European Funds | Republic of Poland | FNP Foundation for Polish Science | European Union

National Science Centre Poland

Where We Go with Liquid Ar-based Dark Matter Searches?

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AstroCeNT, Warsaw

February 14 2023

at Nagoya workshop

DarkSide

AstroCeNT | Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences

WHY DARK MATTER?

- Indirect evidence of dark matter existence are came from Astronomical observation.
- No other clues so far…
- Not known where to search…
- Too many theories to follow…
- The choices are
  - We give up… OR Search wherever we can.

Of course, cost efficiency is important.

FEATURES OF NOBLE LIQUID DETECTORS

- **Dense** and **easy to purify** (good scalability, advantage over gaseous and solid target)
- High **scintillation** & **ionization** (low energy threshold, not low enough to search < 1 GeV/c^2 DM)
- **Transparent** to own scintillation
- No mechanical stress on target materials (one origin of low-energy backgrounds)
- Purification in situ after commissioning

For TPC

- High electron **mobility** and **low diffusion**
- Amplification (electroluminescence gain) for ionization signal
- **Discrimination** electron/nuclear recoils **(ER/NR)** via **ionization/scintillation ratio**

Liquid **Xenon**

- Denser & Radio pure
- Lower energy threshold
- Higher sensitivity at low mass WIMP

Liquid **Argon**

- lower temperature (Rn removal is easier)
- **Stronger ER discrimination** via pulse shape
- Intrinsic ER BG from ^{39}Ar
- Need wavelength shifter

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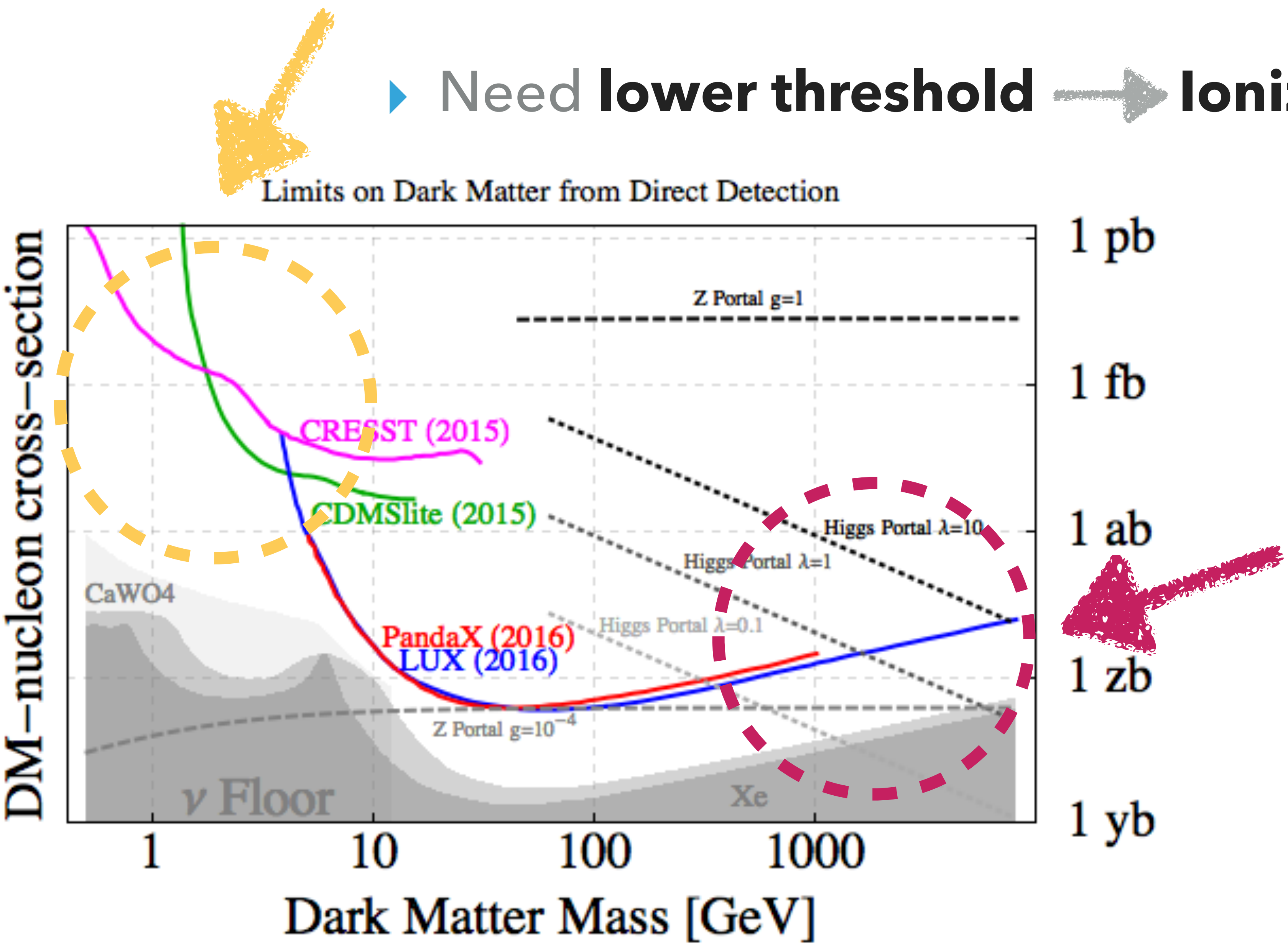
SENSITIVITY TO HIGH AND LOW MASS WIMPS

- Sharpe rise at low mass is due to **detection threshold.**
- Need **lower threshold** → **Ionization signal (S2)**



← High Number Density Low →

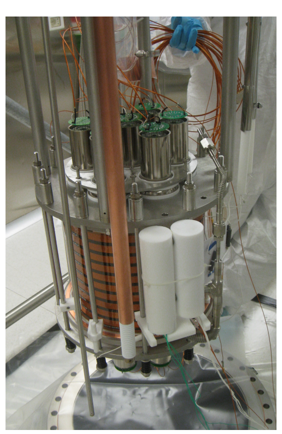
- Rise at high mass is due to **fixed energy density of WIMPs**.
- Need **large target mass.**
- Scalability is important!

Relevant BGs are different!!

plot credit: http://resonaances.blogspot.ca

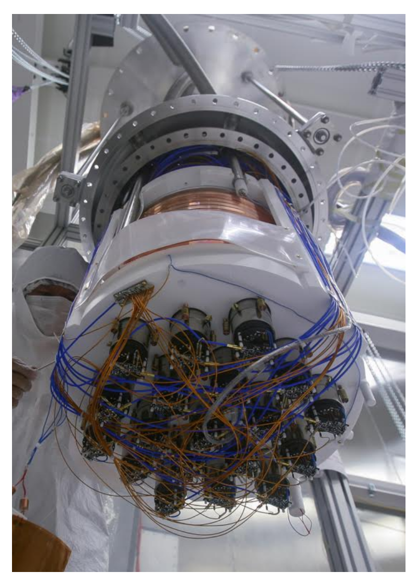
DARKSIDE PROGRAM

- **Direct detection** search for **WIMP** dark matter
- Based on a **two-phase argon** time projection chamber (**TPC**)
- Design philosophy based on having very low background levels that can be further reduced through **active suppression**, for **background-free** operation from both neutrons and β/γ's



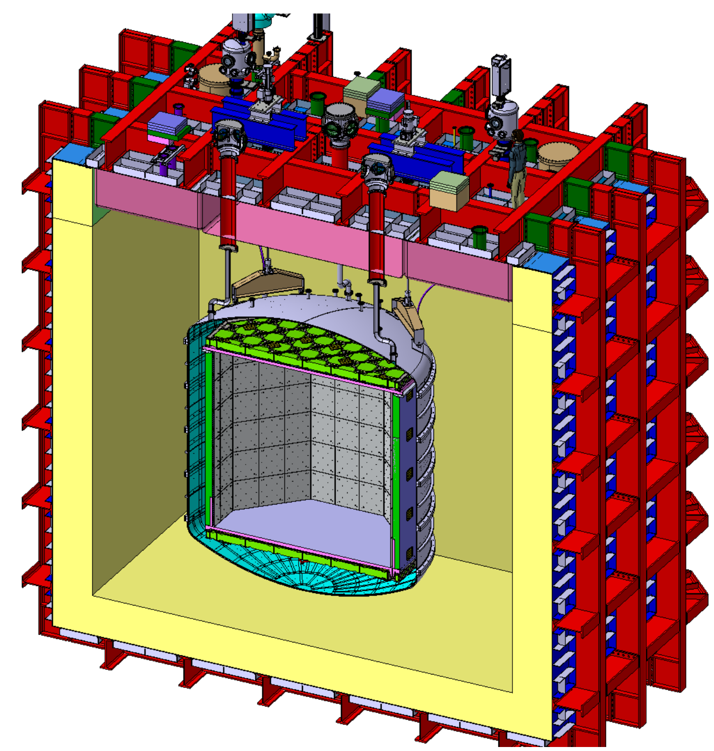
DarkSide-10

10g



DarkSide-50

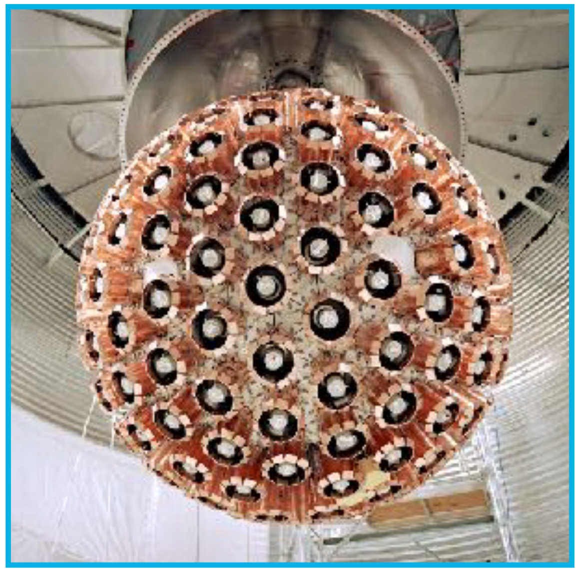
50g



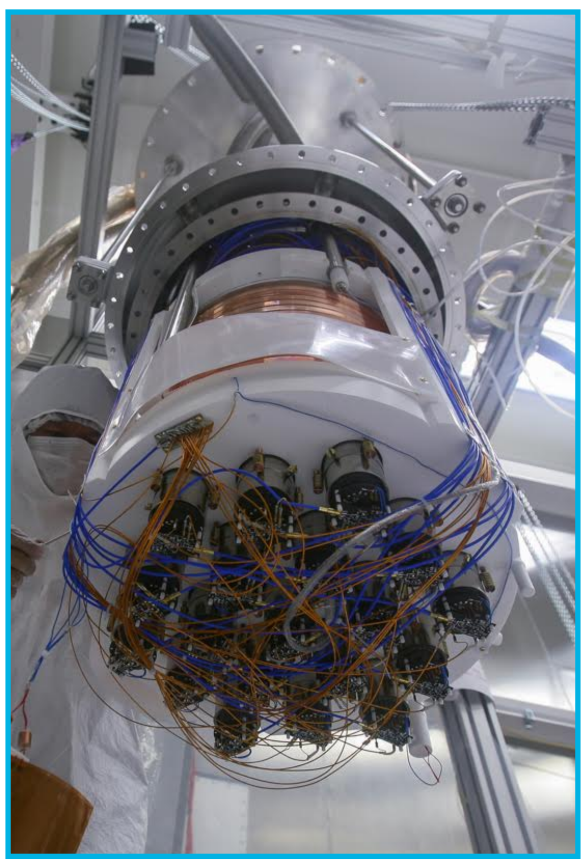
DarkSide-20k 20 t

and **DarkSide-LowMass** 1 t
for low-mass dark matter searches

GLOBAL ARGON DARK MATTER COLLABORATION



DEAP-3600

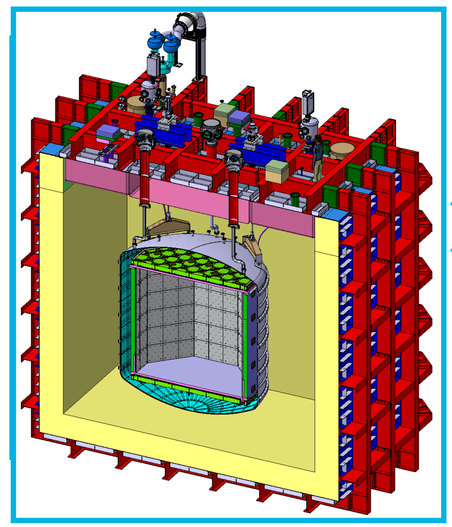


DarkSide-50

More than 400 scientists from past and present argon-based experiments in a single international argon collaboration: **GADMC**

A sequential, two-steps program:

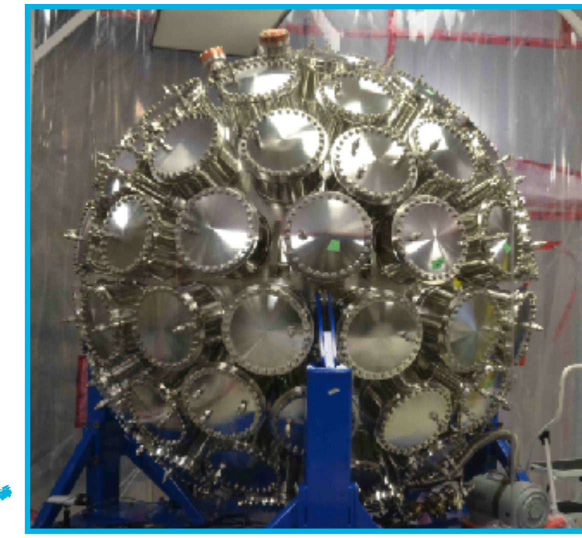
- DarkSide-20k (200 tonne yr fiducial)



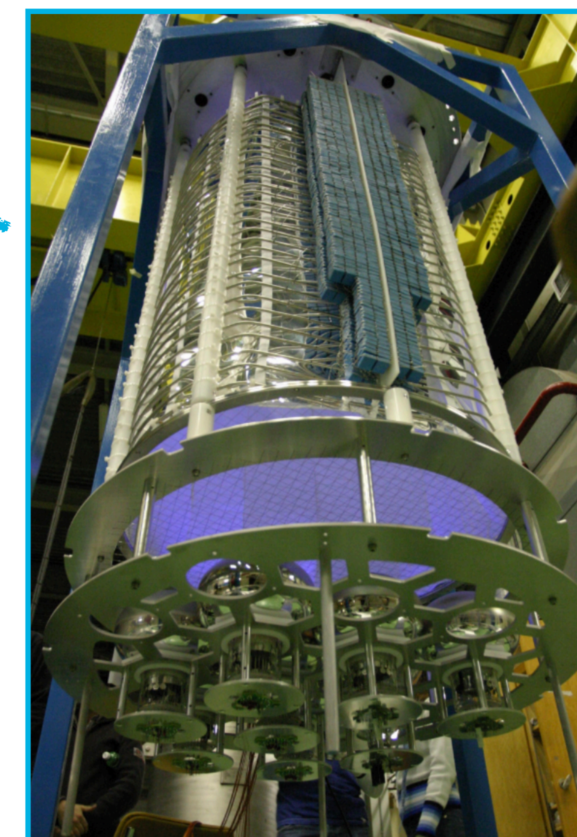
- Argo (3,000 tonne yr fiducial)

At SNOLAB
~203X

The goal: explore heavy dark matter to the neutrino floor and beyond with extremely low instrumental background



MiniCLEAN



ArDM

PULSE SHAPE DISCRIMINATION

β & γ Rejection

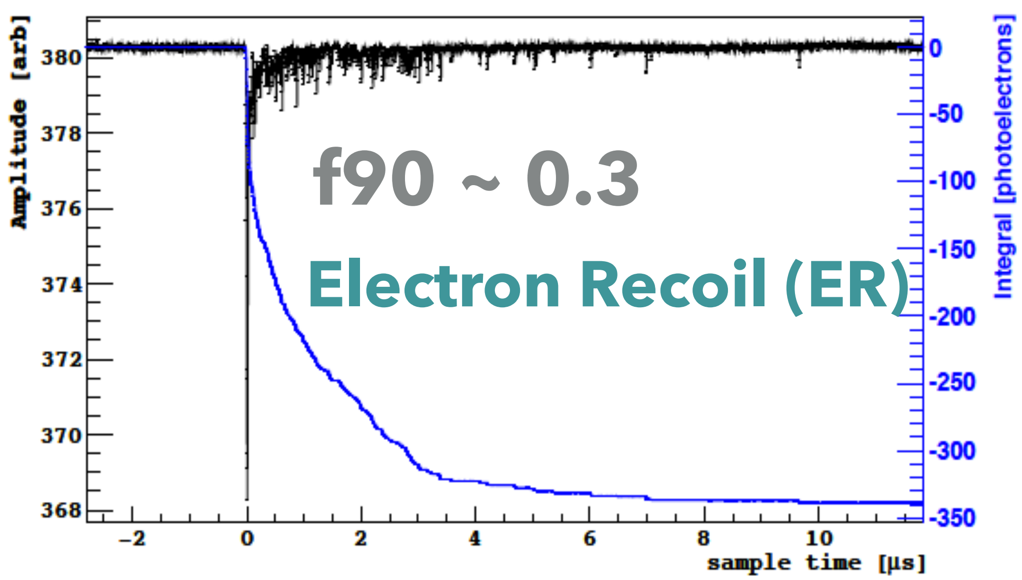
- Electron and nuclear recoils produce different excitation densities in the argon, leading to different **ratios of singlet and triplet excitation states**

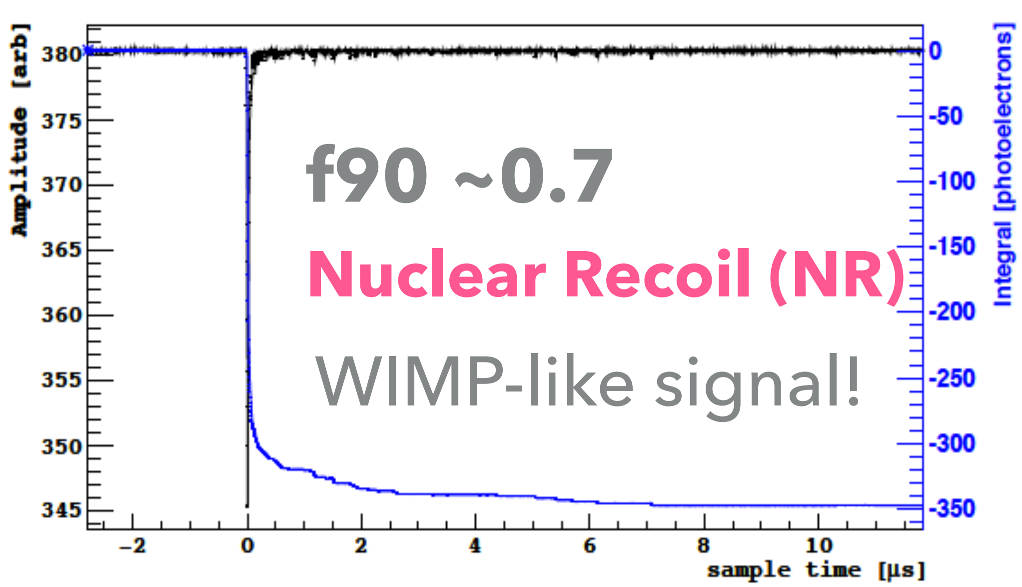
A. Hitachi et al. Phys. Rev. B 27 (1983) 5279

M. G. Boulay and A. Hime, Astropart. Phys. 25 (2006) 179

$\tau_{\text{singlet}} \sim$ 7 ns

$\tau_{\text{triplet}} \sim$ 1500 ns



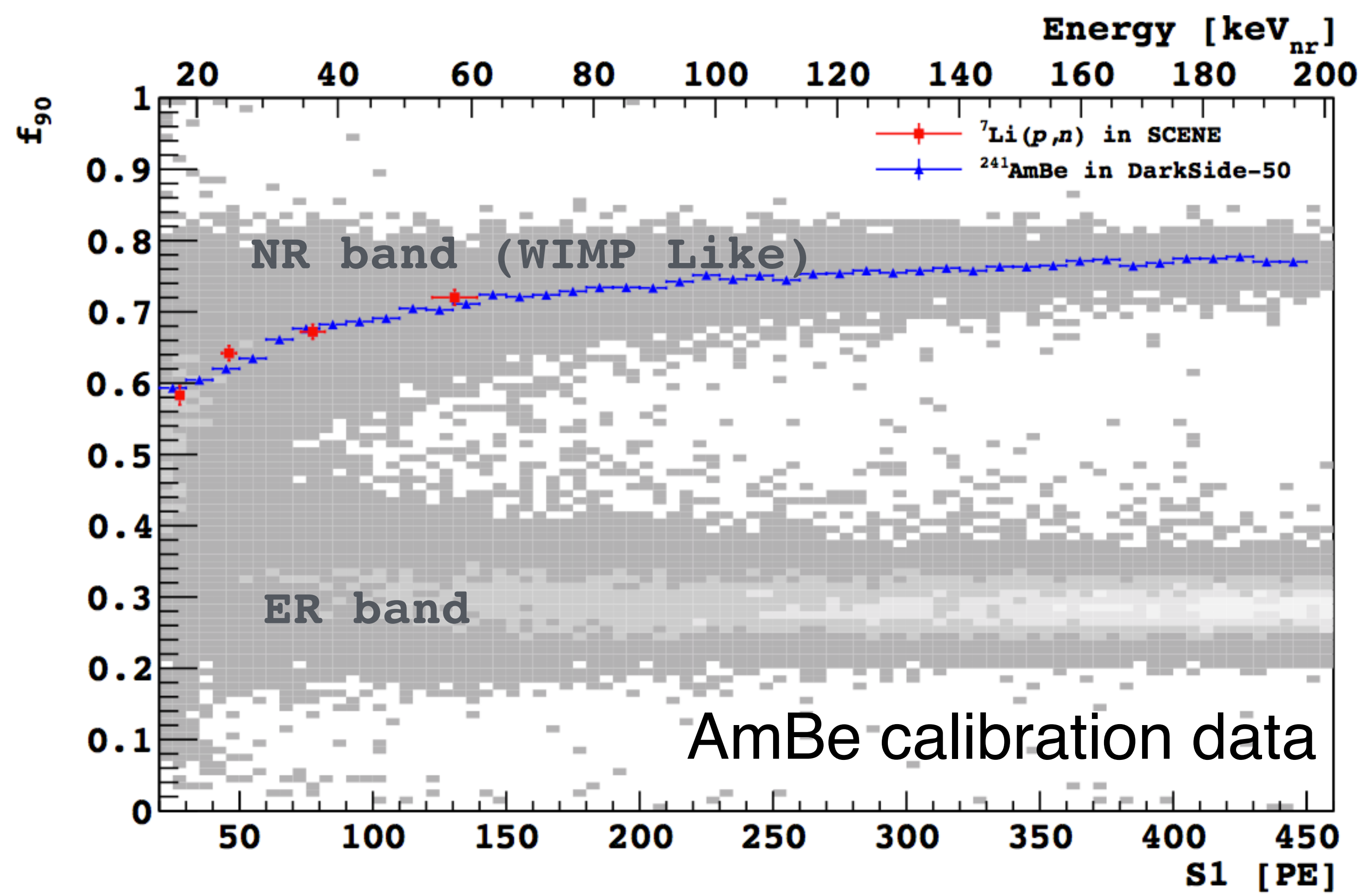


More for PSD: DEAP-3600, Eur. Phys. J. C 81, 823 (2021)

PSD parameter

F90: Ratio of detected light in the first 90 ns*, compared to the total signal

~ Fraction of singlet states

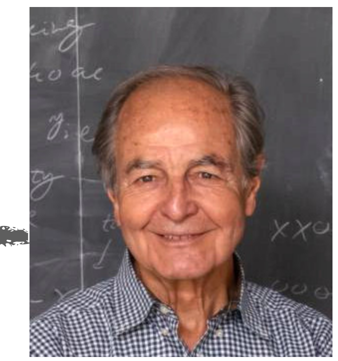


* the 90 ns is optimized value for DS50 and detector dependent parameter.

UNDERGROUND Ar

β & γ Rejection

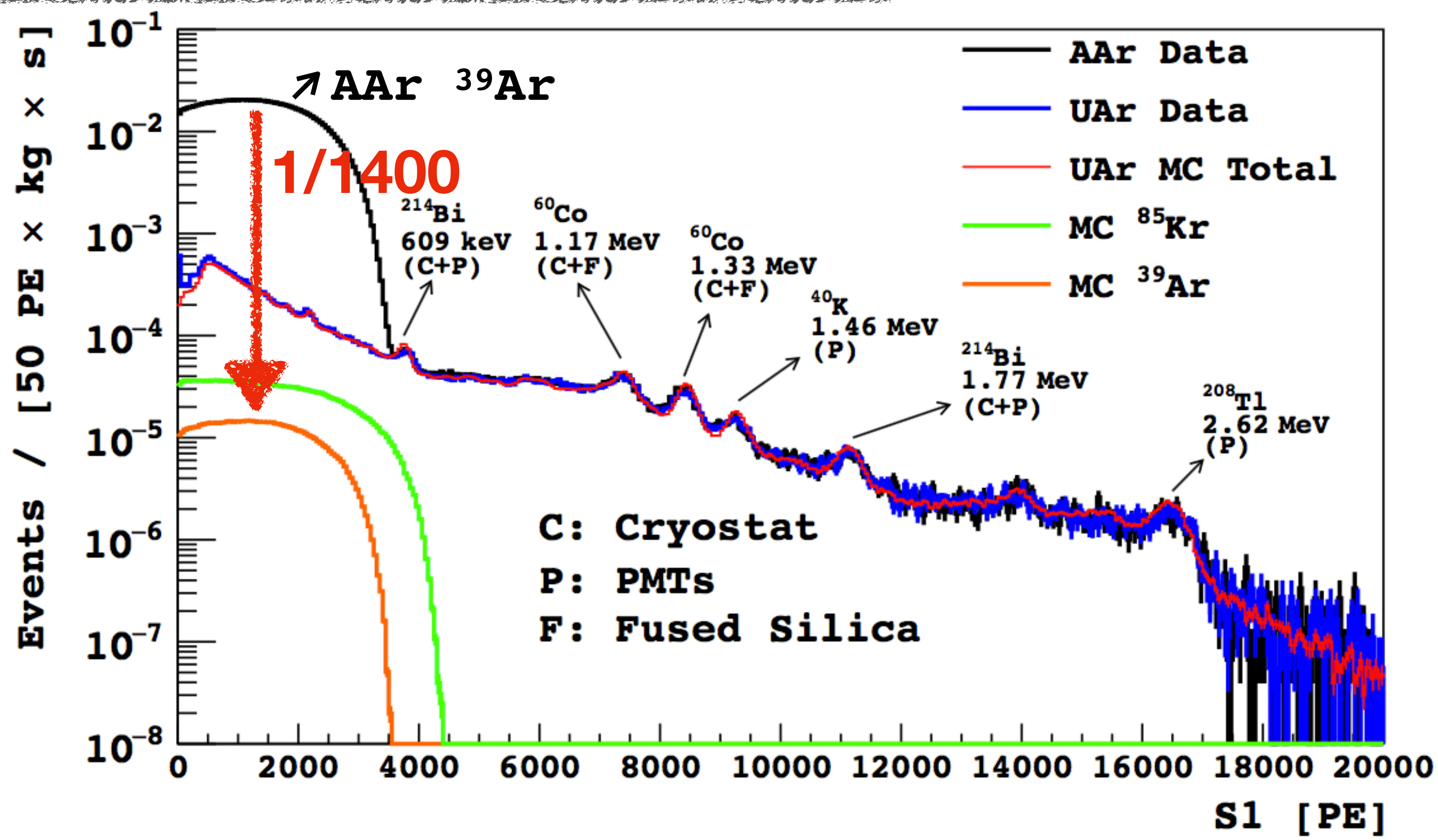
- Intrinsic ^{39}Ar radioactivity in **atmospheric argon** is the primary background for argon-based detectors
- ^{39}Ar activity sets the dark matter detection threshold at low energies (where pulse shape discrimination is less effective)
- ^{39}Ar is a **cosmogenic isotope**, and the activity in argon from **underground sources** can be significantly lower compared to **atmospheric argon**



Frank Calaprice

- We deployed 157kg of underground argon in 2015.

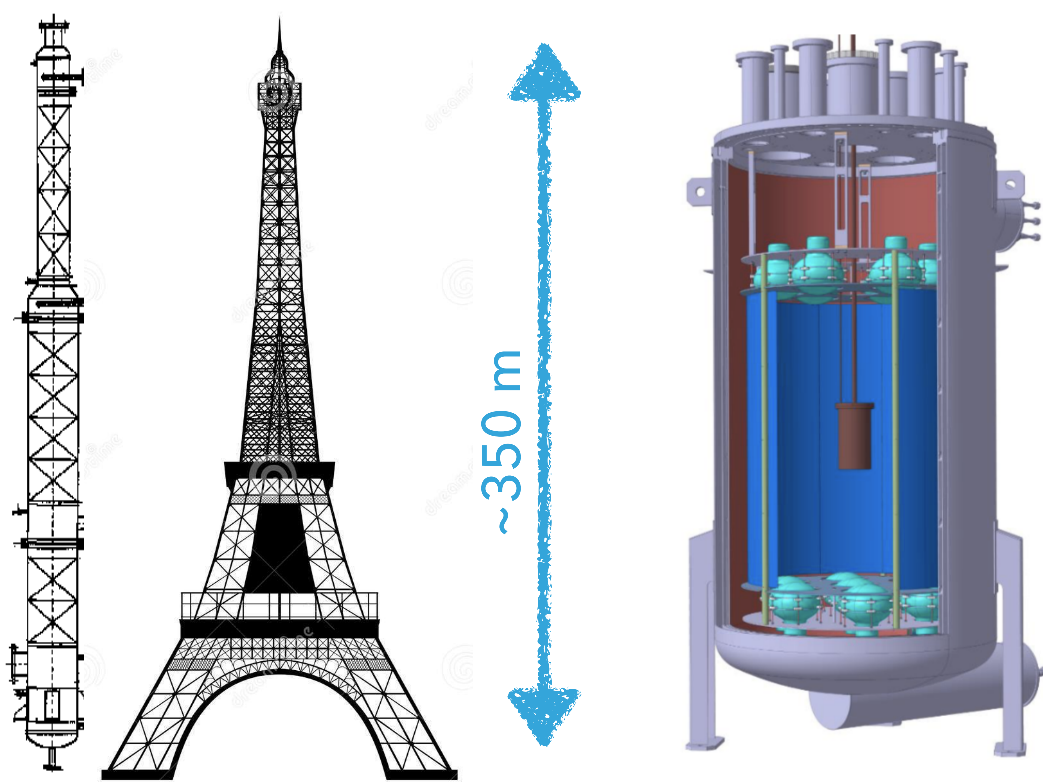
^{39}Ar reduction factor of ~1400!



UNDERGROUND ARGON

See more details in Federico's talk.

- **Urania** (Extraction):
  - Expansion of the argon extraction plant in Cortez, CO, to reach capacity of **330 kg/day** of Underground Argon
- **Aria** (Isotope separation):
  - Very tall column in the Seruci mine in Sardinia, Italy, for high-volume chemical and isotopic purification of Underground Argon. **A factor 10 reduction of ^{39}Ar** per pass is expected with ~10 kg/day.
- **DArT** (assay):
  - A single phase low-background detector to measure the ^{39}Ar depletion factor of different underground argon batches.



ARIA column

DArT in ArDM

WHERE ^{39}Ar COME FROM IN UNDERGROUND Ar?

- We know there were air infiltration operations by the company upstream of our extraction facility.
- In CO2 gas, O2 and Ar concentration are 6.7 ppm and 427 ppm, respectively, by measuring with a gas analyzer.
- Assume **all O2 in the CO2 gas come from the air infiltration**, we can estimate the concentration of Ar originated from air leak by using the Ar:O2 ratio in the air (0.045).
  - [Ar_leak] = 6.7 ppm *0.0045 = 0.3015 ppm
- This means only 0.3 ppm is originated from the air leak and rest of Ar, 427-0.3 = 426.7 ppm, is from UAr (mostly ^{40}Ar).
- So, the ratio of [Ar_leak] to [Ar_UAr] is 0.3015/427 = 7.1e-4.
- It means the concentration of ^{39}Ar originated from air is diluted by this factor relative to AAr after extracting only Ar gas from CO2 gas.
- Thus, the rate/kg of ^{39}Ar due to AAr is 1 Bq/kg * 7.1e-4 = 0.71 mBq/kg.
- If we subtract this from our measured ^{39}Ar rate in DS-50, 0.73 mBq/kg, we get 0.02 mBq/kg = 20 uBq/kg. The **depletion factor of 50,000** relative to AAr and **36.5 relative to UAr in DS-50**.

Source Henning Back's old presentation

HOW ABOUT ^{85}Kr?

- Using the Kr:O2 ratio in the air (5.44e-6)
  - [Kr_leak] = 6.7 ppm * 5.44e-6 = 3.65e-5 ppm
- This further concentrated by extraction of Ar (427 ppm of Ar), assuming the same extraction efficiency as Ar.
  - 3.65e-5 ppm/ 427 ppm = 8.54e-8 = 0.854 ppb in UAr.
- Convert to mol/kg by using the atomic mass of Ar (1kg = 25.03 [mol]),
  - 0.845e-9*25.03 = 21.15e-9 mol/kg of Kr.
- Concentration of ^{85}Kr in natural Kr is ^{85}Kr / ^{nat}Kr = 2e-11 [1].
- So, the concentration of ^{85}Kr is 4.23e-19 mol/kg = 2.55e+5 atom/kg.
- R_0 = 2.55e+5/tau = **0.52 mBq/kg**, where tau for ^{85}Kr is 4.89e+8 s (10.76 yrs).
- The rate of ^{85}Kr decay observed in DS-50 is estimated as R0 = **2 mBq/kg** by G. Koh [2].
- Thus, estimation of ^{85}Kr concentration based on the air-infiltration is ~4 times less than we measured in DS50.
- Given the uncertainties, the order agreement support that **^{85}Kr is from the air-infiltration**.

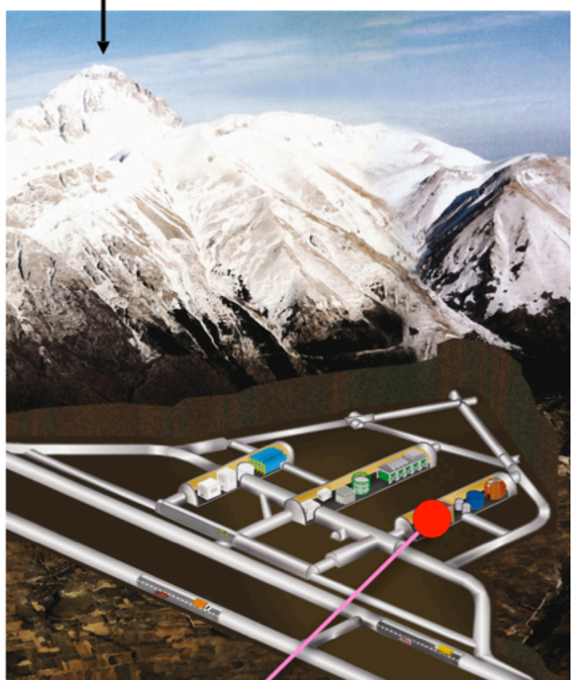
Possible reduction of ^{39}Ar and ^{85}Kr by fixing air infiltration.

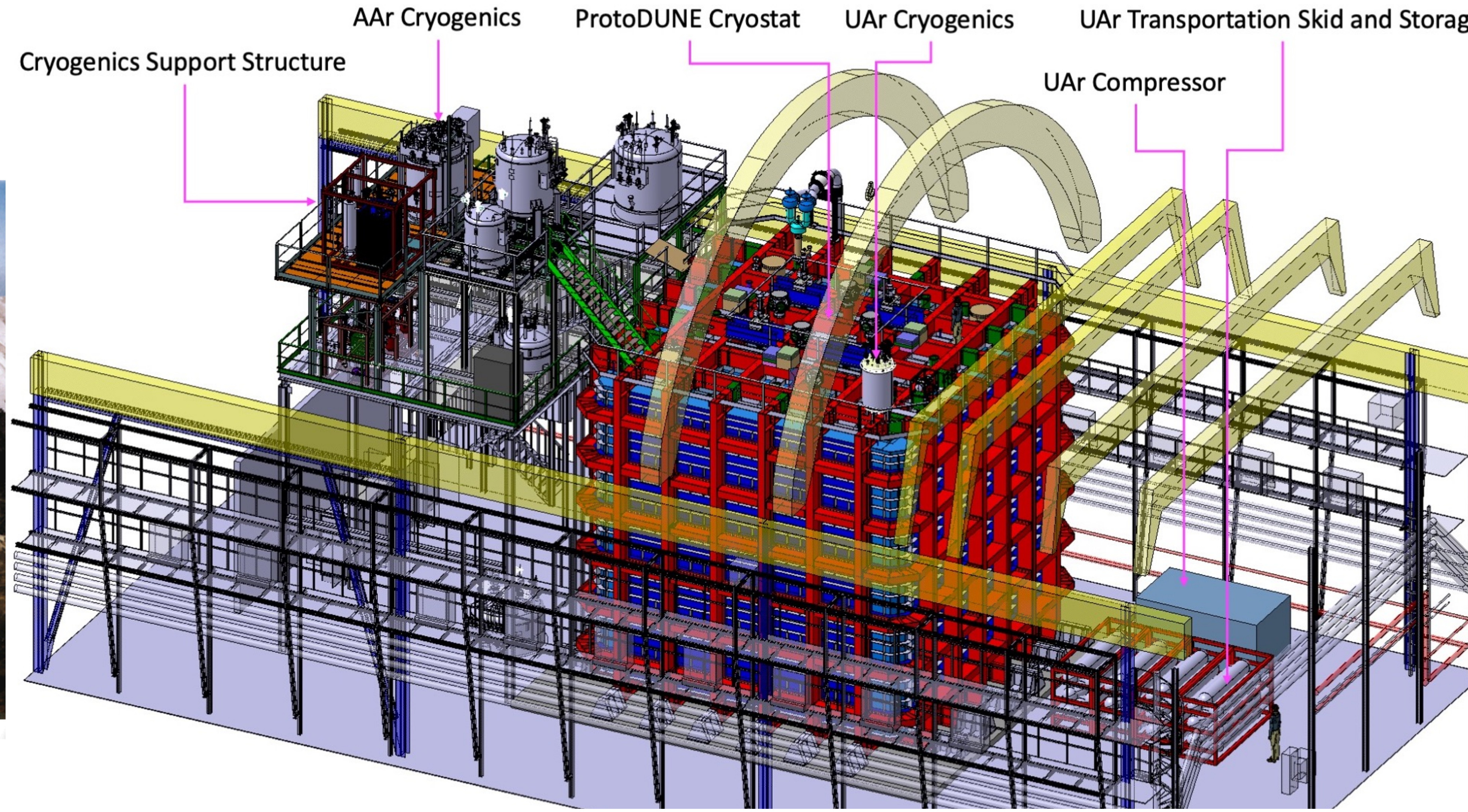
[1] S. Lindemann, and H. Simgen, Eur. Phys. J. C 74, 2746 (2014).
[2] G. Koh PhD dissertation “A dark matter search with DarkSide-50” (2018)

HIGH MASS WIMP SEARCH

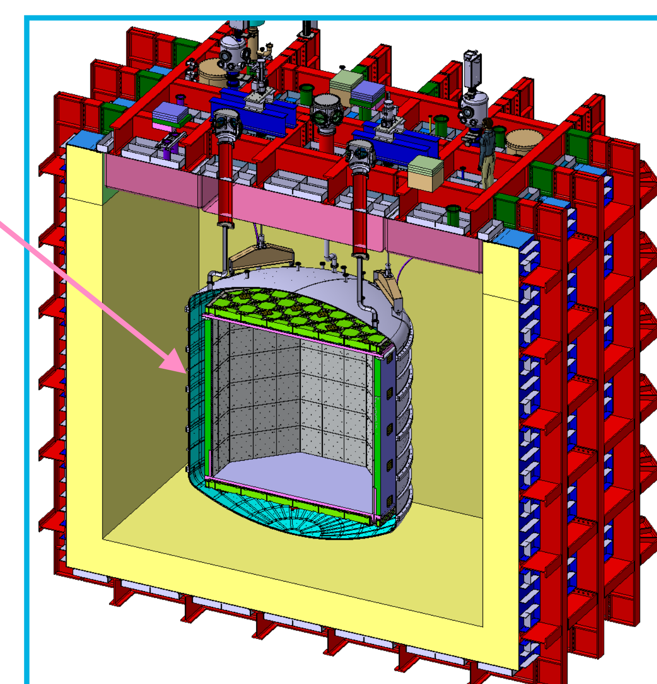

Gran Sasso
3800 m w. e.
Deep underground location at LNGS, Italy.
Slovenia
Zagreb
Trieste
Como
Milan
Verona
Venice
Padua
Turin
Croatia
Bosnia and
Herzegovina
Genoa
Bologna
Zadar
Sarajevo
Pisa
San Marino
Monaco
Cannes
Florence
Split
Italy
Adriatic Sea
National Institute
for Nuclear Physics...
Corse
Rome
Bari
Naples
Pompeii
Matera
Taranto
Lecce
Sardegna
Tyrrhenian Sea
Cagliari
Reggio

DARKSIDE-20K DETECTOR

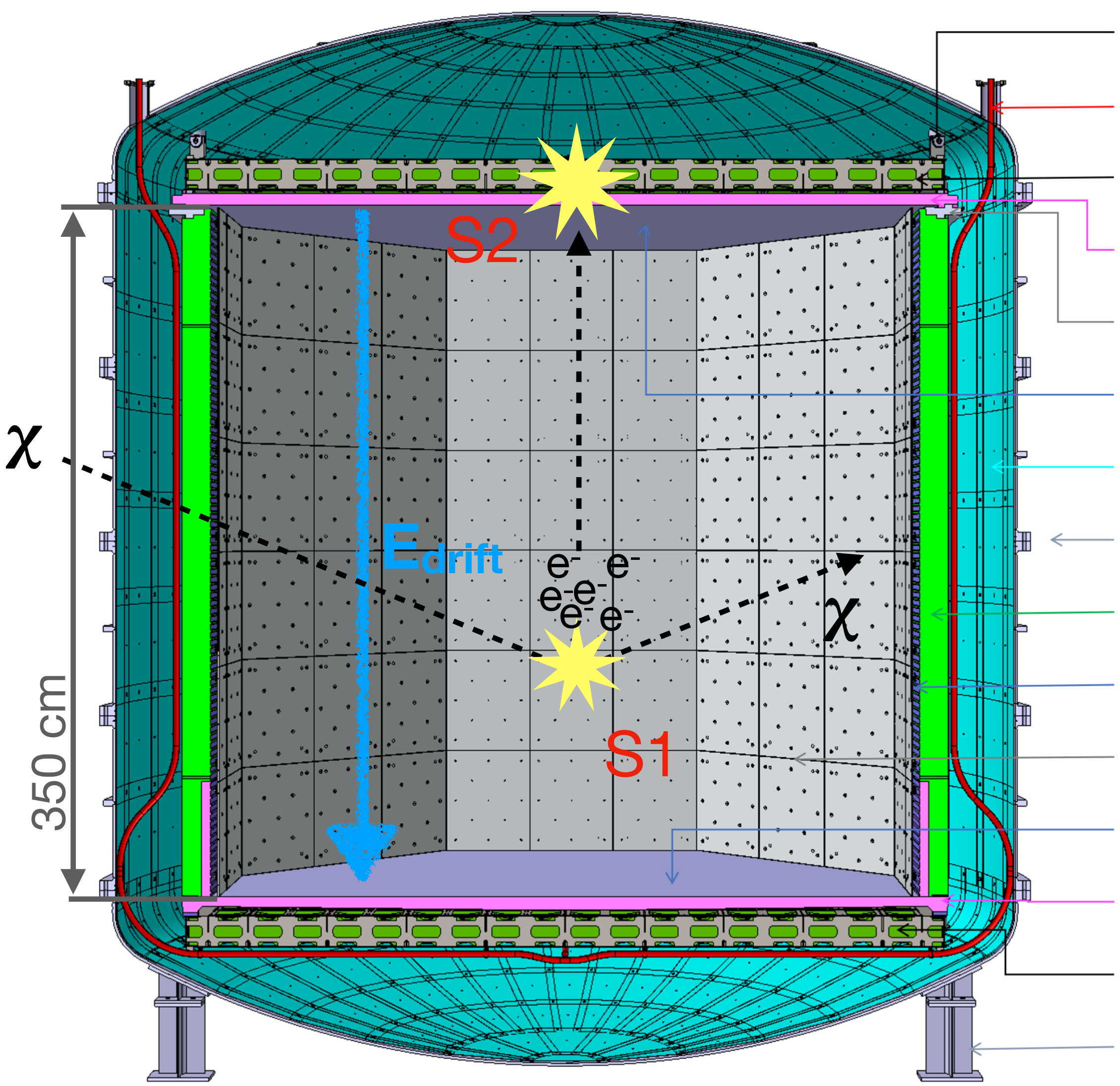


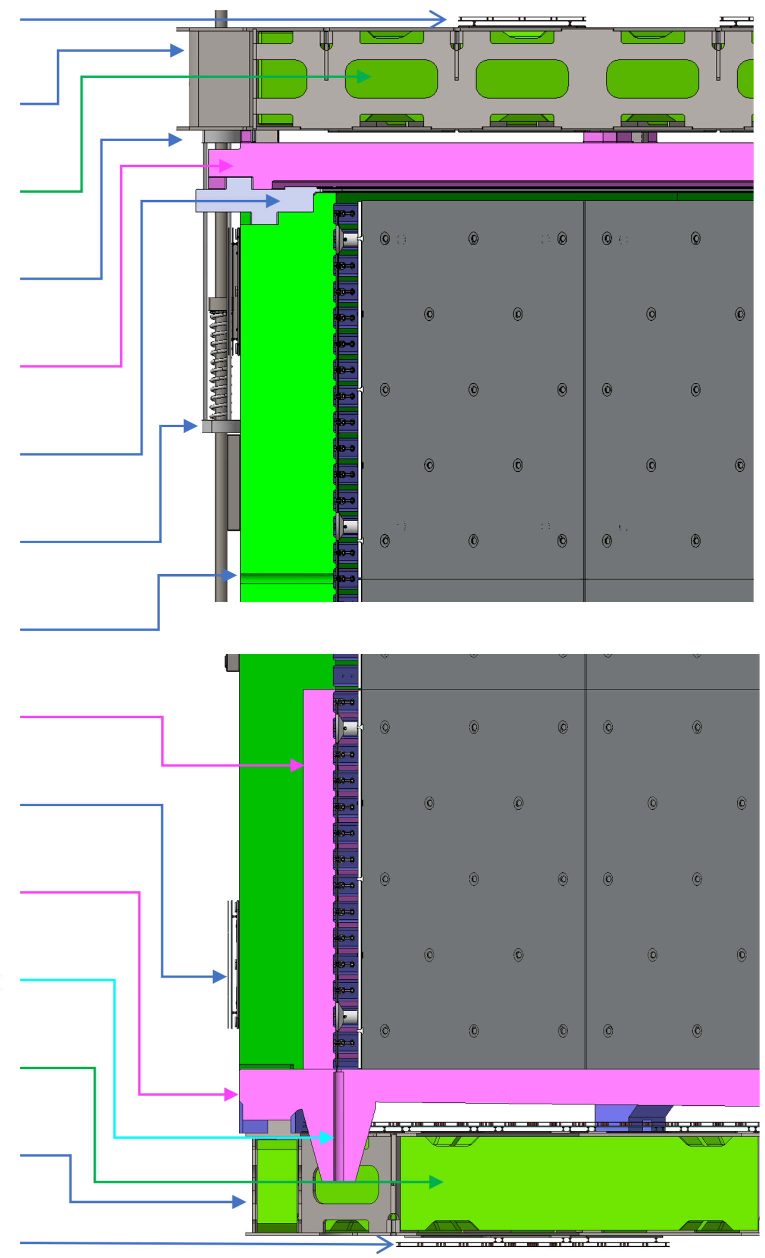


- DarkSide-20k will be installed underground at the Gran Sasso National laboratories, in Italy.
- The detector has a nested structure:
  - Titanium Vessel contain liquid underground argon (100 t)
    - Gadolinium loaded acrylic TPC filled with 50 t of UAr
    - Neutron veto buffer between TPC and Ti vessel
  - Membrane cryostat like the ProtoDune one



TIME PROJECTION CHAMBER





- Gd-doped acrylic, PMMA (polymethylmethacrylate), vessel to capture neutrons
- Octagonal shape
- Cathode and anode coated with new transparent conductor (Clevios) and wavelength shifter
- Grooves with Clevios for field cage (No copper rings)
- Wire grid for extraction and electroluminescence fields
- Sides covered with multilayer polymeric reflector evaporated with wavelength shifter (TPB)
- SiPMs planes external to anode and cathode

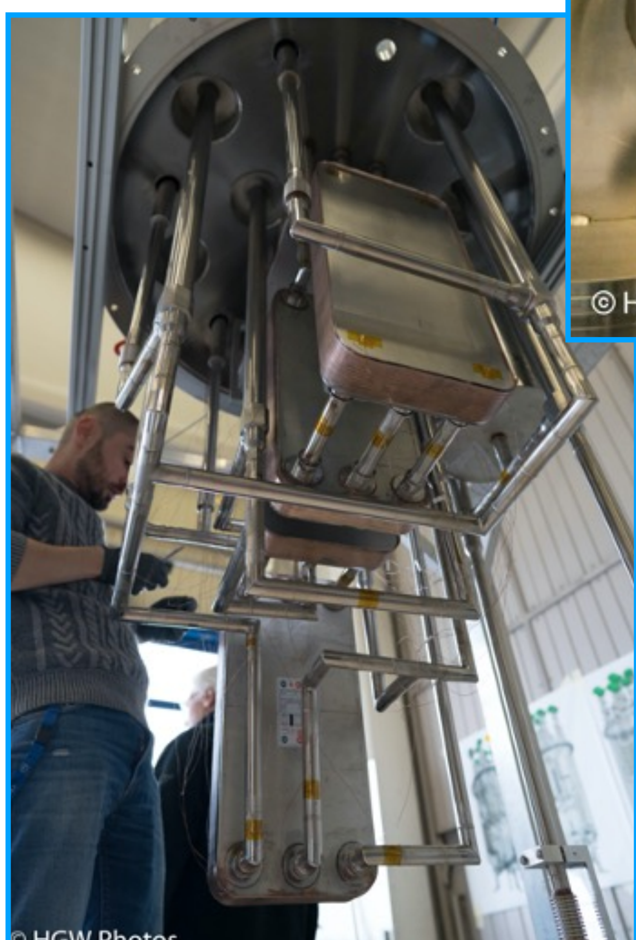
Yi's talk covers more

CRYOGENIC SYSTEM FOR TPC

- Integrated test of the UAr cryogenics is ongoing at CERN.
- Up to 10 kW (latent heat + heat exchanging) adjustable condenser box.
- 1000 SLM circulation speed with two homemade pumps in parallel.
- The first test was taken in July 2021.
- More tests are planned later this year.

DarkSide unique condenser design

Fully instrumented condenser system



In-house fabrication of the gas handling system

TPC Cryogenic system (test installation) at CERN

PHOTO SENSOR

See Giacomo's talk

- Custom cryogenic SiPMs developed in collaboration with Fondazione Bruno Kessler (FBK), in Italy.
- Key features
  - Photon detection efficiency (PDE) ~45%
  - Low dark-count rate < 20 cps
  - Timing resolution ~ 10 ns
- The 28m^2 for the TPC (2112 channels) + 480 channel for Veto detector. Mass production of the raw wafer in LFoundry company and assembly in a dedicated facility at LNGS (NOA).

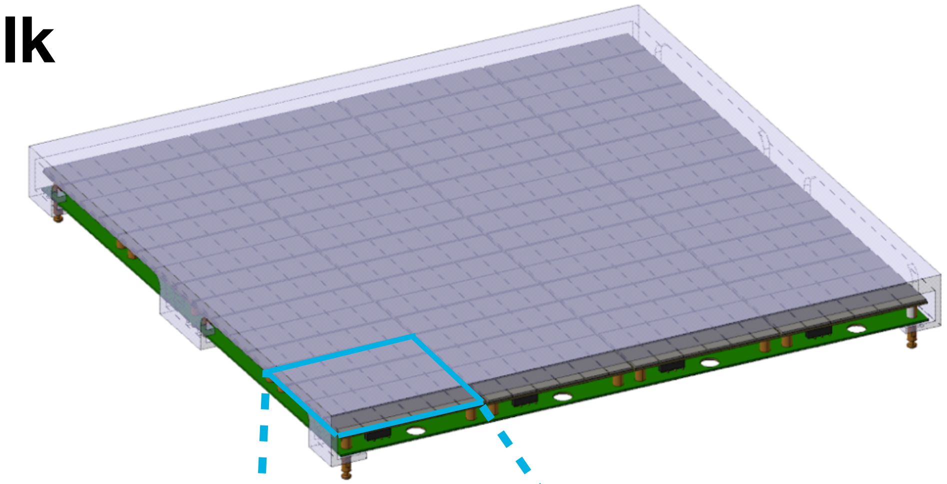
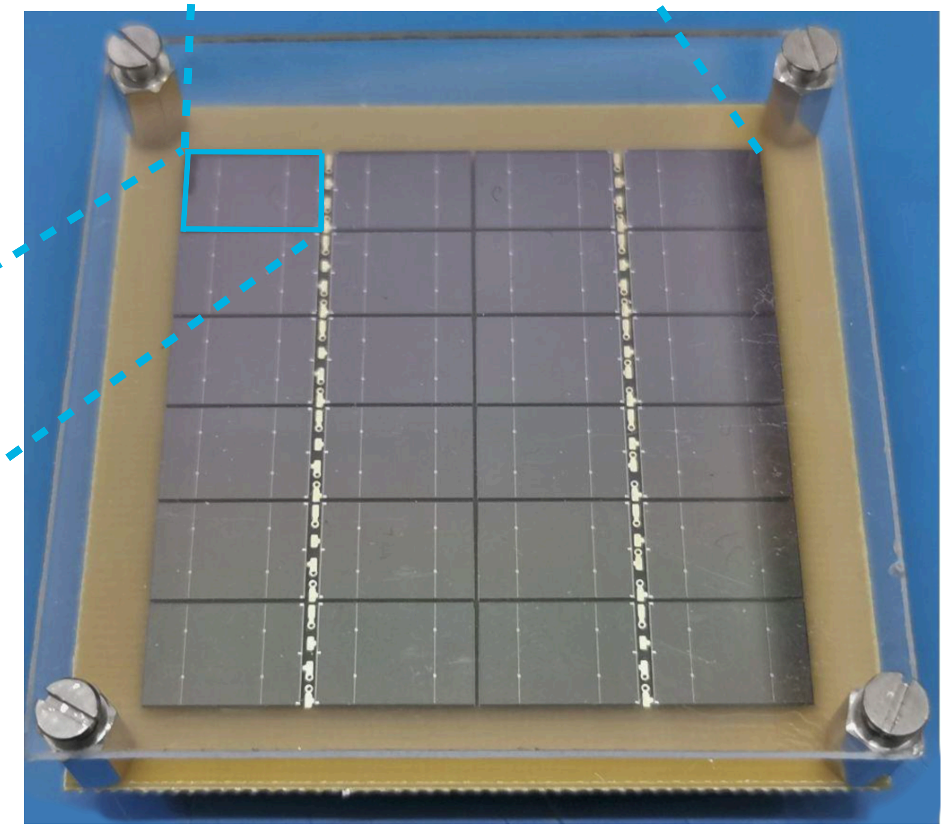
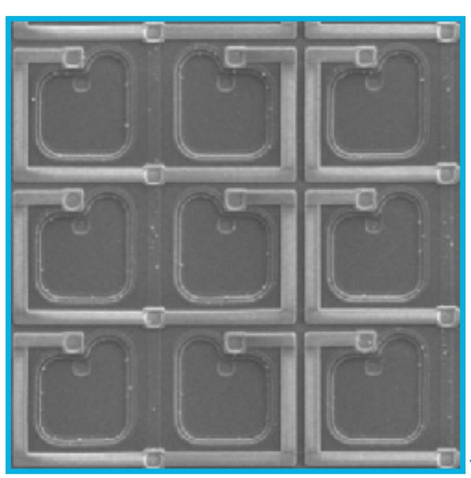


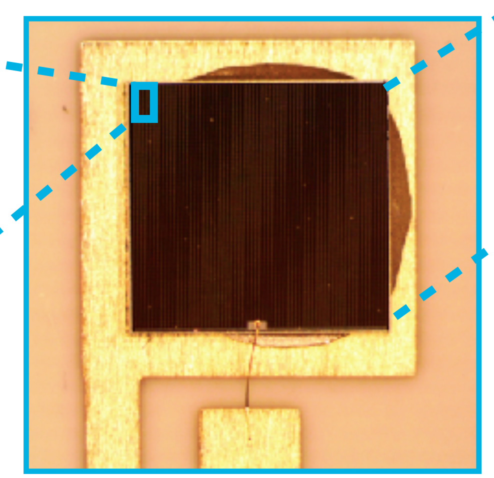
Photo Detector Unit (PDU) = matrix of 16 PDMs
20 x 20 cm^2





Single SPADs

~25-30 μm^2



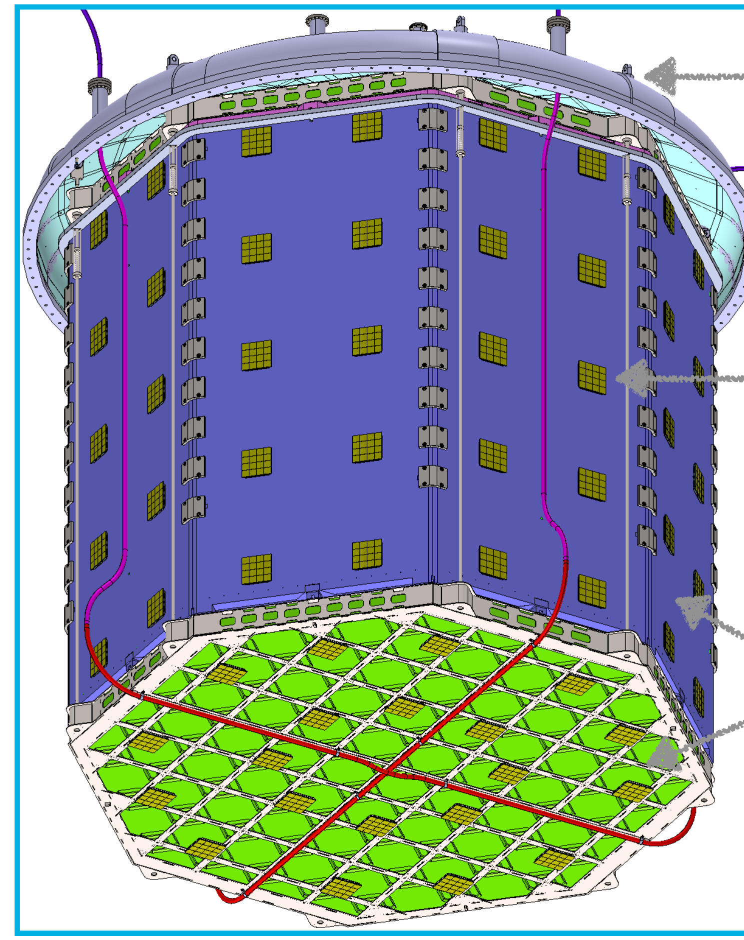
Single SiPM

~1 cm^2

Photo Detector Module (PDM)
= matrix of 24 SiPMs, 5 x 5 cm^2
4 PDUs are summed and read as a single channel
(largest single SiPM unit ever!)

VETO DETECTOR

Neutrons elastically scattering from argon nuclei are indistinguishable from WIMPs signals. PSD is useless against neutron events.

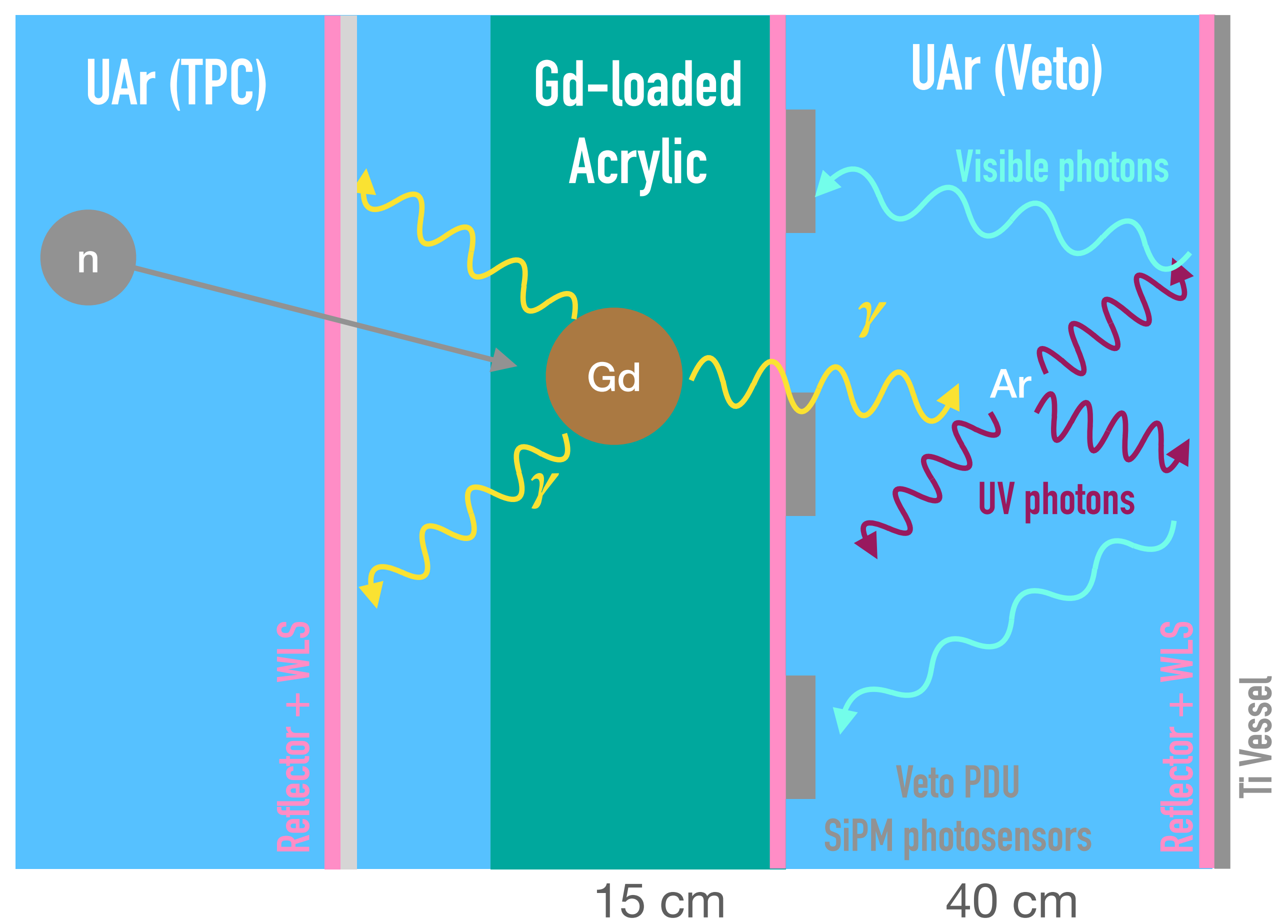


Veto Structure

- 8 vertical panels of acrylic loaded with gadolinium (Gd-PMMA), form lateral walls of the TPC. Acrylic thickness: 15 cm.
- The UAr volume between the Ti vessel and Gd-PMMA serves as a veto volume with ~40 cm thickness.
- Reflector with WLS on all the surfaces

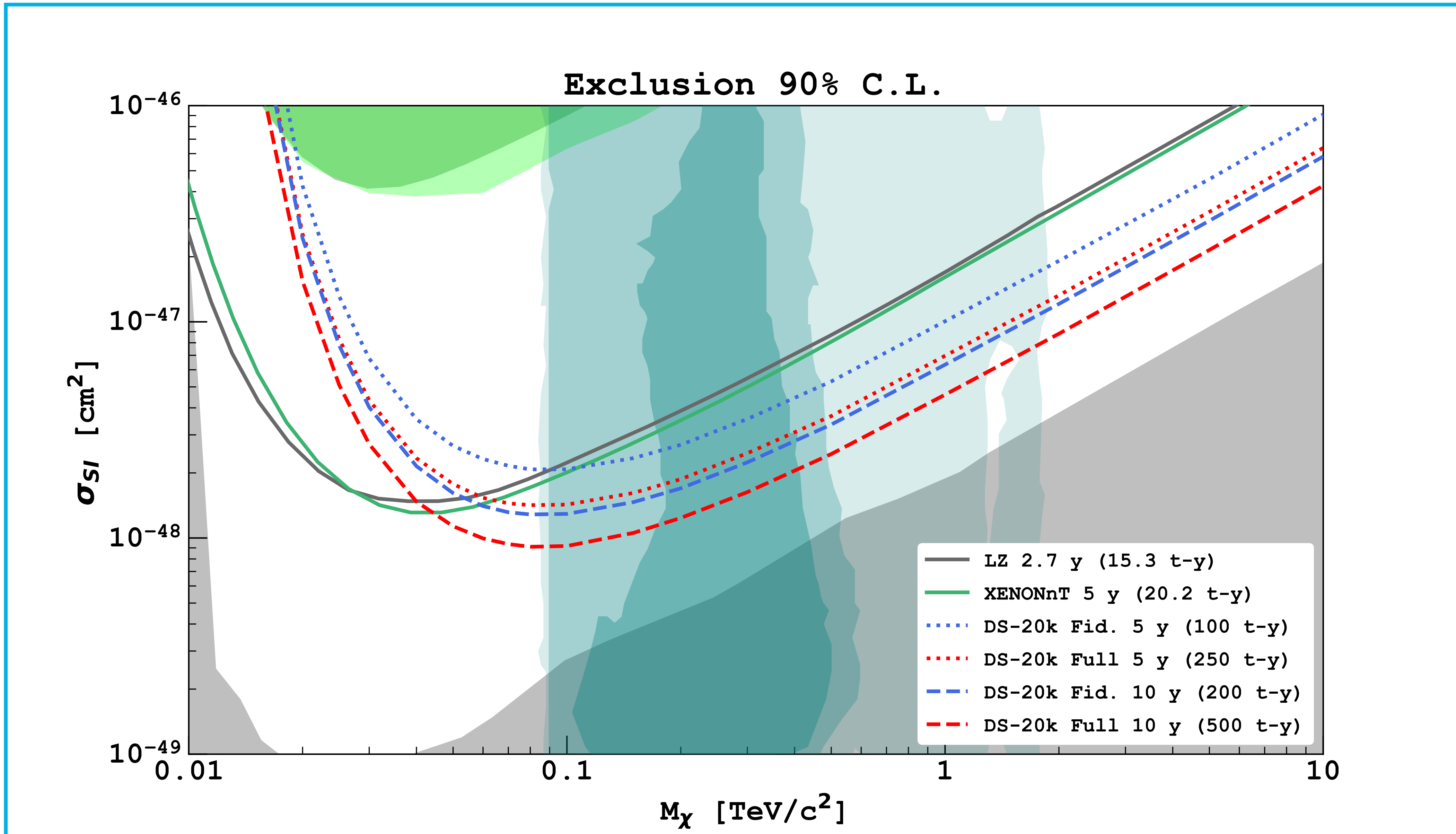
Veto Working Principle

1. Neutrons are moderated in the acrylic shell and then captured by gadolinium.
2. Gd emits multiple γ-rays with energy up to 8 MeV.
3. γ-rays interact in the liquid argon buffers.
4. LAr scintillation light is shifted and detected by ~1920 SiPM-based photosensors.



EXPECTED SENSITIVITY

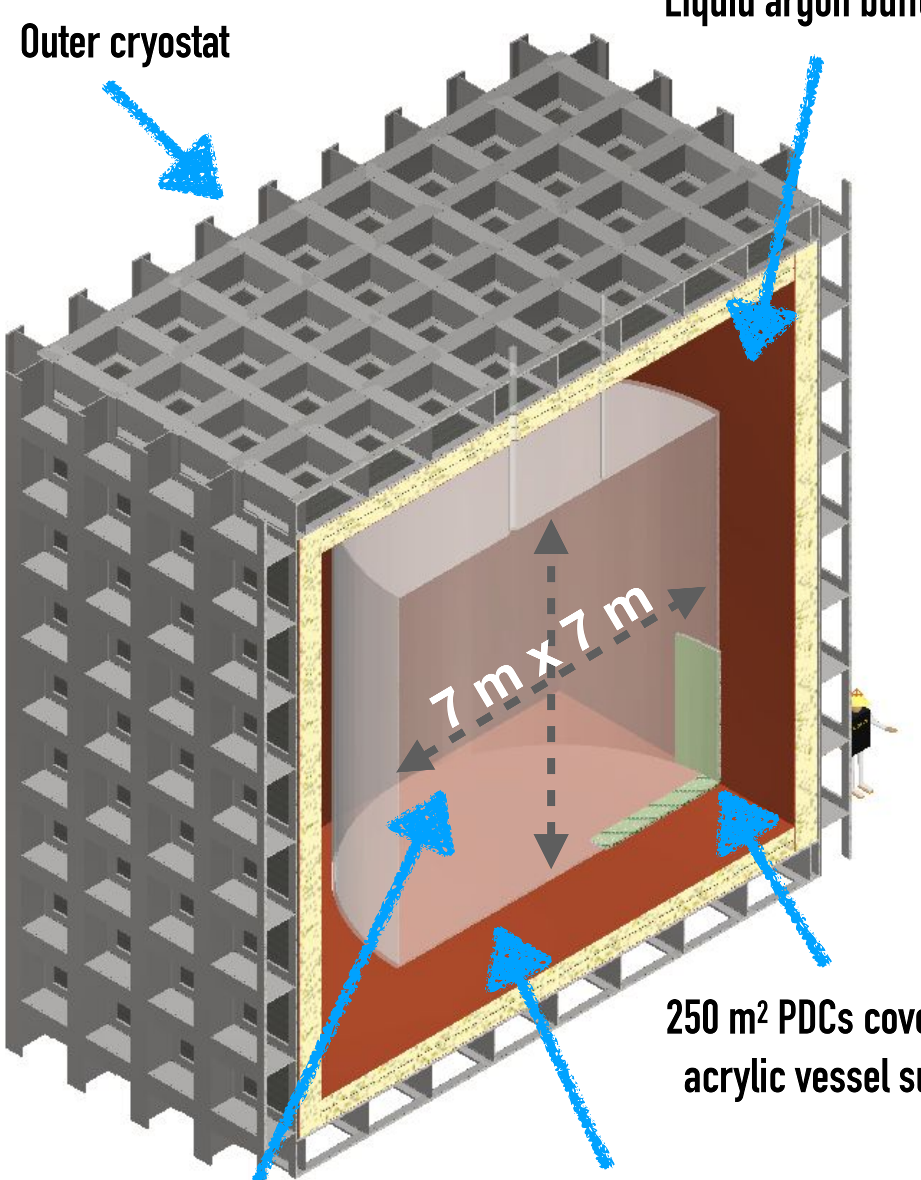
- The sensitivity of DS-20k to spin independent WIMPs for different lengths of runs, with the full exposure and with the fiducial cuts applied, compared to LZ and XENONnT.



- The present projection - based on a 10 yr run, giving a fiducial volume exposure of 200 t yr - is 6.3×10^{-48} cm^2 for 1 TeV/c^2 WIMP for the 90% C.L. exclusion.

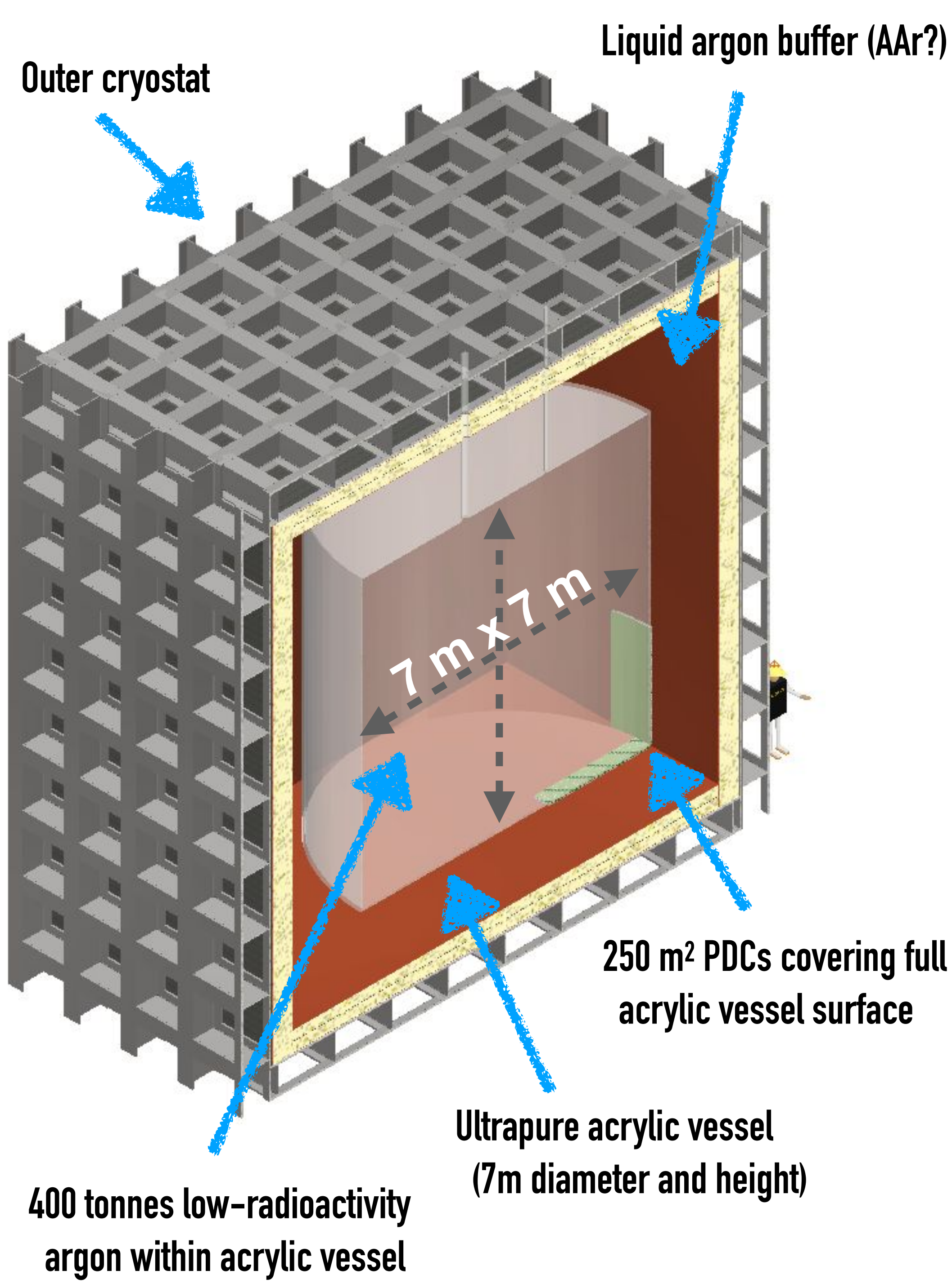
Turquoise filled contours is from pMSSM11 model (E. Bagnaschi et al., Eur. Phys. J. C 78, 87 (2018).

ARGO



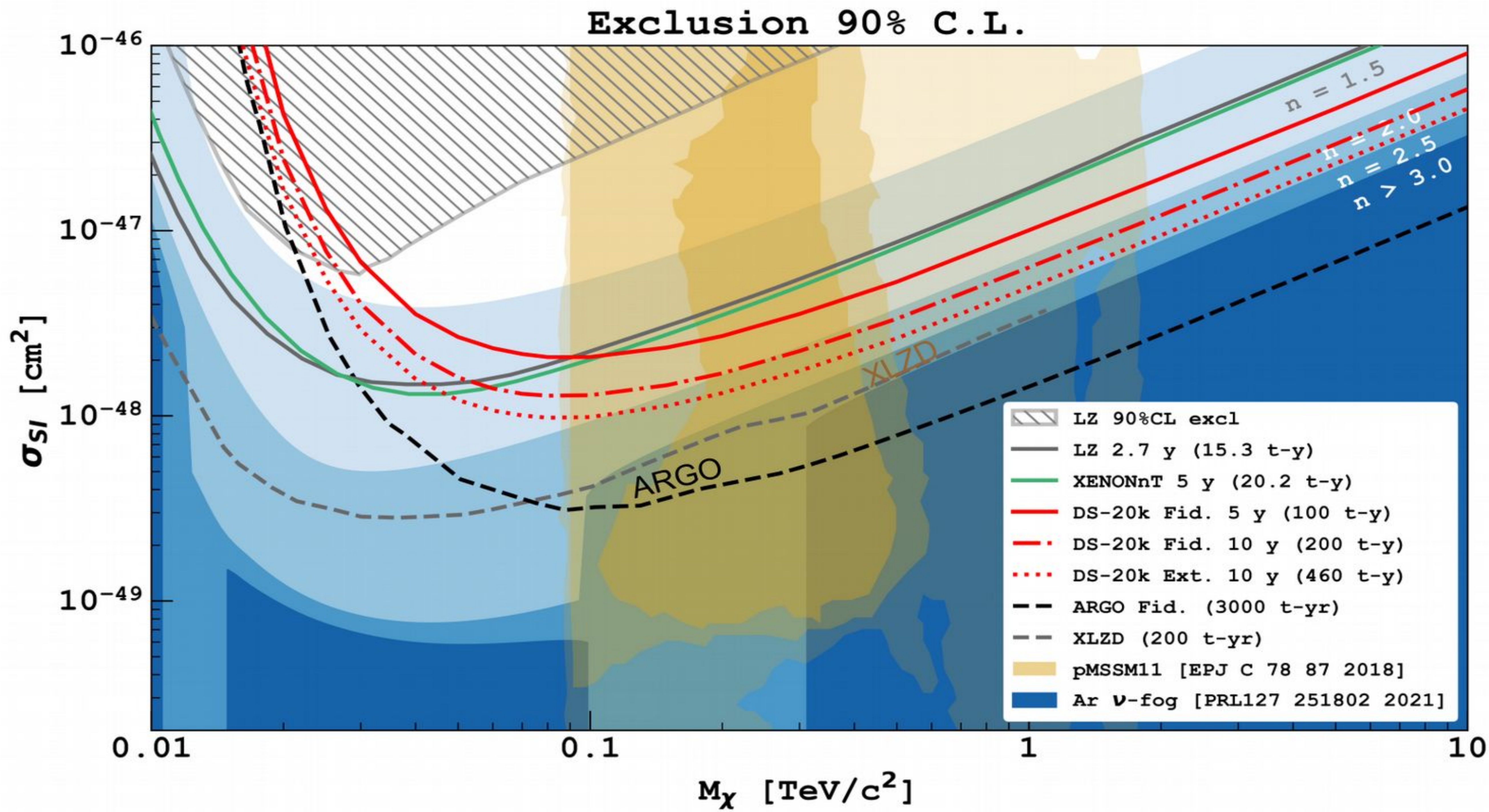
- Location is most likely at SNOLAB.
- Considering front-side SiPMs with wavelength shifter and backside-illuminated VUV-sensitive SiPMs.
- Both options as photon-to-digital converters (PDCs).
- Data rates:
  - nominal 5000 photons/sec/m^2
  - calibration 100k photons/sec/m^2 (max. around 250 Mbytes/s)
- Currently, considered to be single phase. TBD
- Event vertex reconstruction and particle ID using spatial and temporal photon hit pattern.
- Inner 300 tonnes of low-radioactivity argon used in dark matter search.

ARGO



- Questions to be addressed:
  - UAr or AAr for LAr buffer?
    - If UAr, production and storage limited.
    - If AAr, how to separate UAr from AAr? Tight seal w/ acrylic vessel is difficult.
  - SiPMs w/ WLS or VUV-SiPMs w/o WLS?
    - If VUV-SiPMs, PDCs need to be in the acrylic vessel. How penetration for power and signals can be done?
  - Where to store depleted UAr? Activation of ^{39}Ar low enough?
- BG questions:
  - Does PSD strong enough to suppress 0.73 mBq/kg ^{39}Ar x 300 tonne x 10 years (~7e10 evts)? DEAP-3600 achieved ~3.4e-10 PSD suppression.
  - Any neutron veto? High energy neutrons will penetrate the LAr buffer.
  - Degraded alpha from surface can be well located in single phase? How about pile up with S2-only events in double phase?
  - How degraded alpha from dust can be mitigated if the acrylic vessel is sealed?

PROJECTED SENSITIVITY



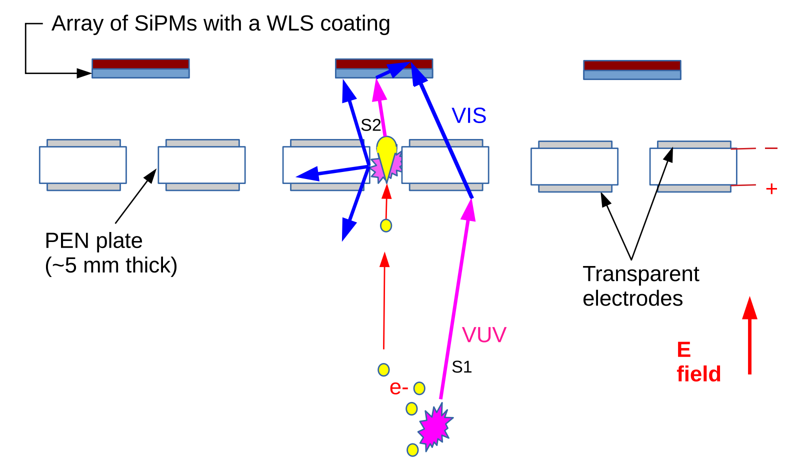
- Down to ν-fog based on simple extrapolation.

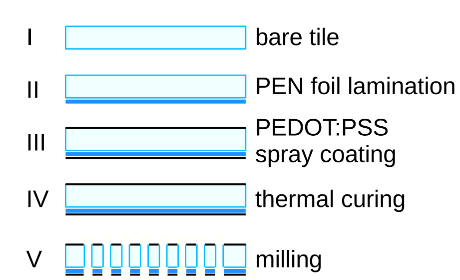
WHAT WE LEARNT SO FAR…

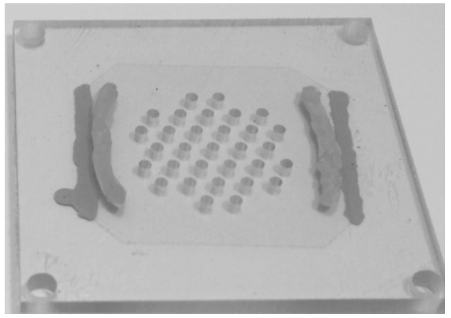
- Main BGs and mitigation methods
  - γ: SiPMs –– pure materials; fiducialization
  - β: ^{39}Ar, ^{85}Kr –– cryogenic distillation; better extraction facility
  - degraded **α**: Rn, dust (seen in DEAP3600) –– keep detector cold as much as possible; clean construction procedure; liquid phase circulation.
  - neutron: detector materials (**α**,n), cosmogenic –– less materials close to the fiducial volume; deeper site; neutron veto.
  - Combined:
    - S1 from **α** and S2 from pileup S1+S2 from γ or β –– less **α**; better reconstruction for S1+S2 separation
    - S1 and S2 from γ or β + Cherenkov –– less material for Cherenkov; fiducialization

CHALENGES FOR LAr ~300 TONNE DETECTOR

- Wavelength Shifter
  - TPB works! But it need a large vacuum chamber, production takes time…
  - Alternative
    - PEN (See M. Kuzniak's talk at DRD Meeting)
    - Dissolving TPB (or other WLS) into LAr
- UAr extraction
  - Risk at the extraction site – the company stop extraction when the price of their products go down.
- Well defined E-field and gas pocket (TPC application only)
  - Large area wire grid – Sagging
  - Large area anode and cathode – Sagging (experienced in DS-50), ITO, conductive polymers, or other solution?
  - Alternative
    - Floating GEM (transparent electrodes+ PEN for WLS). Scalable and sustainable without supporting structures. Insensitive to small variation of gas pocket size.







M. Kuźniak et al. Eur. Phys. J. C **81**, 609 (2021)

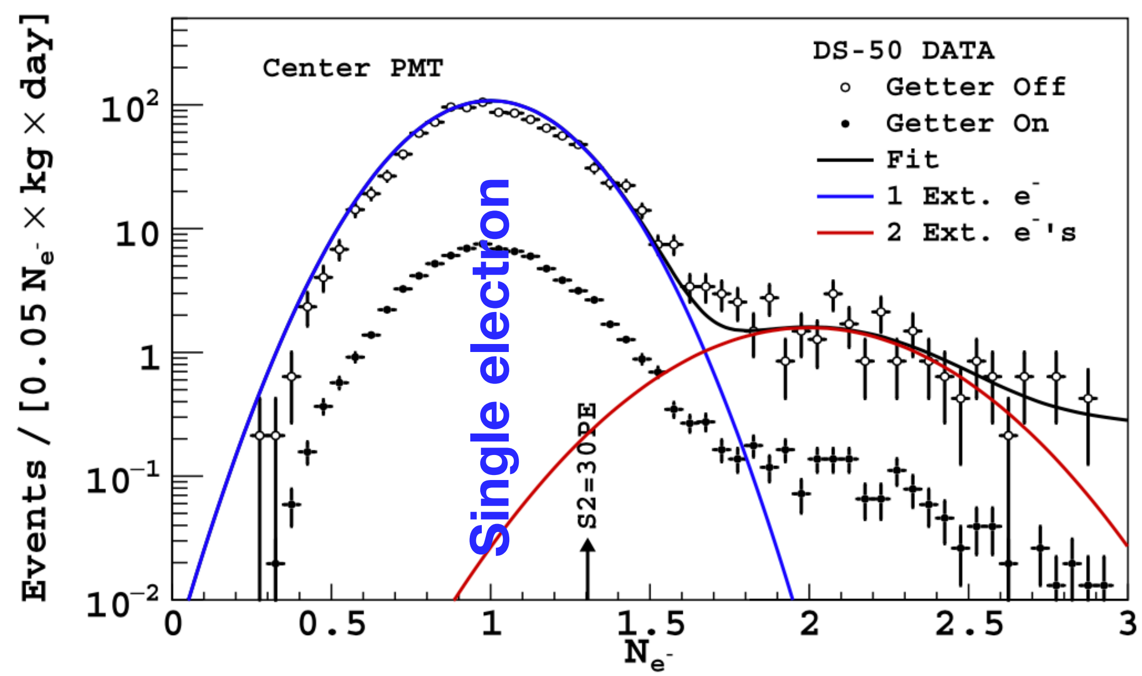
LOW MASS WIMP SEARCH

Ionization Only Channel

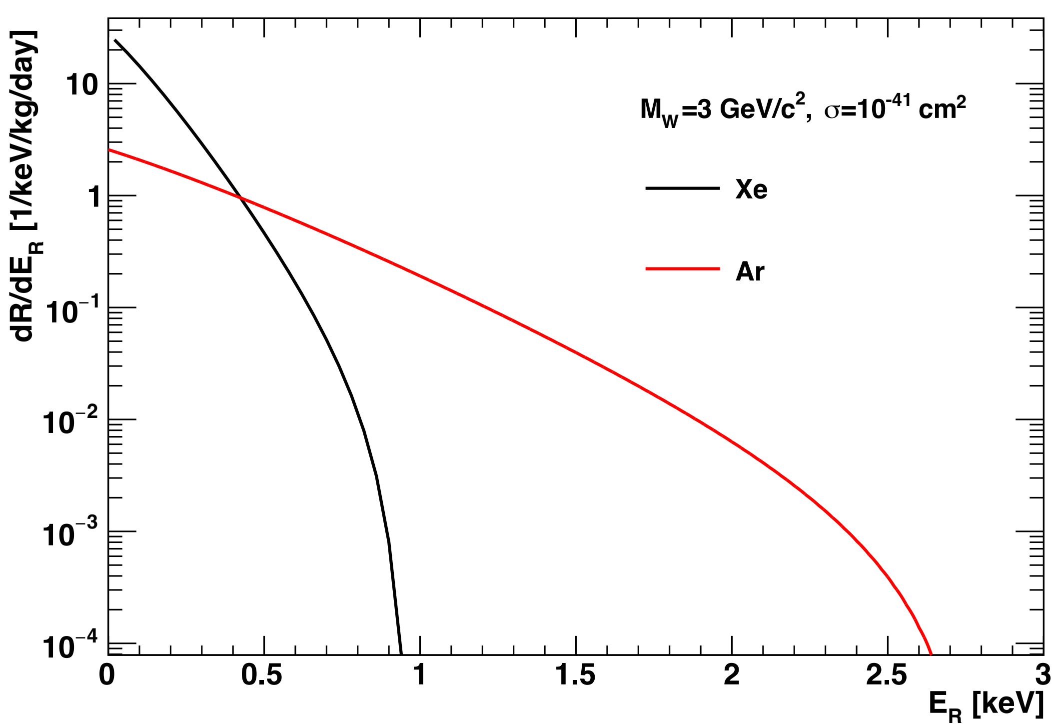
LOW MASS WIMP SEARCH

- **Scintillation signal** (S1): threshold at ~2 keV_{ee} / 6 keV_{nr}
- **Ionization signal** (S2): threshold < 0.1 keV_{ee} / 0.4 keV_{nr} **Can go lower threshold!**

- Use Ionization (S2) Only.
  - Amplified in the gas region (~23 PE/e^- or more)
  - **Sensitive to a single extracted electron!**
  - The electron yield for nuclear recoils increases at low energy



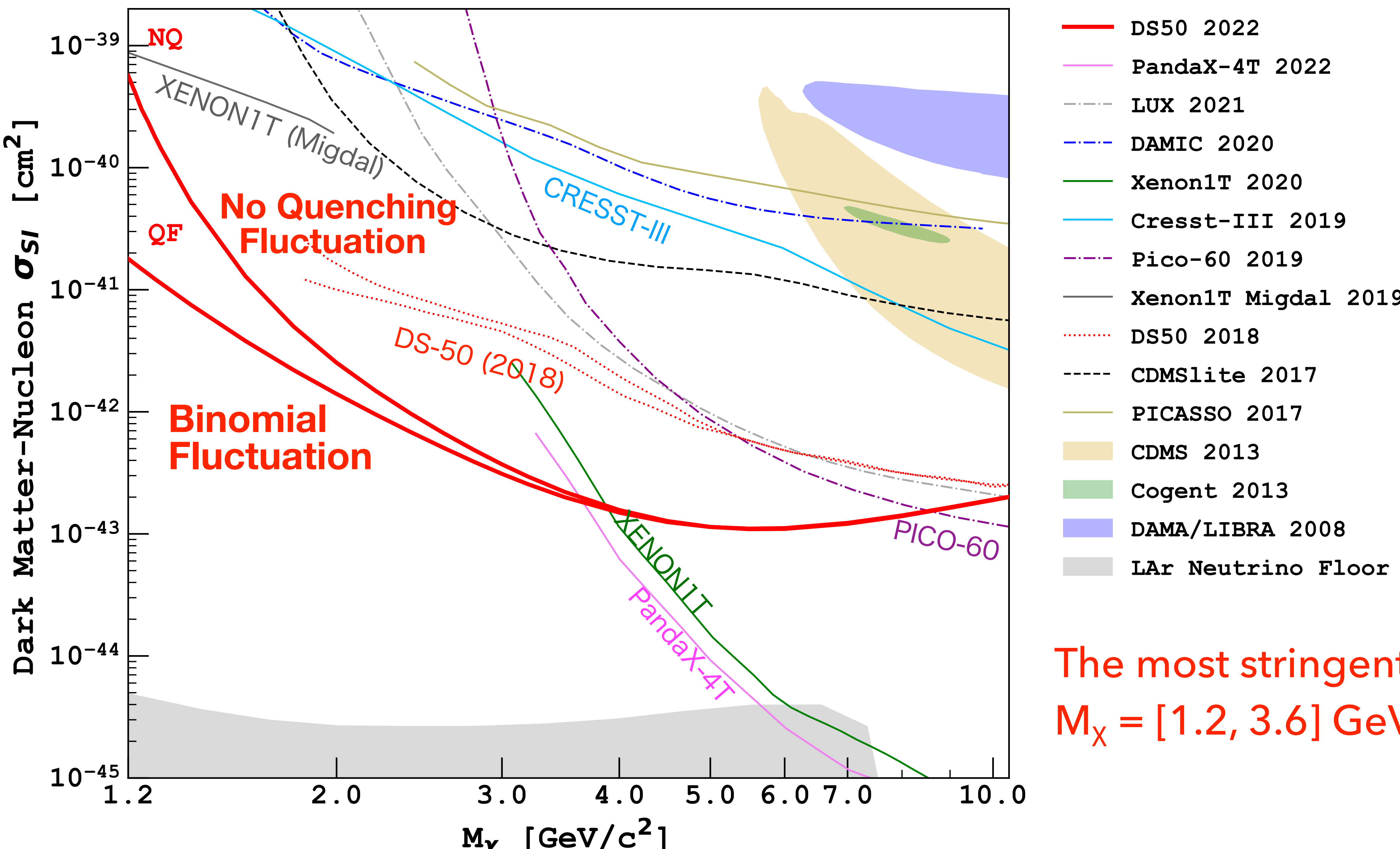
WIMP spectra in Xe and Ar



- Ar has lighter mass than Xe. So, more efficient momentum transfer from low mass DM.

WHAT WE ACHIEVED IN DS-50

Phys. Rev. D 107, 063001



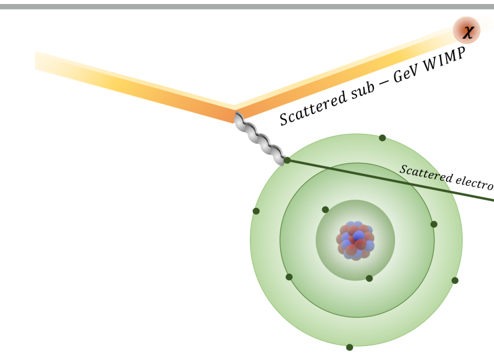
The most stringent limit at M_χ = [1.2, 3.6] GeV/c^2

Annual modulation analysis on arXiv!

arXiv:2307.07249

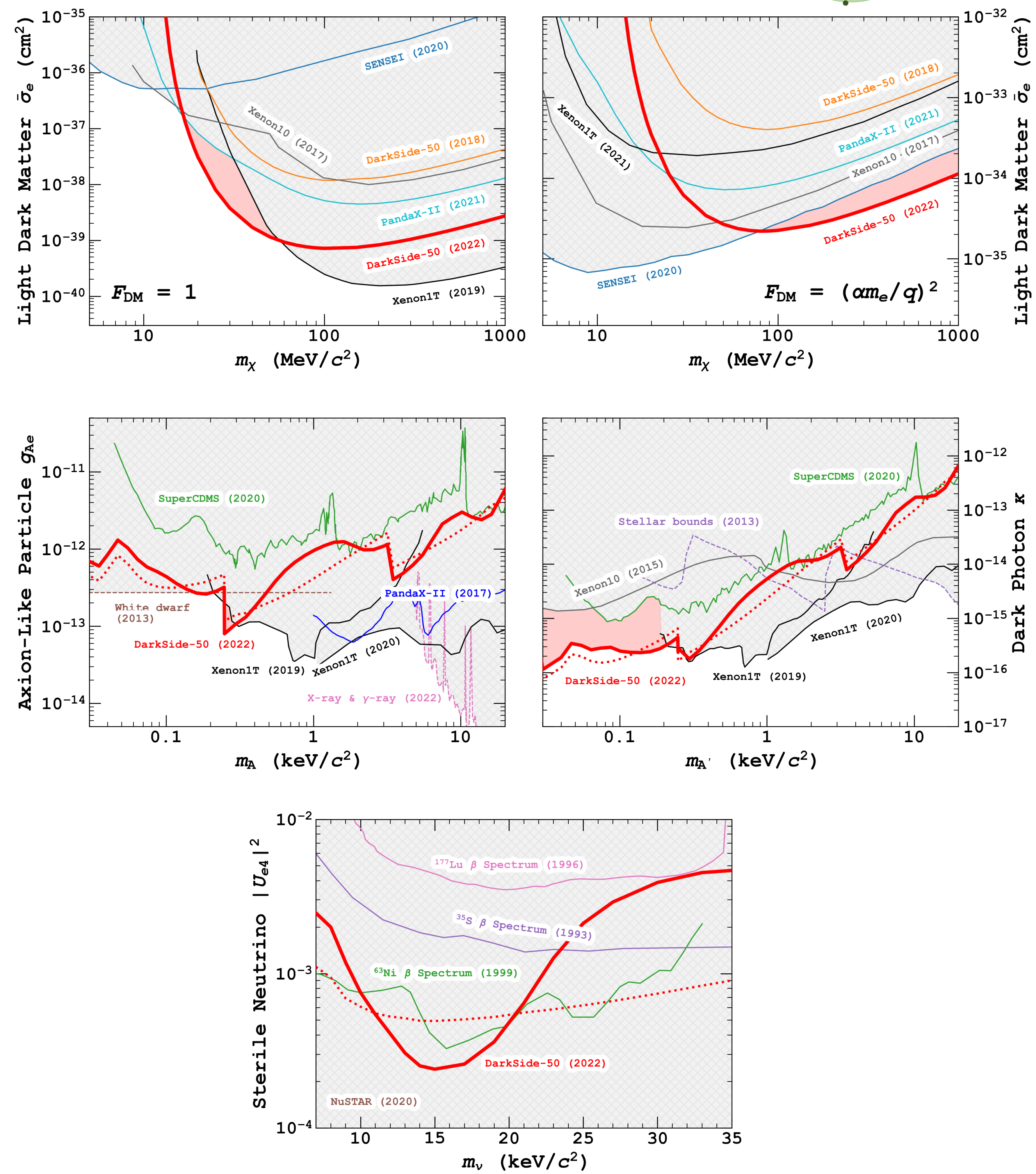
SUB-GEV DARK MATTER

AND OTHER DARK MATTER MODELS



Phys. Rev. Lett. 130, 101002

- With the same dataset, we search for other dark matter models.
- In those candidates, DM signals are also ER.
- Ultra-light DM ($m_\chi \ll 1$ GeV) scatter off electrons.
- Two extreme cases of Dark Matter form-factor are considered
  - $F_{DM}=1$ heavy mediator
  - $F_{DM} \propto 1/q^2$ light mediator
- More for Axion-like particles, Dark photons, and Sterile neutrinos.



Also, results with Migdal effect Phys. Rev. Lett. 130, 101001

WHAT WE LEARNT SO FAR…

- Main BGs and mitigation methods
  - γ: SiPMs –– pure materials; ~~fiducialization~~; less component (less performance requirements)
  - β: ^{39}Ar, ^{85}Kr –– cryogenic distillation; better extraction facility; reduced as much as possible –> small target mass helps
  - degraded **α**: Rn, dust (seen in DEAP3600) –– Less concern. ~~keep detector cold as much as possible; clean construction procedure;~~ liquid phase circulation.
  - neutron: detector materials (**α**,n), cosmogenic –– Less concern. less materials close to the fiducial volume; ~~deeper site; neutron veto~~.
  - ~~Combined:~~
    - ~~S1 from **α** and S2 from pileup S1+S2 from γ or β –– less **α**; better reconstruction for S1+S2 separation~~
    - ~~S1 and S2 from γ or β + Cherenkov –– less material for Cherenkov; fiducialization~~
  - Spurious Electrons (SE) –– in situ and ex situ purification; less total activity in TPC; In LAr, it seems SEs are well confined Ne<4. **See Masato's talk.**

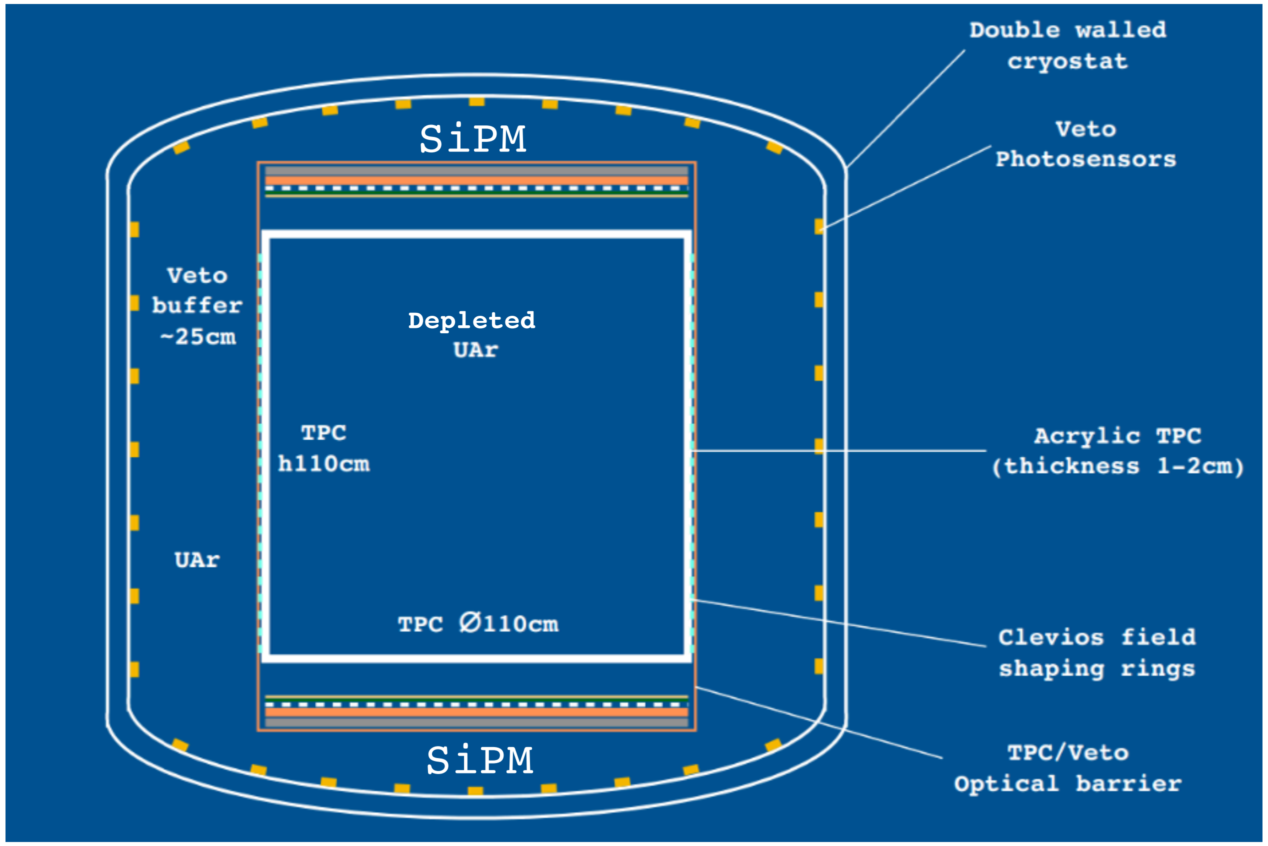
CRITERIA FOR FUTURE LAr TPC

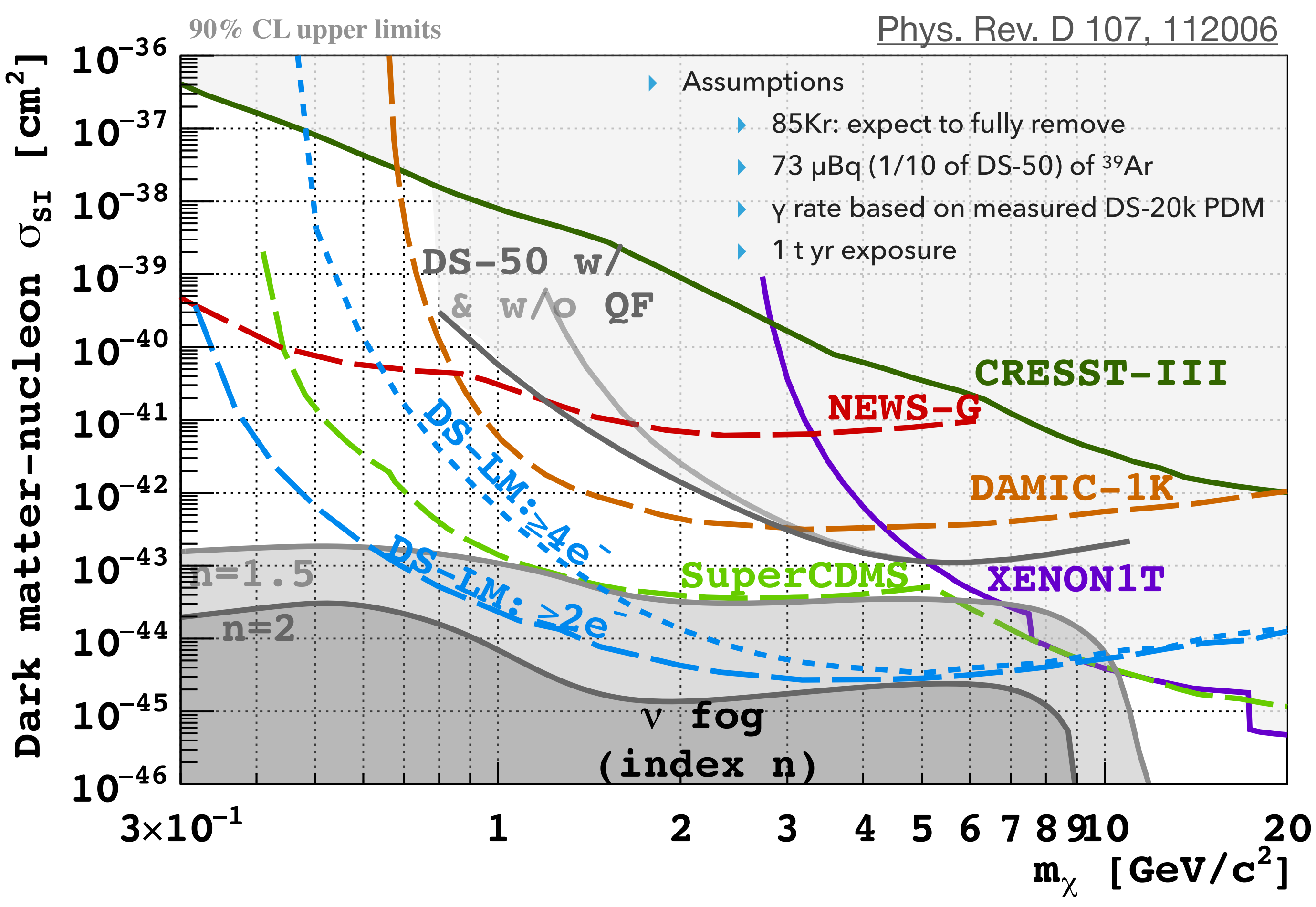
- Low activity of ^{39}Ar
- Low impurity
  - good electron lifetime
  - low rate of the single electron events
- Ultra-pure photo-sensor
- Pure (or no) cryostat
- With 1 t yr exposure, ν-fog is reachable!

The sensitivity of DarkSide-20k for low mass are coming!

Further improvements?

- Lower threshold – remove SE; reduce work function by doping Xe

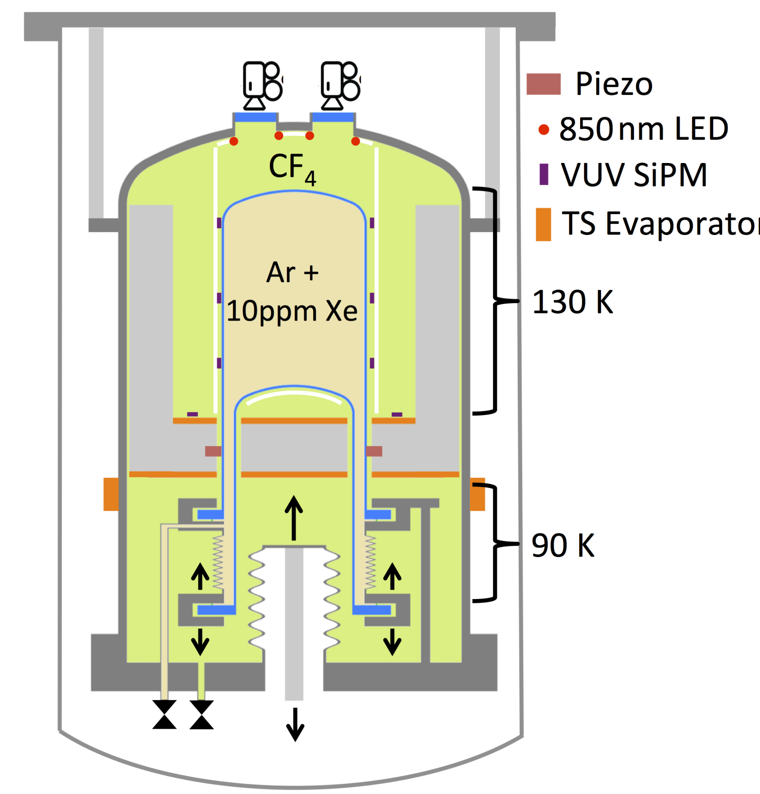


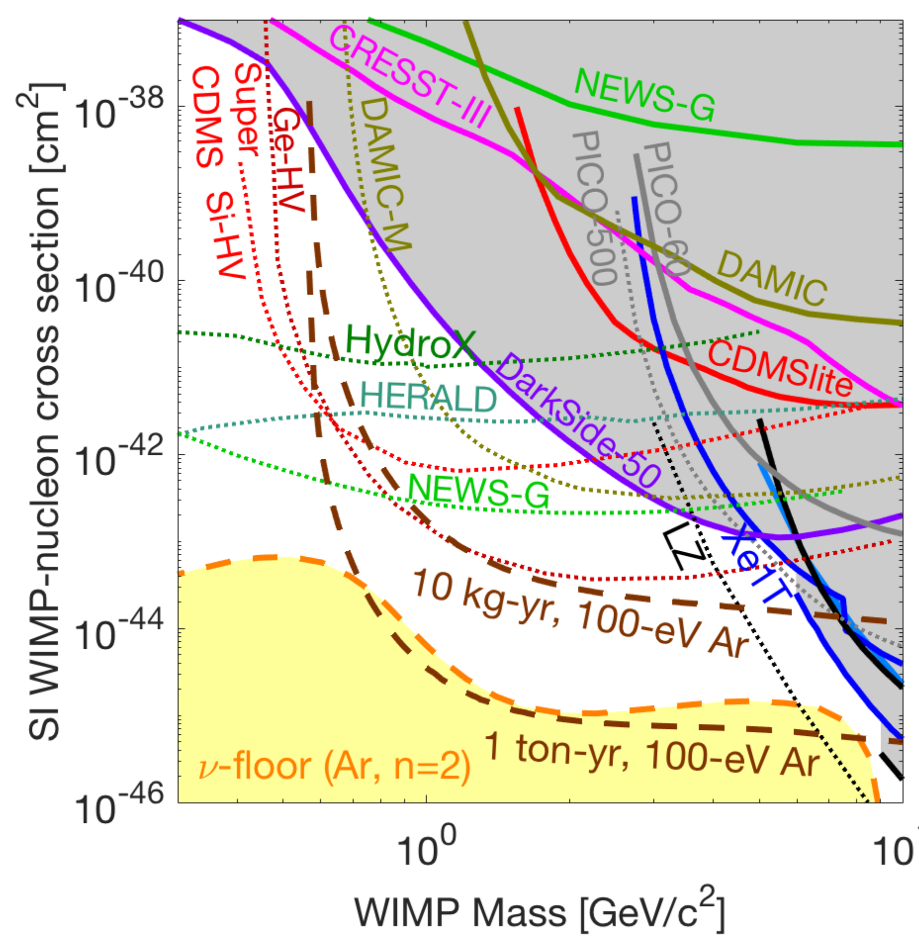


SCINTILLATING BUBBLE CHAMBER

- ER free bubble chamber + good energy resolution of liquid scintillator.
- No bubble formation from ERs via this heat channel.
- BG free even at low energy NRs (<1 keV).
- 1 ton-yr exposure with BG free could be achievable with extrapolation of the current technology.

SBC-LAr10 detector





SUMMARY

- TPC with underground Ar has excellent properties suited to high and low mass WIMP searches.
- Large effort for DarkSide-20k is ongoing and the construction started in LNGS.
- Clear scale up strategies necessary.
- Careful planning of extraction and purification of UAr is necessary.

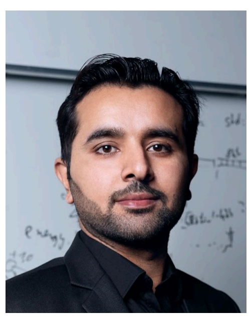
MEMBERS OF MY GROUP

One postdoc position is open!!

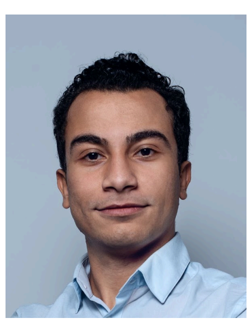
If you are interested, contact me at masayuki@camk.edu.pl

- **Azam Zabihi**
  - **PostDoc** working on Medical applications

- **Andre Cortez**
  - **PostDoc** expert on gas and liquid noble detectors



- **Iftikhar Ahmad**
  - 4th year **PhD student** working on SiPM development



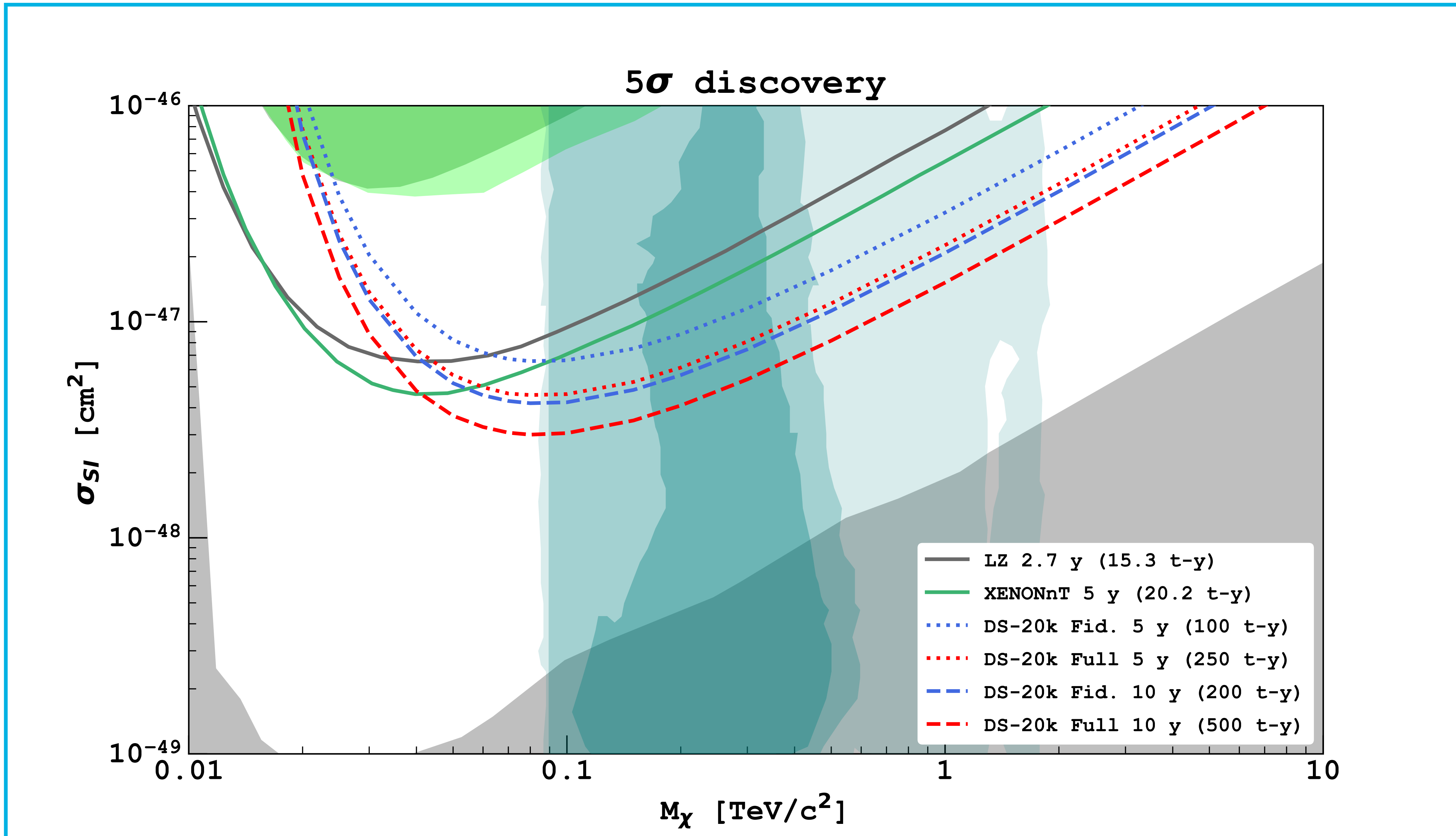
- **Paul Zakhary**
  - 4th year **PhD student** working on low energy calibration

- **Clea Sunny**
  - 2nd year **PhD student** working on low energy calibration

Thank you!

EXPECTED DISCOVERY POTENTIAL

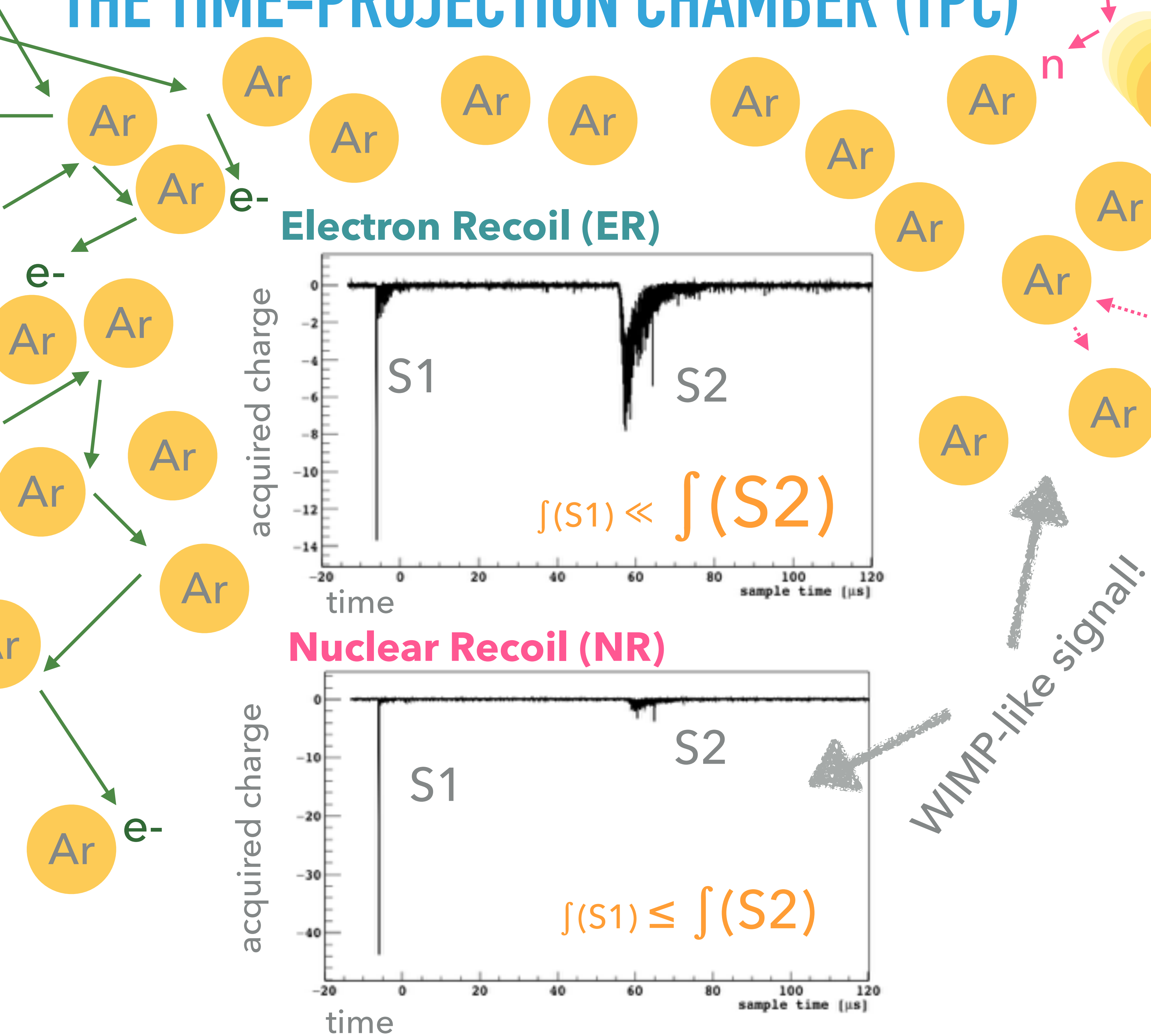
- The 5σ significance of DS-20k to spin independent WIMPs for different lengths of runs, with the full exposure and with the fiducial cuts applied, compared to LZ and XENONnT..

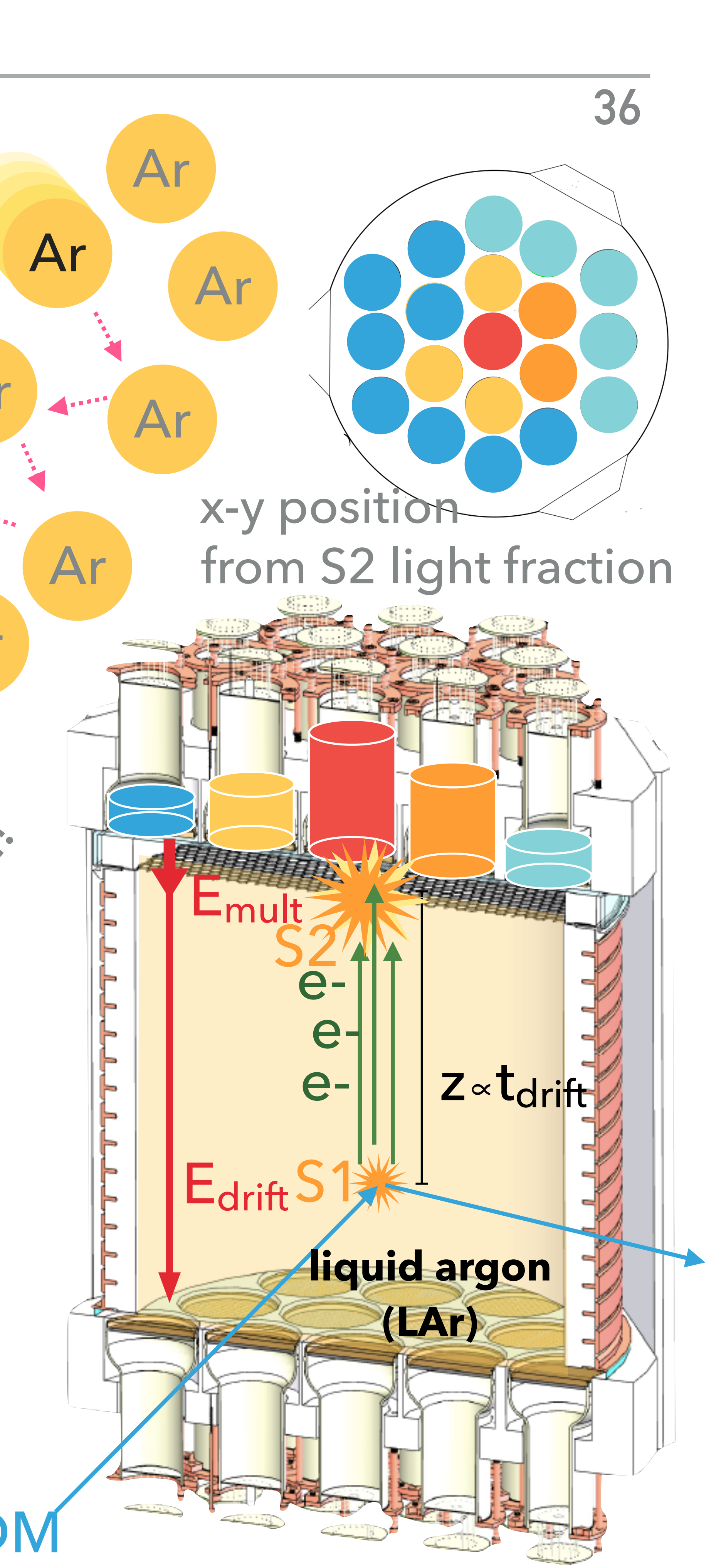


- The present projection - based on a 10 yr run, giving a fiducial volume exposure of 200 t yr - is 2.1 x 10^{-47} cm^2 for 1 TeV/c^2 WIMP for the 5σ discovery.

Turquoise filled contours is from pMSSM11 model (E. Bagnaschi et al., Eur. Phys. J. C 78, 87 (2018).

THE TIME-PROJECTION CHAMBER (TPC)





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

WIMPs will generate nuclear recoils (NRs)