Direct Detection of Dark Matter with DarkSide-20k

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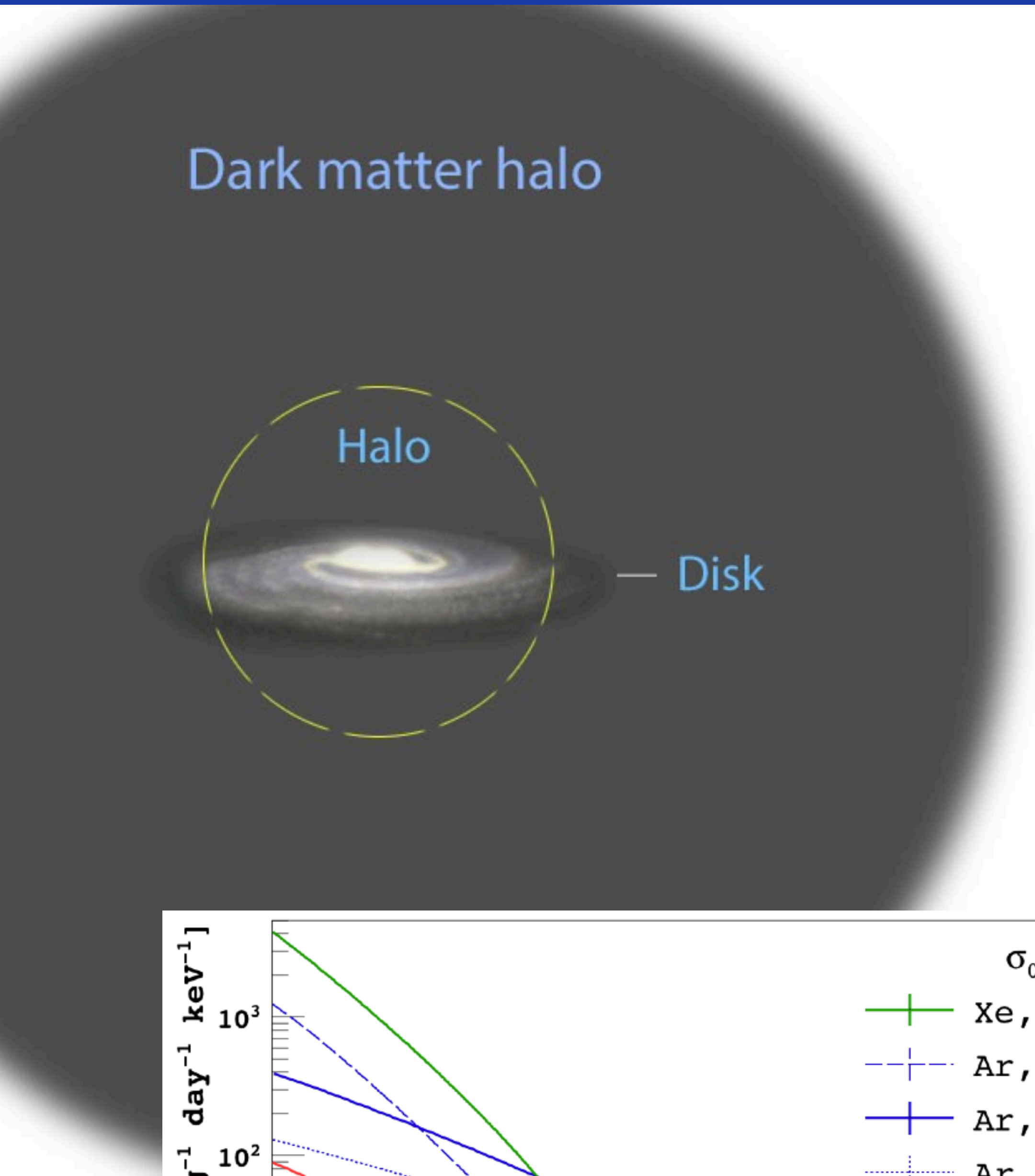
RICAP 2022

Rome, 7th Sept 2022

Expected rate in direct detection



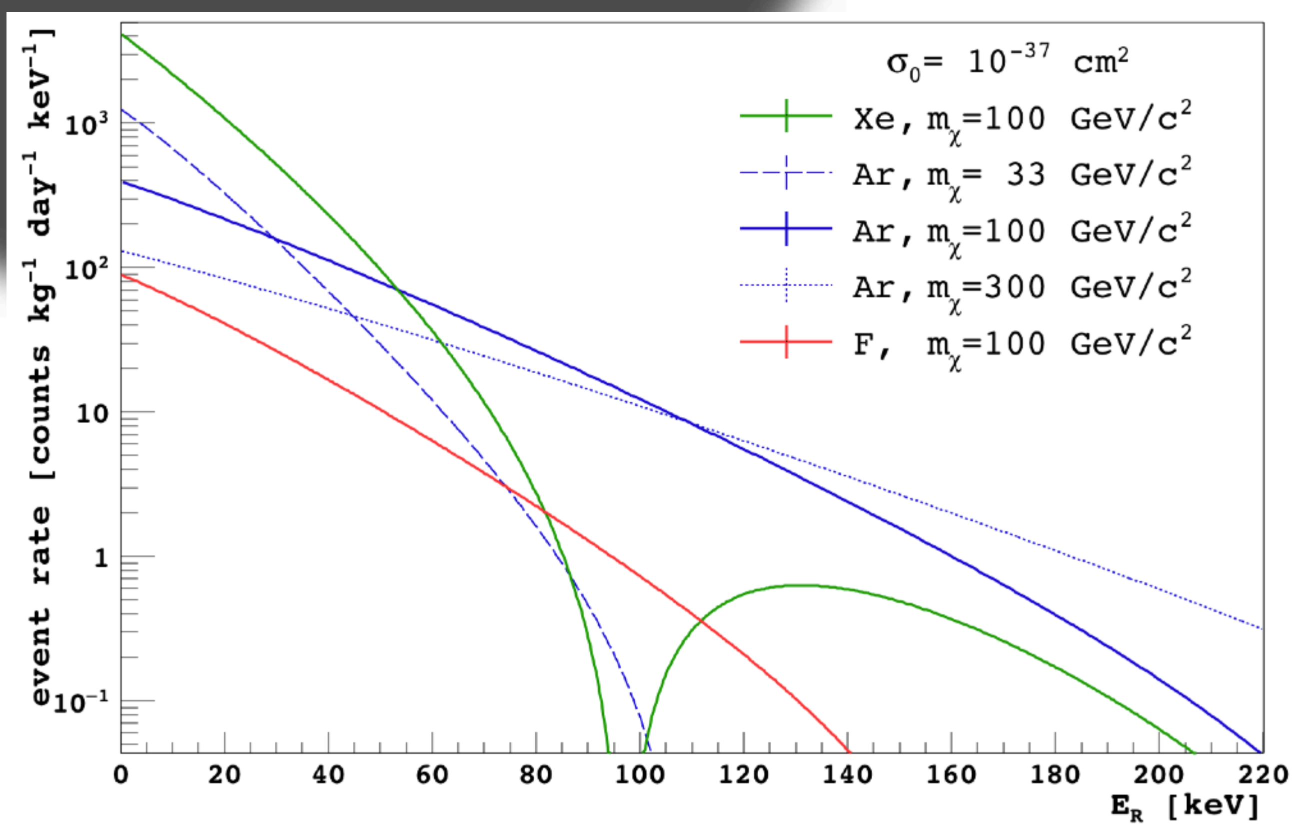
Dark Matter particles:
- are massive
- are stable
- non relativistic
- interact gravitationally
- electromagnetically neutral

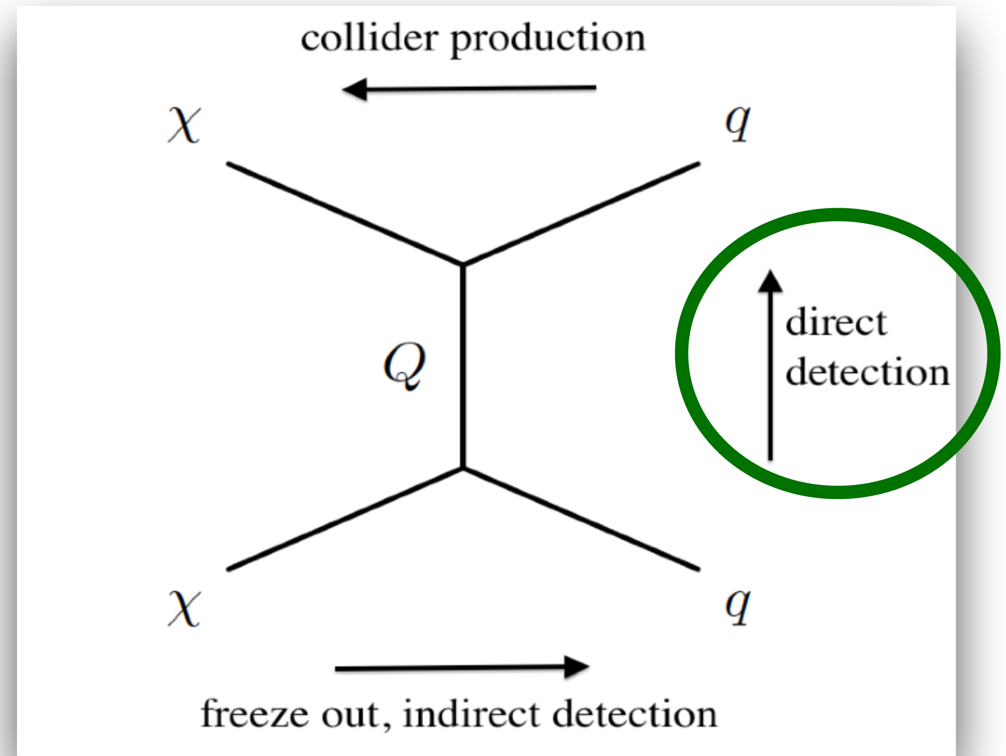
WIMP:
Weakly Interacting Massive Particle

Cross section — Nuclear Form Factor — Astrophysics

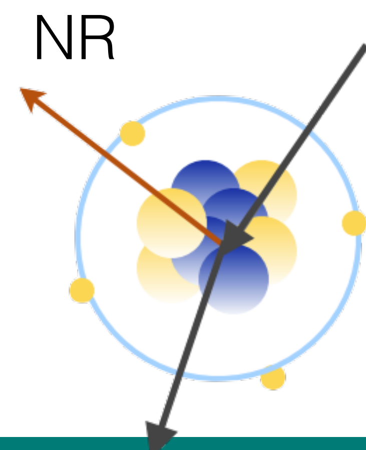
$$\frac{dR^{NR}}{dE_R} = \sigma_n \frac{\rho_\chi}{M_\chi} \frac{m_A}{2\mu_{n\chi}^2} A^2 F_A(q)^2 \int_{v_{min}(E_R)}^{v_{esc}} d^3v \frac{f(v, v_E)}{v}$$

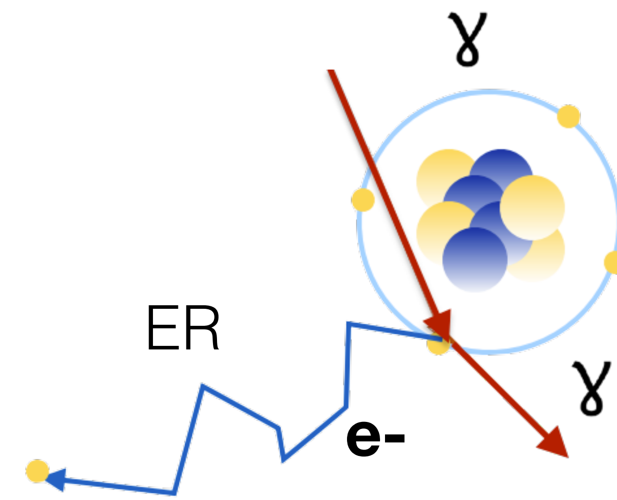
Dark Matter Properties — Target





Noble liquids





- Low energy threshold
(E < 100 keV)

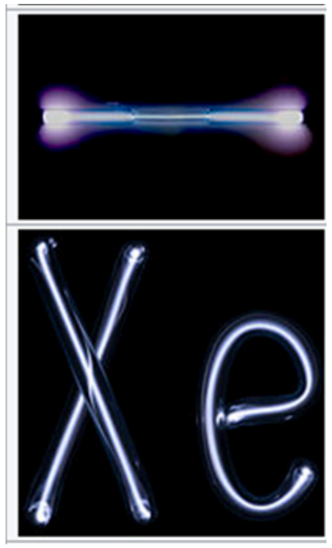
- Large mass
(~ 1 event/tonne/yr @ 10-47 cm2 in noble liquids)

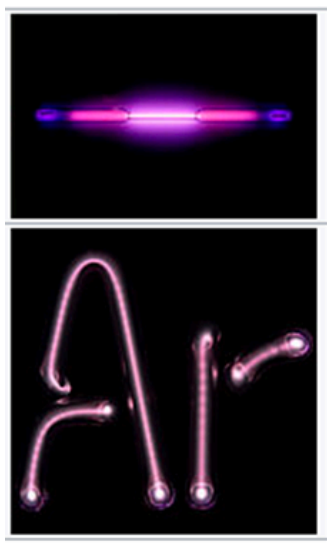
- Background suppression
Deep underground
Passive/active shielding
Low intrinsic radioactivity
ER background discrimination
…

NR backgrounds	ER backgrounds
radiogenic and cosmogenic neutrons α's, ν's	internal and external β's, γ's

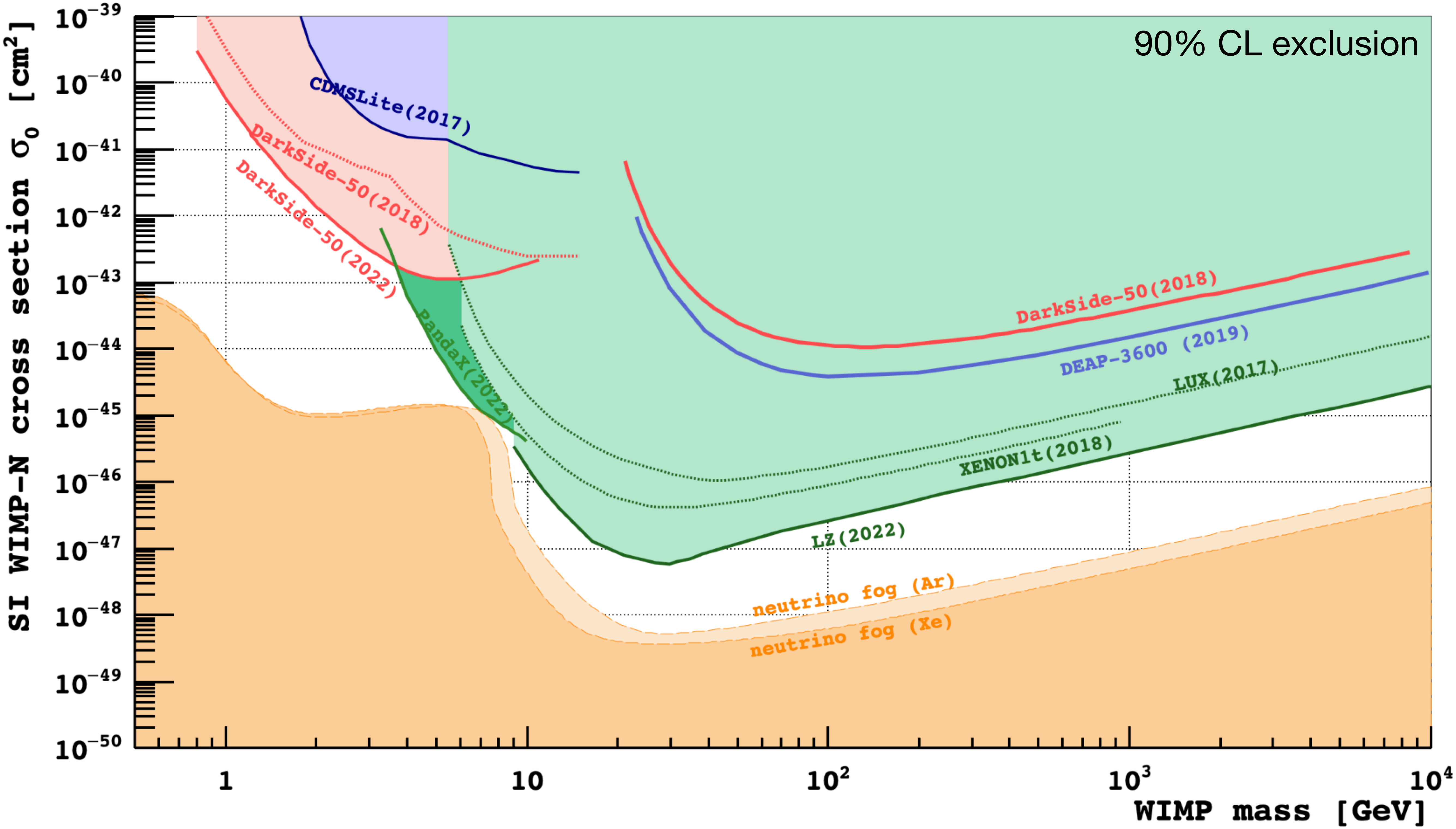
Noble liquids are suitable targets:
☑ scalable, easy to purify
☑ large ionization/scintillation yields (W~10 eV)
☑ ER recoil background discrimination

Complementarity: great value in case of an excess





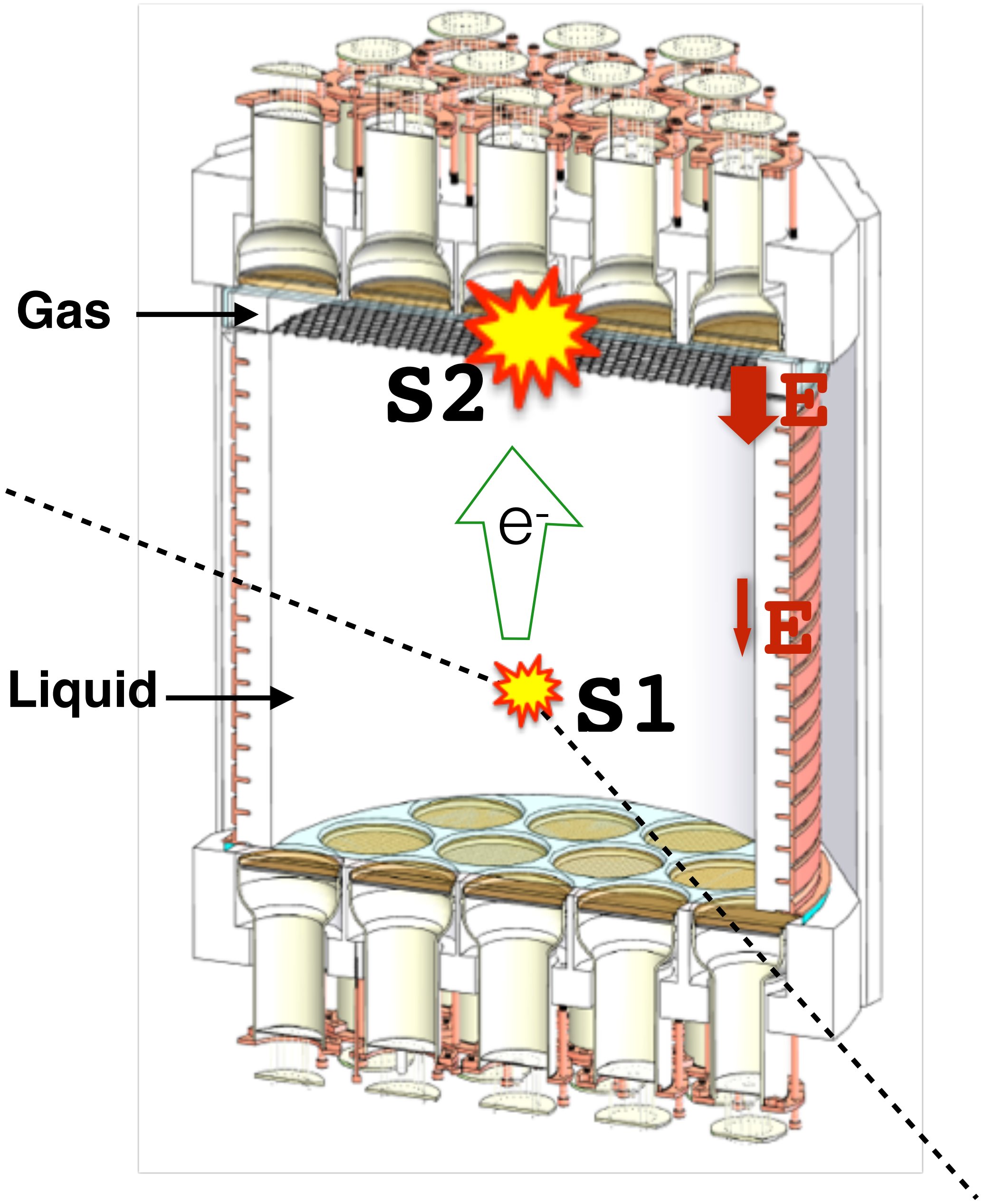
Direct detection of dark matter (SI)



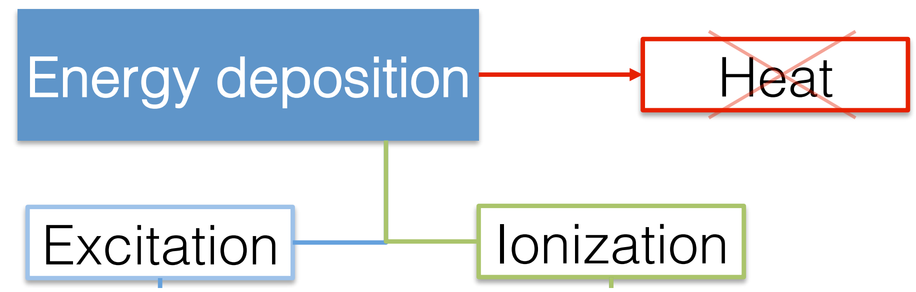
Noble liquids leading searches both at high- and low-mass

Potential of LAr in low-mass WIMP region

Dual-phase TPCs — DarkSide-50



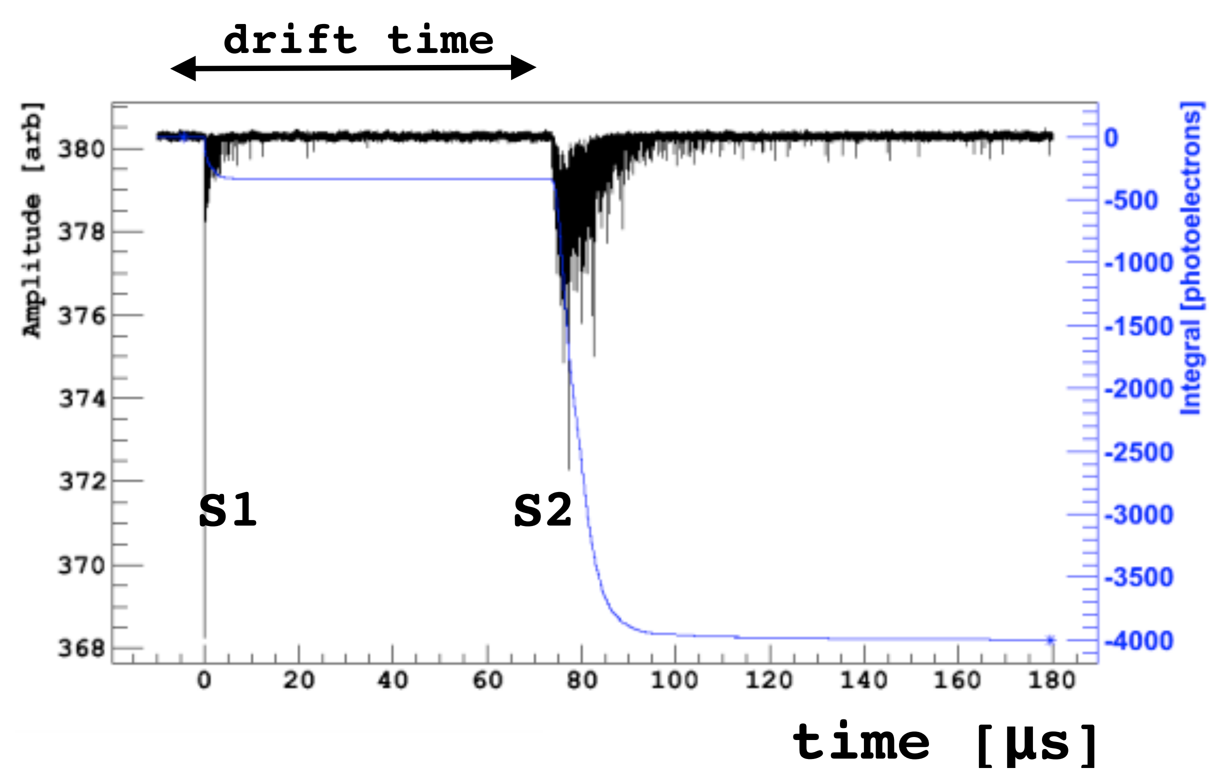
==> 3D vertex reconstruction
(surface events, multi-sited events) !



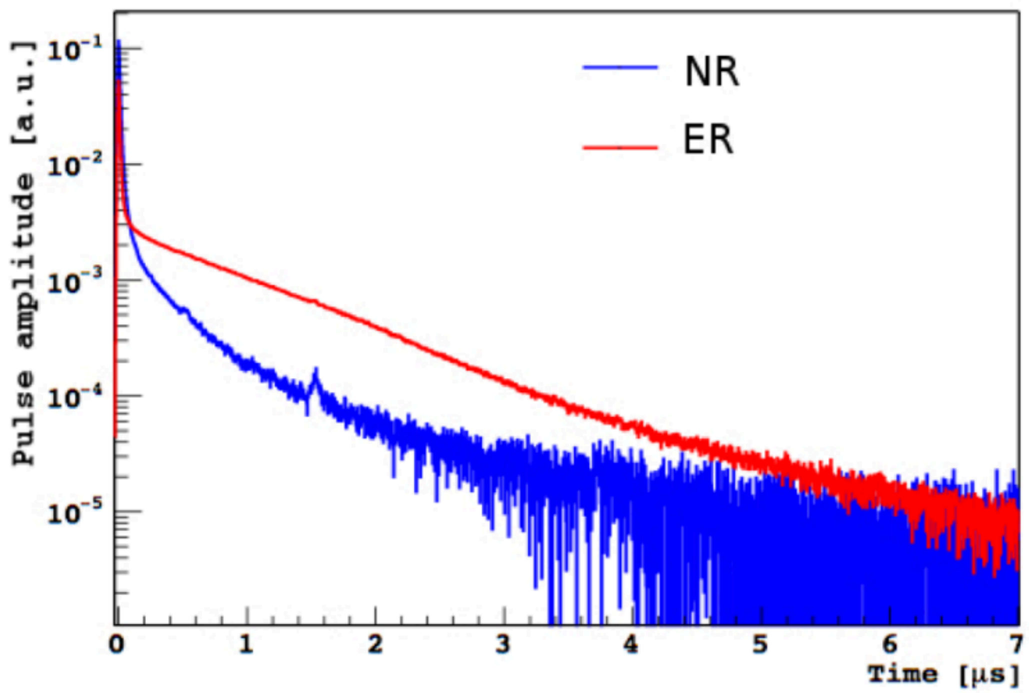
S1 and S2 Yields:

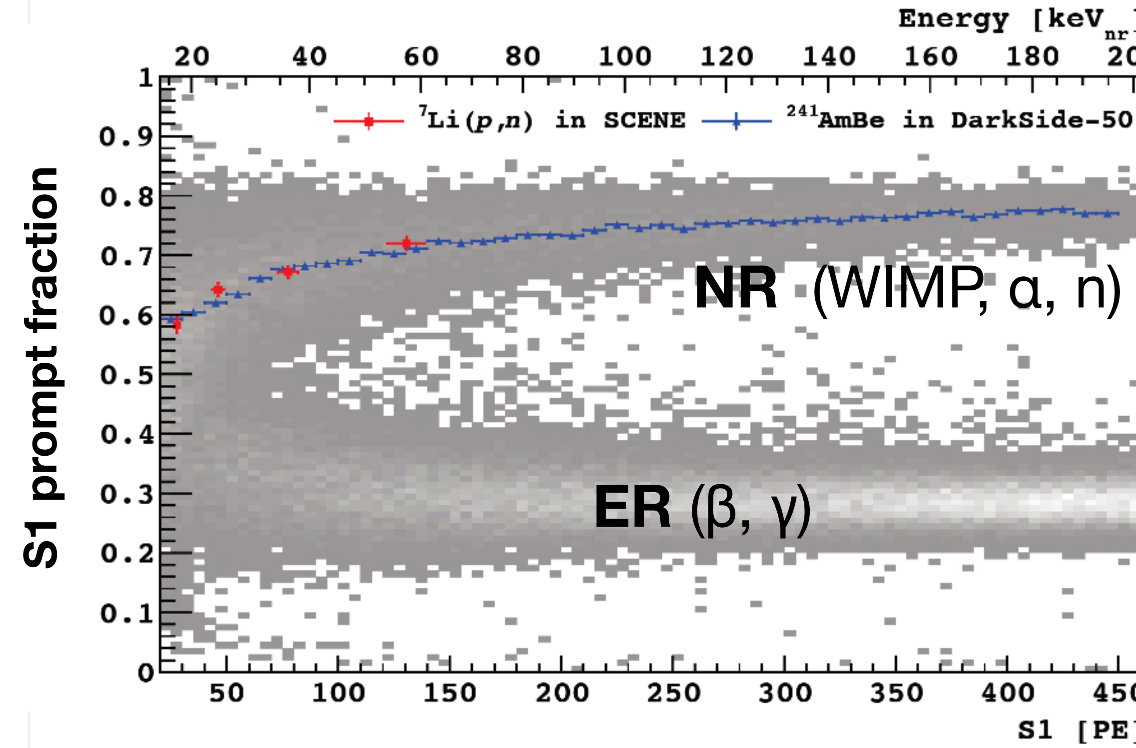
- S1 Yield ~7.9 pe/keV at null field
- S1 Yield **~7.0 pe/keV** at 200 V/cm
- S2 yield **~23 pe / e-**

Electron lifetime > 5 ms
Maximum drift time: 376 μs



Pulse Shape Discrimination in Liquid Argon

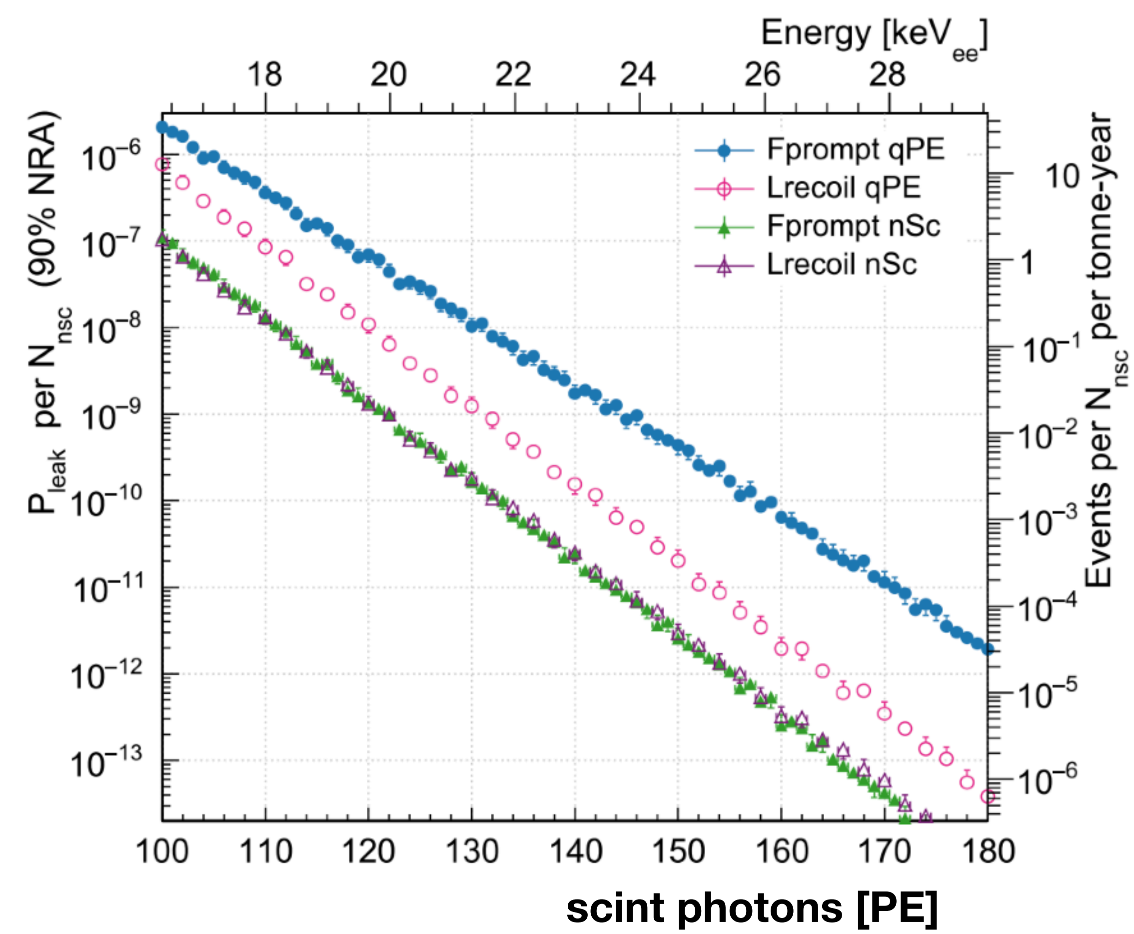




Liquid argon scintillation:
~ 40-50 γ (128 nm) per keV deposited
DEAP: 6.5 PE / keV_{ee}
DarkSide-50: 7.9 PE / keV_{ee}

Excited dimers decay with two decay constants,
τ_{fast} ~ 6 ns and τ_{slow} ~ 1.6 μs

ER and NR excite fast and slow in different proportion



==> ER Rejection factor: ~ 10^8 in LAr

DEAP-3600: Eur. Phys. J. C 81,823 (2021)

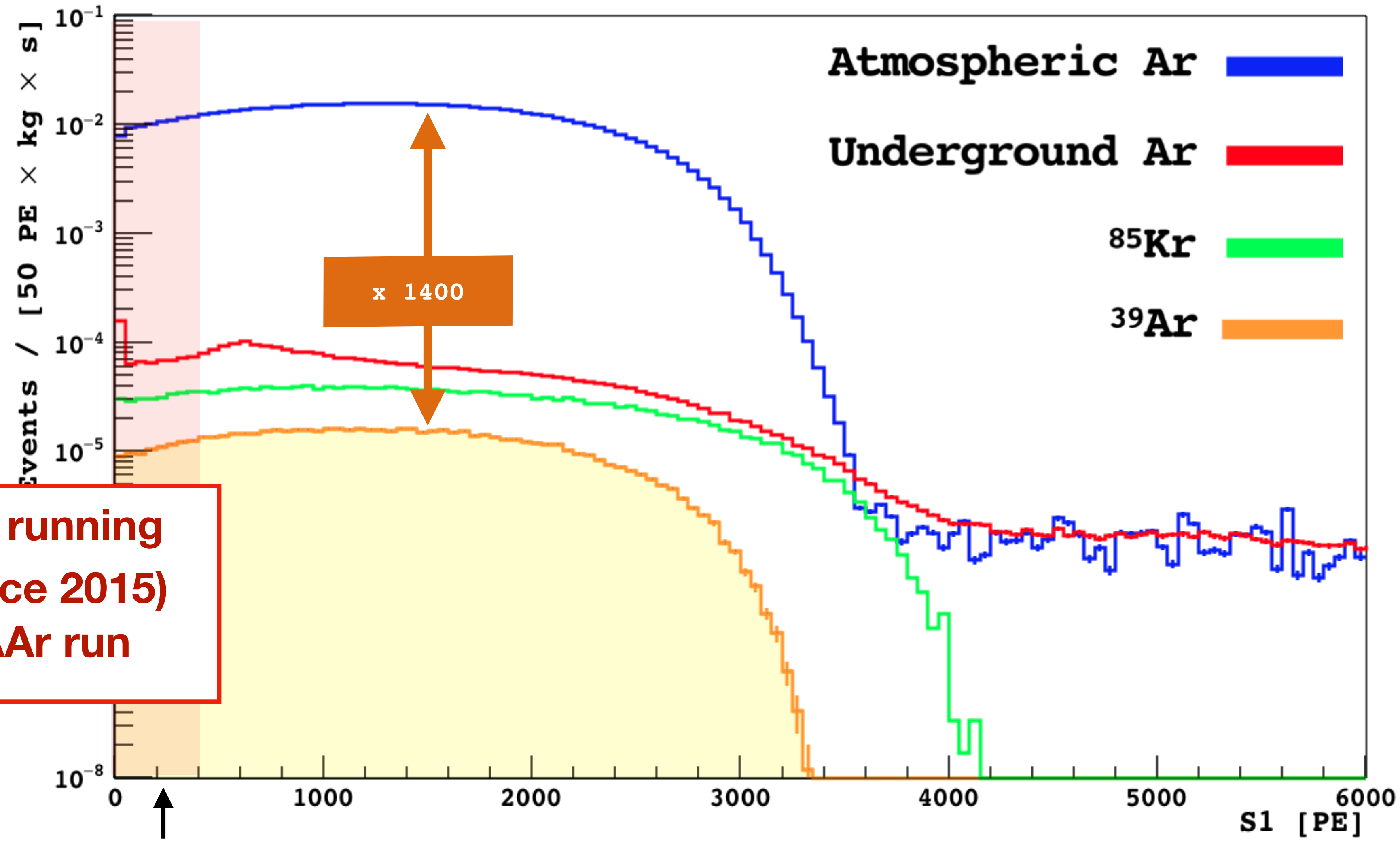
Argon from underground

^{39}**Ar** is produced by cosmic rays in the atmosphere. **β-decay** with **Q = 565 keV**; $\tau_{1/2}$ = 269 yr

- **^{39}Ar activity in atmospheric argon** (~ 1 Bq/kg): limiting dual-phase target mass

==> extract argon from underground (CO_2 well in Colorado) !

- **^{39}Ar activity in underground argon** (0.73 ± 0.10 mBq/kg)
- Possibly smaller: presence of ^{85}Kr indicate possible presence of atmospheric air



Phys. Rev. D 93, 081101 (2016)

The DarkSide Program

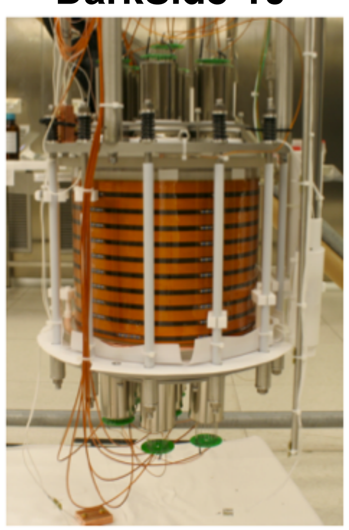
Background suppression
- Ultra-low background materials
- **Depleted Liquid Argon**
- Low background photo-detectors
- Low background material components

Background identification
- **Pulse Shape Discrimination** (PSD)
- Ionization/scintillation ratio
- Position reconstruction (surface events)
- Multiple scatters within the TPC

Active Shielding
- **Active Neutron Veto**
- Water Cherenkov against muons (WCD)

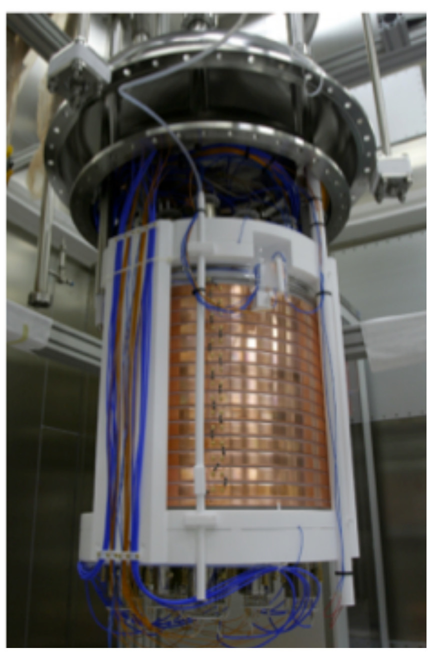
Main goal: bg-free exposure

DarkSide-10



2011

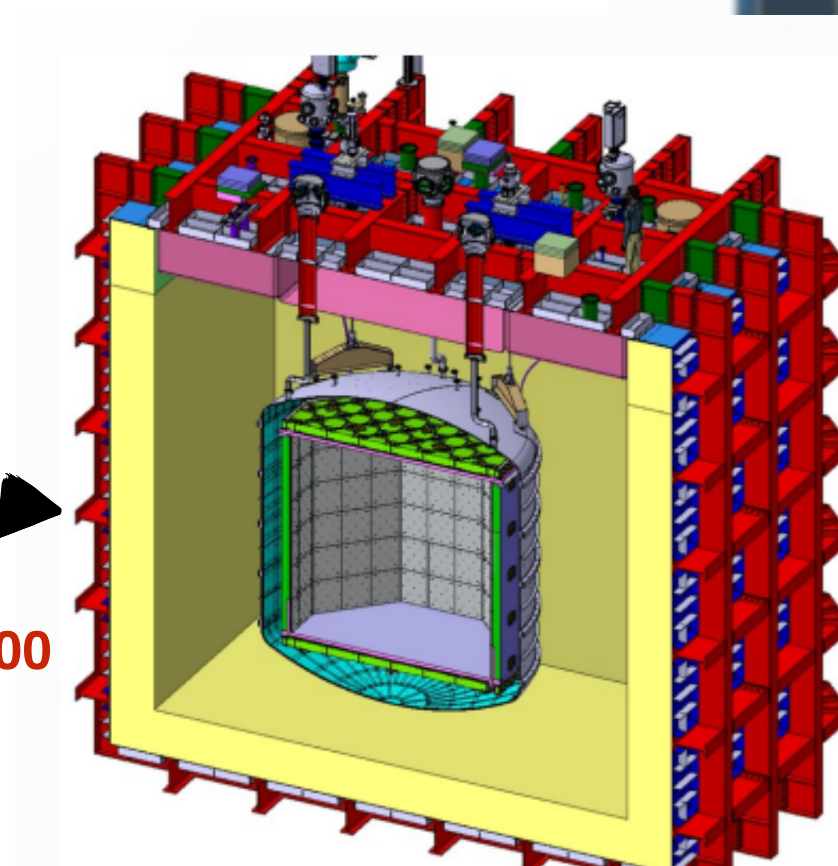
DarkSide-50



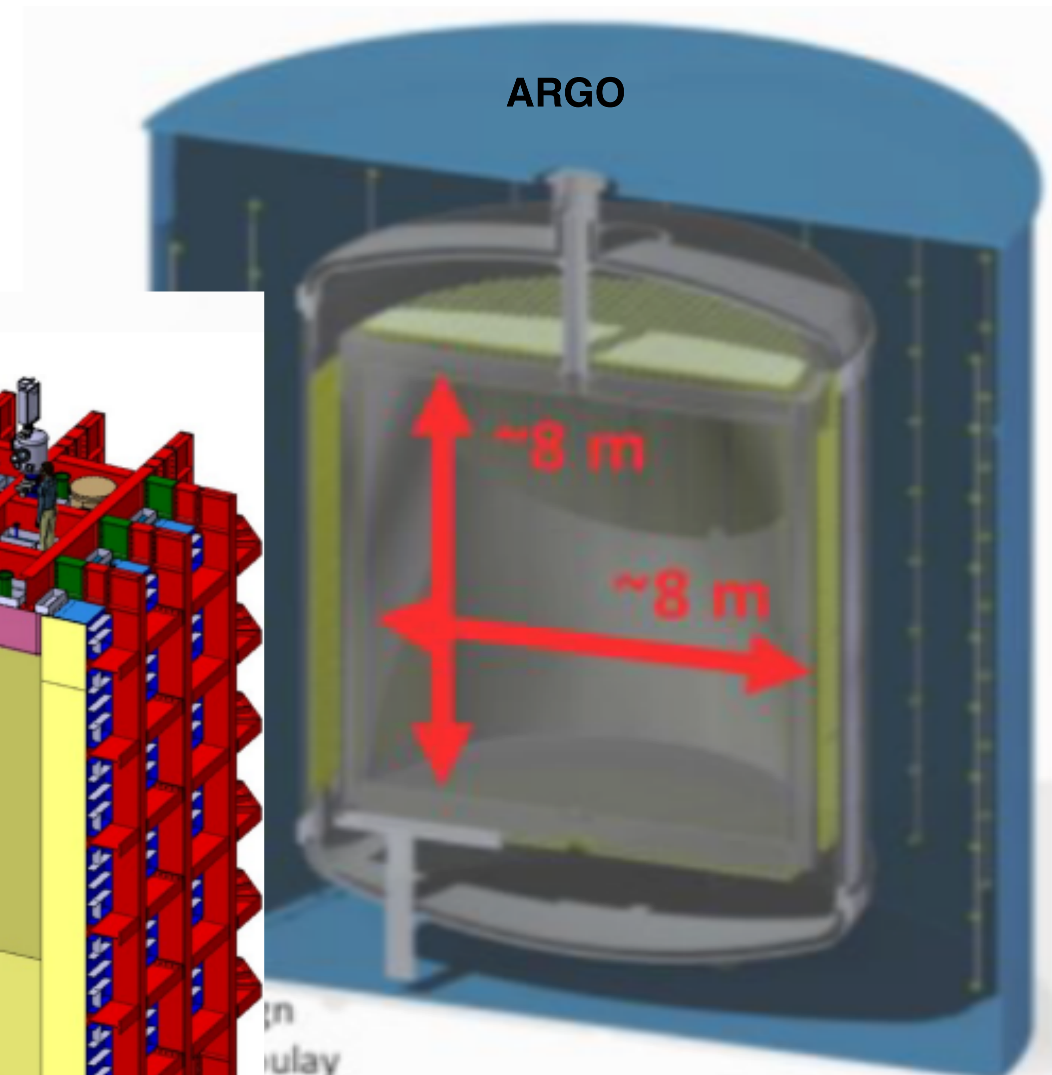
2013-2018 at LNGS
0.03 t.yr exposure

x 1000

DarkSide-20k



2025+
200 t.yr target exposure



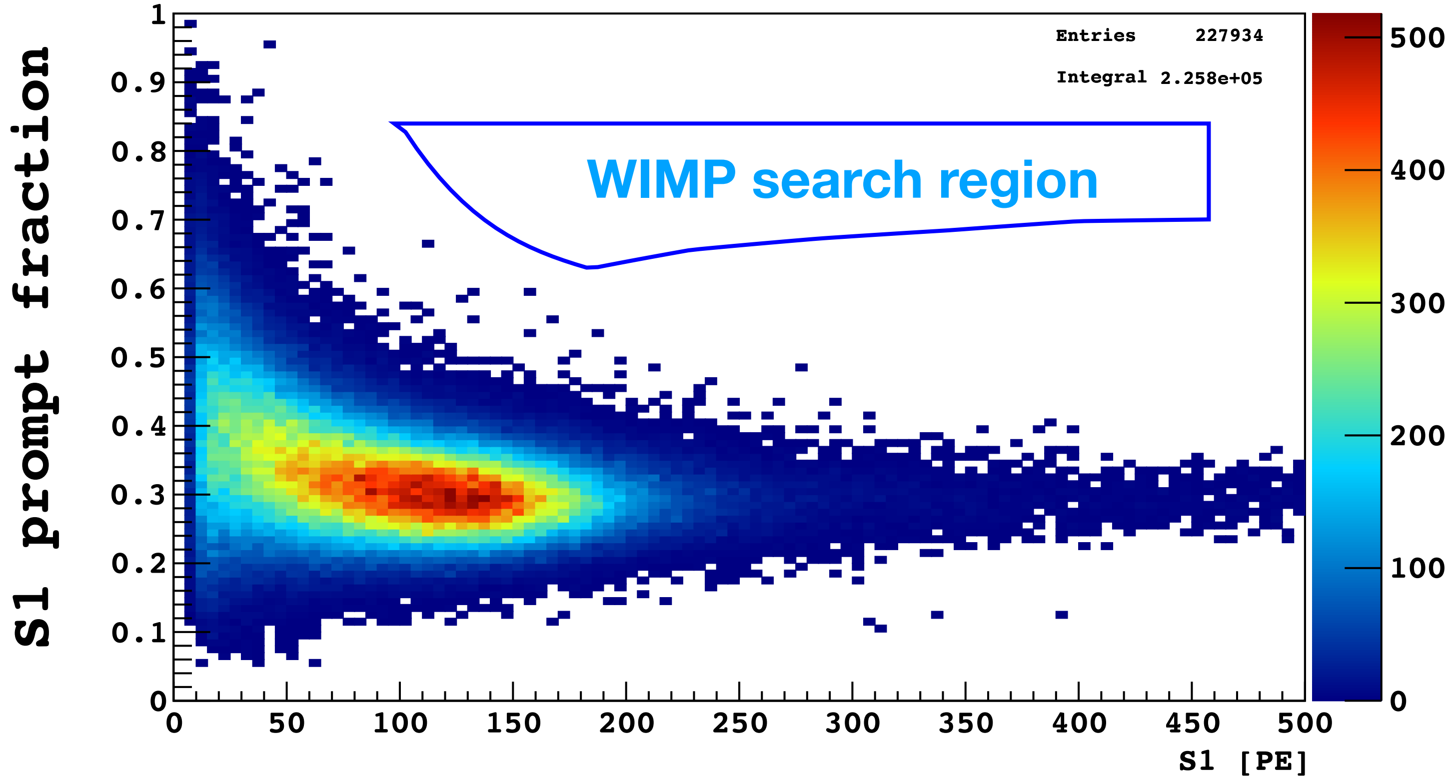
2030+
3000 t.yr target exposure

DarkSide-50 — High-mass WIMP results

Blind analysis published in 2018

- 524 live-days
- Use first 70 days of UAr dataset to tune cuts
- **Minimise backgrounds** while maximising acceptance to NR

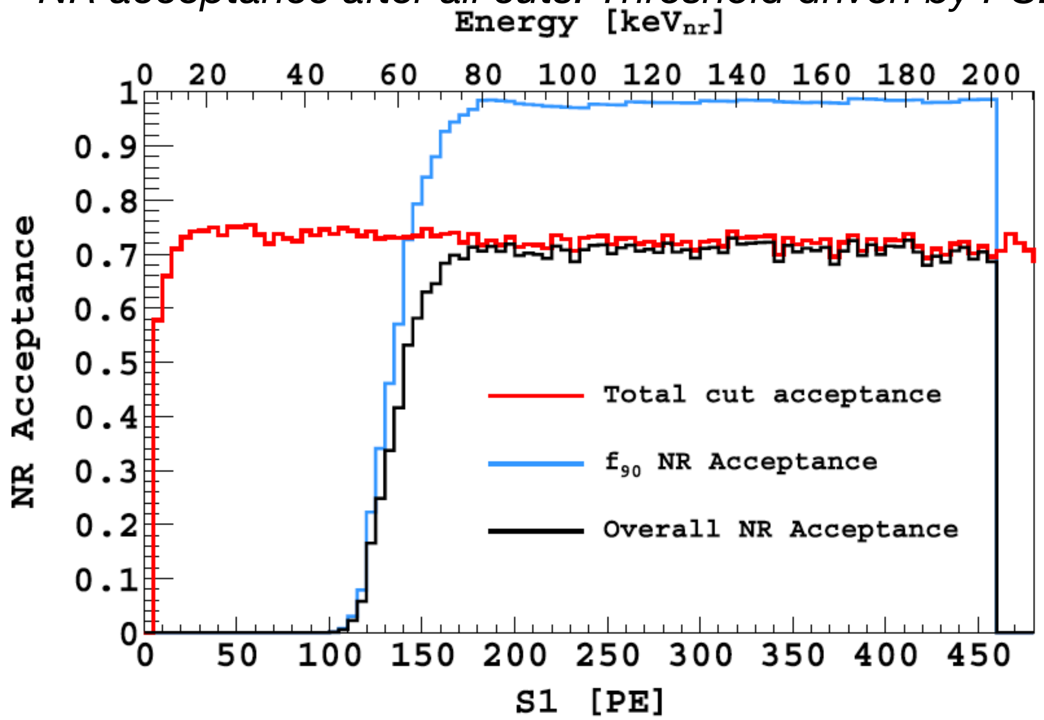
17.10³ kg.d: background free!



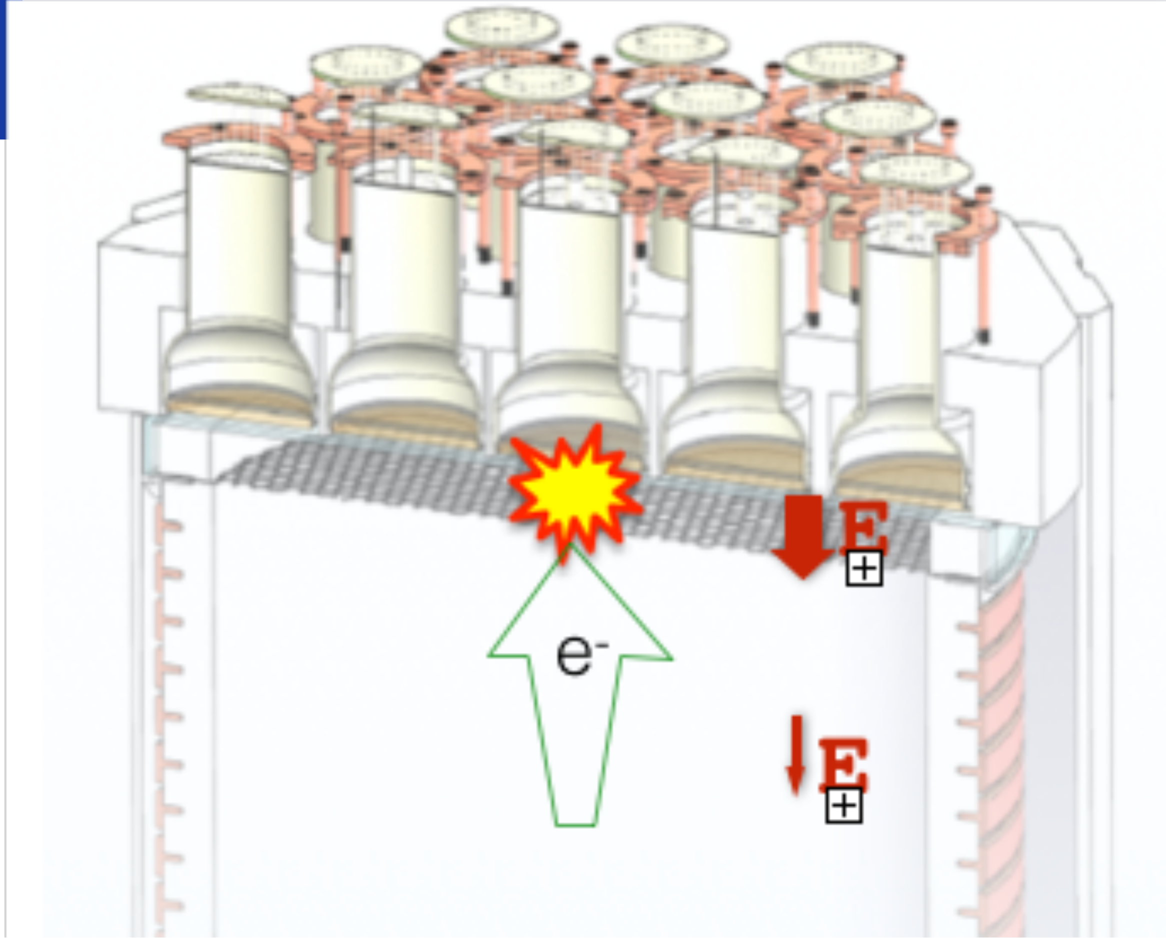
Expected backgrounds in ROI, before opening box

NR	surface alphas	0.001
NR	cosmogenic neutrons	<0.00035
NR	radiogenic neutrons	<0.005
ER	electron recoil	0.08
		0.09±0.04

NR acceptance after all cuts. Threshold driven by PSD:



DarkSide-50 low mass



Look at the **ionization only** spectrum
(W_{ion} = 23.5 eV, gain in the gas: 23 PE/e^-)

Below 3 keV$_{ee}$: give up the scintillation signal (too small to trigger the detector), and thus

- **minimal fiducialization** (only radial)
- **no PSD**

No more background free

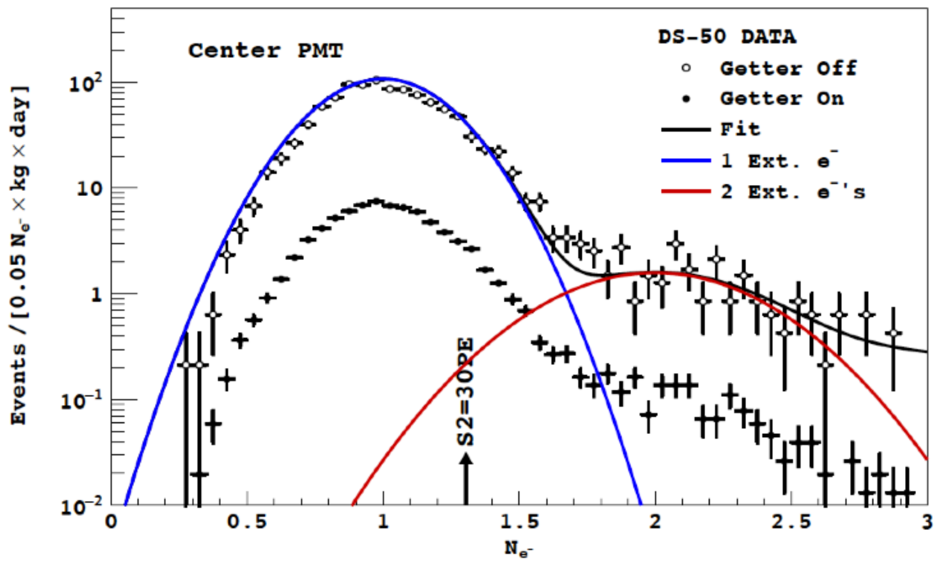
==> Background model for DarkSide-50

First analysis in 2018, recently updated !

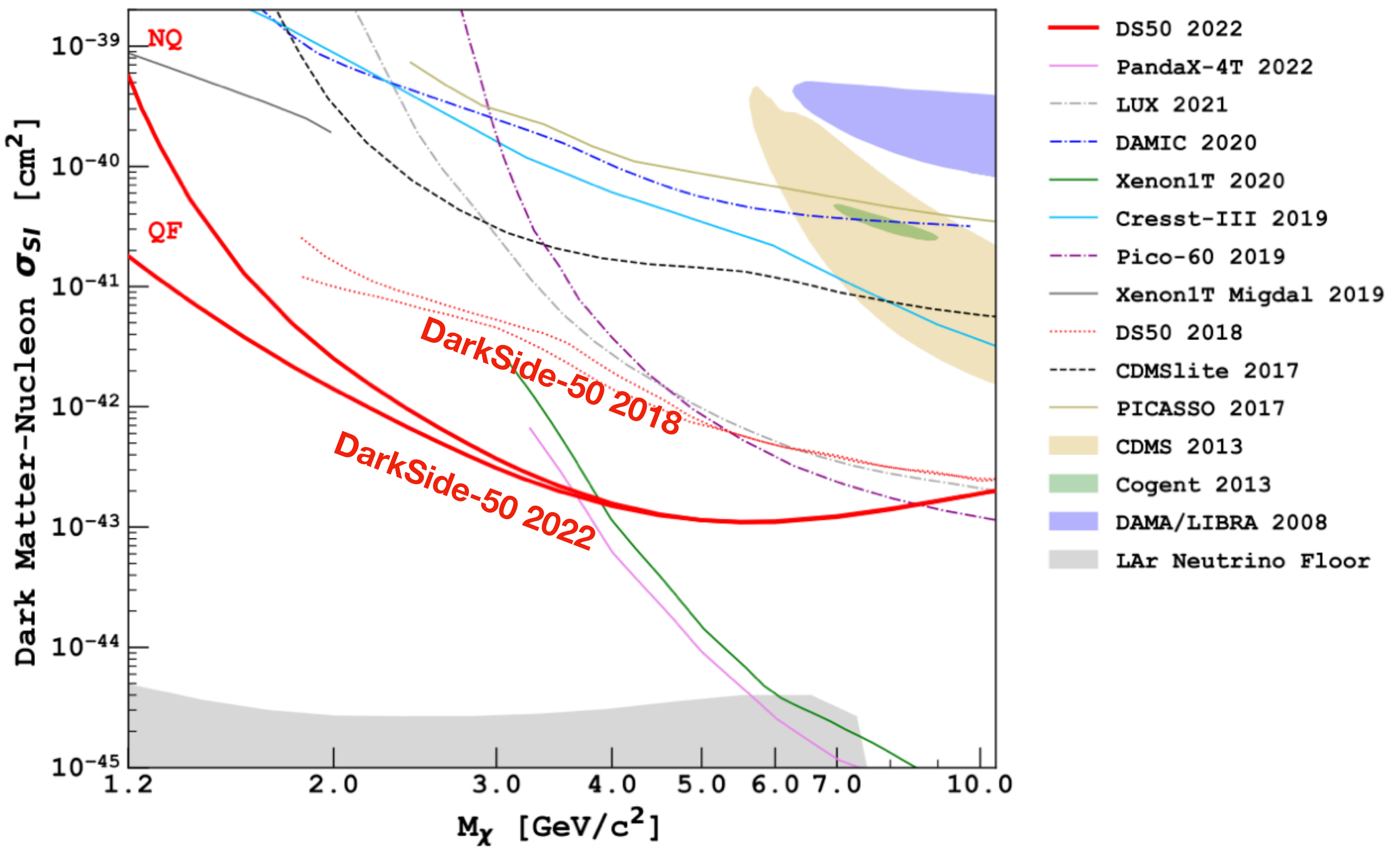
—> WIMP-N *2207.11966*

—> Migdal effect *2207.11967*

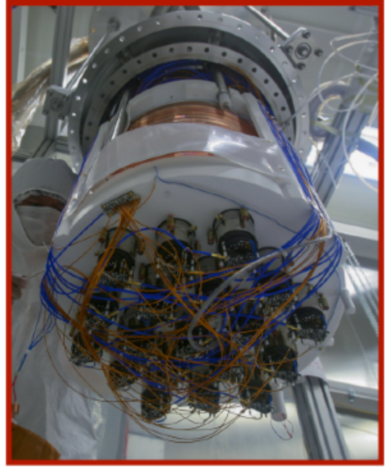
—> WIMP-electron *2207.11968*



N_e



DarkSide-50 @ LNGS



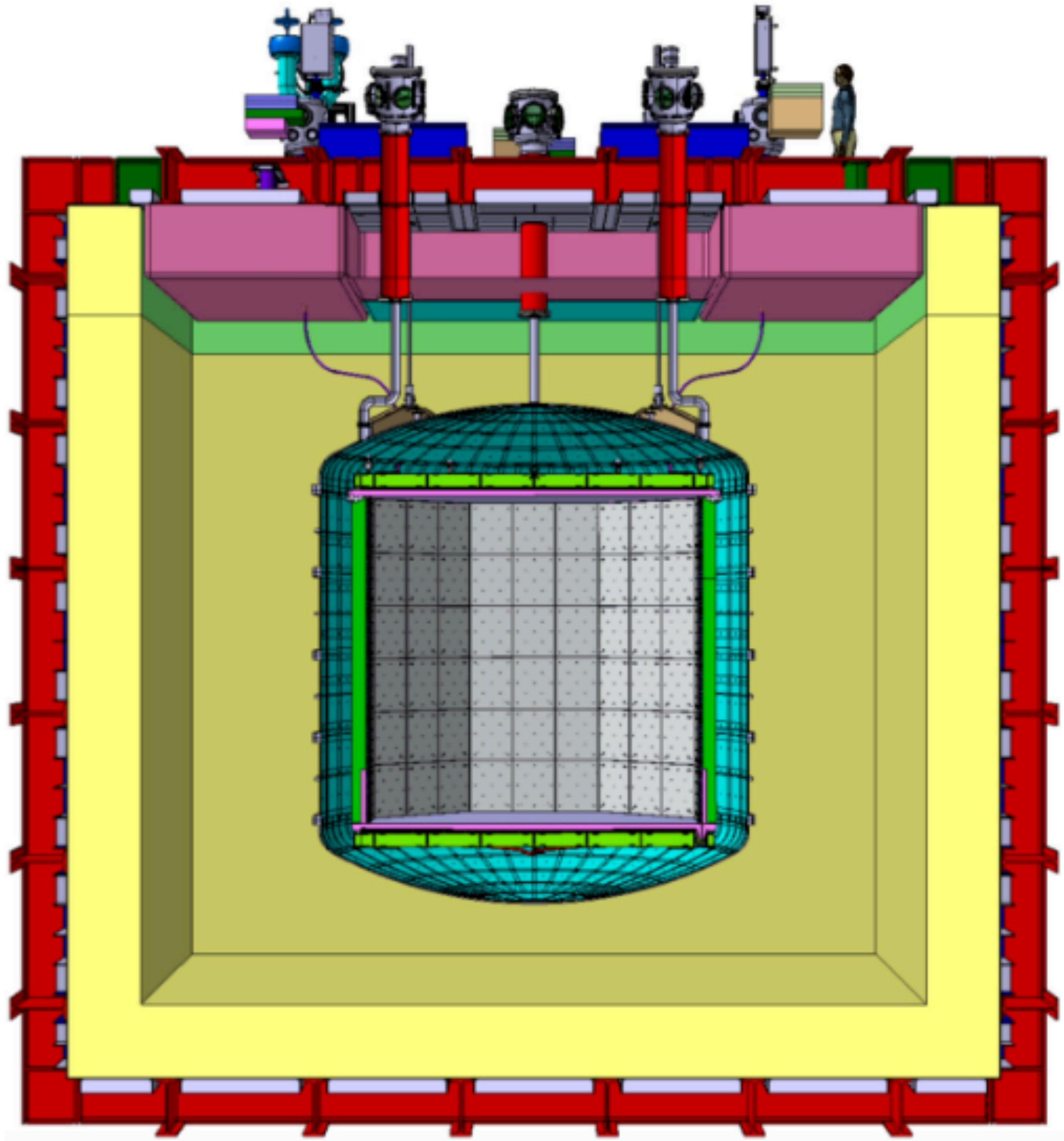
MiniClean @ Snolab

DEAP @ Snolab

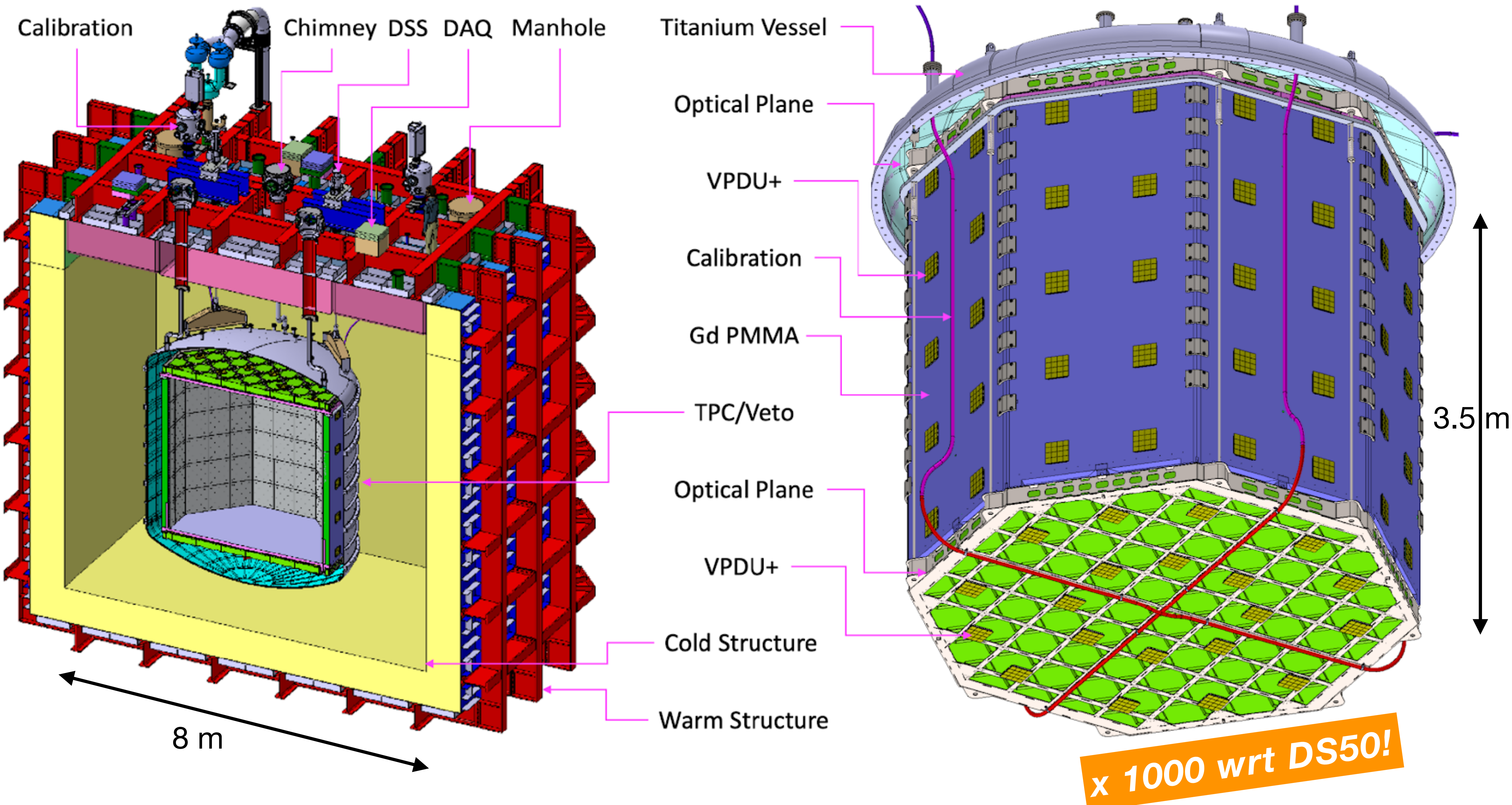
ArDM @ Canfranc

DarkSide-20k

by the Global Dark Matter Argon Collaboration

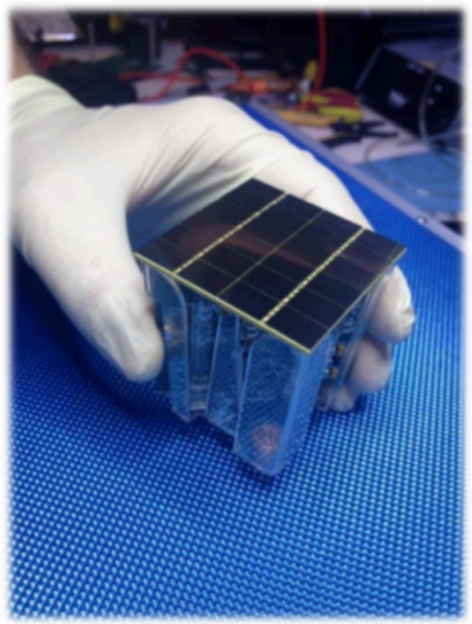


DarkSide-20k



- To be installed in Hall C at LNGS
- Hosted inside a 700 t AAr LAr bath, in a cryostat *à la* ProtoDUNE
- **Target: 50 t UAr as WIMP target**
- **Veto: 35 t UAr + custom developed Gd-PMMA,** optimized for radiogenic neutrons
- **Novel readout** system for the **scintillation light**, based on **grouped SiPM arrays (> 25 m²)**

From PMTs to SiPM arrays

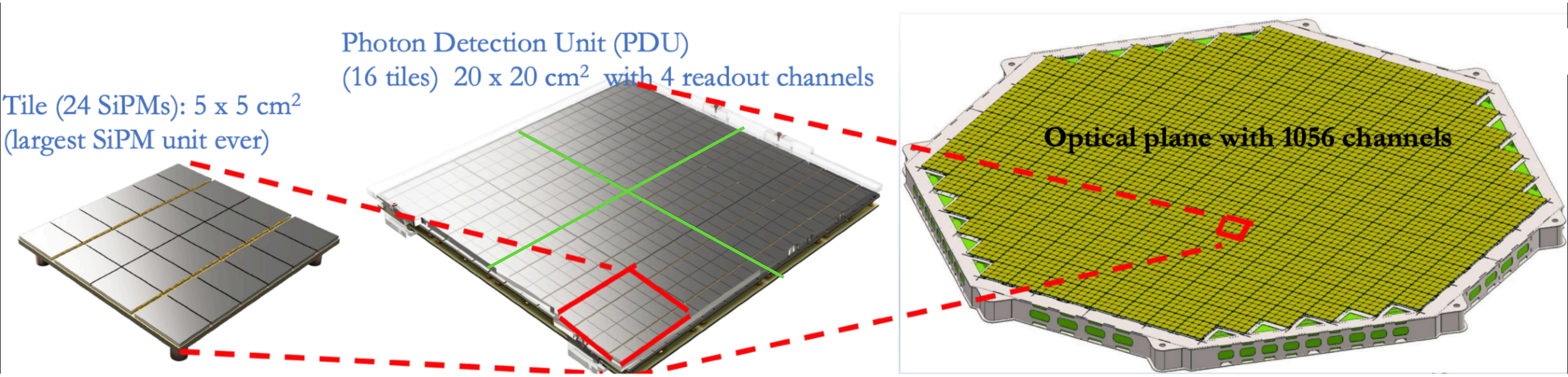


PROS

- Cryogenic temp stability
- Better single photon resolution
- **Higher photo-detection efficiency**
- Low voltage operation
- **Lower background** (Si intrinsically radiopure)
- Lower cost

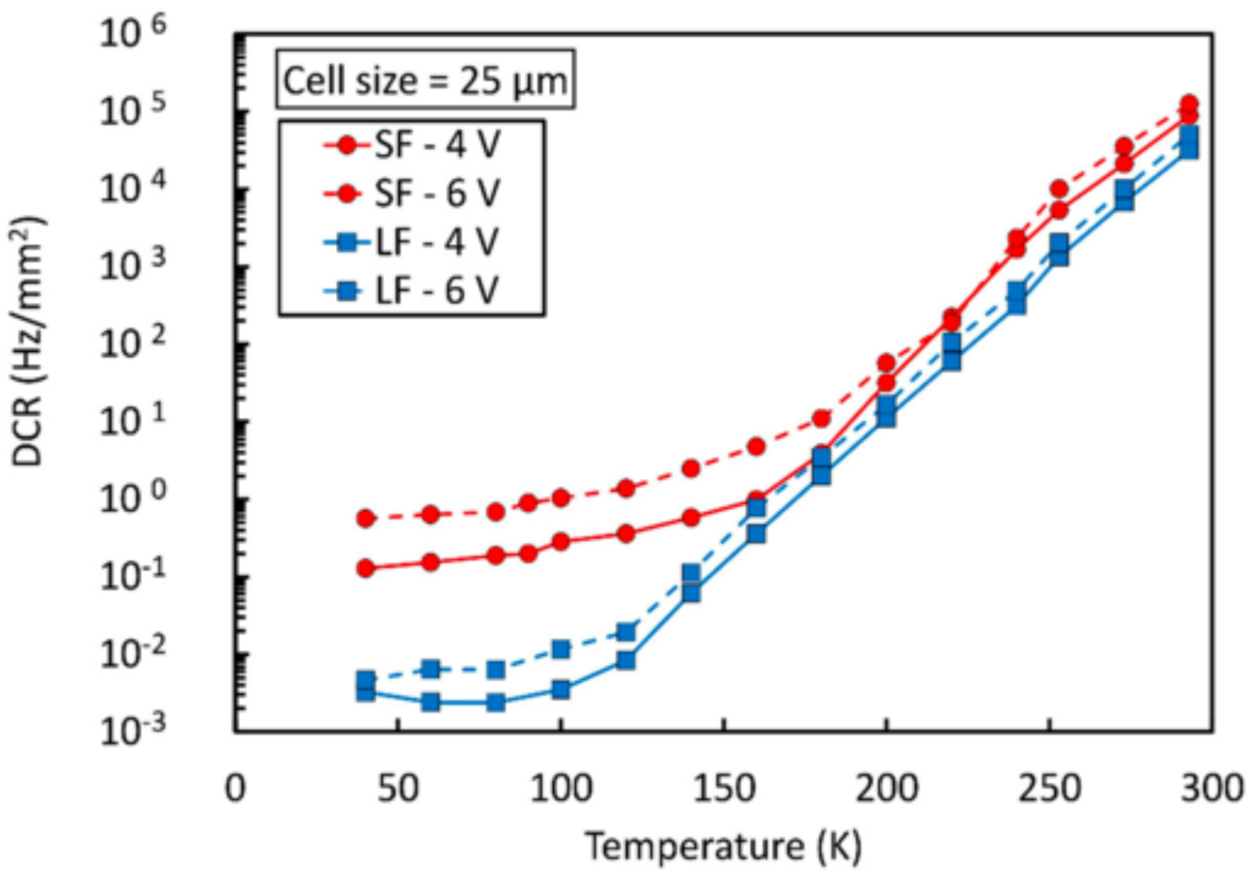
CONS

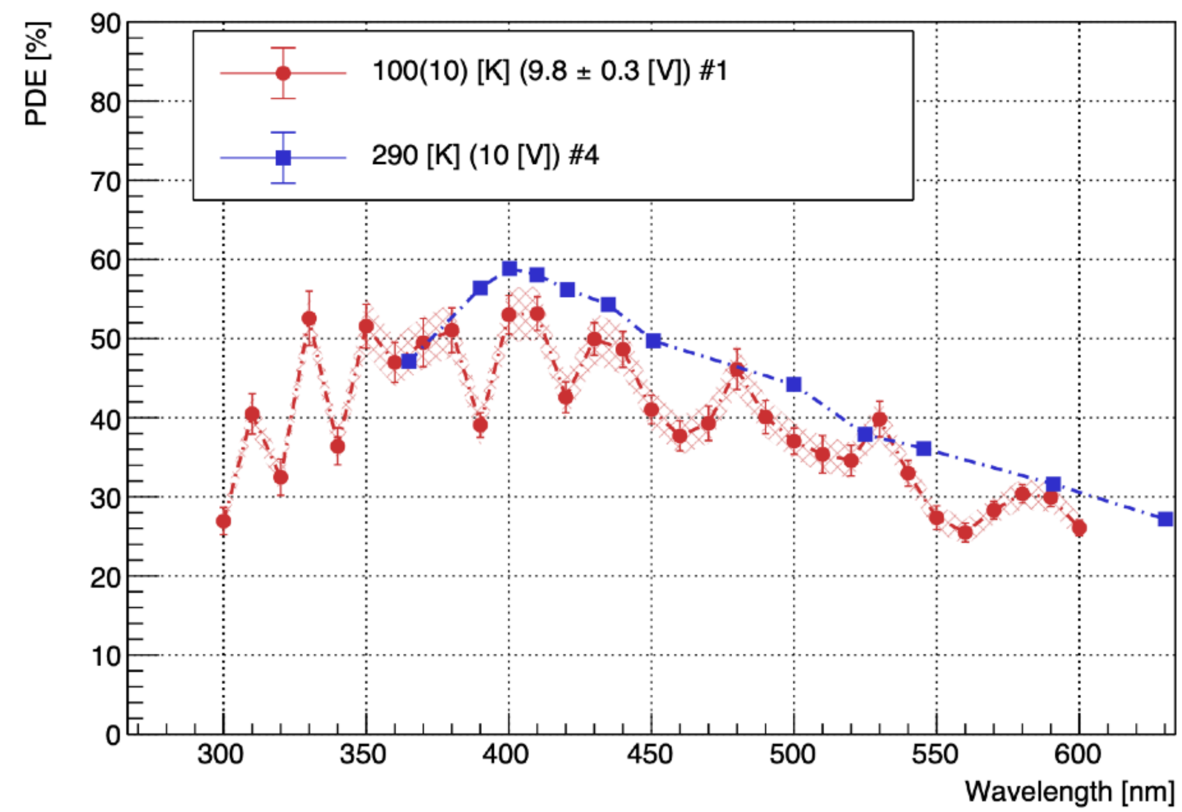
- Small area ≈ cm2 (group them)
- High dark rate (solved, + operated at 87K)
- High output capacitance for large devices (~0.5 us recharge)

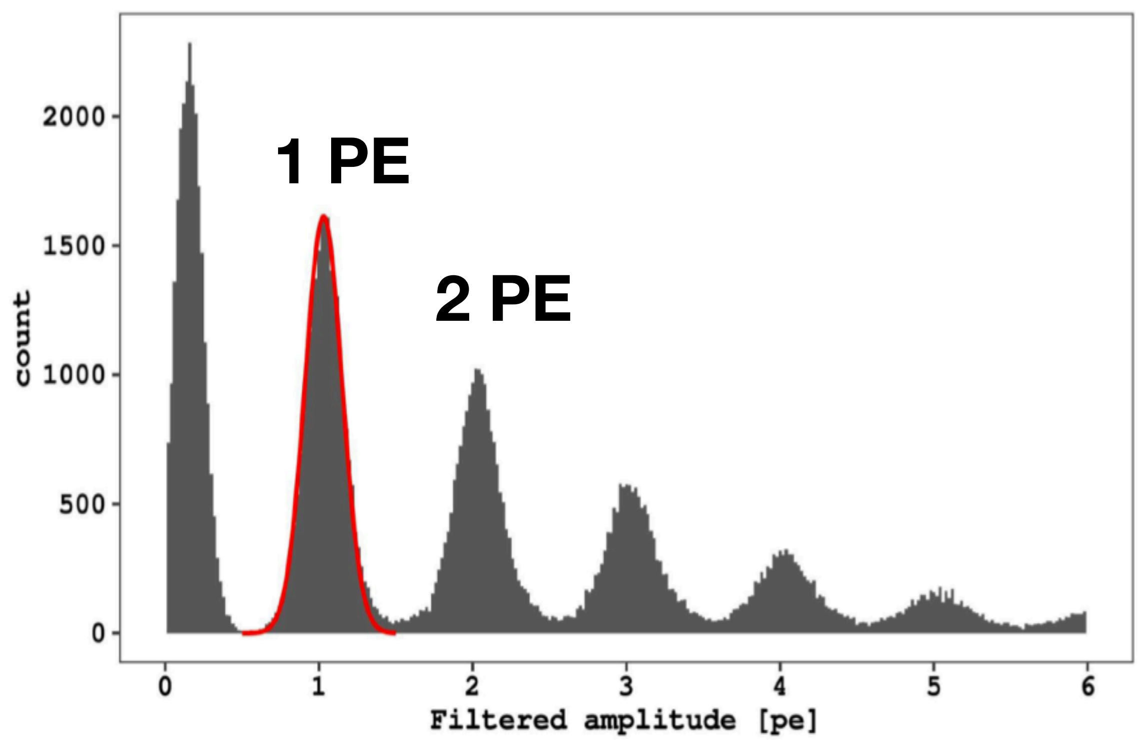


2 optical planes for the TPC
+ 480 channels to instrument the UAr veto

PDU design, results of years of R&D

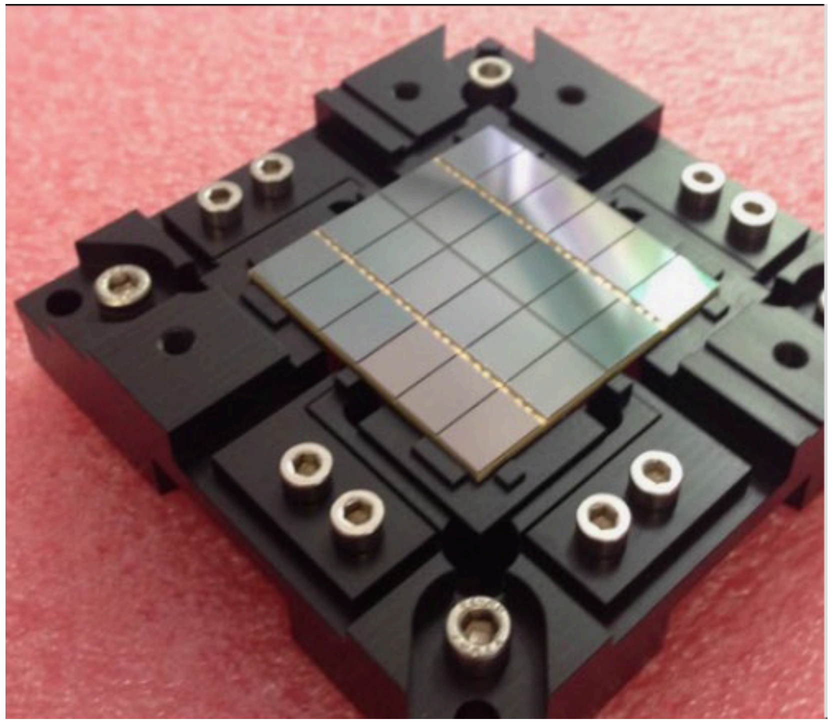


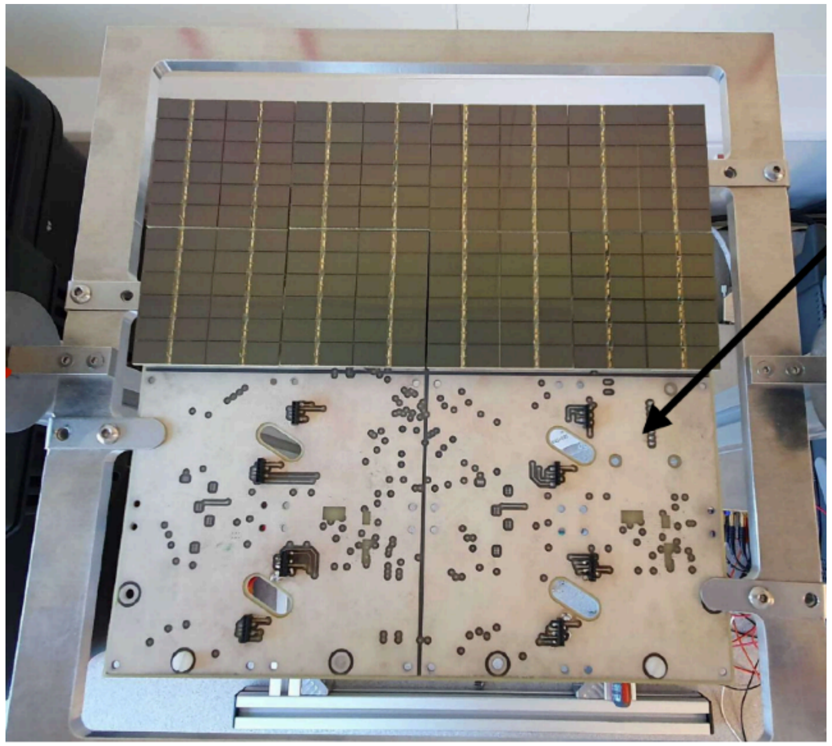


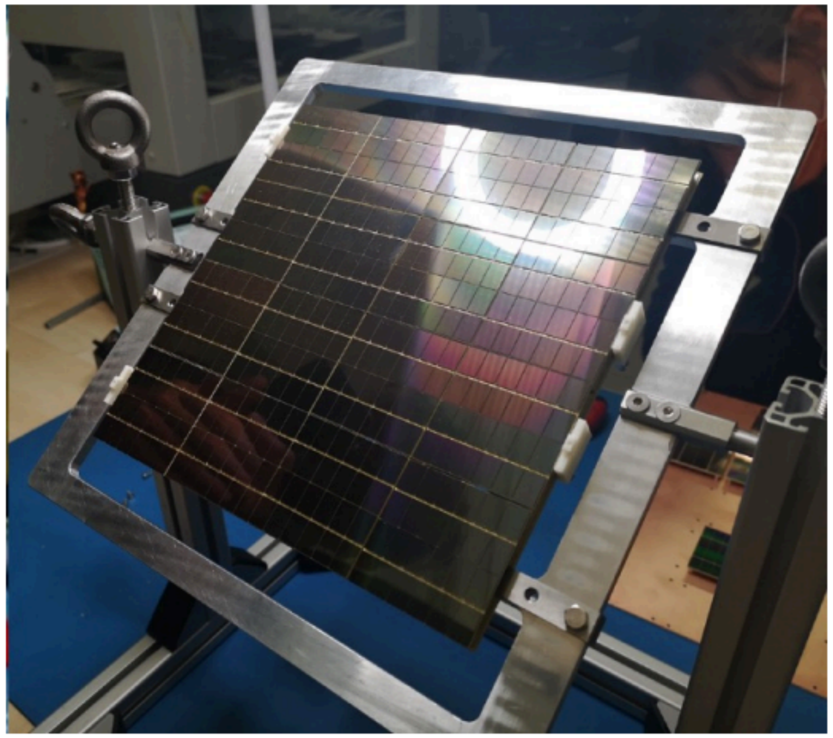


parameter	spec required	spec achieved
PDE @ 420 nm	> 40%	> 42%
DCR (87 K)	250 Hz / tile	~ 20 Hz / tile
correlated noise probabilities (afterpulses, cross talk)	< 50% + 50%	<10% + 35%
SiPM gain	> 1E6	> 1E6
SNR after ARMA filter	> 8	> 15
time resolution	~ 10 ns	~15 ns

PDU mass production (and testing) is starting

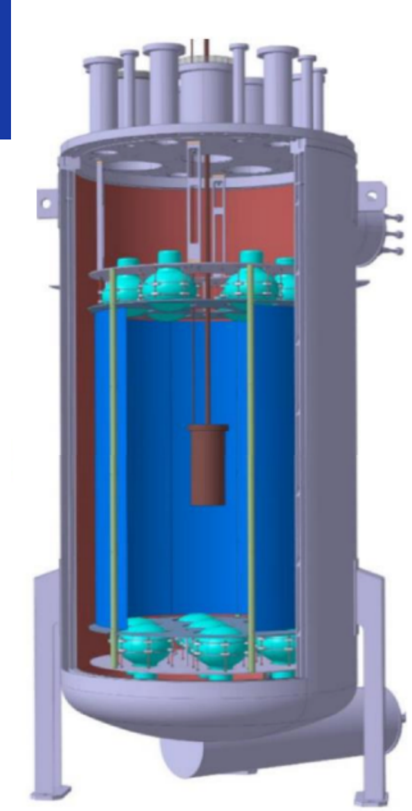






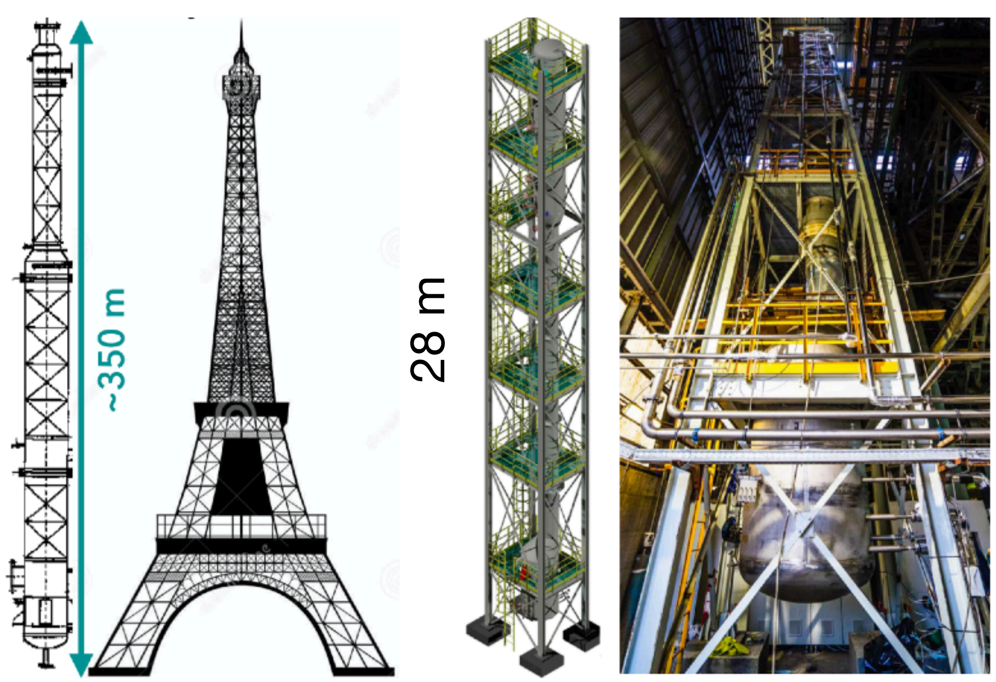
- Wafer delivery from LFoundry started in 2022.
- Packaging and assembly for TPC sensors: **Nuova Officina Assergi** (NOA), about to start operations
- Packaging and assembly for Veto sensors: RAL and Liverpool, UK
- Several test facilities to qualify production: Naples, Liverpool, Edinburgh, AstroCent…

The UAr target: URANIA & ARIA



1) UAr extraction at the URANIA plant.
Industrial CO_2 extraction plant in Cortez, Colorado;
Plant ready to be shipped;
Expected argon purity at outlet: 99.99%;
UAr extraction rate: 250-330 kg/day;

3) Qualification at Canfranc, DArT in ArDM
A single-phase LAr detector with active volume ~1L, capable of measuring UAr to AAr 39Ar depletion factors of the order of 1000 with 10% precision in weeks



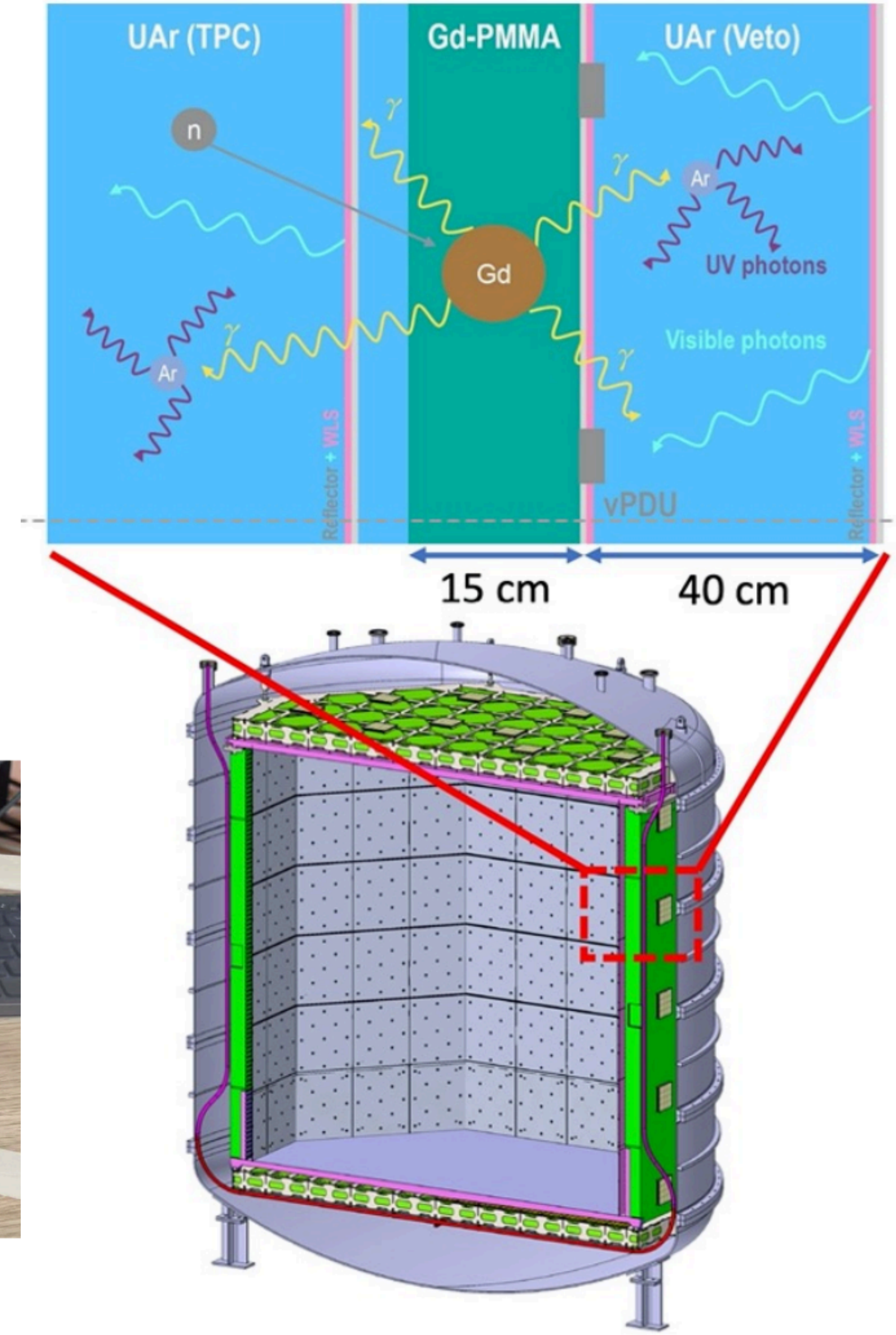
(Eur. Phys. J. C (2021) 81:359)

2) Cryogenic distillation at **the ARIA facility**
Installed in the shaft of a coal mine
Chemical purification rate: 1 t/day
First module operated according to specs with nitrogen
Run completed with Ar at the end of 2020: results to be published soon.
Full assembly about to start

Radiogenic neutron veto

- TPC surrounded by a single phase (S1 only) detector in UAr (35 tonne)
- Neutrons are captured by the Gd-loaded acrylic
- From the capture gamma ray shower up to 8 MeV
- Scintillation light is shifted by PEN wls and detected by SiPMs (400 channels) in both buffer and TPC
- **~90% tagging efficiency from simulation**, acceptable accidental lifetime loss

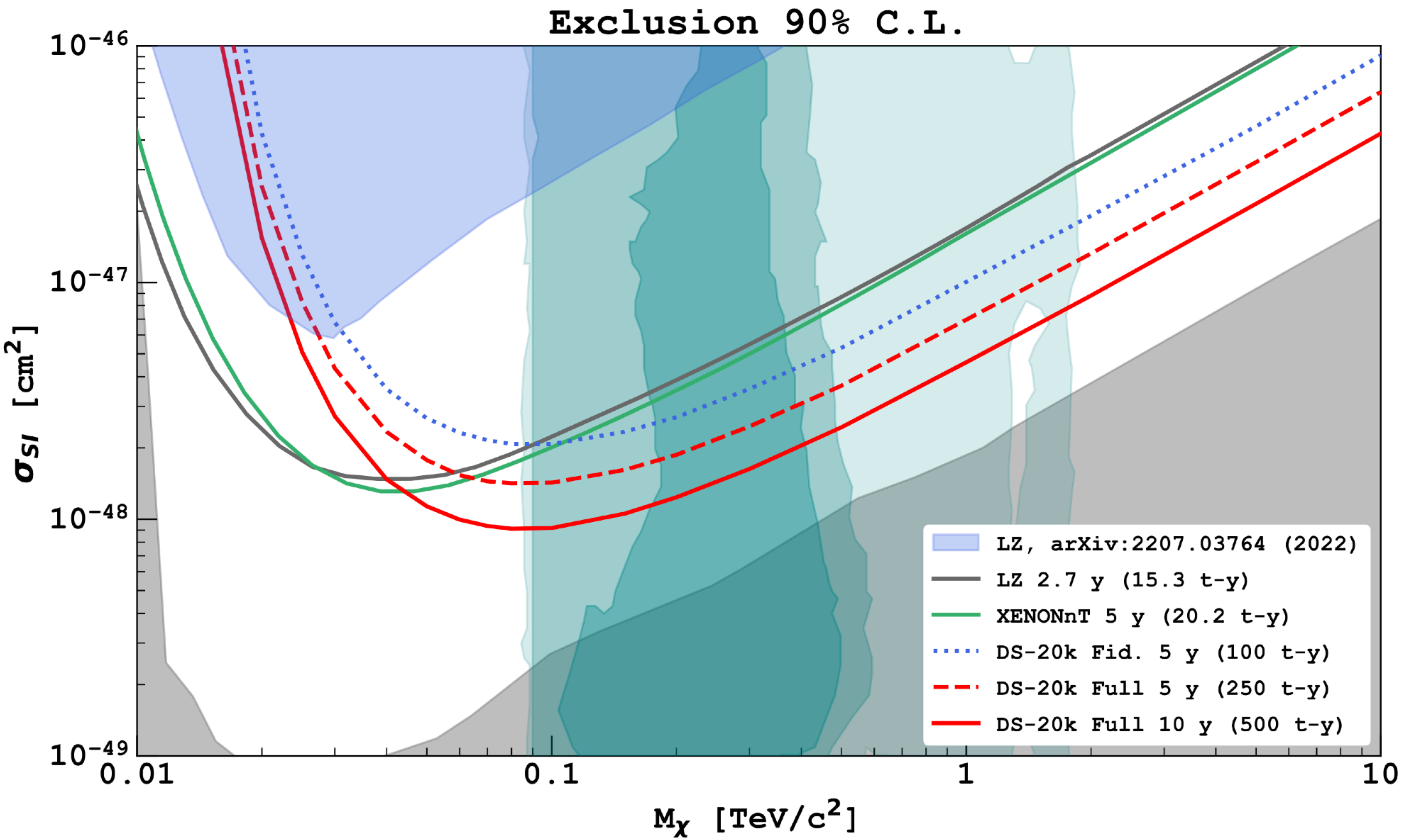
R&D(s) for Gd-loaded acrylic concluded. Radioactivity assay satisfactory. Moving to production



Gadolinium oxide nanograins (Gd O) mechanical dispersion in MMA.

Gd(MAA)$_3$ doped acrylic sheet (5 cm thick)

Projected sensitivity



Projected sensitivity based on bg-free exposure (**<0.1 events in 200 t.yr**) using the FV (innermost 20 tonnes of UAr) AND using **the full active volume** (PLR approach, bg pdfs known)

Main backgrounds (in 200 t.yr)**: CEvNS (3.2 ev),** radiogenic and cosmogenic neutrons, ER+Cherenkvov, S1+S2 accidental coincidence…

Conclusions

- R&D phase for the DS-20k detector completed, **construction is starting**!
- Production of SiPMs started and PDU mass test facility is ready
- Underground Ar procurement and characterisation project is ongoing (URANIA & ARIA & DArT-ArDM)
- Underground Argon cryogenic system has been successfully tested at CERN and is being relocated at INFN-LNGS
- Construction of the DS-20k cryostat will start soon in Hall C
- Mechanical mockup testing scheduled to take place at INFN-LNGS starting this year
- Data taking expected in 2026
- <u>Wide range of physics</u>:
  - **most sensitive WIMP search of the next decade**
  - potential at **lower WIMP masses** being assessed (dedicated detector?)
  - sensitivity to **supernova ν** bursts
  - …

Expected backgrounds

Full background budget obtained thanks to:

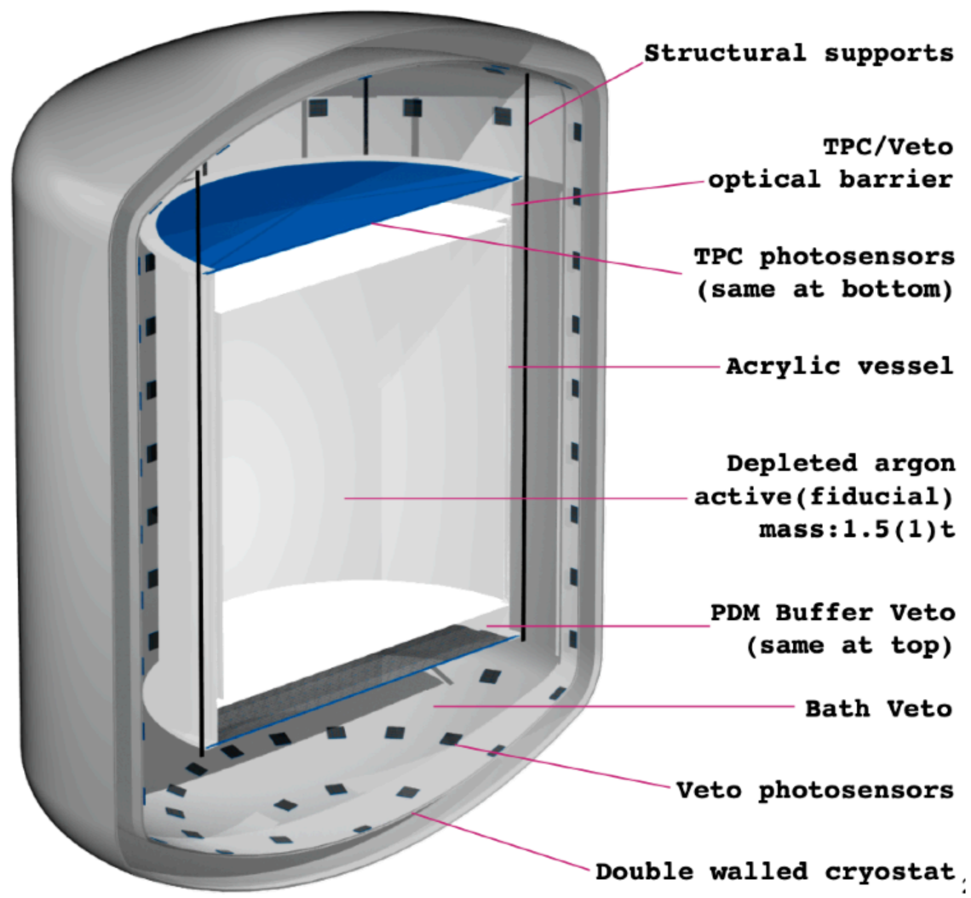
- Massive material screening (Jagiellonian University, CIEMAT, SNO, Canfranc, LNGS, Boulby) and strict material selection (+ account for broken equilibrium)
- Independent tools for (α, n) emission probability (SaG4n: http://win.ciemat.es/SaG4n/)
- Full simulation of detector geometry, particle tracking, UAr scintillation, detector response and analysis strategy

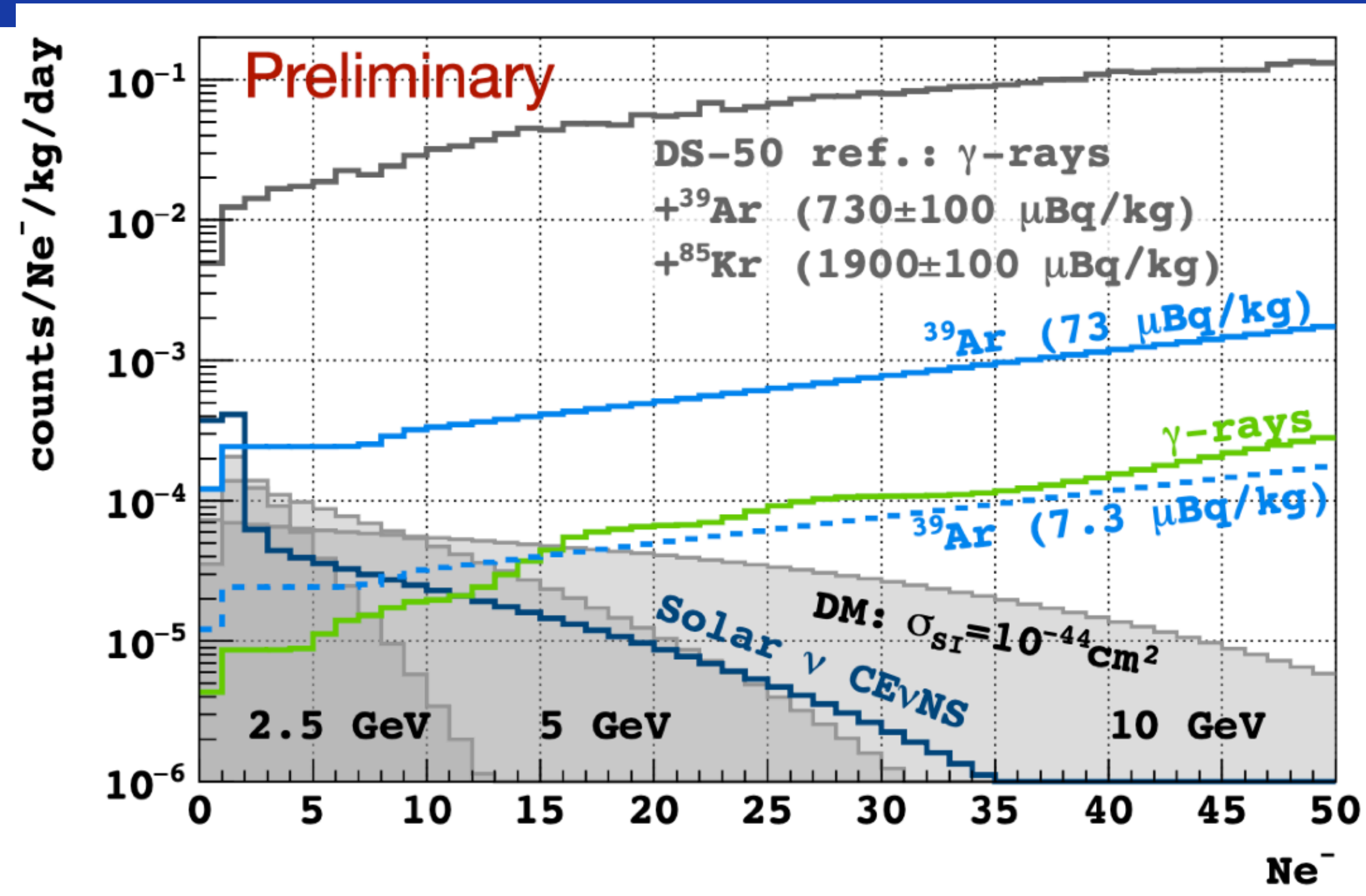
Irreducible CEvNS: 3.2 evts in ROI in 200 t.yr

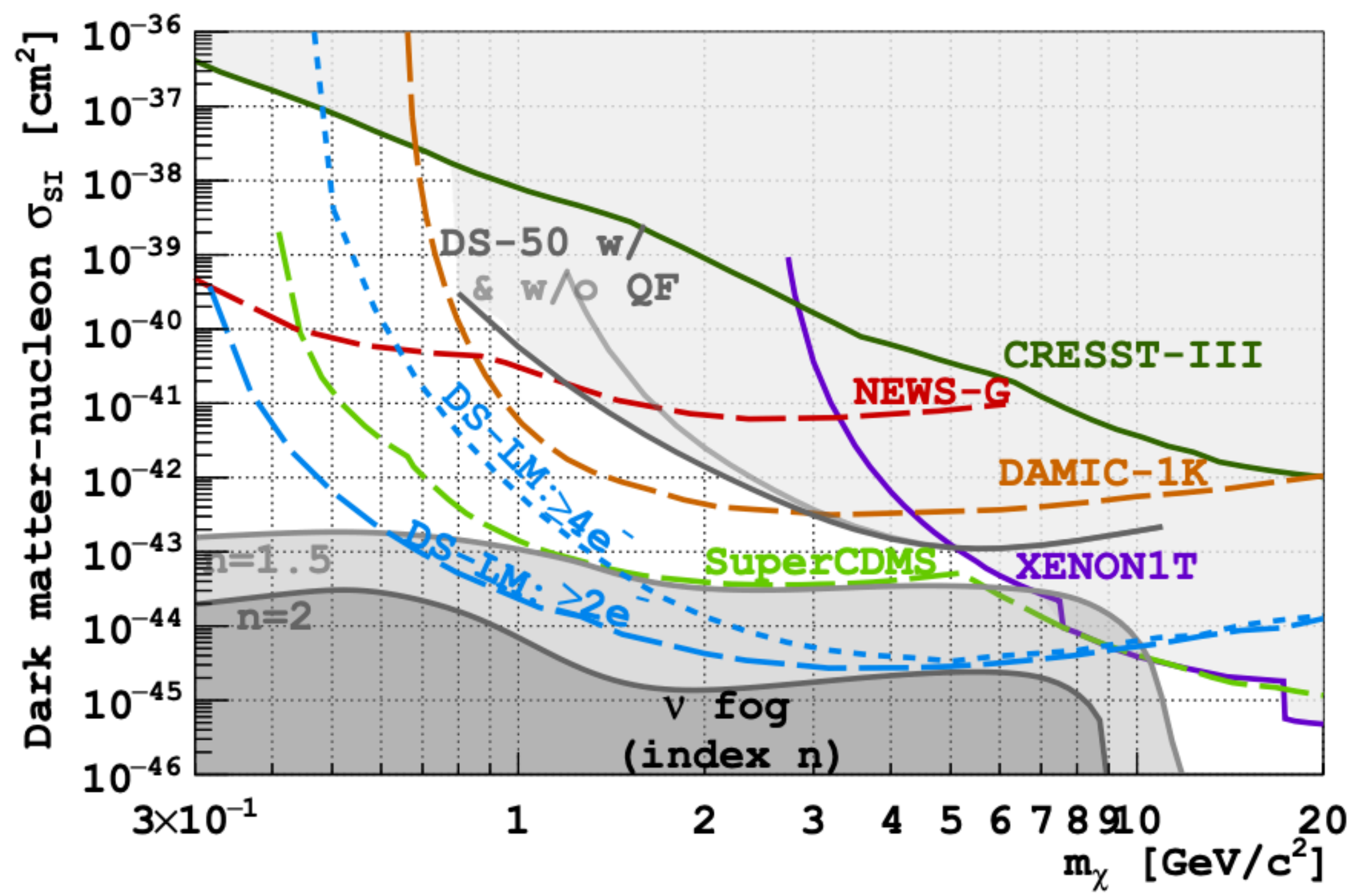
Background type	Bg events in ROI $[200\,\mathrm{t\,yr}]^{-1}$	Material selection	Cleaning and purification	Event Topology	PSD	AAr instrumentation	Neutron veto
(α,n) neutrons from U and Th	9.5×10^{-2}	✓		✓			✓
Fission neutrons from U-238	$<2.3 \times 10^{-3}$	✓		✓			✓
Neutrons from Rn-222 diffusion and surface plate-out	$<1.4 \times 10^{-2}$	✓	✓	✓			
Cosmogenic neutrons (stat limited)	$<6.0 \times 10^{-1}$					✓	
Neutrons from the lab rock	1.5×10^{-2}	✓		✓			✓
Random surface α decay + S2 coincidence	$<5.0 \times 10^{-2}$	✓	✓	✓			
Correlated ER + Cherenkov	$<1.8 \times 10^{-2}$	✓		✓			
Uncorrelated ER + Cherenkov	$<3.0 \times 10^{-2}$	✓		✓			
ER	$<1.0 \times 10^{-1}$				✓		

TABLE 26. Nuclear recoil (NR) backgrounds expected during the full DS-20k exposure, based on current data and Monte Carlo simulations. The right column is the total number of events surviving the veto cut, fiducial volume cut, and PSD.

DarkSide-LowMass







Design optimization:

— to reduce gamma background:

- material choice
- geometry
- active veto
- fiducialization

— to increase single electron sensitivity:

- high extraction field

R&D needed to understand/reduce the single electron bg that dominates < 4 ne