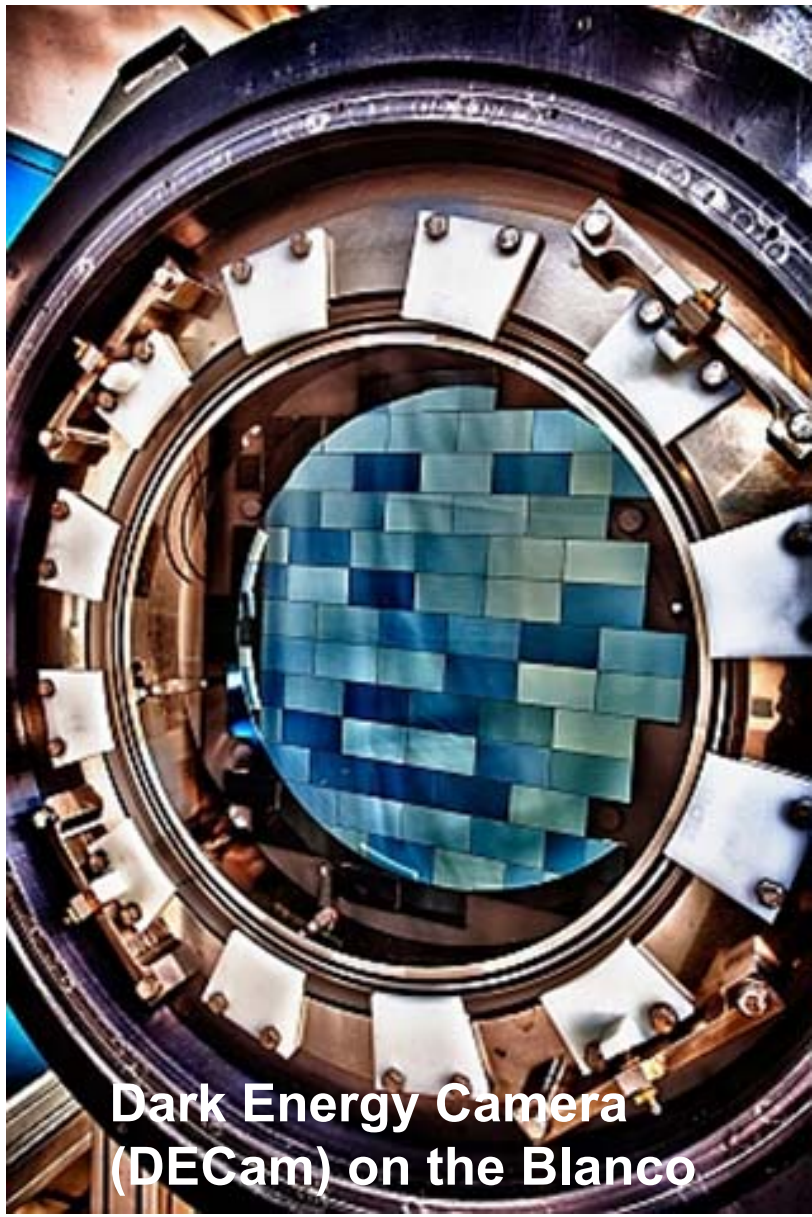
DOE High Energy Physics (HEP)

Cosmic Frontier Program

NAS Committee on Astronomy and Astrophysics

24 October 2017

Eric Linder

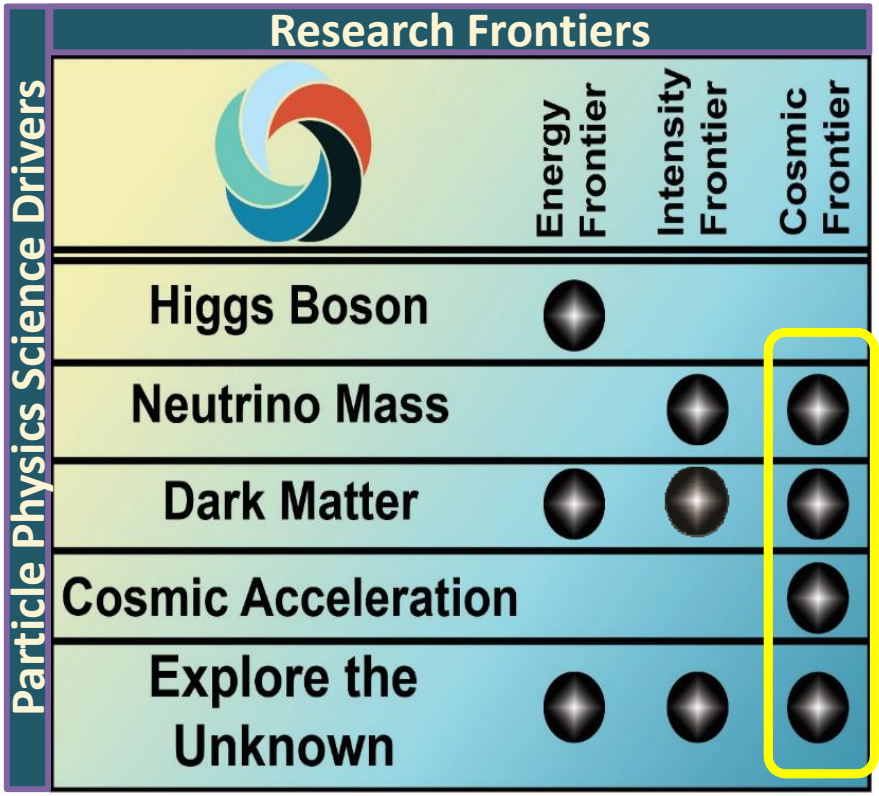

Dark Energy Camera (DECam) on the Blanco

Cosmic Frontier Experimental Research Program

→Through ground-based telescopes & arrays, space missions, and deep underground detectors, research at the cosmic frontier aims to explore dark energy and dark matter, which together comprise approximately 95% of the universe.

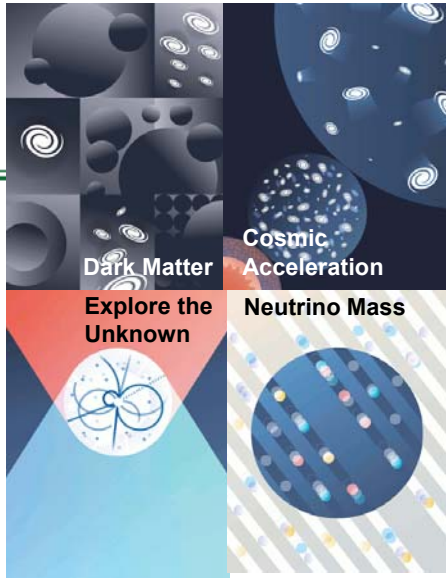
Program Areas:

- Study the nature of **Dark Energy**
- Direct Detection searches for **Dark Matter** particles
- **CMB** – Inflationary Epoch, Dark Energy, Neutrino Properties
- **Cosmic-ray & Gamma-ray studies** – indirect searches for dark matter particles



→ **Strong interaction with Theory, Detector R&D, Computational HEP**

May 2014 P5 Report – Cosmic Frontier Recommendations



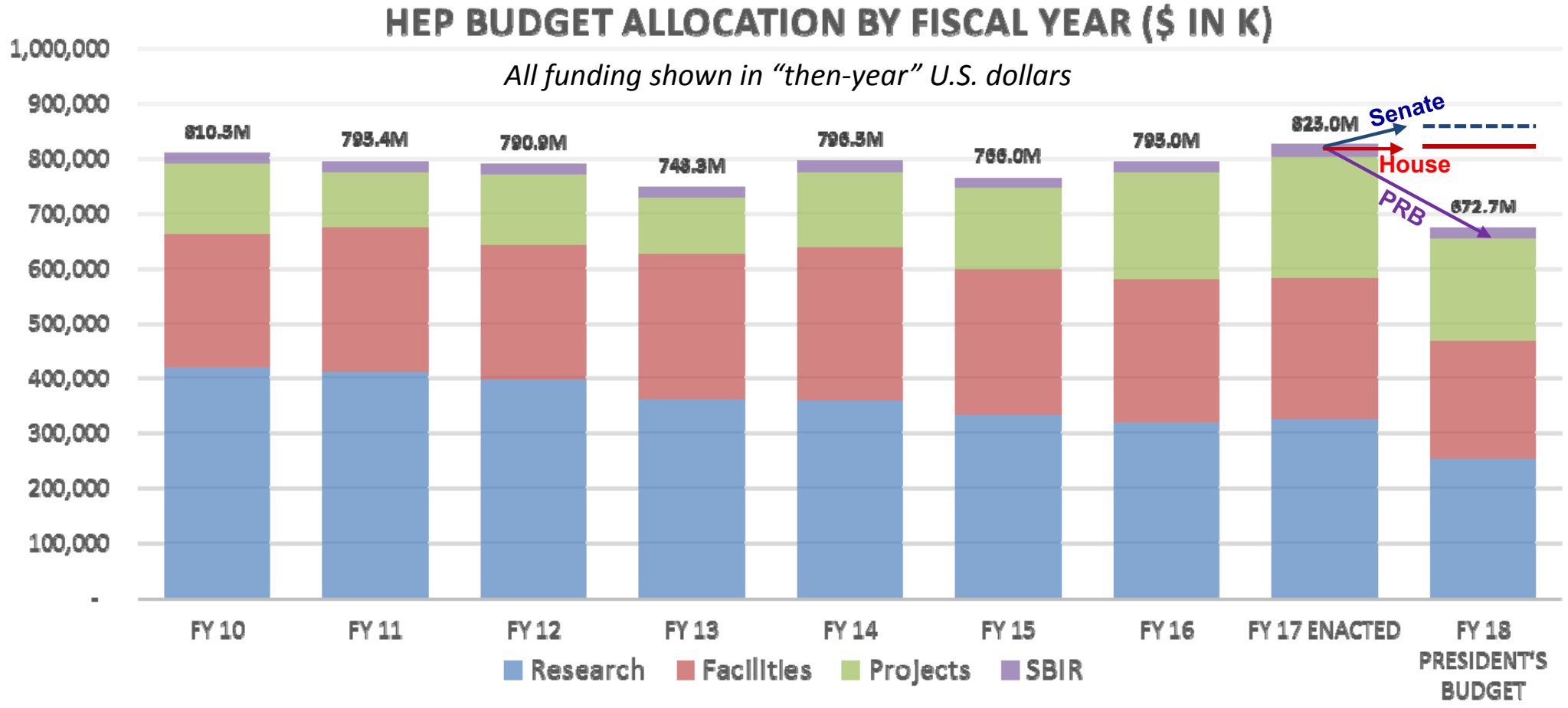
P5 report recommendations addressed to the Cosmic Frontier ➔

- **Dark Energy**
  - Complete LSST as planned
  - Build DESI as a major step forward in dark energy science
- **Dark Matter**
  - Proceed immediately with a broad second-generation (G2) dark matter direct detection program with capabilities described in the text
    - Invest in this program at a level significantly above that called for in the 2012 joint agency announcement of opportunity
  - Support one or more third-generation (G3) direct detection experiments
    - Guide G3 by the results of the preceding (G1, G2) searches
    - Seek a globally complementary program and increased international partnership in G3 experiments **(DM-G3 Project is in the P5 plan in later part of their 10 year plan.)**
- **Cosmic Microwave Background (CMB)**
  - Support CMB experiments as part of the core particle physics program
  - The multidisciplinary nature of the science warrants continued multi-agency support

    (CMB-S4 Project is in the P5 plan, starting about mid-way through their 10 year plan.)
- **Cosmic Rays and Gamma Rays**

Overall HEP Budget Trend

- **P5 strategy continues to define investments in future of the field**
- **President's FY18 Budget Request is down, current draft of House FY18 is flat, current Senate draft FY18 is up, relative to FY17**
- **Currently in CR ~FY17; funding level not set until appropriation bill is passed**



HEP Cosmic Frontier Experiments

Aug 2017

Activity	Location	Science	Current Status	# Collaborators	# Institutions	# Countries
Extended Baryon Oscillation Spectrosopic Survey (BOSS)	APO in New Mexico	dark energy stage III (spectroscopic)	operations started 2015	230 (150 US, 40 HEP)	(22 US, 8 HEP)	7
Dark Energy Survey (DES)	CTIO in Chile	dark energy stage III (imaging)	operations started Sept. 2013	300	25 (13 US, 9 HEP)	6
Large Synoptic Survey Telescope (LSST) - Dark Energy Science Collaboration (DESC)	Cerro Pachon in Chile	dark energy stage IV (imaging)	science studies, planning	269 (195 US, 47 HEP)	63 (43 US, 22 HEP)	15
Large Synoptic Survey Telescope (LSST) - LSSTcam Project	Cerro Pachon in Chile	dark energy stage IV (imaging)	FY14 Fab. start; CD3 Aug2015	142 (111 US, 111 HEP)	17 (11 US, 11 HEP)	2
Dark Energy Spectroscopic Instrument (DESI)	KPNO in AZ	dark energy stage IV (spectroscopic)	FY15 fab start; CD3 June 2016	179 (93 US, 74 HEP)	39 (21 US, 19 HEP)	9
DM-G1: Large Underground Xenon (LUX)	SURF in South Dakota	dark matter - WIMP search	Operations ended in 2016	102 (86 US, 64 HEP)	18 (15 US, 13 HEP)	3
DM-G1: Super Cryogenic Dark Matter Search (SuperCDMS-Soudan)	Soudan in Minnesota	dark matter - WIMP search	Operations ended in 2016	83 (72 US, 44 HEP)	20 (17 US, 7 HEP)	3
DM-G2: ADMX-G2	Univ Washington	dark matter - axion search	Operations started Jan. 2017	23 (21 US, 18HEP)	8 (7 US, 4 HEP)	2
DM-G2: SuperCDMS-SNOLAB	SNOLab in Canada	dark matter - WIMP search	FY15 fab start; CD1 Dec. 2015	109 (86 US, 57 HEP)	22 (16 US, 7 HEP)	5
DM-G2: LZ	SURF in South Dakota	dark matter - WIMP search	FY15 fab start; CD3 Feb. 2017	252 (174 US, 161 HEP)	36 (26 US, 23 HEP)	5
SPT-3G	South Pole	CMB stage 3	Operations started Feb. 2017	59	9 (7 US,5 HEP)	3
Very Energetic Radiation Imaging Telescope Array System (VERITAS)	FLWO in AZ	gamma-ray survey	HEP ops completed 2016	109 (76 US, 28 HEP)	20 (16 US, 5 HEP)	4
Pierre Auger Observatory	Argentina	cosmic-ray	HEP ops completed 2016	436 (61 US, 18 HEP)	90 (17 US, 6 HEP)	17
Fermi Gamma-ray Space Telescope (FGST) Large Area Telescope (LAT)	space-based	gamma-ray survey	June 2008 launch; operating	252 (104 US, 18 HEP)	109 (37 US, 3 HEP)	22
Alpha Magnetic Spectrometer (AMS-02)	space-based (on ISS)	cosmic-ray	May 2011 launch; operating	600	60 (6 US, 2 HEP)	16
High Altitude Water Cherenkov (HAWC)	Mexico	gamma-ray survey	Operations started Jan. 2015	120 (60 US, 7 HEP)	30 (13 US, 3 HEP)	4

Cosmic Frontier: Experiment / Project Status

Operating experiments will continue to advance & produce science results:

- **AMS-2, DES, eBOSS, FGST, HAWC**: data taking and analysis continues

Projects: Priority is on executing the 4 P5-recommended Major Item of Equipment (MIE) projects, currently in fabrication phase:

Dark Energy Spectroscopic Instrument (DESI) - Dark Energy Stage 4 spectroscopic
- **CD-3 (Start of full fabrication activities) approved June 2016**

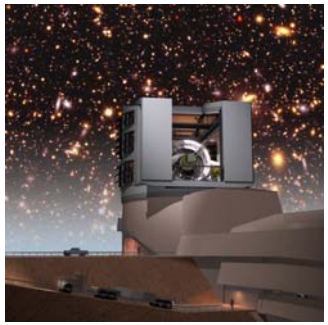
Large Synoptic Survey Telescope (LSST) – Dark Energy Stage 4 Imaging
- **CD-3 for LSST-camera approved August 2015**

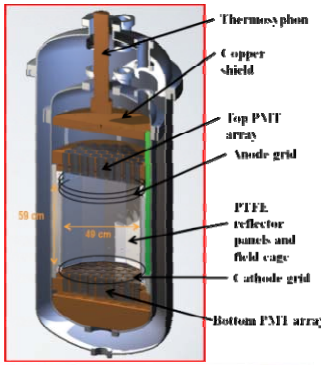
Large Underground Xenon – Zeplin (LZ) - WIMP high mass dark matter search
- **CD-3 approved February 2017**

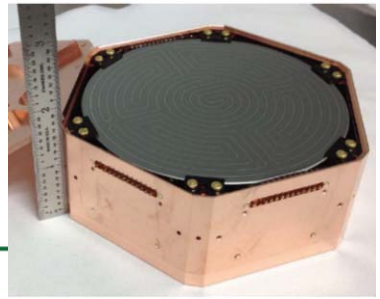
Super Cryogenic Dark Matter Search at SNOLab (SuperCDMS-SNOLab) - WIMP low mass
- **CD-1 approved December 2015; CD-2/3 review January 2018**

2 Cosmic Frontier smaller (below MIE) projects entered operations phase in 2017:
SPT-3G – operations started Feb 2017
ADMX-G2 – operations started Jan 2017

Future Planning: Laying ground work for the future (e.g. **CMB-S4** which starts later in P5 plan, and opportunities for small projects): mainly science studies; R&D funds are VERY limited.

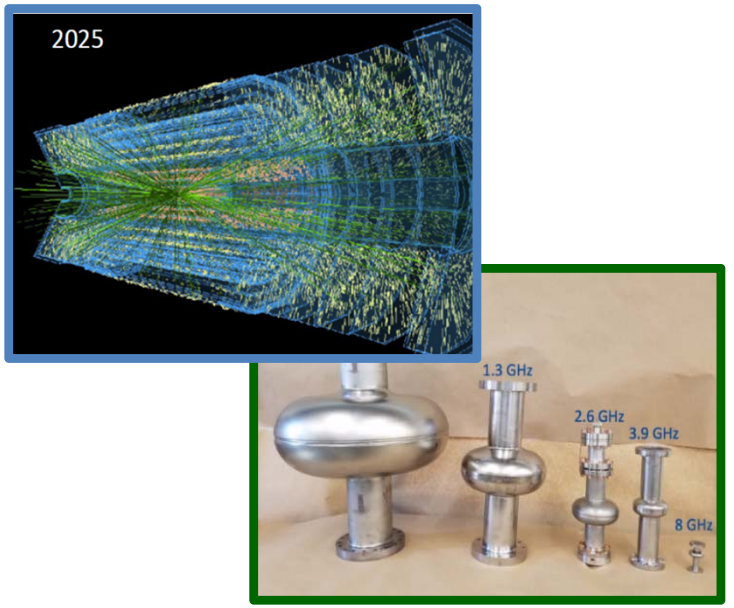






Quantum Information Science for HEP

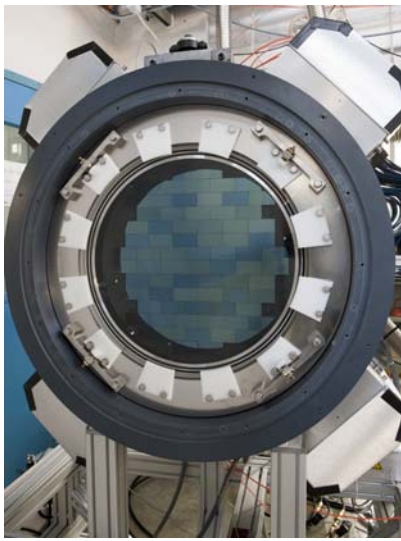
- **Emphasis is on HEP mission, science drivers, and advancement of QIS in the context of the broader SC initiative**
- **Program Manager for QIS at HEP: Lali Chatterjee**
- **FY 2018: Total of ~$15M for QIS, prioritized as:**
  - Fundamental HEP and QIS research
    - Foundational concepts of quantum information
    - Field theory and analog simulations
    - Experiments and emulators
  - Supporting technology for HEP
    - Quantum computing
    - Quantum controls and sensors



- **Funding Opportunity Announcement (FOA) and Lab Program Announcement**
  - in development for potential release after appropriations
- **Potential SBIR topics are being developed to support and complement HEP QIS activities**
- **Community input needed! Request For Information expected to be posted by HEP soon**

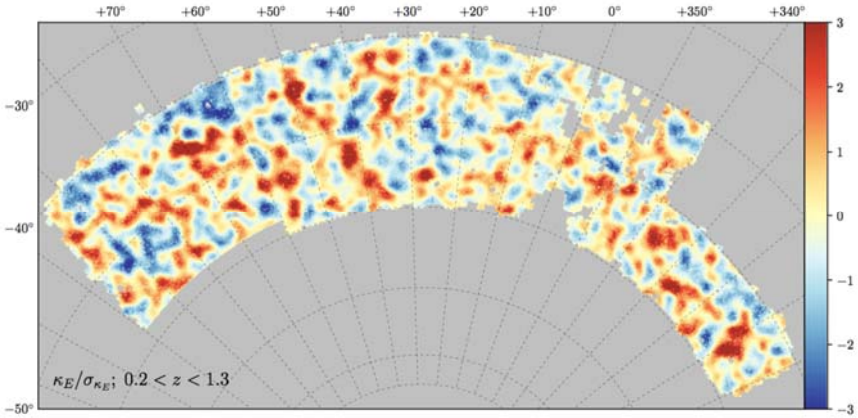
Science Highlight: Dark Energy Survey (DES)

- **DES probes nature of Dark Energy via survey of 300 million galaxies & 3000 supernovae, using 570-megapixel Dark Energy Camera on Blanco 4-meter telescope in Chile**
- Operations started August 2013; now in 5th year (of 5) of observing.
  - Data Release 1 (based on first 3 years of data) planned for December 2017



Results:

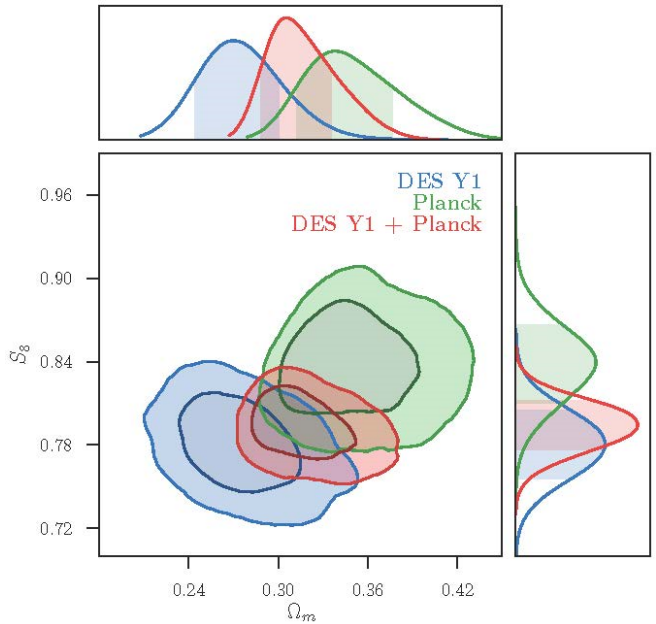
- **Aug. 2017: Year 1 Cosmology results (10 papers)** from galaxy clustering & weak lensing; constraints competitive with Planck CMB
- Well over 100 papers submitted; e.g., most distant supernova, new Milky Way dwarf satellites to constrain dark matter



DES Year 1: largest map of dark matter in the Universe. Based on weak lensing shape measurements of ~30 million galaxies, this map spans ~2.5 billion light years. (Chang, et al. 2017)

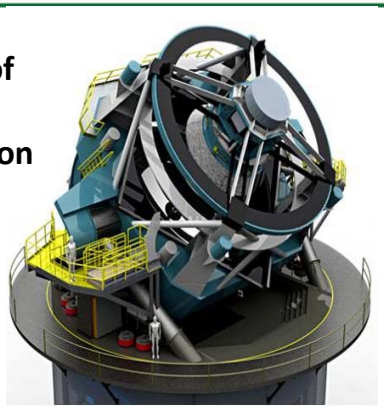
DES Year 1: cosmology results from galaxy clustering and weak lensing (DES Collaboration 2017). Consistent with Planck CMB within ΛCDM. Combined wCDM constraints with Planck, BAO, SN:

$$w = -1.00^{+0.04}_{-0.05}.$$



Large Synoptic Survey Telescope (LSST) status

Drawing of LSSTcam mounted on telecope facility.



The next-generation, wide-field LSST facility in Chile is designed to provide deep images of half the sky every few nights, enabling study of the nature of dark energy using multiple cosmological probes.

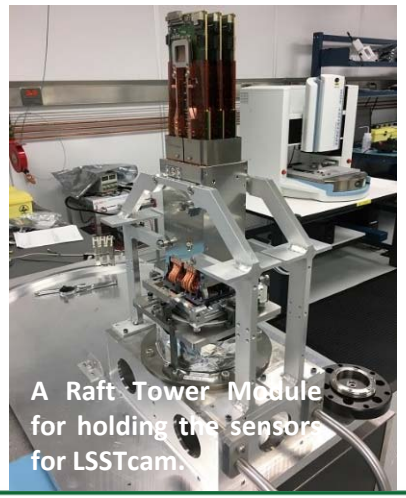
NSF leads the LSST project and is responsible for the 8.4m telescope facility and data management system. DOE is responsible for providing the LSSTcam.

Polishing the LSSTcam L3 lens

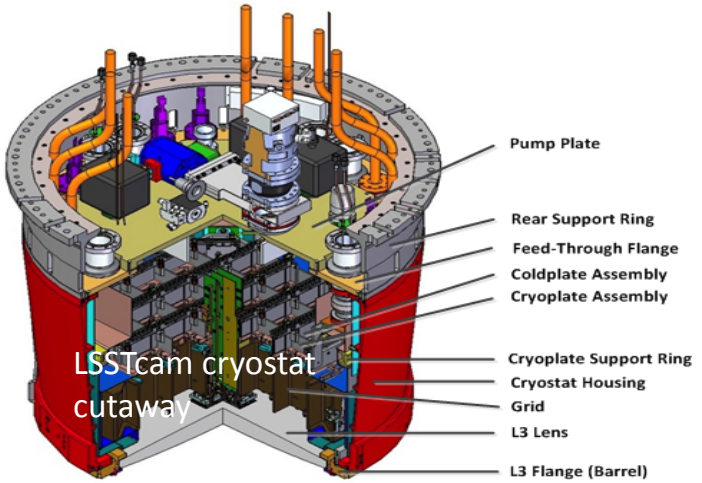
Status

- LSST Project Status review Sept. 2017
- LSST Facility Operations phase proposal review December 2017
- Dark Energy Science Collaboration (DESC) Operations review spring 2017

The finished cryostat grid protected by a Plexiglas shield



A Raft Tower Module for holding the sensors for LSSTcam.



LSSTcam cryostat cutaway

Dark Energy Spectroscopic Instrument (DESI) status

DESI's spectroscopic survey will measure 30 million spectra of galaxies & quasars to map their 3-D positions and determine the growth of cosmic structure over 10 billion years

- Using Baryon Acoustic Oscillation and Redshift Space Distortion growth and other methods

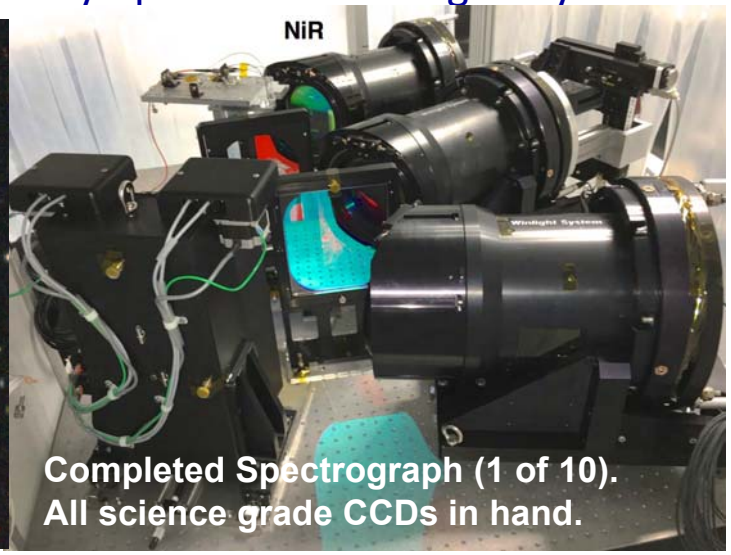
- **DOE leads the DESI project and is responsible for the spectrographs and associated systems.**
- **DOE is leasing NSF's Mayall telescope facility; operations support ramps up FY16-18 and full operations support starts FY19 & continues through the dedicated DESI survey.**

Status

- Targeting surveys mostly complete
- Feb. 2018 : Review of Project status & Operations plan
- Mayall shutdown to get ready for DESI in FY18; Full dark energy survey operations starting early FY20

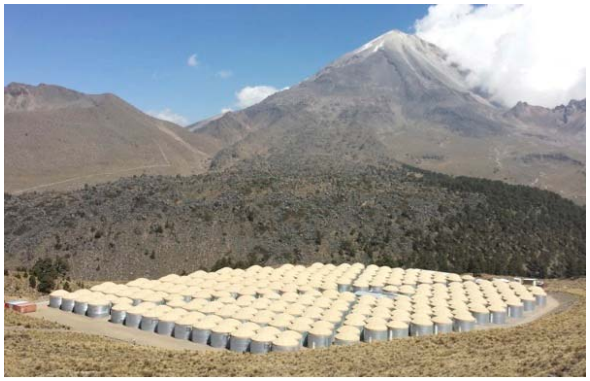

Lens C1 after AR coating. All lenses are now polished to spec.


DESI targeting image from Legacy Survey Data Release 4.



Completed Spectrograph (1 of 10). All science grade CCDs in hand.

Science Highlight: High Altitude Water Cerenkov

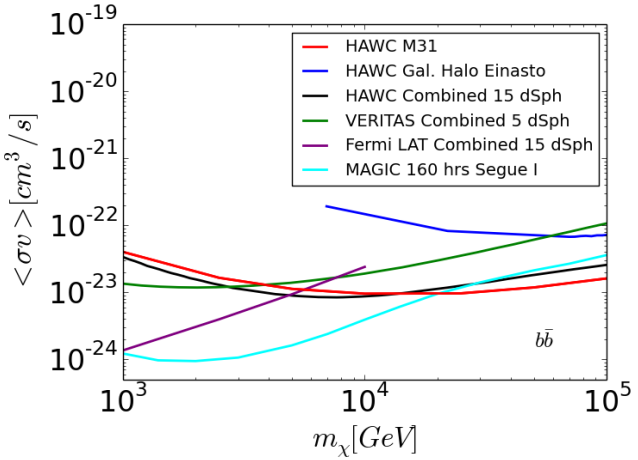


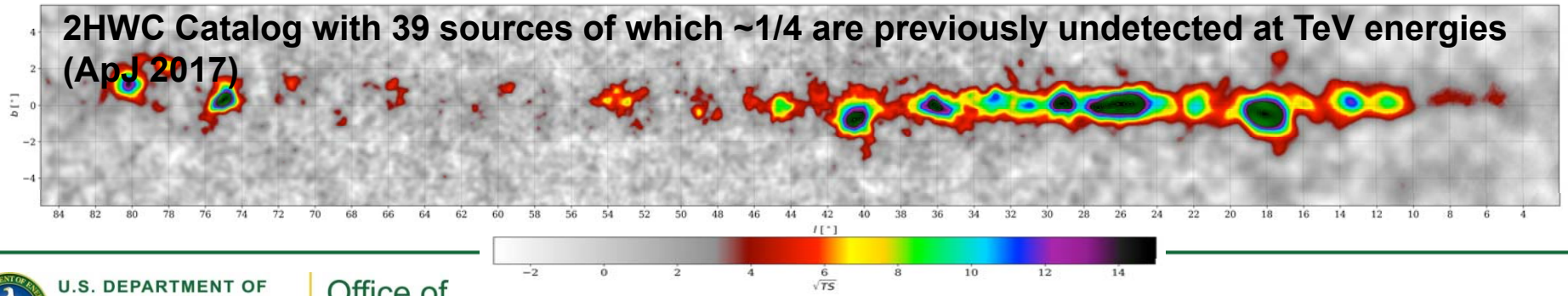
All-sky survey 100 GeV to > 100 TeV γ-rays, in Mexico

- Indirect dark matter search from γ-ray annihilation & decay
- Quantum gravity effects on propagation of γ-rays
- Particle acceleration in extreme magnetic and gravitational fields

Recent results: (July 2017)

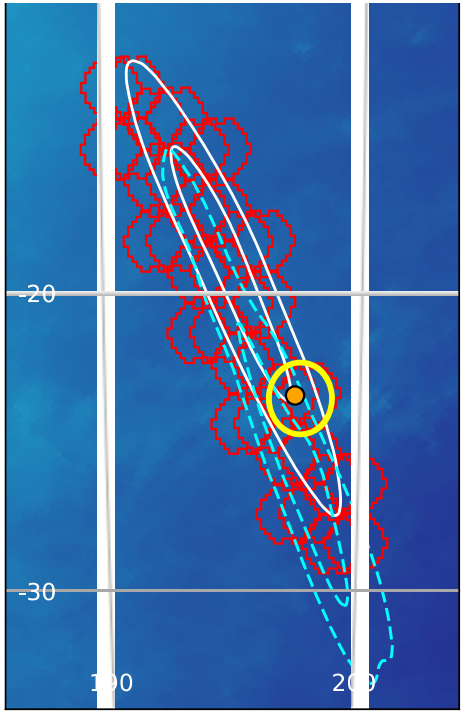
- 6 publications in ApJ in last 2 months including catalog of 39 sources
- HAWC limits on dark matter annihilation constrain cross sections of multi-TeV mass candidates. 15 dwarf spheroidal combined limits submitted to ApJ (arxiv.org/abs/1706.01277)



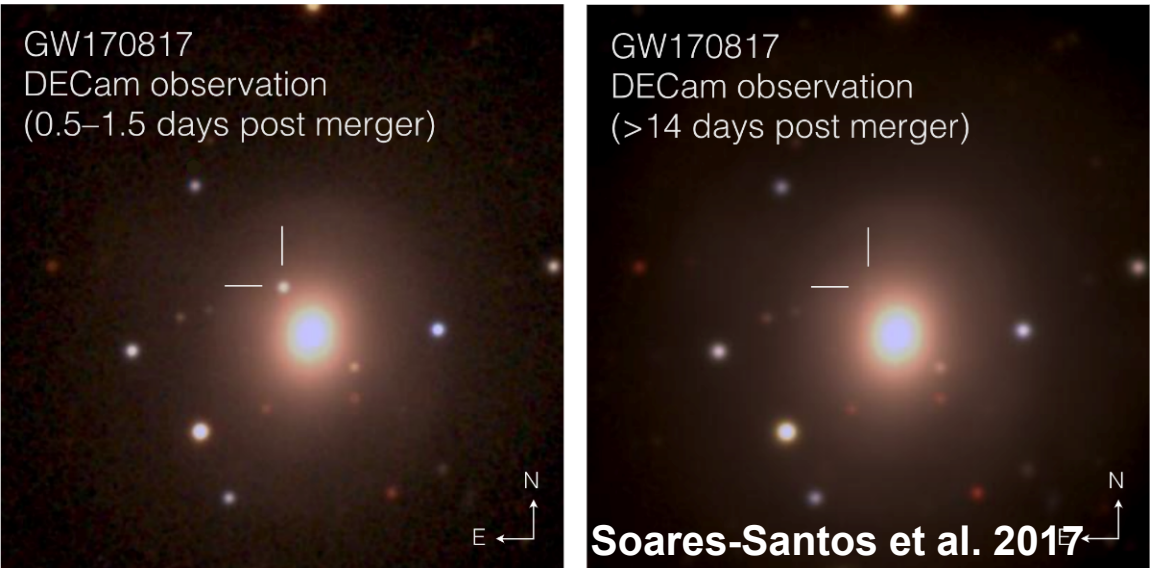


DES-GW Discovery & Follow-up of GW170817 Counterpart

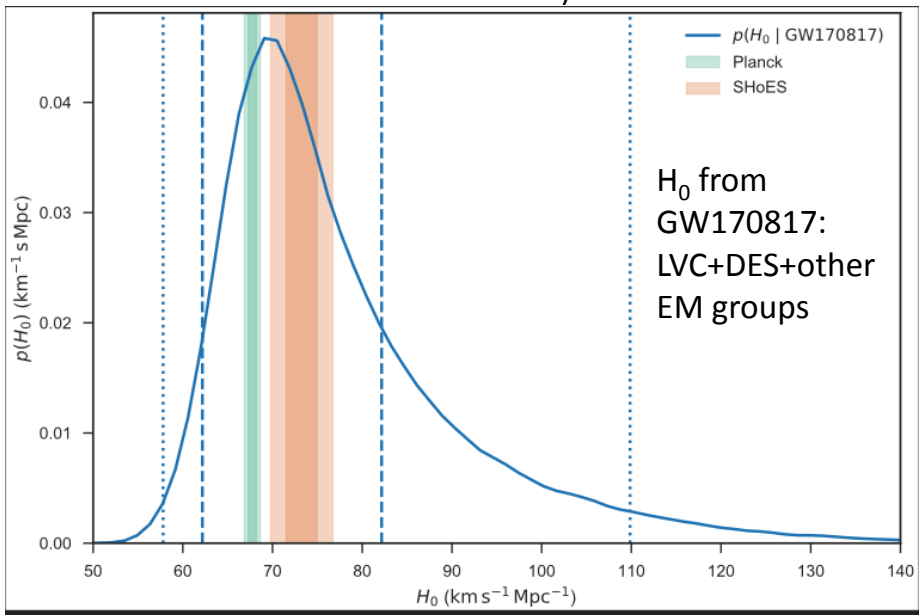
- Wide-FOV DECam on Blanco ideally suited for rapid, deep search of large LIGO/Virgo localization areas in the South. MOU with LVC to follow first events.
- DES in collaboration with community group followed up first 4 LIGO BBH gravitational-wave (GW) events to identify or exclude optical counterparts. Community ToO time allocation from NOAO blended with DES operations.
- Optical redshifts of host galaxies for Binary Neutron Star GW events enables new Standard Siren measurement of the Hubble constant. A precise (~1–2%), external H_0 measurement improves dark energy constraints.
- DES independently discovered and measured multi-band light curve for GW170817 kilonova in galaxy NGC 4993. Covered 70 sq. deg. & excluded all other transients.
- 6 DES collaboration papers (including 2 with LIGO/Virgo), and another 6 from DES-GW team. First standard siren H_0 measurement.



DECam exposures (red) covering the LIGO/Virgo (initial/revised) localization region (white/blue-dashed)



DES/DECam composite image of kilonova counterpart to GW170817 in galaxy NGC 4993 ~1 day (left) and 2 weeks (right) after the GW event.



HEP Cosmic Frontier – Multimessenger Science

Multimessenger Astrophysics – electromagnetic counterpart to GW170817

HAWC observed NGC4993 within 8 hours of GW signal, placed upper limits on TeV emission.

Fermi Gamma Ray Space Telescope detected GRB170817A in keV (with GBM) 1.7 seconds after GW signal. Fermi-LAT off due to SAA but 20 minutes after placed upper limits on MeV emission.

Synchronicity of GW and GRB arrival within 2 seconds after signal propagation for 130 My (400 x 10^{13} s) limits $c_T/c-1<10^{-15}$, ruling out almost all theories of fully modified gravity!

Cosmic Frontier Program

Study dark energy through staged program of complementary surveys (in partnership with NSF-AST)

- **Imaging surveys map cosmic structure over vast volumes of space:** *Dark Energy Survey (DES)* operating, *Large Synoptic Survey Telescope (LSST)* camera in fabrication
- **Spectroscopic surveys build deep, 3D maps of cosmic structure and growth:** *eBOSS* operating, *Dark Energy Spectroscopic Instrument (DESI)* in fabrication

Search for dark matter through direct detection experiments over a wide mass range (in partnership with NSF-PHY)

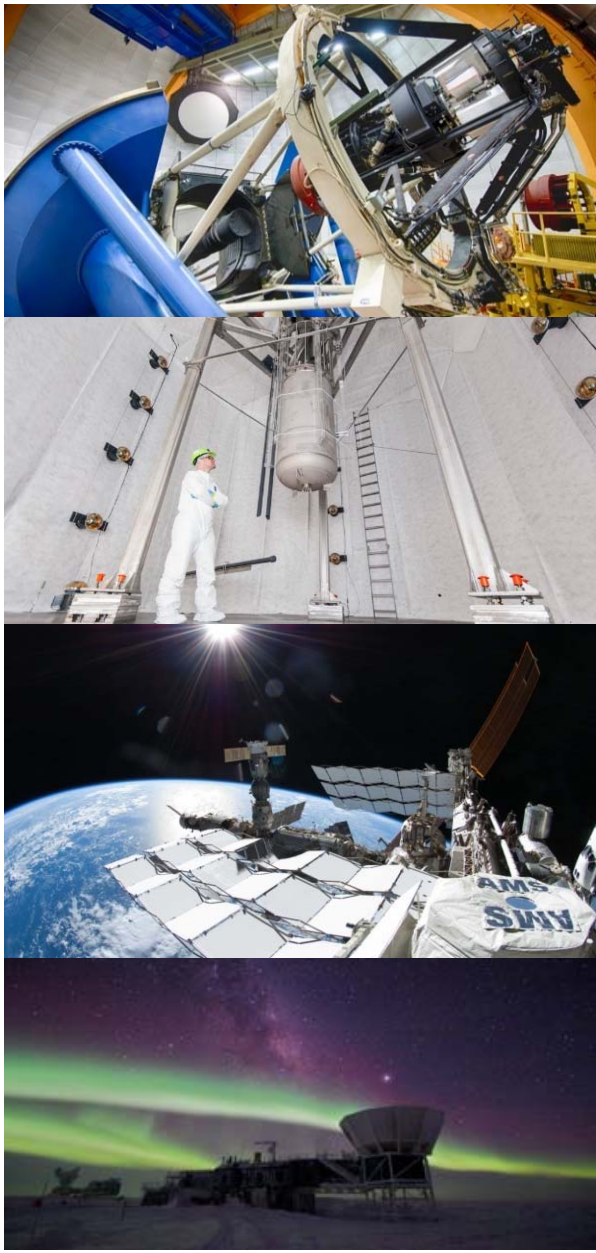
- **High- and low-mass WIMP sensitivity:** *LZ* and *SuperCDMS-SNOLAB*, in fab
- **Axion (ultralow mass) experiment:** *ADMX-G2* in operation

Search for high energy particles, e.g. from dark matter annihilations in cores of galaxies (in partnership with NSF, NASA)

- **Cosmic- and gamma-ray detectors on Earth and in space:** *HAWC*, *Fermi/GLAST*, *AMS* in operation

Study cosmic acceleration (inflation) at energies near the Planck scale and neutrino properties through the cosmic microwave background (CMB) (in partnership with NSF)

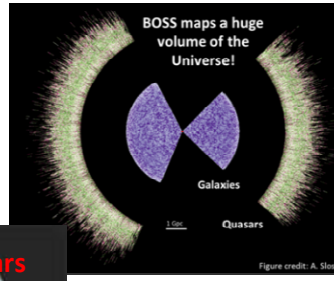
- **New generation South Pole experiment:** *SPT-3G* in operation
- **Next generation array 10x more sensitive:** *CMB-S4* in planning

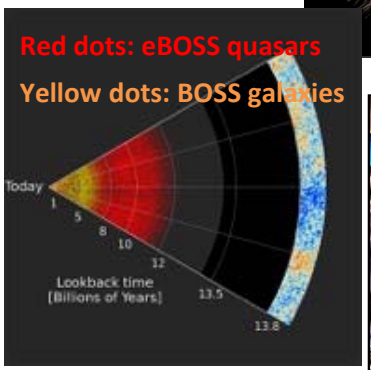


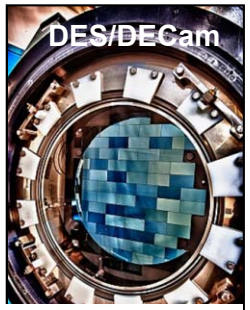
Dark Energy

Precision measurements to differentiate between: cosmological constant and/or new fields; or modification to General Relativity

Staged, complementary suite of imaging and spectroscopic surveys to determine its nature (in partnership with NSF-AST)







Operating/Completed:

– ***BOSS* (spectroscopic)** ended FY14; ***eBOSS* (spectroscopic)** started in 2015

– ***DES* (imaging)** started 5-year survey in late FY13

In Fabrication phase:

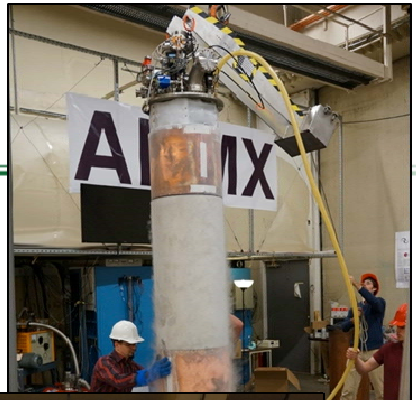
– ***Large Synoptic Survey Telescope* (LSST, Stage IV imaging)**

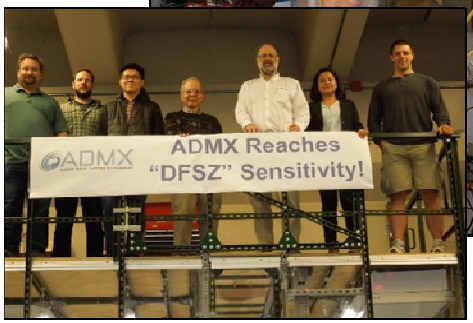
- HEP and NSF-AST (lead agency) partnership; HEP responsible for LSST camera (SLAC)
- LSST is under construction; science operations start FY23
- Planning started for LSST Facility Operations phase and Dark Energy Science Collaboration (DESC) Operations

– ***Dark Energy Spectroscopic Instrument* (DESI, Stage IV spectroscopic)**

- DESI is an "HEP experiment" in the fabrication phase; next review is Feb. 2018
  - Fabricate DESI instrumentation & data management system
  - HEP coordinating w/NSF-AST to use ("lease") the Mayall telescope; ramping up partial support in FY16-18; full support for dark energy operations starting FY19
- Planning for operations phase started

Direct Detection of Dark Matter





Staged suite of complementary direct detection experiments with multiple technologies to search for dark matter particles

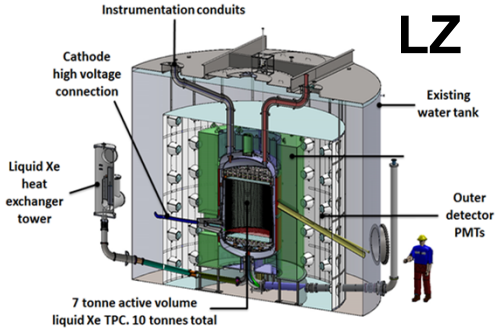
- High- and low-mass WIMP sensitivity; Axion (μeV mass) search

Operating/Completed:

Completed DOE funding for Operations of several current DM-Generation (DM-G1) experiments in FY16/17

In Design, Fabrication:

DM-G2's selected by HEP & NSF-PHY in July 2014 following P5 report:

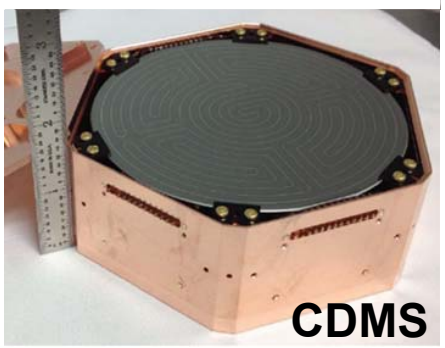


ADMX-G2 axion search at UWash (HEP); science ops started Jan 2017

- Uses a strong magnetic field to resonantly convert dark-matter halo axions into detectable photons; currently searching in range 0.1 to 2 GHz
- **Currently data-taking at design sensitivity!**

LZ at Homestake Mine in South Dakota (HEP)

- WIMP search through dual phase liquid Xe – ~10-1000 GeV mass range
- In fabrication; planning for operations phase started



SuperCDMS-SNOLab in Canada (HEP+NSF-PHY partnership)

- WIMP search using cryogenic solid-state crystals – ~1-10 GeV mass range
- Baseline review Jan. 2018; planning for ops phase started

Cosmic Microwave Background

Gain insight into **inflationary epoch** at the beginning of the universe, **dark energy & neutrino properties** by studying oldest visible light.

Current Experiments:

- ***SPT-3G* – HEP provided support for major upgrade of the camera to greatly increase sensitivity; Operations started Feb 2017 (NSF-led)**

➔**CMB-S4 Community-based Collaboration brought together ground based community to plan future**

- **Notional array of several telescopes in Chile & South Pole with on the order of 0.5 M detectors**
- **Needs scale-up of detector fabrication, testing, and readout**

***CMB-S4 Collaboration* Science, Technology Books:**
https://arxiv.org/abs/1610.02743 ; https://arxiv.org/abs/1706.02464

Future Planning:

As recommended by P5, HEP is planning to participate in CMB Stage 4

- **HEP labs already heavily involved in R&D to align with P5**
- **HEP will coordinate efforts & roles within HEP program**

- **Working with NSF to coordinate planning and a path forward**
- **CMB-S4 Concept Definition Taskforce report approved by AAAC**
  - **DOE will study the report and continue to work with NSF and the community on a path forward**

Cosmic-ray / Gamma-ray Physics

Use ground-based arrays, space telescopes, and an experiment on the International Space Station to perform indirect searches for dark matter, fundamental physics

Many significant inter-agency & international partnerships

HEP Roles Completed:

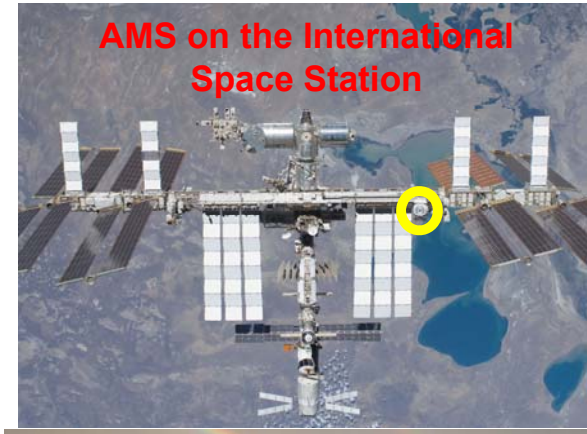
- VERITAS, Pierre Auger

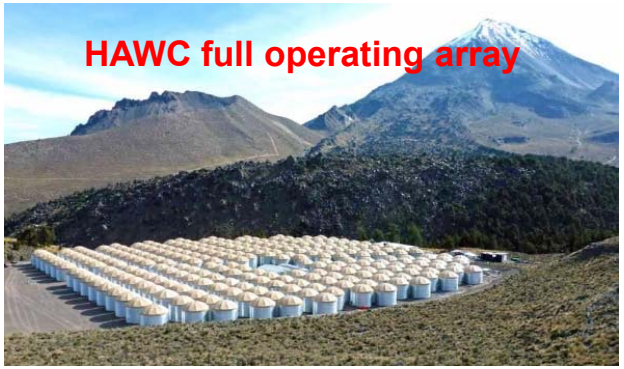
Operations continuing:

Fermi/GLAST (w/NASA)
- HEP is supporting the Instrument Science Ops Center at SLAC;
- In coordination with NASA, HEP is planning to continue support of critical efforts at SLAC if operations > 10 years

AMS (w/NASA)
- Operations continuing on ISS

HAWC (w/NSF)
- 5 year operations started early 2015
- Site and staff are safe following recent earthquakes

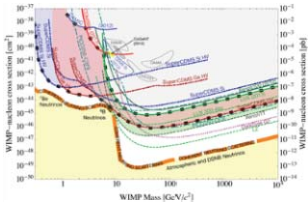




Cosmic Frontier – looking toward the future

HEP "Cosmic Visions (CV)" groups in several areas – 3 groups set up

- Allows interactions with small HEP community groups as 2-way line of communication for HEP-funded efforts and directions recommended by P5



CV-CMB: Coordinate HEP technology R&D & planning efforts for future CMB-S4

CV-DM: Coordinate HEP R&D (mainly DM-G2 science optimization now)

CV-DE: Investigate future HEP directions in the LSST & DESI era

CMB-S4 Concept Definition Team – AAAC subpanel

- Report on science goals & strawman concepts approved yesterday!

Dark Matter Community workshop held March 2017 to update identification of scientifically compelling areas to search; concepts for small projects in new areas of phase space? https://arxiv.org/abs/1707.04591

Dark Energy future directions community workshop held – Investigate optimizing science in DESI/LSST era and/or follow-on projects

- Workshop held in 2016 at UChicago; upcoming workshop Nov 14-15 at LBNL
- White paper on small "enhance" efforts in Jan 2018

→ **Looking towards planning for the 2020 Astronomy/Astrophysics Decadal Survey**

Other HEP Efforts Related to Cosmic Frontier

Theory program

- Vibrant Theory Program supporting all areas including Cosmic Frontier; Support for Theory centers and groups at several universities and labs.

Advanced Detector Development program

- Active R&D developing next generation detectors, including CCDs, TES superconducting bolometers, MKIDs, readout electronics, optics. Key elements for DES, LSST, CMB-S4. Important impact on X-ray detector, medical detectors.

Computational HEP program

- Coordinates DOE Supercomputer allocations via various ASCR and DOE Competitions
  - Cosmic Simulations, Emulators, Data Analysis
  - Computational HEP, SCIDAC – focused computational challenges
  - HEP Center for Computational Excellence
- High Performance Computing – Comp HEP & ASCR coordination & partnerships on some efforts, including Cosmic Simulation and Data analytics
- Manages allocations on NERSC facility for HEP Cosmic Frontier Simulations and Experiments

  NERSC used for analysis of many CMB experiments: in 2014 ~10 experiments with ~100 users, with ~10M CPU-hours

  HEP has an MOU with NASA for Planck analysis at NERSC – in 2014, 100M CPU-hours.

  NERSC Allocations 2015:
  - Total HEP Target Plus OT: 340 M Hours (expected to triple by 2018); Cosmic Frontier related is ~ 40% of this.

Data Management

- Each Project/Experiment has provided a Data Management Summary to HEP
- Used for referencing in research proposals; also to check against *AAAC Principles for Access in Astrophysics* and *SC Statement on Digital Data Management*

NAS Astro Decadal Survey – HEP comments on planning

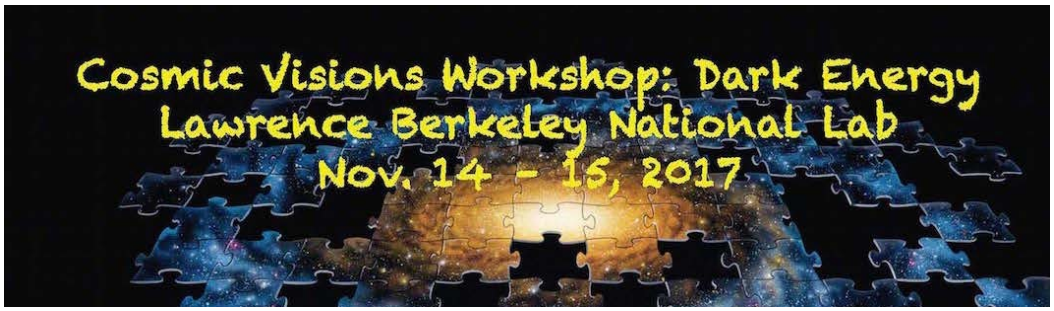
HEP is currently following the 2014 HEPAP P5 strategic plan.

➔ Starting preparations for the next P5 strategic planning process, timed to be after the large projects, HL-LHC upgrades and LBNF/DUNE have Critical Decision 2 approval.

The P5 study would be carried out in early 2020's (completes ~2022) and will develop the US particle physics strategy for the next 10 years. This is entwined with the European particle physics strategy process.

P5 Inputs:

- **Snowmass process to collect HEP community science input starts ~ 2019**
- **Particle physics European strategy update, starting early 2019, report May 2020**
- **Astro Decadal Survey, expected to start Dec. 2018 and complete Dec. 2020**
  → A 6-month delay in results could probably be accommodated; if it's much longer, the results may not feed into the next P5 plan.



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Cosmic Frontier – looking toward the Future

DOE Office of Science
Early Career Award
FY17 winners in the Cosmic Frontier

Anja von der Linden
Stony Brook University
Expert in galaxy clusters

Michael Schneider
Lawrence Livermore National Lab
Expert in weak gravitational lensing

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... and Detector R&D and Theory in Cosmic Frontier areas

Zeeshan Ahmed
SLAC
Expert in CMB detectors

Marilena LoVerde
Stony Brook University
Expert in cosmological neutrinos