Search for processes beyond the Standard Model

in the GERDA experiment

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on behalf of the GERDA collaboration

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All in one

(non-conservation of *L, B, Q* charges and candidates for *DM*)

The **GERDA** collaboration tried to find in one experiment the answers to several fundamental questions in modern physics and cosmology which go **beyond the Standard Model**:

 # 1: $0\nu\beta\beta$ - search **neutrinoless double-beta decay of ^{76}Ge:**

$\Rightarrow \Delta L \neq 0$ - **non-conservation of the lepton number** and evidence of the **Majorana nature of ν** - what may support the arguments in favor of ***Leptogenesis*** as the source of ***baryon asymmetry*** in the early Universe.

 # 2: Search for **decay/disappearance of nucleons** bound inside the ^{76}**Ge** nucleus:

$\Rightarrow \Delta B \neq 0$ **- baryon number non-conservation** is one of 3 fundamental criteria necessary for origin of ***matter-antimatter asymmetry*** in the Universe, ***Baryogenesis*** [***A.D. Sakharov, 1967*** – *see **Backup Slides #1** and **2***].

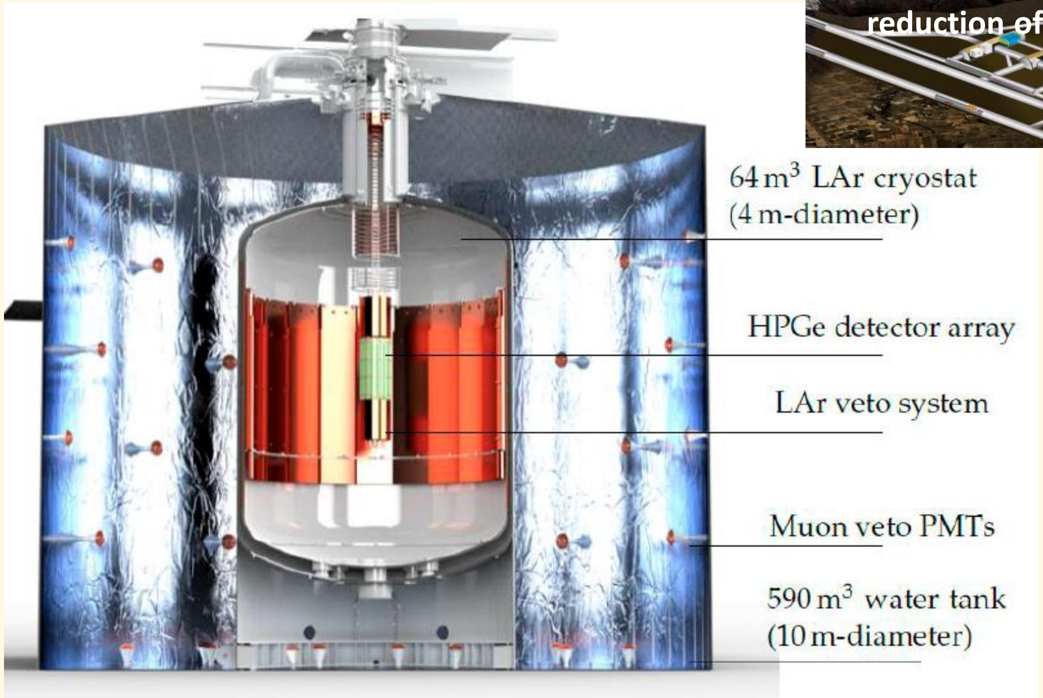
 # 3: Search for **decay of electron** in **Ge** atoms:

$\Rightarrow \Delta Q \neq 0$ **- non-conservation of the electric charge** as one of the experimental tests of the fundamental U(1) gauge symmetry.

 # 4: Search for **bosonic DM particles** (**SuperWIMPs**) interacting with electrons of ^{76}**Ge** atoms,

$\Rightarrow$ ***DM*** – registration of signals from **possible candidates for the role of Dark Matter**.

GERDA experiment *(Phase II)*

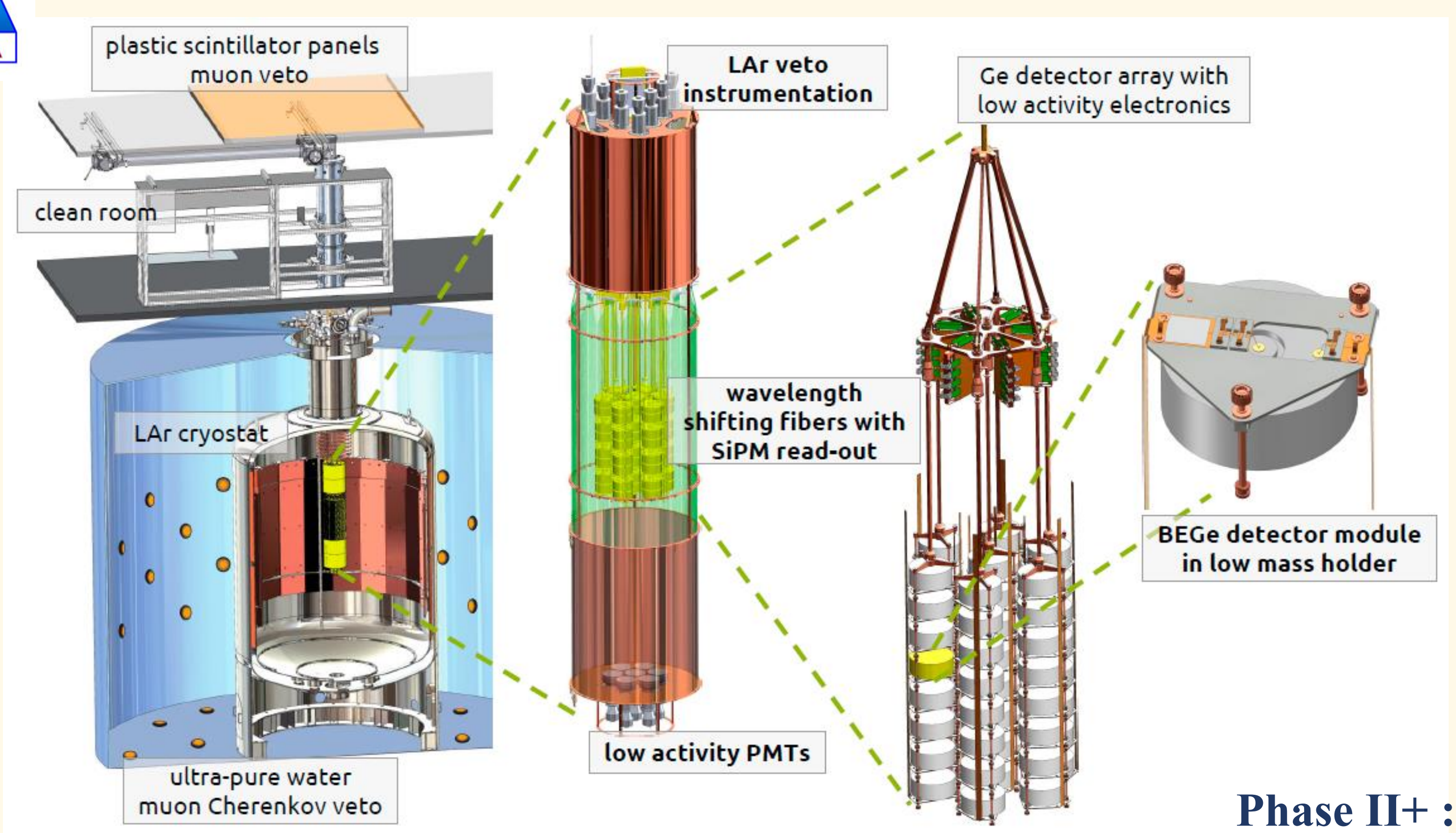


GERDA operated with bare germanium detectors (made from enriched ^{76}**Ge**) immersed directly in liquid argon (**LAr**).

The stainless steel **cryostat** with internal copper shielding **filled with LAr** (*64m³, ~90 tons*) is placed inside a **tank filled with water** (*590m³*) which is viewed by 64 PMTs (Muon Veto)

The **Ge detector array** is located in the center of the cryostat and consists of 7 strings with detectors and surrounded by the **LAr-veto** signal collection system.

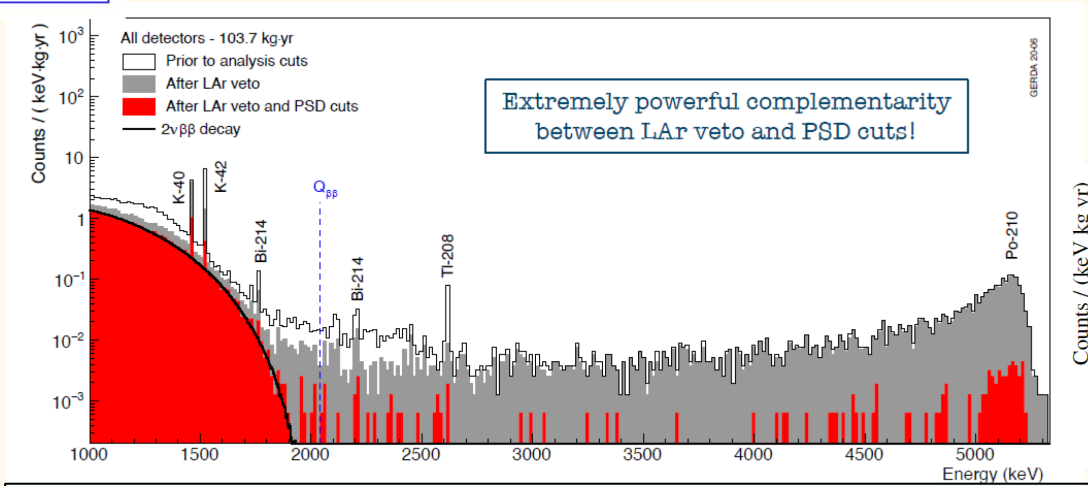
GERDA Phase II



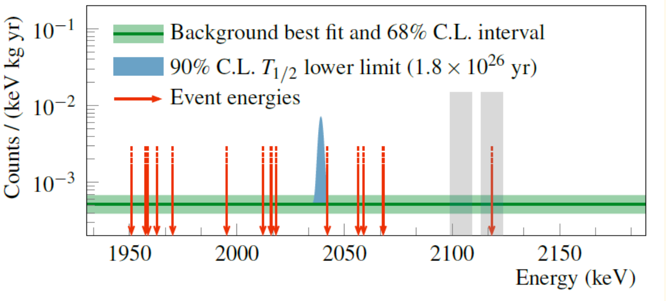
Phase II+ :

Number of Ge-detectrors = 41
M(Ge) total = 44.2 kg

Search for 0νββ-decay of ^{76}Ge



Background level = 5.2·10^{-4} cts / (keV kg yr)



GERDA (GERmanium Detector Array) has achieved an **unprecedentedly low background index**:

5·10^{-4} counts/(keV · kg · yr) in the ROI of the **0νββ** signal ($Q_{\beta\beta}$ = 2039 keV)

For a total exposure (Phase I and Phase II) of **127.2 kg · yr** (*1288 mol yr ^{76}Ge*), the desired **signal was not observed** and a **limit was set on the half-life of 0νββ** for **^{76}Ge** :

$$T_{1/2}(0\nu\beta\beta) > 1.8\cdot10^{26}\ \text{yr},\quad (90\%\ \text{C.L.})$$

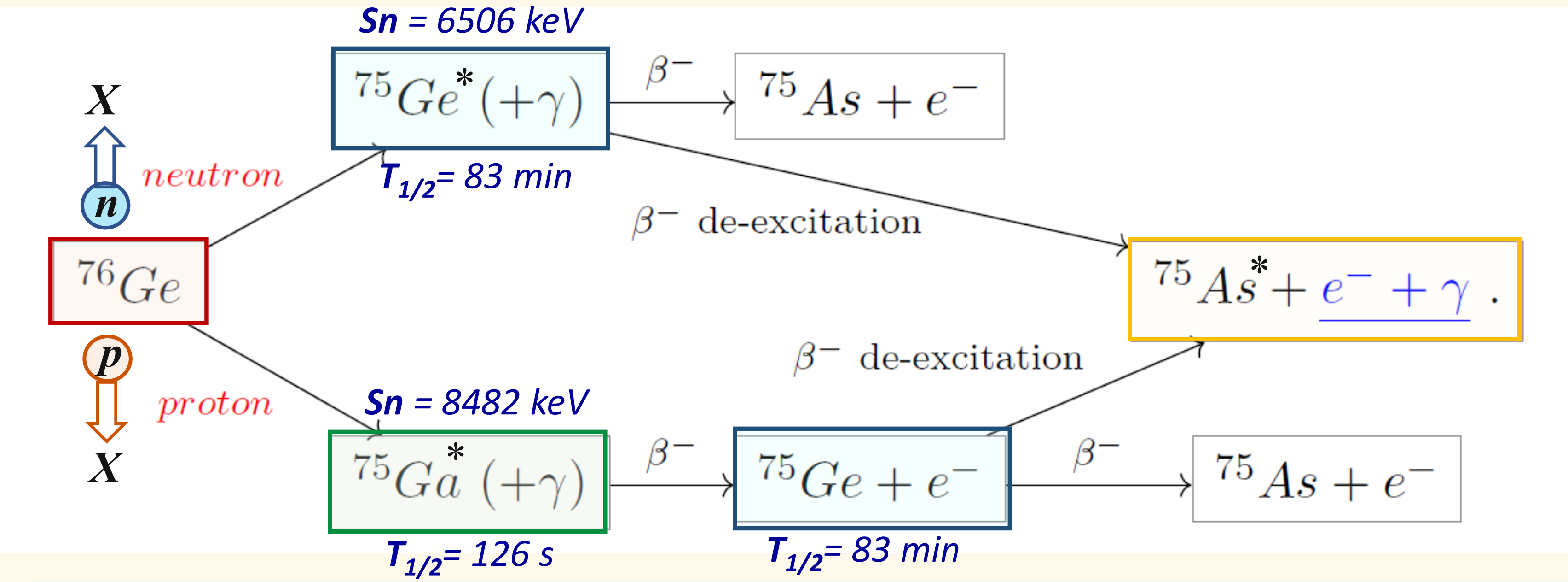
and the **limit on the effective mass of a light Majorana neutrino** has been extracted as:

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

(*depending on the range of the calculated NME values*).

Phys. Rev. Lett. 2020, 125, 252502

Single nucleon decay inside ^{76}Ge



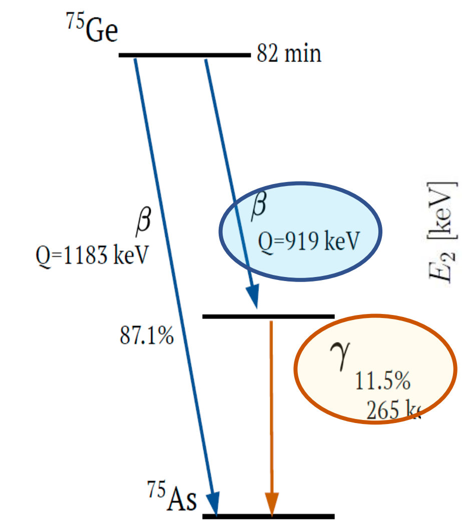
Simplified scheme of neutron /proton decays in ^{76}Ge, with subsequent isotopic transitions.

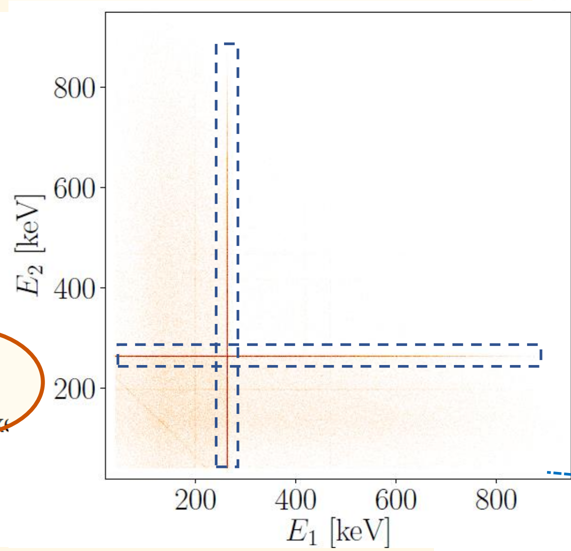
Only those inclusive single-nucleon decays, **n→ X**, **p→ X**, are analyzed, as a result of which **only the bound states of the daughter nuclei (A - 1)** are populated, that is, their levels are stable with respect to the emission of any particles, **except for the de-excitation γ-quanta**.

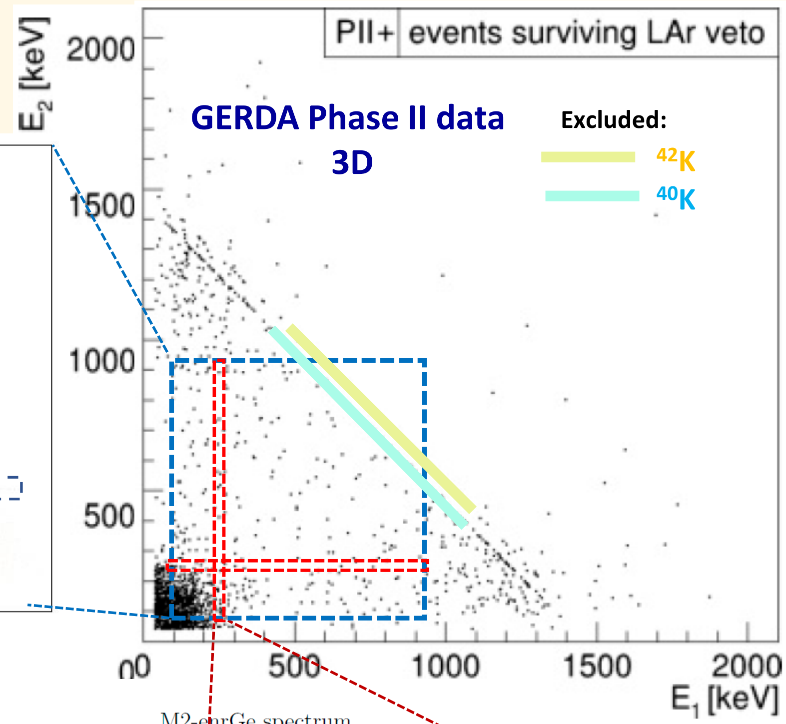
That means that only **β-γ** pairs from **β-**decay of **^{75}Ge** and the subsequent de-excitation of the *arsenicum* isotope **^{75}As** by **γ**-quanta are considered (*highlighted in blue*) .

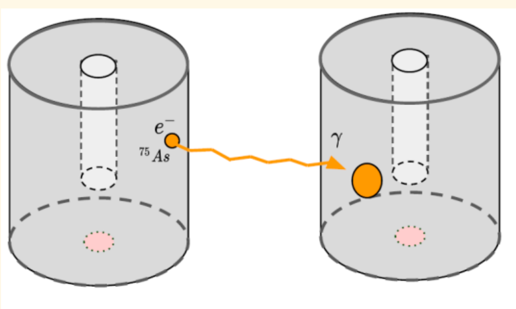
Beta decay of ^{75}Ge -> $\beta^- \rightarrow$ ^{75}As* -> γ $\rightarrow$ ^{75}As

(^{75}Ge → … ^{75}As)
MC simulation 3D

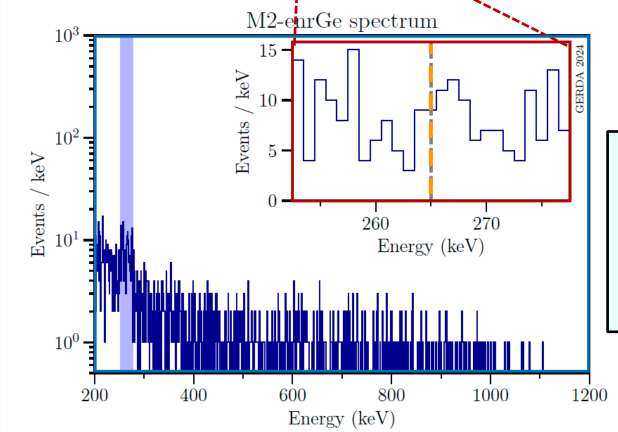








nucleon decay tagging via ^{75}Ge

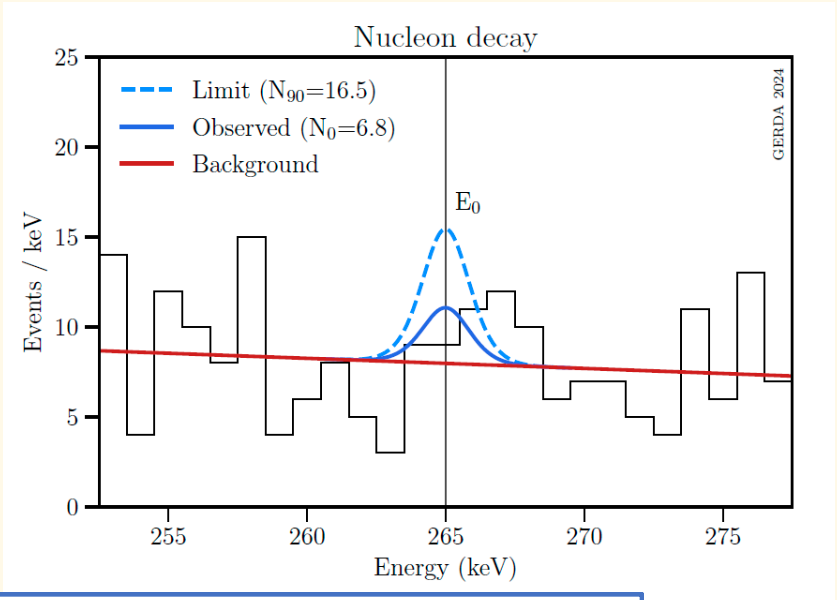


GERDA Phase II data
M2 spectrum
(Sum of projections
to E1 & E2 axes)

Lower limit on lifetime τ_{low}

$$\tau_{\rm low} = \epsilon_{\rm n} \cdot N_{\rm eff} \cdot \frac{N_{\rm A}}{N_{\rm up,n}} \cdot \mathcal{E} \cdot \frac{f_{^{76}\rm Ge}}{M_{\rm tot}}$$

ϵ_n — coincidence detection efficiency electron-photon pair (**0.2%**),
N_{eff} – effective number of nucleons (**16** - n, **14** – p)
N_A — Avogadro's number
Molar weight M_{tot} = **75.66** g/mol
Isotopic fraction $f\ ^{76}Ge$ = **87.5**%
Exposure $\mathcal{E}$ = **105.5** kg years



For the **inclusive decay** of a single neutron in ^{76}**Ge**, a **lower limit on the partial lifetime** of $\tau_n > 1.5\times10^{24}$ years is obtained, and for the proton $\tau_p > 1.3\times10^{24}$ years, at 90% C.I. *(Bayesian)*

Eur. Phys. J. C. 83, 319 ***(2023)***

N.B. It's important to remember that $\tau_{low} = \tau_{tot} / B_i$

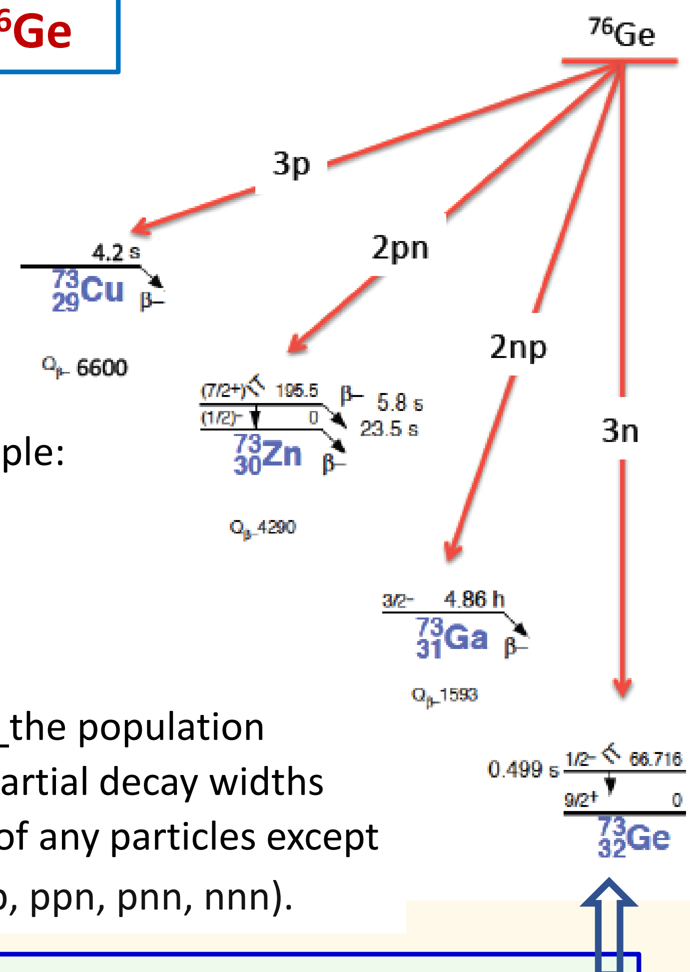
(for our case i the value of B_i is unknown, however $B_i < 1$)

REVIEW OF PARTICLE PHYSICS*
Particle Data Group

The "partial mean life" limits tabulated here are the limits on τ/B_i, where τ is the total mean life and B_i is the branching fraction for the mode in question. For N decays, p and n indicate proton and neutron partial lifetimes.

Tri-nucleon decays in ^{76}Ge

In the paper of *K. Babu et al.* [1] it was shown that within the framework of a model with discrete symmetry $\mathbf{Z_6}$, in which the baryon number **B** is discrete, processes with ΔB **= 1** or **2** **are forbidden**, but **processes with ΔB = 3 are possible**.



Decay modes at ΔB = 3 :

$$ppp \to e^+\pi^+\pi^+$$
$$ppn \to e^+\pi^+$$
$$pnn \to e^+\pi^0$$
$$nnn \to \bar{\nu}\pi^0.$$

and other modes, for example:

$$3\,n \to 3\,\nu$$
$$3\,n \to 3\,\chi$$

....

....

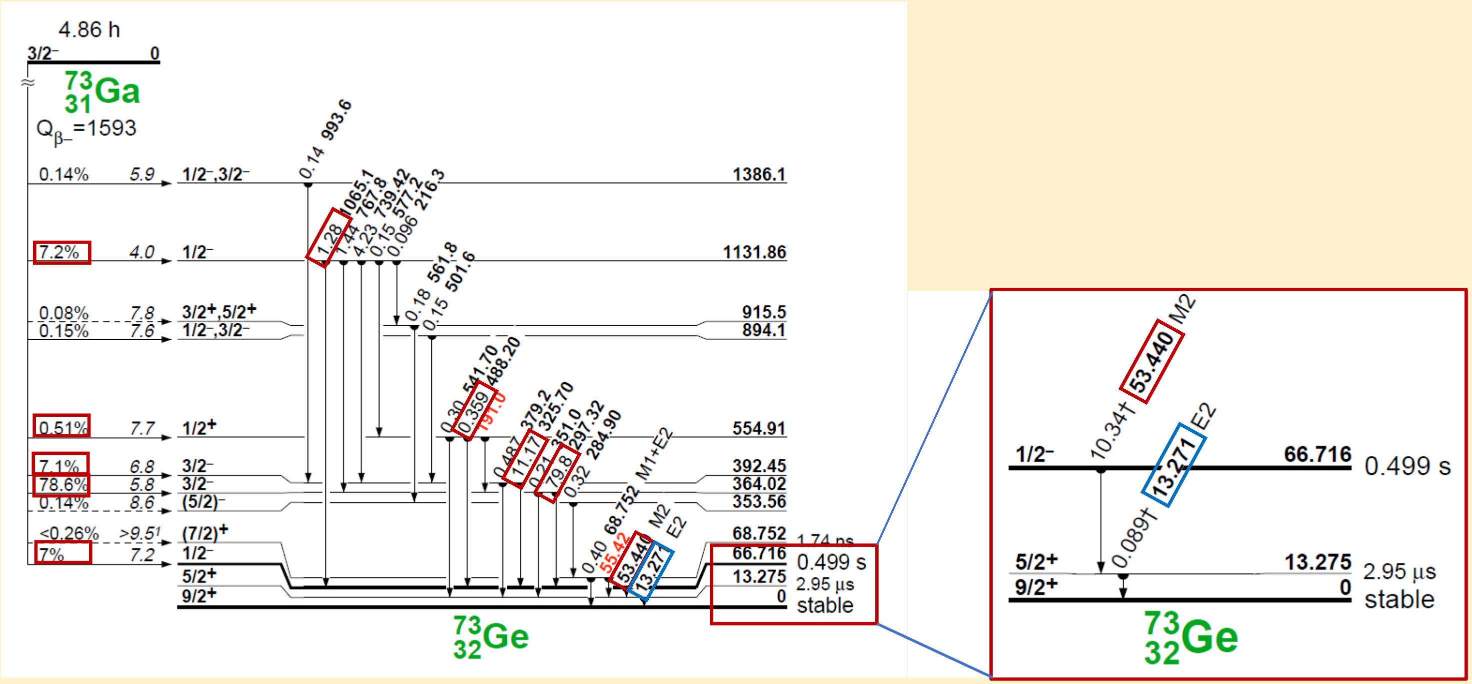
We consider only those **inclusive three-nucleon decays** with the population of only the ***bound states*** of the daughter nuclei **(A - 3)** with partial decay widths $\Gamma_b(x)$, i.e. levels that are stable with respect to the emission of any particles except γ-quanta that remove excitation. $\Gamma_3^b = \sum_x (\Gamma_x^b)$ (x = ppp, ppn, pnn, nnn).

As a result of **ppp**-, **ppn**- and **pnn**- decays in the ^{76}**Ge** nucleus, the isotopes ^{73}**Cu**, ^{73}**Zn** and ^{73}**Ga** are formed, respectively. These short-lived isotopes are unstable and eventually pass to ^{73}**Ge** (stable) as a result of the final beta decay of ^{73}**Ga**.

[1] *K. Babu et al. , "Gauged baryon parity and nucleon stability", Phys. Lett. B 570, 32 (2003)*

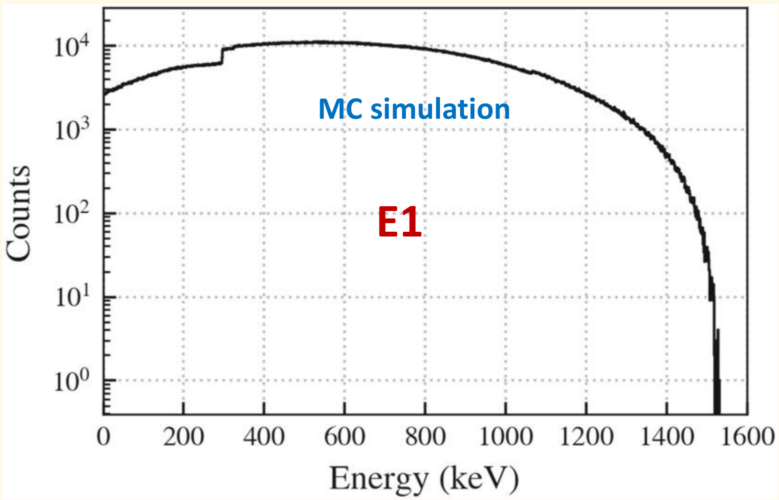
Thus, the search for <u>such three-nucleon decays</u> of ^{76}**Ge** leads to **searching for β-decay of** ^{73}**Ga**, which **predominantly (98.6%) populates the metastable level** ^{73m}**Ge** with an energy of **66.7 keV** and a half-life **of 0.5 s**, which then discharges through the level of **13.3 keV** (**2.95 μs**) to the ground level of ^{73}**Ge** (stable).

Our analysis also includes the **nnn-decay** of ^{76}**Ge**, which goes directly through ^{73m}**Ge**.

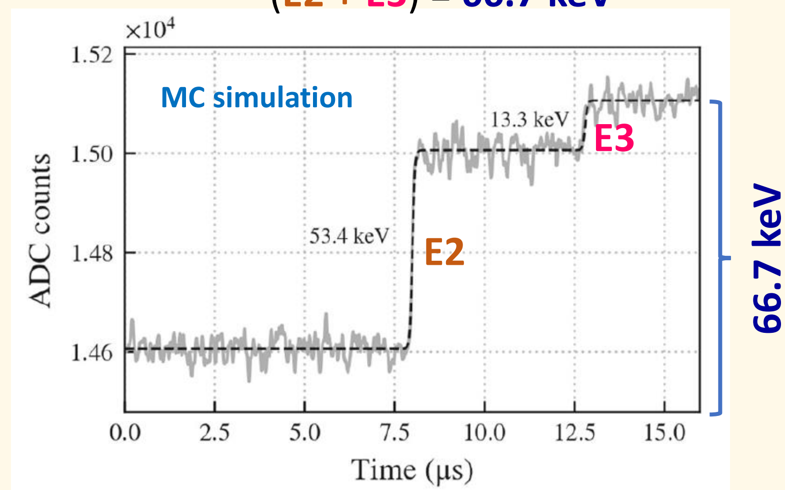


Beta decay of ^{73}**Ga** and subsequent "instant" gamma cascades will cause the <u>1st event</u> in the detector, corresponding to the sum of their energies (≤ **1531** keV) - **E1**.

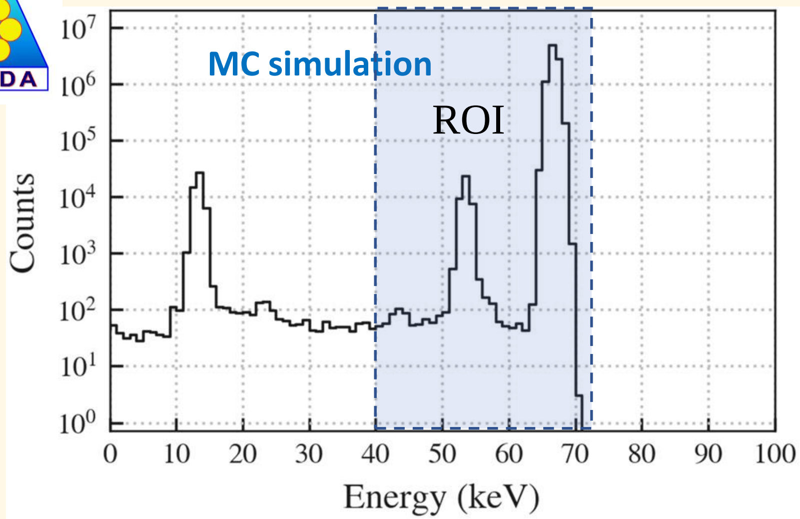
The transition from the <u>metastable level</u> ^{73m}**Ge** will give the <u>2nd delayed</u> (**$T_{1/2}$ = 0.5** s) signal **53.4 keV - E2** and the <u>3rd delayed signal</u> (**$T_{1/2}$ = 2.95** μs) with energy **13.3 keV – E3** .

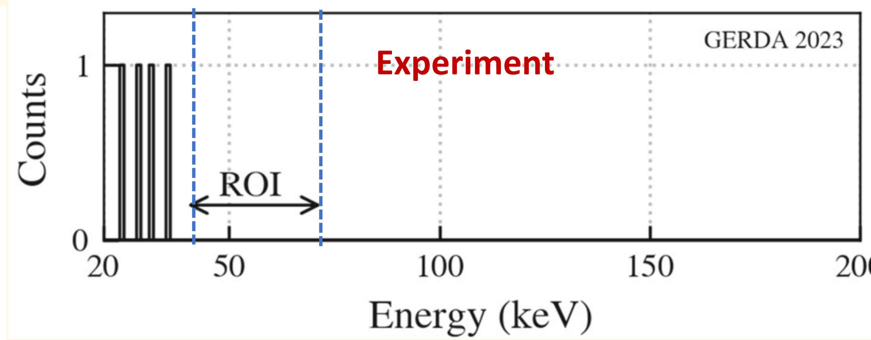


(**E2 + E3**) = **66.7 keV**



Searching for decay of ^{73}**Ga** consists of observation of delayed coincidences of a pair of events with energies **E1** and (**E2 + E3**), that occurred <u>only in one Ge detector</u> during **2.5 sec** (5 half-lives of the metastable level of **66.7 keV**), where the first event **E1** is selected from the continuous spectrum (**20 - 1598 keV**), and the delayed event consists of two steps **E2** = **53.4 keV** and **E3** = **13.3 keV** in the time interval (**5 x 2.95 μs**)





ROI: (**40 – 72**) keV for events (**E2 + E3**)= **66.7** keV

Experiment	Decay	$\tau_b[x]$ (yr)
GERDA	$^{76}Ge \xrightarrow{ppp} {}^{73}Cu + X$	1.20×10^{26}
	$^{76}Ge \xrightarrow{ppn} {}^{73}Zn + X$	1.20×10^{26}
	$^{76}Ge \xrightarrow{pnn} {}^{73}Ga + X$	1.20×10^{26}
	$^{76}Ge \xrightarrow{nnn} {}^{73}Ge + X_{invisble}$	$k \times 10^{26}$
MAJORANA [19]	$^{76}Ge \xrightarrow{ppp} {}^{73}Cu + X$	1.08×10^{25}
	$^{76}Ge \xrightarrow{ppp} {}^{73}Cu\, e^+\pi^+\pi^+$	6.78×10^{25}
	$^{76}Ge \xrightarrow{ppn} {}^{73}Zn\, e^+\pi^+$	7.03×10^{25}
EXO-200 [20]	$^{136}Xe \xrightarrow{ppp} {}^{133}Sb + X$	3.3×10^{23}
	$^{136}Xe \xrightarrow{ppn} {}^{133}Te + X$	1.9×10^{23}
Hazama et al. [21]	$^{127}I \xrightarrow{nnn} {}^{124}I + X$	1.8×10^{23}

Lower limit on lifetime τ low

$$\tau_{\rm low} = \epsilon_{\rm n} \cdot N_{\rm eff} \cdot \frac{N_{\rm A}}{N_{\rm up,n}} \cdot \mathcal{E} \cdot \frac{f_{^{76}\rm Ge}}{M_{\rm tot}}$$

(N_{eff} = 1 – effective number of nucleons for the case of three-nucleon decay)

The total exposure for the low threshold data set: **ε** = **61.89** kg yr at full efficiency $\boldsymbol{\epsilon_n}$ = **0.554** with **no observable signal** N_{up} = **2.3 counts** at 90% C.I. (*Bayesian)*), which gives:

partial lifetime limit

$\tau_{low} > 1.2\times10^{26}$ years, 90% C.I.

for **ppp, ppn** and **pnn** decays in ^{76}**Ge**

(for **nnn** decay $\tau_{low} > k \cdot 1.2\times10^{26}$)

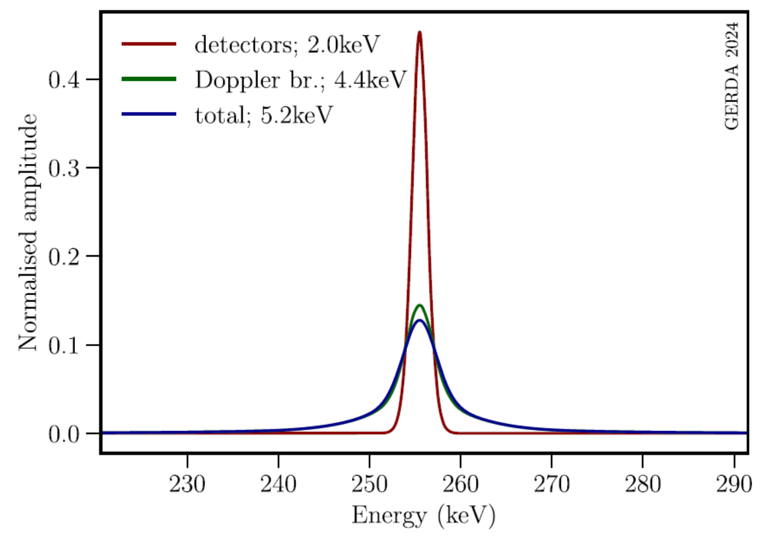
Eur. Phys. J. C (2023) 83:778

N.B. Reminder : $\tau_{low} = \tau_{tot} / B_i$

Electron decay $e- \to \nu_e + \gamma$

Another BSM process of interest is the **decay of an electron** via $e- \to 3\nu_e$ or $e- \to \nu_e \gamma$, where the latter channel is explored in **GERDA**.
Many laboratory tests have been performed to test the fundamental U(1) gauge symmetry ensuring charge conservation, e.g. the stability of electron as well as the zero mass of photon (- *see selected constraints listed in* ***Backup Slide #3***).

Before analyzing the experimental spectrum aimed to search for the **gamma peak** from decay $e- \to \nu_e + \gamma$ in the ROI around **half of the electron mass** (~ **255.5 keV**), it was necessary to obtain the true peak shape, since the release of atomic binding energies causes both **Doppler broadening** (***Backup Slide #4)*** and **shift of the peak position** for different electron atomic levels.

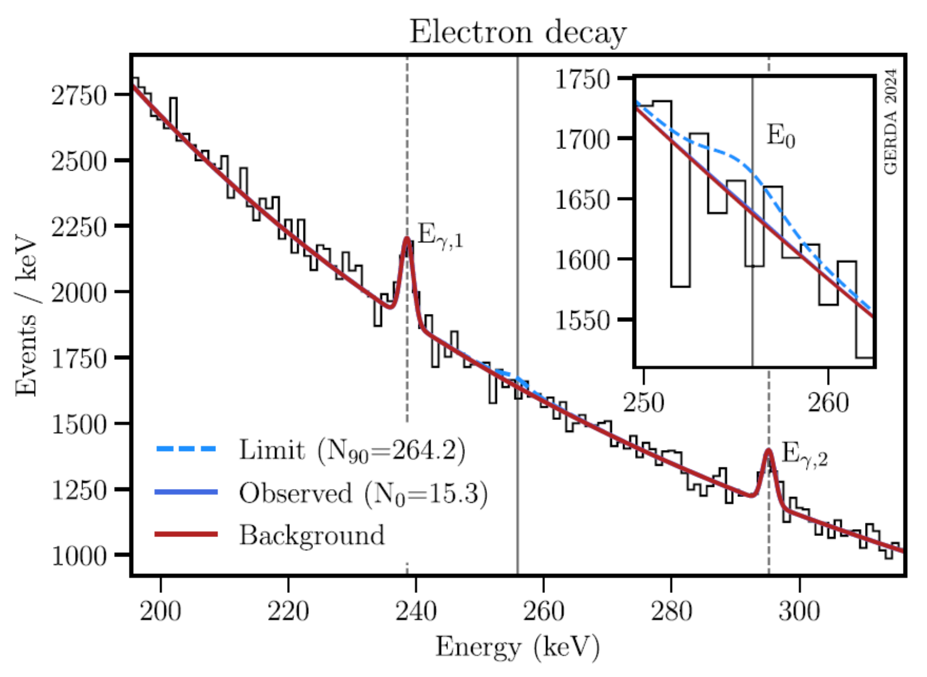


In GERDA ***e- decays*** could occur both **within a Ge-detector** and in its surrounding materials which include **neighbouring Ge-detectors** and **LAr**.

The total signal energy (**peak center**) is **255.9 keV.** The full width at half maximum (**FWHM**) is **5.2 keV** (blue), with contributions from detector resolution **2.0 keV** (red) and the Doppler-broadening **4.4 keV** (green)

Lower limit on electron lifetime τ_{low}

$$\tau_{low} = (\epsilon_{Ge,det} + \epsilon_{Ge,mat}) \cdot N_{e,Ge} \cdot \frac{N_A}{N_{up,e}} \cdot \frac{\mathcal{E}}{M_{tot}} + \epsilon_{Ar} \cdot N_{e,Ar} \cdot \frac{N_A}{N_{up,e}} \cdot \frac{m_{Ar}}{m_{Ge}} \cdot \frac{\mathcal{E}}{M_{Ar}}.$$



$E\gamma,1$ = 238.6 keV (^{212}Pb), $E\gamma,2$ = 295.2 keV (^{214}Pb)

Efficiencies:
for recording detector $\epsilon_{Ge,det}$ = 0.419
for neighbouring Ge $\epsilon_{Ge,mat}$ = 0.034
for LAr ϵ_{LAr} = 0.00070

$N_{e,Ge}$ = **32** and $N_{e,Ar}$ = **18** - numbers of electrons in Ge and Ar atoms,
M_{Ar} = **39.95×10^{-3}** kg/mol - LAr molar mass,
LAr total mass m_{Ar} = **3884.1** kg,
Total Ge mass m_{Ge} = **38.78** kg
Ge molar mass M_{tot} = **75.66** g/mol
Exposure ε = **105.5** kg years

No relevant deviation from the background was observed

The lower limit on electron lifetime:

τ_{low} > 5.4×10^{25} years, 90% (C.I. & C.L.)

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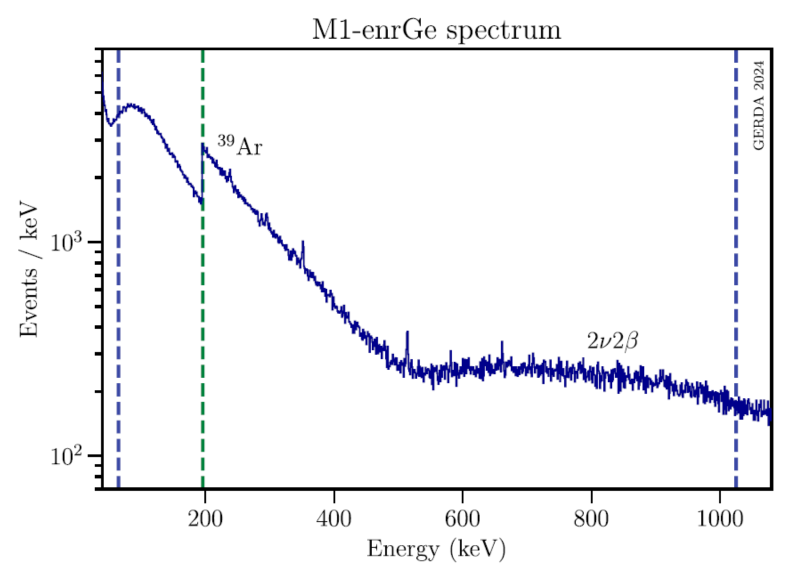
Bosonic Dark Matter

GERDA is sensitive to pseudoscalar (axion-like particles, **ALP**s) and vector (dark photons, **DP**s) **bosonic DM candidates**, also referred to as **superWIMPs**)

A search for full energy depositions from **bosonic keV-scale dark matter candidates** of masses **between 65 and 1021 keV** has been performed. Masses within this range imply a super-weak interaction strength between the DM and the SM sector, much weaker than normal weak-scale interactions, requiring an early thermal decoupling of the DM sector, which happened before the electroweak epoch at T_{EW} ~ **100 GeV** [1].

We are focusing on masses below **$2m_e$ ~ 1022 keV**, since for DM masses $m_{DM} \geq 2m_e$, decays into ***e-e+* pairs** are possible, making long-lived DM highly unlikely.



GERDA analysis aims to scan the energy range **65 (196) - 1021 keV to find some unknown peak** not associated with the well-known background γ-lines.

The exposure-weighted energy resolution ***σ*** *(*standard deviations of a Gaussian peak) ranges from **0.9 keV** up to **1.2 keV** in the bosonic DM range of interest.

[1] *M. Pospelov, A. Ritz, M.B. Voloshin, Bosonic super-WIMPs as keV-scale dark matter, Phys. Rev. D* ***78****, 115012 (2008)*

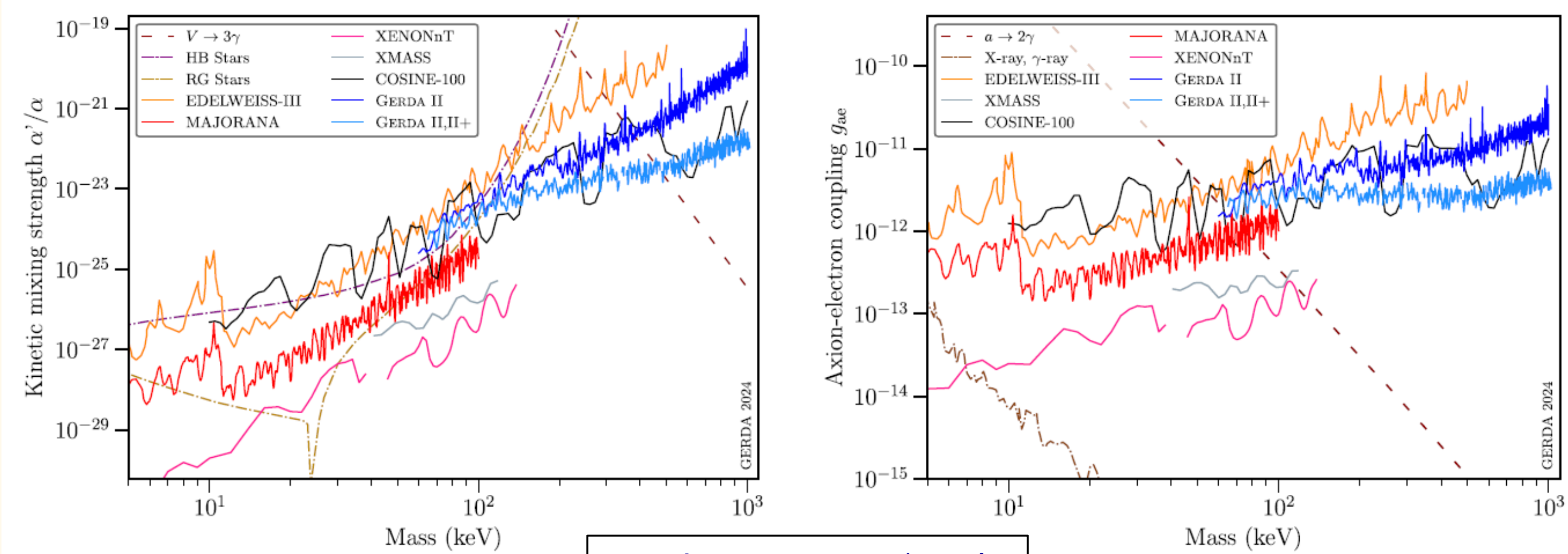
GERDA analysis includes **direct DM absorption** as well as **dark Compton scattering**

The dark Compton scattering DM + *e-* → *e-* + *γ* leads to release of *e-* and *γ* with fixed energies - the **recoil energy** ***T*** **of the electron** and the **energy** ***ω'*** **of the emitted photon** .

GERDA analysis focused on events in which **both the final electron and photon** are detected **within a single Ge detector**, leading to a **peak at energy** $T + \omega = m_{DM}$.

Equations for the **DM photoelectric-like absorption** and **Compton interaction rates -** *in Backup Slide #5*

With a total exposure of **105.5 kg yr**, **no evidence for a signal** above the background has been observed. The resulting exclusion limits are the **most stringent direct constraints** in the major part of the **140–1021 keV mass range.** The ALPs and DPs dimensionless couplings to electrons are parametrized via g_{ae} and α'/α, where α' denotes the hidden sector fine structure constant. As an example, **at DM mass of ~150 keV** : $\alpha'/\alpha < 8.7 \cdot 10^{-24}$ and $g_{ae} < 3.3 \cdot 10^{-12}$ at 90% CI.



Eur. Phys. J. C. 83, 319 (2023)

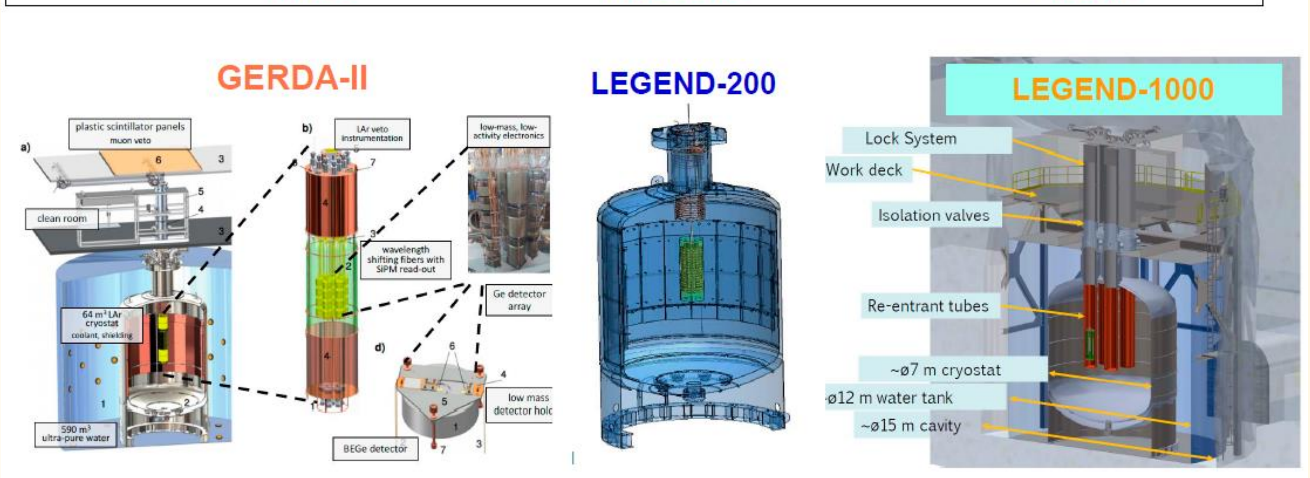
Conclusion and Prospects

The **GERDA** collaboration has demonstrated an unique opportunity to search for answers to the most exiting questions of modern physics and cosmology in a single experiment: non-conservation of **lepton $\Delta L \neq 0$** , **baryon $\Delta B \neq 0$** and **electric $\Delta Q \neq 0$ chargers** and possible **candidates for *DM***.

In addition to the result of searching for **$0\nu\beta\beta$** -decay of ^{76}Ge, **GERDA** has obtained many results in searching for other processes beyond the Standard Model. Among them, the results in searching for **inclusive decay of single nucleons** (*firstly for ^{76}Ge*), some modes of **three-nucleon decays** in the 76Ge nucleus (*1–3 orders of magnitude better than previous results*), **electron decay** (*the best for medium mass nuclei*), as well as *the stringiest exclusion limits* on the **bosonic keV-scale DM.**

These initial results of **GERDA** are **planned to be significantly improved** in the currently launched **LEGEND-200** and the future **LEGEND-1000** experiments.

Past	Present	Future



Thanks
for your attention !!!

Backup slides

#1

НАРУШЕНИЕ CP-ИНВАРИАНТНОСТИ. C-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д. Сахаров

(ЖЭТФ. Письма в редакцию. 1967. Т. 5, вып. 1. С. 32 — 35)

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует принять, что в природе отсутствуют тела из антивещества, т.е. Вселенная асимметрична в отношении числа частиц и античастиц (C-асимметрия). В частности, отсутствие антибарионов и предполагаемое отсутствие неизвестных барионных нейтрино означает отличие от нуля барионного заряда (барионная асимметрия). Мы хотим указать на возможное объяснение C-асимметрии в горячей модели расширяющейся Вселенной (см. [1]) с привлечением эффектов нарушения CP-инвариантности (см. [2]). Для объяснения барионной асимметрии дополнительно предполагаем приближенный характер закона сохранения барионов.

Принимаем, что **законы сохранения барионов и мюонов не являются абсолютными** и должны быть объединены в закон сохранения "комбинированного" барион-мюонного заряда,

т.е. в современной интерпретации барион-лептонного числа B-L (в ряде моделей **B+L**)

1. *Зельдович Я.Б.//* УФН. 1966. Т. 89. С. 647.
2. *Окунь Л.Б.//* УФН. 1966. Т. 89. С. 603.

#2

БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д. Сахаров

(Физический институт им. П.Н. Лебедева АН СССР)

(Обзорный доклад на конференции, посвященной 100-летию А.А. Фридмана. Ленинград, 22 — 26 июня 1988 г.[1]*)*

3. Третье направление в проблеме барионной асимметрии — отвергающее сохранение барионного заряда. Первые указания и работы: Вейнберг (1964) [4], Сахаров (1967) [5], Кузьмин (1970) [6].

Три основные предпосылки космологического образования барионной асимметрии (ВА).

I. Отсутствие закона сохранения барионного заряда.

II. Отличие частиц от античастиц, проявляющееся в нарушении СР-инвариантности.

III. Нестационарность. Образование В А возможно лишь в нестационарных условиях при отсутствии локального термодинамического равновесия.

Weinberg S.// Lectures on Particles and Fields/- N.Y.: Prentice, Hall, 1964, p. 482.
Сахаров А.Д.// Письма в ЖЭТФ. 1967. Т. 5. С. 32.
Кузьмин В.А.// Письма в ЖЭТФ. 1970. Т. 13. С. 335.

#3

Table Selection of constraints on the electron lifetime τ_e at 90% CL

Experiment	Nuclei	Decay	τ_e (years)
Borexino [61]	C, H, N, O	$e^- \to \nu_e \gamma$	6.6×10^{28}
* HdM [18][a]	Ge	$e^- \to \nu_e \gamma$	* 9.4×10^{25}
MAJORANA [62]	Ge	$e^- \to 3\nu_e$	2.8×10^{25}
EDELWEISS-III [38]	Ge	$e^- \to 3\nu_e$	1.2×10^{24}
GERDA	Ge	$e^- \to \nu_e \gamma$	5.4×10^{25}

* HdM [18][a] - more likely overestimate
[*R.L. Workman et al. (PDG), Review of particle physics. Prog. Theor. Exp. Phys. 083C01 (2022); A. Derbin, A. Ianni, O. Smirnov,arXiv:0704.2047 [hep-ex]*]

#4

Table Germanium and argon electron binding energies $E_{b,i}$ for different atomic shells [*] together with electron shell occupation numbers n_i. The corresponding FWHM contributions to the Doppler broadening of the electron decay signal are separately shown for the dominant contributions coming from Ge source detectors (K, L1-L3, M1-M5, N1-N2) and from the LAr (K, L1-L3, M1-M3). The FWHM value of each atomic shell are shown too.

Shell	n_i	$E_{b,i}$ (keV)		$FWHM_i$ (keV)	
		Ge	Ar	Ge	Ar
K	2	11.103	3.2059	90.6	47.4
L1	2	1.4146	0.3263	31.7	15.2
L2	2	1.2481	0.2506	29.8	13.3
L3	4	1.217	0.2484	29.5	13.3
M1	2	0.1801	0.0293	11.4	4.6
M2	2	0.1249	0.0159	9.6	3.4
M3	4	0.1208	0.0157	9.4	3.3
M4	4	0.0298	–	4.8	–
M5	6	0.0292	–	4.8	–
N1	2	0.0143	–	3.2	–
N2	2	0.0079	–	2.4	–

[*] *T. Carlson, Photoelectron and Auger Spectroscopy (Plenum Press, New York, 1975*)

#5

GERDA analysis includes **direct DM absorption** as well as **dark Compton scattering**

Absorption interaction rate
for **ALPs** (**a**) and **DPs** (**v**):

$$R_{\mathrm{a}}^{\mathrm{A}} = \frac{1.47 \times 10^{19}}{M_{\mathrm{tot}}} g_{\mathrm{ae}}^2 \left(\frac{m_{\mathrm{a}}}{[\mathrm{keV}]} \right) \left(\frac{\sigma_{\mathrm{pe}}}{[\mathrm{b}]} \right) \mathrm{kg}^{-1}\,\mathrm{d}^{-1}$$

$$R_{\mathrm{V}}^{\mathrm{A}} = \frac{4.68 \times 10^{23}}{M_{\mathrm{tot}}} \frac{\alpha'}{\alpha} \left(\frac{[\mathrm{keV}]}{m_{\mathrm{V}}} \right) \left(\frac{\sigma_{\mathrm{pe}}}{[\mathrm{b}]} \right) \mathrm{kg}^{-1}\,\mathrm{d}^{-1}$$

M_{tot} (g/mol) is the molar mass of the target material, the ALPs and DPs dimensionless couplings to electrons are parametrized via g_{ae} and α' / α, respectively, and is related to the kinetic mixing strength κ of DPs via $\alpha' = \alpha\kappa^2$

The photoelectric-like absorption cross section at a given mass is:

$$\sigma_{\mathrm{a,e}}(m_{\mathrm{a}}) = g_{\mathrm{ae}}^2 \frac{m_{\mathrm{a}}^2 \sigma_{\mathrm{pe}}(m_{\mathrm{a}})}{\beta} \left(\frac{3}{16\pi\alpha m_{\mathrm{e}}^2} \right)$$

$$\sigma_{\mathrm{V,e}}(m_{\mathrm{V}}) = \frac{\alpha'}{\alpha} \frac{\sigma_{\mathrm{pe}}(m_{\mathrm{V}})}{\beta}$$

Here, m_a (m_V) is the ALP (DP) mass and σ_{pe} is the photoelectric cross-section of Ge

Dark Compton interaction rate
for **ALPs** (**a**) and **DPs** (**v**):

$$R_{\mathrm{a}}^{\mathrm{C}} = f_{\mathrm{a}}^{\mathrm{C}} N_{\mathrm{e}} \frac{1.27 \times 10^{24}}{M_{\mathrm{tot}}} g_{\mathrm{ae}}^2 \left(\frac{[\mathrm{keV}]}{m_{\mathrm{a}}} \right) \mathrm{kg}^{-1}\,\mathrm{d}^{-1}$$

$$R_{\mathrm{V}}^{\mathrm{C}} = f_{\mathrm{V}}^{\mathrm{C}} N_{\mathrm{e}} \frac{7.79 \times 10^{22}}{M_{\mathrm{tot}}} \frac{\alpha'}{\alpha} \left(\frac{[\mathrm{keV}]}{m_{\mathrm{V}}} \right) \mathrm{kg}^{-1}\,\mathrm{d}^{-1},$$

N_e is the number of electrons of the target atom and mass-dependent factors for ALPs and DPs are:

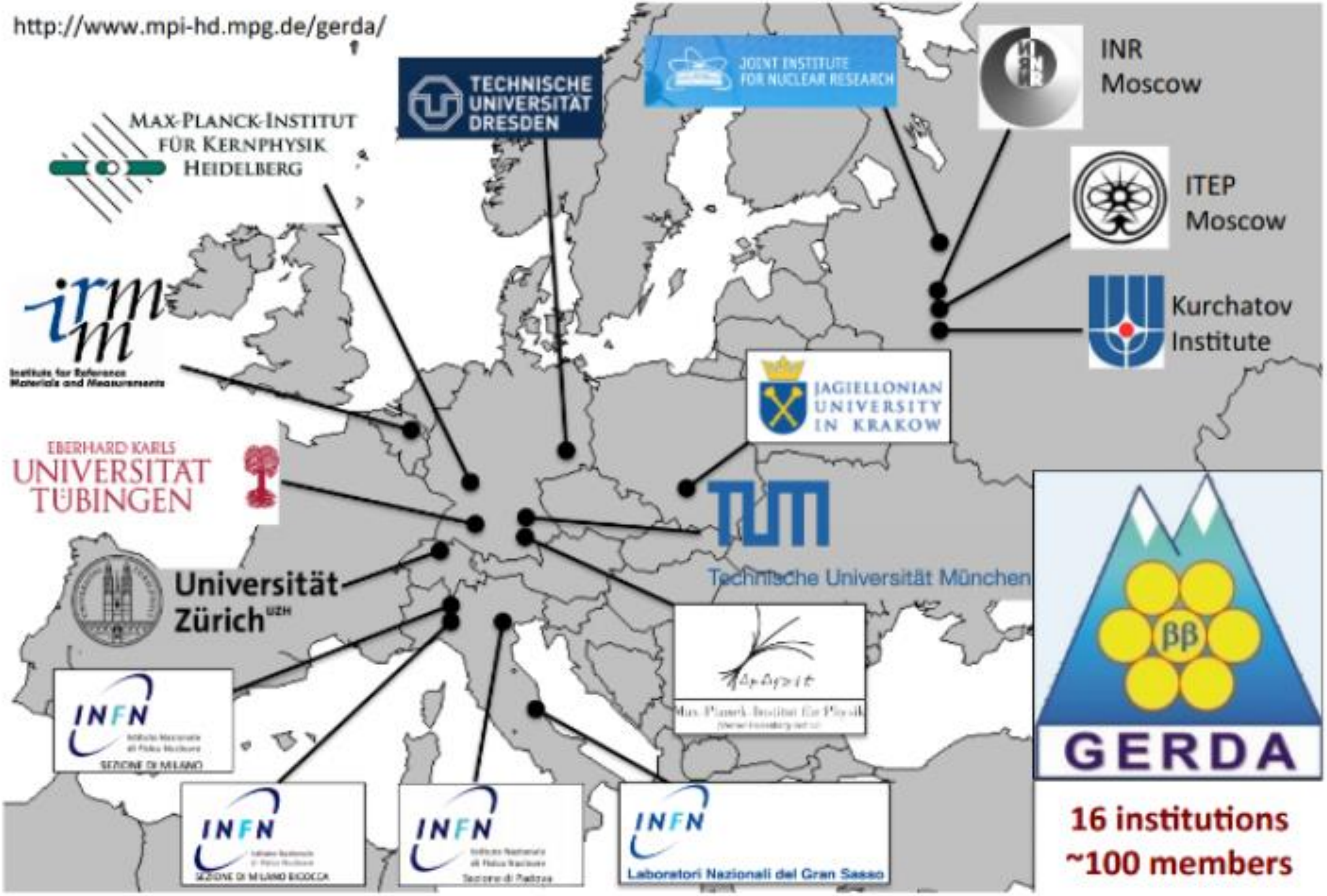
$$f_{\mathrm{a}}^{\mathrm{C}}(m_{\mathrm{a}}) = \frac{m_{\mathrm{a}}^2 (m_{\mathrm{a}} + 2m_{\mathrm{e}})^2}{(m_{\mathrm{a}} + m_{\mathrm{e}})^4}$$

$$f_{\mathrm{V}}^{\mathrm{C}}(m_{\mathrm{V}}) = \frac{(m_{\mathrm{V}} + 2m_{\mathrm{e}})\left(m_{\mathrm{V}}^2 + 2m_{\mathrm{e}}m_{\mathrm{V}} + 2m_{\mathrm{e}}^2\right)}{(m_{\mathrm{V}} + m_{\mathrm{e}})^3}.$$

For a non-relativistic incident DM particle having an energy equal to $\omega \approx m_{DM}$, the recoil energy T of the electron and the energy ω' of the emitted photon are:

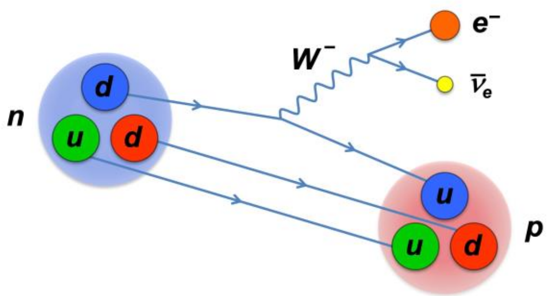
$$T = \frac{\omega^2}{2(m_{\mathrm{e}} + \omega)} \quad \text{and} \quad \omega' = \sqrt{T^2 + 2m_{\mathrm{e}}T}\,.$$

The GERDA Collaboration

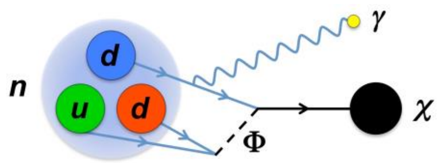


Neutron **dark** decay

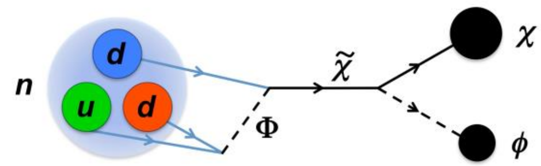
Общим механизмом для объяснения асимметрии материи-антиматерии во Вселенной и природы ТМ может быть альтернативное решение проблемы ТМ с помощью **“темных”** или **“зеркальных”** нейтронов - смотри, например, в [1]



Neutron β-decay in SM



Neutron → dark matter + γ



Neutron → two dark particles

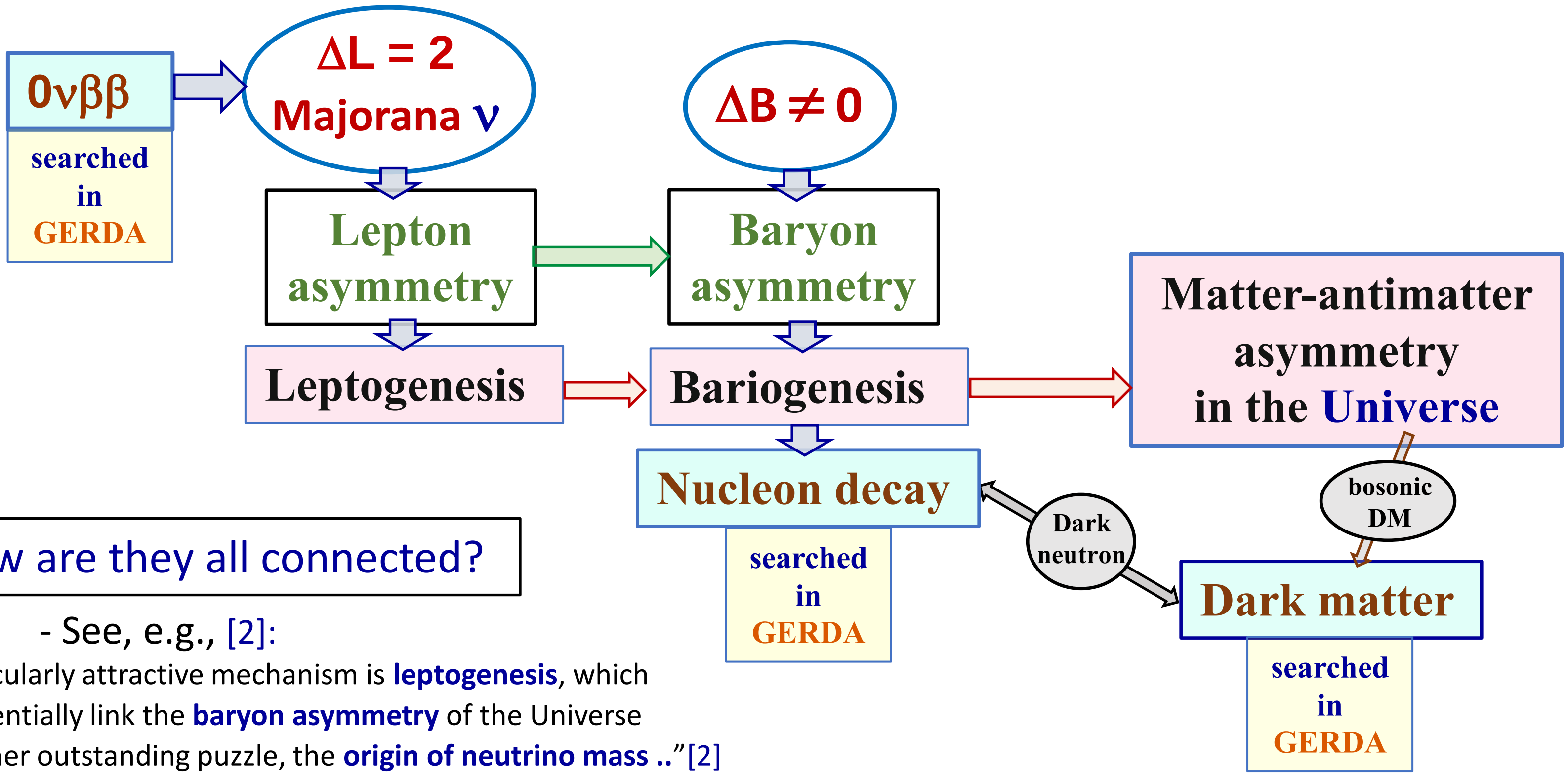
χ и ***˜χ*** - один или два **“зеркальных” (“темных”)** нейтрона, а ***Φ и ϕ*** - **“темные”** бозоны.

Кроме * **исчезновения нейтрона при рождении его темного собрата**, т.е. при переходе из обычного в зеркальный мир, возможен и ** **альтернативный процесс** – **аннигиляция нейтрона** в ядре при его столкновении с темным (анти-)нейтроном из галактического гало ТМ [2]

*** Исчезновение нейтрона с переходом в невидимый зеркальный может быть **объяснением разницы** (~ 4σ) **между измеренными временами жизни нейтрона** в нейтронном пучка (”beam” experiments) и при распаде ультрахолодных нейтронов в замкнутом объеме (“bottle” type) [3].

[1] *H Ejiri and J D Vergados, Journal of Physics G, 46.2 (2019)*
[2] *M. Jin and Y. Gao, Phys. Rev. D 98 , 7 (2018)*
[3] *B.Fornal and B. Grinstein, Phys. Rev. Lett. 120.19 (2018); Mod. Phys. Lett. , A 35.31 (2020)*

Baryon asymmetry could be caused by **lepton asymmetry**: ***leptogenesis*** [1].
If the neutrino is a Majorana particle, then the decay of the heavy Majorana neutrinos into leptons and Higgs particles in the early Universe looks like an ideal scenario for leptogenesis.
That is, the **discovery of the Majorana nature of neutrinos** in the **neutrinoless double beta decay** observation can prove the arguments in favor of **leptogenesis as a source of baryon asymmetry of the Universe** [2]



How are they all connected?

- See, e.g., [2]:

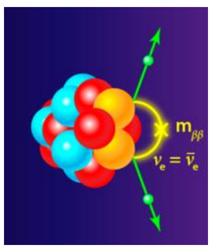
"A particularly attractive mechanism is **leptogenesis**, which can potentially link the **baryon asymmetry** of the Universe to another outstanding puzzle, the **origin of neutrino mass** .." [2]

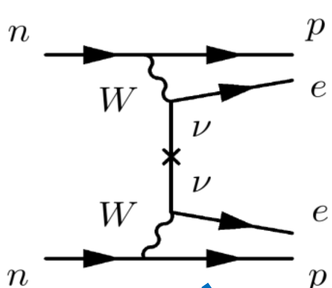
[1] *S.Davidson, E. Nardi, Y. Nir, "Leptogenesis", Physics Reports, 466, 4–5 (2008);*
[2] *G.Chauhan, P.S.B.Dev, "Interplay between resonant leptogenesis, neutrinoless double beta decay and collider signals ...",* Nuclear Physics B 986 *(2023) 116058*

Neutrinoless double-beta decay ^{76}Ge

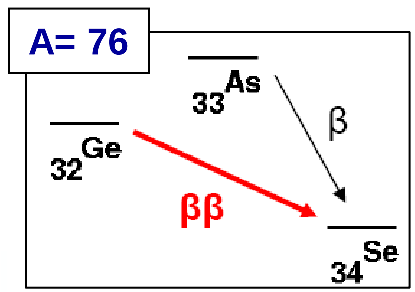
The main goal of the **GERDA (GERmanium Detector Array)** experiment was to search for **neutrinoless double beta decay of ^{76}Ge (0νββ).**

0νββ-decay must violate the global lepton number by two units (**ΔL=2**) and is possible only if **neutrinos are Majorana particles with non-zero mass**. In the Standard Model all neutrinos are massless, what means that observing **0νββ** -decay will provide a unique tool for **penetrating beyond the Standard Model.**





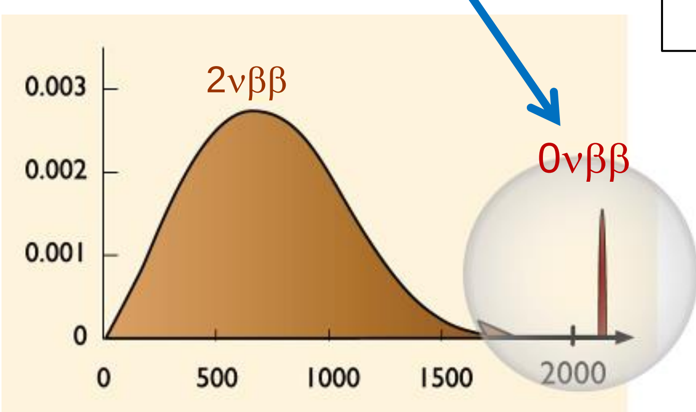
0νββ: (A,Z) → (A,Z+2) + 2e$^-$ **ΔL = 2**



$Q_{\beta\beta}$ = 2039 кэВ

Detection of 0νββ will provide information about:

- **violation of L number (ΔL=2)**
- **nature of ν (Dirac or Majorana)**
- **effective mass of ν**
- **neutrino mass hierarchy**



0νββ-decay rate (for light ν_M)

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

Majorana neutrino effective mass

Table 1 Currently leading experimental lifetime constraints for single nucleon decays at 90% confidence level (CL) in different isotopes. The decay channels refer either to neutrons (n) or protons (p), where n_{eff} is the effective number of nucleons N that are available for the decay of a given isotope. Invisible channel ($N \to inv.$) results where no visible energy is deposited by charged particles in detectors are shown, together with inclusive channel ($N \to X$) results looking for the decay of radioactive daughter nuclei after the N decay.

Experiment	Decay	n_{eff}	τ_{low} (yr)
SNO [14] $^{(a)}$	$^{16}\text{O} \xrightarrow{n} {}^{15}\text{O} + inv.$	8	1.9×10^{29}
	$^{16}\text{O} \xrightarrow{p} {}^{15}\text{N} + inv.$	8	2.1×10^{29}
SNO+ [15] $^{(a)}$	$^{16}\text{O} \xrightarrow{n} {}^{15}\text{O} + inv.$	8	2.5×10^{29}
	$^{16}\text{O} \xrightarrow{p} {}^{15}\text{N} + inv.$	8	3.6×10^{29}
Borexino [16] $^{(b)}$	$^{12}\text{C} \xrightarrow{n} {}^{11}\text{C} + inv.$	4	1.8×10^{25}
	$^{13}\text{C} \xrightarrow{p} {}^{12}\text{B} + inv.$	4	1.1×10^{26}
DAMA/LXe [17]	$^{136}\text{Xe} \xrightarrow{n} {}^{135}\text{Xe} + X$	32	3.3×10^{23}
	$^{136}\text{Xe} \xrightarrow{p} {}^{135}\text{I} + X$	26	4.5×10^{23}
DAMA [18]	$^{129}\text{Xe} \xrightarrow{p} {}^{128}\text{I} + X$	24	1.9×10^{24}
NaI(Tl) [19]	$^{127}\text{I} \xrightarrow{n} {}^{126}\text{I} + X$	34	1.5×10^{24}
	$^{127}\text{I} \xrightarrow{p} {}^{126}\text{Te} + X$	20	3.0×10^{24}
Geochemical [20, 21]	$^{130}\text{Te} \xrightarrow{n} {}^{129}\text{Te} + X$	28	8.6×10^{24}
	$^{130}\text{Te} \xrightarrow{p} {}^{129}\text{Sb} + X$	24	7.4×10^{24}

$^{(a)}$ Searches for γ rays coming from the de-excitation of a residual excited nucleus following the disappearance of a nucleon in ^{16}O.
$^{(b)}$ Searches for decays of unstable nuclei left after nucleon decays of parent ^{12}C, ^{13}C nuclei.

Proton decay, and the decay of nucleons in general, constitutes one of the most sensitive probes of high-scale physics beyond the Standard Model. Most of the existing nucleon decay searches have focused primarily on two-body decay channels, motivated by grand unified theories and supersymmetry. However, many higher-dimensional operators violating baryon number by one unit, $\Delta B = 1$, induce multibody nucleon decay channels, which have been only weakly constrained thus far. While direct searches for all such possible channels are desirable, they are highly impractical. In light of this, we argue that inclusive nucleon decay searches, $N \to X +$ anything (where X is a light Standard Model particle with an unknown energy distribution), are particularly valuable, as are model-independent and invisible nucleon decay searches such as $n \to$ invisible. We comment on complementarity and opportunities for such searches in the current as well as upcoming large-scale experiments Super-Kamiokande, Hyper-Kamiokande, JUNO, and DUNE. Similar arguments apply to $\Delta B > 1$ processes, which kinematically allow for even more involved final states and are essentially unexplored experimentally.

Leptogenesis

The baryon asymmetry could have been induced by a lepton asymmetry: *leptogenesis*. If neutrinos are Majorana particles, the decays of the heavy Majorana neutrinos into leptons l_{α}plus Higgs particles φ in the early Universe provide an ideal scenario for leptogenesis.

Heavy Majorana neutrinos are their own antiparticles, so they can decay to both $l_{\alpha}\varphi$ and $l_{.\alpha}.\varphi$ final states. If there is an asymmetry in the two decay rates, a net lepton asymmetry will be produced.

Finally, this lepton asymmetry can be efficiently converted into a baryon asymmetry via the so-called *sphaleron processes*.
for leptogenesis to occur, three conditions must be met. These conditions directly follow from the ingredients that are required to dynamically generate a baryon asymmetry (*Sakharov's conditions*):

1. Presence of lepton number violating processes;
2. Beyond-SM sources of CP violation[17];
3. Departure from thermal equilibrium, so that the inverse processes do not wash out the generated lepton asymmetry.

“При высоких температурах в Стандартной модели происходит прямое нарушение барионного числа совместно с нарушением лептонных чисел. Это открывает возможность построения таких механизмов генерации барионной асимметрии, которые происходят за счет нарушения лептонных чисел и частичной переброски в рамках СМ этих лептонных чисел в барионное число при высоких температурах.”

В.А.Рубаков

V.A. Kuzmin, V.A. Rubakov, M.E. Shaposhnikov,
“On anomalous electroweak baryon-number non-conservation in the early universe”,
Physics Letters B ,Volume 155, Issues 1–2, 16 May 1985

A particularly attractive mechanism is leptogenesis [1] , which can potentially link the baryon asymmetry of the Universe to another outstanding puzzle, namely, the origin of neutrino mass. …
The central idea of thermal leptogenesis is the production of a net leptonic asymmetry in the early Universe, via the CP-violating out-of-equilibrium decays of heavy right-handed neutrinos , which is then converted to a net baryon asymmetry…

There are **two qualitatively different types of direct neutron lifetime measurements**: **bottle and beam experiments**. In the first method one obtains [3]:

$$t_n(\text{bottle}) = (879.6 \pm 0.6)\text{s}$$

$$\tau_n(\text{beam}) = (888 \pm 2.0)\text{s}$$

The discrepancy between the two results is 4.0 sigma.

since in the ”‘beam”’ experiment the result is obtained by studying the decay, the lifetime they measure is related to the actual neutron lifetime by

$$\tau_n(\text{beam}) = \frac{\tau_n}{\text{Br}(n \to p + \text{anything})}$$

the discrepancy can be explained by considering an extra channel in the beam experiment, which involves the **emission of a dark fermion particle** χ, which goes undetected. Then they proposed a model which can give a branching ratio of 1% to this new channel, while the standard channel covers only 99%,

For a free neutron this cannot occur without the emission of another particle, e.g. a photon to conserve energy momentum. Since the emitted particle is assumed not to carry any baryon number [6], this scenario is very interesting, since if true, it will demonstrate the existence of baryon number violating DB = 1 interactions. This scenario seems, however, to be excluded from astrophysical data involving neutron stars.

The neutron in the nucleus seems to behave differently, due to the nuclear binding. In certain cases it decays like in the beta decay, but the produced proton cannot escape due to nuclear binding, while a daughter nucleus appears with its charge increased by one unit. Decays of well-bound nucleons (neutrons) into invisible particles have been searched by measuring g rays long time ago [11, 12]. In the model considered above the produced dark matter particle χ, interacting very weakly, can escape. In this case energy-momentum can be conserved without the emission of additional particles, like the photon, and the decay width is expected to be much larger.

The effective number of decaying neutrons (protons)

Inside the parent 76Ge nuclei, whose decay could produce the specific daughter nucleus 75Ge (75Ga).

The effective number Neff = 16 (14) for neutrons (protons) was obtained by using the single particle shell model with a modified Woods-Saxon potential, and the set of parameters adjusted for 76Ge.
The calculations were done with the shell-model codes KSHELL and CoSMo comparing, where possible, our full range of the sub-shell nucleon binding energies with the values obtained in other works .

if Eexc is less than the binding energy of the least bound nucleon in the 75Ge daughter nucleus, **energy conservation requires** that nucleus to de-excite by gamma emission rather than other particle emission. This gives **the following restriction on the Eb (n in A,Z)** for the neutron decay of the (A,Z) nucleus to the (A,Z-1) nucleus only:

Eb (n in A,Z) ≤ Sn(A,Z) + min{Sn(A-1,Z), Sp(A-1,Z)},

and the similar for the proton decay of the (A,Z) nucleus to the (A-1,Z-1) nucleus only:

Eb (p in A,Z) ≤ Sp(A,Z) + min{Sn(A-1,Z-1), Sp(A-1,Z-1)},

For n decay 76Ge → 75Ge: Eb (n in 76Ge) ≤ Sn(76Ge) + min{Sn(75Ge), Sp(75Ge)},
Eb (n) ≤ 9.43 + 6.51= **15.94** MeV. (1)
For p decay 76Ge → 75Ga: Eb (p in 76Ge) ≤ Sp(76Ge) + min {Sp(75Ga), Sn(75Ga)},
Eb (p) ≤ 12.04 + 8.49 = **20.53** MeV. (2)
Therefore, it is necessary to determine the number of nucleons in 76Ge that have binding energies less than **15.94** MeV for neutrons and less than **20.53** MeV for protons.