 60 days of measurement (8 Si pixel detectors)

| Data set | All event/h | | SSE/h (all criteria) | | DSE/h (all criteria) | |
|---|---|---|---|---|---|---|
| | Total | ROI | Total | ROI | Total | ROI |
| SPT Full shielding | 6.41 | 0.15 | $6.34\times10^{-3}$ | $5.44\times10^{-5}$ [a] | $1.90\times10^{-2}$ | $6.34\times10^{-5}$ [a] |
| TGV II in full shielding | 1.18 | 0.036 | 0.34 | $9.82\times10^{-3}$ | $9.18\times10^{-3}$ | $1.42\times10^{-5}$ |

| 1425 h of data | All events/h | In ROI/h |
|---|---|---|
| Total | 32.23 ± 0.15 | 0.81 ± 0.02 |
| SSE with dist. | 0.05 ± 0.0059 | < 9.09 x $10^{-4*}$ |
| DSE | 0.06 ± 0.0067 | < 9.09 x $10^{-4}$ |

*View of full shielding partially opened*




*Scatter plot of SSE and DSE events from measurement with full shielding*

# SPT setup proposal

Estimation of limit for EC/EC decay of $^{106}$Cd for 1 pair of Timepix quads:

If background = 0 :

$T_{1/2} > (e \cdot t \cdot N_{at} \cdot \ln 2) / \ln(1\text{-}CL) = 1{,}95 \times 10^{20}$ years

90% CL $\Rightarrow$ ln (1-CL) = 2.3

e ..... full efficiency (for SPT = 8,54 %)

t ..... time of measurement [years], expected 4 years

$N_{at}$ ... number of $^{106}$Cd atoms in foil, 98% of enrichment

$\Rightarrow$ $N_{at} = 1.89 \times 10^{21}$ atoms

To reach limit of $10^{21}$ years:

We would need 5-7 quad Timepix pairs

(for 8 gr. we need 25-30 quad pairs)

# Future large-scale promising experiments (after 2020)

| Experiment | nucleus | mass (kg) | status | $T_{1/2}$(y) | $<m_\nu>$ meV |
|---|---|---|---|---|---|
| CUORE | $^{130}$Te | 11 | current | $5x10^{24}$ | 230 - 820 |
| | | 600 | in progress | $10^{26}$ | 50 - 180 |
| GERDA | $^{76}$Ge | 35 | in progress | $1,5x10^{26}$ | 90 - 200 |
| | | 1000 | R&D | $6x10^{27}$ | 15 - 35 |
| MAJORANA | $^{76}$Ge | 35 | in progress | $1,5x10^{26}$ | 90 - 200 |
| | | 1000 | R&D | $6x10^{27}$ | 15 - 35 |
| EXO | $^{136}$Xe | 200 | current | $4x10^{25}$ | 100 - 320 |
| | | 1000 | R&D | $10^{27}$ - $10^{28}$ | 10 - 50 |
| SuperNEMO | $^{82}$Se | 7 | in progress | $6,5x10^{24}$ | 240 – 560 |
| | | 100-200 | R&D | $2x10^{26}$ | 44 – 140 |
| KamLAND-Zen | $^{136}$Xe | 383 | current | $4x10^{25}$ | 100 – 320 |
| | | 1000 | R&D | $6x10^{26}$ | 25 – 80 |
| SNO+ | $^{130}$Te | 600 | in progress | $10^{26}$ | 50 - 180 |
| | | 8000 | R&D | $10^{27}$ | 15 - 60 |

**Neutrinoless double beta decay could provide for us:**

- Lepton number non-conservation
- Nature of neutrino mass (Dirac or Majorana?)
- Absolute mass scale (value or limit on $m_1$)
- Type of hierarchy (normal, inverted, quasi-degenerated)
- CP violation in the lepton sector

There is a hope to reach sensitivity to $<m_\nu>$ on the level **~ (0,01-0,05) eV** in 2020-2025 (**Degenerate**: can be tested; **Inverted**: maybe it can be tested; **Normal**: inaccessible, new approach is needed)

**Present status (simplified):** experiments with <10 kg of enriched isotopes are finished (precise detection of $2\nu\beta\beta$, $0\nu\beta\beta$ ~ 100 meV)
Present generation – ~ 100 kg of enriched isotopes are running or under construction ($10^{26}$ years), reasonable teams and detector dimension.
**Problems:** background (~μBq/kg), enrichment of isotopes in big amount, not big enough (we need 1 ton experiment)

# Conclusion:

- Significant progress in $2\nu\beta\beta$ decay (NEMO 3, EXO, GERDA,…)
- Present limit for $<m_\nu>$ is ~ 100 meV
- 4 running experiments (GERDA-I, EXO-200, KamLAND-Zen, CUORE-0)
- 2015-2016 new experiments are expected to start (SuperNEMO 1. module, GERDA-II, Majorana-demonstrator, CUORE, SNO+)

For 1 ton detectors (10 meV region) – we need "improved or new" detection techniques and methods for more effective suppression of background

- to investigate different isotopes (3-4)
- to use different experimental techniques

# Cuore Experiment

→ $^{130}Te$

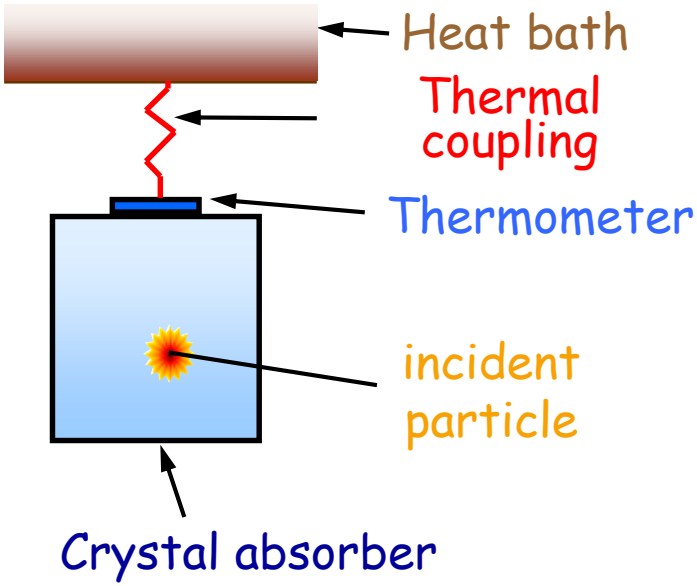
$Q_{\beta\beta}$ = 2530 keV

~ 34% natural abundance

Detector: array of 62 5x5x5 $cm^3$
$TeO_2$ bolometers @ ~ 10 mKelvin

Energy resolution: 0.28% @ Qvalue

Location: LNGS (Italy)




Thermal signal

$$\Delta T = E/C$$

↓

Detector works at low temperature

## $2\nu\beta\beta$ decay:

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} = G_{2\nu}|M_{GT}^{2\nu\beta\beta}|^2$$

$G_{2\nu}$ - phase space integral
$M_{GT}^{2\nu\beta\beta}$ - nuclear structure matrix element

## $0\nu\beta\beta$ decay (mass mechanism):

$$\left[T_{1/2}^{0\nu\beta\beta}\right]^{-1} = G_{0\nu}|\langle m_\nu\rangle|^2|M_{m_\nu}^{0\nu\beta\beta}|^2$$

$G_{0\nu}$ - phase space integral
$M_{m_\nu}^{0\nu\beta\beta}$ - nuclear structure matrix element. Note: $M_{m_\nu}^{0\nu\beta\beta} \neq M_{GT}^{2\nu\beta\beta}$
$\langle m_\nu\rangle$ - effective Majorana neutrino mass

$\Rightarrow$ Phase space can be calculated "easily"

$\Rightarrow$ Uncertainty completely dominated by $M_{GT}^{2\nu\beta\beta}$, $M_{m_\nu}^{0\nu\beta\beta}$

# CUORE (Gran Sasso)

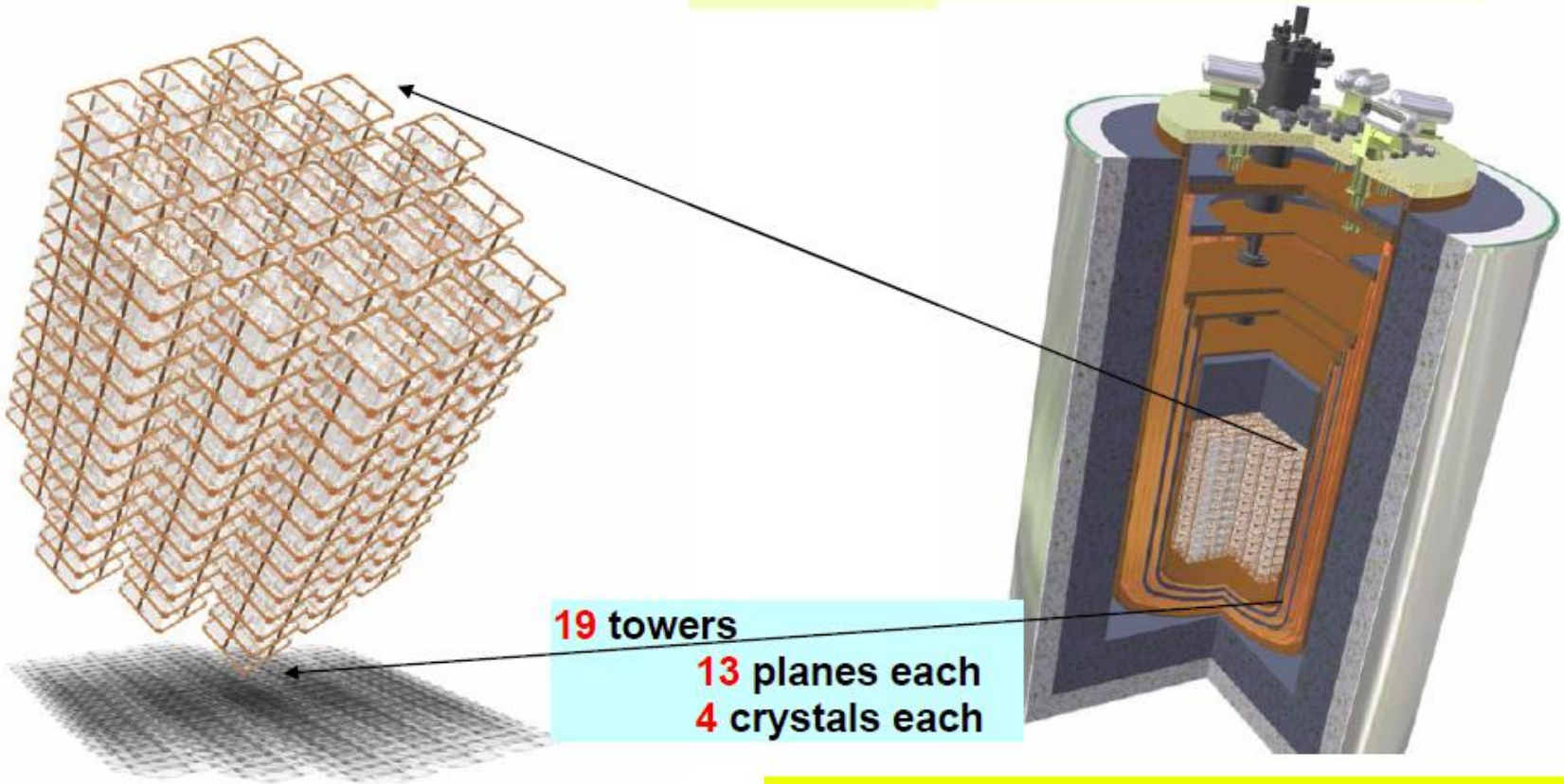
**Cryogenic Underground Observatory for Rare Events**

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

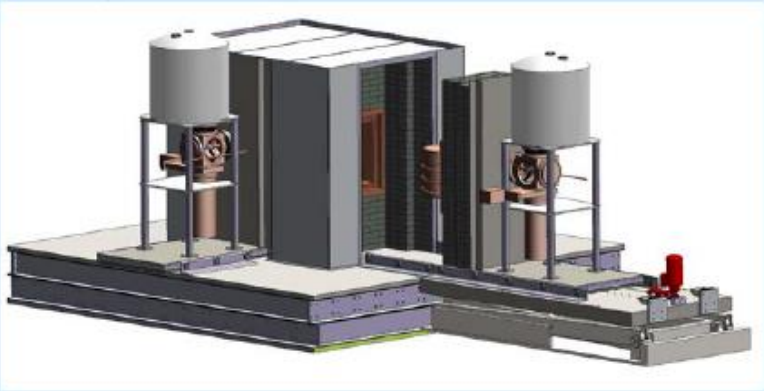



Beginning of measurements ~ 2015

CUORE-0 is operated in Gran Sasso now

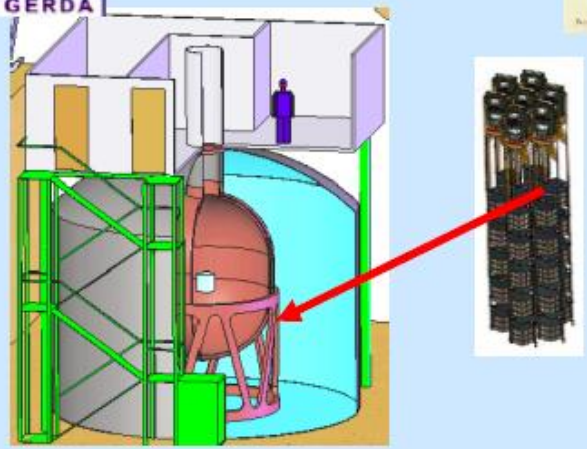
# Towards 1TGe

MAJORANA



- Modules of $^{enr}$Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D demonstrator module: Total ~40 kg (up to 30 kg enr.) - 2015

GERDA



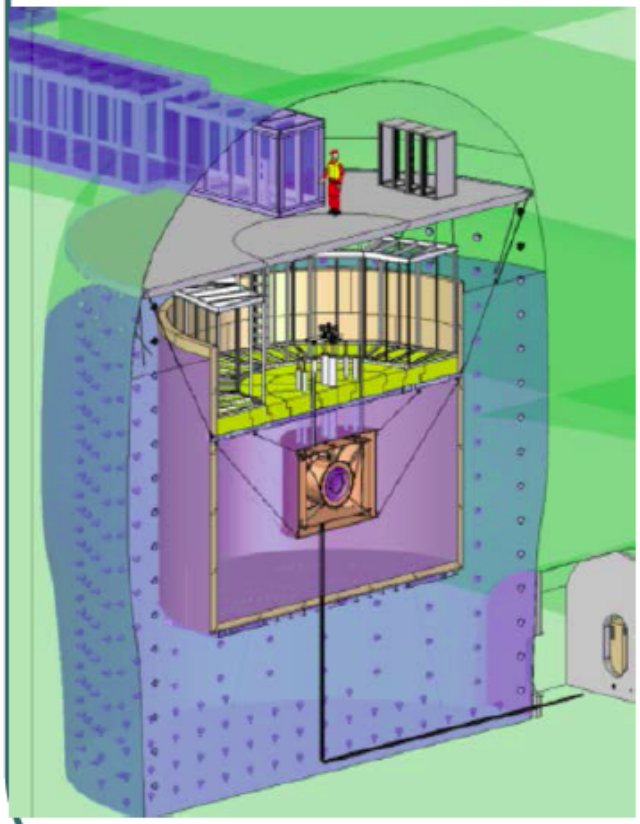
- 'Bare' $^{enr}$Ge array in liquid argon
- Shield: high-purity liquid Argon / $H_2O$
- Phase I (2011): ~18 kg (HdM/IGEX diodes)
- Phase II (2015): add ~20 kg new detectors - Total ~35 kg

**Joint Cooperative Agreement:**

- **Open exchange of knowledge & technologies (e.g. MaGe, R&D)**
- **Intention is to merge for 1 ton exp. Select best techniques developed and tested in GERDA and MAJORANA**

**1 t detector: ~ 2020-2025**

# nEXO



**Overall mass: 5 tonnes, 90% enriched $^{136}Xe$**

**Time Projection Chamber (TPC)**

**Location: SNOLAB (Canada)**

**Running time: 10 years**

**Energy resolution: 2.35% (FWHM)**

**Sensitivity:** **$\sim 4 \cdot 10^{27}$ yr (without Ba)**
**$\sim 2 \cdot 10^{28}$ yr (with Ba)**

**Design still not finalized**

**Start of data tacking ~ 2025**

# SNO+

**Reuse of SNO equipment with Liquid Scintillator in the Acrylic Vessel (Energy resolution is ~ 10.5% (FWHM) at 2.5 MeV)**

**Original plan: $^{150}$Nd**

**Current plan: $^{130}$Te (using natural Te)**
- good Te solubility is demonstrated (0.3-3%)
- 34.5% vs 5.6% natural abundance

**Scintillator fill in 2015**

**Initially 0.3% loading (~ 800 kg of $^{130}$Te; maybe increased)**

**Sensitivity is ~ $10^{26}$ yr (Phase I)**
**~$10^{27}$ yr (Phase-II)**

**Start of data taking in ~ 2016**

There are many experiments on the search for $0\nu\beta\beta$ of different nuclei. The process was not observed. Very large lower bounds for half-lives were obtained

Some recent data

EXO-200.

$T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 1.1 \cdot 10^{25}$ y (90%$CL$) $|m_{\beta\beta}| < (1.9 - 4.5) \cdot 10^{-1}$ eV

KamLAND-Zen

$T^{0\nu}_{1/2}(^{136}\mathrm{Xe}) > 2.6 \cdot 10^{25}$ y (90%$CL$)$|m_{\beta\beta}| < (1.4 - 2.8) \cdot 10^{-1}$ eV

GERDA, Heidelberg-Moscow, IGEX

$T^{0\nu}_{1/2}(^{76}\mathrm{Ge}) > 3.0 \cdot 10^{25}$ y (90%$CL$) $|m_{\beta\beta}| < (2 - 4) \cdot 10^{-1}$ eV

$|m_{\beta\beta}|$ can be predicted only if we make assumption about neutrino spectrum. If there is the inverted hierarchy ($m_3 \ll m_1 < m_2$) and neutrinos are Majorana particles from oscillation data it follows

$|m_{\beta\beta}| \simeq \mathrm{a\ few} \cdot 10^{-2}$ eV

Next experiments on the search for $0\nu\beta\beta$ are planned to reach this region

## *Future plans:*

1. Continuation of the measurement with enriched $^{106}$Cd (2νEC/EC decay on the level $10^{21}$ yrs.)

2. Conceptual design study (MC, theoretical calculations, background study) – a) the possibility to measure 2νEC/EC decay with other isotopes ($^{162}$Er, $^{156}$Dy) V.Ceron, J.Hirsch, arXiv:nucl-th/9911021v1
   b) the study of the posibility to measure 0νEC/EC decay ($^{152}$Gd g.s., $^{112}$Sn exc. state– resonance enhancement of the 0νEC/EC process if $Q - Q_r < 1$ keV)
   Z.Sujkowski, S.Wycech, Phys. Rev. C70, 052501, 2004
   J.Bernabeu, A. deRujula, C.Jarlskog, Nucl. Phys. B223, 15 (1983)
   signature – X-rays < 100 keV + γ or $e^-e^+$ or Majoron
   advantage: good value of the rates between 0νEC/EC and 2νEC/EC processes

3. Pixel detectors (Si or Ge) in EC/EC decay – thickness between 300 μm-1 mm (coincidence measurement, position of detection, energy of X-ray)

Table I: present results on neutrinoless DBD

| Nucleus | Experiment | % | $Q_{\beta\beta}$ | Enrich | Technique | $T_{0\nu}$ (y) | $<m_\nu>$ |
|---|---|---|---|---|---|---|---|
| 48Ca | Elegant IV | 0.19 | 4271 | | scintillator | >1.4x1022 | 20-28 |
| 76Ge | IGEX | 7.8 | 2039 | 87 | Ionization | >1.6x1025 | .23 – .64 |
| 76Ge | Klapdor et al | 7.8 | 2039 | 87 | ionization | 1.2x1025 | .29-.81 |
| 82Se | NEMO 3 | 9.2 | 2995 | 97 | tracking | >1.x1023 | 1.7-4.5 |
| 100Mo | NEMO 3 | 9.6 | 3034 | 95-99 | tracking | >1x1024 | .46-1.1 |
| 116Cd | Solotvina | 7.5 | 3034 | 83 | scintillator | >1.7x1023 | 1.2 – 2.7 |
| 128Te | Bernatovitz | 34 | 2529 | | geochem | >7.7 × 1024 | .82-1.9 |
| 130Te | Cuoricino | 33.8 | 2529 | | bolometric | >2.8 x1024 | .3-.7 |
| 136Xe | DAMA | 8.9 | 2476 | 69 | scintillator | >1.2x1024 | .64 -1.6 |
| 150Nd | Irvine | 5.6 | 3367 | 91 | tracking | >1.2x1021 | 14 - ? |

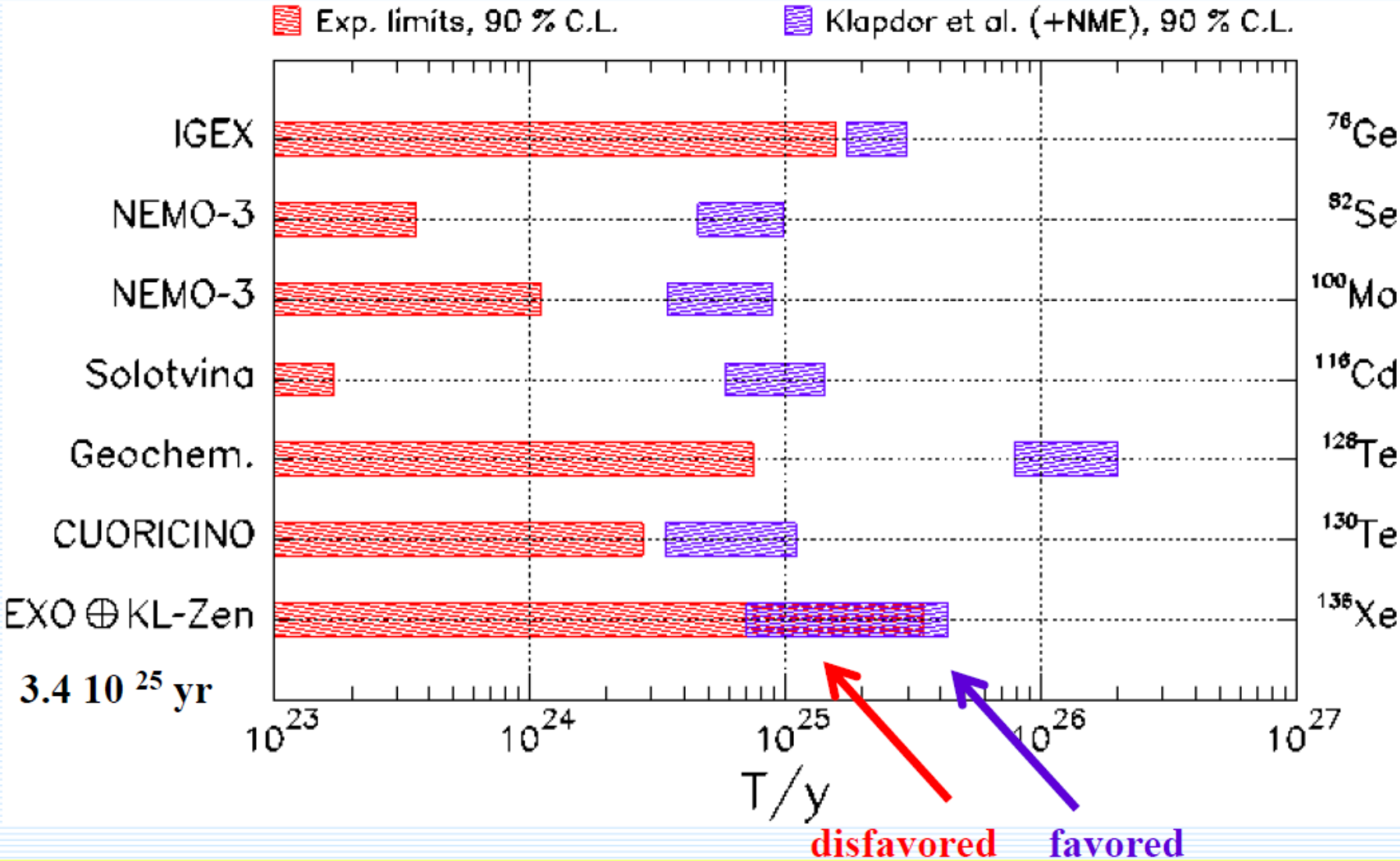
EXO $T^{0\nu}_{1/2}$ (136Xe) $> 1.6 \times 10^{25}$ yr $<m_\nu>$ 140–380 me

KAMLAND-ZEN $> 3.4 \times 10^{25}$ yr 120-250

GERDA I $^{76}$Ge to be filled by S.Shoenert

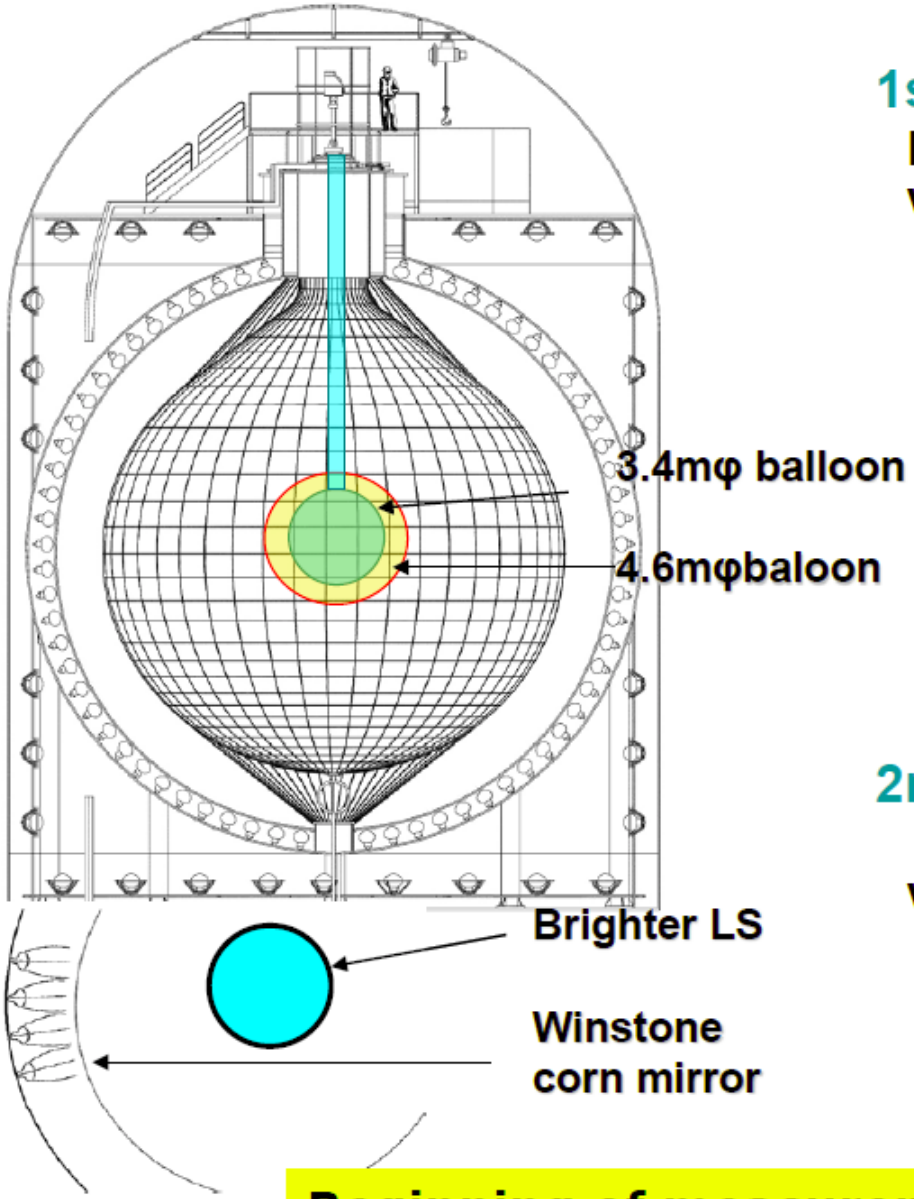
CUORE0 (New) $^{130}$Te $> 4 \times 10^{24}$ yr 270-760

**Range of half-lives preferred at 90% C.L. by the 0νββ claim of evidence compared with the 90% exclusion limits placed by other experiments.**




**The comparison involves the NME and their errors as well as their correlations**

# KamLAND2-Zen project




**1st phase enriched Xe 400kg (2011)**

R=1.7m balloon

V=20.5m$^3$,S=36.3m$^2$

LS : C10H22(81.8%)+PC(18%)

+PPO+Xe(~2.5wt%)

ρLS: 0.78kg／ℓ

high sensitivity with low cost

tank opening (2015)

**2nd phase enriched Xe 1000 kg**

R=2.3m balloon

V=51.3m$^3$,S=66.7m$^2$

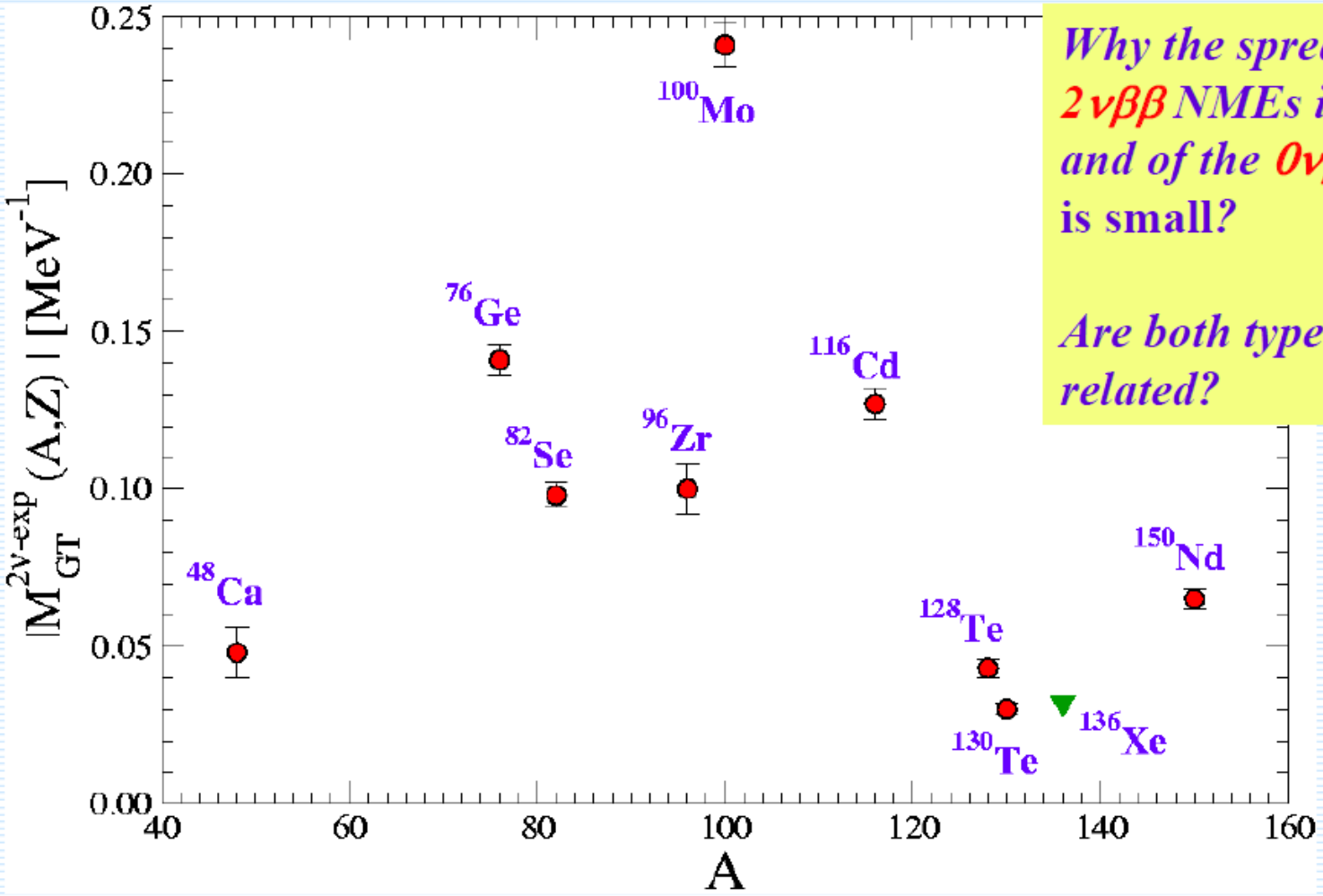
improvement of energy resolution

(brighter LS, higher light concentrator )

**Beginning of measurements with 1000 kg - after 2017**

## *2νββ-decay NMEs*

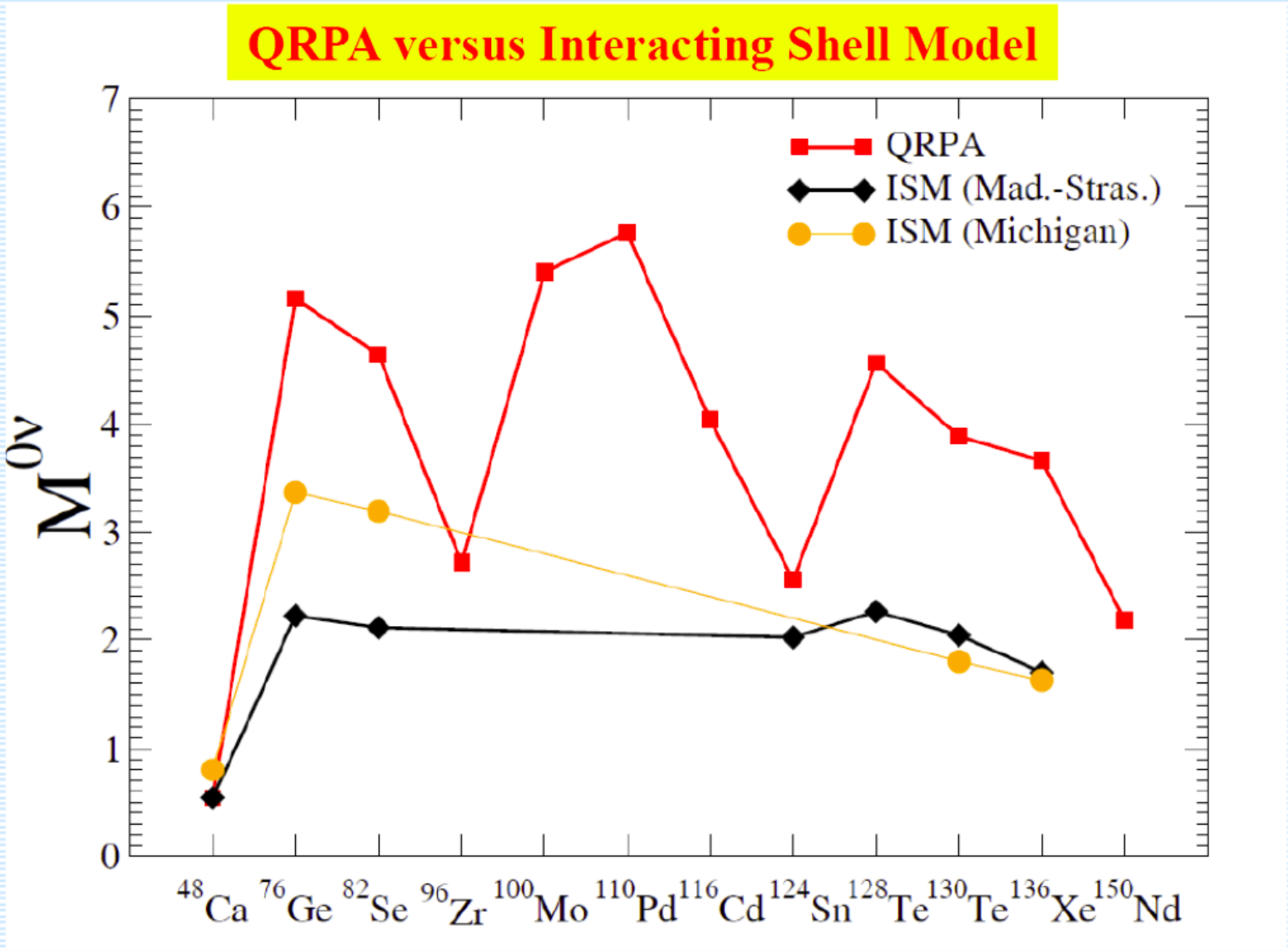
$$\frac{1}{T_{1/2}^{2\nu-exp}} = G^{2\nu}(E_0, Z)\ g_A^4\ |M_{GT}^{2\nu}|^2$$




***Why the spread of the 2νββ NMEs is large and of the 0νββ NMEs is small?***

***Are both type of NMEs related?***

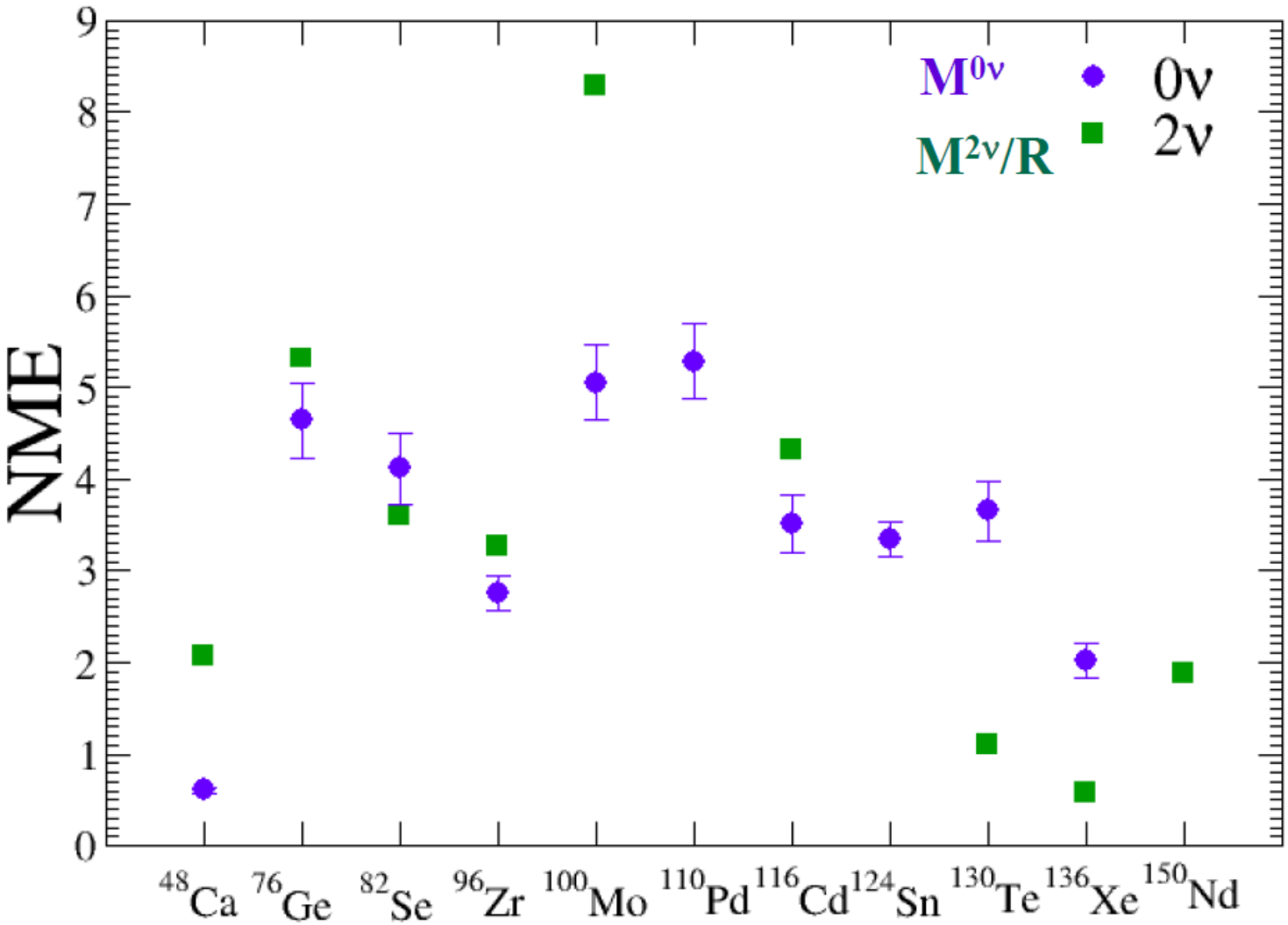
***Differencies among 2νββ-decay NMEs: up to factor 10***




IBM: Interacting Boson Model (F. Iachello)

EDF(energy density functionality)/PHFB(Projected Hartree-Fock-Bogoliubov): Rodrigez, PRL 105, 2010/K. Rath, PRC 85, 2012, 014308

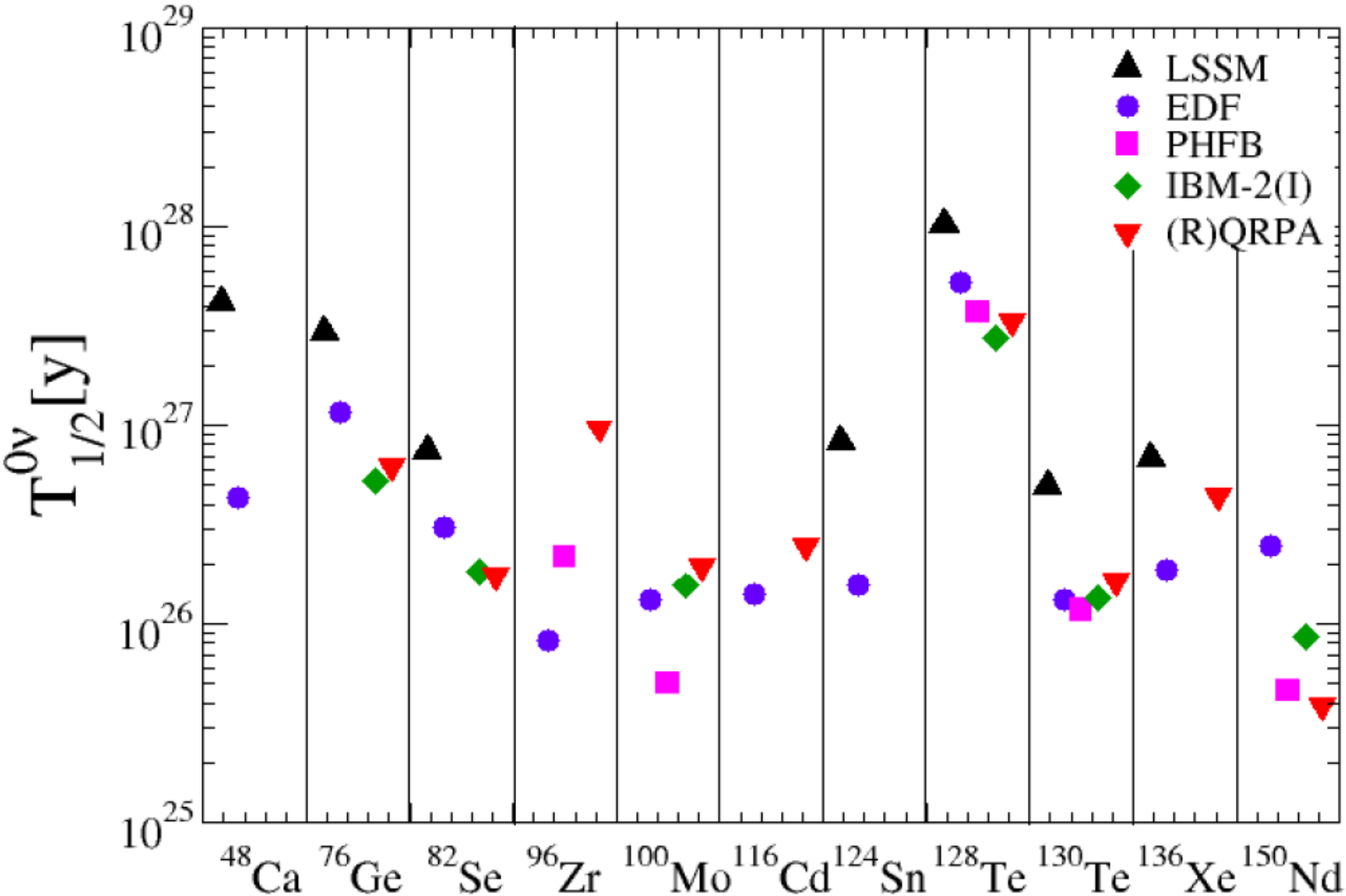
# *Is there a connection between 0νββ- and 2νββ-decay NME?*




**F. Š., Nucl. Phys. B, Proc. Suppl. (2014) – Proceeding of NOW14 conference**

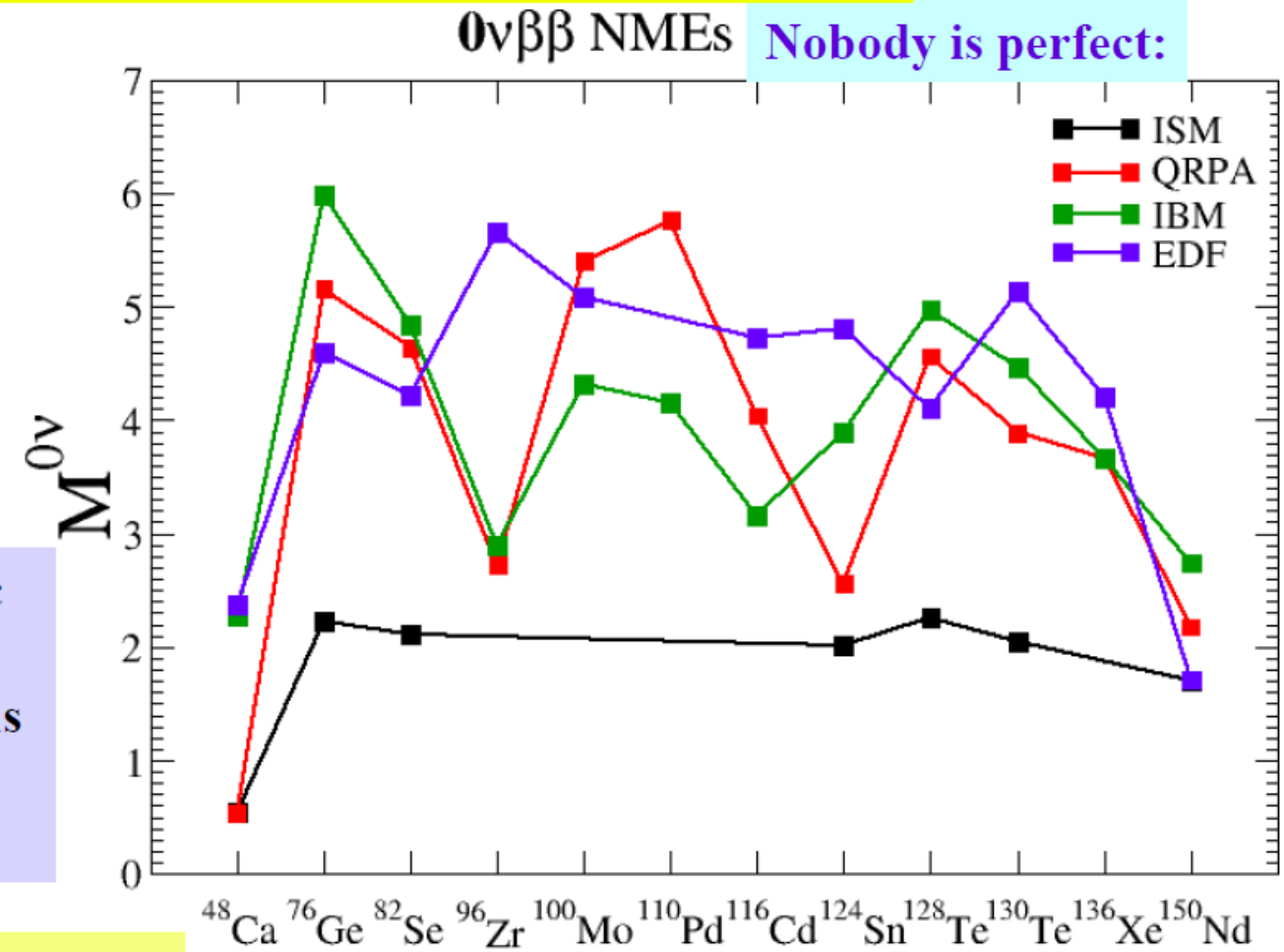
# 0νββ-decay half-life

$m_{\beta\beta}$=50 meV



# *The 0νββ-decay NMEs (Status:2015)*

**Nobody is perfect:**




**$g_A$=1.25(7), CCm or UCOM s.r.c., $r_0$=1.20 fm**

**Systematic errors – Calculations can be improved**

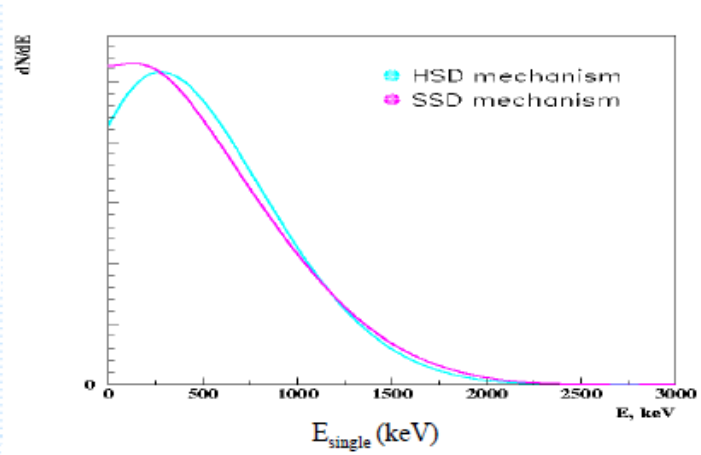
***Differences:***

*i) mean field;*
*ii) residual int.;*
*iii) size of the m.s.*
*iv) many-body appr.*

**LSSM (small m.s., negative parity states)**
**PHFB (GT force neglected)**
**IBM (Hamiltonian truncated)**
**(R)QRPA (g.s. correlations not accurate enough)**

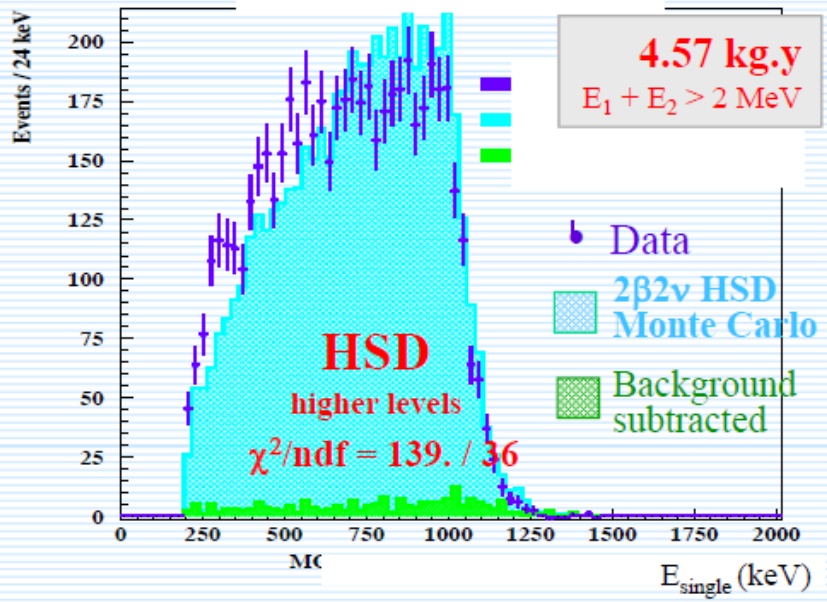
# $^{100}$Mo 2β2ν: Experimental Study of SSD Hypothesis

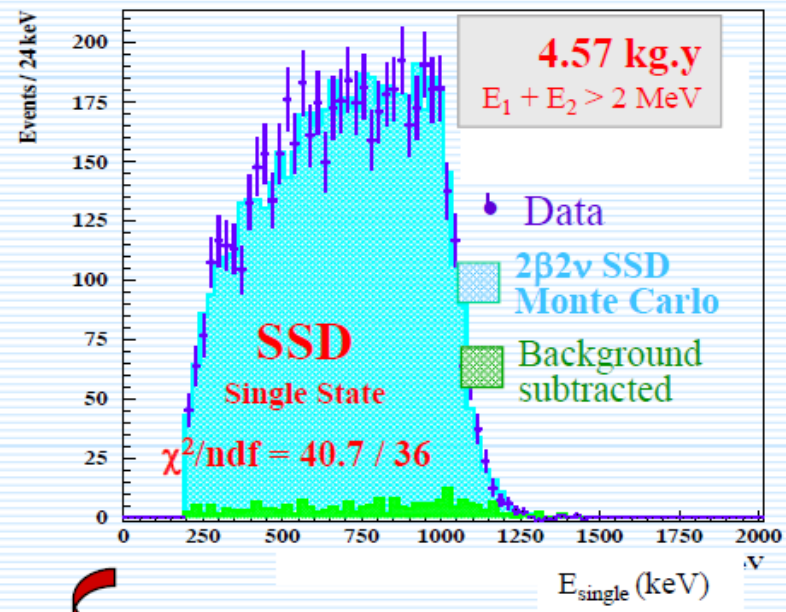
**NEMO 3 exp.**




**Single electron spectrum different between SSD and HSD**

**Šimkovic, Šmotlák, Semenov**
**J. Phys. G, 27, 2233, 2001**




**HSD:** $T_{1/2} = 8.61 \pm 0.02\ (stat) \pm 0.60\ (syst) \times 10^{18}$ y

**SSD:** $T_{1/2} = 7.72 \pm 0.02\ (stat) \pm 0.54\ (syst) \times 10^{18}$ y

**$^{100}$Mo 2β2ν single energy distribution in favour of Single State Dominant (SSD) decay**

# From NEMO to SuperNEMO

**NEMO-3 successful experience allows to extrapolate tracko-calo technique on larger mass next generation detector to reach new sensitivity level.**

$$T_{1/2}^{0\nu}(y) \propto \frac{a\varepsilon}{W} \times \sqrt{\frac{M \times t}{N_{BGR} \times \Delta E}}$$

| NEMO-3 | $\Rightarrow$ | SuperNEMO |
|---|---|---|
| $^{100}$Mo, 7kg | Isotope, mass | $^{82}$Se,100-200 kg |
| $^{208}$Tl: < 20 μBq/kg<br>$^{214}$Bi: < 300 μBq/kg | Background in ββ-foil | $^{208}$Tl: < 2 μBq/kg<br>$^{214}$Bi: < 10 μBq/kg |
| 8% | Efficiency | 30% |
| 8% @ 3 MeV | Energy resolution (FWHM) | 4% @ 3 MeV |
| $T_{1/2} > 2 \times 10^{24}$ y<br>$\langle m_\nu \rangle < 0.3 – 0.8$ eV | Sensitivity | $T_{1/2} > 1\text{-}2 \times 10^{26}$ y<br>$\langle m_\nu \rangle < 40 – 100$ meV |

**SUPERNEMO R&D was finished, 1st module in 2016**