Whitepaper for astroparticle physics in Switzerland

Additional information to inform the SNSF FLARE instrument 2021-24
Endorsed by the CHIPP[1] Board on 11.02.2021

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for the Pillar 3 community

Finding answers to the fascinating big questions about the existence and the evolution of our universe, its fundamental constituents and their interaction requires new initiatives for large research infrastructures, which can only be designed, constructed and operated in powerful, world-wide collaborations. The scientific quests are addressed in the Roadmap document, while this White Paper addresses the need for priorisation and coordination in the Pillar III for construction contributions to experiments. The Swiss research community realises that our small country must coordinate its efforts in order to be able to continue to play a significant and visible role in the ever increasing collaborations, some of which are planning or doing R&D on detectors and some others are in construction phase. Infrastructures to address the big questions of astroparticle physics and cosmology are becoming larger and larger. They also imply technological challenges and research and development to build them, while they have important innovation returns. This document was prepared in parallel to the drafting of the "CHIPP Roadmap for Research and Infrastructure 2025-2028 and beyond" and its recommendations are also reflected in the prioritisation input to the FLARE Panel for 2021-2024 (link).

Given the limited number and size of Swiss particle physics research groups and the modest financial resources, a concentration on only a few projects seems indispensable. With this whitepaper we propose to concentrate our efforts on a few projects as detailed below, all of which are already described in the CHIPP Roadmap for Astroparticle and Particle Physics in Switzerland.

- The LST is the large size telescope project that delivers telescopes to CTA. They constitute the driving components of the science of CTA, since the energy region they cover maximizes the gamma-ray fluxes and overlaps with satellites. The consortium is regulated by its own MoU. Despite the CTA Swiss community is currently financed by interim funds of SERI, the R&D activities for the future of the LST project and of gamma-ray astronomy are not financed;
- The direct detection of DM is essential for the quest to understand the nature of the dark matter in the cosmos. The LXe projects have a long-standing leadership role in Switzerland. The XENON projects evolved to the many-tonne configuration and probe dark matter particles over a wide range of masses (100 MeV to multi-TeV) with unprecedented sensitivity. The DARWIN project, under Swiss leadership, will probe the experimentally accessible parameter space and will allow for a diversification of the physics programme beyond the search for WIMP dark matter.

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- DM may not interact as a weakly interacting massive particle, but instead may be part of a hidden sector that mixes weakly with SM particles. The DAMIC-M project use the silicon in CCD detectors as targets to probe hidden photons and hidden-sector DM with masses from an eV up to 10^7 MeV. With a decade of leadership in DAMIC, the Swiss community is positioned to contribute to the next decade of hidden-sector searches in CCDs.

This whitepaper summarises the projects, lists the Swiss intellectual and technical contributions and the resources needed in the future.

1 R&D developments for the Large Size Telescope (LST) for the future of gamma-ray astronomy

The Swiss community involved in high-energy multi-messenger astrophysics has by now acquired expertise on photosensing at room temperature and in noisy environments. For the coming years, R&D developments relevant for the international project Large Size Telescope (LST), which aims at providing large Imaging Atmospheric Cherenkov Telescopes(IACTs) to the Cherenkov Telescope Array [1], are very important for the future of gamma-ray astronomy.

Currently, the LST project is composed by about 280 scientists from Germany, Japan, Spain, Italy, France, Switzerland, Poland, Bulgaria, Croatia, Brazil, India and it is regulated by an independent MoU from the CTA one. Its mandate is to provide 4 telescopes for the Northern site of CTA by 2025. The first LST telescope (LST-1) (see Fig.1) has been built at the La Palma Observatory of Roque de Los Muchachos, close to the two MAGIC telescopes. The LST-1 is under commissioning and has been regularly taking data on gamma sources successfully since October 2019. The Crab Nebula, which is the first TeV source ever discovered and also the 'standard candle' for gamma-ray astronomy, has been detected at very high significance levels, as well as the pulsations beyond 100 GeV of the pulsar inside the Nebula [2, 3].

For commissioning and to reach best performance for science, the MAGIC telescopes and LST-1 can be operated in joint observation mode. A MoU had been signed for joint LST-1 - MAGIC collaborations and it was recently adjusted to also cover the other three LSTs. As a matter of fact, the first science verification results are beginning to flow.

The construction of three additional LSTs at the La Palma site is ongoing and is fully financed. They will be added into the acquisition system of LST-1 during the coming five years, as well as several Middle Size Telescopes (MSTs). The two MAGIC telescopes are taking data close to LST-1.

Similarly to the LST Consortium, other two consortia and projects exist to provide to the CTA Observatory (CTAO) smaller size telescopes, after acceptance through a Critical Design Review (CDR): the 12 m diameter MSTs and the 4 m Small Size Telescopes (SSTs). Current planning implies that at the La Palma site the 4 LSTs are accompanied by 5 to 9 MSTs. In the Southern site in Chile, 15 MSTs with 50 SSTs should be deployed. Until they are not accepted, telescopes are property of the contributing sub-consortia and they act as independent experiments, with data not belonging to CTAO. Once handled to CTAO ERIC, the legal entity governing the Observatory, it will operate them for 30 years. Currently, the

Figure 1: The first LST telescope at La Palma and the full panorama including the two MAGIC telescopes and the small FACT telescope that pioneered SiPM cameras under leadership of ETHZ.

CTAO GmbH, established in the past, is serving in this role until the ERIC starts operations. Hence, the LST is technically an experiment of its own within a larger consortium, CTA.

Relevant discussions for the future work in LST of the Swiss groups are ongoing to implement 4 additional LSTs in the Southern site of CTA. This is blessed by LST management and by several institutions in the LST Consortium and in Switzerland (UNIGE, ETHZ, EPFL), given the impact on the physics reach of the Southern CTA array. The cameras of these 4 LSTs require R&D to achieve a cost-effective and performing design based on SiPM rather than PMTs, which can operate for the long term with high stability. This activity is related to the LST project, but can also be useful for other experiments like MAGIC [4] and LHAASO [5].

The LSTs are indispensable for all of these Key Science cases of CTA [6], since they are the telescopes accessing the low energy region down to about 20 GeV, where gamma rays are more abundant than at higher energies. This region is critical to overlap with satellite experiments, such as Fermi-LAT, and to explore dark matter, gamma-ray bursts and studies on the extragalactic background light which provide, information on galaxy formation as well as fully independent measurement of the Hubble constant. The Key Science cases can be clustered in three major themes [6]: *i)* Understanding of the origin of the cosmic rays; *ii)* Probing extreme environments, such as neutron stars, black holes and gamma-ray bursts; *iii)* Exploring frontiers in physics, such as the nature of dark matter, axions and their interplay with magnetic fields, and quantum gravitational effects in photon propagation.

An initial funding line of 8 MCHF was approved in Sep. 2016 by the Swiss Parliament to finance the CTAO before 2021. Since this amount could not yet be spent because CTAO ERIC will only be finalized by end of 2021, the Parliament will decide if to extend this amount to 2024 by the end of 2020, as indicated in the recent SERI Dispach [7]. If approved, an accession of Switzerland to CTAO ERIC would remain possible also between 2021 and 2024. The Swiss groups are involved currently mostly in CTA software development and data analysis. For the moment the SERI interim funds do not cover the hardware R&D developments related to LST or CTA. In particular they do not finance the SiPM-based camera prototyping and engineering work to build it. The SERI dispach also states that there is a request to open a credit for international cooperation and research and innovation, out of which it is intended – among many other things - that SERI can support Swiss institutions involved in the preparation of CTA with specific measures. *This project, provided that there is a positive decision by the end of the year, could fall in this category of possible projects to finance.*

Activities of the Swiss groups in the LST project: All Swiss groups are directly or indirectly involved in the LST Consortium and also in other working packages of CTA. This work is currently financed by SERI on interim funds until the CTAO ERIC will be finalized in 2021. Currently, CTA is coordinated by UNIGE. The DPNC group, led by Prof. Montaruli, leads the System Engineering work package (Dr. D. della Volpe, together with M. Heller) in the LST Organigram (see 2). UNIGE covered a fundamental role for the approval of the CDR in Spring 2020 in the interactions with the CTAO project office. DPNC also leads since July 2020 the SiPM R&D Work Package (Dr. M. Heller) on future LST cameras (see Fig. 2), replacing previous coordinators from INFN-Padova. This replacement was proposed by INFN-Padova itself, and approved by the LST management, after a series of joint meetings, which aimed at establishing an international project on the future camera prototypes for the LST in the Southern site of CTA. The group in the UNIGE Astronomy Department, led by Dr. Walter, works on the Telescope Control Unit with responsibility in the organigram of the LST project. In CTA the group has leading roles on ACADA, the software for control of the array of telescopes. ETHZ has a leading role in MAGIC that supports and closely interacts with LST (Prof. A. Biland is Co-Chair of the Collaboration Board, member of the Executive Board and Member of the MAGIC-LST coordination board). UZH (led by Prof. P. Saha) works with UNIGE on the stellar intensity interferometry R&D, to operate gamma-ray telescopes in the optical for achieving best angular resolution in interferometry mode. The EPFL group, led by Prof. Charbon, is interested in joining the LST R&D activities with DPNC and ETHZ on the future cameras for gamma-ray telescopes with silicon photomultiplier (SiPM) sensors.

Scope of the R&D on SiPM-based camera project and International Context: UNIGE, EPFL and ETHZ are interested in R&D development work on a prototype for silicon photomultiplier SiPM-based cameras for LSTs and future instruments. Photomultiplier (PMT)-based cameras have a typical lifetime of about 10–15 years, due to the fragility of PMTs against light and the high counting rates of 10 kHz and more to which they are subject during data taking. On the other hand, SiPM ageing and robustness towards direct light is significantly reduced with respect to PMTs. This development could offer a solution for the LST in the Southern array, if approved, and also for replacing current cameras in the Northern site, if it proves to be cost effective with respect to replacements of PMT modules, which will start malfunctioning. The LST management encouraged and blessed a joint effort of UniGe, ETHZ, EPFL, INFN, Max-Planck Institute of Munich (MPP), Japanese, Spanish and INAF institutions to explore a solution for next generation of cameras and for the LST structure in the CTA Southern site. In particular, this R&D development will be conducted with Japanese institutions for sensor qualification and readout, with Max-Planck Munich for the specification definition, with the Krakow University for the readout, with IFAE for the mechanics and INFN Padova and Torino for the electronics of frontend and readout and simulations. The coordination of the Work Package (WP) on this R&D to DPNC recognises the unique expertise on SiPM-based cameras of the Swiss community acquired with the experience in the field first by the pioneering camera for the FACT [8] telescope, and the SST-1M [9] telescopes built to offer a solution for the CTA SST array. The design and construction of SST-1M and FACT have been led by DPNC and ETHZ, respectively, with international consortia. The SiPM cameras for those telescopes were built by those institutions and are shown in Fig. 3.

The prototype of a SiPM-based camera development matters also for other international collaborations and experiments. The two MAGIC telescopes would also take great advantage of such camera prototype development to extend their lifetime, as well as the LHAASO experi-

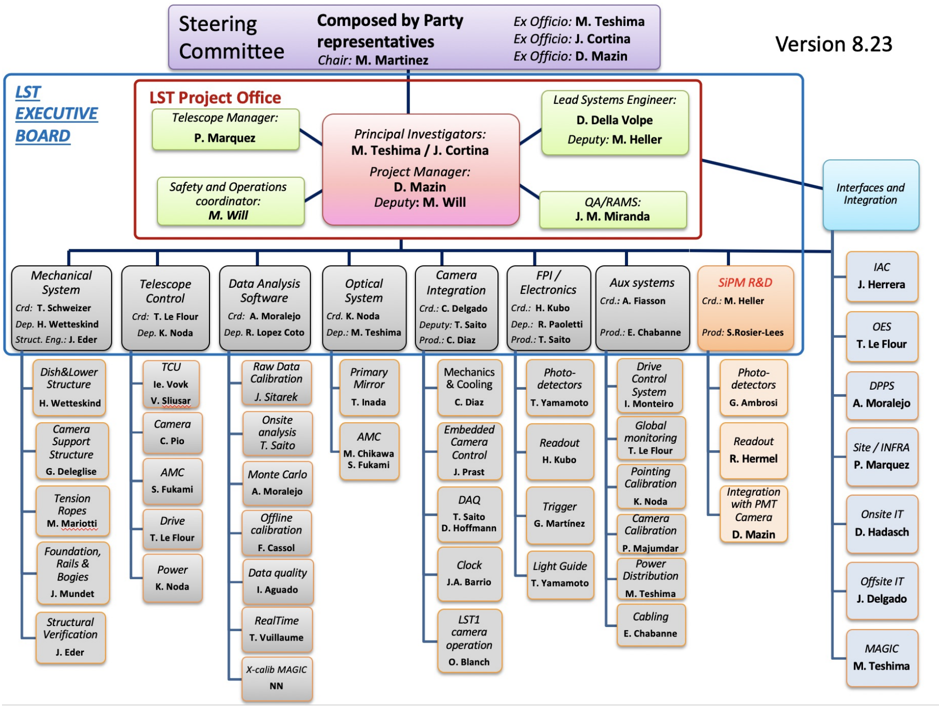

Figure 2: LST project organigram.

ment in China, which uses fluorescence and Cherenkov telescopes [5], and which is planning to build further large size Cherenkov telescopes. The prototype is also a major element of a futuristic view, called PORTAL [10] for future ground based high-energy observations. For IACTs, the field of view as well as the maximum size of the mirror are limited by fundamental optical and timing constraints. S. Mueller developed at ETHZ the ingenious idea of replacing normal cameras by light-field sensors, allowing to mitigate all constraints intrinsic to IACTs. To reach this, it is necessary to replace each pixel by an array of smaller sensors and an optical lense. It seems possible to construct instruments that could reach an energy threshold an order of magnitude lower than possible with CTA array as well as a field of view exceeding 30°, and a preliminary system design named PORTAL was designed together with the civil engineering department of ETHZ. The DiPC sensor development and fast readout we propose to in this R&D project could be what needed to achieve PORTAL.

Work outline of the LST R&D project and Swiss activities: We build on past experience with the FACT [8] and SST-1M [9] cameras for the future prototype that we aim at building with this FLARE proposal. The proposal aims at a four years project where the Unige/DPNC (Prof. T. Montaruli, Dr. della Volpe, Dr. M. Heller), the EPFL (Prof. E. Charbon and Dr. A. Koukab) and the ETHZ (Prof. A. Biland) will collaborate with institutes from Italy, Japan, Germany, Poland and Spain. The planned work can be distributed over 4 years and requires substantial engineering work (2 engineers for 4 years based at EPFL and DPNC). The work is divided in work packages (WPs) (see Fig. 4 with the WBS), to be executed also in cooperation with external partners.

The development follows two main paths, depending on the sensors which will be selected according to specifications on the performance (on photodetection efficiency, uniformity, dead

Figure 3: The SiPM-based camera on the SST-1M (left) and FACT (right) telescopes.

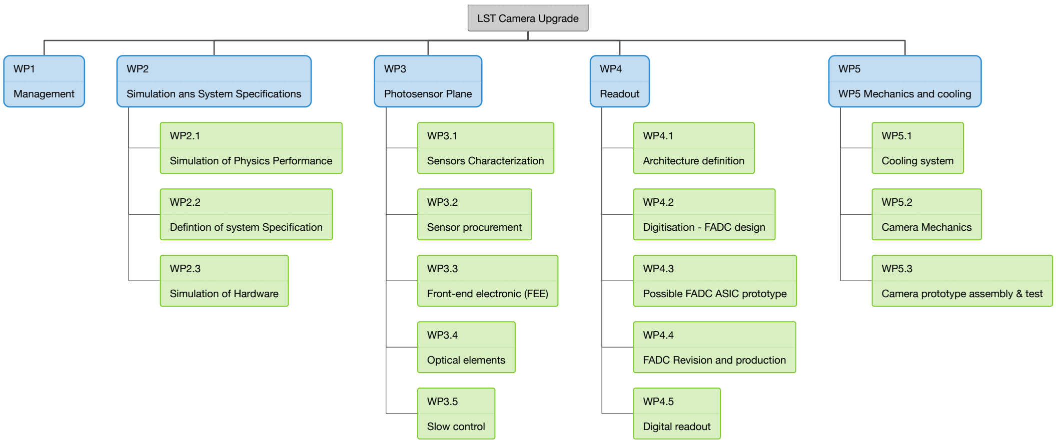

Figure 4: Work breakdown structure for R&D for future SiPM cameras.

space on the plane of the camera, and interfaceability with the electronics, which has to cope with 10 kHz rates of events. On one path, DPNC will pursue the idea to adopt the current SST-1M camera pixels, which are realised by a hollow light guide coupled to a SiPM sensor, and distribute them over a larger detection plane suitable for the LST with a substantially improved electronics. On the other path, ETHZ will pursue sensor R&D to develop a Digital Photon Counter (DiPC), meaning a SiPM with integrated electronics. EPFL will have a key role, since the development of innovative ASICs and DiPC will rely on the expertise of the laboratory AQUA of Prof. Charbon and on the expertise of engineer A. Koukab and on the electronic and mechanic workshops at involved institutions.

The angular size of a reasonable SiPM pixel is half of a PMT in the current LST camera design. This requires about 4 pixels to replace 1 PMT pixel of the current camera. From the hardware perspective, handling four times more channels compared to the existing camera (from 1855 to 7420 channels), poses big challenges for power consumption and data throughput, which, therefore, impact the entire architecture of the readout chain. In order to decrease the power consumption and cost, Application Specific Integrated Circuits (ASICs) will be preferred over discrete electronics at all possible stages. Hence, this proposal focuses on such developments. Additionally, this sort of advanced electronics, which needs to be produced in cooperation with Swiss industry, can be used by other experiments in particle and astroparticle physics or astronomy and can be also interfaced to DiPC, which will be studied by ETHZ and EPFL.

From the physics performance perspective, the proposed geometry with smaller pixels (see Fig. 5-top) improves shower reconstruction and gamma/hadron separation, thus improving the sensitivity and the energy and angular resolution. This requires to be fully proved, and is the subject of work done by a DPNC PhD student on an SNF grant. Until now, initial studies with simulations have been performed, as shown in Fig. 5-bottom. The higher granularity over-samples the image, thus defining better the elongated shape of showers for gamma-rays and the more blurred distribution of charge for more irregular hadronic showers. This allows more efficient discrimination between electromagnetic and hadronic extensive air showers. Such features are being exploited by machine learning based data analysis being performed in collaboration with a group in LAPP (France), expert on machine learning techniques for gamma ray astronomy.

Aside from the challenge of the high number of channels, a relevant aspect that will have to be address with the proposed work is that SiPMs collect more noise than PMTs. This additional noise results in an increase of the threshold on the measured charge to acquire shower events. As a matter of fact, SiPMs have a higher sensitivity compared to PMTs for wavelengths larger than 500 nm, where the Night Sky Background (NSB) dominates the Cherenkov signal. Secondly, the analogue signal from large SiPMs is slower than for PMTs, due to their large capacitance. This means that the electronic response to a single detected photon will extend more in time, increasing the pile-up of the intrinsic random noise of sensors (order of 7 MHz for the SST-1M camera pixels) and of the NSB (order of 30 MHz for a smaller FACT pixel during darkest nights).

These aspects are potential limitations of SiPMs to reach better performance than PMTs in the lowest energy region, which is very interesting from the physics point of view for LSTs, while advantages are clear (cost effectiveness, robustness, uniformity of response, capability of distinguishing single photoelectrons). These limits require R&D on sensors and on an optical filter to be placed on the camera entrance window or on the top of the available sensors or DiPC, to cut out wavelengths longer than 500 nm; on improved low-power electronics with

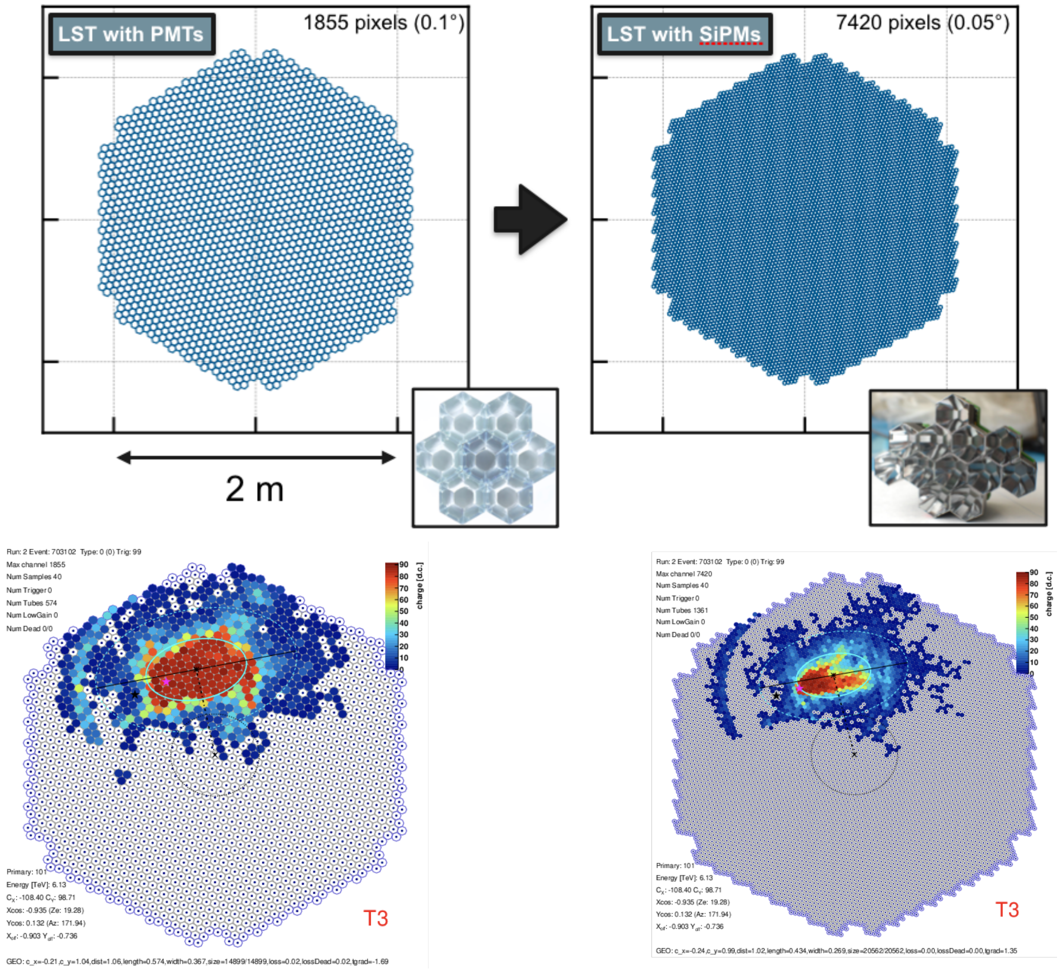

Figure 5: Top: Actual LST camera featuring PMTs as photo-sensors (left) and upgraded camera using SiPMs (right). Bottom: Simulation for the current LST camera (left) and the proposed camera(right) of the light footprint of a proton-induced extensive air shower.

shaping of the SiPM pulses in a frontend FEE-ASIC or DiPC, which already returns digital signals; on the readout scheme. Option 1 will require that the FEE-ASIC signals are digitized with GHz FADC and then a ML-ASIC capable of cleaning waveforms from the noise or a triggerless acquisition scheme. Option 2 will require the realization of the innovative fully digital readout of DiPC interfaced to FPGA for the trigger. These approaches would allow to drastically improve the single-photon timing information to values better than reachable with PMTs and to produce an extremely flexible digital readout.

Foreseen cost: The fund request will cover:

- the salary of 2 engineers, based at DPNC and EPFL, for 4 years for the design and realisation of the electronics boards, sensor testing and interfaces, and for the ASIC design and production;
- the cost for the hardware:
  - production of DiPC prototypes by ETHZ and EPFL;
  - production of 50 hexagonal sensors in the latest UV high performing technology (by Hamamatsu or FBK depending on performance), together with the cost of the required photo-mask;
  - the cost of an engineering run for the ASICs that will be developed (front-end and trigger/FADC);
  - the realization of the electronics boards for tests and pre-production;
- the travel for engineers for meetings with LST partners and involved industrial companies.

Nom/class	Duration [months]	Activity rate [%]	Salary/year	Charges 24%	Cost [chf]
Electronics Engineer for front-end ASIC	24	100	106'770	25'624	264'789
Electronics Engineer for ML ASIC	24	100	106'770	25'624	264'789
Electronics Engineer for PCB design	24	100	106'770	25'624	264'789
Electronics Engineer for FPGA FW & HW Simulation	24	100	106'770	25'624	264'789
				TOTAL	**1'059'158**

Table 1: Direct cost for manpower including the social charges of 23%

Category	Sub-category	Short description	cost [chf]
Hardware	Sensors	Photo-mask for sensor + 50 sensors	40'000
	DiPC	Photo-mask for sensor + prototypes	100'000
	Readout	ASIC productions	190'000
		PCB productions	50'000
Other	Travels	Working group and collaboration meetings	20'000
		TOTAL	**400'000**

Table 2: Indirect costs for the 4 years of the project. The spending profile is in Tab. 3.

Future outlook This project may position the Swiss participants in gamma-ray experiments in an excellent position to contribute in the coming future to the construction of the

LST R&D	2021	2022	2023	2024	2025	26-28
UniGE HW+travel	25'000	73'000	51'000	20'000	3'000	800'000
Salary	66'000	132'000	132'000	132'000	67'000	530'000
ETHZ HW+travel	40'000	21'000	22'000	20'000	1'000	800'000
Salary						800'000
EPFL HW+travel	25'000	25'000	46'000	25'000	3'000	500'000
Salary	66'000	132'000	132'000	132'000	67'000	530'000
Total 2021-2025	222'000	383'000	383'000	329'000	141'000	1'458'000
Total 2025-2028						3'990'000

Table 3: Summary table of foreseen request.

future cameras for the LST telescopes in the Southern array, which is of interest for various institutes in the LST project. It will also lead to Swiss and Intenational institutions into innovative developments that may really change the scenario on silicon photosensors and associated electronics. These developments are not only important to address the 30 years duration of CTA and the future beyond CTA, but also for many other domains where photosensing is relevant (such as medical imaging, lidar, particle physics,...). This will surely be a project that will involve electronics and mechanic industry in Switzerland.

2 DAMIC-M and beyond

The goal of the DAMIC-M project (DArk Matter in CCDs at Modane) is to produce an experiment with sub-electron noise and sufficiently low background rates as to be capable of searching for theoretically motivated scenarios for low-mass DM that are beyond the WIMP paradigm.

DAMIC-M represents a step-wise advancement of CCD experiments that search for the interaction of DM with matter. The original DAMIC experiment, installed in 2008 in a shallow underground site (∼100m rock overburden) at Fermilab, provided in 2012 the best limits for WIMPs of mass around 5 GeV [11], a mass region preferred by asymmetric dark-matter models [12] that connect the baryon asymmetry to the DM relic abundance. The next experiment, DAMIC@SNOLAB, brought CCDs to the SNOLAB deep underground laboratory (∼2000m rock overburden). DAMIC@SNOLAB has a factor of 10 increase in detector mass, with improved shielding and materials, leading to more than two orders of magnitude in improved sensitivity to low-mass WIMPs [13, 14]. DAMIC@SNOLAB was also able to open up new ways of searching for DM, through its possible interaction with electrons, via a hidden sector that can interact with SM particles through kinetic mixing of a hidden photon with the SM photon [15–17]. DAMIC@SNOLAB produced the best sensitivity for light DM particles, with mass of around 1 MeV, that interact with electrons, as well as the best direct sensitivity to the interactions of hidden-photons with mass around 1 eV [18, 19]. The SENSEI CCD experiment, also at SNOLAB, made use of a new technology called "skipper" readout to reduce the energy resolution in CCDs from the 1.6 e- in DAMIC@SNOLAB down to the level of 0.14 e- [20], making possible a factor of ten reduction in energy threshold, enough to measure single electrons of ionization precisely.

The DAMIC-M project builds on a decade of experience with DM searches using CCDs. With

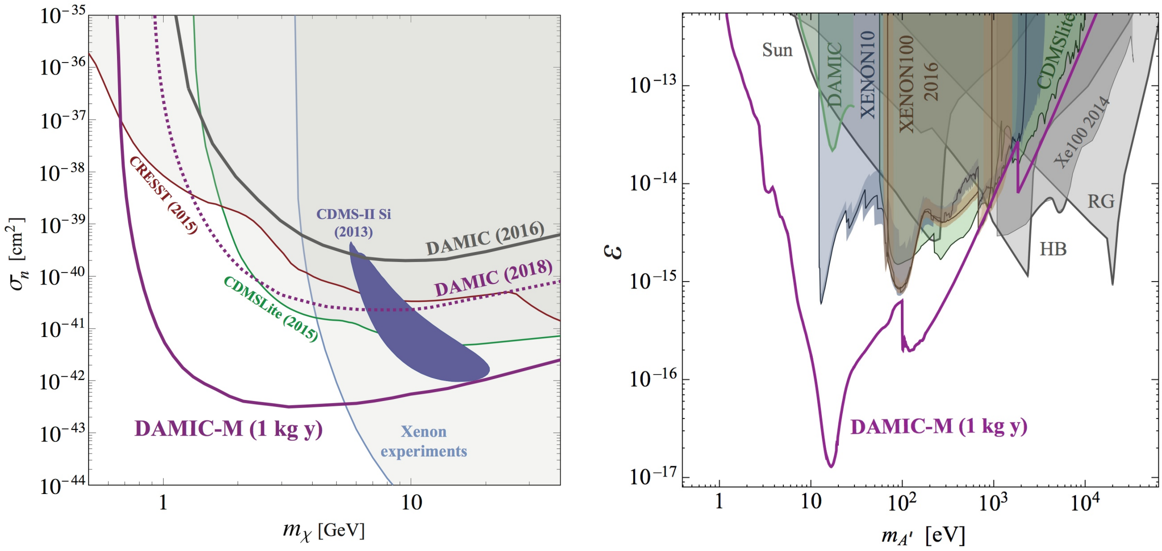

Figure 6: Left: Reach of DAMIC-M in the upper limit on the DM cross-section depending on the DM mass (labeled as m_χ). Right: Upper limits on the kinetic mixing parameter ϵ vs mass of the hidden photon A', for models assuming that DM is entirely constituted by hidden photons. In this scenario, DAMIC-M probes a new range of rates for eV-scale masses of DM.

respect to DAMIC@SNOLAB, the goals of DAMIC-M are a factor of ten increase in active detector mass, a factor of ten reduction in energy threshold, and a factor of 50 reduction in background rates. With these improvements, DAMIC-M is poised to be the first experiment to achieve sensitivity to the theoretically predicted rates for over seven orders of magnitude (1- 10^7 MeV) of DM masses via the DM interaction with hidden photons, which kinetically mix with the SM photon, yielding electromagnetic interactions in the CCDs. Should the hidden photon constitute all DM, DAMIC-M can probe for the first time another 3 orders of magnitude (1-10^3 eV) in dark-matter mass. In addition, DAMIC-M can produce world-leading searches for WIMPs with mass in the range around the proton mass (0.5 - 5 GeV).

DAMIC-M is therefore a project with opportunities for discovering unexplored DM candidates, as well as a new sector of hidden particles, that span over 10 orders of magnitude in mass. Figures 6 and 7 demonstrated the expected performance of DAMIC-M.

2.1 Project overview and ongoing R&D

The DAMIC-M project is in the design and prototyping phase, which is funded mainly by a 2017 advanced ERC grant from P. Privitera. The main challenges in realizing the successful experiment are increasing detector mass, reducing the energy threshold, and reducing backgrounds.

To achieve sensitivity to new realms of DM, and access lower dark-matter masses than achieved previously, DAMIC-M aims to have an energy threshold ten times smaller than DAMIC@SNOLAB. This is achieved using so-called “skipper-CCD" technology [21]. A standard CCD uses 3 phases of voltage gates per pixel to shift charge accumulated in each pixel to a readout node, where the charge is destructively converted to a voltage level using a very

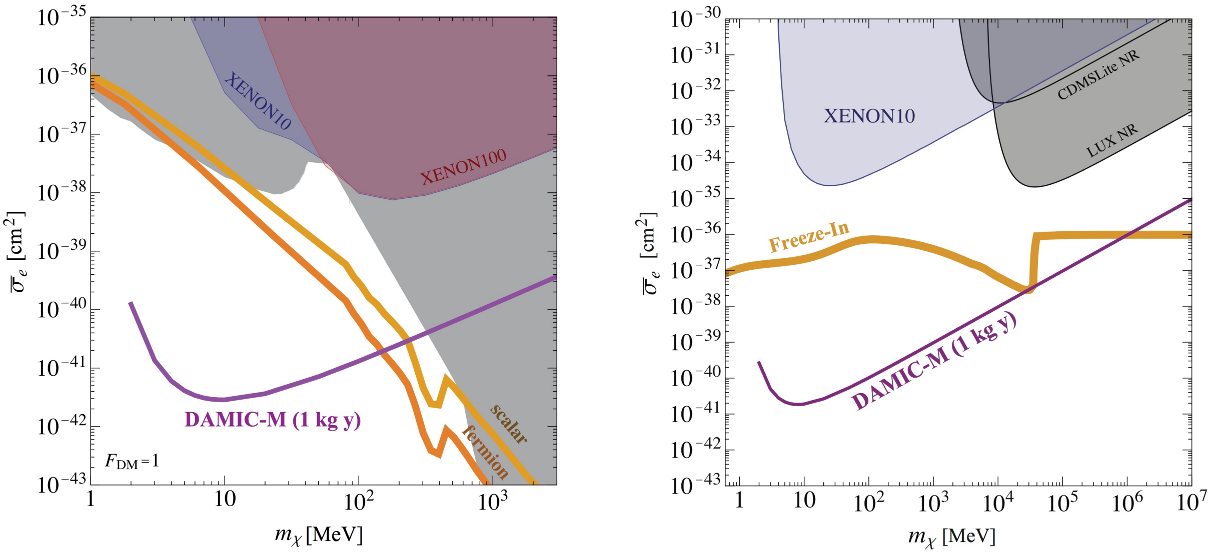

Figure 7: The 90% CL sensitivity of DAMIC-M on the upper limit of the cross section for DM to interact with electrons as a function of the DM mass m_χ. On the left, a heavy A' mediator is assumed, such that $m_{A'}$ is much heavier than a keV. Orange lines represent theoretical expectations assuming that χ constitutes all of the DM, while “scalar" and “fermion" refer to the nature of the DM particle. On the right is the case where $m_{A'}$ is much less than a keV. The orange curve represents the theoretical prediction of the cross-section assuming that χ does not reach thermal equilibrium, and so its relic abundance comes from "freeze-in".

small capacitance to reduce noise. A skipper CCD has non-destructive readout, such that the charge on each pixel is multiply sampled on a floating voltage gate. The charge resolution improves with the number of readouts N by a factor of $1/\sqrt{N}$, feasibly allowing for a factor of ten reduction in readout noise, the dominant contribution to the energy resolution. This technology has achieved expected readout performance [22], and now been used in the SENSEI experiment for world-leading physics results [20]. The DAMIC-M collaboration has produced and tested skipper CCDs, and achieved a charge resolution of 0.07 electrons, allowing single electrons of ionization to be measured, which can be produced by as little as 1 eV of energy.

In order to achieve sensitivity to lower cross-sections, the background rates must be sufficiently low, 50 times smaller than those achieved in DAMIC@SNOLAB. Backgrounds consist mainly of radio-impurities in the CCD detectors and copper and lead shielding materials that lead to ionization signals that mimic DM. To reduce these backgrounds, a careful program of radio-assay of all materials to be used and a GEANT simulation of the radioactivity of these materials has been devised. This procedure has been developed for DAMIC@SNOLAB, providing good agreement between data and expected backgrounds [14]. One background, intrinsic in silicon, is the isotope ^{32}Si, which undergoes β decay, which can be a limiting background in silicon-based detectors. DAMIC has developed a procedure for measuring and vetoing such decays, along with other isotopes from the Uranium decay chain, by using the excellent spatial correlations of decays in the CCDs to identify decay chains that occur over time at the same pixels in the CCD [23]. Perhaps the limiting background in the CCDs themselves is tritium, which arises from cosmogenic activation. To reduce this to manageable levels, the silicon, before and after it is fabricated into CCDs, must be stored underground and shipped at sea level in shielded containers. Outside of the CCDs, radioactive backgrounds are reduced using shielding of electroformed copper, fabricated underground at PNNL [24], as well as ancient lead that was forged hundreds of years ago. With careful material choice and fabrication steps, the necessary background of 0.1 dru is expected to be achieved.

Finally, in order to integrate a large enough exposure to produce world-leading sensitivity, DAMIC-M will use an active detector mass ten times larger than DAMIC@SNOLAB. This is achieved partly by fabricating larger CCDs with an area of 9 x 9 cm^2 and a thickness of 0.675 mm, for a mass of 14 grams. Such CCDs would be the heaviest ever produced, however, to maximize yield, the area may be split into four. At this time, we have tested 1k x 6k prototypes, and have achieved a readout noise of 0.07 electrons, twice as good as required. The other way more mass is achieved is increasing the number of CCDs in DAMIC-M. Compared with DAMIC@SNOLAB, which had a capacity for nine, DAMIC-M will have either 50 CCDs with an area of 9 x 9 cm^2, or 200 CCDs of an area one fourth as large. The increase in the number of CCDs, as well as the increase in readout bandwidth necessary to sustain the repeated non-destructive readout of skipper mode, requires that the entire readout chain of the CCD be redeveloped. Electronics boards, designed with new ADCs, FPGAs, control chips, clocking signals, voltages and readout are currently being designed.

In order to test critical aspects of DAMIC-M, a prototype detector called the LBC (Low Background Chamber) is being installed in Modane with a goal of collecting data by the end of 2021. The LBC is a small chamber, capable of testing several CCDs, and obtaining an intermediate background level below DAMIC@SNOLAB but above DAMIC-M. The LBC will most importantly allow the testing of pre-production CCDs in order to confirm their performance in terms of leakage current and readout noise, but it will also establish infrastructure needed at the Modane lab for DAMIC-M operation. In addition, it is expected that some world-leading physics results can be produced from the LBC, considering its energy threshold and background rate will be lower than was achieved in DAMIC@SNOLAB.

2.2 Swiss contributions

The Swiss group at UZH is led by Ben Kilminster, who was a founding member of DAMIC since 2008, and serves as collaboration board chair of both DAMIC@SNOLAB and DAMIC-M.

For DAMIC-M, the UZH group has developed several options of low-noise ADCs for reading out the CCDs, and is currently developing FPGA firmware for processing the ADC values to determine the signal produced through the correlated double sampling method. These ADCs have shown promising results, fulfilling requirements for DAMIC-M, and these components will be used in the new readout chain that will be implemented in DAMIC-M. The UZH group will be leading the CCD qualification, which will involve cold-probing of the CCDs in the clean facilities at Modane, before the CCDs are packaged. The UZH group has also developed a DCS (Detector control and Safety) system based on CompactRIO technology for control and safety of the DAMIC-M experiment, and is currently integrating components for control and monitoring of voltages, vacuum, temperature, and radon levels. This system will also be deployed for the LBC. To achieve low background levels, material choice and handling must be held to strict standards. The UZH mechanical workshop is machining copper parts for the inner detector components of the LBC, which requires special tooling, underground storage, and special cleaning and etching techniques designed to reduce surface contamination. Finally, UZH is designing an in-situ calibration system for DAMIC-M that would allow all of the CCDs to simultaneously be uniformly calibrated through measurements of a short-lived ^{83m}Kr isotope that is injected into the DAMIC-M chamber.

Funding for Swiss personnel comes from institute and SNF funding, while funding for core and non-core R&D prototyping and construction for DAMIC-M comes mainly from the SNF FLARE.

2.3 Collaboration, timeline, and costs

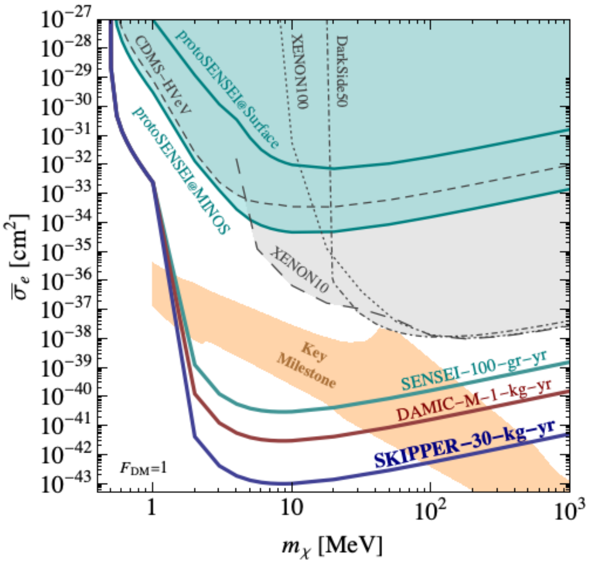

Figure 8: Future sensitivity of CCD experiments for the scattering of dark matter on electrons via a heavy hidden photon mediator. DAMIC-M is shown with its successor, a 30-kg-year proposed skipper CCD experiment named OSCURA. A key milestone is shown indicating the cross-section expected if the entire DM density observed today is due to hidden-sector DM.

While DAMIC@SNOLAB was originally mostly an American effort centered at Fermilab, the DAMIC-M collaboration, with Kilminster as chair of the collaboration board, now has 14 institutions, including 8 European institutions from the 4 countries of Denmark, France, Spain, Switzerland, but also maintaining important contributions from the U.S. and South America. The new location at Laboratoire souterrain de Modane (LSM) in France is supported by a local LSM group, and the DAMIC-M effort has strong support from 5 French laboratories and universities.

The DAMIC-M collaboration has a spokesperson, Paolo Privitera (U. Chicago, LPNHE), a project manager, an LSM site coordinator, scientific coordinator, a conference and publications committee, and a collaboration board. There are dedicated groups for the specific tasks of LSM infrastructure, detector design, low background materials, electronics, DAQ, CCD qualification, and data analysis.

DAMIC-M is in a current period of design and prototyping, which will be followed by a construction phase that should be completed by 2024. The LBC demonstrator, which will test several key aspects of DAMIC-M, has been designed and is being fabricated in 2020, with results expected in 2021. Of key importance is that the performance of the pre-production CCDs is validated, and this can only be accomplished in a low-background environment as provided by the LBC.

The largest individual cost for DAMIC-M is about 1.1 MCHF for 24 wafers of prototype CCDs, 24 wafers of pre-production CCDs, and 24 wafers of production CCDs. The total costs for core detector components including CCDs, shielding, electronics, safety systems, and experimental infrastructure are expected to reach 2-3 MCHF for DAMIC-M, including the LBC prototype. Costs of non-core components necessary for R&D, prototyping, CCD testing, and lab equipment are expected to reach a similar magnitude. The main funding is achieved through an advanced ERC, along with funding from individual countries, such as the Swiss FLARE funding instrument.

2.4 Beyond DAMIC-M: OSCURA

Beyond 2025, the institutes pursuing DM in CCDs from the DAMIC@SNOLAB, DAMIC-M, and SENSEI communities are merging efforts towards the next-generation CCD experiment, called OSCURA, which has several million CHF in funding for feasibility studies supported by a U.S. DOE grant. OSCURA will achieve a mass of 10kg, ten times that of DAMIC-M, and reach a background of 0.01 dru, which is ten times lower than DAMIC-M. With thousands of CCD detector modules, OSCURA will face similar challenges as those of the CMS and ATLAS inner trackers, in which Swiss groups also play prominent roles. Strong SNF FLARE support will be pursued to ensure that Switzerland continues to plays a leading role in the future of DM searches with CCDs with OSCURA.

Year	Cost (kCHF)	Explanation
2021	150	LBC construction & DAMIC-M design
2022	150	LBC operation & DAMIC-M construction
2023	100	DAMIC-M construction
2024	100	DAMIC-M operation
2025	100	DAMIC-M operation & OSCURA design
2026	200	DAMIC-M operation & OSCURA design
2027	200	OSCURA design & prototyping
2028	100	OSCURA prototyping

Table 4: DAMIC-M is the next stage of DAMIC (Dark Matter in CCDs) in the Subterranean Laboratory at Modane. The LBC (Low Background Chamber) is the test chamber at Modane for DAMIC-M prototypes. OSCURA is the next generation experiment, with R&D currently funded by U.S. DOE.

3 DARWIN

The goal of the DARWIN project (*DA*rk matter *WI*mp search with liquid xeno*N*) is to construct and operate a low-background, low-threshold observatory for astroparticle physics with a liquid xenon (LXe) target that features a background that is only limited by irreducible neutrino interactions [25–27]. The technology selected for DARWIN's inner detector is the xenon dual-phase (liquid and gas) time projection chamber (TPC). Some of the main advantages of this technology are: a very low energy threshold of $\sim$1 keV$_{ee}$ and $\sim$5 keV$_{nr}$ when reading out both light (S1) and charge signals (S2); a further reduced energy threshold by conducting a search using only the charge signal [28]; 3D-reconstruction of the interaction position with mm precision as well as the identification of multiply scattered events; rejection of electron recoil (ER) backgrounds at the 10^{-3} level at 50% nuclear recoil (NR) acceptance down to the

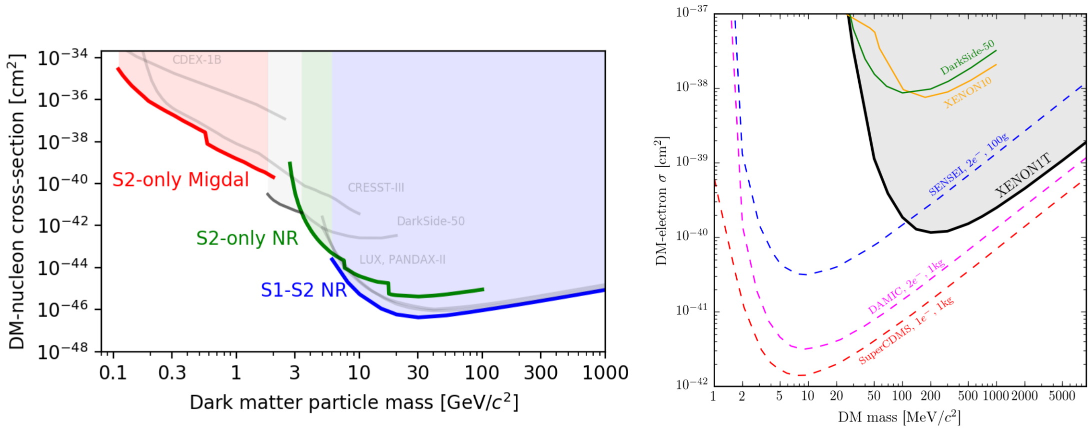

Figure 9: (Left) Upper limits on spin-independent DM-nucleon cross section from XENON1T (colored) and selected other experiments (gray). The blue line is based on the (S1,S2) analysis [35], the red and green lines are based on S2-only analyses [36,37]. (Right) Upper limits on DM-electron scattering cross section from XENON1T [36] (black) and projections for other experiments (dashed lines).

low energy threshold based on the charge-over-light (S2/S1) ratio; a good energy resolution based on the S1 and the S2 signal ($\sigma/E = 0.8\%$ at $E = 2.46$ MeV [29]).

Over the last decade, the lowest background levels for the dark matter search were always achieved by dual-phase LXe detectors, with rates *before* ER rejection as low as 76 events t y keV in the 1-30 keV range [30]. Apart from the very long-lived isotopes ^{124}Xe [31] and ^{136}Xe [32], which constitute no significant background for the dark matter search [26], there is no long-lived radioactive Xe isotope. The target-intrinsic backgrounds ^{85}Kr and ^{222}Rn can be suppressed to extremely low levels: The removal of $^{\text{nat}}$Kr from Xe to levels required for DARWIN has already been demonstrated [33]. Rn will be removed by a combination of xenon purification [34], material selection and surface treatment, detector design as well as S2/S1-based discrimination.

DARWIN will follow the successful concepts of XENON1T (which took data until December 2018) and XENONnT (currently under commissioning at LNGS). The large xenon mass and the exceedingly low background level allowed XENON1T to lead the direct detection field, and probe DM over a wide range of masses, both via DM-nucleus and DM-electron scattering, we show examples in Figure 9.

The main *dark matter (DM) physics channels*, the focus of this White Paper, in DARWIN are summarized here. DARWIN's other science channels, e.g., in neutrino physics [25,32,38,39], are described elsewhere:

- **WIMPs**: weakly interacting massive particles as dark matter candidates will be searched for via DM-nucleus and DM-electron scattering. The search will cover a large range of masses, from ∼100 MeV/c^2 up to ∼10 TeV/c^2, using the S1-S2 and S2-only channels. Regarding DM-nucleus scattering, xenon is sensitive to spin-independent WIMP-nucleon interactions, to spin-dependent interactions thanks to the combined ∼50% abundance of ^{129}Xe and ^{131}Xe with nonzero nuclear spins and to a number of models of inelastic

WIMP-nucleus scattering. Dark matter-electron scattering will explore the mass regime below $100\,\mathrm{MeV}/c^2$.

- **ALPs**: Axion-like-particles are pseudo-scalar bosons which could make up the dark matter in the Universe. They would interact in the LXe target via the axio-electric effect or the inverse Primakoff process, generating a mono-energetic line at their rest mass m_a. DARWIN will be able to explore the mass range from $\sim 0.2\,\mathrm{keV}/c^2$ to $\sim 1\,\mathrm{MeV}/c^2$. It will also be sensitive to solar axions. While these do not constitute dark matter, their detection would strengthen the case for axion cold dark matter.

- **Dark Photons** are vector bosonic DM candidates, which could couple to the Standard Model photons via kinetic mixing. As in the case of ALPs, the detection signature would be a mono-energetic peak at their rest mass m_v, broadened by the energy resolution of the detector. DARWIN will probe dark photons with masses m_v between $0.2\,\mathrm{keV}/c^2$ and $\sim 1\,\mathrm{MeV}/c^2$.

DARWIN is designed such that the main backgrounds for the electronic and nuclear recoil DM channels are solar neutrinos via elastic neutrino-electron interactions and coherent neutrino-nucleus interactions, respectively [27], both allowing for a $200\,\mathrm{t{\cdot}y}$ exposure before becoming relevant. Neutrino-induced nuclear recoils from coherent neutrino-nucleus scatters cannot be distinguished from a WIMP-induced signal, and solar ^{8}B neutrinos yield up to 10^3 events/(t·y) at NR energies below 4 keV. NRs from atmospheric neutrinos and the diffuse supernovae neutrino background will yield event rates which are orders of magnitude lower but at higher recoil energies [25]. These will dominate the measured spectra at WIMP-nucleon cross sections around $10^{-49}\,\mathrm{cm}^2$ for DM masses above $\sim 10\,\mathrm{GeV/c^2}$.

4 Project overview and ongoing R&D

The core of DARWIN is a dual-phase LXe TPC [27, 40, 41]. In the baseline design scenario the prompt (S1) and proportional scintillation signals (S2) are recorded by two arrays of photosensors installed above and below the LXe target. The selection of the photosensor is subject to ongoing R&D. The TPC is a cylinder of 260 cm diameter and height, with a target volume containing 40 t of LXe, as illustrated in Figure 10. A light-weight TPC design minimizes material backgrounds. It is enclosed in a low-background, low-mass double-walled titanium cryostat which itself is surrounded by a Gd-doped (0.2% by mass) water Cherenkov shield - as in XENONnT [42] - to mitigate the radiogenic neutron background from materials. The outermost layer is a water Cherenkov muon veto also acting as a passive shield against the radioactivity of the laboratory environment.

The design of the DARWIN detector follows the successful concepts of XENON10/100/1T/nT, also considering the experience obtained by LUX/LZ and PandaX as well as from the single-phase LXe project XMASS. However, several technical aspects require R&D studies such as the TPC design, the VUV-sensitive photosensors, low-background materials, neutron veto, cryogenics and target purification, and calibration systems. The R&D effort is supported by two European ERC grants, a significant startup grant by DFG/SIBW (Germany), the German Ministry for Education and Research (BMBF), the Swiss National Science Foundation (SNF) as well as by smaller grants at various collaborating institutions. Two large-scale

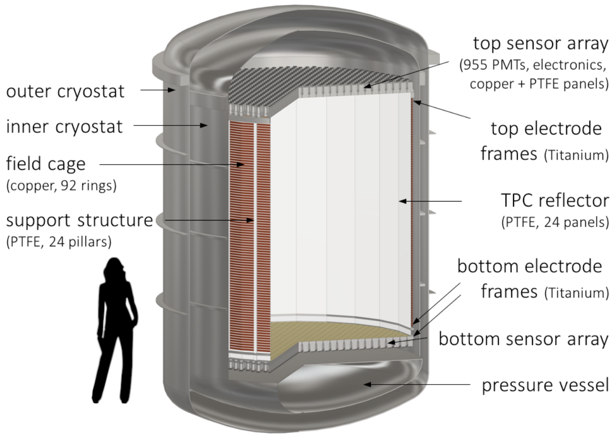

Figure 10: The DARWIN time projection chamber instruments about 40 tons of LXe as active dark matter target. The sketch shows the baseline realisation with two photosensor arrays made of 1910 PMTs of 3″ diameter. This geometry was optimized in and used for sensitivity studies [32].

demonstrators to develop and test components and operation methods for DARWIN at the real scale of ∼2.6 m are under construction: one full scale demonstrator for the xy-dimension, and a second one in the full z-dimension, facilities which will be used by the entire collaboration. By using about 400 kg of LXe each, the platforms will allow for testing full-scale DARWIN electrodes in LXe/GXe, the drift of electrons over the full TPC length, the HV feedthrough, large-scale photosensor arrays, efficient LXe purification, the slow control system, etc.

Swiss contributions: The Swiss group is a founding and leading group in DARWIN, with Laura Baudis being the spokesperson since September 2018 (and project coordinator until 2018). The group also co-leads two working groups: Science and Sensitivity (Patricia Sanchez) and Detector (Michelle Galloway). This defines also the main Swiss contributions: to the time projection chamber (design, new photosensors and their readout, cables and connectors, material radio-assay, outgassing measurements) and to the Monte Carlo and sensitivity study efforts (two publications were recently submitted under UZH leadership).

The Swiss group aims to develop, build and operate a full vertical scale time projection chamber (TPC) as a prototype for the DARWIN experiment, together with its associated cryostat, cryogenic and gas recirculation and purification systems. It will feature a TPC with a drift region of up to 2.6 m, with the main goal of demonstrating electron drift over the large distances. This project, *Xenoscope* is financed by an ERC Advanced Grant and as mentioned above, it will also be an R&D platform available to the full collaboration.

Collaboration, timeline and costs: DARWIN incorporates members from the XENON collaboration as well as new groups from (astro-)particle and neutrino physics. It will follow the successful experience from the XENON project, where the more sensitive instrument was always designed and built while the current stage of the project was under operation and collecting data.

The collaboration includes a total of 30 groups from Europe, USA and Asia. The spokesperson is Laura Baudis (UZH), and the co-spokesperon is Marc Schumann (U. of Freiburg). The technical coordinators are Uwe Overlack (Mainz) and Luca Grandi (U. Chicago), the speakers coordinator is Ranny Budnik (WIS), the outreach and publication coordinators are Rafael Lang (Purdue) and Patrick Decowski (U. Amsterdam and Nikhef) and the treasurer is Guido

Drexlin (KIT). There are six working groups in DARWIN (Science and Sensitivity, Liquid Xenon Target, Backgrounds and Veto, Detector, Light Sensors and Readout, Xenon Properties and Calibration), each with two leaders.

The goal of the current R&D efforts in DARWIN is to inform a conceptual design report, to be ready by the end of 2021, followed by a technical design report in 2023. DARWIN is planned be constructed in 2024-2025, while the XENONnT experiment is still taking data. The commissioning phase will start after the completion of XENONnT, namely in 2026. The start of data taking will be in 2027. At present, after a successful LoI submission to the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, the collaboration was invited to prepare and submit a CDR to LNGS.

For the upcoming FLARE calls, the following costs are foreseen for XENONnT (operation funds) and DARWIN.

- **2021-2024**
- Common funds and operation: 20'000 CHF/y
- R&D 2.6 m TPC: 40'000/y CHF (for 2021, 2022)
- Xe gas: 100'000 CHF/y (for 2021, 2022)
- TPC construction, photosensors, electronics, screening, etc: 240'000 CHF/y (for 2023, 2024)
- Engineer for TPC design: 140'000 CHF/y

- **2025-2028**
- Common funds and operation: 20'000 CHF/y
- TPC construction, photosensors, electronics, screening, etc: 240'000 CHF/y
- Engineer for TPC design: 140'000 CHF/y

Funding per FLARE call:

- 2021-2024: 1350 kCHF
- 2025-2028: 1600 kCHF

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