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Overview of Fermilab Cosmic Program

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Fermilab Institutional Review

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Particle Astrophysics at Fermilab

Fermilab (and HEP) mission: study the fundamental nature of matter, energy, space and time

Cosmic studies uniquely probe deep mysteries: dark matter, cosmic acceleration, neutrino mass, gravity

Challenging experiments benefit greatly from unique capabilities of national laboratories: technologies, development, engineering, scale, management

DOE labs and University community share many cosmic experiments

Fermilab's plan is based on the scientific drivers in the HEPAP P5 report, as shaped by community needs, agency funding opportunities, and unique laboratory capabilities

Fermilab Astrophysics Strategic Plan: alignment with P5

| 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/ acceleration | DES, DESI, LSST |
| CMB/acceleration | 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 |

Dark Matter

Astrophysical evidence suggests that most of our Galaxy is made of a new form of matter

Theory suggests that it may be detectable in this decade

- Weakly Interacting Massive Particles (WIMPs)
- Axions (solution to CP problem of strong interactions)

P5 recommends a diverse program for direct detection of WIMPs and axions
We only know about these particles from their gravity

Generation 1 technologies allow broad exploration and followup
DAMIC, PICO, Darkside, SuperCDMS Soudan
Low mass, spin-dependent interactions, etc
Many world leading results (bounds) already published

Generation 2 experiments will extend parameter reach
SuperCDMS SNOLAB, LZ (WIMPs)
ADMX (axions)

G3 experiments will extend down to the neutrino solar and cosmic neutrino “floor”
Fermilab pursues R&D towards these larger experiments of the 2020’s

Fermilab Dark Matter Experiments

| 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 $> 1 \text{ TeV}/c^2$ |
| DAMIC | SNOLAB | Operating | CCDs | WIMPS $< 1 \text{ GeV}/c^2$ |
| 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 |

Fermilab Roles in G2 Dark Matter Experiments

Fermilab has been lead lab in CDMS since 1997, now shares with SLAC

Management, operations, design, engineering, science

Fermilab participation in LZ and ADMX after G2 selection was invited by collaboration leaders because of unique Fermilab technical capabilities and young scientist talent

ADMX: RF cavity design, magnets, axion science

LZ: noble liquid TPCs, process control, underground ops

Effort will migrate from other experiments

Fermilab Roles in Dark Matter Experiments (highlighting Wilson Fellows, Early Career awardees)

| Experiment | Fermilab roles | Fermilab scientist/ postdocs FTEs (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) |

Dark Energy

Astrophysical evidence suggests that the expansion of the universe is accelerating

Signals a new deep form of energy and/or space-time

P5 recommends precision studies of cosmic structure and evolution
Order of magnitude improvement is possible with new experiments

Wide, deep imaging probes evolution of expansion and structure via supernovae, galaxy distribution and photometry (DES, LSST)

Wide, deep spectroscopic surveys increase precision of redshift measurements, particularly BAO, AGN, RSD (DESI + ??)

Fermilab effort migrates from DES to new surveys, and to CMB
FNAL collaboration members: 20 in DES, 8 in DESI, 4 in LSST-DESC

Dark Energy Experiments

| 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) |

Fermilab roles in Dark Energy experiments

| Experiment | Fermilab roles | Fermilab scientists/ postdoc FTEs (Leaders) |
|------------|--|---|
| DES | Project, operations, management, DECam, Calibration, Science, collaboration leadership Computing, data management | 13/2 (Frieman, Flaugher, Diehl) |
| DESI | CCD packaging, optics, science | 2/0 (Flaugher) |
| LSST | Dark Energy Science, survey operations | 1/0 (Dodelson) |

Fermilab leadership started with SDSS in 1990

Now leading DES (fabrication, operations, collaboration)

New experiments will benefit from deep scientific and technical expertise

DESI: CCD packaging, corrector engineering, survey design and operations

LSST: Framework for combined analysis (COSMOSIS), operations

Cosmic Microwave Background

Anisotropy of CMB temperature and polarization depends on new physics: dark energy, neutrino mass, dark radiation, cosmic inflation

New opportunity: map of polarization at high angular resolution over most of the sky will measure sum of neutrino masses

P5 recommends Stage 4 CMB experiment, supported by NSF, DOE and national labs, in the next decade

CMB experiments

| Experiment | Location | Status | Operations | Physics Focus |
|------------|-------------------------|-------------|------------|---|
| SPT-3G | South Pole | Fabrication | 2016-2020 | CMB polarization |
| CMB-S4 | South Pole + Chile + ?? | Design | 2020-2025 | Wide-area CMB polarization, neutrino masses |

Fermilab is currently a partner in Stage 3 experiment at the South Pole Telescope (SPT-3G)

DES was strategically planned with SPT

Collaboration with ANL and U Chicago

Camera being built and tested at Fermilab; deploys this year

Fermilab helping to shape S4 design, collaboration, consortium

Order of magnitude more detectors than 3G

Fermilab Roles in CMB experiments

| Experiment | Fermilab roles | Fermilab scientists/ postdocs (Leader) |
|------------|--|---|
| SPT 3G | Cryostat and focal plane design and fabrication, integration, detector testing | 2/1 (<i>Benson</i>) |
| CMB S4 | R&D, design, collaboration development | 2/1 (<i>Benson</i>) |

Builds on Fermilab technical experience with CMS, QUIET, DECam

Scientific ties with DES, U Chicago, ANL

SiDet capabilities are now being extended to sub-Kelvin cryogenics

Many applications of advanced superconducting detectors tie different experiments together (CMB, Dark Matter, MKIDs)

High Energy Particles

| Experiment | Location | Status | Operations | Physics Focus |
|--------------|-----------|-----------|---------------------------------------|---|
| Pierre Auger | Argentina | Operating | 2008-2015 (Fermilab participation) | Very high energy cosmic ray flux, composition |

Fermilab co-founded and operated Pierre Auger Observatory
Recently transferred leadership to Karlsruhe Institute of Technology

Fermilab Auger group led recently published study of cosmic ray composition at the highest energies

Effort at Fermilab is winding down

Fermilab Holometer

| Experiment | Location | Status | Operations | Physics Focus |
|------------|-----------|-----------|------------|------------------------|
| Holometer | Meson Lab | Operating | 2014-2016 | Structure of spacetime |

Unique experiment to study Planck scale quantum geometry

Pair of correlated Michelson interferometers explores quantum coherence of space-time position with Planck precision for the first time

- Now operating with design sensitivity

- Science results will appear in 2015 and 2016

- First PhD (of 4) passed last week

Funded by Early Career grant to A. Chou

Effort will migrate to ADMX

Fermilab Experimental Leadership

(highlighting Wilson Fellows, Early Career awardees)

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| SuperCDMS | Project/Operations management, Cryogenics/ shielding/electronics, Data analysis/Science | 3/1 (Bauer) |
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| 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 (<i>Benson</i>) |
| Holometer | Project/operations management, science | 2/0 (<i>Chou</i>) |

Cross cut: Cosmic Detector R&D

Fermilab can uniquely empower new directions in research

Generic Detector R&D leads to new experiments

Early Career awards and Wilson Fellowships have propelled development of new technologies (building on old ones)

DAMIC (DES), Holometer (GammeV), PICO (COUPP), DarkSide (LAr)

New synergies, capabilities

Sub-Kelvin cryogenics: CDMS, CMB, MKIDs, ADMX

Important collaboration with U Chicago, ANL

RF cavities: ADMX and accelerators

P5 recommends sustained commitment to technical innovation

Cross Cut: Theory

Fermilab's Theoretical Astrophysics Group

- Ties many threads together

- Connects to particle theory (and Particle Theory Department)

- Works to extract fundamental physics from cosmic data

- Brings versatility in modeling, phenomenology, statistics

- Simulation, model building, projection, analysis, tool development

- Gravity, particle phenomenology, complex astrophysical systems

Shapes and leads the experimental program

- Leadership in Fermilab and national program for >30 years

- Many experiments conceived in the theory group (eg, B modes)

- Hands-on involvement includes important leadership positions in experimental collaborations

High praise for Fermilab group in 2014 3-year program review

- Clear endorsement for strong support

Cross cut: Collaboration with Universities and Other Labs

HEP labs share effort on almost all cosmic projects

- Leverage science, funding and technical resources from whole complex

- Effort is typically widely distributed according to capabilities and capacities of various labs

Fermilab supports experimental collaborations with technical resources

- Operations, workshops, visitors, collaboration meetings

- Examples: CDMS, DES (see breakout)

Special relationships with U. Chicago, KICP, ANL

- Joint appointments, collaborative seed grants, students, shuttle

Local universities: Northwestern, UIUC, NIU

- Joint appointments, students

Cross cut: Cosmic Computing

HEP experience translates to cosmic surveys and experiments

Data management

DESDM: partnership with NCSA; code development, real-time processing, reprocessing

Dark Matter: ArtDAQ data acquisition platform used for Darkside

Holometer: fast real-time reduction

Analysis

FermiGrid for data processing, storage and simulation

Professionalized analysis tools

COSMOSIS: framework for multiple cosmological probes with multiple, disparate datasets

DES now; will be used in CMB, DESI and LSST

Simulation

Versatile DOE system enables advanced code development

Summary of long term plan and vision

Long term commitment to dark matter direct detection

- Increase sensitivity by orders of magnitude

- Take WIMP search to the solar limit across large mass range

- Explore axion parameters across the QCD window

Long term commitment to dark energy surveys

- Dominant effort on DES will migrate to DESI and LSST

- Beyond LSST: next generation spectroscopic survey?

Long term theory, development, initiatives, exploration

- Sow seeds for future

Growing effort on CMB

- Effort will migrate from other areas

- CMB S4 will become the largest effort in the next decade

Program will adapt to discoveries and opportunities