Craig Hogan
Director, Center for Particle Astrophysics
630.840.5523
cjhogan@fnal.gov

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Strategic Plan for the Future of the Particle Astrophysics Program at Fermilab

This documents outlines a broad plan for the development of Fermilab's astrophysics program over about the next ten years. It starts from Fermilab's 3-year particle astrophysics program proposal, approved after DOE peer review in the summer of 2013. Important inputs since then include the HEPAP/P5 report, the DOE/NSF Generation 2 Dark Matter program plan, the January 2015 PAC, the February 2015 Institutional Review, early implementations of Fermilab's new labwide strategic planning process, Fermilab's new LDRD program, and progress with collaborations and other labs in planning details of the next generation of experiments, particularly G2 dark matter, DESI, LSST and CMB/S4.

The basic organizing principle is based on science impact:

Our goal is to maximize Fermilab contributions to the scientific drivers in the HEPAP/P5 report.

Our cosmic experimental effort is organized along two main thrusts, cosmic surveys and dark matter. Within each of these there is considerable coordination among several experiments, that takes maximum advantage of the special capabilities of Fermilab. Both groups are in a period of transition from the successful current generation of operating experiments to a new generation. We first survey the program by experiment, and then provide a summary of how the transition will occur.

Cosmic Surveys to measure cosmic acceleration and neutrino properties

About half of Fermilab's experimental effort on the cosmic frontier supports precision surveys of cosmic structure, building on an enterprise that Fermilab helped establish about 25 years ago with the Sloan Digital Sky Survey (SDSS). Measurements of the structure and evolution of the universe reveal the action of new physics responsible for the acceleration of the expansion during inflation as well as today. Precision measurements also provide new information about the masses of neutrinos, and about possible new species of relativistic dark matter.

Dark Energy Survey (DES)

The main Fermilab survey effort is the Dark Energy Survey, with approximately 12 FTE scientists and 2 postdocs (which we aim to increase back to at least 3). Fermilab led the foundation of the project and collaboration, and the construction of its main instrument, the Dark Energy Camera. Fermilab continues to provide scientific leadership (including the Director), technical support for the collaboration, and management of survey operations.

The survey finished its second year of data taking in 2015, and will conclude survey operations in 2019. It will be the world's leading imaging survey until the Large Synoptic Survey Telescope starts operations in

~2022, and will significantly advance the frontier of precision cosmological measurement. Science results based on survey data began to appear this year.

Dark Energy Spectroscopic Instrument (DESI)

DESI, led by LBNL, is the successor to the SDSS/BOSS spectroscopic survey, and will extend its reach by an order of magnitude, particularly for precision measurement of cosmic parameters using baryon acoustic oscillation (BAO) structure. Fermilab is a major partner in the DESI project and collaboration, with both science leadership (including the co-Project Scientist) and well specified technical design and construction tasks. Fermilab contributions build on the scientific and technical expertise developed from leading design, construction, operations and science in the SDSS and DES surveys. As in DES, Fermilab will lead the development of key structural elements of the image corrector system, and the packaging and testing of the detectors; it will also build a telemetry database and fiber targeting software, building on SDSS.

Fermilab technical effort on DESI will grow with construction of the instrument over the next few years. DESI should start its multi-year spectroscopic survey around 2019. Fermilab effort will grow over these years, with activities including design, construction, operations and science. We anticipate a Fermilab team of about half a dozen scientists (about 3 to 4 FTE's), and two postdocs.

Large Synoptic Survey Telescope (LSST)

LSST has started construction of a dedicated imaging facility with an order of magnitude greater survey speed than DES, dedicated to a full time, ten-year survey that will produce a database of unprecedented precision, depth and coverage, to begin in the early 2020's. Fermilab will bring its scientific and technical experience from SDSS and DES to the LSST team, which is led by SLAC. Before and during survey operations, Fermilab is undertaking active participation and leadership in the LSST Dark Energy Science Collaboration, including development and support of software frameworks for dark energy science analysis, based on those now being developed and tested with DES. Discussions are now underway with project and collaboration leaders to clarify Fermilab's formal technical responsibilities during the operations phase, as well as the level of funded technical effort at Fermilab. Because of the broad scope and versatility of LSST, we anticipate that more than a dozen Fermilab scientists will eventually participate part time, with a peak total of about 3 to 4 FTE scientists and about 2 postdocs.

Cosmic Microwave Background (CMB) Surveys

Since the 1992 discovery of primordial fluctuations in cosmic background radiation by the COBE satellite, the quality of maps has rapidly improved, largely as a result of advances in detector technology. They now provide astonishingly precise cosmological measurements, that complement the information available from optical surveys.

Although individual detectors are now almost at the quantum limit, further significant advances are possible with larger cameras that can survey much faster. As was the case for digital optical surveys at the advent of SDSS, the next generation of CMB camera systems are too large and complex to be developed mainly by university PI groups, and will require the capabilities of national labs, similar to those employed by optical surveys. Thus, the P5 report enthusiastically endorsed a new venture by DOE, leading to deployment of a "stage 4" CMB S4 experiment in the 2020's.

Fermilab is currently a partner with U. Chicago, ANL and others in a third generation CMB experiment, SPT-3G. This survey will be operational in 2016, and in addition to bringing an order of magnitude increase in speed over existing surveys, will serve as a pathfinder for CMB S4. Building on expertise developed for DECam, and on technical facilities at SiDet, we are packaging and testing detectors, designing and building the cryostat, and integrating and assembling the main elements of the complete SPT-3G camera system. We aim to undertake similar technical tasks in CMB S4. The Fermilab group will grow to 3 or 4 FTE scientists and 2 postdocs in the S4 era.

R&D on MKIDS

Microwave Kinetic Inductance Detectors (MKIDs) have the unique potential to provide a simultaneous measurement of imaging, spectral and timing information for each photon. This new technology could enable unique precision "chronospectrophotometric" studies of supernovae or other transient sources, as well as follow up of specific imaging targets from DES or LSST, and possibly in the long run, a wide field spectrophotometric survey. Working with researchers from UC Santa Barbara and others, a team at Fermilab is developing detectors and associated electronics for the world's first optical MKIDs camera, to be deployed on the SOAR telescope in Chile. This is an example of a small pathfinding R&D effort, motivated by long-range directions set by the HEP community.

Direct Detection of Dark Matter

The Fermilab dark matter program is comprised of a set of experiments aimed at directly detecting Weakly Interacting Massive Particles (WIMPs) and axions, the favored particle dark matter candidates. These experiments use a variety of technologies, and are sensitive to a wide range of particle masses and interactions with normal matter. Such a broad program was a major recommendation in the P5 report, and has been adopted as the baseline future plan by OHEP. Fermilab supports a diverse but highly integrated program, transitioning from the current suite of G1 experiments to three G2 experiments, as well as R&D over a broader range of technologies building towards a more capable third generation.

G2: Cryogenic Dark Matter Search (SuperCDMS)

CDMS has long been a leader in dark matter direct detection, and Fermilab has been a leading institution in the experiment since 1997. Currently, Fermilab operates the G1 experiment at the Soudan Underground Laboratory in Minnesota. A new detector design ("iZIP", for interleaved z-sensitive ionization and phonon detection in the ultra-cold silicon and germanium target masses) now provides active discrimination against surface background events. In addition, a new mode of operation for CDMS detectors, called CDMSlite, has provided greatly improved sensitivity for low-mass WIMPS.

These new technologies will be deployed with much larger germanium and silicon target mass in a G2 experiment called SuperCDMS SNOLAB, in Canada. This project is in the design phase and will be constructed during 2016-2018. In four years of operation, it aims to definitively explore the low WIMP mass region < 20 GeV, down to the ultimate background from solar neutrino interactions. This low-mass region is particularly favored in 'dark sector' models that posit a family of dark matter particles with behaviors resembling those of normal matter. Fermilab will partner with SLAC in managing the SuperCDMS SNOLAB project and will continue to play leading scientific, technical and management roles in the experiment (including the Spokesperson), including leadership of the bulk of the DOE project funded construction on the experimental facility. We anticipate a growing Fermilab effort, about 4 or 5 FTE scientists, 3 postdocs, and a considerable technical effort on project funds.

G2: Liquid Xenon Dark Matter Search (LZ)

The successor to the LUX two-phase liquid xenon experiment, which currently places the tightest constraints on massive WIMPs favored by most particle models, LZ has been chosen by DOE as the main G2 liquid xenon experiment. (There is also some US participation in XENON-1T, funded by NSF and under construction at LNGS in Italy). LZ has the potential to improve on the current LUX sensitivity by over two orders of magnitude. The project is led by LBNL, with important collaboration leadership also at SLAC and UCSB, and participation by many university groups.

A small group of Fermilab scientists with extensive experience in dark matter experiments and noble liquid TPC technology, including LUX and other prototype detectors of this type, has joined the LZ collaboration. Fermilab plans to play a key technical role in designing the Xe veto , cryogenic and process control systems. The group will ultimately have about 3 scientists and 2 postdocs.

G2: Axion Dark Matter Experiment (ADMX)

Axions have long been a leading candidate to constitute particle dark matter, motivated not by the "WIMP miracle" but by an elegant solution to the strong CP problem. The G2 ADMX direct-detection search employs a resonant RF cavity variably tuned to search for a tiny coherent excitation at the (unknown) axion mass, caused by galactic dark matter. In a strong magnetic field, dark matter axions excite cavity modes that are measured with ultra-low-noise superconducting detectors. ADMX collaborators have developed the detector, RF cavity and magnet technology over many years. Recent advances in detectors now enable sufficient sensitivity to start searching efficiently over a range of axion masses, upwards of a few micro-eV, that could plausibly explain the dark matter abundance.

A group of Fermilab scientists with experience in axion searches is moving their effort from other experiments and has joined the ADMX collaboration. Over the next several years, ADMX will extend the search to higher axion masses, which requires significant additional R&D, particularly on development of high frequency cavities. Fermilab is contributing its technical expertise on RF cavity materials, design and development to enable the higher mass axion search. As the experiment grows, it will also need more project management and other national lab support. The Fermilab effort will be about 3 FTE scientists, 2 postdocs, and technical staff.

G1 and R&D: Dark Matter searches using Superheated Liquids (COUPP/PICO)

Together with the University of Chicago, Fermilab pioneered the resurrection of the bubble chamber as a tool for dark matter direct detection searches. Target liquids containing nuclei with large spin produce world-leading sensitivity to spin-dependent WIMP-nucleus scattering. Superheated liquids provide extraordinary rejection of electromagnetic backgrounds, since those interactions do not provide sufficiently localized energy densities to nucleate bubble formation. Acoustic sensors distinguish between alpha particle backgrounds and nuclear recoils.

Currently, the PICO collaboration (formed from the merger of the COUPP and PICASSO collaborations) is operating two G1 experiments at SNOLAB: PICO-2L and PICO-60 (formerly COUPP-60). Recent results from PICO-2L represent the world's best direct detection limits on spin-dependent proton interactions of dark matter, for the first time probing regions of supersymmetric parameter space in that channel. The collaboration is working on understanding remaining backgrounds to improve on those results by more than an order of magnitude in the existing G1 experiments. DOE and NSF chose not to proceed with a G2 experiment using this technology, but it may be a part of the G3 direct detection portfolio, particularly given its unique capabilities. As other institutions take on a stronger role in the collaboration, Fermilab is reducing its support effort, moving effort to G2 experiments and G3 R&D.

G1 and R&D: Two Phase Argon TPC for Direct Detection of Dark Matter (DarkSide)

Building on its expertise in liquid argon technology and data acquisition software, Fermilab has played important roles in the development of the G1 DarkSide-50 experiment, which uses an argon time projection chamber to search for dark matter. The DarkSide-50 program has demonstrated both outstanding rejection of electromagnetic backgrounds and the elimination of the radioactive background from 39Ar in atmospheric argon by exploiting underground sources of argon. While this technology was not selected in the G2 process in the US, the DarkSide collaboration, with leadership at Princeton and hosted by INFN/LNGS in Italy, intends to conduct larger experiments. Fermilab sustains a very small effort, bringing unique technical expertise closely aligned with its liquid-argon neutrino detector development.

G1 and R&D: Dark Matter in CCDs (DAMIC)

Thick CCDs of the type developed for the Dark Energy Survey can be read out with extremely low noise amplifiers, thus providing the lowest energy thresholds of any current technology. Fermilab led the effort to apply these detectors dark matter detection, with small (10 g) prototypes in an experiment at SNOLAB. An enlarged DAMIC collaboration is currently upgrading to 100 g of target mass. Despite the small mass, the prototype already yields the strongest limits on very low-mass (~1 GeV) WIMPs. The DAMIC collaboration has expanded to an international consortium, with support from the University of Chicago, the University of Michigan and international partners, with a small level of unique Fermilab effort.

Theoretical Astrophysics

The Theoretical Astrophysics Group has led the conceptual development, design and/or analysis of many experimental efforts in cosmology and particle astrophysics, not just at Fermilab, but worldwide. Its members play active, central scientific leadership roles in the lab's experimental programs in dark matter and dark energy. Their work spans a wide range of particle phenomenology in the cosmic realm, from cosmological measurements, modeling and simulations, to dark matter interactions and other signatures of physics beyond the Standard Model, including connections of cosmic studies with results from accelerator experiments. A strong theory group is vital to shape and inform the experimental program.

The strengths of the Fermilab group, and the need to maintain their capabilities with the infusion of young talent, were clearly recognized by exceptional reviews in the 2014 DOE triennial lab theory program review. We aim to strengthen the current group, which has 5 FTE scientists and 3 postdocs. Planning is also underway to strengthen connections between particle and astrophysics theory, which may include a greater overlap in neutrino physics.

Future Evolution of the Program as a Whole

Fermilab has leadership roles in most of the current generation of DOE particle astrophysics experiments, and Fermilab scientists hold key technical and scientific positions in many of the collaborations. Over the next ten years, our effort will make a transition to a new generation of experiments, where we intend to maintain leadership roles.

It is sometimes suggested that Fermilab should seek a "flagship" cosmic frontier project--- a single experiment with a dominant Fermilab effort, similar to DES today. The plan here does not adopt that agenda as a priority. We believe that, through coordinated prominent efforts on a mix of experiments in different stages of their life cycles (R&D, design, construction, operations, analysis), Fermilab can better provide unique laboratory capabilities at every stage, and maximize the science impact of the unique skill mix of its scientific and technical staff. Fermilab can provide a special opportunity for different but scientifically related experiments to come together at many stages, from shared technology to eventual combination of data. Gradual consolidation into fewer and larger projects is projected over these years, but in our plan, the pacing of this transition is driven by the science opportunities of the field.

Even so, it is important for Fermilab to make a unique and critical contribution to each experiment in which we participate. This means commitment of a critical mass of scientist effort, in a focused way for each experiment. It is also important that Fermilab maintain leadership in key cosmic frontier thrusts, which means shaping a coherent program where the efforts of the various groups reinforce each other.

Thus, Fermilab's experimental program will be organized around just two principal science thrusts, Cosmic Surveys and Dark Matter. The Cosmic Surveys group will make precision measurements of cosmic structure and evolution, and combine their results to learn about fundamental physics of cosmic acceleration, the gravitating dark sector, and neutrinos. The Dark Matter group will undertake a coordinated campaign of deep direct searches for cosmic dark matter particles. In the next generation, each group will support three experiments. Each group will also support a small R&D effort directed to the needs of future experiments.

In cosmic surveys, the team that is now predominantly working on DES will transition to one that combines effort on three new surveys: DESI, LSST, and CMB. The complementary measurements of cosmic structure and evolution by the new surveys have many scientific synergies, and will provide the most powerful cosmic probes when combined with each other. Many technical contributions overlap among DECam, DESI, MKID and CMB camera and detector systems. Individual Fermilab scientists will make critical technical and scientific contributions to one or more of the new surveys at an appropriate stage, depending on their area of expertise. The unified group, together with the astrophysics theory group, will form around a cohesive science program that combines unique Fermilab contributions to each survey, and adds unique scientific value by blending their analyses.

The dark matter group similarly has a broad and cohesive science program that is intellectually unified, in conjunction with astrophysics and particle theory groups. Our roles in the experiments share technical strengths with each other (for example, in ultra low background and cryogenic technologies), and with Fermilab's other experimental programs.

The R&D program will remain embedded in the Dark Matter and Cosmic Surveys groups, where it is best aligned with plans for future experiments. Strategic study groups for dark matter and cosmic surveys meet regularly and invite visitors with a broad range of visions to help seek out the most promising future directions, and to broaden our scientific perspective.

In the next few years, the bulk of our effort will transition to six experiments: three G2 dark matter searches and three cosmic surveys. Each major experiment will have a critical mass: between three and five FTEs of experimental effort, two or three postdocs, and support for technical effort from DOE project funds. This level of effort is achievable within approximately the current size of the experimental program, about 32 FTEs of scientist effort. The top priority for growth will be in the postdoc program, from its current size of 9 experimental and 3 theory postdocs; given the science and technology opportunities, there should be at least 12 experimental and 5 theory postdocs.

The Fermilab Center for Particle Astrophysics recently held a strategic retreat with the specific goal of planning the migration of effort over the next five to ten years. We found that plans of scientists are largely aligned with this overall plan, so implementation is realistic. Almost all of the migration to the new arrangement will occur by existing staff moving their effort to optimize their scientific impact. Over this period we will aim to hire several new staff to replace retirements. We will seek new capabilities appropriate to the new program, particularly to reinforce the CMB effort.