IPP Brief to the 2025-2026 Long Range Planning Committee

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1 Executive Summary

Particle physics in Canada is an extraordinary success story, with critical national contributions to some of the most pressing questions in physics today. Canadians are currently at the forefront of experiments both locally and throughout the world, and are developing techniques, instruments, and machine learning algorithms to further enhance our understanding of the world of the most elementary particles. Canada boasts laboratories with unique capabilities, an outstanding community of researchers and a pool of eager young researchers ready to tackle the open questions in the field. The community's success was most dramatically highlighted when ten years ago Art McDonald won the Nobel prize with Takaaki Kajita for the discovery of neutrino oscillations at SNOLAB, and thirteen years ago when Peter Higgs and François Englert were awarded the Nobel prize for the prediction of the Higgs boson, discovered at the LHC in 2012. These current successes have helped to build a framework of support for particle physics that has enabled the development of Canadian leadership in a diverse set of experiments deploying a range of detector technologies. Many of these new technologies are now at a point where significant investment is required. This long range planning process aims to guide the community towards maximal impact and very high Canadian visibility.

The large-scale projects on the threshold of seeking infrastructure funding will only be successful if the community support is sufficient and adquate funding can be secured. Four possible funding scenarios are discussed here to frame the opportunities Canada can realize. These should be taken as guidance when evaluating the details of the experimental descriptions that follow, and are further elaborated in Section 11.

If the *current funding level* is maintained, Canada will continue losing touch with international leaders and Canadian research capacity will decrease [6], [10], [11]. In such a scenario, Canada can hope to minimally support CERN based activities under the assumption that nearly all Canadian collider physicists collaborate to maintain a visible impact. For astroparticle physics, the current level of support makes attracting a leading next-generation experiment in the field of double beta decay or dark matter to SNOLAB difficult, if not impossible. The global leadership position that P-ONE offers will also be difficult to realize within the current framework of funding. In this scenario, Canadian researchers, especially in astroparticle physics, could soon be expected to have to join Chinese efforts to keep up. A small amount of the impact of this loss of capacity can be mitigated by organizing the field to maximize impact of the remaining projects in the *structured decline* scenario and by additional investments in infrastructure and support of the existing institutes. Such a scenario will require terminating successful projects in order to maintain critical mass for core projects.

To realize the many opportunities that are ahead in particle physics, the *leadership* scenario that comes with added funding as well as a structural evolution of the funding landscape is required. In such a scenario it would be likely that the CERN based program will see significant Canadian leadership both in the technological developments towards the next generation of accelerators and detectors [1] [4], and the cutting edge analysis and machine learning algorithms that enable progress in the field. Furthermore, on Canadian soil high energy neutrino detection in the ocean will see Canadian leadership solidify in a large array of underwater detectors for P-ONE, driving technological developments for deep ocean access. SNOLAB will be empowered to build its impressive portfolio into the next generation by hosting a large new experiment with technological leadership and very high international relevance. Overall, Canada will be enabled to show that its national research sovereignty can not be easily compromised, building on the existing strength in HQP training and enhancing and renewing the particle physics education at Canadian universities.

The *optimal* scenario [6] builds on the leadership scenario, utilizing improved cooperation between funding agencies, explicitly empowered national laboratories (TRIUMF, PI, SNOLAB, ONC, CERN, via a formal membership) and a university framework that is programmed for growth in the natural sciences in general and particle physics in particular. The CFI IF program is grown into an opportunity to foster development of large international projects with decadal timelines supporting projects with O($100M) Canadian funding horizon. The subatomic envelope grows to allow existing faculty to live up to their ability to supervise students and to attract outstanding national candidates into the field. The level of funding available also energizes Canadian universities to invest in a sustained growth of particle physics. In this scenario, a national institution similar to other highly impactful national organizations (NIKHEF [14] in the Netherlands, INFN [15] [16] in Italy and CNRS/IN2P3 [17] in France) would combine distributed efforts from IPP, CINP and possibly the McDonald Institute into a new national institute with a long term funding perspective and clear mandate to represent Canada internationally.

The IPP community strongly urges all decision makers and university leaders to support a framework that will allow Canada to remain relevant in this technology- and knowledge-driven research field. The "*current funding level*" and the "*structured decline*" scenarios are guaranteed to damage this field of historic strength instead of building on the opportunities that were carefully created in the past decades. Now is an excellent time to capitalize on the investments already made and build Canadian leadership.

2 Introduction

Particle physics is is reaching a critical turning point. The Standard Model is complete, and with minor modifications to accommodate neutrino oscillation, has passed all major experimental tests. And yet open questions in dark matter, the antimatter asymmetry, naturalness, and more all suggest that physics beyond the Standard Model must exist. Many precision measurements and searches to address these tensions are underway, and insights from new facilities such as the HL-LHC and its successor, from B-factories, from neutrino experiments, dark matter detectors, and precision-designed smaller-scale experiments are eagerly awaited. All of this experimental work rests on a foundation built on advances in particle theory, requiring continued advances in predictions in both Standard Model precision and in BSM models.

2.1 Subatomic Physics in Canada

The Canadian subatomic physics (SAP) community is actively involved in a wide range of scientific programs, including **collider physics**, **medium-energy experiments**, **underground/low background experiments**, **accelerator physics**, **neutrino physics** and **nuclear physics**. It is engaged in current and future research endeavours having substantial overlap with those of the European particle physics community. The subatomic physics community in Canada is fully engaged in a number of detector development activities for both accelerator and non-accelerator experiments in Europe, North America and Japan.

The community, which includes accelerator physicists, is also involved in high energy accelerator research that includes collider technology development such as superconductive cavities, high intensity beams, automatic beam tuning and beam instrumentation for colliders located at CERN, KEK and BNL, as well as R&D work for other accelerator technologies with applications for nuclear and neutrino physics with facilities at CERN, TRIUMF, FNAL, BNL, and KEK/J-PARC. TRIUMF is also collaborating with DESY and HZDR on electron accelerator technologies and with GSI on heavy ion accelerator systems and beam physics.

Canada is well-positioned to play a major role in the future development of the field, hosting the Perimeter Institute for Theoretical Physics (PI) in Waterloo, Ontario, and two world-class experimental facilities: SNOLAB deep underground laboratory in Sudbury, Ontario, and TRIUMF, Canada's particle accelerator centre in Vancouver, British Columbia. The Canadian community pursues projects at these domestic facilities while also making strategic investments in international laboratories that provide world-leading and complementary infrastructure. Recently another CFI MSI funded laboratory, Ocean Networks Canada (ONC) also started to host particle physics with its unique digital under water infrastructure.

The Canadian subatomic physics community consists of approximately 250 investigators, of which approximately 25% are theorists [2]. The research profile of the Canadian community has evolved over the past two decades to reflect progress and opportunities in the field. The changing research trends within the community over the past 20 years—such as an increased focus on neutrino properties and searches for dark matter—align with global trends and leverage the presence of SNOLAB in Canada. Experimental collider physics represents a significant research focus for approximately 25% of the subatomic physics community members.

3 Goals

This brief is the principal input from the particle physics community to the Long Range Planning committee for the long range planning period from 2027 to 2034. This brief aims to give a status update of the projects with significant Canadian interest currently underway. It describes the status of the Canadian theory community. It will try to identify the major projects that are expected to dominate the landscape in the 2027 to 2034 time frame. This brief also advocates for changes to the funding framework underpinning the particle physics activities in Canada in order to prepare for the challenges expected arrive in that time frame. This involves significant changes to the interactions and the mandate of our funding agencies to align better with both international expectations and national capacities. Finally, this brief will strongly advocate to maintain and expand national investment in particle physics through both continued investment in facilities (TRIUMF, SNOLAB, ONC, Perimeter Institute, McDonald Institute), infrastructure (CFI) and people (NSERC discovery grant subatomic envelope).

4 Structural Limitations of Canadian Subatomic Physics

4.1 Canadian Funding Agencies and Mandate

Subatomic Physics Individual and Project Discovery, Research Tools and Instruments (SAP-RTI), and Major Resources Support (SAP-MRS) grant applications are evaluated together by the Subatomic Physics Evaluation Section (SAPES). This comprehensive approach is essential given the complexity and inter-dependency of many proposals, which are often linked to international programs and collaborations, and may involve many universities and national laboratories. This approach is also essential for the planning and stability of execution of large-scale and long-term projects, and for maintaining a balance between large projects and the smaller research efforts that are essential to the breadth and future success of the Canadian subatomic physics program.

Despite the increased budget of the SAPES envelope in past years, it has been challenging for the SAPES to financially support the community's short- and long-term objectives at an appropriate and competitive level to ensure the maximum scientific return on investments already made. This is partially due to the internationally recognized excellence of Canadian SAP research leading to increased responsibilities in both national and international experimental projects. The success of the subatomic community in securing infrastructure funding through the Canada Foundation for Innovation (CFI) has also led to increasing demands on the SAPES envelope for operational funds [3].

All Canadian funding agencies are proposal driven, providing no active management of the portfolio of existing projects by the funding agencies.

4.2 Infrastructure Support

Support through TRIUMF, SNOLAB, MacDonald Institute, Perimeter, the Digital Research Alliance and the several subatomic MRS grants is available for projects of all sizes. The large projects currently in the planning phase will need to have certainty that this support will be aligned with their projects.

5 Theoretical Particle Physics

Theoretical particle physicists build consistent mathematical descriptions of the fundamental components of the Universe. Such descriptions are essential to understanding experimental data and observations, and they guide new experimental searches. Developments in particle theory are also valuable in their own right, revealing new and surprising connections between seemingly unrelated phenomena or research disciplines. The overall takeaway from this section should be *breadth*: at its best, theory work brings expertise in from many different directions to rapidly progress on new and emerging ideas, to inform the experimental program, and to find new ways of looking at and understanding existing results. This cannot be done by focusing on a single idea or topic, but by bringing together a strong cast of theorists that are diverse along all axes.

Theorists in Canada work on a very wide range of topics and try to answer all of the "Big Questions" mentioned previously, from the dynamics of the strong force to the origin of dark matter to the nature of quantum gravity. The research product of the theory community is diverse and can include:

- **Precise predictions** for the Standard Model (SM) and beyond. These very challenging calculations are essential to testing the SM with experimental data and searching for new physics beyond it.

- **New theoretical methods** to better understand quantum field theory. The language of particle physics is quantum field theory, but this language is still being deciphered. Developments in quantum field theory enable more precise calculations in particle physics and other fields, and are of great mathematical interest in their own right.
- **New theories** that address deficiencies of the SM. Theories that go beyond the Standard Model (BSM) attempt to explain the mysteries and unresolved experimental shortcomings of the SM including the identity of dark matter, origin of neutrino masses and mixings, origin of the cosmic baryon asymmetry, nature of the electroweak symmetry breaking, the strong CP problem, as well as the dynamics behind dark energy.
- **Proposals for new experiments and techniques**. Theories that extend the SM often predict new signals that motivate novel search techniques at existing experiments and new experimental approaches in the future. In many cases, theorists are helping to drive the next generation of experiments as well as expand the scientific output of the current experimental program.
- **Complementary observational methods**. As the scale and cost of particle and astroparticle experiments grow, interest in complementary probes to search for new physics have also grown. This includes theoretical prediction of the effects on BSM microphysics on planets, stars, galaxies and large scale structure, often exploiting freely available data from astrophysics and cosmology.
- **Developments in quantum gravity**. A full quantum mechanical understanding of gravity is still in progress. Recent advances in the field have provided new insights into the nature of spacetime and cosmology as well as new connections with quantum information and computing.

High-energy theory, particle theory and cosmology have a well-established history in Canada, both at universities across the country, and at institutes including Perimeter and CITA. Recent years have seen strong growth in theory, especially in the direction of astroparticle theory. While the McDonald Institute contributed to a modest 3 new faculty positions in theory, recent hires at McGill, Carleton, McMaster, Toronto, SFU, York, Alberta and Montréal demonstrate substantial growth, supported by departments across the country. In contrast, the portion allocated to theory in the SAPES envelope has been flat at 13% since 2021, leading to pressure on the size of individual grants.

5.1 Emerging research directions

Theory research programs tend to be quite nimble, and theorists will typically tackle a portfolio of research directions with the ability to rapidly pivot towards exciting new directions as they emerge from theory or experiment. It is difficult to precisely predict where theoretical particle physics will head over the next decades, and so the best theory groups benefit form adaptability and versatility.

Current efforts (cosmology, dark matter, dark energy, neutrino properties, gravitational waves) will continue into the foreseeable future, but some directions that appear on the rise are listed below. This list is by no means exhaustive.

Exploiting new big data While collider physics started confronting large datasets over a decade ago, the advent of large-scale astrophysical surveys opens an opportunity to look for signatures of microphysical interactions on the largest scales. Surveys of supernovae and, large scale structure, 21cm cosmology, all promise incredible riches of data that may contain hints of new physics.

The quantum frontier As experiments get larger, and time scales get longer, theorists have been exploring methods of exploiting quantum mechanics as methods to overcome these limitations. Coherent enhancement of detector sensitivities yields much promise in the

Table 1: Theory members of IPP

Name	Institution	Subject	Name	Institution	Subject
Mohammad Ahmady	Mount Allison	hep-ph	Richard MacKenzie	Montréal	hep-ph, hep-th
Aleksandrs Aleksejevs	Memorial	hep-ph, hep-th	Alexander Maloney	McGill	hep-th
Svetlana Barkanova	Memorial	hep-ph, hep-th	Kim Maltman	York	hep-lat, hep-ph
Nikita Blinov	York	hep-ph	Rob Mann	Waterloo/PI	gr-qc, hep-th
Vincent Bouchard	Alberta	math-ph	Luc Marleau	Laval	hep-ph
Nassim Bozorgnia	Alberta	astro-ph, hep-ph	Pierre Mathieu	Laval	hep-th, math-ph
Joe Bramante	Queen's/PI	hep-ph	Ewan McDonough	Winnipeg	hep-th, astro-th, hep-ph
Robert Brandenberger	McGill	astro-ph, hep-th	David McKeen	TRIUMF	astro-ph, hep-ph
Alex Buchel	Western/PI	hep-th	Vladimir Miransky	Western	cond-mat
Cliff Burgess	McMaster/PI	gr-qc, hep-ph, hep-th	Nader Mobed	Regina	gr-qc, hep-th
Margaret Carrington	Brandon	hep-ph, hep-th	John Moffat	Waterloo/PI	gr-qc
James Cline	McGill	hep-ph	Gopolang Mohlabeng	SFU	hep-ph
Gilles Couture	UQAM	hep-ph	M. de Montigny	Alberta	gr-qc
David Curtin	Toronto	hep-ph	David Morrissey	TRIUMF	hep-ph
Andrzej Czarnecki	Alberta	hep-ph	Robert Myers	PI	hep-th
Keshav Dasgupta	McGill	hep-th	Rachid Ouyed	Calgary	astro-ph, nucl-th
Rainer Dick	Saskatchewan	hep-ph	Manu B. Paranjape	Montréal	cond-mat, gr-qc, hep-th
Jean-François Fortin	Laval	hep-th, hep-ph	AW Peet	Toronto	hep-th
Mariana Frank	Concordia	hep-ph	Alexander Penin	Alberta	hep-ph
Andrew Frey	Winnipeg	hep-th	Levon Pogosian	SFU	astro-ph
Steve Godfrey	Carleton	hep-ph	Erich Poppitz	Toronto	hep-th
Jaume Gomis	PI	hep-th	Maxim Pospelov	Victoria/PI	astro-ph, hep-ph
Thomas Gregoire	Carleton	hep-ph	Saeed Rastgoo	Alberta	gr-qc
Derek Harnett	Fraser Valley	hep-ph	Adam Ritz	Victoria	hep-ph
Seyda Ipek	Carleton	hep-ph, hep-th	Moshe Rozali	UBC	hep-th
Yonatan Kahn	Toronto	hep-ph	Ruben Sandapen	Acadia	hep-ph
Calvin Kalman	Concordia	ed-ph	Katelin Schutz	McGill	hep-ph
Pat Kalyniak	Carleton	hep-ph	Gordon Semenoff	UBC	cond-mat, hep-th
Joanna Karczmarek	UBC	hep-th	Kris Sigurdson	UBC	astro-ph
Gabriel Karl	Guelph	hep-ph	Rafael Sorkin	PI	gr-qc, hep-th
Achim Kempf	Waterloo/PI	gr-qc, quant-ph	Tom Steele	Saskatchewan	hep-ph
Nikolay Kolev	Regina	hep-ph	Daniel Stolarski	Carleton	hep-ph
Pavel Kovtun	Victoria	hep-th	Sean Tulin	York	astro-ph, hep-ph
Helmut Kroeger	Laval	hep-lat, hep-th	Mark Van Raamsdonk	UBC	hep-th
Gabor Kunstatter	Winnipeg	gr-qc, hep-th	Aaron Vincent	Queen's	astro-ph, hep-ph
Randy Lewis	York	hep-lat, hep-ph	Richard Woloshyn	TRIUMF	hep-lat
Heather Logan	Carleton	hep-ph	Yue Zhang	Carleton	hep-ph, astro-ph
Michael Luke	Toronto	hep-ph	Ariel Zhitnitsky	UBC	astro-ph, hep-ph

search for dark matter and neutrino properties, as well as in probing other new physics such as fifth-forces or (non-dark matter) dark photons and axion-like fields.

Quantum computing as a tool for discovery Other theorists see the growth of quantum computers as a potential tool to augment searches for new physics. The Canadian quantum information community has a strong complementary presence, so interdisciplinary collaboration has high potential.

Ultra high-energy astrophysics A surprising discovery in recent years has been the observation of galactic "Pevatrons", nearby regions that accelerate particles to produce gamma rays with some of the highest energies recorded. Truly understanding these extreme environments (pulsars, supernova shocks, novae) will require refined understanding of cosmic ray production and transport, involving plasma physics, nuclear physics and sophisticated computational efforts.

Thermal field theory Thermal field theory has long been a core component in understanding high-temperature, high-density systems such as heavy ion collisions or compact stellar objects. It is becoming increasingly apparent that these techniques are helpful in precision calculations of BSM physics searches using stars and early-Universe cosmology.

The Cosmic Frontier Much of particle cosmology has historically focused on high redshifts, focusing on the homogeneous early universe and perturbations going into the dark ages. New ideas, new computational technology, as well as a wealth of new and upcoming data about the Universe from cosmic dawn to today have enormously broadened the range of particle astrophysics and cosmology, with many themes emerging:

Dark Sectors – Multicomponent dark matter models, including dark matter, interactions, and possibly dark energy. Models with mixture of ultralight and heavy DM components (e.g. an ultralight axion and a heavy stable-ish scalar).

Non-thermal dark matter – production of DM from freeze-in, inflationary production (e.g. of Dark Photons), entropy dilution, other new mechanisms. These open up the mass range and parameter space.

Generalized axion DM – Ultralight dark matter beyond axions, and multicomponent axion dark matter scenarios. These lead to new observables.

The next big collider The next generation of collider, be it FCC or Muon Collider, will require large community buy-in. The Canadian particle theorists have the expertise necessary to help with this push. Joining forces with the international community will be essential in the push for one of these large experiments to be funded and built over the next decades.

5.2 Theory in support of experiment

Theoretical works are complementary to and support the experimental efforts in a number of ways. Theorists base their work on certain principles and often are driven by experimental findings to speculate on new, well-motivated theories and phenomena that will guide further searches. Theorists provide in-depth, precision calculations in the context of the Standard Model and beyond for understanding the expected background and signal rates in an experiment, and take existing analyses and recast them to cover much wider swaths of model space. Given the current broad program in search for new physics and the spirit of leaving no stones unturned, there is not a clear boundary between the theoretical and experimental approaches. Many theorists take on the role of exploring experimental data that are made public. Others propose novel experimental ideas and contribute as part of an experimental collaboration, with the goal of covering blind spot of existing searches.

5.3 Resources required

Resource requirements and availability for theory are very different from experiment, and theory programs live or die on Individual grants (the discovery-equivalent SAP-IN). These make up a majority of theory funding, with 30% of respondents stating that 100% of their funding is from this program. Theory expenses are mainly HQP, and PIs report needing between 100 and 250k$ per year to support the range of master's, PhD and PDFs necessary to tackle their research goals. Significant training is required to lead and direct theory projects, so postdocs are an invaluable resource, and act as force multipliers in terms of group productivity. Typical theory grants in Canada have a difficult time fully supporting even a fraction of a postdoc, so theory funding and independent theory postdoctoral scholarships are essential. Travel funds for HQP are extremely important, given how tight the job market is. A typical theory postdoc position will have several hundred qualified applicants. This large pool simultaneously represents an opportunity to recruit high-quality PhD scholars to Canada.

5.4 Training outcomes

Theory graduates from around Canada have taken up prestigious positions in both academia and industry. This includes placement in top Canadian and international graduate programs (Waterloo, Toronto, EPFL, Harvard, MIT, ...), named postdoctoral fellowships, and faculty positions in Canada (e.g. SFU), US (e.g. Harvard) and worldwide. Industry/government positions include Statistics Canada, government cybersecurity, quantum computing, data analytics and finance.

6 Core Projects

Table2 summarizes the full list of submissions to the IPP from the projects, including experimental self-assessments of impact and size.

6.1 Dark Matter Searches

The global search for dark matter elastic scattering via so-called direct detection experiments has a strong Canadian component, including science leadership and R&D for experiments located

Experiment	Self-Reported Impact	Duration	Size	Lifecycle
Dark Matter experiments				
GADM	Essential	15+ years	Medium	growth
PICO	Potential	5+ years	Small	steady
sCDMS	Impactful	5 years	Large	growth
SBC	Impactful	5+ years	Small	growth
SENSEI	Potential	5+ years	Small	growth
HeLiOS	Impactful	5+ years	Tiny	growth
XLZD	Essential	15+ years	Large (potential)	growth
Exotic physics searches				
MoEDAL	Impactful	15+ years	Tiny	growth
Mathusla	Essential	10+ years	Small	growth
DarkLight	Impactful	5 years	Small	steady
Cosmic Ray Physics				
Veritas	Winding down	5 years	Tiny	end
Accelerator based experiments				
ATLAS	Essential	15+ years	Dominant	steady
Belle	Essential	15+ years	Large	growth
FCC	Essential	15+ years	Dominant-huge (expected)	growth
Moeller	Impactful	5+ years	Small	growth
Pioneer	Essential	15+ years	Small	growth
Neutrino experiments (accelerator based)				
DUNE	Essential	15+ years	Small	growth
HyperK	Essential	15+ years	Large	growth
T2K	Essential	5 years	Tiny	end
Neutrino experiments (non-accelerator)				
SNO+	Essential	5+ years	Medium	steady
nEXO	Impactful	10+ years	Medium	growth
Theia	Essential	15+ years	Medium	growth
High Energy Neutrinos	Essential	15+ years	Medium	growth
Ricochet	Potential	15+ years	Tiny	growth
HALO	Impactful	15+ years	Tiny	steady
Other experiments and topics				
Accelerator Physics		permanent		growth
Quantum Science		15+ years		growth
Scientific Computing		permanent		steady
SNOLAB				

Table 2: A summary table of projects in Canada. Included are the self-reported project impact, duration, size, and status in lifecycle.

internationally, as well as operation of experiments that are deployed or planned in SNOLAB. Direct detection relies on low-background environments to isolate a target detector from solar and atmospheric neutrinos, cosmic rays, and natural radiation, and employs various technologies to discriminate dark matter-like nuclear recoils from electronic recoils caused by beta or gamma radiation. These design parameters are far from universal, for example with searches for low-mass (sub-GeV) dark matter looking specifically for DM-electron interactions.

6.1.1 Large-scale WIMP searches

The leading experiments in the search for WIMP-like dark matter, with masses from tens to thousands of GeV, currently use liquid noble gas (LNG, argon and xenon) in time-projection chambers (TPCs). Current leading experiments include LZ in the US, XENON in Europe, and the PANDA-X program in China. The technology behind these LNG TPCs is fairly mature, with total exposure being the limiting factor. The next generation of LNG experiments promises to significantly scale up the effective target volume of these experiments, pushing down into the "neutrino fog". Because of the scales involved, this next generation is likely to see collaborations combine resources: the Global Argon Dark Matter Consortium (GADMC) is leading the charge with liquid argon, while XLZD (XENON-LUX-ZEPPLIN-DARWIN, an acronym of acronyms) has just formed with the goal of exploring a next-generation liquid xenon dark matter detector. Given the size and scope of these experiments, significant resource commitments from many international partners will be necessary, especially if one is to be housed in Canada.

6.1.2 DarkSide/ARGO/DEAP 3600

Physics Goals / Highlights: The Global Argon Dark Matter Collaboration aims to detect dark matter using liquid argon argon technology developed over the past decades with DEAP-3600 and DarkSide. The program builds on the DEAP-3600 experiment at SNOLAB and progresses through a phased approach with DarkSide-20k and ARGO. DarkSide-20k, under construction in Italy, will begin operations in 2029 with a 20-tonne fiducial mass, using purified underground argon. ARGO, the ultimate experiment with a 300-tonne target, is in the conceptual design phase for deployment at SNOLAB. These detectors promise leading sensitivity across a wide WIMP mass range, with DarkSide-LowMass (DS-LM) targeting low-mass candidates. A key advantage of argon detectors is their ability to suppress electron recoil (ER) backgrounds using pulse-shape discrimination (PSD), enabling cleaner signals compared to xenon-based detectors. DarkSide-20k and ARGO also plan to use purified underground argon, to lower the ^{39}Ar background as much as possible. ARGO is expected to have only 46 background events from atmospheric neutrinos, compared to tens of thousands in xenon detectors. The program also includes sensitivity to supernova and solar neutrinos, contributing to multi-messenger astronomy and neutrino physics. The ultimate design of ARGO (spherical counter/TPC, single-phase/dual phase) has not yet been established.

Canadian Impact: Canadian institutions play a central role in GADMC, leading DEAP-3600 operations, contributing critically to DarkSide-20k, and spearheading ARGO development. Contributions include detector construction, data acquisition systems, and underground argon extraction. The ARGOlite prototype, developed in Canada, will test key technologies and support R&D for ARGO. Collaborations extend to the University of Naples and Canadian Nuclear Laboratories, with efforts such as ALARM2 for nuclear security and argon distillation systems. Canadian researchers are also involved in developing digital photon detectors and intelligent DAQ systems. The synergy with other Canadian subatomic physics projects, including SNO+, nEXO, SBC, and theoretical frameworks, strengthens the national impact.

Funding Expectations: Funding for DEAP upgrades and DarkSide-20k was supported by a 2020 CFI grant of approximately $17M CAD. A new $17M CAD request was submitted in 2025 for ARGOlite, PDC development, ALARM2, and lab upgrades. Additional funding will be sought for DS-LM around 2030. NSERC and McDonald Institute support will continue for HQP.

ARGO received SNOLAB Gateway 1a approval in 2025, and further funding will be pursued for detailed engineering and construction, with total capital costs estimated at $500M CAD. Computing resources from DRAC are currently insufficient, and future applications aim to scale up to 12,500 cores and 10,000+ TB of storage.

HQP Roles and Impact: Since 2015, over 75 graduate students and postdocs have been trained, with numbers expected to grow. HQPs are involved in all aspects of the projects, including detector construction, data acquisition, simulations, and analysis. They gain expertise in low-background techniques, electronics, software, and machine learning. Leadership roles such as analysis coordinator, run coordinator, and DAQ expert are held by HQPs. Many alumni have transitioned to careers in academia, industry, and government, including positions at Health Canada, NIKHEF, UC Riverside, and TRIUMF.

Timeline:

- **2025–2028**: Final DEAP-3600 science runs, DEAP-3600 decommissioning; DarkSide-20k commissioning and operation begins.
- **2028–2034**: ARGOlite operation and prototyping; DS-LM development and commissioning.
- **2031–2035**: ARGO detailed engineering and construction planning.
- **2035–2041**: ARGO construction and commissioning; data collection expected to begin near end of this period.

6.1.3 XLZD

Physics Goals / Highlights: XLZD is the large-scale successor to the XENON and LZ programs. Using a dual-phase time projection chamber (TPC) filled with 60–80 tonnes of liquid xenon, XLZD will search for WIMPs, neutrinoless double beta decay ($0\nu\beta\beta$) of ^{136}Xe, solar axions, and supernova neutrinos. The observatory will operate with ultra-low backgrounds and high sensitivity, probing the neutrino fog and achieving discovery potential for $0\nu\beta\beta$ with half-life sensitivities approaching 10^{28} years. The project is expected to begin construction by 2028, with commissioning and science operations starting in the mid-2030s.
Canadian Impact: Canada is not yet formally part of the XLZD collaboration, but SNOLAB is one of four shortlisted sites for hosting the observatory. If selected, Canada would be expected to contribute significantly, potentially at the 20–33% level, which is roughly projected to involve 75–150 researchers. Canadian expertise from the nEXO project—such as photon detection, muon veto systems, calibration, and background mitigation—would be highly relevant. Discussions with nEXO Canada are ongoing to explore collaborative opportunities.
Funding Expectations: The total project cost is estimated at $750M USD, including infrastructure, xenon procurement, and international contributions. If hosted at SNOLAB, Canada would be expected to contribute proportionally, with funding requests anticipated from NSERC and CFI. Infrastructure support from SNOLAB would include underground construction, cleanroom facilities, and engineering oversight. TRIUMF may contribute to sensor testing and electronics development, similar to its role in nEXO.
HQP Roles and Impact: XLZD builds on the legacy of LZ and XENON, which have trained approximately 24 PhD students per year. HQP are expected to take leading roles in operations, analysis, and publications. Undergraduate involvement is projected to be 1.5 times that of PhD students. The collaboration emphasizes mentorship, leadership development, and inclusive training environments.
Timeline:

- **2026**: Site selection decision.

- **2028–2034**: Construction and commissioning of the observatory.
- **2035–2050**: Full science operations, with a 15-year run planned.
- **Post-2035**: Potential detector maintenance and upgrades; no major R&D yet planned beyond initial deployment.

6.2 Sub-tonne-scale experiments

At lower masses than the $\sim$ 10-GeV scale, a number of different technologies provide or promise leading dark matter results. The PICO program has led spin-dependent dark matter searches for many years, relying on nuclear scattering to nucleate bubble formation sites in a superheated fluid. SuperCDMS is in the family of cryogenic, ultrasensitive "phonon" detectors, searching for minuscule heat and charge depositions to identify dark matter. Finally, NEWS-G is a unique technology, effectively exploiting the simplicity of the proportional counter to search for lower-mass dark matter interacting in pressurized gas inside a very large spherical capacitor.

6.2.1 SuperCDMS

Physics Goals / Highlights: The SuperCDMS experiment aims to detect dark matter particles through their interactions with regular matter using cryogenic detectors. The current deployment includes 18 germanium and 6 silicon detectors, totaling about 30 kg, located at SNOLAB. The experiment targets low-mass dark matter candidates (0.5–5 GeV/c^2) via nuclear recoils (NRDM), and is also sensitive to electron-recoiling dark matter and bosonic dark matter particles such as dark photons and axion-like particles. The cryogenic technology enables ultra-low energy thresholds, making it ideal for low-mass searches. Future upgrades could double the payload and push sensitivity into the neutrino floor or down to $\sim$100 MeV/c^2. Research goals also include detector response calibration using HVeV detectors and exploring novel materials like diamond, silicon carbide, and Dirac/Weyl semimetals.

Canadian Impact: Canada plays a central role in SuperCDMS, responsible for cryogenic infrastructure, data acquisition systems, simulation software, and analysis. Canadian groups are expected to lead future detector development, calibration methods, and DAQ upgrades. If background reduction becomes critical, Canada may lead efforts to establish underground detector production facilities at SNOLAB. Canadian institutions contribute significantly to operations, analysis, and future planning, with Canadian researchers comprising about 25% of the collaboration.

Funding Expectations: The current SuperCDMS project will wind down by 2029, with no major new equipment needs. However, future upgrades may require 1–2 million CAD for cryostat improvements and computing infrastructure, and 2–5 million CAD for underground detector production facilities. Funding will be sought primarily from the Canada Foundation for Innovation (CFI), with international collaborators covering additional R&D and hardware costs.

Timeline:

- **2025**: Detector cooldown and commissioning.
- **2026–2029**: Primary data-taking period.
- **2029–2032**: Data analysis and harvesting science.
- **2032–2037**: Potential upgrade and extended operations.
- **2035–2041**: Next-generation cryogenic detector development, underground fabrication facility, and global collaboration.

6.2.2 PICO

Physics Goals / Highlights: The PICO collaboration aims to detect dark matter using superheated bubble chambers located at SNOLAB. This innovative technology involves maintaining a target fluid in a metastable superheated state, where nuclear recoils from dark matter interactions trigger rapid phase transitions, forming bubbles that are captured via cameras and acoustic sensors. The detector resets by compressing the fluid to collapse the bubbles. PICO's approach is notable for its ability to distinguish dark matter signals from background noise using multiple data sources—acoustic, optical, and pressure signals. The flagship experiment, PICO-500, is scheduled to operate from 2027 to 2030, with possible extensions depending on performance and scientific relevance. One of the strengths of this technology is its adaptability; the detector can be reconfigured with different target liquids, such as hydrogen-rich compounds or R134a, to explore various dark matter mass ranges. This flexibility makes PICO a discovery-ready platform capable of responding dynamically to new findings.

Canadian Impact: Canada plays a leading role in the PICO collaboration, with 62% of its members being Canadian and many occupying key leadership positions in analysis, operations, and planning. The project has received substantial funding from Canadian agencies, including the CFI IF program and provincial governments in Ontario, Quebec, and Alberta, with additional support from international partners in India and the Czech Republic. Canadian institutions have also provided critical infrastructure and engineering support, particularly through SNOLAB, the McDonald Institute, and MRS facilities in Alberta and Montreal. Furthermore, PICO maintains strong collaborative ties with the SBC experiment, which also uses superheated liquids. This partnership has led to shared advancements in bubble nucleation simulations and acoustic emission studies, reinforcing Canada's central role in cutting-edge dark matter research. PICO has trained 7 MSc students, 7 PhDs and one PDF over the past decade, with HQP going on to key positions in academia and industry.

Funding Expectations: PICO-40L is expected to remain operational until 2026 and will be used primarily for research and development of alternative target materials. PICO-500 will begin operations in 2027 and run for at least three years, with decommissioning anticipated between 2032 and 2034. Should the detector be upgraded with new target liquids, such as R134a, the cost of transition is estimated at approximately $250,000, making it a relatively low-cost extension compared to the initial investment. Computing needs are modest, with each detector generating around 40 TB of data annually and requiring 200 core-years of processing power, which is well within the capabilities of the Alliance infrastructure. PICO will continue to rely on SNOLAB for operational support, including IT, engineering, and project management, especially if future refurbishments are needed.

Timeline: After decommissioning, data analysis and final publications are expected to continue until 2035. If upgrades are pursued, such as switching to R134a for lower mass dark matter detection, the transition would take approximately 18 months, followed by another 18–24 months of data collection. These upgrades could extend the project's timeline into the 2040s, although no firm plans exist beyond 2035 unless new collaborators and funding are secured.

6.2.3 Scintillating bubble chamber (SBC)

Physics Goals / Highlights: The Scintillating Bubble Chamber (SBC) experiment is a direct dark matter detection project using superheated liquid argon. It aims to detect low-energy nuclear recoils, potentially caused by dark matter interactions, while suppressing electron recoil backgrounds. The detector's design allows for operation at thresholds below 1 keV, opening sensitivity to low-mass dark matter candidates. SBC also investigates coherent neutrino-nucleus elastic scattering (CEνNS), background characterization, and scintillation behavior in noble liquids. The current 10-kg detector will operate at SNOLAB from 2026–2028. A ton-scale detector is planned for development starting in 2028, with operations expected by 2034, targeting the solar neutrino fog region. This future phase would require a 1-tonne argon volume pressurized to 350 psi and ultra-low background materials.

Canadian Impact: Canadian groups play a central role in SBC, contributing to detector design, low-background component sourcing, and logistics for the SNOLAB installation. They are responsible for the inner detector assembly, including fused silica jars, hydroformed bellows, and SiPM panels. Canada also leads the engineering certification process and provides ongoing support through SNOLAB and the McDonald Institute. The collaboration includes 43% Canadian members and maintains strong ties with SNOLAB, TRIUMF, and international partners in the US and Mexico.

Funding Expectations: The current 10-kg phase is fully equipped, with future costs focused on certification and engineering for the ton-scale detector. Estimated total project cost is $10M CAD, with $5M CAD expected from Canadian sources. Certification of pressure-bearing components is a major cost driver, requiring extensive engineering hours. Future computing needs will grow to 500 TB of storage and 1000 core-years of CPU time. Funding will be sought from CFI and other Canadian agencies, with continued support from SNOLAB and MI.

HQP Roles and Impact: SBC provides HQP with leadership opportunities across design, construction, calibration, and analysis. Senior HQP lead subsystems, while junior HQP contribute to impactful analyses. HQP are encouraged to present at conferences and participate in career development through the McDonald Institute. SBC maintains a supportive and inclusive environment, with a code of conduct, ombudspersons, and flexible work arrangements. Despite its relative youth, 11 HQP have been trained over the experiment's history, with alumni pursuing careers in research, industry, and graduate studies at institutions such as CNL, Queen's, Cambridge, MIT, and McGill.

Timeline:

- **2025**: Completion of 10-kg detector construction.
- **2026–2028**: Operation of SBC at SNOLAB.
- **2028–2030**: Design and procurement for ton-scale detector.
- **2030–2032**: Assembly and installation of ton-scale detector.
- **2034**: Commencement of ton-scale operations.
- **2035–2041**: Expansion to multi-tonne volumes, CEνNS studies, and potential cross-checks with other noble liquids.

6.2.4 NEWS-G

Physics Goals / Highlights: The NEWS-G experiment searches for low-mass WIMPs using spherical proportional counters (SPCs) filled with light gases such as neon, methane, and helium. These detectors offer ultra-low energy thresholds and are optimized for sub-GeV dark matter detection. The SPC design enables single-electron detection and discrimination of background events via pulse rise-time analysis. World-leading results from the first NEWS-G experiment at Modane were recently published. The current phase involves a 140 cm SPC made from ultra-low radioactivity copper, installed at SNOLAB, and equipped with a multi-anode ACHINOS sensor to enhance electric field performance. Future upgrades include electroformed copper spheres and high-pressure operation to improve sensitivity and reduce backgrounds. Initial runs at SNOLAB have uncovered a host of low-energy background behaviours that have highlighted the uncharted territory explored by these detectors.
Canadian Impact: Canadian institutions lead key aspects of NEWS-G. Queen's University oversees sensor R&D, calibration, data analysis, and project management. The University of

Alberta handles gas systems and simulations, and is exploring directional detection. SNOLAB/Laurentian leads underground installation and operations. RMC is responsible for Argon-37 source production, and RMTL is developing a neutron beam facility for quenching factor measurements. Canada contributes 3.1 FTEs across multiple institutions and plays a central role in engineering, operations, and scientific leadership.

Funding Expectations: The main background challenge is ^{210}Pb contamination in copper. To mitigate this, the collaboration plans to produce an electroformed copper sphere underground at SNOLAB. SNOLAB provides infrastructure, utilities, and support teams, and has contributed to lifting equipment and seismic platform costs. Additional resources include computing infrastructure, with a 32-CPU server at Queen's and plans for expansion at Alberta. Future scaling will require increased computing capacity and continued investment in low-background materials and fabrication capabilities.

HQP Roles and Impact: NEWS-G offers HQP hands-on experience in hardware, software, and scientific analysis. Training includes experimental design, gas handling, simulations, and data interpretation. HQP regularly participate in collaboration meetings and receive mentorship through one-on-one sessions. The Queen's lab provides access to multiple SPCs for training. The modest size of the experiment allows HQP to take on leadership roles and develop a broad skill set in experimental physics.

Timeline:

- **2025–2027**: Background characterization and initial data collection at SNOLAB.
- **2027–2036**: R&D on electroformed copper spheres, ACHINOS sensors, and directional detection; scale-up to 5 m SPC at Boulby Lab.

6.2.5 Low-mass WIMP searches: DAMIC/SENSEI/OSCURA

At even lower dark matter masses (sub-GeV), energy depositions become too low to trigger traditional WIMP direct detection experiments. Quantum technologies have emerged over the past several years to overcome these limitations, and push towards light dark matter, including searching for electron recoils directly produced by dark matter interactions. For fixed local mass density, low-mass dark matter translates into high number densities, and therefore potentially high rates. This obviates the need for large experiments, and competitive sensitivities can be achieved with kilogram or even gram-scale experiments.

Physics Goals / Highlights: The SENSEI and OSCURA experiments aim to directly detect sub-GeV dark matter particles, a class of candidates that interact with electrons and produce energy transfers of only a few electronvolts. This requires ultra-sensitive detection technology, which is provided by skipper-CCDs—advanced silicon detectors capable of counting individual electrons with sub-electron resolution. SENSEI was the first experiment to use skipper-CCDs and has already set constraints on sub-GeV dark matter. It also achieved the lowest background rate ever recorded in a silicon detector. The next phase, OSCURA, will scale up to a 10 kg skipper-CCD array at SNOLAB, increasing sensitivity by two orders of magnitude and aiming to probe key regions of theoretical dark matter models.

Canadian Impact: Canada plays a central role in the SENSEI and OSCURA collaborations, primarily through SNOLAB, which has provided critical infrastructure and technical support. Starting in 2026, Université de Montréal will establish a new research group led by Ana Martina Botti, significantly expanding Canadian leadership in dark matter detection. This group will contribute to sensor testing, data analysis, software development, and experimental operations. The Canadian team is expected to grow in size and influence, enhancing international partnerships and positioning Canada at the forefront of low-threshold dark matter research. Today, PIs are contributing with 1.0 FTE that is projected to grow for 2030 to 2.3 FTE.

Funding Expectations: To support the expansion of Canadian involvement, several funding applications are planned. An NSERC Discovery Grant will be requested for foundational research support. A CFI John R. Evans Leaders Fund (JELF) application under $1 million will support laboratory infrastructure and equipment. Additionally, a CFI Innovation Fund application under $10 million is anticipated within three years to help construct the full OSCURA experiment and advance sensor technologies.

Timeline: From 2026 onward, the Université de Montréal group will begin contributing to SENSEI and OSCURA, with major experimental deployments and upgrades occurring through 2034. During this period, the focus will be on scaling up detector mass, refining background suppression techniques, and conducting high-sensitivity measurements. From 2035 to 2041, the project will either pivot to characterizing a detected signal or continue advancing detection technologies to probe deeper into dark matter parameter space. This phase will involve significant R&D efforts, including the development of new sensor designs, faster readout systems, and modular detector architectures.

6.2.6 HeLiOS

Physics Goals / Highlights: The HeLIOS project is a Canadian-led initiative designed to detect ultralight dark matter (UDM) in the mass range of 10^{-14} to 10^{-11} eV, a regime inaccessible to traditional particle-based detection methods. UDM is expected to behave as a coherent wave, producing sinusoidal accelerations or strains on test masses. The HeLIOS detector uses superfluid helium as an acoustic resonator, exploiting its lack of viscosity and ultra-high quality factors at cryogenic temperatures to achieve minimal thermal noise. The resonant frequencies of the helium can be tuned via pressurization, allowing for high-sensitivity scans. The detector is capable of simultaneously probing scalar and vector dark matter through distinct mechanical modes. A prototype has already demonstrated the feasibility of this approach, and future versions are expected to outperform existing space- and ground-based experiments within hours of operation. A key innovation is the planned upgrade from microwave to optical fiber optomechanical readout, which will reduce noise to the thermal limit and enable rapid, broadband detection of transient signals.

Canadian Impact: Canada plays a central role in the development and leadership of HeLIOS. The Davis Lab at the University of Alberta provides expertise in quantum fluids and cryogenic systems, including custom-built dilution refrigerators and electromechanical helium chambers. McGill University's Sankey group contributes advanced optomechanical technologies, such as high-finesse fiber cavities, quantum-limited photodiodes, and stabilization techniques. These capabilities are unique to Canada and form the technological foundation of the HeLIOS detectors. The Canadian team also leads the development of analytical models and simulation tools for optimizing detector performance and interpreting data. Today, PIs are contributing with 0.54 FTE that is projected to grow for 2030 to 0.6 FTE.

Funding Expectations: To support its goals, the HeLIOS project will seek funding from NSERC for HQP training, collaborative travel, and dissemination of results. A CFI application may be submitted to fund large infrastructure components, such as a new dilution refrigerator required for scaling up the helium sensing volume. The computing requirements are modest and expected to be met through standard allocations from the Digital Research Alliance of Canada.

Timeline: Between 2028 and 2034, the team will complete the design, prototyping, and commissioning of next-generation detectors, build a geographically distributed network of sensors, and develop a theoretical framework for interpreting spatiotemporal data. From 2035 to 2041, the project will explore upgrades based on insights gained during the initial phase, including scaling the sensing volume, optimizing readout systems, and expanding the detector network. There is also potential for the HeLIOS concept to be adapted for gravitational wave detection in the kilohertz range, opening new avenues for astrophysical research beyond the Standard Model.

6.3 Search for the neutrinoless double beta decay

6.3.1 Physics and challenges

The neutrino is a lepton without electric charge that could be a Majorana fermion, contrary to the rest of the known elementary particles. Therefore, processes that violate lepton number conservation would be possible and the neutrinoless double beta ($0\nu\beta\beta$) decay has been proposed as the optimal exploration tool. The double beta decay with the emission of two electrons and two anti-neutrinos ($2\nu\beta\beta$) is allowed in the Standard Model and has already been observed for many isotopes.

The $0\nu\beta\beta$ decay which has only two electrons in the final state (e.g. through the exchange of a virtual light Majorana neutrino) is particularly interesting experimentally because the decay energy is mostly taken by the electron recoil leading to a sharp peak in energy, in strong contrast with the broad spectrum of the $2\nu\beta\beta$ decay. This is enabling the definition of an effective region of interest (ROI) where the signal to background ratio is significantly enhanced with respect to the rest of the spectrum.

Isotope selection is critically important to the success of the experiment, but no ideal candidate exists. An important consideration is the natural abundance of the specific isotope required. Most candidates for the $0\nu\beta\beta$ decay search are found naturally at a rather low fraction and require enrichment for the design of compact ultra-low background detectors. One exception is tellurium which has two $0\nu\beta\beta$ decay candidates Te-130 and Te-128 occurring at about 30% natural abundance each.

Isotope procurement and enrichment is an important practical consideration for the $0\nu\beta\beta$ decay search as the expected half-life is very long, probably well beyond 10^{25} years, ultimately requiring an exposure at the kTonne-year scale to be able to explore most of the parameter space defined by theory.

Another important aspect is the decay energy which impacts the expected rate of the double beta decay but, most importantly, a higher energy places the expected signal above more of the residual radioactive background. $0\nu\beta\beta$ decay searches have traditionally invested enormous resources and efforts into material screening, purification before construction and during detector operation, and installation at deep underground sites to protect against cosmic ray induced neutron activation of the isotope and detector materials.

Larger detectors provide improved self-shielding, and the ultimate backgrounds are the $2\nu\beta\beta$ decay and neutrinos for detectors that don't have final state tagging. Therefore, excellent energy resolution is a critically important aspect of any practical search for the $0\nu\beta\beta$ decay, especially for experiments planning to scale up to the highest sensitivity possible. A more subtle consideration is the half-life of the $2\nu\beta\beta$ decay, especially when considering the operation of the least sensitive detectors.

Three major candidates are employed in current world-leading experiments using various techniques. Ge-76 enriched detectors provide excellent energy resolution, low residual radioactive contamination but poor self-shielding for large-scale detectors. Te-130 provides excellent procurement advantages, especially for very large detectors. It can be implemented as a set of cryogenic bolometers with great energy resolution but poor self-shielding, or be dissolved in an organic scintillator with poor energy resolution but excellent self-shielding. Xe-136 can be used to build sophisticated detector configurations, for example as a cryogenic liquid xenon time projection chamber (TPC), to obtain good energy resolution and efficient suppression of radioactive backgrounds, or be dissolved in an organic scintillator with much worst energy resolution but excellent self-shielding.

Te-130 has the highest natural abundance and both Ge-76 and Xe-136 require some sort of enrichment to be able to deploy compact detectors. Xenon is quite an excellent material for shielding external gamma rays, but a highly enriched detector provides a very costly self-shielding. The decay energy of Ge-76 is significantly lower than that of Te-130 and Xe-136 which are very similar. The $2\nu\beta\beta$ decay of Te-130 has a lower half-life than that of Xe-136 and Ge-76 which again are very similar. Interestingly, Te-128 has a $2\nu\beta\beta$ decay half-life three orders of magnitude longer but also its decay provides much less energy.

Organic scintillators are operated at room temperature, and all the other detection techniques require cryogeny with the most severe constraints imposed by bolometry.

Conversion between half-life of various isotopes depends on various nuclear models which remain difficult to compute accurately and spread significantly. In general, these three isotopes would have relatively similar half-lives for the same underlying neutrino model parameters, in particular the so-called effective neutrino mass.

6.3.2 nEXO experiment

Physics Goals / Highlights: The next-generation Enriched Xenon Observatory (nEXO) is a large-scale experiment designed to search for neutrinoless double beta decay ($0\nu\beta\beta$) in ^{136}Xe. nEXO aims to use a 5-tonne liquid xenon time projection chamber (TPC) enriched to 90% in ^{136}Xe, with advanced readout systems for sub-1% energy resolution, event topology reconstruction, and powerful background discrimination. Housed at SNOLAB within a nickel cryostat and a 1.5-kilotonne water-Cherenkov veto, the detector design integrates Canadian expertise in large liquid detectors and complements international neutrinoless double beta experiments (using different isotopes) like LEGEND-1000 and CUPID. nEXO is aiming to begin physics data collection by 2034 with a target sensitivity beyond 10^{28} years. nEXO aims to probe effective Majorana masses in the 5–15 meV range, covering the entire inverted hierarchy and significant phase space of the normal ordering, while also enabling ancillary studies of solar neutrinos, double beta decay to excited states, and possible new physics.

Canadian Impact: nEXO is a global collaboration of over 200 researchers from 39 institutions in 9 countries, with Canada providing the second-largest team and major leadership in both science and technology. In this context, Canada has led critical developments in photodetectors, outer detector and muon veto developments, radiopurity screening, DAQ, and simulations. In addition, SNOLAB is positioned as the ideal host site, with Canadian institutions holding key leadership roles.

nEXO is one of the experiments in a wider international effort to use multiple isotopes to fully probe neutrinoless double beta decay. The nEXO collaboration is currently reorganizing and trying to gather new momentum following the U.S. DOE's 2024 decision to prioritize LEGEND-1000. In case of a successful reorganization and future funding of nEXO, Canada would be uniquely positioned to assume leadership of the global xenon-based $0\nu\beta\beta$ program.

Funding Expectations: Due to the reorganization of the nEXO project the funding structure is being redeveloped as well at this point. The collaboration has listed a total anticipated funding of approximately CAD$150M in the next years to redefine nEXO as a Canadian led project (approx. CAD$20M were already previously allocated). This cost is estimated for the lower enrichment phase at the start of the project and support from Canadian and international partners is being explored. Additional funding would be required for Xenon enrichment phases and Ba-tagging developments to potentially further suppress backgrounds.

Timeline: From 2028–2034, nEXO aims to progress from design and subsystem R&D into construction, assembly, and eventual commissioning, aiming to begin physics data collection by 2034. The detector will be built in stages, allowing for incremental xenon enrichment to balance risk, cost, and scientific return. It is expected by the collaboration that nEXO is in full science data-taking phase in the period 2035 to 2041.

6.3.3 SNO+ experiment

Physics Goals / Highlights: SNO+ aims at performing multiple neutrino physics measurements using solar neutrinos, geoneutrinos, reactor antineutrinos and supernovae neutrinos. In addition, they will conduct searches for dark matter. In 2026 the detector will be loaded with

1.3 tonnes of Te-130 and the experiment will focus on the search for neutrinoless double beta decay. They plan to increase the amount of Te-130 to 4 tonnes by the end of the decade and, subsequently, operate for the next 5 years at least. The collaboration expects to reach a sensitivity of better than 10^{27} years for the $0\nu\beta\beta$ decay half-life using the enhanced detector. In terms of probing the effective Majorana mass, this translates to a 15 to 65 meV range depending on the nuclear matrix elements used.

Canadian Impact: The SNO+ collaboration has a relatively small to medium size with 11 principal investigators from Canadian institutions out of 25 in total. The collaboration has extensive experience operating at SNOLAB, with considerable support from the underground laboratory, and advanced expertise with large scale purification and chemical processing systems. They also operate a significant collection of computer resources for Monte Carlo simulations and data analysis.

Funding Expectations: An ongoing CFI-IF grant request would allow the collaboration to triple the amount of Te-130 isotope available. The exact cost hasn't been specified but it could be estimated to be in the few million CAD, with immediate availability from commercial providers. NSERC SAP grants the for experiment operation and HQP training will be requested continuously. This is an experiment delivering science at a steady pace.

Timeline: Concluding operation with the pure organic scintillator and loading 1.3 tonnes of Te-130 in 2026. Then planning to increase gradually the detector loading to 4 tonnes from 2028 to 2030. Data taking for $0\nu\beta\beta$ decay search and auxiliary neutrino physics continues until 2037.

6.3.4 THEIA

Physics Goals / Highlights: Theia is a proposed hybrid neutrino detector targeting a new, large cavern at SNOLAB, included as part of SNOLAB's 15-year Facility and Operations plan. Locating Theia in this new underground space anchors the project within Canada's long-term vision for subatomic physics and ensures access to one of the world's lowest-background environments.

Theia combines the directional sensitivity of Cherenkov light with the calorimetric precision of scintillation light. This dual capability enables a rich physics program reaching from solar neutrinos, geoneutrinos, supernova neutrinos and neutrinoless double beta decay.

Canadian Impact: Theia is expected to be hosted at SNOLAB. The Canadian members of SNO+ are expected to pivot to Theia after SNO+ is concluded as most of the methods and goals align well.

Funding Expectations: As Theia is still in its R&D phase, the total project cost and sharing between international partners are still to be defined. The full experiment is expected to cost up to $800M, with the Canadian contribution expected to come from CFI investments.

Timeline: Theia will only start construction once a new, large cavity at SNOLAB becomes available, and only after SNO+ is concluded. For the LRP period Theia will largely prepare the technology for the full experiment.

6.4 Long baseline neutrino oscillation experiments

6.4.1 Physics and challenges

Long baseline neutrino oscillation experiments are composed of truly multipurpose large-scale detectors paired with an accelerator-based neutrino beam, e.g. DUNE and Hyper-Kamiokande, or reactor neutrinos, e.g. JUNO. The primary goal of this type of experiment is to study the fundamental properties of neutrinos, with a focus on discovering CP violation in the lepton sector and determining the mass hierarchy of neutrinos. Measuring a non-zero CP phase would help in modeling the early universe matter-antimatter asymmetry. One interesting characteristic of these searches is their broad physics potential allowing to target precision measurements of neutrino parameters, in parallel with investigations for new physics beyond the Standard Model. In addition to significant sensitivity for CP violation and neutrino mass hierarchy, as well as precision oscillation physics with atmospheric neutrinos, these experiments can search for proton decay, detect diffused and localized supernovae neutrinos, and investigate exotic physics models. These detectors also have excellent sensitivity for indirectly detecting dark matter.

The DUNE experiment benefits from a much longer baseline enhancing the matter effect and boosting the mass hierarchy sensitivity, whereas the Hyper-Kamiokande experiment employs the largest water-based Cherenkov detector ever built providing unrivaled statistics, when paired with the highest intensity neutrino beam. The Hyper-Kamiokande far detector will be operated with excellent calibration and understanding of its systematic errors. The Hyper-Kamiokande experiment will provide proton decay detection or set the highest limit far beyond current bounds. Both experiments are sensitive to galactic supernovae but the Hyper-Kamiokande far detector can be used to study the core collapse mechanism and neutrino mass ordering by detecting thousands of events. In parallel, searching for sterile neutrinos and exotic physics is particularly advantageous at the DUNE far detector due to the precise 3D reconstruction possible with a liquid argon time projection chamber (LAr TPC). JUNO employs a notable approach targeting precision neutrino physics by observing multiple oscillations in the reactor's anti-neutrino energy spectrum, which is possible by employing high yield organic scintillator and a very large number of photosensors to obtain unrivaled energy resolution. JUNO will provide complementary information about the neutrino mass hierarchy, study geo-neutrinos, detect supernovae neutrinos and search for new physics. All these experiments have a very long duration of operation with possible future upgrades, and will provide excellent and sustained opportunities for HQP training.

6.4.2 HyperK and T2K

Physics Goals / Highlights: The discovery of neutrino oscillations by Super-Kamiokande and SNO revealed unexpected physics and opened paths to addressing fundamental questions like matter-antimatter asymmetry and dark matter. Over three decades, experiments have precisely measured neutrino mixing angles and mass-squared differences, though the neutrino mass ordering and CP violation phase (δ_{cp}) remain uncertain.

The T2K experiment in Japan, operating since 2009, studies neutrino flavor mixing by observing how muon neutrinos (and antineutrinos) produced at J-PARC transform into other types at the Super-Kamiokande detector, 295 km away. Its success depends on a powerful neutrino beam, a massive water Cherenkov detector, and precise modeling supported by beamline instrumentation, hadron production data, and near detectors. Since the last LRP planning exercise, T2K has increased neutrino statistics by 30% and aims to boost antineutrino data similarly, while also reducing systematic uncertainties through improved interaction models, gadolinium enhancement at SuperK, and a new proton beam monitor. The installation of a fine-grained near detector in 2024 has greatly enhanced sensitivity to neutrino interactions, and T2K has strengthened its results through joint analyses with SuperK's atmospheric neutrino data and NOvA's long-baseline measurements.

T2K will complete operations in 2028 and its successor Hyper-K will expand statistics by a factor of 20. Hyper-K will be eight times larger and use a more powerful J-PARC neutrino beam. As part of the Hyper-K experiment, Canada is leading the design and construction of the Intermediate Water Cherenkov Detector (IWCD) to refine neutrino interaction models. Hyper-K aims to achieve a first measurement of the δ_{cp}, precisions measurements of θ_{23} and $\Delta m^2{}_{32}$, determine neutrino mass ordering, detect supernova and diffuse neutrino backgrounds, search for nucleon decay and dark matter, and study solar neutrinos.

Canadian Impact: Canadians are making major contributions to the T2K and Hyper-K projects today, particularly through the design, construction, and operation of critical detector subsystems such as multi-PMT photosensors, calibration at the far detector, and water monitoring systems, with responsibilities extending into 2028–2034. The Canadian group is responsible for the design, installation and operation supervision of the IWCD near detector. They are also leading in machine learning–based event reconstruction, supernova localization methods, and the operation and upgrade of the J-PARC beamline's Optical Transition Radiation monitor. Canadian researchers are involved in proposals for power-efficient "green" accelerator upgrades, radiation-tolerant materials development, and remote maintenance technologies, leveraging TRIUMF's expertise. Internationally, Hyper-K is a collaboration of 650 scientists from 22 countries, with Canada contributing 44 members, about 15% of the non-Japanese construction cost, and filling numerous leadership roles, including coordination of IWCD, detector subsystems, calibration, and safety committees. Today, PIs are contributing with 0.75 FTE and 8.1 FTE to T2K and Hyper-K, respectively. The projection for 2030 is to have no active work on T2K and 7.1 FTE on Hyper-K.

Funding Expectations: T2K-Canada does not foresee any requests for additional equipment or infrastructure needs. Funding through CFI-IF has secured Canada's major contributions to Hyper-K calibration and construction, IWCD design and construction, a potential future request planned for upgrades to the OTR beam monitor, remote handling at J-PARC, and expanded computing resources. In particular, the required computing resources are expected to be significant with the total Canadian computing need for Hyper-K and IWCD through 2033 being approximately 10,420 core-years and 8.33 PB of storage. Construction efforts are supported by TRIUMF and Carleton University technical staff, who will continue to provide modest operational support after Hyper-K begins in 2028. The non-renewal of the Winnipeg MRS in 2025 left a gap in support for photogrammetry equipment, but this remains essential for Hyper-K and IWCD. Canada could grow opportunities in the future to expand its role in accelerator and neutrino beamline operations, particularly through TRIUMF.

HQP roles and Impact: Over the last 10 years both experiments combined have trained 26 graduate students and 15 postdocs.

Timeline: T2K is expected to complete operations in 2028. At this point, Hyper-K is expected to start data taking and will take data with beam for 10 years and 20 years in total.

6.4.3 DUNE

Physics Goals / Highlights: The Deep Underground Neutrino Experiment (DUNE) aims to study neutrino behavior with unprecedented precision by measuring electron neutrino appearance in a broad-spectrum muon neutrino beam produced at Fermilab. With a 1,300 km baseline to its far Detector at Sanford Underground Research Facility, DUNE aims to resolve the neutrino mass hierarchy, probe CP violation, and explore tau neutrino interactions for potential Beyond Standard Model physics. It will also aim to detect supernova, solar neutrinos, and contribute to multi-messenger astronomy. The experiment features a Near Detector at Fermilab and a Far Detector composed of 17-kilotonne Liquid Argon TPC modules, built in two phases: Phase I (two modules, beam delivery by 2032) and Phase II (expanded detector mass and beam intensity). Between 2028 and 2034, DUNE is expected to begin data taking. Canadian researchers are actively contributing to both natural and accelerator-based neutrino studies.

Canadian Impact: The University of Toronto has major contributions to the Far Detector Data Acquisition and trigger systems and plans to contribute to the commission of the far detectors. York University focuses on simulation and reconstruction for the liquid argon Near Detector. The DUNE-Canada team, comprising three professors, three postdocs, six graduate students, and three undergraduates, holds prominent leadership roles within the international collaboration of over 1,400 scientists from 35 countries. Key leadership includes positions on the Data Acquisition Management Board, the Near Detector Consortium Institutional Board, and co-leading detector reconstruction efforts. Today, PIs are contributing with 1.7 FTE that is projected to grow for 2030 to 2.5 FTE.

Funding Expectations: The Canadian team will request further CFI-IF contributions to the development of DUNE's Trigger and Data Acquisition (TDAQ) system, which manages massive data rates from the Near and Far Detectors. The system uses high-performance servers, a custom Timing system, and modular software to reduce data by four orders of magnitude. Funding requests from the 2026 CFI Innovation Fund will support commercial servers, network cards, SSDs for supernova buffering, and custom Near Detector components, with an estimated cost of 1.2 million CAD.

HQP roles and Impact: Over the last 10 years both experiments combined have trained 3 graduate students and 8 postdocs.

Timeline: Dune is expected to start data taking with first beam data in 2032 and will consequently have a projected duration of at least 15 years.

6.5 High-energy and astrophysical neutrino observatories

6.5.1 Physics and challenges

High-energy Cherenkov neutrino telescopes, detecting neutrinos from a few GeV of energy to beyond the PeV-scale, provide a unique window with which to study the extreme universe. An overarching goal of these projects is the study of the origin of astrophysical neutrinos, and the use of high-energy neutrinos as probes of our knowledge of particle physics. The realized enormous datasets of neutrino interactions, at energies unreachable by human-constructed accelerators, have become a powerful tool for studies of rare-event particle physics. Experiments like IceCube and P-ONE instrument cubic-kilomete-scale natural bodies of ice (South Pole ice cap) or water (Pacific ocean) with a photosensor array capable of detecting the light emitted by the products of neutrino induced interactions. Current and proposed detectors are at the cubic-kilometer scale and beyond.

In comparison to IceCube, which uses the ultra-transparent Antarctic glacial ice as a detector medium, water-based detectors such as P-ONE experience significantly reduced light scattering and can thus achieve significantly improved pointing resolution. This in turn increases sensitivity to neutrino point sources. The geographic location of P-ONE offers excellent complementarity to IceCube, KM3Net, and Baikal-GVD (other water-based neutrino observatories) in achieving an all-sky coverage for HE neutrino sources. In particular, P-ONE occupies an excellent geographic location to view transient Galactic sources.

The key design goal of P-ONE is to achieve a muon-neutrino angular resolution of $0.05\,^\circ$ at $100\,\mathrm{TeV}$ (compared to current IceCube with an angular resolution of above $0.2\,^\circ$ at the same energy) as well as improved neutrino flavor identification. This will deliver proportionate improvement in its sensitivity to HE neutrino point sources and neutrino property measurements. In a simplistic Euclidean Universe approximation, a factor of 4 improvement in flux sensitivity would result in identifying about an order of magnitude more neutrino sources than IceCube currently has detected. Given our current knowledge, P-ONE aims to raise this emerging research field to the next level and provide significant clarity on the classes of sources that are responsible for the extra-galactic neutrino flux.

Sophisticated detector calibration schemes are necessary, especially for water-based experiments as the marine environment is dynamic and constantly changing and biological activity affects the detector operation. Robust infrastructure support is mandatory as these observatories are installed in complex and difficult environments like the seabed and polar ice cap. These detailed calibration data of environmental conditions (acoustical and optical) will further complement interdisciplinary science and open new horizons in oceanography and climatology, empowering research in topics such as bioluminescent activity and biodiversity, tracking and studying vertically migrating ocean animals and whales, or to monitor seismic and tectonic activity.

6.5.2 IceCube and P-ONE experiments

Physics Goals / Highlights:
The Canadian collaborators share interest in both experiments IceCube and P-ONE due to the overlapping similarities of their physics scope. The IceCube Neutrino Observatory at the South Pole, operational since 2011, is the world's largest neutrino telescope. Its long-term stability has enabled the collection of over half a million atmospheric neutrinos and thousands of high-energy astrophysical neutrinos, leading to the identification of the first astrophysical neutrino sources and new tests of neutrino physics and the Standard Model. An upgrade scheduled for the 2025–26 deployment season will add seven new detector strings featuring advanced photodetectors and calibration instruments. Canadian researchers are focusing on leveraging these improvements to achieve precision measurements of atmospheric neutrino oscillations, test the limits of the three-flavor neutrino model, and enhance sterile neutrino searches. They are also contributing to detector recalibration efforts to improve event reconstruction and background discrimination.

Looking toward the next generation of neutrino astronomy, Canada is also spearheading the Pacific Ocean Neutrino Experiment (P-ONE), a multi-cubic-kilometer observatory planned for deployment off the coast of Vancouver Island. This initiative leverages the existing infrastructure and expertise of Ocean Networks Canada's NEPTUNE Observatory in the Cascadia Basin. The immediate focus is the successful execution of the fully funded Demonstrator phase, which will validate the project's technology and deployment strategies. The first line of the Demonstrator is being assembled at TRIUMF, with deployment scheduled for spring 2026, followed by the completion of additional detector lines to form the full Demonstrator array by 2028. Depending on the performance outcomes of this initial phase, a conceptual design for a cubic-kilometer-scale detector is being developed with the goal of realizing full deployment by 2034. This large-scale facility would significantly expand the global detection volume for astrophysical neutrinos above 1 TeV, enhance technological innovation in detector design and data acquisition, and strengthen Canada's leadership role in the rapidly evolving field of multi-messenger astrophysics.

Canadian Impact: On the IceCube project, the group has recognized key roles in detector performance and calibration studies and is responsible for several analysis software tools to analyze future data from the IceCube Upgrade. For the P-ONE project, Canadians are leading the development of many key detector components. These P-ONE elements leverage four (CFI-funded) laboratories located at the UofA, SFU, Queen's, and ONC to design, construct and build primary instrumentation for the detector. In addition, the team is leveraging infrastructure at TRIUMF to execute the final detector line integration and commissioning. In the IceCube collaboration, many Canadian members hold important responsibilities and the Canadians form 40% of the P-ONE collaboration with many assuming leadership positions.

Funding Expectations: Both experiments are supported by NSERC SAP grants. P-ONE pathfinder tests and the demonstrator have been funded by CFI JELF and IF infrastructure awards. International collaborators and Canadians are planning funding of the cubic-km P-ONE observatory which is estimated to cost of the order of 100 million CAD. The strategy to meet the Canadian commitments is based on a series of CFI-IF requests in synergy with international partners contributions. P-ONE computing requirements are significant and broad with need for

CPU, GPU and storage to support simulation and data processing efforts.

HQP roles and Impact: Over the last 10 years both experiments combined have trained 20 graduate students and 10 postdocs. HQP within both experiments currently have the unique opportunity to lead or contribute to world-leading analysis efforts using IceCube data and develop crucial hardware for the next generation neutrino telescope. In this context, PDFs are essential contributors and represent a significant part of the HQP training effort.

Timeline: In the near term, physics exploitation of IceCube and its extension are planned until 2032. The complete P-ONE construction and commissioning is planned by 2034, but the detector operation starts much earlier by 2030, after the installation of its first components. The P-ONE observatory intends to operate for at least 10 years.

6.5.3 HALO

Physics Goals / Highlights: HALO is a specialized detector with high live time fraction aimed at measuring a galactic supernova. HALO is re-using detector components from the third SNO phase to detect neutrons from neutrino captures on the lead target material. HALO is part of the global SNEWS supernova early warning system alerting other experiments of neutrino signals that resemble a supernova signal.

Funding Expectations: HALO will continue to request small operational funds from NSERC to allow HQP training to continue and in the process keep the detector systems current. While there are ideas to upgrade the detector, both the person power situation and the opportunity to enhance the detector would have to present a compelling case to justify the expense.

Timeline: Halo is likely going to be continuing to run with very high uptime, contributing a highly relevant data set in case a galactic supernova is identified.

6.6 Collider and Accelerator-Based Physics Projects

Particle accelerator-based experiments are an extremely broad category, unified by their common usage of particle beams to create particles and study their subsequent decays. A huge range of approaches are possible, ranging from traditional general-purpose experiments at the energy frontier such as ATLAS at the LHC (and future experiments at the Future Circular Collider), to purpose-built smaller detectors at the LHC such as MATHUSLA and MoEDAL/MAPP, to precision experiments with their own range of generality such as Belle2, Moller, and PIONEER, to smaller scale purpose-built experiments such as DarkLight. These experiments span the range of experimental approaches to searches for BSM physics, from precise measurements of sensitive Standard Model properties to direct searches for spectacular signatures of new particles. This section summarizes the experimental status and needs for this class of experiments.

6.6.1 Belle II

Physics Goals / Highlights: The Belle II Experiment is located at the SuperKEKB e^+e^- collider at the KEK Laboratory, Tsukuba, Japan. Belle II and SuperKEKB are substantial upgrades of the highly successful Belle and KEKB projects, which operated from 1999–2010. SuperKEKB is designed to achieve 30 times the peak luminosity of KEKB, which will allow Belle II to integrate a dataset totalling 40 times the size of the combined data sets of the previous generation B-factory experiments. During the period 2028–2034, SuperKEKB is projected to continue to ramp up towards its design luminosity of 6×10^{35} cm^{-2} s^{-1}. Belle II will also progress towards its long-term dataset objective to accumulate a collision dataset totalling 50 ab^{-1}. Belle II will achieve several key milestones as it surpasses the combined BaBar+Belle dataset. On the road to achieving this ultimate objective, Belle II will continue to pursue an encompassing physics program that includes:

- Searches for rare/forbidden decays of heavy hadrons and leptons
- Studies of B-meson decays to address the leptonic anomalies observed by BaBar, Belle, and LHCb
- Dark sector searches
- Precision measurements of QCD observables, including cross-sections that are essential for computing the Standard Model prediction of the muon anomalous magnetic moment
- Measurements that probe Standard Model predictions at the precision frontier, including CP violation, lepton universality, etc.

To fully exploit the unprecedented luminosity of SuperKEKB, the Canadian Group is leading an upgrade proposal to introduce polarized beams to SuperKEKB, referred to as Chiral Belle, which substantially augments the existing Belle II program described above. Using the polarization-upgraded SuperKEKB and the existing Belle II detector, Chiral Belle will give the most precise measurement of $\sin^2\theta_W$ from a single experiment, probe its running, provide unique sensitivity to new physics, such as dark sector parity violating mediators, and yield universality studies of unprecedented precision. The broader polarization program also includes a tau anomalous magnetic moment (g-2) measurement at the 10^{-5} precision level, orders of magnitude more precise than any other proposed method. Moreover, measurements of the Michel parameters of tau leptonic decays will have precisions an order of magnitude more precise than current world averages with only 1 ab^{-1} of polarized data. Implementation of Chiral Belle will stimulate innovations in accelerator technologies as it requires a low emittance polarized electron source, a compact spin rotator, and non-invasive high precision beam polarimetry. The Canadian group submitted a CFI-IF application in 2025 for the Chiral Belle spin rotator prototype and Compton polarimetry development, which is currently under review.

The period from 2028–2034 would see a large expansion to the Canadian and international R&D efforts in order to achieve polarized SuperKEKB collisions during the 2030's. It will involve a request in the next CFI-IF round to complete the Chiral Belle upgrade.

Canadian Impact: The Canadian Belle II group is composed of 12 PI's, with approximately 6-7 FTE of research time devoted to the project. There are currently 12 graduate students on the team, and 2 postdoctoral researchers. The Canadian team is approximately 3% of the full collaboration.

The Canadian group has made major contributions to several critical areas of the Belle II calorimeter including developing the majority of the reconstruction software, leading the photon energy and timing calibrations, and leading/undertaking performance studies. During the ongoing operations phase of the experiment, the group's expertise is crucial to maintain essential calibrations including photon energy, photon timing, and pulse shape discrimination. The group additionally contributes a large fraction of remote and on-site calorimeter sub-detector shifts.

The Canadian group has been instrumental to implementing and maintaining flexibility in the Belle II trigger, which ultimately decides which events are saved for physics analysis or detector studies, and which are discarded. Demonstrating a leading role in this critical area, one Canadian PI is responsible for the entire experiment's trigger menu. The group has ensured novel "Dark Sector Trigger" lines that target a range of low multiplicity detector signatures (single energetic photon, displaced vertex, single muons) have remained active through the entire Belle II run period. These trigger lines allow Belle II to explore a variety of dark sectors and have facilitated several Belle II publications in this area.

The Canadian group deployed and currently operates the Belle II Thermal Neutron Monitoring System, which provides direct feedback to the accelerator control room on the beam-induced thermal neutron background in the detector region. The information from this system is used by accelerator operators to enable them to maximize the delivered luminosity while minimizing the associated beam background levels. Beyond facilitating invaluable hands-on detector hardware training, operation of these detectors enables exceptional opportunities for HQP to collaborate with KEK accelerator experts.

Funding Expectations: The Belle II Canada group is funded by a NSERC project grant, and the operation and construction of a Raw Data Center (storing 15% of Bell II's data) was funded by a CFI award. Extra hardware for the Belle II high-level trigger was funded by a $130k NSERC RTI grant. Ongoing costs for the experimental M&O are $70k/year, but are reduced by direct contributions such as for the trigger.

The largest expected short-term funding requirements come from the Chiral Belle upgrade, for which as 2025 CFI-IF application was submitted. A further request in the 2028 CFI-IF application period is anticipated to finish the upgrade program. In the longer term, funding may be also required for calorimeter maintenance/operations as the detector ages.

HQP Roles and Impact: Over the past decade, 34 PhD or MSc degrees or postdoc terms have been completed with the Canadian Belle II group. The Belle II group currently includes two postdocs or research associates, nine PhD students, and three MSc students. With Belle II projected to surpass the combined Belle+BaBar dataset during this period, the group is expected to expand the number of HQP to capitalize on the additional discovery opportunities that will be opened. Over the next four years, they expect the number of postdocs to increase to three or four and graduate students to increase to approximately fifteen and to remain at that level at least through the early 2030's.

Timeline: The nominal Belle II data-taking has essentially just begun, as data-taking is expected to take data until the mid 2030's and currently 1% of the target dataset has been recorded. The luminosity of the collider is expected to continue to increase towards its design target of 6×10^{35} cm^{-2} s^{-1}, more than a factor of 10 higher than currently achieved. The Chiral Belle upgrade project would begin data-taking in the mid-2030's and operate for several additional years. There are still ample opportunities for Canadian contributions to continue to grow over the next several decades of operation.

6.6.2 ATLAS

Physics Goals / Highlights: ATLAS is one of two general-purpose particle detectors designed to record data from high-energy proton-proton (pp) collisions produced by the Large Hadron Collider (LHC) at CERN, in Geneva, Switzerland. The LHC is the world's premier energy-frontier facility, producing collisions at higher energy than any other collider and enabling probes of some of the most important scientific questions of our time. For example, the 2012 discovery of the Higgs Boson by ATLAS and CMS enabled significant insights into the nature of electroweak symmetry breaking, but many open questions about the process remain and study of the boson continues. The unprecedented energies of the LHC also enable world-leading searches for new physics from a broad range of models, motivated by open questions in dark matter, the baryon asymmetry, and naturalness. The enormous datasets collected during the LHC's Run 2 and 3 further enable precision measurements of the Standard Model, often interpreted as limits on Effective Field Theories of potential BSM physics.

ATLAS continues to produce leading physics results, with over 1381 papers submitted by the end of April, 2025. The original LHC program is essentially completed, and Canadians lead efforts in several aspects of ATLAS detector upgrade R&D and deployment, for both Phase-1 (now installed) and Phase-2, for which new detector elements are currently under construction for installation in Long Shutdown 3 (LS3), to begin in mid 2026. ATLAS expects to acquire about 10x more data than previously recorded, and is entering an exciting era of high-precision physics and extensions of our sensitivity to new physics; the LHC continues to be unique, with no peer facility expected for two decades.

The physics goals of ATLAS in the coming years are to continue to search for new physics by both direct searches and precision measurements of the Standard Model. The newly collected Run 3 data is already nearly twice as large as the previous Run 2 dataset, allowing for significant reductions in statistical uncertainties in many searches. Dramatic optimizations of detector reconstruction (led by Canadians) have also enabled entirely new searches, such as for new classes of long-lived particles that decay away from the collision point. Detector upgrades, such as the Muon New Small Wheels and the upgraded Level 1 calorimeter trigger (both with significant Canadian contributions) have also enabled improved triggers even in the face of more challenging conditions (due to the increase of simultaneous pp collisions, referred to as pileup). Important thresholds in the study of the Higgs Boson will also likely be met in the next few years, as the first 5σ evidence for the $H \to \mu\mu$ decay will be able to constrain the Higgs coupling to 2nd generation fermions for the first time, and the potential 3σ observation of Higgs pair production will enable first measurements of the Higgs self-interaction, a key ingredient to understanding the nature of the Higgs potential and electroweak symmetry breaking's role in the universe's baryon asymmetry. With the full High-Luminosity LHC dataset, it is expected that ATLAS and CMS together will be able to constrain the Higgs self-interaction to better than 30% precision, a number that will likely not be surpassed till far-future higher energy colliders begin operation. The HL-LHC will also provide unique and powerful probes of new physics such as the observation of longitudinally polarized $W_L W_L$ scattering and 4 top-quark cross-section at 6% precision.

Canadian Impact: Canada has been involved in ATLAS since the collaboration was first formed (c. 1992), and made significant contributions to the design, construction, installation and commissioning of the ATLAS Liquid Argon (LAr) calorimeter and High Level Trigger (HLT) systems, and important contributions to the ATLAS inner tracker and muon systems, beam conditions monitors, radiation monitors and luminosity detectors. Canada, via TRIUMF, also made significant contributions to the LHC accelerator and injectors. Beyond contributions to the production of the dataset used for ATLAS analyses there have been direct Canadian contributions to the analysis in 28% of ATLAS publications, including leading Canadian roles in the 2012 discovery of the Higgs boson as well as in countless other physics results.

At the time of writing, the ATLAS Collaboration comprises 177 institutions in 40 countries, with about 2646 active scientific authors. ATLAS-Canada members comprise about 4% of this total. Canadians serve in important roles in the collaboration, which reflects the standing within ATLAS. In recent years, two of our members have served as deputy spokespeople, one as physics coordinator and publications committee chair, and a significant number as working group conveners. The current number of ATLAS Canadian investigators is 33 FTE, and is projected to be 32 in 2030. ATLAS Canada currently has 35 PDFs, funded mainly via NSERC, and has maintained a steady state of 80 graduate students for the past few years.

Funding Expectations: Canadian physicists have committed significant research time to ATLAS and the LHC. Canadian funding agencies have committed significant capital funds towards our contributions to ATLAS detector upgrades, and the Federal government directly contributed \$12M to the HL-LHC for construction of cryo-modules at TRIUMF that will house the crab cavities that are the heart of the luminosity upgrade. In ATLAS alone, CFI supported Phase-1 upgrades with a \$6M award and Phase-2 with more than \$30M. NSERC continues to funds ATLAS operations in Canada with a Project Grant exceeding \$6M per year. No further significant construction projects (and therefore CFI applications) are currently expected, though ongoing support from NSERC to finish and operate the Phase-2 upgrades will be required.

HQP Roles and Impact: Canadian contributions to ATLAS rely heavily on a contingent of postdoctoral research associates (PDFs) and graduate students. PDFs are essential contributors to the ATLAS-Canada research effort and represent a significant part of the HQP training effort. A typical ATLAS-Canada PDF makes a leading contribution to at least one physics paper per year, while simultaneously making a significant and recognized impact on ATLAS operations or upgrades. Students also play an essential role in all aspects of the ATLAS-Canada research effort, in the operation of the experiment, the production of physics results and in upgrades and computing. Currently ATLAS Canada has about 35 PDFs and 80 graduate students, although a reduced NSERC award is resulting in a reduction in PDF hires and graduate admissions.

From a survey of ATLAS Canada PhD graduates, about 41% continued in academic research, 38% found positions in industry, and 7% were hired by the Canadian government. ATLAS Canada graduates and PDFs have found positions as a quantum algorithm engineer in Toronto's IBM Quantum Computing division, as a process engineer developing coatings for laser diodes at nLIGHT Vancouver WA, as Design Specialist at Teledyne DALSA Waterloo, as Head of Product and Technology in AI and visualisation at Canscan Inc. Montreal, as Seismic Analyst at Viridien Calgary, as Applied Physicist at Canadian Nuclear Laboratories Ottawa, and as a Canada Research Chair at the University of Victoria.

Timeline: The HL-LHC experimental program will extend into the 2040s, including upgrade completion, detector operation, data processing. and physics analysis. This project has been one of the highest priority elements of the Canadian (and international) high-energy physics program for more than two decades, and seems poised to remain so for at least two more. The importance of completing (and fully exploiting) the HL-LHC experimental program is emphasized in the European Strategy for Particle Physics. Construction of the Canadian contributions to the Phase-2 detector upgrades will provide an important HQP training ground, in particular for the next generation of Canadian detector builders.

In the longer term future, should CERN and Europe decide to pursue a future collider program at CERN, it is likely that some fraction of the ATLAS Canada collaboration will shift to the design and construction of a future detector. As any future facility is expected to begin operations no earlier than 2045, it is expected that there will be a smooth transition of FTE between ATLAS and the future collaboration.

6.6.3 FCC-ee/FCC-hh

Physics Goals / Highlights: The currently-named Future Circular Collider (FCC) is a proposed collider facility to be built at CERN, in Geneva, Switzerland, as a successor to the Large Electron-Positron Collider (LEP) and the Large Hadron Collider (LHC). The collider would have two general stages: an electron-positron first stage, to begin in 2045 and operate at $\sqrt{s}$ = 90-365 GeV, and a proton-proton second stage, to begin in 2070-2080 at $\sqrt{s}$= 84 TeV.

After almost 15 years of LHC operation, the remarkable precision measurements and the many exploratory searches have demonstrated the validity of SM and excluded signs of new physics across an order of magnitude of energies around the TeV scale. Despite this, several fundamental experimental facts remain unexplained in the current framework, such as the abundance of matter over antimatter, the evidence for dark matter, or the nonzero neutrino masses, and many theoretical issues definitively also require physics beyond the present Standard Model (BSM), altogether calling for intensified collider exploration. However, the field of possible explanations to these unanswered questions provides little guidance for what form this exploration may take. Solutions could exist at even higher energy, at the price of either an unnatural value of the weak scale or an ingenious but still elusive structure. Radically new physics scenarios have recently been devised, which often include light and feebly coupled structures. Neither the mass scale (from meV to ZeV) of this new physics nor the intensity of the couplings to the SM are known, thus calling for a new, broad, and powerful tool of exploration. The two-stage approach of the FCC, beginning with a precision ee collider and following with a search-oriented hh phase, allows for the broadest and most complete exploration of the energy frontier and solutions to questions for the SM.

Canadian Impact: While there is no current FCC-Canada project organization, a recent IPP-organized community poll indicated that a plurality of Canadian researchers prefer the integrated FCC-ee and FCC-hh option for CERN's next collider project in the face of several alternatives. The poll indicated that the FCC was the most exciting option for Canadian investigators, and showed strong interest in Canadian participation in the FCC. For accelerator and industrial contributions, approximately half of respondents highlighted TRIUMF's capabilities for contributing to the FCC accelerator complex. Of particular strategic importance is Canada's resource potential: the Niobec mine in Quebec is one of only three primary niobium producers globally. Niobium is a key mineral for superconducting magnet and RF cavity construction, representing a potential major Canadian industrial opportunity.

It should also be noted that on March 25th, 2025, Canada and CERN signed a Statement of Intent [4] covering general partnership aspects and specifically addressing FCC collaboration. This agreement emphasizes the mutual intention to enhance collaboration in planning future projects, to continue and expand cooperation on innovative detector, accelerator, and computing technologies, to strengthen collaboration on FCC studies, and to promote joint efforts in developing advanced techniques and tools. This level of support from the Federal government at a very early stage is encouraging for future Canadian participation in the FCC.

Funding Expectations: Should Canada join the FCC, several funding streams will likely need to be accessed to enable success for the Canadian collaboration. Early seed funding from NSERC in the late 2020's and early 2030's would enable collaboration building and detector optimization in the pre-construction phase. An in-kind contribution to the accelerator, analogous to contributions to the LHC and HL-LHC from TRIUMF enabled by a direct contribution from the federal government, will likely be required at the \$20M level. A large CFI-IF application (\$50M+) would be expected in the mid 2030's for detector construction, and ongoing support from NSERC at that point would be critical for Canadian contributions to the project.

HQP Roles and Impact: In terms of HQP training, during the period of this LRP the FCC-Canada collaboration will play a critical role in allowing for the training of the next generation of physicists in detector design and construction. Especially as the ATLAS Phase-2 upgrade project finishes, there will be few other opportunities to work on optimization of the detector and the technology development. The FCC-ee project will ramp up at the appropriate time to provide an important training-ground for the next generation, who will in turn be ready to lead the design and construction of the FCC-hh detectors further in the future.

Timeline: The European Strategy Update process is currently ongoing. On September 30, 2025 it released a Physics Briefing Book [1] summarizing the physics case of the various proposed projects. On October 21 2025 an assessment of the proposed flagship projects by an expert working group was released, with no show-stoppers for the FCC project identified. Finally, the recommendation on the next project is expected to be released in early 2026. Should CERN and Europe decide to pursue the FCC, the period 2028-2034 will be an era of collaboration building and detector design. This period will constitute the TDR (technical design review) phase for the FCC-ee collider as is typical of any large experimental project at CERN. As the four expected collaborations – based on different detector concepts – form, FCC-Canada will have to make a decision as to which experiment to join. This will likely be based on the best fit of Canadian expertise to the chosen detector concept and systems as well as the potential impact of Canadian contributions.

6.6.4 PIONEER

Physics Goals / Highlights: PIONEER is an international experiment proposed to take place at the Paul Scherrer Institute (PSI), utilizing the world's most intense beam of pions. The experiment is approved by PSI at highest priority, is an IPP project, and has been highlighted in the Agile experiments category of the American Physics Project Prioritization Panel. Detector construction and operation are expected to take place during the 2028-2034 period.

PIONEER is primarily a test of lepton universality, measuring the ratio of pion decays to electrons and muons ($R^{\pi}_{e/\mu}$). This value is extremely well predicted in the Standard Model, at the 0.01% level, and the current experimental reach (achieved by PIENU at TRIUMF) is at the 0.2% level, allowing a significant region where new physics effects may appear. This ratio is extremely sensitive to contributions from new physics effects ranging from new particles at scales between MeV and PeV, allows for measurements of quark mixing effects, and enables a new measurement of $|V_{ud}|$ that is complementary to existing beta-decay experiments.

Canadian Impact: The Canadian team composes nearly 20% of the international collaboration, and has played leading roles since the establishment of the experiment, including as spokesperson of the experiment. Currently there are three investigators and one emeritus. The Canadian group has taken a leading role in the design (and eventual construction) of the extremely precise and full-coverage LXe calorimeter. Canadians are also leading an important auxiliary measurement of the pion lifetime taking place at TRIUMF utilizing cyclotron beams.

Funding Expectations: The Canadian team is currently supported by NSERC Discovery grants and MITAC support for HQP. A CFI application to develop a calorimeter prototype has been submitted for the 2025 IF round, backed by international contributions from Japan. The primary anticipated cost of the experiment is driven by the calorimeter system. A decision between the LXe option and a LYSO-crystal based option is expected in 2027, and will drive the eventual funding requirements from the Canadian team, which are expected to be in the range of O(10 M$).

Timeline: PIONEER has a long outlook, with operations expected to continue through 2045. The period of 2028-2035 is expected to focus on construction and commissioning, and 2035-2040 would encompass the final data-taking for the $R^{\pi}_{(}e/\mu)$ measurement. Beyond this, an upgrade program is envisioned to enable a Phase II of the experiment, focusing on higher pion beam intensities that would enable unique measurements of pion beta decay.

6.6.5 MATHUSLA

Physics Goals / Highlights: MATHUSLA is a proposed large scale experiment, planned to be built above one of the high-intensity collision points at the CERN HL-LHC. The approximately 45x45x15 m detector, placed within ≈100 m of the collision point and composed of overlapping layers of scintillators read out with wavelength shifting fibers and silicon photomultipliers, is expected to be able to provide a background-free measurement of decays of potential long-lived particles (LLP) produced during *pp* collisions at the LHC. For a wide range of masses and lifetimes for these hypothetical particles, trigger and background limitations at the primary LHC detectors significantly limit sensitivity, and MATHUSLA could enable discovery. MATHUSLA could also deliver a trigger signal to the primary detector above which it is situated, enabling characterization of the collision process that produced the LLP.

A wide variety of models predicted long-lived particles at the weak scale, and these could be copiously produced at the LHC via a variety of processes, such as the decay of the Higgs to dark-sector particles. With the HL-LHC expected to operate until 2045, a dedicated detector will maximize the physics potential of the LHC investment, allowing discovery for an otherwise difficult to access parameter space.

Canadian Impact: The Canadian team is currently playing a leading role in the experiment, as existing NSERC and MDI funding has enabled the establishment of test-stands at Toronto and Victoria. Canadians also played an early role in establishing the experiment and motivating new interest in long-lived particle searches. The Canadian team is expected to lead the construction phase of the project, with most of the detector modules being produced at Victoria, Toronto, and potentially Alberta. 4 Canadian investigators are part of the project.

Funding Expectations: The Canadian team is currently supported by NSERC for personnel and hardware development. The total detector cost has been established by a detailed CDR, and is expected to be near 60 M$. Further contributions will be required from CERN for local civil engineering and constructing the building to house the detector. Applications are expected for upcoming CFI-IF rounds, where Canada would likely be expected to be a leading contributor to the experiment.

Timeline: During 2026-2028 the team is expecting to gather funding and finalize the approval of the experiment. Construction would take place in 2028-2029, and it is expected that individual modular detector "towers" could begin cosmic commissioning or collision data-taking as they are installed, without waiting for the full set of detectors.

6.6.6 MoEDAL-MAPP

Physics Goals / Highlights: MoEDAL-MAPP is a Canadian-led experimental initiative designed to expand the LHC's sensitivity to new physics with a series of highly specialized detectors. All the detectors utilize cavern space at IP8, nearly the LHCb experiment. The first detector concept, MoEDAL, has been in operation since 2010 with dedicated nuclear track detectors, magnetic monopole traps, and radiation monitoring stations located close to the collision point. The MoEDAL detector was designed to search for highly ionizing particles such as monopoles, dyons, Q-balls, strangelets, and long-lived supersymmetric particles. The subsequent MAPP (MoEDAL Apparatus for Penetrating Particles) is finishing construction in 2025, and is composed of a large array of scintillators read out with photomultiplier tubes positioned in the UA83 gallery away from the experimental cavern, sensitive to milli-charged particles and long-lived particle searches benefiting from shielding. A final MAPP-2 proposal features is aimed to begin data-taking in 2030, and features a large decay volume surround by position-sensitive scintillator layers.

Canadian Impact: The Canadian group has long led the collaboration and raised the bulk of the funding for the passive detectors, operations, and data analysis via NSERC operating grants. The Canadian group has also raised the bulk of the funding for the MAPP detector via NSERC RTI grants. The Canadian group has also contributed readout electronics to the MAPP-1 outrigger, an upgrade currently being constructed. It is expected that the Canadian group will grow to take additional responsibilities should the MAPP-2 phase be approved and funded.

Funding Expectations: The ongoing operations of the MoEDAL passive detectors ($O(100k\$)$ and MAPP-1 are expected to be covered by NSERC project grants and contributions from international collaborators. The MAPP-2 project, as a substantially larger detector than the previous stages, is expected to cost a total of 10 M$, and the Canadian group expects to contribute a substantial fraction of the cost.

Timeline: MoEDAL and MAPP-1 are expected to take data throughout 2026 and the full run of the HL-LHC. In 2027, MAPP-1 is planned tobe upgraded with higher-yield scintillators to enable sensitivity to lower milli-charged particles. If MAPP-2 is approved and funded, construction would take place between 2028 and 2032, with operations beginning when the detector is finished and continuing for the full HL-LHC run.

6.6.7 Moller

Physics Goals / Highlights: Moller is a currently under-construction experiment designed to precisely measure the weak mixing angle $\sin^2\theta_W$ at low energy utilizing the 12 GeV continuous electron beam facility (CEBAF) at Jefferson Lab (JLab). The target precision of 0.1% is 5x improved over previous measurements at similar energy scales, and will be comparable to the most precise measurements at the Z-pole. The theoretical prediction for the weak mixing angle value is very well predicted in the Standard Model, but many of the most precise measurements at high values are at tension with each other and with the SM prediction. An ultra-precise measurement at lower energies will enable a further test of the consistency of the Standard Model, and deviations from the SM prediction could point to physics beyond the SM.

Canadian Impact: The Canadian team of 8 investigators is playing a large role in the experiment, with primary responsibility for the construction of the 224 main electron detector components. The Canadian group represents 10% of the total collaboration, but is responsible for approximately half of the detector construction costs, reflecting their significant impact. Canadians have been involved in all stages of the main detector design and construction and readout.

Funding Expectations: The Canadian group has been supported by NSERC for personnel costs, and a 3.9 M$ (+2.1 M$ in-kind) CFI-IF award in 2020. No further construction or detector-related funding is required, but the group notes that with larger operating grants they have the capacity to train additional HQP.

Timeline: Parts production and main detector module assemply is ongoing at the University of Manitoba throughout 2025. Effort is expected to shift towards final assembly at JLab through the end of 2025 and into 2026, with final assembly in the Fall. Physics data taking is expected to run between 2026 to 2030 in 3 major runs. Analysis and final data-taking will continue to take place after 2030, but by 2035 the experiment is expected to be decommissioned.

6.6.8 Darklight

Physics Goals / Highlights: Darklight is a small spectrometer experiment at the TRIUMF Ariel e-Linac. The primary measurement goal is a search for a dark photon, which could be produced in scattering the electron beam from a tantalum target. The dark photon would be measured via its decay to an electron positron pair, measured by the detectors as a peak over the background distribution. The search is particularly motivated by the X17 anomaly which can be explained by a new boson (potentially a dark photon) at a mass of 17 MeV. The experiment is currently constructed and undergoing commissioning with a 30 MeV beam, and a subsequent upgrade of the TRIUMF e-Linac to 50 MeV would enable the search for the X17 anomaly.

Additional nuclear physics measurements, such as radiative corrections to Møller scattering, Bethe-Heitler cross-sections, and elastic electron scattering at low Q^2, could also be performed by the DarkLight detector or small upgrades.

Canadian Impact: The Canadian team has played a leading role in the experiment. Canadian responsibilities have included overall project management (with an investigator as spokesperson), beam delivery, trigger design and construction, simulation and data analysis, and data acquisition. Canadians have also led the detector integration and commissioning phase, and are expected to play a key role in data taking and subsequent analysis. 8 Canadian investigators are part of the project.

Funding Expectations: The Canadian group is funded by NSERC for both personnel costs and detector development and construction. A NSERC RTI award is also being used to fund the 50 MeV accelerator upgrade. No significant further funding requests are expected for this phase of the DarkLight project, though upgrades for the nuclear physics oriented measurements may lead to later CFI applications.

Timeline: DarkLight is expected to take data at 30 MeV in 2025-2026, and to upgrade the beam energy during 2026-2027. Data taking at 50 MeV with a goal of 1000 hours of stable beams would take place in 2028, at which point the current main physics goal will be in reach after data analysis. The collaboration may later turn its attention to the nuclear-physics related goals or further upgrades to enable other measurements at the ARIEL e-Linac.

7 Community Infrastructure

7.1 Accelerator Science

Accelerator Science is a discipline that enables research, drives discoveries, and fosters innovation across many fields of science. It is supported by a vibrant Canadian community of internationally recognized researchers and students. Particle accelerators support a wide range of experimental subatomic physics programs. The Accelerator Science community actively pursues R&D to improve existing facilities and develop technologies for future ones. These efforts open new opportunities in subatomic physics and push the boundaries of achievable performance.

TRIUMF is Canada's centre of excellence for Accelerator Science and Technologies, leveraging its infrastructure and expertise to develop new technologies, expand capabilities, and train the next generation of talent. The laboratory has internationally recognized strengths in three key areas of Accelerator Science: superconducting radio-frequency (SRF), beam dynamics, and high-power targets for secondary particle production, including remote handling technologies.

The TRIUMF accelerator R&D program focuses on upgrading beam intensities, developing advanced high power targets, enhancing post-acceleration capabilities for instance in beam energy, SRF fundamental science and integrating machine learning into accelerator tuning. Applied developments include high-gradient cavities, remote handling systems, model-based control systems, and the next generation of ion sources. Collaborative efforts leverage national and international partnerships, notably through partner universities, CERN, the RADIATE collaboration, and US accelerator projects.

On the medium-term, planned milestones include the completion and full operational ramp-up of the ARIEL facility, modernization and enhanced capabilities of ISAC accelerators, and initial upgrades to the TRIUMF cyclotron for higher beam intensities, required for the ARIEL ramp-up. Nationally, TRIUMF will support the development of THz radiation technologies and the realization of a compact accelerator based neutron source (CANS). Internationally, TRIUMF will: deliver five cryomodules for HL-LHC; prototyping a wire corrector for the long-range beam-beam effects in LHC; strengthen contributions to Electron Ion Collider (EIC) beam physics and SRF technology and to the Future Circular Collider. Education efforts will expand with enhanced national courses and a broader student training network. Critical infrastructure like upgraded high-power beamlines, enhanced SRF support infrastructure, new ion sources, and material testing facilities will be developed. Special focus will be placed on targeted R&D efforts aimed at enabling technologies that are reaching a tipping point, such as high-temperature superconducting accelerator magnets, SRF materials and processes, machine learning and robotic assembly.

7.1.1 TRIUMF 7 Year Outlook

From 2027 to 2034, TRIUMF will focus on realizing significant milestones: achieving 400 µA cyclotron operation, commissioning ARIEL at full capacity, and delivering 100 kW e-linac operation for RIB production. Essential upgrades to the H- source, injection beamline, and BL1A refurbishment will enhance high-intensity operations and reliability.

For ISAC, the full exploitation of CANREB capabilities will optimize beam preparation, employing advanced charge breeders, mass separators, and yield stations. Target development will be accelerated, including the demonstration of 100 kW capabilities for the electron-to-gamma converter and the installation of the first ARIEL laser ion source for element-selective RIB delivery.

At the same time, groundwork for next-phase upgrades will be laid: design studies for a multi-reflection time-of-flight (MR-TOF) analyzer, plans for an additional e-linac cryomodule. Depending on the support of the SAP community, we will produce a Technical Design Report (TDR) for a low-energy heavy ion storage ring at ISAC-I, and explore electron scattering on trapped radioactive ions, with the goal of producing a TDR for a high-brightness SCRIT-like facility that would leverage TRIUMF's record-breaking RIB intensities. TRIUMF also aims at gaining expertise in the rapidly developing high-Tc coil technology by constructing a first demonstration high-temperature superconducting (HTS) accelerator magnet on site. International collaborations, particularly contributions to the EIC through spin dynamics studies via SuperKEKB and in-kind contributions of SRF technology will strengthen Canada's accelerator science presence on the world stage.

7.2 Computing Resources

Computing is an essential component and integral part of the overall Canadian subatomic research programs. The subatomic physics community has access to both specialized facilities, including the Canadian ATLAS Tier-1 Centre, and shared resources provided by the Digital Research Alliance of Canada or "Alliance", which recently replaced Compute Canada. Large-scale distributed computing and data storage, and their efficient and reliable management and operation, are paramount to the success of several high-profile experiments and projects, requiring an agile complement of highly skilled and experienced personnel. Equally important, development and applications of state-of-the-art machine learning techniques has significantly increased during the past number of years and is continuing to rapidly grow with paradigm shifts underway. Additional personnel supporting this area is key going forward.

7.2.1 ATLAS Tier-1 Centre and Distributed Computing Operations

For more than a decade, TRIUMF has been hosting and operating the Canadian ATLAS Tier-1 Centre, one of ten centres worldwide as part of the Worldwide LHC Computing Grid (WLCG). The centre provides large-scale and dedicated resources necessary for the storage of the raw and secondary data sets, as well as computing capacity for data processing, simulation, and physics groups activities. The Tier-1 Centre is fully integrated within the overall ATLAS distributed computing operations worldwide and provides essential services to the entire collaboration and needs to be operated 24/7 by dedicated personnel. The Tier-1 systems and associated services are maintained in a highly secure environment and designed for high resiliency and performance. In 2018 the centre has been relocated to Simon Fraser University and co-located with Cedar at the Alliance in response to a national policy to consolidate high performance computing in a limited number of sites for efficiency and economy of scale. The Tier-1 Centre is funded by CFI and continues to be operated by TRIUMF personnel.

The ATLAS Tier-1 centre must also expand significantly to process dozens of petabytes (PB) each year. Upgrading the Canadian Tier-1 Centre is a substantial endeavor, requiring considerable effort and the coordinated deployment of hardware and software frameworks, beginning in 2026 when critical aging infrastructure needs to be refreshed, enabling participation in upcoming HL-LHC data challenges. An innovative storage and networking infrastructure will be essential to efficiently store and distribute data around the clock, in alignment with international commitments. The required personnel will focus on developing crucial software frameworks to maximize the research program's full potential through the efficient use of a hybrid computing infrastructure. Scientific Computing will continue to identify opportunities and guide the execution of AI and Quantum Computing projects enhancing science outcomes in the domain of accelerator-based science at TRIUMF and across Canada. This includes playing an important role in the evolution of the national digital research infrastructure strategy, and collaborating with institutions regarding the AI Sovereign Compute Infrastructure Program recently announced by the Canadian Federal Government.

7.2.2 Status of the Alliance Support for Subatomic Physics

It is important to note that the Alliance has stated that no current funding program exists for which the ATLAS Tier-1 Centre is eligible, rendering the CFI IF 2025 competition program the only viable federal source of funding going forward.

7.2.3 Summary of the Computing Landscape for particle physics

Canadians are members of the Worldwide LHC Computing Grid (WLCG) via ATLAS, where we are required to pledge resources annually to the experiment. Canadians also play a leading role in the use of cloud computing for high-energy physics. That work has also been funded by CFI, through CyberInfrastructure awards. We anticipate that there will be further requests for support of this program in the coming years, though there are no future CyberInfrastructure competitions planned, so this funding may need to be sought from other sources. Details of future Tier-2 and Tier-3 computing, which is based on shared resources, will depend on the evolving infrastructure refreshment and expansion model of the Alliance.

7.2.4 Large Computing Requests from Other Collaborations

Most other IPP-related projects have more modest computing needs that can be accommodated through the usual allocations obtainable on Allinace resources. A few experiments require specialized infrastructure, which in some cases may require substantial additional funding. These are listed below.

- Belle 2: The Canadian group operates a RAW Data Center that holds 15% of the raw data sample. This facility was funded by a CFI award and is operational since 2024. The facility is expected to grow in coming years as the dataset grows.
- HyperK: The experiment will require substantial computing resources over the decades of operation and analysis. A detailed operational and funding plan is being drawn up to allow Canadians to contribute the 10% share commensurate to their size of the collaboration, which may include a Tier-1 style center at TRIUMF and Tier-2's at other locations. The total computing needs through 2033 are estimated to be 8 PB of storage and 10,000 core-years of CPU.
- GADMC: The DEAP collaboration utilizes 800 cores per year, along with 2 PB of disk and 3 TB of tape, through the Alliance research group allocation. The ARGOLite detector, and simulations for ARGO, are expected to require 1500 cores per year, with 20 PB of total storage. Support of DarkSide-20k will require 12,500 cpu cores, 4.6 PB of tape, and 5.8 PB of disk storage. These are currently handled through yearly Allinace research group allocations, which present significant planning uncertainty and instability compared to other computing support schemes.

7.3 Emerging Precision Technologies (Quantum Sensing, etc.)

Advances in particle physics and fundamental research have often been precipitated by developments in detector technology. In recent years, new developments in experiments and devices utilizing quantum technologies have become more accessible. These technologies in many cases build on previous developments in the SAP community, such as superconducting transition-edge sensors in CDMS, or precision optical tests of atoms such as in ALPHA. Planned and ongoing experiments in this area also include interferometers for dark matter and tests of gravity, EDM experiments such as TUCAN and RadMol with powerful sensitivity to BSM physics, quantum detectors for sterile neutrinos in the BeEST experiment, and precise experiments utilizing entangled quantum states.

The community has pointed out that there is an opportunity to expand Canada's utilization of these technologies by exploiting connections to the national quantum ecosystem. Canada's current National Quantum Strategy is focused fairly narrowly on commercialization of computing and sensing applications, and misses an opportunity to develop technology and applications in fundamental physics, which have long been able to push the technological state of the art and enable later benefits to industry. International funding bodies have established dedicated funding streams to nurture the development of the application of these quantum technologies for fundamental research, and given Canada's strong existing experience in this arena motivates a similar approach. TRIUMF is aiming to develop a center for quantum sensor development in its 20-year outlook, which could provide a critical mass to make significant developments in this arena.

8 Training of Highly Qualified Personnel

One of the benefits of training excellent particle physics students is the impact they have in the world after they are no longer our students. We list here a small selection of stories of our highly qualified personnel (HQP), which provides a taste of the types of impact the field has in training them.

- Doug Schouten: completed an ATLAS PhD at SFU in 2011, then worked for three years as an ATLAS Research Associate at TRIUMF. In 2014 he took a position working for CRM Geotomography Technologies, at that time a tech-transfer spin-off company working out of TRIUMF. He rapidly rose to the position of Chief Technology Officer, and has been a key member of the team that has brought the company to full independence as Ideon Technologies Inc, based in Richmond BC. Ideon is a world pioneer in the application of cosmic-ray muon tomography, with a discovery platform integrating proprietary detectors, imaging systems and AI techniques to provide X-ray-like visibility up to 1 km beneath the Earth's surface. By transforming the data into geophysical surveys and 3D density maps, Ideon helps geologists identify new mineral and metal deposits with precision and confidence, reducing cost and minimizing environmental impact. Doug is the co-founder and CTO of Ideon.

- Lorraine Courneyea: following a ATLAS PhD with the University of Victoria in 2011, Dr. Courneyea continued as a postdoc with the Victoria group before moving into a position as a Clinical Medical Physics Fellow at the Mayo Clinic. In addition to the clinical training, this residency included a research component. She led research projects that focused on preparations for the Mayo Clinic proton centre which began patient treatments in June 2015. These projects included hardware design, improvement of patient immobilization, and simulations of RBE dose in particle therapy, all of which benefited from her past experience in particle physics. Dr. Courneyea is now a Medical Physicist at the Odette Cancer Centre at the Sunnybrook Health Sciences Centre and holds an academic appointment in the Department of Radiation Oncology at the University of Toronto.

- Jorge Armando Benitez: is originally from Bogota, Colombia, where he completed two Bachelor degrees, in Physics and Electrical Engineering, at the Universidad de Los Andes. After obtaining his PhD in particle physics from Michigan State University, Lansing, USA, he joined York University as an ATLAS postdoc in 2009, where he worked on electronics and firmware troubleshooting for the Transition Radiation Tracker Readout Drivers and performed a search for stable massive particles in the SUSY group. In 2015, he joined Patym Labs as a Data Scientist and founded a very active Data Science and Deep Learning Meetup group in Toronto. He moved to BMO Capital Markets in 2016, where he is now Managing Director and Head of Quantitative Engineering and AI. He has also been teaching continuing-education courses in data engineering and machine learning at the University of Toronto, since 2017.

- Andrée Robichaud-Veronneau: started in particle physics as an undergraduate summer student at McGill, working on data acquisition electronics for a spark chamber. She later became a McGill MSc student on ZEUS, spending most of her time at DESY. She did a PhD at the University of Geneva and a postdoc at Oxford, before returning to McGill to work, from 2014–2017, on the ATLAS NSW project, where she was instrumental in setting up the lab for the sTGC cosmic-ray testing. She is now with Ciena, a Telecommunication company in Montréal, as a Data Scientist. She writes in her LinkedIn page: "Particle Physicist by training, delving into the telecommunications world and applying statistical and data analysis concepts to the industry and customer needs" and "Software development and machine learning for the Telecom service industry." In this role, she quickly recruited another ATLAS-Canada trained HQP, Lévis Pepin, who did an ATLAS MSc at McGill.

- Rocky So, data engineer at Softmax Data, a consulting firm, and at delecta Technologies, a start up, both based in Vancouver. In one of his projects, he worked with Technical Safety BC to develop methods to identify abnormalities in elevator operations using internet-connected accelerometers, a project that was beyond the capabilities of the in-house data scientists.

- David Asgeirsson: His career has included being the Chief Operating Officer of QD Solar, a start up developing new solar energy technology, and the Director of Business Development for physical sciences at TRIUMF. He is currently the president of Runewheel Management Services, a technology venture consulting firm specializing in academic spinoffs.

- Alexandre Beaulieu: Alex's undergraduate training as an engineer, combined with his MSc and PhD in particle physics, has led him into career in an engineering consulting firm. He is currently Vice President of Skadra (formerly LTI) Software and Engineering in Montreal after serving as Regional Director. Skadra is a consulting firm of IT experts, scientists and engineers with a focus on helping manufacturers improve productivity through the application of science and technology.

> *I am a Graduate Seismic Analyst at Viridien, Calgary Alberta. The data analysis skills learned in particle physics are invaluable in interpreting complex data sets and arriving at summaries and conclusions for clear presentation.* Charlie Chen, University of Victoria, PhD 2024.

> *I am a process engineer working for nLIGHT, Vancouver Washington, responsible for designing and implementing high-quality and reproducible optical coatings for high-power infrared laser diodes used in various applications. The skills learned in particle physics are ideally suited towards developing expertise in technical fields, and leading teams in complex projects.* Evan Carlson, University of Victoria, PhD 2024.

IPP would be glad to assist the LRP in highlighting examples of successful HQP training.

9 Equity, Diversity, and Inclusion

The IPP community has long acknowledged the pervasive systematic barriers that lead to underrepresentation of women, 2SLGBTQI+, indigineous peoples, and racial minorities in the participation of particle physics in Canada. While there is no single action plan for improving conditions and opportunities in order to address this inequality, all submissions for the LRP process were asked to submit information about their activities addressing Equity, Diversity, and Inclusion (EDI). The report here highlights some **examples** of successful community efforts.

9.1 ATLAS

Equity, diversity and inclusion is a key priority of ATLAS-Canada, and after discussions in a dedicated task force in 2022 ATLAS-Canada expanded its management structure to include an EDI Coordinator, who chairs the newly formed EDI Committee with representation from graduate students, postdocs and faculty. The EDI committee regularly reports to the rest of the collaboration on best practices and ongoing concerns, allowing management to respond as needed.

The international ATLAS Collaboration has both an Early Career Scientist Board (ECSB), established in 2015, and an Equity, Diversity and Inclusion Office, established in 2024 expanding the work of the Contacts for Diversity and Inclusion, which were in place since 2017. Two Canadian faculty members were instrumental in the creation of the ATLAS EDI Office. Canadians are also very involved in the ECSB, with a range of students, postdocs, and faculty with ties to Canada sitting on the Board. Canadians also contribute to the work of these groups via ATLAS Management roles, in particular, as Deputy Spokesperson.

The diversity of ATLAS-Canada is similar to that of the international ATLAS Collaboration, with a broad variation of age, gender identity, sexual orientation, physical ability, race and ethnicity represented. The makeup of the ATLAS-Canada faculty group is determined more by university hiring practices than by ATLAS Canada policies, but one notes that four of the six new investigators who have joined the ATLAS-Canada group since 2019 are women, including three former ATLAS graduate students. In terms of the faculty FTE committed to ATLAS, women now represent almost 20%. The PDFs are arguably the group for which ATLAS Canada has the most control over the gender balance; currently, about 20% of ATLAS Canada PDFs are women. Among ATLAS Canada graduate students, the fraction is about 25%. These student and PDF fractions are similar to those in recent years. Finally one notes that about 33% of ATLAS Canada current HQP identify as racialized.

9.2 Belle II

The Belle II collaboration is governed by a set of bylaws and policies, including a Code of Conduct that explicitly affirms a commitment to principles of equity and inclusion. One Canadian PI, as a former chair of the collaboration Institute Board (IB) and chair of the Governance Committee, was instrumental in defining these policies and the Code of Conduct. A second PI, as chair of the Belle II Executive Board, is committed to ensuring that the principles contained within these documents are respected. This Code of Conduct helps address the varied EDI experience across the internationally diverse Belle II collaboration and helps foster an inclusive working environment for all members. Two Canadian PIs have served as one of the two Diversity Officers for the collaboration. The Diversity Officer serves as the point of contact and Ombudsperson for issues related to EDI and the Code of Conduct, as well as being responsible for new EDI initiatives within the collaboration. A Canadian PI currently holds the position, organizes and chairs regular Belle II Diversity and Inclusion Sessions, which provide a forum for HQP to discuss ongoing EDI initiatives and propose new action items. A noteworthy highlight of local initiatives from collaboration members is the support of the Dr. Verna J. Kirkness Science and Engineering Education Program for Indigenous High School Students, which runs at the University of Victoria and University of Manitoba. This program invites Indigenous high school students from across Canada to visit the university and engage in a week of physics demonstrations, lectures, and hands-on tutorials. Programs like this are critical in engaging some of the most underrepresented and marginalized groups in Canada, and should be considered by all IPP members.

9.3 PIONEER

Canadians have also been leading the EDI activities of the PIONEER collaboration. A Canadian PI was the founder and first elected chair of the EDI committee, which instituted a formally adopted Code of Conduct for the experiment. The EDI committee has pursued several noteworthy initiatives. First, they have created a mentoring program to support junior members of the collaboration, and adjust the program to take into account feedback from previous rounds. Additionally, the EDI committee invites outside speakers to discuss EDI matters during collaboration meetings, allowing for perspectives from different communities to cross-pollinate. These outside speakers often present at events that are open to the community, allowing a broader impact for the discussions.

9.4 HyperK

While the above examples focus on community outreach and establishing better working conditions within collaborations, the Canadian HyperK has taken a unique approach by actively pursuing applications of detector technology which can be useful to marginalized communities. In particular, the HyperK group has taken the lead on developing water-quality monitoring technology using pulsed LEDs and SiPM readout. This technique was developed primarily for the purposes of the HyperK experiment to validate the optical properties of water, but is also senstitive to common pollutants and microbes. The HyperK team has been actively collaborating with First Nations University to transfer the technology to applications for in-situ drinking water testing in remote communities. Currently testing can only be performed in laboratory settings after water samples are collected and shipped, so an in-situ monitoring could have dramatic impacts on the reliability of water supply monitoring in remote locations.

9.5 IceCube and P-ONE

The research team regards EDI as foundational to the advancement and sustainability of scientific, academic, and broader societal communities. Guided by the Gender-Based Analysis Plus (GBA+) framework, the team integrates EDI principles at critical stages of the research process to foster environments that are open, inclusive, and safe for all participants. Within IceCube, the team established the initial EDI Task Force, which conducted comprehensive environment surveys to assess the collaboration's research culture and identify areas for improvement. These efforts directly informed the development and ratification of key governance structures, including a Code of Conduct, an Ombuds program, and a formal complaints policy. Additionally, the team initiated the IceCube Impact Awards to recognize individuals and groups whose contributions advance the collaboration's mission through EDI, education, and outreach. The EDI Task Force has since evolved into a core working group that coordinates events highlighting underrepresented groups in science, such as the International Day of Women and Girls in Science, LGBTQ+ in STEM, and Black in Physics. Building upon this foundation, the team is applying similar EDI principles to the governance of the P-ONE project, where one of the first official actions was the appointment of EDI officers to ensure that inclusive practices are embedded from the project's inception.

9.6 GADMC

The GADMC is composed of several different experimental collaborations, and each has taken serious steps to ensuring EDI concerns are addressed appropriately. THE GADMC itself has an appointed EDI officer position, who is responsible for creating, updating, and enforcing the Code of Conduct for the collaboration. Additionally, the DEAP, DarkSide, and ARGO collaborations each have a number of ombudspersons whose role it is to mediate and resolve sensitive issues between collaboration members. Additionally, two "younger members' representatives" are selected to join the DEAP Board, to significantly broaden the representation in the experiment's governing body.

9.7 Conclusions

Canadians have for many years played a leading role internationally in establishing EDI practices in our communities. While much remains to be done in terms of increasing diversity and accessibility along the lines of gender, racial, disability, and other forms of protected status, nearly all the community submissions to the IPP process showed a strong commitment to improvement and awareness of the issues. Moreover, many groups are clearly innovating in the structures of their collaborations to provide new mechanisms to address these problems, and even finding new applications for technology to address societal equity issues. **We recommend that all projects consider their organizational structures and whether ideas from the community could be useful for addressing EDI. We also recommend that all**

projects continue to encourage outreach to address access pipelines, and to consider technology spin-offs when appropriate.

10 Outlook

This section provides an executive outlook for all research areas within IPP that is based on the project submissions. Future challenges related to projected funding requests are highlighted but no recommendations for specific projects are made. As highlighted in the past within the IPP, the Canadian particle physics community is sufficiently small that its physics reach is better served by focusing efforts on one project in each field/area/accelerator where there is direct competition with little or no complementary [5].

10.1 High energy frontier

At the energy frontier, ATLAS is the essential project in Canada. ATLAS covers a breadth of physics studies, including the direct search for new TeV-scale particle production, and also precision measurements of the Higgs Boson properties, top-quarks, vector bosons, and other Standard Model particles. Such precision measurements are sensitive to physics at very high energy scales. The upcoming High-Luminosity (HL-LHC) period is a major upgrade to be installed at CERN during the Long Shutdown 2026-2030. Most of the ATLAS contingent are heavily involved in this program. ATLAS-Canada has received about $30M from CFI in equipment, labour and infrastructure costs for detector upgrades for the HL-LHC. In addition, Canada is designing and building cryogenics modules to house new magnets which will focus the HL-LHC beams and increase the number of proton collisions in ATLAS and CMS; this $12M project is managed by TRIUMF, working with Canadian industry to produce five crab cavity cryomodules from (2025-27). As the *largest* subatomic physics project in Canada in terms of numbers of engaged grant-eligible researchers, and with a uniquely broad physics program, it is essential that ATLAS be adequately supported during the HL-LHC period.

The FCC-Canada collaboration is expected to be formed in the next few years and first physics and detector studies are likely to begin as the European Strategy for Particle Physics is updated. Seed funding for these R&D stages will be required in the short-term, with larger requests to be expected in the mid 2030's for detector construction and installation at CERN. It is a core focus of the ATLAS-Canada collaboration to preserve current detector development and construction knowledge and allow for a seamless transfer from the ATLAS upgrade activities to FCC detectors. This will cement Canadian leadership in future FCC experiments.

10.2 Precision collider physics

Belle II is an essential project at the precision frontier and the physics program is complementary to the ATLAS program. Belle II operates at much lower energies and explores how new physics might subtly alter known particle behaviors through precision measurements. The statistical power enabled by the unprecedented size of the Belle II dataset will allow such precision measurements and searches for rare or forbidden decays to constrain virtual interactions from new heavy mediators at mass scales up to several TeV. The Canadian Belle II collaboration is *large* within the particle physics community. The Belle II precision physics goals will require data to be collected throughout the 2030's. Canadian collaborators are heavily involved in the studies for a future Chiral Belle phase. This SuperKEKB upgrade would introduce polarized beams and improve the sensitivity for targeted precision measurements further. If the Chiral Bell upgrade would be approved the collaboration is expected to request substantial CFI funds for this phase and data taking would continue through approximately 2040.

10.3 Small accelerator-based projects

Targeted, smaller scale experiments such as PIONEER, MATHUSLA, Moedal-MAPP, and Moller complement the larger accelerator-based projects and provide important physics reach that is otherwise inaccessible. The self-declared Canadian collaboration size for all these projects ranges between *tiny* and *small*. Going forward, it will be important to enable affordable contributions commensurate to the Canadian interest. The Moller experiment is a good example of a successful formula, with a substantial Canadian community supporting a critical but moderately-costed contribution to the international experiment. In the coming LRP period, several experiments in this category will be seeking significant funding for construction, and it is unlikely that several of these projects will receive the CFI funding needed to move forward. Prioritization, based on community engagement and complementary physics reach, will be required.

10.4 Long baseline neutrino oscillation experiments

In Canada, the Hyper-Kamiokande (HyperK) experiment has a significant participation due to a long-term involvement with the previous experiments like Super-Kamiokande and T2K to which the Canadians have extensively contributed instrumentation and data analysis. The Canadian leadership on the Intermediate Water Cherenkov Detector (IWCD) design and construction, as well as the Water Cherenkov Test Experiment at CERN, along with essential contributions to the calibration of the far detector have been supported by significant CFI-IF grants. The HyperK experiment offers an excellent opportunity for discoveries in the neutrino sector via the study of fundamental properties of neutrinos, probing CP violation in the lepton sector, and studying their mass ordering hierarchy. For the next decade, increasing the Canadian participation to HyperK would be highly constructive to capitalize on previous hardware and instrumentation contributions and ensure Canadian leadership in key physics searches.

In parallel, DUNE offers interesting detector R&D challenges, detector system developments, and the opportunity to work with novel LAr TPC signal extraction techniques for which the Canadians are leaders. DUNE has a strong physics potential on a longer time-scale than the HyperK experiment. The key research goals of both experiments are very similar but the respective approach and technologies are complementary. The current Canadian group in DUNE is *small* with a projected modest growth until 2030.

Resource limitations within the Canadian funding agencies will make it very challenging for the Canadian community to play leading roles in two major flagship experiments that share the same key research goals.

10.5 High Energy Neutrinos

The IceCube experiment has opened the new field of neutrino astronomy and is starting to identify a first catalog of neutrino sources. New physics searches, cross-section measurements, and the successful detection of ν_τ and Glashow events demonstrate that neutrino telescopes are versatile high-energy particle physics experiments. Additionally, IceCube has accumulated a high statistics data set of neutrino events that allows to set world-leading neutrino oscillation measurements. These measurements will further improve with the IceCube-upgrade (installed during season 2025/26) that contains new calibration instrumentation and additional detection modules. Canadian activities in IceCube will focus on data analyses that are enabled and further improved with the IceCube upgrade. The astrophysical neutrino flux extends well beyond the observed PeV range, and the success of IceCube has demonstrated that groundbreaking neutrino physics can be explored with neutrino telescopes if a new generation of detectors would be available. Looking toward this next generation of neutrino astronomy, Canada is spearheading the Pacific Ocean Neutrino Experiment (P-ONE), a complementary multi-cubic-kilometer observatory planned for deployment off the coast of Vancouver Island. This initiative leverages the existing infrastructure and expertise of Ocean Networks Canada's (ONC) NEPTUNE Observatory and has the potential to continue Canadian leadership in neutrino experiments hosted in Canada. The Canadian high-energy neutrino group is *medium* in size and expects to grow throughout the next years coinciding with the completion of the CFI funded P-ONE Demonstrator phase. Together with international partners and ONC, the Canadian P-ONE collaboration is expected to request substantial CFI funds for the next project phase.

10.6 Direct dark matter detection

The field of experimental dark matter searches is heading towards a decision point in the near future. Up to now, many experiments, methods, laboratories and target materials are competing with very limited pressure for experiments to join forces. In the past years one technology has been leading the field: liquid xenon detectors for both spin dependent and spin independent interactions in the mass range of vanilla WIMPs. These experiments have made significant progress constructing and operating very large liquid xenon time-projection chambers with three international collaborations in competition: LZ (largely UK-US), Xenon (largely European) and Panda-X (largely Chinese). The LZ and Xenon collaborations have decided to combine efforts, forming the XLZD collaboration. Internationally, this experimental technology has the largest momentum, community, and builds on an outstanding record of scientific results. This next generation xenon program has a clear path to utilize the presence of double beta decaying isotopes in the target mass, making a multi-purpose detector easier to conceptualize, unlocking synergies between these two physics goals. Such an experiment could have the potential to build on the Canadian expertise in xenon based double beta decay experiments. XLZD has not made a final selection of host laboratory. Attracting the experiment to Canada would be a major achievement for our community, challenging Canadian researchers to join this effort.

In the field of low mass dark matter searches several technologies are still vying for the most promising detector technology: bolometric, CCD, and bubble chamber detectors all promise to cover interesting phase space. Significant progress has been achieved by the skipper CCD based experiments. With SuperCDMS coming on-line in 2025 the reach of the improved high voltage detectors will be demonstrated and the sensitivity of CCDs can be compared to the larger SuperCDMS detectors and soon also to the argon based bubble chamber of SBC. One advantage of the CCD based detectors is the strong industrial connection that exists for the production of CCDs. Many of the low mass dark matter projects have no strong industrial backing, less community support or face difficulties to demonstrate effective scaling of the method to the next generation.

Dark matter searches, because of the large range of viable masses, will for some time have room for small scale experiments exploring particular areas of the mass range, such as HeLioS.

The currently operating projects with significant Canadian involvement are the DEAP-3600, PICO, SBC and sCDMS experiments. All of these experiments are expected to reach a natural end once their design sensitivity is reached during this LRP period or shortly thereafter. If new experimental breakthroughs of their respective technologies allow these experiments to significantly progress and reach scientifically relevant sensitivities, these experiments can be expected to thrive and grow further. In this context, Argon based dark matter searches have advanced significantly in recent years, owing to DEAP and the DarkSide liquid Argon TPC. DarkSide-20t is aiming to demonstrate successful delivery of a large argon based TPC with excellent background control until 2028. The realization of a future ARGO experiment in Canada would require a very large CFI funding request within the next ten years.

10.7 Search for neutrinoless double beta decay

Canada has a significant investment in neutrinoless double beta decay experiments. Both the Canadian SNO+ and the nEXO groups are sizable and are pursuing promising technologies to measure half-lives that will rule out most of the remaining parameter space of the inverted neutrino mass hierarchy. Both experiments are competing with the proven technology of Germanium-based detectors as pursued by the LEGEND experiment and the bolometric measurement used by Cuore. SNO+ and Kamland-Zen are pursuing isotopes (Xe and Te) dissolved in liquid scintillator, which allows good (affordable) isotope scaling and offers a well understood background model, but lower energy resolution. Kamland-Zen is currently leading the field with the longest excluded neutrinoless double beta decay half-live. CUORE, nEXO and Legend are pursuing a detector with low backgrounds and high energy resolution. The choices of isotope by nEXO and Legend (Xe and Ge) are making isotopic enrichment necessary which results in very high capital costs of these experiments. CUORE requires cryogenic operation, complicating the experimental setup. SNO+, using tellurium, offers a possibility of low cost scaling of the active mass if the background and the absorption of the loaded liquid scintillator can be well controlled.

The Canadian groups in both nEXO and SNO+ are impacted by a subcritical number of PIs compared to their extensive research objectives. The nEXO collaboration is currently reorganizing and trying to gather new momentum following the U.S. DOE's 2024 decision to prioritize LEGEND-1000. The collaboration would require a massive build-up of additional PIs in order to make a compelling case for the required large infrastructure investments into the experimental future.

10.8 Overview of project timelines

To better visualize the ongoing projects and their various timelines, Figure 1 shows a summary of what all the submissions have reported for their plans in the period 2027-2041.

There are six projects with potential overall Canadian project costs on the order of $100M or more under development. P-ONE is the only one that is technically ready to proceed in 2026. Four projects are aiming to be hosted by SNOLAB: ARGO, XLZD, nEXO and THEIA, all with slightly different timelines. The community will have to choose which of these projects are viable, based on their Canadian person power, international support and possible Canadian investment.

The future of the CERN program will likely be decided without Canadian representation since Canada is not a CERN member state. Once the decision for the new accelerator is made, Canada should be ready to contribute to secure access to the technological developments this machine will bring with it. It would also be good to position Canadian industry to participate meaningfully in the production of the high tech components that will be needed both for the machine and for the detector, as well as for the computing infrastructure.

This expected timeline highlights clearly that a decisive selection mechanism of projects and an adequate funding mechanism for such large scale projects is lacking. The absence of such a funding mechanism will be impacting Canadian science very significantly in the coming decade.

11 Scenarios to Study

11.1 Optimal Scenario

This scenario would be in line with the recommendations of the Report of the Advisory Panel on the Federal Research Support System [6], for “an annual increase of at least 10% for five years to the granting councils' total base budgets for their core grant programming.” Such a scenario would allow Canada to play a leading role in the physics (topics, projects) we deem essential, not decline any student admissions, and grow the number of postdocs and faculty accordingly. This scenario would financially look like this:

- CFI IF calls every two years, with envelope growth and special subatomic grant types that allow for project development and delivery. The Innovation Fund would grow +10% for every call.
- NSERC SAPES envelope would grow at least 8% year over year for ten years to allow increased output of HQP and attract incoming students to the field. This will allow new projects to grow and succeed and leadership in international flagship experiments to become even more visible.
- TRIUMF would get another significant injection of funds after the current 5 year plan is complete. This would allow the lab to build new infrastructure and lab space to support projects from across the country at a much increased rate and with new BAEs on national priority projects.

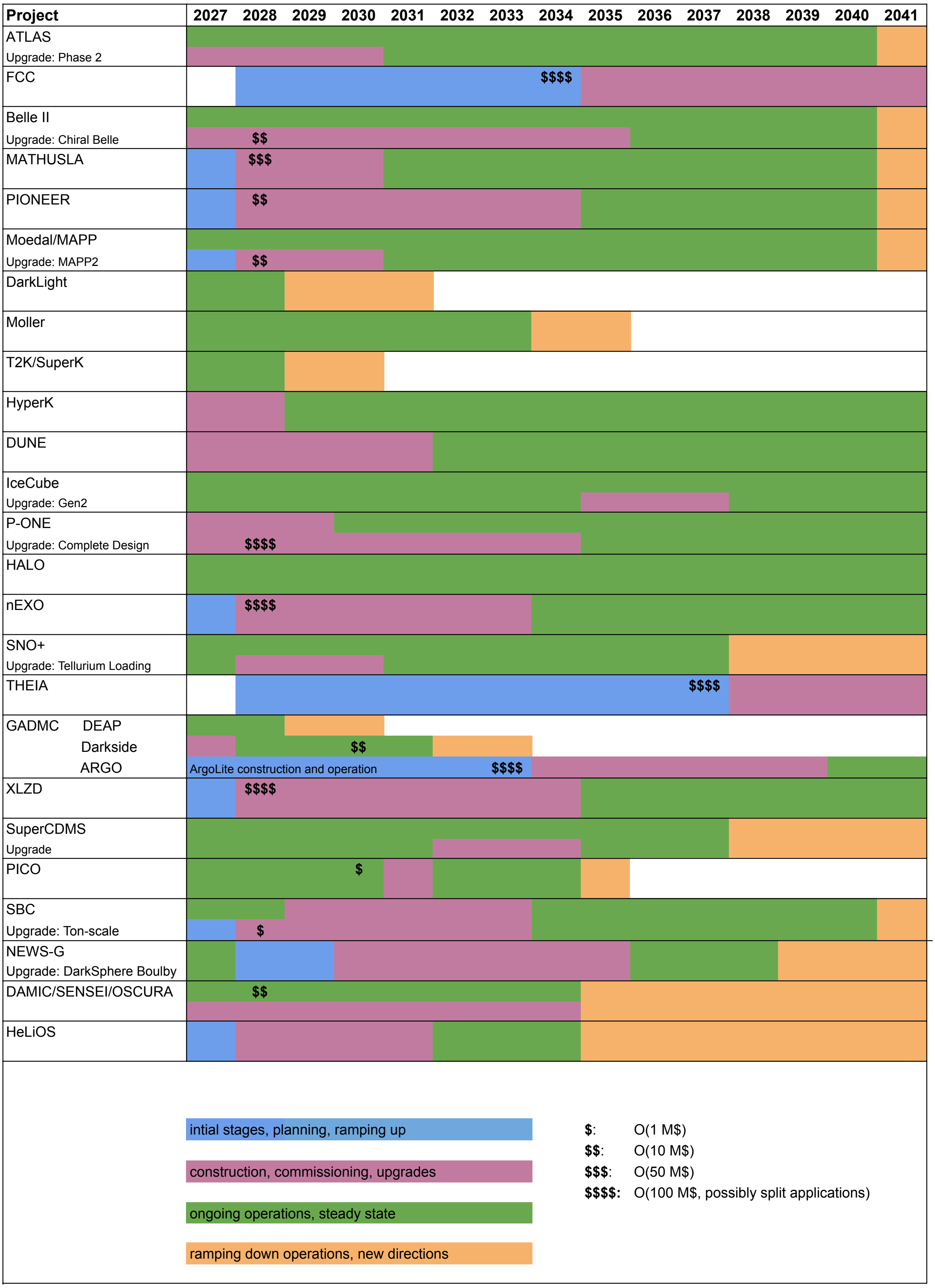

Figure 1: A sketch of the timelines of proposed projects related to the IPP. Filled colour bars indicate the stage of the project. Secondary rows indicate upgrade stages of ongoing experiments. Large CFI funding requests are indicated, including rough funding request levels by the number of $.

- The IPP would have to be developed into a larger organization with larger footprint, regular (predictable) hires and leadership potential. The funding would be decoupled from the SAPES envelope.

- The MacDonald Institute would become permanent and evolve into a national entity with global leadership ambitions supporting astroparticle physics. The funding stream should be independent of NSERC to allow the institute to hire faculty where needed. Evolving the Institute to cover more than just astroparticle physics and taking on the role of the IPP and CINP in the process could unlock additional synergies.

- SNOLAB and ONC would continue to be funded stably with an increasing funding profile allowing laboratory personnel to be involved in direct research efforts to fully leverage the existing expertise.

- Universities would have to subscribe to the idea of growing particle physics groups across the country to allow more principal investigators to be hired and more expertise to contribute to the flagship projects.

- Canada would become first an associate member of CERN, with the potential in time to become a full member. This would match Canada's leading role at the European Space Agency (ESA) via a formal Cooperation Agreement that has been renewed since 1979. CERN membership would allow Canada to reap the industrial benefits of membership and benefit from the training of engineers and scientists that only CERN can provide.

- Canada will be able to make world-leading contributions to future large scale projects, for example Niobium mined and produced by industry in Canada to develop superconductivity technology for the FCC at CERN.

11.2 Leadership Scenario

This scenario will allow Canadian leadership to blossom in one or two core projects inside or outside the country and hiring, infrastructure investment and student attraction would all be strategically be focused on these leadership projects.

This scenario is defined specifically by the following developments:

- In this scenario, the funding agencies would agree to support at internationally competitive levels a small number of flagship particle physics projects. All other projects would have to compete for a reduced pie. This formalizes a two-tier funding system that can result in many inequities, yet ensures competitive funding for the flagship projects.

- To allow the natural sciences to thrive, the project funding level would be increased so that all students in the field can get livable stipends.

- SNOLAB, TRIUMF, ONC and other host institutes of particle physics experiments would receive stable, predictable funding allowing to continue building world class infrastructure to support the Canadian knowledge industry.

- Canada would strive to become an associate member of CERN, or at least initially an Observer if this membership opportunity becomes available in the future. Funding for CERN membership would be separate from the SAPES envelope [7].

- Merging IPP, CINP and the McDonald Institute could make the roles of all three institutes sustainable and elevate their status to play a formal role in the community and internationally.

11.3 Structured Decline Scenario

In this scenario new funding would be focused to several core projects inside and outside the country with no now hires at universities and only a small increase of infrastructure funding. This will mean an overall loss of capacity as the grants are eroded by inflation, but the increased focusing on core projects would allow to maintain key leadership, involvement, and relevance. This scenario is defined specifically by the following developments:

- No or little new funding will be made available through NSERC and CFI for particle physics. However, changed priorities and collaboration between agencies allows support for a small number of flagship particle physics projects at levels allowing researchers to compete internationally. All other projects have to compete for a much reduced pie. This formalizes a strong two-tier funding system that can result in many inequities, but ensures predictable funding for the flagship projects. CFI and NSERC achieve improved outcomes by improved integrated long term management of projects.

- The role of TRIUMF, SNOLAB and ONC as host organizations for local and international experiments is diminished by their ability to mobilize funding to provide key contributions.

- Student and postdoctoral stipends continue to erode leading to reduced attractiveness to both national and international candidates, impacting Canadian research and intellectual capacity negatively.

11.4 Loss of Capacity (Flat-Flat) Scenario

In this scenario no new funding would be injected into the system, all capacity will erode over time and only partial relevance and strength can be maintained by individual choices and ideally community organization. Leadership opportunities will be missed, students will be turned away in increasing numbers and existing facilities are at risk. This scenario is defined by the following outcomes:

- Grant sizes continue shrinking and success rates are kept stable. NSERC grants lose more and more weight, while CFI grants fail to deliver the needed impact to international partnerships to get Canadians a place at the table.

- Student stipends and postdoctoral salaries further stagnate, attracting fewer and less impactful candidates. This impacts the ability of Canadian investments to be exploited to their full extent.

- Canadian Laboratories lose the ability to maintain their existing infrastructure and fail to attract international partners and risk becoming irrelevant.

11.5 Potential Economic Impact

In 2018, the European Physical Society (EPS) commissioned an independent economic analysis [8] from the Centre for Economics and Business Research (CEBR) on the importance of physics to the economies of Europe. The physics-based sector typically accounts for 16% of the total turnover of the EU28 business economy, which is more than the gross turnover contribution of the entire retail sector. The turnover (or revenue) of the physics-based industries within Europe has exceeded €4.40 trillion in every year of the period 2011-2016. Employment of people in physics-based industries within Europe reached 17 million people in 2014.

Canada's dedication to innovation, measured by R&D expenditure as a percentage of GDP, declined from 1.87% in 2021 to 1.81% in 2022 [9] and to 1.7% in 2023 [12]. This places Canada behind the G7 average and even further behind the OECD average. This decline is significant, especially as major competitors like the U.S., Japan and Germany increased their R&D investments during the same period. China's total R&D spending was 2.68% of GDP in 2024. A recent study [13] by the Institute of Physics in the UK concluded: "Increasing R&D investment to 2.4% of GDP by 2027 would generate an additional 80,000 jobs and £30.5bn in GDP."

12 Recommendations

1. SAPES needs to be strengthened:
   - The SAPES envelope needs to be retained and strengthened to maintain international competitiveness.
   - Closer integration with the CFI: The NSERC-CFI communication needs to happen at the scientific level, not only at the bureaucratic level.
   - A stronger strategic element of decision making needs to enter into the allocation of the SAPES envelope.
   - NSERC needs to be empowered to decide that a project has reached its natural conclusion.
   - Projects should be measured by how they lived up to the deliverables they set out to achieve in the previous grant. This level of accountability is currently absent in the NSERC review criteria.
   - A discussion within the community about the SAPES discovery grant success rate should be part of the LRP process.

2. The creation of a national institution, similar to other highly impactful national organizations (NIKHEF [14] in the Netherlands, INFN [15] [16] in Italy and CNRS/IN2P3 [17] in France) combining the efforts from IPP, CINP and possibly the McDonald Institute into a new national institute with a long term funding perspective and clear mandate to represent Canada internationally would allow to elegantly address the lack of stability in the funding for IPP and CINP within the envelope and the lack of dedicated Canadian representation at the international level. It could also open a pathway to make the McDonald Institute permanent by sharpening its mission to encompass all particle physics. Within this framework the stability of the current IPP research scientists program could also be addressed. To enhance Canada's impact internationally, the very highly regarded and very impactful IPP research scientists program should grow, yet in the current framework it is set to contract. We recommend maintaining full support for the IPP Research Scientist program.

3. Theory funding should be commensurate with the total theory community, acknowledging strong growth in recent years. It should be recognized that postdoc opportunities in Canada form a core, indispensable component of a healthy theory program, as it can take many years for students to build up to being able to make meaningful science contributions.

4. The CFI IF program should evolve to allow for continuous, long term projects that enable Canadian researchers to participate and lead international projects at the O($100M) level. The program would benefit building processes into the competitions that allow to consciously augment a project to react to evolving scientific realities as well as sunset a project that is not delivering.

5. The McDonald Institute has been providing critical services and technical support to the astroparticle physics community for the past 8 years. It is excellent to see that the Institute was extended. The IPP would like to see the funding path used by the McDonald Institute opened up to competitive proposals. This funding stream would close a significant gap in the national funding landscape. This would also allow the McDonald Institute to compete for a further continuation of its very impactful and successful service to the community.

6. TRIUMF is Canada's centre of excellence for Accelerator Science and Technologies. To ensure Canada remains competitive in accelerator science and its applications, targeted investments are necessary. Increased funding for research tools and infrastructure (RTI) is critical. Currently, Canada faces challenges both in training sufficient technical personnel for the accelerator science job market and in developing a robust domestic industry for

specialized high tech equipment. As a result, institutions are often forced to recruit internationally and purchase key technologies from abroad. Strengthening support for RTI would directly address this gap, boosting Canada's capacity to educate and retain highly qualified personnel while fostering domestic technological expertise.

7. SNOLAB has been an outstanding Canadian success story building on the legacy of the Sudbury Neutrino Observatory. In order to allow the lab to continue to evolve and become an international leader able to attract large next generation experiments, the evolution to the MRS funding envelope is overdue. If a large experiment is identified for SNOLAB, the funding framework for civil construction, infrastructure, and operation needs to be put into place. This would enable XLZD, ARGO or THEIA to consider choosing Canada as host location, benefiting the landscape and HQP enormously.

8. The MRS needs to be implemented and funded to allow large laboratories to maintain their leadership position. As part of this process, scientists that are currently funded through the CFI MSI program **need** to evolve to fully grant eligible scientists, similar to TRIUMF board appointed scientists.

9. In conclusion, we strongly support the recommendations of the Advisory Panel on the Federal Research Support System: "Given the staggering investments we see in other countries and the stagnating investment levels we see in Canada, a top priority must be increasing funding for research and talent. It is critically important that core funding of the granting councils be significantly increased to address:

    - the effects of inflation; and
    - the importance of nurturing a globally competitive research and talent base.

    Despite recent investments, research funding has not kept pace with these pressures over the past twenty years. An initial step would involve an increase of at least ten percent annually for five years to the granting councils' total base budgets for their core grant programming.

    Without internationally competitive funding for investigator-initiated research, Canada will fall behind in an increasingly competitive global marketplace and lose its status as an international magnet for talent and a research collaborator of choice" [6].

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