First direct detection contraints on Planck scale mass dark matter in DEAP-3600[1]

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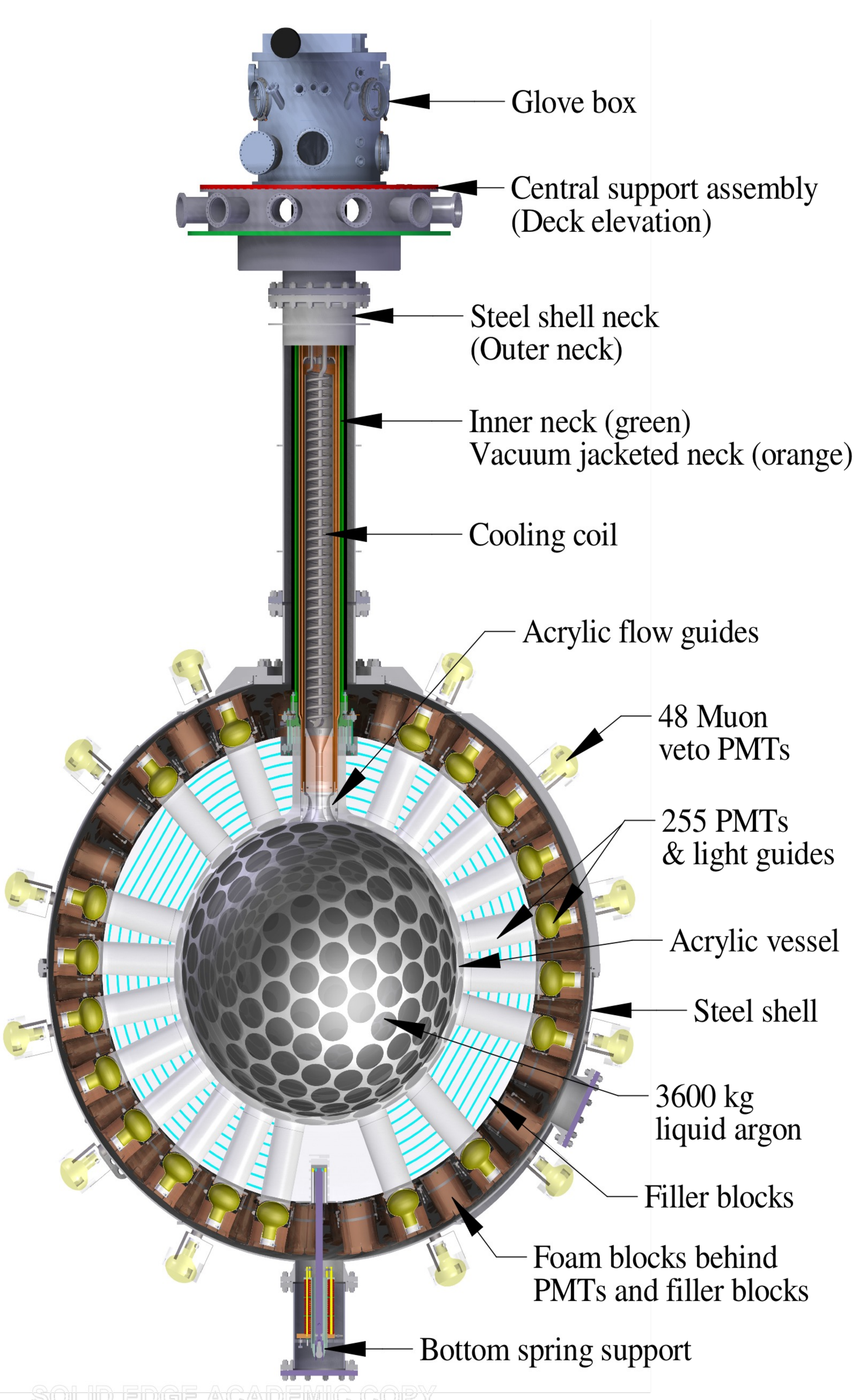
According to several astrophysical measurements only 5 % of the Universe is observable, baryonic matter. While about 67 % of the energy is called Dark Energy, and lacks of direct detection in ground-based experiments, the left component, the **Dark Matter**, can in principle be detected also in laboratories, if composed by particles holding some other interactions, besides the gravitational one. These dark matter particles are uniformly distributed in the galactic halo, in thermal equilibrium with baryonic matter. As our solar system moves along the galactic center, we are hit by a "wind" of dark matter particles. The eventual excitation of a baryonic nucleus brings to scintillation light, ionization electrons and/or phonons, in a unique signatue that would point to a dark matter event.

One of the most promising candidates is **Weakly Interacting Massive Particles (WIMPs)**, which would have a weak coupling with standard model particles and masses between O(1) GeV and O(100) TeV. WIMPs would have decoupled from the baryonic matter bath during the Universe expansion, after the inflation, in a radiation-dominated epoch, so that their abundance was frozen at the present observed dark matter percentage. As these candidates would also answer to other theoretical pending questions, related for instance to SUSY theories or Kaluza-Klein compactification, a wide range of experiments has been built in the last decades to detect this feeble, rare signal. After decades of data taking, **no detection was confirmed**, pushing the constraints on WIMPs interactions down to about 10^{-44} cm^2 for the dark matter-nucleon cross-section.

The lack of detection brought attention to other dark matter candidates. **Much heavier dark matter** candidates, well above the WIMP limit at O(100) TeV, are expected in Great Unification Theories, and can be produced by the decay of out-of-equilibrium beyond standard model fields in an Early Matter Dominated Era happening before the Big Bang Nucleosynthesis. These heavy dark matter candidates can also be produced by decays from **inflational gravitation**, as well as in freeze-out mechanisms in a secluded sector, or as relics from magnetic **primordial black holes**. These heavy dark matter candidates can reach **Planck scale masses**, and eventually carry a U(1) charge which would allow for a **unique observational signature**.

DEAP-3600 is the **largest running dark matter detector** filled with noble liquid, designed for the search of WIMPs. The experiment, shown in Figure 1, is set at **SNOLab**, Ontario, 2 km underground (6 m.w.e.).

Its target are 3.3 tonnes of liquid argon, contained in an ultraviolet-absorbing acrylic vessel of 85 cm of radius, filled up to 551 mm from its equator. An array of photomultipliers tubes (PMTs) is coupled to the vessel through acrylic light guides. In order to shift the liquid argon scintillation light, which peaks at 128 nm, towards the PMT maximum efficiency at 420 nm, the wavelength shifter 1,1,4,4-tetraphenyl-1,3-butadiene (TPB) is evaporated on the inner vessel surfaces. The space between the light guides is filled with high-density polyethylene, to help for suppression of cosmogenics. The PMTs are set on a stainless steel sheel, which is submersed in a cylindrical tank filled with ultrapure water. The water is observed by 45 PMTs set on the outern surface of the stainless steel shell. The tank serves as muon active veto, and helps for the rejection of comogenics produced by spallation on the surrounding rocks [2].



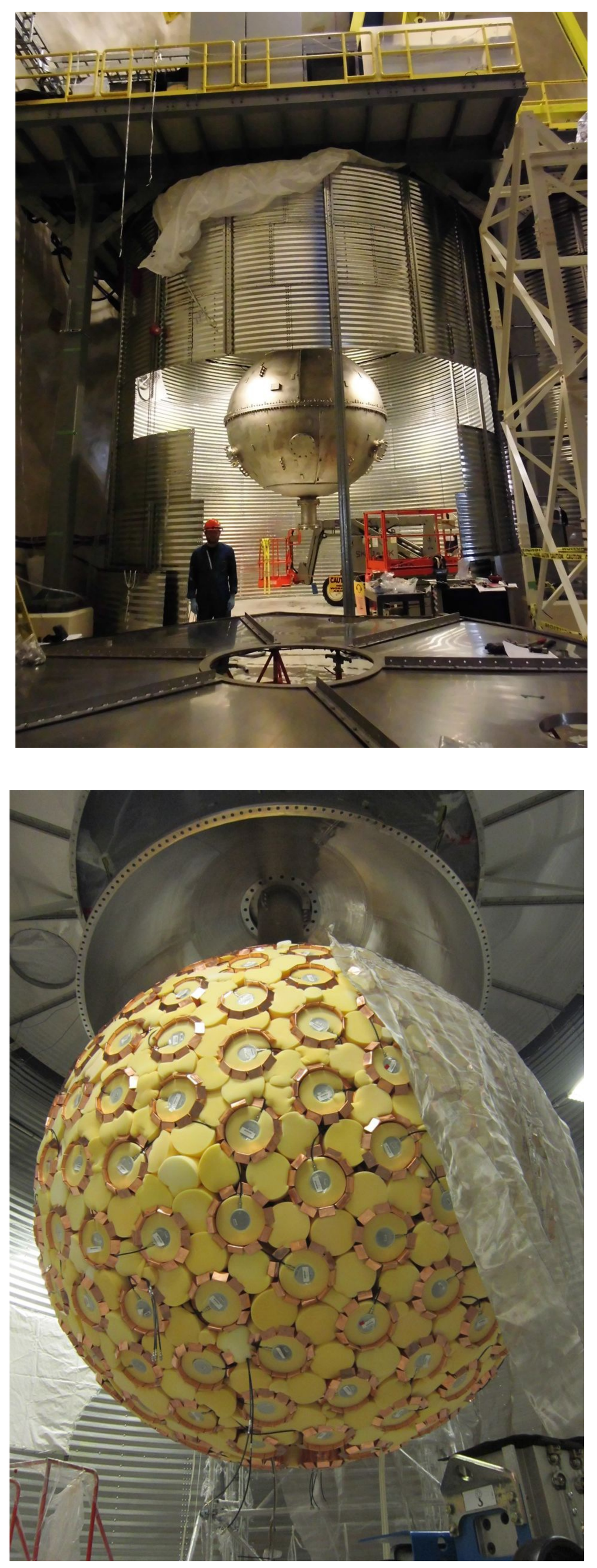


Figure 1. Left: cross-sectional representation of DEAP-3600. Right, top: the stainless steel shell, containing the acrylic vessel and the instrumentation, inserted into the cylindrical water tank. Right, bottom: acrylic vessel after the mounting of the PMTs and the polyethylene inserts.

In 2018 the experiment set the **most stringent exclusion limit** for WIMP spin-independent interactions in liquid argon for WIMP masses above 100 GeV [3][4]. Still, the same experiment shows **sensitivity to ultra-heavy dark matter** candidates, up to Planck scale masses. The detection of these candidates is mainly limited by the low flux; to compensate for that, a high cross-sectional area of the detector is required, together with a higher dark matter-nucleon cross-section, at about 10^{-25} cm^2. In DEAP-3600 this means that, differently from WIMPs, the candidate won't perform a single scatter, but tens, even thousands, giving a **collinear track of nuclear recoils**, each with a observable energy of O(10) keV. This results in a **unique multi-scatter signature**, like the one shown in Figure 2.

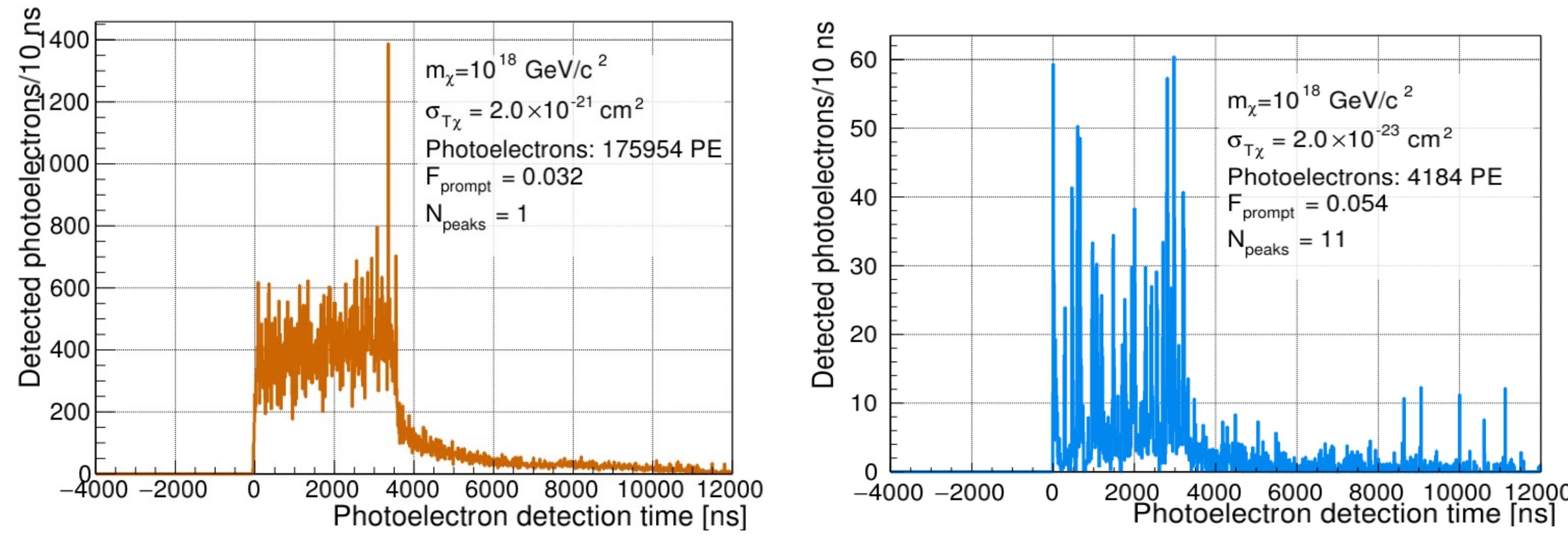


Figure 2. Photoelectron time distribution of two simulated ultra-heavy dark matter candidates, compared at the same mass and different cross-section. The high number of photoelectrons is due to the multiple hits with the liquid argon nuclei. The value of the two main variables is reported, namely the fraction of the prompt scintillation light and the number of dominant peaks.

In the simulation, the dark matter particles for a given cross-section and mass are propagated from 80 km from the Earth's ground down to SNOLab, taking into account the composition of the atmosphere and the earth. This allows evaluating the loss of kinetic energy before reaching the underground detector. If the particle enters the detector, it always interacts with the liquid argon, giving a multi-scatter signal, which would have been rejected by the usual WIMP search, requiring single scatter events. Hence a custom analysis was developed to enhance the detector sensitivity to ultra-heavy, multi-scattering dark matter candidates. Figure 3 shows a few representative populations of candidates at different per-nucleus cross-sections and at the same mass, as the signal is observed to be insensitive to changes in mass. Both the fraction of the prompt scintillation light $\mathbf{F_{prompt}}$ [5] and the number of dominant peaks along the pulse, $\mathbf{N_{peaks}}$, **decrease as the cross-section increases**.

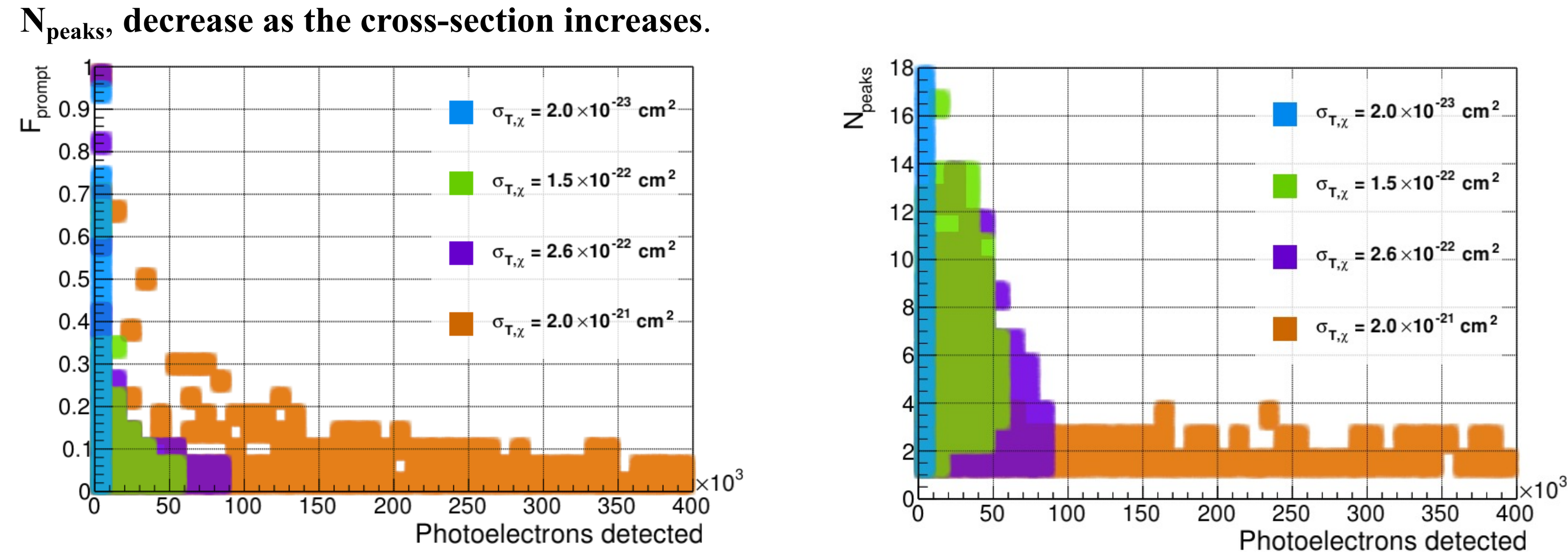


Figure 3. Comparison between a few representative populations of candidates at different cross-sections. As the cross-section increases, the number of photoelectrons also does, while both the fraction of the prompt scintillation light and the number of major peaks decreases.

The threshold $N_{Peaks} > 1$ removes any single scatter event. Still, two or more background event can happen in the same acquisition window: these are the **"pile-up"**, like the one shown in Figure 4 (left). **Pile-ups overlap on the expected signal** from heavy and multi-scatter candidates, and hence require a custom selection cut in N_{peaks}. The maximum value for N_{peaks} given by pile-up events was evaluted thanks to the knowledge of the electromagnetic single scatter backgrounds, giving an **analysis threshold on $\mathbf{N_{Peaks}}$** changing with the energy range, driven by the rate of single scatter electromagnetic background [6].

Above 10 MeV the number of pile-ups in three years of data taking is negligible, whereas the dominant backgrounds are muons entering the liquid argon vessel. Most of them are removed by applying the muon veto cut, so by removing any event happening within [-10,90] us from the water tank trigger. An upper cut on F_{prompt} is applied to further reduce the background level. **Four Regions of Interest (ROI) are defined,** each with its energy range, photoelectron range, and its selection cut in F_{prompt} and N_{peaks}, all reported in Table 1; the acceptance for all the selection cuts for a few representative cross-section is reported in Figure 4 (right).

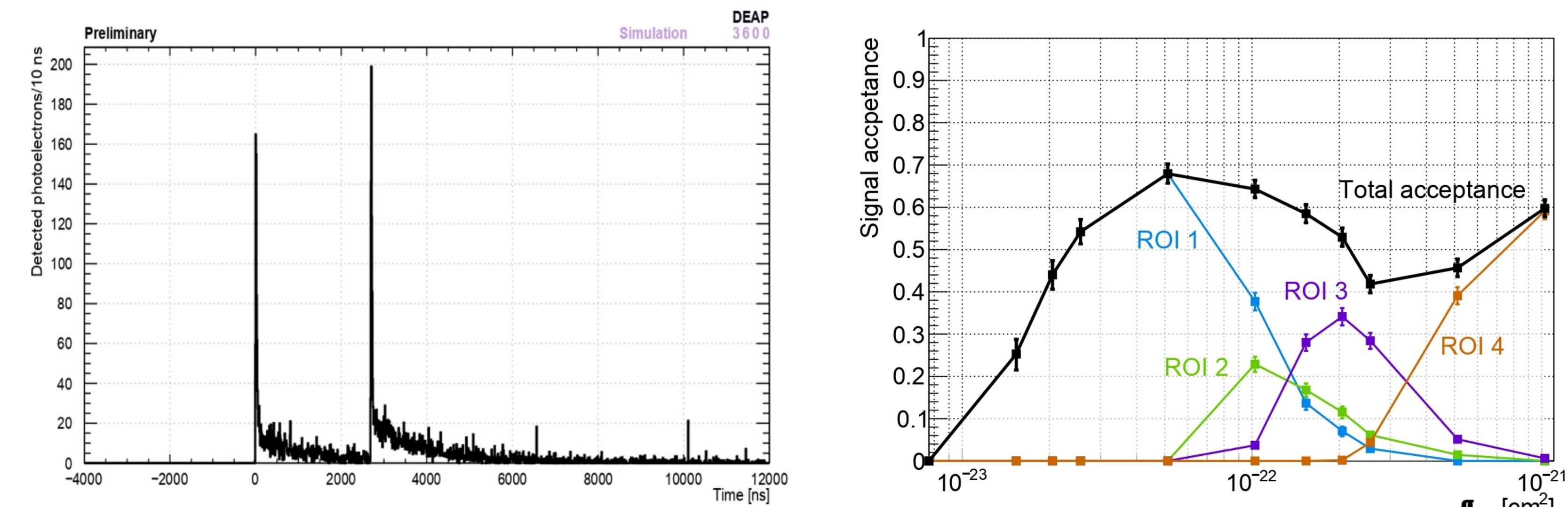


Figure 4. Left: photoelectron time distribution for a simulated pile-up event due to two ^{39}Ar beta-decays happening in the same acquisition window. Right: signal acceptance for a few representative cross-sections for all the applied selection cuts.

ROI	PE range	Energy [MeV]	N_{peaks}^{min}	F_{prompt}^{max}	μ_b
1	4000–20 000	0.5–2.9	7	0.10	$(4 \pm 3) \times 10^{-2}$
2	20 000–30 000	2.9–4.4	5	0.10	$(6 \pm 1) \times 10^{-4}$
3	30 000–70 000	4.4–10.4	4	0.10	$(6 \pm 2) \times 10^{-4}$
4	70 000–4×10^8	10.4–60 000	0	0.05	$(10 \pm 3) \times 10^{-3}$

Table 1: Regions of Interests identified in the present analysis, each with its photoelectron and energy range, assuming 7.1 PE/keV for the light yield, the threshold on the number of dominant peaks and the upper cut on the fraction of the prompt scintillation light. The last column reports the expected background level after the application of these selection cuts in 813 ± 8 days of lifetime.

A **blind analysis** was performed, and specifically each ROI was opened one after the other, in order to be able to analyze them as four different channels. Still, no event was left in any of the ROIs in 813 ± 8 days of lifetime, allowing to set world-leading exclusion limits for **ultra-heavy dark matter candidates**. The constraints, shown in Figure 5, are set within 90% of C.L. for **two composite models**. Model 1 refers to composite models opaque to the nucleus, so that the cross-section at null-transferred momentum corresponds to the geometric cross-section. Model 2 is a dark matter nugget, where the number of dark nucleons are chosen to assure to have a dark nucleus radius much larger than 1 fm, while the dark nucleus form factor goes to the unity. The limits are set for ROI 1-3 in black, while the extrapolated limits in grey refer to the cross-sections relying on ROI 4. Here the simulations were computationally limited and no calibration was available, so the exclusion limits are set by assuming a conservative acceptance at 35 %. Thanks to the high cross-sectional area and the custom-developed analysis in the **multi-scatter game**, DEAP-3600 is the only experiment excluding dark matter candidates up to Planck scale masses.

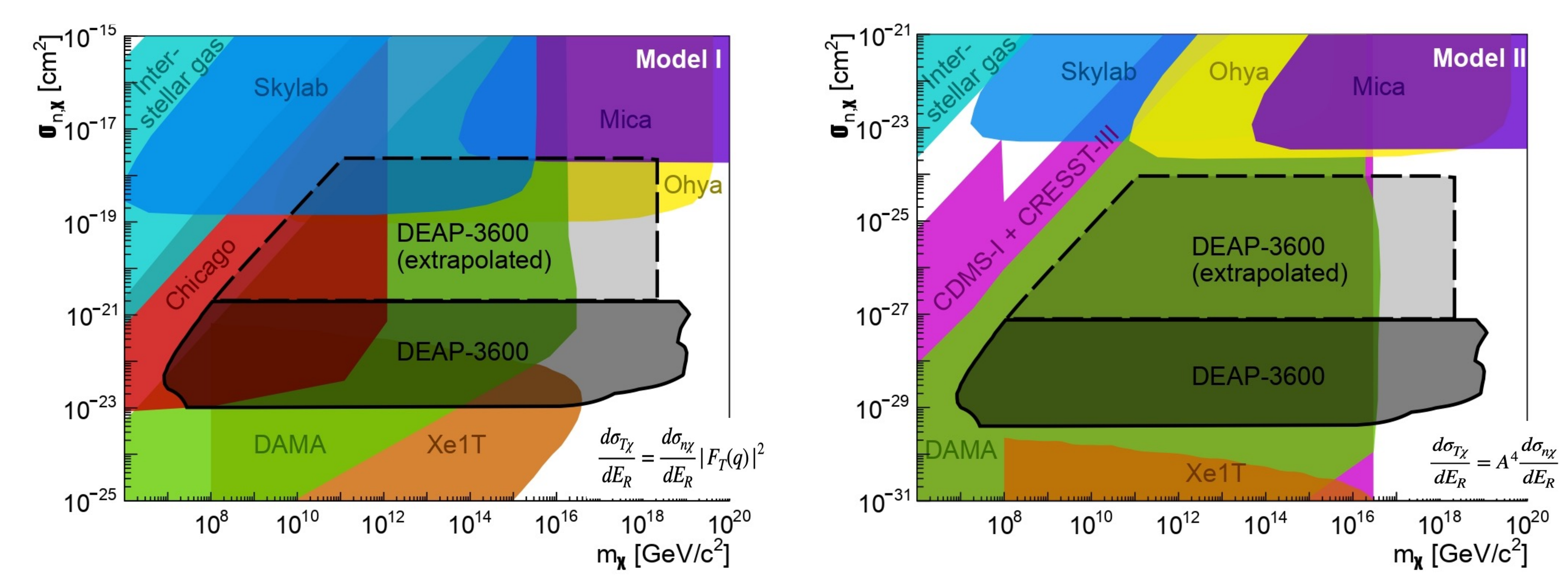


Figure 5: Exclusion limits set within 90% of C.L. after finding no event in the whole dataset, shown for two different model of composite candidates. Thanks to the high cross-section area and the custom-developed multi-scatter analysis, DEAP-3600 is the only experiment which could exclude dark matter up to Planck scale masses.

[1] Adhikari, P. et al (DEAP Collaboration), 2022, Phys. Rev. Lett. 128, 011801
[2] Amaudruz P et al. (DEAP Collaboration) 2019 Astropart. Phys. 108 1–23
[3] Ajaj, R. at al., (DEAP Collaboration) 2019 Phys. Rev, D 100(2) 022004
[4] Adhikari P et al. (DEAP Collaboration) 2020,Phys RevD 102(2), 082001
[5] Adhikari P et al. (DEAP Collaboration) 2021 Eur. Phys. J. C 81 823
[6] Ajaj R et al. (DEAP Collaboration) 2019 Phys. Rev. D 100(7) 072009