Neutrinoless Double Beta Decay

- Neutrinoless double beta decay: general aspects
- Experimental general aspects
- GERDA experiment as an example

Double Beta Decay: is the ν a Majorana particle?

We know that neutrino is:

1) fermion
2) electrically neutral
3) massive

$\Longrightarrow$ **It could be a Majorana particle**

Search for 0νββ decay is the only practical way to test Dirac/Majorana nature of neutrinos

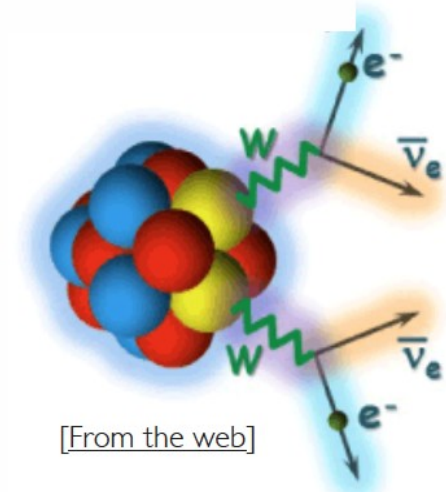
If Majorana particle exists, there are interesting implications for particle physics:

- Lepton number violation must occur: $\nu \equiv \nu^c \rightarrow |\Delta L| = 2$
- GUT, Leptogenesis model, See-Saw mechanism

Double Beta Decay in a nutshell

$$(A, Z) \to (A, Z+2) + 2e^- + 2\bar{\nu}_e$$

- 2nd order process allowed in the SM
- Single β decay forbidden (energy & angular momentum)
- 11 isotopes have been experimentally observed undergoing 2νββ decay



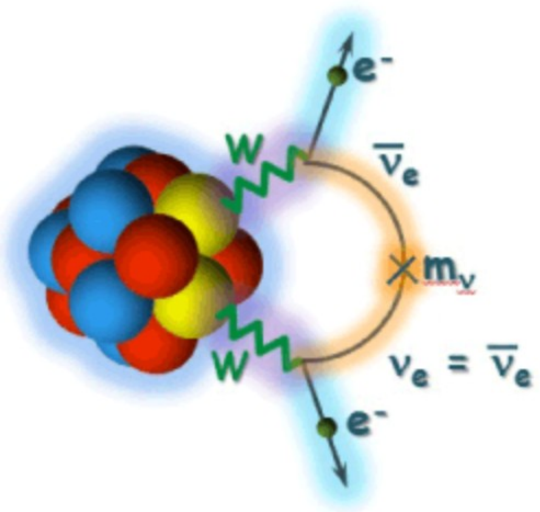
[From the web]

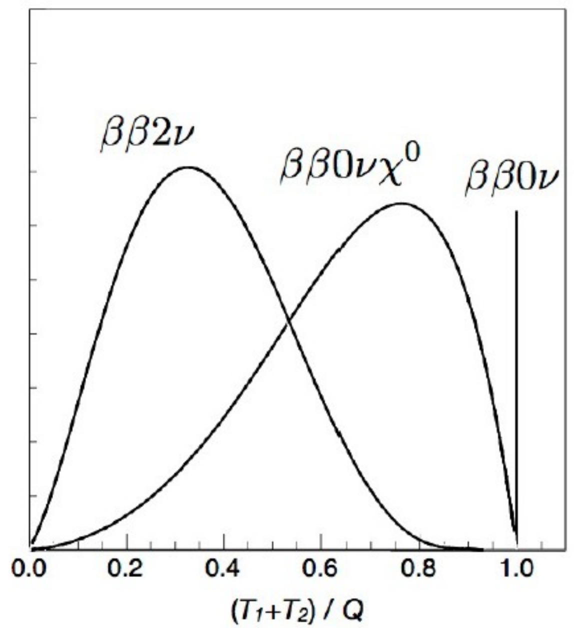
$$(T^{2\nu}_{1/2})^{-1} = G_{2\nu}(Q_{\beta\beta}, Z)|M_{2\nu}|^2$$

Neutrinoless Double Beta Decay in a nutshell

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

- Process forbidden in the SM
- Half-life strongly suppressed





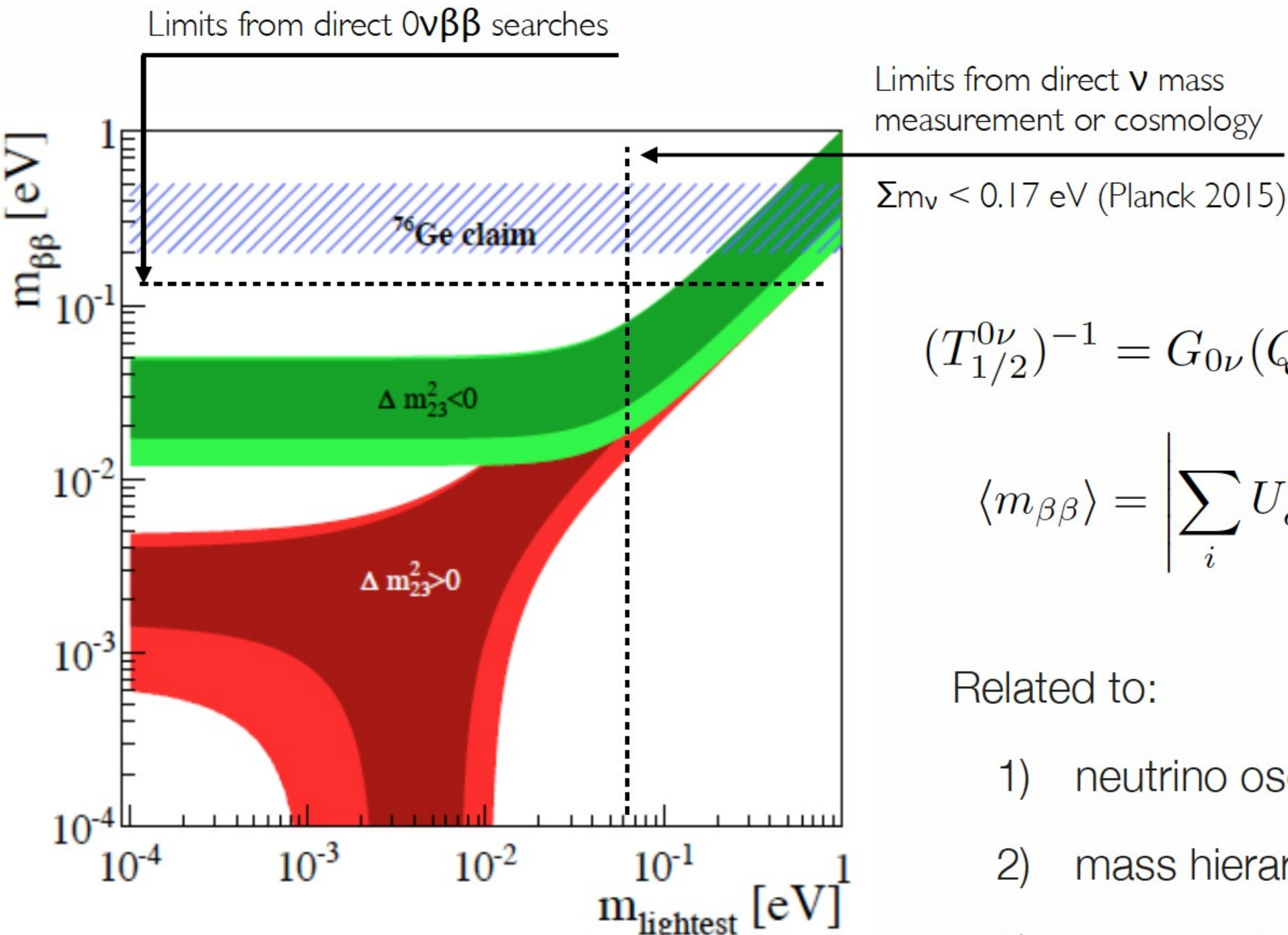
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\eta^2$$

Few different mechanisms may induce 0νββ

- Light Majorana neutrino exchange
- Right-handed current (V+A), SUSY, Majoron(s), etc.

Different topology in the final state!

Sensitivity to the light Majorana neutrino



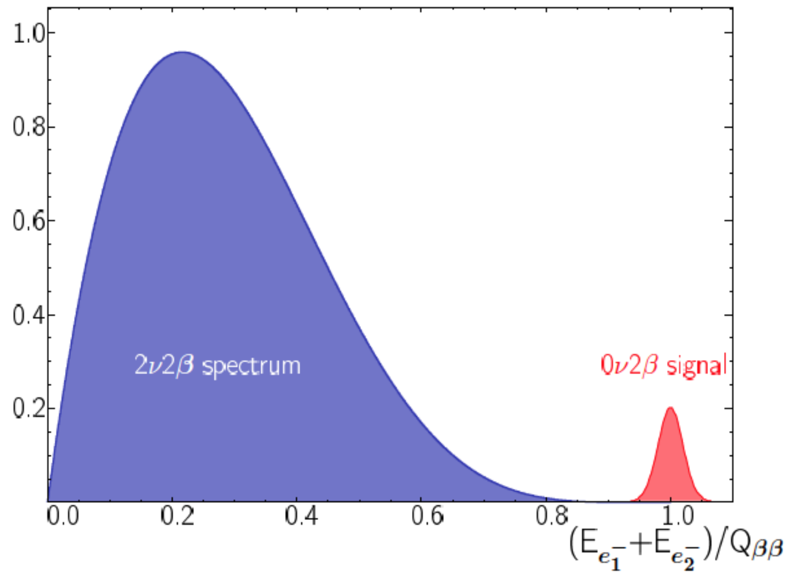
$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

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

Related to:

1) neutrino oscillation
2) mass hierarchy
3) mass scale

0νββ searches in practice



Measure the 2 e⁻ energy spectrum

- 2νββ signature → Broad spectrum
- 0νββ signal signature → Peak @ $Q_{\beta\beta}$

If no signal → set a limit on half life

In case of sizeable bkg

$$T^{0\nu}_{1/2} > \frac{N_A \ln 2}{n_\sigma} \times \frac{\epsilon}{A} \times \sqrt{\frac{M \times t}{B \times \Delta E}}$$

Detection efficiency

ββ emitter mass

Exposure time

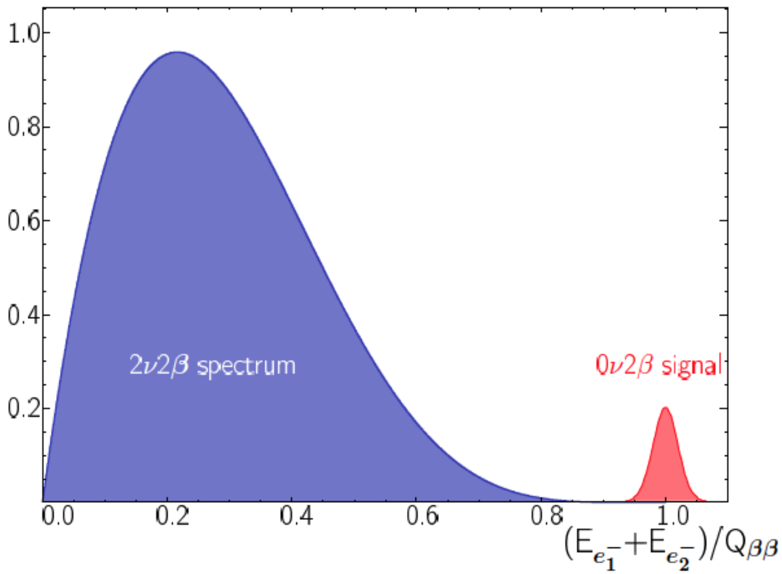
E res. @ Qββ

Excluded events at a given C.L.

Atomic mass

Bkg. index

0νββ searches in practice



Measure the 2 e^- energy spectrum

- 2νββ signature → Broad spectrum
- 0νββ signal signature → Peak @ $Q_{\beta\beta}$

If no signal → set a limit on half life

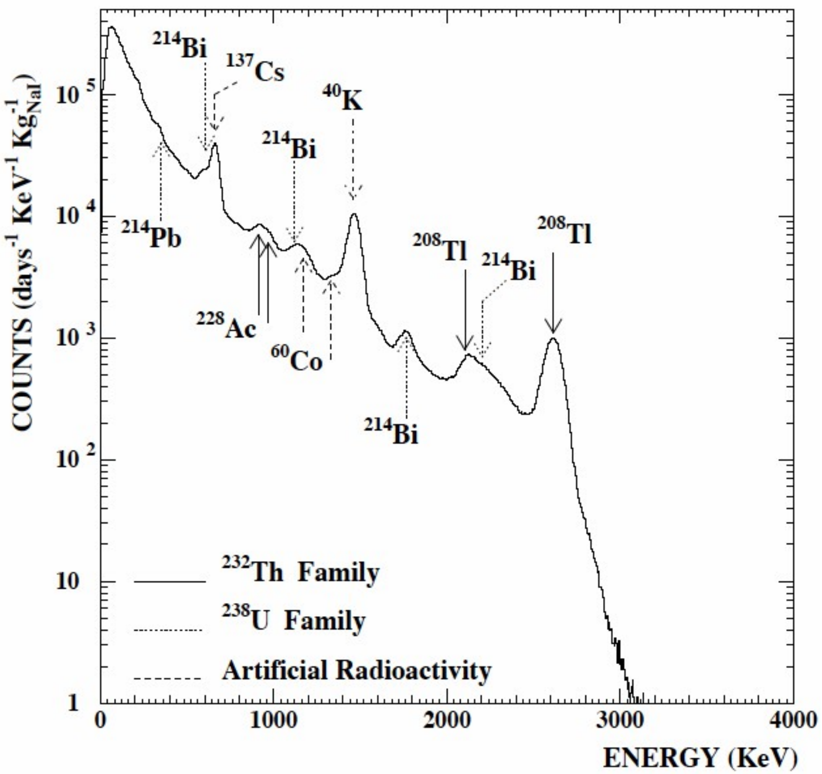
In case of zero bkg

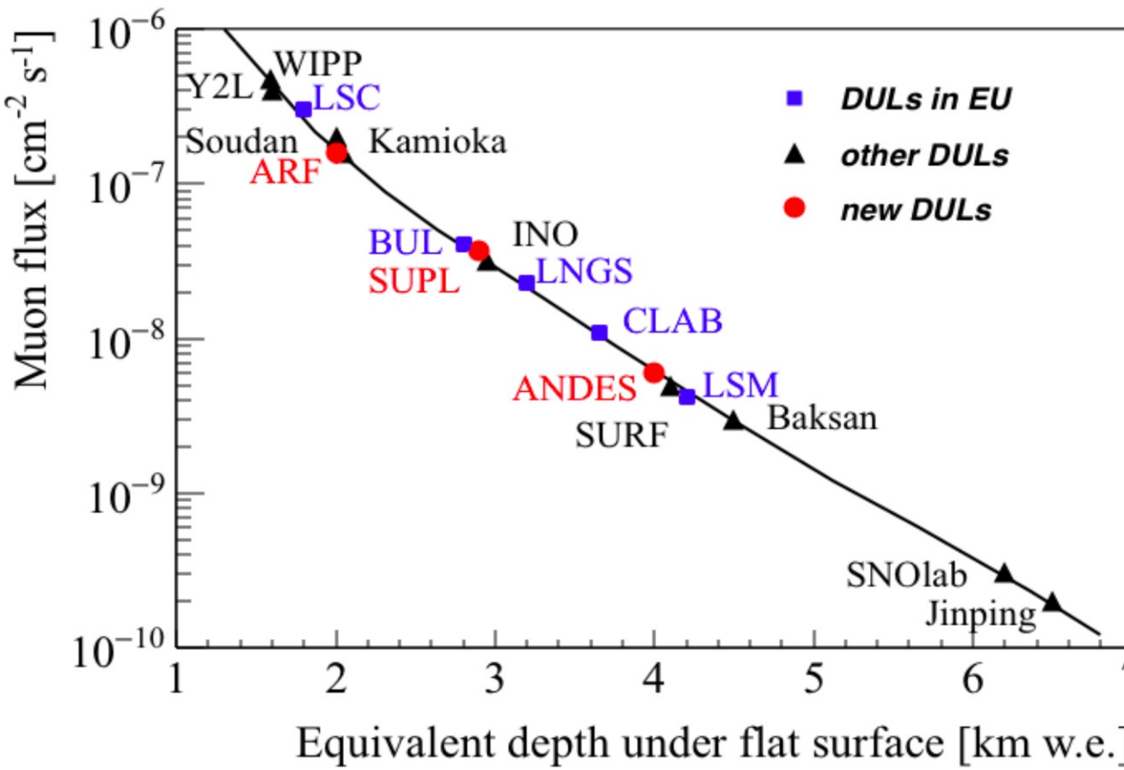
$$T_{1/2}^{0\nu} > \frac{N_A \ln 2}{n_\sigma} \times \frac{\epsilon}{A} \times (M \times t)$$

Few important aspects …

Low energy process ($Q_{\beta\beta} \lesssim 5$ MeV):

- Natural radioactivity is an issue (^{238}U , ^{232}Th)
- Cosmic muons are an issue



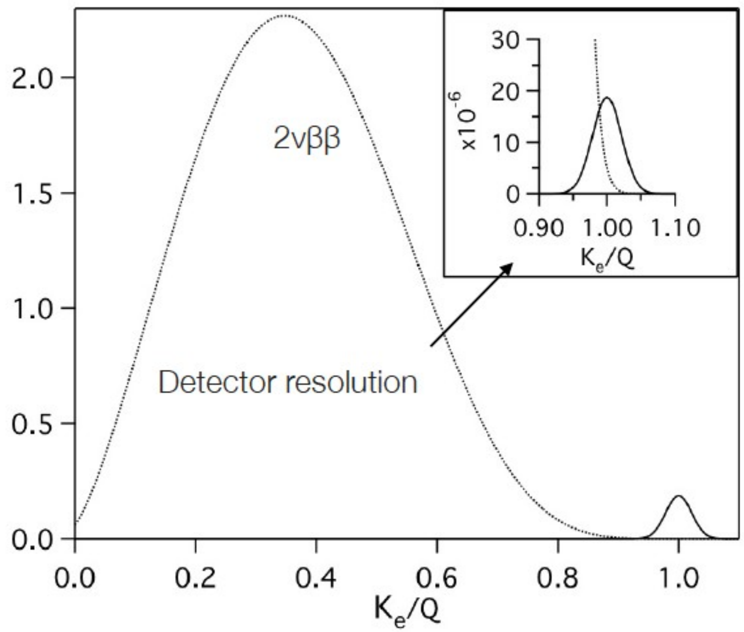


Few important aspects …

Distinguish 0ν from 2ν mode → irreducible background

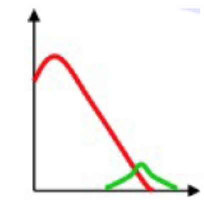
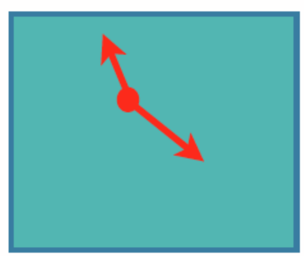
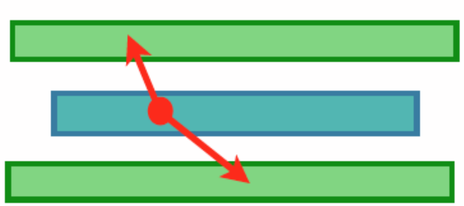
- Good detector energy resolution

Few available isotopes → multiply experimental efforts



Isotope	$Q_{\beta\beta}$ [keV]	Nat. abund. (enrich.) [%]
^{48}Ca → ^{48}Tl	4270	0.187 (73)
^{76}Ge → ^{76}Se	2039	7.8 (86)
^{82}Se → ^{82}Kr	2995	8.7 (97)
^{96}Zr → ^{96}Mo	3350	2.8 (57)
^{100}Mo → ^{100}Ru	3034	9.6 (99)
^{110}Pd → ^{110}Cd	2018	7.5
^{116}Cd → ^{116}Sn	2802	7.5 (93)
^{130}Te → ^{130}Xe	2527	34.5 (90)
^{136}Xe → ^{136}Ba	2480	8.9 (80)
^{150}Nd → ^{150}Sm	3367	5.6 (91)

Which technology?

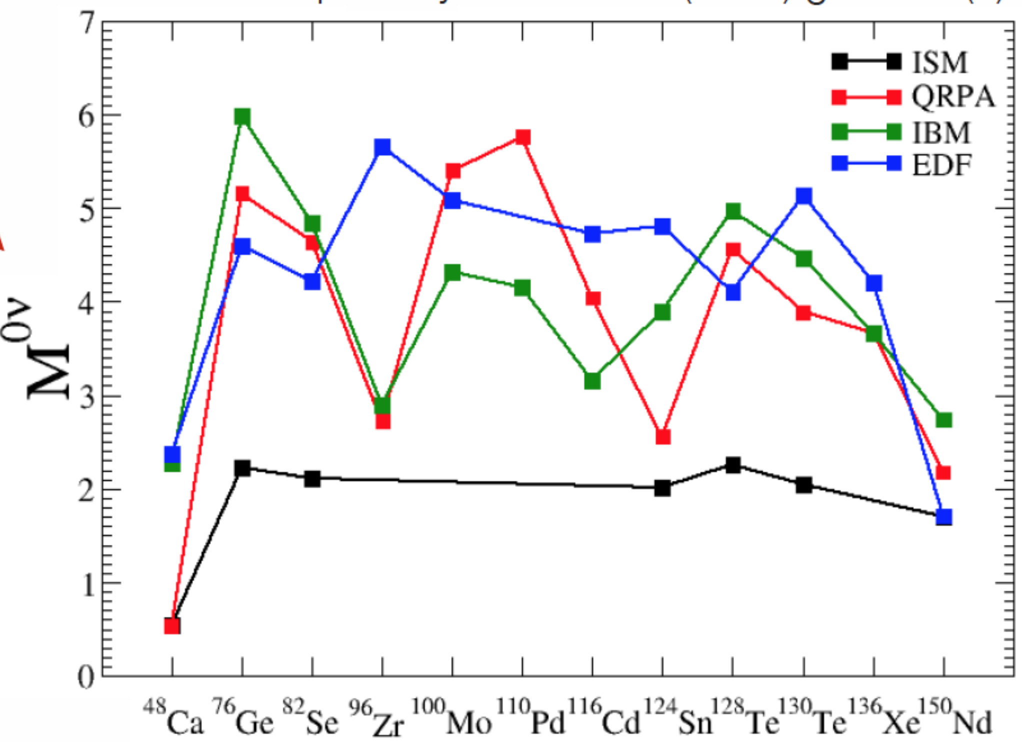
Technique \ En. resolution	< 1 % 	> 1 % 
Calorimeter  **Detector = Source**	Diodes ^{76}Ge	Liquid scintillators ^{136}Xe, ^{150}Nd, ^{48}Ca, ^{100}Mo
	Bolometers ^{130}Te, ^{82}Se, ^{100}Mo	Liquid/Gas TPC ^{136}Xe
Electron Tracking 		Tracking + Calorimetry ^{82}Se, ^{150}Nd, ^{48}Ca, ...
		Pixelized Scintillator ^{116}Cd

Watchout for the NME...

$$(T^{0\nu}_{1/2})^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2\eta^2$$

- Contain nuclear structure effects
- Many approximation methods
- Different among isotopes
- Measuring NME in 2νββ does not help

Compiled by F. Simkovic (2014) g_A =1.25(7)

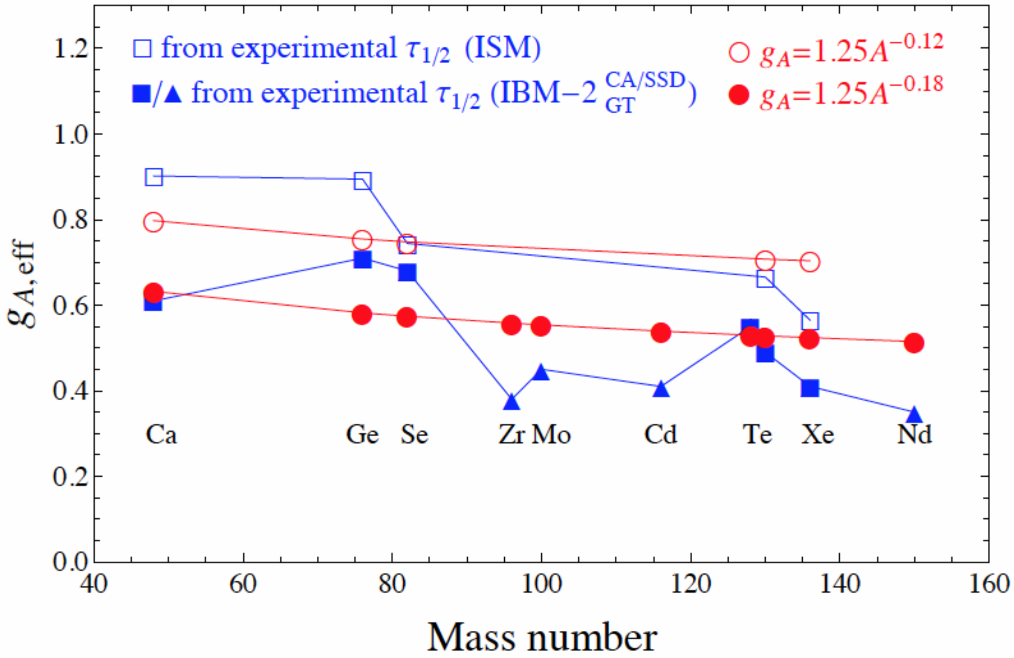


Main limitation in interpreting results & comparing among different isotopes

… but also the axial coupling constant

- g_A is know to be quenched in β and ββ decay
- An effective constant is extracted from experimental measurement
- Quenching factor ~0.8 — 0.5
- g_A quenched in 0νββ as much as in 2νββ?

[Phys. Rev. C 87, 014315 (2013)]

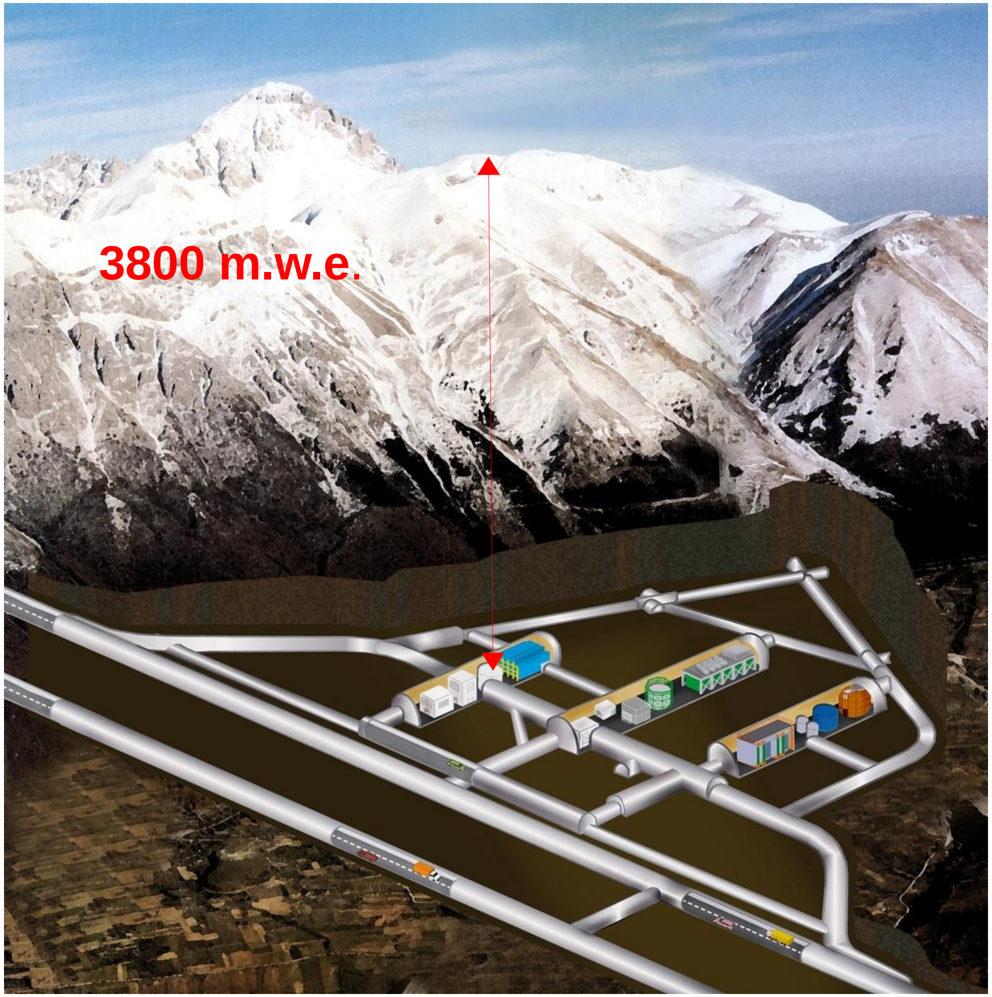


g_A appear at the 4th power in $T_{1/2}$ calculation
→ it may impact ⟨$m_{\beta\beta}$⟩ sensitivity up to x6–34

GERDA experiment as an example

Gerda @ LNGS: Background reduction

- **GERDA situated in LNGS underground laboratories**
- 3800 m.w.e.



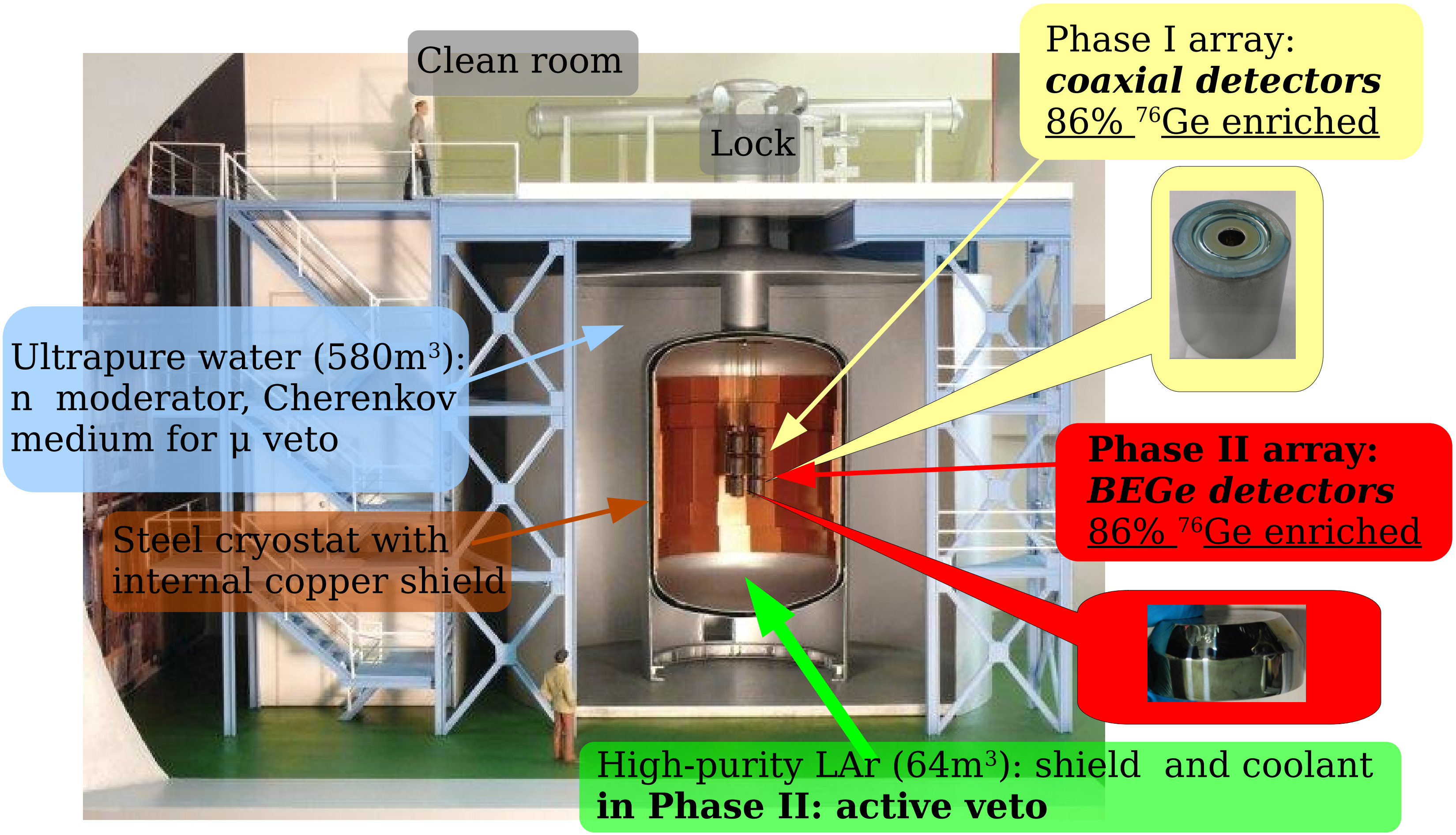
Possible **backgrounds** from:

External:
- γ from Th and U chain
- neutrons
- μ from cosmic rays (prompt and delayed)

Internal:
- cosmogenic ^{60}Co ($T_{1/2}$=5.3 yr)
- cosmogenic ^{68}Ge ($T_{1/2}$=271 d)
- Radioactive surface contaminations

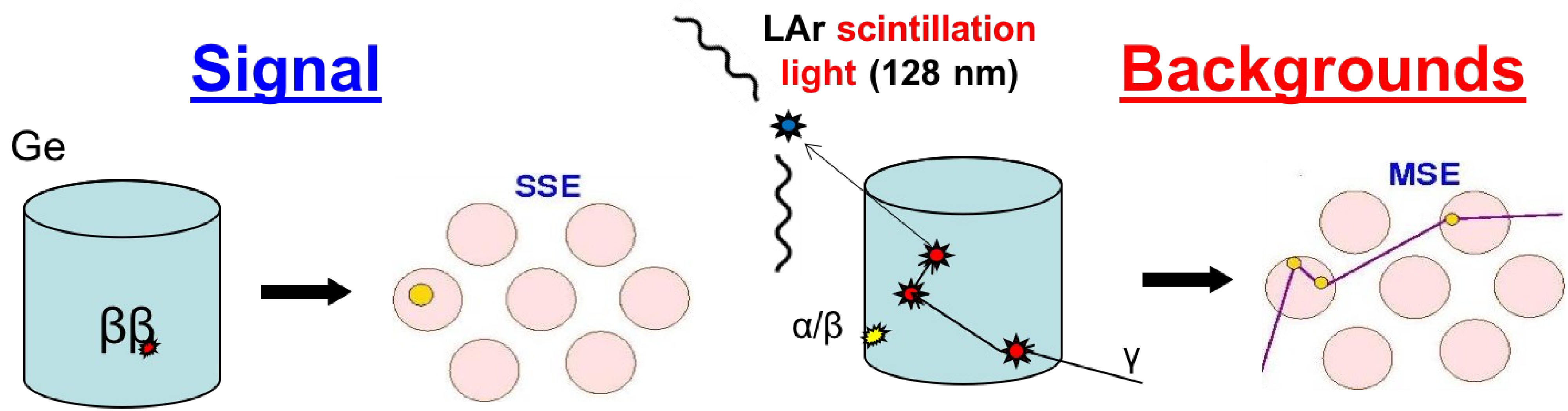
Gerda @ LNGS: Background reduction

- Graded shielding against ambient radiation
- Rigorous material selection,
- Avoid exposure above ground for enriched (86% ^{76}Ge) Ge detectors
- Active background suppression



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

Active background reduction tools

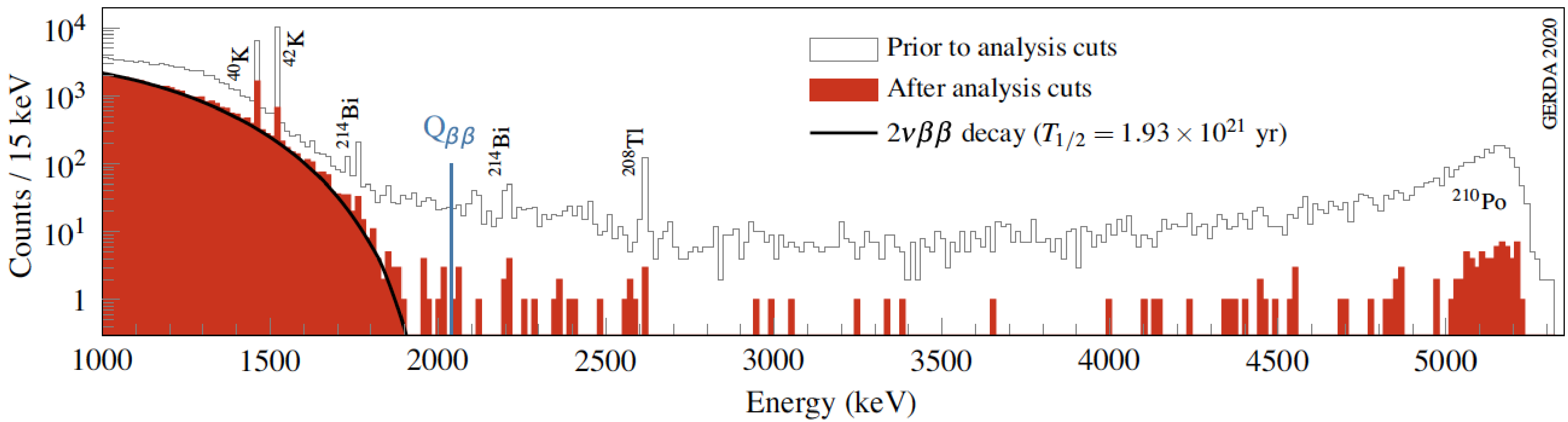


Point-like (single-site) energy deposition inside one HP-Ge diode

Multi-site energy deposition inside HP-Ge diode (Compton scattering), or **surface** events

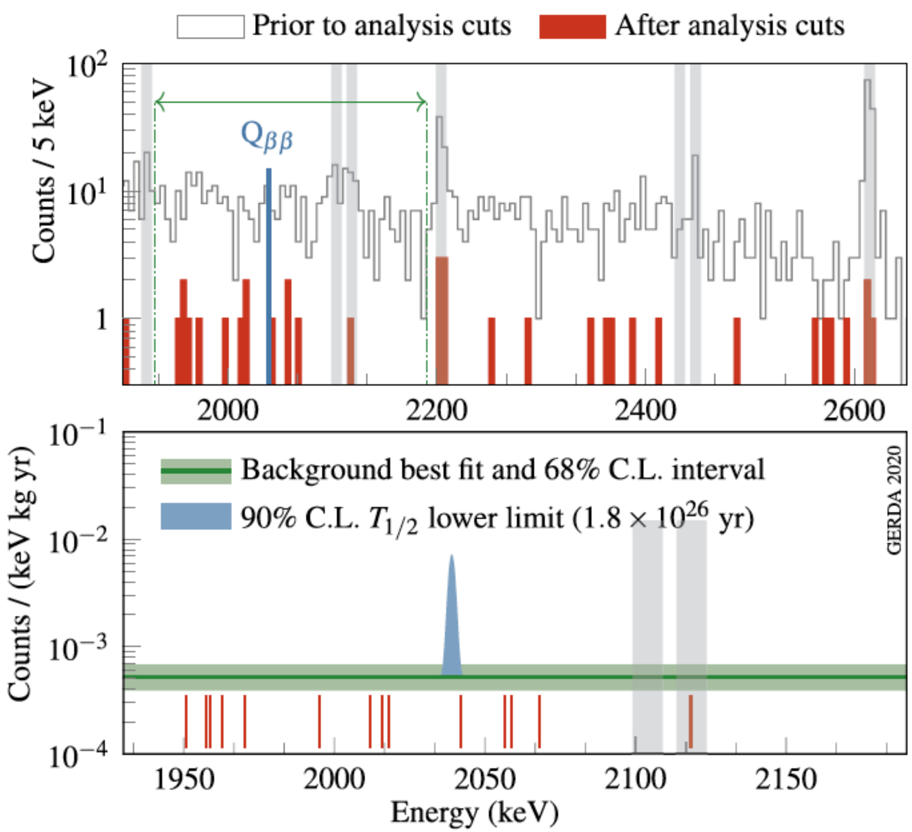
- **Anti-coincidence** with the **muon veto** (MV)
- Anti-coincidence **between detectors** (cuts multi-site) (AC)
- **Active veto** using LAr scintillation (LAr Veto)
- **Pulse shape** discrimination (PSD)

Phase II GERDA spectra



- Full statistics
- LAr and PSD highly effective cuts
- Final background at $Q_{\beta\beta}$ $O(10^{-3}$ counts/keV· kg· yr)

Statistical Analysis



- **Frequentist analysis**:
  Best fit $N^{0\nu} = 0$
  $T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ **yr @ 90% C.L.**
  Median Sensitivity (NO Signal)
  $T^{0\nu}_{1/2} > 1.8 \cdot 10^{26}$ **yr @ 90% C.L.**

- upper limit on
  $m_{\beta\beta} < 79 - 180$ **meV**

- **Bayesian analysis**:
  $T^{0\nu}_{1/2} > 1.4 \cdot 10^{26}$ **yr @ 90% C.I.**
  Median Sensitivity:
  $T^{0\nu}_{1/2} > 1.4 \cdot 10^{26}$ **yr @ 90% C.I.**