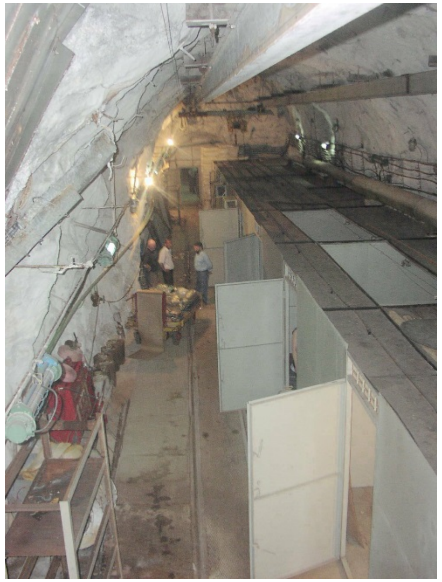
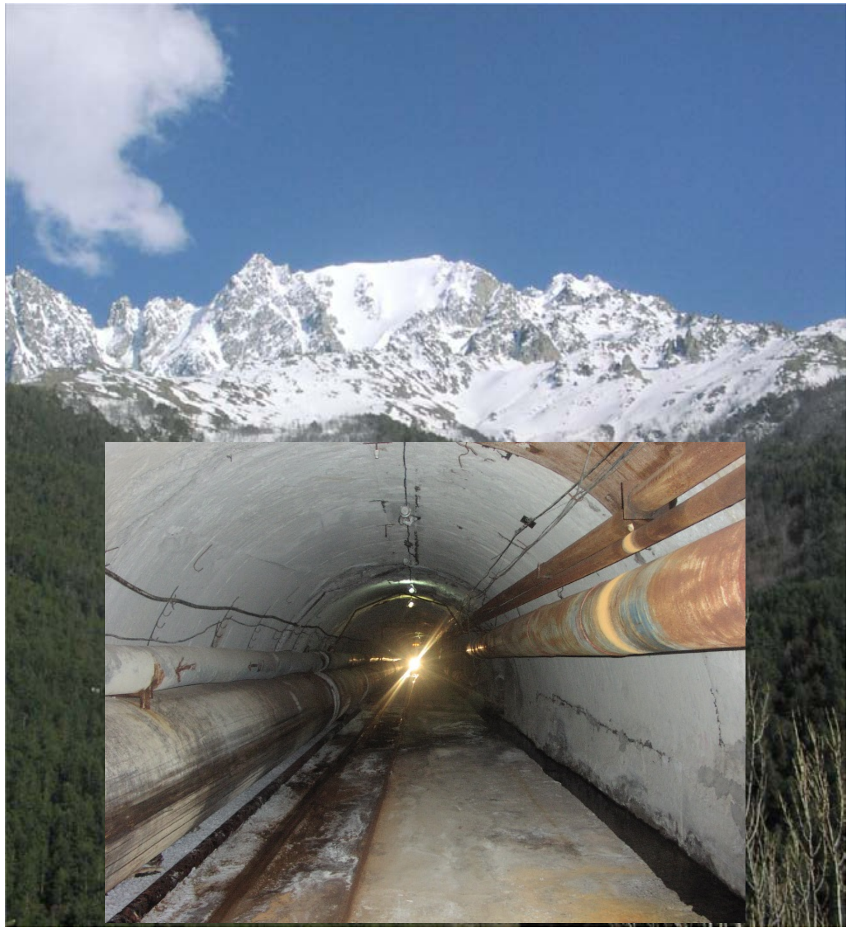
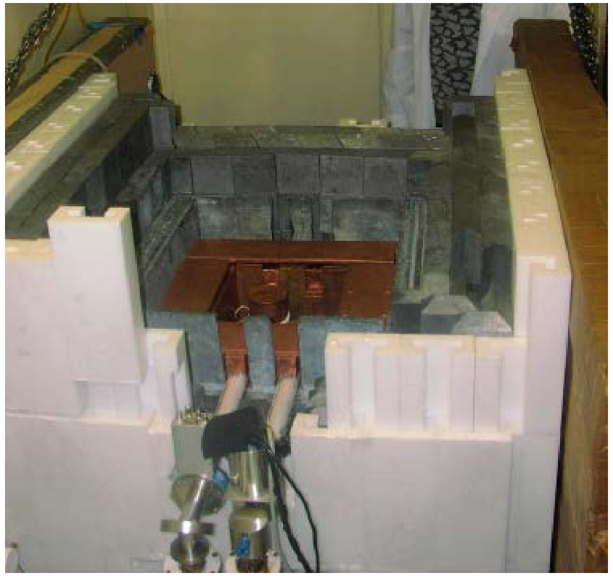
From Baksan to ->







A.Smolnikov

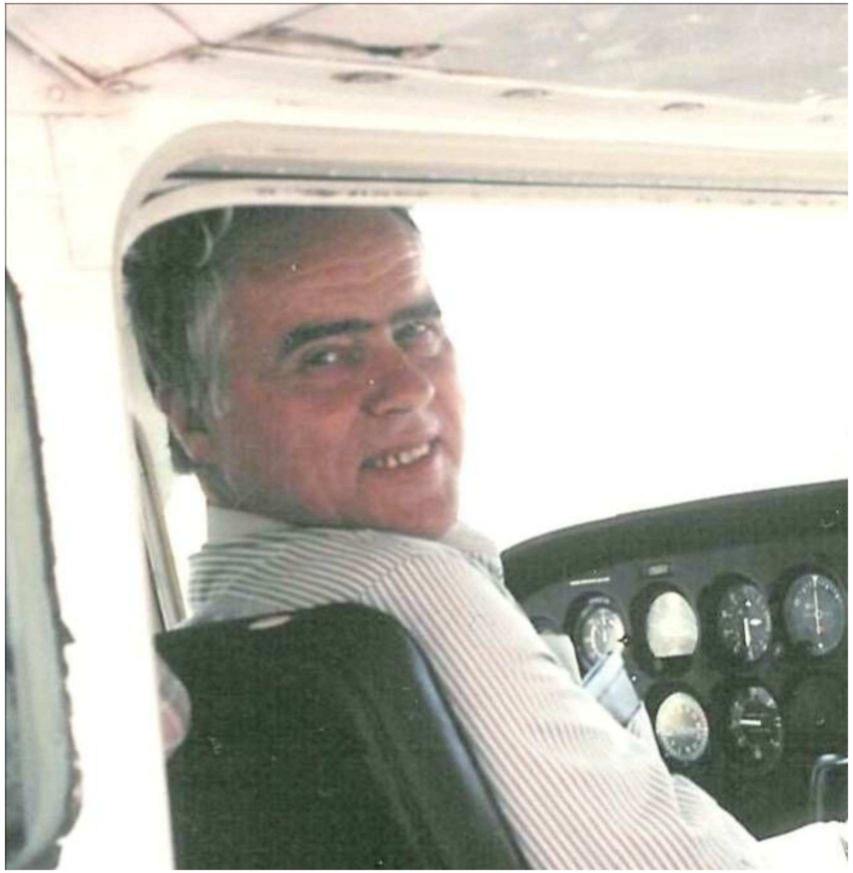
International Session-Conference of RAS "Physics of fundamental interactions“
dedicated to 50th anniversary of Baksan Neutrino Observatory, Nalchik, Russia, June 6-8, 2017

-> to worldwide experiments searching for neutrinoless double beta decay

A.Smolnikov,

International Session-Conference of RAS "Physics of fundamental interactions“
dedicated to 50th anniversary of Baksan Neutrino Observatory, Nalchik, Russia, June 6-8, 2017

Dedicated to the memory
of the first Director of Baksan Neutrino Observatory



Alexander Alexandrovich Pomansky

Double Beta Decay

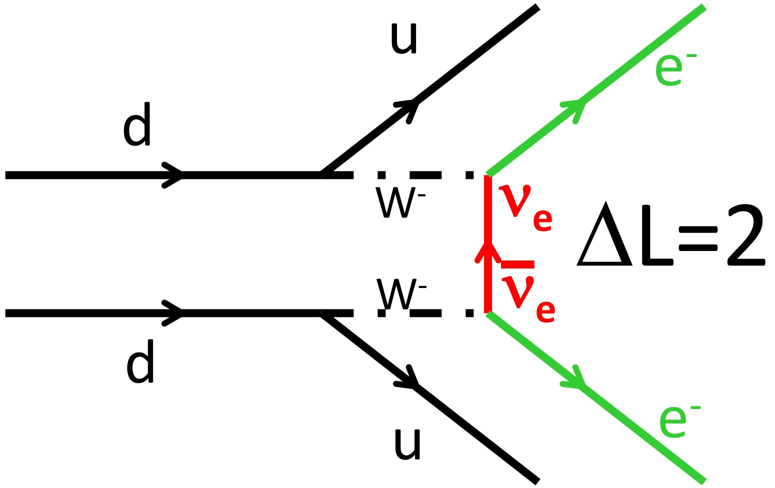
•DBD unique tool to study neutrino properties:

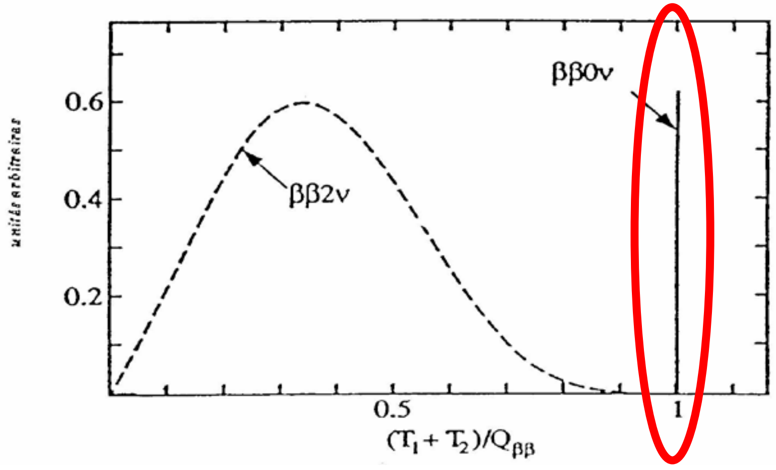
•Majorana vs. Dirac, mass scale, hierarchy, CP phases

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

(Observed for several nuclei, test of nuclear matrix elem. calculations)

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





$1/\tau = G(Q,Z)\ |M_{nucl}|^2\ \mathbf{m_{ee}}^2,$ $\mathbf{m_{ee}} = |\sum_i U_{ei}{}^2\ m_i|$

0νββ decay rate
Light neutrino exchange

$$1/\tau = G(Q,Z) \cdot |M_{nucl}|^2 \cdot \langle m_{\beta\beta} \rangle^2$$

Phase space factor ($\sim Q_{bb}^5$)

Nuclear matrix element

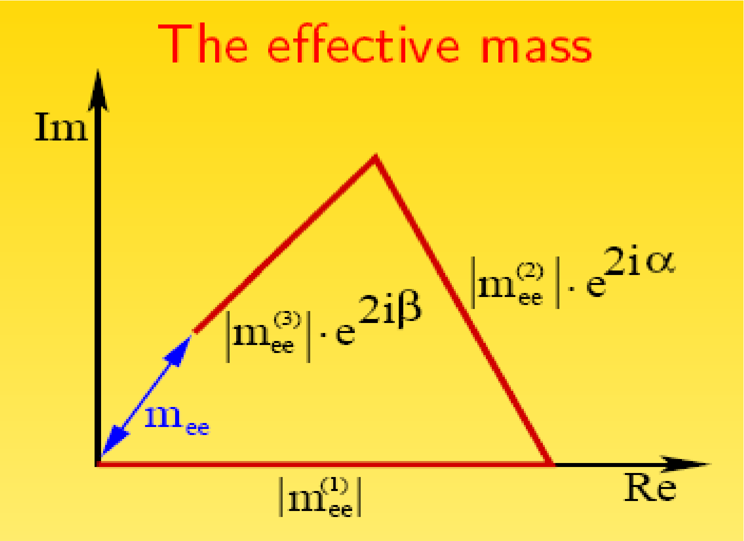
Effective Majorana neutrino mass

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

$$\langle m_{\beta\beta} \rangle = \left| \sum_j m_j U_{ej}^2 \right| = \mathbf{m_1 |U_{e1}|^2} \cdot$$

U_{ei} (complex) neutrino mixing matrix

$\alpha_{1,2}$ - complex CP-violating Majorana phases



9 physical parameters in neutrino mass matrix m_ν

- θ_{12} and $m^2_2 - m^2_1$
- θ_{23} and $|m^2_3 - m^2_2|$
- θ_{13} (or $|U_{e3}|$)
- m_1, m_2, m_3
- sgn $(m^2_3 - m^2_2)$
- Dirac phase δ
- Majorana phases α and β (or $\alpha 1$ and $\alpha 2$, or $\phi 1$ and $\phi 2$, or. . .)

$0\nu\beta\beta$ $\rightarrow$ 7 out of 9 parameters of neutrino mass matrix !

$$\mathcal{L} = \frac{1}{2} \nu^T m_\nu \nu \quad \text{with} \quad m_\nu = U \, \text{diag}(m_1, m_2, m_3) \, U^T$$

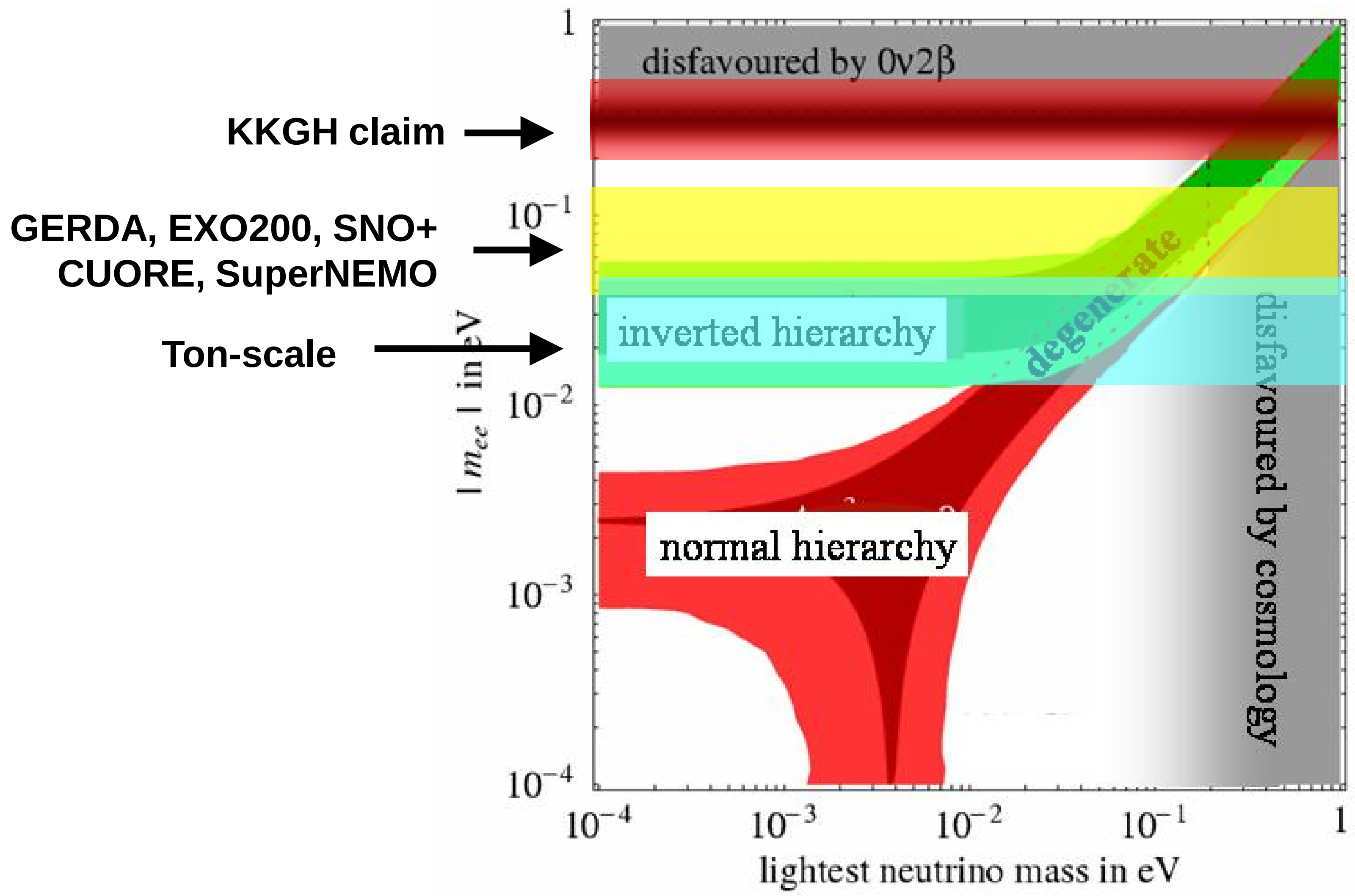
where

$$U = \begin{pmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta} & c_{23}\, c_{13} \end{pmatrix} P$$

with $P = \text{diag}(e^{i\alpha}, e^{i\beta}, 1)$

(only show up in Lepton Number Violating processes, if neutrinos are Majorana)

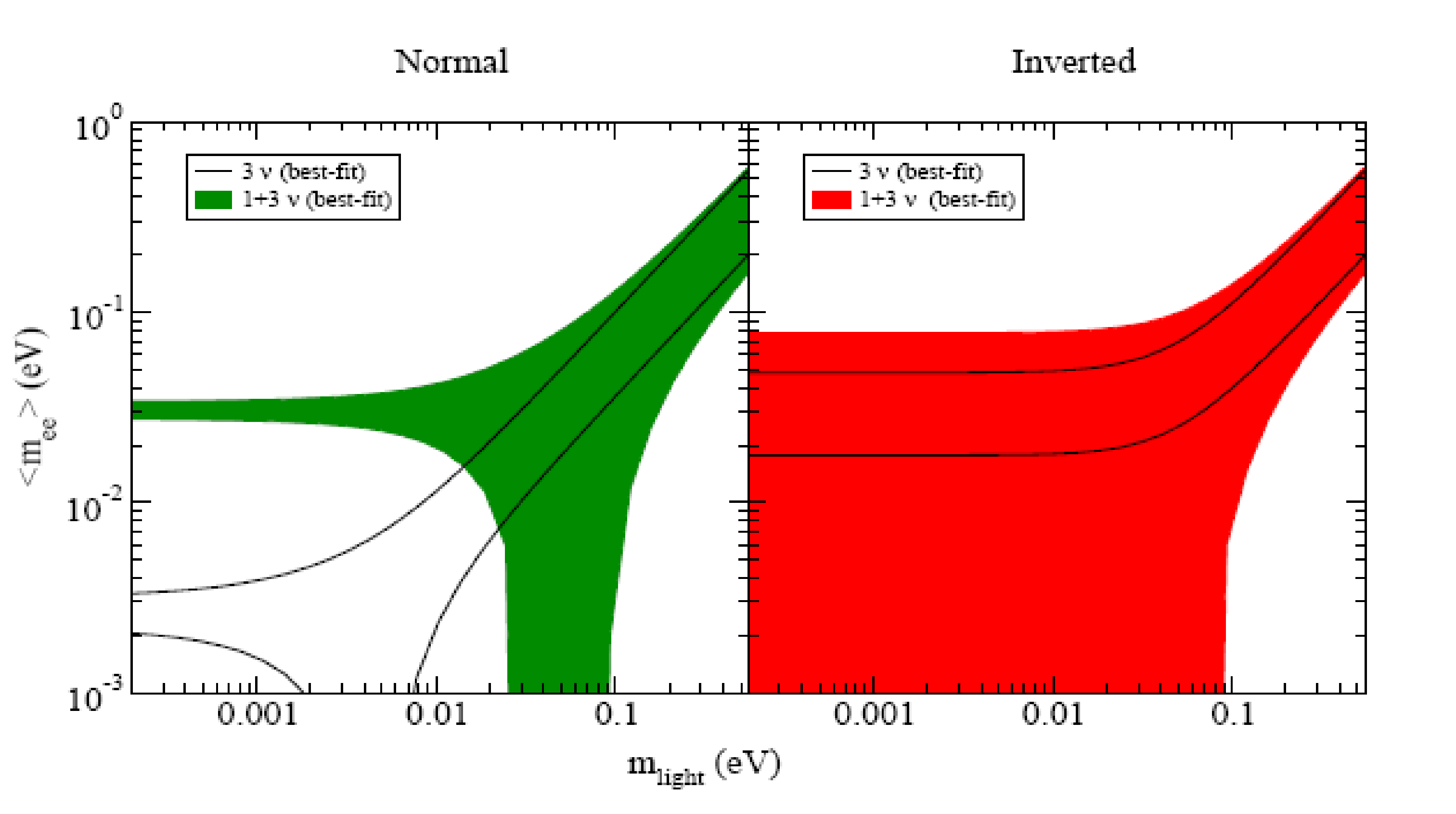
$\Rightarrow$ 3 angles, 3 phases, 3 masses



KKGH claim
GERDA, EXO200, SNO+
CUORE, SuperNEMO
Ton-scale
disfavoured by 0ν2β
inverted hierarchy
degenerate
normal hierarchy
disfavoured by cosmology
$| m_{ee} |$ in eV
lightest neutrino mass in eV

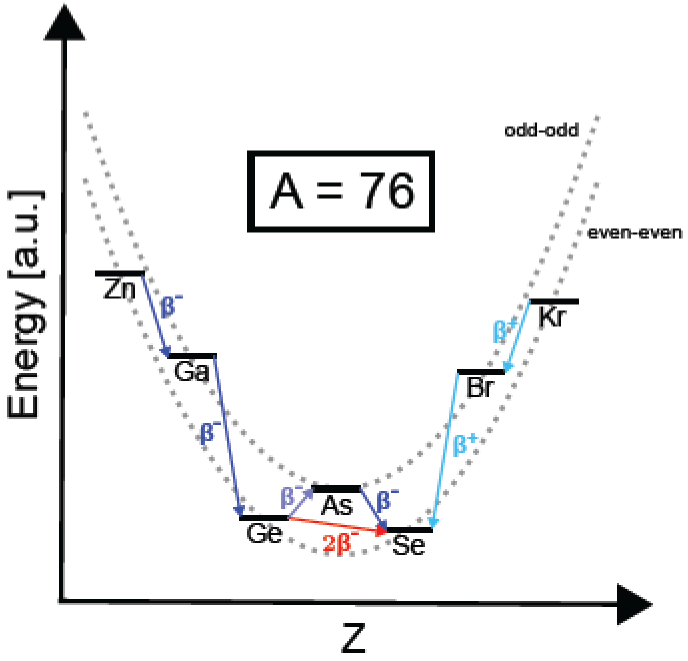
Sterile Neutrinos:

the usual plot for double beta decay gets completely turned around!



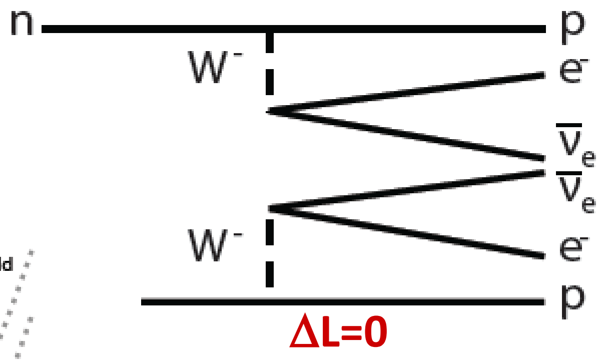
Barry, W.R., Zhang, JHEP **1107**; Giunti *et al.*, PRD **87**; Girardi, Meroni, Petcov, 1308.5802

What we should observe in experiments ?



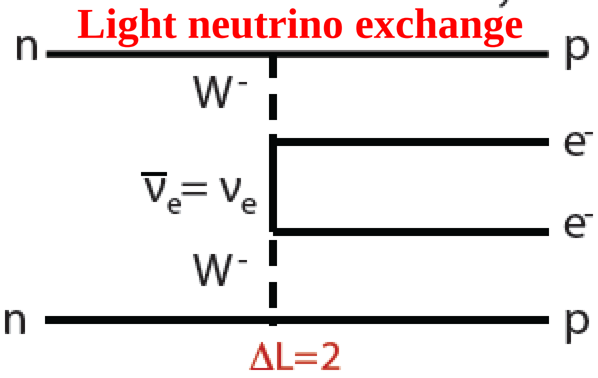
2νββ

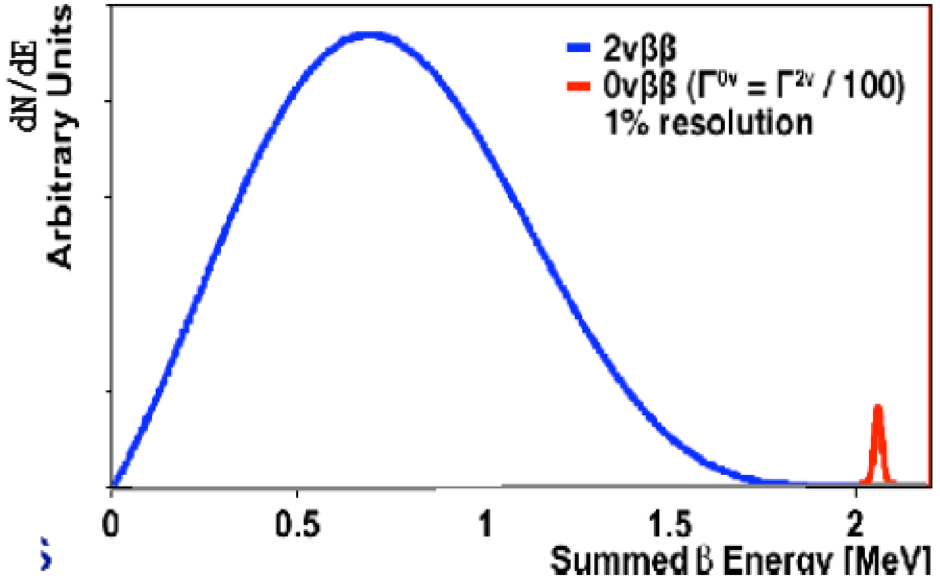
Neutrino accompanied Double-Beta Decay:



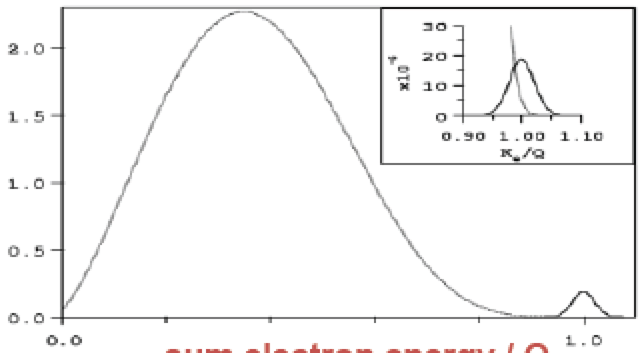
0νββ

Neutrinoless Double-Beta Decay:



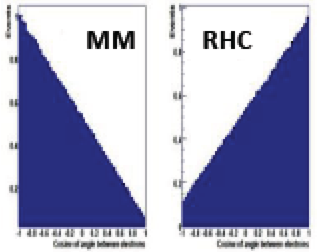


What we can observe in experiments ?

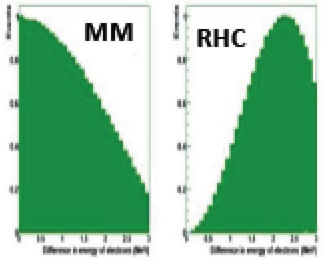


sum electron energy / Q

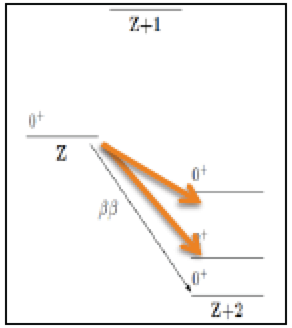
Angular distribution



$Ee_1 - Ee_2$ distribution



Mass vs Right-Handed Current mechanism



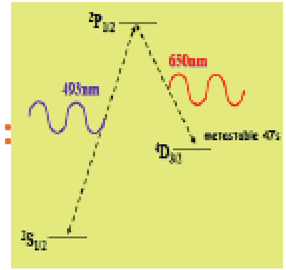
Decay to Excited States

(A,Z) → (A, Z+2) + 2 e⁻ + 1,2 γ

1 or 2 additonnal γ-rays

Identification of daugther nucleus :

Xe → Ba^{++} + 2 e^-



The experimental challenge

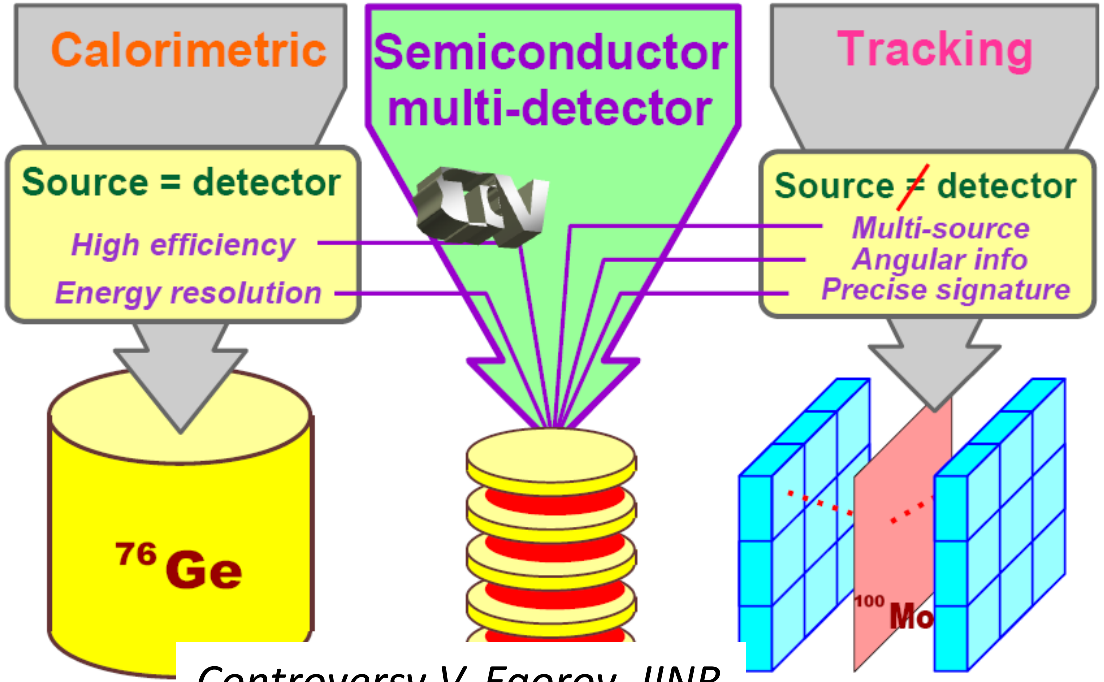
Experiment observes $N^{0\nu} = \ln 2 \frac{N_A}{A} \cdot a \cdot \epsilon \cdot M t / T_{1/2}$

sensitivity on $T_{1/2} \propto \epsilon \cdot A \cdot \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$

ϵ	detection efficiency
A	isotopic abundance
M	active target mass
T	measuring time
b	background rate (cts/(keV kg yr))
ΔE	energy resolution

Experimental approach:

→ reduce background b, improve resolution ΔE, increase exposure (M·T),



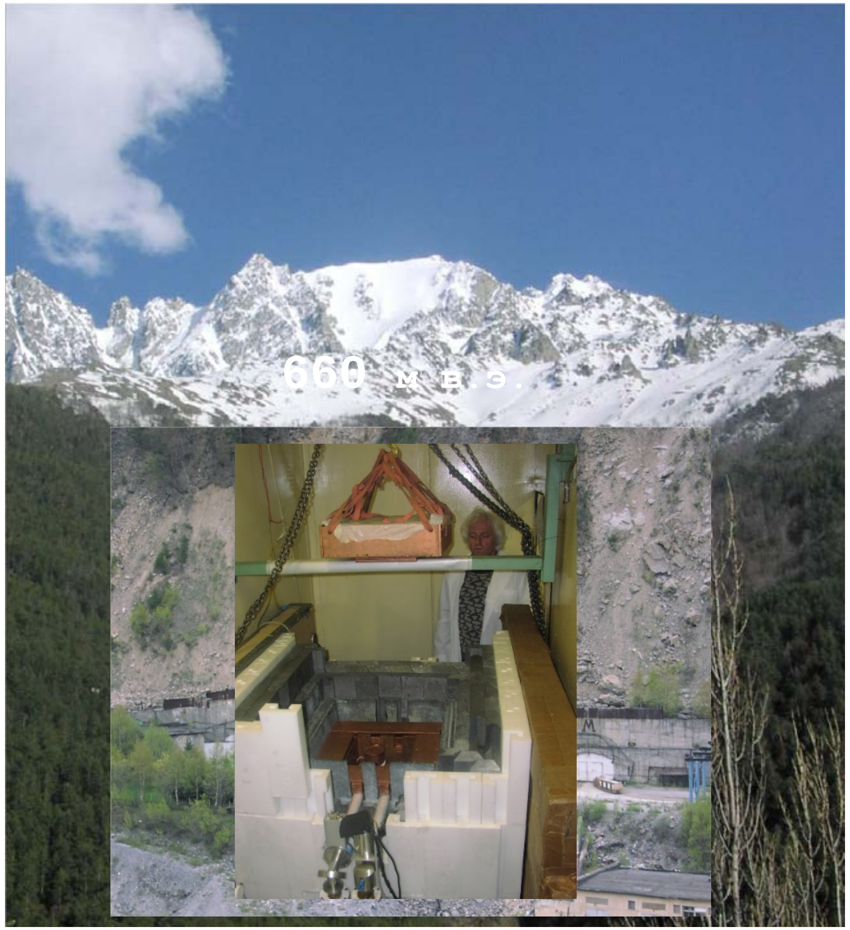
Controversy V. Egorov, JINR

Баксанская нейтринная обсерватория ИЯИ РАН
Поток мюонов (см⁻² сек⁻¹)
Высота над уровнем моря (м)
гора Андырчи
A - Сцинтилляционный телескоп
B - Галлий-германиевый нейтринный телескоп
D-3 - Дальняя низкофоновая лаборатория
A
D-1
D-2
B
D-3
река Баксан
1000
2000
3000
4000 м
1700
2200
2700
3200
3700
4200
Расстояние от входа в штольню (м)

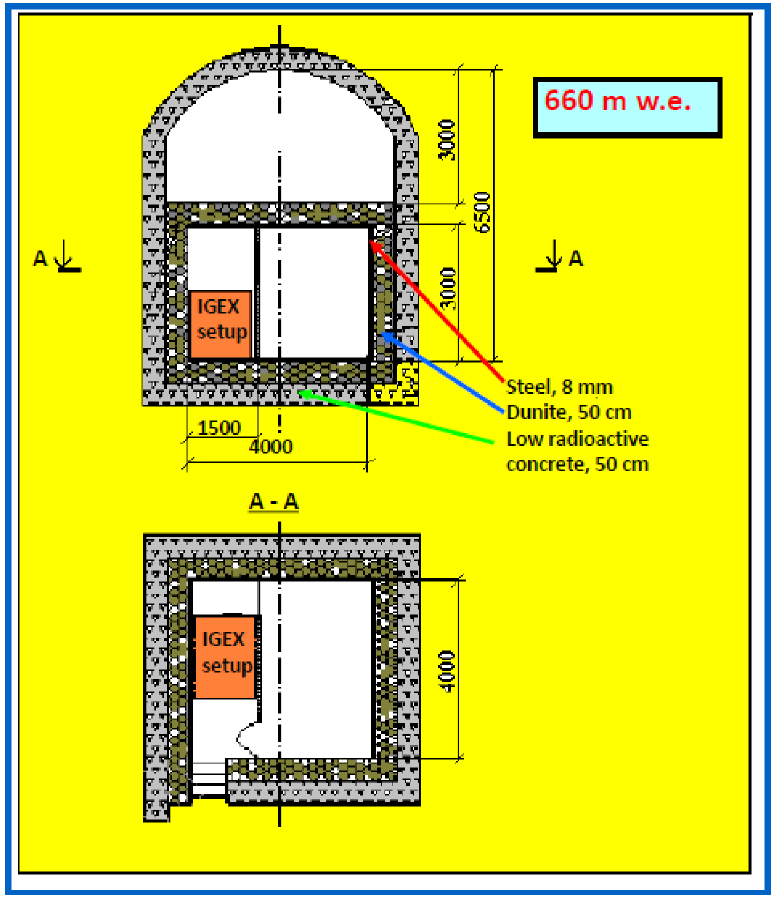
IGEX-DB / Baksan Phase

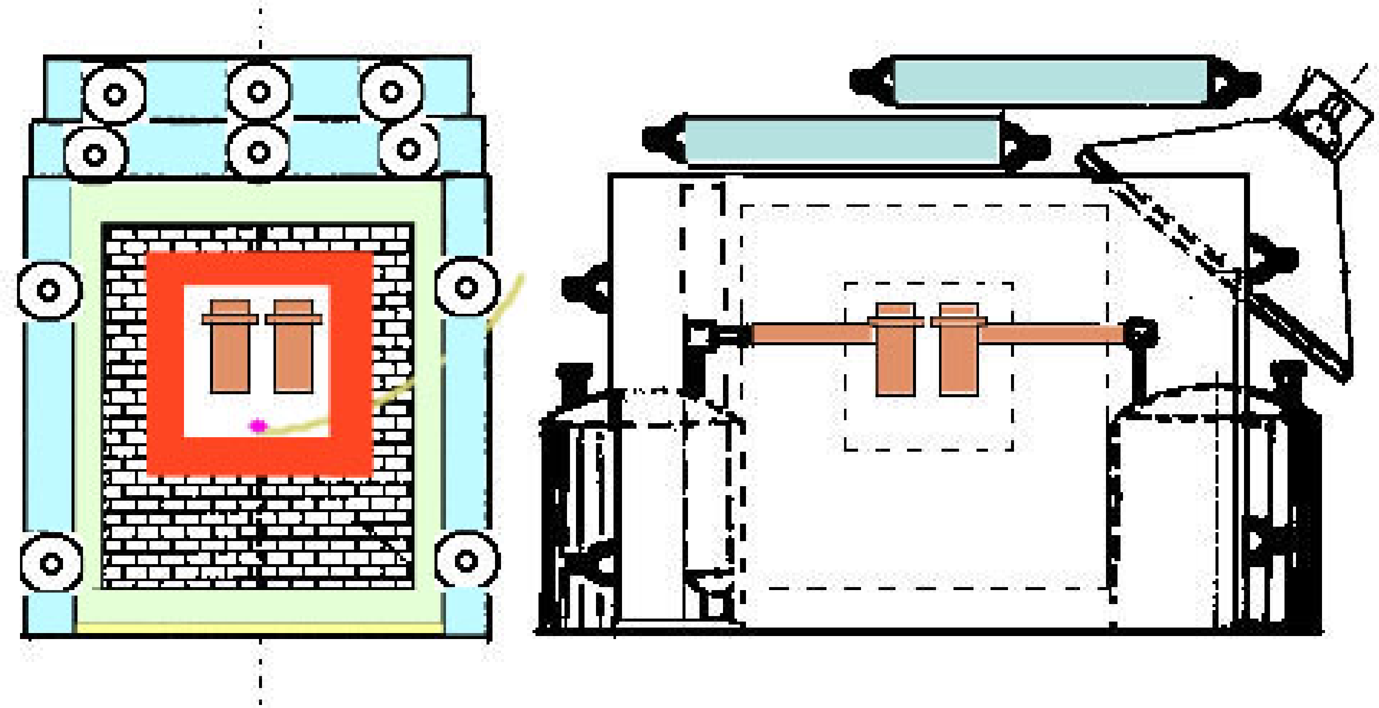
in the Laboratory for Low Background Experiments

BNO INR RAS

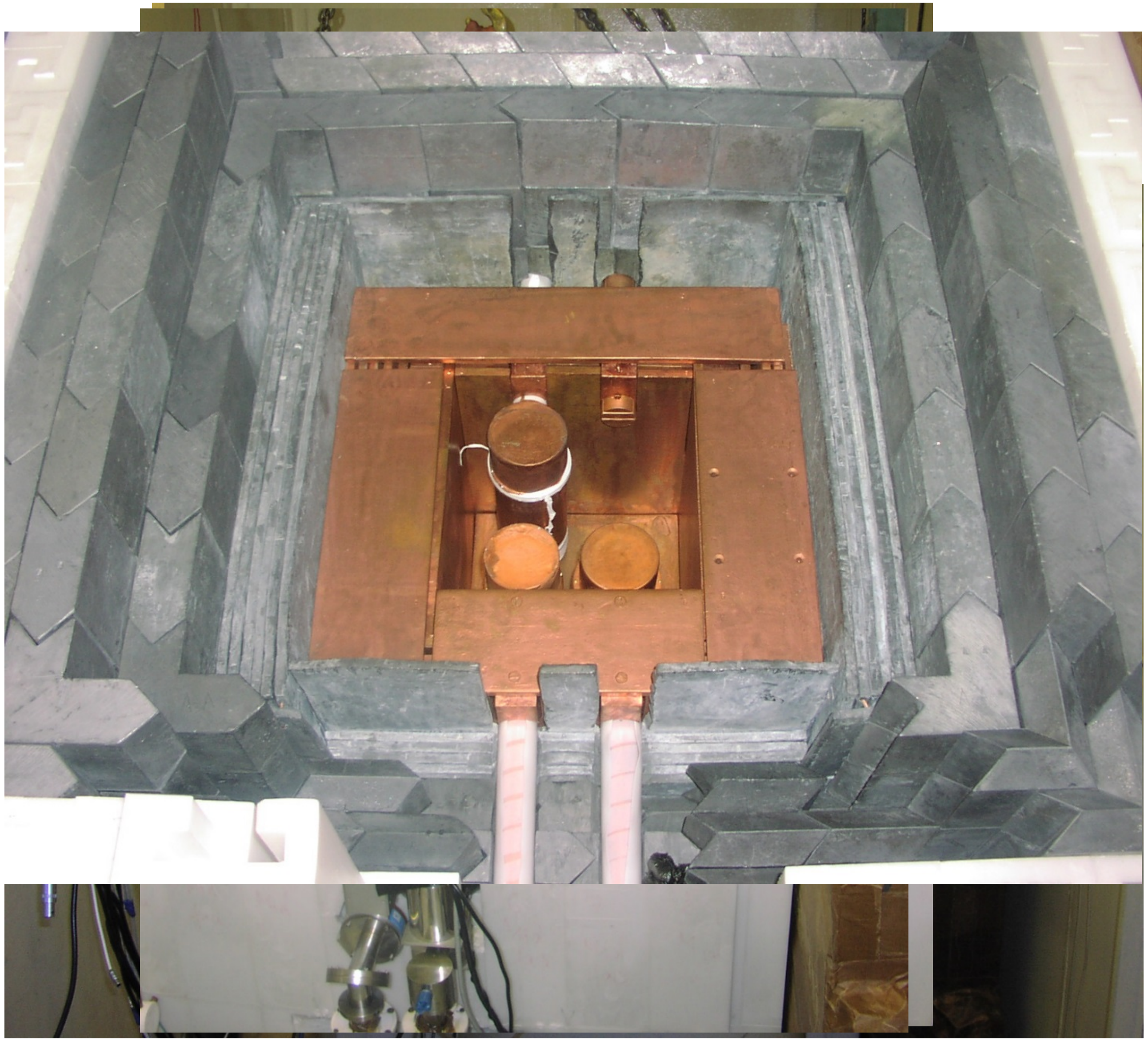


IGEX-Baksan
in operation
from 1991 -> up to now





IGEX – Baksan



IGEX – Baksan + IGEX - Canfranc

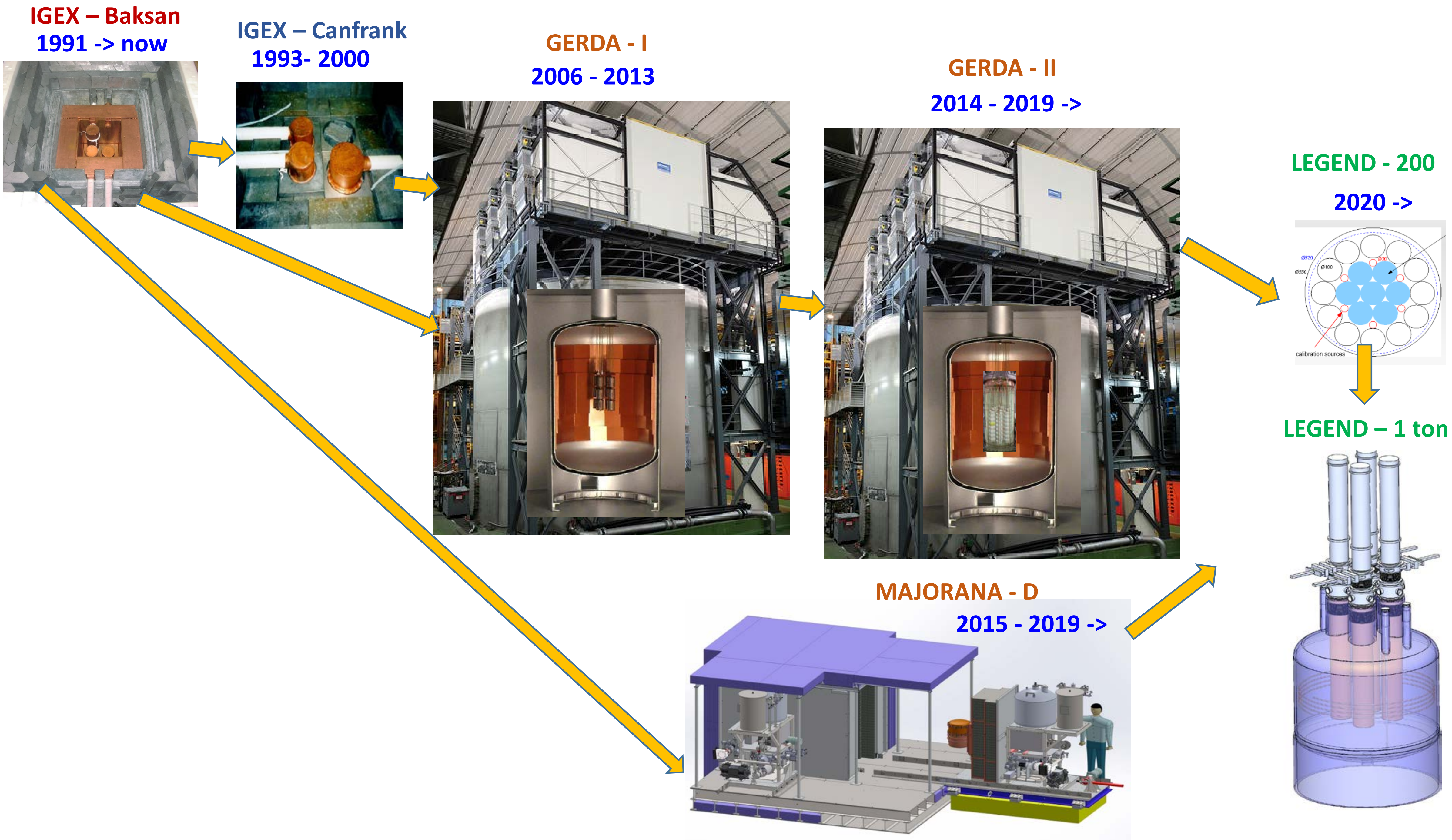
6.8 kg of enriched Ge detectors

8.5 kg yrs of data

0.17 Counts/(kg keV y) around 2040 keV

$T_{1/2} \geq 1.6 * 10^{25}$ years (90% C.L.)

Aalseth et al., Phys.Rev.D 65 (2002)092007


IGEX – Baksan
1991 -> now
IGEX – Canfrank
1993- 2000
GERDA - I
2006 - 2013
GERDA - II
2014 - 2019 ->
LEGEND - 200
2020 ->
calibration sources
LEGEND – 1 ton
MAJORANA - D
2015 - 2019 ->

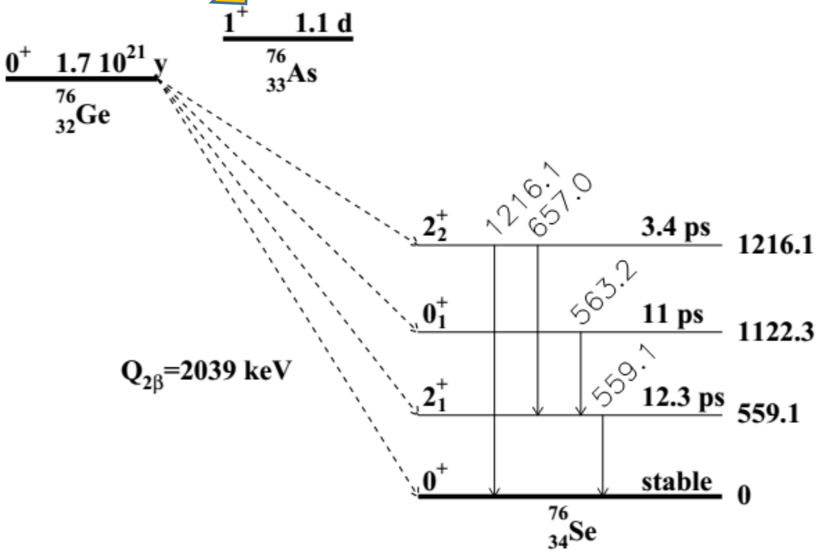
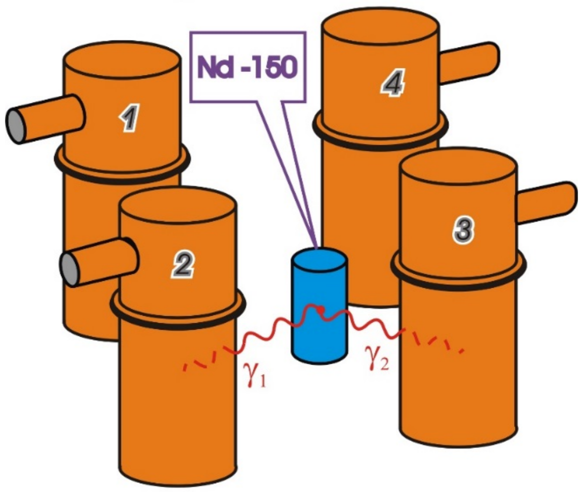
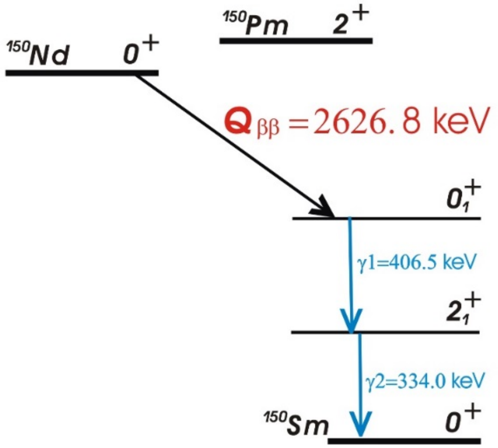


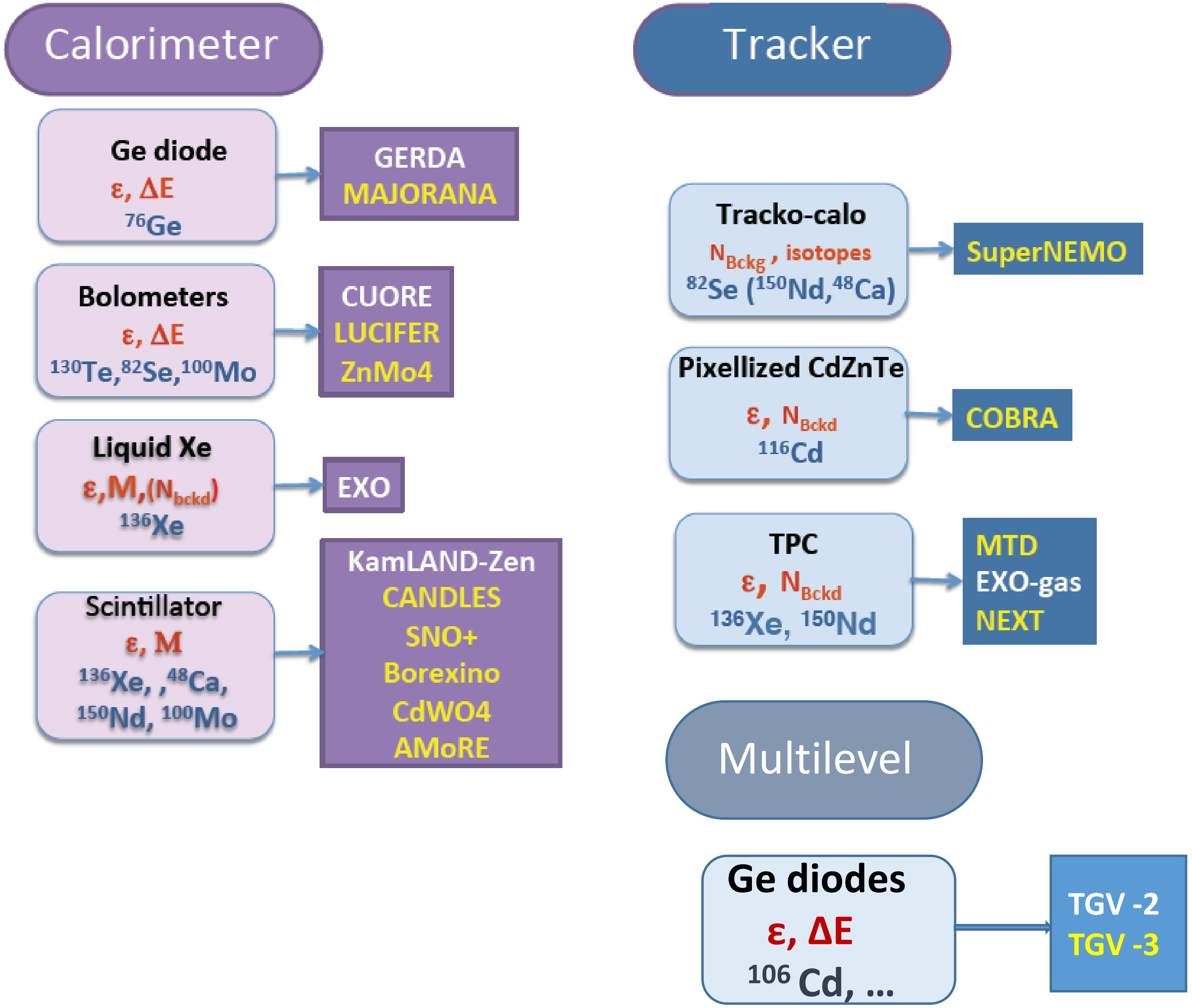
Fig. 1. Lowest energy levels of ^{76}Se which can be populated in the double beta-decay of ^{76}Ge. The energies of the excited states and of the de-excitation γ-rays are given in keV [21].

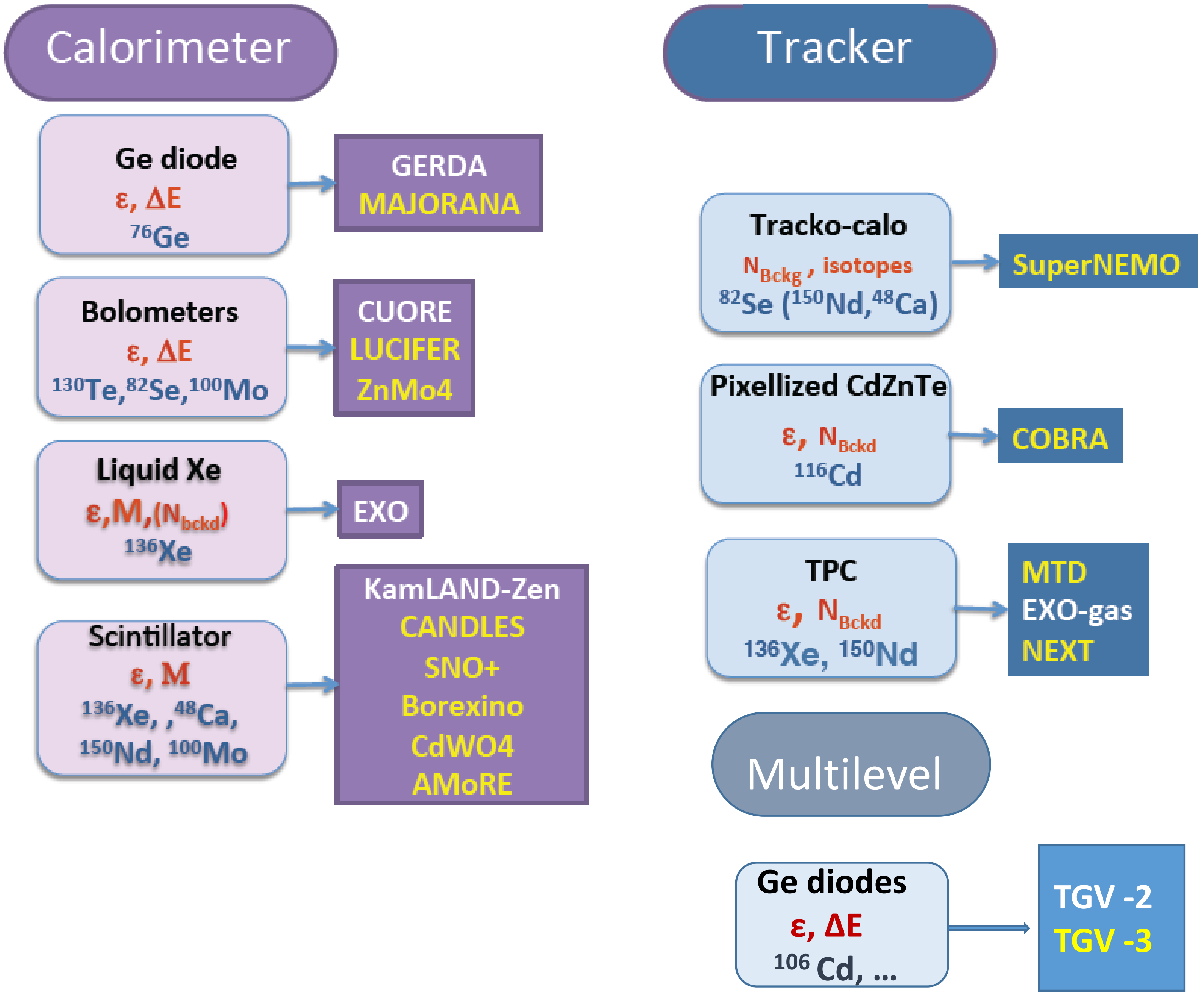




Available experimental techniques:

Ionization detectors, Scintillation detectors, Time Projection Chambers, Cryogenic bolometers, …




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
Multilevel
Ge diodes
ε, ΔE
106 Cd, ...
TGV -2
TGV -3

Presently used isotopes

^{116}Cd	COBRA, $CdWO_4$
^{76}Ge	GERDA, MAJORANA
^{82}Se	SuperNEMO, LUCIFER
^{136}Xe	KamLAND-Zen, EXO, NEXT
^{100}Mo	$ZnMoO_4$, AMoRE
^{130}Te	CUORE
$^{Nat(48)}Ca$	CANDLES
$^{Nat(150)}Nd$	SNO+, Borexino

A dream ?

^{48}Ca	CANDLES, SuperNEMO, AMoRE
^{150}Nd	SNO+, SuperNEMO, MTD, Borexino

No favorite isotope / experimental techniques

Several experiments using different isotopes and methods **are needed**

Completed, operating, under construction and R&D

Experiment	Isotope	Technique	Mass $\beta\beta(0\nu)$ isotope	Status
CUORICINO	130Te	TeO2 Bolometer	10 kg	Complete
NEMO3	100Mo/82Se	Foils with tracking	6.9/0.9 kg	Complete
GERDA I	76Ge	Ge diodes in LAr	15 kg	Complete
EXO200	136Xe	Xe liquid TPC	160 kg	Operating
KamLAND-ZEN	136Xe	2.7% in liquid scint.	380 kg	Operating
CUORE-0	130Te	TeO2 Bolometer	11 kg	Operating
GERDA II	76Ge	Point contact Ge in LAr	15+30kg	Operating
Majorana D	76Ge	Point contact Ge	30 kg	Operating
CUORE	130Te	TeO2 Bolometer	206 kg	Construction
SNO+	130Te	0.3% natTe suspended in Scint	55 kg	Construction
NEXT-100	136Xe	High pressure Xe TPC	80 kg	Construction
SuperNEMO D	82Se	Foils with tracking	7 kg	Construction
CANDLES	48Ca	305 kg of CaF2 crystals - liq. scint	0.3 kg	Construction
LUCIFER	82Se	ZnSe scint. bolometer	18 kg	Construction
1T Ge - LEGEND	76Ge	Best technology from GERDA and MAJORANA	~ tonne	R&D
CUPID	-	Hybrid Bolometers	~ tonne	R&D
nEXO	136Xe	Xe liquid TPC	~ tonne	R&D
SuperNEMO	82Se	Foils with tracking	100 kg	R&D
AMoRE	100Mo	CaMoO4 scint. bolometer	50 kg	R&D
MOON	100Mo	Mo sheets	200 kg	R&D
COBRA	116Cd	CdZnTe detectors	10 kg/183 kg	R&D
CARVEL	48Ca	48CaWO4 crystal scint.	~ tonne	R&D
DCBA	150Nd	Nd foils & tracking chambers	20 kg	R&D

Table adopted from presentation of O.Cremonesi at TAUP-2015

Current results (limits on $0\nu\beta\beta$)

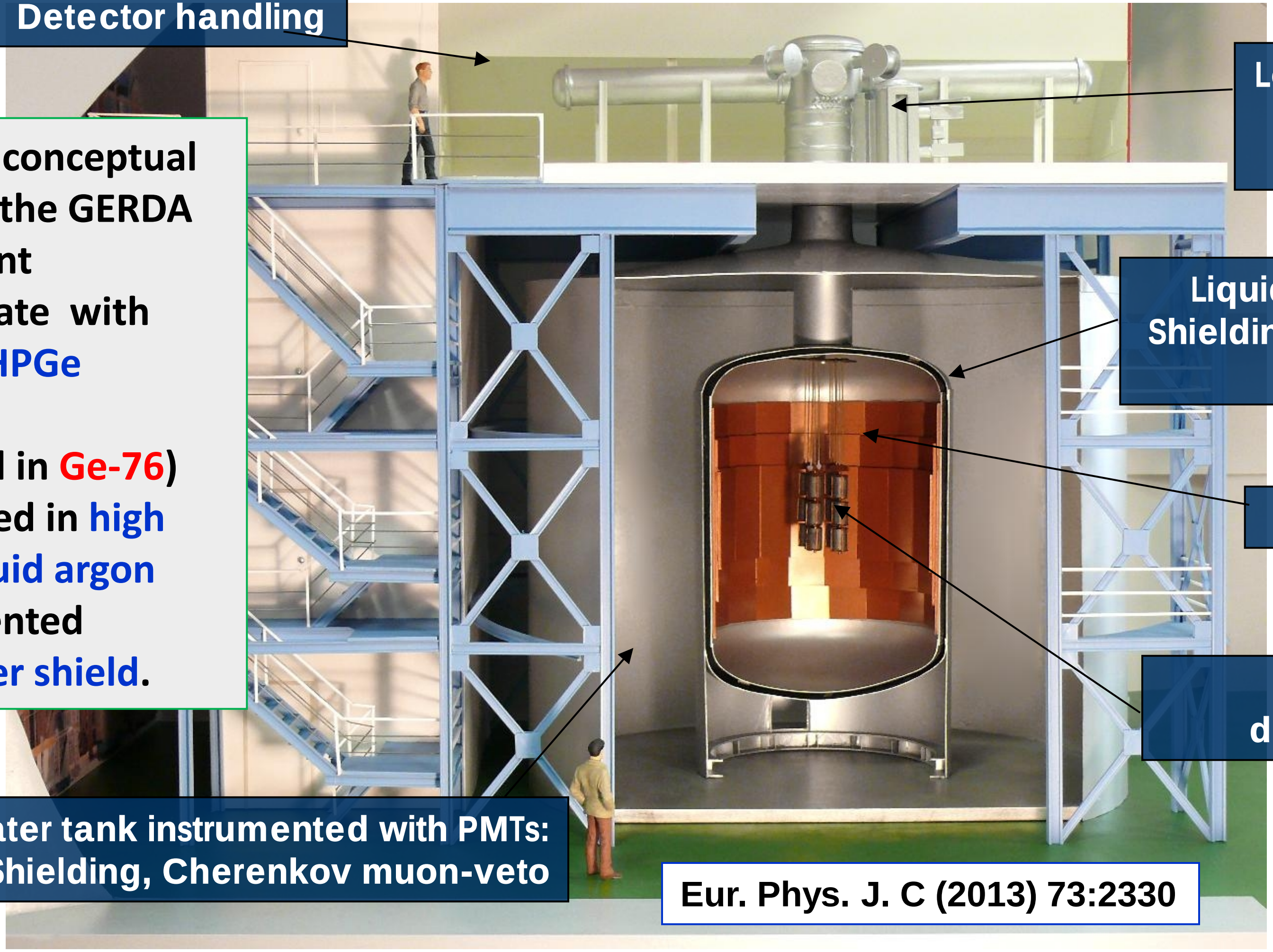
Isotope	Experiment	Technique	Mass	$T^{0\nu}_{1/2}$ (90%) limit [y]	$m_{\beta\beta}$ limit [eV]
^{48}Ca	CANDLES	Scintillation	0.01 kg	$> 5.8 \times 10^{22}$	$<$ 3.55 - 9.91
^{76}Ge	**GERDA I+II-A**	Ionisation	17/36 kg	$>$ **5.3 × 10^{25}**	**< 0.14 - 0.33**
^{82}Se	NEMO-3	Tracko-calo	930 g	$> 3.2 \times 10^{23}$	$<$ 0.85 - 2.08
^{96}Zr	NEMO-3	Tracko-calo	9.43 g	$> 9.2 \times 10^{21}$	$<$ 3.97 - 14.4
^{100}Mo	NEMO-3	Tracko-calo	6.9 kg	**> 1.1 × 10^{24}**	**< 0.33 - 0.62**
^{116}Cd	Solotvina	Scintillation	80 g	$> 1.7 \times 10^{23}$	$<$ 1.22 - 2.30
^{130}Te	CUORE-0+cino	Bolometer	~20 kg	$> 4.0 \times 10^{24}$	**< 0.23 - 0.48**
^{136}Xe	EXO-200	Liquid TPC	~110 kg	$> 1.1 \times 1025$	**< 0.17 - 0.43**
^{136}Xe	KamLAND-Zen	Scintillation	~500 kg	$> 1.1 \times 10^{26}$	**< 0.06 -0.161**
^{150}Nd	NEMO-3	Tracko-calo	36.5 g	$> 2.0 \times 10^{22}$	$<$ 2.23 - 8.21

GERDA: the GERmanium Detector Array

Neutrinoless Double Beta Decay Experiment

http://www.mpi-hd.mpg.de/gerda/

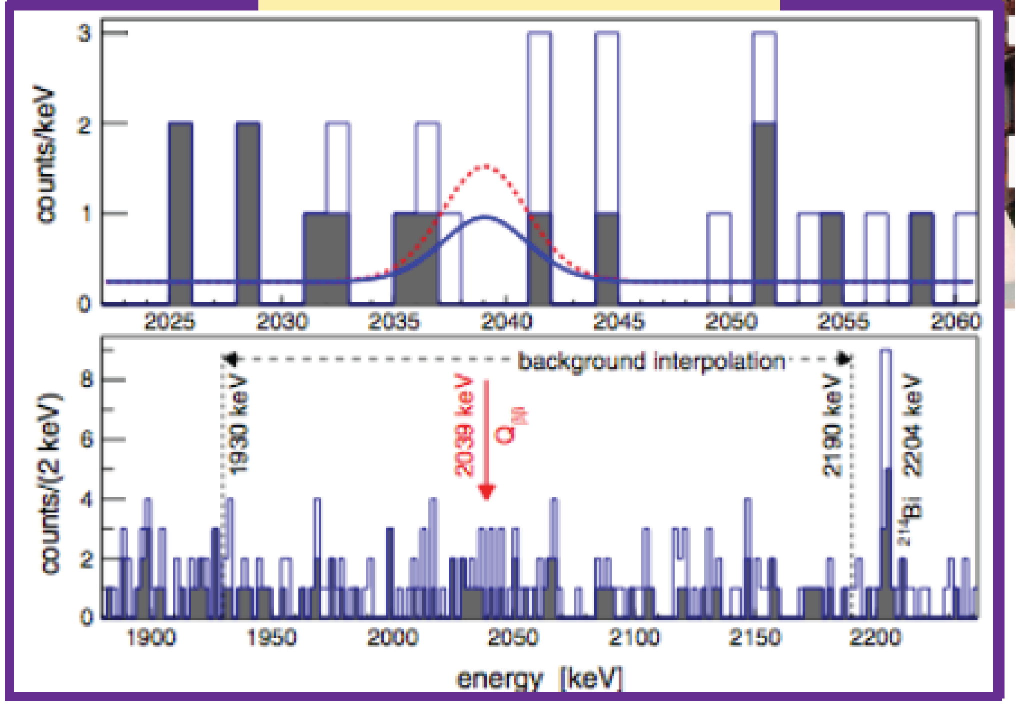
The main conceptual design of the GERDA experiment is to operate with "naked" HPGe detectors (enriched in Ge-76) submerged in high purity liquid argon supplemented by a water shield.

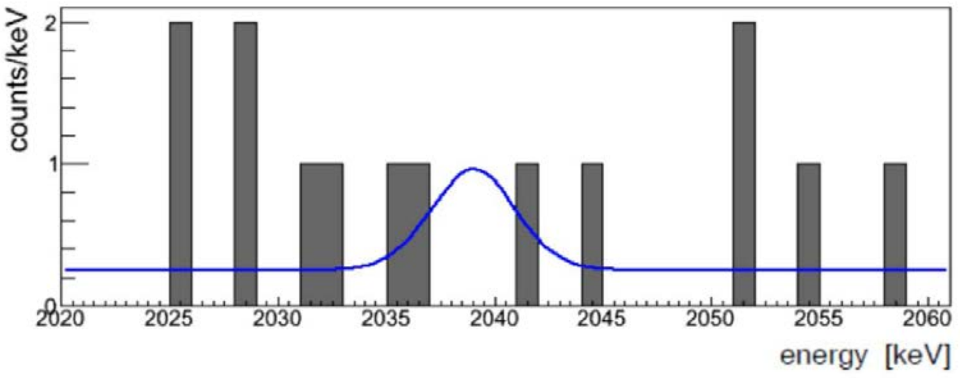


Eur. Phys. J. C (2013) 73:2330

Results of GERDA Phase I

PRL 111, 122503 (2013)





profile likelihood (PL) fit:

signal = a*flat background + b*line

➔ best fit: $N^{0\nu} = 0$; upper limit: $N^{0\nu} < 3.5$ (90%CL)

➔ half life limit $T_{1/2}(0\nu\beta\beta) > 2.1 * 10^{25}$ yr (90% C.L.)

$T_{1/2} > 2.1 \times 10^{25}$ years

M. Agostini *et al.*, (GERDA Collaboration), Phys. Rev. Lett.**111**, 122503 (2013).

GERDA:

Phase II– started Dec 2015

7 strings of HPGe detectors deployed:
37 detectors enriched in 76Ge (**35.8 kg**)
3 natural detectors (7.6 kg)

Liquid Argon veto for GERDA Phase II

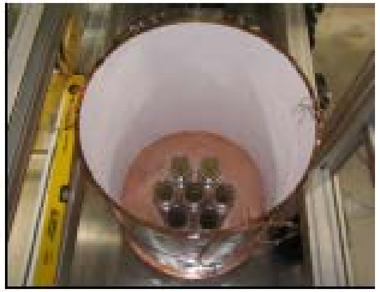
LAr veto

9 off 3” PMTs

GERmanium Detector Array

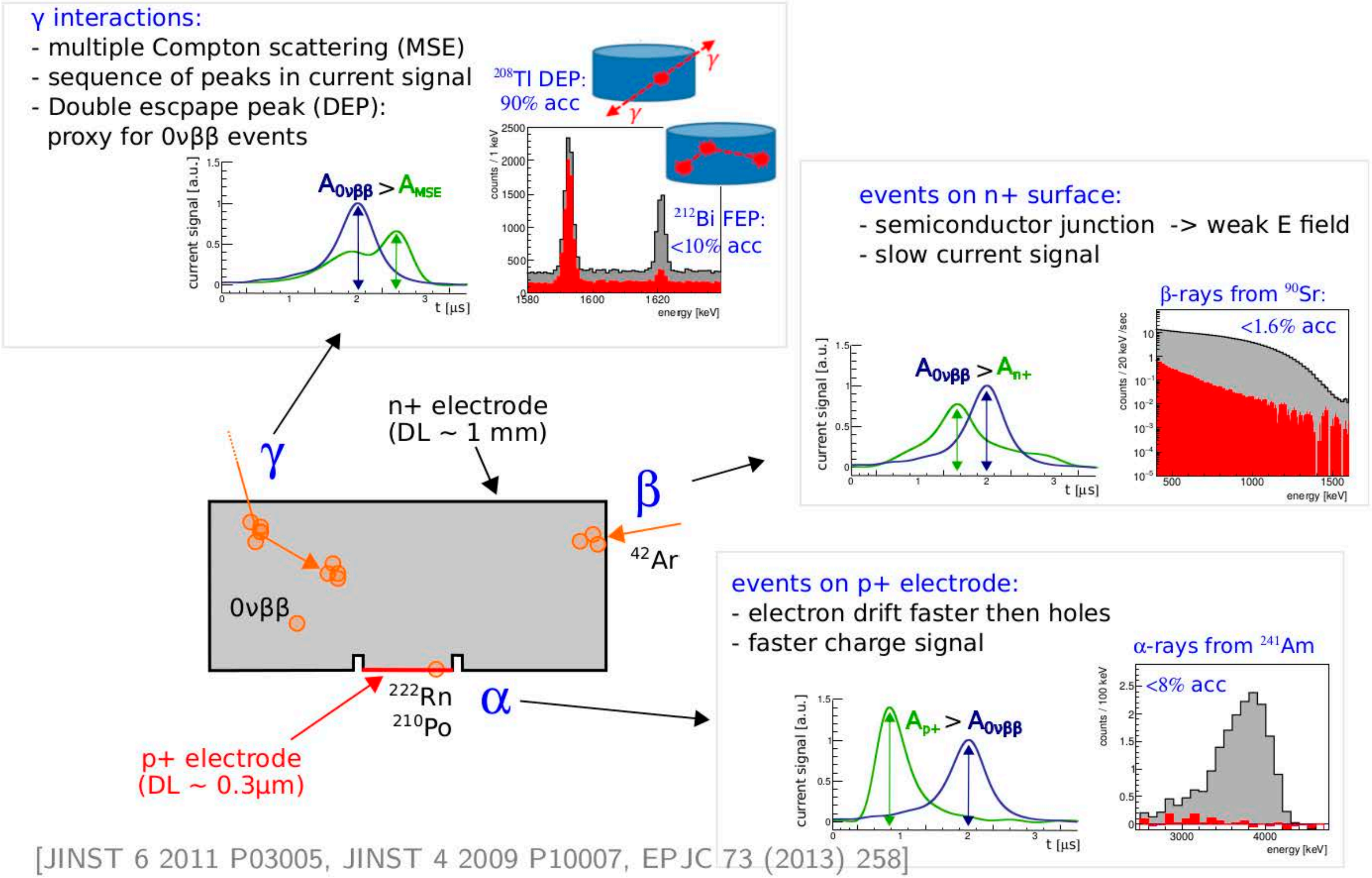
copper shroud lined with reflecting TPB coated Tetratex

TPB coated fiber shroud with SiPMs



7 off 3” PMTs

GERDA Phase II - PSD of BEGe



[JINST 6 2011 P03005, JINST 4 2009 P10007, EPJC 73 (2013) 258]

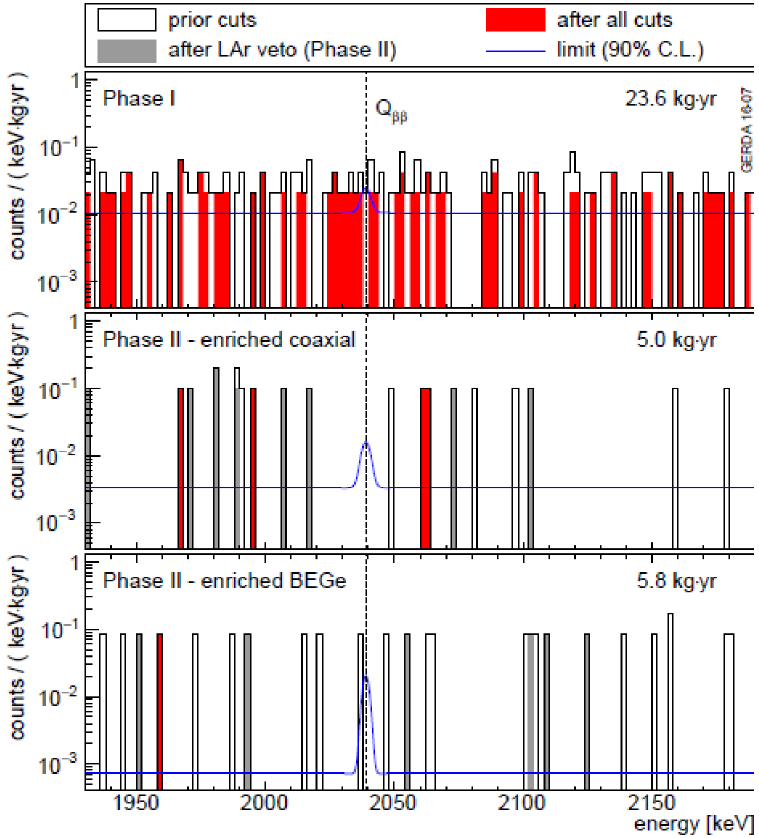
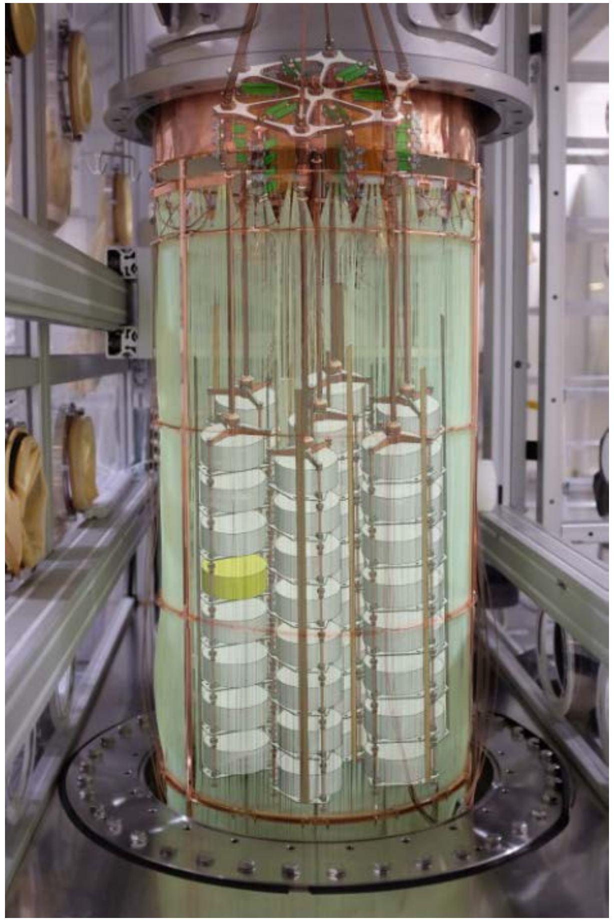


FIG. 4. Combined Phase I data (top), Phase II coaxial (middle) and BEGe detector spectra (bottom) in the analysis window. The binning is 2 keV. The exposures are given in the panels. The red histogram is the final spectrum, the filled grey one without pulse shape discrimination and the open one in addition without argon veto cut. The blue line is the fitted spectrum together with a hypothetical signal corresponding to the 90 % C.L. limit of $T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}$ yr.



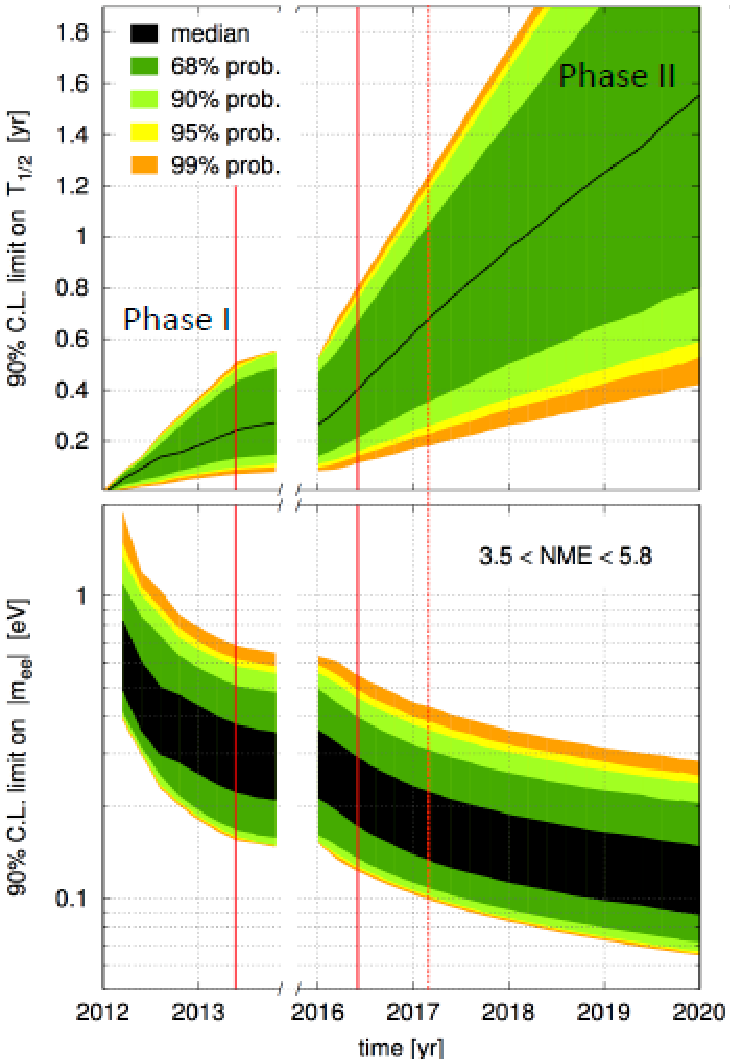
The best fit yields

zero signal events and a 90% C.L. limit of 2.0 events in 34.4 kgyr total exposure

or T1/2 > 5.3 x 10^25 yr

M. Agostini *et al.*, (GERDA Collaboration), Nature, 21717 (2017).

GERDA-PhaseII: first **background-free** 0νββ experiment



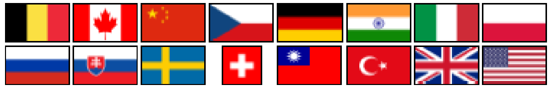
Phase I achievements	
background	$\sim 10^{-2}$ cts/(keV · kg · yr)
exposure	21.6 kg · yr
limit	$\mathbf{T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}}$ **yr (90% CL)**
	[Phys.Rev.Lett. 111 (2013) 122503]

first Phase II achievements	
background	$\sim 10^{-3}$ cts/(keV · kg · yr)
exposure	10.8 kg · yr (34,4 kg · yr)*
limit	$\mathbf{T^{0\nu}_{1/2} > 5.3 \cdot 10^{25}}$ **yr (90% CL)**
	$\boldsymbol{m_{\beta\beta} < 0.15 - 0.33}$ **eV (90% CL)**
	[arXiv:1703.00570; acc. Nature]

Phase II goals	
background	$\sim 10^{-3}$ cts/(keV · kg · yr)
exposure	$\gtrsim 100$ kg · yr
sensitivity	$\mathbf{T^{0\nu}_{1/2} \gtrsim 10^{26}}$ **yr**

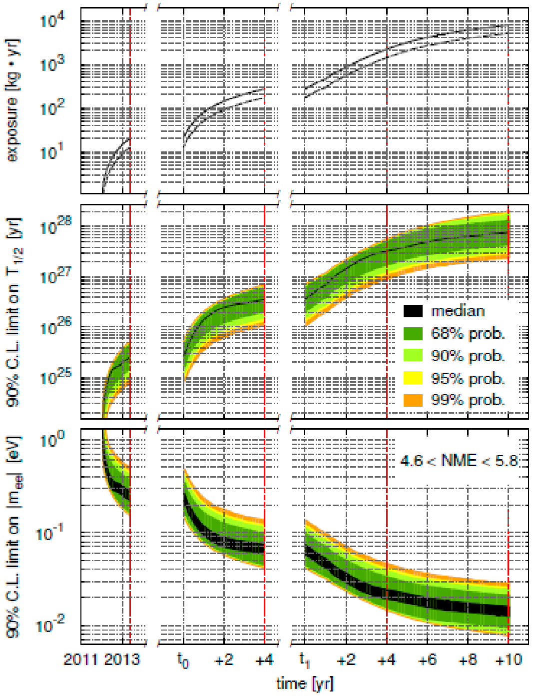
LEGEND (Large Enriched Germaium Experiment for Neutrinoless ββ Decay)

- LEGEND (Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay) collaboration has been formed in October 2016
  - 219 members, 48 institutions, 16 countries
  - www.legend-exp.org



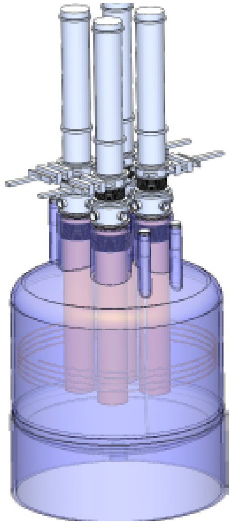
LEGEND goals	
background	$\sim 10^{-4}$ cts/(keV · kg · yr)
detector mass	$O(1t)$
discovery potential(!)	$\mathbf{T^{0\nu}_{1/2} > 10^{27}}$ **yr**

- first stage: 200 kg in upgrade of existing infrastructure at LNGS



[Eur.Phys.J. C76 (2016) 176]

First stage:
- (up to) 200 kg in upgrade of existing infrastructure at LNGS
- bgd reduction by factor 3-5 w.r.t GERDA



Subsequent stages:
- 1000 kg (staged)
- timeline connected to DOE down select process
- Bgd factor 30 w.r.t GERDA
- Location tbd
- Required depth (Ge-77m) under investigation

NEMO 3

Tracking detector: drift chambers (6180 Geiger cells)
$\sigma_t = 5$ mm, $\sigma_z = 1$ cm (vertex)
Calorimeter (1940 plastic scintillators and PMTs)
Energy Resolution FWHM=8 % (3 MeV)

Identification e^-, e^+, γ, α
Very high efficiency for background rejection

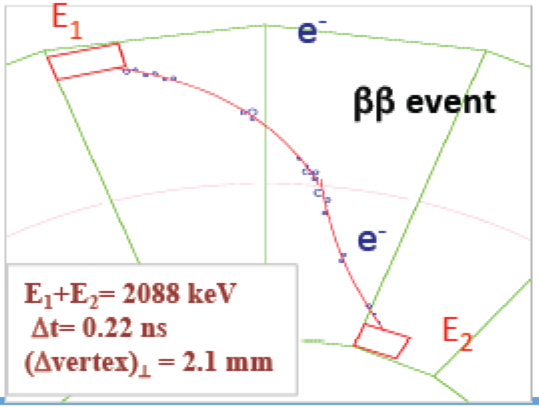
Background level @ $Q_{\beta\beta}$ [2.8 – 3.2 MeV] : 1.2 10^{-3} cts/keV/kg/y

Multi-isotope (7 measured at the same time)

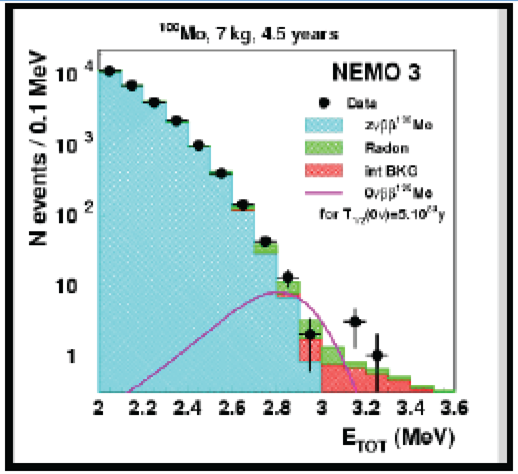
Running at Modane underground laboratory (2003 - 2011)

Unique feature

Measurement of all kinematic parameters: individual energies and angular distribution



Measurement of 7 isotopes ββ(2ν) half-lifes
Excited states, Majoron limits for ββ(0ν)



[2.8 – 3.2] MeV 18 observed events, 16.4 ± 1.3 expected

^{100}Mo $T_{1/2}$ ($\beta\beta0\nu$) > 1.0 10^{24} y (90% C.L.)

$<m_\nu>$ < 0.31– 0.79 eV

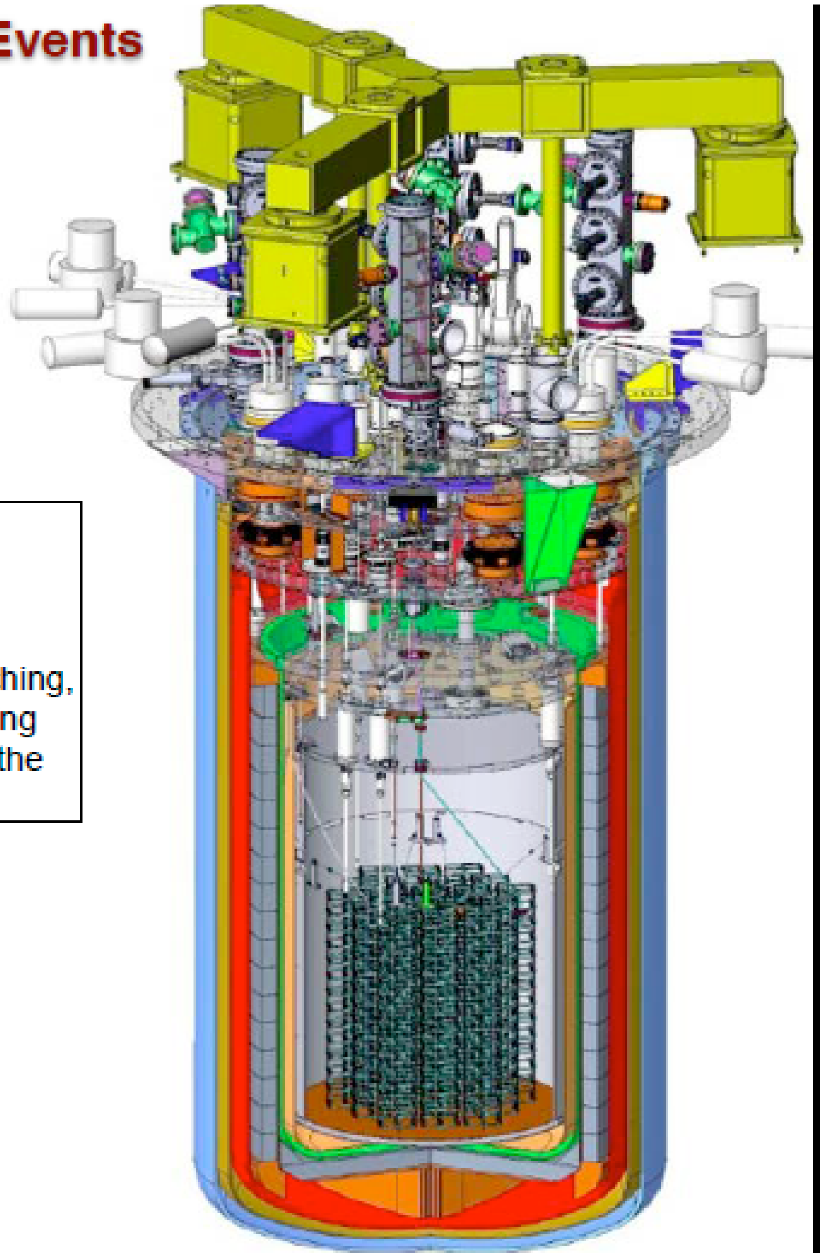
Cryogenic Underground Observatory for Rare Events

CUORE detector

- 988 TeO_2 crystals run as a bolometer array
  - 5x5x5 cm^3 crystal, 750 g each
- 19 Towers; 13 floors; 4 modules per floor
  - 741 kg total - 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei
- Excellent energy resolution of bolometers
- Radio-pure material and clean assembly to achieve low background at ROI
  - strict radiopurity control protocol to limit bulk and surface contaminations in crystal production
  - transportation at sea level to LNGS
  - bolometric test to check performances and radio-purity
  - TECM protocol (Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching) for copper surface cleaning
  - limited exposure to cosmic rays: underground storage of the copper parts in between production and cleaning

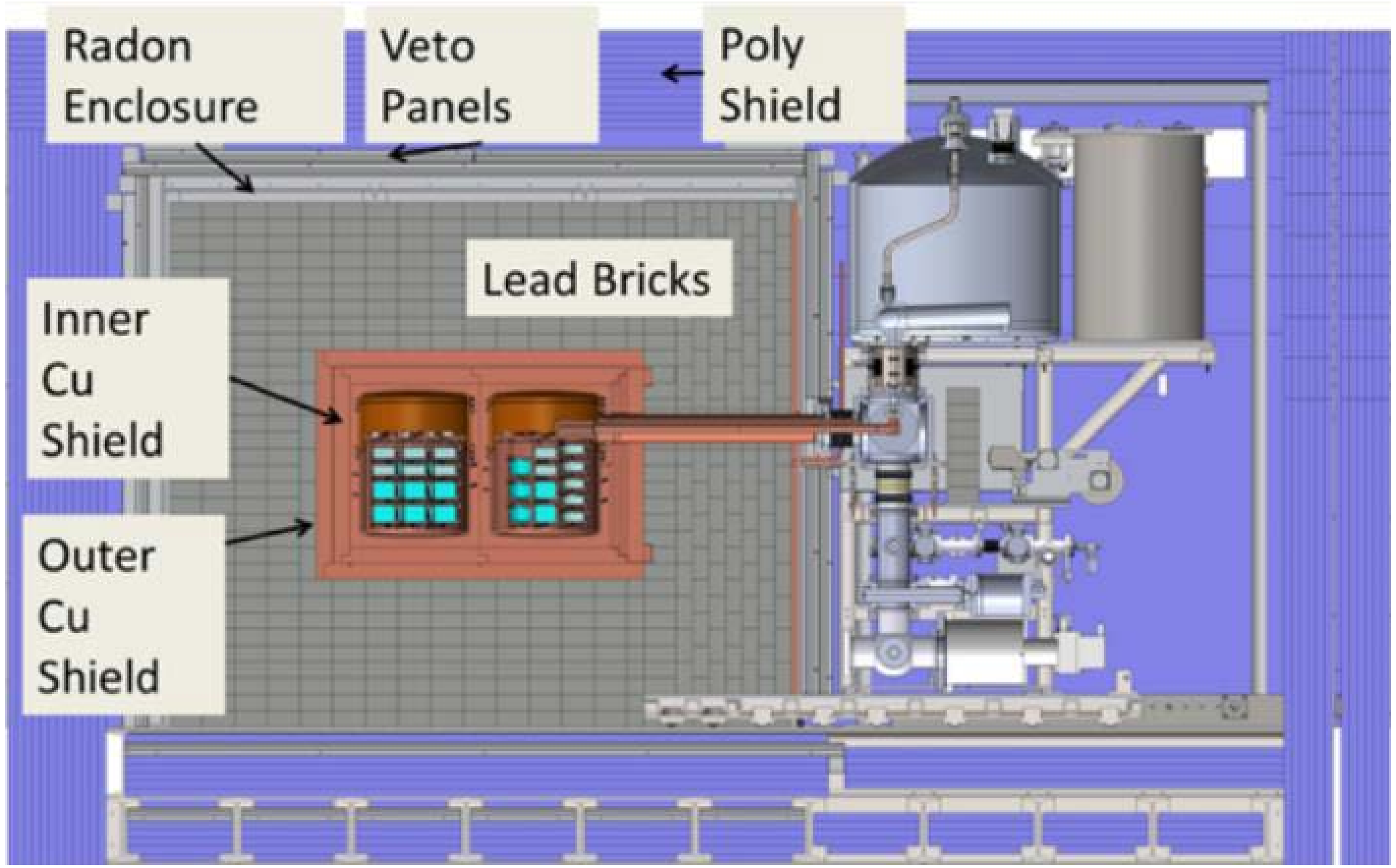
Complex cryogenic set-up

- Fully cryogen-free system:
  - custom cryostat
  - 5 pulse tubes
  - a powerful dilution refrigerator and
- ~10 mK operating temperature
- Independent suspension of the detector array
- An embedded detector calibration system
- Radio-pure materials
- Heavy low temperature shield



Majorana Demonstrator

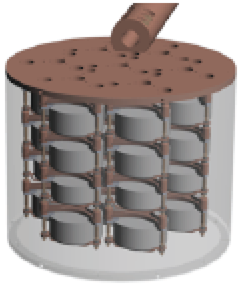
started in 2015



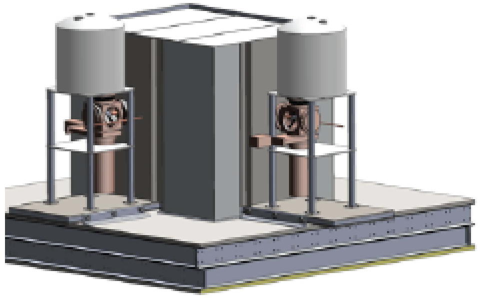
MAJORANA

^{76}Ge offers an excellent combination of capabilities & sensitivities.

(Excellent energy resolution, intrinsically clean detectors, commercial technologies, best $0\nu\beta\beta$ sensitivity to date)



- 40-kg of Ge detectors
  - Up to 30-kg of 86% enriched ^{76}Ge crystals required for science and background goals
  - Examine detector technology options focus on point-contact detectors for DEMONSTRATOR
- Low-background Cryostats & Shield
  - ultra-clean, electroformed Cu
  - naturally scalable
  - Compact low-background passive Cu and Pb shield with active muon veto

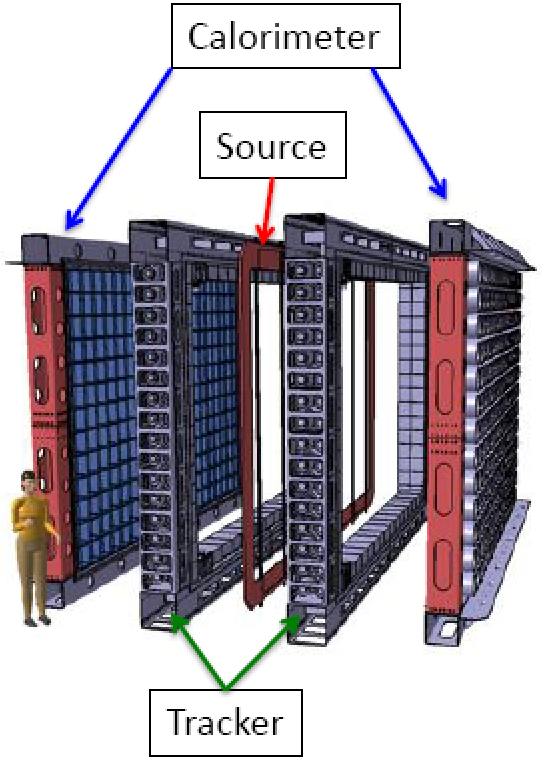


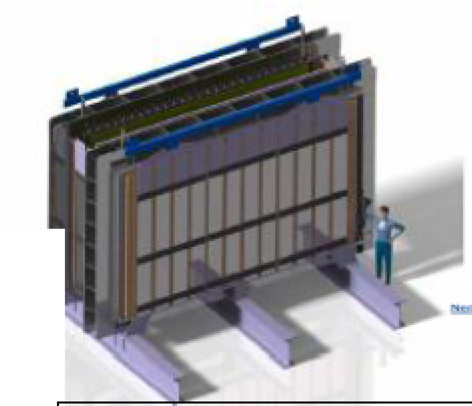
- Agreement to locate at 4850' level at Sanford Lab
- Background Goal in the $0\nu\beta\beta$ peak ROI(4 keV at 2039 keV)

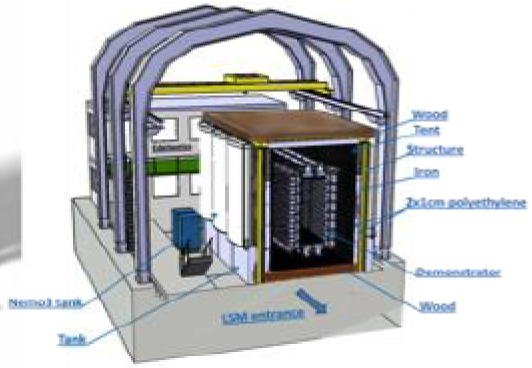
~ 3 count/ROI/t-y (after analysis cuts) (scales to 1 count/ROI/t-y for tonne expt.)

Plan to start in 2017

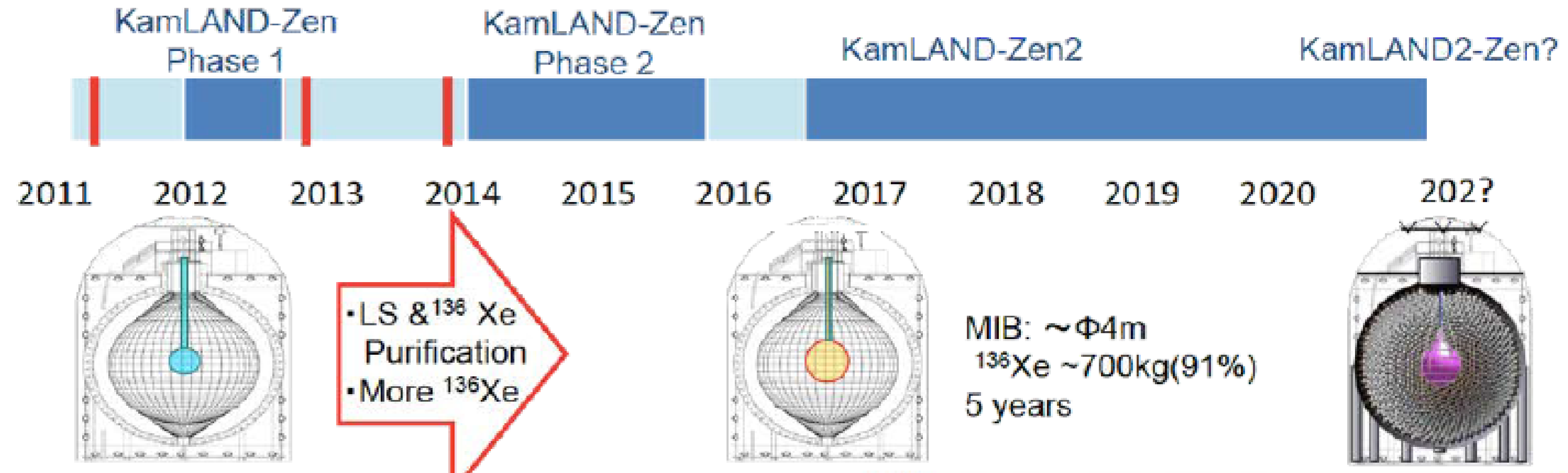
Super NEMO Demonstrator
Design







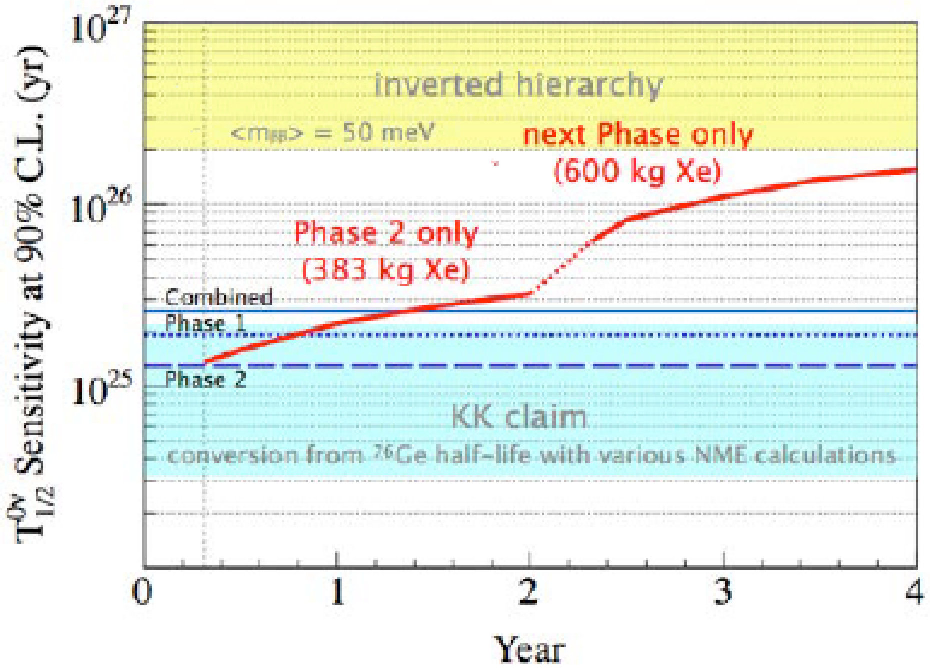
- Ultra low background detector
- Modular detector with 3 main components :
  - Central source foil frame : 7 kg of isotope
  - Tracking : 2 000 drift chambers
  - Calorimeter : 712 scintillators+ PMTs
- Shielded by iron (300 tons) and water
- Installed at LSM (Modane Underground Laboratory – 4800 m.w.e.)



MIB: ~Φ3.12m
Livetime 112.3 days.
^{136}Xe ~320kg(91%)
FV: ^{136}Xe 125 kg.

Livetime >600days.?
^{136}Xe ~383kg(91%)

- 2014: KamLAND-Zen w/ lower ^{110m}Ag
  - Just resumed with 380 kg
- 2017: KamLAND-Zen 700 kg
  - with clean mini-balloon
- Future: KamLAND-Zen2
  - high QE PMT
  - high yield LS
  - light concentrator
  - σ_E(2.6 MeV) < 2.5%
- Super-KamLAND-Zen



CUORE

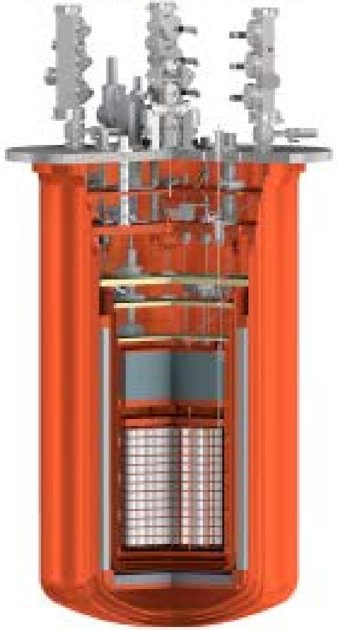
Successor of Cuoricino will start at LNGS soon

19 towers array of 988 TeO_2 5 cm cubic detectors at ~10 mK

A total mass of 206 kg of ^{130}Te

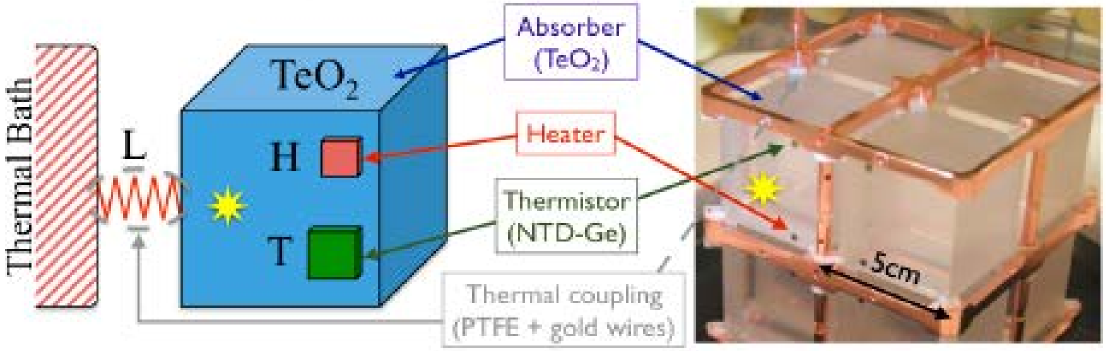
Energy resolution of 5 keV FWHM at $Q_{\beta\beta}$ = 2530 keV

Background goal: 10^{-2} cts/(keV·kg·y)



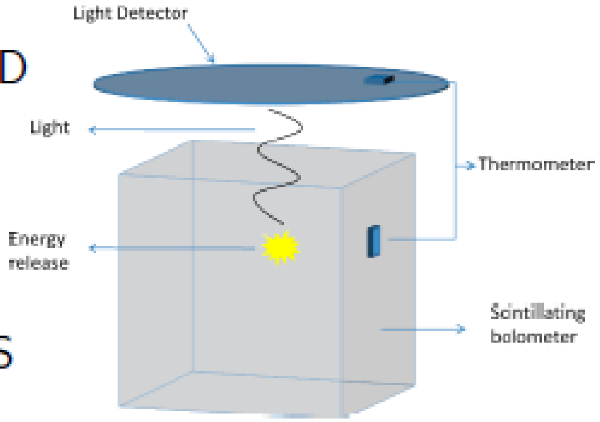
Sensitivity after 5 y: $T^{0\nu}_{1/2} > 9.5 \times 10^{25}$ y

$|m_{\beta\beta}| <$ 50 - 130 meV



CUPID

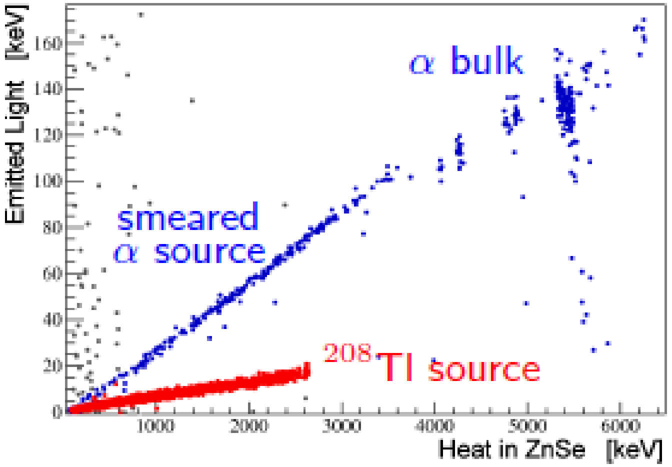
CUORE Upgrade with Particle IDentification
to further reduce backgrounds with $\beta/\gamma - \alpha$ PSD
and investigate the IH band



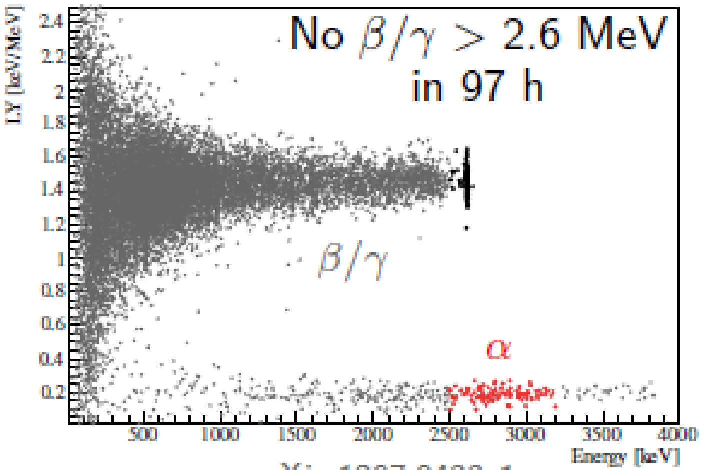
Scintillating bolometers:
TeO_2, $ZnMoO_4$, ZnSe, $CdWO_4$ arXiv:1504.03599

R&D with Lucifer & Lumineu at LSM and LNGS

PSD example with ZnSe



PSD example with $ZnMoO_4$



arXiv:1207.0433v1

Nearest future

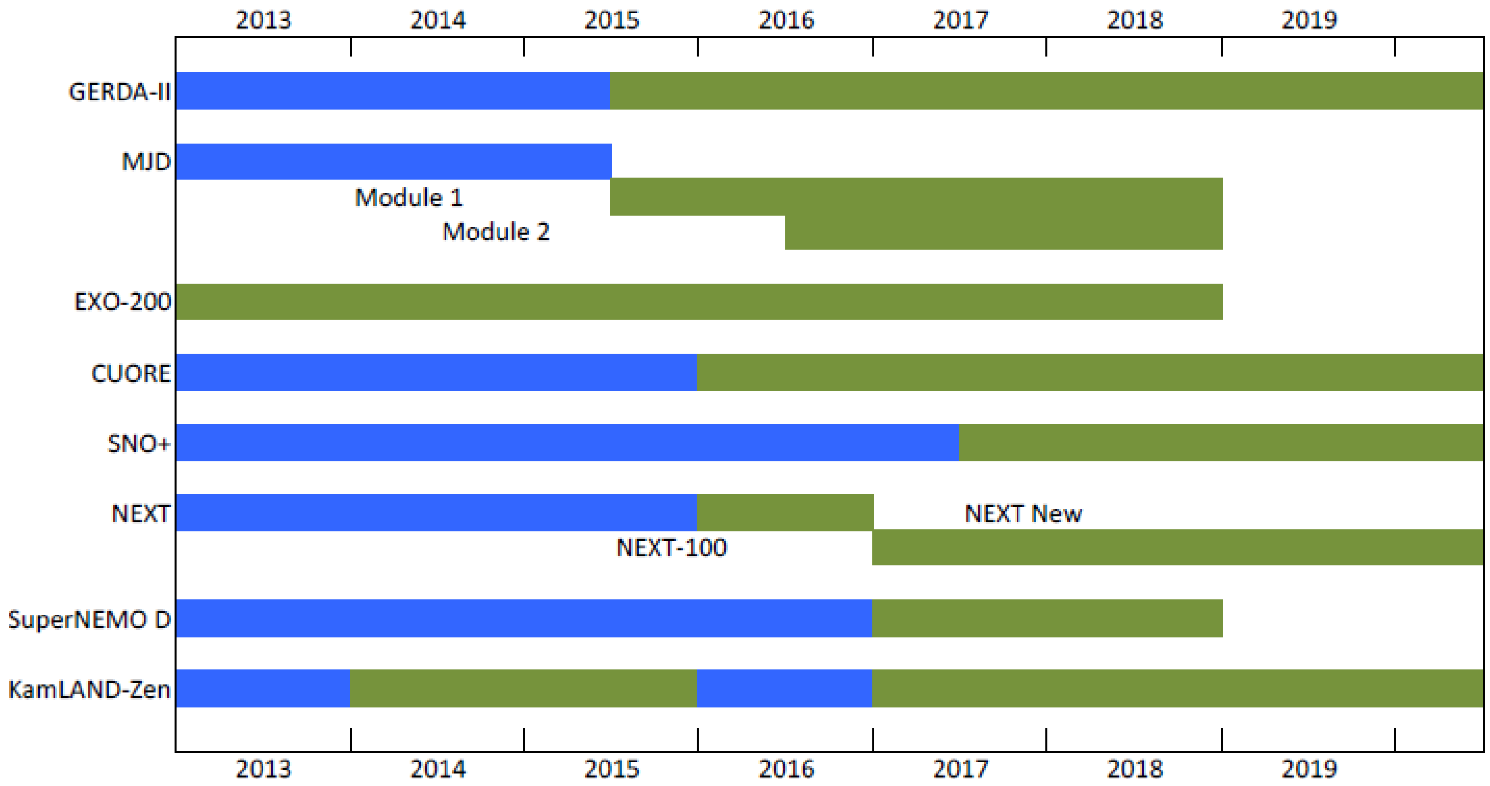
Current experiments							
		mass [kg]* (total/FV)	FWHM [keV]	background[&] [cnt/mol yr FWHM]	$T_{1/2}$ limit [10^{25} yr] after 4 yr	<m_{ee}> limit [meV]	date
Gerda II	Ge	35/27	3	0.0004	15	80-190	-2019
MajoranaD	Ge	30/24	3	0.0004	15	80-190	-2019
EXO-200	Xe	170/80	88	0.03	6	80-220	-2019
Kamland-Zen	Xe	383/88 (600/?)	250	0.03	20	44-120	-2018
NEXT	Xe	100/80	17	0.0036	6	100-200	-2020
Cuore	Te	600/206	5	0.02	9	50-200	-2019
SNO+	Te	2340/160	270	0.02	9	50-200	-2020

* total= element mass, FV= $0\nu\beta\beta$ isotope mass in fiducial volume (incl enrichment fraction)

[&] mol of $0\nu\beta\beta$ isotope in active volume and divided by $0\nu\beta\beta$ efficiency

Note: values are design numbers except for EXO-200 and Kamland-Zen

Ge experiments have lowest background → similar sensitivity despite small mass



2013
2014
2015
2016
2017
2018
2019
GERDA-II
MJD
Module 1
Module 2
EXO-200
CUORE
SNO+
NEXT
NEXT New
NEXT-100
SuperNEMO D
KamLAND-Zen

Far future -> Proposals for ton scale experiments

Next generation experiment with sensitivities $T_{1/2} \sim 10^{27}$-10^{28} yr

Isotope	Experiment	Description
^{76}Ge	**LEGEND** (GERDA & MAJORANA)	Large Scale Ge, O(tonne) HPGE crystals
^{82}Se	SuperNEMO	Se foils, tracking and calorimeter, 100 kg scale
^{136}Xe	nEXO	Liquid TPC, 5 tonnes
	NEXT/BEXT	High pressure gas TPC, tonne scale
	KamLAND2-Zen	^{136}Xe in scintillator
^{130}Te	CUPID	Bolometers with light sensor (also ^{82}Se, ^{116}Cd, ^{100}Mo)
	SNO+ II	^{130}Te in scintillator

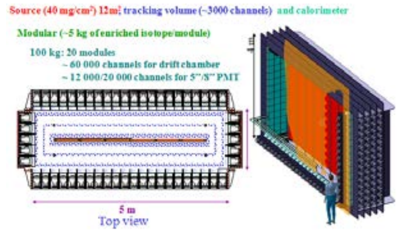
Many other experimental R&D efforts that can not be discussed in detail:

Lucifer – phonons and scintillation

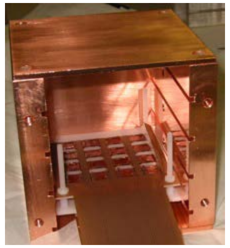
COBRA – pixelized CdZnTe semiconductor detector,

SuperNEMO – full scale,

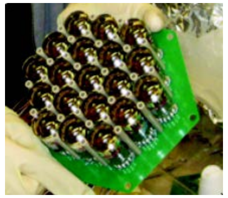
SNO+, Moon, DCBA, NEXT,.....



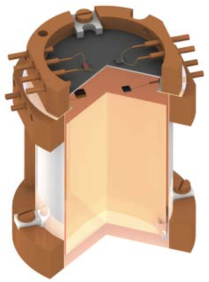
Super NEMO



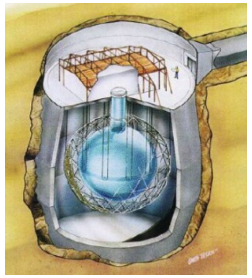
COBRA



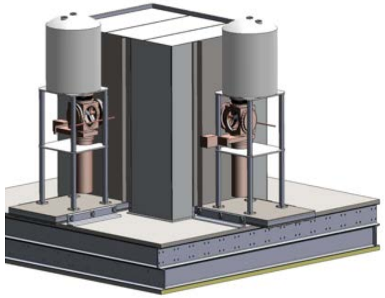
NEXT



LUCIFER

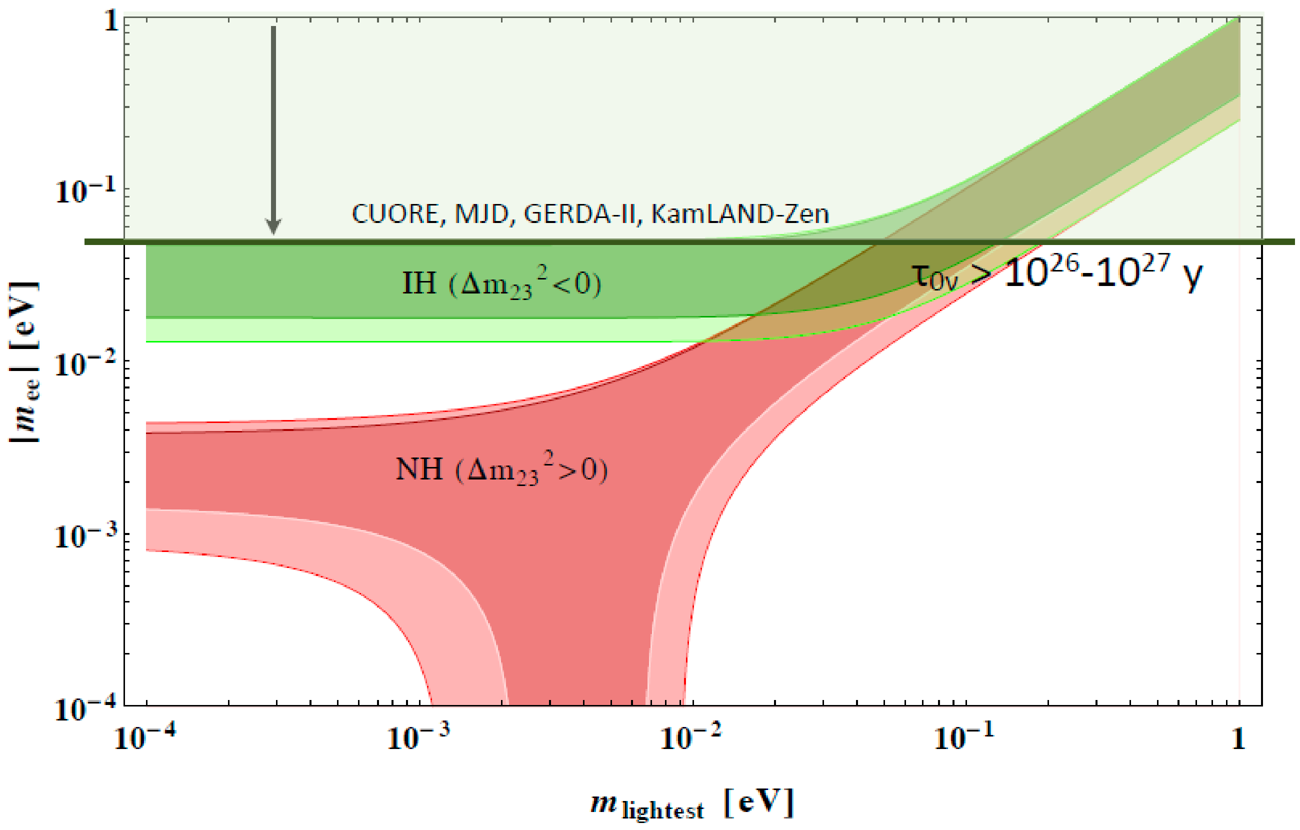


SNO+

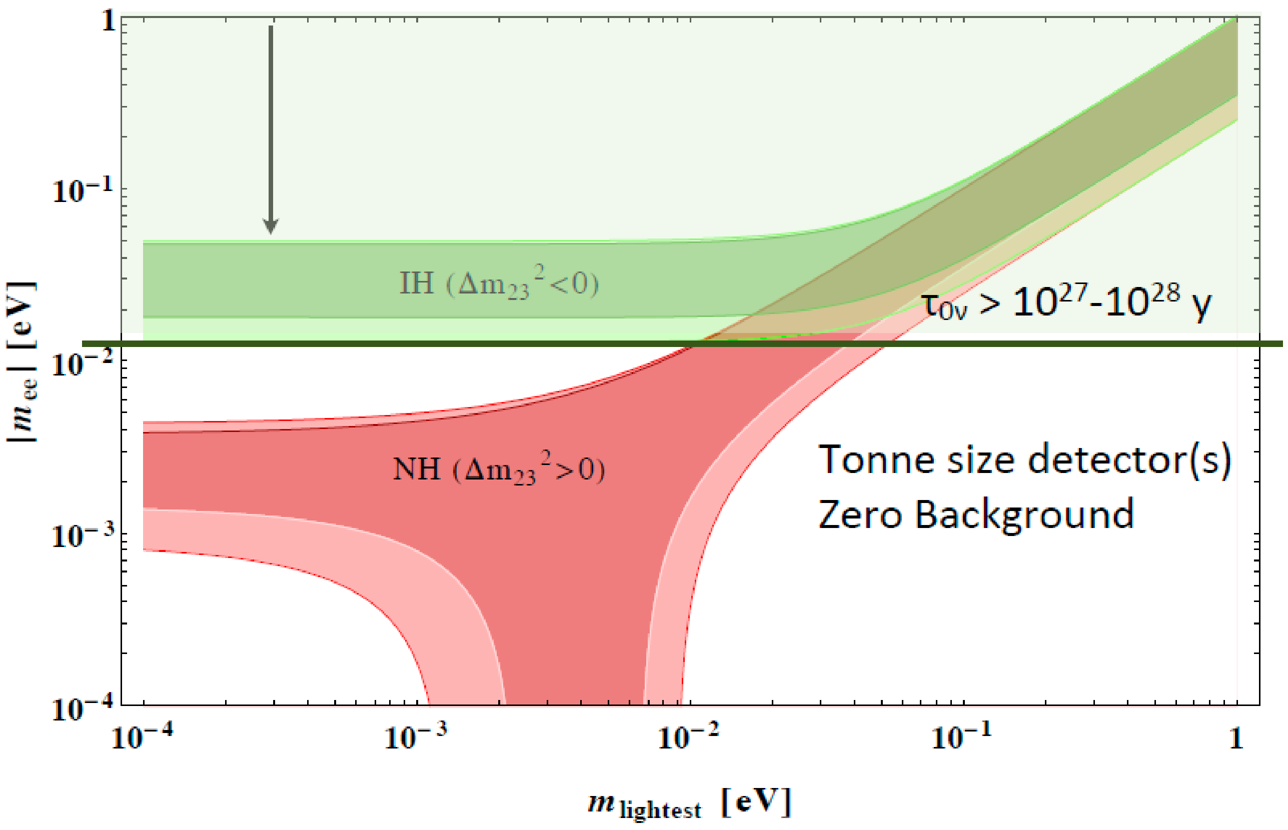


MAJORANA

Status: near future

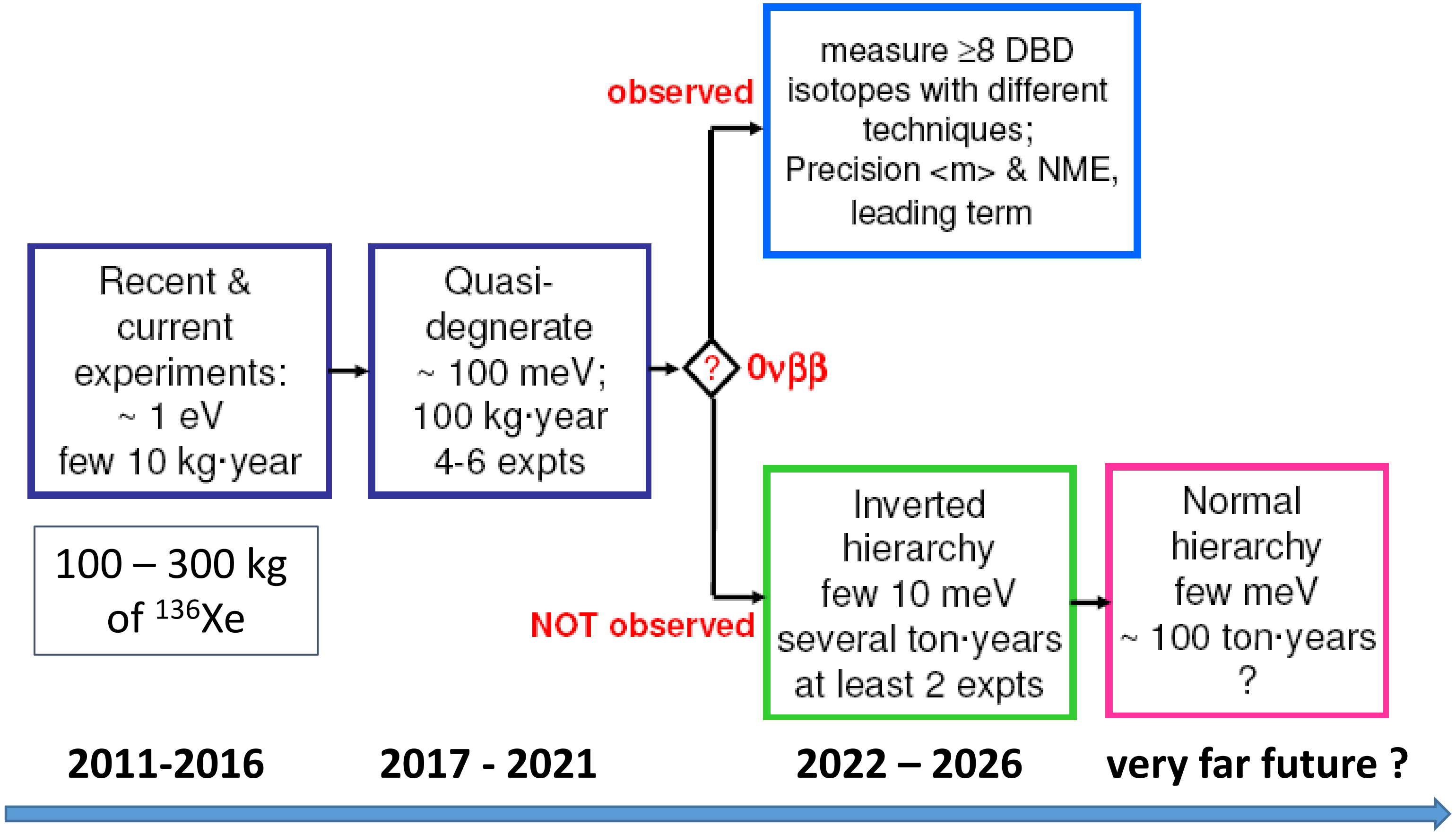


Future challenge



Summary

$0\nu\beta\beta$ experimental strategy during the next decade



Controversy S. Schönert, NME WS, LNGS Nov. 2011

Conclusion

New sensitive experiments are starting operation ->
-> new important information is expected

5 experiments have reached [$m_{\beta\beta}$]< 1 eV sensitivity with 4 isotopes:
GERDA - EXO - KamLAND-Zen – CUORE, NEMO

Upgrades and new experiments coming to investigate
the inverted hierachy region of [$m_{\beta\beta}$] < 10 - 50 meV

Extra slides