Journal of Physics: Conference Series **2391** (2022) 012005 doi:10.1088/1742-6596/2391/1/012005

The MESA science program: dark matter and more

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Abstract. The Mainz Energy-recovery Superconducting Accelerator MESA will allow precise measurements in hadron and nuclear physics, as well as exciting opportunities in dark matter searches. Three experiments will be built around this new and unique facility: MAGIX, P2, and DarkMESA. In this contribution, the MESA science program will be presented, with focus on dark matter and new physics searches.

1. Introduction

In this contribution, the physics program of MESA will be discussed. **MESA** is a new experimental facility centered around the **M**ainz **E**nergy-recovery **S**uperconducting **A**ccelerator. The experiments at MESA will cover a wide program from dark matter searches to nuclear astrophysics.

A variety of astrophysical and cosmological observations point to the existence of Dark Matter (DM). In the last decades, an effort was made for searching for DM with particle colliders, fixed-target experiments, indirect detection techniques, and underground direct detection experiments. Still, the nature of DM remains elusive, and more sensitive and diversified experiments are required. A large class of models describe DM as a relic from the early Universe where DM was in thermodynamic equilibrium with Standard Model (SM) particles. In these models, the DM abundance is set when its annihilation rate in SM particles became smaller than the expansion rate of the universe in a process known as *freeze-out*. While this mechanism is very compelling, it allows for a broad range of DM masses (keV/c^2-TeV/c^2) and interaction cross sections. The prime target of many experiments is a DM candidate called WIMP (Weakly-Interacting Massive Particle), motivated by models of physics beyond the SM (most notably supersymmetric models). This range can be effectively tackled by high-energy colliders and direct detection experiments. In the light dark matter (<GeV/c^2) range (LDM), these methods become less effective, and different techniques are needed. LDM production at accelerators can in principle overcome the limitations of direct detection experiments (the detection energy threshold) by producing DM particles with enough momentum to be detected, even if they are relatively light. High-energy colliders are not optimised for the low-mass range, and lower energy accelerators coupled with fixed targets can have an advantage in LDM searches. In this context, low-energy accelerator searches can also contribute to the "X17 puzzle" [1] or in the search of axion-like particles (ALPs). On top of direct new physics searches, a high intensity, low-energy electron accelerator has the strong potential to contribute to precision measurements in hadron and nuclear physics. A prime example is the opportunity to measure the nucleon form factors

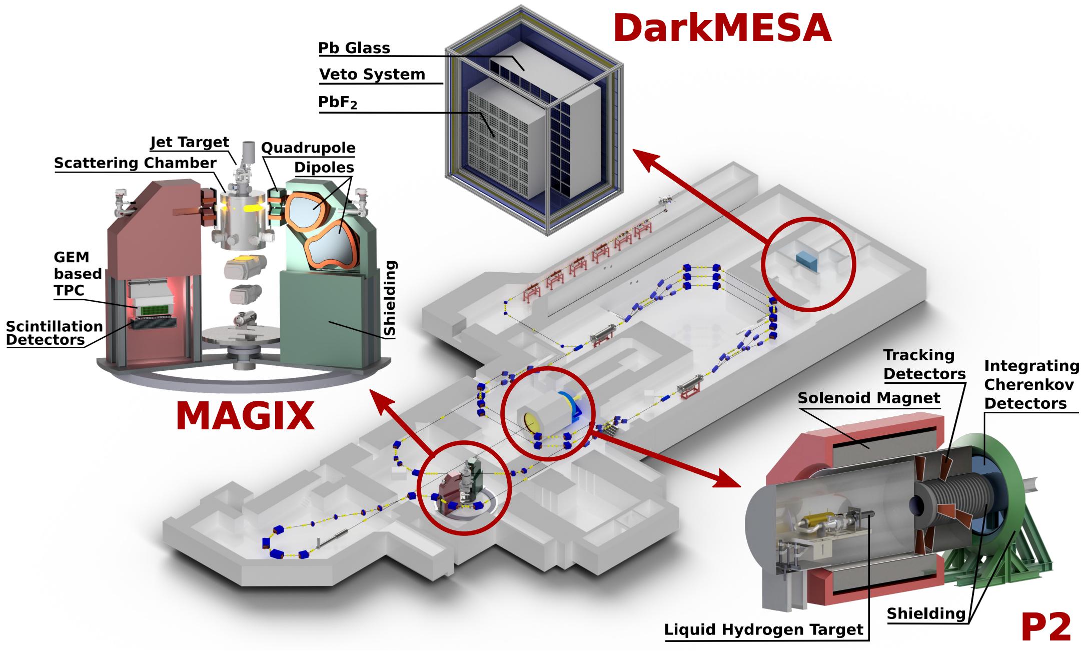

Figure 1. The MESA accelerator floor plan with the three experiments: DarkMESA, MAGIX, and P2.

at low momentum transfer, clarifying recent disagreements between electron scattering and spectroscopy measurements. Another research direction consists in the precision measurements of nuclear cross sections of few-body nuclear systems for elucidating properties of the nuclear potential, also in connection with effective field theories. Furthermore, MESA can contribute to the measurement of S-factors for nuclear reactions of astrophysical interest.

2. The MESA accelerator

The Institute for Nuclear Physics at the Mainz University is building a new multi-turn, 100% duty-cycle, energy recovery linac for precision experiments with a beam energy of 100-200 MeV [2] (see Fig. 1). MESA (Mainz Energy-Recovering Superconducting Accelerator) will operate in two modes: energy recovery mode (ERM) and external beam mode (XBM).
In ERM, the accelerator will provide a beam current of up to 1 mA at 105 MeV for the MAGIX internal target experiment with multi-turn energy recovery capability. In XBM, a polarised beam of 150 μA will be provided to the P2 experiment [3]. An additional experiment, DarkMESA, will be placed after the P2 beam dump, running in parallel to P2 and searching for LDM particles.
The MESA accelerator will consist of a polarised source followed by a low energy beam transport system containing a spin manipulation system and a chopper-buncher section. Normal conducting cavities will accelerate the beam up to 5 MeV before injection into the main linac equipped with a total of four ELBE-like 9-cell superconducting cavities [4] installed in two cryomodules. The linac will provide an energy gain of 50 MeV/pass.

3. Light Dark Matter

In this section, we briefly introduce a simple model for light dark matter, which also constitute a benchmark for the sensitivity of experiments in this field [5, 6].

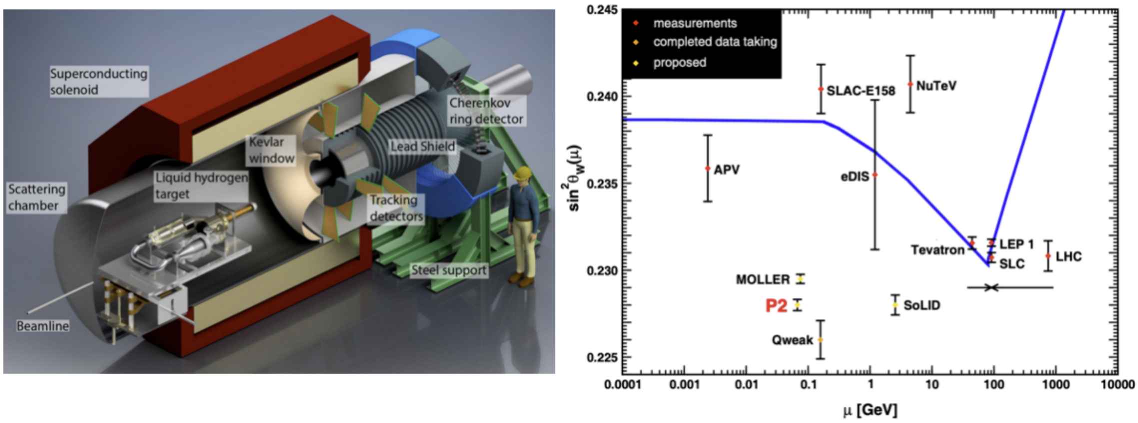

Figure 2. Left: Technical view of the P2 experiment. **Right:** Evolution with the energy scale of the Weinberg angle together with the existing experimental results and the planned experiments.

In the $<$GeV/c^2 range, for retaining a thermal origin of DM, the existence of additional interactions has to be postulated. For small masses, considering only electroweak-scale cross sections, the annihilation rate would not be sufficient, leading to DM overproduction. A relevant class of LDM models is based on the idea that DM particles belong to a *dark sector* interacting with the SM via one (or more) mediator particle(s). Dark sector models can be classified by the type of mediator particle (the *portal*) and the type of DM particle. In general, the dark sector might contain more mediators and particles. A simple model which captures the essence of dark sector physics contains a massive vector mediator particle (a "dark photon") and one DM particle. The model's Lagrangian is

$$\begin{aligned}\mathcal{L} \supseteq & -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{\epsilon_Y}{2}F'_{\mu\nu}B^{\mu\nu} \\ & + \frac{m^2_{A'}}{2}A'_\mu A'^\mu + g_D A'_\mu J^\mu_\chi + g_Y B_\mu J^\mu_Y \quad ,\end{aligned} \tag{1}$$

where $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$ and $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ are the dark photon and the hypercharge fields, g_D is the dark gauge coupling, and J^μ_χ and J^μ_Y the DM and hypercharge currents, respectively. After electroweak symmetry breaking, the dark photon mixes with the SM photon and the Z boson

$$\frac{\epsilon_Y}{2}F'_{\mu\nu}B^{\mu\nu} \to \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu} + \frac{\epsilon_Z}{2}F'_{\mu\nu}Z^{\mu\nu} \quad , \tag{2}$$

where $\epsilon = \epsilon_Y/\cos\theta_W$, $\epsilon_Z = \epsilon_Y/\sin\theta_W$, and θ_W is the weak mixing angle. After diagonalization, the coupling of the dark photon with DM and the SM photon is

$$g_D A'_\mu J^\mu_\chi + g_Y B_\mu J^\mu_Y \to A'_\mu(g_D J^\mu_\chi + \epsilon e J^\mu_{EM}) \quad , \tag{3}$$

where J^μ_{EM} is the SM electromagnetic current. The form of the DM current J^μ_χ depends on the exact nature of the DM particle. The coupling of the dark photon to SM particles happens via the coupling constant ϵe, while the dark fine structure constant $\alpha_D = \sqrt{4\pi g_D}$ describes the coupling with DM.
It is useful to define the dimensionless combination of the model parameters

$$y = \epsilon^2\alpha_D\left(\frac{m_\chi}{m_{A'}}\right)^4 \quad , \tag{4}$$

which is proportional to the thermally averaged DM annihilation rate.

4. The P2 Experiment

The main aim of the P2 experiment [3] is the measurement of the parity violating asymmetry

$$A^{PV} = \frac{d\sigma^{+}_{ep} - d\sigma^{-}_{ep}}{d\sigma^{+}_{ep} + d\sigma^{-}_{ep}} \quad , \tag{5}$$

where $\sigma^{\pm}_{ep}$ is the elastic electron-proton cross section with electrons of helicity $\pm 1/2$ respectively. The observable A^{PV} depends on the weak form factor of the proton $Q_W(p) = 1 - 4\sin^2\theta_W$ (neglecting radiative corrections) and thus allows the extraction of the Weinberg (or weak) angle θ_W. The Weinberg angle is a key parameter of the Standard Model and its dependence on the energy scale can be precisely calculated (see Fig. 2, right). P2 aims at a $\sim 0.15\%$ precision measurement of $\sin^2\theta_W$ complementing the other precise measurement at colliders made at the Z-pole. Measuring a deviation from the Standard Model predictions would be a signal for the presence of new physics.

P2 employs a cryogenic target placed at the center of a superconducting solenoidal magnetic field. Elastically scattered electrons are measured by 82 fused-silica bars. Given the high-precision goal of the experiment and the need for keeping a reasonable measuring time, electrons are not counted as single events, but the silica bars will measure an asymmetry in the output current (the rate will be of the order of 10^{12} Hz in the detector). Tracking is provided by High-Voltage Monolithic Active Pixel Sensors (HV-MAPS, [7]) which, in combination with the magnetic field, will measure the momentum of the tracks. A technical drawing of the P2 detector is shown in Fig. 2 (left).

5. The MAGIX Experiment

The **MA**inz **G**as **I**njection Target E**X**periment **(MAGIX)** is a flexible experiment exploiting the unique combination of a supersonic gas-jet target and the MESA continuous beam in energy recovery mode. The experiment is based on two magnetic spectrometers ("STAR" and "PORT") which can be operated in coincidence with momentum resolution $\delta p/p \sim 10^{-4}$ and low-material budget focal plane tracking detectors (Fig. 1). The tracking detectors are time projection chambers (TPCs) with GEM (Gas Electron Multiplier) readout. To shape the drift field and keep the material budget as low as possible (at low momenta, multiple scattering degrades resolution), field shaping extensions are used instead of a more common field cage on the entrance face of the TPC. A new approach is adopted for online calibration by employing a 266 nm laser system to release ionisation electrons from fixed positions on the cathode for producing a snapshot of the dynamic field distortions.

MAGIX will feature a gas-jet target [8] which will allow beam recirculation in MESA. The jet target was already successfully tested at the A1 collaboration setup with hydrogen and argon as targets [9].

MAGIX will allow precision measurements in a variety of fields ranging from hadron physics to nuclear astrophysics and dark sector searches.

Dark Matter.

For LDM searches, candidate particles are for example dark photons introduced in Sec. 3. The dark photon can be produced through a mechanism similar to bremsstrahlung on a heavy nuclear target Z via the reaction $e^-Z \to e^-Z\gamma'$ or e^+e^- annihilation. If the dark photon decays into SM particles, *e.g.* $\gamma' \to e^+e^-$, the electron/positron final state can be detected in coincidence in the two spectrometers and a peak-search on the QED background can be performed [10, 11]. A similar strategy can be employed for the search for the X17 particle or axions.

If the dark photon decays invisibly (*e.g.* into light dark matter particles $\gamma' \to \chi\bar{\chi}$), this will require the measurement of the recoil target nucleus for fully reconstructing the kinematics. A peak-search on the reconstructed missing mass $m^2_{\gamma'} = (p_{beam} - p_Z - p_{e'})^2$ will be performed in

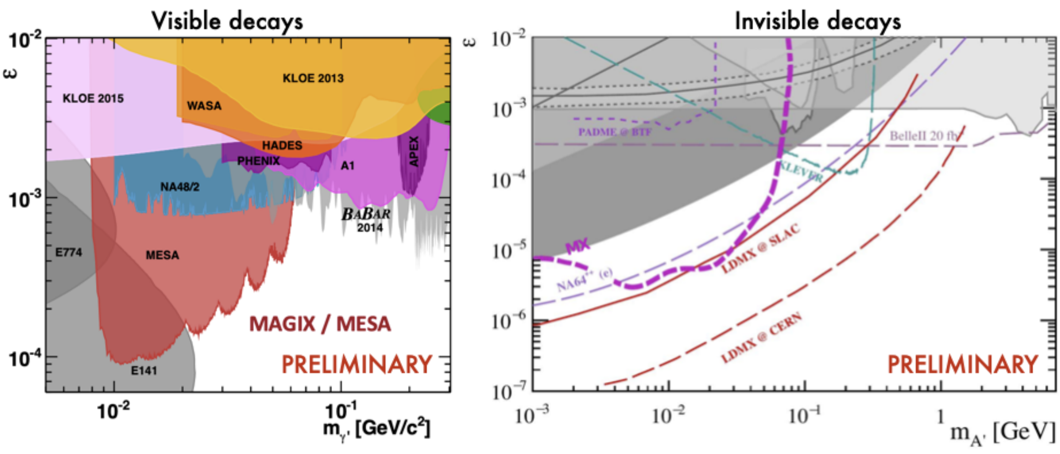

Figure 3. Simulated exclusion limits for the MAGIX experiment where a dark photon γ' is produced by the bremsstrahlung process on a heavy nucleus Z: $eZ \to eZ\gamma'$.
Left: Exclusion limits for the dark photon visible decay $\gamma' \to e^+e^-$. **Right:** Exclusion limits for the dark photon invisible decay $\gamma' \to \bar{\chi}\chi$ where χ is a fermionic light dark matter particle.

this case with the addition of a silicon detector for detecting the recoil proton or nucleus.
A preliminary simulation of the exclusion limits for dark photon decays achievable with MAGIX is shown in Fig. 3.

Form Factors.

Form factors are a fundamental quantity describing the low energy properties of the nucleon. They can be accessed through electron scattering measuring the cross section

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{\epsilon(1+\tau)} \quad , \tag{6}$$

where ϵ is the virtual photon polarisation, $\tau = Q^2/(4m_p^2)$, with m_p the mass of the proton, $Q^2 = -q^2$ the squared momentum transfer, and G_E, G_M the Sachs form factors (the electric and magnetic form factors, respectively). $(d\sigma/d\Omega)_{\text{Mott}}$ is the Mott cross section.
In particular, the radius of the proton can be derived from

$$\langle r_p \rangle = -\frac{6}{G(0)} \frac{dG_E(Q^2)}{dQ^2}|_{Q^2=0} \quad . \tag{7}$$

In recent years, the determination of the radius from electron scattering [12] became inconsistent with the high-precision number extracted from spectroscopic measurements of muonic atoms [13]. The disagreement became known as the "proton radius puzzle".
MAGIX can perform a high-precision measurement of the cross section in Eq. 6 focusing on low-momentum transfers in a region very sensitive to the value of r_p. The new measurements have the potential for elucidating the disagreement of electron scattering analyses with the spectroscopy value.

Nuclear Astrophysics.

Stellar burning is driven by nuclear fusion reactions in the core of the stars. Nuclear fusion starts from the lightest elements (hydrogen, helium), and builds heavier nuclei. The nucleosynthesis process $^{12}C(\alpha, \gamma)^{16}O$ is of key importance since its S-factor is a major parameter for determining the abundance ratio of oxygen to carbon in stellar nucleosynthesis and moreover, it plays a crucial role in the pre-supernova star evolution. At MAGIX, the idea is to measure the

electro-disintegration reaction $^{16}O(e,e'\alpha)^{12}C$, scattering an electron on oxygen and detecting in coincidence the α particle. This inverse kinematics reaction is connected with the stellar one only by kinematical factors dependent on the angular momentum of the involved particles [14]. The electro-disintegration has some advantages over the exact inverse photo-disintegration reaction $^{16}O(\gamma,\alpha)^{12}C$. An advantage is that the background from cosmic rays is strongly suppressed by the coincidence measurement of the electron and the recoil α. Furthermore, the virtual photon flux is higher and can be fixed by choosing electron scattering angle and beam energy. Another advantage is that the energy resolution of the (virtual) photon can be precisely measured detecting the scattered electron in a high-resolution detector.
A relevant disadvantage is that the longitudinal and interference terms of the electron-scattering reaction are currently unknown. These terms must be determined experimentally and employed in the extrapolation to small energies. Another disadvantage is that target gas contamination by other isotopes (^{17}O, ^{18}O, ^{14}N) causes additional backgrounds.
The simulations predict that MAGIX will be able to measure the S-factor for center of mass energies above 1 MeV with a precision similar to the existing data [15]. With the addition of a zero-degree tagger (ZDT), it would be possible to detect the scattered electrons with a scattering angle $< 0.5°$. The ZDT detector will exploit a MESA dipole downstream of the MAGIX beamline and will also play the role of luminosity monitor for the whole experimental program.
Few-Body Systems.
Modern *ab initio* nuclear physics aims at a coherent description of few- and intermediate-body nuclei solving the quantum nuclear problem exactly together with the use of potentials derived with effective field theory (EFT).
EFT allows for theoretically controlled calculations where the strong force among nuclei contains interactions beyond the nucleon-nucleon coupling, such as the three-nucleon force. These techniques can be extended to intermediate-mass nuclei, also through the use of cluster EFT, where nuclei can be viewed as bound systems of α particles.
Given the perturbative nature of the electromagnetic force, electron accelerators are very well suited for the investigation of nuclear systems since the electron interaction part is completely known and disentangled from the strong force component to be studied.
MAGIX will allow the precise study of nuclear systems like ^2H, $^{3,4}He$ and the “cluster nucleus” ^{12}C for validating EFT theories and modern *ab initio* codes for the solution of the quantum many-body problem.

MAGIX is currently in its advanced design phase. The design of the magnets is complete, as well as the rotation system. The conceptual design of a GEM-based low-material budget TPC has been finalised and prototypes are tested in the laboratory. The experimental hall is completed and installation of the first components will start at the end of 2022. Significant progress has been achieved in the simulation and analysis software development, with a focus on the simulation of the dark photon production and astrophysical reactions. A key part of the experiment, the jet target, has been already built and tested at the A1 Collaboration experimental setup [8, 9].

6. The DarkMESA Experiment
DarkMESA is a beam dump experiment currently actively developed [16, 17, 18]. DarkMESA will take advantage of the P2 beam dump installing a calorimeter ~ 23 m downstream of it in a radiation-shielded area. Referring to the simple LDM model described in Sec. 3, a dark photon could be produced in the beam dump (through bremsstrahlung or e^+e^- annihilation) and then decay into pairs of DM particles. DM will be then detected (via dark photon exchange) in the calorimeter.
The advantage of such an experiment is the possibility to investigate both the dark photon

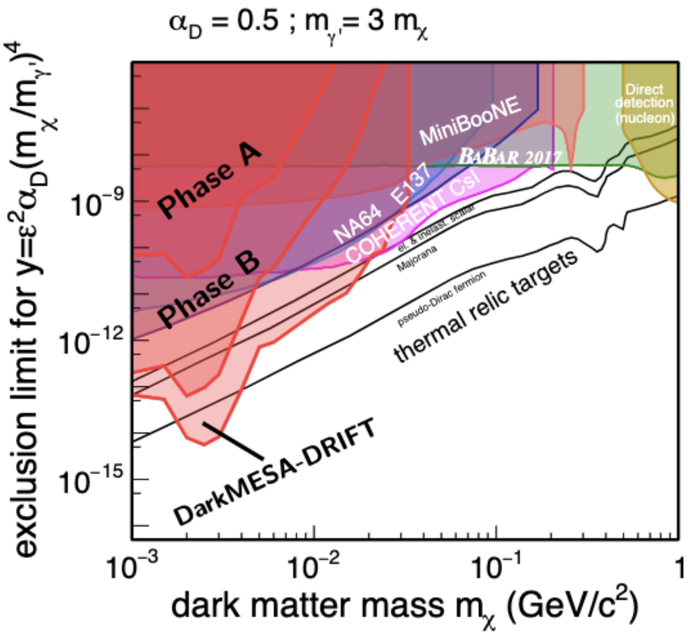

Figure 4. Simulated exclusion limits for the DarkMESA experiment where a dark photon γ' is produced by the bremsstrahlung process and e^+e^- annihilation in the P2 beam dump followed by the decay $\gamma' \to \bar{\chi}\chi$ where χ is a fermionic light dark matter particle. The exclusion limits of the two experimental phases (A,B) are indicated together with the projected limits employing the DRIFT TPC detector.

production and the DM interaction (rescattering in the detector).
The current plan for the construction of the experiment is divided into two phases. Phase-A consists in the construction of a prototype calorimeter module comprised by a matrix of 5×5 PbF_2 Cherenkov crystals for a total volume of ∼4 dm^3 surrounded by a hermetic cosmic ray veto system built with two plastic scintillator layers and one lead layer (Fig. 5). The design follows successful tests by the BDX Collaboration, which is proposing a similar experiment at Jefferson Lab [19].
In particular, a dedicated electronics has been developed for the readout of silicon photomultipliers optically coupled to the veto plastic scintillator planes. In Phase-B, the full volume available in the experimental hall will be exploited with the construction of a PbF_2, 0.12 m^3 calorimeter and a lead-glass, 0.58 m^3 calorimeter. The advantage of Cherenkov crystals is their speed and relatively low sensitivity to background neutrons. Exploiting the 2.2×10^{22} (6600 hours) electrons on target delivered to the P2 experiment at 150 μA of beam current, a total charge of ∼5400 C will be deposited in the beam dump and will be available for DarkMESA. Besides the calorimeters, it is under study also the opportunity to add a negative-ion TPC to the experimental setup. In particular, the chamber will leverage the technology of the DRIFT experiment optimised for dark matter searches with 20 keV nuclear recoil detection threshold [20].
In Fig. 4, simulated 90% exclusion limits for the two experimental phases and for the DRIFT detector technology are shown.

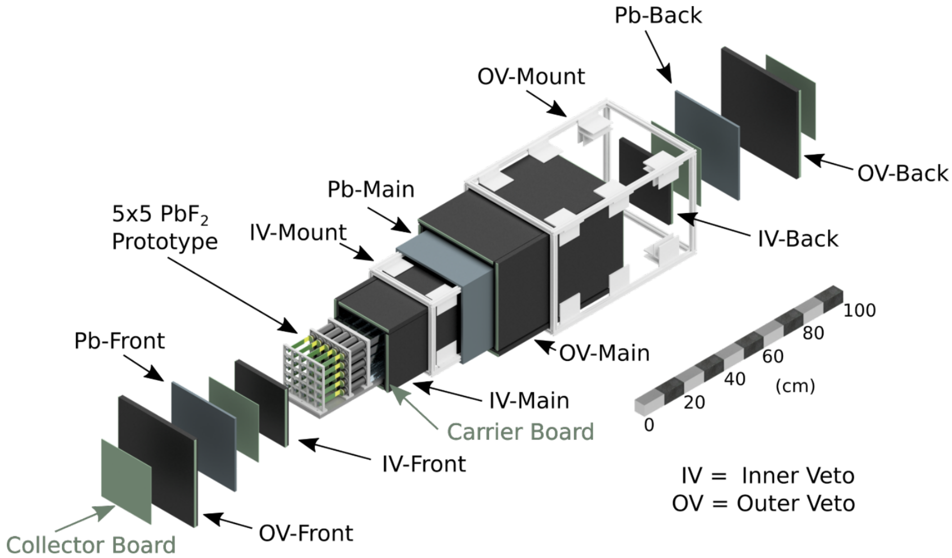

Figure 5. Exploded view of the DarkMESA prototype detector. A matrix of 5x5 PbF_2 Cherenkov crystals is placed inside two hermetic layers of active veto plastic scintillators and one layer of lead. The active shielding will be used for vetoing cosmic rays, while the crystals will be used for DM detection.

6.1. Acknowledgments
The author is indebted to the MAGIX/DarkMESA collaboration and the $PRISMA^+$ Cluster of Excellence at the Johannes Gutenberg University Mainz. He wishes also to thank the organisers of the "New Scientific Opportunities at the TRIUMF ARIEL e-linac" workshop for the kind invitation.

7. References
[1] A. Krasznahorkay *et al.*, *Phys. Rev. Lett.*, 116, 042501 (2016).
[2] F. Hug *et al.* LINAC16 Conference Proceedings MOP106012, pp. 313–315 (2017).
[3] D. Becker *et al.*, *Eur. Phys. J. A*, **54**, 11, 208 (2018).
[4] T. Stengler *et al.*, Proceedings of SRF2015, Whistler, BC, Canada (2015).
[5] J.D. Bjorken *et al.*, *Phys. Rev. D* **80**, 075018 (2009).
[6] E. Izaguirre *et al.*, *Phys. Rev. Lett.* **115**, 251301 (2015).
[7] I. Peric *et al.*, *Nucl. Instrum. Methods* **A 731**, 131 (2013).
[8] S. Grieser *et al. Nucl. Instrum. Methods* **A 906**, 120-126 (2018).
[9] B.S. Schlimme *et al. Nucl. Instrum. Meth. Phys. Res.* A **1013**, 165668 (2021).
[10] H. Merkel *et al.*, Phys. Rev. Lett. **106**, 251802 (2011).
[11] H. Merkel *et al.*, *Phys. Rev. Lett.* **112**, 221802 (2014).
[12] J.C. Bernauer *et al. Phys. Rev. C* **90**, 015206 (2014).
[13] R. Pohl *et al. Nature*, 466, 213 (2010).
[14] I. Friŝĉić *et al.*, Phys. Rev. C **100**, 025804 (2019)
[15] S. Lunkenheimer, PhD Thesis (2022), `https://openscience.ub.uni-mainz.de/handle/20.500.12030/6819`
[16] L. Doria *et al.*, Proceedings of CIPANP 2018, arXiv:1809.07168.
[17] M. Lauß *et al. Nucl. Instrum. Meth. Phys. Res.* A 1012, 165617 (2021).
[18] M. Christmann *et al.*, *PoS*, **EPS-HEP2021**, 129, (2022).
[19] M. Battaglieri *et al.*, submitted to JLab PAC 45, arXiv:1712.01518 (2017).
[20] J.B.R. Battat *et al.*, *Astroparticle Physics*, 91, 65-74 (2017).