Darkside-20k: A global direct dark matter search experiment

Daria Santone, University of Oxford
Warwick seminar, 12/10/2023
Global Argon Dark Matter Collaboration (GADMC) is a joint effort among all dark matter experiments with Ar target: >400 collaborators from ~100 institutions towards DarkSide-20k
OUTLINE

• Dark matter evidence
• Dark matter candidates and their detection
• New low mass results from Darkside-50
• Darkside-20k:
  • Detector overview
  • Silicon photomultiplier (SiPMs) light detection system
  • Neutron veto design optimisation
DARK MATTER EVIDENCE

Cluster galaxies

Gravitation lensing

CMB observation

27% Dark Matter
5% Regular Matter
68% Dark Energy
1960 - 1970: Dark matter observation in spiral galaxies

Vera Rubin (1928-2016)
Astronomer

Vera Rubin saw something unusual in galaxies: outer stars orbit just as quickly as those in the centre. She surmised that each galaxy must contain more mass than meets the eye. It was the first observational evidence of dark matter, which today is one of the most studied topics in cosmology.
DARK MATTER PROPERTIES

- *Dark*: does not interact electromagnetically
- *Stable*: very long lived
- *Cold*: not relativistic at freeze-out
- Only gravitationally, or, very weakly interacting
- Local density around 0.3 GeV/cm$^3$

Beyond the Standard Model of Particle Physics
DARK MATTER CANDIDATES

WIMP “Miracle"

- Weak scale interaction lead to correct density in the universe
- Mass scale: MeV - 100 TeV
- Motivated by many theories
DARK MATTER DETECTION

Collider Production

Indirect Detection

Normal Matter

Dark Matter

Early Universe Annihilation

Direct Detection
DIRECT DETECTION

Interaction rates depend on:

- Our model of how the sun and heart move through the galaxy
- How fast earth travel relative to WIMPs
DARK MATTER SEARCH IN DARKSIDE

Dual phase Time projector Chamber (TPC)

- Signal: S1 (primary scintillation) + S2 (charge signal)
- S2 light pattern gives x-y position
- Drift time give z position
- S1-S2 relative size give particle information

DarkSide Target material: liquid Ar from underground (UAr)

S2/S1_{NR} < S2/S1_{ER}
LOW MASS DARK MATTER SEARCH
DARKSIDE-50

- Dual phase liquid argon filled with 50 kg of Underground Argon (UAr)
- Light detector: PhotoMultiplier (PMTs)
- Veto:
  - Liquid scintillator as neutron moderator
  - Water Cerenkow as cosmogenic veto
- Data taking: 2013 - 2018, total exposure of 0.03 tons x years

- **Low mass search**: \([1.2, 3.6] \text{ GeV/c}^2\)-WIMP mass range
DARKSIDE is located in HALL C at LNGS, Italy
At 3400 m of water equivalent

Muon flux Reduced by Factor 1000
WIMP SIGNAL & BACKGROUND

WIMP SIGNAL

• Single nuclear recoil
• Energy recoil between 1 and 100 keV

BACKGROUND

<table>
<thead>
<tr>
<th>Background source</th>
<th>Mitigation strategy</th>
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</thead>
<tbody>
<tr>
<td>39Ar $\beta$ decay</td>
<td>Use Underground Argon + pulse shape discrimination</td>
</tr>
<tr>
<td>$\gamma$ from rock and $\gamma,e$ from material</td>
<td>Pulse shape discrimination</td>
</tr>
</tbody>
</table>
| **Radiogenic neutron**  
**($\alpha,n$) reaction in detector material**         | Selection material                                            |
| Surface contamination due Rn progeny                   | Material screening & selection                                 |
|Muon induced background                                 | Definition of Fiducial volume in the TPC                       |
|Neutrino coherent scatter                               | **Veto to reject neutron signal**                             |
|                                                        |Surface cleaning                                               |
|                                                        |Reduce the number of surfaces                                  |
|                                                        |Installation of Rn abated system                               |
|                                                        |Cosmogenic veto                                                |
|                                                        |Irreducible                                                    |

Surface contamination due Rn progeny

Muon induced background

Neutrino coherent scatter
TPC and veto are filled with UAr in order to reduce Ar-39, which is produced in Atmospheric Argon by cosmogenic activation with activity $\sim 1$ Bq/kg. It is a beta emitter with endpoint to 565 keV and half life of 269 years.

WIMP NUCLEON INTERACTION

Re-analyse the full DS50 dataset with a more detailed calibration model

Electron recoil modelling using $^{37}$Ar, $^{39}$Ar decay naturally in the early LAr dataset, focus on ionisation signal below 180 eV$_{er}$

Nuclear recoil from in-situ neutron calibration (AmC), energy down to 500 eV$_{nr}$
Background spectra compared with expected WIMP spectra below 10 GeV/c²
The dominant background comes from $^{85}$Kr,$^{39}$Ar

**Phys. Rev. Lett. 130, 101001**

Best limit in the region between 1.2 and 3.6 GeV/c²
MIGDAL Effect

- Reinterpretation of published Ar and Xe resulting including Midgal effects benchmarked against published results

- New constrain on sub-GeV WIMP mass through Migdal effect

Best limit below 3 GeV/c² and down to 40 MeV/c²

Kings + Manchester + RHUL main contributors!
DM-e-SCATTERING RESULTS

Phys. Rev. Lett. 130, 101002 (2023)

• Exclusion limits at 90% C.L. on DM particle interactions with electron final states
• Limits on dark matter-electron scattering in the [16, 56] MeV/c² mass range for a heavy mediator and above 80 MeV/c² for a light mediator
Outer cryostat filled with 600 tonnes of Atmospheric Argon (AAr) acts as cosmogenic veto.

Gd-PMMA acts as neutron Veto surrounded by 35 tonnes of UAr.

Dual phase time projection Chamber (TPC) filled with 50 tonnes of UAr.
INNER DETECTOR

1. **Dual phase time Projected chamber (TPC)** filled with 50 tonnes of Underground Argon -> 20 tons of fiducial volume

2. **Neutron veto**: Gd-PMMA immersed in a 35 tonnes of underground liquid argon

TPC and veto are equipped with a large area silicon photomultiplier (SiPMs) arranged in a photo detection unit (PDU)

- 518 PDU in the TPC
- 120 PDU in the veto

The inner detector is enclosed in a SS vessel, total mass of 12 tons
INNER DETECTOR: TPC

- Octagonal shape

- Drift field: 200V/cm

- Extraction field: 2.8 kV/cm

- Cathode voltage: -73.38 kV

- ESR as reflector, TPB as wavelength shifter

- SS wire grid
INNER DETECTOR: TPC

• TPC equipped with 518 PDU placed on top and bottom

• Total SiPMs in the TPC: 198912

• Light yield: 10 pe/keV

• S2 yield > 20 pe/e-
INNER DETECTOR: neutron veto

- Novel technology: TPC+veto integrated system -> Gd-PMMA (11.2 tons needed) around TPC wall to capture neutrons (4π coverage)

- SiPMs matrix (assembled in veto photodetector unit-> vPDU) around TPC wall for light detection -> 120 vPDU in total (Light yield: 2.0 pe/keV)

- Reflector+ PEN for light collection optimisation

- Enclose in a SS vessel filled with around 35 tonnes of underground Argon
**OUTER VETO**

- Proto-dune like outer cryostat filled with 600 tons of Atmospheric Liquid Argon
- Equipped with 32 PDUs placed on SS vessel
- Tywek + PEN for light optimisation
- Light yield: 1 pe/MeV
- Acts as cosmogenic veto
DARKSIDE-20k: this week!

Darkside-20k installation has started
Data taking will start in 2026
LIGHT DETECTION SYSTEM: Large area Silicon Photomultipliers (SiPM)
DARKSIDE SIPM REQUIREMENTS

From PhotoMultiplier (PMT)

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakdown voltage</td>
<td>26.8 +/- 0.2 V</td>
</tr>
<tr>
<td>SiPM response - recharge time</td>
<td>300 - 600 ns</td>
</tr>
<tr>
<td>Single Photoelectron (SPE) spectra</td>
<td>distinct PE</td>
</tr>
<tr>
<td>Gain</td>
<td>stable gain</td>
</tr>
<tr>
<td>Signal to noise ratio (SNR)</td>
<td>&gt; 8</td>
</tr>
<tr>
<td>Dark count rate (DCR)</td>
<td>&lt; 0.01 Hz/mm$^2$ (7 Vov)</td>
</tr>
<tr>
<td></td>
<td>&lt; 0.1 Hz/mm$^2$ (9 Vov)</td>
</tr>
<tr>
<td>Internal cross talk (CT) probability</td>
<td>&lt; 33 % (7 Vov)</td>
</tr>
<tr>
<td></td>
<td>&lt; 50 % (9 Vov)</td>
</tr>
<tr>
<td>Afterpulsing (AP) probability</td>
<td>&lt; 10 %</td>
</tr>
</tbody>
</table>

To

SiPM Photomultiplier (SiPM)
**SILICON PHOTOMULTIPLIERs (SiPMs)**

**Why SiPMs**

- Cryogenic temperature stability
- Better single photons resolution
- **Higher detection photo-detection efficiency**
- Low voltage operation
- **Radio-purity an order of magnitude lower than PMTs**
- Lower cost

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**SPADs - Single Photon Avalanche Diodes:**

Semiconductor devices based on a p-n junction, reverse biased well above breakdown voltage (operating in Gieger mode).

**SiPMs - Silicon Photomultiplier:**

A single SiPM consists of around 94,900 SPADs.
SPADs - Single Photon Avalanche Diodes: semiconductor devices based on a p-n junction, reverse biased well above breakdown voltage (operating in Gieger mode).

SiPMs - Silicon Photomultiplier: A single SiPM consists of around 94,900 SPADs.

Tile: single printed circuit (PCB) for SiPMs & electronics
- Side 1: array of 24 SiPMs for a total size of 24 cm², The signals of all SiPMs are summed
- Side 2: front-end electronics for Signal amplifier -> ASIC for veto And discrete element for TPC

Veto Tile (vTile)
PHOTO DETECTION MODULE (PDU)

- 16 tiles are assembled together in a Photon Detection Unit (PDU)
- 1 large PCB for control signal, bias each tile and summed the signal of the tile
- 4 tiles are summed together, i.e. 4 tiles correspond to 1 DAQ channel
- 4 outputs
PDU FACILITIES

NOA at LNGS:
TPC PDU production and tileTesting

Naples: PDU testing facilities
UK FACILITIES: PCB production

PCB production @Birmingham

Application of Solder paste using stencil printer

Pick and Place machine – PCBs to come as 4x3 sheet

New Reflow oven:
3 temperature probes
5 minutes at 150°C
1 minute at 200 °C

ESSEMTEC SP-002 Manual
Stencil printer
Solder paste, CHIPQUICK

MECHATRONICA M60 pick and place

C.I.F FT05 advanced forced convection oven

Accumulating Statistics to define QA/QC acceptance criteria

ISO-7 Clean room
Radon controlled system
(<5 Bq/mm²)

Amplitude distribution

Rise time
Around 480 ns

Amplitude around 880 mV
UK FACILITIES: Tile assembly @STFC interconnect

Glue dispense

Die attach

Wire Bonding

ISO7 Clean room
UK FACILITIES: Tile assembly @Liverpool

SiPMs Wafers inspection

SiPMs testing before put on the tile

Wire Bonding a vTile

ISO7 Clean room
UK FACILITIES: PDU assembly @Manchester

first three vPDUUs assembled, 4th vPDU ongoing
vPDU TEST FACILITIES

WARM testing setup @Manchester/@Warmick

Warm breakdown around 67 V
vPDU TEST FACILITIES (2)

Cold testing setup @Liverpool

PHAIDRA

- Main cold test facility
- Test capability: 10 vPDU/day
- Ready for vPDU testing
vPDU TEST FACILITIES (3)

smaller cold test setups @Edinburgh

Test capability: 4 vPDU/time
vPDU TEST FACILITIES (4)

@Lancaster

Test capability: 4 vPDU/time

@ASTROCENT
SiPM wafer characterization

Breakdown voltage
Around 27 V

Quenching resistor
around 46 Ohm

Current at 20 V
Around 8 uA

major contributions from Lancs, RHUL
**vTILE TESTING**

**Tile testing @RHUL**

In liquid nitrogen

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**Waveforms Example**
At 77 K

**PE distribution**
1 PE around 3.8 mV

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**SNR = 1 PE amplitude**
RMS baseline

- Improvement on test stand to optimise throughput
- Accumulating statistics to define QA/QC acceptance: **SNR > 8**

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**Two new test stand @Oxford/STFC interconnect**
vPDU testing

PE distribution per quadrant = sum of 4 tiles = 10 cm x 10 cm area
1 PE around 14 mV

Improvement of SNR
Relative to single tiles thanks additional filtering to optimise the noise on vPDU

Breakdown around 55 V
BACKGROUNDs in DARKSIDE-20k
1. **Urania: UAr extraction**
   - CO₂ well in Cortez, CO, USA;
   - Industrial scale extraction plant;
   - UAr extraction rate: 250-330 kg/day;
   - Purity 99.99%
   - Plant ready to be shipped

2. **ARIA: UAr purification**
   - Cryogenic distillation column in Sardinia (Italy)
   - Chemical purification rate: 1 t/day
   - Ar-39 separation power > 1000
   - First module operated according to specs with Nitrogen in 2019
   - Run completed with Ar at the end of 2020

**DArT:**

**Ar purity measurement**

Located at LCS, Canfranc

- Double phase TPC with active volume of 1.4 kg of liquid UAr
- Two 1 cm\(^2\) SiPMs at the top & bottom
- External acrylic support
- Internal acrylic covered with TPB (WLS)
- Ar-39 depletion factor sensitivity: \(6 \times 10^4\) 90% C.L
Reduction of Ar-39 thanks UAr successfully demonstrated by Darkside-50k

Ar-39 deplaction factor: around 1400
Total UAr:
• TPC = 50 tons -> 36 Hz of Ar-39
• Veto = 35 tons -> 26 Hz of Ar-39

Mitigated with pulse shape discrimination:
• Residual background is < 0.01 events / 200 tonne x year
• Dead time negligible

ELECTRON RECOIL

S1 pulse shape in LAr

Electronic recoils are rejected by Pulse shape discrimination, demonstrated by DS-50 & DEAP

Pulse shape parameter

$$PSD = \frac{PROMPT \ \text{LIGHT}}{PROMPT + LATE \ \text{LIGHT}}$$

DEAP Collaboration, Phys.Rev.D 100 (2019) 2, 022004

NUCLEAR RECOIL

Neutron background
Is the most dangerous
Background -> same recoil
As WIMP

Neutron sources:
- $^{238}$U and $^{232}$Th contaminations of the detector material
- Cosmogenic interaction due the cosmic ray
- $(\alpha,n)$ reaction in the detector material
- Spontaneous fission decays

Neutron background budget for different Detector components

Cryostat 59.7%
TPC 4.0%
Veto 9.4%
PE 3.7%
PE TPC 23.3%

major contributions to radio-assay campaign from Boulby
NEUTRON IDENTIFICATION

• Gd-PMMA is highly efficient at moderating and then capturing neutrons
• Gd-PMMA 15 cm thick
• Gd concentration chosen to have neutron capture on Gd dominates w.r.t capture on H
• Neutron capture on Gd produced a gammas cascade with a energy of 8 MeV

Gd concentration chosen to 1%

—> maximise neutron detection and minimize background from Gd-PMMA
Gd-PMMA RECIPE

- Gd(MMA)$_3$ doped acrylics with 1wt% of Gd concentration successfully developed by Yangzhou University

- Technology transferred to DonChamp company: produced 5 cm thick samples and finalise the production -> **ready for full production**

- DonChamp: low background environment -> already used for JUNO PMMA production

- Pure-PMMA radio-purity satisfies DarkSide-20k requirement
Neutron capture on Gd detected in TPC and veto

- Neutron identification:
  - Single NR
  - Energy in ER: $7.5 < E_{ER} < 50 \text{ keVee}$
  - R-z position cuts $\rightarrow FV = 20 \text{ tons}$
  - Energy deposit in ER in the TPC $> 50 \text{ keV}$ OR energy deposit in UAr veto $> 200 \text{ keV}$
  - TPC-veto window of 800 $\mu$s

Monte-Carlo simulation to define neutron detection inefficiency looking energy deposit in TPC and veto

<table>
<thead>
<tr>
<th>Neutron source</th>
<th>Fraction inducing at least 1 NR in the TPC</th>
<th>Fraction surviving TPC and WIMP ROI</th>
<th>Fraction surviving TPC and Veto cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPC PDMs</td>
<td>1.80e-01</td>
<td>3.6E-5</td>
<td>2.2E-6</td>
</tr>
<tr>
<td>Veto Gd-Acrylic</td>
<td>8.55e-02</td>
<td>1.5E-4</td>
<td>5.8E-6</td>
</tr>
<tr>
<td>Veto PDMs</td>
<td>1.43E-02</td>
<td>5.4E-7</td>
<td>8.7E-7</td>
</tr>
<tr>
<td>Vessel</td>
<td>3.40E-03</td>
<td>6.8E-6</td>
<td>6.8E-6</td>
</tr>
<tr>
<td>Cryostat</td>
<td>4.0E-4</td>
<td>4.9E-9</td>
<td>2.2E-10</td>
</tr>
</tbody>
</table>

TABLE 51. Neutron Veto inefficiency from topical positions in the detector.

Total neutron Detection Inefficiency is 1.6E-5
NEUTRON DETECTION (2)

More realistic MonteCarlo Simulation introducing:
  • Electronics response
  • SIPMs noise
  • Pile up effects

- Neutron detection inefficiency increased by 20% including electronics response, SIPMs noise and pile-up effects
- Neutron background after veto cuts: < 0.1 event in the full exposure of 200 tons x years -> satisfies DarkSide-20k requirement

major contributions from RHUL
• Sensitivity to high mass WIMP-nucleon scatter cross section of $7.4 \times 10^{-48}$ cm$^2$ for a 1 TeV/c$^2$ WIMP for a total exposure of 200 tons x years

• Total background events after all cuts: < 0.1 neutron wimp like events in a total exposure of 200 tons x years

• S2-only analysis sensitivity projection coming soon...
SUMMARY AND OUTLOOK

• The Global Argon Dark Matter Collaboration (GADMC) is a joint effort among all dark matter experiments with Ar target: >400 collaborators from ~100 institutions, collaborating to build DarkSide-20k

• **DarkSide-20k is pushing the state-of-the-art in several directions:** SiPM technology, underground argon extraction & purification, Gd-PMMA, background assay campaign

• **DarkSide-20k is in position to lead the search for WIMPs**, with complimentary reach above the LHC center of mass energy

• **Fundamental role played by UK groups in producing 25% of the SiPM readout modules (7 m^2!), to instrument the veto detector** which is key to achieving the <0.1 instrumental backgrounds to the dark matter search! And expanding the reach beyond heavy WIMPs...

• **Darkside-20k construction has started, data taking will start in 2026**