Latest DarkSide Results

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For the DarkSide collaboration
Outline

• DarkSide-50 (DS50) detector concept
• Recent results:
  • Blind analysis of 532 live days of Underground Argon data (S1+S2), target high mass WIMP
  • Low mass DM searches interactive through electron or nuclear recoils with a ionization only measurement (S2-only)
• Future DarkSide program:
  • DS-proto
  • DarkSide-20k
• Conclusions
DarkSide-50

35.6 height diameter x 35.6 cm height TPC
46.4 Kg of Active Liquid Argon

Filled with Low Radioactivity Argon (150 Kg total) tapped from underground CO₂ wells in Cortez, CO (UAr)

Viewed by 38 Hamamatsu R11065 PMT

1,000 tonnes of ultrapure water instrumented with 80 photomultiplier tubes as Cherenkov veto for cosmic rays. 4-m diameter liquid scintillator sphere equipped with 120 photomultiplier tubes as a high-efficiency neutron veto.
Two Phase (LAr) TPC

**THE TIME-PROJECTION CHAMBER (TPC)**

- Electron Recoil* (ER)
  - Wide $S_1$ peak
  - $\int (S_1) \ll \int (S_2)$

- Nuclear Recoil (ER)
  - Narrow $S_1$ peak
  - $\int (S_1) \leq \int (S_2)$

S2/S1 ratio and **Pulse Shape Discrimination (PSD)**

WIMPs are nuclear recoils

* usu. caused by incident $\gamma$'s or $^{39}\text{Ar}$ decay, not incident $e^-$'s
Two Phase-TPC fiducialization method

Dual phase TPC allow precision fiducialization in Z (mm resolution) if both S1 and S2 is measured.

Only x-y fiducialization possible for analysis relying only on S2 signal.
ER rejection using PSD in LAr

- Bkg rejection in LAr based on S1 pulse shape
- Light emitted from Ar2+ dimers triplet 103 times slower than singlet.
- Triplet vs singlet excitation depends on particle type
- Bkg rejection $>10^7$ reached in DS50 with atmospheric argon target
- DEAP-3600 projects $>10^{10}$ rejection

- Xenon bkg rejection based on S2/S1 ratio, limited to few $10^3$
DS50 UAr data set (>800 life days)

Analyzed S2 only data-set

Analyzed S1+S2 data-set

- Overall accounted Data:
  - LifeTime ≈ 840 days
  - High Trigger Efficiency

- Reduction in trigger efficiency are due to system maintenace, DAQ crashes, PMTs shut downs, and problems to be fixed...

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**Analyzed S2 only data-set**

- 100 days
- 70 live days

**Analyzed S1+S2 data-set**

- 500 days
- 532 live days

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**PRD 93, 081101(R) (2016)**

**arxiv:1802.06994**

**arxiv:1802.06998**

**arxiv:1802.07198**
S1+S2 ANALYSIS
First blind analysis of UAr data

• Design of an analysis delivering a signal region with less than 0.1 bkg events expected
  • Use data driven measurement and methods to identify and reduce background sources
  • First use of radial fiducialization in addition to the usual in Z
  • Extensive external sources campaign to calibrate detector response and efficiencies
DS50 Background modeling

\[ \text{39} \text{Ar} \text{ emits } \beta^- \]

Activity in atmospheric Argon

\( \sim 1 \text{ Bq/Kg} \)

Reduced by a factor 1400 using Argon from underground sources

\( ^{85} \text{Kr} \) also found in the tapped source

\[
\begin{array}{c|c|c|c|c|c|c|c|c|c|c}
\text{Source} & \text{Activity [Bq]} \\
\hline
^{232} \text{Th} & 0.277 \pm 0.005 \\
^{40} \text{K} & 2.74 \pm 0.06 \\
{60} \text{Co} & 0.15 \pm 0.02 \\
^{238} \text{U}_{\text{low}} & 0.84 \pm 0.03 \\
^{238} \text{U}_{\text{up}} & 4.2 \pm 0.6 \\
^{235} \text{U} & 0.19 \pm 0.02 \\
^{85} \text{Kr} & 1.9 \pm 0.1 \text{ mBq/kg} \\
^{39} \text{Ar} & 0.7 \pm 0.1 \text{ mBq/kg} \\
\end{array}
\]

TABLE I. TPC component activities, estimated by fitting {\( ^{232} \text{Th},^{238} \text{U},^{40} \text{K},^{60} \text{Co} \)} in sequence, followed by \( ^{238} \text{U}_{\text{low}},^{238} \text{U}_{\text{up}},^{235} \text{U},^{85} \text{Kr} \), while \( ^{39} \text{Ar} \) is fixed at their measured rates as reported in [15]. Cryostat activities \((c)\) are summed across all cryostat locations, and fixed at their respective measured rates from assays. PMT activities \((p)\) are summed across all PMT locations, and across all 38 tubes.
Neutron veto cuts:
- Prompt: 1PE in [-50,250] ns of the TPC S1 trigger
- Delayed: 6PE in 500 ns sliding window in [0,185] µs of the TPC trigger

<table>
<thead>
<tr>
<th>Prompt cut only</th>
<th>Delayed cut only</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9927 ± 0.0005</td>
<td>0.9958 ± 0.0004</td>
<td>0.9964 ± 0.0004</td>
</tr>
</tbody>
</table>

- Neutron Veto efficiency from AmC / AmBe calibrations

- VETO PROMPT TAG (pass all cuts but fail veto prompt selection) sample with neutrons identified by the late coincidence
- Only 1 neutron consistent with radiogenic origin
- Scale 1 event with data driven efficiency to estimate final neutron background
Blind analysis/ER+Cherenkov

Single Scatters (γ’s or β’s) + Unresolved multi-scatters + Scintillation + Cherenkov
Blind analysis/ER+Cherenkov

Making an hybrid model using Ar39 data (model pure ER) + Cherenkov light in PTFE and Fused Silica (simulation)
Check rate and shape with a background enhanced sample from Na22 source
Final check/normalization in VETO PROMPT TAG sample
Blind analysis/unblinded data

FIG. 9. Observed events in the $S_1-\chi_0$ plane, comparing the effect of S2/S1 cuts for various samples. The contour lines represent 1%, 50%, and 99% acceptance regions for nuclear recoils, as derived from fits to our data. The dark blue region indicates the DM search region. The 1%, 50%, and 99% acceptance contours for nuclear recoils are shown as the dashed lines.
Blind analysis/results

Currently Published Limits

\[ \chi M^{2} \quad | M^{2} | \leq 1 \times 10^{-1} \]

\[ \sigma_{SI} \quad | \sigma_{SI} | \leq 4 \times 10^{-43} \text{ cm}^{2} \]

Dark Matter-Nucleon

LUX (2017)

PANDAX-II (2017)

XENON1T (2017)

WARP (2007)

DarkSide-50 (2015)

DEAP-3600 (2017)

DarkSide-50 (2018)

arXiv: 1802.07198
S2-ONLY ANALYSIS
S2-only/S2 Pulse Shape

Electrons extracted from the liquid and accelerated through a \( \sim 6 \) mm gas volume. Proportional emission of VUV photons amplify signal.

Rise-time is influenced by diffusion of the charge cloud in the liquid and transit time through the gas.

Decay constant of light in gaseous Argon different then in liquid (\( \tau_{\text{slow}} \sim 3.2 \) us)

\( \rightarrow \) Slow signal!

We are looking for very small excitations!

FIG. 8: Examples of S2 pulse shape fits for the electron diffusion measurement. Left: Event with a 22 \( \mu \)s drift time. Right: Event with a 331 \( \mu \)s drift time. The waveforms have been re-binned to 32 ns sampling, and the x-axes redefined such that \( t = 0 \) is at the S2 start.

\[ \text{arXiv: 1802.01427} \]
S2-only/ S2 PE per extracted e⁻ from S2 echoes

380 us = max drift length

Single electron extracted from the cathode by S2 VUV photon (S2 echoes):

<table>
<thead>
<tr>
<th>Det. zone</th>
<th>$\varepsilon^{\text{le}}_2$ [PE/e]</th>
<th>$\langle k \rangle$</th>
<th>$\varepsilon^{\text{le}}_2 (\text{corr})$ [PE/e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CENTER</td>
<td>22.76 ± 0.15</td>
<td>0.94</td>
<td>24.2 ± 0.2</td>
</tr>
<tr>
<td>INNER RING</td>
<td>15.58 ± 0.07</td>
<td>0.70</td>
<td>25.2 ± 0.1</td>
</tr>
</tbody>
</table>

S2-only/ S2 PE per extracted e⁻ from impurities

- Electronegative molecules (e.g. O₂, H₂O), might be present at the ppb levels in LAr
- Ionization electrons might attach to impurities during drift and later be released with time scales of O(10 ms)
- Signals are time/spatially correlated with preceding ionization events
- Rate increased significantly during the several days where filter (getter) was excluded from the Argon circulation due to servicing

S2-only/ S2 PE per extracted e⁻ from impurities

23±1 PE/e⁻

Overall rate from single electron events in normal condition: $0.5 \times 10^{-5}$ e⁻/e⁻ (x 10 with getter off)
**S2-only/Detection Threshold**

Trigger on two PMT hits (60% efficiency for single Photo-Electrons) in 100 ns:
reach 100% at ~30 PE (50% ~15 PE)

Fid. Vol. 43% ~20 Kg

events within the inner circle of PMT

S2-only/Detection Threshold

Fiducialization

× Trigger efficiency

× S2 Identification (f_{90}<0.15)

Trigger on two PMT hits (60% efficiency for single Photo-Electrons) in 100 ns:
reach 100% at ~30 PE (50% ~15 PE)

Extraction efficiency for ionization electrons >99.9%
Software pulse finding efficiency 100% for S2>30 PE
S2-only/ER scale

![Graph showing events per 0.5 Ne^-/kg/day](image)

**Events / [0.5 N_e^- x kg x day]**
- **First 100 days**
- **Last 500 days**
- **Single S2 (500d)**
- **S1 + S2 (500d)**

L/K BR Ratio = 0.11 ± 0.01

37Ar from cosmic ray activation during UAr transport: 35 d $\tau_{1/2}$ to $^{37}$Cl via electron capture
S2-only/NR scale (in situ)

**• In situ calibration with $^{241}$Am$^{13}$C source**

**• Low rate source with little gamma activity**

**• Find NR scale by fitting simulated spectrum to data + bkg distribution**

**• Allow measure down to 4 Ne threshold**

**• In situ calibration with $^{241}$AmBe source**

**• High rate source: neutrons produced with associated gamma**

**• Find NR scale by fitting simulated spectrum to data with 4.4 MeV $\gamma$ in LSV detector**

**• Deep at low Ne due to LSV data available only for S1 triggers. Joint fit with AmC data for Ne>50**

**arxiv:1802.06994**
S2 only/NR scale (external)


arXiv:1801.06653

Aris\- Measurement of $L_{\text{eff}}$ down to 7.1 keV
+ AmBe S2 vs S1 to provide Qy

SCENE – Direct Measurement @~ 200 V/cm
Uncertainties in the expected signal yield above the analysis threshold are dominated by the average event rates normalized at 500 days (same as blue histogram in Fig. 2).

The ionization yield from SCENE and ARIS. The choice of ionization yield as extracted from the DarkSide-50 calibration to ionization yield using the DarkSide-50 calibration is systematically lower than the ionization distribution of nuclear recoils and are not aware of measurements in liquid argon in the en-

FIG. 5. Data and MC fit of the 241AmBe and 13C run in DarkSide-50. The dashed line shows the lower edge of fit range.
S2-only/ Ne spectrum

arxiv:1802.06994

DM spectra $\sigma_x=10^{-40}$ cm$^2$
- $M_x=2.5$ GeV/c$^2$
- $M_x=5.0$ GeV/c$^2$
- $M_x=10.0$ GeV/c$^2$

Events / [N$_e$ x kg x day] vs. $N_e$

Analysis Threshold:
- $4e^- \sim 100$ eVee / $7e^- \sim 170$ eVee
- $600$ eVnr / $1.1$ keVnr
S2-only/ Result

arxiv:1802.06994
Sub GeV DM interacting with $e^-$

- Interpretation of the same spectrum in the context of DM coupled to light mediators. Masses below 1 GeV of interest
- Generally have couplings to electrons $\rightarrow$ easier to detect
- Require evaluation of atomic physics effects for the exact orbitals of the target material. First calculation for Argon in this paper (M.Lisanti et al.)
- Two kinds of form factors generally employed:
  - Constant (high mass mediator - top)
  - $\alpha m_e/q^2$ (low mass mediator - bottom)

\[ \text{Events} / [N_e \times \text{kg} \times \text{day}] \]

\[ \text{DM spectra } \bar{\sigma}_e = 10^{-36} \text{ cm}^2 \]
- $F_{DM} = 1$
- $10 \text{ MeV}/c^2$
- $100 \text{ MeV}/c^2$
- $1000 \text{ MeV}/c^2$

\[ \text{DM spectra } \bar{\sigma}_e = 10^{-33} \text{ cm}^2 \]
- $F_{DM} \times 1/q^2$
- $10 \text{ MeV}/c^2$
- $100 \text{ MeV}/c^2$
- $1000 \text{ MeV}/c^2$

\[ \text{Events} / [N_e \times \text{kg} \times \text{day}] \]

arxiv:1802.06998
Sub GeV DM interacting with e⁻
DS50 + ReD and future LAr DM program

• Main thrust on improved calibration for low energy nuclear recoil
  • A significant reduction in $Q_y$ uncertainty and “some” indication of the underlying distribution of the number of ionization electrons at very low recoil would allow significant improvement in the sensitivity at lower masses (1-2 GeV/$c^2$)

• DS50 will be extremely valuable to perform a number of optimization studies for low energy ionization search: optimize fields, recirculation, trigger
  • Reduction and/or modeling of the single-electron background would allow to move the analysis threshold down to 1-2 e$^-$ corresponding to 2-300 eVnr and possibly extend the sensitivity well below 1 GeV/$c^2$

• Darkside-Proto is around the corner in the path towards the construction of Darkside-20k (20 Ton Fiducial Mass dual phase TPC)
S2-ONLY PROSPECTS
ReD experiment

- ReD experiment has first beam in June @ LNS TANDEM

- Original goal is the directionality measurement (high energy nuclear recoils), now aiming also at a direct measurement of low energy nuclear recoil with same TPC by tuning appropriately the beam and geometry setups
A physics-case for a ton size LAr TPC (DS-proto)

Background limited in DS50 S2-only analysis.
Potential breakthroughs:
• Urania/Aria program
• Use of SiPM
• Larger mass in Ds-Proto
Investigating the possibility to use DS-proto for a physics run

Bkg [0-50 Ne] composition

Test bed for DS-20k technology
370 SiPM tile photo-sensors
Low background SS cryostat
Possible installation in LNGS in late 2019.
Run in 2020?
39Ar depletion in Urania+Aria

- Urania plant is able to remove 85Kr
- By design more air leak tight wrt to DS50 plant (also possible a reduced 39Ar content)

- Relative volatility b/w 39Ar and 40Ar is 1.0015±0.0001*
- Thousands of distillation stages in a 350 m tall column (Seruci I) under construction in Nuraxi-Figus mine (Sulcis Iglesiente)
- Would allow reduction of 39Ar content by a factor 10 per pass
- Seruci I production rate is calculated at 10 kg/day, perfectly matching the capacity needed to feed Ds-Proto (800 Kg total LAr)

*from calculations
Aria modules shipped and assembled at Seruci (May 2018)
Low radioactivity photo-sensor

- 5x5 cm SiPM tile with a front-end amplification & summing stage in an acrylic cage: a Photo Detector Module (PDM)
- Intrinsically radio-pure Silicon
- Screening of cryogenic electronic components and substrates to achieve the lowest possible radioactivity
- Current estimate – including all services– is about 2 mBq/PDM, dominated by Arlon 55 NT substrates (for SiPM and front-end)
- On-going fused silica substrates R&D can achieve factor 10 reduction (200 μBq/PDM)
- Remind, even 2 mBq/PDM much better than current DS50 PMT (compare to ~200 mBq/PMT)!
First PDM performance (prelim.)

![Amplitude Spectrum of Signals of the First PDM](image)

**Fig. 24.** Amplitude spectrum of signals of the first PDM (NUV-HD-LF 2018 with triple dopant concentration, preliminary result).

- Gain: 52.68
- $\sigma_b$: 2.19
- SNR: 24.1
Future Darkside Low-Mass Searches

1 year data taking with DS-proto underground vs radiopurity levels of target and electronics (ambitious).
DARKSIDE-20K PROSPECTS
DS20K conceptual design/
Proto-Dune Cryostat

Two identical cryostats already built @CERN in ~40 weeks

About 8x8x8 m³ inner volume,
750 ton of LAr

Cryostat technology and expertise from Liquefied Natural Gas industry
DS20K conceptual design/in Hall-C

Relative sizing of the DarkSide-20k system in Hall-C

Temporary TPC Test Dewar

Hall-C Limit

TPC Test Dewar

Open top Cryostat to insert tested TPC from the top

TPC and Vessel Hang from top cover

Overall DarkSide-20k System Installation Procedure

TPC must be able to move closer to top cover during installation (limited head room)
**DS20K conceptual design/PS veto**

- TPC thin copper vessel to be surrounded by an active plastic scintillator layer as a neutron veto

- Considering options to load with Boron or Gadolinium for increased capture cross section

- Cryogenic SiPM sensors in Liquid sensors similar to those developed for the TPC

- Detector concept minimize internal neutron background sources and allow easier scaling for bigger target mass
DS20K sensitivity prospects

WIMP-nucleon $\sigma_{SI}$ [$\text{cm}^2$]

- WARP (2007)
- DarkSide-50 (2015)
- DarkSide-50 (2018)
- LUX (2017)
- PANDAX-II (2017)
- DEAP-3600 (proj.)
- XENON1T (2017)
- XENON1T (proj.)
- XENONnT (proj.)
- WARP (2007)
- DarkSide-50 (2018)
- DEAP-3600 (2017)
- LUX (2017)
- PANDAX-II (2017)
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- WARP (2007)
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- DEAP-3600 (2017)
- LUX (2017)
- PANDAX-II (2017)
- XENON1T (2017)
- XENON1T (proj.)
- XENONnT (proj.)

Neutrino floor

Future 300-tonne GADMC detector (1kt yr proj.)
Future 300-tonne GADMC detector (3kt yr proj.)

WIMP mass [TeV/c$^2$]
Summing up

90% CL upper limit on $\sigma_{\chi n}$ [cm$^2$]

- DarkSide-20k (100 t yr proj.)
- DarkSide-20k (200 t yr proj.)
- Future 300-tonne GADMC detector (1kt yr proj.)
- Future 300-tonne GADMC detector (3kt yr proj.)

WIMP mass [TeV/c$^2$]
Conclusions

- A new search window from DS50 S2-only search for LAr
  - Threshold in sub keV range
  - Background at ~1 count/keVee/day (to be reduced further)

- More data in hands:
  - In total almost 3 annual cycle for the S2-only analysis, with a quite stable detector
  - Working on an improved analysis including all data

- A clear path to approach the neutrino floor with the next generation of Liquid Argon dark matter experiments for both the low and high mass WIMP searches
SPARES
Blind analysis/ Radial cut

Non trivial x-y reconstruction for Ds50 geometry and optics. Algorithm find best position based on expected light sharing among the PMT on the top plane. Resolution ~6 mm for large enough signals.

In addition usual 40 µs cut in Z direction from anode and cathode (~4 cm)
Blind analysis/acceptance & bkg

<table>
<thead>
<tr>
<th>Cut</th>
<th>Livetime/Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>All channels</td>
<td>545.6 d</td>
</tr>
<tr>
<td>Baseline</td>
<td>545.6 d</td>
</tr>
<tr>
<td>Time since prev</td>
<td>545.3 d</td>
</tr>
<tr>
<td>Veto present</td>
<td>536.6 d</td>
</tr>
<tr>
<td>Cosmo activ</td>
<td>532.4 d</td>
</tr>
<tr>
<td>Muon signal</td>
<td>0.990</td>
</tr>
<tr>
<td>Prompt LSV</td>
<td>0.995</td>
</tr>
<tr>
<td>Delayed LSV</td>
<td>0.835</td>
</tr>
<tr>
<td>Preprompt LSV</td>
<td>0.992</td>
</tr>
<tr>
<td>N pulses</td>
<td>0.978</td>
</tr>
<tr>
<td>S1 start time</td>
<td>1</td>
</tr>
<tr>
<td>S1 saturation</td>
<td>1</td>
</tr>
<tr>
<td>Min uncorr S2</td>
<td>0.996</td>
</tr>
<tr>
<td>xy-recon</td>
<td>0.997</td>
</tr>
<tr>
<td>S2 F90</td>
<td>1</td>
</tr>
<tr>
<td>Min corr S2/S1</td>
<td>0.995</td>
</tr>
<tr>
<td>Max corr S2/S1</td>
<td>0.991</td>
</tr>
<tr>
<td>S2 LE shape</td>
<td>1</td>
</tr>
<tr>
<td>S1p max frac</td>
<td>0.948</td>
</tr>
<tr>
<td>S1 TBA</td>
<td>0.998</td>
</tr>
<tr>
<td>Long S1 tail</td>
<td>0.987</td>
</tr>
<tr>
<td>Radial cut</td>
<td>0.84</td>
</tr>
<tr>
<td>S1 NLL</td>
<td>&gt;0.99</td>
</tr>
<tr>
<td>Combined</td>
<td>0.609</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Background</th>
<th>Events surviving all cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Type 1</td>
<td>0.0006 ± 0.0001</td>
</tr>
<tr>
<td>Surface Type 2</td>
<td>0.00092 ± 0.00004</td>
</tr>
<tr>
<td>Radiogenic neutrons</td>
<td>&lt;0.005</td>
</tr>
<tr>
<td>Cosmogenic neutrons</td>
<td>&lt;0.00035</td>
</tr>
<tr>
<td>Electron recoil</td>
<td>0.08±0.04</td>
</tr>
<tr>
<td>Total</td>
<td>0.09 ± 0.04</td>
</tr>
</tbody>
</table>
S2-only/ER scale

\[ \Delta N_e / N_e \sim 4\% \]
@ 200 eVee

\[ (\text{K-shell, } 2.82 \text{ keV}) \]
\[ (\text{L-shell, } 0.27 \text{ keV}) \]

\[ \text{Ar} \quad (\text{K-shell, } 2.82 \text{ keV}) \quad \text{Ar} \quad (\text{L-shell, } 0.27 \text{ keV}) \]

\[ \text{^{83mKr}} \]

\[ N_e \]
\[ E_{\text{keV}} \]

\[ \text{keVee} \]
Compare with Xenon100 – ionization only

**FIG. 4.** Energy distribution of the events remaining in the data set after all data selection cuts. As an example, the expected spectrum for a WIMP of 6 GeV/c² and a spin-independent WIMP-nucleon scattering cross section of $1.5 \times 10^{-41}$ cm² is also shown. The corresponding nuclear recoil energy scale is indicated on the top axis. The charge yield model assumed here has a cutoff at 0.7 keV, which truncates the WIMP spectrum. The optimum interval (thick red line) is found in the S2 range [98, 119] PE and contains 1173 events.

**TABLE I.** Acceptances of the different data selections and cuts are applied sequentially. The number of events is in the number of DM candidate events passing the selections. The low acceptance is necessary because of the gas event background in this analysis. We also apply a loose S2 asymmetry cut (as determined from the AmBe data).

<table>
<thead>
<tr>
<th>Description of cut</th>
<th>Xenon 100</th>
<th>Darkside-50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Events / [N ev/kg × day]</td>
<td>13560</td>
<td>49041</td>
</tr>
<tr>
<td>Events / [N keVnr/kg × day]</td>
<td>$10^3$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Events / [N keVnr/kg × day]</td>
<td>$10^2$</td>
<td>$10^1$</td>
</tr>
<tr>
<td>Events / [N keVnr/kg × day]</td>
<td>$10^1$</td>
<td>$10^0$</td>
</tr>
<tr>
<td>Events / [N keVnr/kg × day]</td>
<td>$10^0$</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>Events / [N keVnr/kg × day]</td>
<td>$10^{-1}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Events / [N keVnr/kg × day]</td>
<td>$10^{-2}$</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Events / [N keVnr/kg × day]</td>
<td>$10^{-3}$</td>
<td>$10^{-4}$</td>
</tr>
</tbody>
</table>

Compare with Xenon100 – ionization only

NR scale
Low Mass Region Projections

≈2020

DAMIC/SENSEI CCD
NEWS-G (Spherical Proportional Counter)
Low temperature calorimeters: SuperCDMS, CRESST, Edelweiss)
90% CL upper limit on $\sigma_{\text{SI}}$ [cm$^2$] vs. $M_\chi$ [GeV/c$^2$]
Nuclear recoil spectra

\[ \frac{dR}{dE} \text{ (per keV/day/kg)} \]

\[ M_W = 1.5/5.0 \text{ GeV} \quad \sigma_{\text{Si}} = 1 \times 10^{-41} \]

Xenon
Argon

Low Thr. 4e
High Thr. 7e
Ar39 and Kr85 forbidden spectra

FIG. 12. Updated energy spectra of $^{39}\text{Ar}$ (red curve) and $^{85}\text{Kr}$ (blue curve). The dashed curves represent $\pm 1\sigma$ theoretical uncertainties. The $x$-axis is units of MeV.
Prompt and delayed Veto signals

Borated-liquid-scintillator neutron veto
• \((\alpha, n)\) from PMT U and Th are the dominant neutron source.
• Separately detect both thermalization and capture signals from neutron.
• Rejection measured with AmC neutrons giving WIMP-like TPC signature.
• Rejection for radiogenic neutrons \(~500\).
• Also effective for cosmogenic neutrons.
Single Electron Response

- PMT #0
- PMT #1
- PMT #2
- PMT #3
- PMT #4
- PMT #5
- PMT #6
- PMT #7
- PMT #8
- PMT #9
- PMT #10
- PMT #11
- PMT #12
- PMT #13
- PMT #14
- PMT #15
- PMT #16
- PMT #17
- PMT #18

- PMT #19
- PMT #20
- PMT #21
- PMT #22
- PMT #23
- PMT #24
- PMT #25
- PMT #26
- PMT #27
- PMT #28
- PMT #29
- PMT #30
- PMT #31
- PMT #32
- PMT #33
- PMT #34
- PMT #35
- PMT #36
- PMT #37

Time [day]

ADC [ns]

1200 1250 1300 1350 1400 1450 1500 1550 1600
Fighting ER+Cherenkov

- 1 " thick PTFE coated with TPB WLS used as a reflector in DS50
- Cherenkov from electrons in Teflon produce visible light that can be seen in the TPC, dangerous bkg when a coincident ER recoil occurs
- For DS20k replace PTFE with a sandwich of thin acrylic transparent sheets and 3M enhanced specular reflector foils
- PTFE has high \((\alpha, n)\) cross due to Fluorine. Reduces also second largest radiogenic neutron source in the original Ds20k design
S2-only/ NR scale

\[ Q_y \left[ \text{e}^-/\text{keV}_{nr} \right] \]

\[ E_{Xe} \left[ \text{keV}_{nr} \right] \]

Xe Data
- LUX 2016
- ZEPLIN-III 2011
- XENON10 2011
- Manzur et al. 2010
- XENON10 2009
- Joshi et al. 2014
- Joshi et al. 2014 Cross Calibrated

Ar Data
- AmBe - AmC - ARIS - SCENE
- Aprile et al. 2006
- Bezrukov et al. 2011

arxiv:1802.06994