IPHU-018 : Direct search for WIMP Dark Matter

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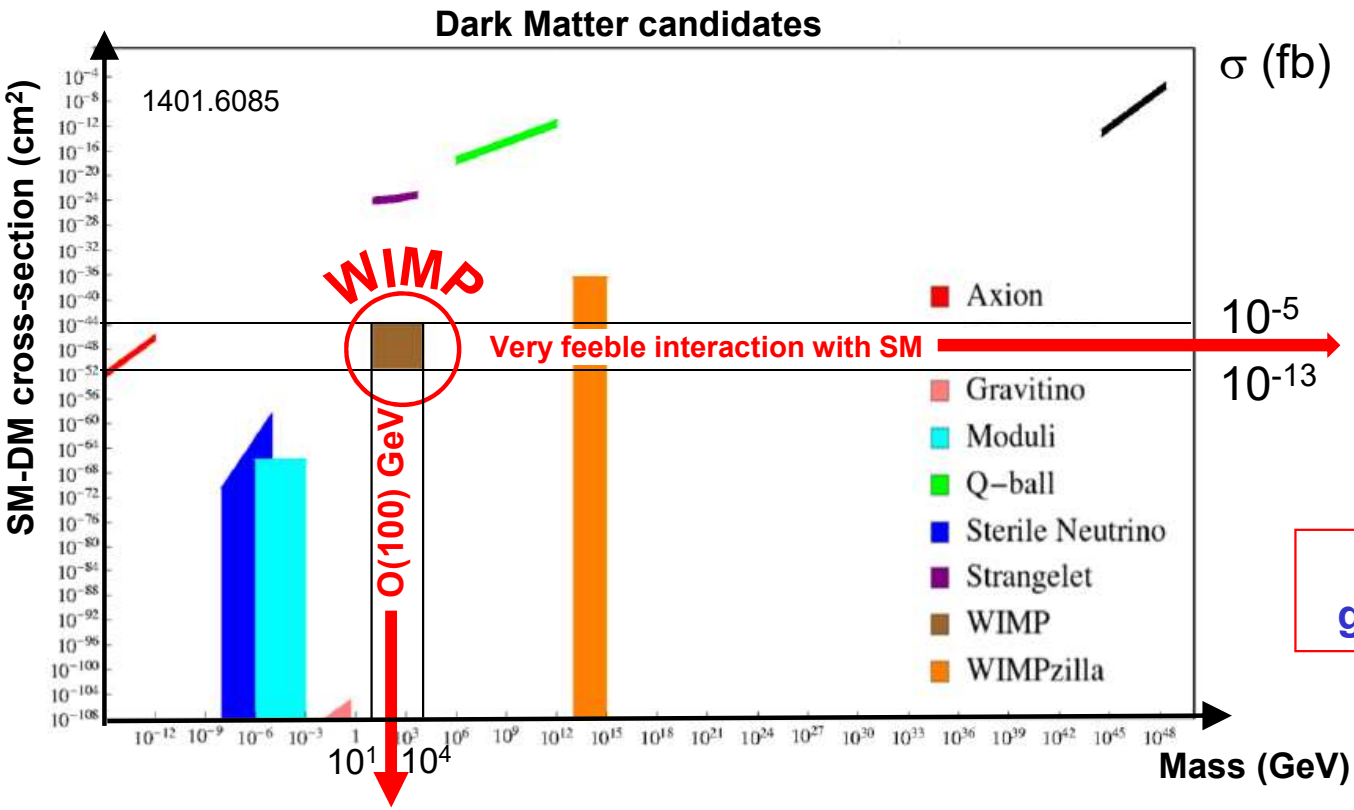
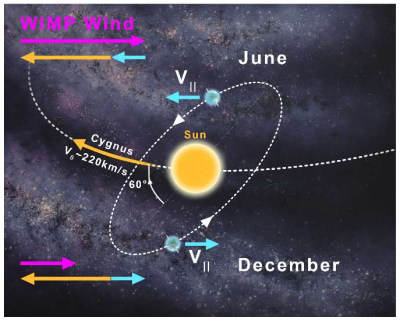
1- Status of direct WIMP searches
2- DarkSide-20k experiment
3- IPhU Project : Status and prospects
4- Conclusions

WIMP Dark Matter challenges

❑ WIMP is one of the best motivated candidate



Lattice QCD SM-DM computation (CPT)



is balanced by the abundance of WIMPs in the galactic halo → O(0.1) GeV/cm³ moving at v=10⁻³c w.r.t earth

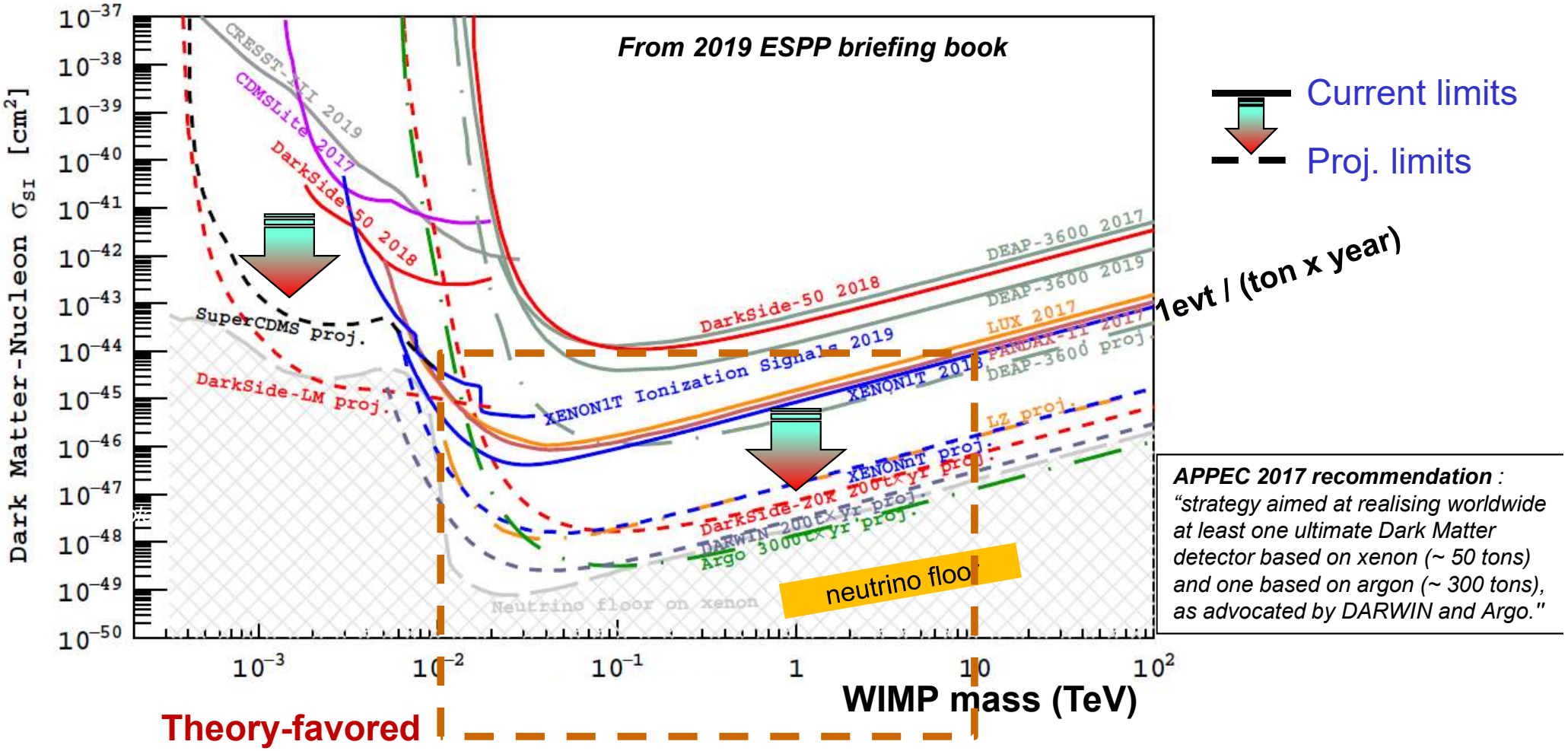
Description of the local galactic halo (LAM, LUPM)

- High mass → visible signal
- O(10⁻³)/cm³ → **Low occupancy**
- Large detector → **background**

Detector with large volume and very low background (CPPM)

3 challenges matching the IPhU perimeter → coordinated in this project

WIMP Search : Status and Future



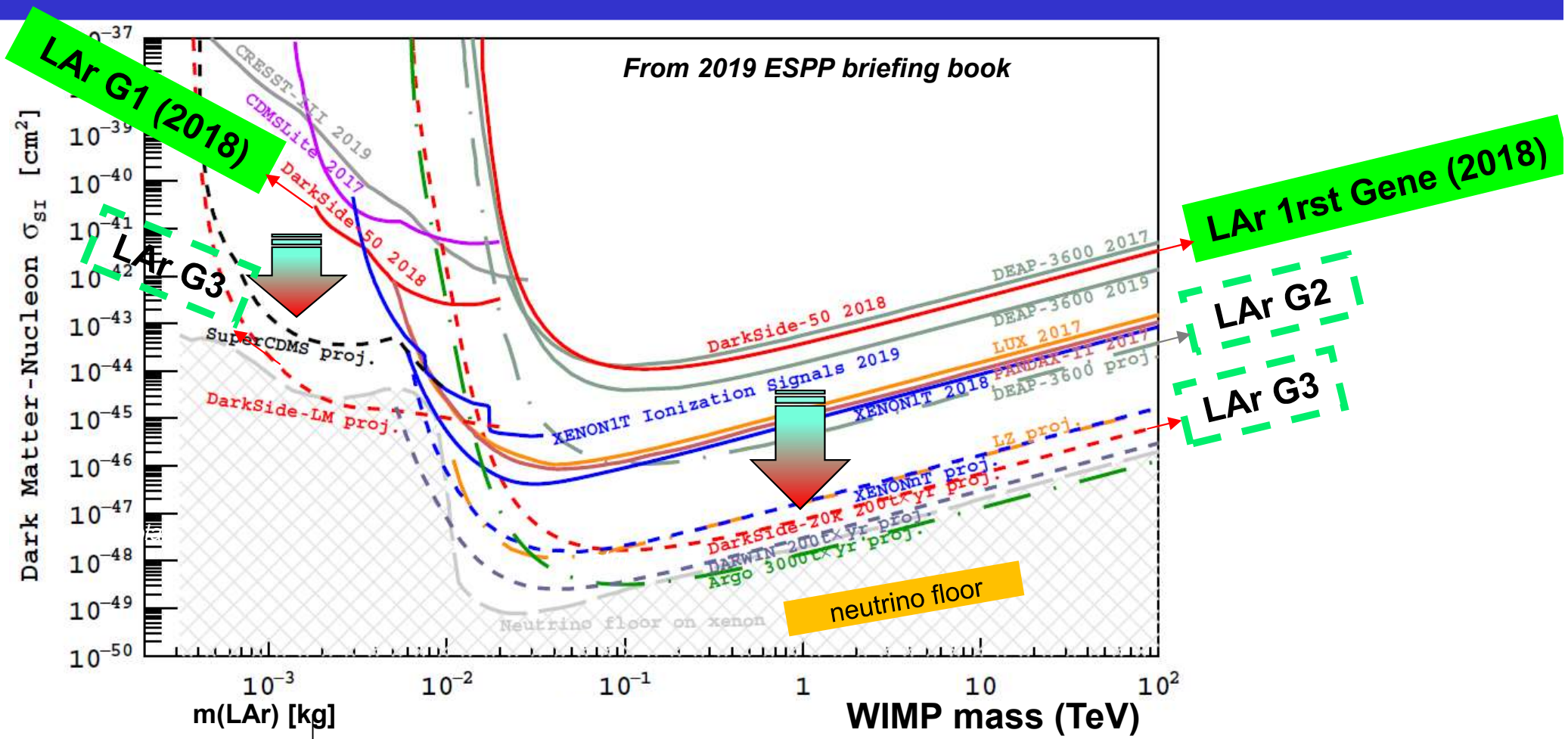
APPEC 2017 recommendation *: "strategy aimed at realising worldwide at least one ultimate Dark Matter detector based on xenon (~ 50 tons) and one based on argon (~ 300 tons), as advocated by DARWIN and Argo."*

L = Liquid TPC = Time Projection Chamber

LXe/LAr dual phase TPCs lead the WIMP search from GeV → 100 TeV

Xenon-1T, LUX, Panda-X, LZ, Xenon-nT, Darwin / Darkside-50, DarkSide-20k, Argo

WIMP Search using LAr TPC



- ✓ **G1: DarkSide-50** : Run in 2013-17 *[low+high mass]* → Results 2018 *(2022)*
- ✓ **G2: DEAP 3600** : Run 2016-22 *[high mass]* → Results 2017, 2019 *(2024)*
- ✓ **G3: DarkSide-20k** : Start construction in 2022 → Start data taking in end-2025

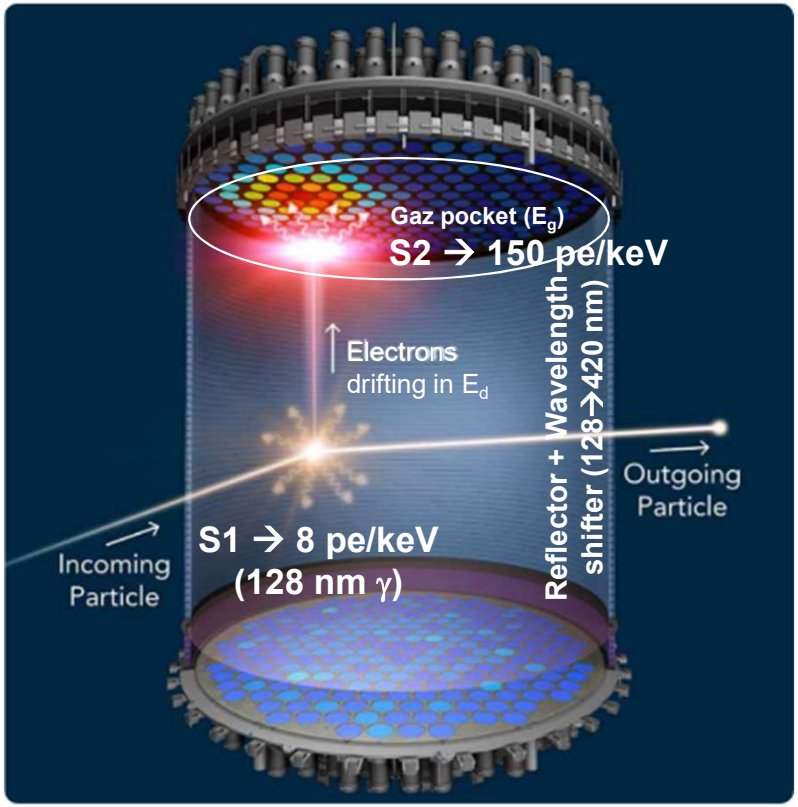
DarkSide-20k has high discovery potential both at low and high WIMP mass

DarkSide-20k (1/2)

❑ Next generation Liquid Argon dual phase experiment …

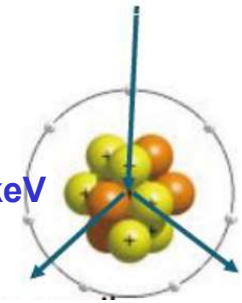
- Dual phase combines scintillation signal (S1) and ionization signal (S2)

TPC Principles



* 100 keV photon in DarkSide-20k, E_d=200 V/cm [E_g~3kV/cm]
Note: 80% of electrons recombined with Ar^+ → γ

WIMPs/Neutrons

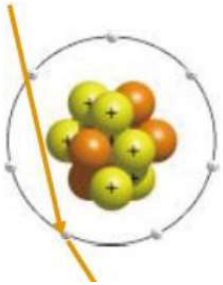


Nuclear Recoil (NR):
- fast. scint. (6ns)
- few ionization el.

NR bkg irreducible → mitigate it !

- ✓ Deep Underground expt.
- ✓ Material selection + assay
- ✓ Neutron veto around the TPC

Gammas / **Electrons**



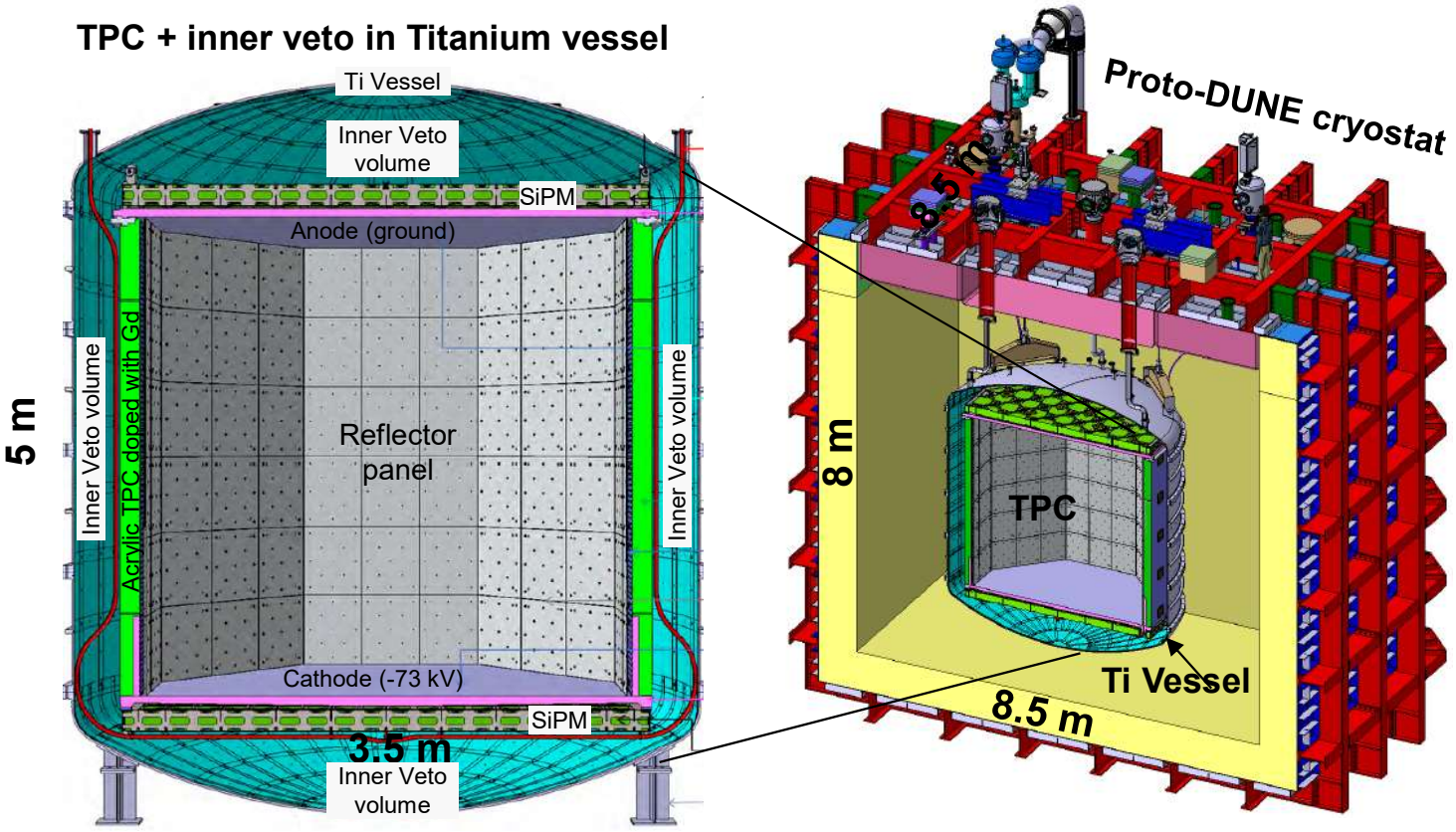
Electron recoil (ER):
- slow scint. (1600 ns)
- many ionization el. (5xNR)

ER bkg fully reducible by analysis

- ✓ Purified argon (esp in ^{39}Ar)
- ✓ S2/S1 (ER) >> S2/S1(NR)
- ✓ S1 pulse shape less peaky than NR

DarkSide-20k (2/2)

- **… located in Grand Sasso underground lab (Italy)**
  - CPPM Team joined DarkSide-20k in 2020
  - Design frozen in TDR in Dec. 2021 *(construction starts in 22, data taking in end-25)*



Main Characteristics:
- 350 collaborators
- Dual Phase TPC
- Inner/outer neutron veto
- 100 t Purified Ar (Ti vessel)
- 250k SiPM → 2500 Ch.

Bright sides
- Background free at high WIMP mass (>100 GeV)
- Run 10 years (200 t.yr)
- High discovery potential (GeV → 100 TeV)

Will be the largest TPC ever build for Dark Matter searches !

IPhU018 project

- **Submitted Dec. 2020 → accepted Apr. 2021 for 4 years**
  - 4 labs (inc. CPPM, LAM and CPT) → 6 people. Organized 2 meetings in 2021
  - One PhD has also been granted : Marie Van Uffelen (Oct. 2021 – Oct. 2024)

IPhU science working group(s) involved:
Astroparticle and HE Universe ☒ Galaxies and Cosmology ☒ Particle Physics ☒
Quantum Field Theory and Quantum Gravity ☐

Project title: Direct search for WIMP dark matter

Project time frame:
Start date: 01/01/2021 duration (months): 48

Project coordination:
Coordinator's name: Pascal Pralavorio
Lab/team: CPPM/Matière Noire email: pralavor@cppm.in2p3.fr tel: 04 91 82 72 69

List of other teams involved:

Lab/team: CPPM/Matière Noire	Team project leader: Fabrice Hubaut
Lab/team: LAM/GECO	Team project leader: Emmanuel Nezri
Lab/team: CPT/PP	Team project leader: Laurent Lellouch
Lab/team: LUMP/IFAC	Team project leader: Julien Lavalle

Two main goals

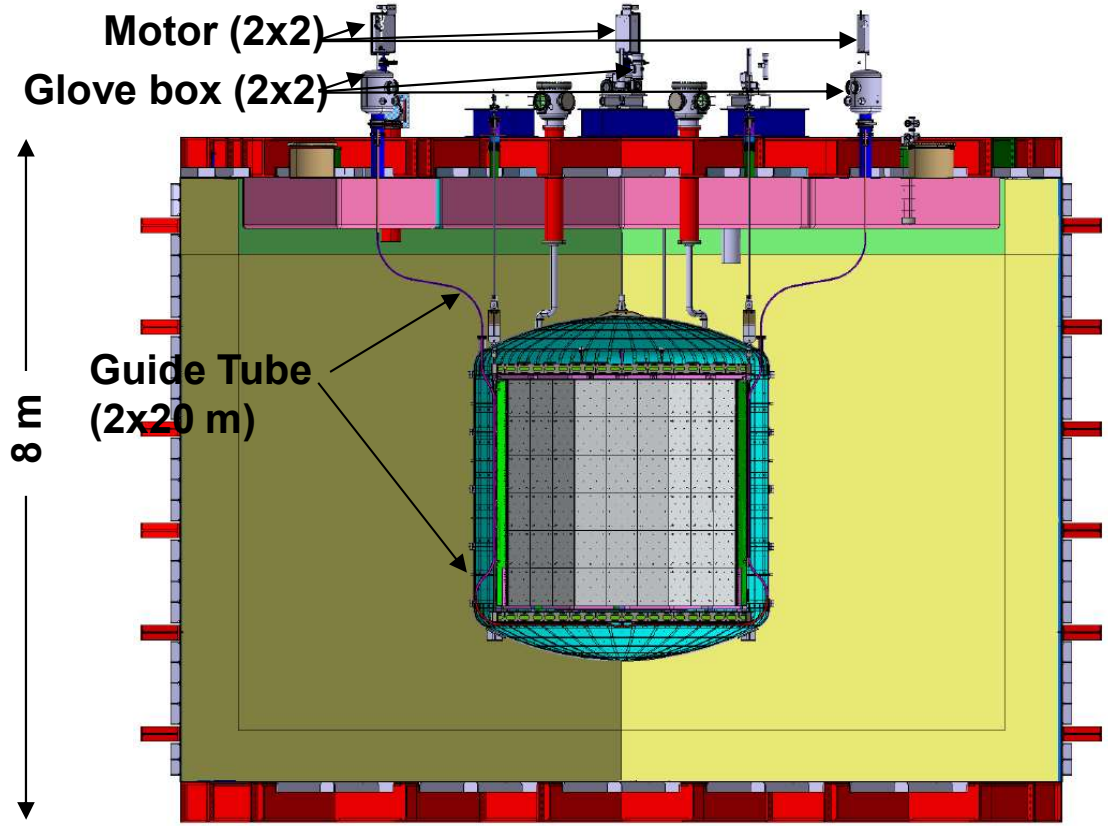
Reduce experimental syst.
Calibration + Optimal signal / bkg separation (using AI)

Reduce theory syst.
Improve knowledge on WIMP local density / WIMP speed / WIMP -- Argon atom interaction

Prepare at best the WIMP searches in DarkSide-20k
using new close exp / theory connections provided by IPhU

DS-20k Calibration (1/3)

- **CPPM responsible for the TPC calibration system**
  - Goal : circulate radioactive sources in a guide tube around the TPC *(2 x 20m tubes)*
  - Establish the calibration program *(using Geant4 simulation)* → *See Marie presentation*



Guide tube sources
(electron + nuclear recoil)

External gamma sources (^{60}Co, ^{137}Cs, ^{133}Ba, ...) Precisely positioned, electron lifetime (bottom) O(10) cm TPC penetration	0.1-1 MeV γ
External neutron sources (AmBe, AmC) Precisely positioned Non monochromatic	1-10 MeV n
DD gun Monochromatic neutrons Recoil energy reconstruction	2.45 MeV n

Included in DarkSide-20k TDR *(released in Dec 2021)*

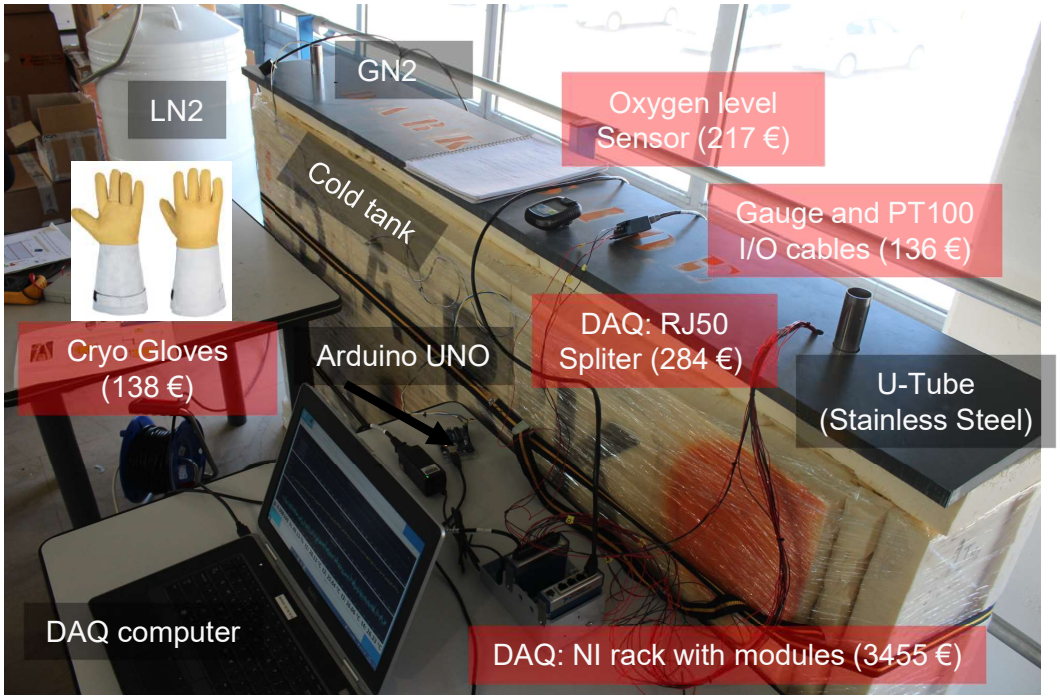
DS-20k Calibration (2/3)

Contrib IPhU (Prix HT)

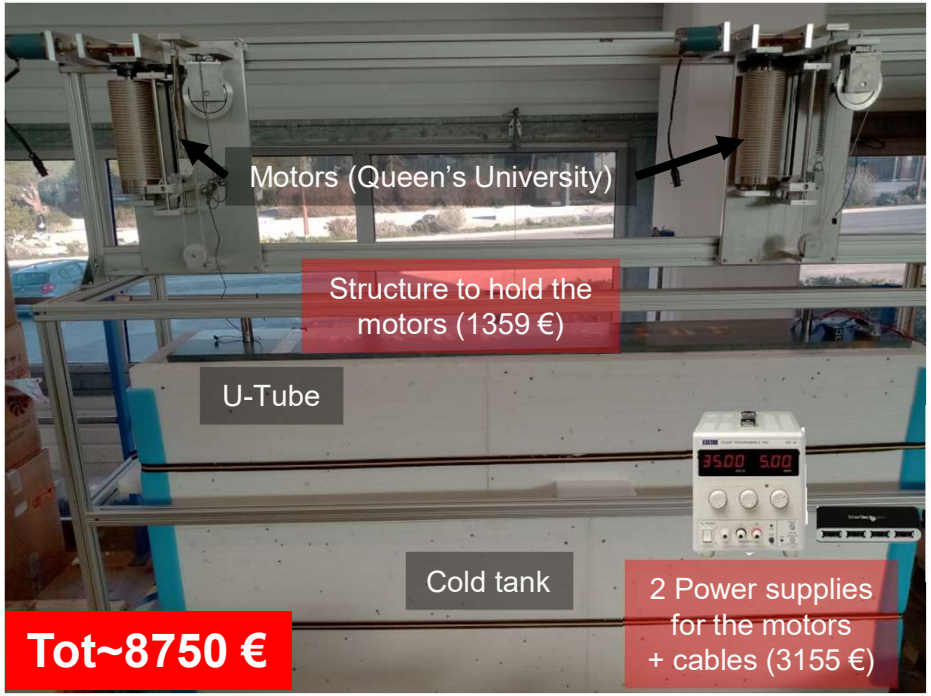
❑ Build a mock-up at CPPM to validate the design

- Started in 2020. Successful cold test in July 2021 → *See Marie presentation*
- Then install equipment to run with the motors *(send by Queen's University)*

Set-up for the cold test (July 2021)



Set-up (as of January 2022)



Most of the mock-up equipped in 2021 thanks to IPhU !

DS-20k Calibration (3/3)

❑ 2022-23 mock-up tests at CPPM (and CERN)

- Develop monitoring of the motors *(in sync. with Queen's University)*
- Produce titanium pipes *(to replace the stainless steel one)* and 2 glove boxes
- Put in place gaseous nitrogen flushing in the tube to avoid ice

➔ Warm tests at CPPM 07-09/2022

➔ Cold tests at CPPM 12/2022 – 02/2023

➔ Long duration runs at CERN 01-03/2023

Amounts in €	Requested for 2022	*Requested for 2023*
Equipment	6500	4500
Computing	0	0
Travel expenses	500	4500
Colloquia	500	500
Operating budget	500	500
TOTAL	**8000**	**10000**

Request a (very experienced) **visitor from Queen's University**

Laboratories involved *(acronyms)*: CPPM and Queen's University (Toronto Canada)

Duration of stay *(up to 3 months)*: 3 weeks
Expected starting date: June 2022
Lab where the visitor will be administratively located *(acronym)*: CPPM

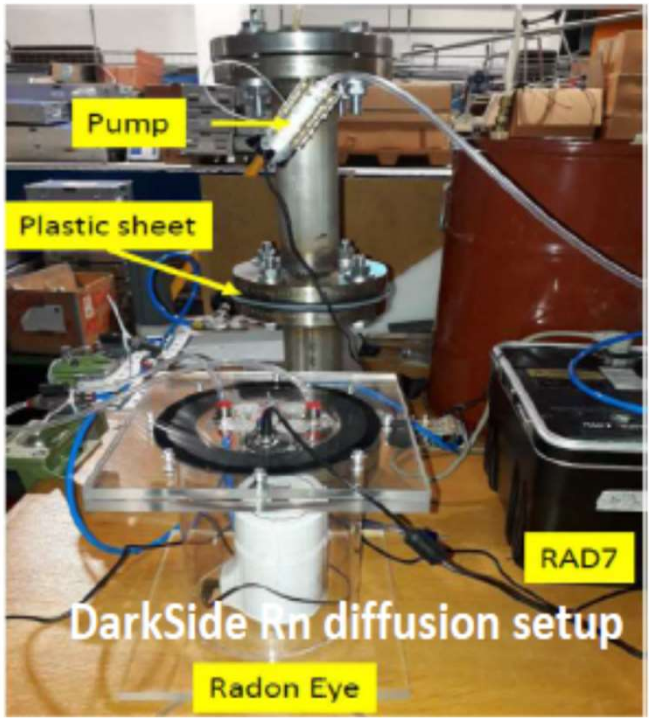
Collaborators *(name, first name – lab acronym - email - phone)*:
Skensved Peter – QU - skensved@queensu.ca - +1 613-533-2676

Validate the guide tube design with mock-ups in 2022-23
(2024 will see installation in Gran Sasso)

Radon

❑ Radon contamination

- Radon progeny [^{210}Pb, ^{210}Po] plates-out on detector material surfaces exposed to air → n bkg [α 5, 8 MeV]
  - ✓ Limit the exposure time by using hermetic plastic bags (transport + storage)
- Plateau Radon at CPPM participates to the radio purity assay program of DS-20k
- Visit of Oleksandra Veselska (CTU Prague): 2 months paid by IPhU
  - ✓ Titanium Zeolite could adsorb Radon → could be used to purify Ar (publication in prep.)

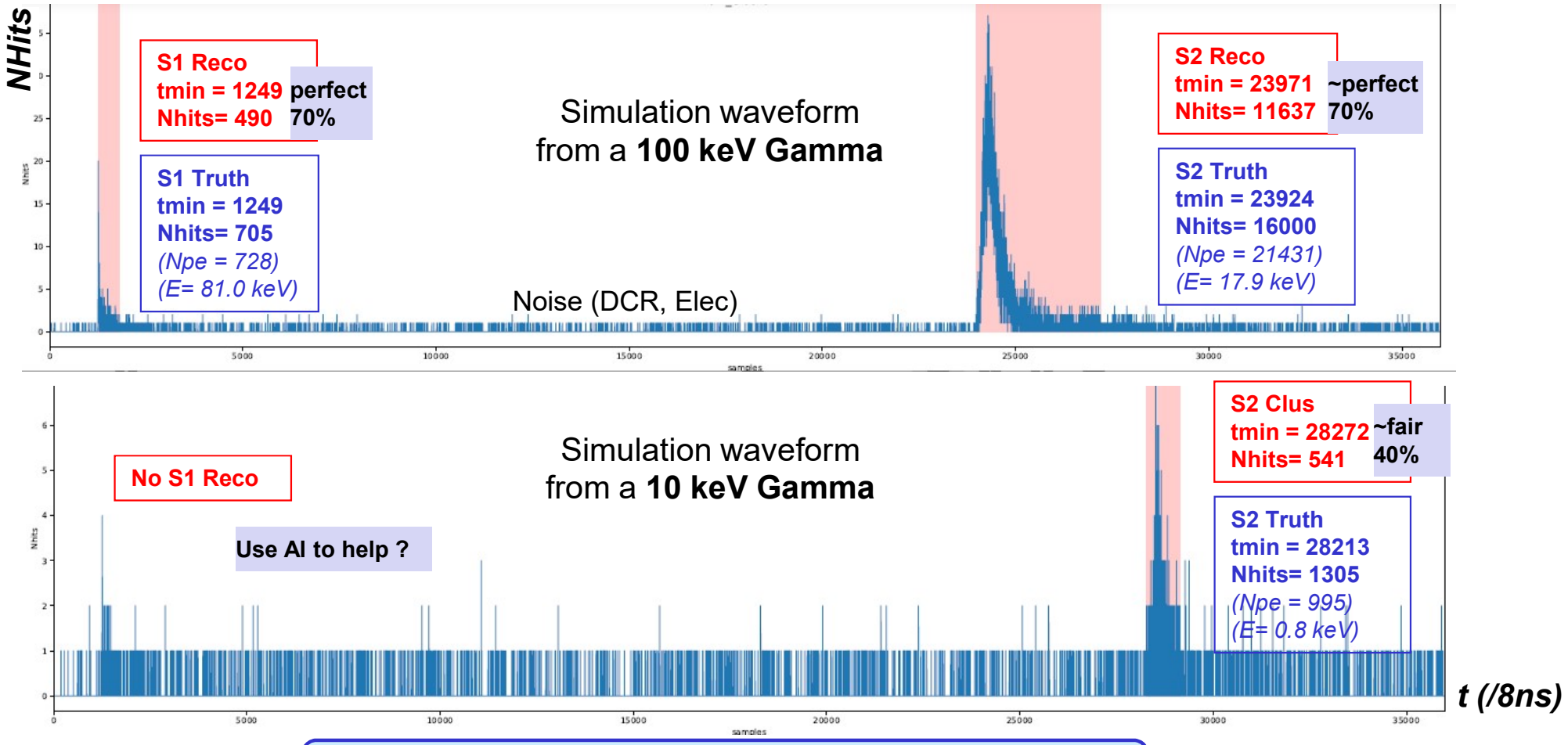


Radonisation Chamber

Signal reconstruction

❑ Optimize signal / background separation

- Started by developing the algorithm to reconstruct / identify S1 and S2

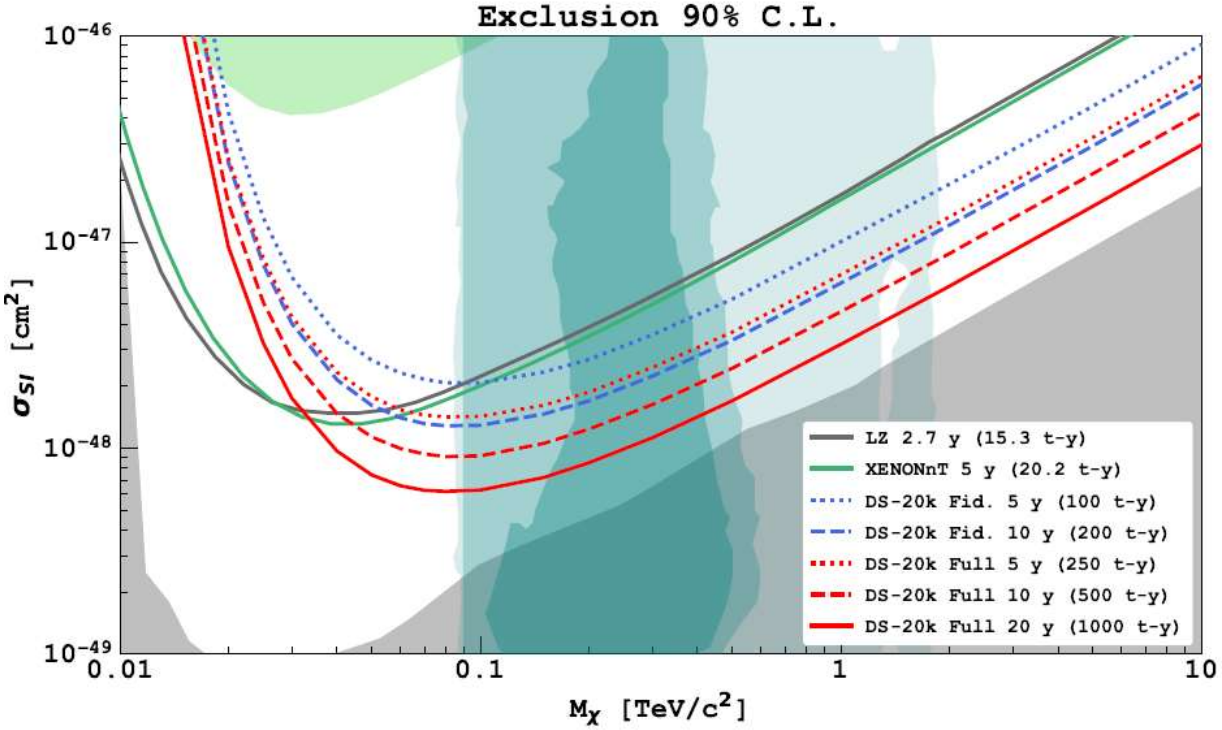


Stronger involvement foreseen in 2022

Galatic Halo model

❑ Impact on DarkSide-20k sensitivity

- Generate more realistic inputs than the "Standard Halo Model" (v_{esc}=544 km/s, v_0=220km/s, v_{Earth}=232km/s, ρ_{DM}=0.3 GeV/cm^3) using semi-analytical approaches and cosmological hydrodynamics simulations of spiral galaxies
- Start from TDR DarkSide-20k expectations



Work started in Jan 2022 → *see Marie Presentation*

Conclusions

❑ Direct Search for WIMP Dark Matter project helped by IPhU

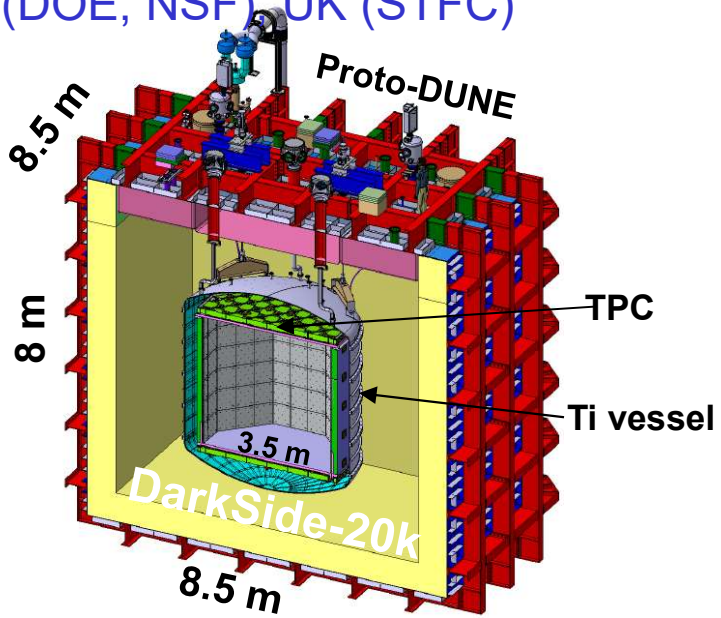
- New PhD student, Marie Van Uffelen, recruited in 2021
  - ✓ Did also her internship *(financed by IPhU)* at CPPM on DarkSide-20k
- Equip the DarkSide-20k calibration mock-up *(power supplies, NI Racks, …)*
  - ✓ will be ready to start warm tests in July 2022
  - ✓ would benefit from a visitor (3 weeks) to prepare these tests
- Started work on signal reconstruction *(optimize signal / background separation using AI)*
- Generate synergy between LAM, CPPM and CPT *(2 meetings in 2021)*
  - ✓ Work on galactic modelling impact on DarkSide-20k sensitivity just started
  - ✓ Next meeting planned 31-03-2022

Name	Position[1]	Laboratory	#PM² 2022	#PM² 2023	Nature of the contribution to the project
F. Hubaut	DR	CPPM	3	3	Optimal algorithms for signal/background separation
P. Pralavorio	DR	CPPM	3	3	Optimal algorithms for signal/background separation
I. Wingerter-Seez	DR	CPPM	3	3	Calibration of DarkSide-20k
J. Busto	PR	CPPM	1	1	Calibration of DarkSide-20k
M. Van Uffelen	PhD	CPPM/LAM	12	12	DarkSide-20k calibration, S/B separation and phenomenology
E. Nezri	CR	LAM	4	2	Improved modelling of the galactic halo
L. Lellouch	DR	CPT	0	1	Fully-controlled QCD uncertainties on WIMP-nucleus cross-sections
J. Lavalle	DR	LUPM	2	1	Improved modelling of the galactic halo

Back-up

DarkSide

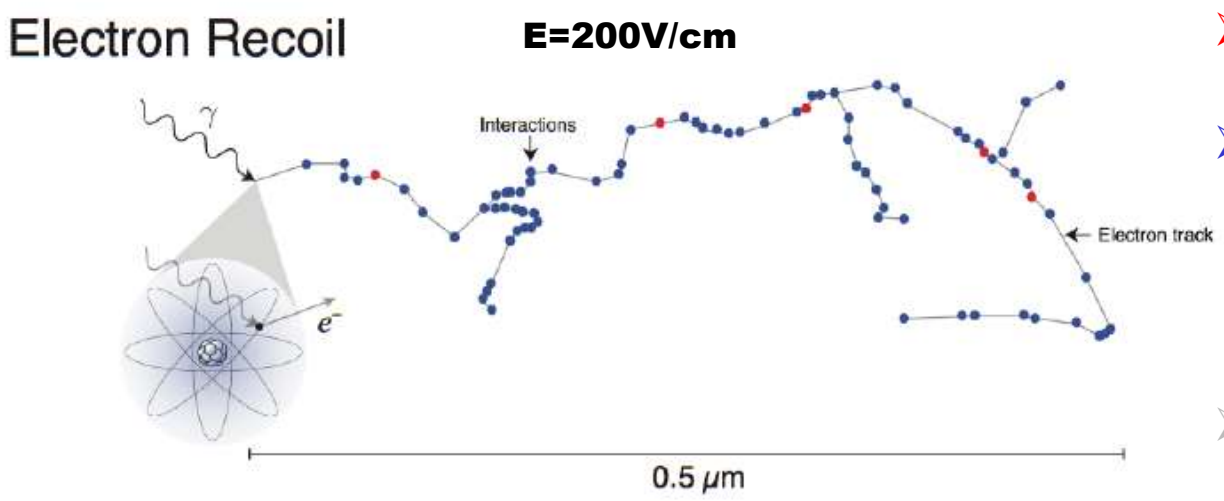
- **Technology is now mature**
  - DarkSide-20k scales from G1 and G2 running expts
  - Only one global collaboration (GADMC): 350 people, profit from best technologies
  - Fundings from Canada (CFI), Italy (INFN), United States (DOE, NSF), UK (STFC)



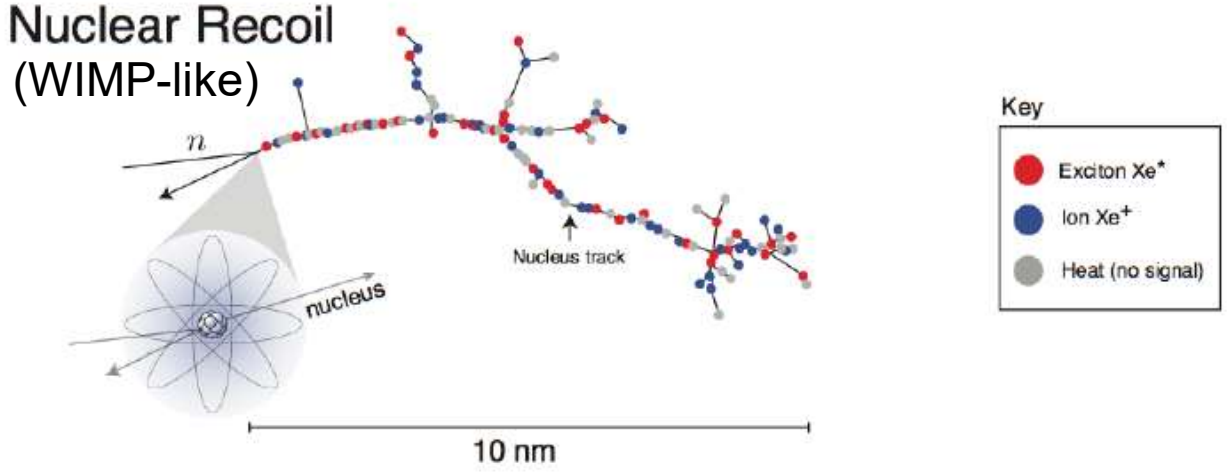
Lab (fid. data)	LNGS (0.05 t.yr)		SNOLab (3 t.yr)		LNGS (200 t.yr)
TPC target	50kg Purified Ar	x70 →	3.6 t *Atmosph. Ar*	x14 →	50 t Purified Ar
TPC wall	*Stainless Steel*		Acrylic		Acrylic
TPC nb ch.	*38 PMT*	x7 →	*255 PMT*	x8 →	~200k SiPM → ~2000 channels
TPC techno	Dual Phase		*Single Phase*		Dual Phase
Veto	*Scint (30 t)* [inner]	*+ Water (1000 t)* [outer]	*Water (250 t)*		Ar in vessel (30 t) [inner] + ProtoDUNE (700 t) [outer]

Electron / nuclear recoil

❑ **Super simplified scheme on interactions in the TPC (E=1keV – 1 MeV)**



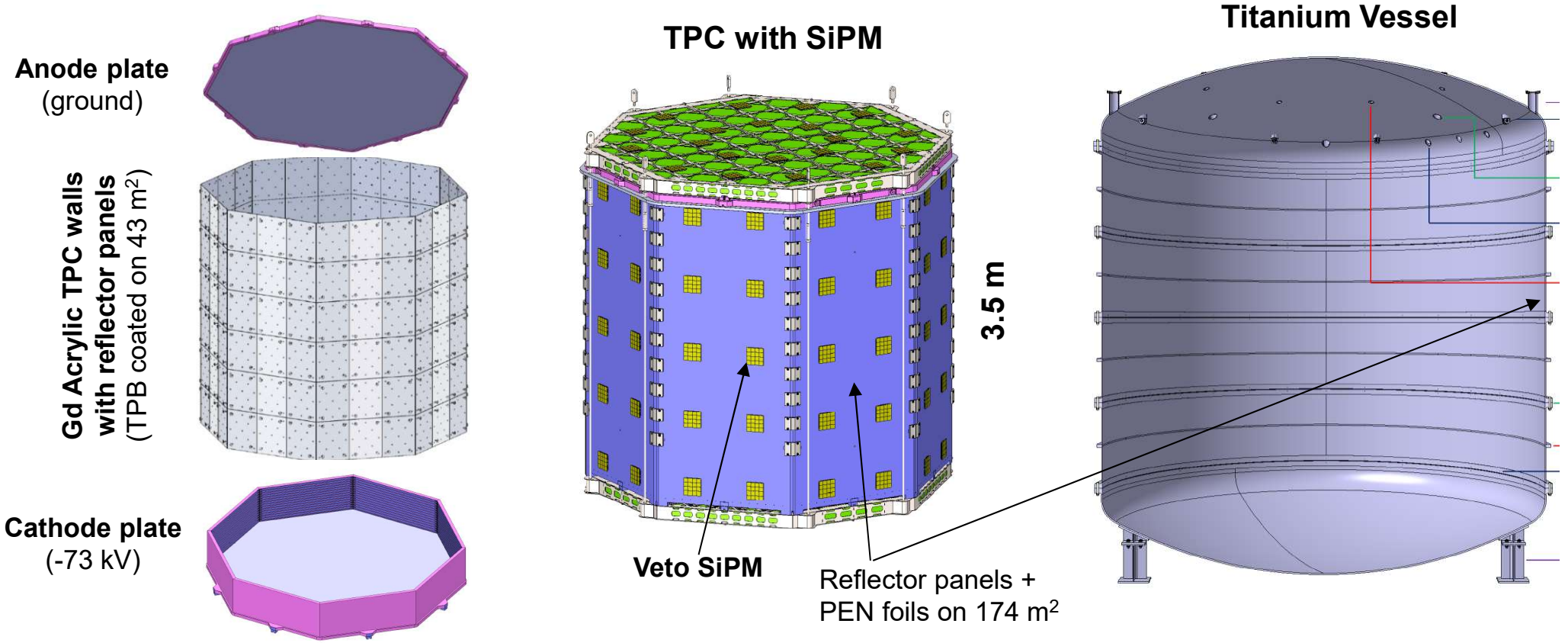
- **Few excitons** → photons → S1
- **Many ionization** → electrons drifted in an electric field (~200V/cm) → electroluminescence in gaz pocket → S2
- ~No loss per heat *(elastic collision)*



- **Many excitons** → photons → S1
- **Many ionization** → electrons → electroluminescence in gaz pocket → S2
- Abundant loss per heat (quenching)

DarkSide-20k TPC

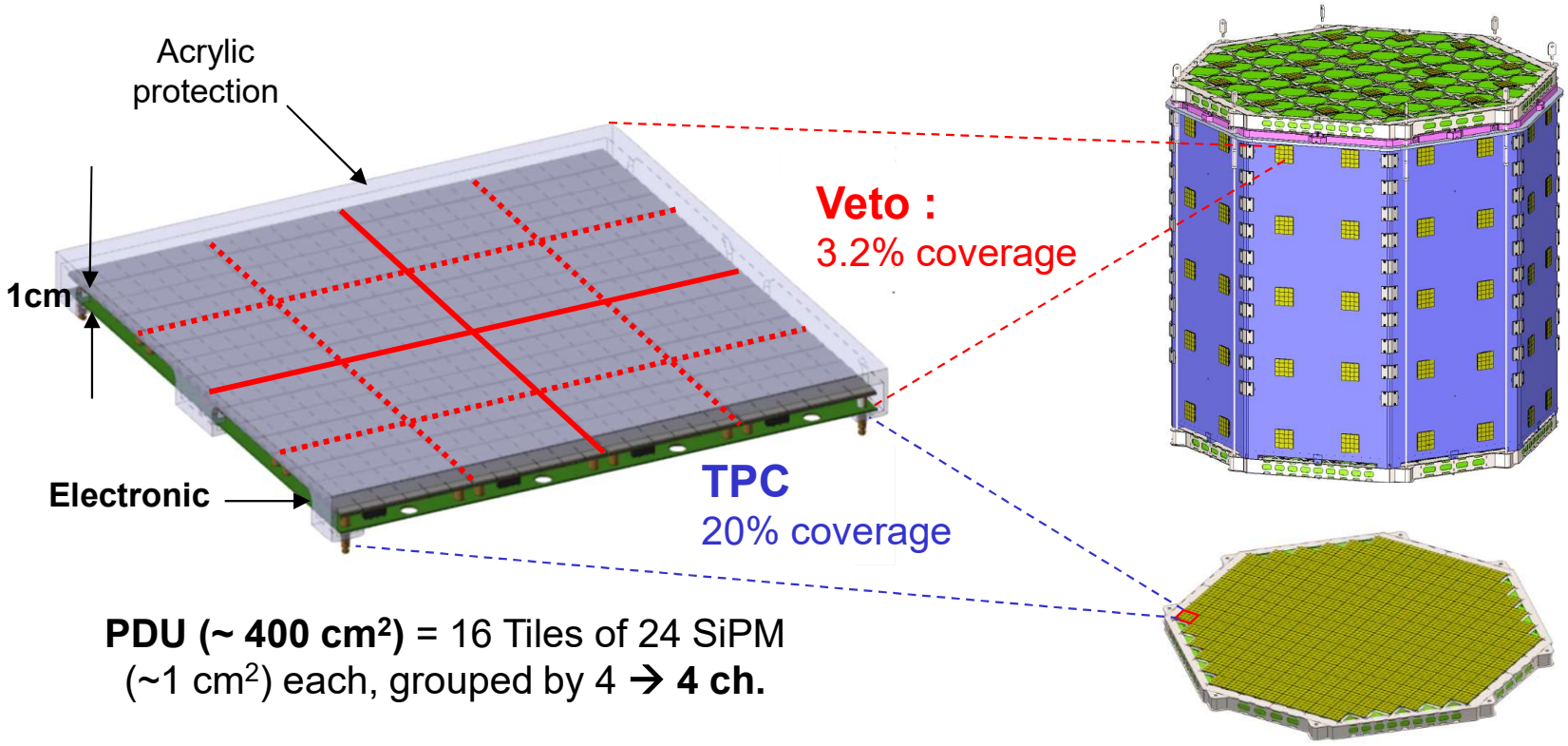
- **Titanium vessel hosts the inner detector (TPC + veto)**
  - High degree of integration in the TPC : compact and simple
    - ✓ TPC walls also serve as overall mechanical structure, Faraday cage, grounding, …
    - ✓ Minimize type and amount of passive material to lower the background *(e.g. same acrylic used for TPC walls & SiPM support structure [20t with 2% Gd], anode and cathode plates [with Clevios for HV])*
  - TPC – Ti vessel gap used for the veto : instrumented with SiPMs



DarkSide-20k PE

❑ Photosensors

- Custom cryogenic SiPMs developed in collaboration with FBK *(PDE ~45% at 420 nm Low dark count rate <20 cps, 3.5 ns time resolution)*. Production at LFoundry.
- PDU = SiPM packaging inc. electronics in LNGS *(TPC)* and UK *(Veto) :* SNR=8
- Installation outside the TPC *(inner veto)* and top/bottom inside the TPC *(TPC)*

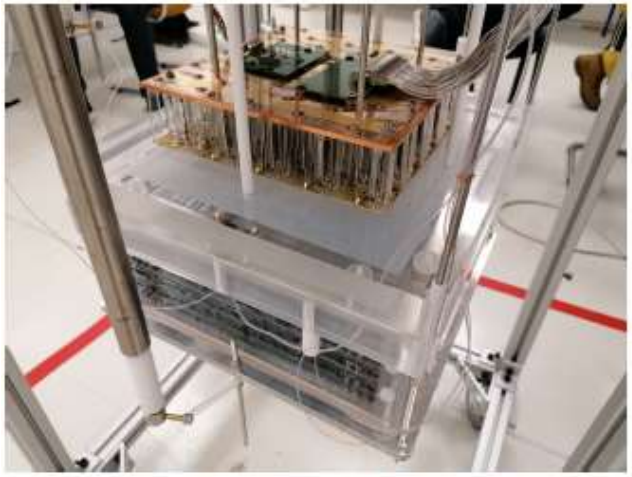


- Outer Veto : 8 arrays lowered from the proto-DUNE flanges *(0.5% coverage, 1 pe/MeV)*

DarkSide-20k proto

- **Prototyping**
  - Validate technological choices (e.g. integrated TPC)
  - Test the cryogenic system for the TPC (at CERN)
  - Measure on-site performance of the SiPM → input for simulation

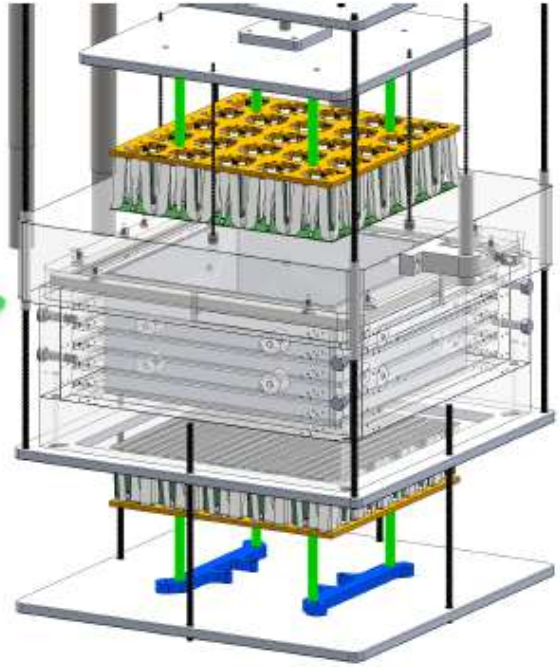
October 2019



Proto-0 at CERN

25x25x10 cm^2
1 PDU

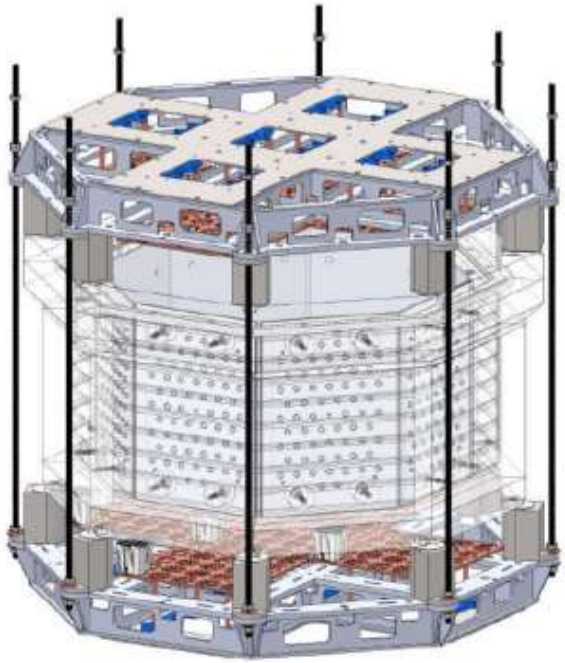
Spring 2022



Proto-0 at Naples

25x25x10 cm^2
2 PDUs

from Summer 2022



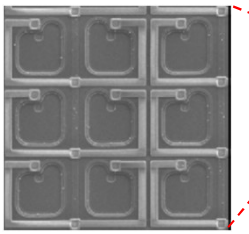
Proto-1T at CERN

60x60x40 cm^2
10 PDUs

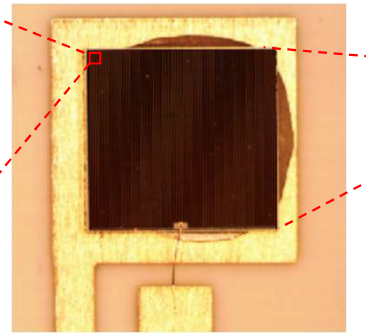
DarkSide-20k SiPM

❑ Photosensors

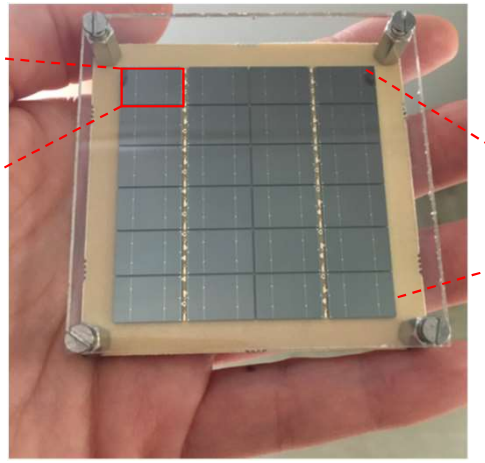
- Custom cryogenic SiPMs developed in collaboration with FBK (Italy) : PDE ~45%, Low dark count rate <20 cps, 10 ns timing resolution
- PDU = SiPM packaging inc. electronics in LNGS (TPC) and UK (Veto)



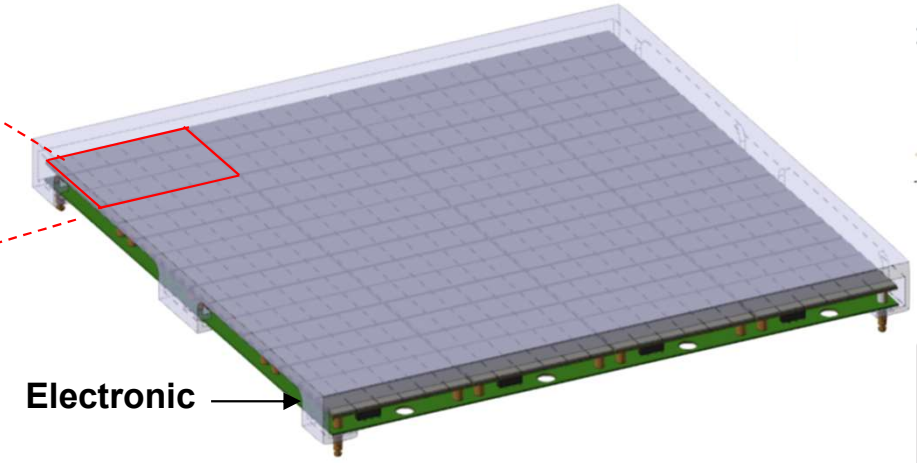
Single SPAD
(~ 900 μm²)



Single SiPM
(~ 1 cm²)



Tile = 24 SiPM
(~ 25 cm²)

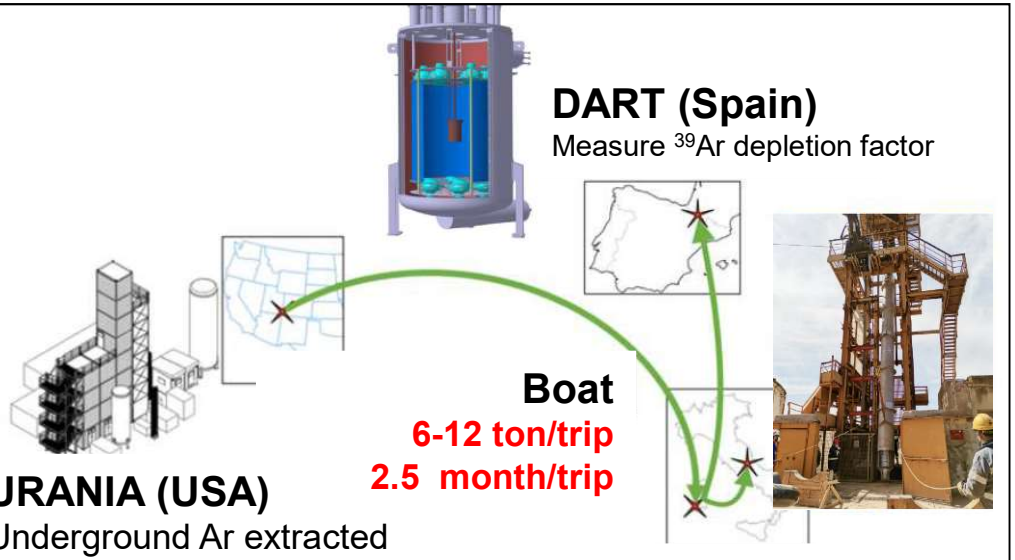


PDU = 16 Tiles (~ 400 cm²)
grouped by 4 → 4 channels

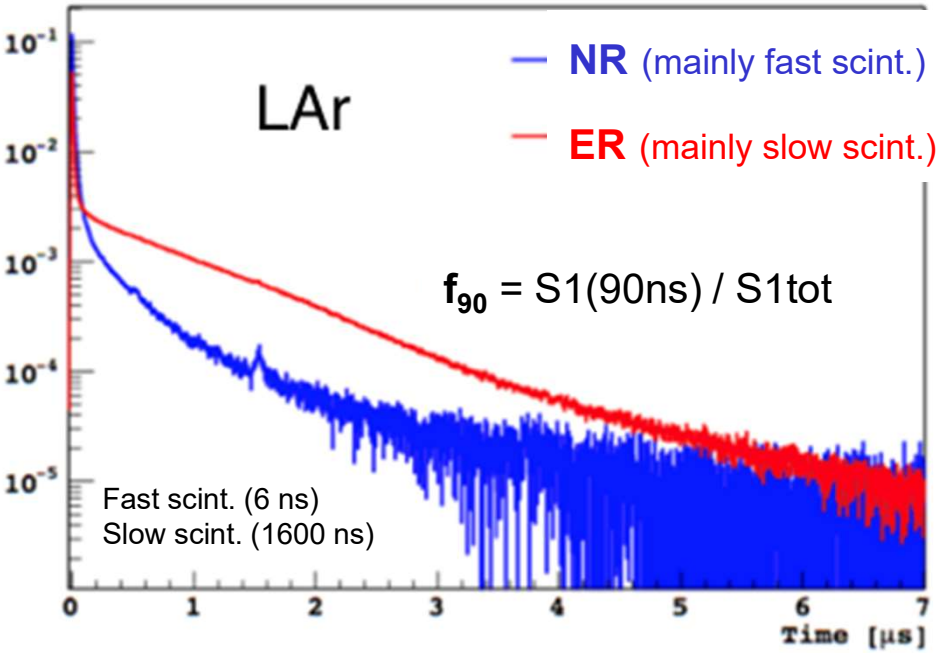
Bright sides of DarkSide (1/4)

- **Optimized to be background free for high mass WIMP search**
  - **Selection**: 70 (30) cm away in z (r) from the TPC walls → 20 t UAr, single scatter
  - **ER background suppression**: purified argon (depleted in ^{39}Ar cosmogenic argon), S2/S1, S1 Pulse Shape Discrimination (PSD) <1 mBq/kg β, $T_{1/2}$=269 year, ~1 Bq/kg R=10^3

Purified argon ($R_{39Ar}>10^3$)



S1 Pulse Shape Discrimination ($R_{ER}>10^8$)*

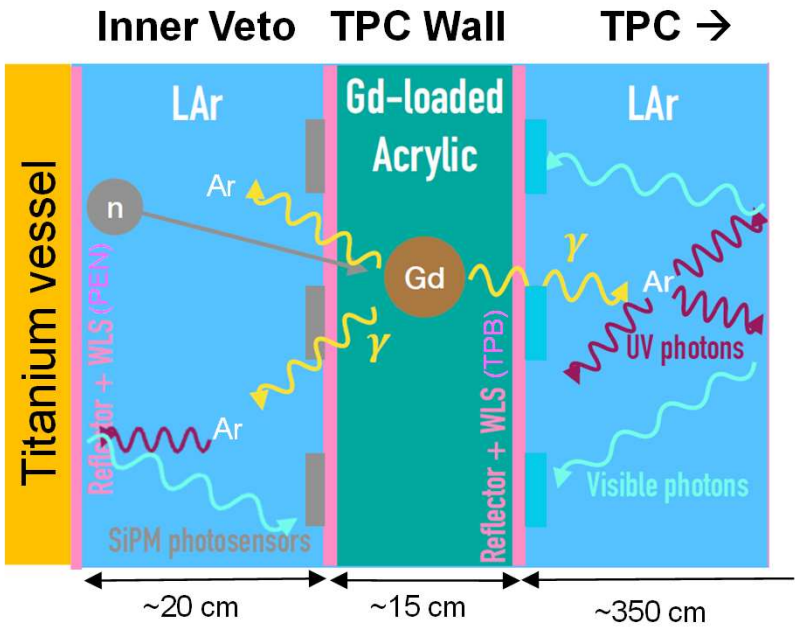


* PSD measurement by DEAP-3600 in PRD 100 (2019) 022004

ER background <<0.1 event in 200 ton.year

Bright sides of DarkSide (2/4)

- **Optimized to be background free for high mass WIMP search**
  - **Selection**: 70 (30) cm away in z (r) from the TPC walls → 20t Ar, single scatter
  - **ER background suppression**: purified argon, S2/S1, S1 PSD → **negligible**
  - **NR background suppression**: LNGS, material selection+cleaning+assay, neutron veto

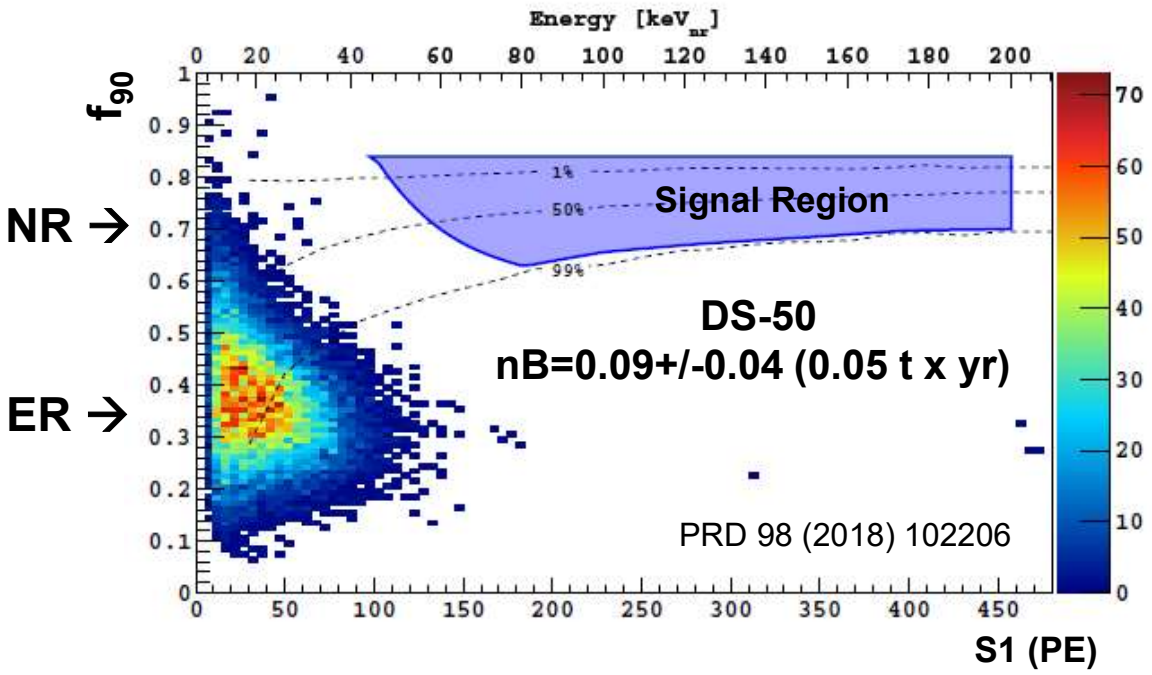


Veto: **2000 pe / MeV** (3.2% SiPM coverage of 175 m^2 surface)

<mBq/kg ^{238}U, ^{235}U, ^{232}Th activity → O(10^{-7}) n / decay, E ~ MeV

^{222}Rn daughters O(500)

Neutron moderated by Acrylic
Captured by Gd → ≤ 8 MeV γ



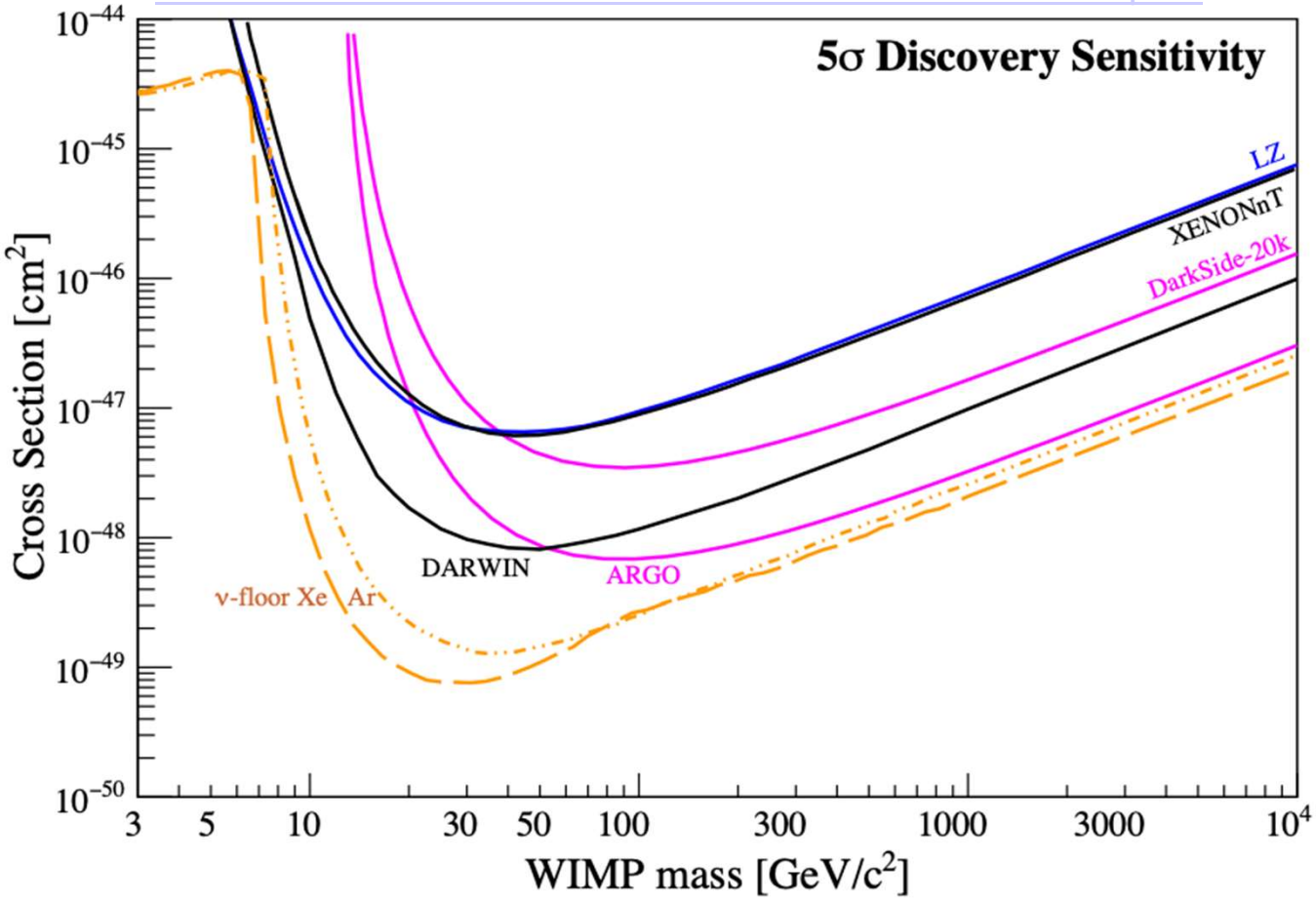
Expect ~0.1 bkg event in 10 years of running (200 ton.year)*

** Note: expect ~3 irreducible evts from ν NR*

Bright sides of DarkSide (3/4)

- **Good discovery potential of high mass WIMP**

Direct Detection of Dark Matter – APPEC Committee Report



DarkSide-20k and Xenon expts complementary for high mass WIMPs

Bright sides of DarkSide (4/4)

❑ Bonus: very sensitive to low mass (1-5 GeV) WIMP

- S2-only APC, LPNHE leadership : ARIS measurements @ IPNO + analysis
  - ✓ Very good signal / background separation at low N_e
  - ✓ Good background description for $N_e \geq 7$

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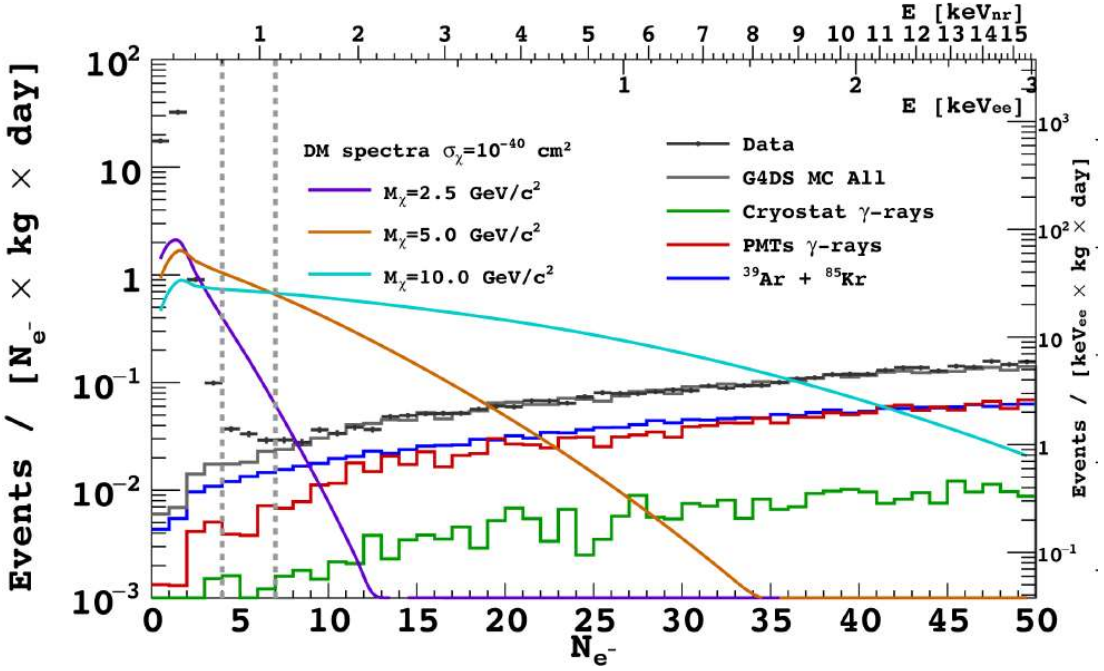

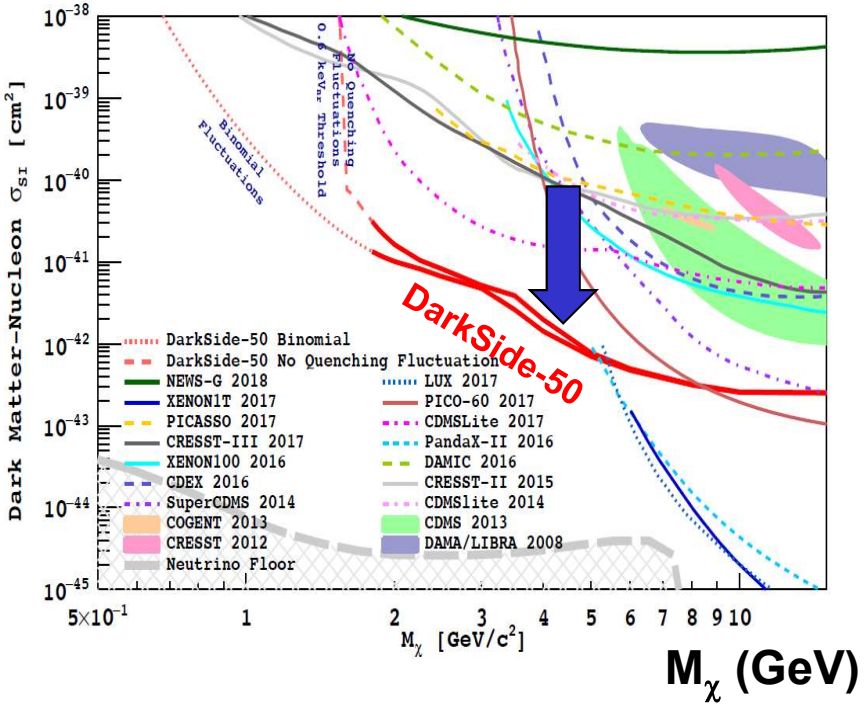

DarkSide-50 world leading sensitivity in 1-5 GeV WIMP (since 2018)