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

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Strategic Overview of the Evolution of the Particle Astrophysics Program at Fermilab

Astrophysics at Fermilab started in the early 1980's with the establishment of the Theoretical Astrophysics Group, a pioneer of new "Inner Space/Outer Space" connections between fundamental physics and cosmology. A critical mass of particle theorists and cosmologists at Fermilab and the University of Chicago applied the ideas, tools and motivation of particle theory to interpret the universe. They used the cosmos to explore the new physics associated with the quantum origins of cosmic nuclei, dark matter, expansion, and structure.

It was soon realized that Fermilab was an ideal place to nurture the new discipline of particle astrophysics, and expand it to include experiment as well as theory. Laboratory capabilities in project management, mechanical and electrical design and data handling could significantly accelerate the development of a new generation of more capable and precise cosmic experiments. In the early 1990's, Fermilab established the Experimental Astrophysics Group to support the Sloan Digital Sky Survey, the first digital survey of the universe. SDSS transformed cosmology into a statistically controlled tool for studying fundamental physics, and laid the foundation for a series of more advanced surveys to study what we now call "dark energy". By some measures, SDSS has been the most scientifically productive observatory in history; along with CMB studies, it was recognized in 2003 by the AAAS as the breakthrough of the year in all areas of science. Later in 1990's, Fermilab broadened its program to support CDMS, the first in the expanding modern program of experiments to directly detect WIMP dark matter, and led the development of the Pierre Auger Observatory to study the highest energy cosmic rays. In the last decade, Fermilab has applied its expertise on silicon vertex detectors to build the Dark Energy Camera, and has continued to develop new particle detector technologies in the search for dark matter.

Today, dark energy and dark matter remain central themes in the national particle-astrophysics program, as well as at Fermilab. The physics reach of precision cosmological experiments now extends to topics such as neutrino masses and cosmic inflation. These studies are included in the top scientific drivers for particle physics, as summarized in the 2014 community-driven P5 report. That report also recommends a further expansion of precision cosmology at the national labs to include studies of cosmic microwave background anisotropy.

Fermilab's future program plan is prioritized based on supporting the scientific organizing principles in the P5 report, as shaped by community support needs, agency funding opportunities, and unique laboratory capabilities.

The following plan is based on Fermilab's 3-year particle astrophysics program proposal, approved after DOE peer review in the summer of 2013. It has been updated to reflect new developments over the past year, including the release of the P5 report and the DOE/NSF Generation 2 Dark Matter program plan.

Table 1 shows the core elements of the Fermilab plan.

P5 Driver	Experiments
Dark Matter	G1: SuperCDMS Soudan, COUPP/PICO, Darkside, DAMIC G2: SuperCDMS SNOLAB, LZ, ADMX G3: R&D towards advanced WIMP and Axion experiments
Dark Energy	DES, DESI, LSST
CMB	SPT-3G, CMB-S4
Exploring the Unknown	Holometer, Pierre Auger
Detector R&D	R&D on new techniques for particle astrophysics experiments
Astrophysics Theory	Strong coupling with particle astrophysics experiments

Table 1: Main components of the Fermilab particle astrophysics program by P5 driver

Dark Energy

About half of Fermilab's experimental scientific effort on the cosmic frontier (~12 FTE scientists) supports dark energy studies. Over the next decade, the scientific effort will transition from DES to a combination of new projects, including DESI, LSST, and CMB.

Dark Energy Survey (DES)

The main Fermilab dark energy effort after SDSS has been the Dark Energy Survey. Fermilab led the foundation of the project and collaboration, and the construction of its main instrument, the Dark Energy Camera. Fermilab, as the leading institution, continues to provide scientific leadership, technical support for the collaboration, and management of survey operations.

The survey will finish its second year of data taking in 2015, and conclude survey operations in 2019. It will be the world's leading imaging survey until the Large Synoptic Survey Telescope starts operations in the 2020's, and will significantly advance the frontier of precision cosmological measurement. During these years, DES science will be the main science focus of Fermilab's Dark Energy team.

Dark Energy Spectroscopic Instrument (DESI)

DESI is the successor to the massive SDSS/BOSS spectroscopic survey, extending 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 (led by LBNL) and collaboration, with both science leadership and technical construction tasks. Fermilab contributions build on the scientific and technical expertise developed from leading design, construction, operations and science from SDSS and DES surveys. For example, as in DES, Fermilab will lead the development of key structural elements of the massive image corrector system, and the packaging and testing of the detectors.

Fermilab technical effort on DESI will grow with construction of the instrument over the next few years. DESI will likely be our largest dark energy technical effort after the conclusion of DES. It should start its multi-year spectroscopic survey around 2019.

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 is working to transfer scientific and technical lessons of SDSS and DES to the LSST team, which is led by SLAC. Before and during survey operations, Fermilab plans active participation and leadership in the LSST Dark Energy Science Collaboration, including development and support of software frameworks for dark energy science (e.g., "COSMOSIS"), based on those now being developed and tested with DES.

Table 2 summarizes the Fermilab dark energy experimental plan.

Experiment	Location	Status	Operations	Physics Focus
Dark Energy Survey (DES)	CTIO, Chile	Operating	2013-2018	Deep imaging survey (supernova, BAO, Weak Lensing, Clusters)
DESI	Kitt Peak	Design	2019-2023	Deep spectroscopic survey (BAO to redshift ~3)
LSST	Chile	Fabrication	2021-2030	Very deep, all-sky imaging survey (Broad science program)

Table 2: The Fermilab dark energy experimental program

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 will support a diverse program including a suite of three second-generation (G2) experiments, as well as R&D over a broader range of technologies building towards a possible next generation (G3).

Cryogenic Dark Matter Search (CDMS/SuperCDMS)

CDMS has long been a leader in dark matter direct detection, and Fermilab has been a leading institution in this 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 both 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.

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). This technology has potentially the deepest reach to find weakly interacting dark matter over a wide range of masses. The project is led by LBNL, with important collaboration leadership also at SLAC and UCSB, and participation by many university groups.

A group of Fermilab scientists with extensive experience with 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 and fabricating the cryogenic process control system for LZ. Fermilab effort on LZ will be significant for the duration of the experiment, with a similar time frame to SuperCDMS.

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.

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. As the experiment grows, it also needs more help with project management and national lab support. A group of Fermilab scientists with experience in axion searches plans to move their effort from other operating experiments to join the ADMX collaboration. Fermilab aims to contribute technical expertise on RF cavity design and development for the higher mass part of the axion search.

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 collaboration is operating two G1 experiments at SNOLAB: PICO-2l and COUPP-60, now also renamed PICO after a newly formed, larger collaboration. They are both being used to study remaining backgrounds and understand how this technology might be used in the future to confirm and complement possible WIMP signals seen by other 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, and even the G1 experiment now uniquely approaches theoretical expectations for spin-dependent WIMP interactions. While the expanded collaboration now includes many Canadian groups, Fermilab scientists will continue to participate in future operations and R&D at a low level.

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 DarkSide-50 G1 experiment, which uses an argon time projection chamber to search for dark matter. This technology has demonstrated extremely good rejection of electromagnetic backgrounds, and control of the intrinsic radioactive background from 39Ar by exploiting and purifying underground sources of argon. A recent first physics result demonstrates the potential for liquid argon TPCs to play a role in confirming possible high-mass WIMP signals. 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 continue R&D towards larger experiments. Fermilab will participate at a low level of effort, bringing unique technical expertise closely aligned with its liquid-argon neutrino detector development.

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 has led the effort to realize this potential with small (10 g) prototypes in an experiment at SNOLAB, and 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 include NSF-funded university groups, and will continue this R&D program. Fermilab will support this effort at a low level.

Table 3 summarizes the Fermilab dark matter direct detection experimental program.

Experiment	*Location*	*Status*	*Technique*	*Physics Focus*
G1 experiments (2012-2017)				
SuperCDMS	*Soudan*	*Operating*	*Cryogenic Solid-State*	*Background-free WIMP search*
COUPP/PICO	*SNOLAB*	*Operating*	*Bubble Chamber*	*Spin-dependent dark matter*
Darkside 50	*LNGS*	*Operating*	*Liquid Argon TPC*	*WIMPS > 1 TeV/c²*
DAMIC	*SNOLAB*	*Operating*	*CCDs*	*WIMPS < 1 GeV/c²*
G2 experiments (2018-2023)				
SuperCDMS	*SNOLAB*	*Design*	*Cryogenic Ge/Si target*	*Low-mass WIMPs to neutrino floor*
LZ	*SURF*	*Design*	*Liquid Xenon TPC*	*High-mass WIMPs*
ADMX	*U. Wash*	*Fabrication*	*Cryogenic resonant cavity*	*Axion dark matter*

Table 3: The Fermilab dark matter experimental program

Cosmic Microwave Background (CMB)

Since the 1992 discovery of primordial fluctuations in cosmic background radiation by the COBE satellite, the quality of maps, made by satellites, balloons and ground based telescopes, has rapidly improved, largely as a result of advances in detector technology. They now provide astonishingly precise cosmological measurements, enabling many unique measurements of fundamental physics.

The highest resolution maps must be made from the ground, simply because of the required size of antennas. 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. Thus, the P5 report enthusiastically endorsed a new venture by DOE, leading to deployment of a "stage 4" CMB experiment in the 2020's.

Fermilab is partnering with the University of Chicago, Argonne National Lab and others to develop the camera system for a new "stage 3" experiment at the South Pole Telescope (SPT). Fermilab will integrate and test detectors, and assemble and test the SPT-3G cryostat. These tasks build on Fermilab's experience with similar large scale integration and testing of the Dark Energy Camera, and also involves adding new lower-temperature cryogenic capabilities at the lab that synergize with our efforts in dark matter experiments and detector R&D.

The initial SPT-3G camera will be deployed at the South Pole in early 2016, with upgrades in following years. Fermilab will gradually expand its effort in this area, and work with a large network of partners to develop and align our efforts with the next generation S4 project. It will likely be our largest technical construction effort on the cosmic frontier in the 2020's.

New Initiatives and R&D

Fermilab has an active detector R&D program, from which many ideas have been developed into particle astrophysics experiments. One example is the Holometer, which developed experimental techniques to cross-correlate laser interferometers in the MHZ range, well above the region covered in most gravitational wave detectors, to explore possible quantum fluctuations in geometry. The Holometer is now an operating experiment and should produce physics results with Planck scale sensitivity in 2015.

Such synergy continues with efforts by several young particle astrophysicists at Fermilab to develop new detectors for cosmic surveys. In the following examples, R&D programs are taking advantage of unique technical infrastructure and support available at Fermilab. They also help incubate new capabilities at the lab; for example, new, sub-Kelvin cryogenic capabilities at Fermilab are being developed and shared for MKIDs, CMB, ADMX, and CDMS detector development.

MKIDS

Magnetic Kinetic Inductance Detectors (MKIDs) have the potential to provide a unique combination of spectral and timing information for each photon received with large telescopes. This 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 spectral survey. Working with researchers from UC Santa Barbara and others, a small team at Fermilab is developing these detectors and associated electronics towards a full-scale prototype to be deployed on the SOAR telescope in Chile.

CCDs

Thick CCD detectors have become the workhorse for optical surveys such as DES, DESI and LSST, and have shown promise as low threshold dark matter detectors (DAMIC). Development work continues towards reducing readout noise especially for the latter application, but also for low noise spectroscopy.

CMB

While SPT-3G is proceeding towards construction, the community is preparing for an order of magnitude larger CMB-S4 experiment to operate in the 2020's. Through an LDRD grant, our team at Fermilab is developing the facilities and methods that would be needed to package, test and integrate such a large array of TES-based detectors.

Table 4 summarizes the CMB and new initiatives experimental program.

Experiment	Location	Status	Operations	Physics Focus
SPT-3G	South Pole	Fabrication	2016-2020	CMB polarization
CMB-S4	South Pole +	Design	2020-2025	Wide-area CMB polarization, neutrino masses
Pierre Auger	Argentina	Operating	2008-2015	Very high energy cosmic ray flux, composition
Holometer	Meson Lab	Operating	2014-2016	Structure of spacetime

Table 4: The Fermilab CMB program, and experiments for "exploring the unknown".

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, critical scientific leadership roles in the lab's experimental programs in dark matter and dark energy. Their interests span 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. Their work is critical to connect cosmic studies with results from accelerator experiments. A strong theory group will continue to be critical 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 theory program review.

Future Evolution of the Strategic Plan

This plan is a work in progress that will undergo regular updates. While the main directions are clear, it also includes several important contingencies and decision points that remain to be resolved.

Some of the uncertainties are simply budget related. The size of the program depends on Cosmic Frontier research budget allocations, and also the still-unknown schedule for construction of many projects. For some approved projects, such as ADMX G2 dark matter experiment, details of Fermilab participation remain to be clarified, and even some basic design elements are still in the development stage.

The largest new element in the long-term plan is the CMB Stage 4 project. Here, the collaboration itself is still in the formative stage, as well as the main technical design elements of the experiment, such as the suite of telescopes and cameras. Fermilab is an active participant, along with the other labs and leading university groups, in shaping all aspects of this enterprise. We expect the collaboration plans to take shape and clarify considerably in the next year. Again, CMB is likely to be our largest experimental effort on the cosmic frontier ten years from now.

We will also adapt our strategy based on advances in scientific knowledge. For example, any of the current and future dark matter experiments has the potential to make a transformative discovery; a confirmation (or not) of the claimed discovery of primordial CMB B-mode polarization anisotropy by BICEP-2 will have a significant impact on plans for CMB-S4; and positive detection of Planck scale geometrical quantum noise in the Holometer would launch a new suite of proposals for follow-up experiments. We aim to preserve enough flexibility in the program to be able to adapt to such opportunities.

Fermilab has leadership roles in most of the current generation of particle astrophysics experiments, and Fermilab staff hold key technical and scientific positions within the collaborations. Table 5 summarizes these leadership positions, and the level of scientist involvement in each experiment, highlighting especially the key contributions of young scientists. Fig 1 shows how we expect the scientist effort to evolve over the next decade, with dark matter effort continuing at the same level, but gradual migration from dark energy experiments to CMB-S4. We expect that G3 dark matter experiments and CMB-S4 will be the leading Fermilab particle astrophysics experiments 10 years from now.

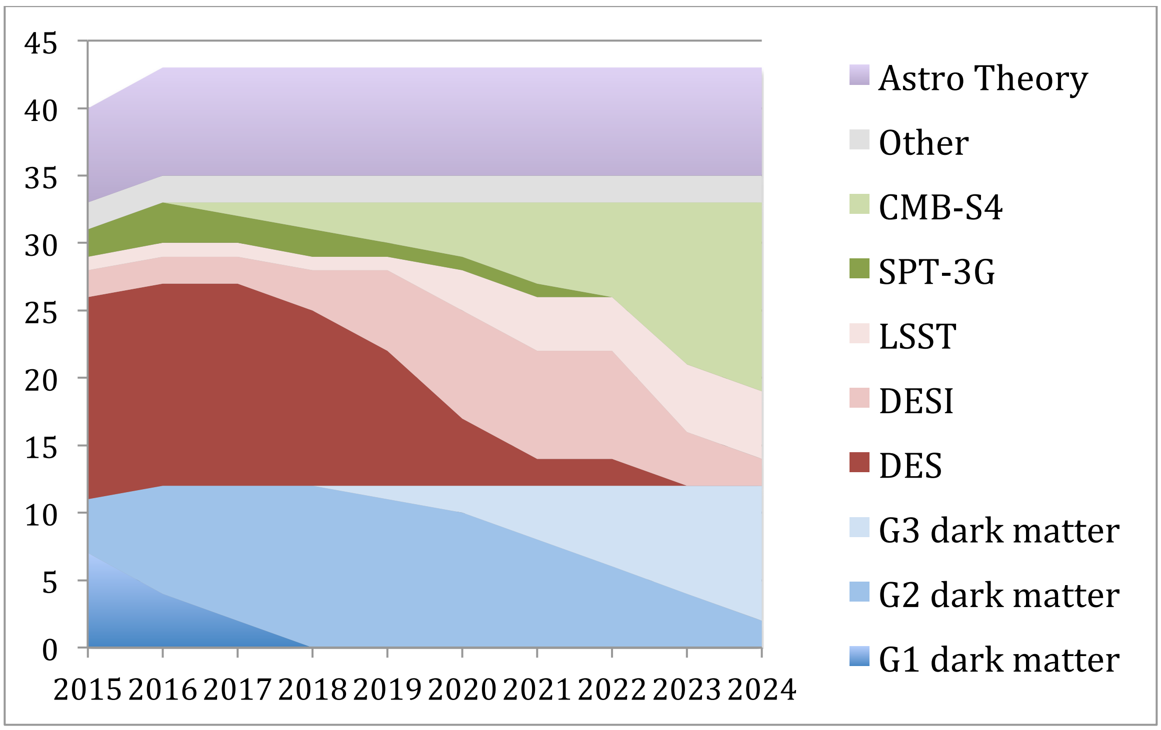

Figure 1: Scientist staff (including ~12 postdocs) mapped onto the Fermilab particle astrophysics program over the next decade

Experiment	**Fermilab roles**	**Fermilab scientists/postdocs (Leader)**
SuperCDMS	Project/Operations management, Cryogenics/shielding/electronics, Data analysis/Science	3/1 (Bauer)
COUPP/PICO	Project/Operations management, Fabrication Data Analysis/Science	3/1 (***Sonnenschein***)
Darkside 50	LAr expertise, data acquisition	1/1 (Pordes)
DAMIC	CCDs, management,	1/1 (***Estrada***)
LZ	TPC, process control, science	1/1 (***Lippincott, Dahl***)
ADMX	Project management, R&D	1/0 (***Chou***)
DES	Project/operations management, DECAM, Calibration/Science	13/2 (Frieman, Flaugher, Diehl)
DESI	CCD packaging, optics, science	2/0 (Flaugher)
LSST	Dark Energy Science	1/0 (Dodelson)
SPT/CMB	Cryostat assembly, testing, design for S4	2/1 (***Benson***)
Holometer	Project/operations management, science	2/0 (***Chou***)

Table 5: The Fermilab experimental particle astrophysics program, showing key Fermilab leadership, technical and science roles. The rightmost column indicates the scientist/postdoc staff effort in FTE's, with the Fermilab group leader in parentheses.