White paper for astroparticle physics in Switzerland for the period 2025-2032.
Endorsed by the Swiss Institute for Particle Physics (CHIPP)

Laura Baudis[1], Adrian Biland[2], Domenico della Volpe[3], Ben Kiliminster[1], Teresa Montaruli *[3], Prasenjit Saha[1], Björn Penning[1], Steven Schramm[3], Nicola Serra[1], Marcelle Soares-Santos[1], Andrii Tykhonov[3], Roland Walter[4], and Xin Wu[3]

[1]Physik-Institut, University of Zürich, Switzerland
[2]Institut für Teilchenphysik und Astrophysik, ETH, Zürich, Switzerland
[3]Département de Physique Nucleaire et Corpusculaire (DPNC), Faculté de Sciences, University of Geneva, Switzerland
[4]Département d'Astronomie, Observatoire de Sauverny, Faculté de Sciences, UNIGE, Switzerland

Abstract

This white paper of Pillar 3 confirms and updates priorities of the Swiss Community in astroparticle physics for the long term (2025-2032). The shorter term (2025-2028) concerns the FLARE and SERI roadmap for research infrastructures. The previous update, released on February 11, 2021, served as the basis for the Swiss Institute of Particle Physics (CHIPP) Roadmap 2025-2028 and beyond [Com21].

1 Introduction

The Swiss community in Pillar 3 recognised at the CHIPP Meeting in Balsthahl in January 2024 that its scientific priorities in astroparticle physics concern two large lines of research: **multi-messenger astrophysics** and **dark matter**. Both fields overlap with Pillar 1 and 2 and are also of interest for astronomers, theorists in cosmology, and researchers in particle physics. Two scientific recommendations summarise the interest into these two broad fields:

1. **Multi-messenger Astrophysics:**
   In the last decade, astrophysics and cosmology were revolutionised by multi-messenger probes. Gamma rays provide a serendipitous view of acceleration processes in the most extreme high-energy relativity laboratories in the cosmos, such as supermassive black holes and their jets, supernova shocks and kilonova; probe dark matter coupling with themselves clumped into masses or axion-like pervading the cosmos; reveal sources not seen in other electromagnetic bands. Their measurement from ground will reach the precision era within this decade with the operation of the Cherenkov Telescope Array Observatory (CTAO). Two new messengers, gravitational waves (GWs) and neutrinos, offer complementary deeper observations of the universe and require the establishment of new larger ground-based detectors of second generation with at least a factor of 10 larger sensitivity: the Einstein Telescope (ET) ground-based interferometers for gravitational waves and the the cubic-kilometer neutrino telescope IceCube-Gen2. In addition, the space-based interferometer LISA foreseen to be ready after 2035, will provide access to the gravitational wave cosmic background and detect the signal of coalescing massive black holes giving clues on their formation history.

   Multi-messenger astrophysical processes bring together researchers in different observational domains and a variety of data, necessitating a common platform of analysis, early alert distribution, high-reduction factors, and efficient processing in sustainable data centres in Switzerland, including the CSCS supercomputing centre in Lugano, also Tier 2 for LHC, and other data centres distributed in institutes or elsewhere.

2. **Dark Matter:**
   The identification of dark matter is one of the major quests in cosmology and particle physics, requiring multiple approaches. Direct detection probes the nature of dark matter and has explored a substantial fraction of the weakly interacting massive particle (WIMP) parameter space of masses around 100 GeV/c^2 with the most stringent constraints coming from the currently operating XENONnT and LZ multi-tonne liquid xenon experiments. The next generation detector, DARWIN/XLZD, will be constructed by the new XENON-LZ-DARWIN (XLZD) collaboration. It will probe the WIMP paradigm down to the so-called neutrino fog and will also explore other, light dark matter candidates at the MeV and keV mass scale, as well as second order weak nuclear decays.

---

*corresponding author: teresa.montaruli@unige.ch

Further, such a multi-ten-tons liquid xenon observatory will also detect astrophysical neutrinos, and thus enter the multi-messenger domain.

It is also important to search for other candidates for dark matter. Hidden-sector dark matter, which interacts electromagnetically with standard-model (SM) particles via the mixing of the hidden photon with the SM photon and causing very low-energy electromagnetic signals, is a leading candidate. Currently operating is the DAMIC experiment, which has an extremely low ionization energy threshold, and which has placed the most stringent constraints on such DM in the 1-1000 MeV/c^2 mass range. DAMIC-M, an upgraded version of DAMIC, is under construction and will be installed and collect data from 2025. Tesseract is a cryogenic experiment utilising superconducting readout to achieve ultra-low energy thresholds. Tesseract aims to explore entirely new phase space for low-mass DM candidates, and is expected to begin operations by 2026.

Besides direct detection of dark matter, GW future experiments (ET and LISA) probe gravitational effects and with large scale surveys (e.g. DES, DESI, LSST, involving also scientists in Switzerland) have the potential to probe cosmological signatures of dark matter and dark energy. Indirect detection of dark matter is also conducted by space-based detectors of cosmic rays, and gamma-ray and neutrino ground-based large observatories, which seek for signatures of dark matter coupled with standard particles or radiation and can potentially locate dark matter in its sites in the cosmos.

From the 2021 white paper and the realised roadmap to now, there has been enormous progress on these fields. This update document acknowledges explicitly the interest of CHIPP members, with a strong theory component and in synergy with astrophysicists and cosmologists in CHAPS to finalise the CTAO establishment and enter ground-based GW science in preparation for the construction of ET. GWs have revealed an unprecedented scientific potential concerning the exploration of matter in extreme conditions, from the equation of state of neutron stars revealing the quark hadron transition, to the origin of heavy elements on the Earth. The existence of new populations of black holes and the role of primordial black holes for dark matter is a needed exploration that only the gravitational channels can offer. With ET reaching in some mass regions of black hole mergers redshifts of up to 100 and with the now approved LISA interferometer in space reaching primordial epochs and having access to the observation of the cosmic gravitational wave background, GWs will play an important role in cosmology. Additionally, GW will play a role in multi-messenger astronomy, in synergy with gamma rays as observed for the neutron star binary merger on August 17, 2017.

The dark matter community in Switzerland strongly confirms with this update the common goal of establishing DARWIN as G3, while keeping technological innovation and exploration active.

2 Multi-messenger Astrophysics and cosmology from ground

The following experiments concern the gamma-ray and gravitational waves.

2.1 The Cherenkov Telescope Array Observatory (CTAO)

Short description: The Cherenkov Telescope Array Observatory [Col24a] will be an observatory accessible by scientists worldwide through a science-driven observing time allocation process. CTAO is a distributed infrastructure composed of the 2 telescope arrays, a headquarter in Bologna, a Science Data Management Centre in DESY-Zeuthen coordinating 4 off-site data centres, one of which will be in CSCS, Lugano. The 2 arrays of Imaging Atmospheric Cherenkov Telescopes (IACTs) are at about 2000 m a.s.l. at the ESO premises in Paranal, Chile, and at the site of Roque de Los Muchachos La Palma, Canary Islands. The observatory is driven by a consortium of about 1500 scientists from 25 countries and by a final legal entity CTAO European Research Infrastructure Consortium (ERIC) that should start operation in 2025. The construction of the first four telescopes will be completed at the end of 2026 and the construction of the telescope arrays should be completed by 2030. In the baseline configuration (named Alpha) there will be 4 Large-Sized Telescopes (LSTs) with optical surfaces with 23 m diameter and 9 Middle-Sized Telescopes (MSTs) with 12 m diameter reflectors in the Northern Site. At the Southern Array, 14 MSTs and 37 Small-Sized Telescopes (SSTs) with 4-m diameter optical surfaces will cover an area of a few km^2. CTAO will have a leading role in Multi-Messenger High-Energy Astrophysics in the future years. It is the successor of the H.E.S.S., MAGIC and VERITAS gamma-ray telescope arrays, bringing together the European particle physicists and high-energy astrophysicists' communities, namely order of 1'400 scientists and engineers from about 30 research institutes in the world. It is the most prominent priority of international Roadmaps, e.g. the APPEC Roadmap 2017-2026 and the ESFRI Roadmap, in which it is a landscape project together with SKAO and E-ELT to shape astrophysics in the next future.

The CTAO Key Science Cases [CA$^+$19] concern: cosmic rays (how and where they are accelerated; their propagation and their impact on the environment); probing extreme environments and the processes close to neutron stars, black holes and relativistic jets, winds and explosions; exploring cosmic voids and magnetic fields; physics frontiers beyond the standard model of particle physics (the nature of the dark matter and how is it distributed, the existence of axion-like particles, violations of Lorentz invariance for high-energy photons.

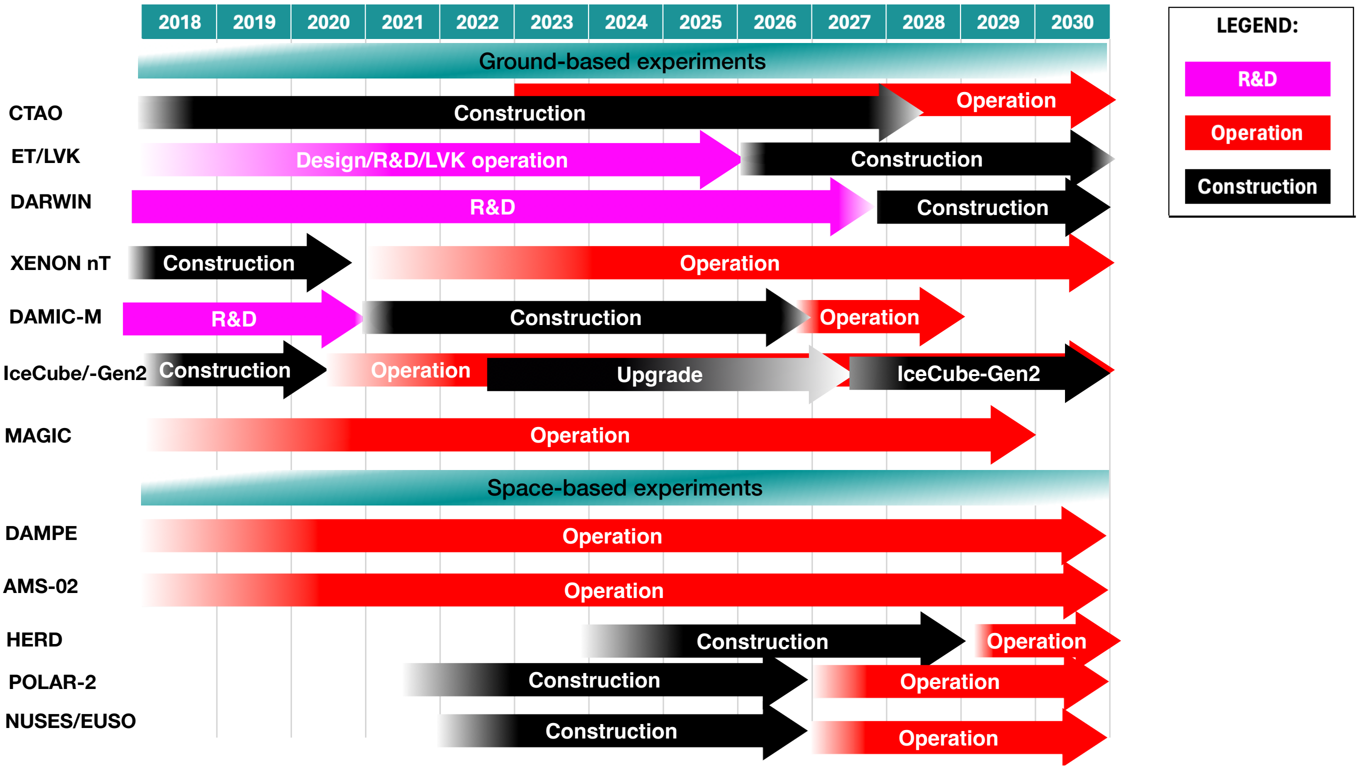

Figure 1: Foreseen Schedule of astroparticle experiments of interest for scientists in Switzerland.

Involved PIs in Switzerland Professors, CHIPP Board Members: Adrian Biland (ETHZ), Domenico della Volpe (UNIGE), Teresa Montaruli (UNIGE), Prasenjit Saha (UZH), Nicola Serra (UZH), Roland Walter (UNIGE). Other PI Professors: Edoardo Charbon (EPFL), Jean Paul Kneib (EPFL), Andrii Neronov (EPFL), Stephan Paltani (UNIGE), Thomas Schulthess (CSCS/ETHZ), Maurizio Falanga (UBern). Senior Scientists/Engineers: Ermanno Bernasconi (EPFL), Pablo Fernandez (CSCS), Matthieu Heller (UNIGE), Victor Holanda (CSCS), Nicolas Produit (UNIGE), Luca Giangrande (UNIGE), Magda Stodulska (UNIGE).

Swiss participating Institutions: UNIGE, EPFL, ETHZ, UniZH, U.Bern.

Swiss Investment level: about 2.7% of 350 M€ for the Alpha phase, for which funding is secured and the Costbook approved.

Timeline 2018-2032: Construction (2018-2021); Construction and Operation (2022-2029); Operation (2030- 2060)

Current state and remarkable highlights (2020-2024: The Swiss community has heavily contributed and contributes to the construction of CTAO concerning:

1. the SSTs, where their cameras adopted a new technology in the field, silicon photomultipliers (SiPMs) (Montaruli, della Volpe) thanks to the Swiss community pioneering work on FACT (Biland, Walter) [A+13b] and SST-1M [HSP+17];

2. the system engineering, where UNIGE adopted professional management methodologies to achieve the CDR approval at the end of 2023 by CTAO of the first of the CTAO telescopes, the LST-1. UNIGE coordinates the WP and is in the LST collaboration management (della Volpe). This work is key for the construction of the LST2-4 completing the LST array in the North and LST5-6 in the South (see Fig. 1). The LST commissioning for the delivery to CTAO should be completed in 2028 for the Alpha Configuration;

3. The first operative Off-site Data Centre of CTAO, which is hosting the first Data Challenge of CTAO in 2024, has been set up at CSCS (Neronov and Kneib (EPFL),Fernandez (CSCS)).

4. The Array Control and Data Acquisition System (ACADA) has passed the CDR and was successfully integrated for the operation of LSTs (Walter) and the Data Handler in CTAO is coordinated by Eng. E. Lyard [OAB+19];

5. The telescope control unit system (TCS) is installed on LSTs and now being transferred to SSTs and Dr. V. Sliusar (Walter's group) coordinates the WP in the LST project. [SWL+17].

6. The Data Processing and Preservation System Software (DPPS) is strongly advanced by the CTAO-CH. Its first version is going to be installed soon on the LST-1. Dr. Dalchenko (Montaruli's group) oversees the Quality and Calibration Pipelines and is also seconded to the CTAO central project as DPPS system architect; the DPPS Bulk Archive is overseen by Prof. Walter.

7. Dr. M. Heller (Montaruli's group) coordinates the WP on R&D with SiPM cameras for the replacement of current cameras of LST-1 and for long term operation. Prof. Montaruli is PI of a FLARE grant on this which will be submitted for continuation. The Swiss Institutes are also strongly committed in the LST construction and Diener AG will be financed for actuators and other companies for the advanced electronics and fixation points of mirrors.

Objectives 2020-2032: A recently produced white paper described the scientific ambitions and the work of the CTAO Swiss Community [Col23]. Such community is organised in the CTAO-CH Collaboration, currently coordinated by Montaruli, through a Collaboration Agreement between involved Institutes. The Swiss community's ambitions for the future are:

1. To secure access to CTAO ERIC by 2025. Currently, the project is still being run by the CTAO GmbH, originally funded by DESY, UniZH and INAF. In the last phase of the approval of the ERIC, foreseen in fall 2023, the EC legal office raised issues on ESO being a founding member of the ERIC as it is an international organization, which cannot solve disputes in the European court. A solution to the issue has been agreed and final step documents are under EC final evaluation. In the meanwhile, construction and preparation of the infrastructures at the sites are advancing.

2. To secure the end of construction of the Alpha Configuration + 4 LSTs in Chile and delivery of the telescopes to CTAO ERIC by 2028-2029;

3. To secure the long-term operation (up to at least 2045) of the CSCS offsite data center of CTAO in synergy with SKAO. Such data center will deal with 10 to 100 PByte per year and requires securing similar long-term support to the Tier 2 of LHC (350 kCHF / yr HW (2025-2028) + FTE). Exponential cost decrease does not apply anymore to costs due to the energy crisis, and this is an issue to address globally by CHIPP also for the LHC community.

4. To secure provision of all software in-kind contributions of Swiss leadership by 2028: the Array Data Handler of the Array Control and Data Acquisition System (ACADA); The CalibPipe, the Bulk Archive and the QualityPipe of the Data Processing and Preservation System (DPPS).
5. The construction of an Advanced Camera for LSTs in cooperation with Swiss Industry, Spain, INFN and Japan to replace the current LST-1 camera with PMTs in 2028-2029 for robust and long-term running of LSTs and future LSTs in the South [H+23]. The current FLARE program (Jun 2021-Jun 2025) offers microelectronics solutions for low-power preamplifiers and shaper and GHz data digitization and a new digital sensor. A future FLARE program for 2025-2029 will provide prototype modules for the camera with mechanical design. The project also requires the support of SERI and a collaboration with Spain, Italy and Japan.
6. Some Swiss PIs also work on stellar intensity interferometry (SII) for providing CTAO with excellent angular resolution and sensitivity in the optical (Sinergia grant coordinated by Walter, with Saha (UZH) and della Volpe (UNIGE)) [CAB+22].

Impact:

Scientific: CTAO will unravel the mysteries of the non-thermal highest energy universe in partnership with the recently inaugurated new astronomies with neutrino and gravitational wave messengers, together with the large observatories on the ground and space-based satellites exploring radiation from the radio to the gamma-rays. At energies beyond the mass of the proton, gamma-ray astronomy has the potential to unravel the sources of cosmic rays, which continuously bombard our atmosphere up to energies well beyond those achievable by any possible accelerator conceivable on Earth. The Key Science Projects (KSP) of CTAO were studied and are now collected in the Science Book [CA+19] and reserved observation time during the operation of CTAO is planned to bring the foreseen results. The KSP are built around 3 major pillars of CTAO Science:

1. Cosmic rays (how and where they are accelerated; their propagation and their impact on the environment);
2. Probing extreme environments and the processes close to neutron stars, black holes and relativistic jets, winds and explosions; exploring cosmic voids and magnetic fields;
3. Physics frontiers beyond the standard model of particle physics (the nature of the dark matter and how is it distributed, the existence of axion-like particles, violations of Lorentz invariance for high-energy photons.

Economical and Technological: CTAO includes high-technology instrumentation to which the Swiss Community heavily contributed. The SSTs for the first time will adopt SiPMs instead of photomultipliers, until now adopted by the LSTs and MSTs. SiPMs were first pioneered in Switzerland by the FACT (ETHZ and UNIGE) project and by the SST-1M (UNIGE, ETHZ, Poland, Czech Republic). The LST Advanced camera project inherits from these projects and substantially advances them [H+23]. The project might include a new compression and readout system based on AI being integrated in microchips with CSEM. An INFRA-TECH 2024 proposal on this (M2TECH) providing innovative technical solutions to advance the state of the art of CTAO, MAGIC, ET, Virgo and KM3NeT is on reserve if budget becomes available in the short term after very positive evaluation Possibly M2TECH and future projects such FLARE, will foster not only SiPM technology but also more energy-efficient associated electronics with AI software for more efficient filtering of noise, early alerts, synchronisation, remote sensing techniques and more durable and more sensitive coatings and substrates.

Societal and knowledge transfer: The number of scientists attracted to the still-young field of gamma-ray astronomy is growing at a steady rate, drawing from other fields such as nuclear and particle physics, in addition to the increased interest by other parts of the astrophysical community, such as radio and X-ray astronomers. CTAO with other multi-messenger infrastructures (the Vera Rubin Observatory, SKAO, ET, EUCLID, E-ELT) are shaping the new era of astronomy where shared fast alerts will be critical to reconstruct the full picture of transient phenomena. Thanks to the need to observe same phenomena with different instruments, astronomy has pioneered the open data domain. CTAO and SKAO, with other experiments dealing with large data rates named above, will bring Switzerland into the domain of big data in astronomy. A huge effort in Swiss CTAO institutions is being devoted to efficient AI filtering of data to make the data handling of CTAO more sustainable. AI has many transfers in current society and current work is already happening in cooperation with Swiss Industry (Enclustra) and research institutes (CSEM). The Swiss CTAO community is already offering multi-messenger open data platforms as MMODA.

Operation and sustainability in the long term: The operation of CTAO is foreseen to last order of 20-30 yr from its completion. As CSCS will be one of the 4 off-site data centres this will require securing a longterm funding mechanism of the community of scientific users and of the data centres processing the data from the arrays of telescopes and the simulation productions.

Finding and Recommendation: The Cherenkov Telescope Array Observatory (CTAO) will explore the Universe at the highest energies based on the imaging air Cherenkov technique with three types of telescopes optimized for different field of views and energy bands from 10 times to 300'000 the proton rest mass. It will consist of two arrays of Cherenkov telescopes located in La Palma, Canarian Islands, Spain and Paranal in Chile, driven by a consortium of about 1500 scientists from 25 countries. CTAO is a landmark of the ESFRI and in the Swiss SERI infrastructure roadmap. Gamma rays are used to trace violent events in the Universe where a small fraction of the particles can undergo non-thermal acceleration processes. The main topics of interest in the Swiss groups are to understand 1) the origin and feedback of cosmic rays, their acceleration in supernova remnants, starbursts, black hole jets or in other catastrophic phenomena such as galaxy mergers; 2) astrophysical systems such as pulsars, X/gamma-ray binaries, micro-quasars, magnetars, active galactic nuclei, gamma-ray bursts also via multi-messenger techniques; 3) the nature of matter in the universe and searching for the sites where dark matter agglomerates; 4) the cosmological evolution of early galaxies measuring the extragalactic background light and determining magnetic fields in cosmic voids. Finally, Swiss scientists are also looking for physics beyond the Standard Model, as violation of Lorentz invariance or axions. They have proposed to use the 4000 $\mathbf{m^2}$ mirror area of the CTAO telescopes together with classical extremely large telescopes to reach micro- arcsecond resolution in the optical to resolve accretion disks around galactic compact sources and quasars.
Recommendation: CTAO exploration of the gamma-ray sky with high precision enables a new era in multi-messenger astrophysics opening unexplored paths to study cosmic particle accelerators and the origin of cosmic rays, dark matter, cosmic magnetic fields, star formation in synergies with new messengers. The accession of Switzerland as a member of the almost finalized CTAO ERIC legal entity is an essential next-future step to profit of all Swiss investments in the CTAO-CH Collaboration, widely spread between relevant Institutions in Switzerland, since 2005. Sustaining a strong community of scientists and a forefront data center at CSCS will secure the exploitation of CTAO for the next 30 years. |endrecommendation

2.2 The Major Atmospheric Gamma Imaging Cherenkov telescopes (MAGIC)

Short description: MAGIC [Col24b], located at the Canary island La Palma, celebrated in 2023 the 20^{th} anniversary of operation. Consisting of two Cherenkov telescopes with 17 m diameter each, it measures the dim flashes of Cherenkov light emitted from showers of secondary particles induced when a very high energetic (VHE) photon hits the atmosphere. The main background is due to hadronic showers induced by the several orders of magnitude more abundant charged cosmic ray particles. They have distinctive characteristics from the signal of electromagnetic showers induced by gamma rays which can be evidenced by the telescope atmospheric imaging technique (IACT). Background rejection is significantly improved when at least two IACT telescopes in stereo mode observe the same showers. While the original goal of MAGIC and the similar H.E.S.S. and VERITAS arrays was to search for the sources of the enigmatic high energetic cosmic ray particles, the unexpected richness of galactic and extragalactic sources found so far is turning focus to the newly evolving field of very high energy astronomy. This initiated the CTAO project to significantly improve the sensitivity by using large arrays of Cherenkov telescopes. Due to recent delays and down-scaling of CTAO, the idea exists to refurbish the MAGIC telescopes and add them to the neighboring CTAO array.

Involved PI: A. Biland, R. Walter.

Swiss participant Institutions: ETHZ, UNIGE.

Timeline: in operation.

Current state and remarkable highlights 2020-2024: Both MAGIC telescopes are in good operational conditions. Several new sources have been found and deeper investigation of sources found earlier is going on. Most important recent detection is the very high energy gamma ray emission from the Recurrent Nova RS Ophiuchi, proving for the first time that Nova explosions can accelerate charged particles to energies far beyond those reachable at LHC at CERN within few hours. From the measured gamma-ray spectrum one can conclude that most accelerated particles are protons [A^+22b]. The acceleration process is far from understood. In addition to multi-wavelength observations of celestial objects together with space and ground based observatories to measure photon spectra from radio waves to multi-TeV gamma rays, MAGIC is a key player in multi-messenger astronomy. While gravitational wave measurements identified long-duration Gamma Ray Bursts as the merger of two neutron stars forming a Black Hole, MAGIC detected for the first time that such GRBs do emit very high energy gamma-rays and therefore must accelerate charged particles to enormous energies within minutes [MA^+19]. Together with the Fermi satellite, MAGIC had identified for the first time a blazar as most probable source of an ultra-high energetic neutrino measured by IceCube [A^+18a], and recently observed a starburst galaxy identified as neutrino source [A^+22a]. The lack of high-energy photons does strongly constrain the possible emission models for the neutrinos [A^+19a]. MAGIC is also looking for fundamental physics, setting limits for e.g. indirect search for dark matter annihilation [A^+22c] and Lorentz-invariance violation [CA+24]. Last but not least, MAGIC is pioneering the usage of large reflectors intrinsic to Cherenkov telescopes to explore intensity interferometry. The radius of several stars has been successfully measured [A+24b]. Those measurements can be performed during full-moon nights when normal telescope operation is not possible.

Objectives 2020-2032: In the past few years, MAGIC supported the commissioning of the first large size telescope (LST-1) of CTAO, located in direct neighborhood, by dedicated parallel observations. From 2025 on, it is agreed to regularly operate LST-1 and the MAGIC telescopes together to optimise their sensitivity. These operations also prepare LST-1 to stereo observations with the LST2-4 which are now in construction and will be completed in 20206 [A+23c]. In addition, LST-1 is integrated in the MAGIC interferometry setup to significantly increase the angular resolution in and add sensitivity to optical photons. There exists the idea to refurbish the MAGIC telescopes and either integrate them into the CTAO array or to operate them by CTAO as independent units for science cases not needing the sensitivity of the full CTAO array. The most crucial aspect is the almost 1000 mechanical actuators of the automatic mirror control (AMC) that are reaching their end of life. The cost of this refurbishment would be comparable to the costs of the disassembly of MAGIC. In addition, MAGIC would be the ideal system to get experience with an advanced SiPM camera planned for the LST upgrade, without affecting the normal operation of the CTAO array.

Impact:

Scientific: The MAGIC array, together with the H.E.S.S. and VERITAS arrays did revolutionise our view on the VHE universe. While only a handful of galactic and extragalactic VHE sources were expected to exist, more than 200 objects have been found so far. Among many other discoveries, MAGIC did show for the first time that some pulsars can emit photons at energies far above the theoretical limit of 10 GeV [A+16b] and that variability of VHE emission from blazars can be as short as few minutes, while a limit of one hour (corresponding to the radius of the event horizon of the underlying supermassive black hole) was generally assumed [A+07]. Several other observations confirm those findings. This unexpected success initiated the CTAO project to construct arrays with higher sensitivity to reach more than 1000 observed sources. MAGIC is a pathfinder to multi-messenger astronomy, working together with gravitational wave and neutrino detectors. The concept of using large mirrors of Cherenkov telescopes boosts intensity interferometry [A+24b].

Economical and Technological: While H.E.S.S. and VERITAS use arrays of four telescopes with 12m diameter each (similar to the future MSTs of CTAO), MAGIC is optimised to reach a lower energy threshold by using telescopes with diameter 17m. This goal was succesful and in fact the 23 m diameter LSTs of CTAO are based on the MAGIC design. An additional goal is to be able to point the telescopes to any orientation in less than 30 s to react to alerts of transient events. Therefore, the MAGIC telescopes do not use solid steel structures, but lightweight CFK elements. This results in a reflector dish that deforms under its own weight depending on the pointing direction. Each of the 234 mirror tiles of each telescope is equipped with two stepping motors to compensate for any deformation. A similar AMC is of crucial importance for the LSTs, and to lesser extent also for the MSTs, of CTAO. In addition, the AMC allows to focus fractions of the reflector to different locations and therefore execute some interferometry measurements not possible with any other instrument. The actuators of the AMC for MAGIC as well as for LSTs are mainly produced by the Swiss industry Diener.

Societal and knowledge transfer: Initially, the MAGIC telescopes were built and operated mainly by particle physicists. To be able to measure the dim, fast flashes of Cherenkov light, the about 1000 photo sensors in the camera must be read out at least a billion times per second, and only particle physicist had the necessary experience. Over the time, more astronomers got interested and joined the project. Astronomers and particle physicists have very different cultures about how to perform science, and both do profit from cooperation. The general public is highly interested in astronomy, and Cherenkov telescopes are adding completely new and unexpected information about the VHE sky.

Operation and sustainability in the long term: On the Canary Island La Palma, basically all electricity is produced by Diesel generators. Therefore, MAGIC is initiating the Very Eco-friendly Gamma Astronomy (VEGA) project to install large Photovoltaic panels and novel batteries on the site to drastically reduce the CO_2 footprint. Estimates show that, depending on evolution of electricity prizes, the system would amortise within three to six years. Since the future of MAGIC is currently unclear, the system shall be fully modular to be easily relocated to e.g. the neighboring CTAO site. Currently exists some legal problems because such a large photovoltaic infrastructure by Spanish law is only allowed for official electricity providers. Therefore it must be ensured no surplus electricity can ever go to the public grid. The operation cost of MAGIC is dominated by salaries for onsite personnel and collaboration members on data taking shifts. While it has been proven that such telescopes could largely be operated fully robotic, for safety reasons this does not allow to reduce number of persons on site during operation. If such a large telescope is not fully parked in save position when the sun rises, the concentrated sunlight could easily ignite a catastrophic fire on the mountain. This cost could be drastically reduced if safety tasks would be taken over by the CTAO personnel onsite.

2.3 The Einstein Telescope

Short description: The Einstein Telescope (ET) [Tel24] is the European proposal for a next-generation (under)ground-based gravitational wave (GW) interferometer, with a planned start of operations in 2035, and with an expectation of a roughly 50-year infrastructure lifetime. ET represents a major transition in the field of GW science, and in a collider physics analogy, is like combining LEP and the LHC: it is perfectly adapted both for precision measurements and discovering new phenomena. Statistically, ET will transition from O(100) accumulated GW detections to roughly 10^5 detections per year, thus completely changing the potential of population studies in understanding the gravitational universe. Some of these signals will have enormous signal-to-noise ratios, which will allow for precision measurements of GW quasi-normal modes. ET will also open a new window of the Universe, moving from the local Universe (redshift 1-2) out to the very early Universe (redshift 50-100); ET is thus expected to observe essentially all relevant sources from stellar origins, and to have the sensitivity needed to confirm or refute the existence of primordial black holes (a leading dark matter candidate), in addition to probing dark energy and modifications of gravity at cosmological scales. ET will also serve as a key tool in the multi-messenger science toolkit, with sensitivity to many signals of interest, and with improved low-frequency sensitivity allowing for pre-merger detection of imminent binary coalescence events.

Involved PIs: CHIPP professors: Antonio Riotto (UNIGE), Marcelle Soares-Santos (UZH), Michele Maggiore (UNIGE), Steven Schramm (UNIGE), new hire at ETHZ [pending confirmation] CHAPS professors: Anastasios Fragkos (UNIGE), Corinne Charbonnel (UNIGE). Other professors: Camille Bonvin (UNIGE). Senior scientists: Paul Laycock (UNIGE), Stefano Foffa (UNIGE).

Swiss participant Institutions: UNIGE, UZH, ETHZ planned (hire underway)

Investment level: ET is a major priority for UNIGE. UNIGE led the science case of the ET ESFRI proposal, leads the ET science board, and is represented on the ET executive board (Maggiore). UNIGE also leads divisions within the science board (Riotto) and computing board (Schramm), as well as holding a task leadership position within the ET Organisation and representing Switzerland on the ET Board of Scientific Representatives (Fragkos). UNIGE approved the creation of a cross-departmental centre on gravitational wave science, and recently the three involved departments and physics section joined together to identify solidifying UNIGE's position of leadership in ET as their leading priority for the next four years; this was recognised and supported by the UNIGE rectorate, leading to the creation of one or two new tenured professorship positions (one confirmed, second pending).

Timeline 2018-2032: Design: now to 2025 for the baseline design (staged upgrades will follow) Construction: 2026-2034 for the baseline design (staged upgrades will follow).

Operation: 2035+, with a vision of a 50-year infrastructure lifetime.

R&D: continuous from now to the foreseeable future, for the baseline and upgrades.

Essentially all of this is new since the last roadmap, where ET was only briefly mentioned.

Objectives 2020-2032: ET in general: Selecting the ET configuration and site(s) and the construction of ET.

Swiss involvement:

1. Continue to play a leading role in defining the science of ET;
2. Contribute to the optical system of the low-frequency ET interferometer;
3. Take a leading role in the design and development of the ET data acquisition system;
4. Establish Switzerland as a leader in the ET computing domain (already well on the way), especially related to the overall design of the ET computing model and prototyping critical components like the low-latency multi-messenger alert system;
5. Prepare for data-taking with ET by routinely participating in ET mock data challenges and investigating involvement in future upgrades of Virgo data acquisition systems.

Essentially all of this is new since the last roadmap, where ET was only briefly mentioned.

Impact:

Scientific: (CHIPP-oriented perspective, CHAPS has partial overlap of scientific priorities): Statistics: huge increase compared to current GW detectors, enabling robust and precise population studies. Some of these many events will have enormous signal-to-noise ratios, allowing for precision measurements of phenomena that currently cannot be studied. Sensitivity: LVK sees the local Universe, while ET will see the very early Universe out to redshifts of 50-100. ET should be able to directly demonstrate the presence or absence of primordial black holes, a major Dark Matter candidate, and to be sensitive to the impact of dark energy and modifications of gravity at cosmological scales. Multi-messenger: ET will act as an alert generator, with many signal detections, and with low frequency sensitivity enabling pre-merger alert notifications (for binary neutron star coalescence, up to hours before the merger occurs). This will have a profound impact on the field of multi-messenger science. – Synergies with other fields (focused on CHIPP synergies): ET has many synergies with other fields, two examples of which are provided. As a multi-messenger alert generator, it contributes directly to another field, and has direct implications on the science cases and capabilities of other observatories/experiments. Measuring the equation of state of binary neutron star mergers provides access to hadronic physics at temperature and density scales well beyond what can be produced at earth-based particle colliders, and so provides a complementary picture to understanding hadronic physics.

– mention relevance for Dark Matter searches: ET is sensitive to specific well-motivated DM models that we currently cannot probe, such as primordial black holes and axion clouds around black holes. It is also possible to study dark matter more generically with ET via environmental effects, such as by searching for the accumulation of DM inside of / on top of neutron stars, leading to perturbations in the neutron star equation of state. – mention relevance for Artificial intelligence and Machine Learning: AI/ML will play a significant role in ET. It is already used in Virgo for data quality, signal detection, signal interpretation, population inference, and more. ET increases the scope for the use of AI/ML dramatically, and thus we are already strongly investigating such directions within Switzerland. The recently approved SNSF Sinergia grant, GW-Learn, is directly aimed in this direction (for ET as well as LISA, where LISA is a space-based GW interferometer). –mention relevance for flavour, matter-anti-matter asymmetry, baryon content: Gravitational wave interferometers such as ET are sensitive to some models of inflation, which can have implications for these topics; there is therefore an indirect link.

Economical and Technological Impact: ET is a proposed world-leading infrastructure, requiring the development of technologies that go beyond the leading edge. Swiss involvement is currently planned in mechanics for the interferometer control system, fast electronic readouts for the data acquisition system, and computing infrastructure primarily aligned with the low-latency system. Each of these developments will place Switzerland in a leading role in the development of technologically advanced solutions, and may engage other Swiss stakeholders depending on how the situation evolves.

Societal and knowledge transfer: Gravitational wave astronomy is a fascinating subject, both for the scientific audience and the general public alike. There is a general public fascination with black holes and their role in the Universe, and ET will engage this audience with world-leading research, building upon the successful efforts of LVK. Moreover, the skills required to work on ET, and the relevance of advanced computing skills (such as, but not limited to, AI/ML) will contribute to the training and digital literacy of society.

Current state and remarkable highlights: 2020-2024: UNIGE led the science case of the ET ESFRI proposal, and has held a leading role in the ET science programme since the official formation of the collaboration in 2022, accompanied by holding a spot in the ET executive board. UNIGE also led the so-called cost benefit analysis (COBA) study, in which the scientific potential of different telescope configurations were studied in extensive detail, which is a fundamental step towards the justification of the final decision on which interferometer configuration should be built. UNIGE has since taken on leading roles in many other areas related to ET, cementing the role of UNIGE and Switzerland as a leading player. Beyond the Swiss contributions, the two primary candidate host nations have issued remarkable statements of political support. ET is projected to be a 2.5 B€ infrastructure, and the Dutch government has already pledged 0.9B Euro if their site is selected, while the Italian government has pledged 0.35 B€ and "the political commitment to find what is needed to host the infrastructure in Italy".

Operation and sustainability in the long term, vision for the future: ET plans to start operations in 2035, and an expected infrastructure lifetime of 50 years, and it is therefore a research infrastructure that represents a long-term future for the field. Note that while the infrastructure is expected to last 50 years, the interferometer and the rest of the experimental apparatus will continue to be upgraded on a regular basis, providing better sensitivity and continued training + knowledge transfer activities for the full duration. Every time the interferometer is turned on after a break for technical maintenance or upgrades, it is essentially a new experiment, thus ET will continue to provide an engaging opportunity delivering world-leading science for the long-term future.

Overall vision: Our intention is to create a strong ET community in Switzerland, with strong support from and involvement of members of both the CHIPP and CHAPS communities, to allow our scientists to be at the forefront of the exciting developments in gravitational wave physics that will occur in the decades to come.

2.4 IGWN-Gen2: LIGO and Virgo

Short description: The Laser Interferometer Gravitational-wave Observatory (LIGO) and the Virgo Experiment are second-generation ground-based GW interferometers. Together with the underground-based Kamioka Gravitational Wave Detector (KAGRA), they represent the collaborations active in the International Gravitational Wave Network (IGWN). The second generation observatories have many of the same goals of ET, but are restricted to the local universe (redshift 1-2) and will correspondingly see a much lower number of signals. Nonetheless, the second generation GW detectors are instrumental to the multi-messenger science programme, and as their sensitivity continues to improve through upgrades, they will play an important role in the multi-messenger understanding of the universe leading up to ET.

Involved PIs: CHIPP professors: Marcelle Soares-Santos (UZH), Steven Schramm (UNIGE). CHAPS professors: Anastasios Fragkos (UNIGE), Philippe Jetzer (UZH). Senior scientists: Paul Laycock (UNIGE), Shubhanshu Tiwari (UZH).

Swiss participant Institutions: UNIGE, UZH

Investment level: Participation in Virgo is seen by UNIGE as a stepping stone and technological demonstrator towards ET. The theory department is not involved in the technological aspects and thus is not currently involved in Virgo, but the Geneva Observatory and DPNC are participating with such an intent. The two positions mentioned under the ET investment section (with the Observatory confirmed, and DPNC pending), a well as the cross-departmental centre, are therefore relevant investments for both ET and Virgo.

Timeline 2018-2032 : Not sure if we want to just put two arrows of operation and upgrade on top of each other. Information from the updated link here until 2030. For 2030+, this link is used instead. If we want a more detailed breakdown, see below:

- 2018 to mid 2019: upgrade
- Mid 2019 to mid 2020: operation
- Mid 2020 to mid 2023: upgrade
- Mid 2023 to mid 2025: operation
- Mid 2025 to mid 2027: upgrade
- Mid 2027 to 2030: operation
- 2030 to mid 2031: upgrade
- mid 2031 to mid-2032: operation

Objectives 2020-2032 : Swiss-external objectives include increasing the sensitivity to GW signals and increasing the reach to GW signals originating further away in the Universe. For Switzerland, the objective is to gain experience in developing, deploying, and operating the necessary technologies to scale-up to the future construction of ET.

Impact:

Scientific: Similar general scientific motivation to ET, but with less sensitivity and reduced capabilities.

Economical and Technological: Essentially the same as ET, but on a smaller scale. The intent is to use 2nd generation detectors as a pathfinder towards the implementation in ET for each of the areas under discussion: mechanics for the interferometer control, fast electronics for readout, and low-latency computing infrastructure. The 2nd generation facilities therefore represent the start of the process.

Societal and knowledge transfer: Also the same as ET, where LVK efforts will naturally lead into ET efforts as the transition from 2nd generation to 3rd generation facilities occurs.

Current state and remarkable highlights, 2020-2024: Soares-Santos co-led the team that was responsible for discovering the first binary neutron star merger including both optical and gravitational wave counterparts, thereby starting the era of GW in multi-messenger astronomy.

Operation and sustainability in the long term: The 2^{nd} generation ground-based GW observatories will continue until at least 2029 (the end of the next observing run), and are expected to continue into the mid-2030s through the LIGO A# and Virgo-nEXT upgrade programmes. These upgrades will include demonstrators of the technologies needed for the next generation facilities, notably CE in the USA and ET in Europe. There is therefore a natural progression for the long-term operation and sustainability of (under)ground-based GW observatories.

Recommendations and findings: Recommendation: The Swiss community should make an effort to take a leading role in ET consistent with its status as a flagship project. Participation in LVK is seen as a useful pathfinder towards achieving this objective.

Recommendation: The possibility of building a new Swiss-led telescope, dedicated to multimessenger physics in synergy with the ET flagship project, should be investigated.

2.5 IceCube and IceCube-Gen2

IceCube-Gen2 through infrastructure investments via the FLARE instrument. Nonetheless, the science is compelling for multi-messenger astrophysicists in Switzerland and a future proposal can be envisaged when IceCube-Gen2 will be fully approved after 2028.

Recent highlights of IceCube are: 1) the discovery of a diffuse flux of astrophysical neutrinos reaching up to PeV energies and dominated by extragalactic sources (mostly black holes embedded in active galaxies) [A+13a].
2) the discovery of neutrino and gamma-ray emissions from an active galaxy, TXS 0506+056, during a flare [A+18b, A+18a].
3) The discovery of 7 tau neutrinos of > 100 TeV energy most probably from cosmic neutrino oscillations [A+24a].
4) The discovery of the first standalone neutrino source [A+22a], a Seyfert galaxy, with gamma-ray absorption.
5) The discovery of the diffuse flux of neutrinos from the Galactic Plane [A+23b]. 6) The finding of a ~ 6 PeV electronic neutrinos in region of the Glashow resonance [A+21a].

In Nov. 2023, IceCube started an upgrade construction, which will last to 2026. It will add 7 new strings to the inner core denser strings DeepCore. DeepCore detects an atmospheric neutrino every 15 min, while the upgrade of IceCube will detect a neutrino every 4 min and improve by more than a factor of 3 precision on oscillation parameters. For the upgrade, the drilling tools at the South Pole have been renewed to achieve the capacity to evolve into PINGU with 26 strings, which will deliver important results on neutrino ordering. Indeed, P5 prioritized the readiness of the logistics tools at South Pole with respect to other programs as CMB detection from South Pole and follows up of the South Pole telescope. IceCube and its evolution is a high priority in P5.

The coming publication on neutrino oscillation uses 9.3 yr of DeepCore data including 210k ν-events with 97.3% purity between 5-55 GeV. Impressively, 6.9k ν_τ neutrinos come from ν_μ oscillations. The Upgrade will reach a precision of 6% in 3 yr on the ν_τ normalization and will measure directly tau neutrinos from muon neutrino oscillations with a better sensitivity by a factor of 3. The next step, PINGU, will exclude inverted ordering in 1.5 yr and normal ordering in 3 yrs. Combined with JUNO reactor experiment, it has the potential to determine the mass ordering at 5σ c.l. in 5 yr [A+20b].

The ultimate extension of IceCube is IceCube Gen-2, focusing also on cosmic neutrinos. It is planned to be a factor of 10 bigger than IceCUbe, namely 10 km^3 of instrumented ice with a surface detector as veto which will be very extended and made of radio antennas. It should become fully operational in 2033 [A+20b].

This is an excellent program, complementary to accelerator neutrino physics, that should be continued in Switzerland. Future requests on FLARE might be foreseen once IceCube-Gen2 construction is approved in the next few years. Additionally, data taking by the KM3NeT neutrino telescope in the Mediterranean sea has started. It can provide further synergy in this extra-terrestrial neutrino program.

3 Dark Matter searches

3.1 XENONnT

Short description: The XENONnT experiment [A+24d] is located at the Laboratori Nazionali del Gran Sasso (LNGS) of INFN, at a depth of 3600 mwe. XENONnT operates a two-phase xenon time projection chamber (TPC) with 5.9 t of active Liquid xenon (LXe) mass (8.5 t LXe in total). In a two-phase (liquid and gas) TPC, the interactions of particles are observed via two distinct signals: the first is the prompt scintillation light (S1), while the second is caused by ionisation electrons that are drifted and extracted into the gaseous phase where they produce electro-luminescence (S2). The photons are detected by two arrays of 3-inch diameter PMTs, and the difference in arrival time between the S1 and S2 signals yields the depth, or z-position, of an interaction. The S2 light distribution in the top PMT array yields the (x, y)-position of an event, while the S2/S1 ratio allows to discriminate electronic recoils (ERs) from nuclear recoils (NRs). XENONnT started a first science run in July 2021 and is presently acquiring data towards its design exposure. It achieved the lowest background in the field and was able to exclude the low-energy excess observed in XENON1T [A+22e]. In a blind analysis of its first science run nuclear recoil data, XENONnT also improved constraints on WIMP-nucleon interactions [A+23e].

Involved PI: Laura Baudis.

Swiss participant Institutions: UZH.

Timeline: Construction: 2017-2020, Operations: 2021 - onward

Current state and remarkable highlights: 2020-2024: The XENONnT experiment is currently taking data at LNGS. The TPC was installed underground in early 2020, and a first science run started in summer 2021. First results on searches for new physics in the electronic recoil data were published in 2022. With a background level five times lower than the one of its predecessor, XENON1T, XENONnT achieved the lowest background level reached in a dark matter experiment so far [A+22e]. In 2023, XENONnT published first results on WIMP searches from its first science run, with the world's best limits on WIMP-nucleon cross sections achieved in a blind analysis [A+23e]. Currently, XENONnT acquires data in its third science run, with the goal to accumulate an exposure of 20 t×y and probe WIMP-nucleon cross sections of 1×10^{-48} cm^2 at 30 GeV/c^2. Recently, XENONnT announced the first detection of coherent neutrino nucleus scatters from solar ^{8}B neutrinos. Several other analyses are in progress: the search for solar pp neutrino-electrons scatters down to 1 keV, searches for light dark matter particles, including ALPs and dark photons, as well as for second order weak decays, with and without neutrinos (^{124}Xe, ^{134}Xe, ^{136}Xe).

The UZH group is a founding and leading members of XENON, and contributes to the following efforts: data analysis (with the analysis co-coordinator at UZH), MC simulations (leading the MC working group), design, tests and construction of the TPC; characterisation of the 3-inch photosensors in LXe; design, test and production of the low-background voltage dividers for the photosensors; signal transfer between TPC and DAQ on the cold, xenon side; low-noise, dual-channel amplification of the signals to ensure linearity from about 1 keV to 3 MeV; design and construction of the light calibration system, photosensor calibrations and monitoring of the stability of the photosensors' performance in time; material screening with a high-purity germanium detector, Gator, at LNGS.

Objectives 2020-2032: XENONnT will operate until 2026; afterwards, the infrastructure in Hall B of LNGS will likley be reused to construct a large-scale demonstrator for DARWIN/XLZD. The main goal is to construct and test critical component for the next-generation detector.

Impact:

Scientific: The XENON collaboration has been pioneering the two-phase (liquid and gas) xenon TPC technology since 2006, with the start of XENON10 at LNGS. XENON10 soon surpassed the then best constraints on WIMPs from CDMS and other experiments. The pathfinder experiment later evolved into XENON100, XENON1T and presently XENONnT, gradually scaling up the DM target mass. At the same time, the background levels in the most inner regions constantly decreased, with now unprecedented electronic recoil levels around 15 events/(t y keV) in the energy region below 100 keV. Due to the large target mass and the unprecedented low backgrounds, the xenon-based experiments are not only sensitive to WIMP dark matter, but also to light DM via the ionisation signal. Two-phase Xe-TPCs thus start probing theoretical predictions for different dark matter production scenarios in hidden sectors. Using liquid xenon in its natural isotopic abundance XENONnT is sensitive to double weak decays, such as the double beta decay of ^{134}Xe and ^{136}Xe, with Q-values of 825.8 keV and 2457.8 keV, respectively, and the double electron capture process in ^{124}Xe and ^{126}Xe, at Q-values of 2857 keV and 920 keV. In particular, the observation of the neutrinoless decay modes would be evidence for lepton number violation involving Majorana neutrinos. The observed standard model processes with two neutrinos (so far, $2\nu\beta\beta$ in ^{136}Xe and 2νECEC in ^{124}Xe) allow for comparison to theoretical half-life predictions from nuclear structure calculations in different nuclear physics models, as well as for new physics searches. In its electronic recoil channel, the XENON1T experiment observed for the first time the 2νECEC process in ^{124}Xe by detecting the simultaneously emitted K-shell X-rays/Auger electrons of the daughter atom ^{124}Te with a combined energy of 64.33 keV. With a half-life of $(1.1\pm0.2_{\mathrm{stat}}\pm0.1_{\mathrm{sys}})\times10^{22}$ y, this is the slowest process ever measured directly [A+19c, A+22d]. Finally, XENONnT is the first experiment to observe the so-called neutrino fog from solar neutrinos.

Swiss involvement Professor and CHIPP board member, Laura Baudis of the University of Zurich was a founding member of XENON in 2003 while an assistant professor at the University of Florida, Gainesville. Laura Baudis has served as XENON co-spokesperson, as chair of the collaboration board and is currently chairing the science strategy team in the collaboration. UZH has been a leading member of XENON since 2007, with UZH scientists leading several working groups (PMT, screening, Monte Carlo) and serving as analysis coordinators. The group has made leading contributions to the TPCs, the photosensors, their readout and calibration systems, and to material screening with Gator at LNGS.

Swiss Investment level: Switzerland has supported the XENON suite of experiments through investments from UZH, SNF project funds, and the SNF FLARE since 2007. These investments have supported the design and the construction of the XENON TPCs, the development, together with Hamamatsu, of low-radioactivity, VUV-sensitive photosensors, the characterisation of the photosenors for XENON1T and XENONnT in a local liquid xenon test facility, MarmotX, the development of their readout, of the calibration systems as well as of the low-radioactivity cables and connectors on the cold, xenon side. UZH has also played a leading role in demonstrating, with local setups such as Xurich, new calibration sources for XENON, in measuring the light and charge yields of electronic recoils at low energies, and in measuring the W-value of liquid xenon,

Economical and Technological, Societal and knowledge transfer: Instrumentation and technologies developed for the XENON dark matter experiments, including the measurement of trace radioactivity levels in detector materials, find applications in other fields, as well as in the industry. As an example, two-phase Xe TPCs are developed for PET detectors [R+22], while material with ultra-low activity levels may be used in the quantum computing industry, since gamma radiation from materials surrounding the superconducting qubits can lead to quasi-particle poisoning and thus qubit decoherence [C+21, V+20]. The R&D projects and the small or large-scale TPCs operated in various laboratories offer an ideal training ground for early career researchers, many of whom later work in the industry.

Operation and sustainability in the long term: The xenon currently used by the XENONnT experiment will become part of DARWIN/XLZD. Other infrastructure underground at LNGS, including the muon and neutron vetoes will become part of the large-scale demonstrator for DARWIN/XLZD.

3.2 LUX-Zeplin

Short description: The LUX-Zeplin detector (LZ) is located at the Stanford Research Underground Facility (SURF) at a depth of 1 mile to shield it from cosmic rays. LZ is using 7 tonnes LXe in the inner detector, a TPC, to search for dark matter. When a DM particle interacts with the LXe, it creates a light and charge signal that is very well distinguished from background-like electron recoils (ER), such as from beta and gamma radiation. The remaining background caused by neutrons is vetoed by a dedicated veto detector, the Outer Detector (OD) which almost doubles the sensitivity of LZ. LZ is presently the world's most sensitive dark matter experiment, improving existing sensitivity by about two orders of magnitude with its first results. The plan is to take at least 1000 live days of data, which will allow us to improve present sensitivities by about orders of magnitude. LZ, like XENON, is an observatory for many rare event searches beyond WIMP searches, for example, neutrino physics, multi-messenger astronomy, time-dependent searches, and nuclear searches. Long-term the experience gained is indispensable to the development of Darwin/XLZD and the experiment also can serve to test crucial hardware developments.

Involved PI: Bjoern Penning.

Swiss participant Institutions: UZH.

Timeline: Construction: 2017-2021, Operations: 2022 - onward

Current state and remarkable highlights: 2020-2024: The Swiss community is new to the experiment. However, the group that joined UZH/Switzerland co-led the design, manufacturing, fabrication, installation, operation, and analysis of the Outer Detector (OD). The OD is LZ's active neutron shield and approximately doubles the experiment's sensitivity to DM. In the case of a discovery, the OD is essential to prove that we are detecting DM and not an unexpected neutron flux. The OD detects neutrons by capturing them in 17 tonnes of gadolinium-doped liquid scintillator (Gd-LS). The resulting interaction is viewed by PMTs, detectors with single photon sensitivity. The OD was built by only two groups: UCSB focusing on the Gd-LS, and the Penning group at UZH. Besides the OD, other major contributions are made to the reconstruction of events in the LXe, OD calibration, underground operations, TPC calibration, and detector stability. The UZH group extended LZ's physics program by establishing the high nuclear recoil search group. The group has a large, permanent presence at SURF and has committed to its responsibilities throughout the LZ data-taking phase

Objectives 2020-2032: In LZ we published the world's leading dark matter results. Since then we started a new, extended data-taking period that will push our sensitivity into yet-unexplored territory. We will continue data taking for about five (more?) years and thus LZ is likely to be the most sensitive detector for dark matter for years to come. During this time we continue to lead the operation, hardware improvements, and data-taking of the OD and its optimal use to reject potential DM backgrounds. We will continue to lead the event classification and understanding of the detector including the microphysics and to produce the world's most sensitive results with a high chance to discover DM in the next five years. We further study and pioneer new searches and new signatures. The latter can benefit a lot from the strong Swiss theory community Liquid xenon (LXe) has proven to be the most promising target material for WIMP dark matter and both the experiments in the Swiss community, XENON and LZ are the two most sensitive WIMP search experiments. With both groups present we will have the unique opportunity to have a maximal impact on the future of LXe searches that remain most promising for WIMP-type dark matter. We are involved in the preparation of the next generation of dark matter searches, DARWIN/XLZD, and the group of the Baudis and Penning groups are very complementary, allowing us to take on the lead in the design and preparation of the Darwin/XLZD detector.

The Swiss community's ambitions for the future are:

1. Continue and grow leading participation in LZ throughout the remaining run in operations and analysis. Spearhead combinations with XENON for which UZH is particularly suited.

Impact:

Scientific: Rare event searches such as LZ (and Xenon) provide leading sensitivity to DM. The discovery of DM is potentially one of the biggest scientific breakthroughs in our lifetime with a large impact on particle physics and astrophysics. The search for dark matter is probing and advancing theories beyond the Standard Model. Dark matter also plays a key role in cosmology and its discovery will lead to unique insights into the evolution of the Universe. The interplay between astrophysical observations and laboratory experiments both in direct searches and at the LHC improved the understanding of all of those fields. Further, recent and future generations of DM searches serve as 'observatories' that can provide key insights into neutrino physics, and nuclear physics and potentially even elucidate questions about the matter/antimatter symmetry. Xe-based experiments are sensitive to all flavors of neutrinos emitted from a supernova and therefore can provide a unique contribution to multi-messenger astrophysics.

Economical and Technological: DM searches employ a wide range of instrumentation, electronic, and analysis/ML techniques that lead to the most sensitive detectors in existence. Technological advancements driven by dark matter research find applications beyond Astro- and particle physics. The development of highly sensitive detectors and computational methods has implications for general radiation detection, imaging, and nuclear non-proliferation methods. The expertise accrued in the pursuit of dark matter will have a large impact on addressing challenges in other applied sciences. For example, in our ultracold (mK) searches we observe unexpected backgrounds that are likely also an issue for modern quantum engineering (computing). Further, dark matter experiments often use target materials with unique properties and under extreme conditions. This can lead to advancement in the understanding of materials (solid state crystals, noble liquids), and potential applications in manufacturing, electronics, nuclear detection, and others including quantum technologies such as transition edge sensors and similar. Dark Matter searches also provide an excellent training ground for young scientists. Students and postdocs are deeply involved in hardware and analysis, gaining experience in a wide range of topics such as vacuum technology, high voltage applications, electronics, mechanical engineering, DAQ, analysis, and machine learning to name only a few, leading to a very skilled workforce. Several key technologies used in LZ and XENON are employed beyond DM searches in other science areas (nuclear, neutrino), nuclear non-proliferation, and the nuclear industry.

Societal and knowledge transfer: The pursuit of dark matter has positive implications for society at large. The advancements in technology driven by the need for ultra-sensitive detectors contribute to the growth of the scientific and technological sectors, fostering innovation and creating job opportunities and economic growth. The public is generally very interested in dark matter searches, leading to an increased engagement in science and STEM fields. Outreach programs help improve scientific literacy and attract the next generation of researchers and engineers. The interdisciplinary nature of dark matter research necessitates collaboration between diverse scientific fields. Astrophysicists, particle physicists, and engineers converge to develop novel experimental techniques and theoretical frameworks. This interdisciplinary collaboration facilitates the transfer of knowledge across fields, enriching each one with insights and methodologies from the others. Our experiments in international collaboration, leading to knowledge transfer across borders and not only between different fields.

Operation and sustainability in the long term: LZ's upcoming results are expected to be the world's leading results on WIMP dark matter with a realistic chance of discovery. We expect to finally reach sensitivities at the order of about 10E-48 for a few GeV WIMP and improve existing results by orders of magnitude. Based on the remarkable success and experience gained in LZ and XENON, Darwin/XLZD will be the ultimate direct WIMP detection experiment, probing the phase space to the neutrino floor.

Recommendations and findings N/A

Do you have a proposal of an update: N/A

Executive Summary Recommendation

3.3 The DAMIC experiments

Short description: The DAMIC (DArk Matter in CCDs) are a series of experiments using scientific-grade CCDs with low-ionization energy thresholds to search for low-mass (≤ 5 GeV/c^2) WIMPs and hidden-sector DM candidates with masses in the 1-1000 MeV/c^2 and 1-100 eV/c^2 range. The first prototype DAMIC experiment began operation in 2010, and demonstrated the potential for dedicated, low-energy threshold experiments to probe for low-mass dark matter by setting the most stringent constraints on the cross-section for DM from 1 - 5 GeV/c^2. Since 2014, DAMIC has been operating at SNOLAB, having undergone several phases of upgrades, including to use new "skipper" readout amplifiers with an order of magnitude improvement in noise reduction, to continue to probe new phase space. The next major phase of DAMIC is DAMIC-M in the Laboratoire Souterrain de Modane (LSM). DAMIC-M utilizes skipper readout to achieve an order of magnitude reduction in energy threshold, almost 100 times lower background rates, and has a detector mass 100 times that of DAMIC@SNOLAB. DAMIC-M is under construction with installation planned in 2025. A first prototype of DAMIC-M called the Low Background Chamber (LBC) utilizing skipper CCDs has been operational in LSM since 2022, and has been instrumental in characterizing key DAMIC-M components.

Swiss involvement Professor and CHIPP board member, Ben Kilminster of the University of Zurich was a founding member of DAMIC in 2008 while a scientist at Fermilab, and has served continuously as collaboration board (CB) chair of DAMIC@SNOLAB since 2008 and of DAMIC-M since 2017, overseeing the integration of a number of new European groups into the experiments. UZH has been a leading member of DAMIC@SNOLAB and DAMIC-M since 2012. Permanent UZH scientists, Peter Robmann, Anna Macchiolo and Stefanos Leontsinis, have played important roles on the DAMIC experiments, and the UZH electronics group has made leading contributions to DAMIC electronic components.

Swiss Investment level: Switzerland has supported the DAMIC experiments through investments from UZH, SNF project funds, and the SNF FLARE since 2013. These investments have supported PhD student analyses, operations, mechanical design and construction of DAMIC@SNOLAB vacuum and shielding components, and more recently contributions to the LBC and DAMIC-M. For the LBC, UZH has produced primary mechanical components of the cryostat and developed the detector control system (DCS), which controls, monitors, and implements error handling. For DAMIC-M, in addition to the DCS, UZH has provided important electronic components including the analog-to-digital converter (ADC) hardware and firmware and the front-end board that provides low-noise signal amplification. UZH has also produced an in-situ calibration system that circulates a short-lived isotope into the experiment to characterize the energy response of the detector sensors, and developed a test-stand for quickly characterizing DAMIC CCDs. UZH has played a leading role in calibrating the energy response of nuclear recoils in CCD detectors by performing a dedicated beam-line experiment measuring the response of silicon detectors to neutron recoils. UZH houses a CCD experimental test stand, which is used for CCD characterization and analysis. The total Swiss investment in the DAMIC experiments has been at the level of 500kCHF, providing a significant portion of funding for DAMIC@SNOLAB, and about a 5% contribution to DAMIC-M, which is 90% funded by an advanced ERC grant of Paolo Privitera.

Timeline 2018-2032: Design (2018-2021); Construction (2023-2025); Operation (2026-) DAMIC was first operated as a prototype in a shallow-underground tunnel at Fermilab, before moving to a 2km-deep cavern at SNOLAB laboratory. DAMIC@SNOLAB has been operating since 2014, producing its first physics results in 2016. It was upgraded in 2017 with a higher detector mass and lower background shielding, and again in 2021, with skipper CCDs to achieve sub-electron noise and single-electron resolution. DAMIC-M was conceived in 2017, and has been undergoing simulation, design and prototyping until 2023. It is currently being constructed and will be installed in early 2025 and begin operations. A prototype DAMIC-M detector, the LBC, was installed in 2022 and can be utilized as a test chamber for DAMIC-M once the latter is in operation.

A future experiment known as OSCURA aims to achieve an order of magnitude improvement in detector mass and background levels and is being spear-headed by the U.S. DOE with a target date for commissioning of 2028. Swiss groups may join this effort in the future. However, it is expected that DAMIC-M will continue to provide important physics results into the 2030s.

Scientific highlights (2012-2024: The first DAMIC@Fermilab result in 2012 achieved world-leading constraints on the cross-section of WIMP dark matter with mass below 4 GeV/c^2. In 2016, DAMIC@SNOLAB published a new technique for measuring radioactive backgrounds by utilizing the CCD detector's excellent position resolution for identifying decay chain sequences of alpha, and beta decays, and also published its first WIMP search result. Also, in 2016, DAMIC demonstrated a new type of search for the absorption of hidden-photon DM, providing world's best constraints on DM with masses in the O(1-10 eV/c^2) range, and establishing for the first time the use of direct detection searches to probe energy deposits arising from DM below 10 eV. In 2019, DAMIC@SNOLAB extended its reach to low-mass DM by publishing the world's best constraints on hidden-sector DM with masses between 1 and 1000 MeV/c^2. In 2020, DAMIC@SNOLAB published a WIMP search with 20 times the target mass of its 2016 result that identified an intriguing 3σ excess. Upgrading the detector to make use of skipper CCD readout, DAMIC@SNOLAB published in 2024 a new result, with a much lower energy threshold and improved background descriptoin that confirmed the excess with an independent significance of 3.4σ. This excess, which is either an unknown background or a potential signal, has drawn speculation from the community as to new DM models, which could have evaded other DM experiments. During this time, the first results from the DAMIC-M LBC have been published, providing world's best constraints on DM interacting via an ultra-light mediator in the mass range of 0.6 to 1000 MeV/c^2.

Beyond DAMIC, UZH has been engaged in several CCD measurements with the goal of extending the scientific reach of the technology. In 2017, UZH led a publication on a neutron-beam calibration designed to calibrate the ionization efficiency of nuclear recoils from neutrons as a proxy for DM down to low energies. The results, since confirmed with independent analysis techniques, have demonstrated deviations from the accepted Lindhard theoretical model of ionization response to nuclear recoils, and have an impact on all low-energy, silicon-based detector experiments. UZH has also leveraged its study of radiation damage in silicon that it has developed in the context of the CMS silicon pixel detector in order to develop a new technique for identifying DM interactions. When a DM particle interacts with a solid-state detector, it produces damage to the crystal lattice known as non-ionizing energy loss (NIEL). This damage is mostly permanent under normal operating temperatures, and is expected at nuclear recoil energies as low as 20 eV. A 2023 UZH PhD student thesis demonstrated the measurement of this effect for the first time, leading to a first published result in 2022, and a recent 2024 publication with collaborators providing a more rigorous calibration.

This new detection mechanism provides a way to distinguish nuclear recoils from electron recoils in silicon due to the identification of permanent defects in the silicon that can be detected electronically.

Impact:

Scientific: scientific impact

DAMIC has been pioneering low-mass DM searches since 2012, setting early best constraints on low-mass WIMPs with mass of O(1 GeV/c^2), and recently in 2024 providing the best constraints on hidden-sector DM with masses 1-1000 MeV/c^2. The excess observed and confirmed in DAMIC@SNOLAB is either an unknown background that may plague other low-mass direct-detection experiments, or may later be realized as the first sign of a DM signal. DAMIC-M will continue to probe unexplored cross-sections for low-mass DM, and it is expected that the fully operational experiment will for the first time be able to probe theoretically predicted DM cross-sections for several classes of extremely weakly interacting hidden-sector DM models in the following years. The low energy threshold of DAMIC detectors has also provided the lowest energy measurements of the Compton scattering process, providing important comparisons to theoretical models that are needed for simulating detector response at low enegies.

UZH efforts to establish the use of radiation defects in order to distinguish nuclear recoils from electron recoils in silicon may pave the way for new CCD experiments with greatly improved sensitivity to a wide class of DM models. Theoretically, for very low-energy nuclear recoils, the efficiency for producing measurable lattice defects is much higher than the efficiency for producing ionization. If demonstrated experimentally, this may generate new experimental approaches for nuclear recoil detection.

Economical, societal and Technological knowledge transfer: The DAMIC experiments have provided the lowest energy ionization threshold detectors over the last decade. This technology enables the identification of nuclear and electronic recoils at unprecedentedly low energy scales, and may result in unforseen technological applications.

This CCD technology has been applied towards searching for coherent neutrino elastic scattering of neutrinos from nuclear reactors in the CONNIE experiment, on which the UZH group are contributors. Such an experiment has the potential for providing light-weight detectors that can identify and measure the rate of nuclear reactions for the benefit of nuclear non-proliferation.

New techniques pioneered by UZH for identifying nuclear recoils may provide an interesting new avenue for such an application, as CCD detectors can detect nuclear recoils without being active. In such a passive mode of operation, the CCD would acquire defects from a nuclear process that could later be determined using electrical measurements. This would provide an extremely practical way of detecting nuclear interactions. The microscopic understanding of individual lattice defects resulting from nuclear interactions can also feed back to pillar-one activities, where radiation damage in silicon detectors is a primary concern.

The DAMIC experiments have pioneered low-background detector components and in-situ measurements of radioactivity, enabling the possibilty of solid-state systems with extremely low radioactive background levels.

PhD students and scientists working on the DAMIC experiments develop a detailed understanding of modern scientific approaches, low-energy particle and nuclear physics processes, low radioactive-background materials, and extremely precise and low-noise electronics components.

Operation and sustainability in the long term: The bulk material of DAMIC experiments are low-background lead, ancient lead, low-background copper, and polyethelene shielding materials. The great majority of this material has been reused from previous experiments, and will continue to be used in future experiments as these low-radiation materials are valuable for any experiment wishing to achieve low background levels.

Recommendations and findings: The pursuit of the particle description of dark matter is one of the key questions in particle physics. CCD-based experiments provide a pivotal technology for identifying low-energy electronic and nuclear recoils, enabling the search for low-mass dark matter. It is recommended that Swiss scientists continue their long-standing engagement in CCD experiments, contributing to the success of DAMIC-M and potential future projects such as é. Swiss groups should continue developing the technique of nuclear recoil identification through non-ionizing energy loss mechanisms and apply this in future CCD experiments to increase their sensitivity to a wider class of DM models.

3.4 TESSERACT

Short description: Over the last few years, a strong theoretical motivation to search for particle Dark Matter (DM) in the mass range below the proton mass has emerged. The TESSERACT project will use a liquid helium (LHe) target (HeRALD), as well as GaAs and Sapphire-based targets (SPICE), read out by Transition Edge Sensor (TES)-based phonon sensor technology sensitive to phonon, roton, and light signals from LHe, phonon and light signals from GaAs, and phonon signals from sapphire. This project ultimately seeks to detect collective excitations from DM interactions in both superfluid helium and a polar target in addition to searching for ERDM on a low bandgap scintillator. The multiple targets will be instrumented with identical sensors and readout technology. This commonality provides a powerful tool to identify and discriminate backgrounds and systematics, and also simplifies the design and construction, allowing the use of multiple targets with minimal extra effort. In contrast to most other experiments that use backgrounds causing E-fields ("dark currents"), Tesseract uses no E-fields and hence avoids such backgrounds. The target mass will be composed of O(cm^3) scale identical-sized targets. The experiment is presently in a period of targeted R&D with the first physics results based on demonstrator setups already with leading sensitivities expected this year.

Involved PI: Bjoern Penning

Swiss participant Institutions: UZH

Timeline: R&D 2019-2024, Construction: 2024-28, Operations: 2029 - onward.

Current state and remarkable highlights: 2020-2024: Tesseract was initiated and selected for funding following the 2018 'Dark Matter Small Projects New Initiatives' by the DOE. In the last few years we almost fully defined the experimental setup including shielding, cryostat, and sensors, demonstrated physics measurement with the sensors, secured the Modane underground laboratory as the experimental setting, and added new collaborators in France. The Penning group at UZH is one of the founding members of the experiment and is responsible for many key contributions such as shielding, infrastructure, physics simulation, and its contribution to the measurement of TES sensors at Berkeley Lab. In 2023 French collaborators joined the experiment. This plus the proximity to Modane places the Swiss community in a very favorable position to lead the construction, operation, and scientific exploitation of Tesseract. We will publish a fully defined manufacturing and assembly plan including sensitivity studies in 2025. Construction of the experiment is expected to start shortly afterward and we plan to start operations in 2025. Once Tesseract is operating we will be able to improve DM constraints from presently GeV mass scales down to MeV and less in a few years with upgrade paths to meV sensitivities. Objectives 2020-2032: The Swiss community's ambitions for the future are:

1. Continue and grow leading involvement in Tesseract. Lead the construction of the experiment in Modane, lead simulations and analysis of the Tesseract data, and
2. Explore novel, not yet explored parameter space. Measure and discriminate novel b background to enable the discovery of DM in this new parameter space
3. Develop a testbed for sensor (quantum) technology by purchasing a dilution fridge and performing independent instrumentation R&D
4. Upscale the technology and target masses to increase discovery potential and further increase reach in the low DM mass space.

Impact:

Scientific: Tesseract will probe an entirely new phase space for dark matter and a discovery can come at any moment if a sufficient understanding of this novel phase space is achieved. The discovery of DM is potentially one of the biggest scientific breakthroughs in our lifetime with a large impact on particle physics and astrophysics. The search for dark matter is probing and advancing theories beyond the Standard Model. Dark matter also plays a key role in cosmology and its discovery will lead to unique insights into the evolution of the Universe. The interplay between astrophysical observations and laboratory experiments both in direct searches and at the LHC improved the understanding of all of those fields. Cryogenic low mass searches also employ techniques and study backgrounds that are crucial to quantum computing and engineering. TESs based sensors achieve almost unity detection efficiency that enable novel approaches to quantum computing and backgrounds affecting cryogenic low mass DM searches are also an issue for quantum computing and engineering.

Economical and Technological: DM searches employ a wide range of instrumentation, electronic, and analysis/ML techniques that lead to the most sensitive detectors in existence. Technological advancements driven by dark matter research find applications beyond Astro- and particle physics. The development of highly sensitive detectors and computational methods has implications for general radiation detection, imaging, and nuclear non-proliferation methods. The expertise accrued in the pursuit of dark matter will have a large impact on addressing challenges in other applied sciences. For example, in our ultracold (mK) searches we observe unexpected backgrounds that are likely also an issue for modern quantum engineering (computing). Further, dark matter experiments often use target materials with unique properties and under extreme conditions. This can lead to advancement in the understanding of materials (solid state crystals, noble liquids), and potential applications in manufacturing, electronics, nuclear detection, and others including quantum technologies such as transition edge sensors and similar. Dark Matter searches also provide an excellent training ground for young scientists. Students and postdocs are deeply involved in hardware and analysis, gaining experience in a wide range of topics such as vacuum technology, high voltage applications, electronics, mechanical engineering, DAQ, analysis, and machine learning to name only a few, leading to a very skilled workforce. Several key technologies used in LZ and XENON are employed beyond DM searches in other science areas (nuclear, neutrino), nuclear non-proliferation, and the nuclear industry.

Societal and knowledge transfer: The pursuit of dark matter has positive implications for society at large. The advancements in technology driven by the need for ultra-sensitive detectors contribute to the growth of the scientific and technological sectors, fostering innovation and creating job opportunities and economic growth. The public is generally very interested in dark matter searches, leading to an increased engagement in science and STEM fields. Outreach programs help improve scientific literacy and attract the next generation of researchers and engineers. The interdisciplinary nature of dark matter research necessitates collaboration between diverse scientific fields. Astrophysicists, particle physicists, and engineers converge to develop novel experimental techniques and theoretical frameworks. This interdisciplinary collaboration facilitates the transfer of knowledge across fields, enriching each one with insights and methodologies from the others. Our experiments in international collaboration lead to knowledge transfer also across borders and not only between different fields.

Operation and sustainability in the long term: Tesseract will expand dark matter searches using complementary signatures to sub-GeV and below. The experiment has made significant progress with a large part of the R&D, site settings, and governance being finalized and the physics readiness of the needed detectors demonstrated and published. We expect construction to start in 2025/2026. The effort is complementary to the leading Swiss effort in XENON/LZ/DARWIN/XLZD and is located in a favorable location, placing the Swiss DM community in an ideal position to play a leading role.

Recommendations and findings

Do you have a proposal of update:

Executive Summary Recommendation

Overall vision:

3.5 DARWIN/XLZD

Short description: DARWIN/XLZD will be a new observatory in astroparticle physics, with the aim to identify the nature of dark matter, to reveal the nature of neutrinos (via the search for the neutrinoless double beta decay of ^{136}Xe), to observe solar neutrinos via elastic neutrino-electron and coherent neutrino-nucleus scatters, as well as solar axions and axion-like particles. It will employ a time projection chamber (TPC) filled with liquid xenon (75 tons in total, 60 tons inside the TPC, in the nominal design), viewed by arrays of VUV-sensitive photosensors to detect both light and charge signals after a particle interacts with the xenon target. The TPC and its cryostat will be surrounded by a 12 m water Cherenkov shield, to veto interactions of cosmic muons and their secondary particles. A likely location of the observatory is Hall C of LNGS in Italy, however other locations (SURF in USA, an extensions of the Boulby Laboratory in the UK) are under consideration. The direct dark matter search via collisions of dark matter particles with atomic nuclei is highly complementary to indirect searches with AMS, CTA and IceCube and with direct dark matter production at the LHC, and many of the science channels complement independent experimental efforts in these areas by providing new information.

Involved PI: Laura Baudis, Ben Kilminster, Bjoern Penning.

Swiss participant Institutions: UZH.

Timeline: Construction: 2028-2032, Operations: 2032 - onward

Current state and remarkable highlights: 2020-2024: DARWIN, which has been founded and is currently lead by Swiss groups, is the successor of the very successful XENON program. In July 2021 the members of the DARWIN/XENON collaborations signed an MoU with the members of the LZ collaboration to form the XLZD consortium to design, construct, and operate a new, single, multi-ten-tonne scale xenon observatory and to exploit its science potential. DARWIN has received substantial R&D funding (e.g., 3 ERCs, as well as national funding), and thus conducts R&D and design towards the DARWIN/XLZD detector. The UZH group constructed Xenoscope, a large-scale liquid xenon platform, which houses a 2.6 m tall TPC. The facility operates with ∼400 kg of LXe and aims to demonstrate electron drift over a 2.6 m distance. The TPC, equipped with a top SiPM array, will also allow to study the drift field- and purity-dependent electron cloud transport, particularly the transverse and longitudinal diffusion coefficients, as well as the LXe optical properties. Xenoscope is available to the DARWIN/XLZD collaboration for various R&D projects related to the realisation of a large-scale xenon TPCs.

Objectives 2020-2032: Presently the XLZD consortium is in the process of forming a collaboration. The design and R&D for the detector and its associated systems is ongoing, with a Design Book in final stages of preparation.

Impact:

Scientific: The advances in liquid xenon detectors, presented in this document for XENONnT and LZ, opened the possibility to construct and operate an observatory for several extremely rare processes with far-reaching impact for particle physics, astrophysics, and associated fields [A+23a]. Such a detector is ideal for probing some of the most popular dark matter models, with a discovery potential, allowing for the characterisation of the particle nature of galactic dark matter. In particular, such a detector will test the WIMP paradigm. The same detector can also search for neutrinoless double-beta decay of ^{136}Xe to determine if the neutrino is its own antiparticle, i.e., a Majorana particle. It can also function as an observatory for several astrophysical neutrino sources, including solar pp and ^{8}B neutrinos, atmospheric neutrinos, and neutrinos from a galactic supernova explosion.

As the 'definitive' WIMP discovery instrument, the DARWIN/XLZD experiment will reach into the neutrino fog [O'H21], where its discovery potential becomes systematically limited by CEvNS. Thus, it will deliver an order of magnitude increase in sensitivity and discovery capability compared to current experiments. In this mode, where nuclear recoils are the expected energy deposition from a signal, non-neutrino background event rates are maintained at the order of a single event expected within the entire exposure. The expected reach into the neutrino fog predicts more than one coherent elastic neutrino-nucleus scatter. The other backgrounds arise from neutrons, which can reduced by low-background material selection, vetoed using the outer detector volumes, and discriminated against with potential multiple scatterings inside the detector. In addition, leakage from more electronic recoilbackgrounds into the nuclear recoil signal region will need to be controlled. With adequate suppression of ^{222}Rn and other target-intrinsic radioactive impurities, the processes dominating electron recoils will be those from solar (mostly pp) neutrinos scattering off electrons and naturally occurring ^{136}Xe in the LXe. To be the definitive xenon experiment limited by irreducible backgrounds, the detector must be capable of running up to a 1000 t·y exposure without becoming limited by backgrounds from radioactive impurities.

The DARWIN/XLZD detector will be a prime observatory for low-energy, MeV-scale, astrophysical neutrinos through nuclear and electronic recoil signatures of a few keV of energy. Primarily, several solar neutrino flux components can be measured. The XENONnT experiment observed for the first time solar neutrinos through coherent elastic neutrino-nucleus scattering (CEνNS) [Fre74], from ^{8}B neutrinos. In such a channel, the DARWIN/XLZD detector expects an event rate of $\sim$ 90 events per tonne-year above a threshold of 1 keV$_{\rm nr}$ [BFK+14, A+16a], providing an independent measurement of the neutral component of the solar ^{8}B neutrino flux. In addition, by combining this measurement with neutrino-electron scattering data from other neutrino detectors, DARWIN/XLZD aims to constrain the ν_e survival probability in this energy range. The most critical background for this measurement comes from accidental coincidences (ACs), spurious events created by the incorrect pairing of detector signals.

Regarding ER signals from solar neutrinos, DARWIN/XLZD aims to measure the pp solar neutrino spectrum via neutrino-electron scattering [A+20a], improving the measurement of the neutrino luminosity of the Sun. Furthermore, a high-statistics measurement of the solar pp neutrino flux in will enable a direct measurement of the oscillation probability of the electron-type neutrinos emitted from the Sun in an energy range that is not accessible to any other experiment, as well as an independent measurement of the weak mixing angle, $\sin^2\theta_W$. With an exposure of 600 tonne-year DARWIN/XLZD will constrain the low-energy survival probability to 5%. Such a measurement would test models of neutrino oscillations and probe exotic neutrino properties and non-standard interactions.

XENONnT already participates in the supernova early warning system (SNEWS) network [AK+21, K+24], which prepares and provides an early warning system for galactic SN to facilitate the observation of optical counterparts. DARWIN/XLZD will also be part of SNEWS and will increase the reach to SN neutrinos beyond the Small Magellanic Cloud. Next-generation Xe-TPCs will also start constraining the diffuse supernova background (DSNB). Understanding core-collapse SN depends on probing the DSNB with all neutrino flavours, and currently only upper limits on the $\nu_e, \bar{\nu}_e$ flux the SNO and Super-Kamiokande experiments exist, around $19\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $2.7\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, respectively. Limits on the fluxes of $\nu_{\mu,\tau}, \bar{\nu}_{\mu,\tau}$ are much weaker, around $10^3\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, and a large xenon detector could improve these by about a factor of 100. While this would help in constraining SN models, the actual detection of the DSNB remains challenging, even with a 1000 t y exposure [SBT22].

Swiss involvement Professor and CHIPP board member, Laura Baudis of the University of Zurich was a founding member of DARWIN in 2010 and served as the project coordinator until 2018. Since 2019, Laura Baudis is the DARWIN spokesperson, and currently she co-leads the Steering Committee of XLZD. UZH has been a leading member of DARWIN since 2010, with UZH scientists leading the working groups Science and Sensitivity, and Detector. The group has made leading contributions to the R&D and design for the TPCs, the photosensors, including material radio-assay. Currently the group operates Xenoscope, which houses a 2.6 m tall TPC, which is at the scale of DARWIN/XLZD, in a 3.5 m tall cryostat. Professor Ben Kilminister is also a member of DARWIN, while Professor Bjoern Penning is a member of XLZD.

Swiss Investment level: Switzerland has supported DARWIN through investments from UZH, SNF project funds, and the SNF FLARE since 2010. These investments have supported the photosensors R&D and design of the TPC. The ERC advanced grant project Xenoscope supported the construction of the 2.6 m tall TPC and its associated systems. Xenoscope is also available as an R&D platform for the collaboration.

Economical and Technological, Societal and knowledge transfer: Instrumentation and technologies developed for DARWIN/XLZD, including the measurement of trace radioactivity levels in detector materials, find applications in other fields, as well as in the industry. As an example, two-phase Xe TPCs are developed for PET detectors [R+22], while material with ultra-low activity levels may be used in the quantum computing industry, since gamma radiation from materials surrounding the superconducting qubits can lead to quasi-particle poisoning and thus qubit decoherence [C+21, V+20]. The R&D projects including the large-scale TPCs operated at UZH offer an ideal training ground for early career researchers.

Operation and sustainability in the long term: The DARWIN/XLZD experiment will operate for at least 15 years. Apart from this, the relevant text is similar to the one for LZ and XENONnT.

4 Space-based experiments

Despite FLARE is not traditionally a funding measure for space-based experiment, we indicate the current experiments of interest on cosmic ray physics.
Project name: AMS-02/DAMPE/HERD
Short description: AMS-02: The largest magnetic spectrometer ever installed in space and the only one currently in operation [A+21b]. From its installation on the international space station (ISS) in 2011, it is the most precise cosmic-ray detector in the energy range from 0.5 GeV to few TeV (rigidity from 0.5 GV to 3 TV). It will continue its operation for the entire lifetime of ISS through 2030. DAMPE: The largest calorimeter-based space mission [Cha17]. Since its launch in 2015, it is taking data in excellent working conditions. Its acceptance is a factor of 3 than AMS-02, and is currently providing the most precise cosmic-ray measurements up to 100 TeV. Both the excellent hardware status and the significant scientific returns ensure that its operation will continue for 5—10 more years. HERD: The next-generation calorimeter-based space mission [Kyr22]. Thanks to its unprecedented acceptance (ten times that of DAMPE) and precision, it will extend the energy range of the direct cosmic-ray measurements beyond the PeV. HERD will be also able to perform a gamma-ray full-sky survey from 100 MeV to 100 TeV. HERD is a China-Europe mission that is currently in the final selection phase, and if adopted, will be installed on the China Space Station in around 2028.

Involved PI(s): Xin Wu (UNIGE), Andrii Tykhonov (UNIGE), Chiara Perrina (EPFL), Mercedes Paniccia (UNIGE).

Swiss participant Institutions: AMS (UNIGE):

1. Major hardware, software, and operation contributions:
   - Construction of the AMS silicon tracker.
   - Silicon tracker charge calibration, detector monitoring and operation, Machine Learning (ML) algorithms.
2. Major contributions to data analysis and publications: nuclei and isotopes spectra.

DAMPE (UNIGE, EPFL):

1. Major hardware, software and operation contributions:
   - Proposer and project leader of the DAMPE silicon tracker (STK).
   - DAMPE software framework, STK simulation, reconstruction and tracking software, ML algorithms for tracking, particle ID and energy correction.
   - STK monitoring, calibration, alignment, European Monte Carlo (MC) production.
2. Major contributions to data analysis and publications: protons, electrons plus positrons, nuclei, and gamma rays.

HERD (UNIGE, EPFL):
• Major hardware and software contributions: o Proposer and project leader of the HERD scintillating-fiber tracker (FIT). o FIT reconstruction software. o ML algorithms for data reconstruction and analysis, hadronic model tuning. o MC studies to estimate the HERD sensitivity to a gamma-ray flux from dark-matter annihilation.

TimeLine 2018-2032 [highlight changes since roadmap] AMS-02: operation and data analysis, upgrade in 2025 to increase the detector acceptance by 300DAMPE: operation and data analysis HERD: • Up to launch (2028): detector construction and space qualification, on-ground tests of detector prototypes with particle beams, software development and data analysis preparation, detector sensitivity studies with MC simulations. • After launch: commissioning followed by data analysis.

Objectives 2020-2032: Precise measurements of cosmic ray particles, nuclei, and antiparticles spectra as function of rigidity from 0.5 GV to 3 TV (AMS); first observation of antinuclei in cosmic rays; indirect dark-matter detection through observation of characteristic features in particle and antiparticle fluxes; first measurements of light isotope fluxes up to 12 GeV/n (AMS); first measurements of individual spectra of sub-Fe elements up to 3 TV (AMS); further extension of cosmic-ray spectra to a few hundred TeV (DAMPE) and beyond PeV (HERD); gamma-ray astronomy and search for dark-matter signatures in the diffuse gamma-ray flux (DAMPE and HERD); measurement of proton and nuclei inelastic-scattering cross sections from tens of GeV to a few PeV.

Impact:

Scientific: The direct detection of cosmic rays in space up to the PeV scale is the only key to understand the origin of the most energetic processes in the Galaxy. The first observation of antinuclei in cosmic rays with AMS-02 would establish a genuine probe of matter-antimatter asymmetry in the Galaxy and provide a clean channel for dark-matter detection. A relatively small contribution of astrophysical sources in positron and antiproton fluxes (AMS-02), and electron flux beyond a TeV (DAMPE, HERD), allows to probe dark-matter annihilation or decay signals in the form of characteristic features (breaks) in cosmic ray spectra [DAM18, A^{+}19b]. Precise measurements of isotope fluxes of Li, Be and B, and the individual spectra of heavy secondary nuclei in the sub-Fe group will provide missing information for understanding the cosmic-ray propagation in our Galaxy, crucial to clearly assess the background for searches of signals from dark matter and primordial antimatter. The unprecedented energy resolution of DAMPE and HERD allows pinpointing smoking-gun dark matter signals in diffuse gamma rays, up to 100 TeV [DAM22b]. The broad science program is made possible thanks to the new technology developments: the FIT subdetector of HERD, with the initial concept originating from the LHCb tracker design, will be used in space for the first time to replace conventional expensive silicon-based trackers [P^{+}21]. Moreover, recent developments in Artificial intelligence (AI) and Machine Learning with DAMPE and HERD open new scientific opportunities [T^{+}23]. They enable an order-of-magnitude enhancement in the accuracy of cosmic ray identification and facilitate measurement of hadronic cross sections, complementary to ground-beam experiments.

Economical and Technological, societal and knowledge transfer: instruments and techniques developed for space astroparticle experiments find their industrial application. As an example, a technology transfer project was established at UNIGE in cooperation with Detection Technology Plc, Finland. It is aimed at developing advanced simulations and new instrument designs for X-ray imaging detectors, based on the techniques established by UNIGE for the DAMPE experiment [TWS23].

Current state and remarkable highlights: 2020-2024: AMS-02 made a major progress discovering that while all the spectra of nuclei measured so far harden around 200 GV, both primaries and secondaries exhibit two distinct classes of spectral shapes: the light He-C-O and the intermediate-mass Ne-Mg-Si-S primary classes, and the Li-Be-B and intermediate-mass F secondary classes [A^{+}21b, A^{+}23d, A^{+}21d, A^{+}21c]. Fe belongs to the light He-C-O class. Secondary nuclei spectra harden about twice more than those of their primary progenitor, pointing to a propagation origin of the spectral hardening. Puzzlingly, light secondary-to-primary flux ratios, as B/O, differ from the intermediate-mass secondary-to-primary ratio F/Si. Recent DAMPE results on the helium spectrum confirm the hardening structure previously observed by AMS-02 and reveal for the first time a spectral softening at about 30 TeV [A^{+}21e]. Moreover, for the first time, a hint of spectral hardening at about 150 TeV is observed by DAMPE [A^{+}24c]. A remarkable hardening in B/C and B/O secondary-to-primary ratios at 100 TeV/n, previously indicated by AMS-02, was detected by DAMPE in 2022 with more than 5σ significance [DAM22a]. Finally, DAMPE puts the most stringent constraint on the isothermal dark-matter annihilation rate at 10 GeV, with gamma rays [DAM22b].

Operation and sustainability in the long term, vision for the future: AMS-02 will collect data to achieve precision measurements of individual rigidity spectra of rare heavy secondary nuclei in the sub-Fe group up to 1 TV; with the tracker upgrade it will collect sufficient data to extend measurements of rare nuclei fluxes to 3 TV, positron flux to 2 TeV, and electron flux to 3 TeV. DAMPE and HERD will directly probe cosmic-nuclei spectra towards the PeV frontier, and electrons up to 100 TeV. HERD will perform multi-messenger physics with gamma rays from a few GeV to 100 TeV.

Project name: NeUtrino and Seismic Electromagnetic Signals (NUSES) mission Short description: NUSES is a project financed by the Italian Ministry for cooperation of academia and industry for the development of new space-based technologies. It will foster a new concept of tray for middle-size satellites in collaboration with THALES and mitigation strategies for materials exposed to the effect of radiations like photosensing surfaces. The scientific scopes are the detection for the first time of the Cherenkov light produced by cosmic neutrinos and cosmic protons and heavier ionized nuclei in the poorly explored energy range beyond 100 PeV; Monitoring of low energy (<250 MeV) CR fluxes to study Van Allen belts; space weather and lithosphere-ionosphere-magnetosphere couplings. - Detection of 0.1 MeV–10 MeV photons for the study of transient and steady gamma sources.

Vision for the future: The UNIGE group also involved in CTAO sees this technology as the potential future of multi-messenger high-energy neutrino and cosmic ray astrophysics in space. UNIGE designed the telescope payload

on board NUSES, built the camera in collaboration with FBK for the silicon photosensors, simulated the full detector and its response and defines the readout out chain and analysis. The launch should be in 2026.
Involved PI: T. Montaruli (UNIGE).

References

[A+07] J. Albert et al. Variable very high energy γ-ray emission from markarian 501. *The Astrophysical Journal*, 669(2):862, nov 2007.

[A+13a] M. G. Aartsen et al. Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector. *Science*, 342:1242856, 2013.

[A+13b] H. Anderhub et al. Design and Operation of FACT – The First G-APD Cherenkov Telescope. *JINST*, 8:P06008, 2013.

[A+16a] J. Aalbers et al. DARWIN: towards the ultimate dark matter detector. *JCAP*, 11:017, 2016.

[A+16b] S. Ansoldi et al. Teraelectronvolt pulsed emission from the Crab Pulsar detected by MAGIC. *Astronomy and Astroophysics*, 585:A133, January 2016.

[A+18a] M. G. Aartsen et al. Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. *Science*, 361(6398):eaat1378, 2018.

[A+18b] M. G. Aartsen et al. Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert. *Science*, 361(6398):147–151, 2018.

[A+19a] V. A. Acciari et al. Constraints on gamma-ray and neutrino emission from ngc 1068 with the magic telescopes. *The Astrophysical Journal*, 883(2):135, sep 2019.

[A+19b] M. Aguilar et al. Towards understanding the origin of cosmic-ray positrons. *Phys. Rev. Lett.*, 122:041102, Jan 2019.

[A+19c] E. Aprile et al. Observation of two-neutrino double electron capture in ^{124}Xe with XENON1T. *Nature*, 568(7753):532–535, 2019.

[A+20a] J. Aalbers et al. Solar neutrino detection sensitivity in DARWIN via electron scattering. *Eur. Phys. J. C*, 80(12):1133, 2020.

[A+20b] M. G. Aartsen et al. Combined sensitivity to the neutrino mass ordering with JUNO, the IceCube Upgrade, and PINGU. *Phys. Rev. D*, 101(3):032006, 2020.

[A+21a] M. G. Aartsen et al. Detection of a particle shower at the Glashow resonance with IceCube. *Nature*, 591(7849):220–224, 2021. [Erratum: Nature 592, E11 (2021)].

[A+21b] M. Aguilar et al. The alpha magnetic spectrometer (ams) on the international space station: Part ii — results from the first seven years. *Physics Reports*, 894:1–116, 2021.

[A+21c] M. Aguilar et al. Properties of a new group of cosmic nuclei: Results from the alpha magnetic spectrometer on sodium, aluminum, and nitrogen. *Phys. Rev. Lett.*, 127:021101, Jul 2021.

[A+21d] M. Aguilar et al. Properties of heavy secondary fluorine cosmic rays: Results from the alpha magnetic spectrometer. *Phys. Rev. Lett.*, 126:081102, Feb 2021.

[A+21e] F. Alemanno et al. Measurement of the cosmic ray helium energy spectrum from 70 GeV to 80 TeV with the DAMPE space mission. 5 2021.

[A+22a] R. Abbasi et al. Evidence for neutrino emission from the nearby active galaxy NGC 1068. *Science*, 378(6619):538–543, 2022.

[A+22b] V. A. Acciari et al. Proton acceleration in thermonuclear nova explosions revealed by gamma rays. *Nature Astronomy*, 6:689–697, April 2022.

[A+22c] V.A. Acciari et al. Combined searches for dark matter in dwarf spheroidal galaxies observed with the magic telescopes, including new data from coma berenices and draco. *Physics of the Dark Universe*, 35:100912, 2022.

[A+22d] E. Aprile et al. Double-Weak Decays of ^{124}Xe and ^{136}Xe in the XENON1T and XENONnT Experiments. *Phys. Rev. C*, 106(2):024328, 2022.

[A+22e] E. Aprile et al. Search for New Physics in Electronic Recoil Data from XENONnT. *Phys. Rev. Lett.*, 129(16):161805, 2022.

[A+23a] J. Aalbers et al. A next-generation liquid xenon observatory for dark matter and neutrino physics. *J. Phys. G*, 50(1):013001, 2023.

[A+23b] R. Abbasi et al. Observation of high-energy neutrinos from the galactic plane. *Science*, 380(6652):1338–1343, June 2023.

[A+23c] H. Abe et al. Performance of the joint lst-1 and magic observations evaluated with crab nebula data. *Astronomy and Astrophysics*, 680:A66, December 2023.

[A+23d] M. Aguilar et al. Properties of cosmic-ray sulfur and determination of the composition of primary cosmic-ray carbon, neon, magnesium, and sulfur: Ten-year results from the alpha magnetic spectrometer. *Phys. Rev. Lett.*, 130:211002, May 2023.

[A+23e] E. Aprile et al. First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment. *Phys. Rev. Lett.*, 131(4):041003, 2023.

[A+24a] R. Abbasi et al. Observation of seven astrophysical tau neutrino candidates with icecube. *Phys. Rev. Lett.*, 132:151001, Apr 2024.

[A+24b] S. Abe et al. Performance and first measurements of the magic stellar intensity interferometer. *Monthly Notices of the Royal Astronomical Society*, 529(4):4387–4404, March 2024.

[A+24c] F. Alemanno et al. Measurement of the cosmic p+He energy spectrum from 50 GeV to 0.5 PeV with the DAMPE space mission. *Phys. Rev. D*, 109(12):L121101, 2024.

[A+24d] E. Aprile et al. The XENONnT Dark Matter Experiment. *Eur. Phys. J. C*, 2 2024.

[AK+21] S. Al Kharusi et al. SNEWS 2.0: a next-generation supernova early warning system for multi-messenger astronomy. *New J. Phys.*, 23(3):031201, 2021.

[BFK+14] L. Baudis, A. Ferella, A. Kish, A. Manalaysay, T. Marrodan Undagoitia, and M. Schumann. Neutrino physics with multi-ton scale liquid xenon detectors. *JCAP*, 01:044, 2014.

[C+21] Laura Cardani et al. Reducing the impact of radioactivity on quantum circuits in a deep-underground facility. *Nature Commun.*, 12(1):2733, 2021.

[CA+19] Cherenkov Telescope Array Consortium, B. S. Acharya, et al. *Science with the Cherenkov Telescope Array.* 2019.

[CA+24] MAGIC Collaboration, S. Abe, et al. Constraints on lorentz invariance violation from the extraordinary mrk 421 flare of 2014 using a novel analysis method, 2024.

[CAB+22] Juan Cortina, V. A. Acciari, A. Biland, E. Colombo, C. da Costa, C. Delgado, C. Díaz, M. Fiori, D. Fink, T. Hassan, I. Jiménez-Martínez, E. Lyard, M. Mariotti, G. Martínez, R. Mirzoyan, G. Naletto, M. Polo, N. Produit, J. J. Rodríguez, T. Schweizer, R. Walter, C. W. Wunderlich, and L. Zampieri. First measurements and upgrade plans of the MAGIC intensity interferometer. In Antoine Mérand, Stephanie Sallum, and Joel Sanchez-Bermudez, editors, *Optical and Infrared Interferometry and Imaging VIII*, volume 12183 of *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, page 121830C, August 2022.

[Cha17] Chang, J. and others, the DAMPE collaboration. The DArk Matter Particle Explorer mission. *Astropart. Phys.*, 95:6–24, 2017.

[Col23] The CTAO-CH Collaboration. White Paper on the Swiss Participation to CTAO and perspectives, 2023. .

[Col24a] The CTAO Science Collaboration. The next-generation high-energy discovery machines, 2024. Web Pages .

[Col24b] The MAGIC Collaboration. The MAGIC Telescopes, 2024. Web Pages .

[Com21] The Swiss Particle Physics Community. *CHIPP Roadmap for Research and Infrastructure 2025-2028 and beyond.* 2021.

[DAM18] DAMPE collaboration. Direct detection of a break in the teraelectronvolt cosmic-ray spectrum of electrons and positrons. *Nature*, 552:63–66, 2018.

[DAM22a] DAMPE collaboration. Detection of spectral hardenings in cosmic-ray boron-to-carbon and boron-to-oxygen flux ratios with DAMPE. *Sci. Bull.*, 67:2162–2166, 2022.

[DAM22b] DAMPE collaboration. Search for gamma-ray spectral lines with the DArk Matter Particle Explorer. *Sci. Bull.*, 67:679–684, 2022.

[Fre74] Daniel Z. Freedman. Coherent Neutrino Nucleus Scattering as a Probe of the Weak Neutral Current. *Phys. Rev. D*, 9:1389–1392, 1974.

[H^+23] Matthieu Heller et al. The next generation cameras for the Large-Sized Telescopes of the Cherenkov Telescope Array Observatory. *PoS*, ICRC2023:740, 2023.

[HSP^+17] M. Heller, E. jr Schioppa, A. Porcelli, I. Troyano Pujadas, K. Ziętara, D. della Volpe, T. Montaruli, F. Cadoux, Y. Favre, J. A. Aguilar, A. Christov, E. Prandini, P. Rajda, M. Rameez, W. Bilnik, J. Błocki, L. Bogacz, J. Borkowski, T. Bulik, A. Frankowski, M. Grudzińska, B. Idźkowski, M. Jamrozy, M. Janiak, J. Kasperek, K. Lalik, E. Lyard, E. Mach, D. Mandat, A. Marszałek, L. D. Medina Miranda, J. Michałowski, R. Moderski, A. Neronov, J. Niemiec, M. Ostrowski, P. Paśko, M. Pech, P. Schovanek, K. Seweryn, V. Sliusar, K. Skowron, Ł. Stawarz, M. Stodulska, M. Stodulski, R. Walter, M. Więcek, and A. Zagdański. An innovative silicon photomultiplier digitizing camera for gamma-ray astronomy. *The European Physical Journal C*, 77(1):47, 2017.

[K^+24] M. Kara et al. The SNEWS 2.0 Alert Software for the Coincident Detection of Neutrinos from Core-Collapse Supernovae. 6 2024.

[Kyr22] Dimitrios Kyratzis. Overview of the HERD space mission. *Phys. Scripta*, 97(5):054010, 2022.

[MA^+19] MAGIC Collaboration, V. A. Acciari, et al. Observation of inverse Compton emission from a long γ-ray burst. *Nature*, 575(7783):459–463, November 2019.

[OAB^+19] Igor Oya, Elisa Antolini, Leonardo Baroncelli, Jerzy Borkowski, Andrea Bulgarelli, Alessandro Carosi, Josep Colome, Vito Conforti, Matthias Fuessling, Clemens Hoischen, Jean Jacquemier, Etienne Lyard, Gilles Maurin, David Melkumyan, Klemens Mosshammer, Nicolò Parmiggiani, Iftach Sadeh, Torsten Schmidt, Ullrich Schwanke, Joseph Schwarz, Gino Tosti, Roland Walter, and Peter Wegner. The Array Control and Data Acquisition System of the Cherenkov Telescope Array. In *17th International Conference on Accelerator and Large Experimental Physics Control Systems*, page WEMPR005, New York, United States, October 2019.

[O'H21] Ciaran A. J. O'Hare. New Definition of the Neutrino Floor for Direct Dark Matter Searches. *Phys. Rev. Lett.*, 127(25):251802, 2021.

[P^+21] C. Perrina et al. FIT: the scintillating fiber tracker of the HERD space mission. *PoS*, ICRC2021:060, 2021.

[R^+22] J. Renner et al. Monte Carlo characterization of PETALO, a full-body liquid xenon-based PET detector. *JINST*, 17(05):P05044, 2022.

[SBT22] Anna M. Suliga, John F. Beacom, and Irene Tamborra. Towards probing the diffuse supernova neutrino background in all flavors. *Physical Review D*, 105(4), February 2022.

[SWL^+17] V. Sliusar, R. Walter, E. Lyard, A. Neronov, C. Alispach, I. Al Samarai, F. Cadoux, V. Coco, D. della Volpe, Y. Favre, M. Heller, T. Montaruli, T. R. Njoh Ekoume, I. Troyano Pujadas, P. Pasko, K. Seweryn, D. Mandat, M. Pech, P. Schovanek, A. Frankowski, M. Janiak, R. Moderski, T. Bulik, M. Grudzinska, M. Jamrozy, M. Ostrowski, L. Stawarz, A. Zagdanski, K. Zietara, W. Bilnik, J. Kasperek, K. Lalik, P. Rajda, M. Wiecek, J. Blocki, E. Mach, J. Michalowski, J. Niemiec, J. Rafalski, K. Skowron, M. Stodulska, and M. Stodulski. Control Software for the SST-1M Small-Size Telescope prototype for the Cherenkov Telescope Array. In *35th International Cosmic Ray Conference (ICRC2017)*, volume 301 of *International Cosmic Ray Conference*, page 844, July 2017.

[T^+23] Andrii Tykhonov et al. A deep learning method for the trajectory reconstruction of cosmic rays with the DAMPE mission. *Astropart. Phys.*, 146:102795, 2023.

[Tel24] Einstein Telescope. A new window on the Universe, 2024. Web Pages .

[TWS23] Andrii Tykhonov, Alexander Winkler, and Volodymyr Smoliar. GEANT4 simulation and spectrum restoration of a pixelated X-ray detector. *JINST*, 18(04):T04007, 2023.

[V^+20] Antti Vepsäläinen et al. Impact of ionizing radiation on superconducting qubit coherence. *Nature*, 584(7822):551–556, 2020.