Neutrinoless double beta decay: an experimental overview

- What is so special in neutrinoless double beta decay ($\beta\beta0\nu$)?
- The 1998 revolution: a change of perspective in $\beta\beta0\nu$ searches
- $\beta\beta0\nu$, cosmology and direct searches
- The main experimental challenges
  - Source: what is the "best" double beta emitter?
  - Detector: source=detector versus external source approaches
  - Background
- A look to the current generation of experiments (GERDA, CUORE, EXO-200, Kamland-Zen, NEMO3)
- Conclusions

F. Terranova, Univ. of Milano-Bicocca and INFN sez. di Milano-Bicocca

Double Beta Decay

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$

2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \sim 10^{18} - 10^{21}$ y

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$

Neutrinoless Double Beta Decay (bb0v)
never observed (except a discussed claim)
lifetime > 10^{25} years

violation of total lepton number conservation

② is a very sensitive tests to new physics since the phase space term is much larger for them than for the standard process

interest for ββ0ν lasts for 70 years !
Goeppert-Meyer proposed the standard process in 1935
Racah proposed the neutrinoless process in 1937

But experimental physics is plenty of "sensitive tests of new physics" ☺
What makes the search for ββ0ν decay a milestone in contemporary neutrino physics?

A deep connection with standard neutrino physics

1930 — Pauli's proposal of "neutrinos"

1956 — First observation of neutrinos

1998 — Discovery of neutrino oscillations

now — Precision oscillation physics

1937 — Proposal of Majorana neutrinos

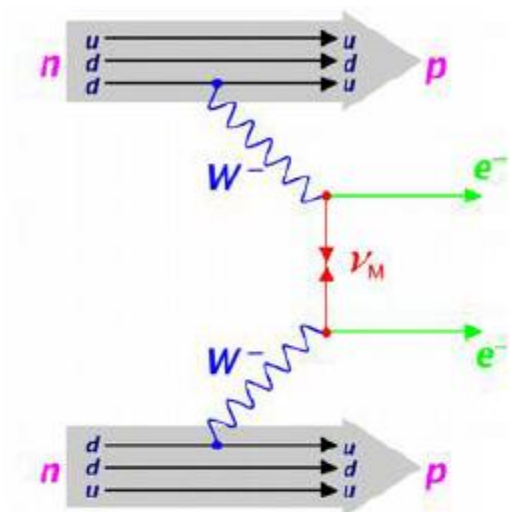
1938 — ββ0ν as a probe of Majorana neutrinos

1977 — The see-saw mechanism

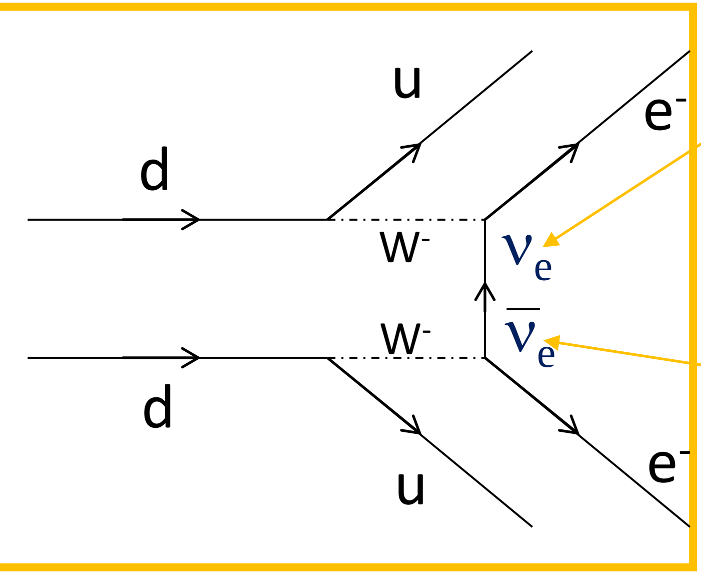
1982 — The Shechter-Valle theorem

now — High sensitivity ββ0ν searches

The link is due to one (not demonstrated ☺) ansatz: neutrinoless double beta decay is mostly caused by



A deep connection with standard neutrino physics



a LH neutrino (L=1)
is absorbed at this vertex

a RH antineutrino (L=-1)
is emitted at this vertex

With **massless neutrinos, the process is forbidden** because neutrino has no correct helicity / lepton number to be absorbed at the second vertex

- IF neutrinos are massive DIRAC particles:

  Helicities can be accommodated thanks to the finite mass,
  BUT Lepton number is rigorously conserved

  $\beta\beta0\nu$ is forbidden

- IF neutrinos are massive MAJORANA particles:

  Helicities can be accommodated thanks to the finite mass,
  AND Lepton number is not relevant

  $\beta\beta0\nu$ is allowed

Decay rate

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu\beta\beta} \cdot \left|NME\right|^2 \cdot \left|\langle m_\nu \rangle\right|^2, \qquad \langle m_\nu \rangle = \sum_i U_{ei}^2 m_i e^{i\alpha_i}$$

Phase space

Nuclear Matrix Element

effective mass

mixing matrix (with phases)

mass eigenvalues

Majorana phases

1) **Single β decay: $m^2_i \neq 0$ alters the spectrum tail. Sensitive* to the so-called "effective mass of electron neutrino":**

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

[Simkovic]

Effective mass in beta decays

2) **Double 0νββ decay: Iff $m^2_i \neq 0$ and ν=anti-ν (Majorana). Sensitive* to the "effective Majorana mass" (and related phases):**

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

[Valle]
[Rodejohann]
[Simkovic]
[Mohapatra]

ββ0ν effective mass

3) **Cosmology: $m^2_i \neq 0$ alters large scale structure formation within standard cosmology constrained by CMB+other data. Measures*:**

$$\Sigma = m_1 + m_2 + m_3$$

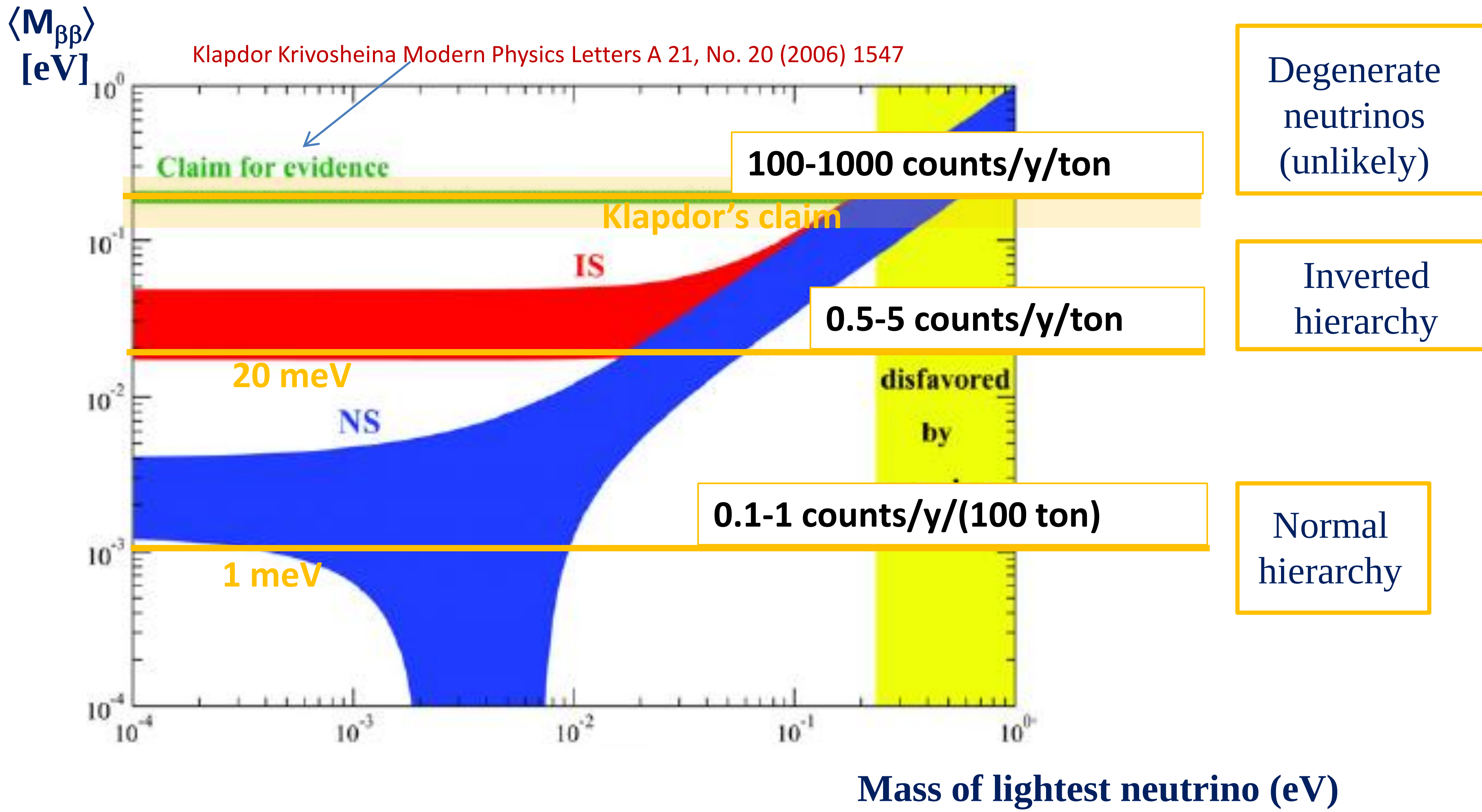
[Wong]

Effective mass in cosmology

Even more, we know (2011!) that s_{13} is rather large (Daya-Bay, RENO, T2K, DoubleChooz)

See e.g. Lisi @ Neutrino2010

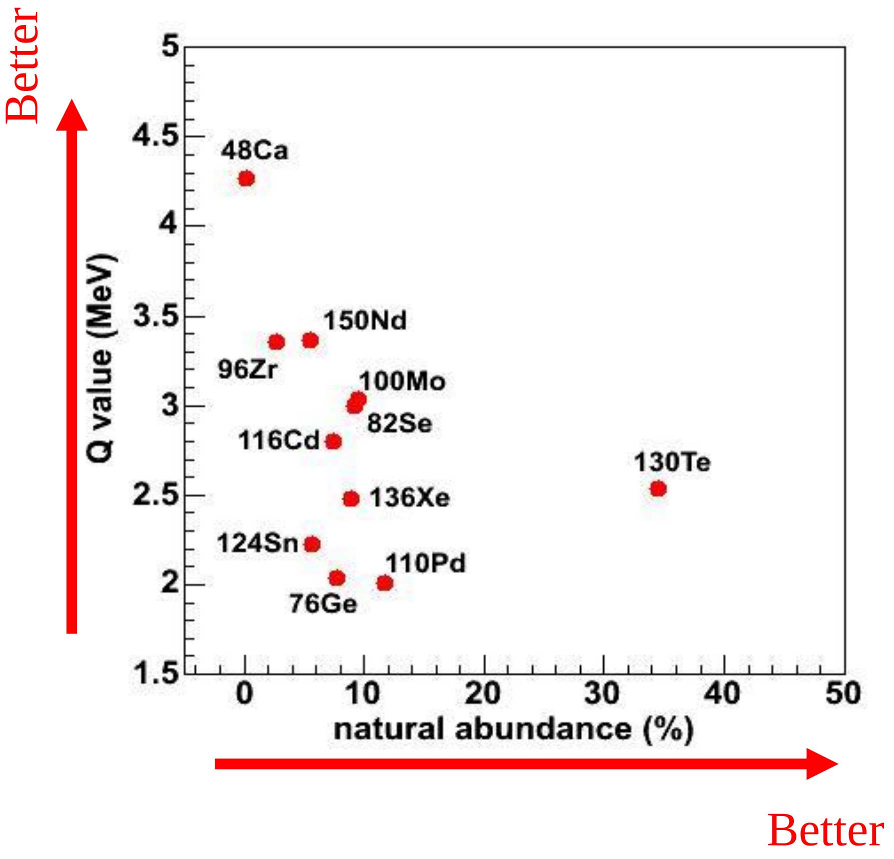
All this info fixes where to look for ββ0ν with reasonable chances of seeing positive results

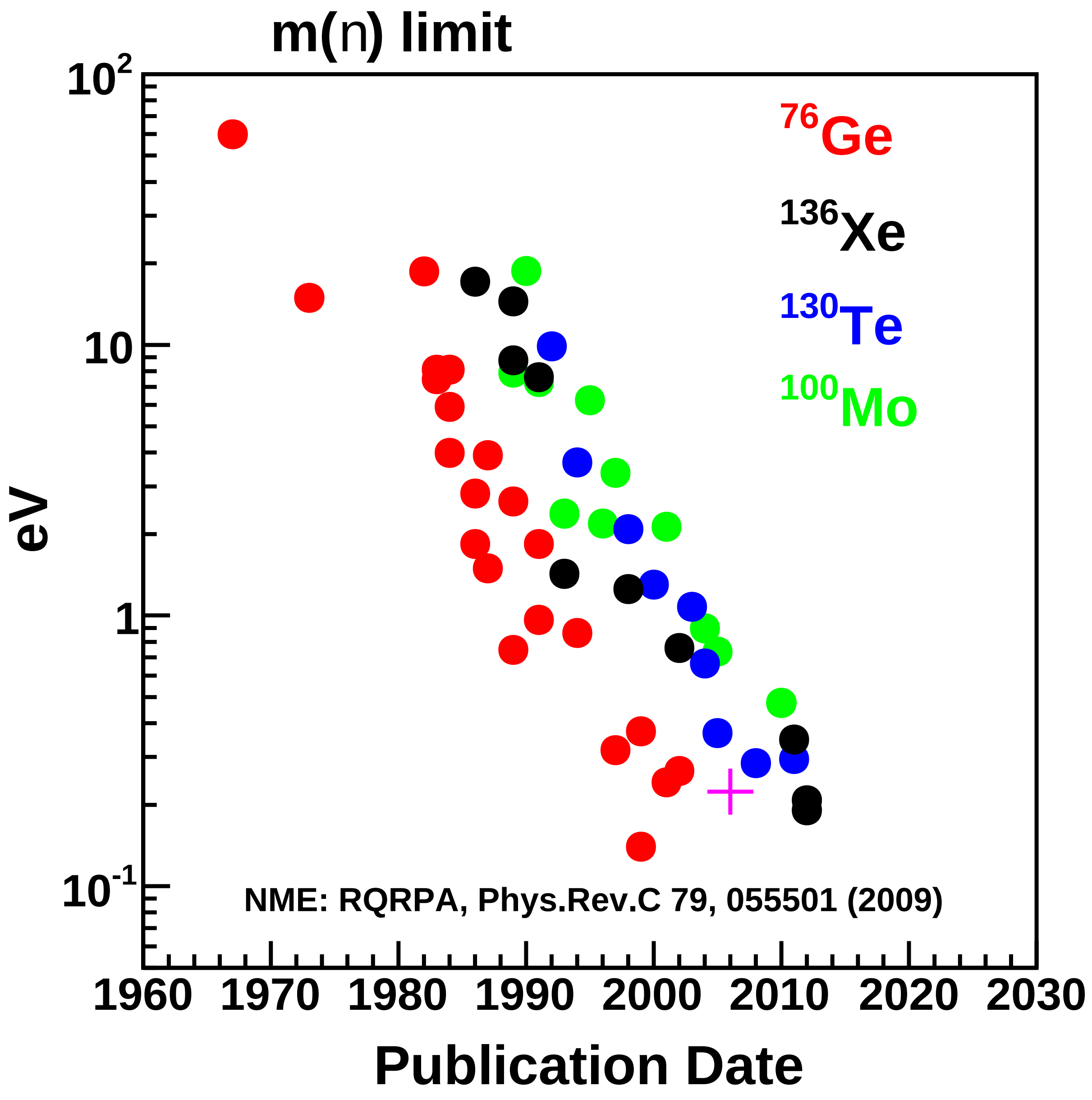


Choice of the isotope

Isotopes where single beta decay is forbidden (or strongly suppressed) due to energy conservation (some Z-even , A-Z even nuclei) and – possibly – the "normal" bb2v decay has a long lifetime

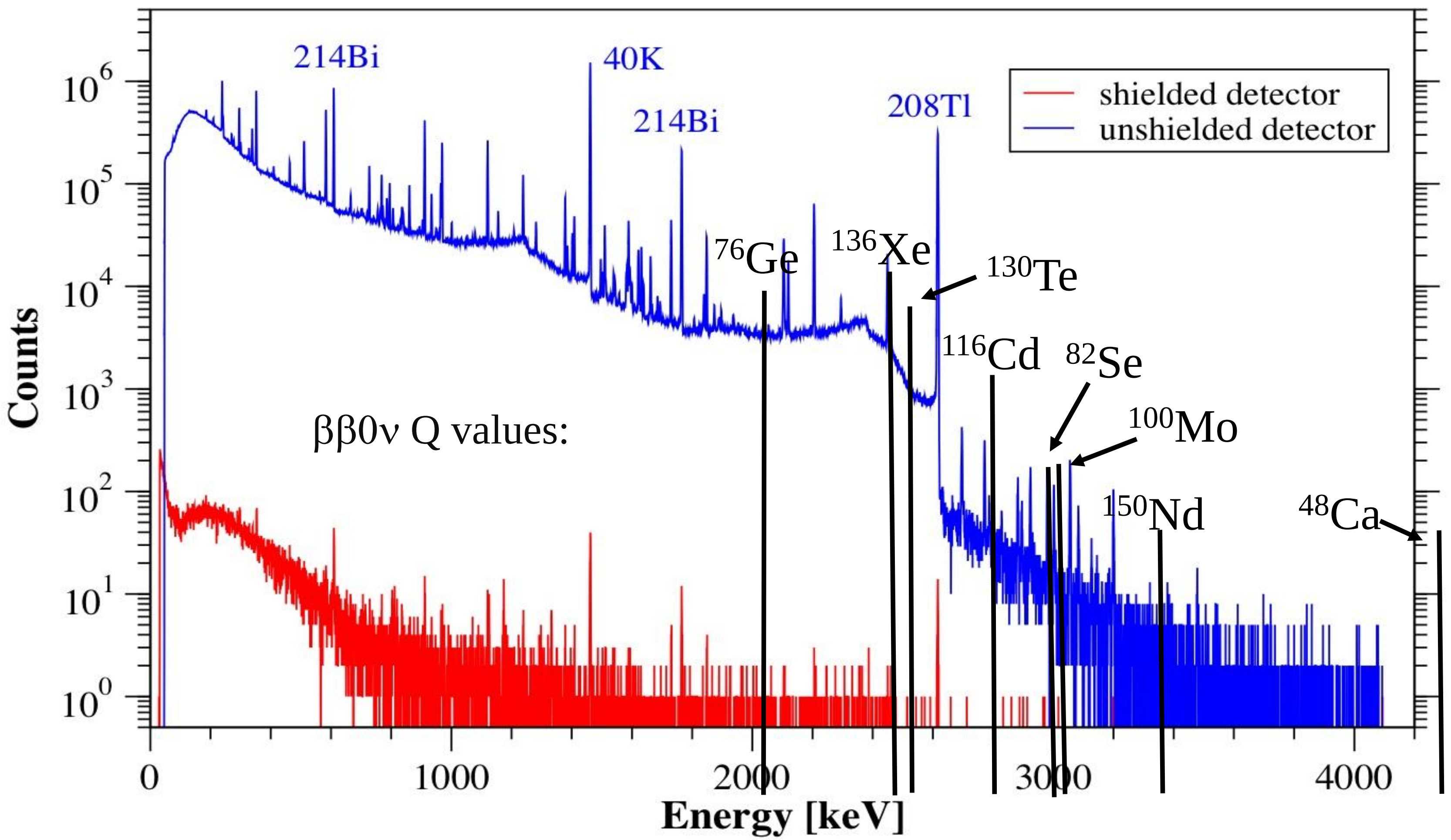
Isotope	Q value (MeV)	Abundance (%)
^{48}Ca	4.271	0.187
^{76}Ge	2.039	7.8
^{82}Se	2.995	9.2
^{96}Zr	3.350	2.8
^{100}Mo	3.034	9.6
^{110}Pd	2.013	11.8
^{116}Cd	2.802	7.5
^{124}Sn	2.228	5.64
^{130}Te	2.533	34.5
^{136}Xe	2.457	8.9
^{150}Nd	3.367	5.6



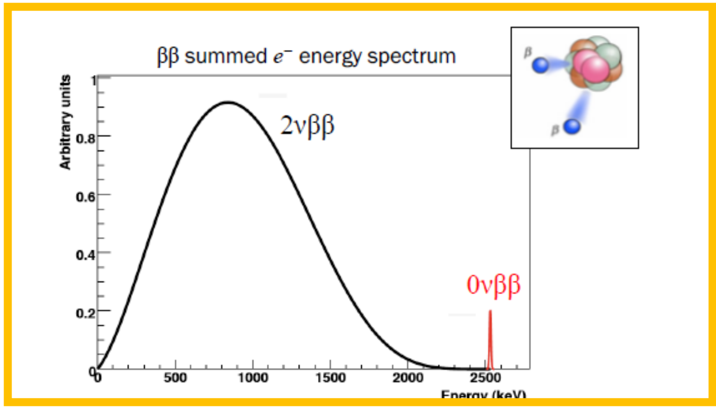

m(n) limit
^{76}Ge
^{136}Xe
^{130}Te
^{100}Mo
eV
10^{2}
10
1
10^{-1}
NME: RQRPA, Phys.Rev.C 79, 055501 (2009)
1960
1970
1980
1990
2000
2010
2020
2030
Publication Date

Signal

No outcoming neutrinos, i.e. no missing energy → a monochromatic peak corresponding to the Q value of the decay



Background



Intrinsic background: ββ2ν

- Energy resolution plays a key role: germanium detectors or bolometers: FWHM O(0.1%)
- Choice of isotopes with long lifetime of 2ν double beta decay (^{136}Xe)

Alpha/beta contamination

- Radiopurity of the chosen material/detector
- Capability of tagging alpha/beta particles and veto external charged particles

Gamma contamination

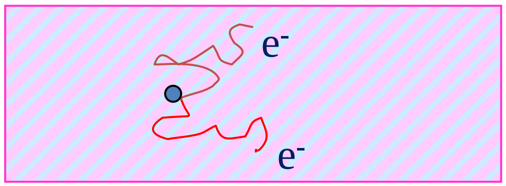
- Radiopurity of the chosen material/detector
- Choice of isotopes with large Q-value (Nd, Ca, Se, Mo)
- Coincidence methods

Muon and neutron induced background

- Passive shielding and neutron absorbers
- Active muon veto

Experimental strategies

①



Source ≡ Detector
(calorimetric technique)

- scintillation
- phonon-mediated detection
- solid-state devices
- gaseous/lquid detectors

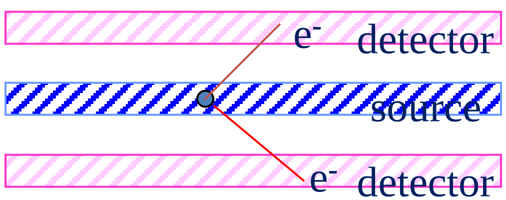
☹ constraints on detector materials

☺ very large masses are possible
demonstrated: up to ~ 100 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

②



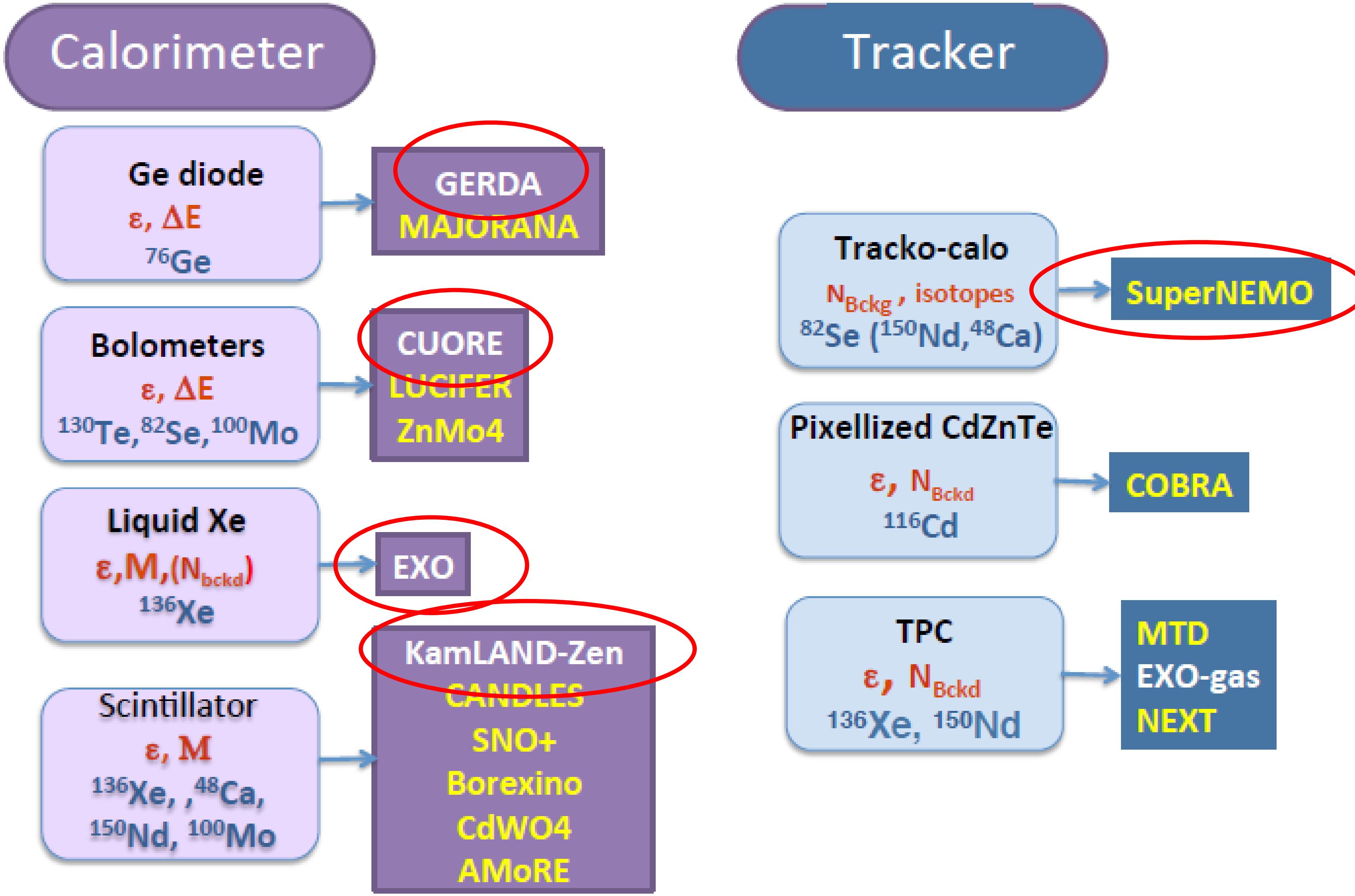
Source ≠ Detector

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

☹ it is difficult to get large source mass

☺ neat reconstruction of event topology

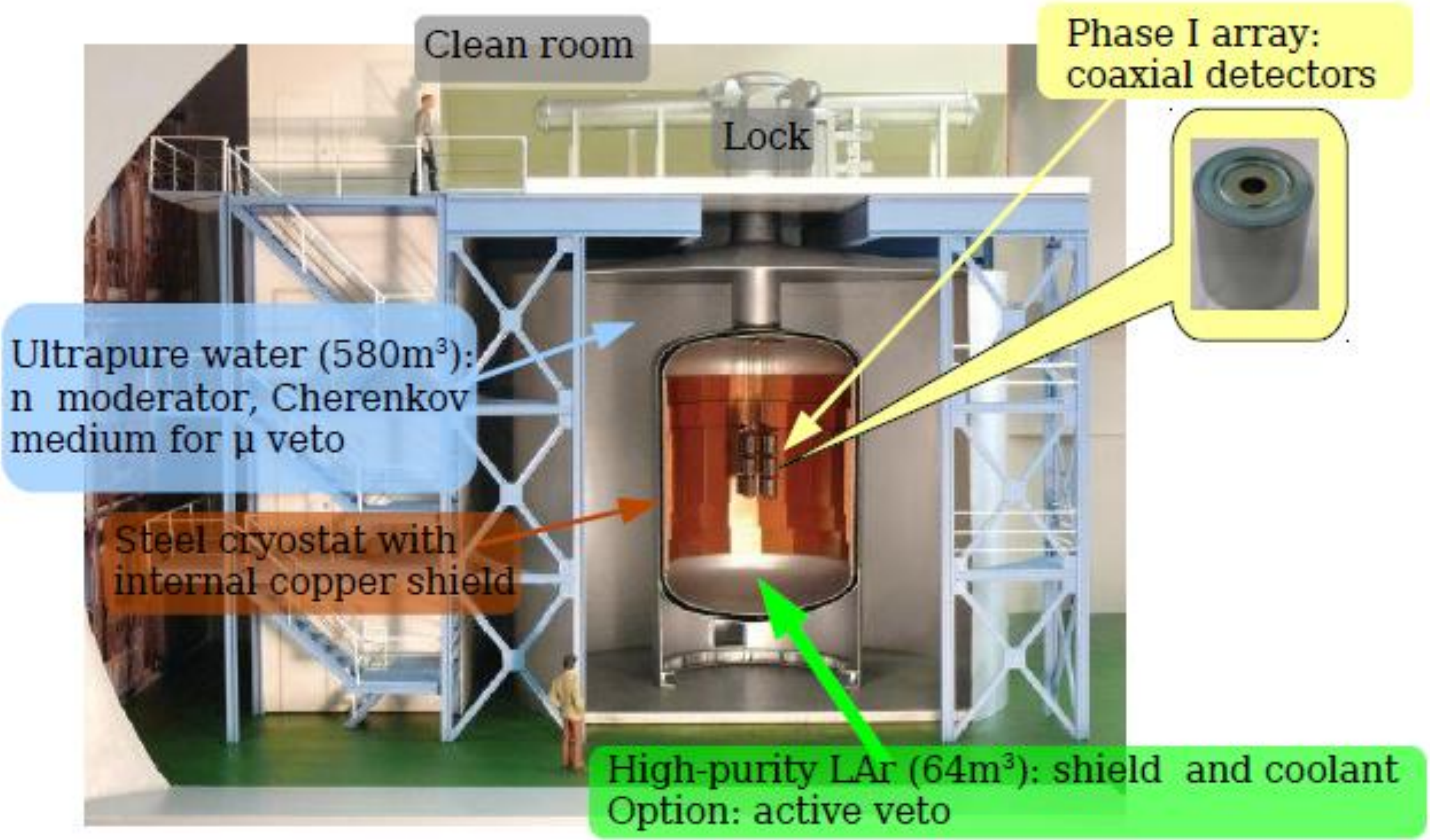
☺ several candidates can be studied with the same detector



Calorimeter
Tracker
Ge diode
ε, ΔE
76Ge
GERDA
MAJORANA
Bolometers
ε, ΔE
130Te, 82Se, 100Mo
CUORE
LUCIFER
ZnMo4
Liquid Xe
ε,M,(Nbckd)
136Xe
EXO
Scintillator
ε, M
136Xe, ,48Ca,
150Nd, 100Mo
KamLAND-Zen
CANDLES
SNO+
Borexino
CdWO4
AMoRE
Tracko-calo
NBckg , isotopes
82Se (150Nd, 48Ca)
SuperNEMO
Pixellized CdZnTe
ε, NBckd
116Cd
COBRA
TPC
ε, NBckd
136Xe, 150Nd
MTD
EXO-gas
NEXT

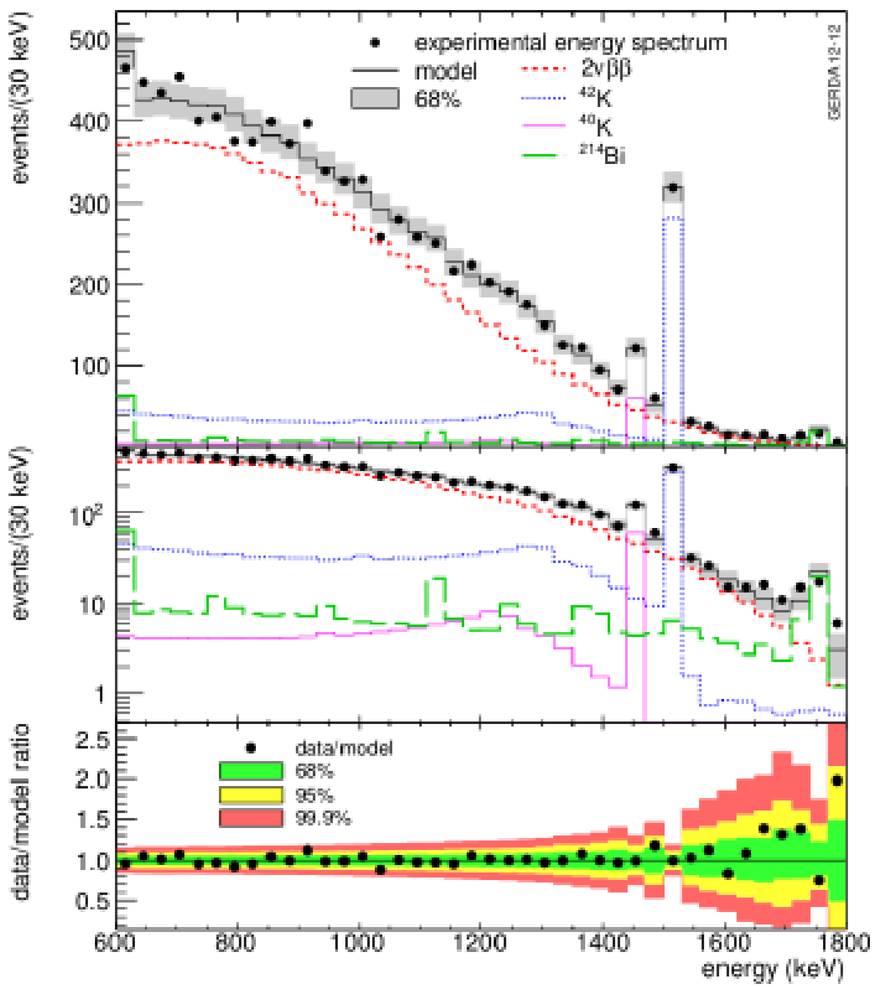
Gerda @ LNGS: Background reduction

- Graded shielding against ambient radiation
- Rigorous material selection, avoid exposure above ground for detectors



The Gerda experiment for the search of $0\nu\beta\beta$ decay in ^{76}Ge
Eur. Phys. J. C (2013) 73:2330

Measurement of $T^{2\nu}_{1/2}$: Result



Signal to background: 4:1

Binned maximum likelihood

Parameters:

- Active detector masses (6+1) *nuisance parameter*
- Fraction enrichment in ^{76}Ge (6) *nuisance parameter*
- Background contributions (3×6) *nuisance parameter*
- $T^{2\nu}_{1/2}$ common to all the detectors (1)

Derive $T^{2\nu}_{1/2}$ after the fit integrating over nuisance parameters

$2\nu\beta\beta$ (80%) ^{42}K (14%)

^{214}Bi (4%) ^{40}K (2%)

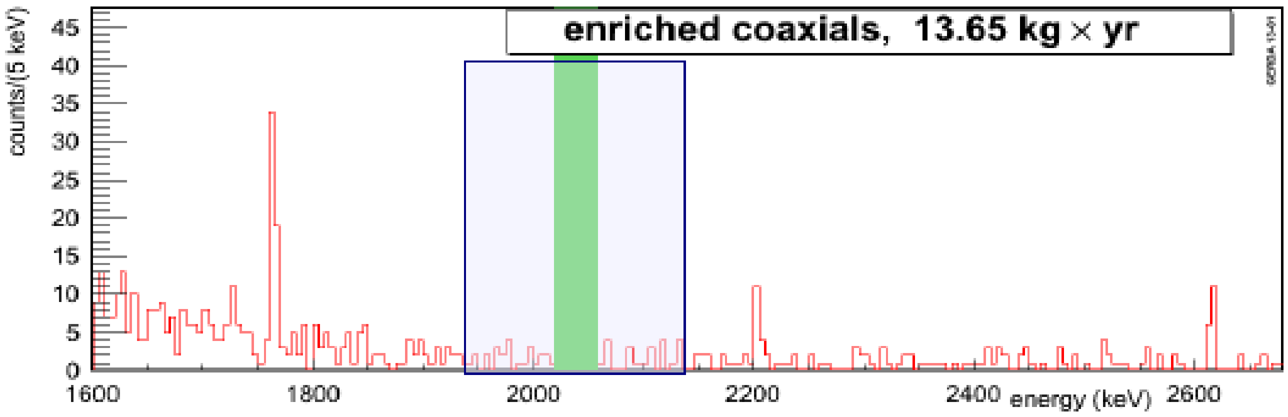
$$T^{2\nu}_{1/2} = (1.84^{+0.09}_{-0.08\ \mathrm{fit}}\ {}^{+0.11}_{-0.06\ \mathrm{syst}}) \cdot 10^{21}\ \mathrm{yr}$$

The GERDA collaboration
J. Phys. G 40 (2013) 035110

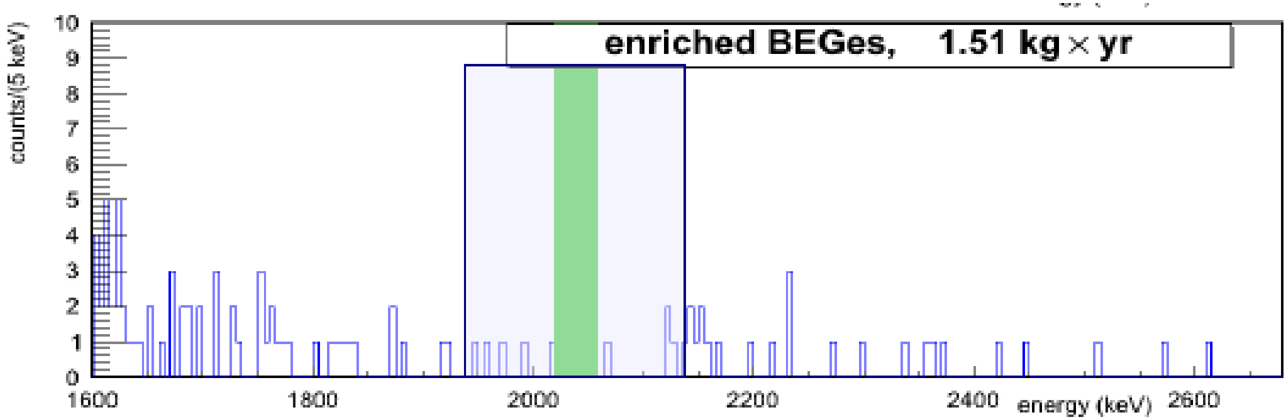
R. Brugnera @ Nutel 2013

Region of Interest

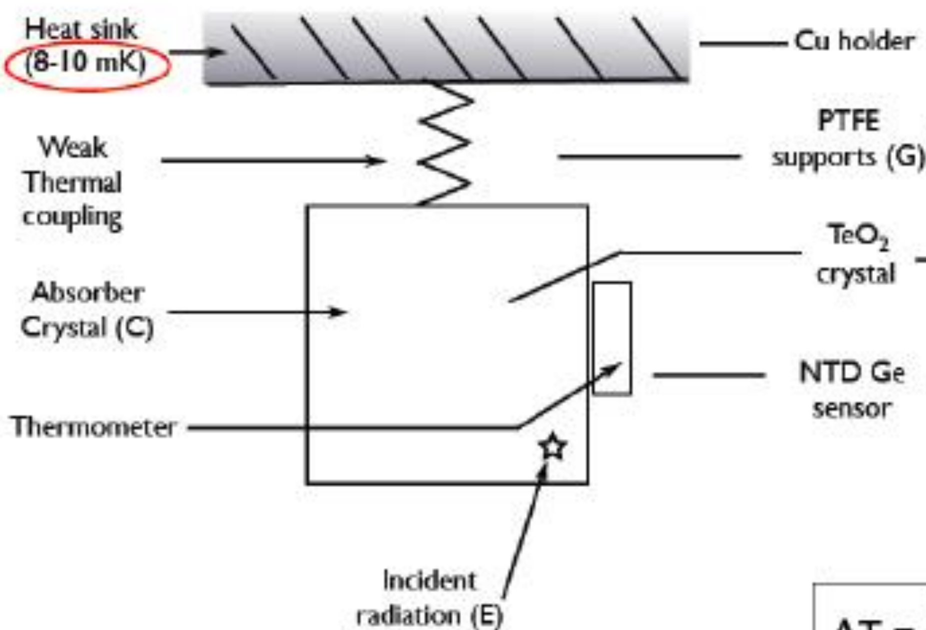
Background rate in ROI ($Q_{\beta\beta}\pm100$ keV, blinded window excluded)

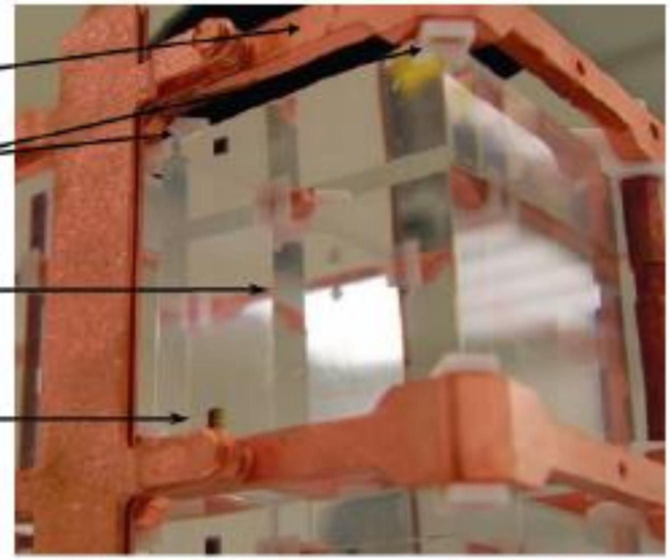


Enriched coaxials: 0.022±0.003 cts/(keV·kg·yr)
(0.017±0.003 cts/(keV·kg·yr) excluding 1.30 kg·yr period with higher background following detector substitutions in July)
➡ **factor ~10 lower than previous experiments (HdM, IGEX)**



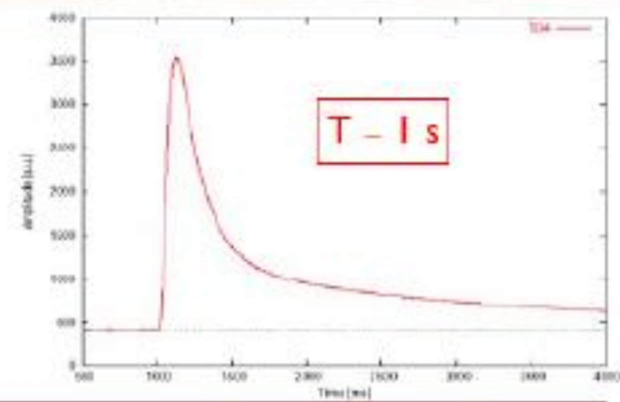
CUORE: the bolometric approach to $\beta\beta0\nu$





$$\Delta T = \frac{E}{C}$$

$$\tau = \frac{C}{G}$$



Pros: - good energy resolution
- different sources could be investigated
- high efficiency (internal sources)

Cons: - no dead layer
- low temperature tech required
- slow pulses

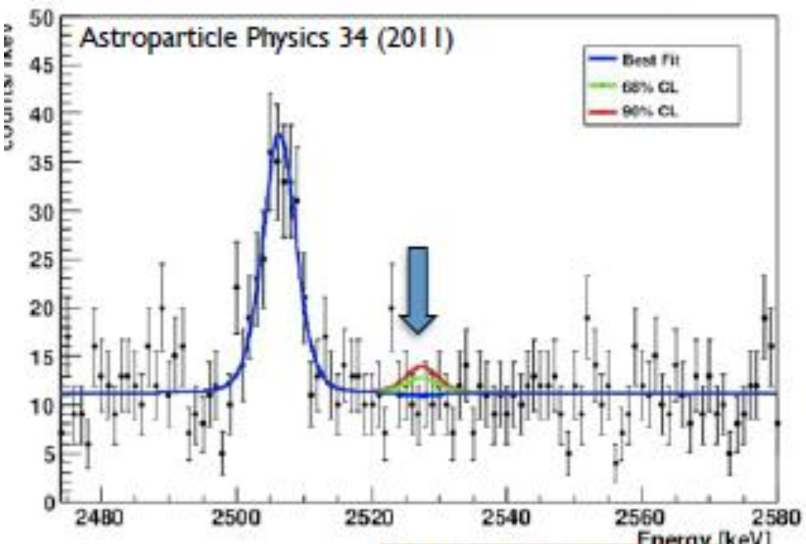
These advantages could be crucial in view of future experiments that aim to investigate all the inverted hierarchy region

Bolometric 0νDBD experiment evolution

$\Delta E = 6.3 \pm 2.5$ keV (~0.3% FWHM)

Bkg = 0.169±0.006 c/keV/kg/y

$T_{1/2}^{0\nu}(y) > 2.8 \times 10^{24}$ y (90% CL)

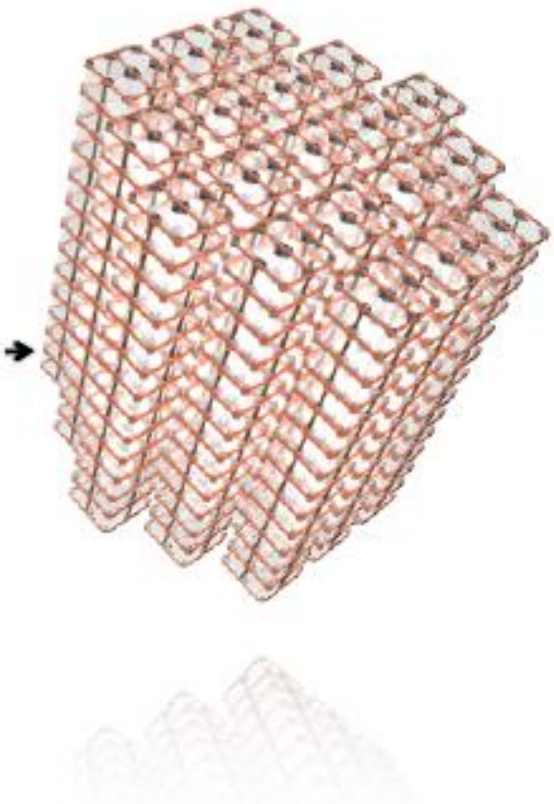


$\langle M_{bb} \rangle < 0.3 - 0.7$ eV

CUORICINO
40 kg
(2003-2008)

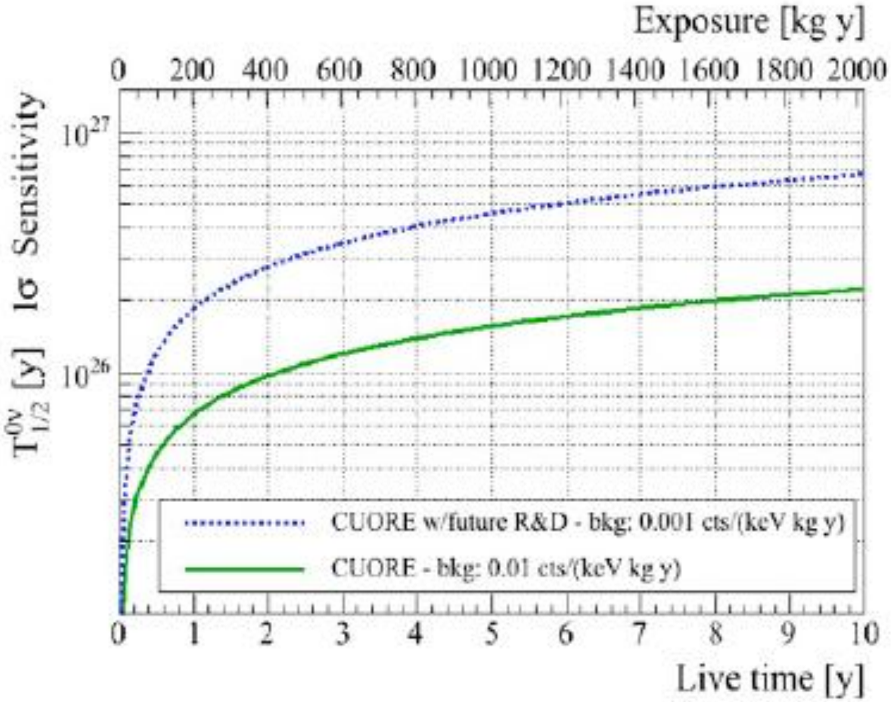
CUORE-0
(2012)

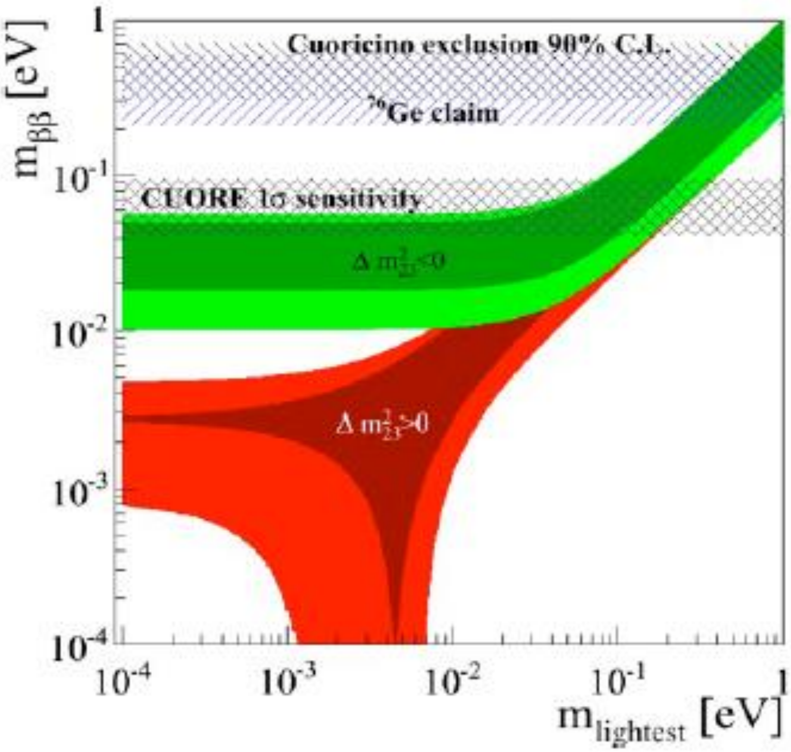
CUORE
1 ton
(~2014)



NME from F.Simkovic et al. Phys.Rev. C77 - J.Suhonen et al. Int.Jou.Mod.Phys. E17 - J.Menendez et al. Nucl. Phys.A818 - J.Barea et al. Phys. Rev. C79

CUORE





Background goal of
0.01 c/keV/kg/y

$T_{1/2}$ = 1.6 x 10^{26} y

$m_{\beta\beta}$ = 41-95 meV

Cuoricino result and CUORE 1σ sensitivity overlaid on plots that show the bands preferred by neutrino oscillation data (inner region: best-fit data; outer region: at 3σ). Both normal (red) and inverted (green) hierarchies are shown.

Construction of the experiment

Assembly clean room area

Underground Storage Area

300 K shield installation

- **Hut and clean room:** fully equipped
- **Detector assembly line:** fully ready
- **Radon abatement system:** installed
- **Cryostat:** commissioning of first 3 vessels (of 6) on-going at LNGS
- **Cryostat Dilution Unit**: commissioning started, ~~T<8~~ mK reached in stable conditions in a test cryostat

5.5 mK now!!

- **Calibration system:** commissioning started
- **Copper parts:** being machined and cleaned, delivered by end 2013
- **Crystals:** all stored underground at LNGS. Some will be reconditioned
- **Thermistors:** production on-going, final delivering in the next few months

Dilution Unit Commissioning

CUORE-0

1 CUORE-like tower of 13 planes - 4 crystals each
52 TeO_2 5x5x5 cm^3 crystals (750 g each)
Detector Mass: 39 kg TeO_2
^{130}Te mass (natural i.a.): 11 kg of ^{130}Te

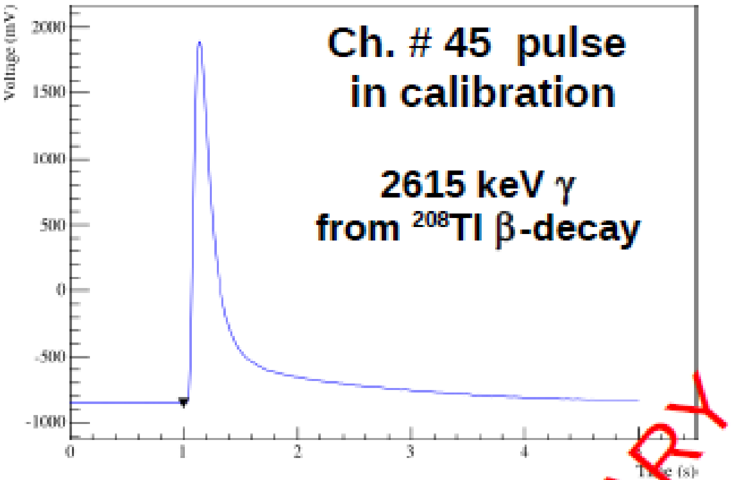
- All detector components manufactured, cleaned and stored with protocols defined for CUORE
- Assembled with the same procedures foreseen for CUORE

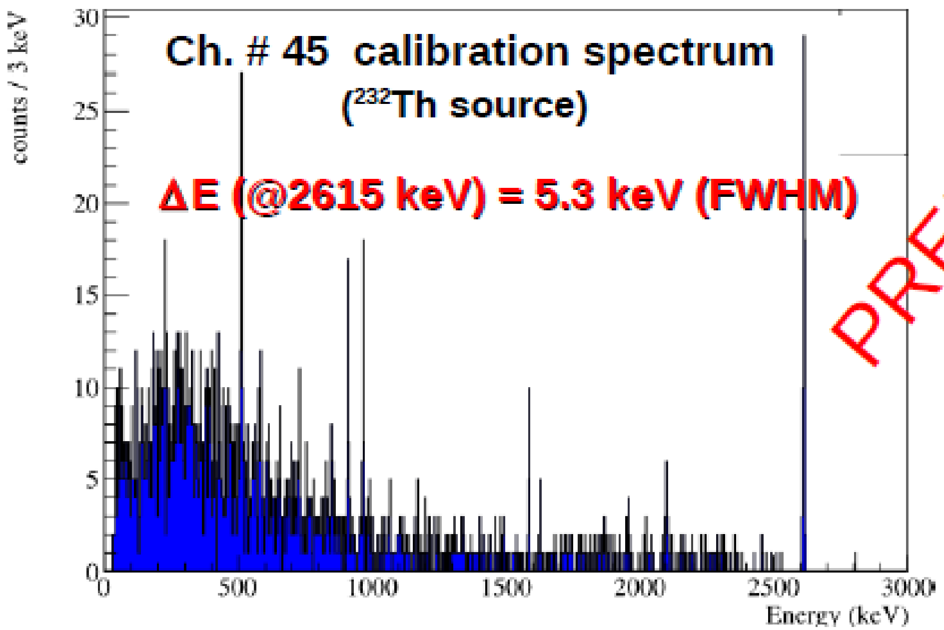
GOALS:

- Proof of Concept for CUORE detector in all stages
- Test and debug the CUORE assembly line
- Test of the CUORE DAQ and analysis framework
- High statistics check of the improved uniformity of bolometric response
- High statistics test of the background reduction achievable
- Extend the physics reach beyond CUORICINO while CUORE is being assembled and confirm the potential of CUORE for DM and Axion detection

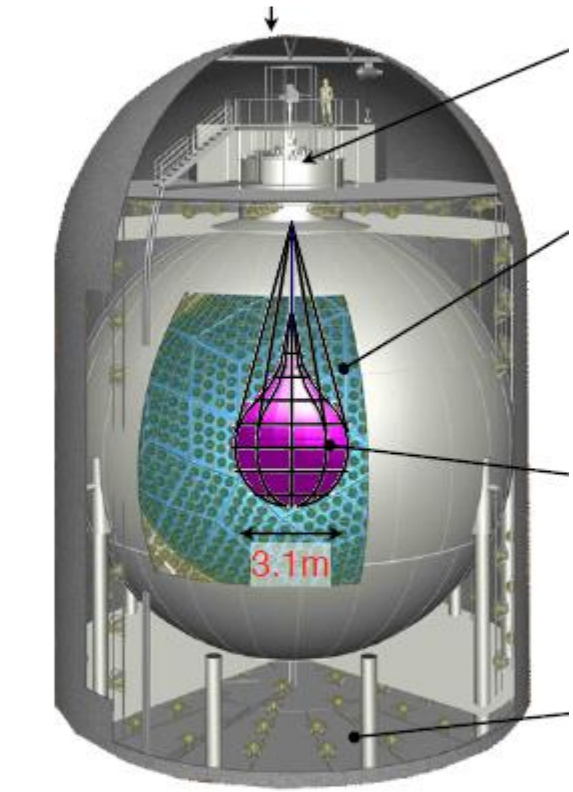
CUORE-0

- **Successfully tested** and defined the CUORE **assembly procedures**
- Demonstrated that **a complete CUORE tower** can be assembled in **less than 4 weeks**
- **51 detectors alive** (out of 52)





From pure calorimetric techniques to tracking



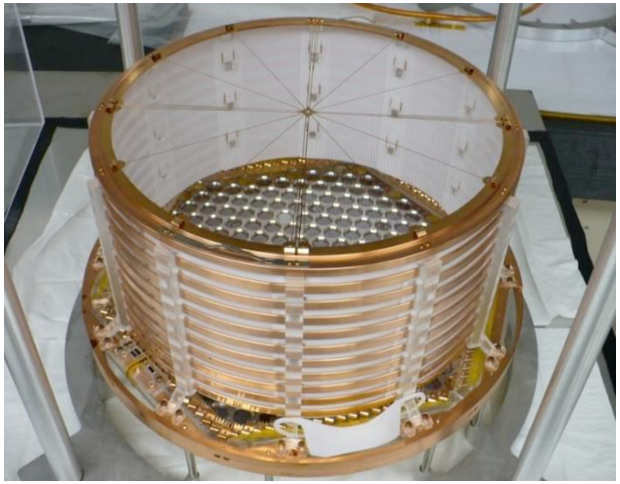
^{136}Xe loaded LS in mini-balloon

320 kg (2.4 % by weight)

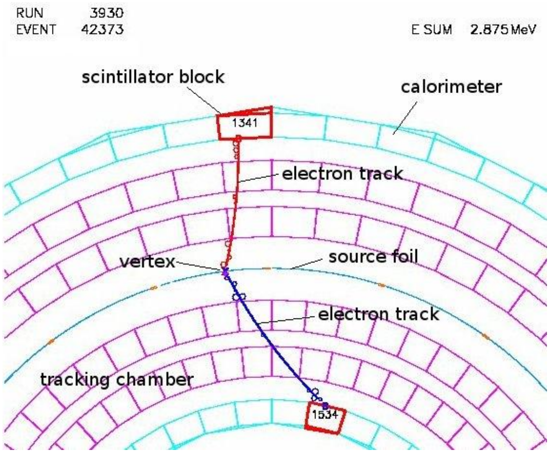
90 % enriched

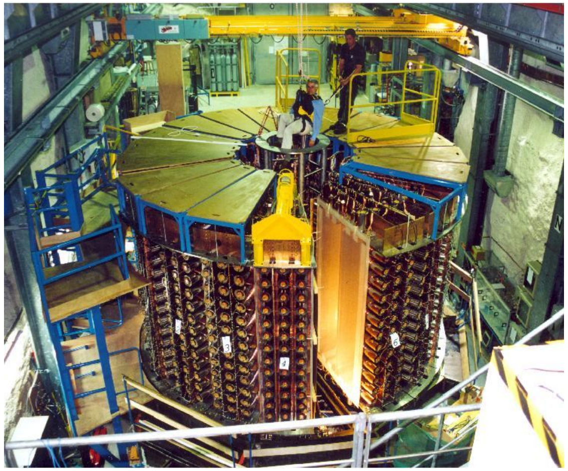
^{238}U: 1.3×10^{-16} g/g ^{232}Th: 1.8×10^{-15} g/g

Kamland-Zen



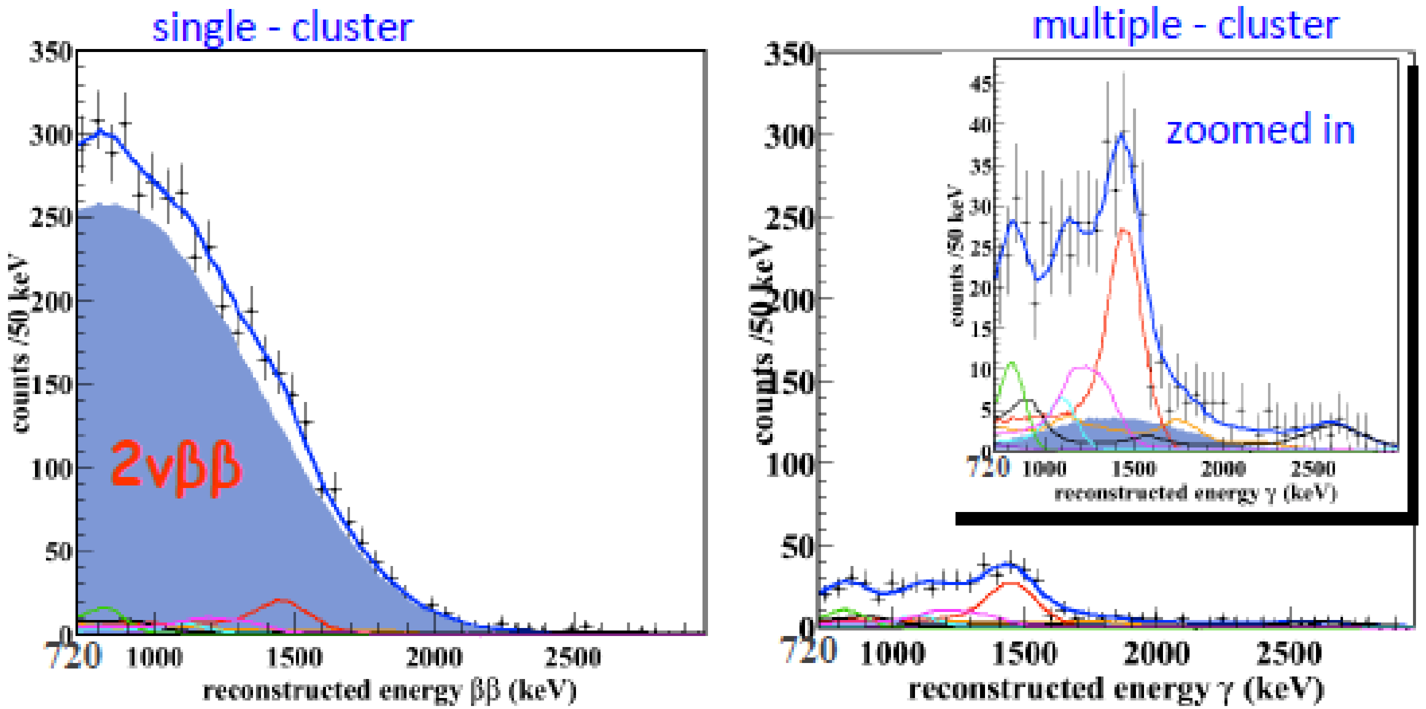
EXO





NEMO3
SuperNEMO

First observation of the $2\nu\beta\beta$ decay in ^{136}Xe



$T_{1/2}$ = (2.11 ± 0.04 stat ± 0.21 sys) · 10^{21} yr

[Ackerman et al Phys Rev Lett 107 (2001) 212501]

In significant disagreement with previous limits:

$T_{1/2}$ > 1.0·10^{22} yr (90% C.L.) (R. Bernabei *et al*. Phys. Lett. B 546 (2002) 23)
$T_{1/2}$ > 8.5·10^{21} yr (90% C.L.) (Yu. M. Gavriljuk *et al*., Phys. Atom. Nucl. 69 (2006) 2129)

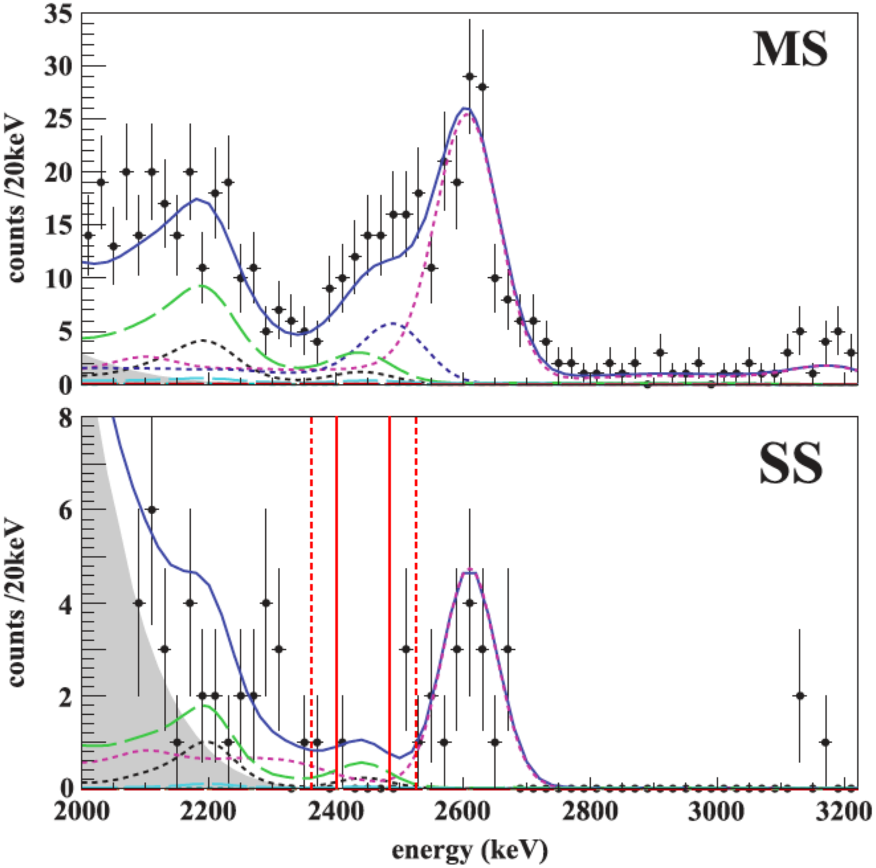
Later confirmed by KamLAND-ZEN

$T_{1/2}$=(2.38 ± 0.02stat ± 0.14sys)·10^{21} yr

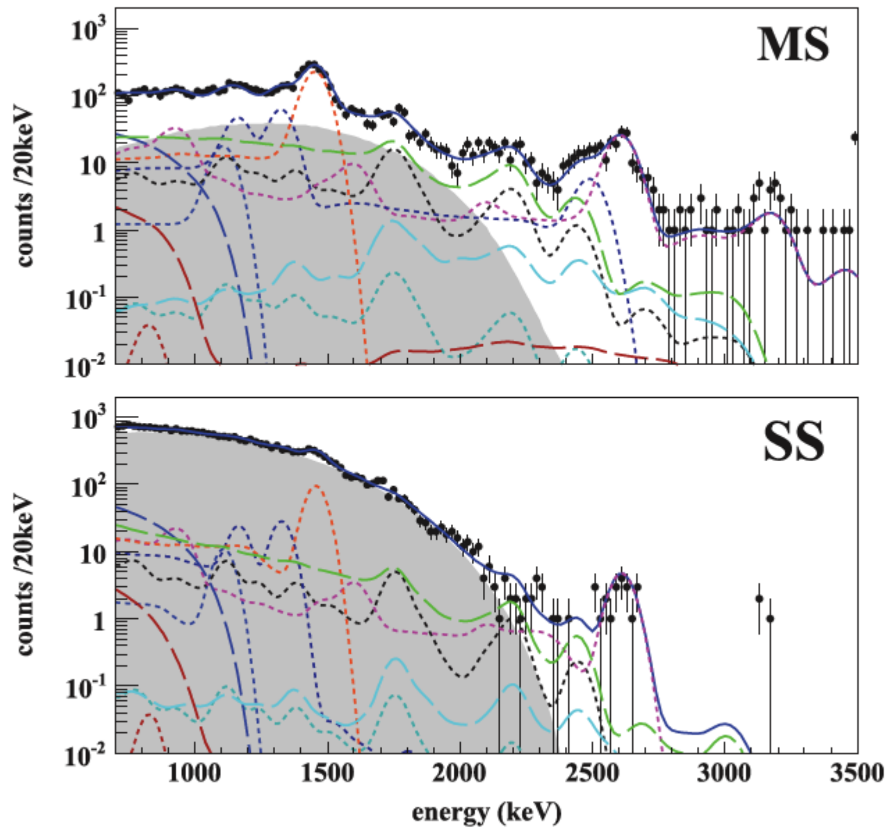
[A.Gando et al. Phys Rev C 85 (2012) 045504]

^{136}Xe: EXO-200

Region-of-interest closeup



Full spectrum

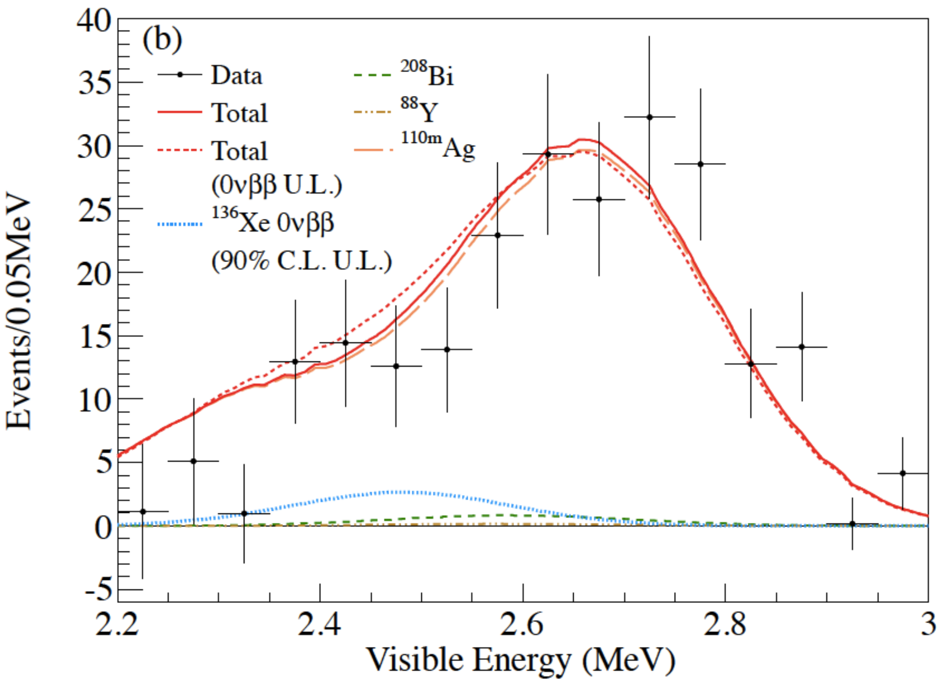


$T_{1/2}(\beta\beta0\nu) > 1.6 \times 10^{25}$ years (90% C.L.)
$m_{\beta\beta} < 140 – 380$ meV
Exposure: 193 mol*years

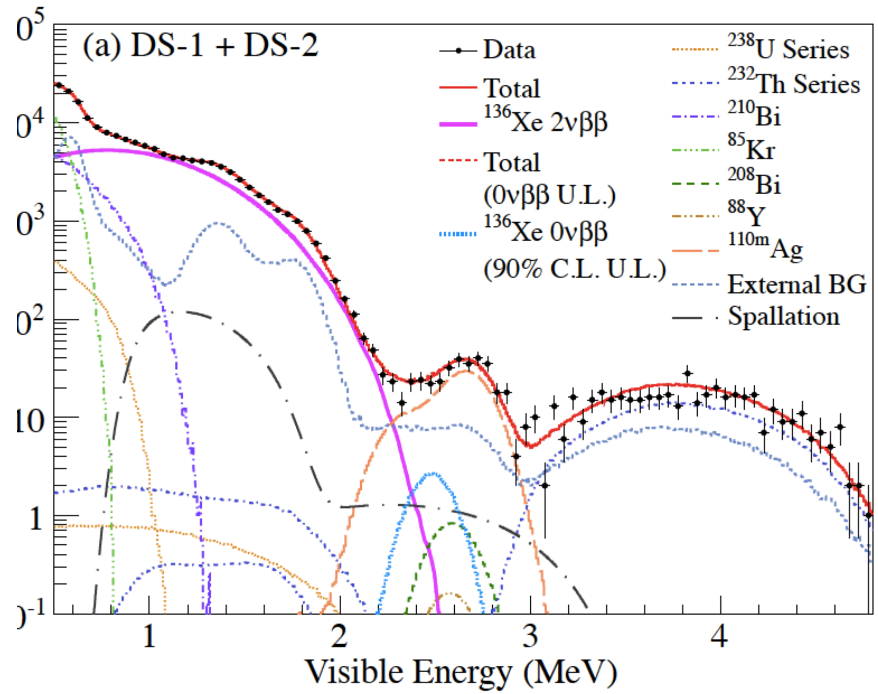
M. Auger et al., Phys. Rev. Lett. 109 032505 (2012)

^{136}Xe: KamLAND-Zen

ROI closeup



Full spectrum

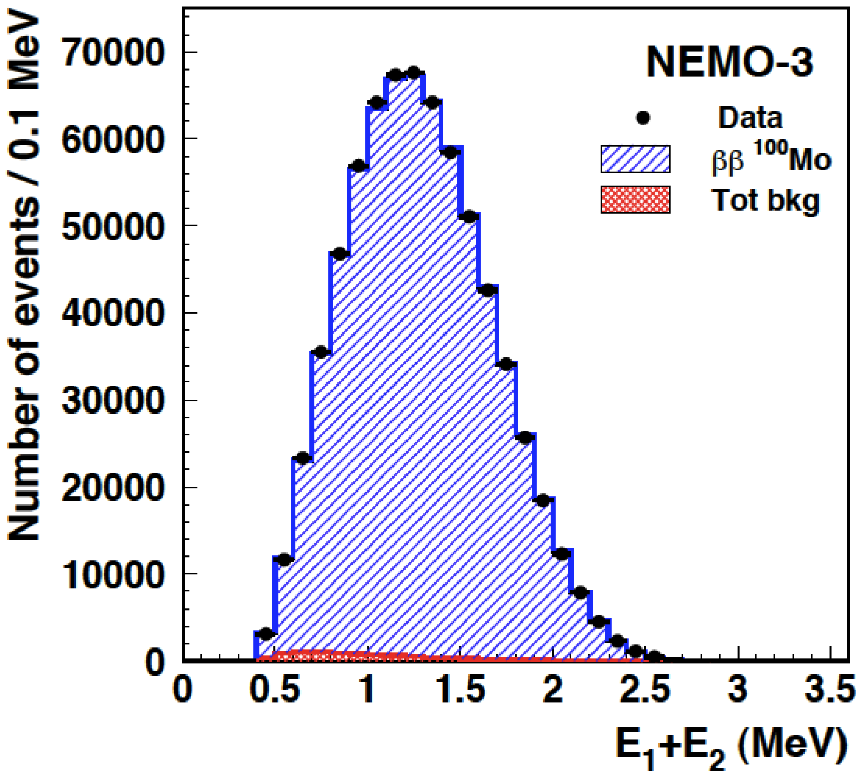


$T_{1/2}(\beta\beta 0\nu) > 1.9 \times 10^{25}$ years (90% C.L.)
$m_{\beta\beta} < 140 – 380$ meV
Exposure: 658 mol*years

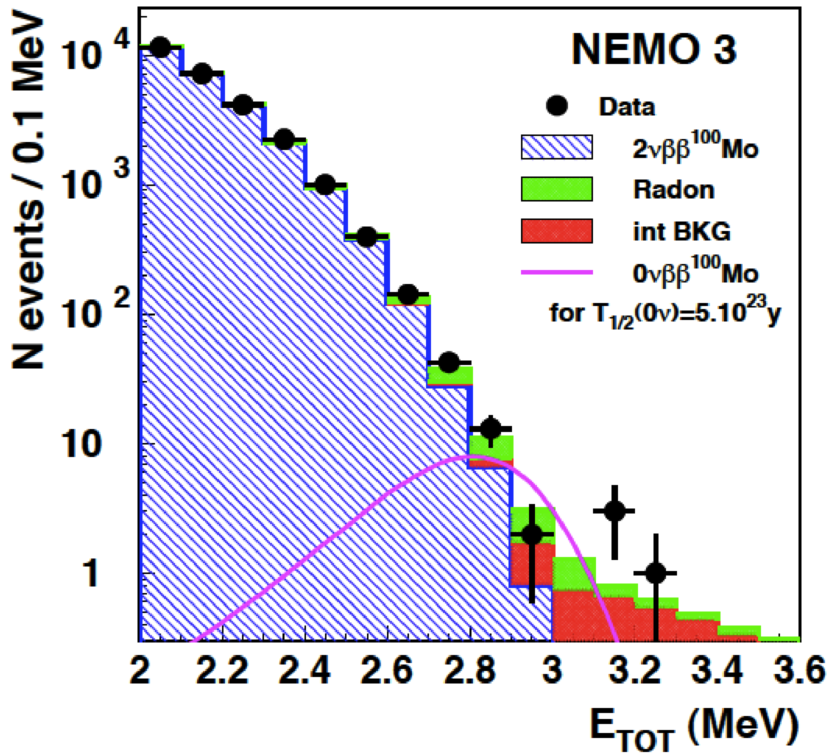
A. Gando et al., Phys. Rev. Lett 110 062502 (2013)

^{100}Mo: NEMO-3

Full spectrum



ROI closeup



$T_{1/2}(\beta\beta0\nu) > 1.1 \times 10^{24}$ yrs (90%C.L.)
$m_{\beta\beta} < 450 – 930$ meV
Exposure: 266 mol*years

A.S. Barabash et al., Phys. Atom. Nucl. (2011) 74 312.

Conclusions

• Neutrinoless double beta decay is no more a corner in the “exotic searches” of physics beyond the Standard Model. Oscillation data and cosmology define uniquely where we expect such rare decay to occurr, if neutrinos are Majorana particles

• The current generation of experiments mostly explore the degenerate region of neutrino masses. We are presently testing the anomaly reported by Klaptor et al. in ^{76}Ge. Early data already challenge this claim and the issue will be set soon

• The experiments under construction will start exploring the inverted hierarchy region but a complete test of Majorana neutrinos in the Inverted Hierarchy hypothesis requires new techniques and/or scaling toward the 1ton target

• **If accelerator experiments confirm the inverted hierarchy, this search will become the top priority in neutrino physics**

• To explore the Normal Hierarchy region, we need novel experimental techniques and be prepared to “accidental cancellations” of the effect due to parameter conspiracy