# Cosmic Frontier at Fermilab

***Overview of Experiments and Strategy***

Craig Hogan
DOE/OHEP 3-year program review
September 17, 2013

# Fermilab Center for Particle Astrophysics (FCPA)

## Intellectual center

- Hub unifies a broad program: offices, seminars, informal talks
- Meetings, workshops, retreats
- Visitors program
- Theory and experiment

## Management

- Reviews, reports
- Matrix role with Fermilab divisions on scientific effort
- Advocacy/partnership on technical effort, resources, staffing
- Direct management of experimental astro postdocs

## Planning

- Stewardship of new initiatives
- Strategic planning, alignment with agency and community
- Coordination, budget planning with DOE
- Coordination with Fermilab R&D and accelerator programs

# Cosmic Frontier Experiments at Fermilab

## Dark Energy

Deep, wide, precise surveys to map expansion, mass, velocity, and structure:  probe new physics of cosmic acceleration

## Dark Matter

Direct detection of WIMP dark matter particles

## Highest Energy Cosmic Rays

Detailed study of rarest, largest cosmic ray showers

## Quantum Space-time

Measure space-time with Planck spectral density position sensitivity

## New Initiatives

Detector R&D to enable new capabilities

New Cosmic Microwave Background polarization experiments

# Dark Energy

## Cosmic expansion is accelerating

## New Physics is unknown

- Energy or gravity?
- "Matter tells space-time how to curve, space-time tells matter how to move": how do they talk to each other?

## Experimental approach: measure the universe

- Expansion history
- Distribution of mass, velocity
- Growth of structure
- Use light from stars, supernovae, quasars, cosmic background

## Progress driven by precision

# Precision Cosmology by DOE: a transformative 40 year experimental campaign (almost like we planned it)

## SDSS (1990 ~ 2014)

- Advent of precision cosmology
- Imaging and spectroscopy
- Many firsts (ISW, BAO, SNe…)
- SDSS I & 2 led by FNAL
- Now BOSS (led by LBNL)

## Dark Energy Survey (DES) (2013 ~ 2018)

- Led by FNAL

## Dark Energy Spectroscopic Instrument (DESI) (2019~24)

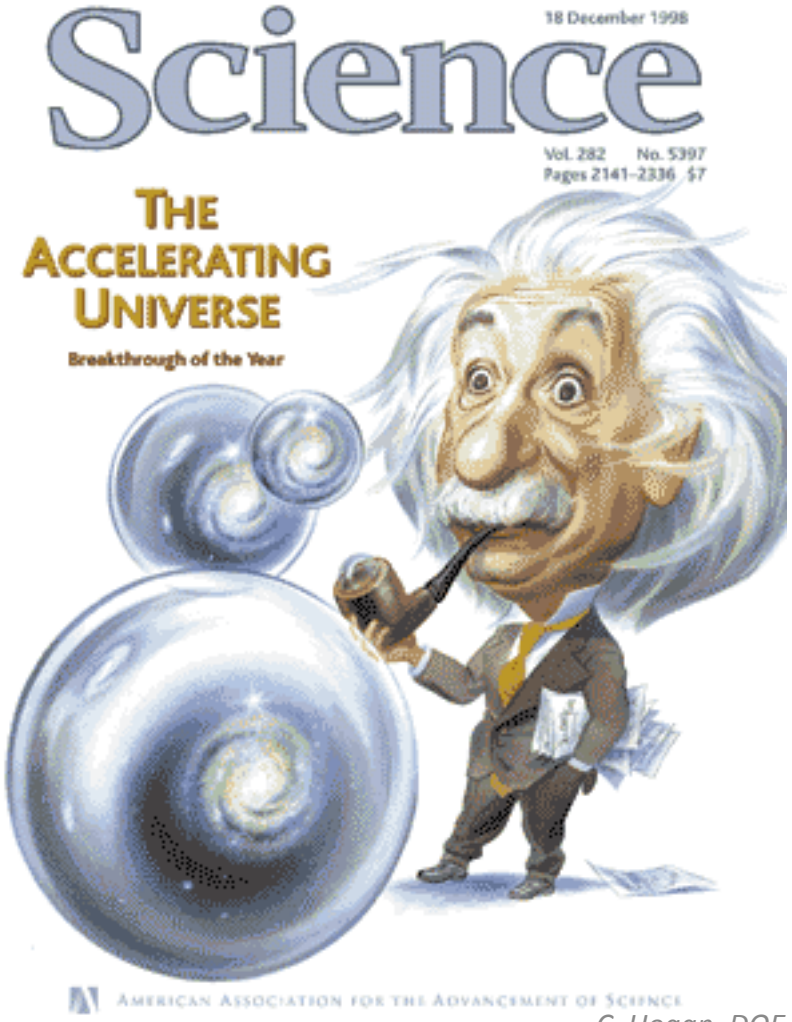
- Led by LBNL

## Large Synoptic Survey Telescope (LSST) (~2020~2030)

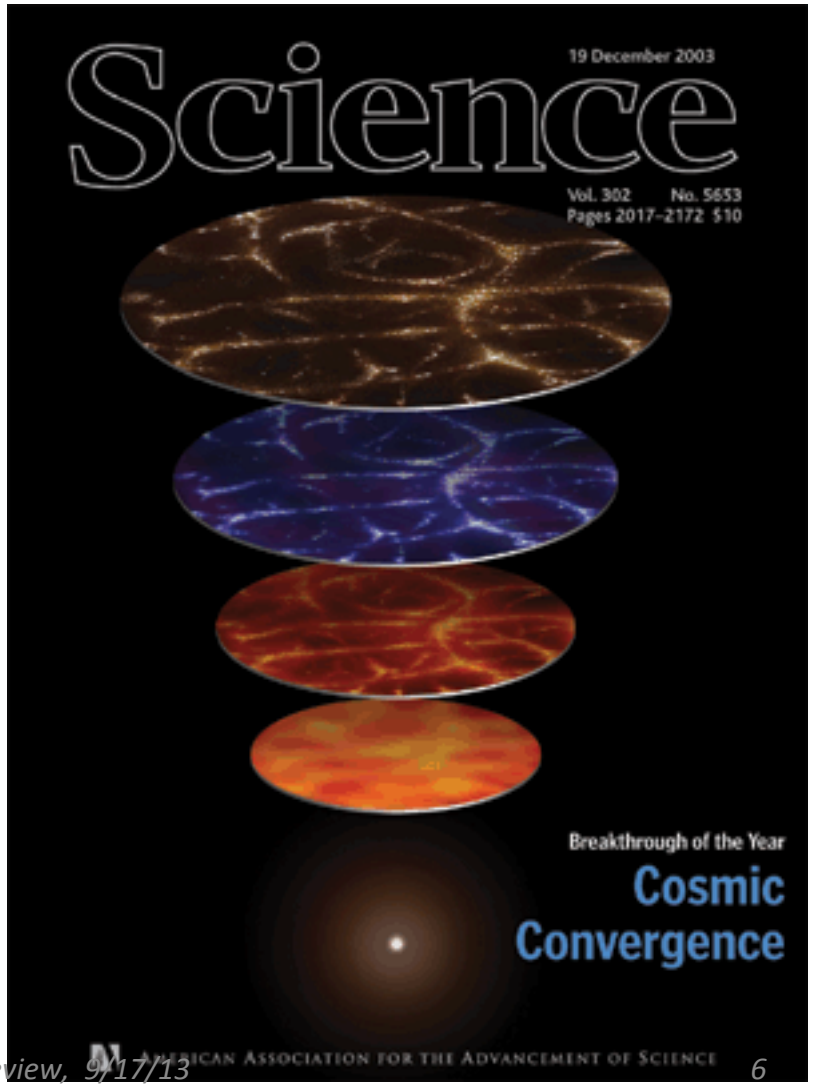
- DOE Camera project led by SLAC

# *Science* Breakthroughs of the Year: 1998 and 2003

*Cosmic acceleration*




*Precision cosmology ( WMAP,SDSS): Imaging, spectroscopy, CMB maps*



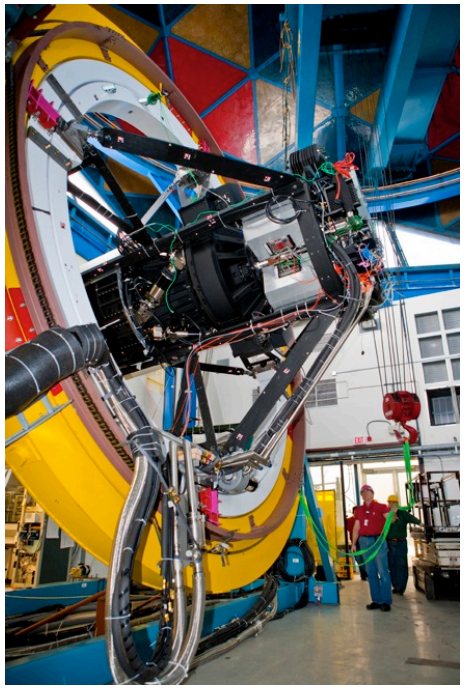
# Dark Energy Survey

Order of magnitude advance in cosmic surveys

Fermilab built Dark Energy Camera, completed 2012

Survey started August 31, 2013

Talk by Josh Frieman



# Dark Energy Spectroscopic Instrument (DESI)

## Added value of high-resolution spectral survey

Deeper than SDSS, bigger volume, 30x more objects

## Previous concepts

DESpec (FNAL)

BigBOSS (LBNL)

## Moving ahead: a single DOE project, DESI

Led by LBNL

## Fermilab technical roles

corrector design, detector packaging and testing

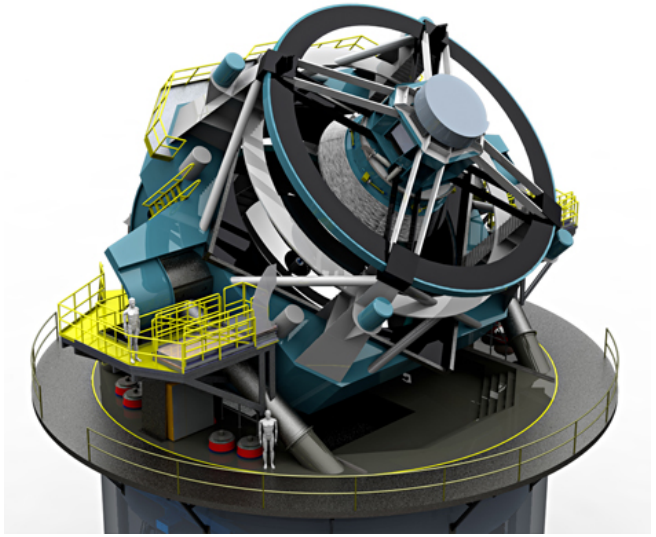
## Fermilab scientific roles

design, planning, management, analysis

## More in talk by Josh Frieman

# LSST: far beyond DES

3x bigger field
3x bigger aperture (**>9x survey speed**)
6x number of pixels
3x larger share of telescope
2x survey duration
4x main survey area
(LSST includes DES survey area)
4x frame rate
Time domain: ~1000-frame movie over 10 years
**>100x as much data**
>10x improvement in Dark Energy precision
>10x as many scientists
>10x the budget
Nearby mountaintop
Starts ~9 years later



LSST
Large Synoptic Survey Telescope

# Fermilab in LSST

## DOE camera project

Led by SLAC

## NSF project: everything else

Led by AURA/LSSTC; Fermilab participates as a member institution

## LSST Dark Energy Science Collaboration

FNAL scientists active in collaboration; activity coordinated by Scott Dodelson
FNAL leading Software Working Group; hosting workshops etc
Fermilab proposes to build science analysis framework

## DES is a pathfinder

Real data like LSST will be flowing this year; impacts many LSST systems
DES analysis coupled with LSST tools

## Interest at Fermilab is high

Typically >15 people at monthly LSST meetings
But DES dominates time and attention right now

*Fermilab asset: team of experienced survey scientists*

# Dark Energy: summary

## Dark Energy Survey

- Fermilab hosts DES project and collaboration leadership
- Support (operations, computing, software, consulting, analysis) for DES collaboration is the main effort for next 5 years
- Ongoing development and integration of DESDM and analysis software
- DES workshops, visitors program will evolve into LSST role

## DESI

- Fermilab participates in shaping and building DESI
- Interaction with DES: target selection, joint analysis
- Construction starts in ~2015, survey starts >2018 after DES is finished

## Large Synoptic Survey Telescope

- Modest technical roles in camera and data management
- Fermilab scientists active in LSST Dark Energy Science Collaboration
- Effort level will increase over time as DES matures

# WIMP Dark Matter Detection

Basic principle: detect collisions of Galactic Weakly Interacting Dark Matter particles with nuclei

Basic challenge: rare events require exquisite control of experimental backgrounds

Masses and detailed interactions of particles are unknown

- Advances require large detector masses with zero background
- Detection, confirmation, study require multiple targets and technologies
- Pursue multiple technologies now, downselect later
- ***Detectors now have sensitivity to make a discovery***
- ***Hints of detections!***

***Fermilab is the lead lab on four experiments, using different technologies and optimized for different kinds of WIMPs***

# WIMP Dark Matter: summary

DOE and NSF  to select G2 experiments soon for construction

Fermilab experiments are contenders

SuperCDMS, COUPP, DarkSide: three of four WIMP experiments in G2

Fermilab plans to stay with WIMPs through the G3 finale

Generic Detector R&D may enable new technologies:

DAMIC, low-threshold directional detectors

More in talk by Dan Bauer

# Highest Energy Cosmic Rays: Pierre Auger

World's leading experiment on the highest energy particles, fully operational since 2008

Fermilab has been the lead lab in a large international consortium

Energy spectrum

- Seeing the GZK cutoff or learning about sources?

Anisotropy

- Do the highest energy cosmic rays point towards matter concentrations? Can we learn about the acceleration mechanism?

Composition

- Learning about sources, or something new in hadronic cross sections at the highest energies? (much higher than LHC)

# Pierre Auger Observatory

Observatory: installed over a 3000 $km^2$ site in Argentina

24 fluorescence telescopes;

1600 surface Cherenkov detectors;

Enhancements: 3 high elevation fluorescence telescopes, 60 infill detectors, muon counter array

Collaboration & Partnership: international collaboration of 19 institutions, 463 people. Fermilab hosted the Project Office until this summer.

# Pierre Auger Observatory: Fermilab Plans

- Continued exciting Auger research results
  - New results on composition, anisotropy, spectrum, cross sections @ 57 TeV
  - Fermilab group making key contributions
  - Array enhancements paying off
- Fermilab effort on Auger has been reduced over the last three years
  - Response to budget pressure and agency, community priorities
  - Effort moved to dark matter, dark energy experiments
- Transition of management to Karlsruhe Institute of Technology now underway
  - Will be complete by December 2013
- No plans for Fermilab to hire additional staff in this area
  - Will continue research group
  - Funded research likely to continue to decrease

# Quantum Space-Time

Quantum behavior of geometry has never been detected

Fermilab Holometer will measure or constrain quantum-geometrical noise in the position of massive bodies, with Planck spectral density position sensitivity

Dual, correlated 40-meter Michelson interferometers now in commissioning, first science results expected in next year

Future plans depend on results

More in talk by Aaron Chou

# Detector R&D

Cosmic Frontier scientists develop new, widely-applicable detector technology

Often leads to new experiments

- At Fermilab: COUPP, Holometer, DAMIC, GammeV/CHASE
- Elsewhere: CHIME

Current efforts

- Magnetic Kinetic Inductance Devices: images with spectral and time resolution (MKIDs)
- Scintillation Efficiency of Nuclear Recoils in Noble Elements (Scene)
- Low noise CCDs: spectroscopic, low background applications

Future efforts

- CMB polarization mapping technologies (w/ANL et al.)

# Cosmic Microwave Background

Large-scale maps of CMB polarization uniquely probe new physics:

- Energy scale of inflation
- Graviton fluctuations
- New relativistic species
- Cosmic neutrino background
- Sum of neutrino masses, information on hierarchy

Complement, enhance precision probes from optical surveys

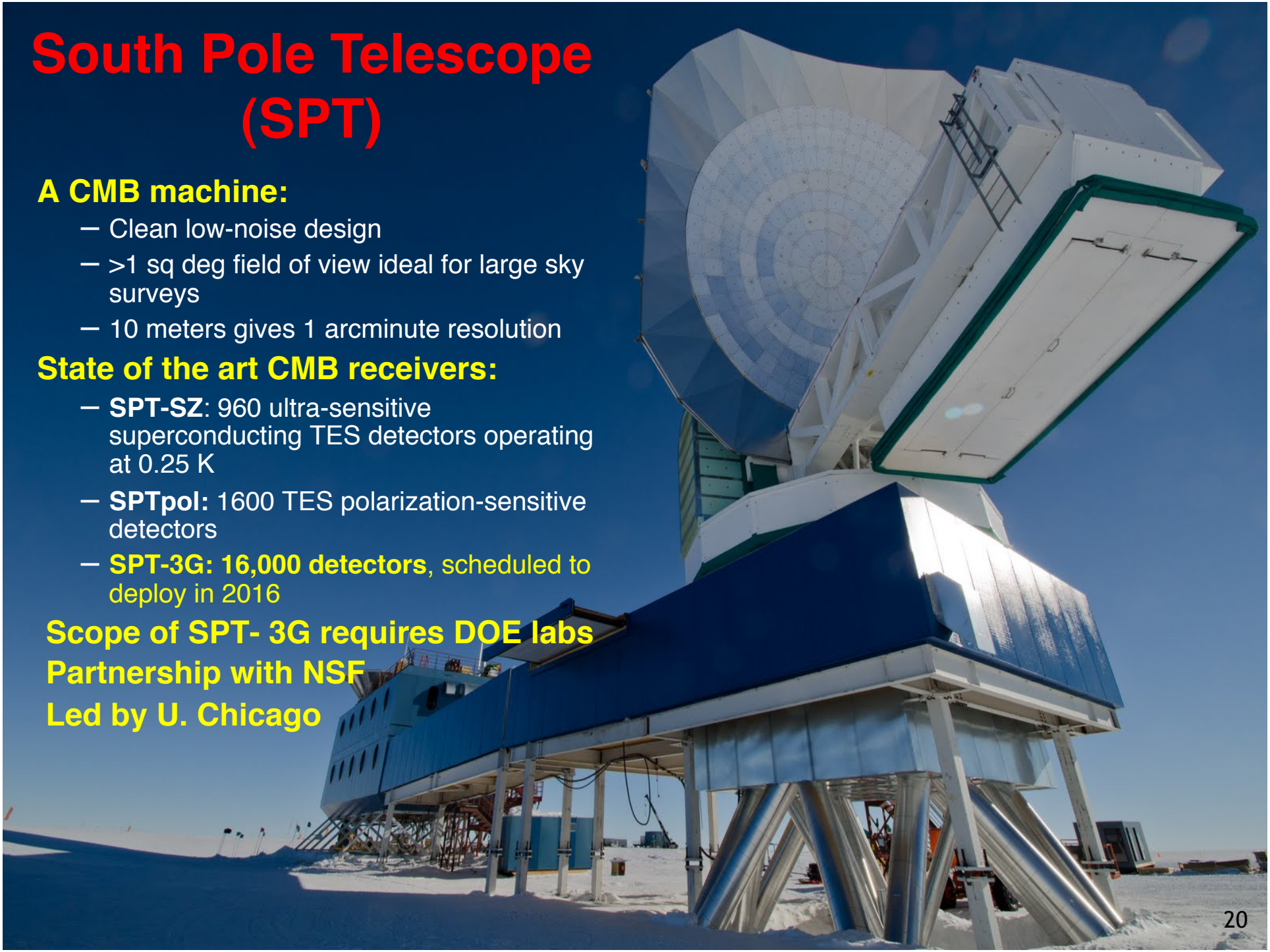
- **DES was conceived with South Pole Telescope in mind**

Fermilab experience with QUIET experiment

Major opportunity highlighted at Snowmass: partnership with DOE labs enables larger detector arrays, faster survey speed and greater precision

***Fermilab proposes to re-engage with CMB experiments***

# South Pole Telescope (SPT)



**A CMB machine:**

- Clean low-noise design
- >1 sq deg field of view ideal for large sky surveys
- 10 meters gives 1 arcminute resolution

**State of the art CMB receivers:**

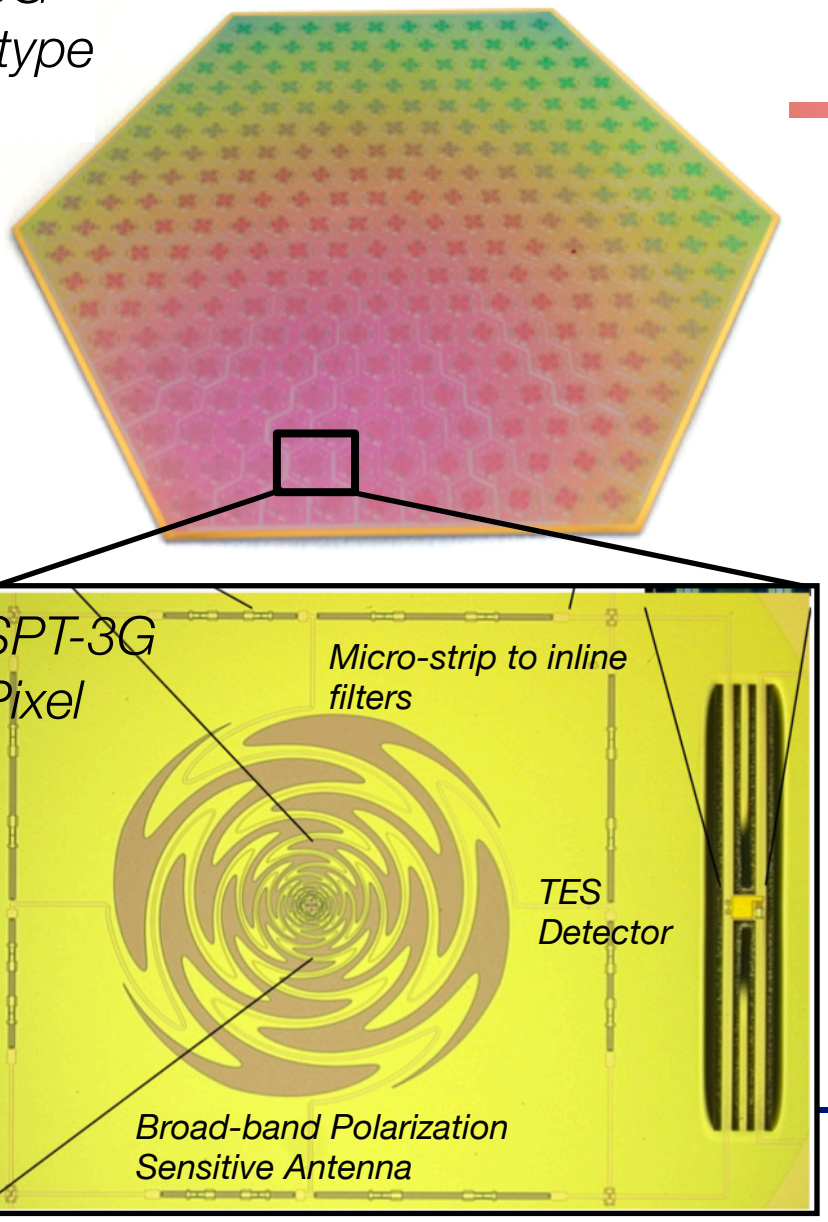
- **SPT-SZ**: 960 ultra-sensitive superconducting TES detectors operating at 0.25 K
- **SPTpol:** 1600 TES polarization-sensitive detectors
- **SPT-3G: 16,000 detectors**, scheduled to deploy in 2016

**Scope of SPT- 3G requires DOE labs**

**Partnership with NSF**

**Led by U. Chicago**

# Fermilab Roles in SPT-3G




- *Primary technical challenge for SPT-3G is development of **thousands of superconducting TES detector arrays**, including fabrication and testing*
- ***Scale requires capabilities of DOE labs***
- *Fabrication of components at UC-Berkeley and Argonne National Lab (ANL)*
- ***ANL is the lead lab***
- ***Proposed Fermilab roles:***
  - *Automated wire-bonding and assembly of detector arrays at SiDet*
  - *Fast-turnaround testing integrated with ANL detector fab*
  - *SPT-3G receiver cryostat design, construction, testing, and integration*
- ***Scientific synergy with DES***

# Program planning

## Priorities based on community process

- Program based on HEPAP/P5, PASAG, AANM
- Fermilab scientists active in Snowmass, P5 followup
- Community workshops
- Internal meetings and retreats
- New initiatives and experiments reviewed by FCPA, PAC

## Long-term technology initiatives

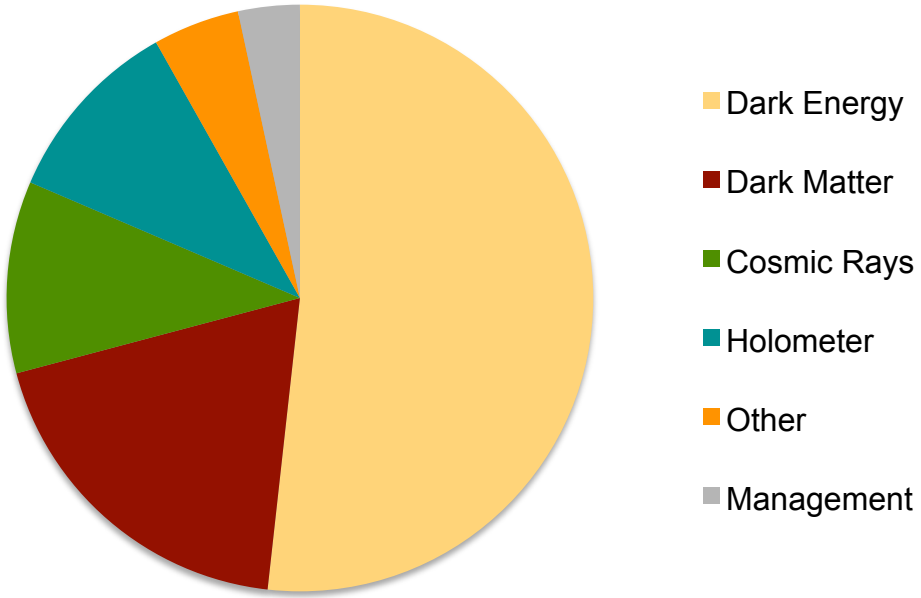
- New detector R&D: MKIDs, SiPM, Directional DM etc

## University partnerships

- Experiments in partnership with many university groups
- Lab provides technical capabilities for larger scope
- Synergies with UChicago/KICP

# Scientist Effort

*32 FTE scientists work on experimental particle astrophysics*




*Additionally:*
*5 staff and 4 postdocs in theoretical astrophysics group*

# Theoretical Astrophysics (mostly not KA23)

## First Particle Astrophysics at Fermilab

Founded in 1983 by Lederman and Schramm, Kolb and Turner

Inner Space/Outer Space: the first “cosmic frontier”

## Vital connections between theory and experiment

Dark Matter phenomenology (Hooper, Buckley, Cholis)

Dark Energy and CMB (Dodelson, Frieman, Stebbins)

Structure formation (Gnedin, Hearin)

## Theory leadership roles in experimental science

Josh Frieman is DES director

Scott Dodelson: coordinating dark energy science from DES and LSST, and developing LSST software frameworks

Dan Hooper: major role in interpreting results from direct and indirect dark matter detection experiments

Hogan: Project Scientist, theory behind the Holometer experiment

# Budget Scenarios

- A: No CMB, rapidly decrease Auger
- B: Slow CMB start, decrease Auger
- C: Ramp up CMB, maintain Auger
- Grow DM, maintain DE in all scenarios

Proposed HEP Funding (KA230102) in $K

| | Scenario A | | | Scenario B | | | Scenario C | | |
|---|---|---|---|---|---|---|---|---|---|
| **Thrust** | **FY14** | **FY15** | **FY16** | **FY14** | **FY15** | **FY16** | **FY14** | **FY15** | **FY16** |
| Dark Energy | 5005 | 5105 | 5236 | 4927 | 5045 | 5166 | 5047 | 5145 | 5076 |
| Dark Matter | 2485 | 2590 | 2721 | 2665 | 2705 | 2766 | 2680 | 2740 | 2801 |
| High Energy Cosmic Particles | 609 | 375 | 165 | 607 | 414 | 205 | 614 | 628 | 643 |
| CMB | 0 | 0 | 0 | 220 | 226 | 330 | 240 | 545 | 568 |
| Other | 1829 | 1858 | 1806 | 1711 | 1740 | 1663 | 2091 | 1871 | 1873 |
| **TOTAL** | 9928 | 9928 | 9928 | 10130 | 10130 | 10130 | 10672 | 10929 | 10961 |

# Big-Picture Plan

- Either we discover something new

  WIMP events, varying dark energy, CMB primordial B-modes, holographic noise,…

  Then discovery sets priorities

- Or we don't

  Choices set by potential for discovery, overall science impact

  Eventually, will move on from WIMP and Dark Energy programs

  Start laying the groundwork now (e.g., Holometer, CMB, MKIDs)

# Fermilab Strategy

## Dark Energy

- Expect 5x improvement in our understanding of dark energy with DES by 2018
- Even better with spectroscopic survey (DESI) ~2019-2024
- Significant roles in dark energy science with LSST in 2020-2030

## Dark Matter

- Operating experiments this year: SuperCDMS, COUPP, DarkSide, DAMIC
- ~3x better sensitivity by 2015
- Strong G2 experiments: 10x additional sensitivity
- Play major role in G3 experiments to probe to neutrino background limit

## Highest Energy Cosmic Particles

- Aim for improved understanding of origin, composition, interaction
- Continued Fermilab research role

## Quantum Space-time

- Unique experiment to look for Planck-scale physics
- Follow on will depend on what is seen with Holometer by 2015

## New Initiatives

- Start now on next generation CMB experiment
- Detector R&D leading to new experiments