DarkSide-20k: Next generation Direct Dark Matter searches with liquid Argon

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University of Birmingham

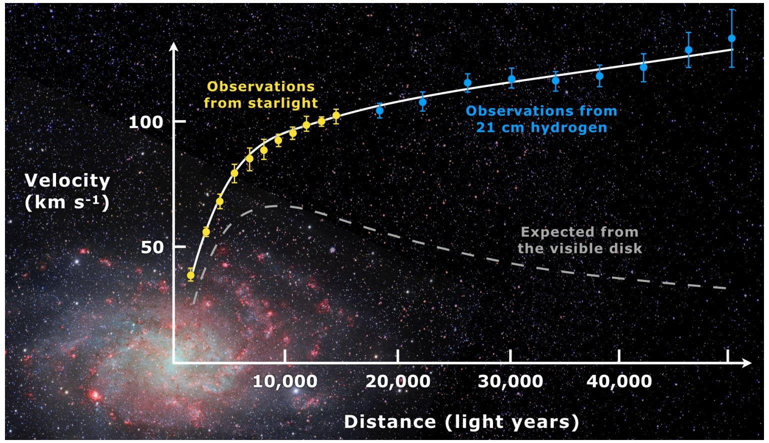
on behalf of the DarkSide-20k Collaboration

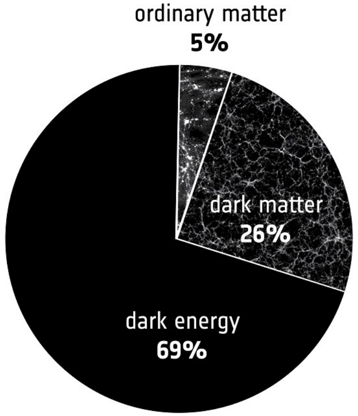
European Physical Society Conference on High Energy Physics (EPS-HEP)
23 August 2023, Hamburg, Germany

The hunt for Dark Matter

Indications of Dark Matter existence

- The rotation curves of galaxies and the movement of galaxies in clusters
- Gravitational lensing
- Formation of large- scale structures
- Inhomogeneities in the microwave background radiation





What we know about Dark Matter

- Non-Baryonic
- Mostly “cold”
- Electrically neutral
- “Weakly” interacting
- $\Omega_{DM}h^2=0.120\pm0.001$
- Stable or $\tau_{DM} \gg \tau_u$

Illustration by Chris Wormell from “A Map of the Invisible”

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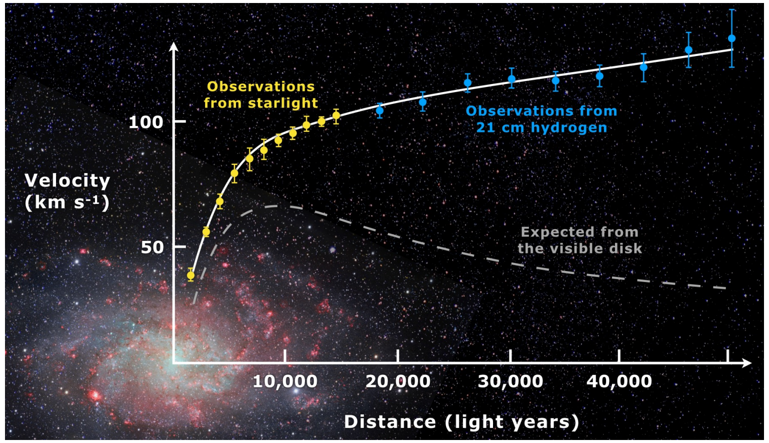

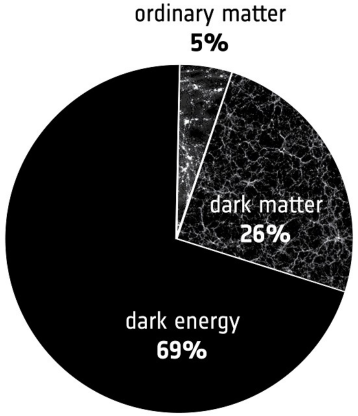

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- Electrically…
- “W… …eracting
- $\Omega_{DM}h^2=0.120\pm0.001$
- Stable or $\tau_{DM} \gg \tau_u$

No known particle fits the bill!

Dark Matter searches

indirect → Observation of DM annihilation/decay products:
- antimatter
- gamma photons
- neutrinos

production → DM particles in accelerators

direct → WIMP scattering with atoms

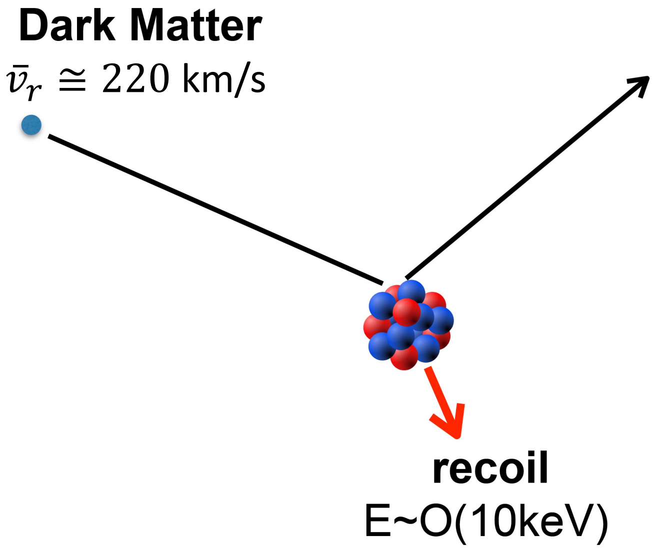
Illustration by Chris Wormell from “A Map of the Invisible”

Direct Dark Matter detection

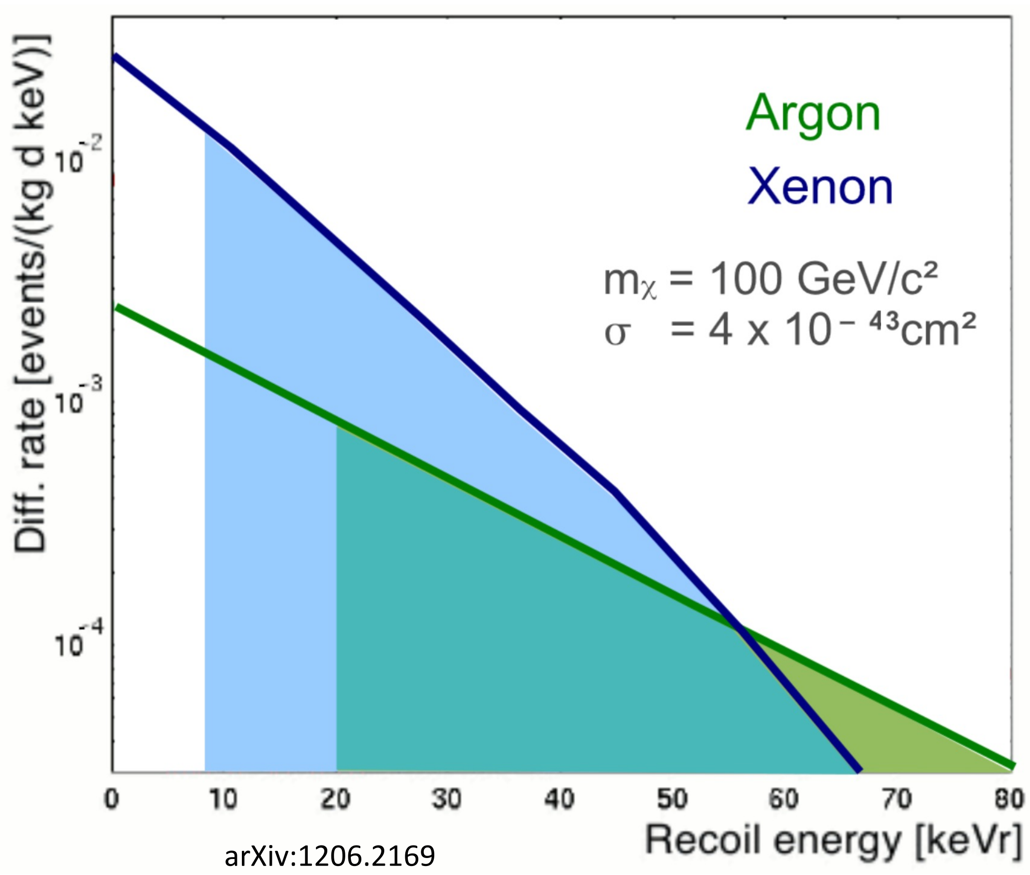
DM properties — Nuclear Form Factor — Astrophysics

$$\frac{dR^{NR}}{dE_R} = \boxed{\sigma_n}\,\boxed{\frac{\rho_\chi}{M_\chi}}\,\boxed{\frac{m_A}{2\mu_{n\chi}^2}A^2}\,\boxed{F_A(q)^2}\,\boxed{\int_{v_{min}(E_R)}^{v_{esc}} d^3v\,\frac{f(v,v_E)}{v}}$$

Cross section — Target



Expected nuclear recoil spectra



DM presents a very small event rate → LAr TPCs conceived for target mass at the kT-scale

DARKSIDE

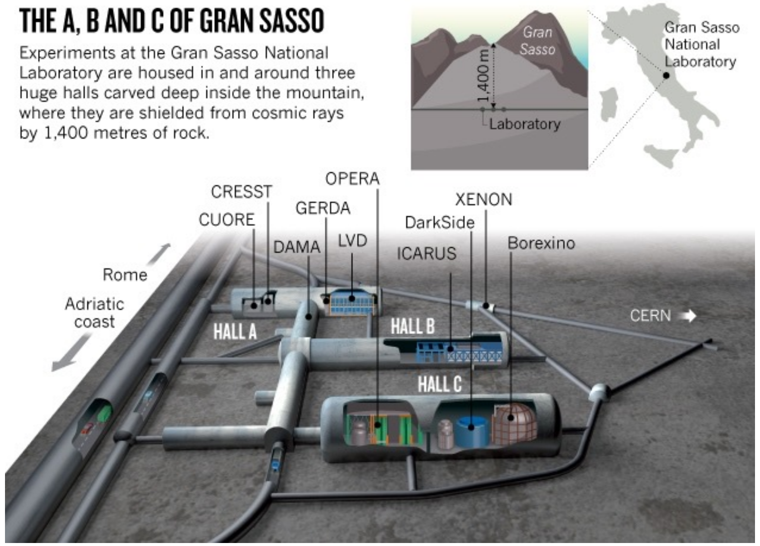
The Global Argon Dark Matter Collaboration

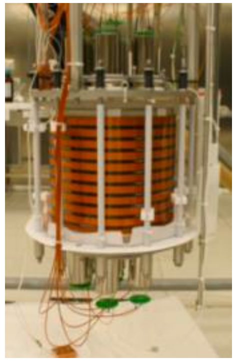
>400 collaborators from **11 countries**, combining the expertise of 4 LAr experiments for direct DM searches

DarkSide-50, DEAP-3600, MiniCLEAN, ArDM

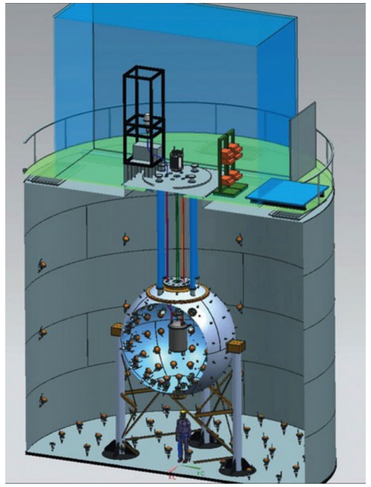
DarkSide-20k:

- LAr dual phase direct detection experiment designed to detect WIMP scattering interactions from the dark matter halo
- Located at LNGS Italy, 1400m underground

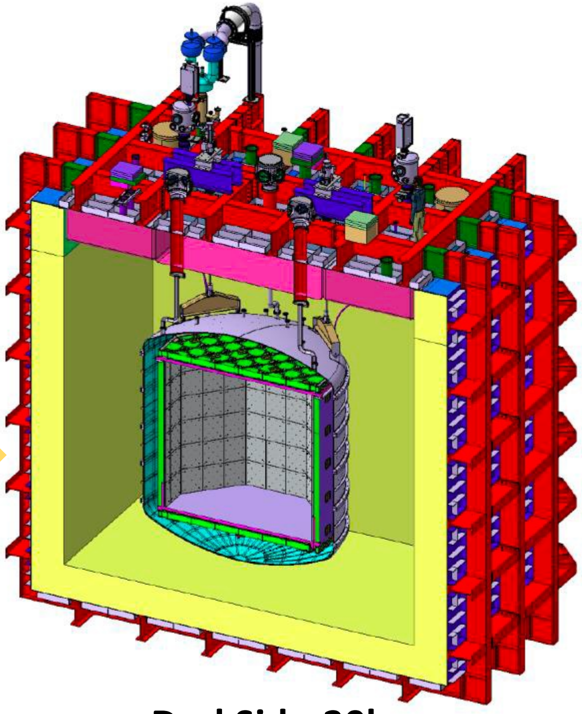




DarkSide-10
2012



DarkSide-50
0.03tyr exposure
2013-2019



DarkSide-20k
460tyr exposure
2026-2036

ARGO
3000tyr exposure
2030s+
High mass focus

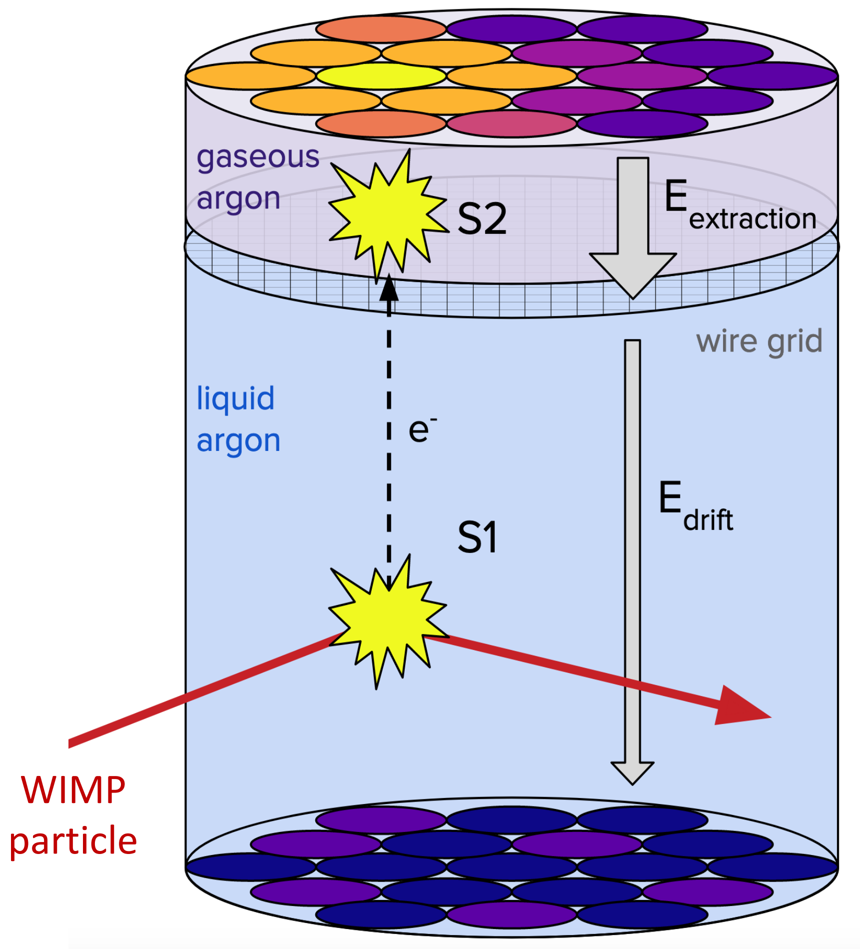
DarkSide-LowMass
1tyr exposure
Low mass focus

DARKSIDE

Dual Phase Time Projection Chamber

<u>WIMP – nucleus scattering</u>

- Single nuclear recoil
- ROI: [30, 200] keV_{nr}



Calorimetry + 3D position

Energy deposition in LAr produces scintillation photons and free electrons

S1: primary scintillation in LAr (energy information and pulse shape discrimination)

S2: secondary scintillation from electroluminescence of electrons in gas pocket (energy information and position reconstruction)

Why Argon?

- ✓ easy to purify, scalable
- ✓ high ionization, good scintillator - transparent to own scintillation
- ✓ strong electron recoil (ER) discrimination via pulse shape (PSD)

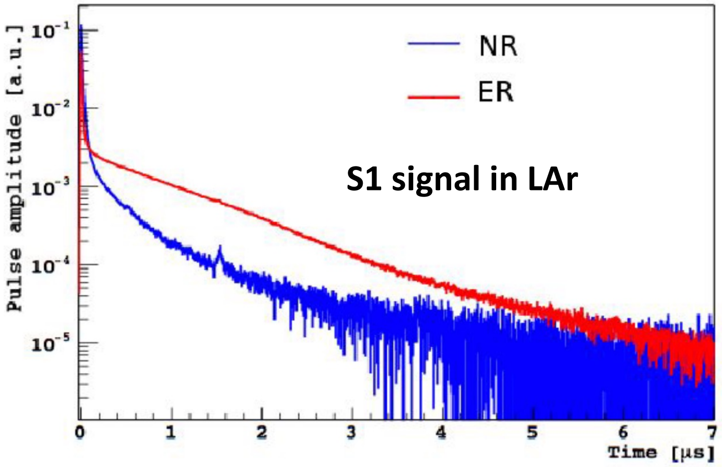
Pulse Shape Discrimination in Liquid Argon

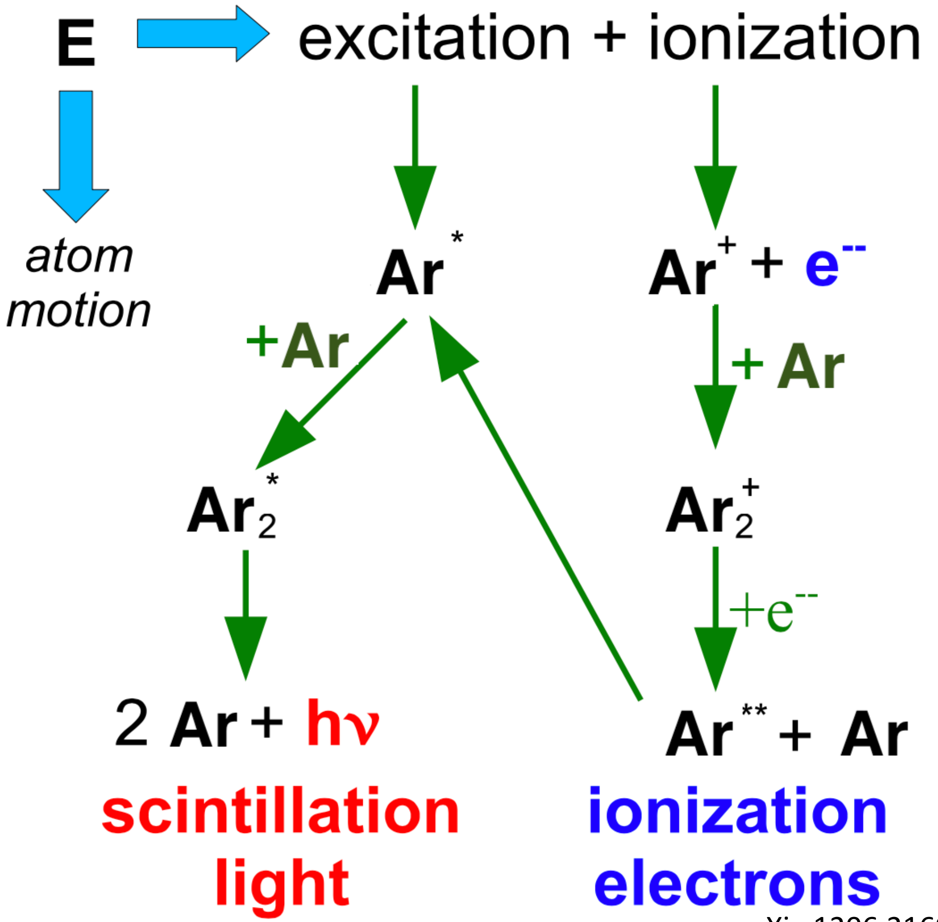
S1: primary scintillation in LAr (energy information and pulse shape discrimination)

2 excited Ar^{2*} states with different lifetimes:

singlet (~7 ns) - triplet (~1.5 µs)

ER/NR events have different ionisation densities → different fractions of singlet/triplet decays.





arXiv:1206.2169

for 10 keV visible energy:

WIMPs,neutron,CEvNS
- N_{ex}/N_i ~ 1
- N_{fast}/N_{slow} ~ 1

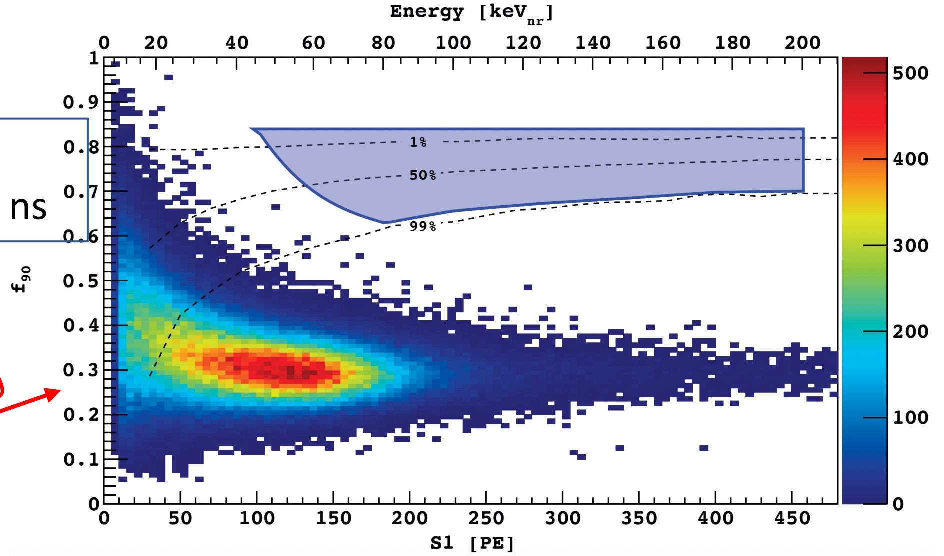
γ, β, low mass WIMPs, neutrinos
- N_{ex}/N_i ~ 0.21
- N_{fast}/N_{slow} ~ 0.4

Electron recoil background discrimination in LAr

Produced by gamma, e⁻:

- U-238 & Th-232 decay chain: principally from Rn-222
- Ar-39 β-decay (reduced with UAr)
- Kr-85 β-decay
- Solar neutrino

f90: fraction of the primary scintillation pulse in its first 90 ns

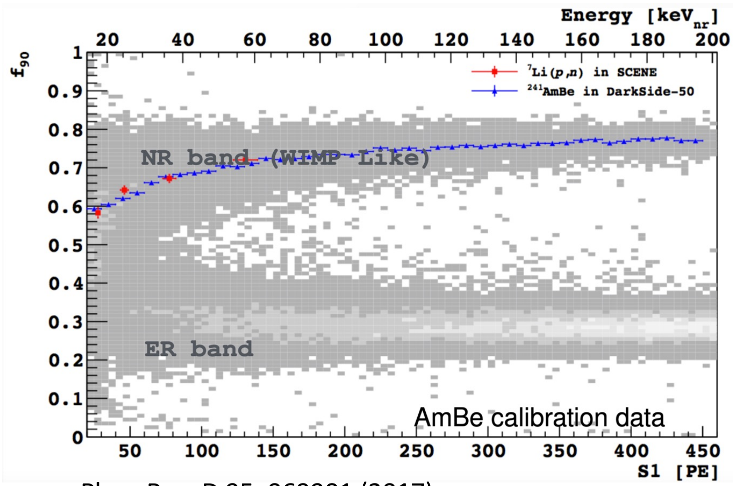


Phys.Rev.D 98 (2018) 10, 102006

DarkSide-50

Electronic recoils are rejected by Pulse Shape Discrimination, demonstrated by DS-50 & DEAP, enabling background free DM searches

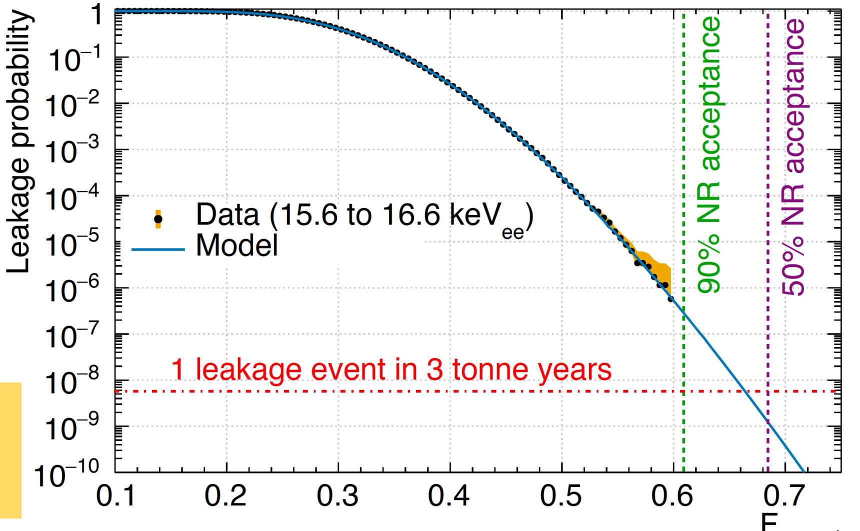
DEAP



Phys. Rev. D 95, 069901 (2017)

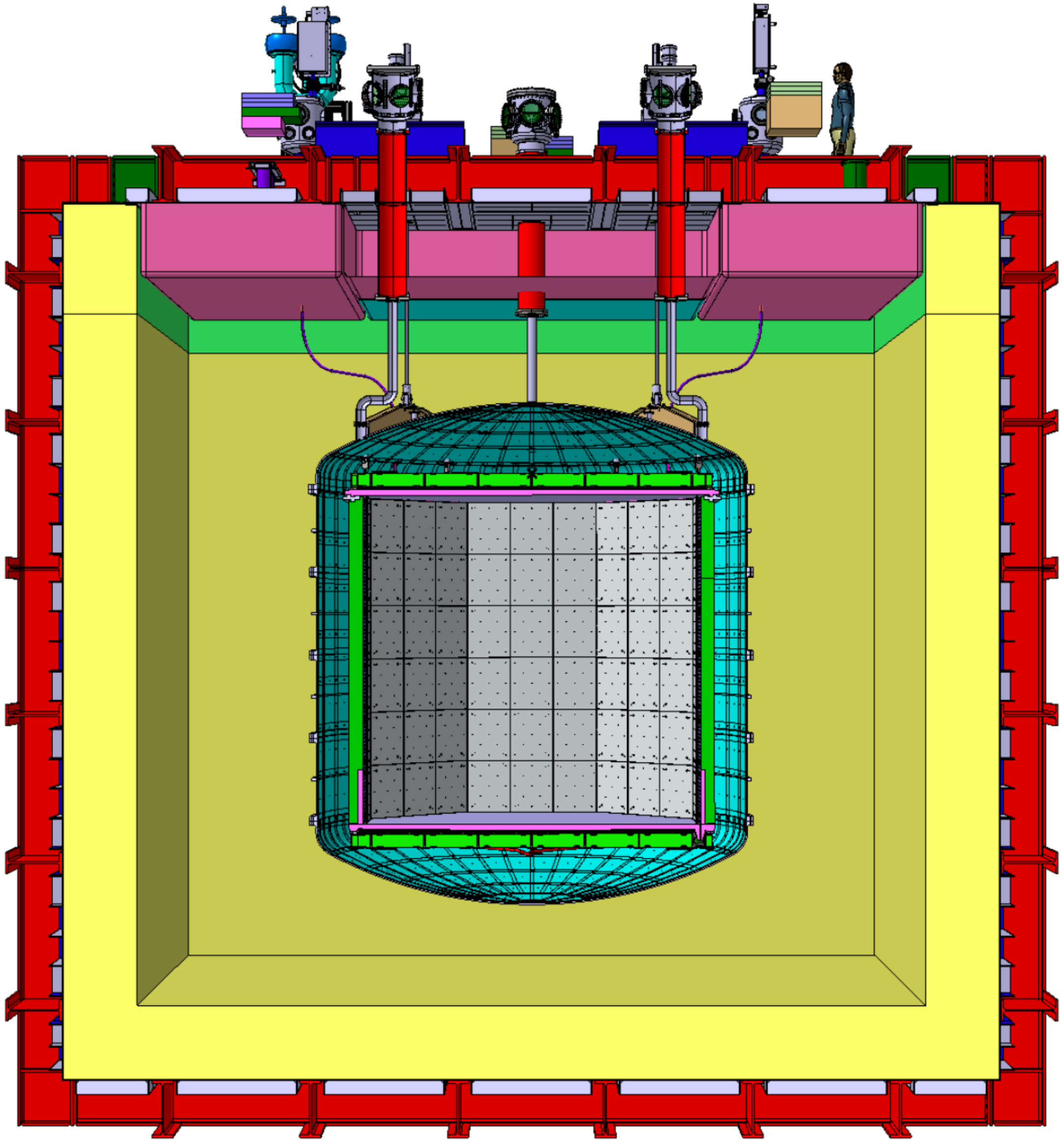
$$F_{prompt} = \frac{\text{Prompt Light}}{\text{Prompt + Late light}}$$

ER background rejection of 2.4×10^{-8} for 44-89 keV$_{ee}$ energy range



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

DarkSide-20k overview



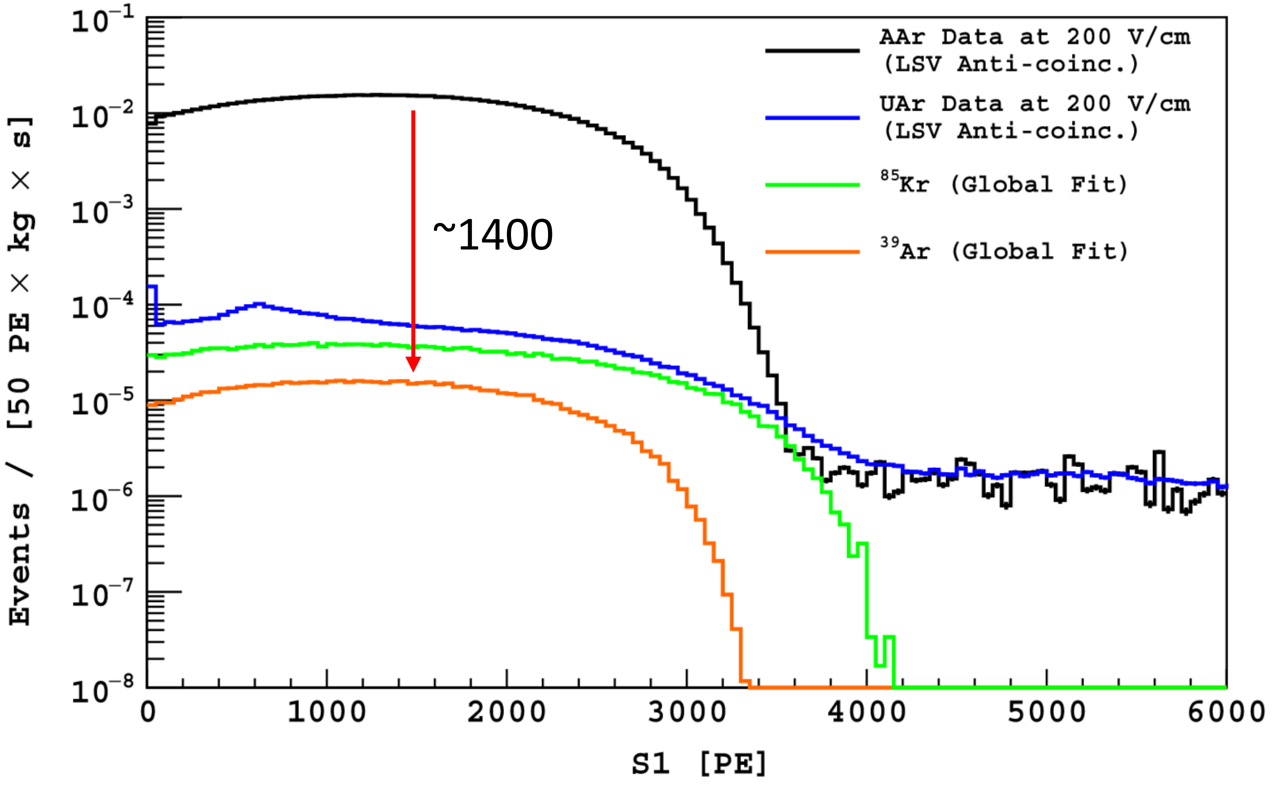
- Time Projection Chamber (TPC) filled with 49.7 t (active) of underground Ar (UAr)
- TPC circumscribed by acrylic panels loaded with gadolinium (Gd-PMMA)
- Neutron veto buffer between TPC and stainless-steel vessel, filled with 32 t (active) UAr
- Stainless-steel Vessel contains UAr (99.2 t)
- Outer cosmic veto filled with 700 t atmospheric Ar (AAr) –shield for muons and their shower products

DARKSIDE

Underground Argon

- ➢ Atmospheric argon (AAr) contains ^{39}Ar, a cosmogenic activated isotope
  - Beta emitter with endpoint to 565 keV and half life of 269 years.
  - Activity: ~ 1 Bq/kg.

- ➢ **TPC and veto are filled with UAr in order to reduce ^{39}Ar**



Phys. Rev. D 93, 081101(R) (2016)

^{39}Ar depletion factor: 1400±200

Total background from UAr:

- ➢ **TPC= 50 tons -> 36 Hz of ^{39}Ar**
- ➢ **Veto = 35 tons -> 26 Hz of ^{39}Ar**

Mitigated with pulse shape discrimination:

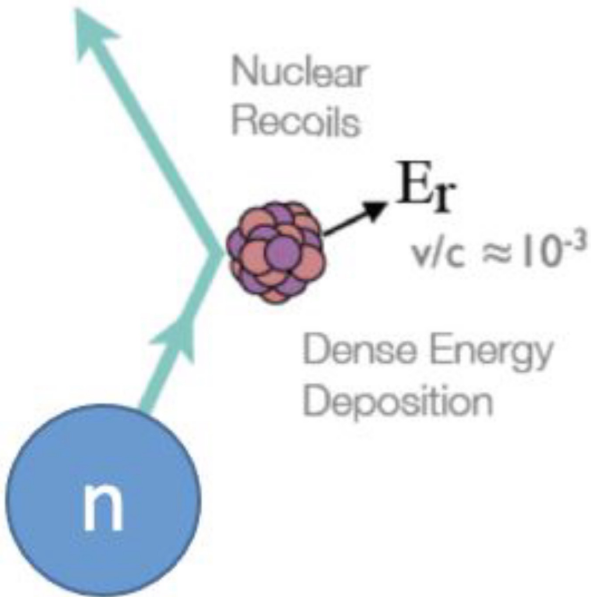
- ✓ Residual background is < 0.01 events/ 200 tonne x year
- ✓ Dead time negligible

Nuclear recoil background

Produced by neutrons, alphas:

- Ur-238 and Th-232 contamination of detector material
- Cosmogenic interactions due cosmic ray (α,n) reaction in the detector material
- Spontaneous fission decay

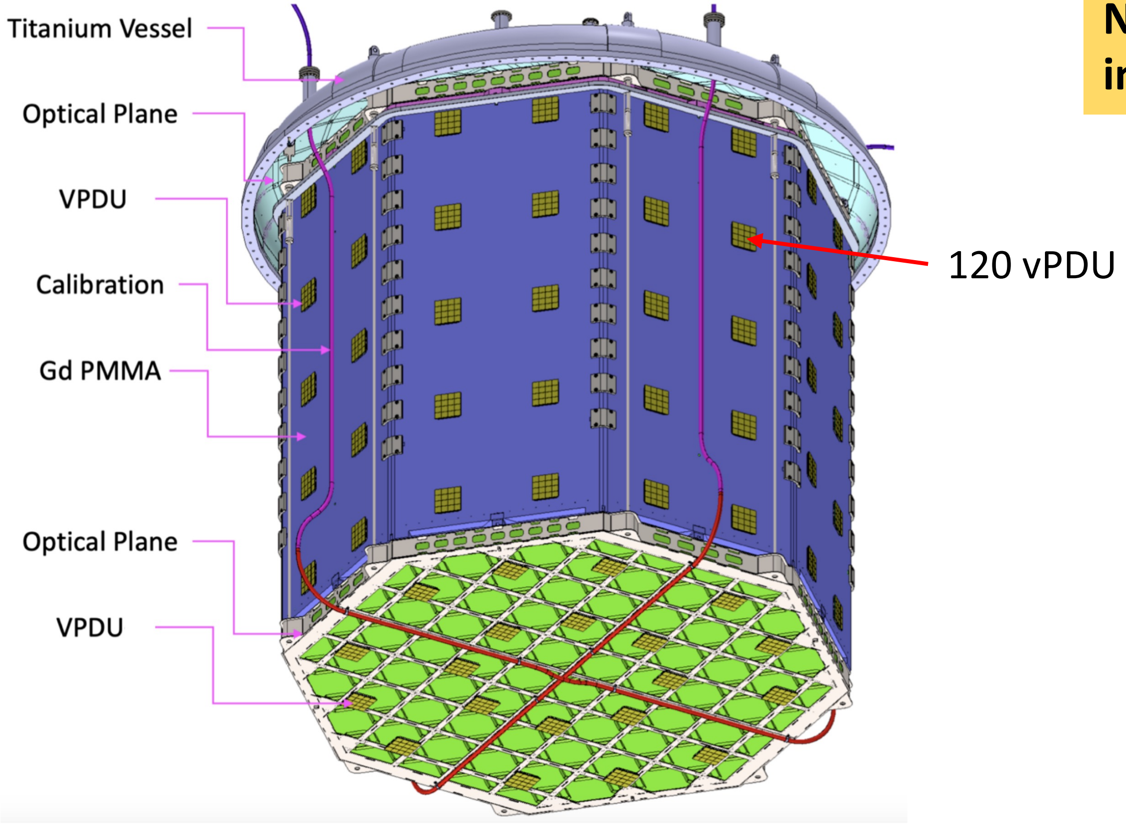
Same recoil as WIMP!!!



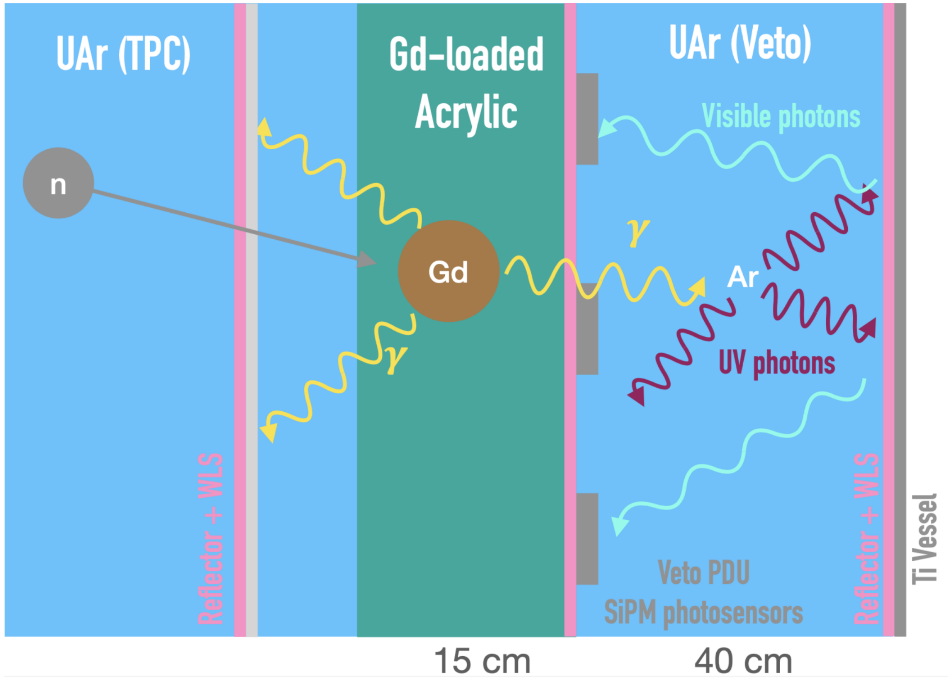
Nuclear recoil reduction:

- Stringent material selection & radiopurity control
- Cut on multiple scatters event
- **Neutron veto:** cut on veto and TPC coincident interactions (within 800μs)

Neutron veto



Neutrons elastically scattering from argon nuclei are **indistinguishable** from **WIMPs**.



- 40 cm thick space between the stainless-steel vessel and Gd-PMMA
- 8 walls made from 15 cm thick Gd-PMMA (1% - 99%)
- ESR reflector with PEN WLS foils on all the surfaces (174 m^2)

- Neutrons are moderated in the PMMA and captured by Gd
- Gd emits multiple γ with energy up to 8 MeV (light yield =2 p.e./keV)
- UAr scintillation light is shifted and detected in both TPC and Veto

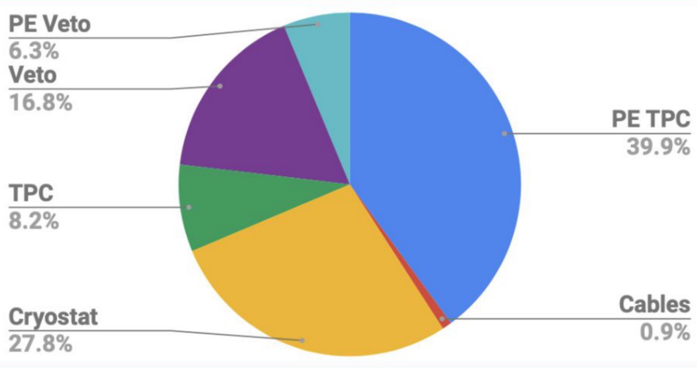
suppression of the dangerous radiogenic neutrons background ≈0.1 n/200 ty from (a,n) reactions

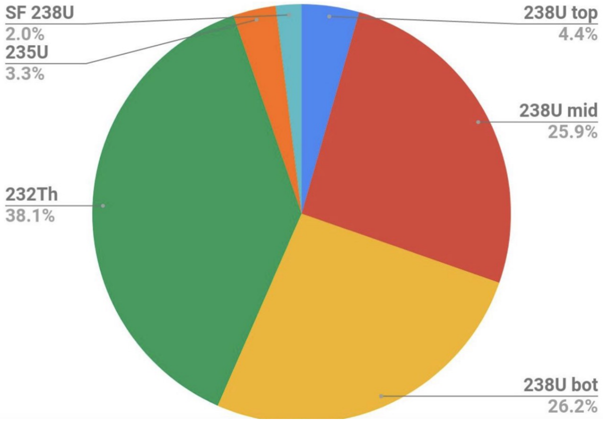
Material selection and radiopurity control

0.1 events after all cuts in a **full exposure** of **200ty**

Assay all materials of the detector

- 3 different techniques: ICP-MS, HPGe, ^{210}Po extraction for Upper, Middle and Lower ^{238}U chain
- 4 underground laboratories (Boulby, LNGS, LSC, SNOLAB)
- **PE** & **cryostat** dominant contribution to background





Full characterization and calculation of the materials background

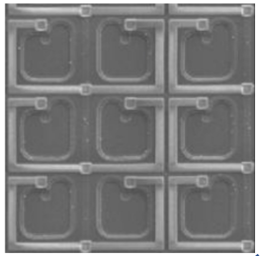
- Control of the cosmogenic activation of materials
- Control of the surface contamination
- Evaluation of the radioactive budget of the experiment including activation UG
- Evaluation of the systematic uncertainty from the material composition
- New MC tools for (α, n) calculations

DarkSide-20k is the first experiment with the (α,n) neutron background fully calculated with Geant4

Nucl. Instrum. Methods A 960, 163659 (2020)
Astropart. Phys. 152, 102878 (2023)

Large area cryogenic SiPM light detectors

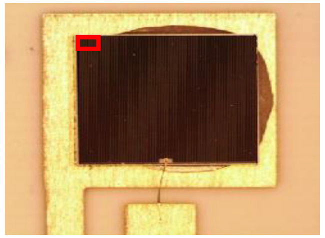
SPAD: Single photon avalanche diode



~25-30 μm^2

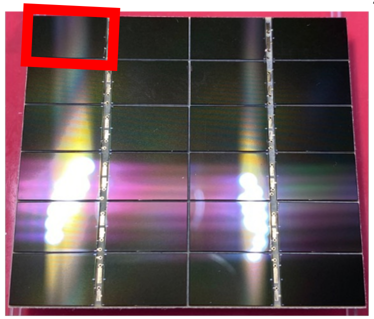
SPADs - **S**ingle **P**hoton **A**valanche **D**iodes: semiconductor devices based on a p-n junction reverse biased well above breakdown voltage (operating in Geiger mode).

SiPM



~ 1 cm^2
94.900 SPADs

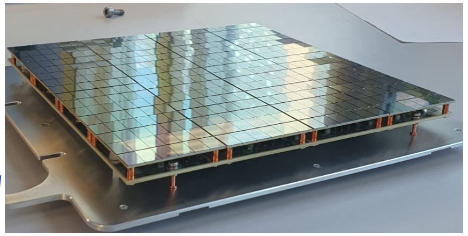
PDM
(Photo Detection Module)



5 x 5 cm^2
24 SiPMs

4 PDMs are summed and read as a single channel
(largest single SiPM unit ever!)

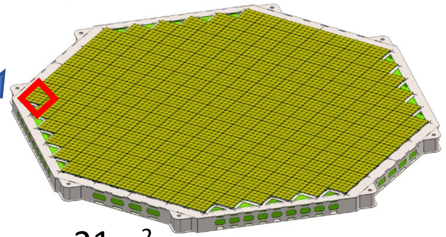
PDU
(Photo Detection Unit)



20 x 20 cm^2
PDU of 16 PDMs

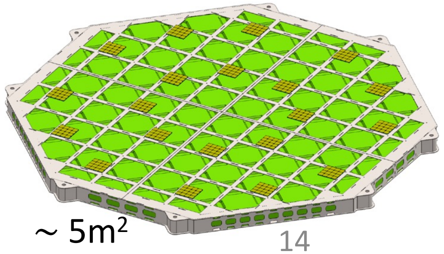
- Mass production of the raw wafers at LFoundry (Italy)
- TPC assembling facility NOA at LNGS
- Veto assembling facility in UK
- Testing facilities in Italy, UK and Poland

TPC optical plane



~ 21m^2
528 PDUs

Backside of optical plane

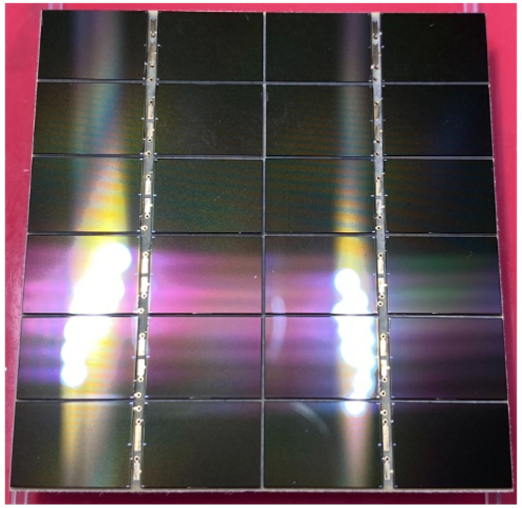


~ 5m^2
120 PDUs

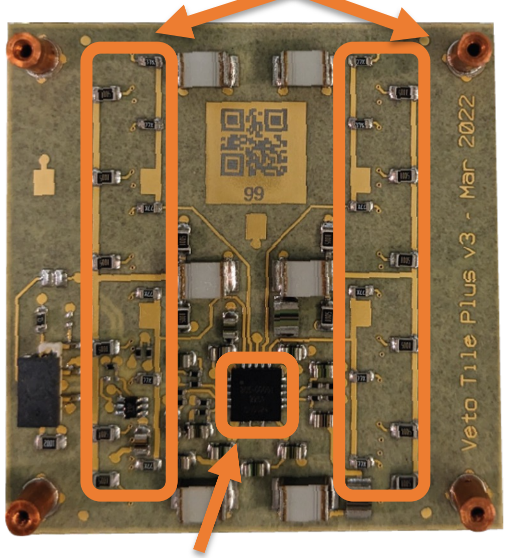
- High **PDE** (~45%) >90% fill factor
- **Gain** ~ 10^6
- **SNR** > 8
- Dark Count rate at 87 K < 5 cps/PDM
- Time **resolution** (sigma) ~10 ns
- **Low power** consumption < 100 μW/mm^2
- **Radiopure:** >10x lower radioactivity/cm^2 than PMTs

Neutron veto SiPM and readout electronics

Construction and QA/QC in UK institutes

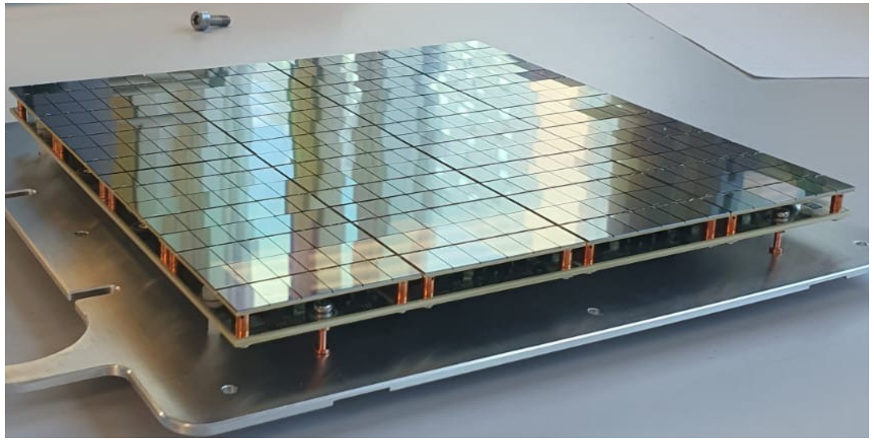


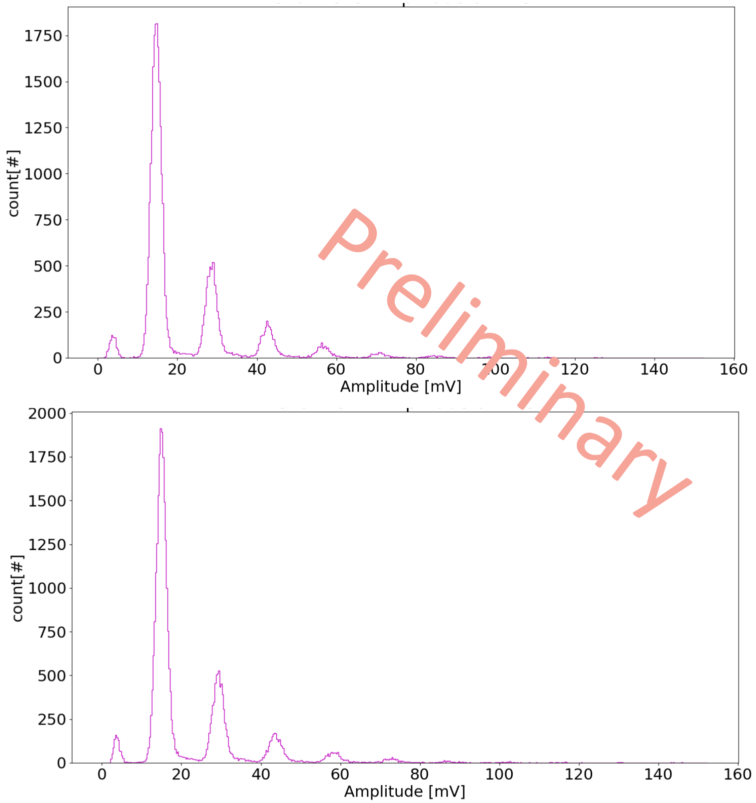
Resistors connected to the SiPMs



ASIC

First complete production quality PDU just tested



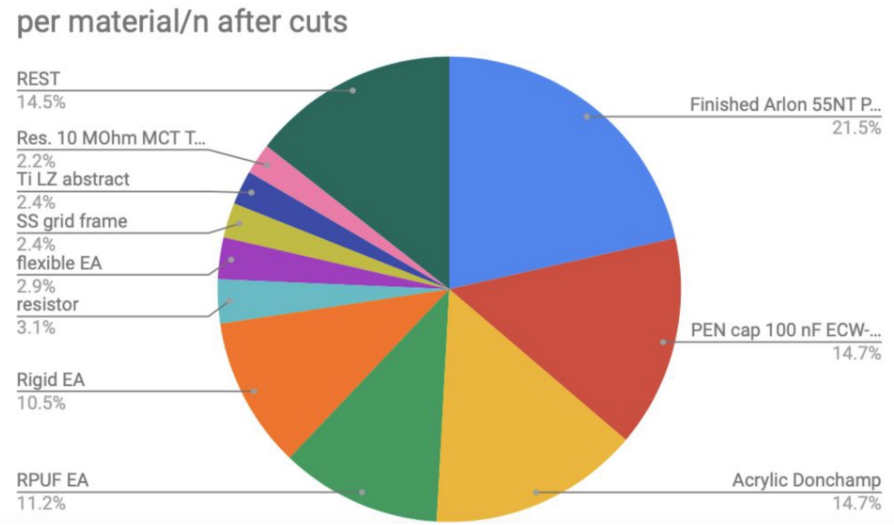


A.M. Szelc, A. Hamer, D. Santone, M. Spangenberg & M.L. Velázquez Fernández

Photoelectronic readout radio assay results

Full readout unit vs. sum of parts validation

- ✓ validates assembly process
- ✓ Preserves radiopurity of raw components



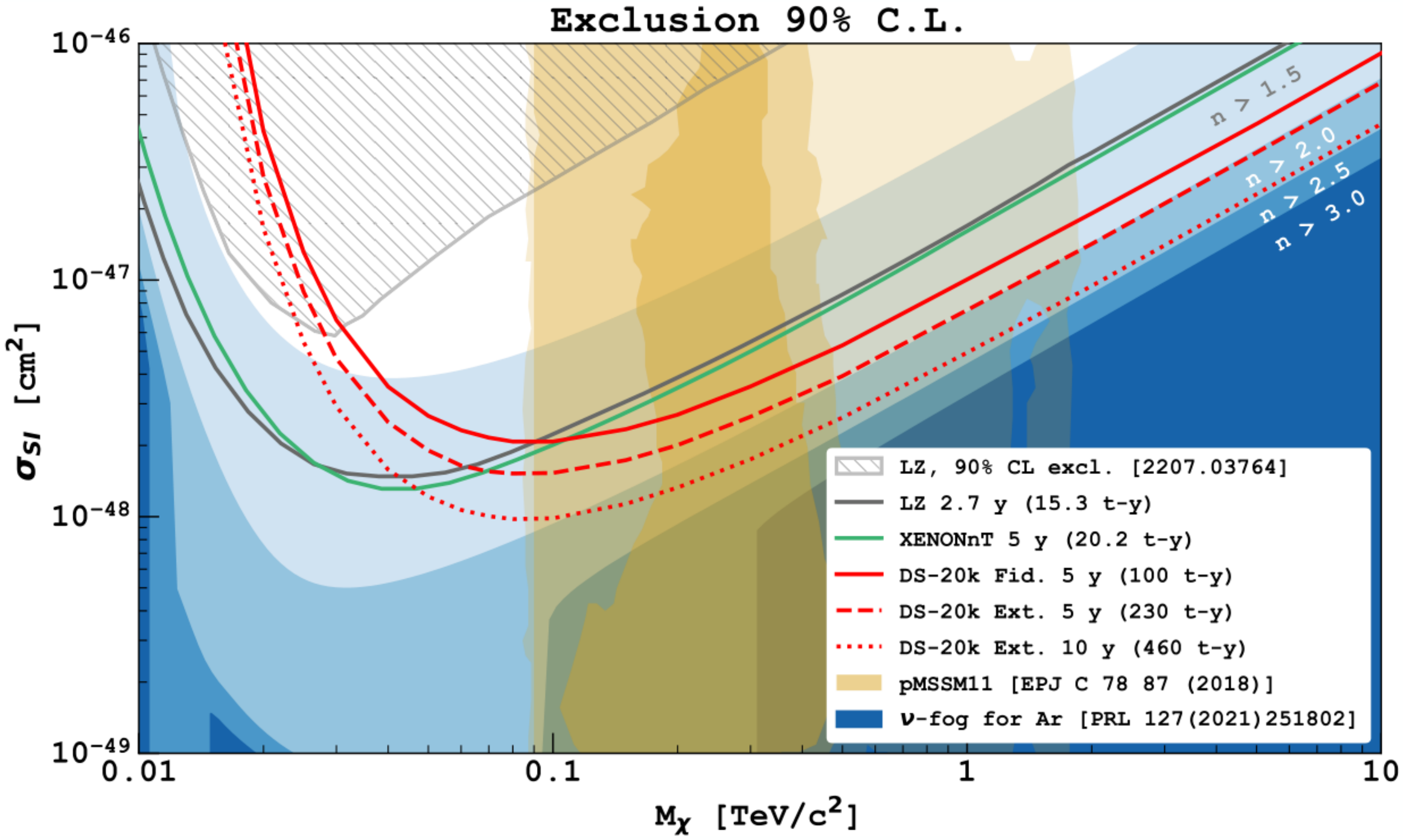
background activity contribution from **all** the veto photoelectronics

	From summing [Bq]	From assay [Bq]
Uup	2.2E+00	2.3E+00
Umid	1.2E+00	1.3E+00
Ulow	5.8E+01	**8.4E+01**
Th232	1.3E+00	1.1E+00
Ur-235	1.6E-01	1.1E-01
K40	1.4E+01	1.3E+01
Cs-137	1.6E-01	-
Co-60	1.5E-01	-

DARKSIDE

DarkSide-20k WIMP sensitivity

The sensitivity of DS-20k to spin independent WIMPs for different lengths of runs, with the full exposure and with the fiducial cuts applied, compared to LZ and XENONnT.



- ✓ Upper limits for a 1 TeV/c^2 WIMP (90% C.L. exclusion) of 6.3 x 10^{-48} cm^2
- ✓ First measurement of the neutrino "fog" for n > 1.5
- ✓ Expected 3.2 neutrinos in 200 t-y

DarkSide-50 demonstrated sensitivity on light-DM
Phys. Rev. Lett. 130 (2023)101002
Phys. Rev. D 107 (2023) 063001
Phys. Rev. Lett. 130 (2023) 101001

For more details:
talk by **P. Agnes**
22/8 @08:30 (T03 Dark Matter)

Direct application to DarkSide-20k

Underground construction of the detector has launched!!!

DarkSide-20k summer collaboration meeting at the Gran Sasso National Laboratory (LNGS), Italy, 12-15 June 2023

DarkSide-20k

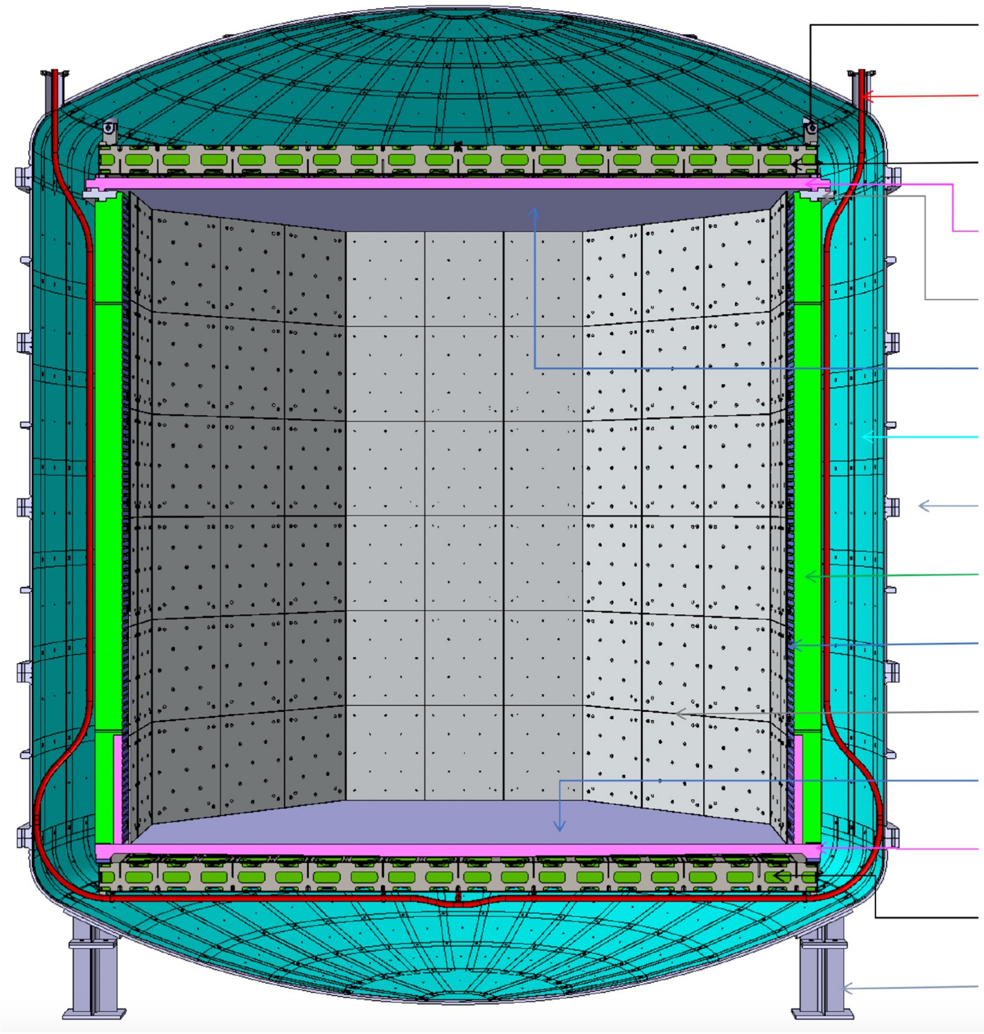
- Instrumental background-free Dark Matter search thanks to radiopure materials, UAr, and novel neutron veto
- construction of the DarkSide-20k cryostat started, operation from 2026

DARKSIDE

Thank you for your attention!!!

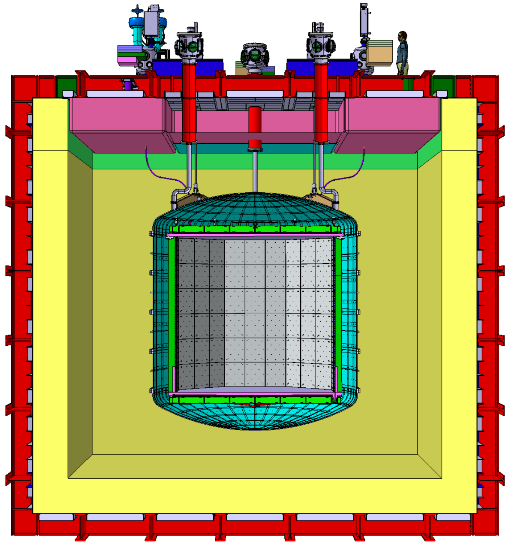
Back up slides

DarkSide-20k: Inner detector



- Octagonal TPC: inscribed diameter 350 cm
- Drift length: 348 cm
- Electron drift lifetime < 5 ms
- Drift field: 200 V/cm
- TPC anode/cathode: transparent pure acrylic coated with Clevios + TPB wavelength shifter (WLS).
- TPB WLS in all TPC inner surfaces
- TPC lateral walls: grooves with Clevios for field shaping (no copper ring)
- Reflector + PEN (WLS) on outer TPC wall and Ti vessel enclosing veto
- Light yield in TPC: >10 pe/keV$_{ee}$ (S1), > 20 pe/e$^-$ (S2)

Underground Argon



URANIA: UAr extraction

- CO_2 well in Cortez, CO, USA
- Industrial scale extraction plant
- UAr extraction rate: 250-330 kg/day
- Purity 99.99%

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

Eur.Phys.J.C 81 (2021) 4, 359

DArT : UAr measurement

- Located at LCS, Canfranc, Spain
- Double phase TPC with active volume of 1.4 kg of liquid UAr
- Ar-39 sensitivity:U.L 90% CL. for 6×10^4 depletion factor

JINST 15, P02024 (2020)

ARIA, Seruci mine in Sardinia