The GERDA Experiment: Search for the Neutrinoless Double Beta Decay

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Ettore Majorana

The Universe Today

All galaxies and stars consist of baryons.

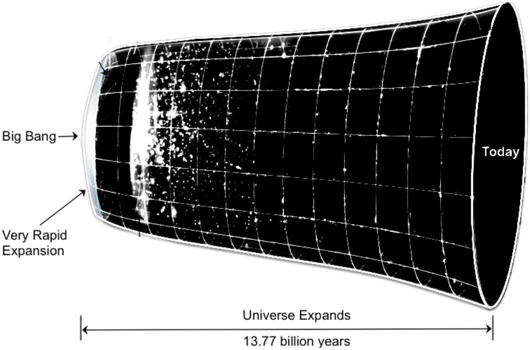
- Universe completely **matter dominated**.
- Antimatter exists only as a product of high-energy particle collisions.
- Antimatter regions of space would be detectable by gamma rays from annihilation reactions along its boundary.

Large Magellan Cloud. Source: nasa.gov

A Symmetrical Universe

According to the Standard Model of Particle Physics:

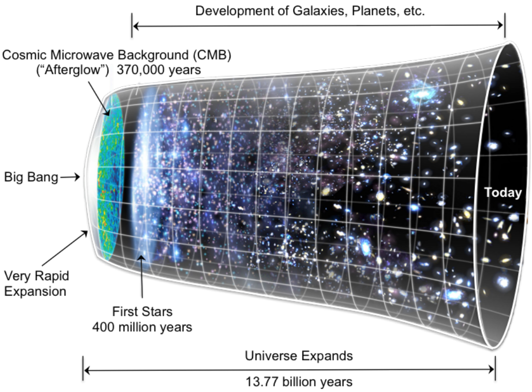
- Early Universe after Big Bang completely symmetrical.
- **Equal** amounts of matter and antimatter.
- Quark and antiquarks annihilate in pairs, producing photons: $n_q, n_{\bar{q}} \approx n_\gamma$.
- Leading to the complete **annihilation** of a perfectly symmetrical early universe.
- Only radiation is left.



The Asymmetrical Universe

In reality:

- Slight **asymmetry** introduced in the early stages of the universe.
- **Surplus** of matter in comparison to antimatter.
- Quark and antiquarks annihilate in pairs, producing photons: $n_q, n_{\bar{q}} \approx n_\gamma$.
- After annihilation, low fraction of matter **survives**.
- All the galaxies and stars descend from this small **excess of matter**.



Neutrinos Beyond the Standard Model

Origin of asymmetry could lie in neutrino nature.

- In 1937, **Ettore Majorana** suggested that neutrino could be its own antiparticle.
- Recent discovery of neutrino **oscillations** establish non-zero **mass** of neutrinos.

Explanation through Standard Model extension:

- See-saw mechanism introduces **right-handed neutrinos**.
- CP violating decays of these particles spontaneously generate leptons resulting in a **lepton asymmetry** in the early universe.
- **Baryogenesis via leptogenesis** could lead to the observed matter antimatter asymmetry. [Phys. Lett. B 174: 45]

Investigation of neutrino nature:

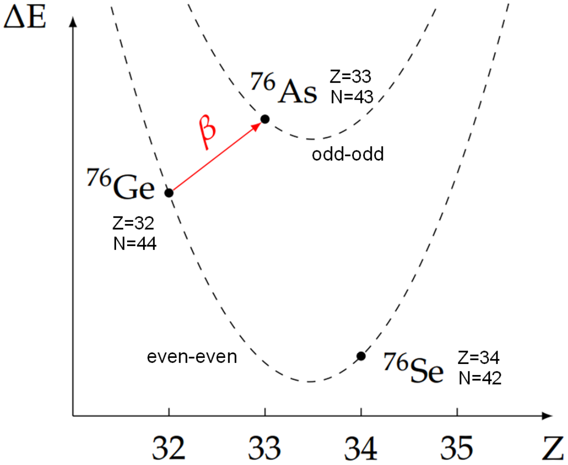
- Prime avenue is **neutrinoless double beta decay**.

Ettore Majorana

Beta Decay of ^{76}Ge

Decay channels of ^{76}Ge:

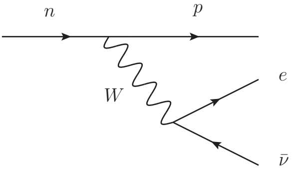
- Beta decay β^- to ^{76}As energetically forbidden.



Beta decay β^-

- Neutron decays to

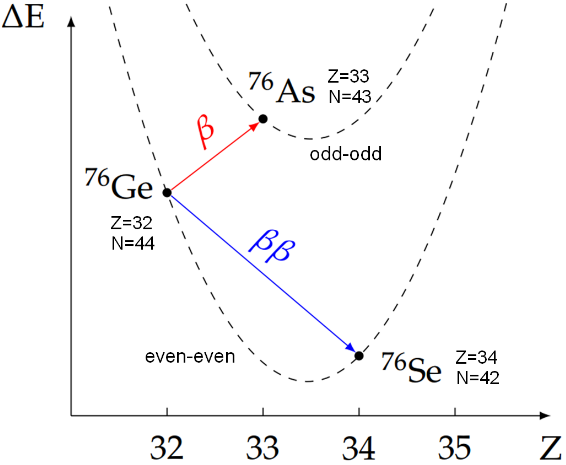
$$\Rightarrow \begin{cases} \text{proton} \\ \text{electron} \\ \text{antineutrino} \end{cases}$$



Double Beta Decay of ^{76}Ge

Decay channels of ^{76}Ge:

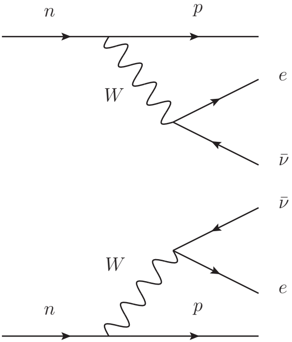
- Double beta decay $\beta\beta$ to ^{76}Se allowed.



Double beta decay $\beta\beta$

- 2 neutrons decay to

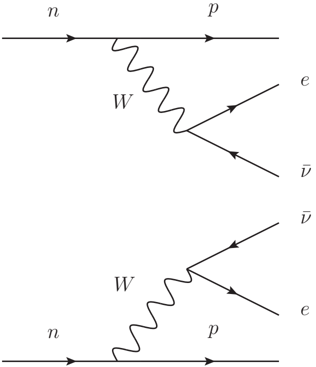
$$\Rightarrow \begin{cases} 2\text{ protons} \\ 2\text{ electrons} \\ 2\text{ antineutrinos} \end{cases}$$



Neutrinoless Double Beta Decay of ^{76}Ge

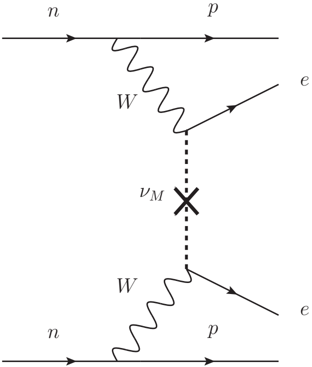
Double beta decay $2\nu\beta\beta$:

- **Rarest** observed decay.
- Possible for Dirac and Majorana neutrinos, SM ΔL=0.
- **2 neutrinos** in the final state.



Neutrinoless double beta decay $0\nu\beta\beta$:

- **Postulated** decay channel.
- Involved Majorana neutrinos **annihilate** off-shell, non-SM ΔL=2.
- **0 neutrinos** in the final state.



Signature of Neutrinoless Double Beta Decay of ^{76}Ge

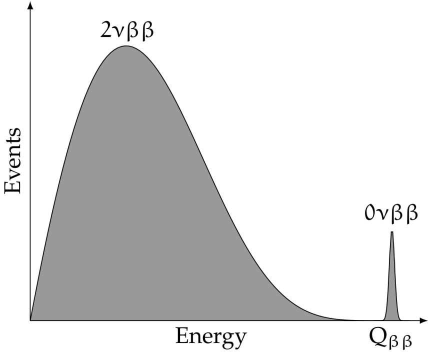
Summed **energy spectrum** of final state electrons:

Double beta decay $2\nu\beta\beta$:

- Continuum

Neutrinoless double beta decay $0\nu\beta\beta$:

- Peak at $Q_{\beta\beta}$= 2039 keV

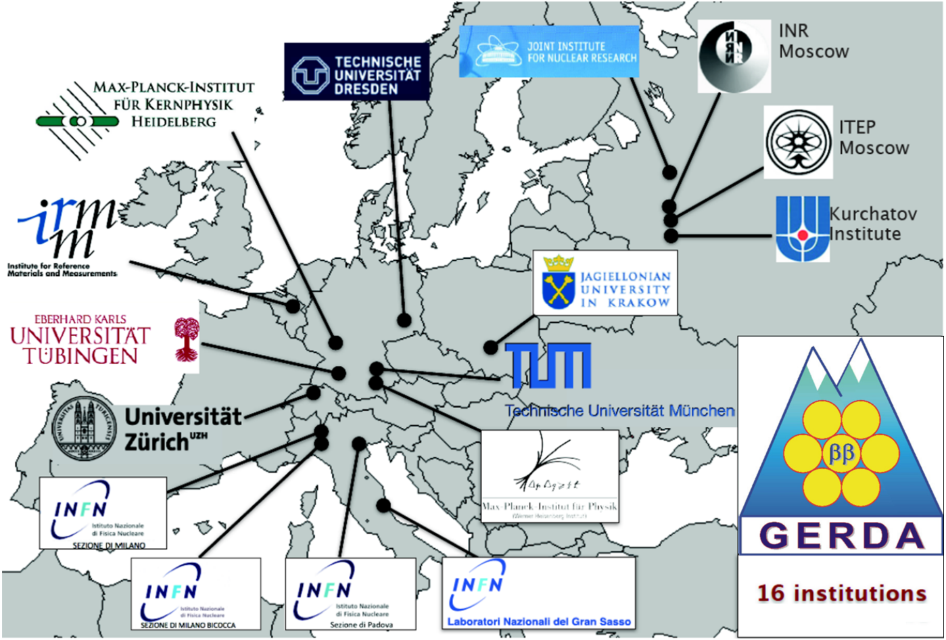


(peak not to scale)

Consequences of discovery:

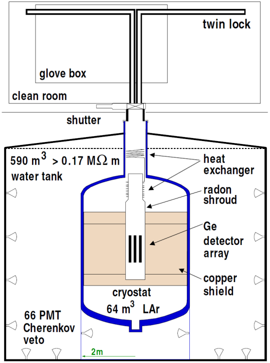
- Neutrinos have Majorana mass component.
- Rate of decay clue on absolute neutrino mass and hierarchy.
- Important step towards solving enigma of matter antimatter asymmetry.

The GERDA Collaboration



The GERDA Experiment [Eur. J. Phys. C 73 (2013) 2330]

- **Germanium Detector Array** directly submerged in **liquid argon (LAr)** cryostat.
- Surrounded by **Cherenkov muon veto** water tank.
- Located underground in Hall A of **Laboratori Nazionali del Gran Sasso (LNGS)**.
- 1400 m overburden (μ flux $\sim 1\ \mathrm{m}^{-2}\mathrm{h}^{-1}$).



Low activity LAr, Water

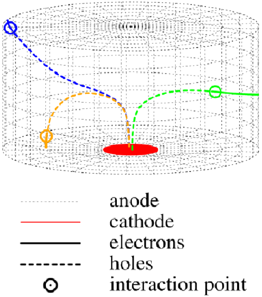
Material	^{208}Tl Activity [μBq/kg]
Rock, concrete	3000000
Stainless steel	~ 5000
Cu (NOSV), Pb	< 20
Purified water	< 1
LN_2, LAr	~ 0

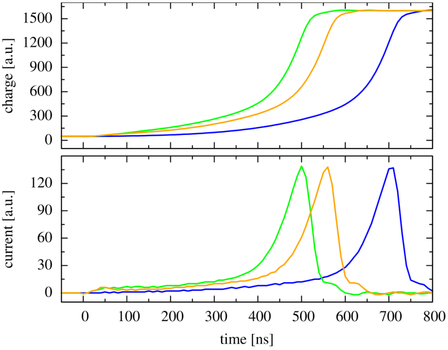
$0\nu\beta\beta$ Decay Search with Germanium Detectors

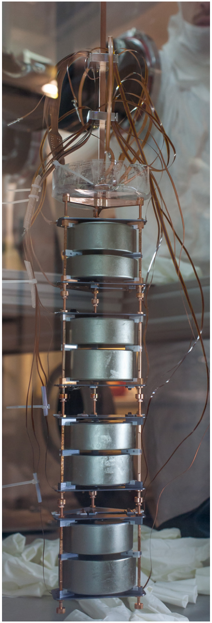
Germanium detectors:

- Concept: Sources = Detectors. Isotopic enrichement to ∼ 86%.
- Reverse bias high voltage: Measurement of **ionisation** energy.
- Excellent **energy resolution**: ∼ 1.5‰ FWHM at $Q_{\beta\beta}$.
- **Pulse Shape Discrimination (PSD)**

$$\Rightarrow \begin{cases} \text{single site events (e.g. } 0\nu\beta\beta) \\ \text{multi site events (e.g. Compton scattered } \gamma) \\ \text{surface events (e.g. } \alpha/\beta \text{ events)} \end{cases}$$





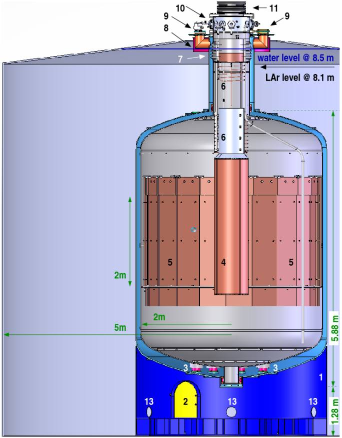


Phase II String

Background Suppression in the Search for $0\nu\beta\beta$ Decay

Rare decay measurement requires low background.

- Operation of the experiment **underground**.
- Background suppression with **water** and **LAr shielding**.
- **Active veto** for cosmic muons and external radiation.
- **Minimise** radioactivity of materials close to detectors.
- **Pulse Shape Discrimination (PSD)**



Background limited scenario:

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

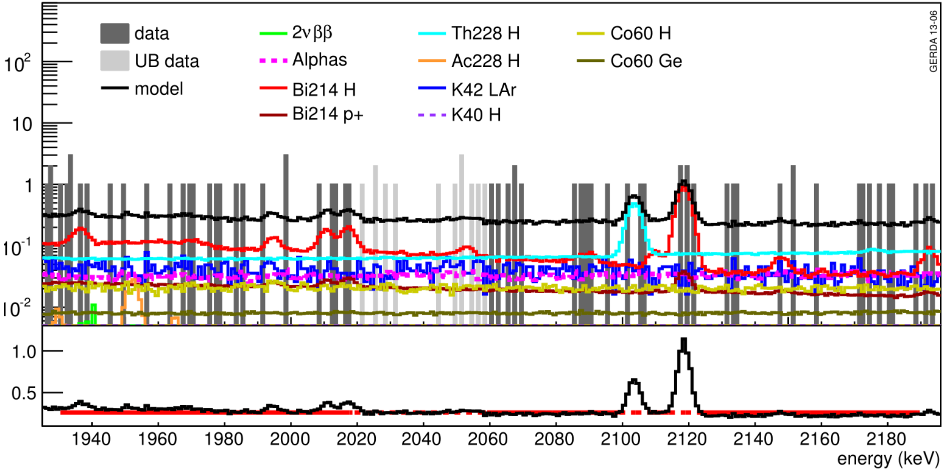
$M \cdot t$: exposure, ΔE: energy resolution, BI: background index.

Zero background regime:

$$T_{1/2}^{0\nu} \propto M \cdot t$$

- Goal: Achieve **zero background regime** to enable proportional scaling with exposure.

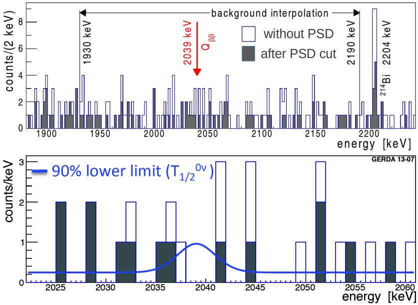
Region of Interest Background Identification [Eur. Phys. J. C 74 (2014) 2764]



- Phase I background best fit **background model** and individual contributions.
- Fit performed **before unblinding** the 40 keV window around $Q_{\beta\beta}$.
- $\mathrm{BI} = 1.0(1) \cdot 10^{-2}$ counts/(keV·kg·yr). Design goal fulfilled.
- Background **one order of magnitude better** than previous experiments.

Main Results of GERDA Phase I

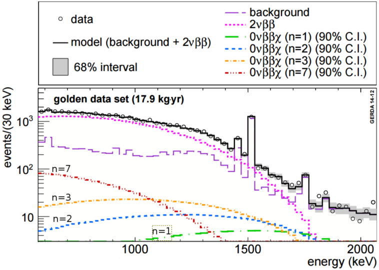
Analysis of $0\nu\beta\beta$ decay [Phys. Rev. Lett. 111 (2013) 122503]



- 10 germanium detectors, 21.6 kg·yr exposure.
- Result: **No signal excess.**
  (expected: 2.5, observed: 3 events)
- **Lower limit** on $T^{0\nu}_{1/2}$ of ^{76}Ge:
  $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr with 90% C.L.

  Combined with HDM and IGEX:
  $T^{0\nu}_{1/2} > 3.0 \cdot 10^{25}$ yr with 90% C.L.

Analysis of $2\nu\beta\beta$ decay and $0\nu\beta\beta$ with Majoron Emission [Eur. Phys. J. C 75 (2015)]



- Measured half life:
  $T^{2\nu}_{1/2} = (1.926 \pm 0.095) \cdot 10^{21}$ yr
- Compatible with [J. Phys. G40 (2013) 035110].
- Search for $0\nu\beta\beta$ decay with Majoron emission performed for spectral index $n = 1, 2, 3, 7$.
- **No signal found**, limits of $O(10^{23})$ yr on half-lives.

Upgrade to GERDA Phase II [PoS (TIPP2014) 109]

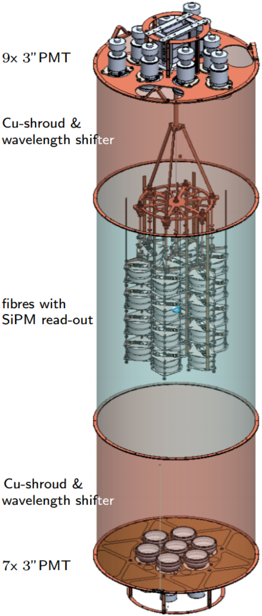
Germanium detector array upgrade:

- Addition of more **Broad Energy Germanium Detectors** ⇒ **Enhanced** PSD capabilities.
- Phase II in total **40 detectors** on **7 strings**.

LAr hybrid veto system:

- Installation of Photomultiplier Tubes **(PMTs)** and optical fibre curtain coupled to Silicon Photomultipliers **(SiPMs)**.
- Detection of **LAr scintillation light** to reject external background events.

Phase	Active Mass [kg]	BI [counts/(keV·kg·yr)]	$T^{0\nu}_{1/2}$ Sensitivity [yr]
I (finished)	15	10^{-2}	$2.1 \cdot 10^{25}$
II (expected)	35	10^{-3}	$1.4 \cdot 10^{26}$



Summary and Outlook

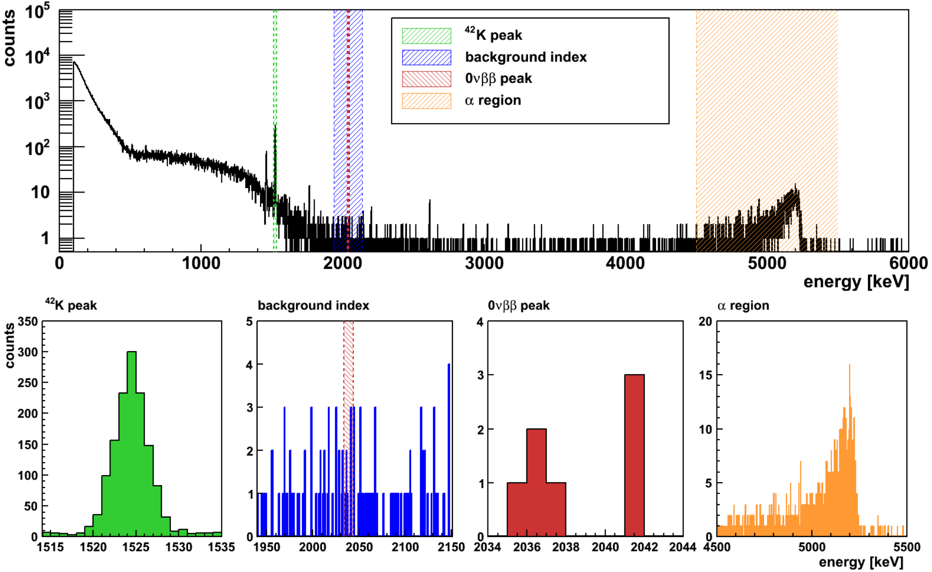
GERDA Phase I Results:

- Limit on the $0\nu\beta\beta$ decay half life: $T^{0\nu}_{1/2} > 2.1 \cdot 10^{25}$ yr (90% C.L.)
- Limit on the effective neutrino mass: $m_{\beta\beta} <$ 0.2-0.4 eV (90% C.L.)

GERDA Phase II Outlook:

- Expected background at $Q_{\beta\beta}$: 10^{-3} counts/(keV·kg·yr).
- Expected sensitivity on the $0\nu\beta\beta$ decay half life: $T^{0\nu}_{1/2} \sim 1.4 \cdot 10^{26}$ yr.
- Expected limit on the effective neutrino mass: $m_{\beta\beta} \sim 0.1$ eV.
- Upgrade of experiment has been **finished**.
- Phase II **data taking** has begun December 2015.

GERDA Phase I Background [Eur. Phys. J. C 74 (2014) 2764]



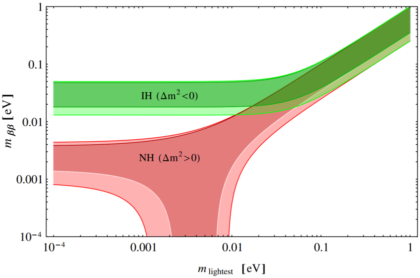
Bonus Slide: Neutrinoless Double Beta Decay Sensitivity

The mass mechanism

- For light Majorana ν exchange:

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\left|M^{0\nu}\right|^2\langle m_{\beta\beta}\rangle^2$$

- $G^{0\nu}(Q,Z)$ = Phase Space integral
- $\left|M^{0\nu}\right|^2$ = nuclear matrix element
- $\langle m_{\beta\beta}\rangle^2 = \sum_i U^2_{ei} m_i$ = effective ν mass
- U_{ei} = PMNS mixing matrix elements



Phys. Rev. D90 (2014) 033005

Experimental sensitivity:

- Number of signal events:

$$n_S = \frac{1}{T^{0\nu}_{1/2}} \cdot \frac{\ln 2 \cdot N_A}{m_A} \cdot f_{76} \cdot \varepsilon \cdot M \cdot t$$

- Number of background events:

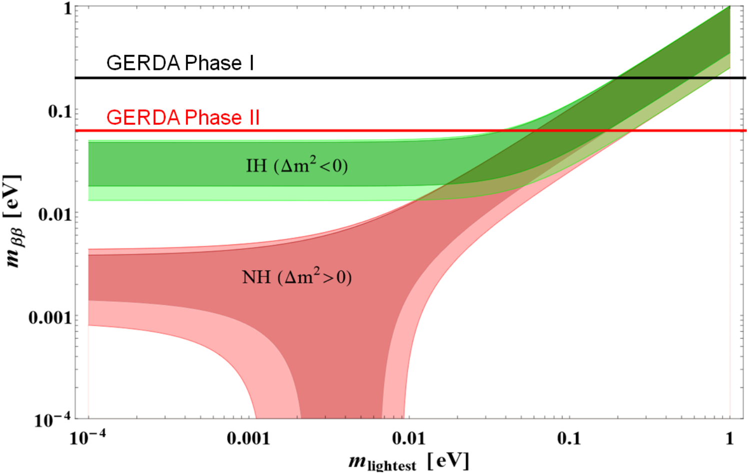
$$n_B = BI \cdot \Delta E \cdot M \cdot t$$

where: f = enrichment fraction
N_A = Avogadro number
m_A = atomic mass
ε = total efficiency
M = detector mass
t = live time
$M \cdot t$ = exposure
BI = Background Index
ΔE = energy resolution

Limits on Neutrino Mass Hierarchy

Neutrino Mass Hierarchy Limits with GERDA:

- GERDA Phase I published.
- GERDA Phase II projected.



Vissani et al. 2014

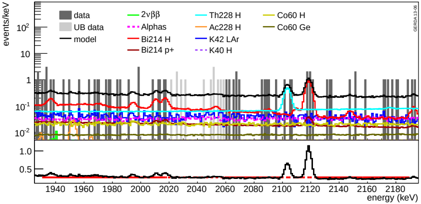
Bonus: The Background of GERDA Phase I

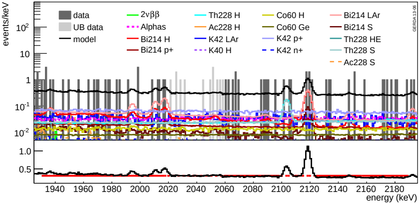
Background models

- Minimum model containing only known and visible background sources
- Alternative (maximum) model containing the same isotopes but more possible locations

⇩

Both models predict a flat background at $Q_{\beta\beta}$



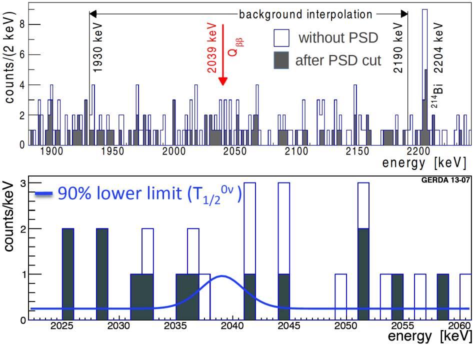


Analysis recipe:

- Fit with Gaussian peak and flat background in the 1930-2190 keV region, excluding known gamma peaks at 2104 (^{208}Tl SEP) and 2119 keV (^{214}Bi).

Bonus: GERDA Phase I Result

PSD	Dataset	Obs.	Exp. bkg
no	Golden	5	3.3
	Silver	1	0.8
	BEGe	1	1.0
yes	Golden	2	2.0
	Silver	1	0.4
	BEGe	0	0.1



Profile Likelihood Method

- best fit $N^{0\nu} = 0$
- No excess of signal over bkg
- 90% C.L. lower limit:

$$T_{1/2}^{0\nu} > 2.1 \cdot 10^{25}\ \mathrm{yr}$$

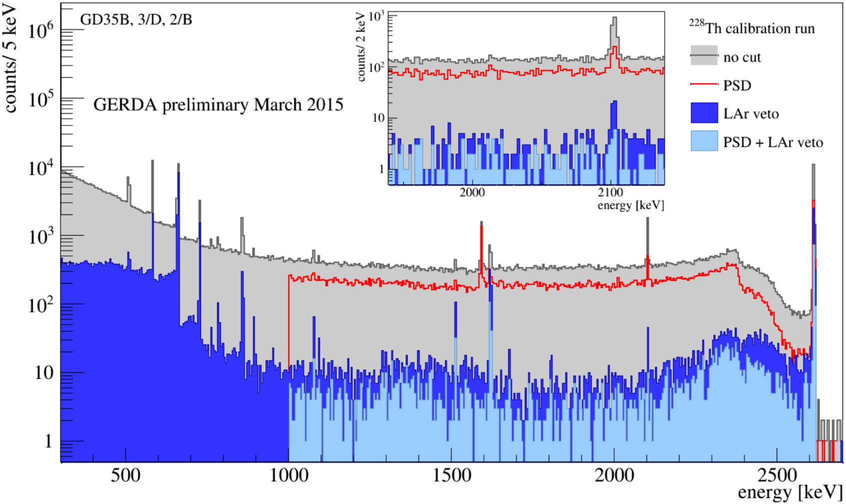
- Median sensitivity: $2.4 \cdot 10^{25}$ yr

Bayesian Approach

- Flat prior for $1/T_{1/2}^{0\nu}$ in $[0; 10^{-24}]$ yr^{-1}
- best fit $N^{0\nu} = 0$
- 90% credibility interval:
  $T_{1/2}^{0\nu} > 1.9 \cdot 10^{25}$ yr
- Median sensitivity: $2.0 \cdot 10^{25}$ yr

GERDA Collaboration, Phys. Rev. Lett. 111 (2013) 122503

First GERDA Phase II Data



- Spectrum from ^{228}Th calibration source
- 3 BEGe detectors (2 depleted, 1 enriched), 15 hours live time
- 15/16 PMTs and 7/16 SiPM working
- Background from ^{228}Th at $Q_{\beta\beta}$ suppressed by a factor ~ 100