The DarkSide-20k detector: a closer look to SiPMs

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13th Rencontres du Vietnam
Exploring the Dark Universe
• **Scientific target:** probe SI WIMP-nucleon interaction cross sections up to $\sim 10^{-47}\text{cm}^2@1\text{TeV/c}^2$.

• **Type of detectors:** double-phase Argon Time Projection Chambers.

• **Appealing feature:** background free search.

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**DarkSide-10**

- **Operation:** 8 months since 2011.
- Demonstrated LAr ER/NR discrimination power.

**DarkSide-50**

- **Operation:** 2013-ongoing.
- Used UAr successfully reducing the $\beta$ background.

**DarkSide-20k**

- **Operation:** 2021 - >2026.
- Use of 23t(20t) of UAr.
- Upgrade from PMT to SiPM technology.
Location: LNGS, Italy

- Natural shield of 1400m of rock (3800 m.w.e.) from cosmic rays. 
  Muon flux suppression factor: $10^6$.

- $\sim 10^3$ reduction in neutron flux with respect to surface due to low U and Th content in dolomite rock.

- Direct access to the labs from the highway.
Dual phase TPC: concept

- A NR induces a first scintillation pulse (S1) and ionizes Ar.
- Electrons are drifted by the E field to the LAr surface.
- A further field extracts the e\(^{-}\), causing a second and brighter light pulse S2 (electroluminescence).
- Δt among S1 and S2 gives the Z coordinate.
- XY position is reconstructed looking at the distribution of S2 photons on the PMTs.
Fighting Background

Observables in LAr

- **ER:** $\beta$ and $\gamma$
- **NR:** neutrons, neutrinos, WIMPs

1. **Active shielding:**
   -Muon Veto (Water Cherenkov Detector)
   -Neutron Veto (Liquid Scintillator)

2. **Passive suppression:**
   -Low radioactive materials
   -**Isotopically depleted Argon**
   -Low radioactive light-detectors

3. **Identification:**
   -Multiple scattering within TPC
   -Surface events (position reconstruction)
   -ER/NR discrimination via S2/S1
   -ER/NR discrimination using PSD
Argon extracted from an underground gas mine in Colorado has an $^{39}\text{Ar}$ activity 1400 times lower than Atmospheric Ar.

$\text{AAr} \approx 1\text{Bq/kg}$

$\text{UAr} = (0.73 \pm 0.11)\text{mBq/kg}$

Strongest background for Ar based experiments is $^{39}\text{Ar}$ induced ER.
ER and NR produce light with different $\tau_{\text{fast}}/\tau_{\text{slow}}$ fractions.

Discrimination Power > $1.5 \times 10^7$

Background-free UAr exposure: 5.5ton·yr

\[ f_{\text{prompt}} = \frac{\# \text{ prompt photons}}{\# \text{ total photons}} \]

LAr scintillation light has 2 decay times: $\tau_{\text{fast}}=7\text{ns}$, $\tau_{\text{slow}}=1600\text{ns}$

In DS-50 90ns is the optimal time window to optimize PSD.

PLB 743, 456 (2015)

1422 kg·d AAr exposure

No NR observed

EDU2017
Latest limits with DS-50

Since then >500 days of data in WIMP search mode acquired.

Blind analysis approach for current dataset.

Unblinding hopefully by end of summer.

Combined Dataset (2015): 50 days with AAr + 70 days with UAr
DS-20k sensitivity projections

DS-20k Letter of Intent on arXiv:1707:08145
Scaling up: DarkSide-20k

- Next generation detector aims to reach a sensitivity $10^{47}\text{cm}^2@1\text{TeV/c}^2$ with 100 ton·yr of exposure.

- A target of 23ton (20ton of fiducial volume) is foreseen.

- A radical upgrade of all the systems is needed to achieve the (reducible) background free condition for such an exposure:
  1. New and bigger veto systems (WCD and LVD).
  2. Ultra-clean stain-less steel/titanium for cryostat.
  3. Underground Argon, possibly further depleted.
  4. New, radio-pure light detectors: Silicon PhotoMultipliers (~$13\text{m}^2$).
Argon purification

Urania

- New bigger plant to extract UAr from the Colorado mine.
- Foreseen operation capacity for DS-20k: 100kg/day.

Seruci-I

- Will remove chemical impurities in UAr to 0.25-1ppm level at the rate of 1 ton/day.

Seruci-II (yet to be funded)

- Could perform a step of isotopic purification for UAr further suppressing the $^{39}$Ar content of a factor 10 per pass.

Aria

Seruci-I  Seruci-II
• **Light Yield** ~10PE/keV (20% higher than DS-50) thanks to SiPMs PDE.

• MC simulations predict a ER/NR discrimination power >3x10^9 for f_{200}.

• f_{200} provides a higher sensitivity with respect to f_{90}.
SiPM technology

SiPM: matrix of SPADs mounted in parallel

SPAD: APD operated in geiger mode

Avalanche quenched with $R_q \sim M\Omega$ resistor

SPAD gain uniformity is essential

Photon Spectra comparison at 77K

PMT

SiPM SensL C series
Good motivations to upgrade to SiPMs, but...

a strong R&D was needed to compete with PMTs.

Comparison among commercial devices at CRYOGENIC temperature (87K)

<table>
<thead>
<tr>
<th></th>
<th>PMT</th>
<th>SiPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias Voltage</td>
<td>~(1000-2000) V</td>
<td>~(30-40) V</td>
</tr>
<tr>
<td>Sensitivity to B fields</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>QE/PDE@420nm@300K</td>
<td>25%</td>
<td>(40-50) %</td>
</tr>
<tr>
<td>Packing efficiency</td>
<td>60%</td>
<td>(80-90) %</td>
</tr>
<tr>
<td>SPE resolution</td>
<td>25%</td>
<td>~(2-5) %</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>(&gt;&gt; 10^3)</td>
<td>(O(10^3))</td>
</tr>
<tr>
<td>Gain</td>
<td>(10^6-10^7) nominal</td>
<td>(O(10^6))</td>
</tr>
<tr>
<td></td>
<td>(3\cdot10^5) real</td>
<td></td>
</tr>
<tr>
<td>DCR</td>
<td>(O(1\text{cps}/\text{PMT}))</td>
<td>(10-1000)\text{cps/mm}^2</td>
</tr>
</tbody>
</table>
From SiPMs to PDMs: DS-20k requirements

**Surface: 50x50 mm²**
In order to contain the number of channels. Foreseen number: 5210

**PDE: ≥ 40%**
Higher PDE wrt Hamamatsu PMTs together with higher active area coverage will boost the light yield.

**Overall Noise Rate: <0.1Hz/mm²**
DCR+TCN+BN <250Hz/PDM ⇒ SNR_{PDM} > 8
Higher rates would impact on trigger efficiency and PSD power.

**Time resolution: O(10ns)**
Necessary to keep the ER/NR discrimination power with $f_{\text{prompt}}$.

**Dynamic Range: ≥ 50PE**
Precise S2 reconstruction.

**Power dissipation density: ≤ 100μW/mm²**
Total Power dissipation per PDM: ≤ 250mW
Avoid bubbling in LAr and excessive thermal load on the cryogenic system.

Strong constraints to SiPMs, electronics and readout performances.
SiPM R&D at FBK/LNGS

Several technologies customized and tested

Deep trenches
Lower dead border region

Fill factor: 42%

All these technologies were tested with different cell sizes.

RGB-HD
- SF
- LRq
Fast Recharge time

NUV-HD
- SF
- LF
Low DCR
Low TCN
Low Field reduces noises

AP probability

Over-Voltage
3 V
4 V
5 V
6 V

Over-Voltage
3 V
4 V
5 V
6 V
7 V

Low Field

Std Field

$\tau_{\text{recharge}} \propto R_q$ which depends on $T$

Temperature
40 K
120 K
200 K
240 K
300 K

Amplitude [µA]

Time [ns]

Temperature
40 K
120 K
200 K
240 K
300 K

Time [µs]
The Choice: NUV-HD-LF

Low Field technology proved to fulfill the strict requirements.

- **DCR** $\sim 4 \times 10^{-3}$ cps/mm$^2$ at 5VOV, LAr temperature.
- **AP+DiCT** probability $< 60\%$ at LAr temperature.
- **PDE** 50% at 5VOV at 420nm.
- **Cell Recharge Time** at LN $\sim 500$ns.
- **Surface**: 1cm$^2$

Measured at room temperature

IEEE Trans. Electron Dev. 64 2, 2017
Some pre-amplification is needed in LAr before sending signals out of the cryostat.

SiPMs present a huge output capacitance (~50pF/mm²).

A Transimpedance amplifier is the most suitable choice: High Bandwidth and Low Noise at cryogenic temperatures.

But a high BW, Low-Noise Op.Amp. is needed!
(and should be stable at 87K)
Texas Instruments SiGe LMH6629

GBP = 13GHz at 80K

Input Noise at 80K: \[ e_n = 0.3nV\sqrt{Hz} \]
\[ i_n = 1.1pA\sqrt{Hz} \]

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\[ \delta g = -3.4 \pm 0.8 \% \]
\[ e_n = 25 \pm 1 \Omega \]
\[ i_o = 3.5 \pm 0.6 \mu A \]
```

Dissipation:
\[ 40mW at 80K \]

arXiv:1706:04213
The Bandwidth of the amplifier rises at cryogenic temperatures.

\[ F_{-3dB} = 65\text{MHz at 80K} \]
with 3.9k\( \Omega \) of gain and \( C_{in} \approx 5nF \).

Test with a 10x10mm\(^2\)
NUV-HD-LF at 80K:

- \( \sigma_{1PE} = 4\% \mu_{1PE} \)
- \( \text{SNR} \equiv \mu_{1PE}/\sigma_b = 30 \)

A matched filtering technique is applied to boost SNR and timing resolution (~1ns).

\textbf{arXiv:1706:04213}
SiPM ReadOut: from 1cm² to 6cm²

Not a trivial task:
- The signal comes from only 1 SiPM but noise is readout from 24.
- The bigger input capacitance reduces the BW of the system.

2s3p configuration (6cm²):
- $C_{in}$ equivalent to 1.5cm².
- $R_p$ stabilizes the bias/gain of each SiPM.
- $R_s$ further reduces the effective $C_{in}$ by decoupling SiPMs and TIA.

Test results with 6 NUV-HD-LF at 80K:
- $\sigma_{1PE} = 6\%$ μ$_{1PE}$
- SNR = 24

The bumps to the right of the peaks are due to AfterPulses.

arXiv:1706:04220
Summing: from 6cm$^2$ to 24cm$^2$

- The noise injected by the summing stage is negligible.
- The summing chip introduces a further x8 amplification.
- Final Dynamic Range: 80–100 PE

**Power budget:** 40mW x 4TIAs + 8mW x 1diff. transmitter

= 168mW per 24cm$^2$ PDM (max allowed is 250mW/PDM)
Matched Filtering

1 Raw Signal

1PE Template

Temperature:
- 300 K
- 77 K

Fit results:
- 300 K: $\tau^+ = 6$ ns, $\tau^- = 220$ ns
- 77 K: $\tau^+ = 8$ ns, $\tau^- = 500$ ns

Clean waveform symmetrical with respect to its max.
Prototype Tile performances

Full 24cm\(^2\) tile with NUV-HD-LF at 80K 5VOV:
- \(\sigma_{1PE} = 9\%\) \(\mu_{1PE}\)
- \(\text{SNR} = 13\)

With such an SNR we don’t expect any baseline noise induced hit.

arXiv:1706:04220

1PE Time resolution: 16ns
Sufficiently good to use PSD. In DS-20k the discrimination variable is \(f_{200}\).

Counts:
- 150
- 100
- 50
A fast recap

<table>
<thead>
<tr>
<th>DS-20k requirement</th>
<th>SiPM tile (PDM)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface</strong></td>
<td>5x5cm²</td>
</tr>
<tr>
<td></td>
<td>24cm² prototype</td>
</tr>
<tr>
<td></td>
<td>25cm² final PDM</td>
</tr>
<tr>
<td><strong>Power dissipation</strong></td>
<td>&lt;250mW</td>
</tr>
<tr>
<td></td>
<td>~170mW</td>
</tr>
<tr>
<td><strong>PDE</strong></td>
<td>&gt;40%</td>
</tr>
<tr>
<td></td>
<td>50% · ε_{geom} = 45%</td>
</tr>
<tr>
<td><strong>Noise Rate</strong></td>
<td>&lt;0.1cps/mm²</td>
</tr>
<tr>
<td></td>
<td>0.004cps/mm²</td>
</tr>
<tr>
<td><strong>Time Resolution</strong></td>
<td>O(10ns)</td>
</tr>
<tr>
<td></td>
<td>16ns</td>
</tr>
<tr>
<td><strong>Dynamic Range</strong></td>
<td>&gt;50</td>
</tr>
<tr>
<td></td>
<td>~100</td>
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</tbody>
</table>

R&D phase can be considered concluded, with some minor steps to be finalized to pass from the prototype to mass production.
Conclusions

• DS-20k aims to probe the spin-independent WIMP-nucleon cross section up to $10^{-47} \text{cm}^2@1\text{TeV/c}^2$.

• The background-free mode will allow to claim a hypothetical discovery of DM with a low number of NR events.

• Many technological challenges.

• SiPMs have come to represent a viable alternative with respect to PMTs.

• SiPM-based light detectors as the one presented can be used in a variety of other experiments (DM, $\nu$, cosmic rays...).