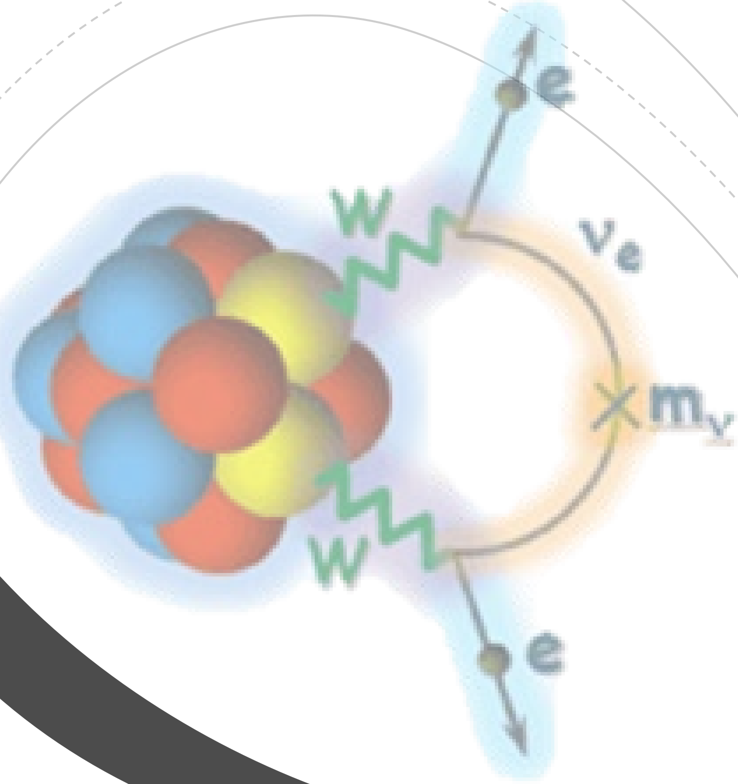
Review of Neutrino-less double beta decay experiment



2022 Jul. 20th

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(Univ. of Tsukuba)

The Vietnam School on Neutrinos (VSON) 2022

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  - NEMO-3/Super-NEMO
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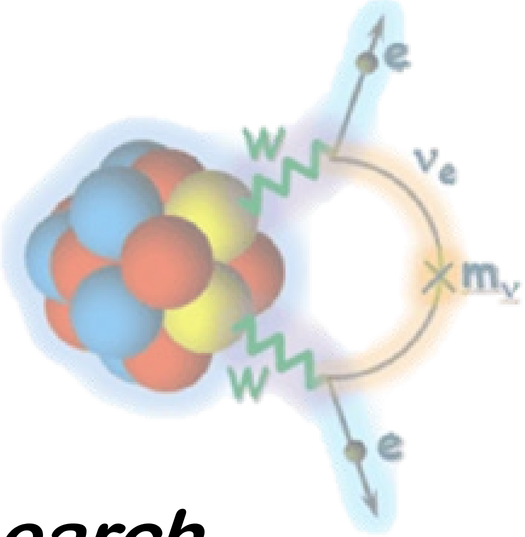
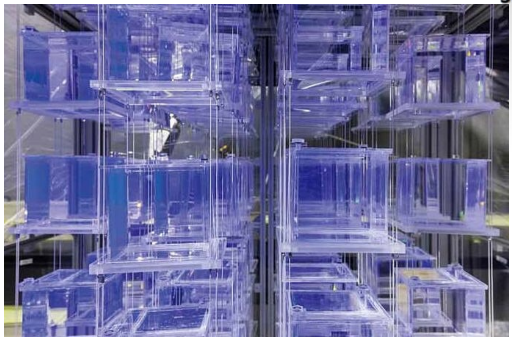
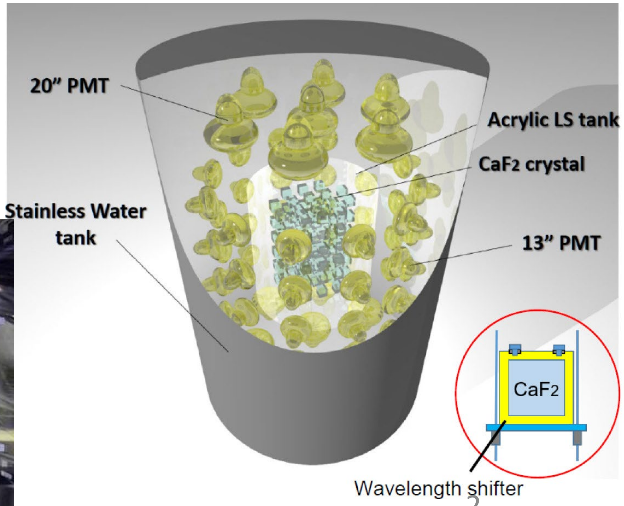
- ***Summary***

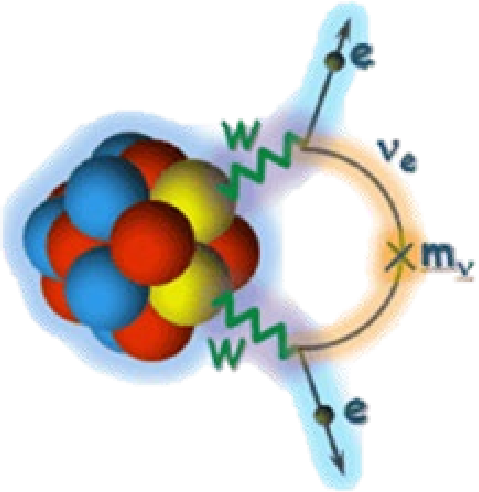


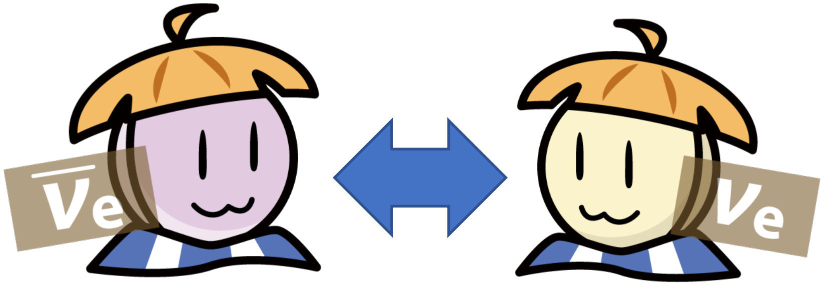




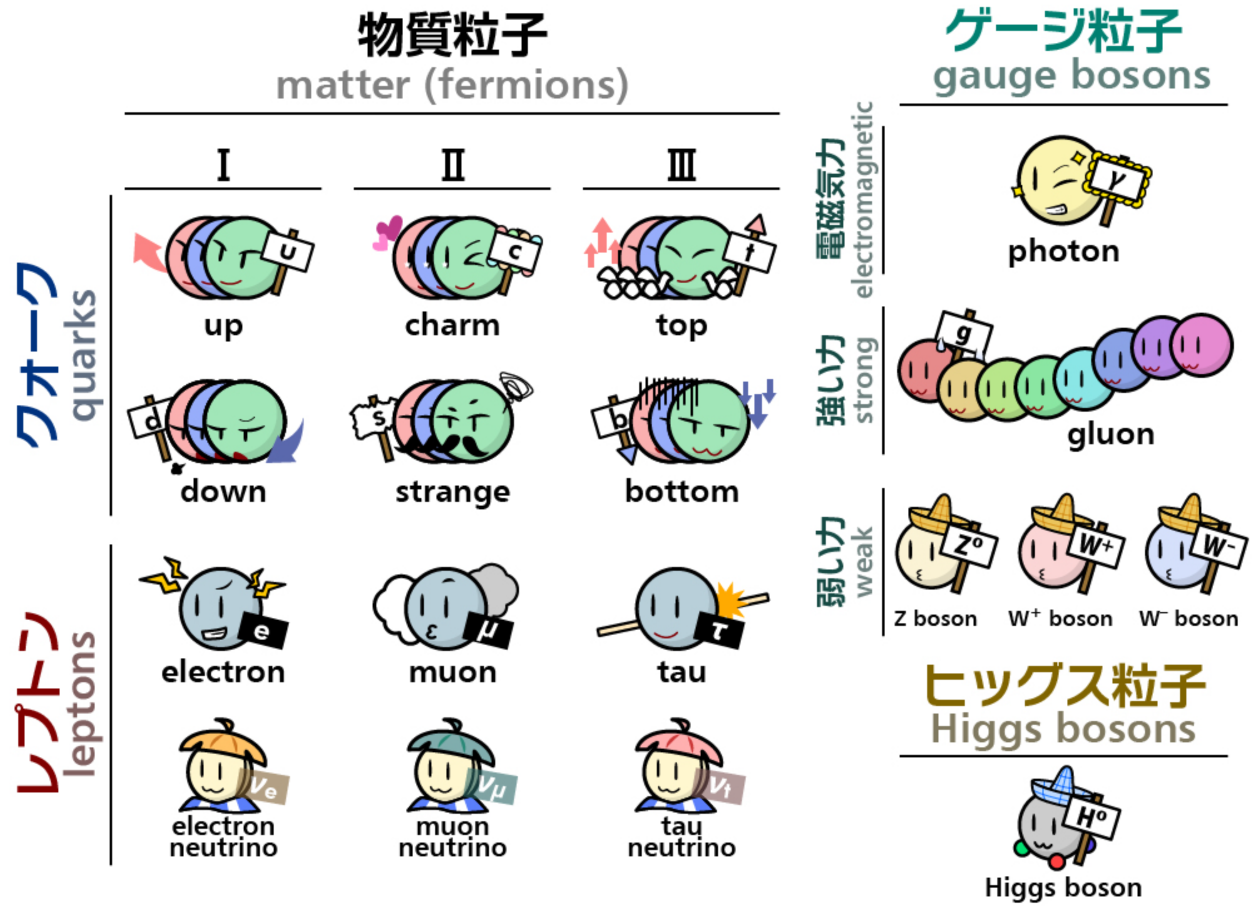
Motivation

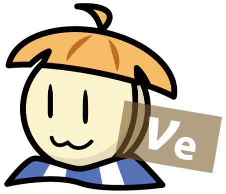
- **Is neutrino Dirac particle or Majorana particle?**
- Observation of Neutrino-less double beta decay ($0\nu\beta\beta$) would prove Majorana nature of neutrinos ($\nu_e = \overline{\nu}_e$).
- This process violate lepton number conservation and is beyond the standard model of particle physics.





What is Known about Neutrino





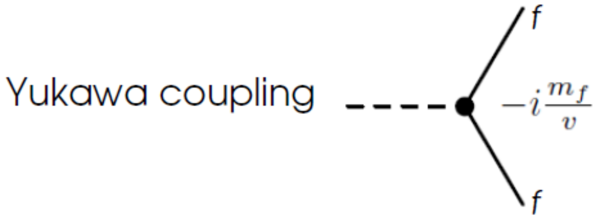
is only fermion which does not have charge in the SM

has extremely small mass

with only left-handed chirality is discovered

Fermion mass in the SM

- In the standard model of particle physics (SM), fermion mass is generated by Yukawa interaction between fermion and higgs.



Dirac mass

$$
\begin{aligned}
m\overline{\psi}\psi &= m\overline{(\psi_L+\psi_R)}(\psi_L+\psi_R) \\
&= \underline{m\overline{\psi_L}\psi_R + m\overline{\psi_R}\psi_L}
\end{aligned}
$$

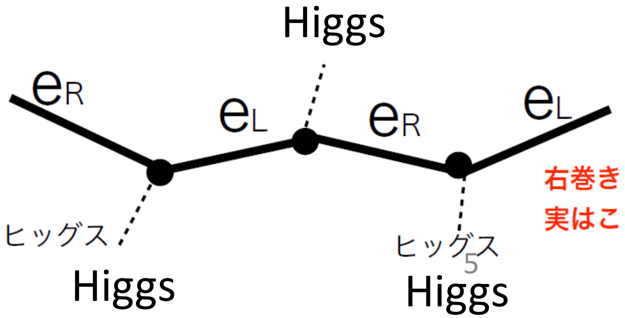
$$\overline{\psi_L}\psi_L = \overline{\psi_R}\psi_R = 0$$

Dirac mass term is described via L-R (chirality) mixing

Note :

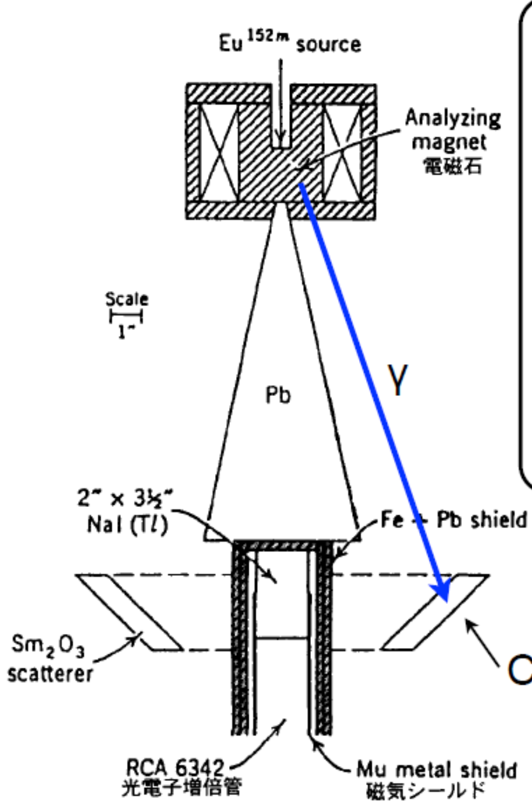
Non-zero mass requires a particle to have both left- and right-handed chirality.

Coupling strength between fermion and higgs is mass.

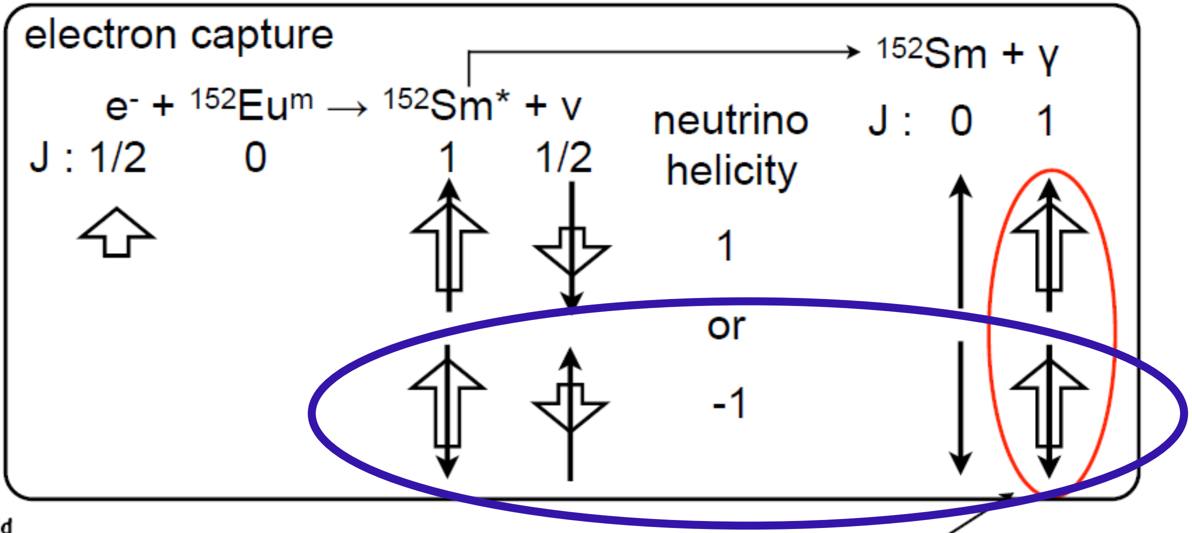


Neutrino helicity

neutrino/anti-neutrino by Goldhaber et.al. (1958)



Coherent scattering of gamma to Sm



electron capture

$e^- + {}^{152}Eu^m \rightarrow {}^{152}Sm^* + \nu \rightarrow {}^{152}Sm + \gamma$

J : 1/2 0 1 1/2

neutrino helicity

1

or

-1

J : 0 1

If you find this gamma polarization which is the same direction as recoil nucleus (${}^{152}Sm$), you can get the neutrino helicity

Neutrino helicity is -1
Left-handed neutrino!!

M. Goldhaber, L. Grodzins, and A. W. Sunyar, Phys. Rev. ***109****, 1015*

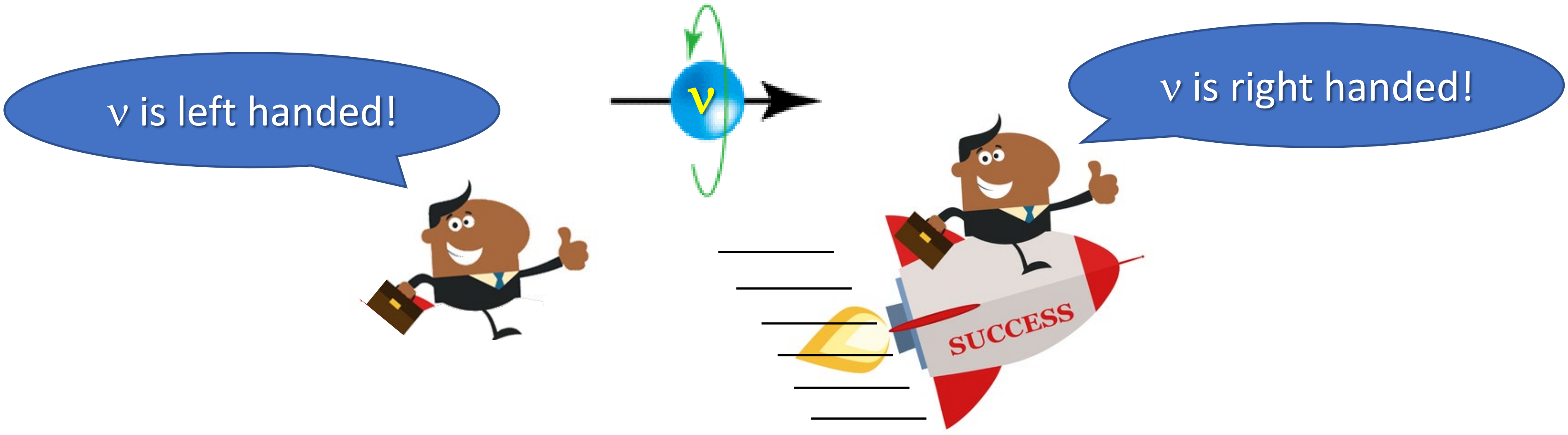
Neutrino mass in the SM

- Right-handed neutrino has not been discovered.
- Dirac mass term can’t be constructed

  only with left-handed state.

$$\boxed{m\overline{\psi_L}\psi_R}$$

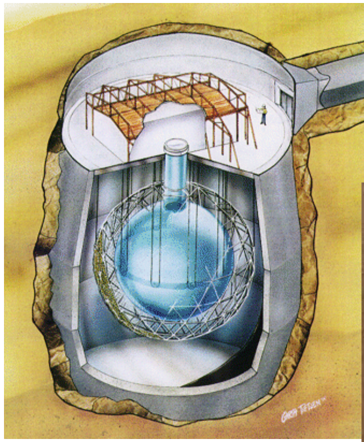
- In other words, if neutrino has mass left-handed can be transformed to right-handed by Lorenz boost.



Neutrino mass was “Zero” in the SM

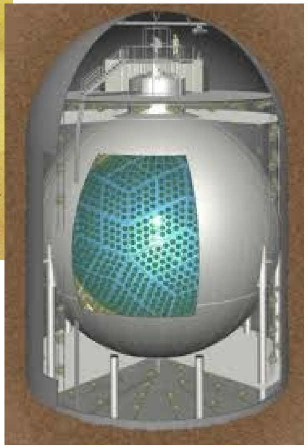
Discovery of neutrino oscillation

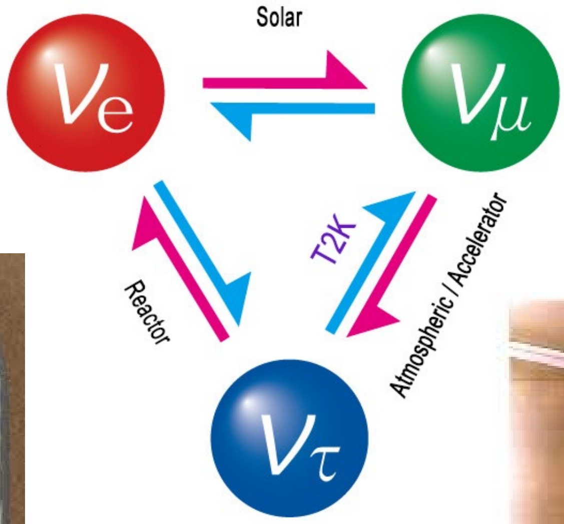
- Neutrino flavor mixing was found in Super-K, SNO and KamLAND…



SNO
(Canada)

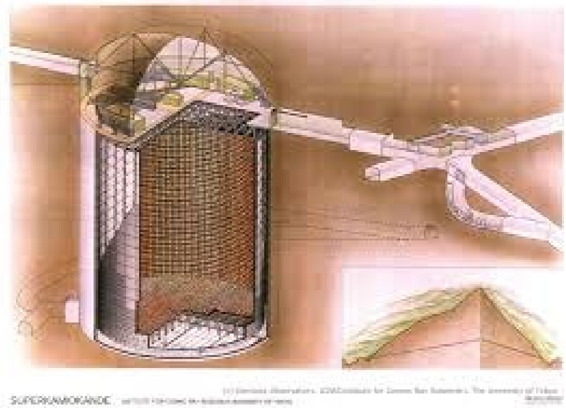
KamLAND
(Japan)





Neutrino oscillation between three generations

Super-Kamiokande
(Japan)



- Neutrino oscillation arises from mixing between the flavor and mass eigenstates of neutrinos.

$$P_{\alpha\to\alpha} = \left|\langle \nu_\alpha | \nu_\alpha(t)\rangle\right|^2 = 1 - \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2[\mathrm{eV}^2]\,L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)$$

Neutrino oscillation revealed the existence of neutrino mass!!

Neutrino mass measurements

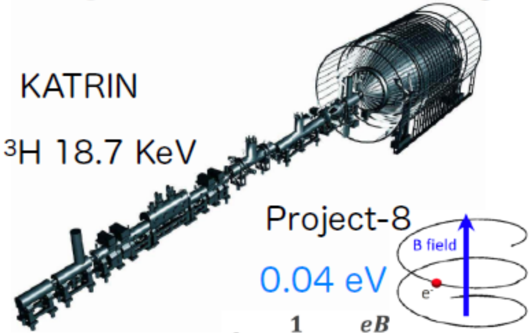
Single beta decay

KATRIN

^{3}H 18.7 KeV

Project-8

0.04 eV



$$f_c = \frac{1}{2\pi}\frac{eB}{(m + E_{kin})}$$

$$\langle m_\beta \rangle^2 = \Sigma\, m_i^2 \, |U_{ei}|^2$$

current limit

< 0.8 eV

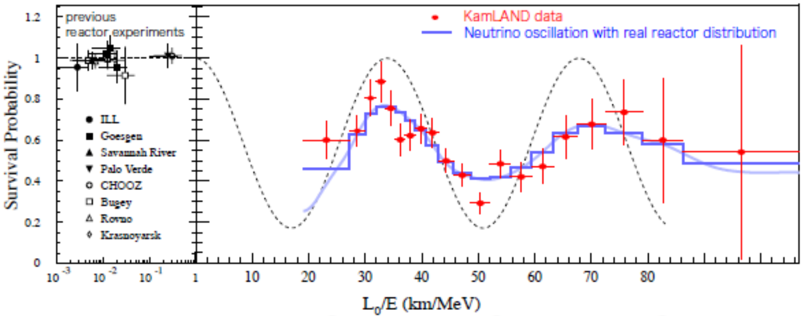
future sensitivity

0.2 eV

m_ν

Neutrino oscillation

solar, reactor, atmospheric, accelerator



$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

precise measurements

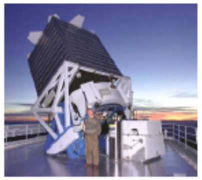
$$\delta m^2 = (7.20 - 7.51) \times 10^{-5}\,\mathrm{eV}^2$$
$$|\Delta m^2| = (2.43 - 2.51) \times 10^{-3}\,\mathrm{eV}^2$$

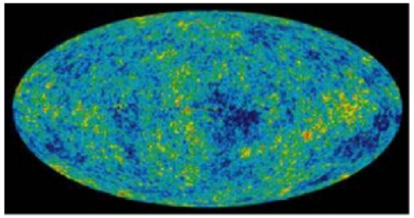
M > 0.06 eV (NO)

M > 0.1 eV (IO)

Cosmology

CMB satellite, galaxy survey, weak gravitational lensing,...





$$M = \Sigma\, m_i$$

< 0.12~0.77 eV

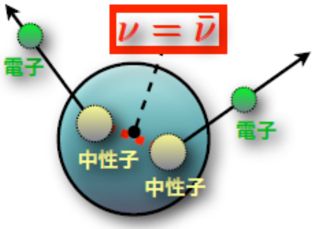
depends on dataset

future precision

0.03 eV

Double beta decay

Ge, Te, Mo, Cd, Ca, Xe, Se, ...

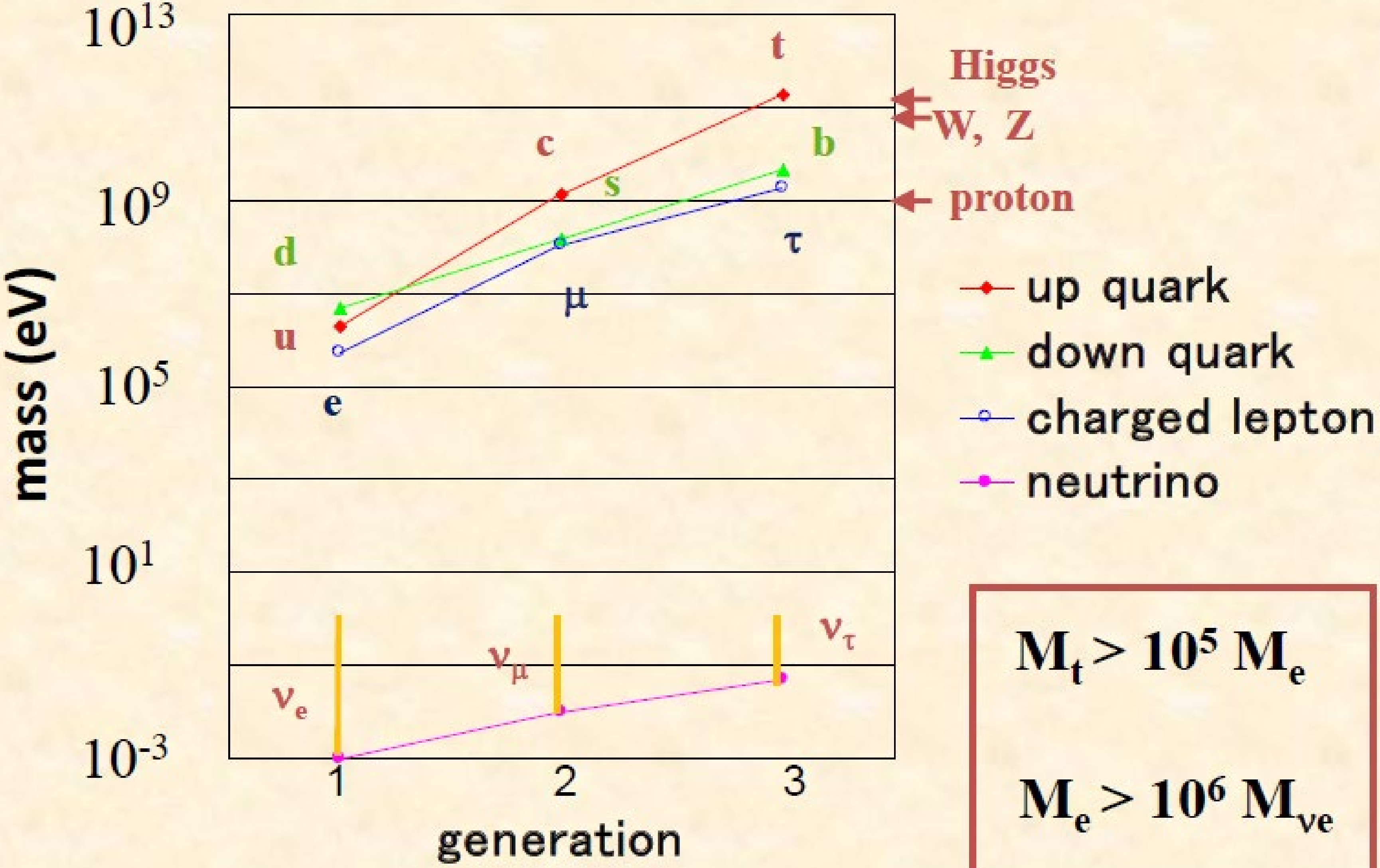


$$\langle m_{\beta\beta} \rangle = |\Sigma\, m_i \, |U_{ei}|^2 \, \varepsilon_i|$$

< ~ 0.1 eV

0.01~0.03 eV

Neutrino mass vs other fermions



$M_t > 10^5 M_e$

$M_e > 10^6 M_{\nu e}$

Majorana neutrino

- Note that, it is possible to construct Dirac mass by assuming the existence of undiscovered right-handed neutrino.
- However, it requires extremely small Yukawa coupling.
- E. Majorana introduced extended Lagrangian including Majorana mass term.

Ettore Majorana

Enrico Fermi said Majorana is one of the geniuses, like Galilei and Newton.

Extended Lagrangian

$$\mathcal{L}_m = -\frac{1}{2} \left(\overline{(\nu_L)^c} \quad \overline{N_R} \right) \begin{pmatrix} m_L & m_D \\ m_D & m_R^* \end{pmatrix} \begin{pmatrix} \nu_L \\ (N_R)^c \end{pmatrix} + \text{h.c.}$$

Dirac mass term:

$$m_D \overline{\nu_R} \nu_L$$

Majorana mass term:

$$m_L \overline{(\nu_L)^C} \nu_L$$

- Neutrino is chargeless, so it can be its own antiparticle.
- Mass is generated via particle-antiparticle mixing .
- In this case, Mass term can be assembled only with left- (right-) handed particles.

Majorana particle = fermion that is its own antiparticle

See-Saw mechanism

Extended Lagrangian

$$\mathcal{L}_m = -\frac{1}{2}\begin{pmatrix} \overline{(\nu_L)^c} & \overline{N_R} \end{pmatrix}\begin{pmatrix} m_L & m_D \\ m_D & m_R^* \end{pmatrix}\begin{pmatrix} \nu_L \\ (N_R)^c \end{pmatrix} + \text{h.c.}$$

Observable masses are eigen values of the mass matrix

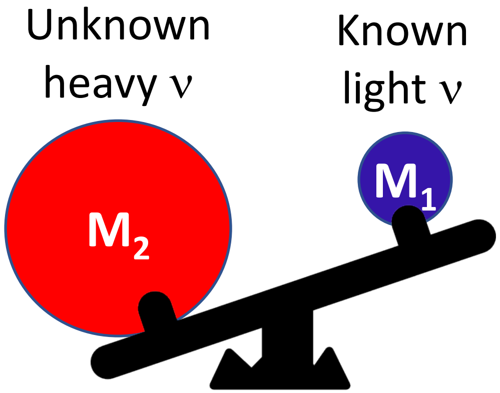
diagonalization

$$M_1, M_2 = \frac{m_L + m_R}{2} \pm \sqrt{\frac{(m_R - m_L)^2}{4} + m_D^2}$$

Let’s assume $m_L=0$, $m_D \sim 10$ GeV and GUT scale ($\sim 10^{16}$ GeV) $m_R >>>>> m_D$

$$M_1 \sim \frac{{m_D}^2}{m_R}, \qquad M_2 \sim m_R$$

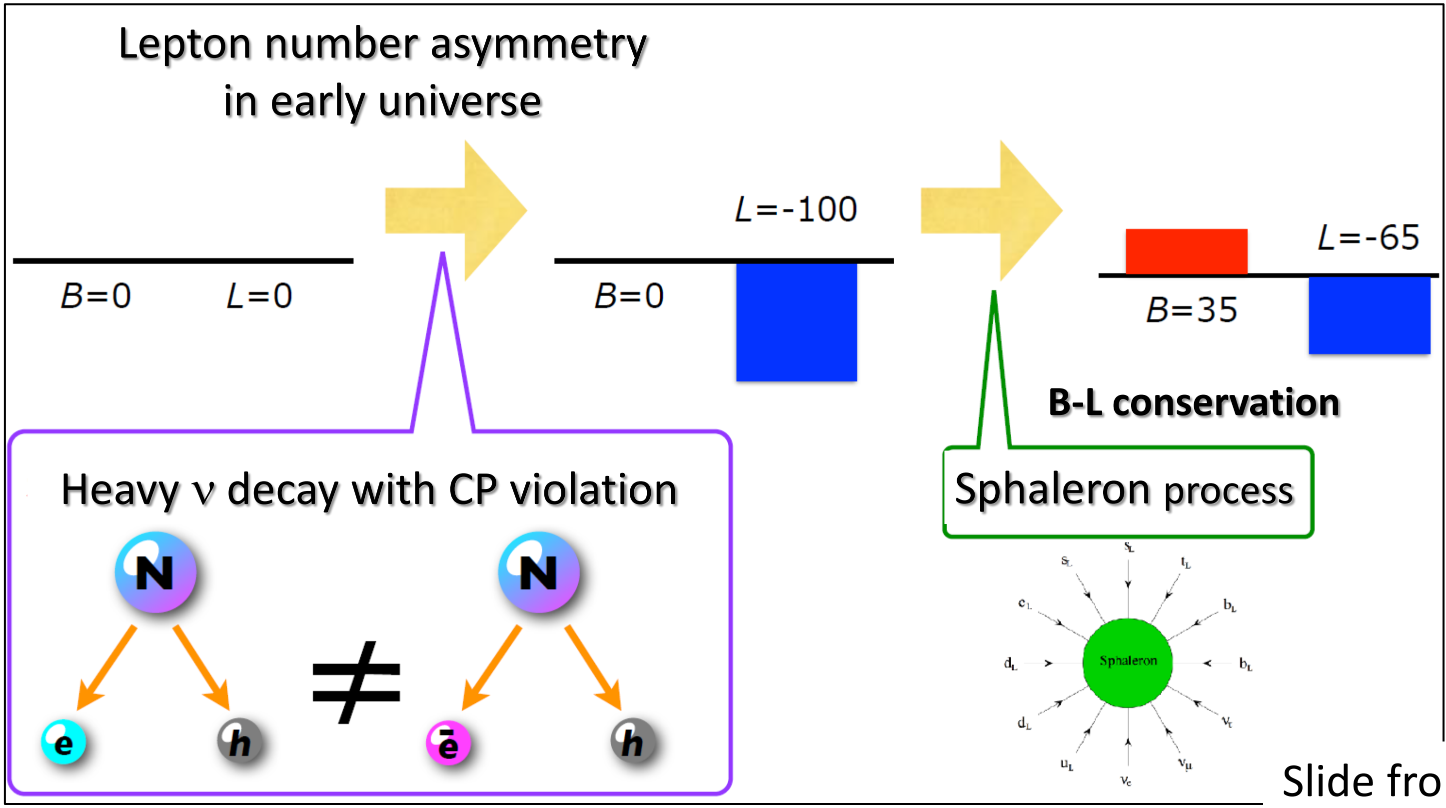
$\sim$ O(meV) $\qquad$ $\sim$ O(GUT scale)



- Small neutrino mass can be naturally explained.
- Right-handed neutrino is not discovered due to its heavy weight. (matches experimental fact.)

Leptogenesis scenario

Matter (baryon) in the universe are generated by neutrino??


Lepton number asymmetry in early universe

Heavy ν decay with CP violation

B-L conservation

Sphaleron process

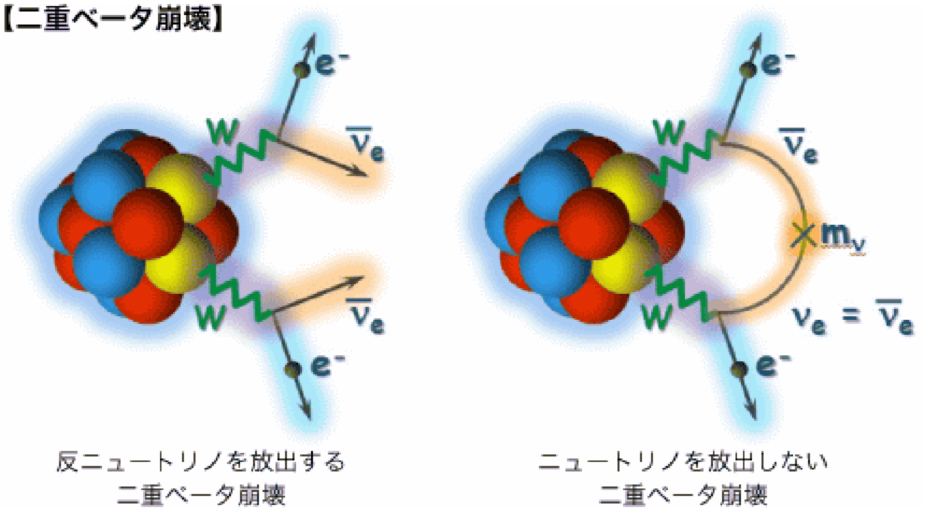
Slide from K. Hamaguchi

- Leptogenesis requires lepton CP-violation and Majorana neutrinos.
- CP-violation is being studied by T2K, and thus we need to investigate the Majorana nature of neutrinos.

Double beta decay

- Neutrino-less double beta decay ($0\nu\beta\beta$) is only practical way to prove Majorana neutrino.

【二重ベータ崩壊】



反ニュートリノを放出する
二重ベータ崩壊

ニュートリノを放出しない
二重ベータ崩壊

theoretical history

1930	light neutral particle (W.Pauli)
1933	β decay theory (E.Fermi)
1935	2ν2β (M.Goeppert-Mayer)
1937	Majorana neutrino (E.Majorana)
1939	0ν2β (W.H.Furry)

W.Pauli

E.Fermi

M.Goeppert-Mayer

E.Majorana

W.H.Furry

$2\nu\beta\beta$: (Z, A) → (Z+2, A) + 2 e^- + 2 ν_e

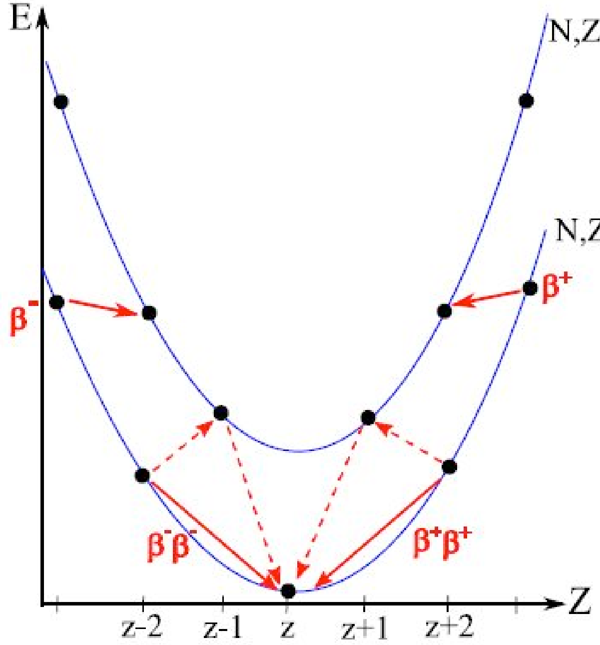
Second order process of weak interaction.

$0\nu\beta\beta$: (Z, A) → (Z+2, A) + 2 e^-

Beyond the SM (lepton number violation) = New physics!

Double beta decay

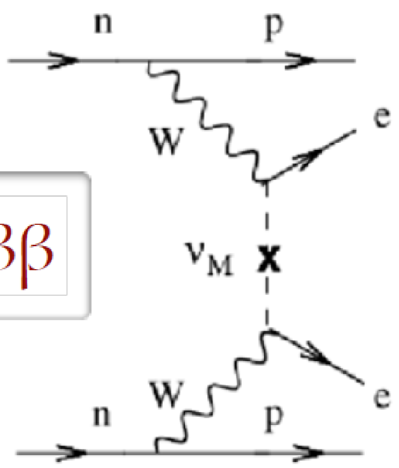
- Double beta decay (DBD) is observable when single beta decay is forbidden.
- Two-neutrino double beta decay is measured in more than 10 isotopes.



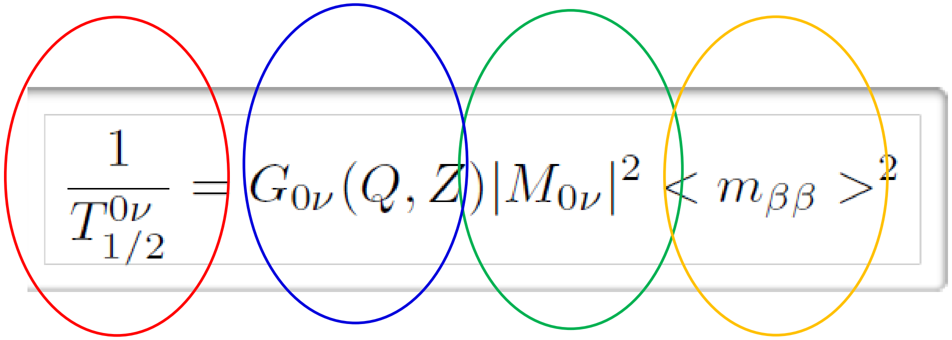
Isotope	Ave. 2ν half-life [yr]	Discovery year
^{48}Ca	$(5.3^{+1.2}_{-0.8}) \times 10^{19}$	1996
^{76}Ge	$(1.88 \pm 0.08) \times 10^{21}$	1990
^{82}Se	$(0.93 \pm 0.05) \times 10^{20}$	1987
^{130}Te	$(7.91 \pm 0.21) \times 10^{20}$	2003
^{136}Xe	$(2.18 \pm 0.05) \times 10^{21}$	2011
^{150}Nd	$(8.4 \pm 1.1) \times 10^{18}$	1993

“Average and recommended half-life values for two-neutrino double beta decay: upgrade-2019”,
A.S. Barabash, AIP Conf.Proc. 2165 (2019) 1, 020002

Half-life of Neutrino-less DBD



$0\nu\beta\beta$



Measurable

Calculable but uncertainty is big

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q,Z)|M_{0\nu}|^2 < m_{\beta\beta} >^2$$

Accurately calculable

We want to know!!

$G_{0\nu}(Q,Z)$: Phase space factor
$M_{0\nu}$: Nuclear matrix element

Effective ββ mass

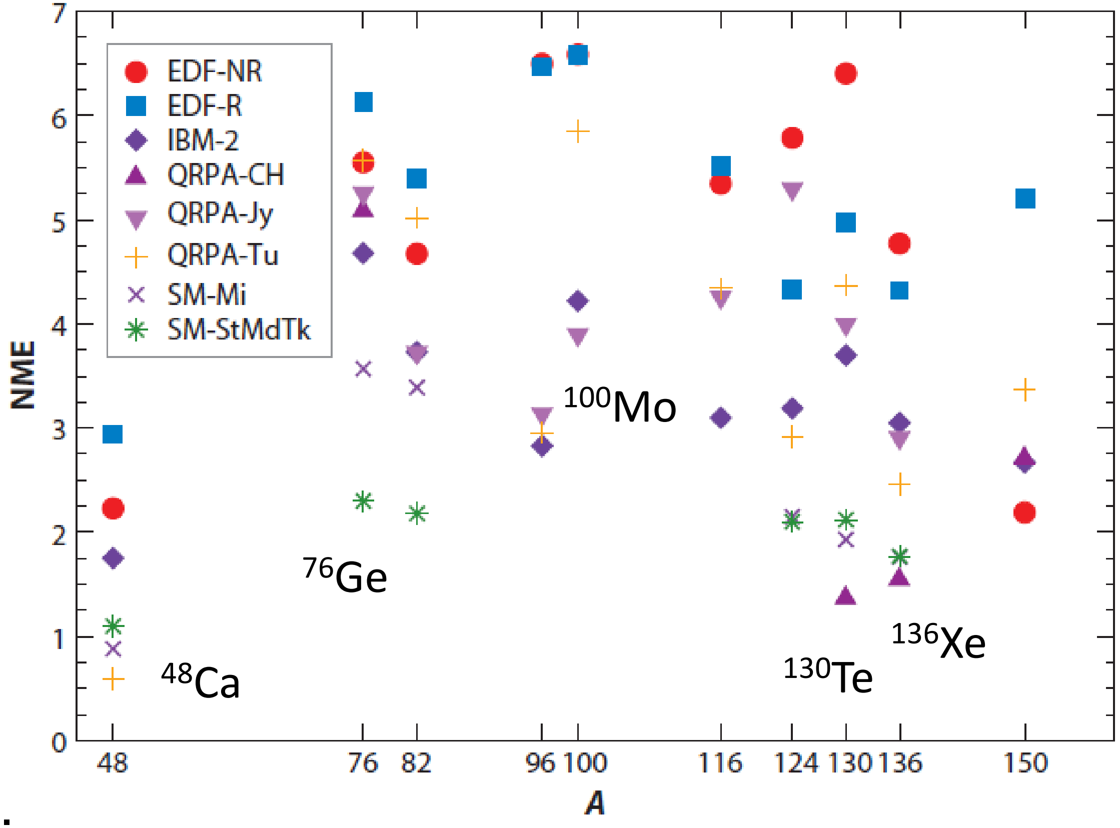
$$\langle m_{\beta\beta} \rangle = \sum_i^3 U_{ei}^2 m_i$$

$$M_{0\nu} = g_A^2 M_{0\nu}^{GT} - g_V^2 M_{0\nu}^F$$

Nuclear Matrix Element

- Factor 2-3 discrepancy between models
- Uncertainty comes from difficulty to consider interaction between nucleons and many body system etc..
- Measurement by multiple target nucleus needed to reduce model uncertainty.

Engel and Menéndez, Rep. Prog. Phys. 80, 046301 (2017)



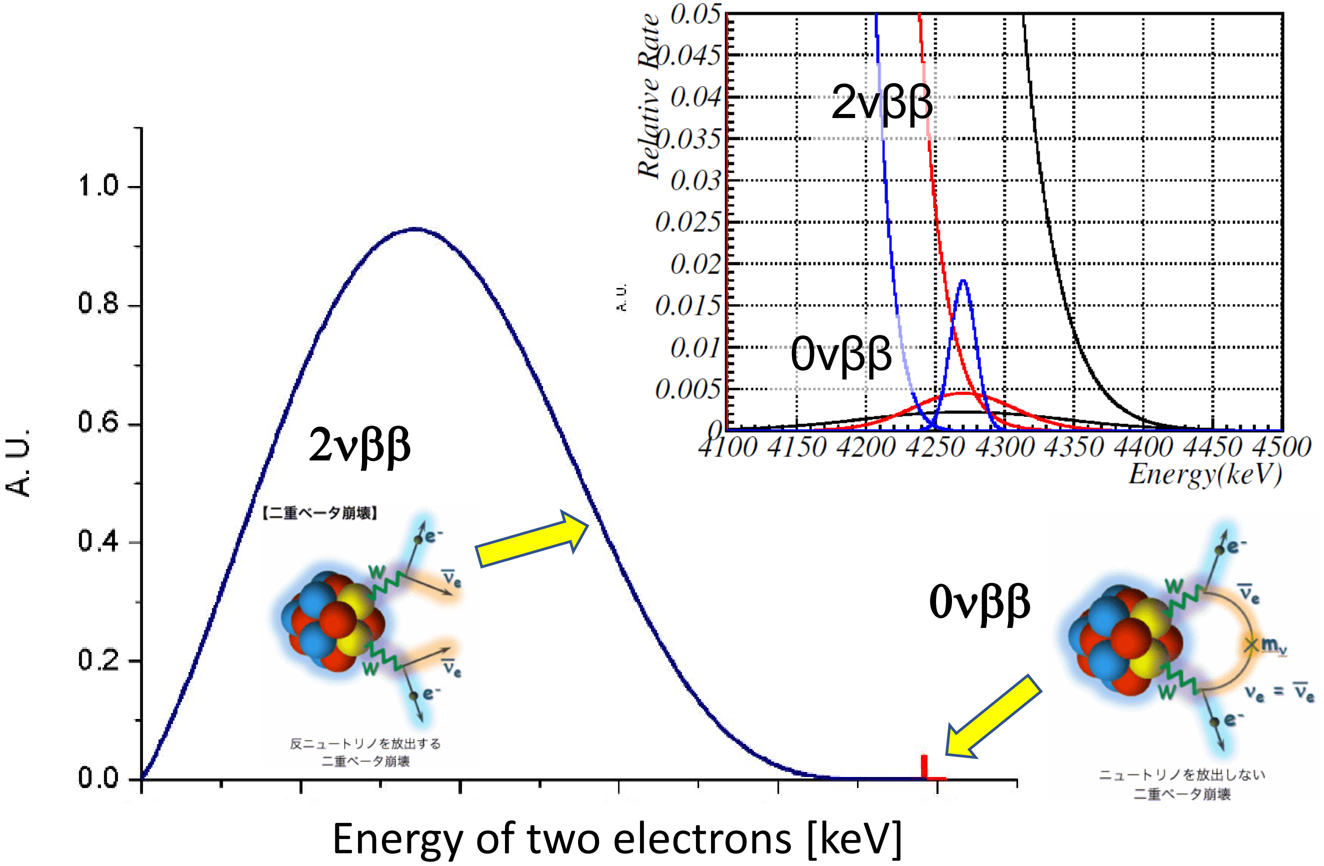
A representative compilation of nuclear matrix element calculations with an unquenched $g_A = 1.27$ for different isotopes (see Reference 87, and references therein, for details). Abbreviations: EDF, energy-density functional; IBM, interacting boson model; NME, nuclear matrix element; QRPA, quasi-particle random-phase approximation; SM, Standard Model.

Double beta candidate nuclei

Isotope	**Q-value [keV]**	**Natural Abundance**	**Good / Bad**	**Experiment**
^{48}Ca	**4268**	0.19%	Large Q, Small N.A.	CANDLES
^{150}Nd	3367	5.7%		NEMO-3
^{96}Zr	3348	2.8%		
^{100}Mo	3034	9.4%		NEMO-3
^{82}Se	2996	8.7%		Super-NEMO
^{116}Cd	2814	7.5%		
^{130}Te	2527	**34.1%**	Large N.A.	CUORE, SNO+
^{136}Xe	2458	8.9%	Easy to enrich	EXO, KL-Zen
^{124}Sn	2288	5.8%		
^{76}Ge	2039	7.6%	Ge semiconductor	HDM, GERDA
^{110}Pd	2018	7.5%		

Energy spectrum of DBD

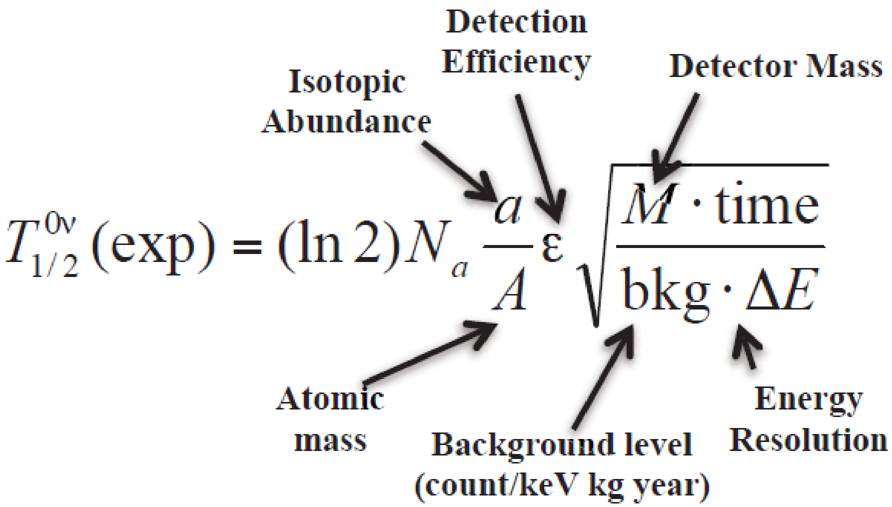
- In the search for “neutrino-less double beta decay", “two-neutrino double beta decay" is the background.
- It is necessary to separate them with high energy resolution.



Energy resolution
4%(FWHM)
2.8%
0.5%

Sensitivity of DBD experiment

For sizeable background case:



Detection Efficiency

Isotopic Abundance

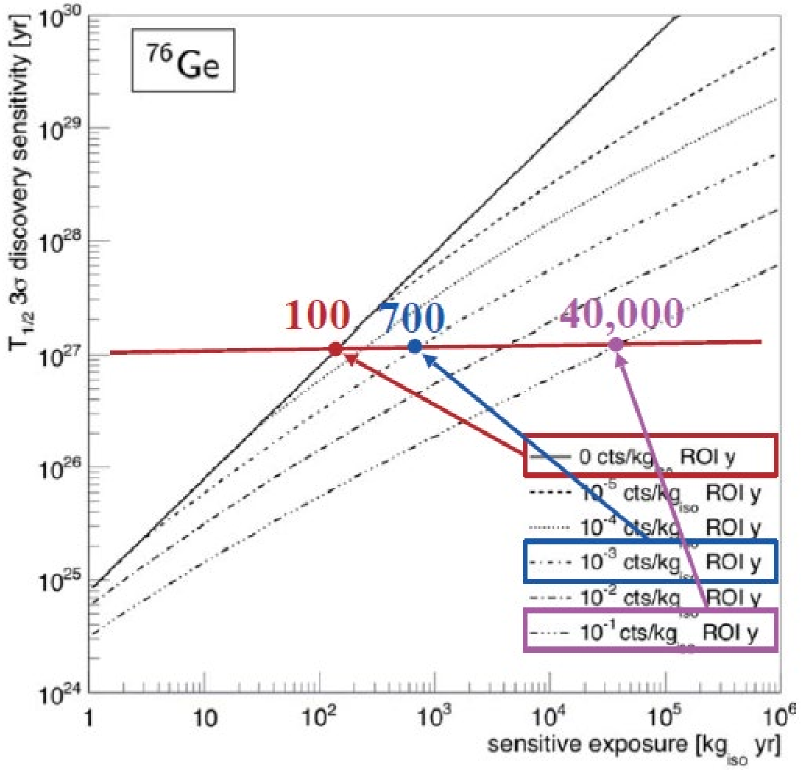
Detector Mass

$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \sqrt{\frac{M \cdot \mathrm{time}}{\mathrm{bkg} \cdot \Delta E}}$$

Atomic mass

Background level (count/keV kg year)

Energy Resolution



For "zero background" case:

(Expected background events in ROI < 1 for given $M \times$ time)

$$T_{1/2}^{0\nu}(\exp) = (\ln 2) N_a \frac{a}{A} \varepsilon \frac{M \cdot \mathrm{time}}{n_{CL}}$$

Slide from
Y. H. Kim @Taup2019

How to increase sensitivity

$$(T_{1/2}^{0\nu}) \propto \begin{cases} a\,M\,\varepsilon t & \text{background free,} \\ a\varepsilon\sqrt{\dfrac{Mt}{B\,\Delta E}} & \text{with background,} \end{cases}$$

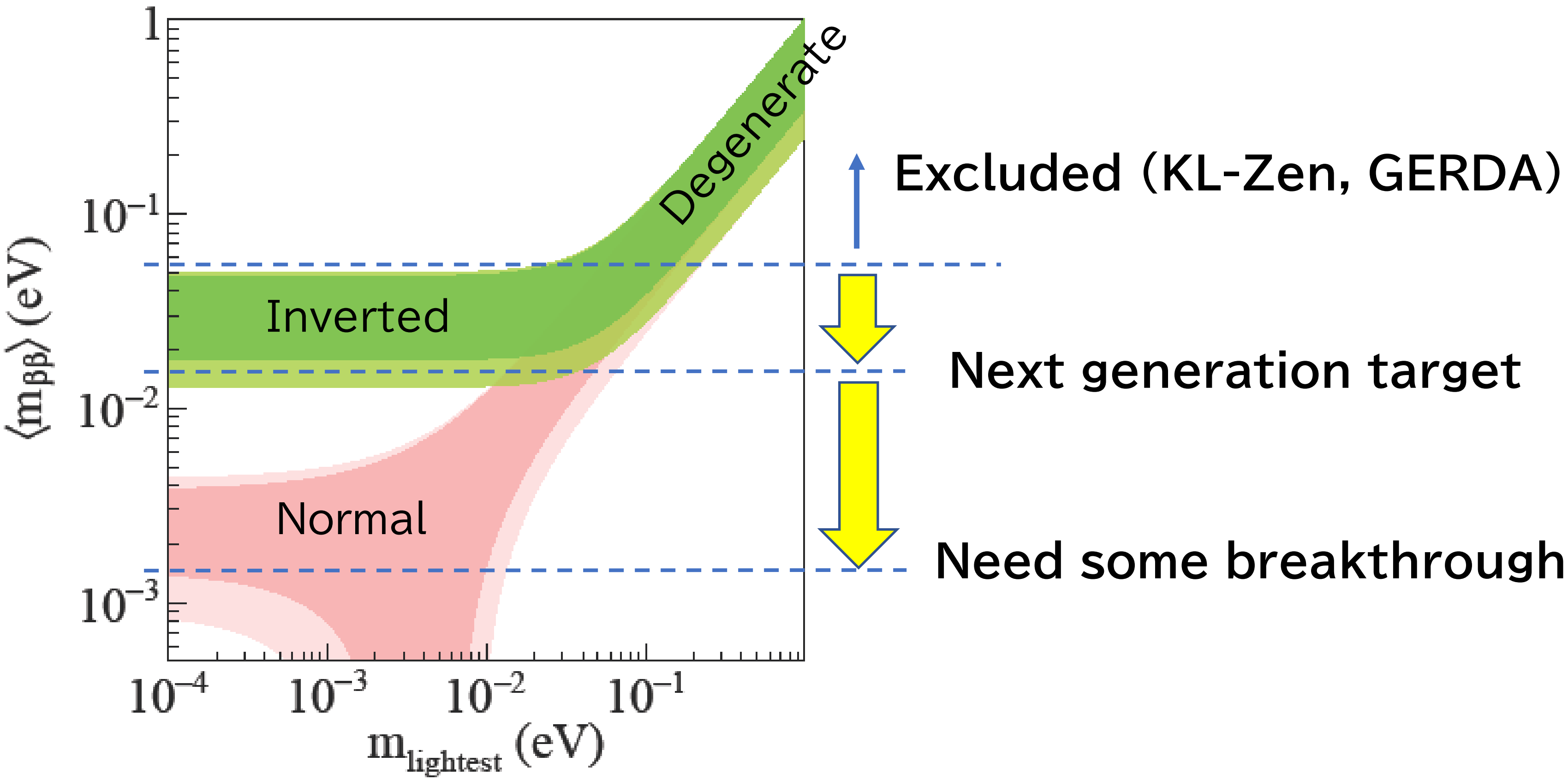
I. Volume
- Large detector mass
- Enrichment of ββ isotope

II. Background
- Low radioactive material
- Background ID by PSD, Active VETO, Heat/Light ratio etc.

III. Energy resolution
- Detector technology dependence
- Semiconductor $\gtrsim$ Bolometer $>$ TPC $>$ Scintillator

Sensitivity for $\langle m_{\beta\beta} \rangle$

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q,Z)|M_{0\nu}|^2 < m_{\beta\beta} >^2$$

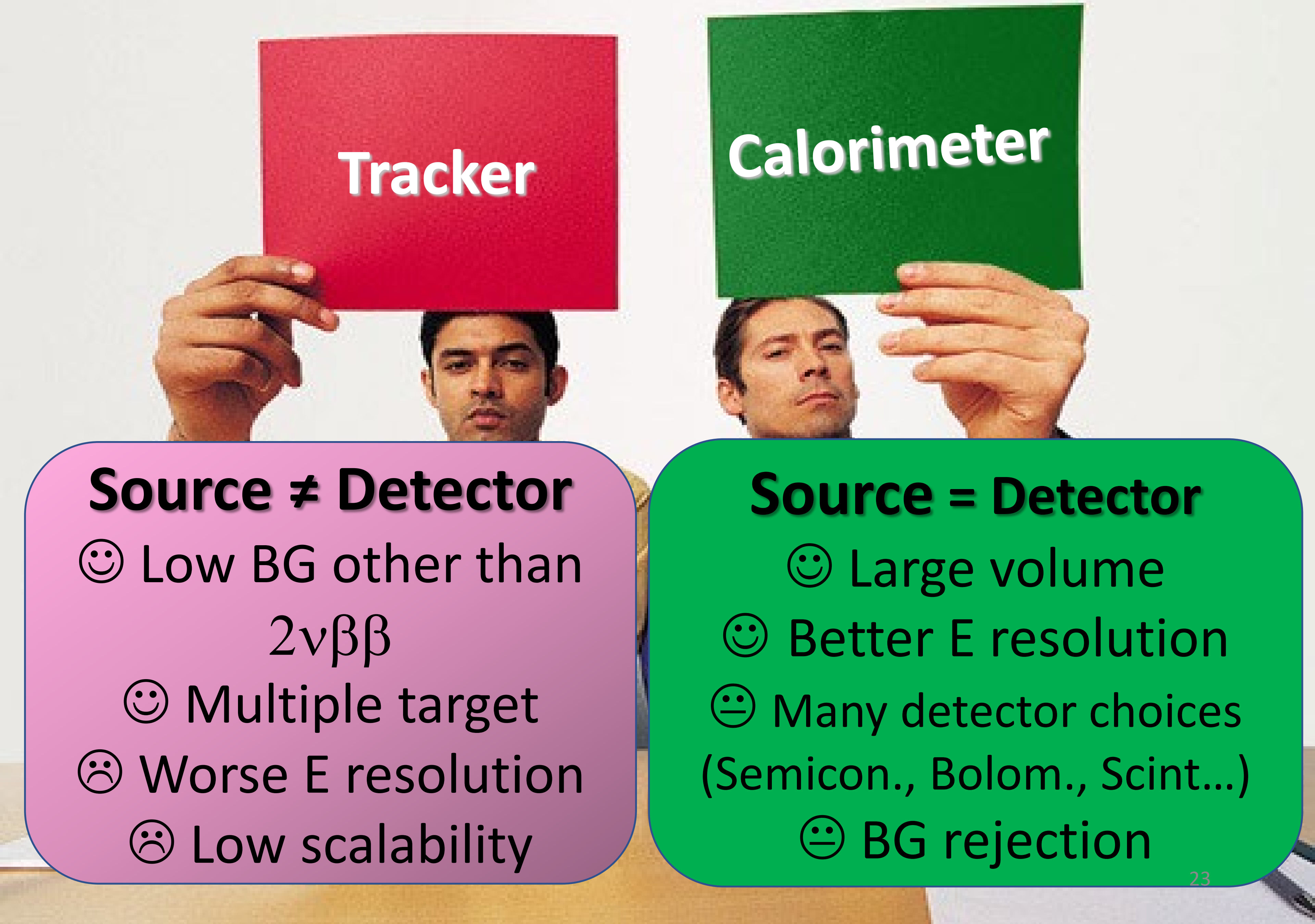


Excluded (KL-Zen, GERDA)

Next generation target

Need some breakthrough

We have two possible choices!!



Source ≠ Detector

☺ Low BG other than $2\nu\beta\beta$

☺ Multiple target

☹ Worse E resolution

☹ Low scalability

Source = Detector

☺ Large volume

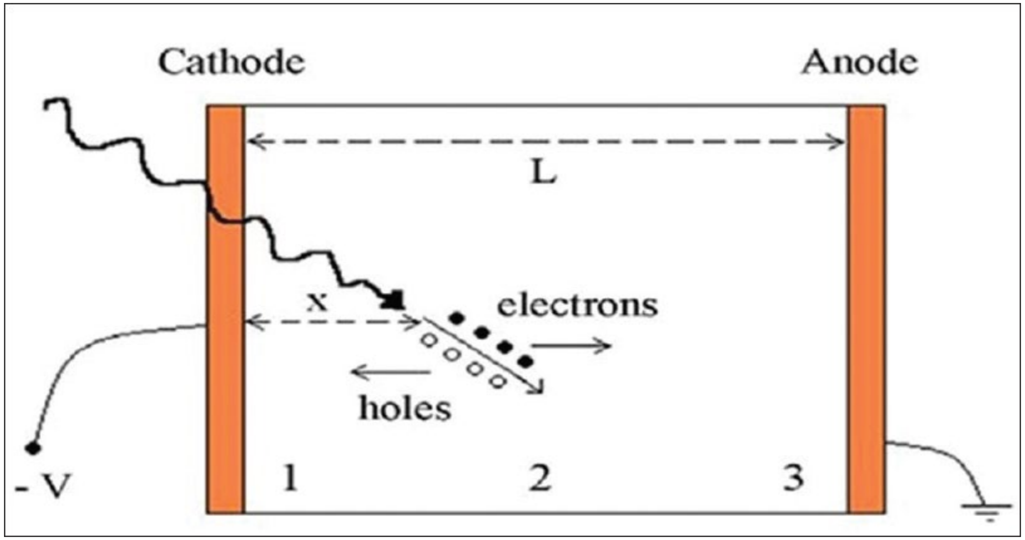
☺ Better E resolution

😐 Many detector choices (Semicon., Bolom., Scint…)

😐 BG rejection

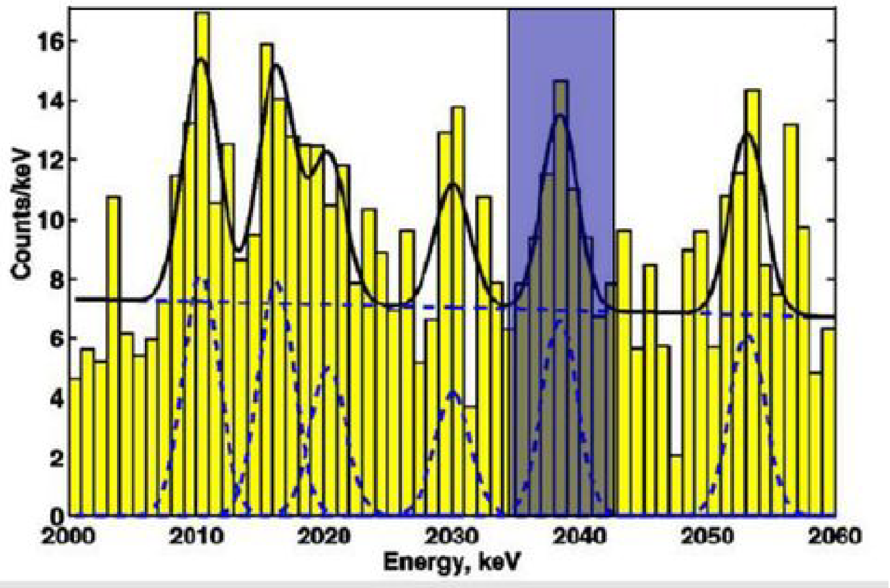
Semiconductor

- Electron-hole pairs, generated by radiation, are swept toward the appropriate electrode by the electric field.
- Ge semiconductor detector including ^{76}Ge isotope has been used for DBD experiment taking advantage of its excellent energy resolution.

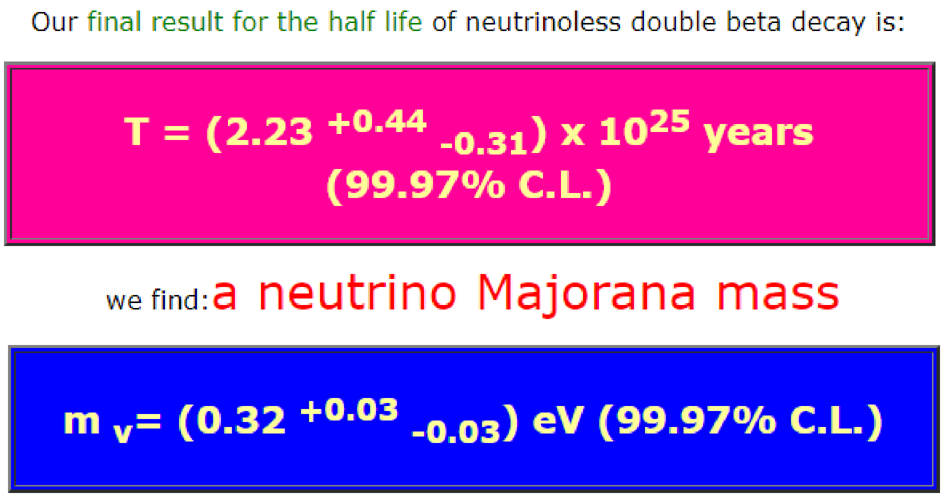


- CdZnTe or CMOS are also the choice for future DBD experiment.
- However, they are still under early feasibility study stage.

Heidelberg-Moscow



- The Heidelberg-Moscow Experiment was operated with 10.9 kg Ge enriched to 86% in the ββ-emitter ^{76}Ge.
- The experiment was located at the Gran Sasso Laboratory in Italy.
- Part of collaboration claimed a detection of 0νββ in 2001 (KK claim).
- This measured half-life was excluded by many experiment later.



Our final result for the half life of neutrinoless double beta decay is:

$T = (2.23^{+0.44}_{-0.31}) \times 10^{25}$ years
(99.97% C.L.)

we find: a neutrino Majorana mass

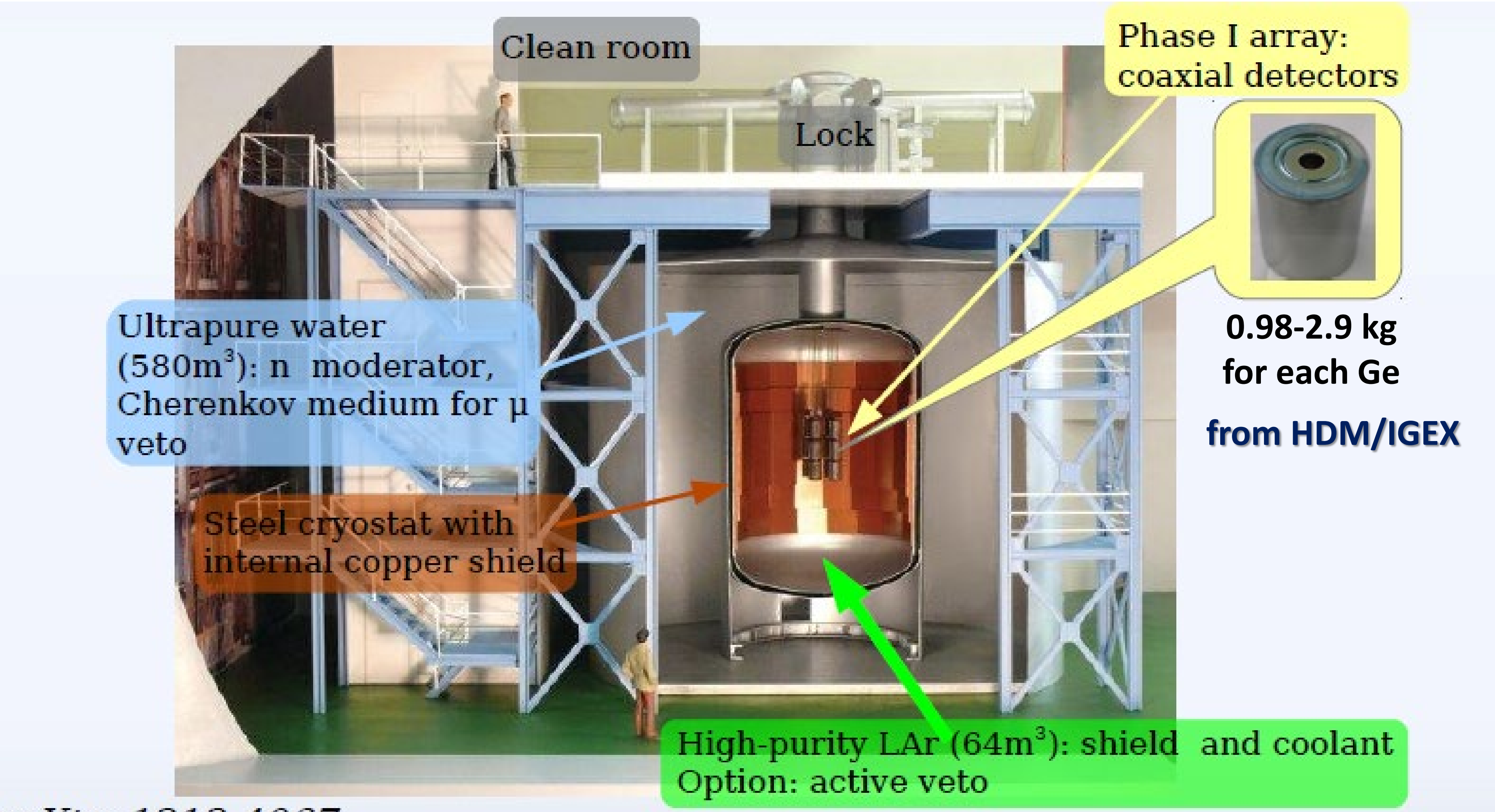
$m_{\nu} = (0.32^{+0.03}_{-0.03})$ eV (99.97% C.L.)

Heidelberg-Moscow	
Technology	Ge semiconductor
Site	Gran Sasso
Volume	10.9 kg
$T_{1/2}^{0\nu}$ limit	1.9×10^{25} yr

GERDA

GERmanium Detector Array

@ Gran Sasso



Clean room

Lock

Phase I array: coaxial detectors

0.98-2.9 kg for each Ge

from HDM/IGEX

Ultrapure water ($580m^3$): n moderator, Cherenkov medium for μ veto

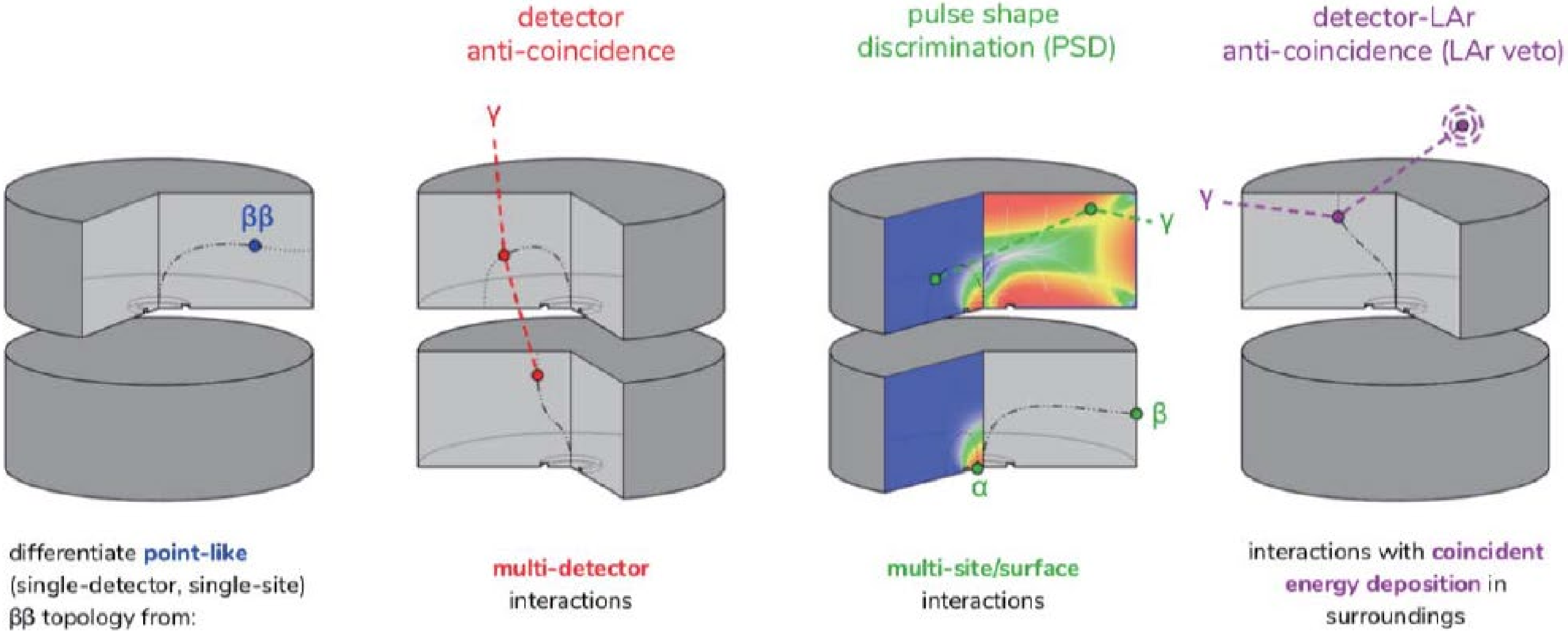
Steel cryostat with internal copper shield

High-purity LAr ($64m^3$): shield and coolant
Option: active veto

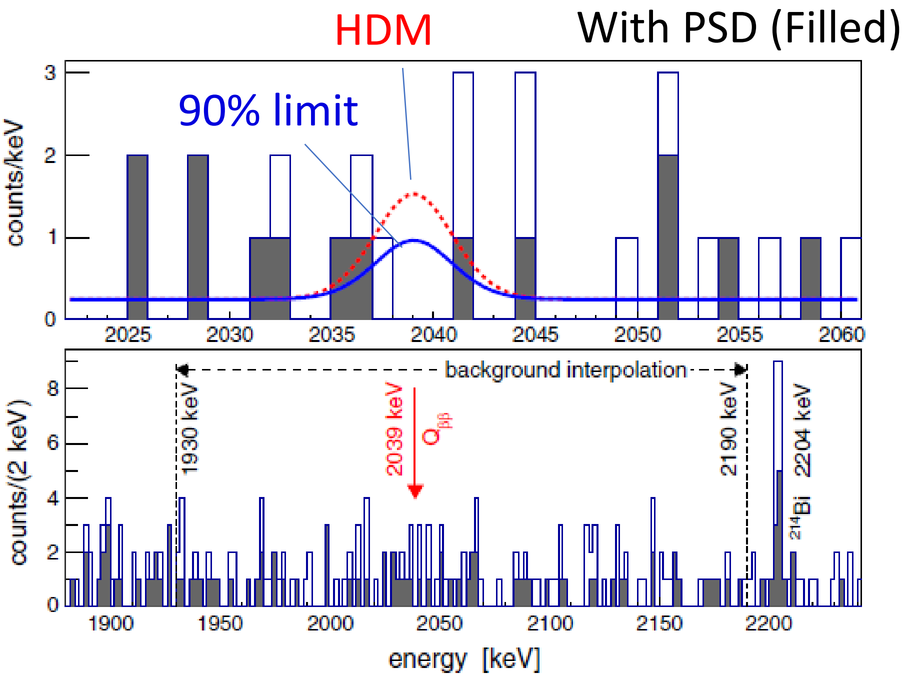
arXiv: 1212.4067

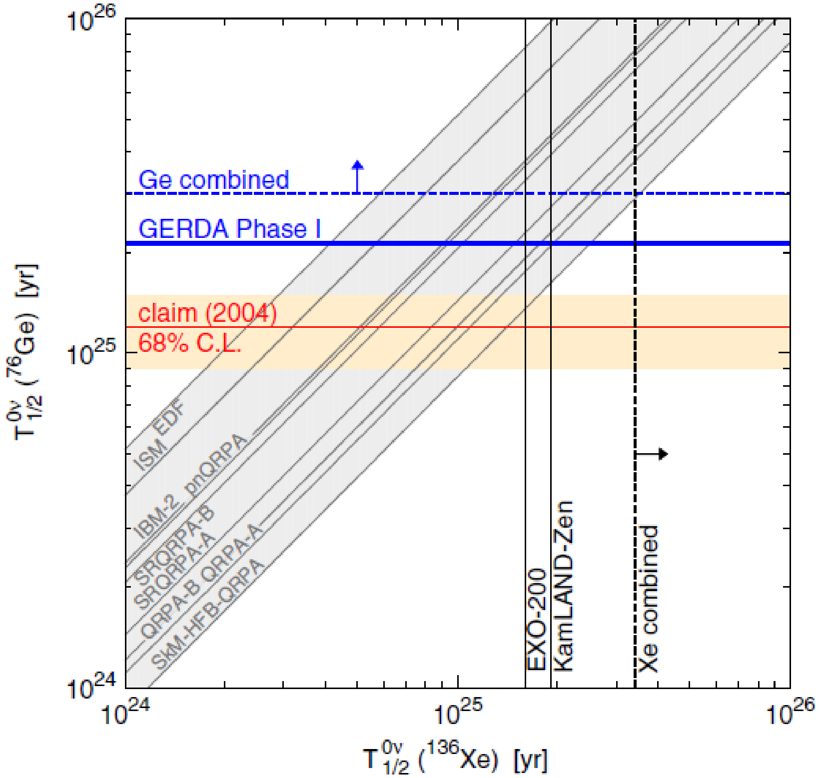
- **Phase I : 18 kg of enriched Ge (~86%) from 2011**
- **Phase II: Added 20 kg of enriched Ge from 2015**

Low BG techniques in GERDA



GERDA Phase-I





$T^{0\nu}_{1/2}$ < 2.1 × 10^{25} yr (21.6 kg)

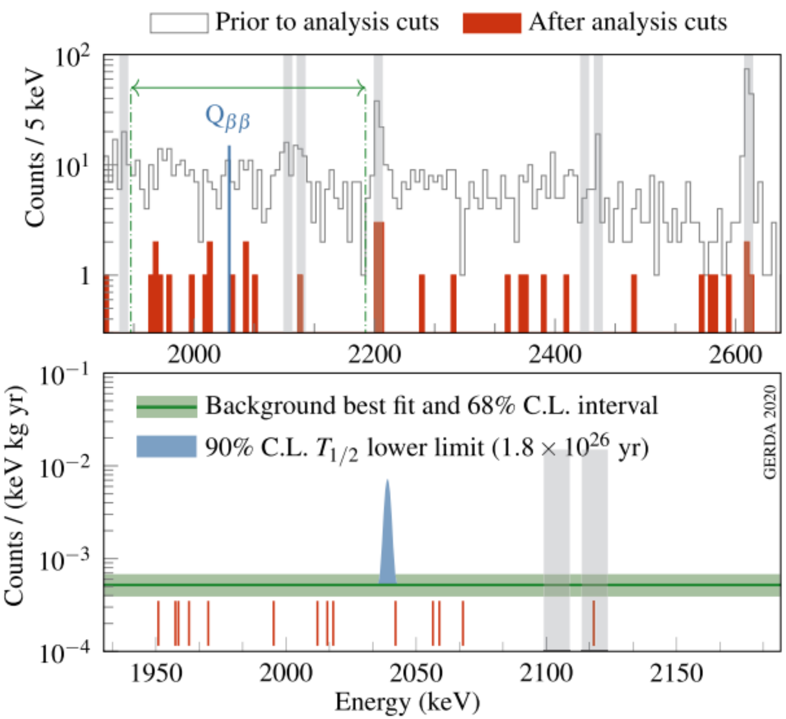
$T^{0\nu}_{1/2}$ < 3.0 × 10^{25} yr (past combined) → $<m_{\beta\beta}>$ < 0.16 – 0.25 eV

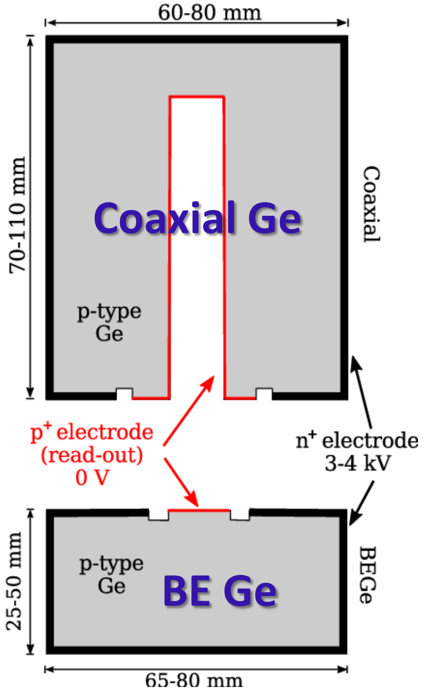
The GERDA-I result refuted the KK-claim of 0νββ observation.

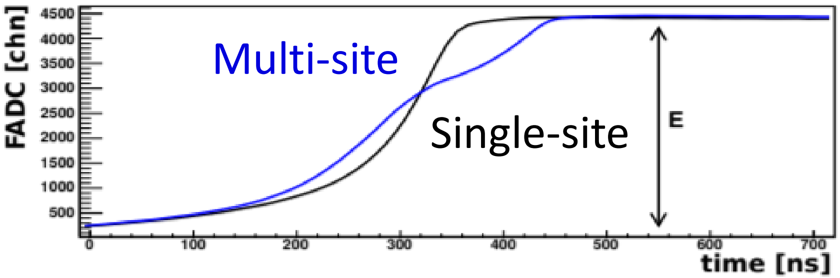
Agostini M, et al. *Phys. Rev. Lett.* 111:122503 (2013)

GERDA Phase-II

- Added totally 20 kg of new Ge detectors.
- Improved BG level by
  - ✓ Broad Energy Ge detector,
  - ✓ Better light collection of LAr veto,
  - ✓ Low radioactivity of detector components.
- Typical energy resolution of 3-4 keV (FWHM) @$Q_{\beta\beta}$.







Good PSD and Good energy resolution in BEGe.

Final result of GERDA

$$T_{1/2}^{0\nu} > 1.8 \times 10^{26}\ \text{yr (combined)}$$

$$\rightarrow \langle m_{\beta\beta} \rangle < 79 - 180\ \text{meV}$$

Agostini M, et al. *Phys. Rev. Lett.* 125:252502 (2020)

GERDA Results

GERDA	Phase-I	Phase-II
Technology	Enriched Ge semiconductor	
Site	Gran Sasso	
E res @$Q_{\beta\beta}$ FWHM	4-6 keV (Coaxial)	3-4 keV (BEGe)
BG [/keV/kg/yr]	2×10^{-2}	5.2×10^{-4}
Size	17.8 kg	35.8 + 9 kg
$T_{1/2}^{0\nu}$ limit	3.0×10^{25} yr	1.8×10^{26} yr

LEGEND

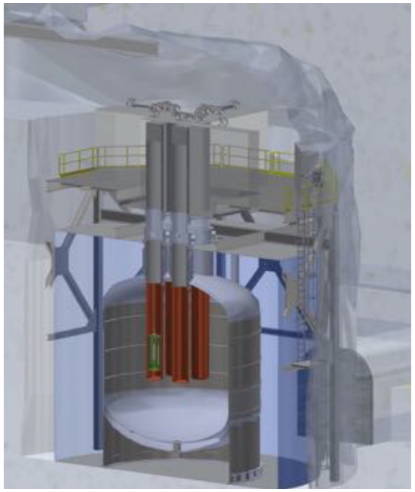
- ➢ GERDA and Majorana join forces to start LEGEND experiment!

LEGEND-200:

- 200 kg, upgrade of existing GERDA infrastructure at Gran Sasso
- 2.5 keV FWHM resolution
- Background goal

  < 0.6 cts/(FWHM t yr)

  < $2\text{x}10^{-4}$ cts/(keV kg yr)
- Now in commissioning, physics data starting in 2022



Sensitivity $T_{1/2}^{0\nu}$ ~ 10^{27} yr

future

LEGEND-1000:

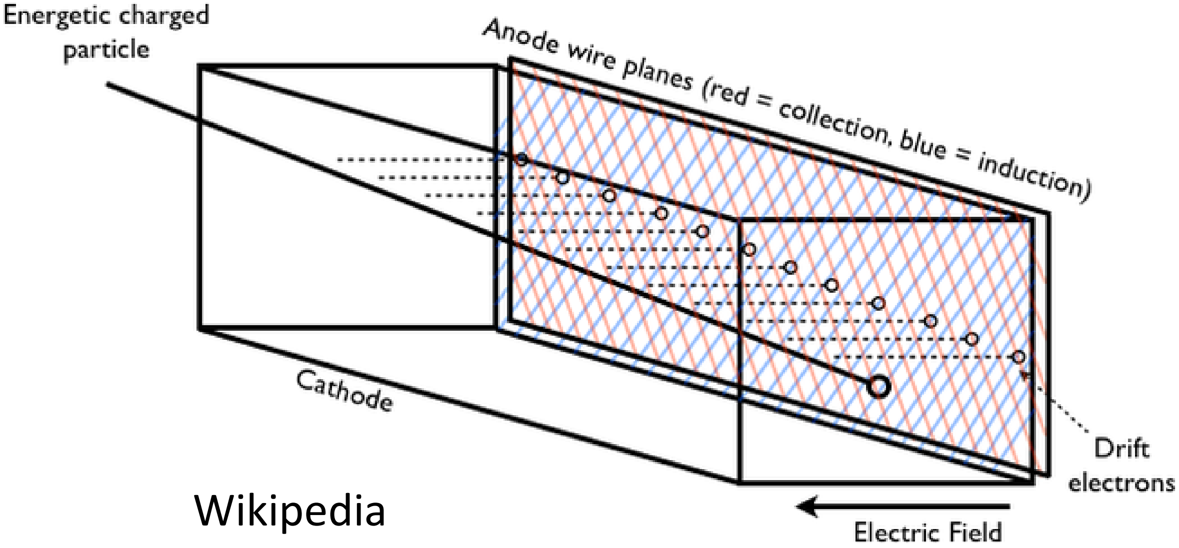
- 1000 kg, staged via individual payloads (~400 detectors)
- Timeline connected to review process
- Background goal <0.025 cts/(FWHM t yr),<$1\text{x}10^{-5}$ cts/(keV kg yr)
- Location to be selected

Sensitivity $T_{1/2}^{0\nu}$ ~ 10^{28} yr

future

Time projection chamber

- Time projection chamber (TPC) is an attractive choice of $0\nu\beta\beta$ search.
- Good scalability and background rejection capability.
- Ionization + Scintillation. Particle ID by signal ratio.
- Liquid TPC offer large density and gas TPC offer tracking.

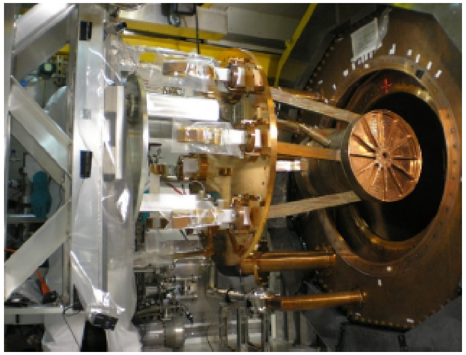


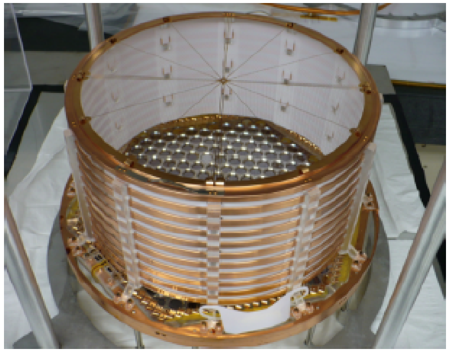
Wikipedia

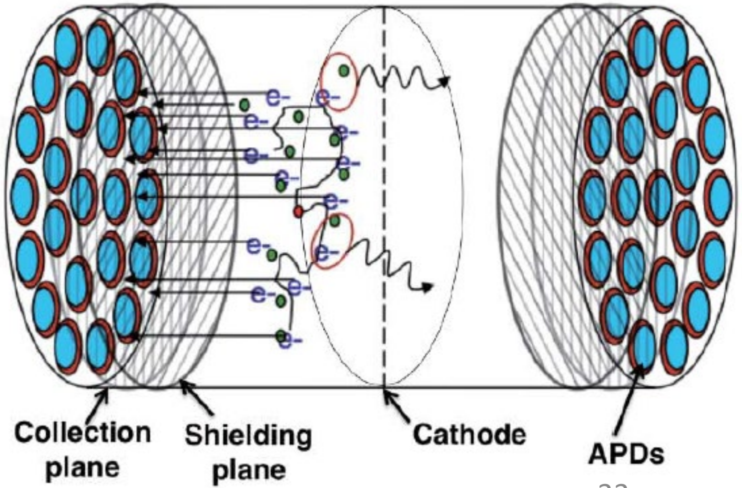
EXO-200

Enriched Xenon Observatory

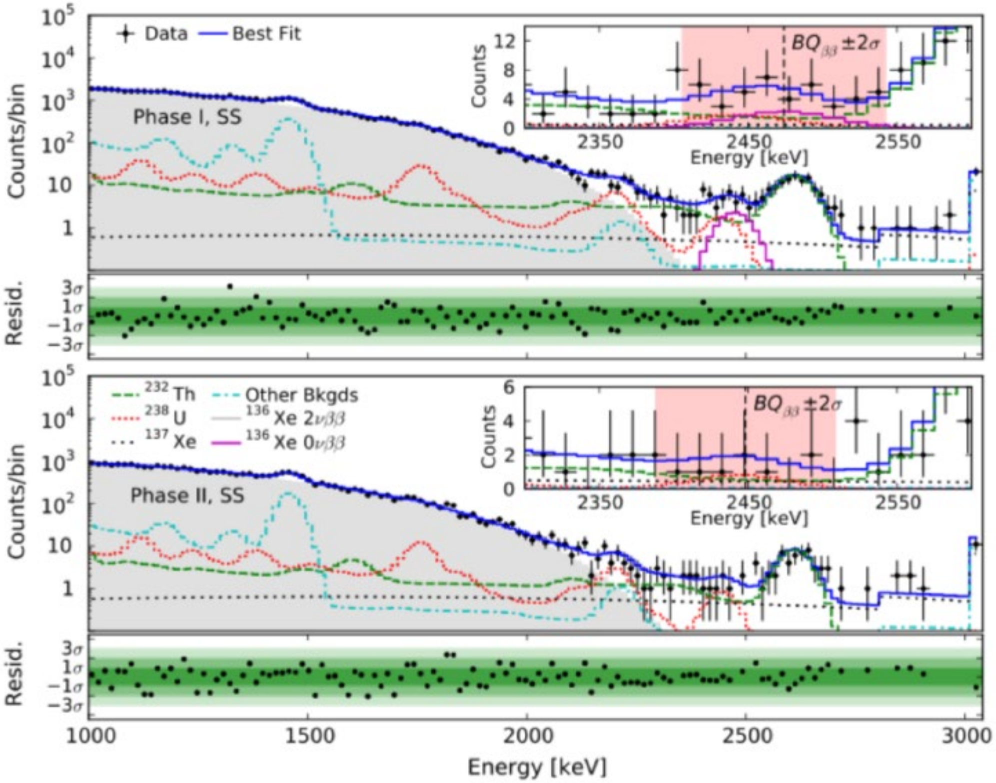
- EXO-200 is a prototype project located Waste Isolation Pilot Plant (WIPP) in US.
- Liquid Xe TPC to search for $0\nu\beta\beta$ of ^{136}Xe (80% enriched ~200 kg).
- Event reconstructed using two signals
  - Ionization signal drifted to crossed wire planes
  - Scintillation (175 nm) collected by APD





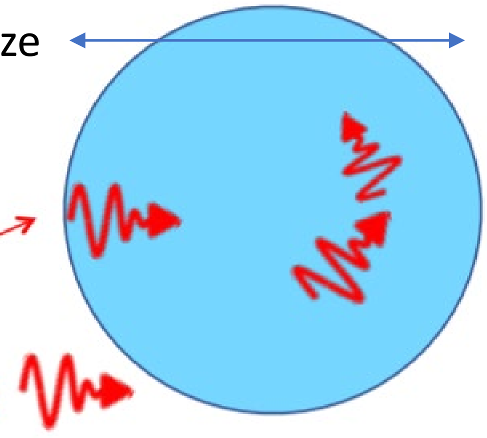


EXO-200 results



EXO-200	Sensitivity	Limit, 90%CL
2012	0.7×10^{25} yr	1.6×10^{25} yr
2014	1.9×10^{25} yr	1.1×10^{25} yr
2018	3.7×10^{25} yr	1.8×10^{25} yr

LXe self-shielding:



40cm size

2.5MeV γ attenuation length: 8.5cm:

EXO-200	
Technology	Liq. Xe TPC
Site	WIPP
E resolution	2.9% FWHM @$Q_{\beta\beta}$
BG /keV/kg/Yr	1.6×10^{-3}
Volume	~200 kg
$T_{1/2}^{0\nu}$ limit	1.8×10^{25} yr

Phys. Rev. Lett. 120, 072701 (2018)

NEXT

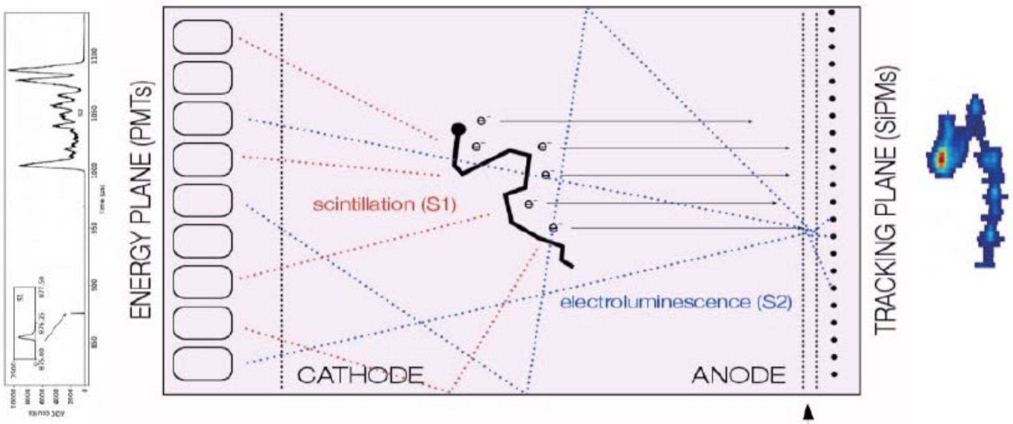
Neutrino Experiment with a Xenon TPC

The NEXT TPC Concept

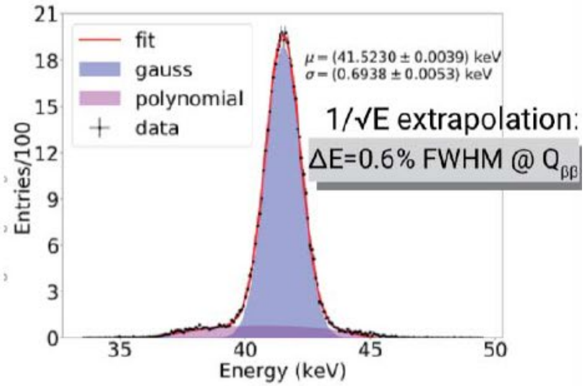
^{136}Xe

15 bar gas

Gas TPC with 2 dedicated readout planes

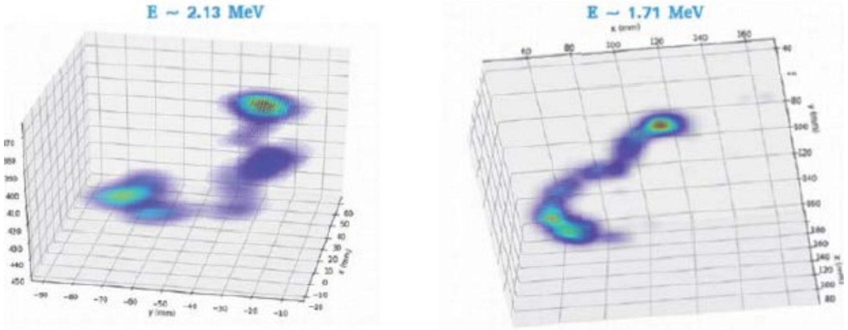


EL: linear gain, no avalanche fluctuations: optimize ΔE



1/√E extrapolation:

ΔE=0.6% FWHM @ $Q_{\beta\beta}$



NEXT-100

2022-2025

- Background measurement
- 0νββ search

NEXT-HD

2026?

- 0νββ search through inverted ν mass ordering

NEXT-BOLD

- Barium tagging for bgr-free experiment

future

BG level : 5 × 10^{-4} /keV/kg/Yr

Sensitivity : $T^{0\nu}_{1/2}$ ~ 10^{27} yr

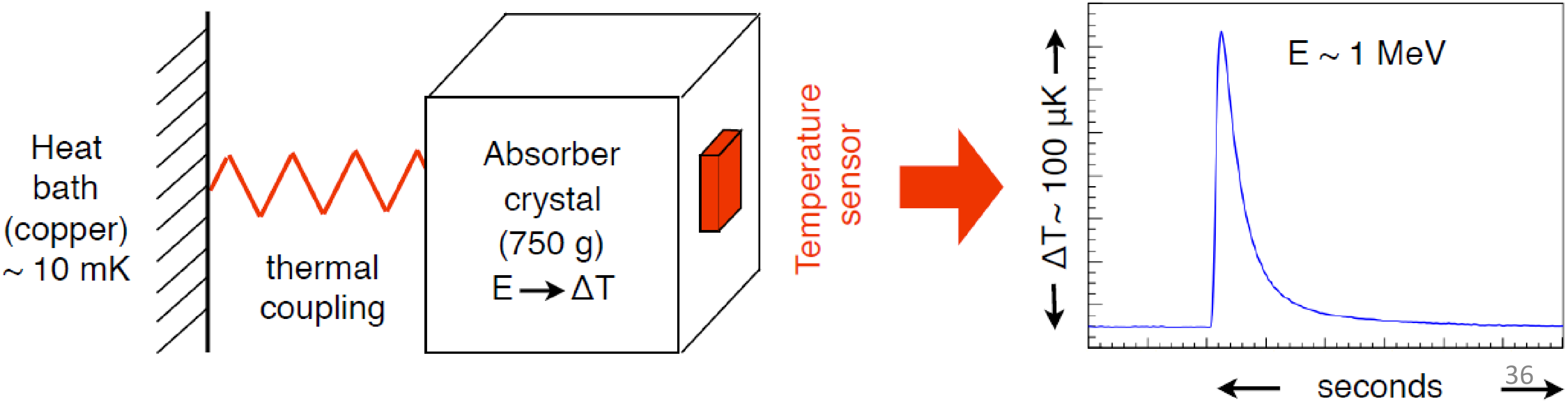
M. Sorel @Neutrino2022

Bolometer

- The bolometric technique was first proposed for $0\nu\beta\beta$ searches in 1984*.

*Fiorini E, Niinikoski TO. *Nucl. Instrum. Methods A* 224:83 (1984)

- Operated at ~10 mK.
- The typical rise in temperature is of the order of ~0.1 mK per MeV of deposited energy.
- Due to high statistics of phonon counting, good energy resolution can be achieved comparable to that of semiconductor.
- Extremely low temperature makes it difficult to develop a large size detector.

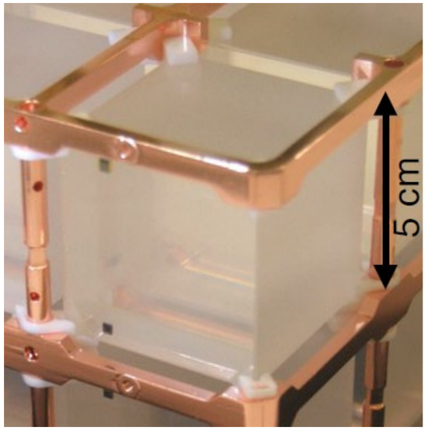


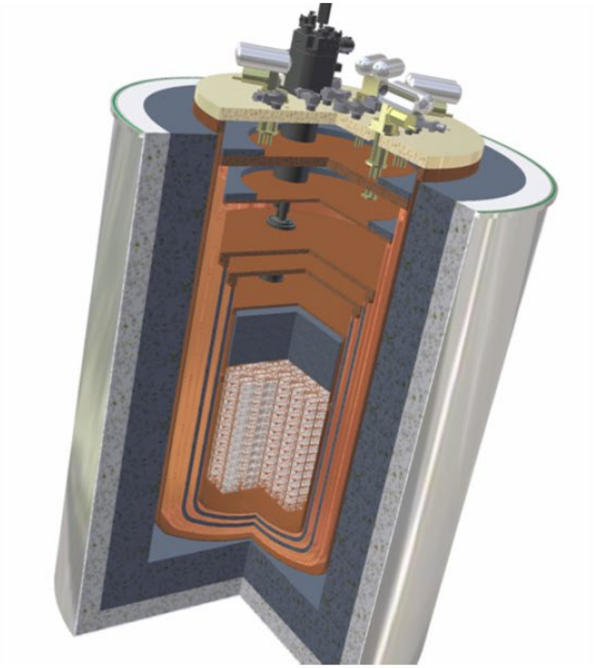
CUORE

Cryogenic Underground Observatory for Rare Events

@Gran Sasso

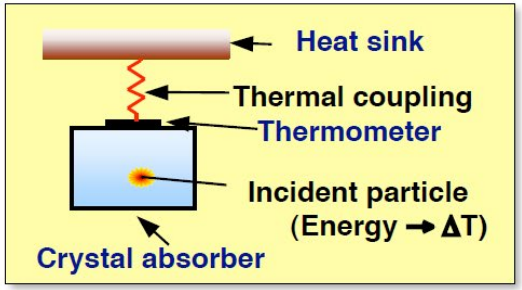
- Bolometer detector using TeO_2 crystals.



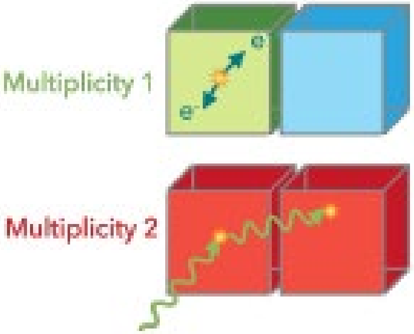


19 towers

988 detectors
741 kg of TeO_2
204 kg of ^{130}Te



Heat sink
Thermal coupling
Thermometer
Incident particle
(Energy → ΔT)
Crystal absorber

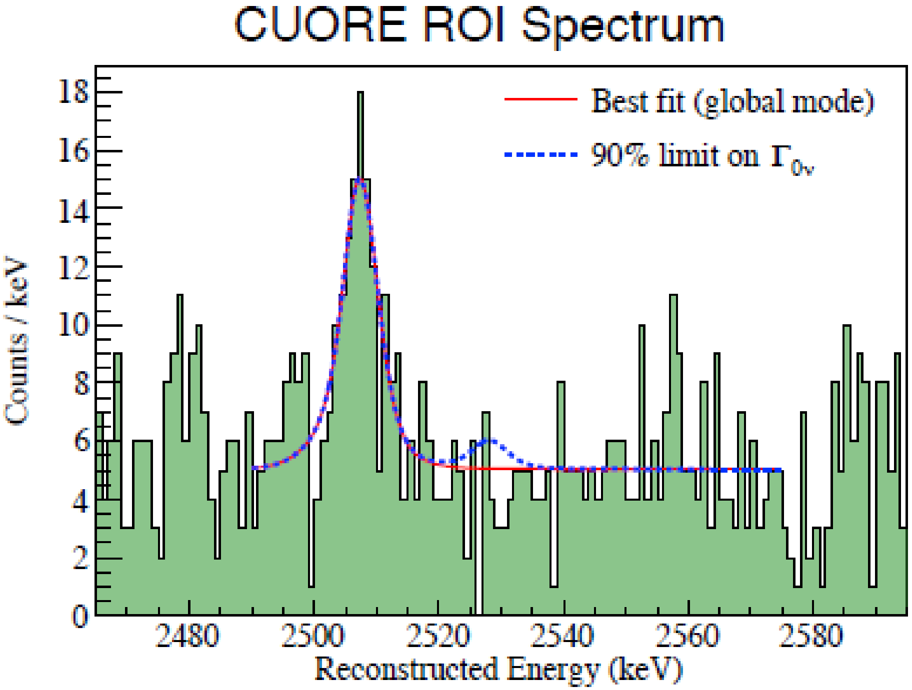


Powerful ^3He-^4He dilution refrigerator
cooling power: 5 μW at 10 mK

Result of CUORE

- $0\nu\beta\beta$ search taking advantage of large natural abundance of ^{130}Te (34%) and good energy resolution (~7 keV @$Q_{\beta\beta}$).
- Peak at ~2500 keV is from ^{60}Co.

D. Q. Adams et al., Phys. Rev. Lett. 124, 122501



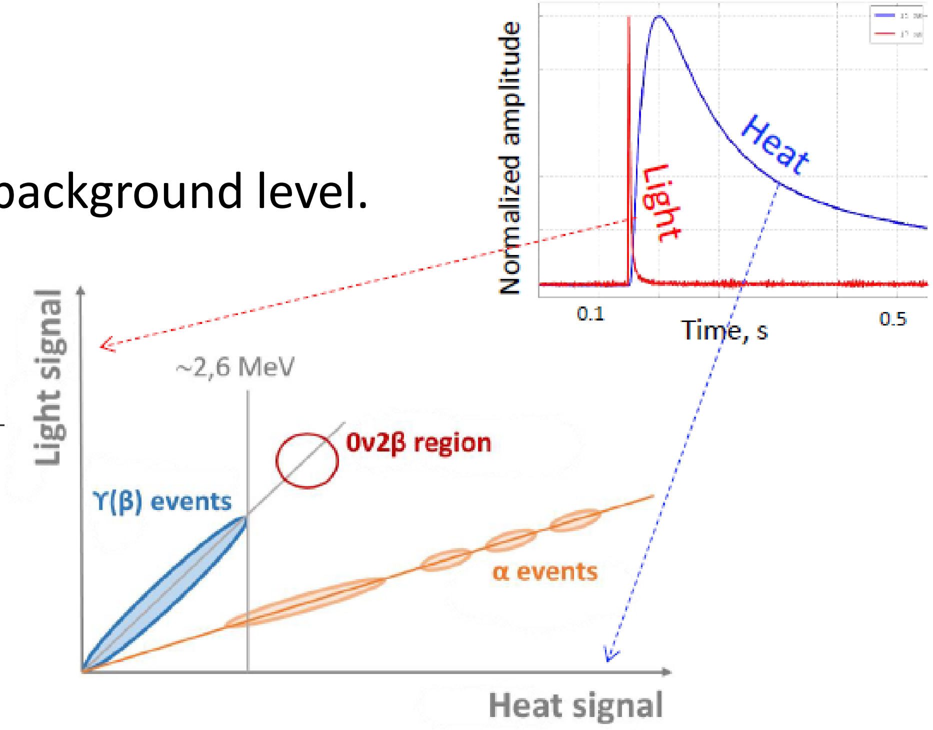
CUORE	
Technology	Bolometer TeO_2
Site	Gran Sasso
E resolution	7 keV FWHM @$Q_{\beta\beta}$
BG /keV/kg/Yr	1.38×10^{-2}
Volume	741 kg
$T_{1/2}^{0\nu}$ limit	3.2×10^{25} yr

→ $<m_{\beta\beta}> < 75 – 350$ meV

CUPID

- Upgrade with PID in order to reduce background level.

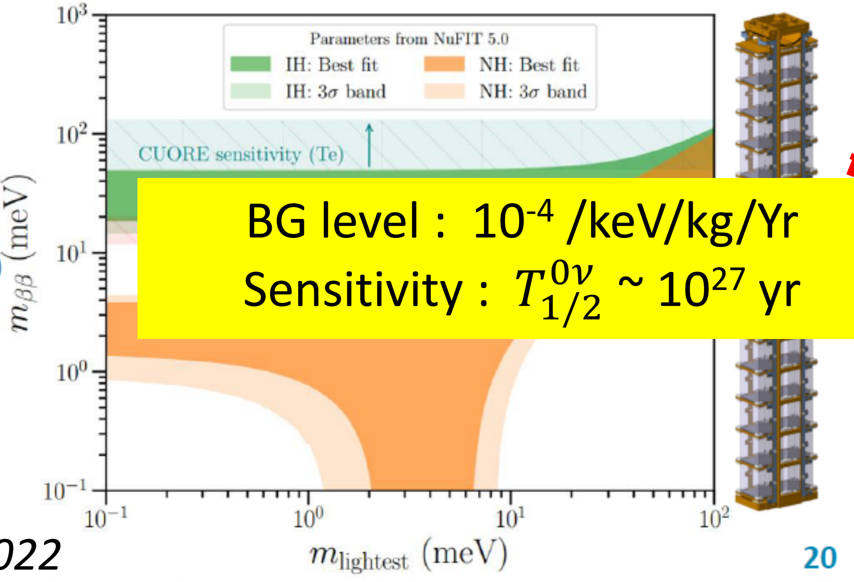
E. Armengaud et al, Phys. Rev. Lett. 126, (2021) 181802



CUPID: baseline

- **$Li_2{}^{100}MoO_4$ scintillating bolometers**
- α rejection using light signal
- Enrichment > 95%
- 1596 crystals and 240 kg of ^{100}Mo
- FWHM <10 keV at $Q_{\beta\beta}$ (3034 keV)

Background goal: 10^{-4} cnts/(keV kg yr)
Discovery sensitivity at 3σ:
$T_{1/2}(^{100}Mo) = 10^{27}$ yr
$m_{\beta\beta}$ ~12-20 meV



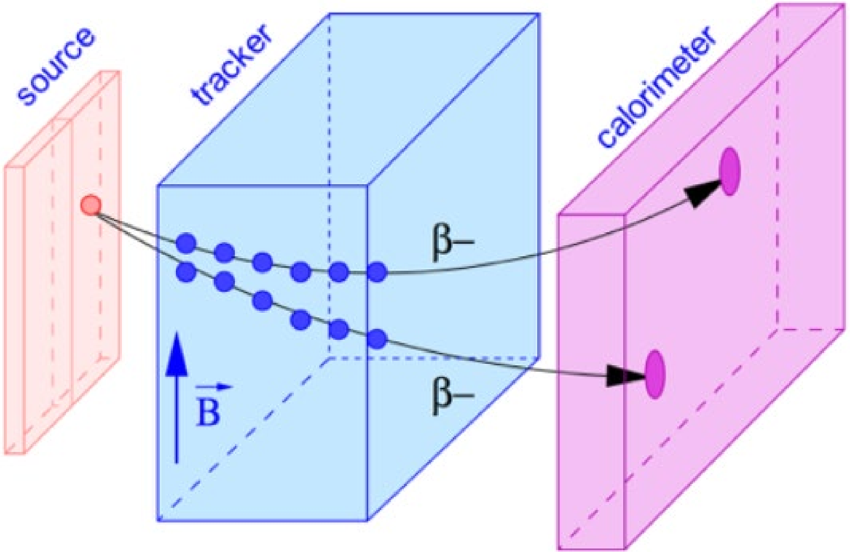
BG level : 10^{-4} /keV/kg/Yr
Sensitivity : $T_{1/2}^{0\nu}$ ~ 10^{27} yr

future

Slide from A. Zolotarova @Neutrino2022

Tracking detector

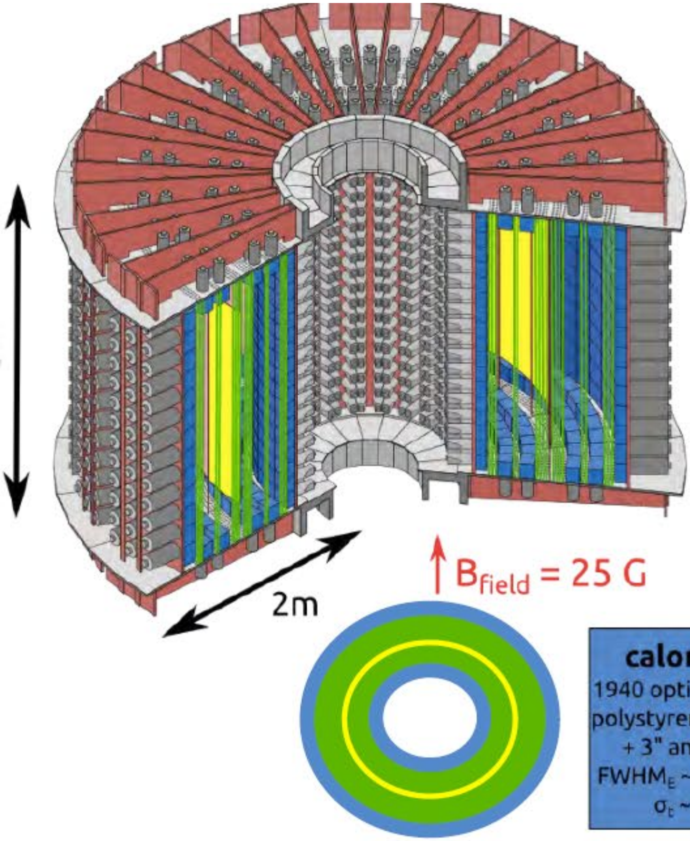
- Tracking detector use a thin source material surrounded first by a low-pressure gas tracking layer to track the two β-rays, and then a calorimetric layer to measure energy.
- Track information gives excellent BG rejection capability and measurement of opening angle of two β-rays.
- Many different isotopes can be measured using same system, although a scalability of system is limited by thin foil.



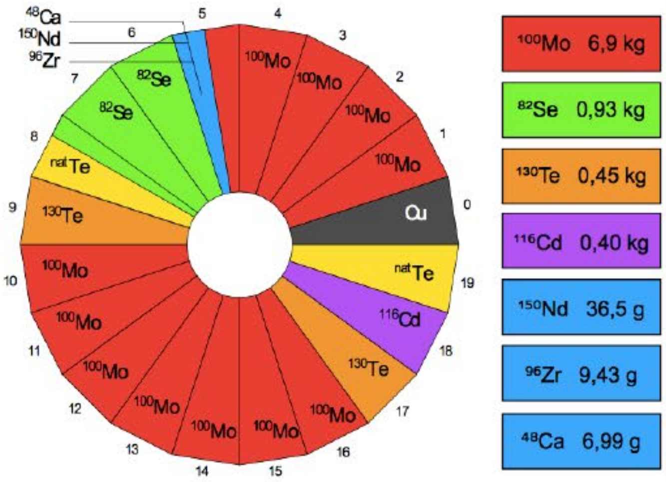
NEMO – 3

Neutrino Ettore Majorana Observatory

@Fréjus Underground laboratory (LSM)



NEMO-3 "camembert" (source top view)



calorimeter
1940 optical modules :
polystyren scintillators
+ 3" and 5" PMTs
$FWHM_E \sim 15\% / \sqrt{E_{MeV}}$
$\sigma_t \sim 250$ ps

tracker
6180 Geiger cells
vertex resolution :
$\sigma_{xy} \sim 3$ mm $\sigma_z \sim 10$ mm

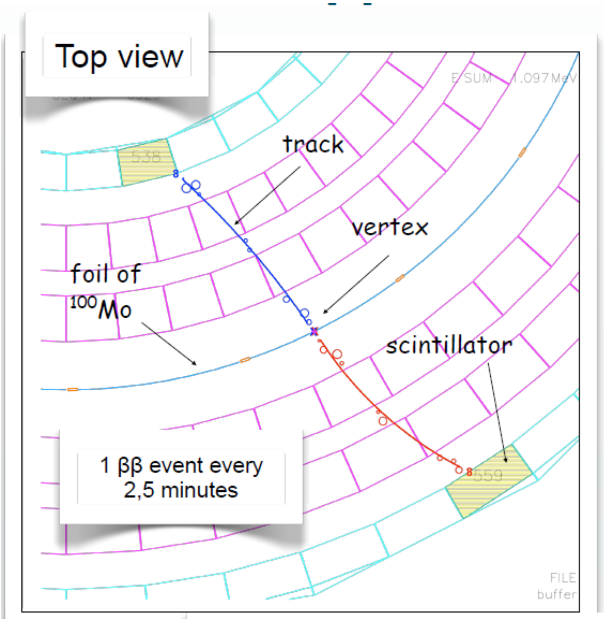
sources
60 mg/cm² foils
10 kg of ββ isotopes

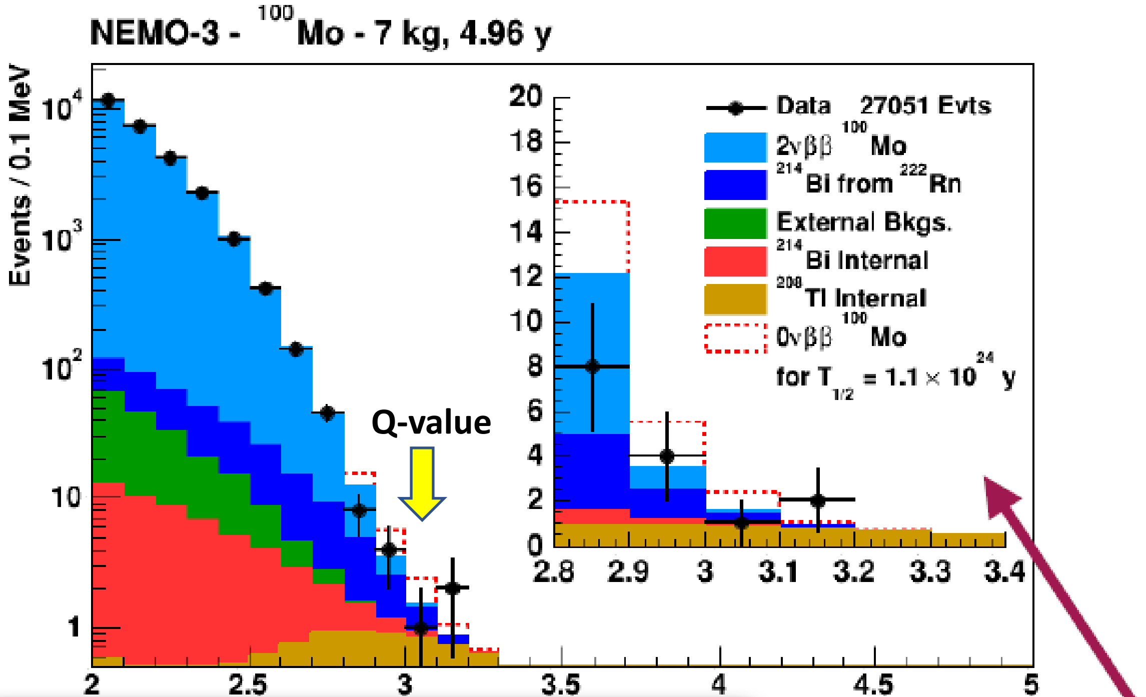
He + 4% ethyl alcohol + 1% Ar + 0.1%H_2O

Result of NEMO-3

0νββ search result with 7 kg ^{100}Mo × 5 years

Event example

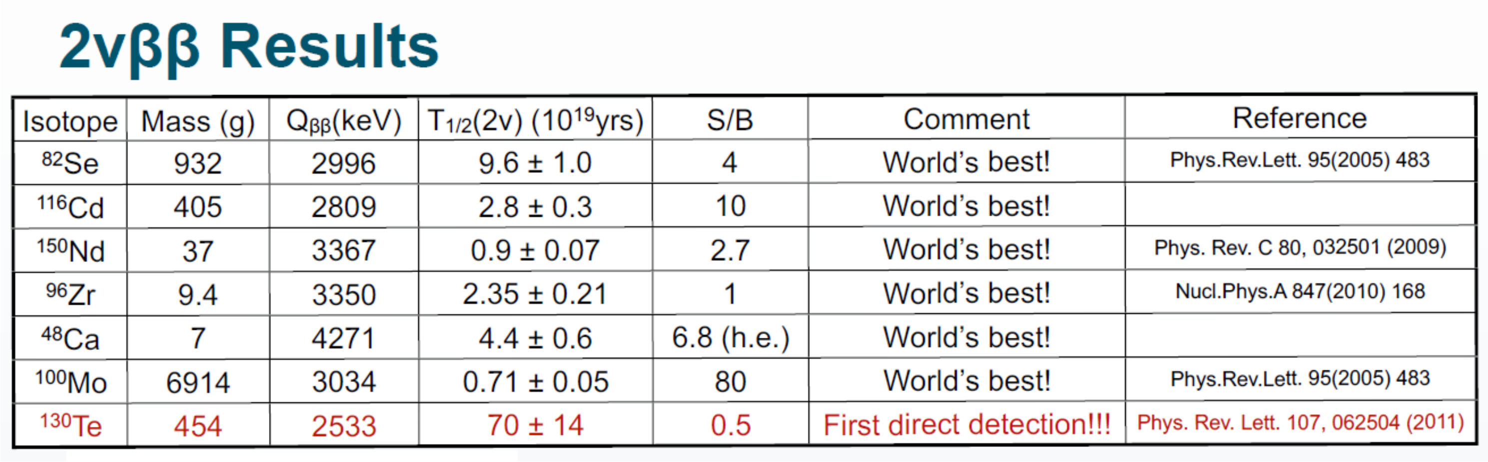




0νββ:
$T_{1/2} > 1.1 \times 10^{24}$ years; $\langle m_\nu \rangle < 0.33 - 0.62$ eV
(90% CL) Close to world's best limit

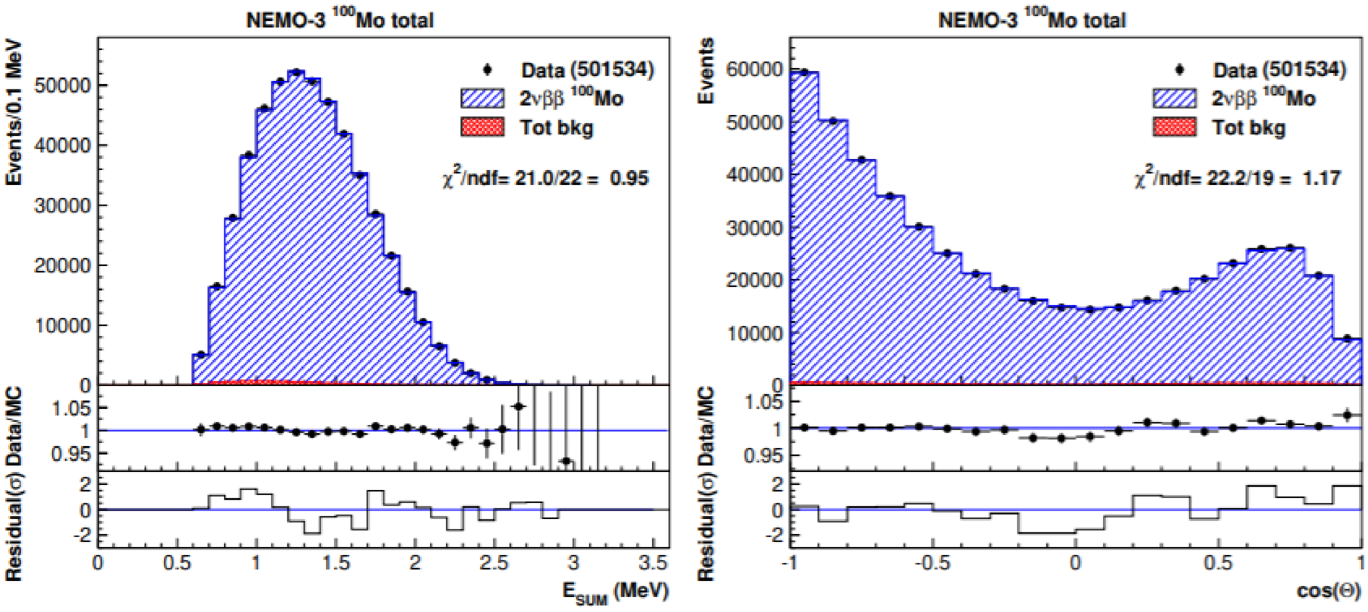
5 years of running
- no backgrounds
over 3.2MeV

Result of NEMO-3

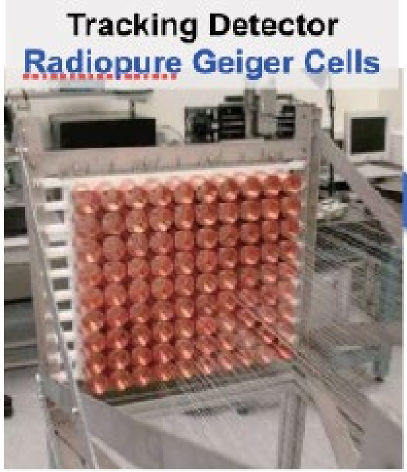


$2\nu\beta\beta$ Results

Isotope	Mass (g)	$Q_{\beta\beta}$(keV)	$T_{1/2}(2\nu)$ (10^{19}yrs)	S/B	Comment	Reference
^{82}Se	932	2996	9.6 ± 1.0	4	World's best!	Phys.Rev.Lett. 95(2005) 483
^{116}Cd	405	2809	2.8 ± 0.3	10	World's best!	
^{150}Nd	37	3367	0.9 ± 0.07	2.7	World's best!	Phys. Rev. C 80, 032501 (2009)
^{96}Zr	9.4	3350	2.35 ± 0.21	1	World's best!	Nucl.Phys.A 847(2010) 168
^{48}Ca	7	4271	4.4 ± 0.6	6.8 (h.e.)	World's best!	
^{100}Mo	6914	3034	0.71 ± 0.05	80	World's best!	Phys.Rev.Lett. 95(2005) 483
^{130}Te	454	2533	70 ± 14	0.5	First direct detection!!!	Phys. Rev. Lett. 107, 062504 (2011)



SuperNEMO demonstrator



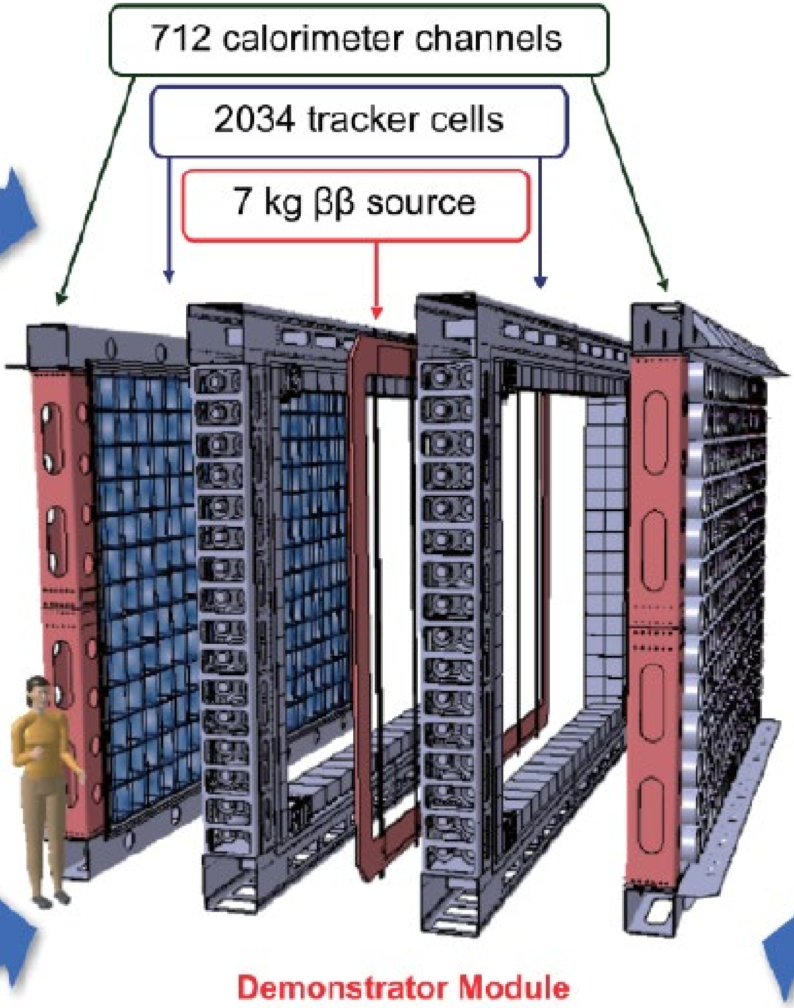
Tracking Detector

Radiopure Geiger Cells

Calo. Optical Module

FWHM 7-8 % @ 1 MeV

Almost half of NEMO-3



712 calorimeter channels

2034 tracker cells

7 kg ββ source

Demonstrator Module

Also :

- Change isotope
  ^{100}Mo ⟶ ^{82}Se
- Reduce radon in gas by factor 30
- Improved efficiency, calibration etc.

"BiPo" Detector

Measure source foil contamination to ^{208}Tl ≤ 2 μBq/kg

^{214}Bi ≤ 10 μBq/kg

More than an order of magnitude lower than that of NEMO-3.

Prospect of SuperNEMO

Demonstrator Module (2.5 year run)

17.5 kg×yr initial exposure :

$$T^{0\nu}_{1/2} > 6.5 \times 10^{24}\ \mathrm{yr}$$

$$\langle m_\nu \rangle < 0.20 - 0.40\ \mathrm{eV}$$

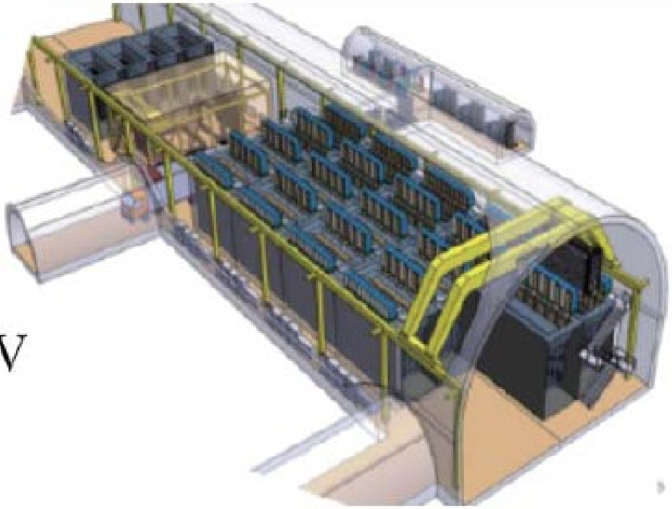
Full SuperNEMO

500 kg×yr :

future

$$T^{0\nu}_{1/2} > 10^{26}\ \mathrm{yr}$$

$$\langle m_\nu \rangle < 50 - 100\ \mathrm{meV}$$



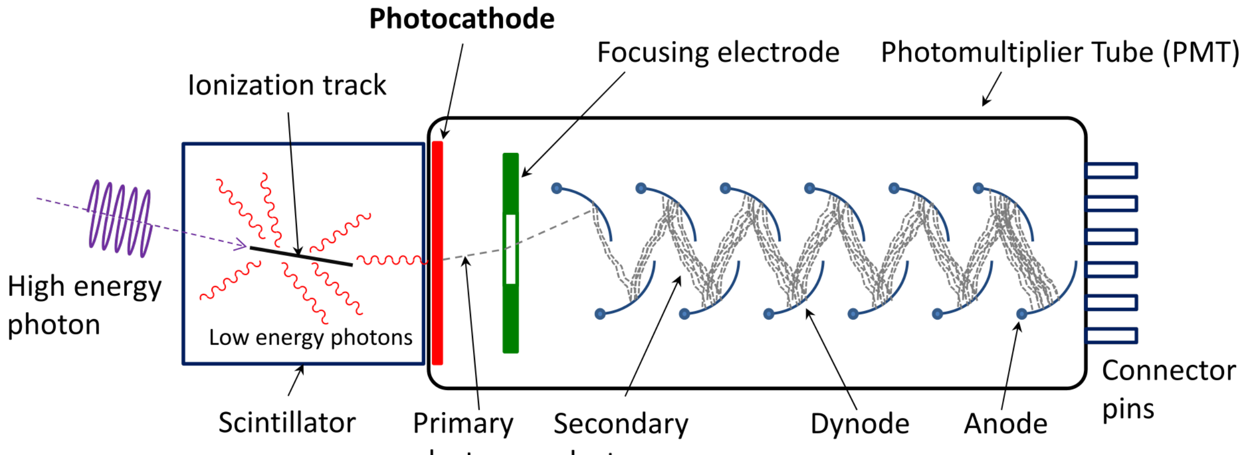
Asian DBD experiments

I focus on these two experiments due to the lack of time

KamLAND-Zen	Japan	^{136}Xe	Xe-loaded liq. scintillator
CANDLES	Japan	^{48}Ca	CaF$_2$ inorganic scintillator
ZICOS	Japan	^{96}Zr	Zr-loaded liq. scintillator
AXEL	Japan	^{136}Xe	Xe gas TPC
DCBA/MTD	Japan	^{150}Nd	Tracking detector
PandaX-III	China	^{136}Xe	Xe gas TPC
AMORE	Korea	^{100}Mo	Scintillating bolometer

Scintillation detector

- Scintillation detector is one of the most major radiation detectors. Organic liquid scintillator and inorganic crystal scintillator exist.
- Injected radiation particles excite electrons inside the scintillator and de-excited electron emit scintillation light which can be detected by PMT.
- Energy resolution depends on photon statistics and is not good compared with semiconductor or bolometer.
- Simple detector setup is superior in scalability.

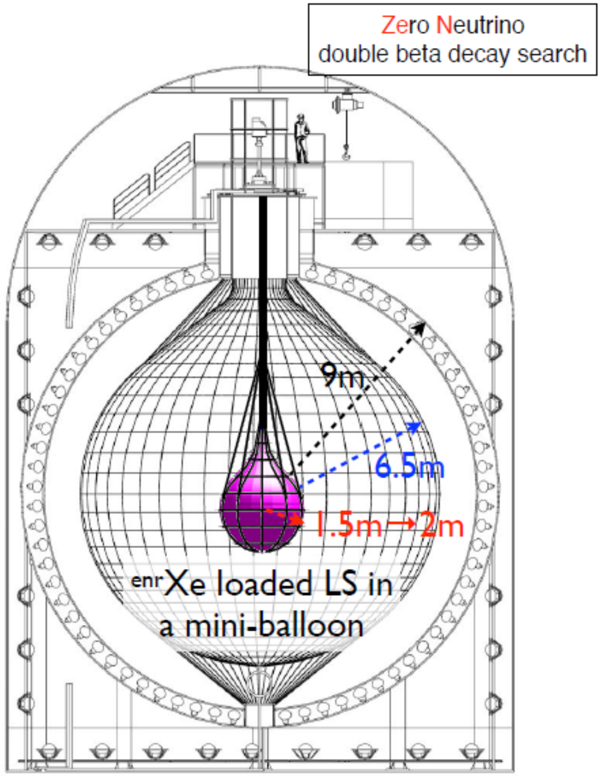


Wikipedia

KamLAND-Zen

Kamioka Liquid scintillator
Anti-Neutrino Detector

- Reuse the existing large KamLAND detector at Kamioka.
- Low RA of U, Th → ~5x10^{-18} g/g, 1.3x10^{-17} g/g



90% enriched ^{136}Xe
320kg for phase-I
380kg for phase-II
745kg for Zen 800 (started in Jan. 2019)

largest amount so far

^{136}Xe

Noble gas
Centrifugal enrichment possible
$Q_{\beta\beta}$=2459 keV
(below ^{208}Tl 3198-5001 keV)

Advantages of using KamLAND

⓪ low cost and quick start (running detector)
① BG can be identified (full active thick shielding)
② In-situ purification possible (liquid media)
③ On/Off measurements possible (xenon is removable)
④ multi-purpose (geo-neutrino)
⑤ easily scalable (mini-balloon)

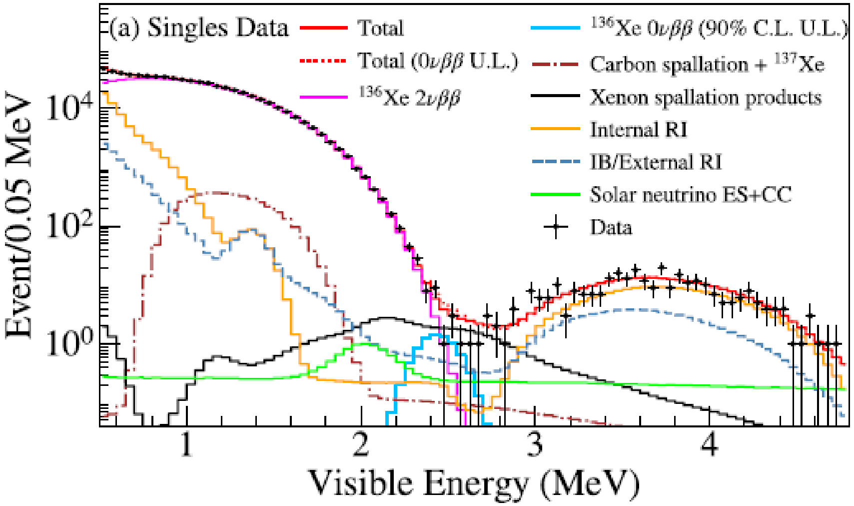
KL-Zen 800 first result

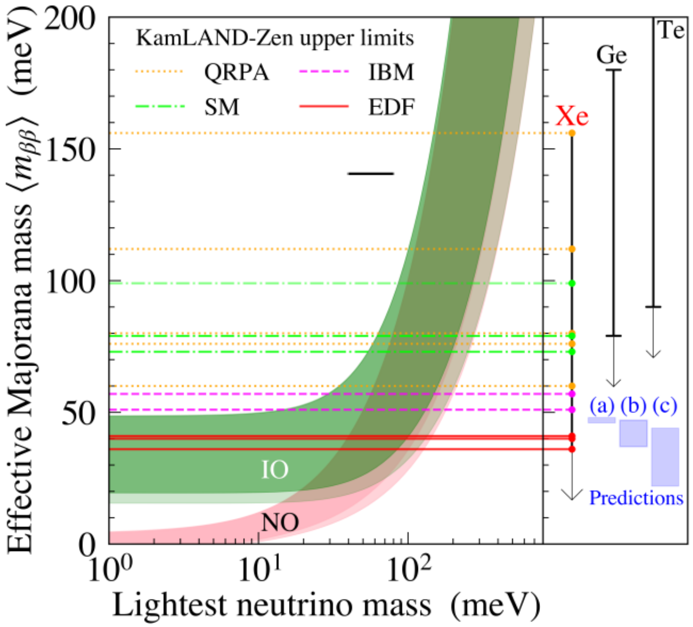
- 745 kg of ^{136}Xe enriched Xe dissolved into LS.
- World best $0\nu\beta\beta$ search limit was obtained.
- First search result in inverted ordering region.

arXiv:2203.02139

Singles data
(sensitive to $0\nu\beta\beta$ rate)

Livetime = 523.4 days





Combined result (90% C.L.)

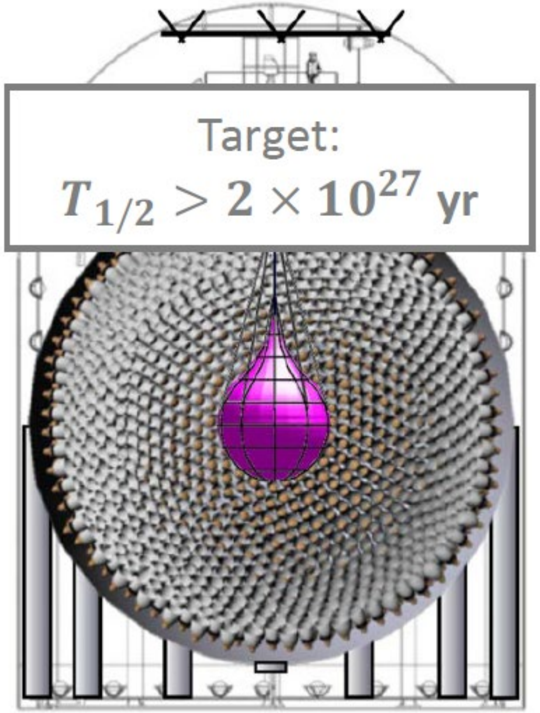
$T^{1/2} > 2.3\times10^{26}$ yr

→ $\langle m_{\beta\beta}\rangle < 36 – 156$ meV

KamLAND2-Zen

Future

Target:
$T_{1/2} > 2 \times 10^{27}$ yr



KamLAND2-Zen

Xenon mass ~ 1 ton

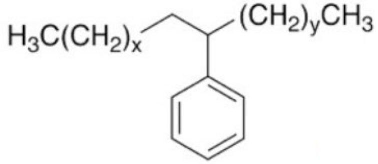
× 5 increase in light collection

Scintillation balloon film

- 1000+ kg of Xenon.

Winston cone	light collection ×1.8
high q.e. PMT 17"ϕ→20"ϕ ε=22→30+%	light collection ×1.9
New LAB LS (better transparency)	light collection ×1.4

LAB (Linear Alkylbenzene)



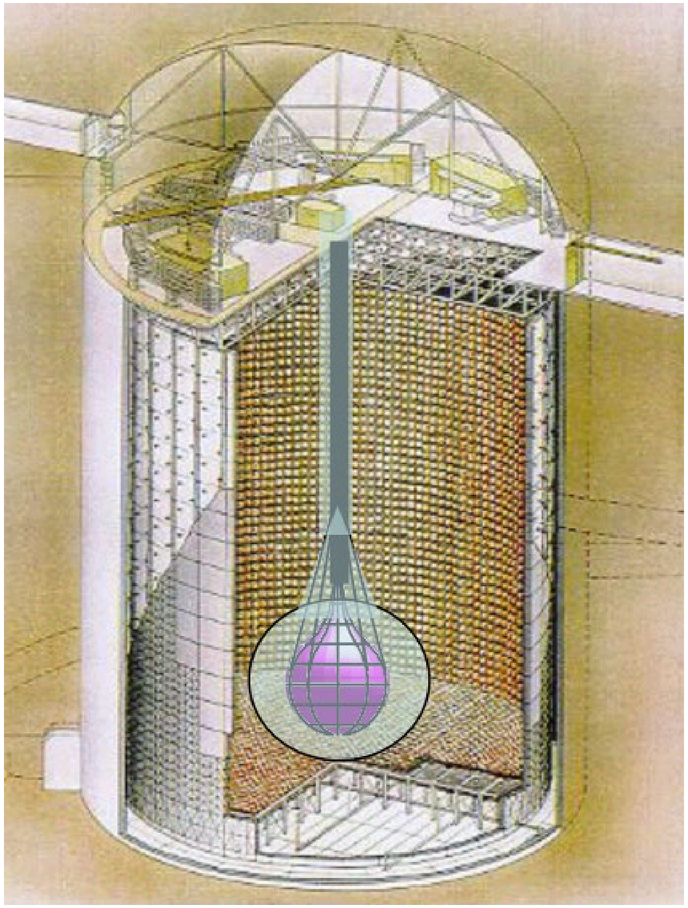
σ(2.6MeV)= 4% → ~2%

Sensitivity $T^{0\nu}_{1/2}$ ~ 2×10^{27} yr
→ $\langle m_{\beta\beta} \rangle$ ~ 20 meV

In 5 years

Further future prospect

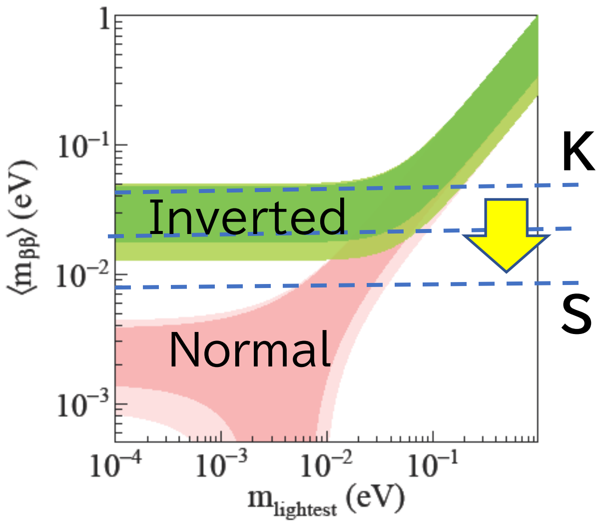
Reuse Super-Kamiokande detector after Hyper-Kamiokande started?



Super-KamLAND-Zen

in connection with Hyper-Kamiokande

target sensitivity 8 meV



KL-Zen 800 (now)

KL2-Zen (in 5 yrs)

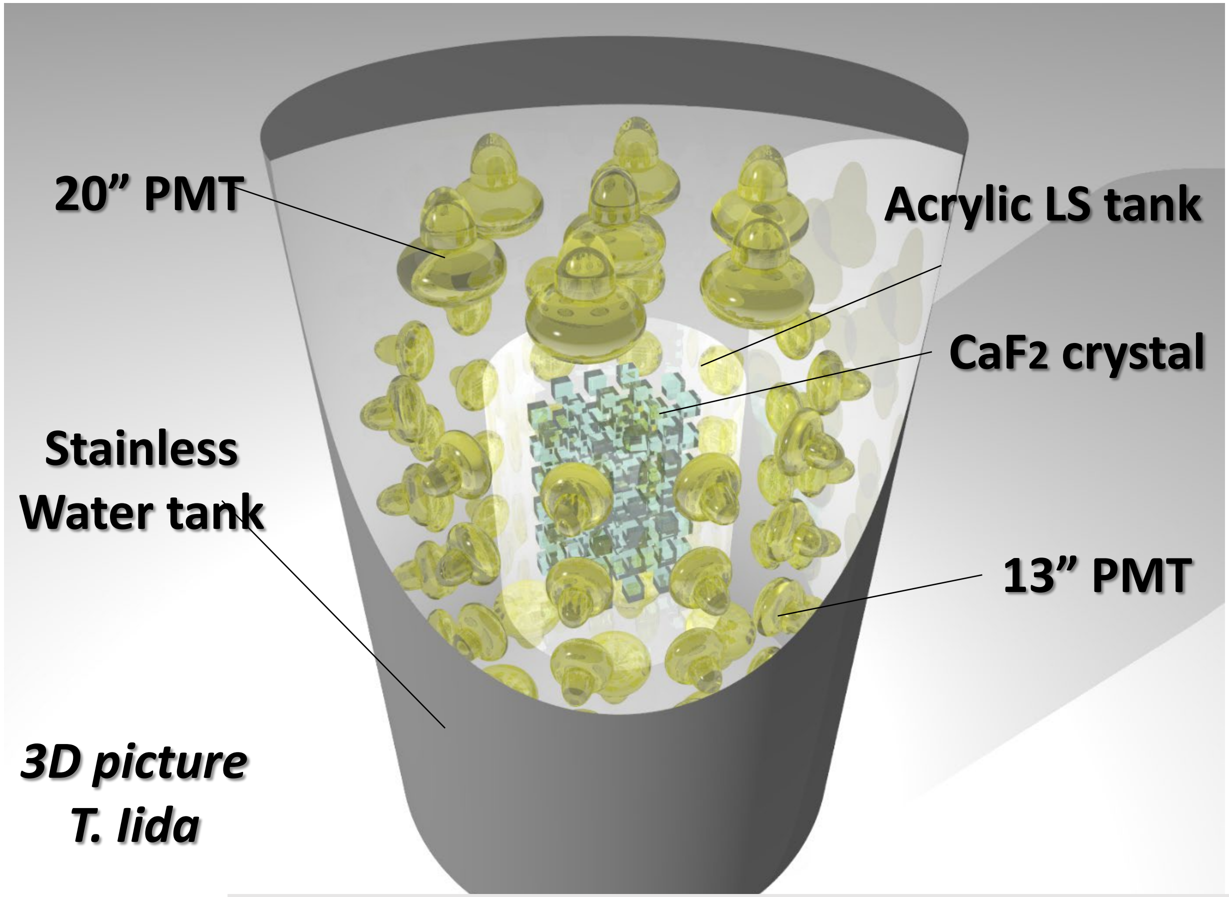
Super KL-Zen (future!)

Idea is interesting! But I don't know if it is realistic…

Double beta decay study by ^{48}Ca

@Kamioka

The CANDLES experiment



3D picture
T. Iida

Collaborating Institutions

大阪大学 OSAKA UNIVERSITY

RCNP 大阪大学 核物理研究センター

国立大学法人 福井大学 UNIVERSITY OF FUKUI

徳島大学 The University of Tokushima

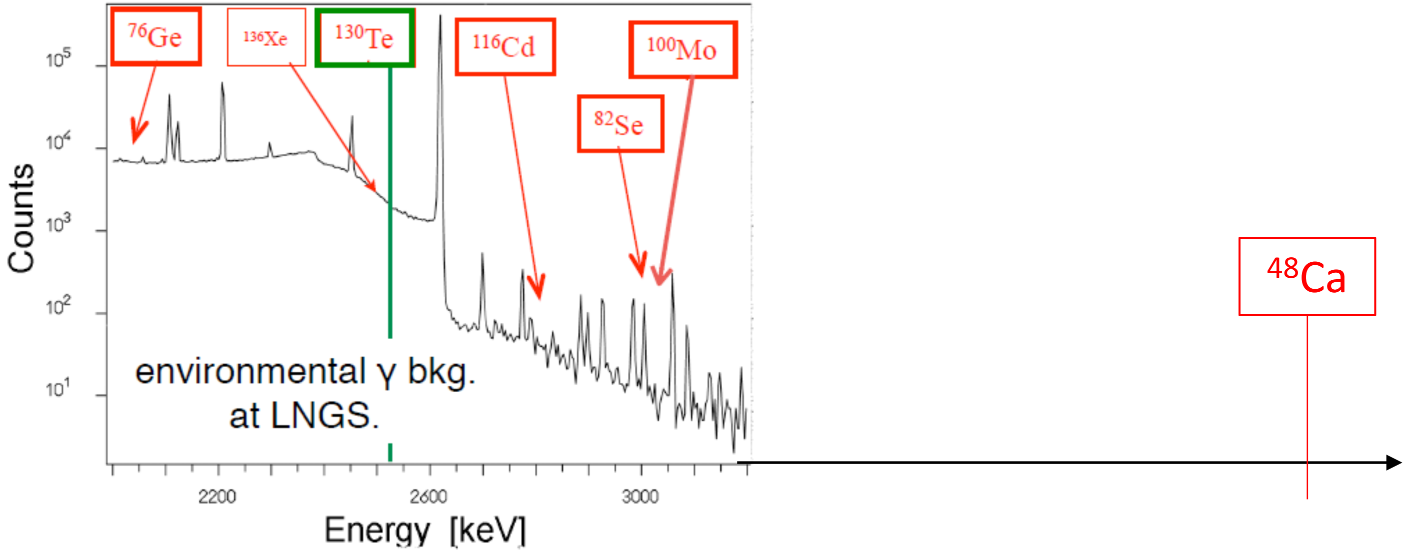
大阪産業大学 OSAKA SANGYO UNIVERSITY

筑波大学 University of Tsukuba

CAlcium fluoride for studies of **N**eutrino and **D**ark matters
by **L**ow **E**nergy **S**pectrometer

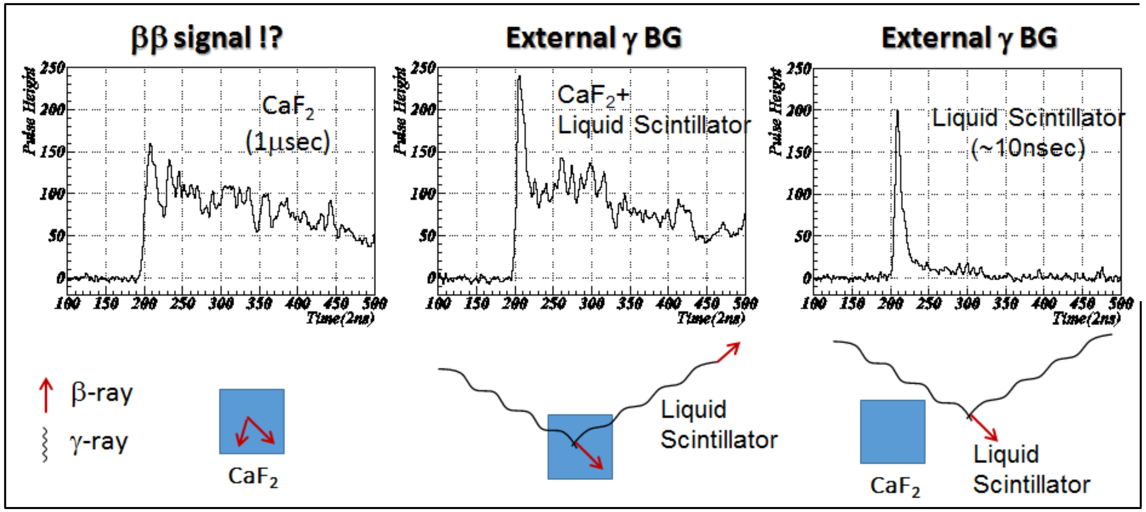
Double beta decay of ^{48}Ca

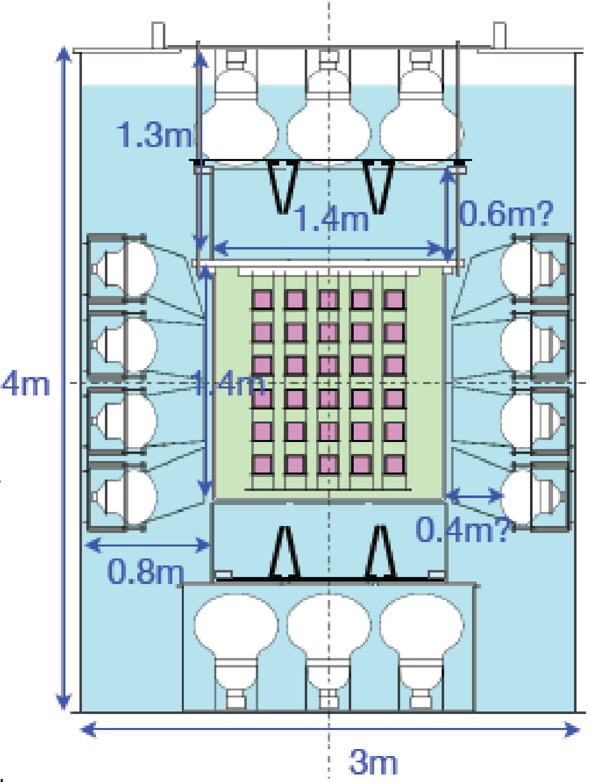
- ^{48}Ca is double beta decay nucleus that has largest $Q_{\beta\beta}$-value (4.27 MeV) among all the double beta candidate isotope. → Low BG condition.
- Since ^{48}Ca is double magic number (p and n) and smallest nucleus used for $0\nu\beta\beta$ search, shell model is suitable for NME calculation.
- Very small natural abundance (0.187%) and no effective enrichment technique exist.



Low BG technique in CNDLES

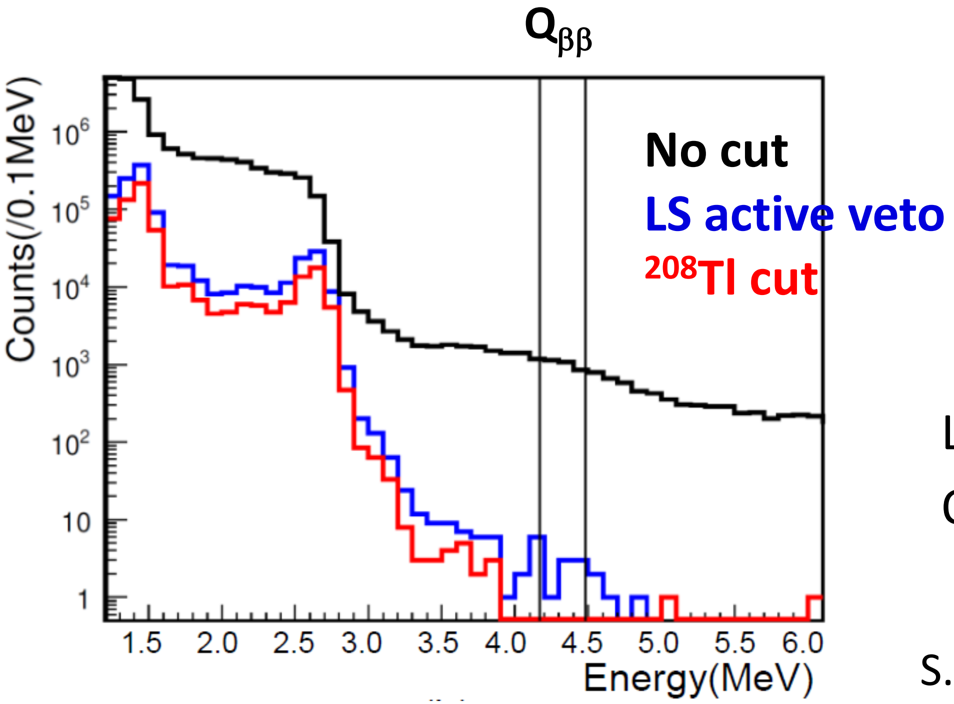
- **CaF_2 crystal （τ ～1 μsec）**
  $10 \times 10 \times 10$ cm$^3 \times 96$（305 kg & 350 g of ^{48}Ca）
- **2m^3 Liquid scintillator（LS, τ ～10 nsec）**
- Light observed by 62 PMTs
  → LY = 1,000 p.e./MeV (～2×KL-Zen)





LS active veto and Pulse shape discrimination analysis can achieve low BG!!

Current result of CANDLES



Energy spectrum for clean 21 crystals (Th < 10μBq/kg)

Livetime : 131 days

$Q_{\beta\beta}$: 4170 - 4480 keV ($Q_{\beta\beta}$ -1σ +2σ)

S. Ajimura et al., Phys. Rev. D 103, 092008

- Background drastically reduced by LS active veto.
- After all the cuts, no event observed in $Q_{\beta\beta}$ region.

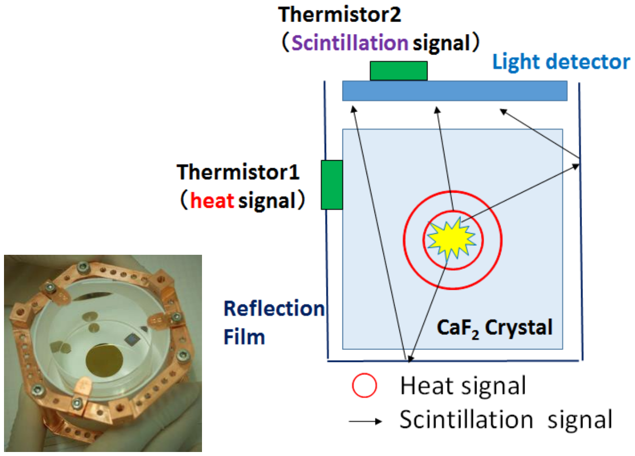
BG level : ~10^{-3} /keV/kg/Yr

$T^{0\nu}_{1/2} > 5.6 \times 10^{22}$ yr (90% CL)

Future R&D of CANDLES

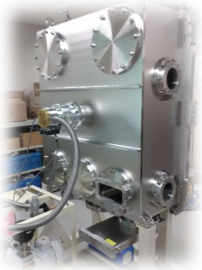
Scintillating bolometer

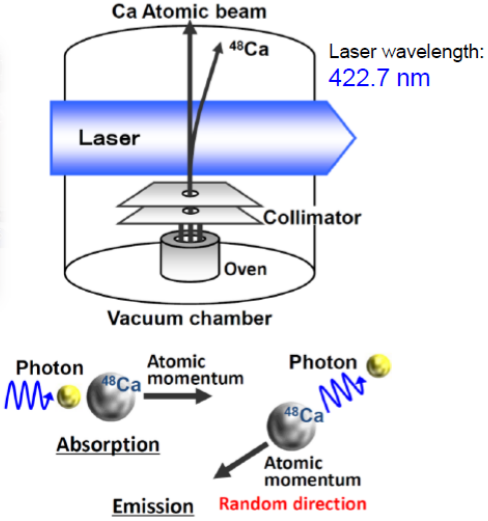
- Scintillating bolometer detector using CaF_2 crystal is under studying (same technique as CUPID).
- Our goal is 0.5% energy resolution (FWHM) and BG free in Q-value region.



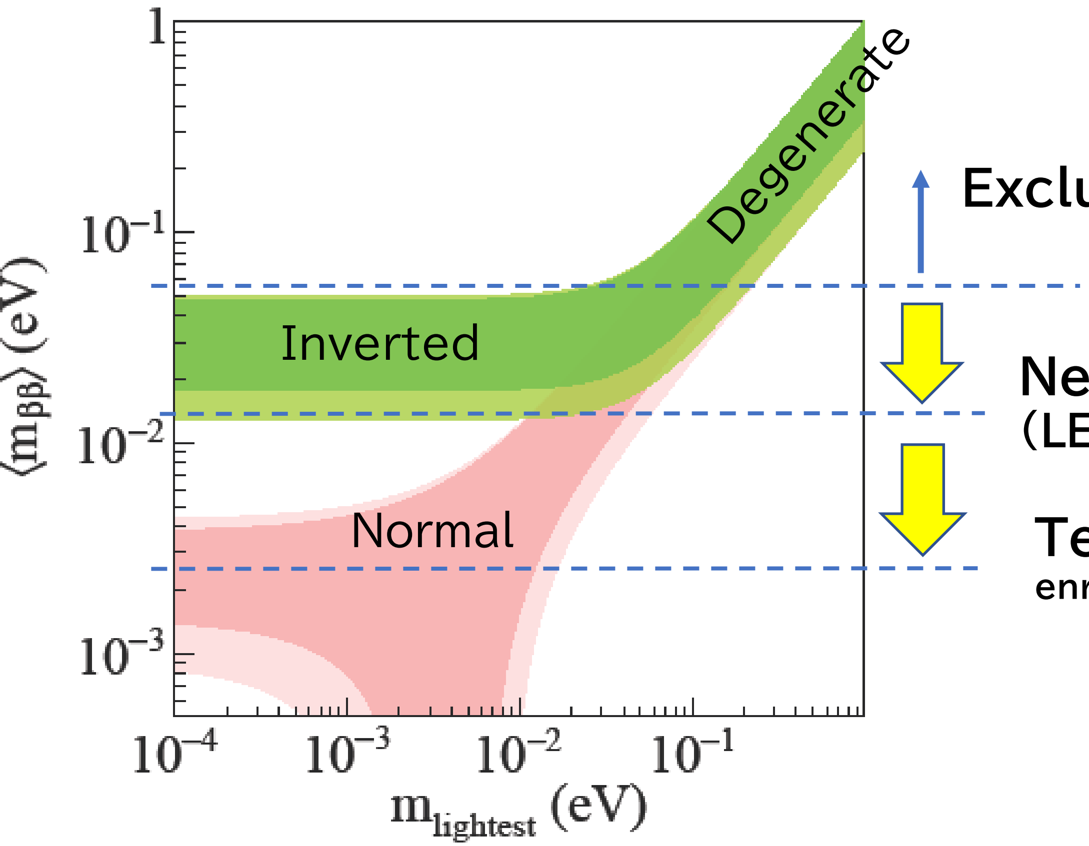
^{48}Ca enrichment

- Laser enrichment techniques are being developed.
- 422 nm and 100 mW laser.
- 1 mol/year production in 2023...





Future prospect



Excluded（KL-Zen, GERDA）

Next generation target
（LEGEND, CUPID, KL2-Zen…）

Tens of tons of
$^{\mathrm{enriched}}\mathrm{CaF}_2$ bolometer

Summary of detector technology

	Scalability	E resolution	BG rejection	Multi target
Semiconductor	○	◎	○	×
Liq. TPC	○	○	○	×
Gas TPC	△	○	○	×
Bolometer	○	◎	○	△
Tracker	×	×	○	◎
Scintillator	◎	△	○	×

NOTE: This is completely my personal opinion!

Summary

- Neutrino-less double beta decay would prove Majorana nature of the neutrinos.
- Majorana neutrino can resolve many problems in SM such as “very small neutrino mass”, “left-handed neutrino” and “matter anti-matter asymmetry”.
- Next generation double beta decay experiment aims to explore Inverted ordering region ($<m_{\beta\beta}>$ ～20 meV).
- Many projects are ongoing!!

◆*If you are interested in CANDLES, you can contact me by E-mail ;)*