THE DARKSIDE EXPERIMENT – PRESENT STATUS AND FUTURE

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for the DARKSIDE Collaboration
OUTLINE

• Introduction to Dark Matter
• The DARKSIDE program
• DARKSIDE-50 detector
• Physics results from DARKSIDE-50
• Future of DARKSIDE
• Summary
DARK MATTER EVIDENCES
DARK MATTER EVIDENCES

Magellan images of the Bullet Cluster, with weak lensing mass contours

Bullet Cluster: Chandra observations of the X-ray emission from hot gas
DARK MATTER EVIDENCES

All-sky map of CMB temperature fluctuations produced by Planck

Power spectrum of CMB temperature as measured by Planck
CONTENT OF THE UNIVERSE

- Dark Matter: 25.9%
- Ordinary Matter: 4.9%
- Dark Energy: 69.2%

Seminar of High Energy Physics, Faculty of Physics and Applied Computer Science AGH, 24.11.2017, Cracow
SEARCHES FOR DARK MATTER

- Indirect (DM annihilation/decay products)
- Colliders (missing momentum/energy)
- Direct (DM particles interactions in terrestrial detectors)
  - WIMPs: produced in the early Universe, interacting weakly, no charge, heavy (10 – 1000 GeV/c²)
DIRECT SEARCHES FOR DARK MATTER

Factor 10 improvement every 3.3 yr

~ 1 event kg\(^{-1}\) day\(^{-1}\)

~ 1 event 100 kg\(^{-1}\) yr\(^{-1}\)
DARK MATTER – EXPECTED SIGNAL RATE

\[ \frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{\text{max}}}^{v_{\text{max}}} \frac{dv f(v)}{\sqrt{(m_N E_{\text{th}})/(2\mu^2)}} \frac{d\sigma}{dE_R} \]

Detector physics: \( N_N, E_{\text{th}} \)

Particle/nuclear physics: \( m_W, d\sigma/dE_R \)

Astrophysics: \( \rho_0, f(v) \)

\[ \text{Cross section} \]

\[ \text{Mass} \]

Ruled out

Accepted
DARK MATTER – EXPECTED SIGNAL RATE

\[
\frac{dR}{dE_r} \sim \frac{m_N}{m^3_\chi} \sigma_{SI} v_0^2 e^{-v^2_{min}/v_0^2} \Rightarrow \sigma_{SI} \sim \frac{m^3_\chi}{m_N dE_r} e^{E_r m_N / 2m^2_\chi v_0^2}
\]
DARK MATTER – EXPECTED SIGNAL RATE

\[
\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{max}} \frac{d\nu f(\nu)\nu}{\sqrt{(m_N E_{th})/(2\mu^2) d\sigma/dE_R}}
\]

Detector physics
\[ N_N, E_{th} \]

Particle/nuclear physics
\[ m_W, d\sigma/dE_R \]

Astrophysics
\[ \rho_0, f(\nu) \]

Signal
Mass
Cross section
DARK MATTER SIGNAL SIGNATURES

• Rate and shape of the recoil spectrum depends on the target
DARK MATTER SIGNAL SIGNATURES

\[ \sigma_{SI} = 10^{-44} \text{ cm}^2 \]
\[ \rho_0 = 0.3 \text{ GeV/c}^2/\text{cm}^3 \]
\[ v_{esc} = 544 \text{ km/s} \]
\[ v_0 = 220 \text{ km/s} \]
\[ v_e = 232 \text{ km/s} \]

\( \sigma_{SI} \) – SI cross section
\( \rho_0 \) – WIMP density
\( v_{esc} \) = MB cut off/escape vel.
\( v_0 \) – halo RMS circular speed
\( v_e \) – target velocity
DARK MATTER SIGNAL SIGNATURES

- Rate and shape of the recoil spectrum depends on the target
- Annual variations of the signal rate (June-December asymmetry ~3 %)
DARK MATTER SIGNAL SIGNATURES

• Rate and shape of the recoil spectrum depends on the target
• Annual variations of the signal rate (June-December asymmetry ~3 %)
• Daily modulation of the recoil nuclei direction (directionality needs to be detectable)
PERFECT EXPERIMENT

- **Background – free** (only DM contributes to the measured signal)
- Low energy threshold (probing interactions of low-mass DM particles)
- Large mass of the active volume to maximize the exposure
- Known detector response
- Easy/cheap scalability
SENSITIVITY CURVE WITH BACKGROUND

Argon: 100 t yr exposure

![Graph showing sensitivity curve with background](image-url)
BACKGROUND SOURCES

• Radioactivity of the target material
  - ultra-pure target (real-time purification)
• Radioactivity of the detector installation and shield
  - selection of radio-pure construction materials
• Radioactivity of surroundings
  - effective shielding
• Cosmic rays and secondaries
  - detector location deep underground
BACKGROUND ISSUE

$B$ – background  \hspace{1cm} \beta$ – background miss-identification

$MT$ – exposure  \hspace{1cm} \alpha$ – signal acceptance

\[ S_{90} \propto \frac{2.3}{\alpha \cdot MT} \]
\[ \sqrt{\frac{\beta(1 - \beta)}{(\alpha - \beta)^2}} \sqrt{\frac{B}{MT}} \]
\[ \frac{B}{\alpha} + \frac{1.28}{\alpha} \sqrt{\frac{\beta B}{MT}} \]
BACKGROUND ISSUE

Factor 10 improvement every 3.3 yr
BACKGROUND ISSUE

\[ \sigma_{SI} = \sim 10^{-46} \text{ cm}^2 \rightarrow R \sim 1 \text{ event/100 kg/year} \]

\[ \downarrow \]

S/B \sim 1 \text{ (very optimistic)}

\[ \downarrow \]

1 decay/100 kg/year \sim 3 \times 10^{-10} \text{ Bq/kg} \]
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Mineral water: \sim 1 \text{ Bq/l} 

100 kg \rightarrow 100 \text{ Bq}

\rightarrow 100 \text{ events/s}

\rightarrow 3 \times 10^{10} \text{ events/year}
BACKGROUND ISSUE

\[ \sigma_{SI} \approx 10^{-46} \text{ cm}^2 \rightarrow R \approx 1 \text{ event/100 kg/year} \]

\[ \downarrow \]

\[ S/B \approx 1 \text{ (very optimistic)} \]

\[ \downarrow \]

\[ 1 \text{ decay/100 kg/year} \approx 3 \times 10^{-10} \text{ Bq/kg} \]

Mineral water: \(~1\text{ Bq/l}\

100 kg \rightarrow 100 \text{ Bq}\

\rightarrow 100 \text{ events/s}\

\rightarrow 3 \times 10^{10} \text{ events/year}\

**Needed reduction factor: \(~10^{10}!\)**
BACKGROUND ISSUE

The most challenging task for DM experiments:

How to **achieve** and **maintain** required radio-purity of the detector target more than $10^{10}$ times below the environmental level ($< 0.1$ ev. for the assumed exposure).

For future experiments existing screening facilities may not be able to provide useful information for background predictions (required specific activities beyond detection limits).

$^{222}\text{Rn} \sim \mu\text{Bq/kg} \rightarrow \sim 2$ atoms/m$^3$ gas (STP)!
THE DARKSIDE PROGRAM

- Multi-stage program for searches of dark matter direct interactions in low-background detectors deployed at the Gran Sasso underground laboratory.
- Based on a two-phase low-radioactivity argon time projection chamber (TPC)
- Ultra-low background design
- Active suppression of residual backgrounds for true background-free operation
THE DARKSIDE PROGRAM

Why LAr?

• Relatively dense (1.4 g/cm³)
• Easy to purify ($^{222}$Rn/$^{85}$Kr)
• Scales to large mass
• Exceptional discrimination power (PSD, S1/S2)
THE DARKSIDE PROGRAM

Why LAr?

• Relatively dense (1.4 g/cm$^3$)
• Easy to purify ($^{222}$Rn/$^{85}$Kr)
• Scales to large mass
• Exceptional discrimination power (PSD, S1/S2)
• $^{39}$Ar at the level of 1 Bq/kg – dead time problem for a ton scale experiment → depletion needed
THE DARKSIDE PROGRAM

Hall A
GERDA
LVD, CUORE
CRESST

Hall B
XENOX-1T

Hall C
BOREXINO
DARKSIDE

© 2012, MPI of Physics, Munich
THE DARKSIDE PROGRAM

DS-10 prototype (2011 - 2013)

DS-50 detector (Since Oct. 2013)

DS-20k (2020 – )
DS-50 DETECTOR

Clean room

Instrumented water tank (1 kton)
- 80 8” PMTs
- 11 m dia. x 10 m high
- Muon and cosmogenic veto (~ 99.5% efficiency)
- Passive γ/n shielding

Liquid scintillator detector

Inner detector: TPC
DS-50 DETECTOR
DS-50 DETECTOR
DS-50 TPC

Anode (15 nm film ITO on silica fused window)

Gaseous Argon

Extraction grid

Liquid Argon

Cathode

PMTs (19 x 3” R11065)

$E_{\text{extr.}}$ (2.8 kV/cm)

$E_{\text{drift}}$ (200 V/cm)

TPC: 36 cm $\phi \times$ 36 cm high
DS-50 TPC

- Nuclear recoil produces primary scintillation light: S1
- Electrons that survive recombination are drifted towards the liquid-gas interface by the electric field
- The electrons are extracted into the gas region, where they induce electroluminescence: S2
- Time difference between S1 and S2 gives Z position, PMT hit pattern gives X-Y position
- Tools for backgrounds rejection:
  - PSD based on S1
  - S2/S1 ratio
  - Position reconstruction
UNIQUE FEATURES OF DARKSIDE

- Argon depleted in $^{39}\text{Ar}$: underground argon (UAr)
- Liquid scintillator veto for neutrons
- Pulse shape discrimination for background rejection
- $^{222}\text{Rn}$-free clean rooms
UNDERGROUND ARGON (UAr)

- $^{39}$Ar radioactivity in atmospheric Ar ($\sim 1$ Bq/kg) limits its usability as a WIMP target
- $^{39}$Ar is of cosmogenic origin
- Source of underground argon (CO$_2$ well near Cortez, Colorado) measured to have $> 150$ times lower rate of $^{39}$Ar (< 7 mBq/kg), compared to atmospheric argon
- Large-scale production possible (multi-ton Ar detectors)
UNDERGROUND ARGON (UAr)

Extraction of UAr at Colorado.
Crude argon gas mixture (Ar, N₂ and He)

Distillation at Fermilab
Separate Ar from N₂ / He

UAr bottles (156 kg) at LNGS
Final purification with getters
LIQUID SCINTILLATOR VETO

- 4 m diameter sphere containing PC + 5% trimethyl borate (TMB) scintillator (30 ton)
- Instrumented with 110 8” PMTs
- Veto of neutrons coincident in the TPC and provides in situ measurement of the neutron background rate
- Neutron capture results in 1.47 MeV α, capture time 23 μs
- Veto efficiency: >99.1% for neutrons detected via delayed capture on $^{10}$B and $^{1}$H (radiogenic) and >95% for cosmogenic neutrons
PULSE SHAPE DISCRIMINATION

Electron and nuclear recoils produce different excitation densities in the argon, leading to different ratios of singlet and triplet excitation states $\rightarrow f_{90}$: Ratio of detected light in the first 90 ns, compared to the total signal ($\sim$ single states fraction)

$f_{90} \sim 0.3$

Electron Recoil

$f_{90} \sim 0.7$

Nuclear Recoil
222Rn-FREE CLEAN ROOMS

- Class 10 - 100
- Radon daughters plating out on surfaces of the detector may cause dangerous alpha-induced nuclear recoils
- Dedicated scrubbing system reducing 222Rn concentration in the air down to ~1 mBq/m³ has been implemented
- DARKSIDE clean rooms are supplied with the 222Rn-free air
- 222Rn content in the clean rooms is monitored online by a dedicated detector

Typical radon in hall C air ~ 30 Bq/m³
Cleanroom radon levels 5 – 50 mBq/m³
$^{222}$Rn-FREE CLEAN ROOMS

![Graph showing $^{222}$Rn specific activity over time]

- Person entering CRH

Date

- 09/11/2013 01:07
- 09/11/2013 07:07
- 09/11/2013 13:07
- 09/11/2013 19:07
- 10/11/2013 01:07
- 10/11/2013 07:07
- 10/11/2013 13:07
- 10/11/2013 19:07
- 11/11/2013 01:07
- 11/11/2013 07:07
- 11/11/2013 13:07

$^{222}$Rn specific activity [mBq/m$^3$]

- 0
- 2
- 4
- 6
- 8
- 10
- 12

Seminar of High Energy Physics, Faculty of Physics and Applied Computer Science AGH, 24.11.2017, Cracow
DS-50 RESULTS (AAr)

47.1 live-days after all cuts, (1422±67) kg day exposure.

Acceptance curves from $\text{Scene}$ (arxiv:1406.4825)

$1.5 \times 10^7 \text{ ER} \rightarrow \text{ER rejection} > 10^7$

$^{39}\text{Ar}$ beta decay (e$^-\text{ recoils}$)

DS-50 RESULTS (UAr)

AAr vs UAr: $^{39}$Ar depletion factor $\sim 1400$ ($C_{Ar-39} = 0.7 \text{ mBq/kg}$), $C_{Kr-85} = 2.1 \text{ mBq/kg}$

Low level of $^{39}$Ar allows extension of DARKSIDE program to a ton-scale detector
70.9 live-days after all cuts, (2616±43) kg day exposure. 
Single-hit interactions in the TPC → **No background events in the WIMP region**

**DS-50 RESULTS (UAre)**

*Phys. Rev. D 93 (2016) 081101*
DS-50 RESULTS (UAr)

70.9 live-days after all cuts, \((2616 \pm 43)\) kg day exposure.
Single-hit interactions in the TPC → **No background events in the WIMP region**
DS-50 RESULTS (UA\(\text{r}\))

Combined result: \(\sigma_{\text{min}} = 2 \times 10^{-44} \text{ cm}^2\) for 100 GeV/c\(^2\)
FUTURE DETECTORS

DS-20k
30 t (20 t fiducial) of UAr

ARGO
300 t (200 t fiducial) of UAr
FUTURE DETECTORS – NEW COLLABORATION

- DarkSide
- DEAP
- ArDM
- MiniCLEAN

DarkSide-20k → multi 100 t experiment

Global Argon Collaboration

Letter of Intent
September 8, 2017
Rev B

Scientists at LNGS, LSC, and SNOLAB are joining in an international effort to mount a phased argon dark matter program with the goal of being sensitive to the neutrino floor. This effort will include a broad collaboration of scientists and will represent the global community for dark matter searches with argon. This letter is an update of a previous communication dating June 2017, which detailed the first conception of the program; this letter was expanded to capture the intent of all institutions and scientists participating in the program.

In this document, the undersigned representatives of groups working on argon dark matter searches, including Brazilian, Canadian, Chinese, French, German, Greek, Italian, Mexican, Polish, Romanian, Russian, Spanish, Swiss, US, and UK groups among others, memorialize their intent to form a Global Argon Dark Matter Collaboration to carry out a program for direct dark matter searches, consisting of two main elements.
AMBITIOUS DISCOVERY PROGRAM

- Complementary to LHC
- Raising the bar: from 1 t yr → 1000 t yr
- “Zero Background” necessary for a discovery program
- Two crucial technologies
  - Liquid argon target depleted in the radioactive $^{39}$Ar
  - SiPMs replacing cryogenic PMTs
DS-20k

- Octagonal TPC filled with UAr/DAr
- 20 t Fiducial Volume (MT = 100 t yr)
- Radio-pure construction materials (ULR Ti/Stainless Steel)
- 15 m² of SiPMs (5210 modules 5×5 cm, lower radioactivity compared to PMTs, custom development by FBK, production in Abruzzo)
- DS-50-like veto design
- Time-line: 2020 – 202x
DS-20k DETECTOR
DS-20k SiPM

- Effective QE $\sim$ 40%
- Geiger-mode gain $>10^6$
- Fast, sub-nanosecond timing
- No HV
- Large area arrays $> 90\%$ coverage commercially available
- Very compact, very low radioactivity

Top + bottom: 5210 channels
DS-20k SiPM
DS-20k SiPM
URANIA TO ARIA TO LNGS
PRODUCTION / DEPLETION OF UAr

**URANIA**

Expansion of the argon extraction plant in Cortez to reach capacity of 100 kg/day of Underground Argon

**ARIA**

Additional purification and depletion of UAr at 150 kg/day: 350 m distillation column in the Seruci mine in Sardinia.
ARIA

- 350 m tall distillation column in the mine in Sardinia for chemical and isotopic purification of UAr
- Exploits finite vapor pressure difference between $^{39}\text{Ar}/^{40}\text{Ar}$ ($^{39}\text{Ar}$ reduction factor of 10 per pass at the rate of 100 kg/day)
- Protocollo di Intesa between INFN and Regione Sardegna

- Cost: 12.5 M€
- INFN (4 M€)
- NSF + other US sources (1.3 M€)
- CARBOSULCIS (4.5 M€)
- Regione Autonoma Sardegna (2.7 M€)
ARIA

Photo by Y.Suvorov

Seminar of High Energy Physics, Faculty of Physics and Applied Computer Science AGH, 24.11.2017, Cracow
DS-20k / ARGO TIME LINE

DarkSide-20k

20-tonnes fiducial dark matter detector
start of operations at LNGS within 2020
100 tonne×year background-free search for dark matter

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Argo

300-tonnes depleted argon detector
start of operations at LNGS within 2025
1,000 tonne×year background-free search for dark matter
precision measurement of solar neutrinos
PROJECTED SENSITIVITY
SUMMARY

• 1422 kg×day of truly background-free exposure has been demonstrated with AAr (> 20 yr of $^{39}$Ar-free operation of DS-50 with UAr)

• So far 2616 kg×day of truly background-free exposure has been demonstrated with UAr, data taking continues

• Concentration of $^{39}$Ar in DS-50 UAr is 1400 times lower than in AAr

• Within DS-50 the strongest WIMP limit among Ar target experiments has been obtained

• DS-20k detector (along with URANIA / ARIA) is under development

• Background-free exploration of DM signal down to the neutrino flor for $M_\chi > 100 \text{ GeV}/c^2$ feasible
IF UJ CONTRIBUTION TO DARKSIDE

- Development and implementation of gas purification techniques (Borexino/GERDA)
- Development of counting techniques down to single atoms
- Ultra sensitive bulk and surface assay, Rn emanation and diffusion tests at a single atom level
- Development of software procedures for background identification/rejection
- Operating very unique apparatus (custom design/construction) for ultra-low level counting
BACKUP SLIDES
SEARCHES FOR DARK MATTER
57.2 keV

- **Parallel to** $\vec{\varepsilon}_d$
- **Perpendicular to** $\vec{\varepsilon}_d$

**S1 yield relative to 0 field**

**Drift electric field [V/cm]**

- 0
- 200
- 400
- 600
- 800
- 1000
TPC CALIBRATION

$^{83m}$Kr $- 41.5$ keV

$E_{\text{drift}} = 0$

$8$ p.e./keVee

$^{39}$Ar, $Q = 565$ keV
LSV CALIBRATION

~0.5 p.e./ keVee sufficient to detect ~50 keVee alphas from n capture
$^{7}\text{Li}(p, n)^{7}\text{Be}$ reaction produces low energy mono-energetic $n$. TOF measurement between target, LAr and organic scintillators allows clean identification of elastic neutron interactions of known energy.