Search for two-neutrino double electron capture on ^{36}Ar with DarkSide-50 detector

Preliminary results

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on behalf of the DarkSide collaboration

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ICPPA-2024, October 26th 2024

Introduction

Two neutrino double electron capture (2EC2v):

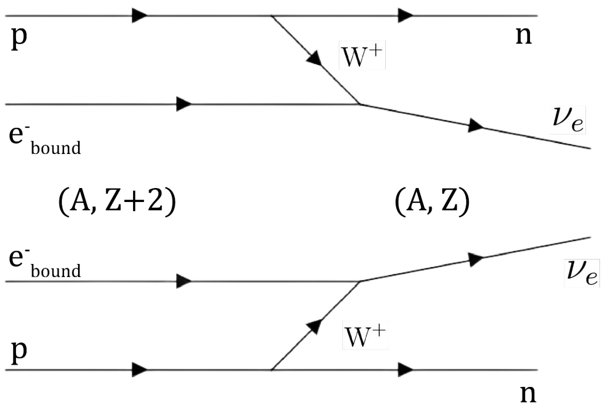
- is possible for 34 isotopes
- the only decay option for 12 isotopes
- the lower theoretical predictions: $T_{1/2} \sim 10^{22}$ yr
- for ^{124}Xe: $T^{2EC2v}_{1/2} = (1.8 \pm 0.5 \pm 0.1) \times 10^{22}$ yr[1]
- for ^{78}Kr: $T^{2EC2v}_{1/2} > 1.9 \times 10^{22}$ yr, CL = 90%[2]

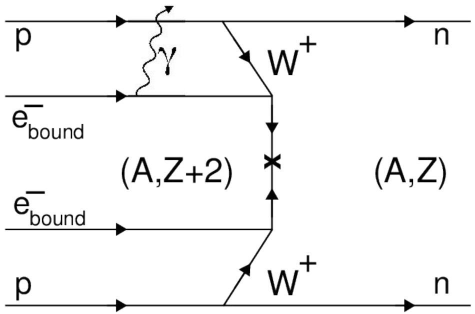
$$(T_{1/2}, 2\nu)^{-1} = \frac{a_{2\nu} F_{2\nu} |M_{2\nu}|^2}{\ln 2}$$

NME

$a_{2\nu} = 2 \times 10^{-22}\ \mathrm{yr}^{-1}$

$F_{2\nu} \sim Q^5$



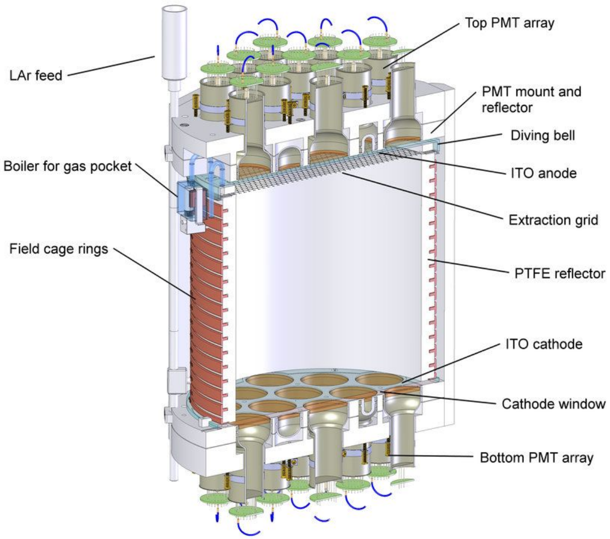


[1] S.S. Ratkevich, A.M. Gangapshev et al. Comparative study of the double K-shell-vacancy production in single- and double-electron capture decay. Physical Review C. 96 (2017)

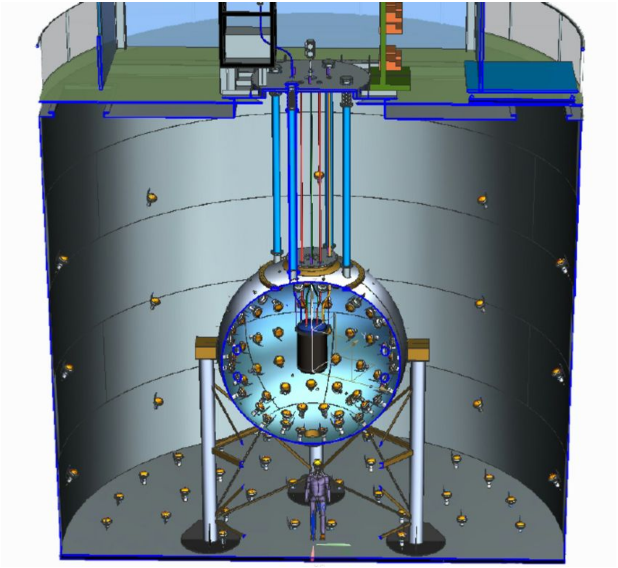
[2] XENON Collaboration, Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T. *Nature* 568, 532–535 (2019)

The DarkSide-50 experiment

DarkSide-50 — experiment to search for dark matter particles; two-phase time-projection chamber filled with liquid ultra-pure argon.
(underground argon data were taken from December 12, 2015, to February 24, 2018)



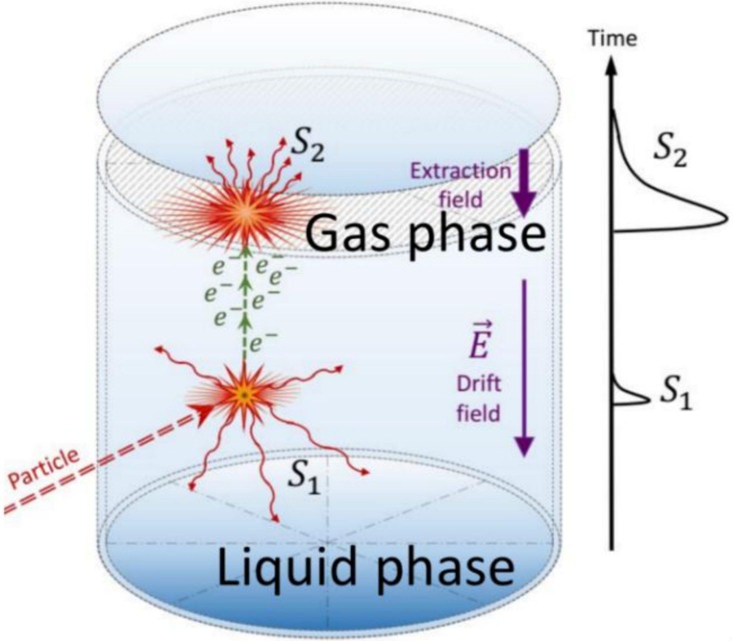
TPC scheme



Detector scheme

The principle of particle detection

- The charged particle causes a scintillation flash (S1) and ionization of the medium;
- Electroluminescence occurs in a gaseous medium (S2);
- The time interval between S1 and S2 allows to determine the Z coordinate;
- S2 position gives XY coordinates of the event;
- The ratio of amplitudes S1 and S2 is used to discriminate events from an electron and a recoil nucleus.



Underground argon — the active medium in the DarkSide

- ^{40}Ar was formed from decay of ^{40}K:
- $$^{40}\mathrm{K} + e^- \rightarrow {}^{40}\mathrm{Ar} + \nu_e + \gamma$$
- ^{39}Ar was formed in the atmosphere by cosmic rays:

$$^{40}\mathrm{K} + n \rightarrow {}^{39}\mathrm{Ar} + 2n + \gamma$$

The use of argon from underground deposits will reduce the contribution of this component.

- **^{39}Ar** is the background source for the experiment and limits the sensitivity at low energies;
- The vast majority of primordial argon consists of isotopes **^{36}Ar** and ^{38}Ar, because on Earth, potassium is 660 times more abundant than argon.

- **^{36}Ar** was formed during the spontaneous fission of heavy nuclei, as well as in the (α, n) reactions on nuclei of light elements contained in uranium-thorium minerals, such as ^{36}Cl and ^{33}S:

$$^{36}\mathrm{Cl} \rightarrow {}^{36}\mathrm{Ar} + e^- + \bar{\nu}_e$$

$$^{33}\mathrm{S} + {}^{4}\mathrm{He} \rightarrow {}^{36}\mathrm{Ar} + n$$

- abundance of ^{36}Ar in AAr and UAr is **0.334%**[3] and **0.012%**[4] respectively.

[3] B. Marty and F. Humbert, "Nitrogen and argon isotopes in oceanic basalts," Earth Planet Sci. Lett. 152, 101–112 (1997)

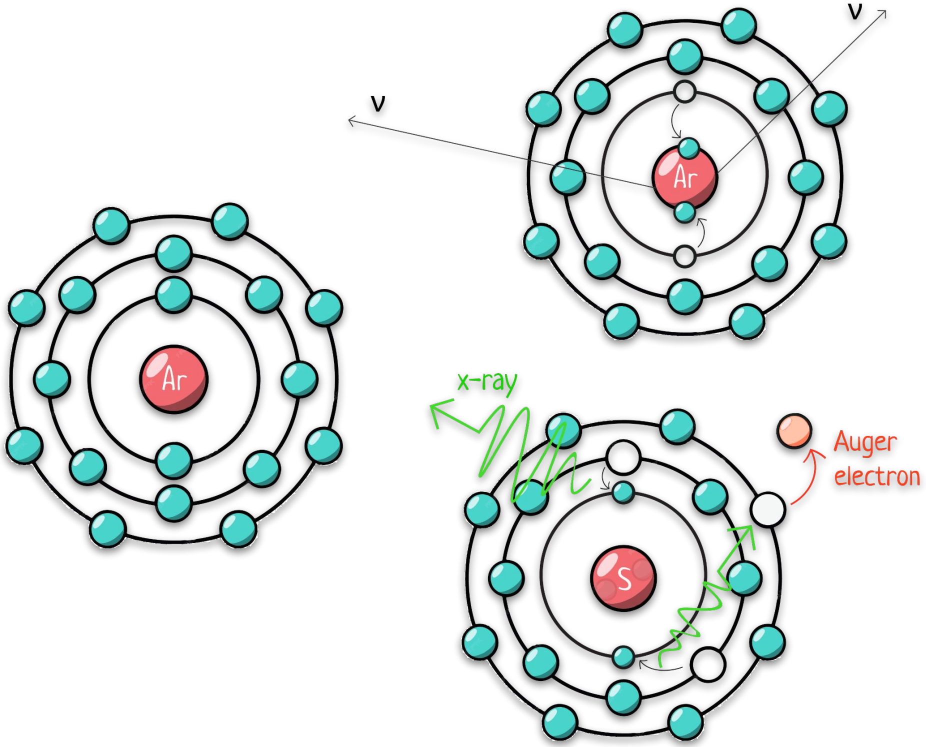
[4] S. Gilfillan, C.Ballentine at al., "The noble gas geochemistry of natural CO2 gas reservoirs from the colorado plateau and rocky mountain provinces, USA". Geochimica et Cosmochimica Acta, 72(4):1174–1198, 2008

2EC2ν on ^{36}Ar

$$2e^- + ^{36}\mathrm{Ar} \longrightarrow ^{36}\mathrm{S} + 2\nu_e$$

The processes of relaxation after 2EC2ν:

- an emission of Auger electrons;
- a characteristic photons.



2EC2ν release as:

- *KK*-capture (~74%)
- *KL*-capture (~26%)

Theoretical calculations:

$$T_{1/2}^{2\mathrm{EC}2\nu}(^{36}\mathrm{Ar} \rightarrow ^{36}\mathrm{S}) = 1.7 \times 10^{29}\ \mathrm{yr}$$

Emission induced by the 2EC2ν reaction

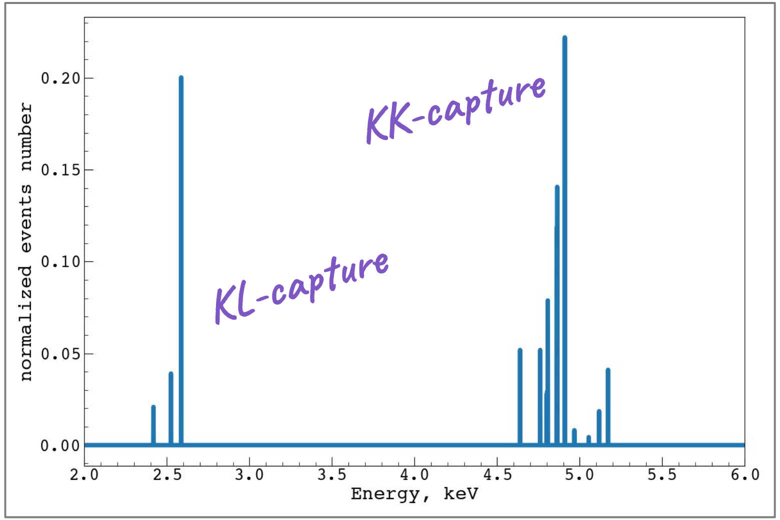
1st step	E_1, eV	P_1	2nd step	E_2, eV	P_2	3rd step	E_3, eV
			$KL_{23}L_{23}$	2099	30%		4×150
$KL_{23}L_{23}$ [1]	2211	62%	KL_1L_{23}	2053	19%	LMM	4×150
			KL_1L_1	1996	6%		4×150
			$\gamma \longrightarrow$ph.e	2100	7%		3×150
			$KL_{23}L_{23}$	2080	16%		4×150
KL_1L_{23}	2181	23.5%	KL_1L_{23}	2024	3.9%	LMM	4×150
			$\gamma \longrightarrow$ph.e	2170	3.8%		3×150
			$KL_{23}L_{23}$	2102	5.6%		4×150
$\gamma \longrightarrow$ph.e	2470	9.4%	KL_1L_{23}	2048	2.5%	LMM	4×150
			KL_1L_1	1985	0.6%		4×150
			$\gamma \longrightarrow$ph.e	2048	1.1%		3×150
			$KL_{23}L_{23}$	2088	4.4%		4×150
KL_1L_1	2119	5.1%	$\gamma \longrightarrow$ph.e	2070	0.7%	LMM	3×150

Table 1: The *KK*-caption de-excitation channels at ^{36}Ar

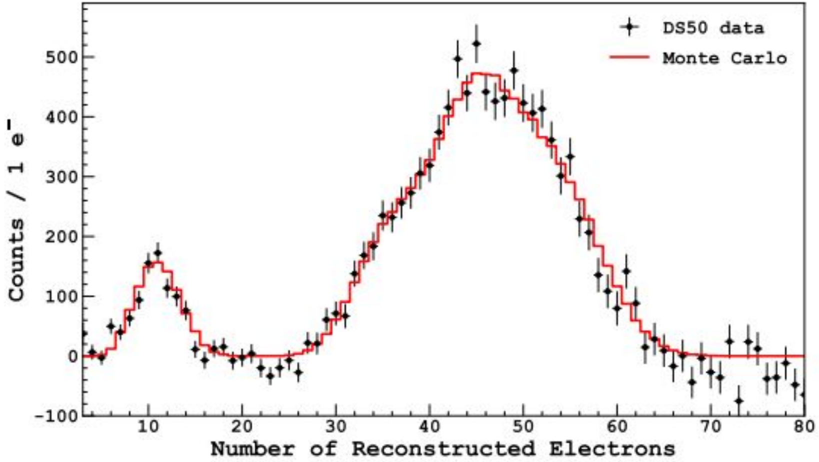
- Software package *DarkSide-50:lowmass*

1st step	E_1, eV	P_1	2nd step	E_2, eV
$KL_{23}L_{23}$	2107	77%		3×160
KL_1L_{23}	2045	15%	LMM	3×160
$\gamma \longrightarrow$ph.e.	2063	8.2%		2×178

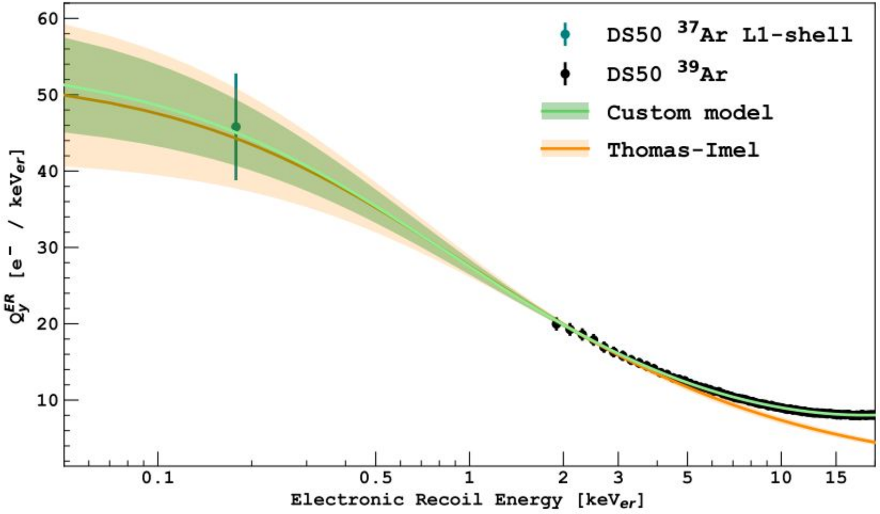
Table 2: The *KL*-caption de-excitation channels at ^{36}Ar



Calibration of the ionization response



Comparison between the best fitted simulated spectrum and ^{37}Ar data as a function of the reconstructed number of electrons.

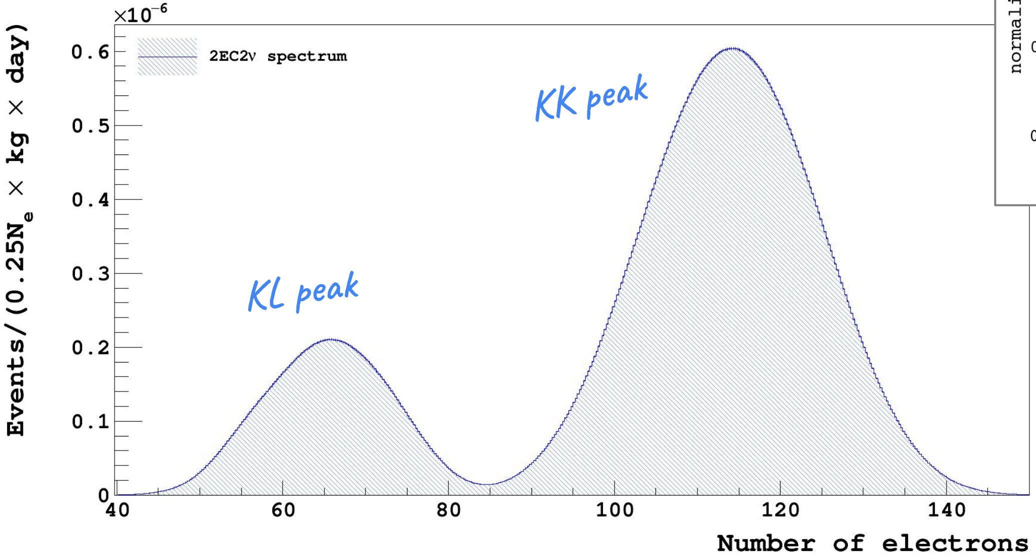


The ER ionization yield, measured from AAr (black) and ^{37}Ar (teal) data with a drift field of 200 V/cm

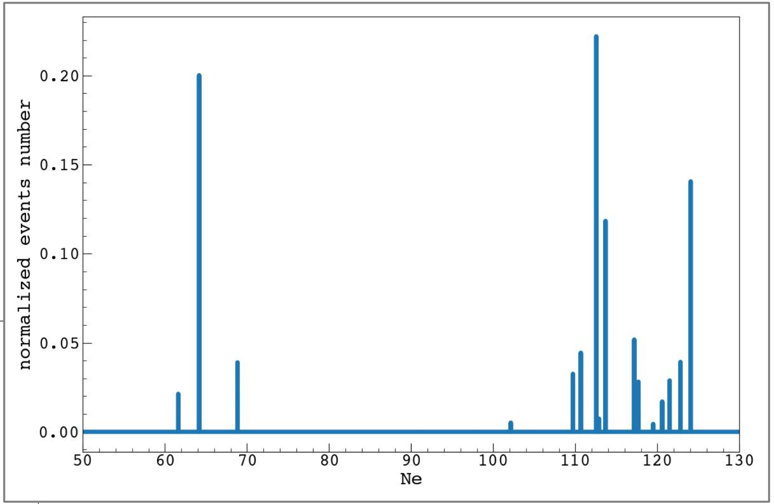
DarkSide Collaboration, Calibration of the liquid argon ionization response to low energy electronic and nuclear recoils with DarkSide-50, Phys. Rev. D 104, 082005 (2021)

Data analysis

Preliminary results



The Monte Carlo generated detector response spectrum of the 2EC2ν process on ^{36}Ar, involving the *KK*- and *KL*-contributions *(preliminary result)*



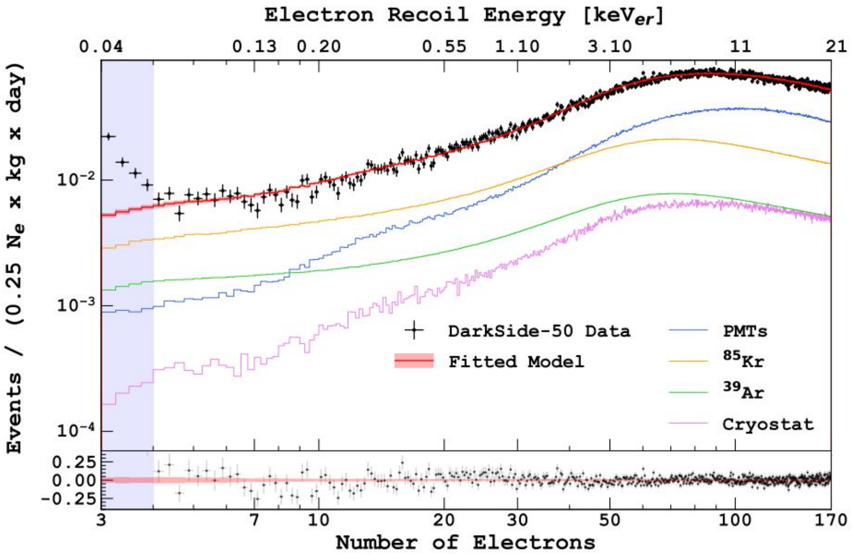
Energy response spectrum of the 2EC2ν process on ^{36}Ar in number of ionisation electrons *(preliminary result)*

Simplification: ionization is independent of each individual decay product

Data analysis

- 653.1 live-days of data (UAr)
- fiducial volume (19.4±0.3) kg
- Ne ∈ [40, 170]

- The search for 2EC2ν is performed with a profile log-likelihood ratio test statistics based on the likelihood function and the generated 2EC2ν signal.
- A free parameter in the fitting is the amplitude of the signal.
- Spectra under simplifying assumption of independent ionization response from each individual decay product *(work in progress)*



Background model and uncertainty (red line and shaded area) from the data fit in the [4, 170] Ne range, and the individual contributions from the internal (39Ar and 85Kr) and external components (cryostat and PMTs).

Preliminary result

Obs. limit at 90% C.L.: $N_{2EC2\nu}$ < 402 events ($N_{2EC2\nu}$=0 for best fit)

DarkSide-50 Collaboration, Search for low-mass dark matter WIMPs with 12 ton-day exposure of DarkSide-50, Phys.Rev.D 107 (2023) 6, 063001

Calculation of the limit

The corresponding half-life for $N_{2EC2\nu}$ is

$$T_{1/2}^{2\mathrm{EC}2\nu} = \ln(2) \times \frac{N_A \times \eta_{\mathrm{Ar}} \times \epsilon}{N_{2\mathrm{EC}2\nu} \times M_A} \times M \times T,$$

where M_A = 0.039 kg/mol is the argon molar mass,
η_{Ar} is the isotopic abundance of the argon isotope,
ε = 100%,
M = 20 kg is the active mass of the LAr volume,
T = 651.3 days is the total lifetime.

Results

Analysis of the DarkSide-50 experiment data gives a 90% sensitivity of

$$T_{1/2}^{2\text{EC}2\nu} > 9.6 \times 10^{21} \times \eta(^{36}\text{Ar}) \ \text{years}$$

Preliminary result

The values for the ^{36}Ar abundance in the DS-50 have not been measured accurately at the moment, so we left it as a free parameter.

Sensitivity for DS-20k experiment

- Fiducial mass ≈ 20 t ($M^{DS\text{-}20k} = 1000M^{DS\text{-}50}$)
- Lower background ($N_{bg}^{DS\text{-}20k} = 0.1N_{bg}^{DS\text{-}50}$)
- higher data collection efficiency
- longer exposure time ($T^{DS\text{-}20k} = 5.6T^{DS\text{-}50}$ yr)

full DS-20k exposure = 200 t· yr

Assuming the DS-20k experiment will be more sensitive to rare events, the result can be improved (with the same concentration of ^{36}Ar):

$$T_{1/2}^{\text{DS-20k}} = \sqrt{\frac{1000 \cdot 5.6}{0.1}} T_{1/2}^{\text{DS-50}} > 2.3 \times 10^{24} \times \eta(^{36}\text{Ar}) \text{ yr (90\% CL)}$$

Preliminary result

Plans for the future

- Plans include measuring the isotopic abundance of argon used in the DS-50 using mass spectroscopy.
- It would be beneficial to verify calculations using a target enriched in ^{36}Ar
- The presented analysis is planned to be carried out for the next generation DarkSide detector.

Thanks for your attention!