Neutrinoless Double-Beta Decay

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ELBA XIV, 27 June 2016

Outline

- Neutrinoless double-beta decay (0νββ)
  Historical background & Motivation
- Neutrino masses
- Overview of (2νββ & 0νββ) detection techniques
- Detector examples & Recent Results
- Future "Ton Scale" experiments
- Summary/Outlook

Historical background and motivation

- 1930: Pauli suggests a “neutrino” which accompanies the electron in the β-decay
- 1932: Chadwick's discovery of the “neutron”
- 1934: Fermi's incorporation of both in his theory of the β decay

$$n \rightarrow p + e^- + \bar{\nu}_e$$

β decay: $(Z,A) \rightarrow (Z+1, A) + e^- + \bar{\nu}_e$

e.g. $^{198}Au_{79} \rightarrow {}^{198}Hg_{80} + e^- + \bar{\nu}_e$

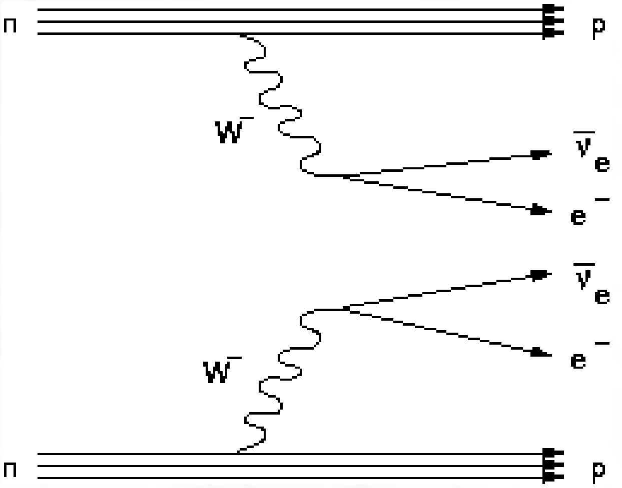
Historical background and motivation

- 1935: M.Goppert-Meyer describes “double -β disintegration”

$$2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e$$

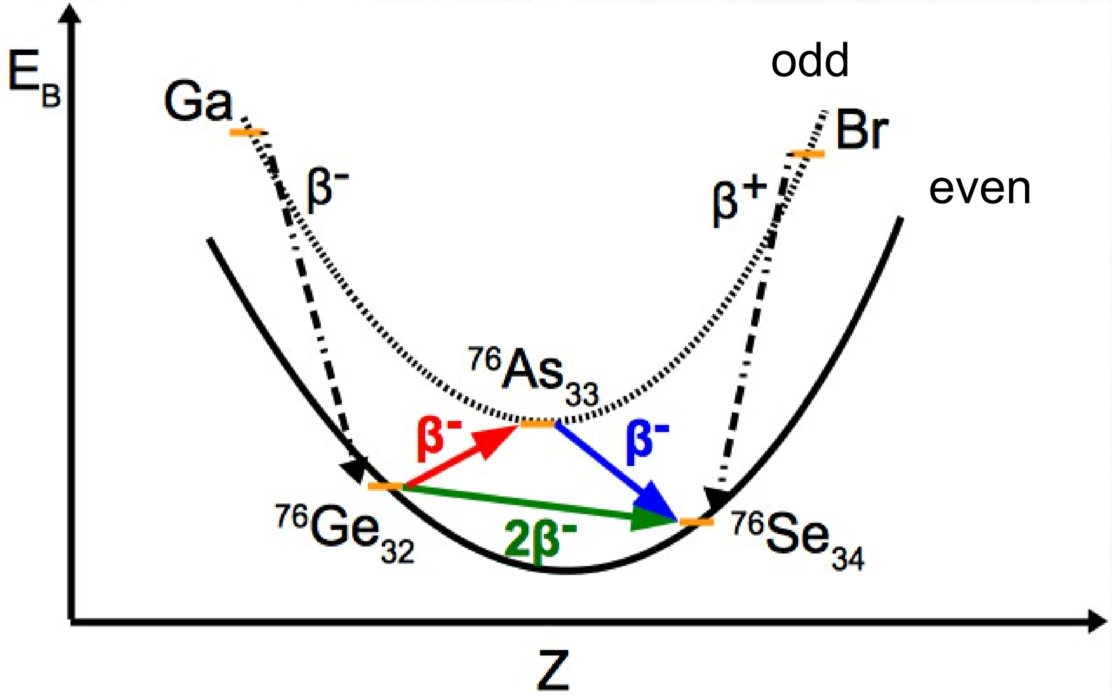
2νββ decay: $(Z,A) \rightarrow (Z+2,A) + 2e^- + 2\bar{\nu}_e$

compatible with standard model



Historical background and motivation

In some isotopes simultaneous decay of two neutrons into two protons possible



2vββ possible in
35 isotopes

Measured in
Ca^{48}, Ge^{76}, Xe^{136}, …

$T_{1/2}$ (2vββ) = (10^{18} – 10^{21}) year

Age of the Universe: ~10^{10} years !

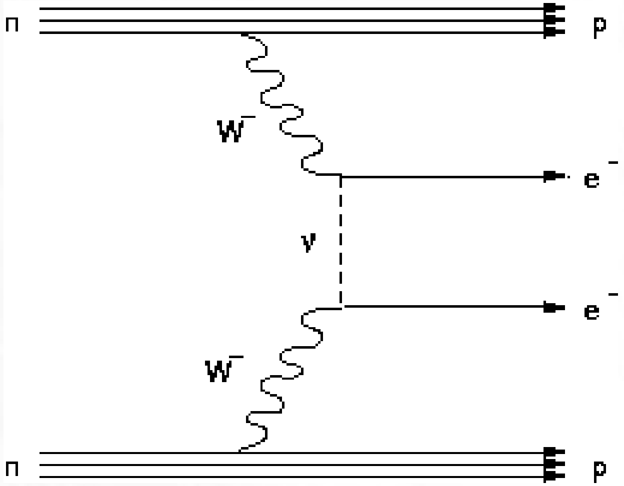
Historical background and motivation

- 1937: Majorana suggests that $\nu_e = \bar{\nu}_e$

0νββ decay: (Z,A) → (Z+2,A) + $2e^-$

not compatible with standard model

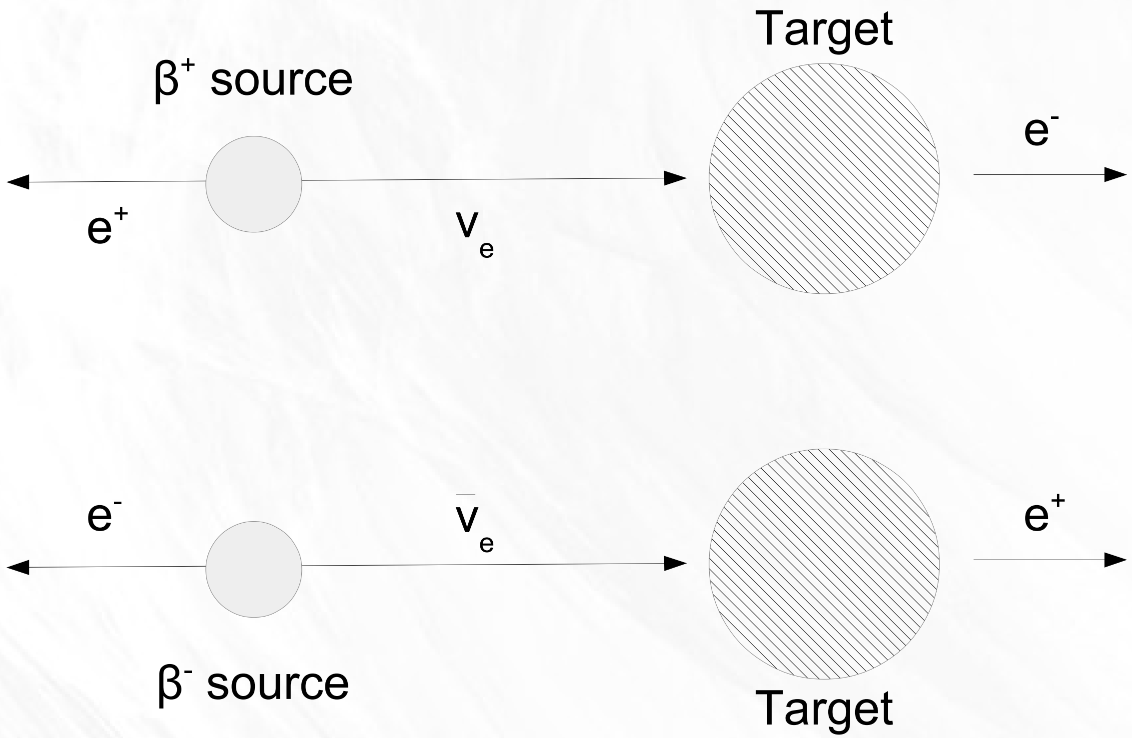
→ ΔL = 2
→ $m_\nu > 0$



- 1937 Giulio Racah points out that Majoranas theory can be tested

Historical background and motivation

How to adress the problem experimentally?



Neutrino and anti-neutrino seem distinguishable, since they produce different final states

Historical background and motivation

1955 Ray Davis in concludes that ν_e distinct from $\bar{\nu}_e$ using anti-neutrinos from reactor

$\bar{\nu}_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	✗	Anti-neutrinos from reactor
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$	✓	Neutrinos from the sun

Introduce Lepton Number 'L' to distinguish between neutrino and anti-neutrino

Allows to define allowed reactions

$$\Sigma L_{IN} = \Sigma L_{OUT}$$

Lepton	L
e^-	+1
e^+	- 1
ν_e	+1
$\bar{\nu}_e$	- 1

Historical background and motivation

- 1957 discovery of parity violation in weak interactions and two component neutrino
- Since parity violation labels the neutrinos to be left-handed, no lepton number needed anymore
- Observations could be explained with neutrino helicity

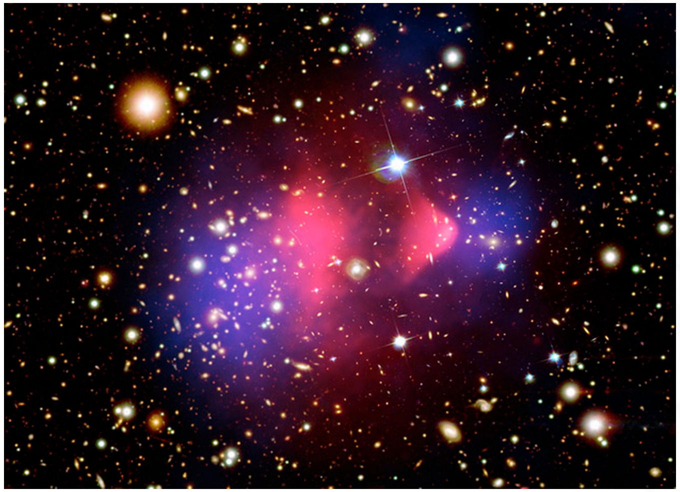
Majorana nature of neutrinos not excluded yet

Neutrino Masses

$$P_{\alpha \to \beta} \sim \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E}\right)$$

We know neutrinos have mass!

Our first hints of physics beyond Standard Model

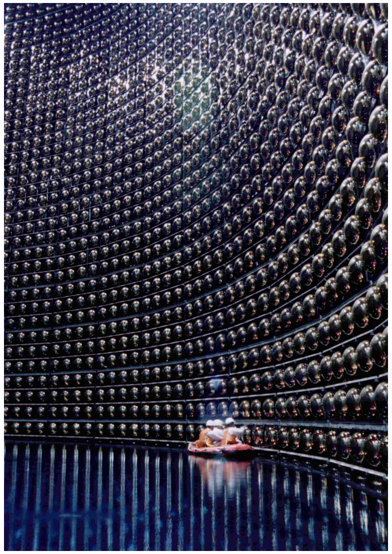


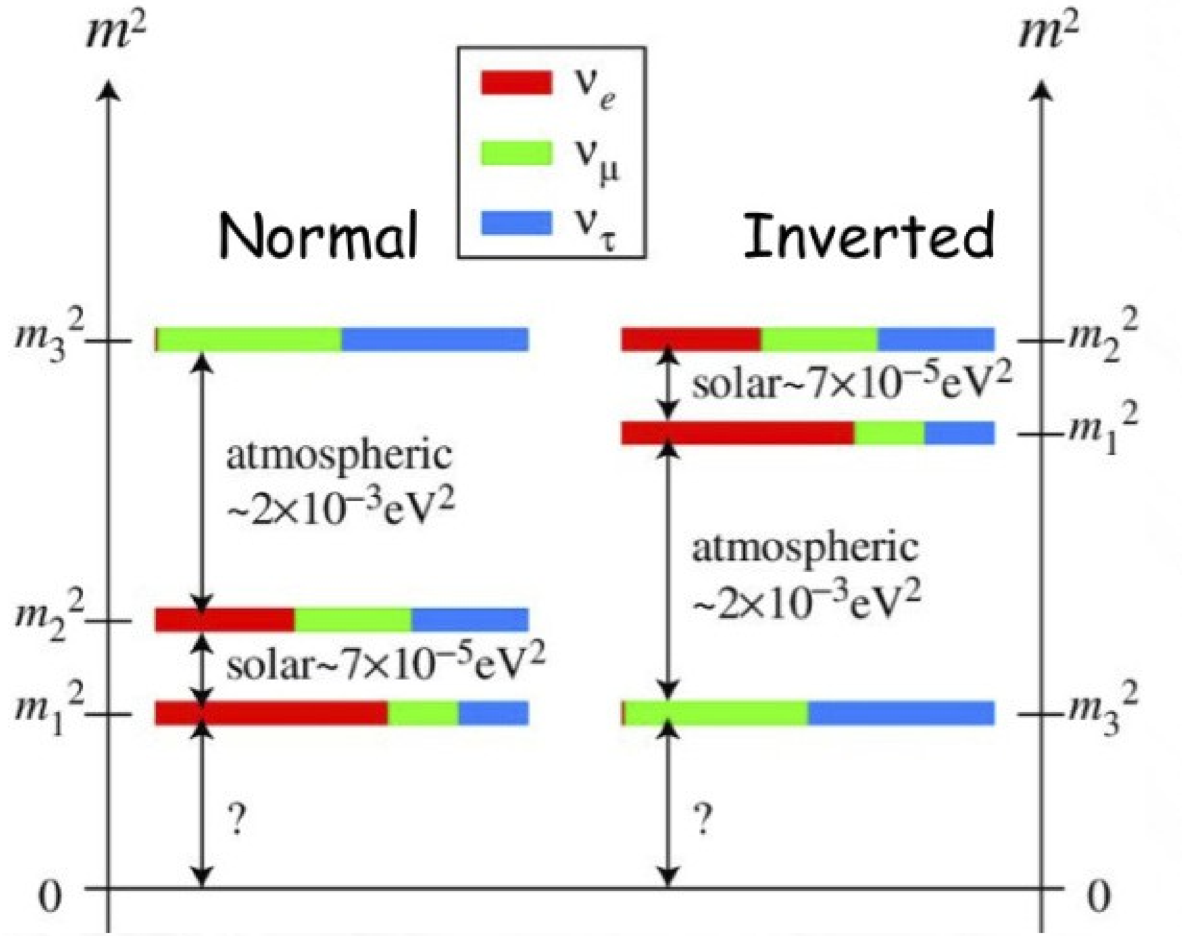
Further hints

- Gravity
- Dark Matter
- Dark Energy
- Matter-antimatter asymmetry

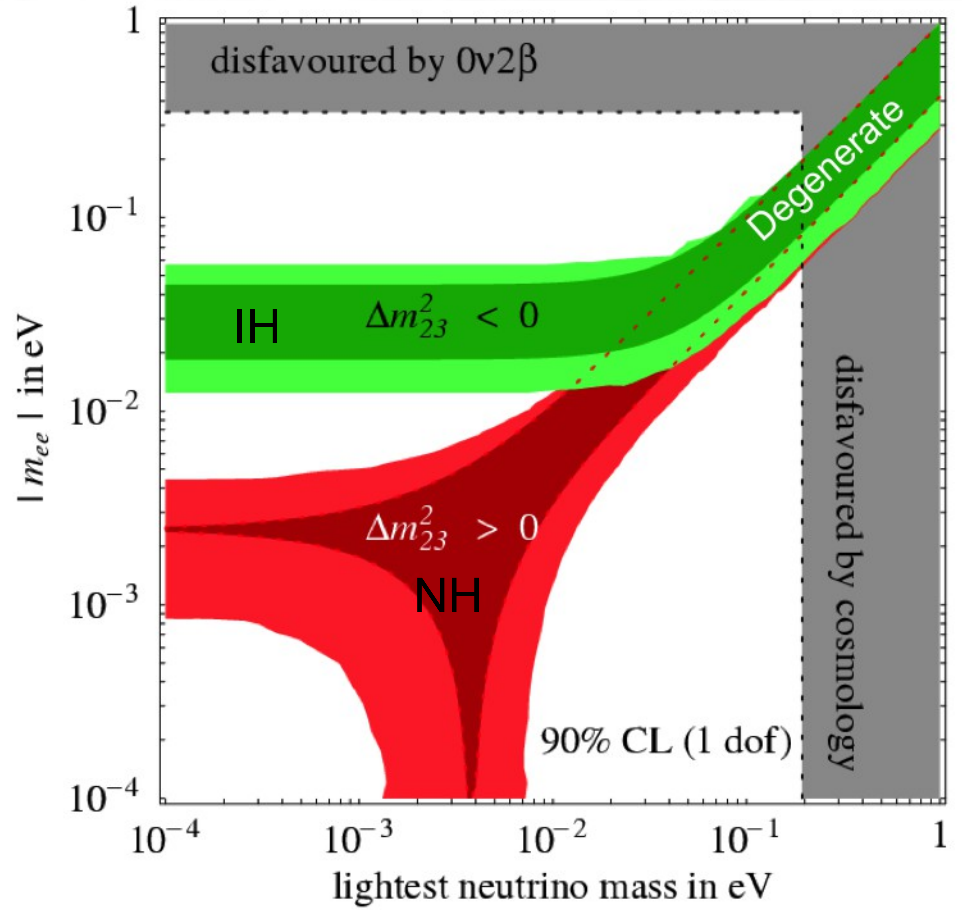
Neutrino Masses

- Solar ν
- Reactor ν
- Atmospheric ν
- Accelerator ν





Neutrino Masses



IH = Inverted Hierarchy

NH = Normal Hierarchy

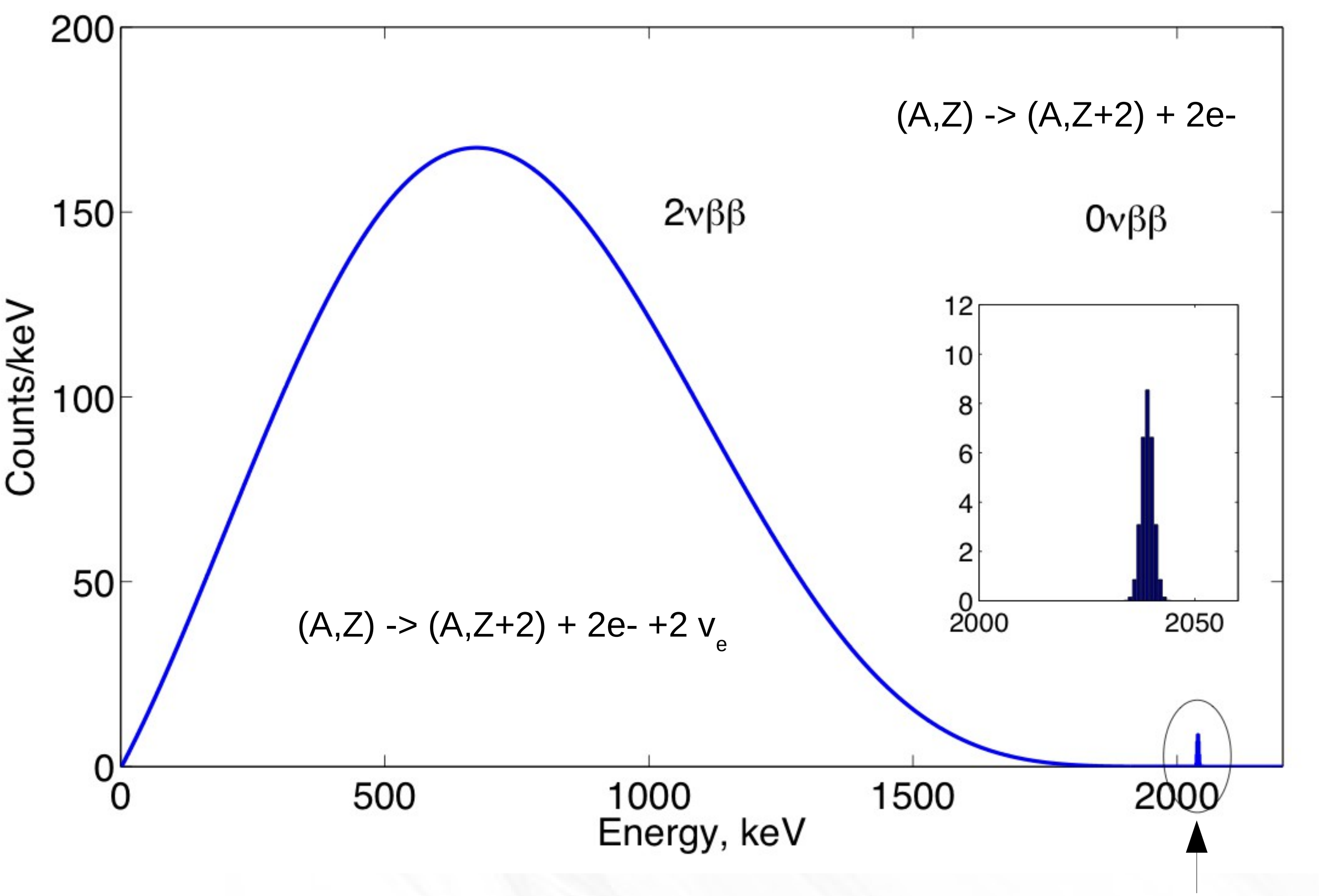
To reach inverted hierarchy region we need sensitivities of:

0νββ: $T_{1/2} \sim 10^{27} - 10^{28}$ years

2νββ: $T_{1/2} \sim 10^{19} - 10^{21}$ years

Overview of detection techniques

Signal signature



Q-value

Overview of detection techniques

Nuclear matrix element

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

Phase space factor

$|\Sigma\, m_i\, U_{ei}^{\,2}|$ = effective Majorana neutrino mass

PMNS mixing matrix

mass eigenstates

Halflifes are determined by:

- Phase space factor
- Nuclear matrix elements
- Effective neutrino mass can be inferred from halflife measurements

Overview of detection techniques

Detector Sensitivity

$$T_{1/2}(0\nu\beta\beta) = a \cdot \varepsilon \cdot \sqrt{(M \cdot T / B \cdot dE)}$$

a=isotopic abundance of source
ε= detection efficiency
M=total mass
T= exposure time
B = background in 0vbb ROI
dE = energy resolution

0νββ source
Isotopically enriched

Detector
High detection efficiency (e.g. source=detector)
Good energy resolution
Low-background

Experiment
Long exposure times
Large source mass

Overview of detection techniques

Half lfes of 2vββ are O(10^{21}) years

1 Mole of source isotope produces ~ 1 decay/day !

Half lfe [years]	Signal [counts/tonne-year]
10^{25}	500
$5\cdot10^{26}$	10
10^{27}	1
10^{28}	0.1

$T_{1/2} = a \cdot \varepsilon \cdot \sqrt{(M \cdot T / B \cdot dE)}$ Background limited

$T_{1/2} = a \cdot \varepsilon \cdot M \cdot T$ Background free

0vββ & 2vββ detector technology challenging due to rare events

Overview of detection techniques

Potential Backgrounds

- Primordial, natural radioactivity in detector components: U, Th, K
- Backgrounds from cosmogenic activation while material is above ground (ββ- isotope or shield specific)
- Backgrounds from the surrounding environment:

  external γ, (α,n), (n,α), Rn,
- μ-induced backgrounds generated at depth
- 2 neutrino double beta decay (irreducible, E resolution dependent)
- Neutrino backgrounds (negligible)

Overview of detection techniques

Reduce Background (passive)

- Ultra pure materials
- Shielding
- Deep underground

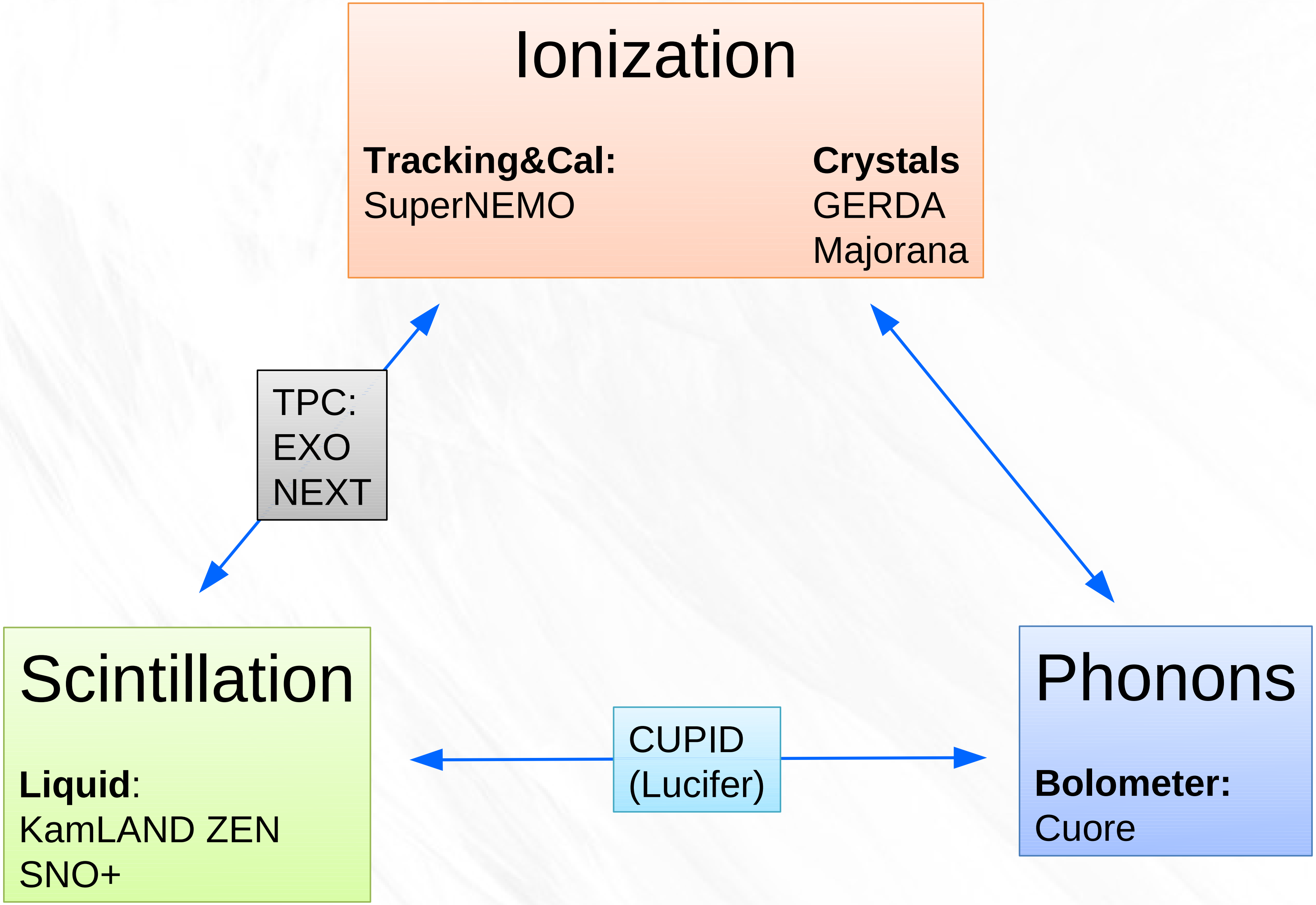
Discriminate Background (active)

- Energy resolution
- Event topology
- Fiducial cuts
- Pulse shape discrimination
- Particle identification

Further issues

- Unknown gamma transitions
- Nuclear matrix elements not accurately known
- Different isotopes require different technologies
- 2-ν background different in each case

Overview of detection techniques



Ionization

Tracking&Cal:
SuperNEMO

Crystals
GERDA
Majorana

TPC:
EXO
NEXT

Scintillation

Liquid:
KamLAND ZEN
SNO+

CUPID
(Lucifer)

Phonons

Bolometer:
Cuore

Overview of detection techniques

- There are 35 naturally occurring isotopes that can undergo a ββ decay.

- Only twelve isotopes have been experimentally observed undergoing 2vββ:

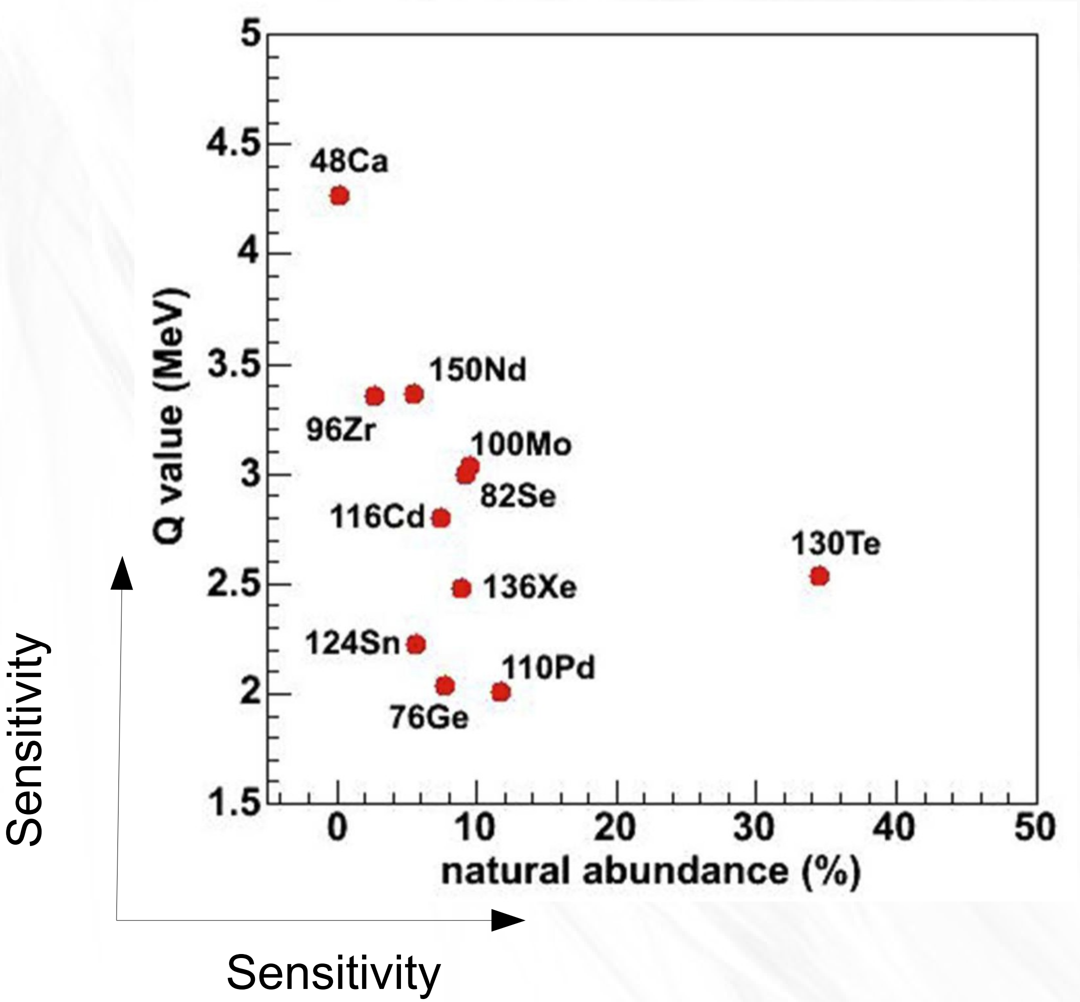
48Ca, 76Ge, 82Se,96Zr, 100Mo, 116Cd, 128Te,

130Te, 130Ba, 136Xe, 150Nd, and 238U

- How do you choose your isotope?

Overview of detection techniques

Choice of isotopes



- **Higher Q-value**

= less background

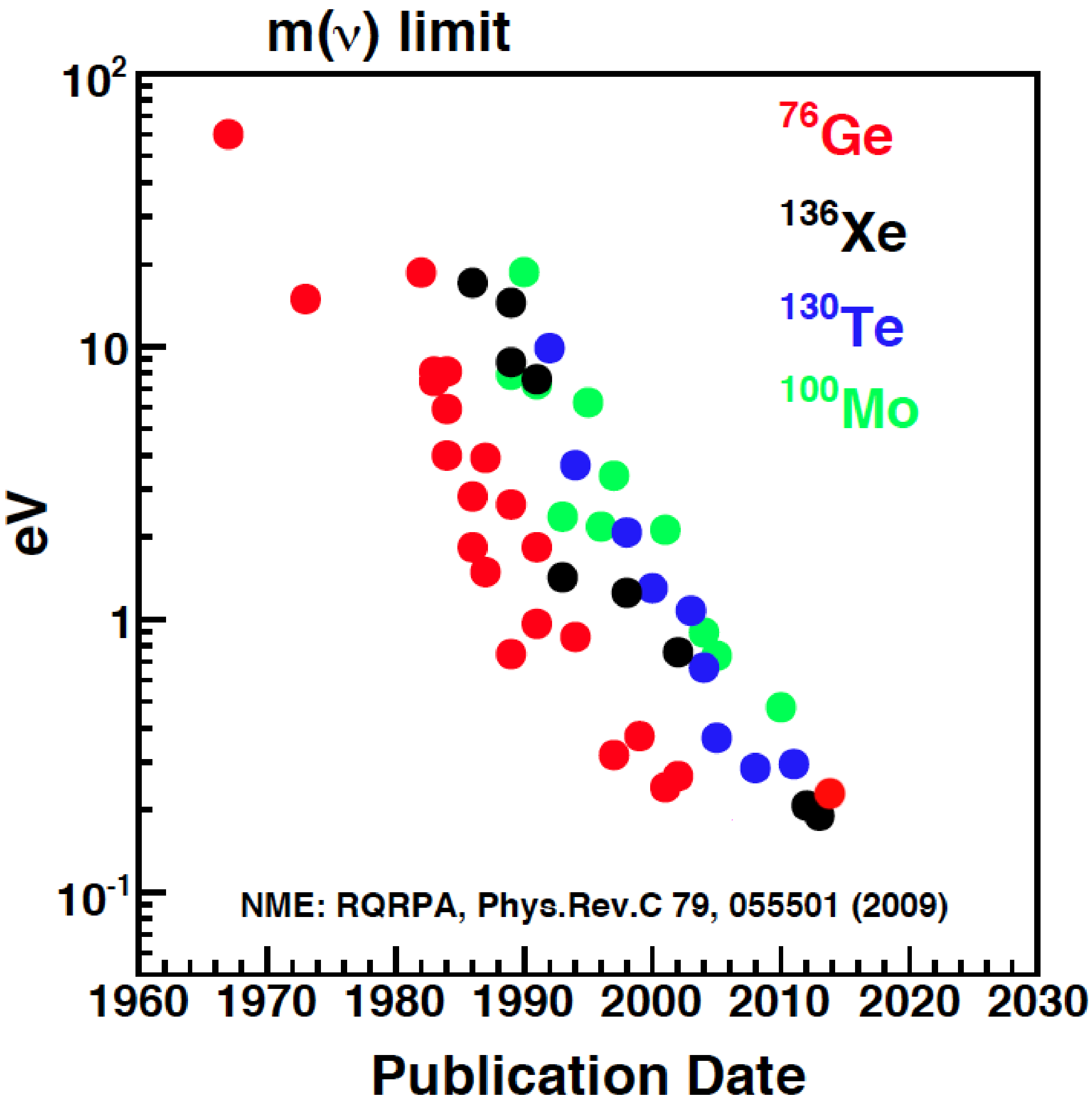
- **Higher nat. abundance**

= better cost efficiency

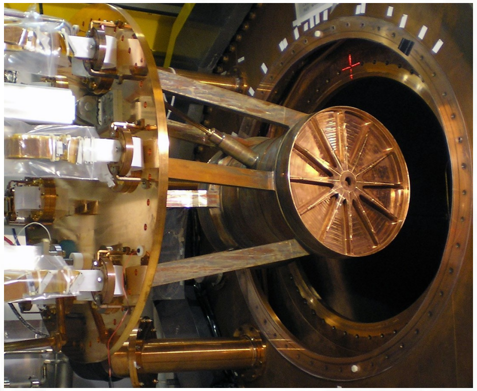
Optimal isotope:

upper, right corner

Overview of detection techniques

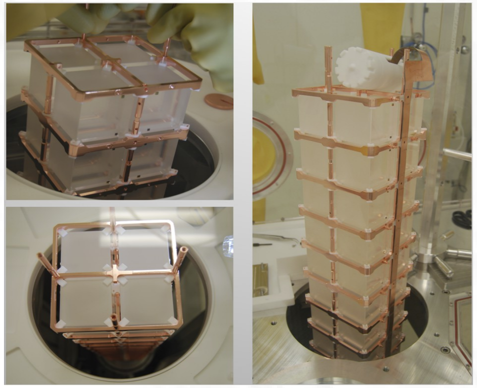


Detector examples & Recent Reults

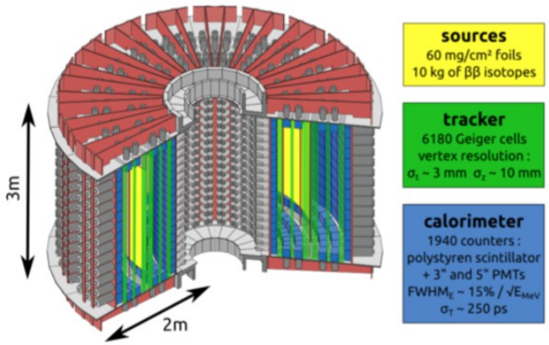


EXO-200, 1600 m.w.e.
WIPP, NM

GERDA, 3500 m.w.e
LNGS, Gran Sasso



CUORE, 3500 m.w.e
LNGS, Gran Sasso



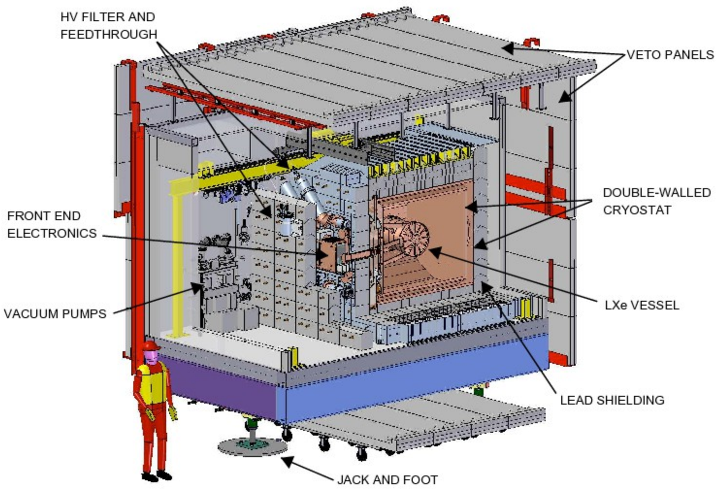
NEMO-3/ SuperNEMO, 4800 m.w.e.
LSM, Modane

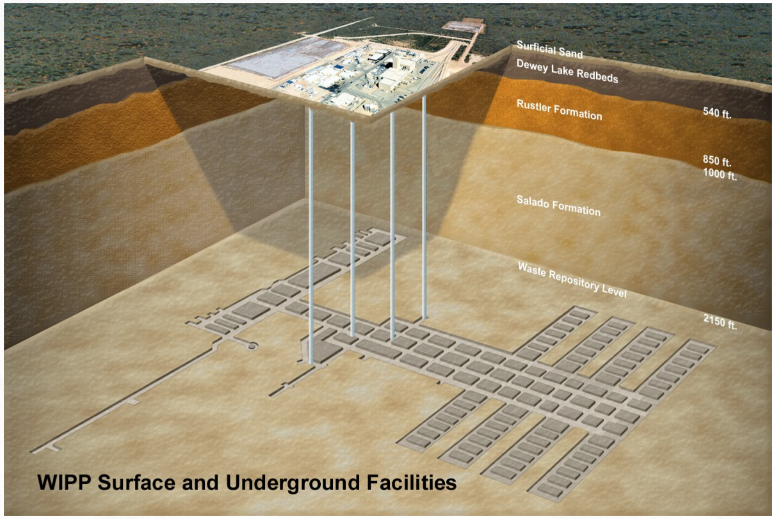
and ~20 more …..

Detector examples & Recent Reults

EXO-200

- EXO – 200 searches for the $0\nu\beta\beta$ decay in Xe^{136}
- Q-value: 2.458 MeV
- Location at WIPP (Waste Isolation Pilot Plant), NM
- EXO-200 drift: 655 m deep, ca. 1600 m.w.e.
- Dual Time Projection Chamber with LXe enriched to 80.6% Xe^{136}

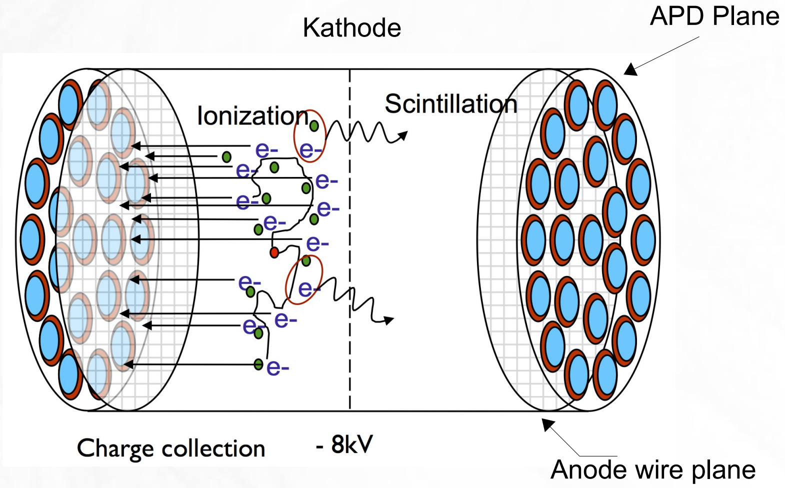


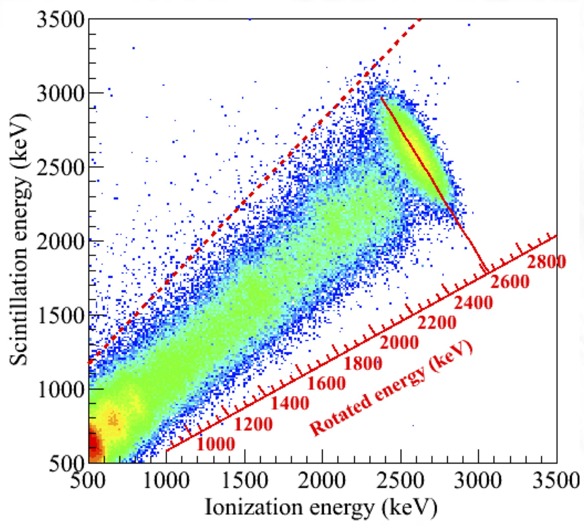


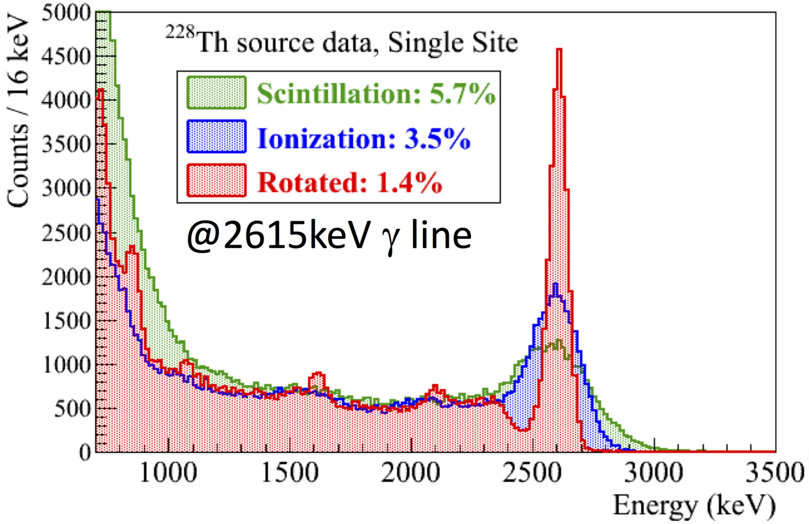
Detector examples & Recent Reults

EXO-200

- Read Scintillation and Ionization signals
- Scintillation light measured with APDs
- Charge Collection (U) wires
- Shielding/Induction (V) wires
- Event topology used for Single-site and Multi-site event discrimination
- Anti-correlation between scint & ionization used to improve energy resolution







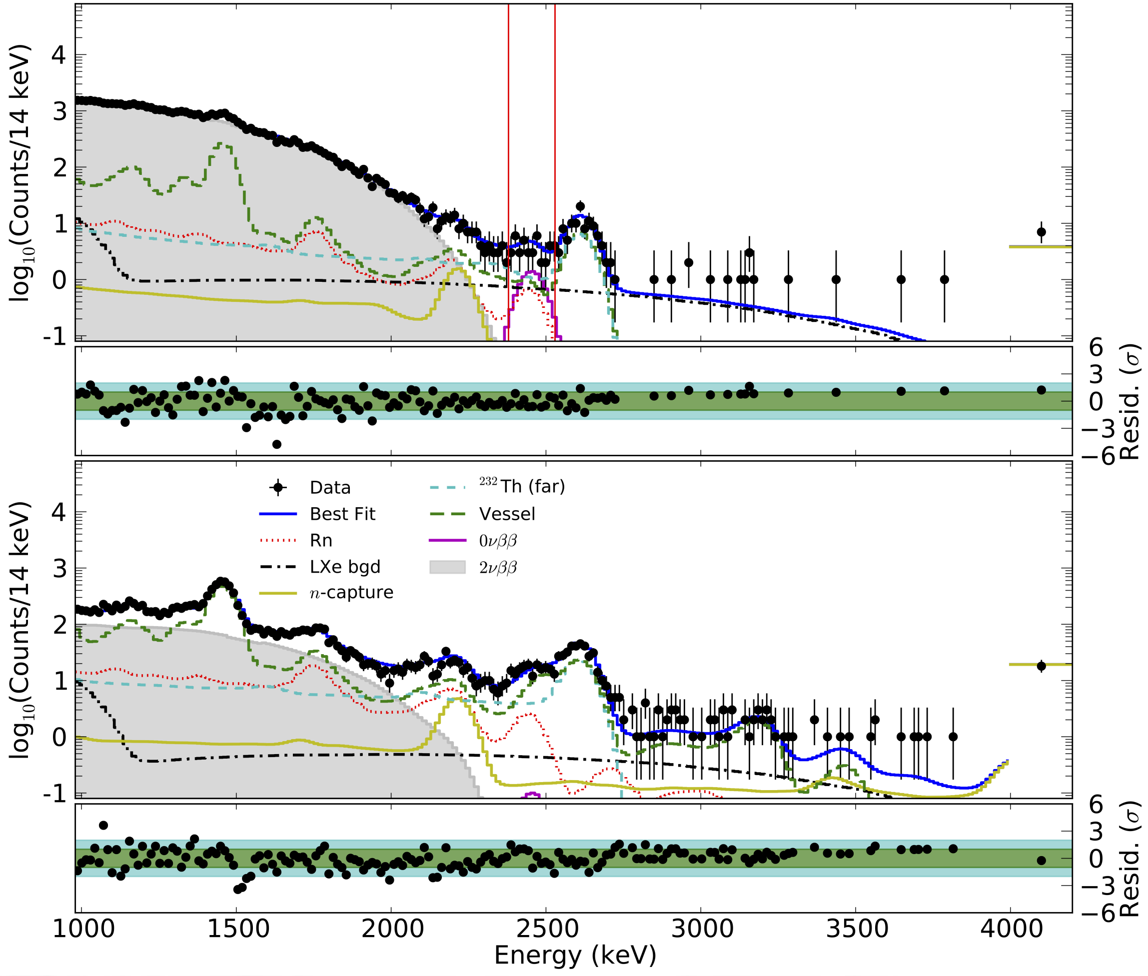
Detector examples & Recent Reults

EXO-200

- Background well understood
- Profile Likelihood Analysis
- No evidence for 0νββ in Xe^{136}
- Current half life limit:

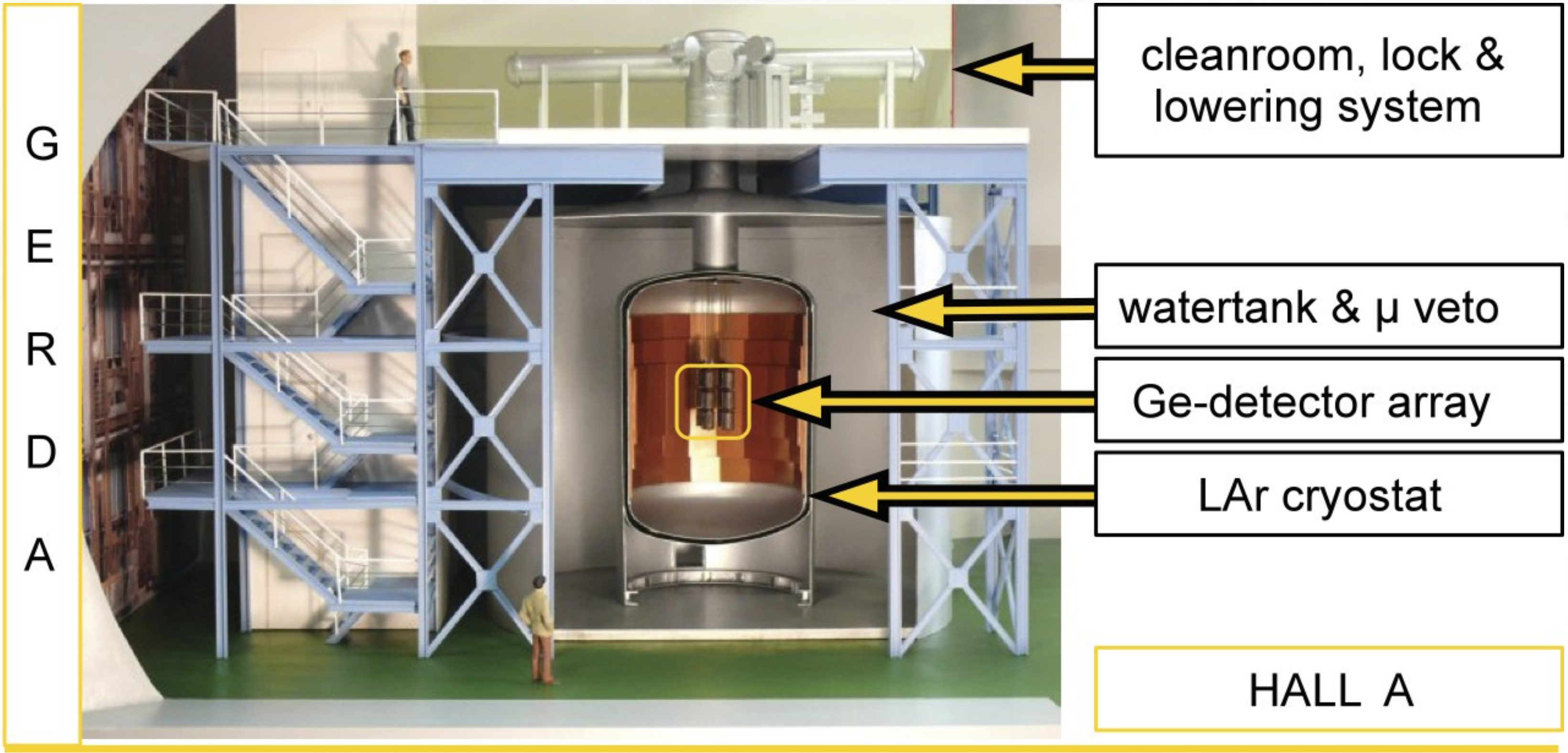
  1.1×10^{25} years, 90% CL
- Majorana neutrino mass:

  (190 – 450) meV



Detector examples & Recent Reults

GERDA


G E R D A

cleanroom, lock & lowering system

watertank & μ veto

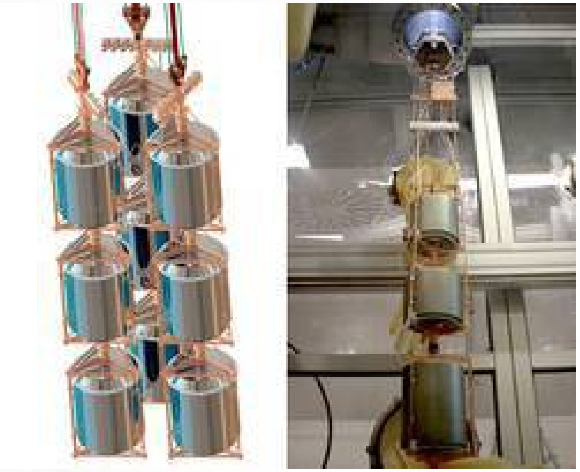
Ge-detector array

LAr cryostat

HALL A

Detector examples & Recent Reults

GERDA



- Strings of Ge detectors immersed in LAr
- Enrichment up to 86% ^{76}Ge possible
- Q-value: 2.039 MeV
- Detector = Source: very good detection efficiency: $\varepsilon \sim 100\%$
- Very good energy resolution: < 0.2% @ 2.6 MeV
- High-purity germanium → low intrinsic background
- Detector technology well established and developed (since ~1960)

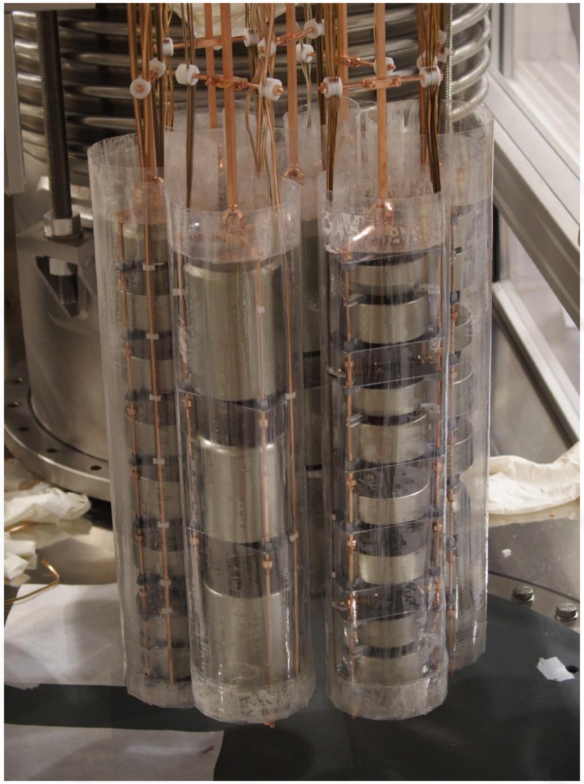
Detector examples & Recent Reults

GERDA - Phase I finished

- Exposure 21.6 kg x year
- Background: (11 ± 2) x 10^{-3} cts/(keV kg year)
- $T_{1/2} > 2.1 \times 10^{25}$ years (90% CL)

GERDA-Phase II, comissioned in Dec 2015

- 30 new Broad Energy Ge (BEGe) detectors
- Active mass 35.8 kg of enriched Ge
- Background reduction to ~10^{-3} cts/(keV kg year)



Goal

Exposure of 100 kg years
Improve limit on $T_{1/2} \sim 10^{26}$ years

Detector examples & Recent Reults

Recent Highlights

- The EXO, GERDA and KamLAND-Zen double beta decay detectors have essentially ruled out a long-standing claim for observation of the neutrinoless decay mode in ^{76}Ge (HdM).

- The CUORE Collaboration has brought the world's largest-volume dilution refrigerator to base temperature (6mK), a major step towards a ton-scale bolometric experiment.

- The MAJORANA DEMONSTRATOR Collaboration has reported record Cu purity from its underground electroforming campaign, and expects to achieve the ultra-low backgrounds specified. Commissioning runs with more than 10 kg of highly enriched ^{76}Ge are beginning in the SURF laboratory.

- The SNO+ experiment has demonstrated the stable suspension of isotopes in the scintillator Linear Alkyl Benzene, another path toward a ton-scale

Detector examples & Recent Reults

Isotope	Experiment	Mass [kg] (Total / FV)	Bckg [counts/y t] in ROI	FWHM in ROI [keV]
Ge^{76}	GERDA I	16/13	40	4
Xe^{136}	EXO-200	170/76	130	88
Xe^{136}	KamlandZen	383/88	210 per t(Xe)	400
Te^{130}	CUORE0	32/11	300	5.1

Isotope	Experiment	Exposure (kg year)	Sensitivity 10^{25} yr	$T_{1/2}$ $*10^{25}$ yr 90%CL	$<m_v>$ (meV)
Ge^{76}	GERDA I	21.6	2.4	>2.1	200-400
Xe^{136}	EXO-200	100	1.9	>1.1	190-450
Xe^{136}	KamlandZen	504	4.9	>11	60-161
Te^{130}	CUORE	19.75	0.29	0.4	270-760

Future “Ton Scale” experiments

Goal of current and future efforts - test inverted hierarchy parameter space with tonne scale experiments

^{76}Ge :

- Large Scale Ge, O(tonne) HPGE crystals (GERDA & MAJORANA)

^{82}Se :

- SuperNEMO : Se foils, tracking and calorimeter, 100 kg scale

^{136}Xe :

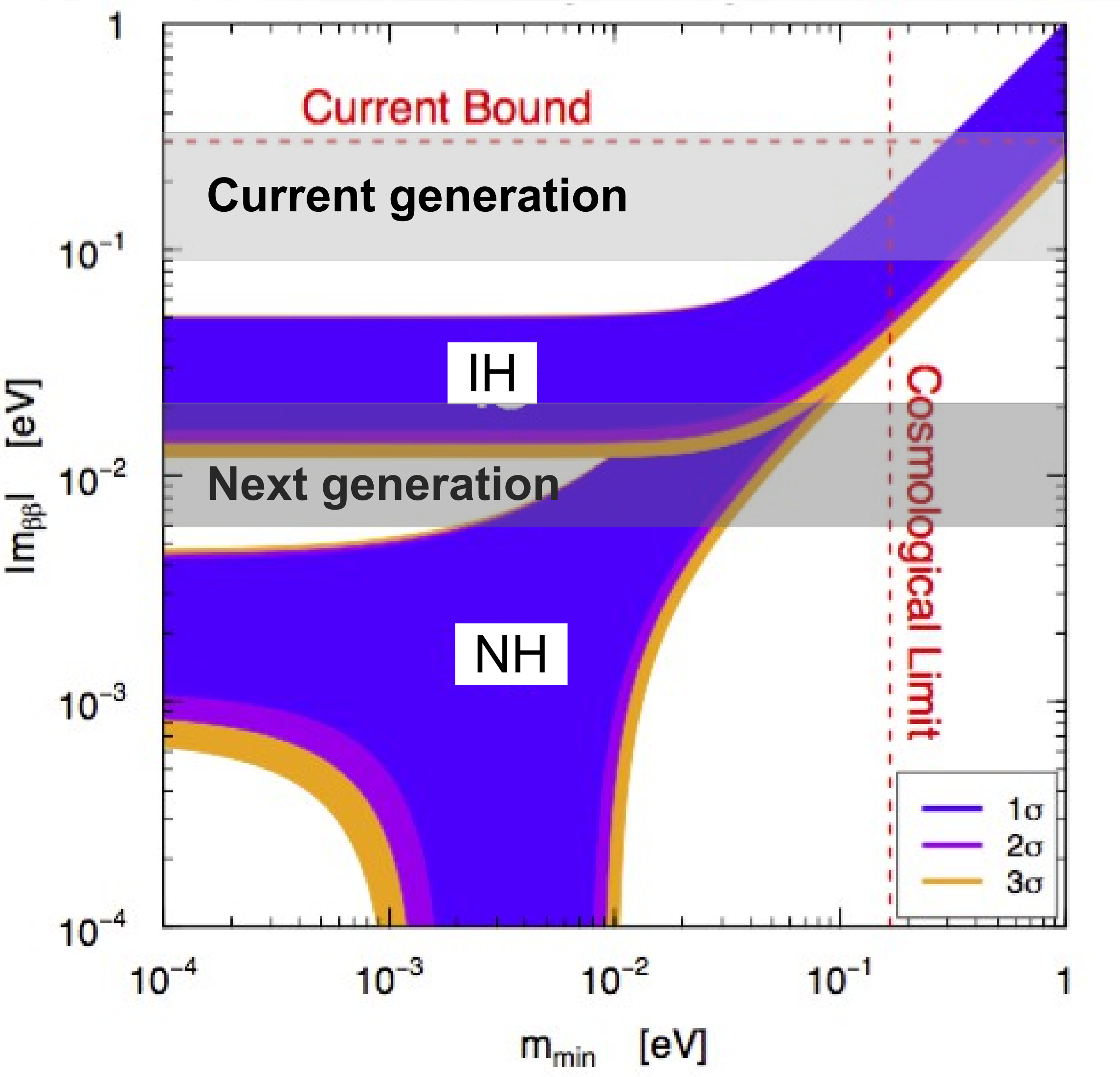
- KamLANDZen — ^{136}Xe in scintillator (several upgrades planned)
- NEXO - Liquid TPC, 5 tonne of ^{136}Xe
- NEXT - High pressure gas TPC, tonne scale LZ (dark matter), liquid TPC, 7 tonne

Future “Ton Scale” experiments

Isotope Mass

10-100 kg

1-10 ton



Background

10-100 cts/yr/ton

0.1-1 cts/yr/ton

Conclusion/Outlook

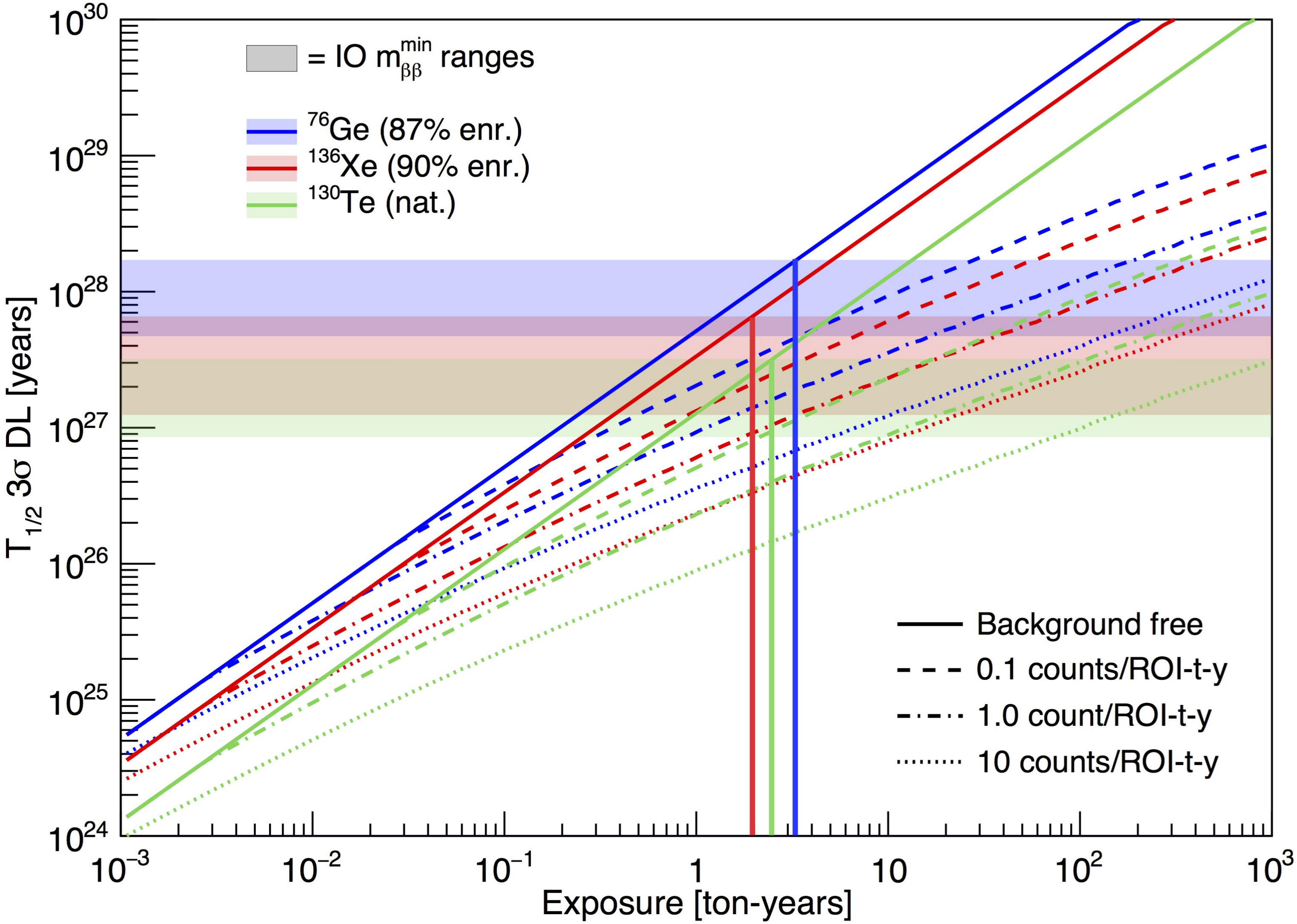
- 0νββ physics is the most sensitive probe of lepton number violation.
- A 0νββ discovery would proof the Majorana or Dirac nature of neutrinos and indicate physics beyond the Standard Model
- Halflife limits of 10^{25}-10^{26} years are currently probed, but no discovery claimed yet.
- Scalability of detector technology will push the limits further down. New results expected in few years
- Covering the inverted hierarchy with 10meV sensitivities is within reach

Many thanks to my collegues from the EXO-200 collabaration
who contributed with slides and comments

Backup slides

Future "Ton Scale" experiments

Discovery level, inverted hierarchy



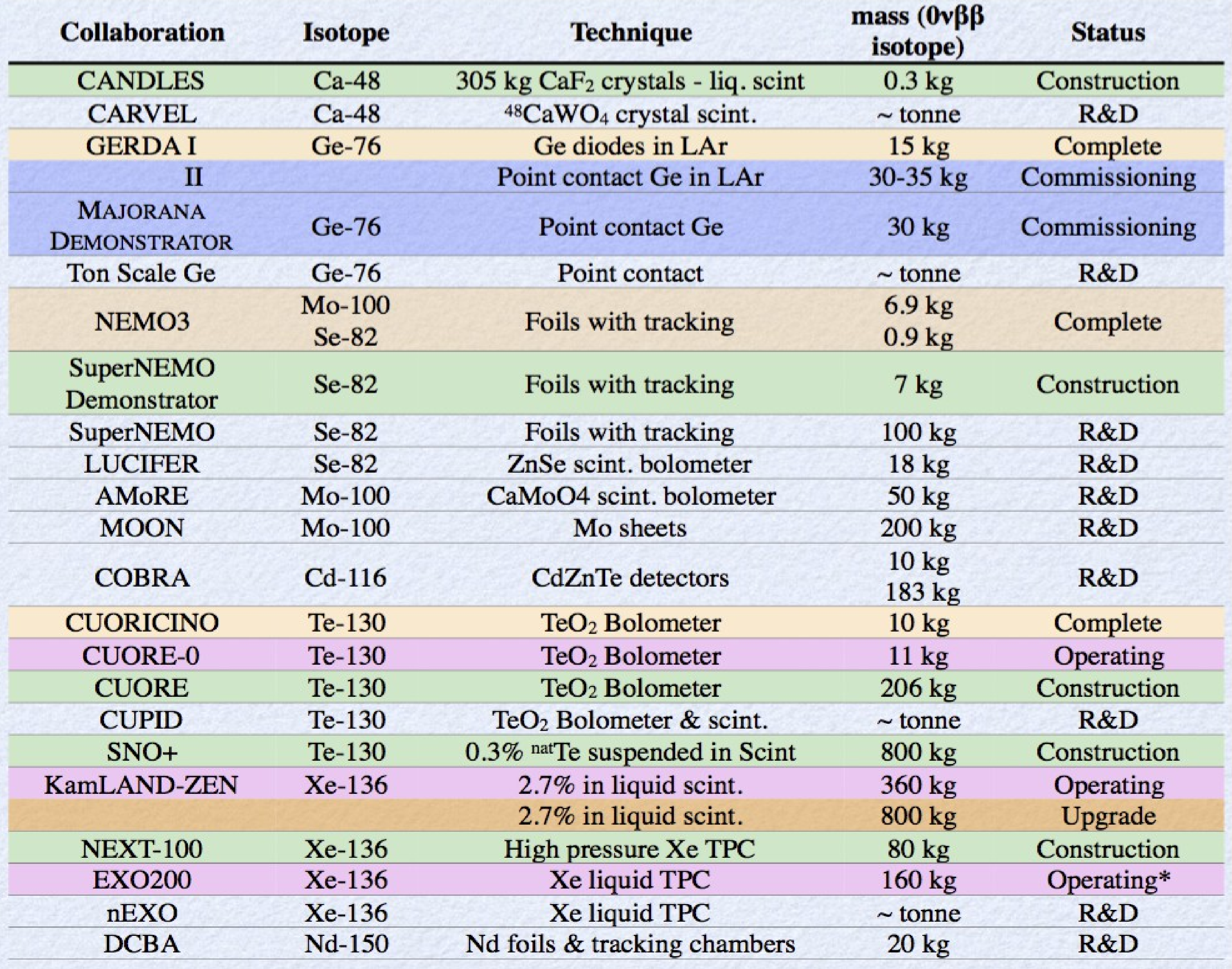
J.Detwiler

Future "Ton Scale" experiments

Ongoing upgrades and their projections

Isotope	Experiment	Mass [kg] (Total / FV)	Bckg [counts/y t] in ROI	FWHM in ROI [keV]
Ge^{76}	GERDA II	35/27	4	4
Ge^{76}	Majorana demonstrator	30/24	3	4
Xe^{136}	NEXT100	100/80	9	17
Te^{130}	CUORE	600/206	50	5
Te^{130}	SNO+	2340/160	45 per t (Te)	240

Global 0νββ Efforts



Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF$_2$ crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	^{48}CaWO$_4$ crystal scint.	~ tonne	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
II		Point contact Ge in LAr	30-35 kg	Commissioning
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	30 kg	Commissioning
Ton Scale Ge	Ge-76	Point contact	~ tonne	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	CaMoO4 scint. bolometer	50 kg	R&D
MOON	Mo-100	Mo sheets	200 kg	R&D
COBRA	Cd-116	CdZnTe detectors	10 kg 183 kg	R&D
CUORICINO	Te-130	TeO$_2$ Bolometer	10 kg	Complete
CUORE-0	Te-130	TeO$_2$ Bolometer	11 kg	Operating
CUORE	Te-130	TeO$_2$ Bolometer	206 kg	Construction
CUPID	Te-130	TeO$_2$ Bolometer & scint.	~ tonne	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	800 kg	Construction
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	360 kg	Operating
		2.7% in liquid scint.	800 kg	Upgrade
NEXT-100	Xe-136	High pressure Xe TPC	80 kg	Construction
EXO200	Xe-136	Xe liquid TPC	160 kg	Operating*
nEXO	Xe-136	Xe liquid TPC	~ tonne	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

Global 0νββ Efforts

Isotope	0νββ half life	Experiment	<m> eV
48-Ca	$> 1.4*10^{22}$ (90%CL)	ELEGANT-VI	< 7 - 44
76-Ge	$> 1.9*10^{25}$ (90%CL)	Heidelberg-Moscow	< 0.35
76-Ge	$2.3*10^{25}$ (90%CL)	Subset of HM coll.	0.32 +/- 0.03
76-Ge	$> 2.1*10^{25}$ (90%CL)	*GERDA†*	< 0.2 – 0.4
82-Se	$> 2.1*10^{23}$ (90%CL)	NEMO-3	<1.2 – 3.2
100-Mo	$> 5.8*10^{23}$ (90%CL)	NEMO-3	< 0.6 – 2.7
116-Cd	$> 1.7*10^{23}$ (90%CL)	Solotvino	< 1.7
130-Te	$> 2.8*10^{24}$ (90%CL)	Cuoricino	< 0.41 – 0.98
136-Xe	$> 1.9*10^{25}$ (90%CL)	*KamLAND-Zen*	< 0.12 – 0.25
136-Xe	$> 1.6\times10^{25}$ (90%CL)	*EXO-200*	< 0.14 – 0.38
150-Nd	$> 1.1*10^{24}$ (90%CL)	NEMO-3	< 0.33-0.62

Neutrino Oscillations

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

$$|\nu_i(t)\rangle = e^{-i(E_i t - \vec{p}_i\cdot\vec{x})}\,|\,\nu_i(0)\rangle$$

with $E_i = m_i c^2$

....

v_α = mass eigenstates

v_i = flavour eigenstates

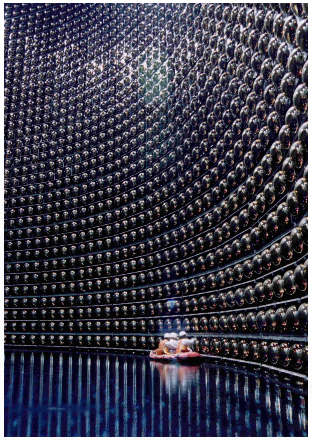
U = Lepton mixing matrix

L = Travel distance

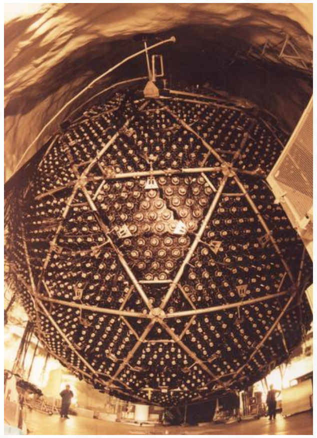
$$P_{\alpha\rightarrow\beta} \sim \sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right)$$

Neutrino oscillations = non-zero neutrino mass

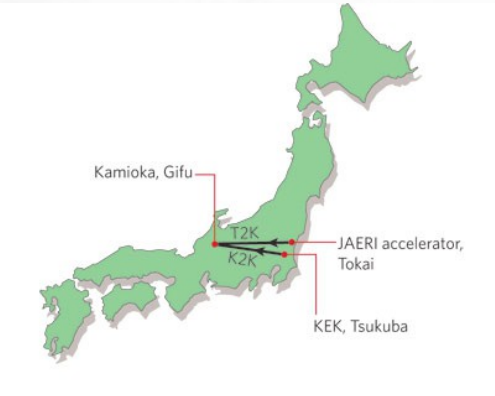
Neutrino Oscillations



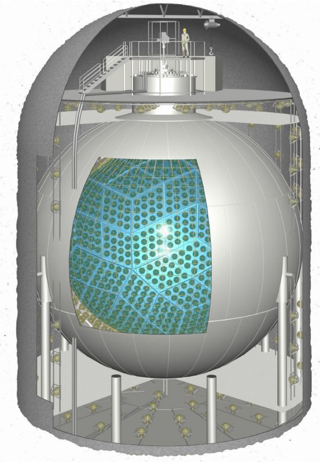
Super-K



SNO



K2K



KamLAND

Super-K: atmospheric v_μ oscillation

SNO: solar v_e flavor oscillation

K2K: accelerator v_μ oscillation

KamLAND: reactor v_e disappearance and oscillation