DarkSide-50 recent results and future prospects

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on the behalf of the DarkSide collaboration

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• **Water Cherenkov** detector (1,000 tons of ultra pure water): active veto for \( \mu \) and passive shield for external radiation

• **Liquid scintillator** detector (30 tons of PC+PPO+TMB): active \( \gamma \)s and neutron detector thanks to \(^{10}\text{B}\) loading

• **LAr TPC** detector (current phase \( \sim \)50 kg of argon in the fiducial volume): inner detector for WIMP
DarkSide-50

Water Cherenkov

Liquid scintillator

Cryogenic amplifiers on PMTs

TPC
Dual phase TPC technology: S1

- **Light signal (S1)** time profile allows Pulse Shape Discrimination (PSD) thanks to $f_{90}$ parameter (fraction of light in the first 90ns)

\[ f_{90} \approx 0.7 \]  
**Nuclear Recoil (NR)**

\[ f_{90} \approx 0.3 \]  
**Electron Recoil (ER)**
Dual phase TPC technology: S2

- Electroluminescence/ionization signal (S2) due to drifted electrons allows 3d position reconstruction, additional discrimination (S2/S1), and improved energy reconstruction

\[ \int (S1) \ll \int (S2) \]

Nuclear Recoil (NR)

\[ \int (S1) \ll \int (S2) \]

Electron Recoil (ER)
DarkSide-50 recent results

• High mass WIMP search (S1+S2)
  
  Physical Review D 98 (10), 102006 (2018)

• Low mass WIMP searches:

  • S2-only
    
    Physical Review Letters 121 (8), 081307 (2018)

  • Sub-GeV
    
    Physical Review Letters 121 (11), 111303 (2018)
High mass WIMP search ($S1+S2$)

• A blind analysis of 532-days (16 660 kg d) exposure using a target of low-radioactivity argon extracted from underground sources: PRD 98, 102006 (2018)

• Blinding box (red solid line) drawn using early 71-days (2616 kg d) results PRD 93, 081101(R) (2016)

• Goal: design an analysis that will have <0.1 background events in the to-be-designed search box

• Backgrounds: $\beta$ and $\gamma$, neutrons, surface $\alpha$, and Cherenkov
Background: ERs

- **β and γ**: External γs but mostly main source is internal (PMTs, cryostat, target itself). UAr has $(0.73 \pm 0.11)$ mBq/kg of $^{39}$Ar, and $(2.05 \pm 0.13)$ mBq/kg of $^{85}$Kr. Rejected by:
  - PSD rejection power in ROI is down to $6 \times 10^{-8}$ for single-site ERs
  - WCD + LSV

- **Cherenkov + scintillation**: γ multiple scatters in LAr and PTFE or fused-silica. Cherenkov ($f_{90} \approx 1$) moves regular scintillation into NR band. Rejected by:
  - light distribution in top PMTs
  - radial fiducialization

Results obtained thanks to intensive background modeling done with a data/MonteCarlo hybrid approach - [JINST 12, P10015 (2017)]
Background: NRs

- **Neutrons:** cosmogenic (produced by muons interaction with surrounding materials) or spontaneous $^{238}$U ($\alpha$,n) reactions. **PMTs are the main source.** Rejected by:
  - Multiple scatter in TPC
  - Coincidence with LSV: measured efficiency with AmC 99.64±0.04% (fraction of event surviving veto cuts)
  - Coincidence with WCD

- **Alphas:** stringent radio pure material selection constrains $\alpha$-emitters to Rn daughters on surfaces (fabrication/assembly process) or in LAr (recirculation).
  - Degraded $\alpha$ can follow in NR band. Rejected by:
    - **Self-vetoing:**
      - Very small or absent S2
      - S2 has long scintillation tail due to TPB scintillation
# Final dataset and dark matter box

## Background

<table>
<thead>
<tr>
<th>Background</th>
<th>Events surviving all the cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmogenic neutrons</td>
<td>$&lt; 3 \times 10^{-4}$</td>
</tr>
<tr>
<td>Radiogenic neutrons</td>
<td>$&lt; 5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Surface $\alpha$</td>
<td>$&lt; 1 \times 10^{-3}$</td>
</tr>
<tr>
<td>Cherenkov + scintillation</td>
<td>0.08</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.09 ± 0.04</strong></td>
</tr>
</tbody>
</table>

Goal of $<0.1$ background events achieve and **final dark matter search box** defined: **let’s open the box!**

![Graph showing energy vs. S1]
90% C.L. exclusion limit

The graph shows the 90% confidence level (C.L.) exclusion limits for WIMP-nucleon cross-sections $\sigma_{SI}$ plotted against WIMP mass $m_{WIMP}$, with the x-axis in units of TeV/GeV and the y-axis in units of $10^{-6}$ cm$^2$. The exclusion limits are indicated for various experiments:

- WARP (2007)
- DarkSide-50 (2015)
- DEAP-3600 (2017)
- LUX (2017)
- DarkSide-50 (2018)
- PANDAX-II (2017)
- XENON1T (2018)
Low mass WIMP searches

- Trigger on S1 imposes a threshold of 13 keV$_{nr}$ → limited sensitivity for WIMPs with mass <10GeV/c$^2$

- But if same threshold is applied to ionization signal S2 → E$_{th}$$<$0.6keV$_{nr}$ allows to explore this parameter space!

- Using S2-only events is possible to search for low mass WIMPs interacting both with nuclei or even with electrons (with background)
Low mass WIMP search (S2-only)

- S2-only signal:
  - Sensitive to single extracted electron
  - No need of PSD

- Acceptance: estimated by data+MC (MC reproduces both spatial and temporal distribution of S2 as measured in electron diffusion - see arXiv:1802.01427)

- Fiducialization: no xy available, but use volume under inner 7 PMTs (position assigned by PMT collecting the largest amount of light)

\[ N_e = \frac{S_2}{\eta} \text{ where } \eta = (23 \pm 1) \text{PE/e} \]
Energy scale for ER and NR

- ER energy scale obtained with $^{37}$Ar
  - Provides 2 X-rays at 0.27 and 2.82 keV
  - decayed with $t_{1/2} = 35$ days and no remain in the last 500d data set (compare black and blue spectra)

- NR energy scale obtained with AmBe and AmC
  - Bezrukov model fitted on calibration data
  - Difference with other measured points taken as systematic
  - Conservative assumption - measured points are higher than fit: less ionization $\rightarrow$ less e$^{-}$ $\rightarrow$ less sensitivity

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**First 100 days**

**Last 500 days**

**Single S2 (500d)**

**S1 + S2 (500d)**

**L/K BR Ratio = 0.11 \pm 0.01**
Background and WIMP signal

- Background is constrained in region of interest by extrapolating from high energy part of the spectrum

- At low energy, excess of events it is not understood

- WIMP recoil energy spectra modeled using
  - Ionization, energy quenching and detector response
Profile likelihood method

- Upper limit $\sigma_{SI}$ extracted observed $N_e$ spectrum using binned profile likelihood (PL) method

- Two signal regions ($N_{e^{th}}$ of 4 and 7e-) which covers WIMP masses in the range $[1.8,10]$ GeV/c$^2$

- PL includes uncertainties both on WIMP signals (NR ionization, single electron yield) and background spectrum (rates, ER ionization yield)

- Average ionization yield dominates uncertainties! Due to lack of knowledge two assumptions about fluctuation at low recoil energy: no fluctuation and binomial
90% C.L. Exclusion limit

![Graph showing 90% C.L. Exclusion limit for Dark Matter-Nucleon cross-section versus mass for various experiments.](image)
Sub-GeV dark matter search

- WIMP-electron interaction parametrized by form factor $F_{\text{DM}} = F_{\text{DM}}(q)$ which, depending on the mass of the mediator ($m_{A'}$), has different asymptotic momentum ($q$) dependence:
  - $F_{\text{DM}} \approx 1$ (heavy mediator)
  - $F_{\text{DM}} \approx 1/q^2$ (light mediator)

- $^{37}$Ar X-rays are used to convert electron recoil spectra to ionization spectra:
  - L-shell: 0.27 keV
  - K-shell: 2.82 keV
Sub-GeV dark matter search

- DM spectra $\overline{\alpha} = 10^{-36}$ cm$^2$
  - Data
  - $F_{\text{det}} = 1$
  - G4DS MC All
  - 10 MeV/c$^2$
  - Cryostat $\gamma$-rays
  - 100 MeV/c$^2$
  - PMTs $\gamma$-rays
  - 1000 MeV/c$^2$
  - $^{39}\text{Ar} + ^{85}\text{Kr}$

- DM spectra $\overline{\alpha} = 10^{-33}$ cm$^2$
  - $F_{\text{det}} \propto 1/q^2$
  - Data
  - G4DS MC All
  - 10 MeV/c$^2$
  - Cryostat $\gamma$-rays
  - 100 MeV/c$^2$
  - PMTs $\gamma$-rays
  - 1000 MeV/c$^2$
  - $^{39}\text{Ar} + ^{85}\text{Kr}$

- Events / $[N_{e^-} \times \text{kg} \times \text{day}]$

- Dark Matter-Electron
  - $F_{\text{det}} = 1$
    - DarkSide-50
    - XENON100
    - XENON10
  - $F_{\text{det}} \propto 1/q^2$
    - DarkSide-50
    - XENON100
    - XENON10

- $m_\chi$ [MeV/c$^2$]
DarkSide program: what’s next?

- DarkSide-20k @ LNGS
- Sealed acrylic TPC containing 50 tonnes of UAr in a ProtoDUNE-like cryostat filled with ~700 tonnes of AAr
- 30 m² SiPMs as photosensors (8280 channels for TPC and ~3000 channels for Veto)
- Gd-doped acrylic panels as neutron veto
SiPMs to replace PMTs

- Developed for LAr by a combined effort between DarkSide and FBK
- Compact and high coverage
- High S/N (>8)
- High PDE (~50%)
- SiPMs mass production by LFoundry and packaging of PDM and in NOA, L’Aquila
- Full production chain largely funded by Regione Abruzzo, Italy
A new neutron veto concept

- $4\pi$ coverage
- 10cm thick passive Gd-loaded acrylic shell to moderate and capture neutrons
- 40cm thick inner and outer active liquid AAr volumes to detect gamma cascade due to neutron captured on Gd
- Faraday cage to optically and electrically isolate both veto and TPC
- Vertical segmentations to reduce pile-up rate of $^{39}$Ar (1Bq/kg in AAr) event from AAr and ESR foil as reflector to maximize light collection
- All internal surface of each sector coated with TPB as wavelength shifter
ProtoDUNE-like cryostat

- Technology developed at CERN for ProtoDUNE experiment
- Membrane + passive thermal insulation
- Matured technique adopted from the Liquified Natural Gas carriers and vessels
- Access and support of TPC and Veto from top roof
Low-radioactive argon procurement and purification

- **Urania**: procurement of at least 60 tonnes of UAr from Colorado, USA (same as DS50) with extraction rate of 250 kg/day, with 99.9% purity

- **Aria**: UAr transported to Sardinia, Italy for final chemical purification via a 350m tall cryogenic distillation column in Seruci, Sardinia, Italy

  - Process ~1 tonne/day with 1000 reduction of all chemical impurities and isotopically separate $^{39}$Ar from $^{40}$Ar

Seruci-0 - prototype

Seruci-I and II
Projected sensitivity

![Graph showing projected sensitivity](image)
Conclusions

• DarkSide-50 results proved LAr technology is competitive both for high- (background free) and low-mass (best sensitivity for 1.8-5.5 GeV) WIMP searches

• Ambitious dark matter search program with DarkSide-20k which is developing essential technologies on several fronts

• LAr technology is very promising to lead the path towards the neutrino floor in both high- and low-mass WIMP regions
Backups
- Trigtime: the first pulse is within expected trigger time window
- S1sat: S1 pulse is not saturated
• Npulses: number of pulse is 2 or 3 if there is S3 (echo of S2)

• Most of surface events are gone
• 40μs fid: remove 40μs from top and bottom in t_drift

• Lots of $\gamma$s from PMTs, unresolved S1+S2 events, and surface close to top are removed

Entries 4147304
Integral 1.838e+06
- **S1pmf**: fraction of prompt light in the maximum PMT is less than a threshold, which is a function of $t_{\text{drift}}$ and S1

- Remove S1+Cherenkov events from fused silica windows
- min S2uncorr: S2≥200 PE

- This is more like quality cut, but remove surface events, which number of electrons are reduced by the surface effect
- *xy-recon*: reasonable x-y reconstructed values
- S2 f90: f90 of S2 pulse <0.20

- Remove S1+S1 pileup events
- min $S_2/S_1$: $S_2/S_1$ need to be above threshold, which is a function of $S_1$

- Remove strangely small $S_2$ events, like surface events
- max S2/S1: S2/S1 need to be below threshold, which is a function of S1

- Remove strangely large S2 events, which we don’t expect, but applied as a safety net
- S2 i90/i1: S2 have reasonable rise time
- Remove events in which S2 is actually S1+S2 pulses
• S1 TBA: z-position from S1 Top-Bottom Asymmetry agrees with t_drift

• Remove random pileup S1 and S2
- TPB Tail: remove events, which have long tail of scintillation caused by TPB scintillation

- Remove surface events, in which α goes through TPB layer
• NLL: Negative Log Likelihood cut, which compare event position from S1 light distribution among PMTs and event position from t_drift and S2 x-y

• Remove S1 + Cherenkov events which deposit energy in separate locations
• R 2: Radial cut as a function of \( t_{\text{drift}} \)
- Veto: all veto cuts
- Remove neutrons
Additional rejection S2/S1

Energy [keV_{nr}]

$S1$ [PE]

Energy levels: 1%, 50%, 99%
• NR energy scale obtained with AmBe and AmC fitted with Bezrukov model