Study of cosmogenic activation above ground of Ar for DarkSide-20k

- GADMC and DarkSide-20k
- Methodology: flux, cross section
- Isotopes
- Production rates
- Activity and counting rates

LIDINE 2023
Light Detection In Noble Elements
20–22 Sep 2023
Madrid

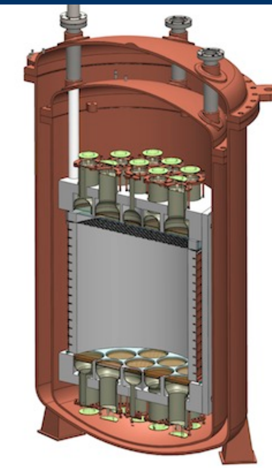
Susana Cebrián scebrian@unizar.es
on behalf of the DarkSide-20k collaboration

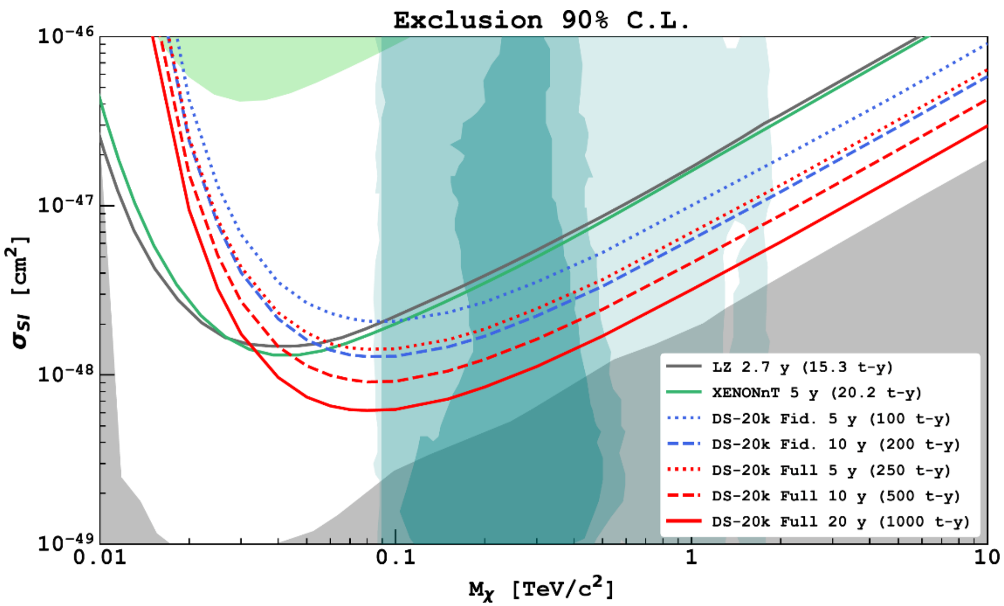
20th September 2023

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza
Universidad Zaragoza

GADMC

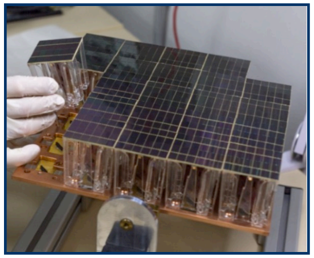
Global Argon Dark Matter Collaboration (GADMC):
joining ArDM, DarkSide-50, DEAP-3600, and MiniCLEAN
to operate LAr TPCs reaching the scale of **multi-ton** detectors
to push the sensitivity for WIMP detection down to the neutrino fog





DarkSide-20k: 20 t (fiducial) at Gran Sasso, starting in 2027
DarkSide-LowMass: 1 t (fiducial), S2 only to lower threshold → more ultrapure Ar needed
P. Agnes et al, Phys. Rev. D 107 (2023) 112006
ARGO: ~360 t, at SNOLAB

Program:
- Development of custom-designed **SiPMs**
- Design of **active vetos** to reject backgrounds
- Procurement of large amounts of radiopure **underground Ar (UAr)**



GADMC: UAr journey

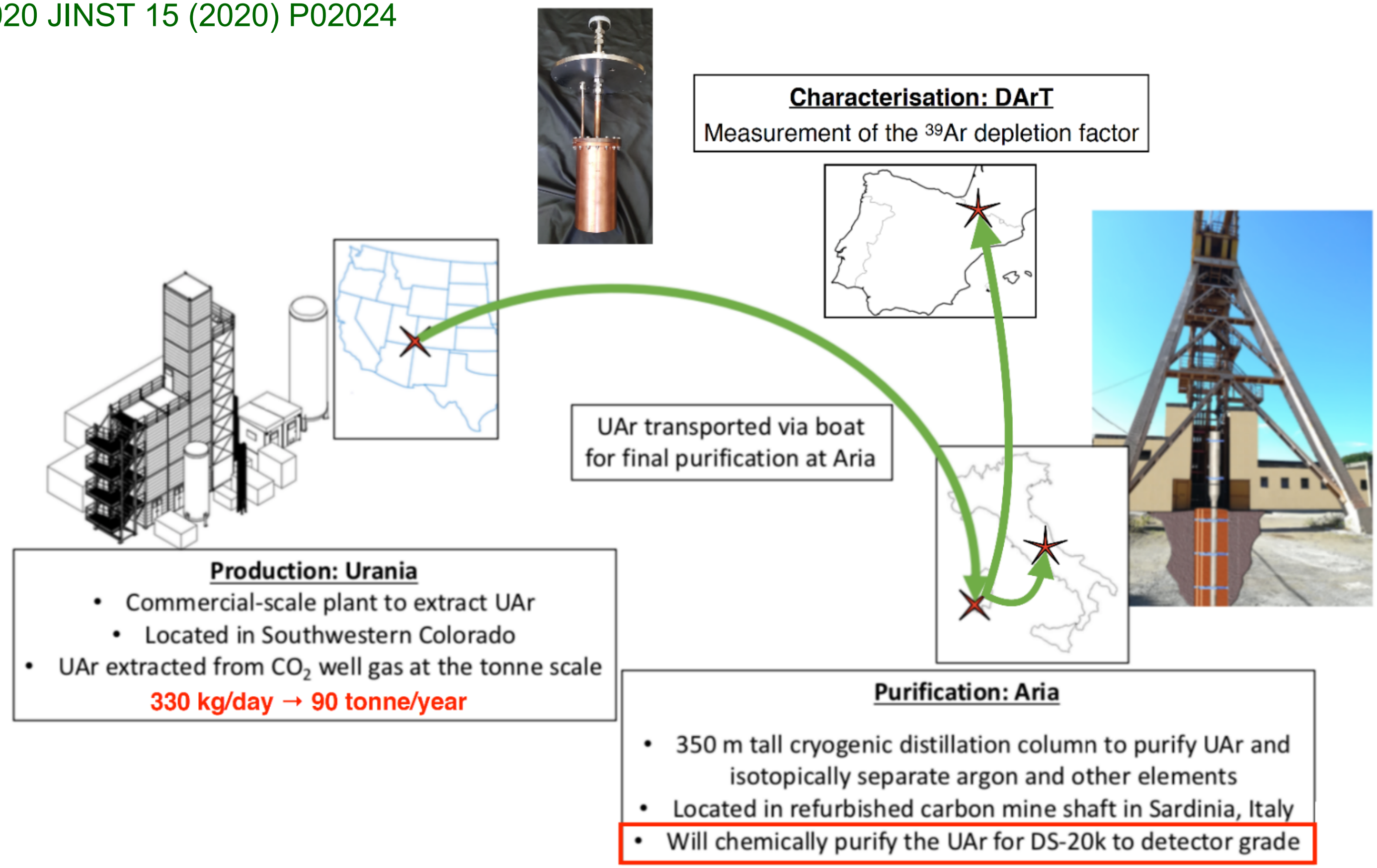
Procurement of **low-radioactivity UAr**

- **Urania:** extraction from CO_2 wells in Colorado (as DarkSide-50)
- **Aria:** purification in a criogenic distillation column in Sardinia

  P. Agnes et al, Eur. Phys. J. C 81 (2021) 359; Eur. Phys. J. C 83 (2023) 453

- **DArT:** quantification of **^{39}Ar** in a chamber in the ArDM detector in Canfranc

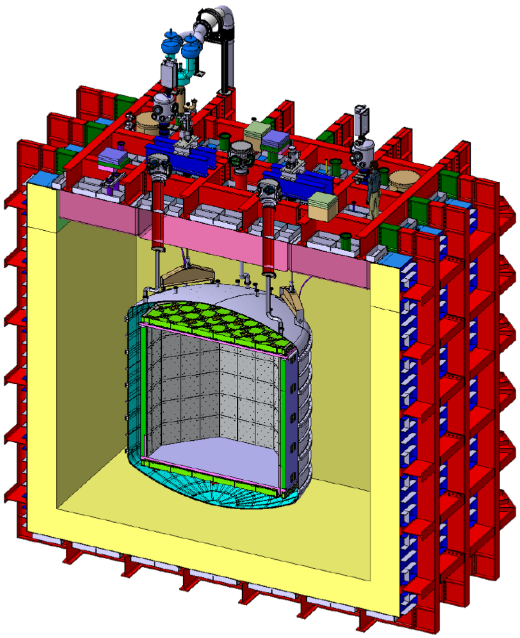
  C.E. Aalseth et al, 2020 JINST 15 (2020) P02024

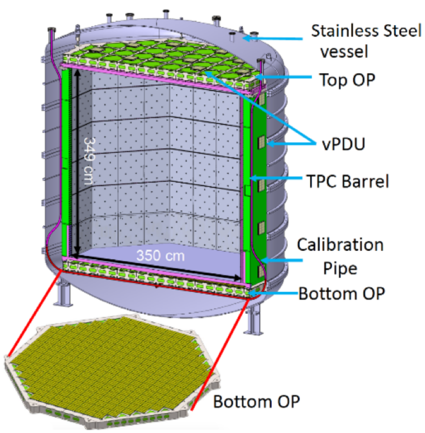


DarkSide-20k

Dual-phase TPC read by **SiPMs** with 3D space reconstruction capability
Filled and surrounded by **UAr**: 99.2 t required, 51.1 t inside TPC, **20.2 t** fiducial mass

- **TPC:** Gd-PMMA vessel to moderate and capture neutrons
- **Inner veto:** stainless steel vessel
- **Outer veto:** 700 t of Atmospheric Argon, ProtoDUNE-like membrane cryostat





Goal: <0.1 events in 200 t·y

- ✓ Very **efficient discrimination** between ER and NR, thanks to PSD and S1/S2
- ✓ **Veto capabilities** for muons and neutrons
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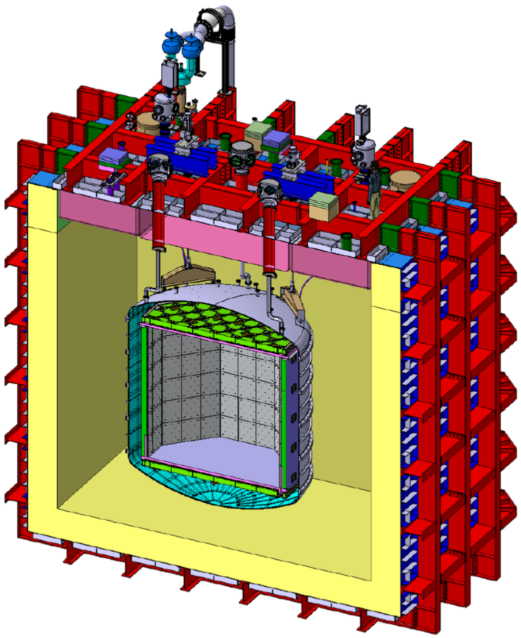

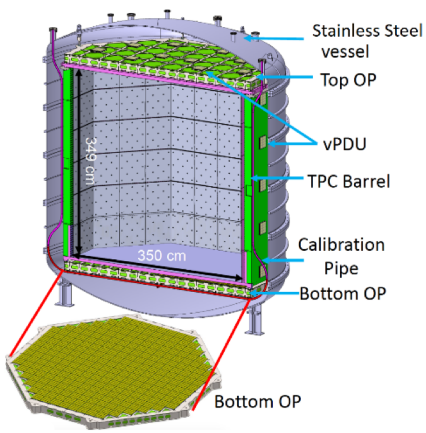

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➡ But **beta/gamma** background from **primordial or cosmogenic radioactivity** must be analyzed due to acceptance losses for ER+NR pile-up in TPC or accidental coincidences between TPC and Veto

Methodology

Goal: to determine if **activity induced by exposure to cosmic rays** during fabrication, transport and storage of components could be an issue in order to identify limits on the surface residency time and assess the necessity of taking some steps:

- Storing materials underground
- Avoiding flights
- Using shields against cosmic rays

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1. To know the **production rates *R*** of relevant isotopes in the targets, from
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$$R = N_t \int \sigma(E)\phi(E)dE$$

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3. To compute the **background rate** generated by Monte Carlo simulation: G4DS

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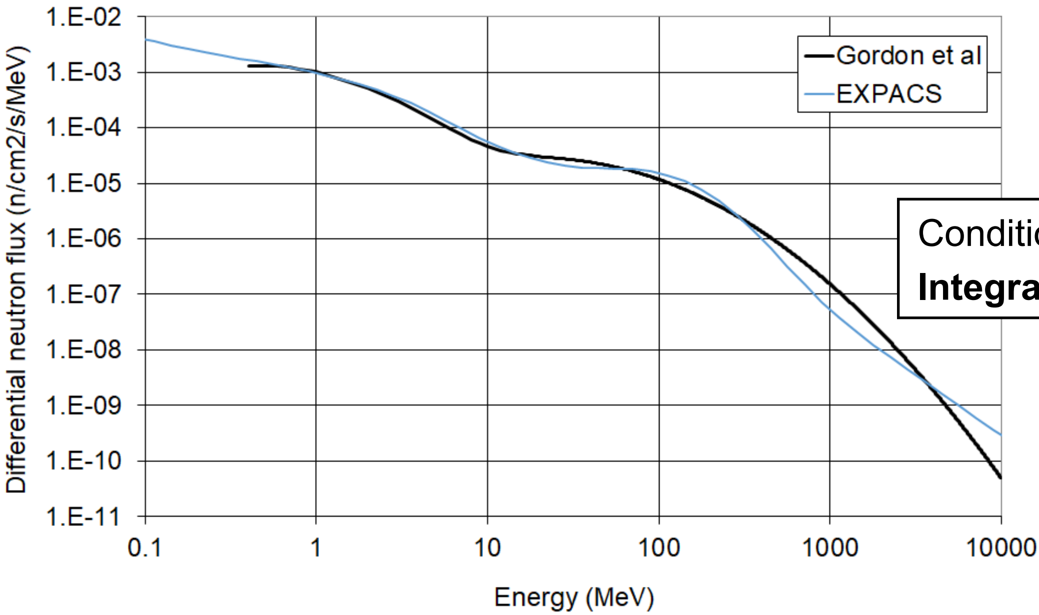
M.S. Gordon et al, IEEE Trans. Nucl. Sci. 51 (2004) 3427



Conditions of New York City at sea level

Integral flux (10 MeV-10 GeV): 3.6×10^{-3} cm^{-2} s^{-1}

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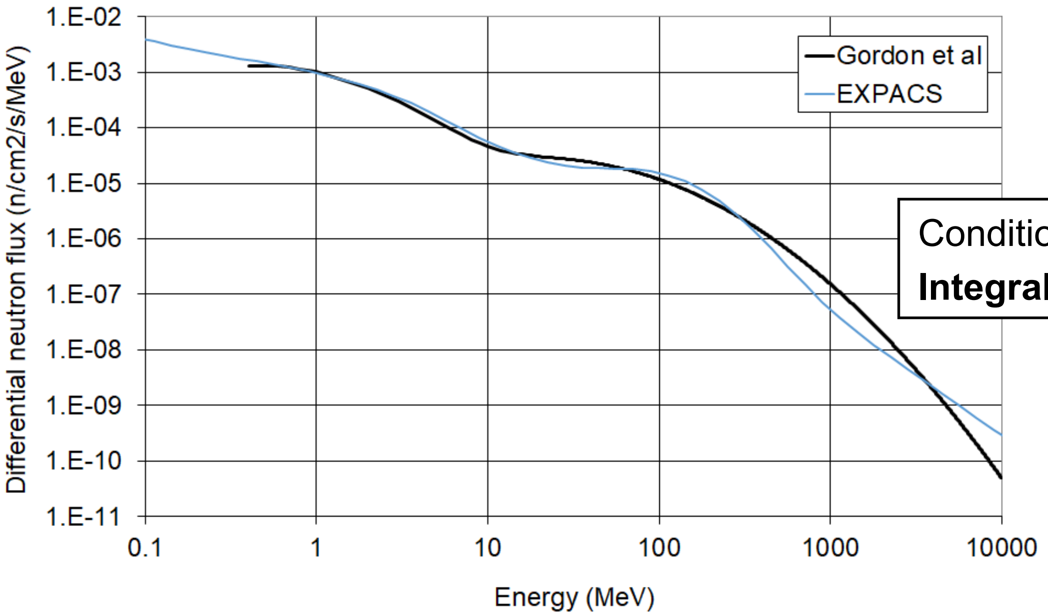

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As it depends on altitude and geomagnetic rigidity, **correction factors** must be applied to the parametrization

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    JENDL (Japanese Evaluated Nuclear Data Library)

    - Using GNASH code
    - For **neutrons and protons up to 200 MeV,** from **20 MeV to 3 GeV** in High Energy File

Isotopes

- **Relevant cosmogenic products**

^{39}Ar: β^- emitter with Q=565 keV, **$T_{1/2}$=269 y** mainly produced by $^{40}\mathrm{Ar}(\mathrm{n,2n})^{39}\mathrm{Ar}$

Measured activity in

- **Atmospheric Ar:** ~1 Bq/kg (WARP, ArDM, DEAP)
- **Underground Ar:** (0.73±0.11) mBq/kg (DarkSide-50)

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^{42}Ar: β^- emitter, Q=599 keV, **$T_{1/2}$=32.9 y** producing **^{42}K** (β^- emitter, Q=3525 keV, $T_{1/2}$=12.36 h) → potential background for neutrinoless double beta decay

In Atm Ar: DBA: 92^{+22}_{-46} μBq/kg, GERDA: 50-100 μBq/kg, DEAP (40.4±0.5.9) μBq/kg

Production mechanisms: two-step neutron capture and $^{40}\mathrm{Ar}\ (\alpha,2\mathrm{p})\ ^{42}\mathrm{Ar}$

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^{3}H: β^- emitter with Q=18.6 keV, **$T_{1/2}$=12.3 y**

- Quantified yields in **Ge** detectors (EDELWEISS, CDMSlite) and observed hints in **NaI(Tl)** crystals (ANAIS, COSINE)
- Purification systems for LAr should remove all non-noble radionuclides, as also assumed in **LXe**, but tritium proposed as a possible explanation for the XENON1T excess

Production rates

- **Production rates R** (sea level): available information

- First <u>measurement</u> for **^{39}Ar** and **^{37}Ar** in an **irradiation experiment** at Los Alamos (LANSCE) with a **neutron beam**, quantifying products with a proportional counter at PNNL + calculations at sea level from alternate mechanisms

R. Saldanha et al, Phys. Rev. C 100 (2019) 024608

Reaction	Estimated ^{39}Ar production rate [atoms/(kg$_{Ar}$day)]	Fraction of total AAr (%)
^{40}Ar (n, 2n)^{39}Ar+ ^{40}Ar(n, d)^{39}Cl	759 ± 128	72.3
^{40}Ar (μ, n)^{39}Cl	172 ± 26	16.4
^{40}Ar (γ, n)^{39}Ar ^{40}Ar (γ, p)^{39}Cl	89 ± 19 23.8 ± 8.7	8.5 2.3
^{40}Ar (p, 2p)^{39}Cl ^{40}Ar (p, pn)^{39}Ar	<0.1 3.6 ± 2.2	<0.01 0.3
^{38}Ar(n, γ)^{39}Ar	≪ 0.1 (UAr) 1.1 ± 0.3 (AAr)	– 0.1
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^{38}Ar(n, 2n)^{37}Ar+ ^{38}Ar(γ, n)^{37}Ar+ ^{38}Ar(p, pn)^{37}Ar	<0.05 (UAr) 0.43 ± 0.05 (AAr)
Total	56.7 ± 7.5 (UAr) 92 ± 13 (AAr)

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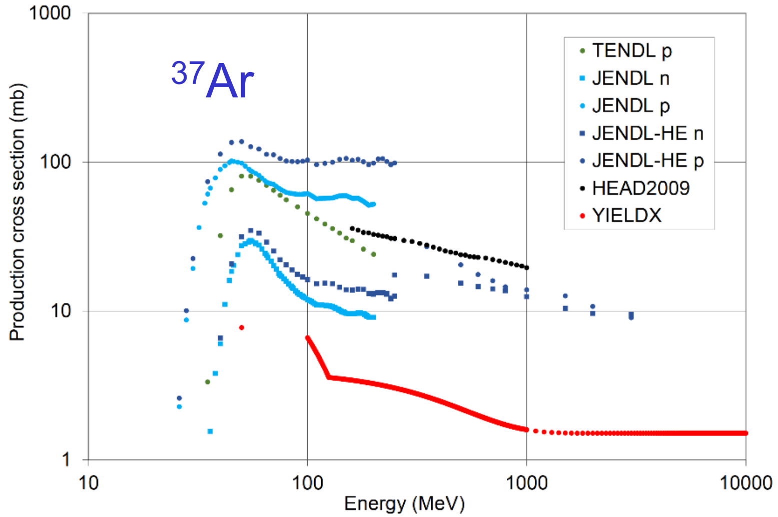
- Rates for **^{37}Ar, ^{39}Ar** and **^{42}Ar** from neutrons, protons and muons estimated by **GEANT4** simulation too

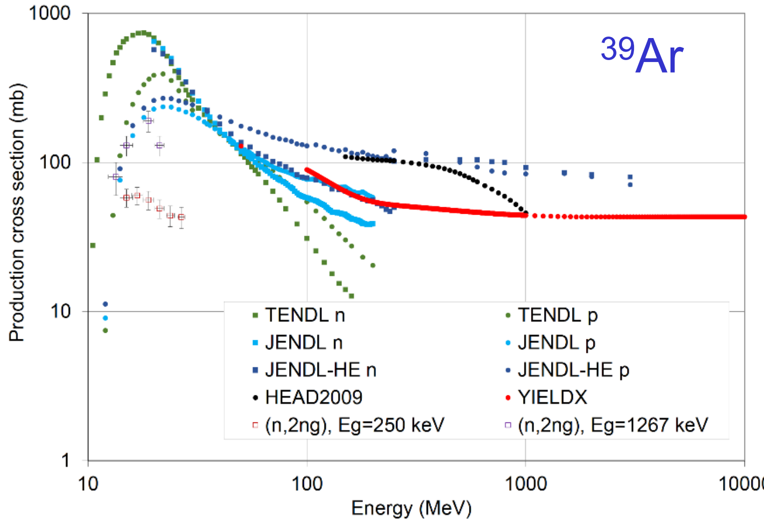
C. Zhang, D.M. Mei, Astropart. Phys. 142 (2022) 102733

Production rates

- **Production rates R** (sea level): new calculations

$$R = N_t \int \sigma(E)\phi(E)dE$$





Astropart. Phys.152 (2023) 102878

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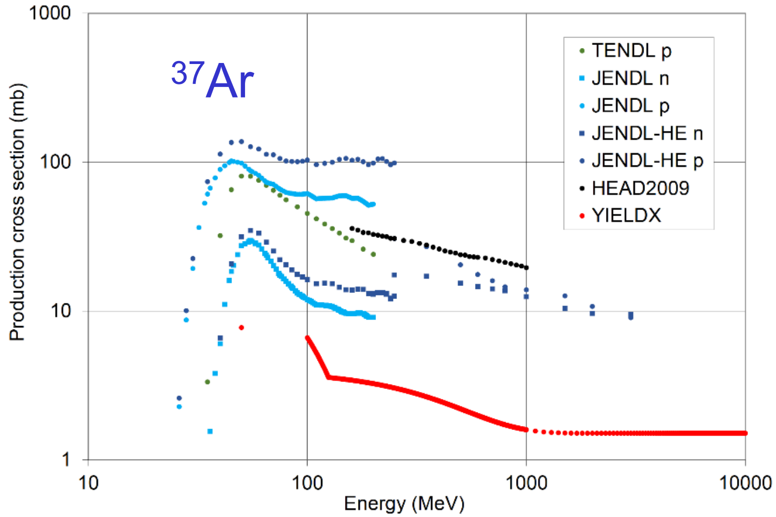

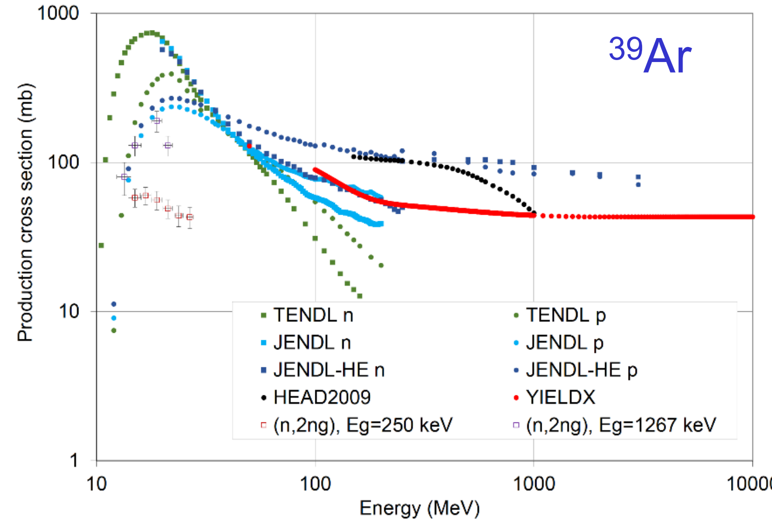

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		^{37}Ar			^{39}Ar
This work: LE+HE	Cut (MeV)	R (atoms/kg/day)	This work LE+HE	Cut (MeV)	R (atoms/kg/day)
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TENDL(p)+YIELDX	100	93.5	TENDL+YIELDX	100	697.1
TENDL(p)+YIELDX	200	122.7	TENDL+YIELDX	200	646.0
JENDL-HE(n)	30	63.9	TENDL+JENDL-HE(n)	20	804.3
Estimated rate in this work		109 ± 45	Estimated rate in this work		725 ± 79
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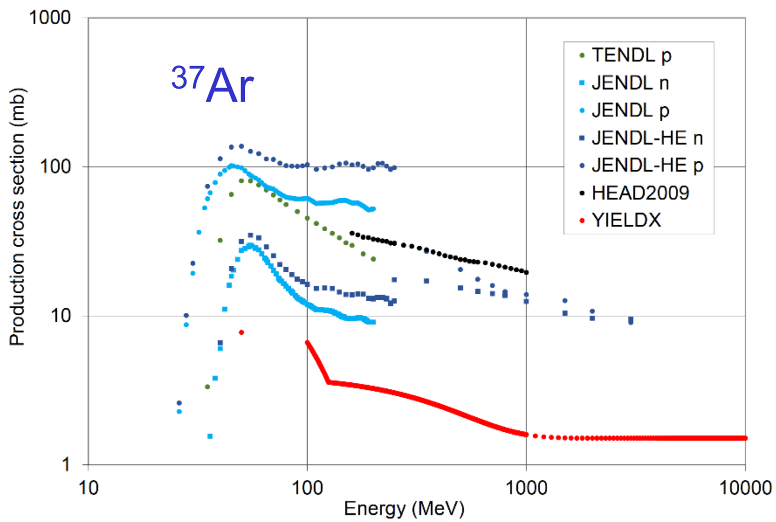

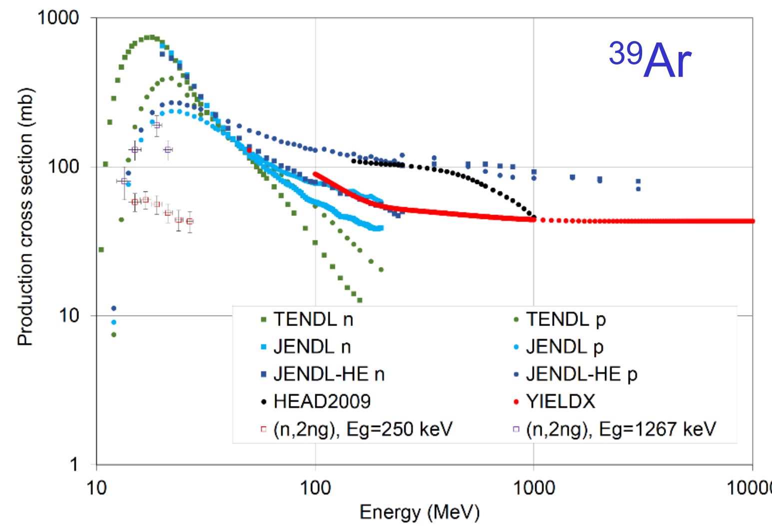

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^{39}Ar: fully compatible with measured value and several calculations

^{37}Ar: larger discrepancies

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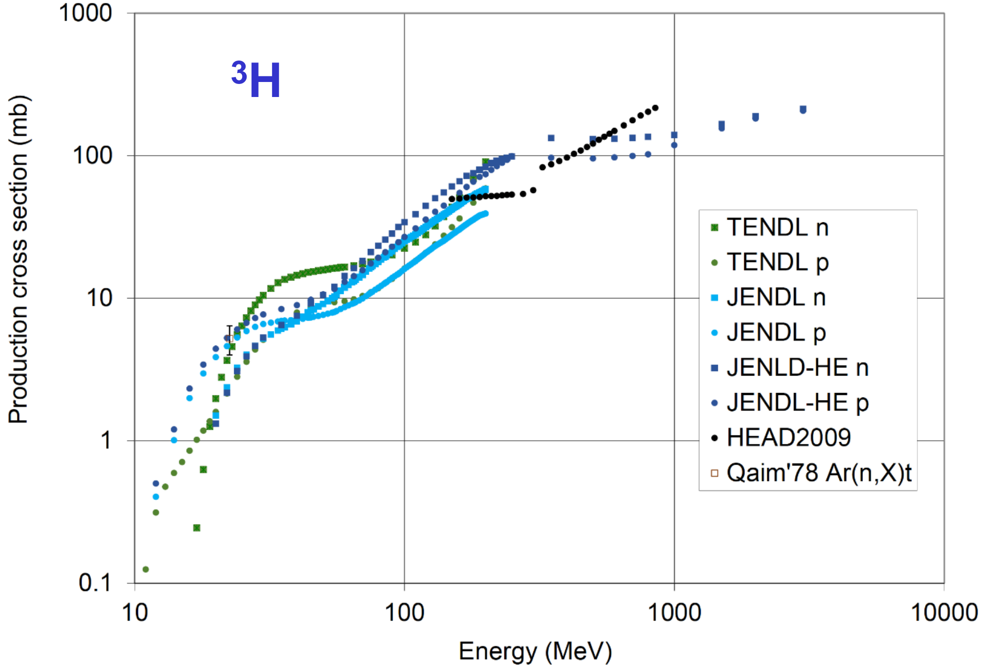

Astropart. Phys.152 (2023) 102878

	R (atoms/kg/day)
TENDL	115.1
HEAD2009	177.2
JENDL-HE	221.6
Estimated rate in this work	168 ± 53
Not used for estimation:	
TALYS [16]	44.4
GEANT4 [33]	84.9
ACTIVIA [33]	82.9

Same approach but including more data

J. Amaré et al, Astropart. Phys.97 (2018) 96

Activity

- **Activity A** from measured production rates for **^{37}Ar, ^{39}Ar** and estimated rate for **^{3}H** for realistic exposure conditions

$$A = R[1 - \exp(-\lambda t_{exp})] \exp(-\lambda t_{cool})$$

Fix tentative **exposure times** and **places (altitude)** for shipping:

URANIA → ARIA → LNGS

Planned to produce **120 t**, shipped in high pressure gas cylinder (2 t per skid)

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Total time: from Urania to Aria 614 days

Activity

- **Activity A** in kg^{-1} d^{-1} for ^{37}**Ar**, ^{39}**Ar** and ^{3}**H**

^{39}**Ar**	Neutrons	Muons	Protons	γ rays	Total
R (atoms/kg/day) [35]	759 ± 128	172 ± 26	3.6 ± 2.2	112.8 ± 20.9	
Urania	0.551 ± 0.093	0.0483 ± 0.0073	0.0035 ± 0.0022	0.0127 ± 0.0024	0.616 ± 0.093
US	0.139 ± 0.024	0.0148 ± 0.0022	0.0009 ± 0.0005	0.0056 ± 0.0010	0.161 ± 0.024
Overseas	0.359 ± 0.061	0.081 ± 0.012	0.0017 ± 0.0010	0.053 ± 0.010	0.495 ± 0.063
Aria	0.321 ± 0.054	0.073 ± 0.011	0.0015 ± 0.0009	0.048 ± 0.0088	0.444 ± 0.056
Italy	0.0536 ± 0.0090	0.0121 ± 0.0018	0.0003 ± 0.0002	0.0080 ± 0.0015	0.0739 ± 0.0093
Final	1.42 ± 0.24	0.229 ± 0.035	0.0078 ± 0.0048	0.127 ± 0.024	1.79 ± 0.24
(%)	79.6	12.8	0.4	7.1	
^{37}**Ar**	Neutrons	Thermal neutrons	Protons	γ rays	Total
R (atoms/kg/day) [35]	51 ± 7.4	0.9 ± 0.3	1.3 ± 0.4	3.5 ± 0.7	
Urania	87 ± 13	2.99 ± 0.92	0.93 ± 0.19	0.239 ± 0.080	91 ± 13
US	24.5 ± 3.6	0.81 ± 0.25	0.453 ± 0.091	0.116 ± 0.039	25.9 ± 3.6
Overseas	37.5 ± 5.4	0.95 ± 0.29	2.57 ± 0.51	0.66 ± 0.22	41.7 ± 5.5
Aria	35.5 ± 5.1	0.90 ± 0.28	2.43 ± 0.49	0.63 ± 0.21	39.4 ± 5.2
Italy	9.2 ± 1.3	0.234 ± 0.072	0.63 ± 0.13	0.162 ± 0.054	10.2 ± 1.3
Final	8.0 ± 1.2	0.209 ± 0.064	0.52 ± 0.10	0.135 ± 0.045	8.9 ± 1.2
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^{3}H	
R (atoms/kg/day)	168 ± 53
Urania	2.66 ± 0.84
US	0.67 ± 0.21
Overseas	1.73 ± 0.54
Aria	1.55 ± 0.49
Italy	0.259 ± 0.082
Final	6.5 ± 2.1

Exposure at Urania produces largest contribution

Neutrons give most of the yield

If no purification applied

Activity and counting rates

Activity A when all UAr is in Gran Sasso and **counting rate** in DarkSide-20k

Isotope	Activity (μBq/kg)	TPC rate (Hz)	Veto rate (Hz)
^{39}Ar	20.7 ± 2.8	1.03 ± 0.14	0.662 ± 0.090
^{37}Ar	103 ± 14	5.15 ± 0.68	3.30 ± 0.43
^{3}H (1)	76 ± 24	3.8 ± 1.2	2.42 ± 0.76
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G4DS simulation of γ/β emissions from the full set of detector components to estimate rates in the TPC and in the Veto from measured activities

- **γ:** ~50 Hz in TPC, ~100 Hz in Veto
- **β**: 36 Hz in TPC, 26 Hz in Veto

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Study of cosmogenic activation above ground for the DarkSide-20k experiment, Astropart. Phys.152 (2023) 102878

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- Results useful to set exposure limitations for the large amounts of LAr necessary in future projects for dark matter (**DarkSide-Low Mass, ARGO**) and even for neutrino experiments (COHERENT, LEGEND-1000, DUNE)

EXTRA SLIDES

Correction factors

- **Production rates R correction factors f** for exposure at Colorado

Urania facilities: 2164 m

$$I_2 = I_1 \exp\left(\frac{A_1 - A_2}{L}\right), \quad (1)$$

where I_1 is the cascade flux at some altitude (pressure) A_1, and I_2 is the flux at altitude A_2, both altitudes being expressed in g/cm^2. To convert terrestrial altitudes to

J.F. Ziegler, IBM J. Res. Develop. 42 (1998) 117.

Table 3. Sea-level particle absorption lengths.

Particle	Length L (g/cm^2)
Electrons	100
Protons	110
Pions	113
Neutrons	136
Muons and muon capture	261

- **Protons:** f=8.67
- **Muons:** f=2.48

- **Neutrons:** extrapolation for Urania location of deduced factors f due to altitude <u>and geomagnetic rigidity</u> at Denver and Leadville.

Location	H (ft)	A (g/cm^2)	f from [47]	Relative I to Urania	Deduced f for Urania
Denver	5280	852.3	4.11	0.659	6.24
Leadville	10200	705.2	12.86	1.942	6.62
Urania	7100	795.5			6.43

Table 1
Cosmogenic activation rates of three argon isotopes: ^{37}Ar, ^{39}Ar and ^{42}Ar. The simulation results are also compared with the ones from measurements and estimations[56].

	^{37}Ar	^{39}Ar	^{42}Ar
		atoms/kg_{Ar}/day	
Neutrons (this work)	176.01	857.73	4.60×10^{-3}
Neutrons (measurement[56])	51.0 ± 7.4	759 ± 128	-
Muons (this work)	2.40	52.27	1.57×10^{-4}
Muons (calculation[56])	-	172 ± 26	-
Protons (this work)	6.20	28.53	1.05×10^{-3}
Protons (calculation[56])	1.73 ± 0.35	3.6 ± 2.2	-
Total (this work)	184.61	938.53	5.81×10^{-3}
Total (Ref.[56])	52.73 ± 7.75	934.6 ± 156.2	-

C. Zhang, D.M. Mei, Astropart. Phys. 142 (2022) 102733

Table 2
Cosmogenic activation rates of other long-lived isotopes.

Isotope, Half Life	Neutron	Muon	Proton
		atoms/kg_{Ar}/day	
^{3}H, 12.32y	3.00×10^{-4}	6.56×10^{-6}	1.05×10^{-4}
$^{7}Be, 1.387 \times 10^{6}y$	3.43×10^{-3}	6.47×10^{-3}	9.62×10^{-3}
$^{10}Be, 53.22d$	7.05×10^{-3}	5.22×10^{-3}	1.10×10^{-2}
$^{14}C, 5.703 \times 10^{3}y$	0.10	9.85×10^{-3}	4.56×10^{-2}
$^{22}Na, 2.602y$	0.37	2.35×10^{-2}	9.92×10^{-2}
$^{26}Al, 7.17 \times 10^{5}y$	0.63	4.24×10^{-2}	0.12
$^{32}Si, 153y$	7.00	0.14	0.47
$^{32}P, 14.268d$	15.7	0.38	1.05
$^{33}P, 25.3d$	22.5	0.42	1.32
$^{35}S, 87.37d$	74.5	1.66	3.18
$^{36}Cl, 3.01 \times 10^{5}y$	75.5	1.23	3.32
$^{40}K, 1.248 \times 10^{9}y$	1.80	5.86×10^{-2}	0.56
$^{41}Ca, 9.94 \times 10^{4}y$	1.85×10^{-3}	1.02×10^{-4}	5.68×10^{-4}

^{42}Ar

Production of ^{42}Ar in underground argon

Production mechanisms:

- Two-step neutron capture: high neutron flux required due to short half-life of ^{41}Ar (1.8 h) → not possible underground
- (α,2p) reaction: zero σ values <15 MeV (TALYS2017) → not possible for α from radioactivity

$$^{40}\mathrm{Ar}\ (\alpha,2\mathrm{p})\ ^{42}\mathrm{Ar}$$

- Neutron reactions on Ca:

Isotope	Natural abundance (%)	Reaction	
43Ca	2.086	43Ca(n,2p)42Ar	Zero σ values <17 MeV (TALYS2017) → not possible for fission or (α,n) neutrons
44Ca	0.135	44Ca(n,n2p)42Ar	Zero σ values <23 MeV (TALYS2017) → not possible for fission or (α,n) neutrons

➡ Precise estimate requires: neutron spectrum underground from other sources, Ca concentration in rock, emanation factor