Particle Astrophysics at Fermilab

Overview, Progress and Plans

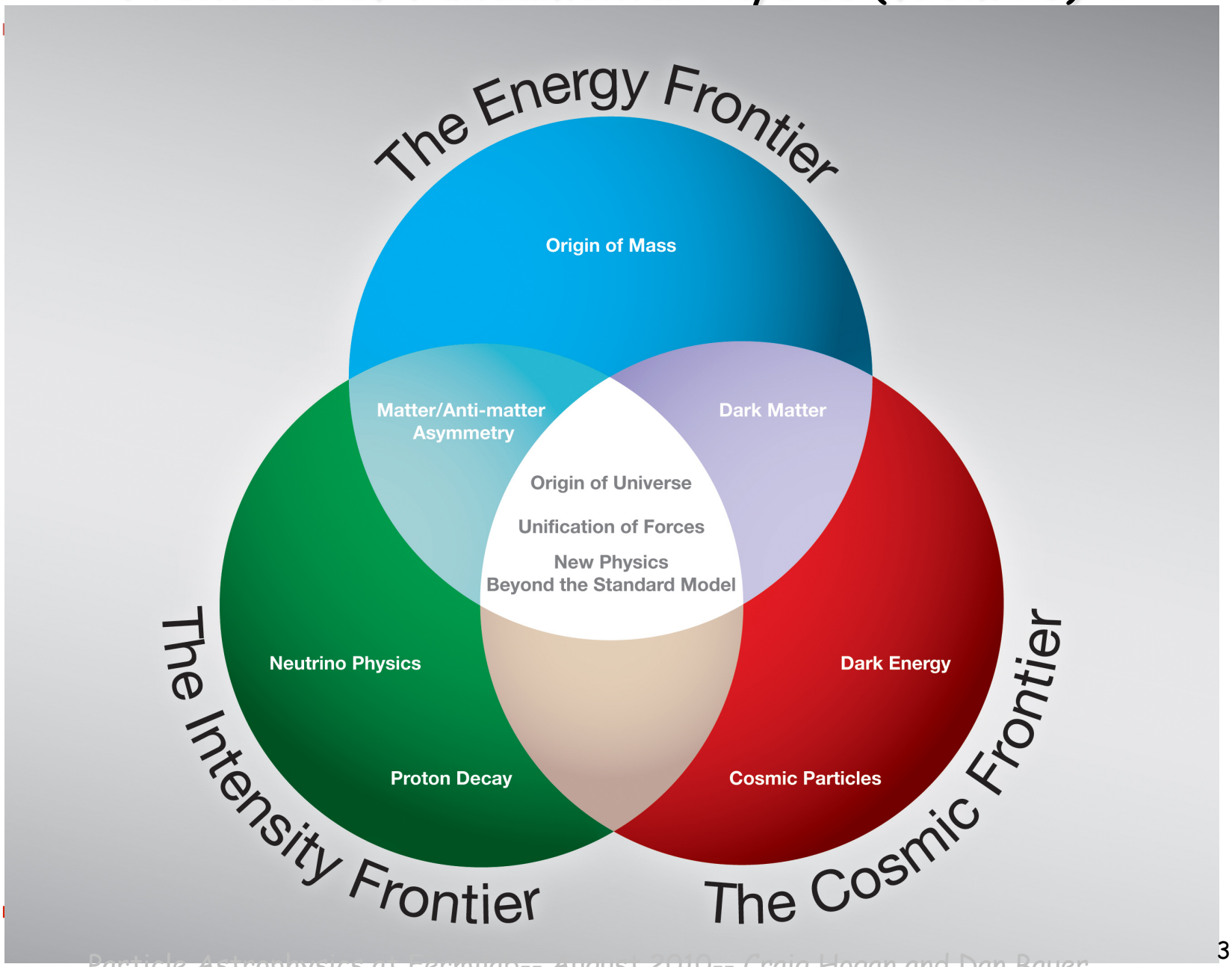
Craig Hogan, Director
Dan Bauer, Deputy Director
Fermilab Center for Particle Astrophysics
DOE Site Visit, August 24, 2010

DOE/OHEP Mission

The mission of the High Energy Physics program is to understand how our universe works at its most fundamental level. We do this by discovering the most elementary constituents of matter and energy, exploring the basic nature of space and time itself, and probing the interactions between them.

---Mission Statement, DOE Office of High Energy Physics

Frontiers of Fundamental Physics (from P5)



Fermilab research on the Cosmic Frontier

Inflation/ early universe/Dark Energy

Cosmic surveys

Dark Matter

Direct Detection

High energy particles

Ultra High Energy Cosmic Rays

Unification far beyond the Terascale

High-finesse, high-frequency laser cavities

Ongoing Fermilab experiments

Inflation/ early universe/Dark Energy

- Dark Energy Survey (DES)

Dark Matter Direct Detection

- Cryogenic Dark Matter Search (CDMS)
- Chicagoland Observatory for Underground Particle Physics (COUPP)

Ultra high energy cosmic rays

- Pierre Auger Observatory (PAO)

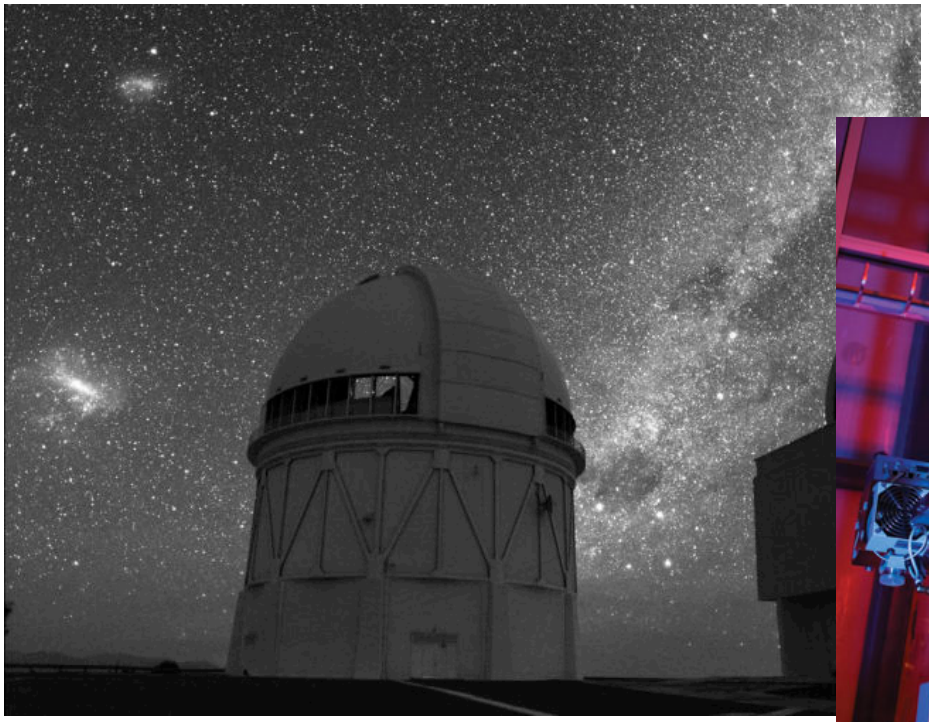
Dark Energy Survey

Next big step in cosmic surveys after SDSS

DE Camera under construction at Fermilab

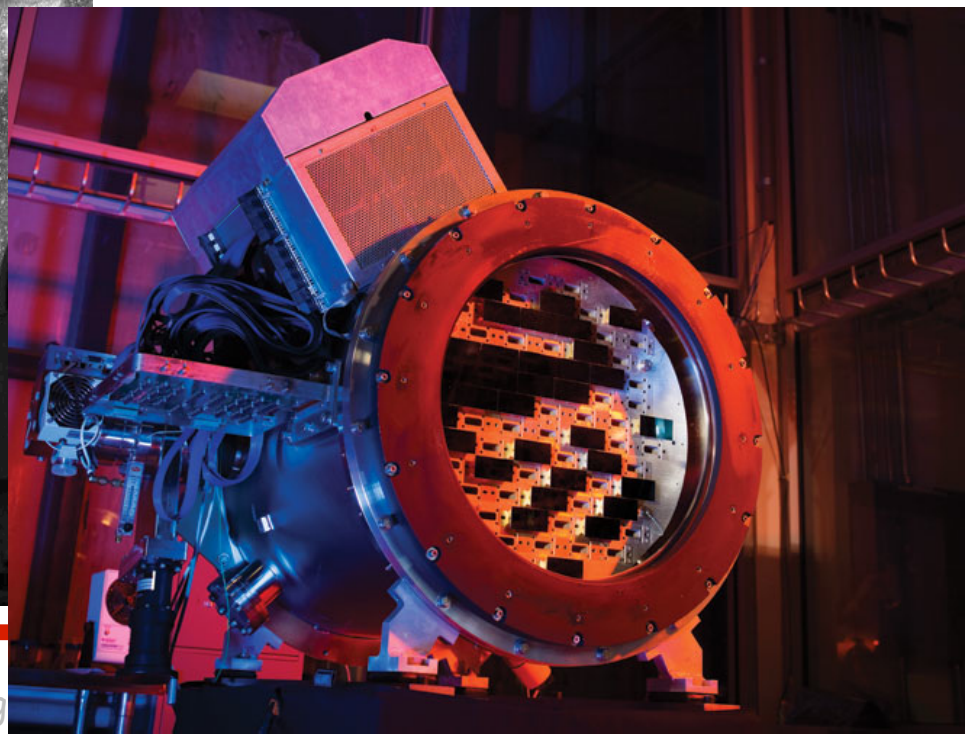
New Director: Josh Frieman

Survey starts in 2012, then runs 5 years



4m Blanco telescope at CTIO

DECam under construction at Fermilab



DES Collaboration

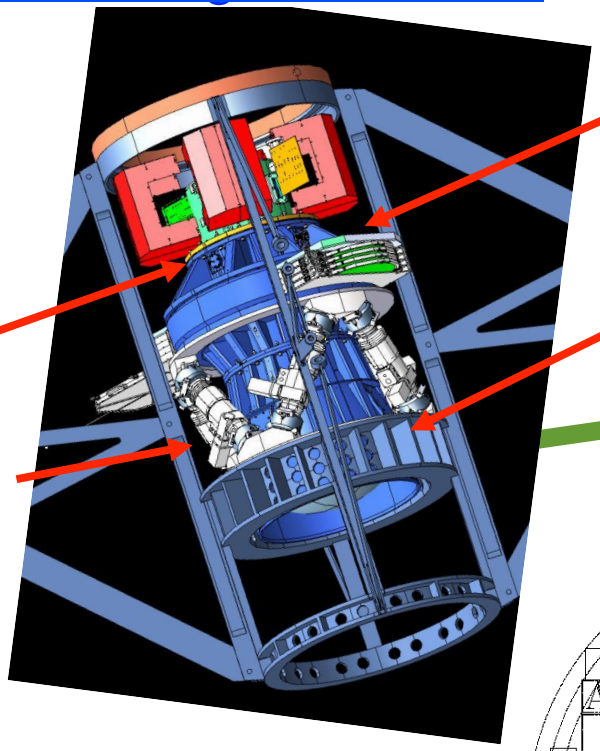
- Fermilab (22 members)
- University of Illinois Urbana-Champaign (10)
- University of Chicago (9)
- Lawrence Berkeley National Lab (9)
- University of Michigan (7)
- NOAO/CTIO (3)
- Spain-DES Consortium: (7)
  - Institut d'Estudis Espacials de Catalunya, Institut de Fisica d'Altes Energies, CIEMAT
- United Kingdom-DES Consortium: (22)
  - University College London, University of Portsmouth, University of Cambridge, University of Edinburgh, University of Sussex, University of Nottingham
- Brazil-DES Consortium (6)
- Ohio State University (6)
- Argonne National Lab (3)
- Santa Cruz-SLAC-Stanford Consortium (7)
- Universitats-Sternwarte Munchen (6)
- Texas A&M University (6)

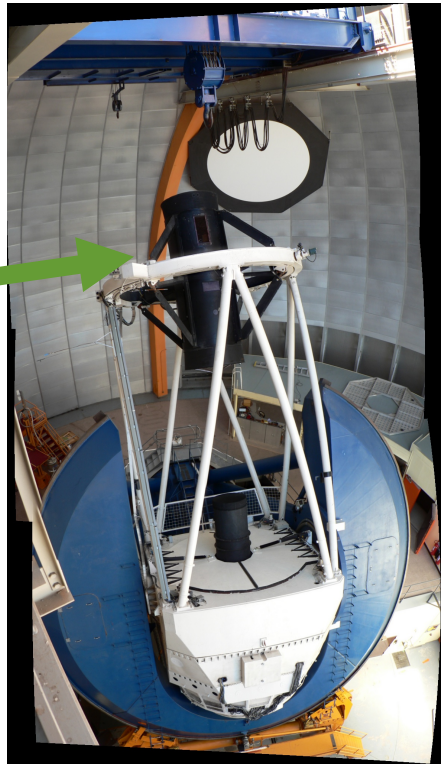
119 Members does not include students and postdocs

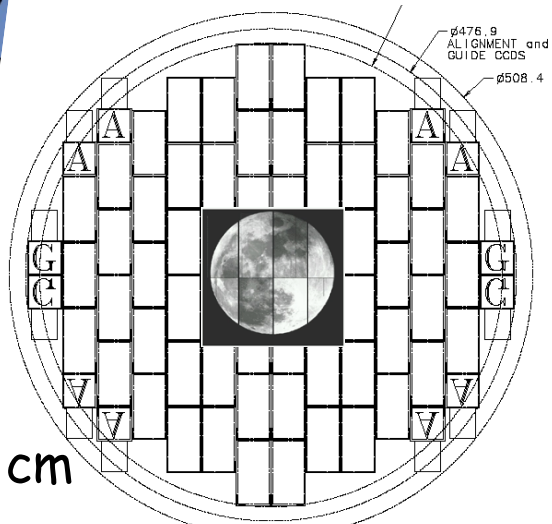
DECam : new instrument for DES

DARK ENERGY SURVEY

Replace PF cage on the CTIO Blanco 4m telescope with a new optical imager.
We are building it at Fermilab.

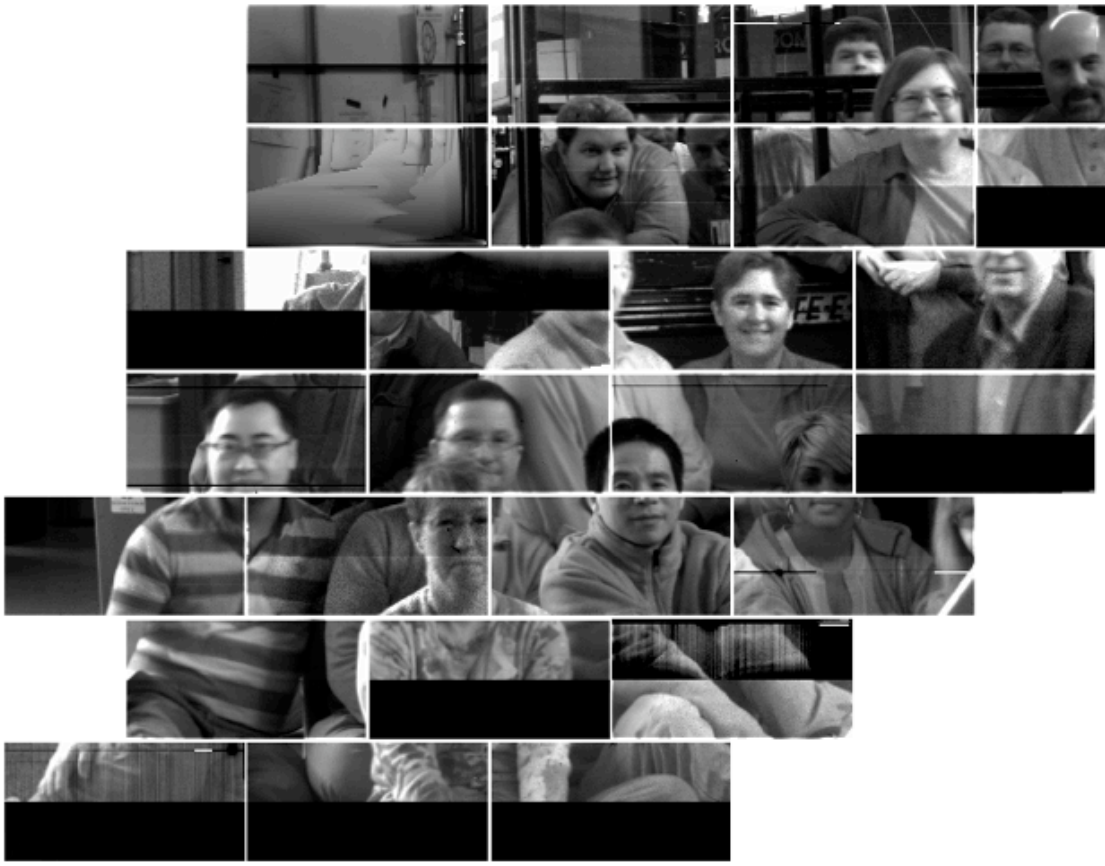




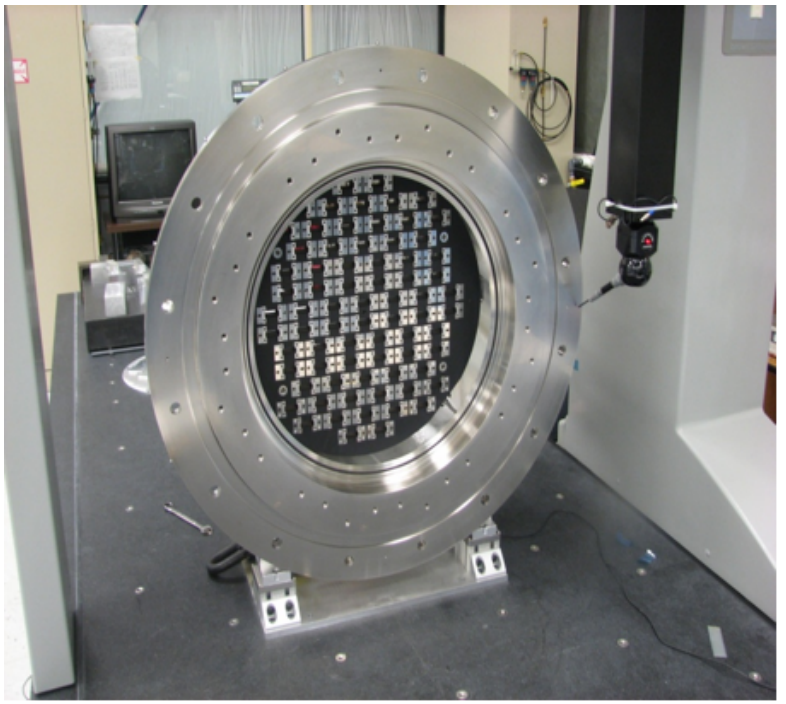


diameter = 48 cm

DECam Construction & Testing



Focal plane of Multi-CCD Test Vessel partially filled with non-science grade CCDs



DECam Imager Vessel

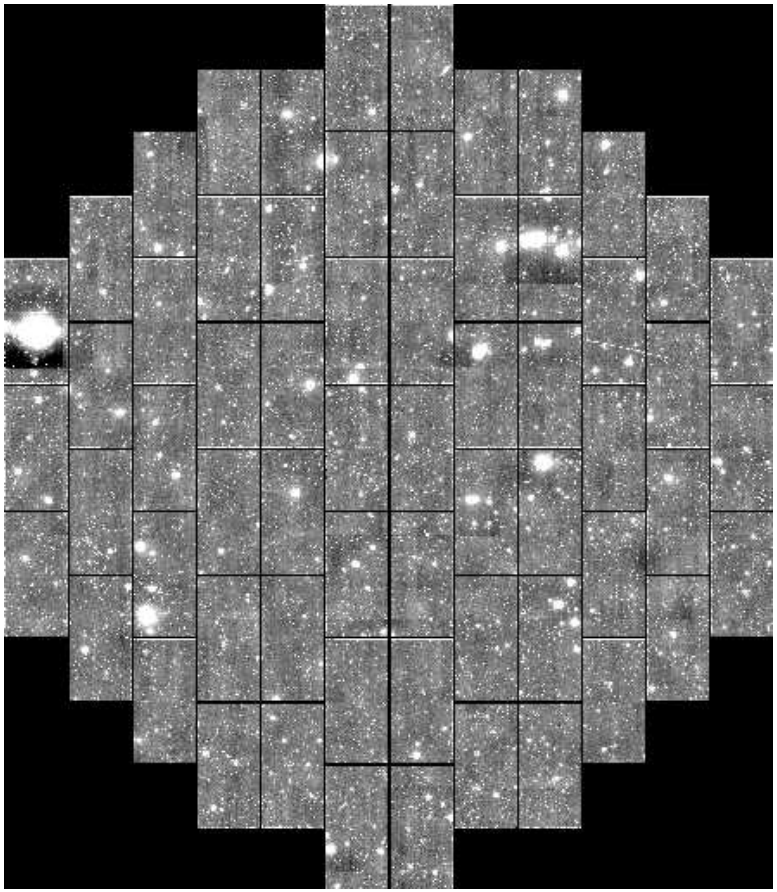
DECam Focal Plane

DARK ENERGY SURVEY

3 sq-deg imager:

62 2kx4k Image CCDs: 520 MPix
8 2kx2k focus, alignment CCDs
4 2kx2k guide CCDs
0.27"/pixel (15x15 μm)

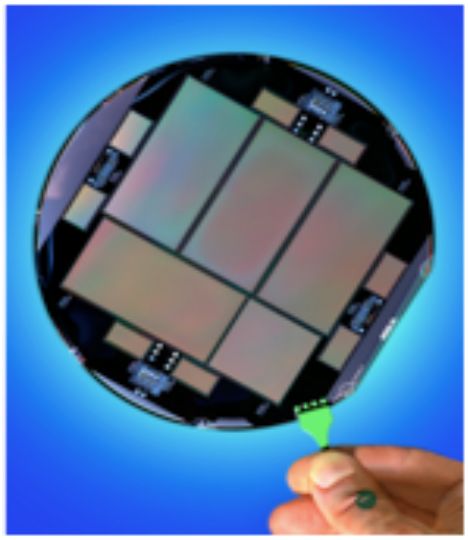
Imager to be delivered early 2011, other components summer 2011, taking data early 2012.



DES Image simulation
FNAL/NOAO

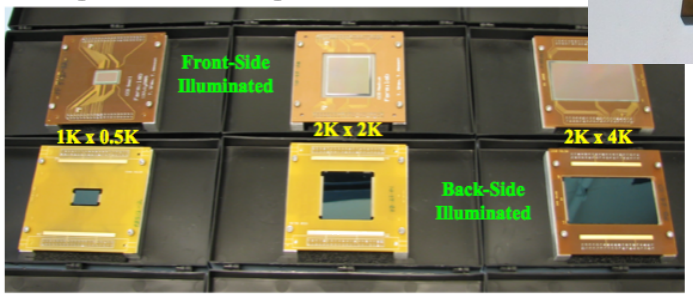
Detectors : CCD

DECam wafer



DECam wafer developed from SNAP R&D effort. We now have 81 science packages ready for installation. Science packaged designed and now building the final detectors

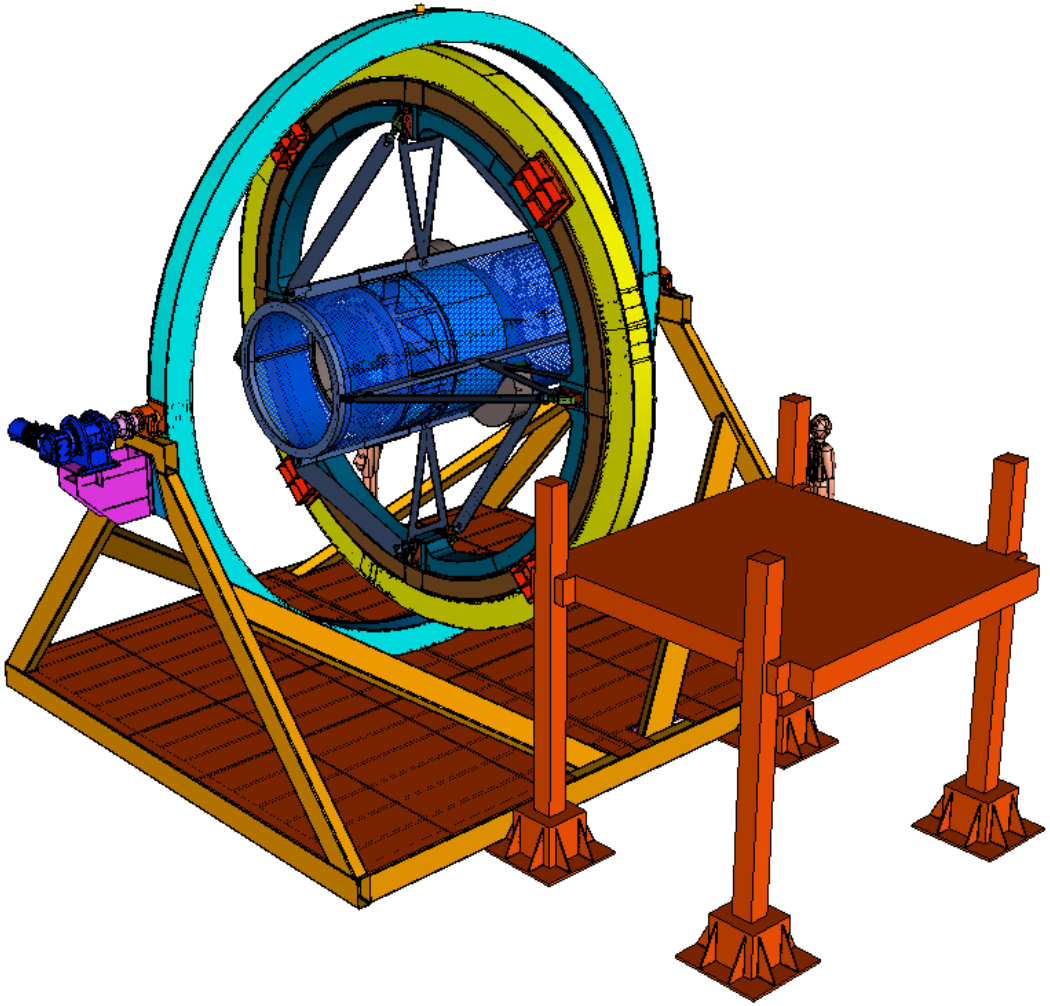
Engineering CCDs

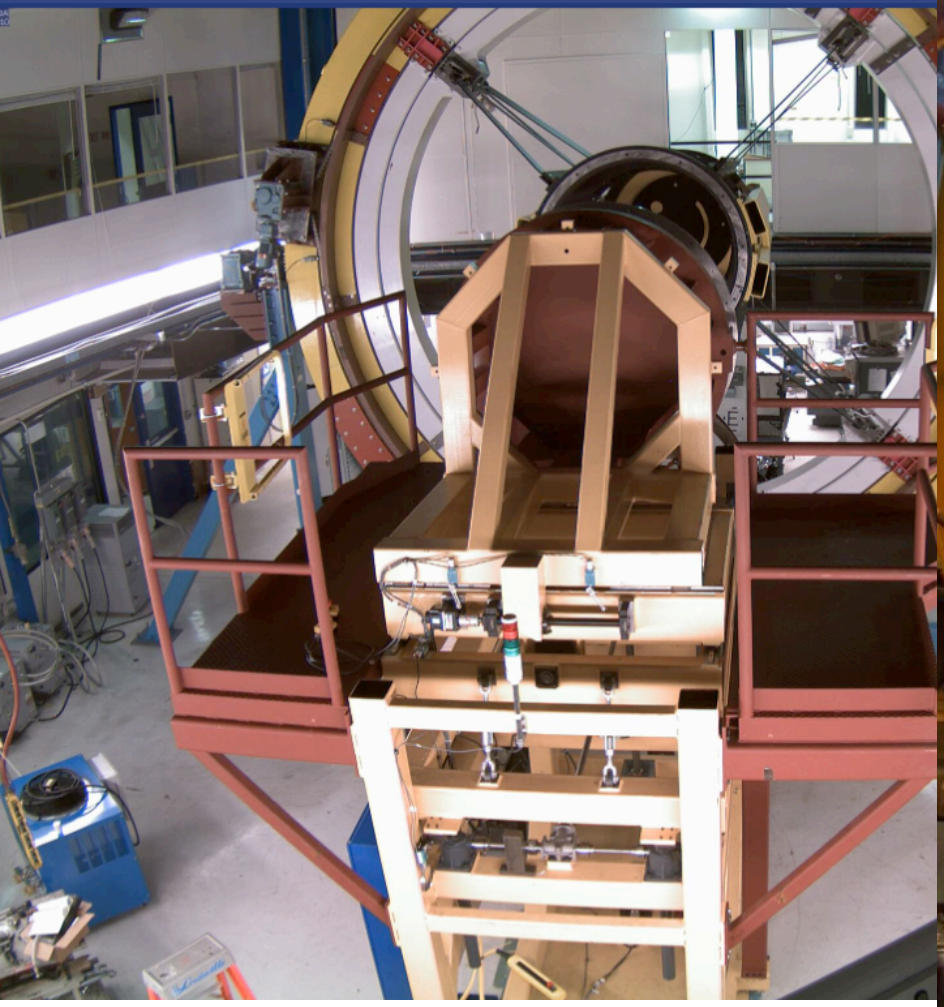


+100 built and tested during our R&D stage

Fermilab's expertise in building silicon trackers has transferred to the design and fabrication of these CCDs (strict mechanical requirements).

Telescope Simulator at Fermilab





Telesc

http://

Dark Energy Science Program

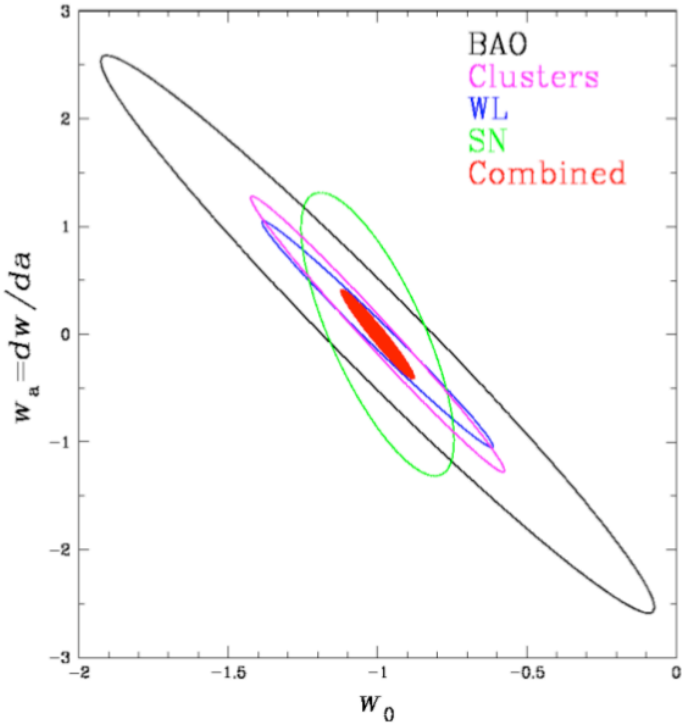
DARK ENERGY SURVEY

Four Probes of Dark Energy

- **Galaxy Clusters**
  - clusters to z>1
  - SZ measurements from SPT
  - Sensitive to growth of structure and geometry
- **Weak Lensing**
  - Shape measurements of 300 million galaxies
  - Sensitive to growth of structure and geometry
- **Large-scale Structure**
  - 300 million galaxies to z = 1 and beyond
  - Sensitive to geometry
- **Supernovae**
  - 15 sq deg time-domain survey
  - ~3000 well-sampled SNe Ia to z ~1
  - Sensitive to geometry

Plus QSOs, Strong Lensing, Milky Way, Galaxy Evolution

Forecast Constraints on DE Equation of State



Stage III project (DETF)

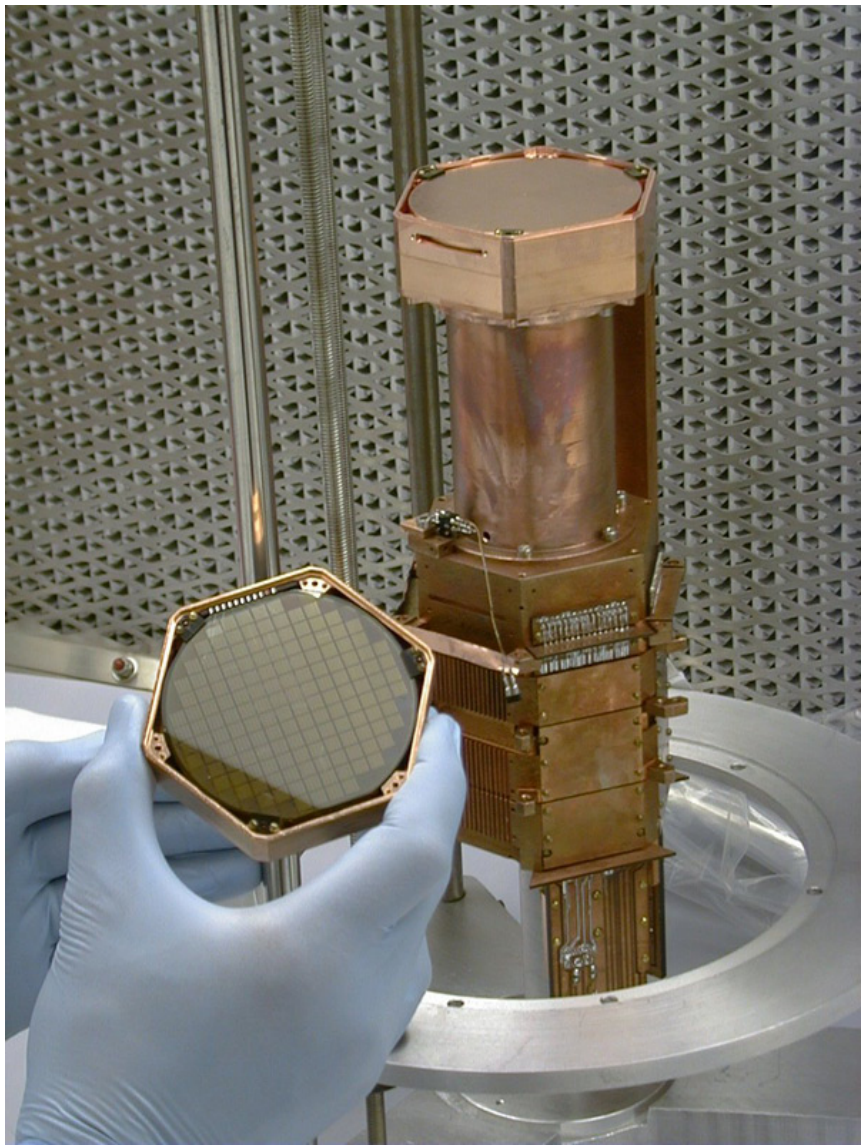
Dark Energy Camera in FY 10 & 11

- DECam in FY 10
  - Passed Lehmann review
  - All CCDs verified
  - Built telescope simulator, testing components
  - Started shipping parts to Chile

- DECam in FY 11
  - All parts to CTIO by June
  - Assembly and commissioning start
  - First light in early FY 12

Dark Matter with Cryogenic Crystals: CDMS

- State of the art in direct detection and background rejection
- Recent press attention: two events (maybe not background?)
- Next deployment: 15kg at Soudan with better detectors, background rejection



The Cryogenic Dark Matter Search

California Institute of Technology
Z. Ahmed, J. Filippini, S.R. Golwala, D. Moore, R.W. Ogburn

Case Western Reserve University
D. Akerib, C.N. Bailey, M.R. Dragowsky,
D.R. Grant, R. Hennings-Yeomans

Fermi National Accelerator Laboratory
D. A. Bauer, F. DeJongh, J. Hall, D. Holmgren,
L. Hsu, E. Ramberg, R.L. Schmitt, J. Yoo

Massachusetts Institute of Technology
E. Figueroa-Feliciano, S. Hertel,
S.W. Leman, K.A. McCarthy, P. Wikus

NIST *
K. Irwin

Queen's University
P. Di Stefano *, N. Fatemighomi *, J. Fox *,
S. Liu *, P. Nadeau *, W. Rau

Santa Clara University
B. A. Young

Southern Methodist University
J. Cooley

SLAC/KIPAC *
E. do Couto e Silva, G.G. Godrey, J. Hasi,
C. J. Kenney, P. C. Kim, R. Resch, J.G. Weisend

Stanford University
P.L. Brink, B. Cabrera, M. Cherry *,
L. Novak, M. Pyle, A. Tomada, S. Yellin

Syracuse University
M. Kos, M. Kiveni, R. W. Schnee

Texas A&M
J. Erikson *, R. Mahapatra, M. Platt *

University of California, Berkeley
M. Daal, N. Mirabolfathi, A. Phipps, B. Sadoulet,
D. Seitz, B. Serfass, K.M. Sundqvist

University of California, Santa Barbara
R. Bunker, D.O. Caldwell, H. Nelson, J. Sander

University of Colorado Denver
B.A. Hines, M.E. Huber

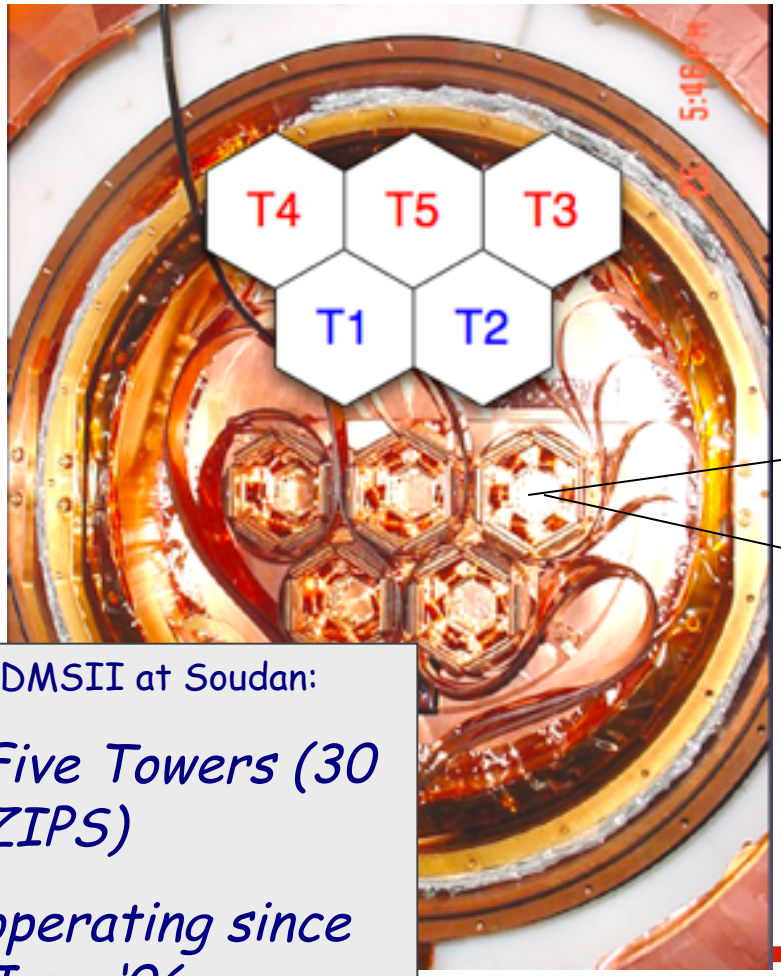
University of Florida
T. Saab, D. Balakishiyeva, B. Welliver *

University of Minnesota
J. Beaty, P. Cushman, S. Fallows, M. Fritts,
O. Kamaev, V. Mandic, X. Qiu, A. Reisetter, J. Zhang

University of Zurich
S. Arrenberg, T. Bruch, L. Baudis, M. Tarka

** new collaborators or new institutions in SuperCDMS*

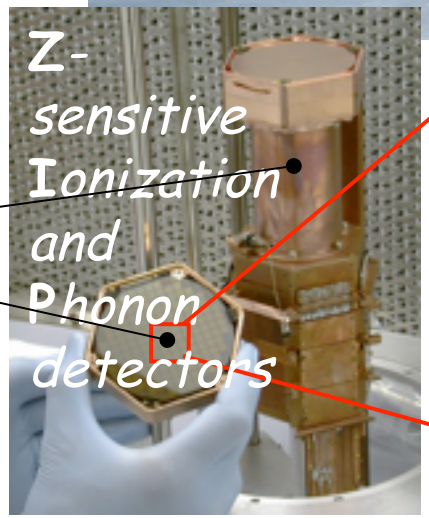
The CDMS-II Experiment

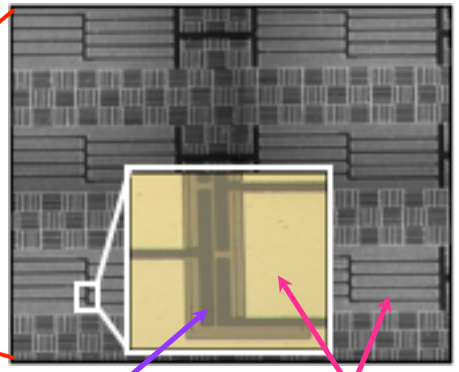


CDMSII at Soudan:

Five Towers (30 ZIPS)

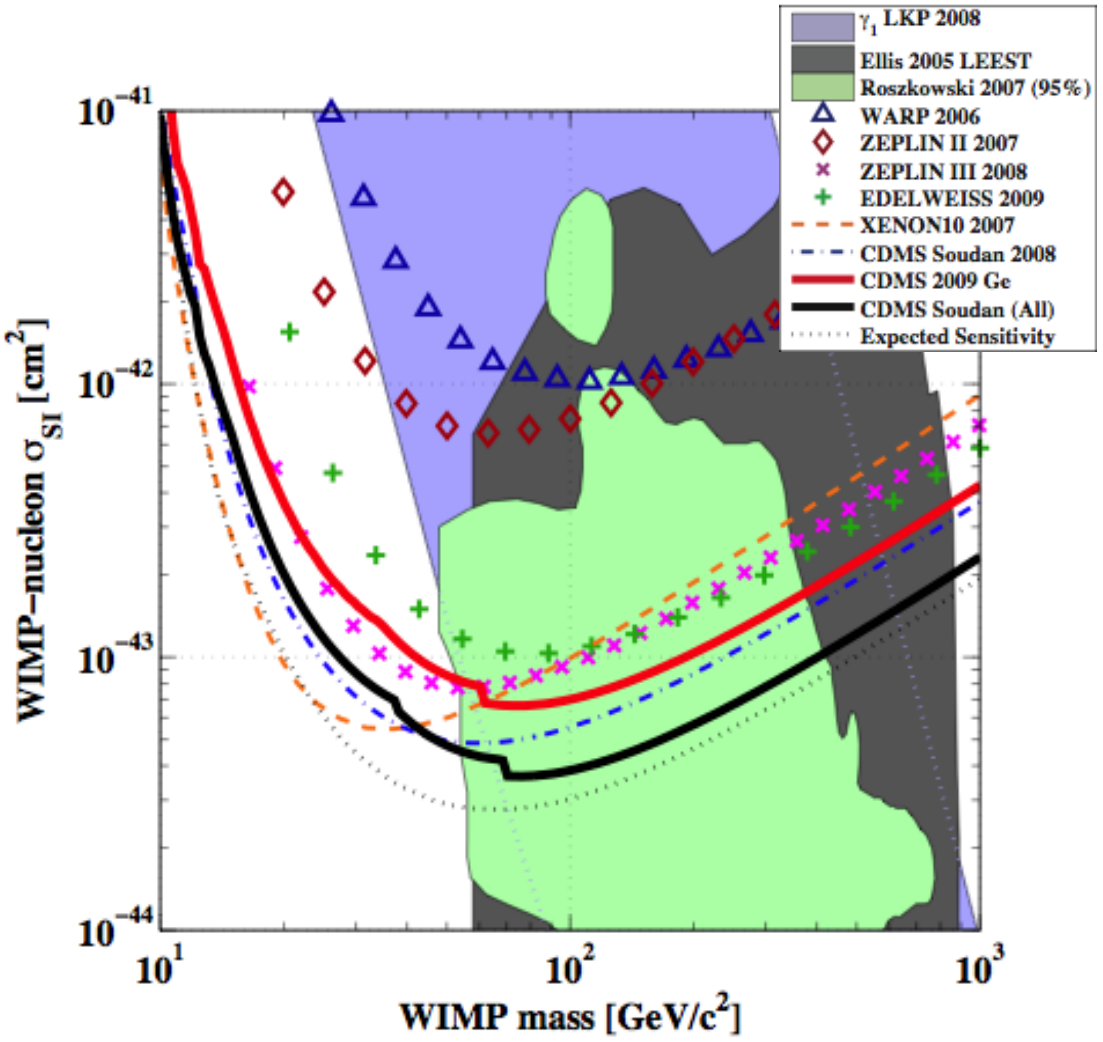
operating since June '06





CDMS Sensitivity

- 2 events with an exposure of 200 kg days
- Low expected background of 0.9 events
- Leading the world in sensitivity to spin-independent WIMP-nucleus elastic scattering



Recent CDMS Results

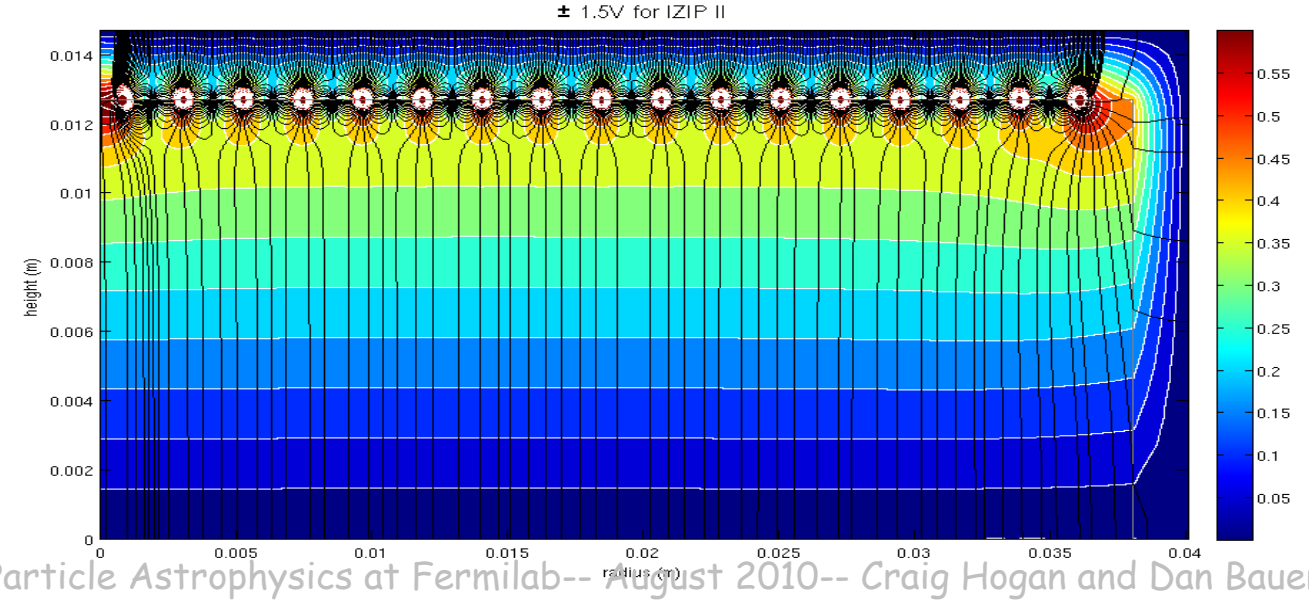
- Dark Matter Search Results from the CDMS II Experiment
  - *Science* 10.1126/science.1186112 (2010)
- Analysis of the Low-Energy Electron-Recoil Spectrum of the CDMS Experiment
  - *Physical Review D* **81**, 042002 (2010)
- Search for Axions with the CDMS Experiment
  - *Physical Review Letters* **103**, 141802 (2009)
- Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory
  - *Physical Review Letters* **102**, 011301 (2009)

CDMS Technology Breakthrough

New symmetric detectors (iZIP) have demonstrated a background rejection improvement of more than an order of magnitude (ton scale CDMS style experiment now feasible); production of iZIPs now ongoing

For FY 11:

- 15 kgTrial run this fall in Soudan facility
- Science run begins next summer



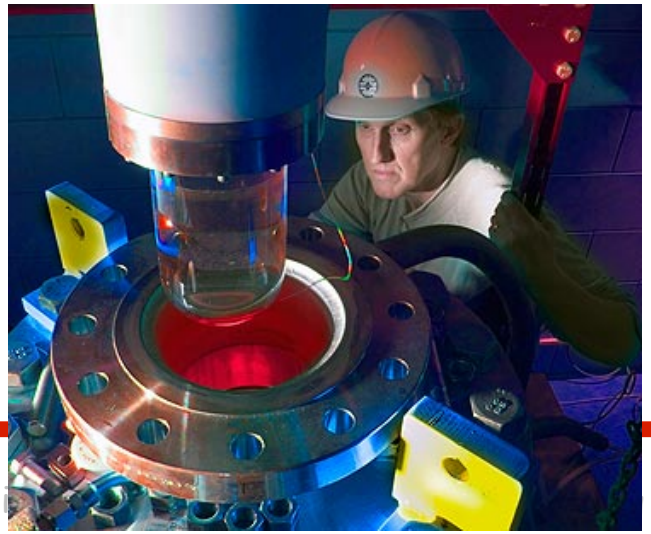
Dark Matter with Bubble Chambers: COUPP

Old technique applied with stunning early success

High-purity 4kg and 60kg chambers, new acoustic rejection

FY10: 4kg to SNOLab, 60kg to NUMI

FY11: Tests of rejection



COUPP

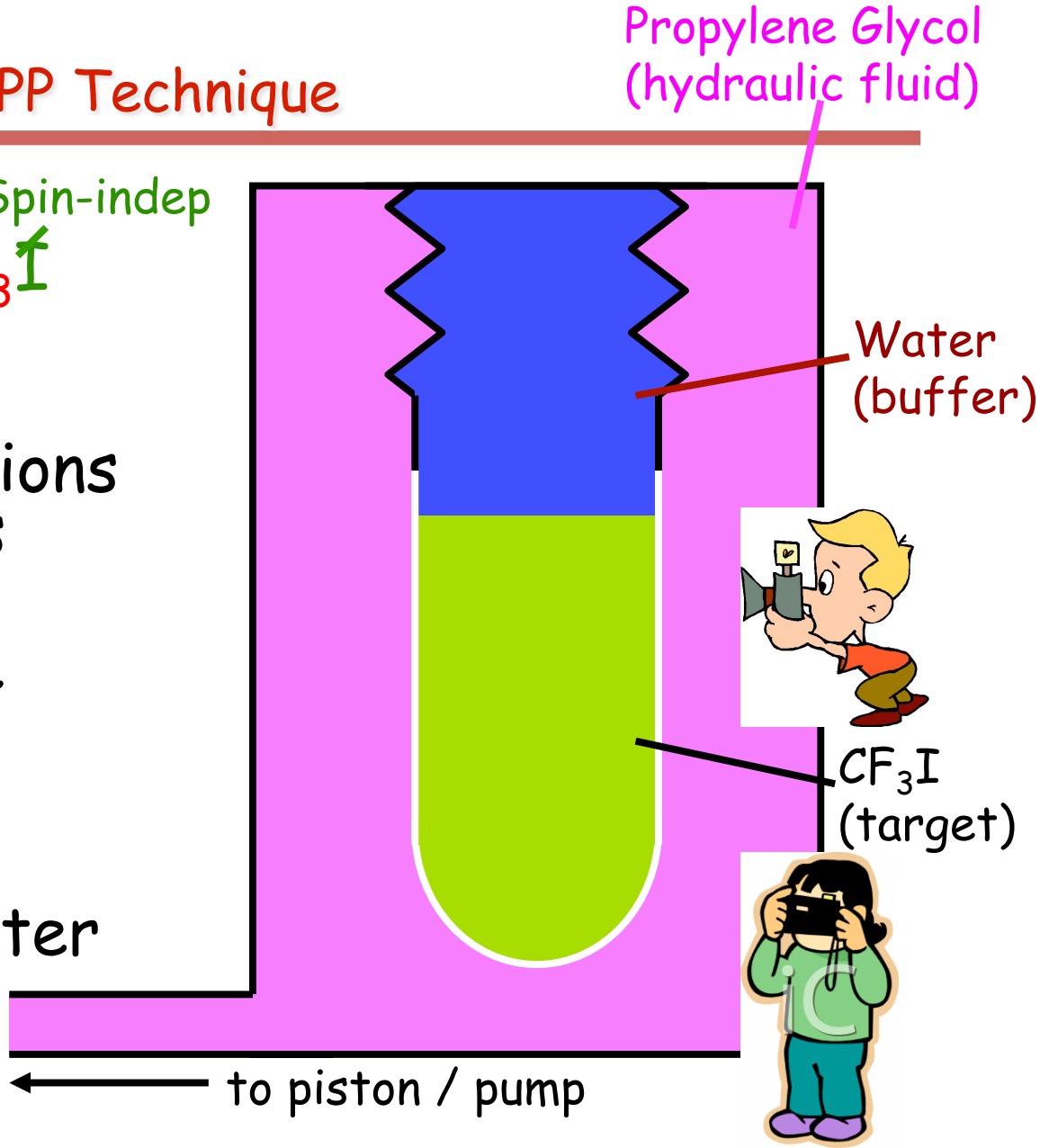
University of Chicago
J. Collar, C.E. Dahl, D. Fustin, M. Szydagis

Indiana University South Bend
E. Behnke, J. Behnke, J.H. Hinnefeld, I. Levine,
A. Palenchar, T. Shepard, B. Sweeney

Fermi National Accelerator Laboratory
S. Brice, D. Broemmelsiek, P. Cooper, M. Crisler, J. Hall, M. Hu, E. Ramberg, A. Sonnenschein

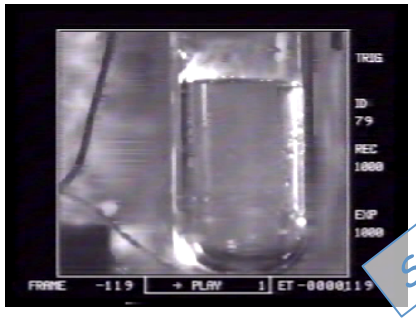
COUPP Technique

- Superheated CF_3I target (Spin-indep: I; Spin-dep: CF_3)
- Particle interactions nucleate bubbles
- Cameras capture bubbles
- Chamber recompresses after each event



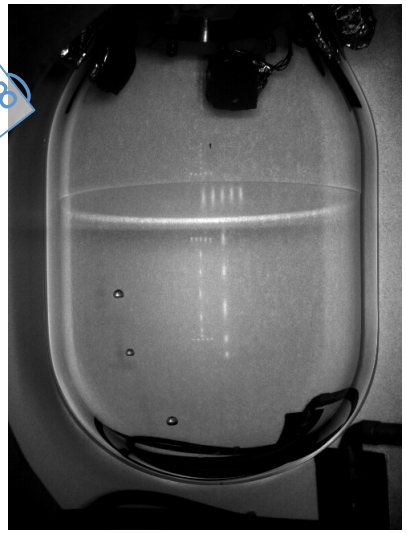
COUPP Bubble Chamber Program

- Take long runs with smaller chambers to understand backgrounds, operations, and for research and development while developing and commissioning an order of magnitude larger chamber



Test tube
(U Chicago)

COUPP 2kg

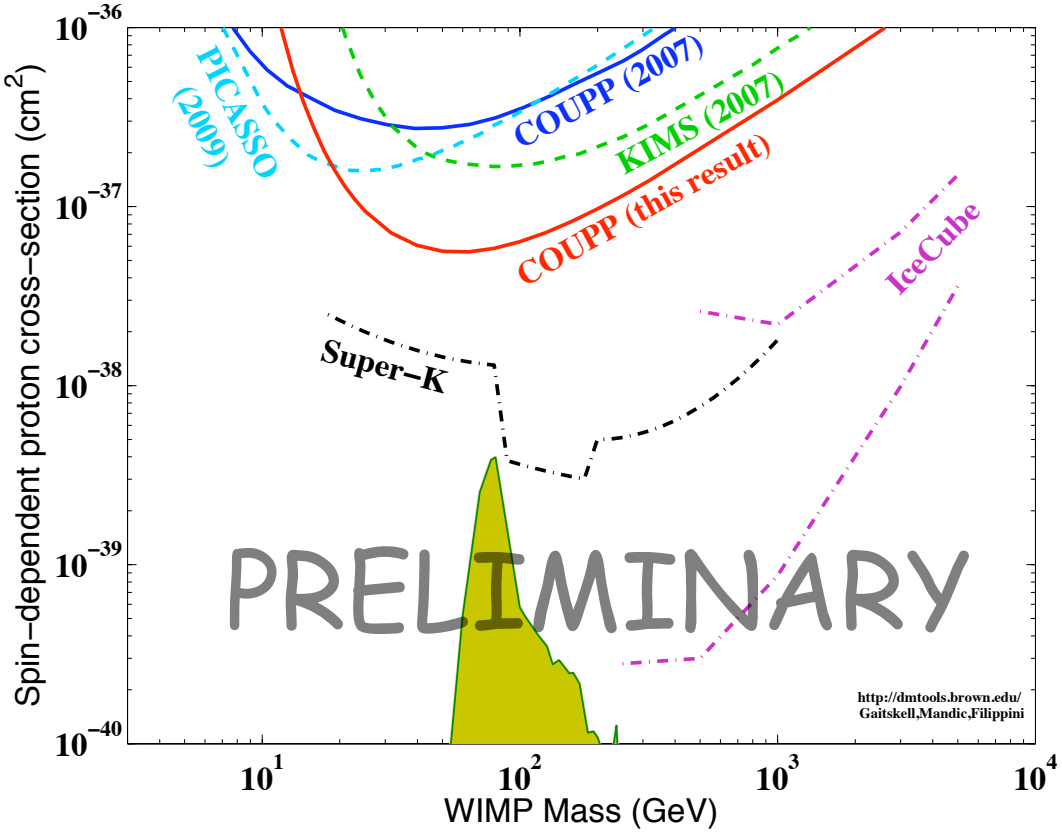


COUPP 4kg

COUPP 60kg

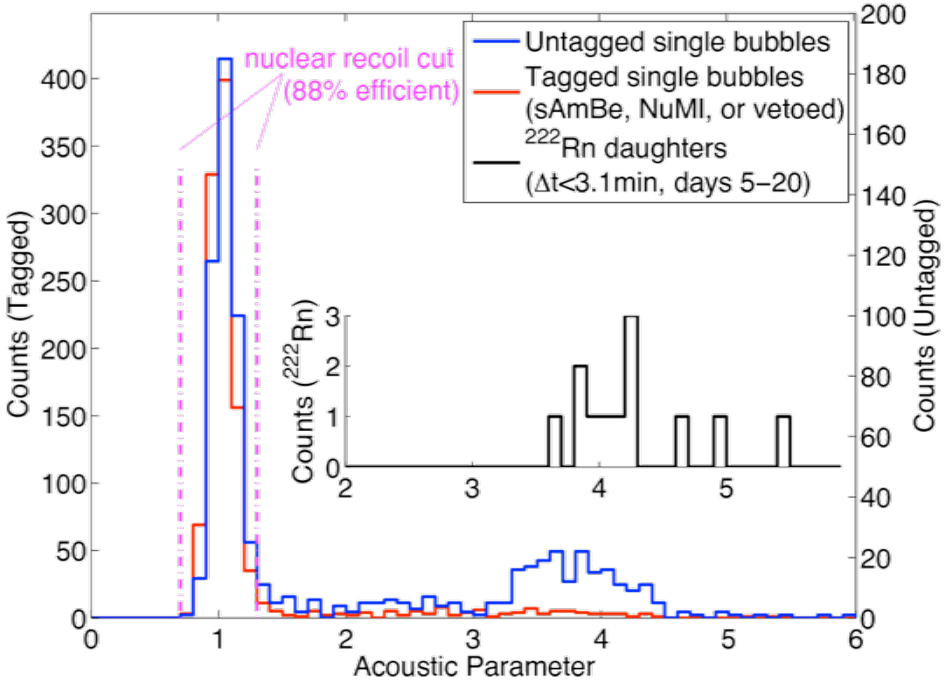
COUPP Results

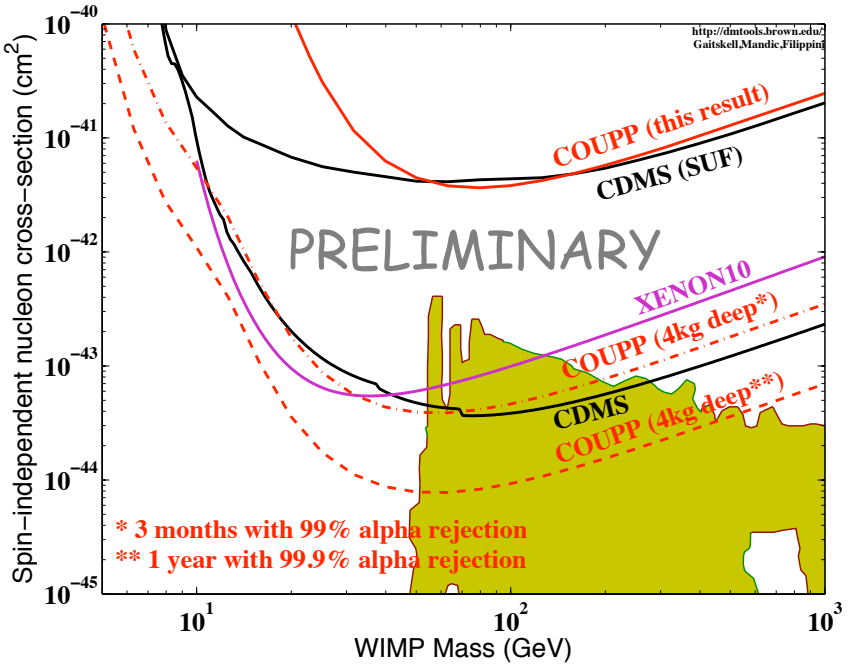
- Blue line –*Science* **319**:933-936 (2008)
- Red line – latest result
- Latest results limited by cosmic radiation in the MINOS near hall



COUPP Technological Advance

- Ultrasound transducers reduce the alpha decay backgrounds by 2-3 orders of magnitude

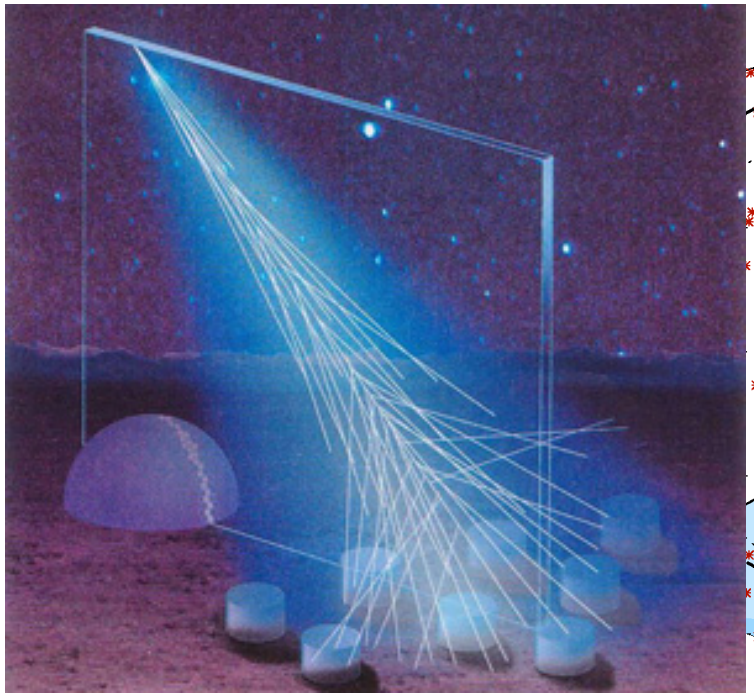


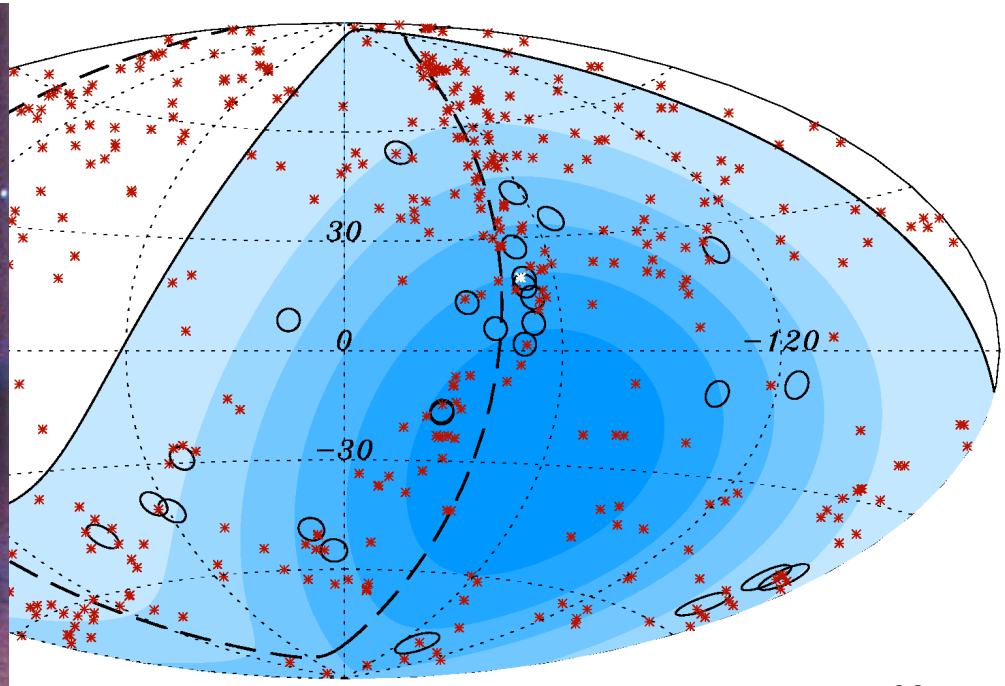


Pierre Auger Observatory

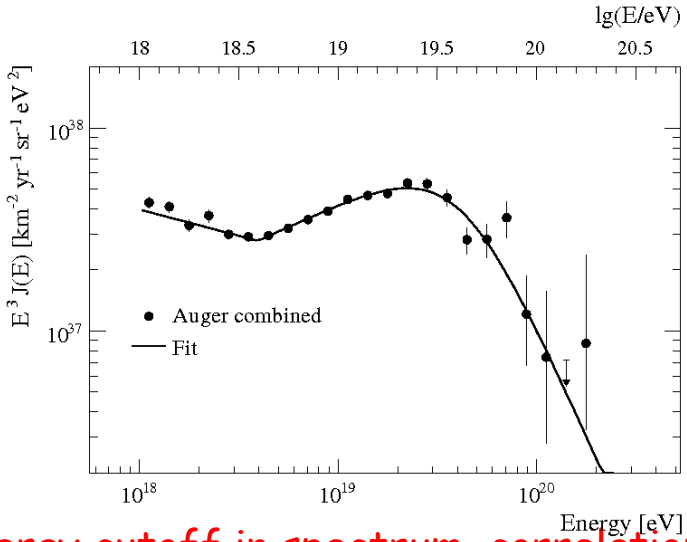
World's leading observatory for highest energy particles

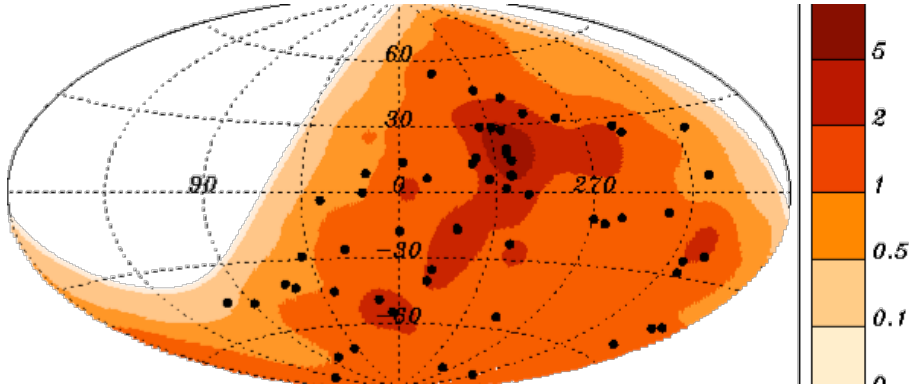
Discoveries: GZK cutoff from CMB interactions, anisotropy from sources, new composition puzzle



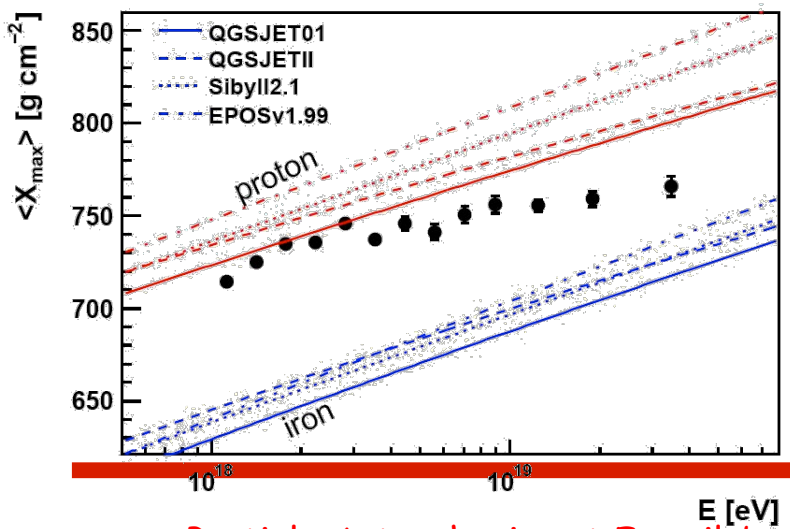


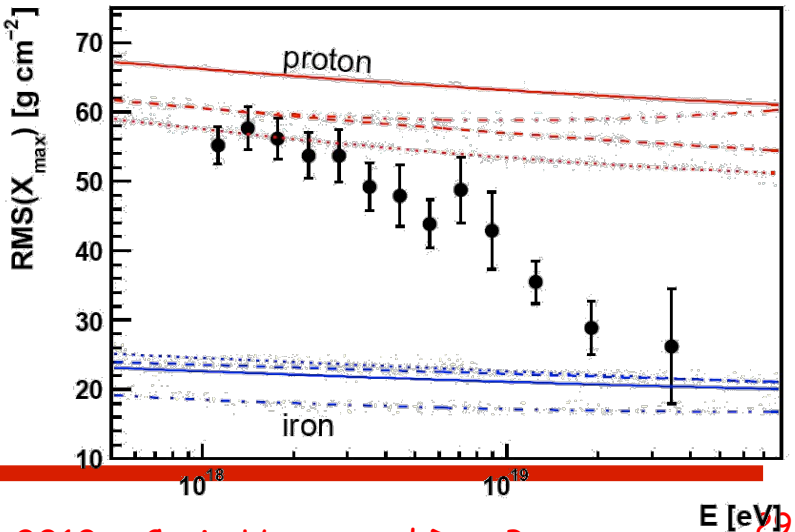
Auger results and puzzles





Energy cutoff in spectrum, correlation with local AGN suggest extragalactic sources and proton composition. Shower penetration depth and fluctuations suggest either violation of unitarity or iron composition. Need more statistics and full sky coverage.





Recent Auger papers

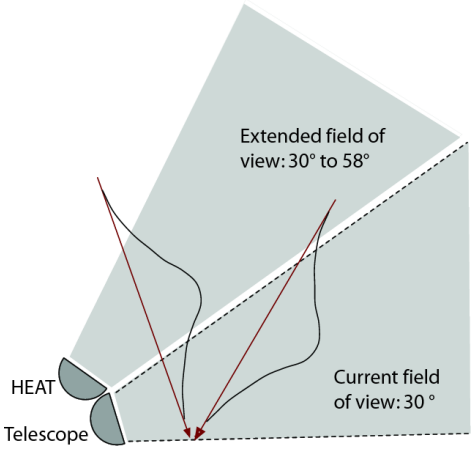
Pierre Auger Observatory — Science Results

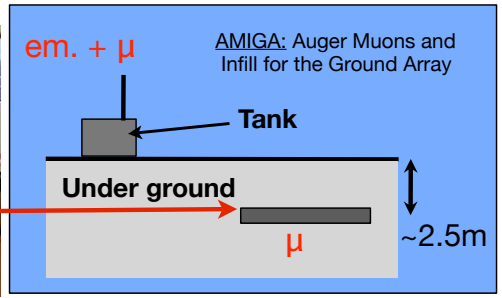
- *Measurement of the energy spectrum of cosmic rays above 10^{18} eV using the Pierre Auger Observatory*, Phys. Lett. B **685** (2010) 239-246
  - First 'hybrid' (fluorescence+ground) and updated surface detector spectrum
- *Measurement of the depth of maximum of extensive air showers above 10^{18} eV*, Phys. Rev. Lett. **104** (2010) 091101
  - Shows a significant difference in shower properties from proton-only model expectation
- *Limit on the diffuse flux of ultrahigh energy tau neutrinos with the surface detector of the Pierre Auger Observatory*, Phys. Rev. D **79**, 102001 (2009)
  - Best experimental limit on neutrino flux at EeV energies
- *Upper limit on the cosmic-ray photon fraction at EeV energies from the Pierre Auger Observatory*, Astro. Part. Phys. **31** (2009) 399-406
  - First experimental limits on photons at energies at 10 EeV

8

Pierre Auger Observatory — Enhancements

- Upgrades further widen the gap between the PAO and other experiments
  - High Elevation Auger Telescope (HEAT) & AMIGA (Infill Array) extend energy range down in energy to 10^{17} eV
  - Coherent radio emission, and molecular bremsstrahlung provide R&D for new, independent detection techniques calibrated to known methods
  - Lightning detection system expands physics potential

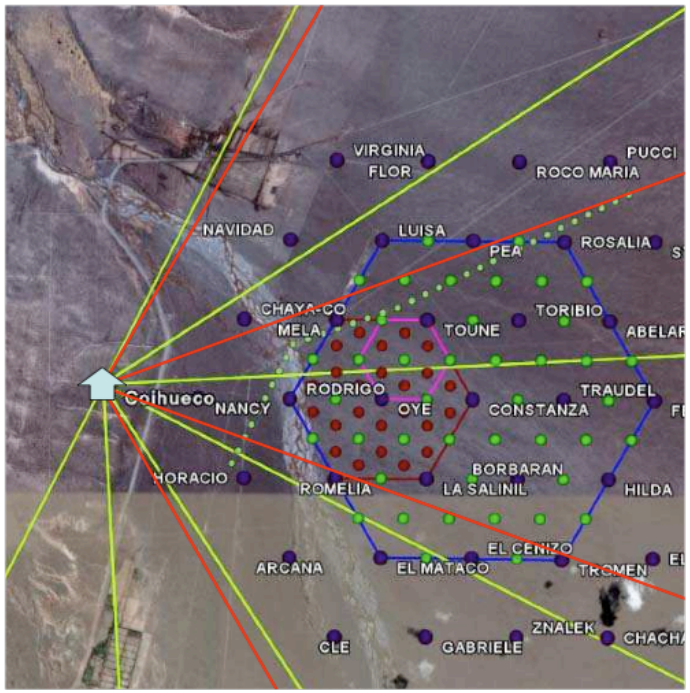




5

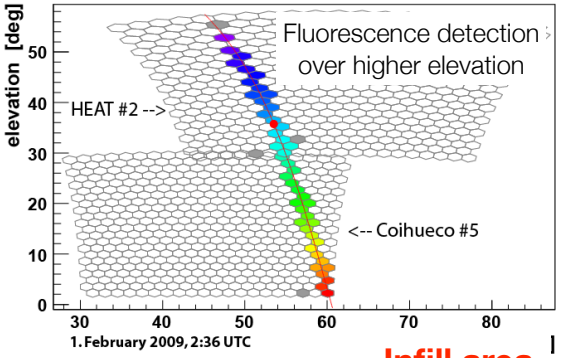
Pierre Auger Observatory — Enhancements

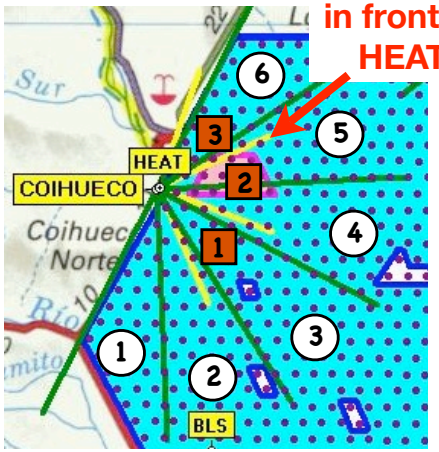
- Upgrades further widen the gap between the PAO and other experiments
  - Auger Muon and Infill for the Ground Array — AMIGA
  - FNAL supporting AMIGA by providing scintillators and manpower — still under construction
  - Muon to electron ratio important for composition measurement — independent of fluorescence measurements



Pierre Auger Observatory — Enhancements

- Upgrades further widen the gap between the PAO and other experiments
  - HEAT — 3 new fluorescence telescopes at same location of Coihueco, both looking over AMIGA
  - Measurement from 10^{17} eV to $>10^{20}$ eV
  - 'Low' energy spectrum with 750 meter Infill surface array is already systematics limited
  - 433 meter Infill will start being installed this year, pushing the energy range even further down
  - Fluorescence Telescope — Surface Detector energy cross calibration at lower energies given by HEAT+Infill
  - Results at next ICRC





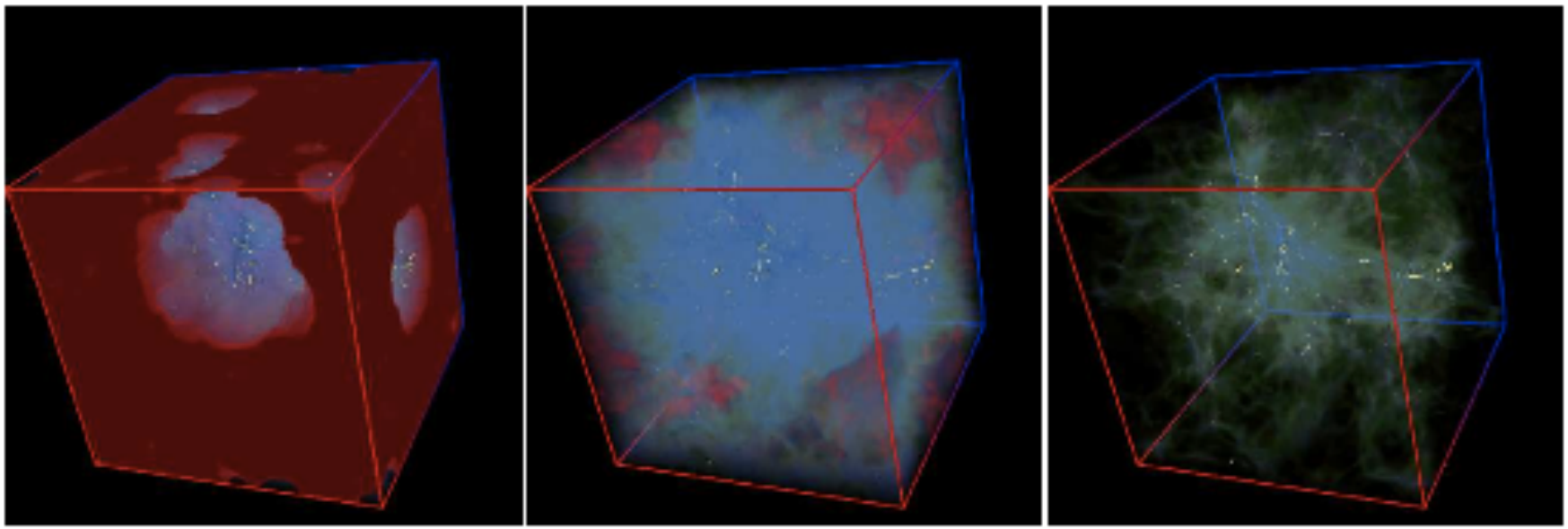
7

Theoretical Astrophysics Group

Leaders in particle-astro theory, phenomenology

Science ideas, analysis, tools, leadership for experimental program

Next step: expanded computing capabilities in partnership with other labs



Present and Future Program

On-going: Dark Energy (DES), Dark Matter (CDMS, COUPP), High Energy Particles (PAO South) and Theory

Will remain the core Particle Astrophysics program

Future projects: depending on review & funding,

- Dark Matter [SuperCDMS SNOLab, COUPP-60 SNOLab, Depleted Argon Kryogenic Scintillation and Ionization Detector (Darkside)]
- Dark Energy after DES (LSST, JDEM [WFIRST], DESpec)

Small new exploratory initiatives:

- Cosmic Microwave Background Polarization (QUIET-II)
- Planck scale unification (Holometer)
- Axion-Like Particles (REPR)

Projects are being developed with strong university collaborations and guided by community priorities

PASAG/HEPAP recommendations (2009)

"In all budget scenarios, the Xenon100 upgrade, the LUX350 detector, an effort on DAr, funding for the MiniCLEAN detector, the additional towers in SuperCDMS Soudan, the COUPP 500 construction, the 100-kg SuperCDMS- SNOLAB experiment and the phase II upgrade to ADMX are supported."

Fermilab is positioned to establish a leading "WIMPstitute"

"PASAG recommends that QUIET II be supported at the proposed scope under all budget scenarios."

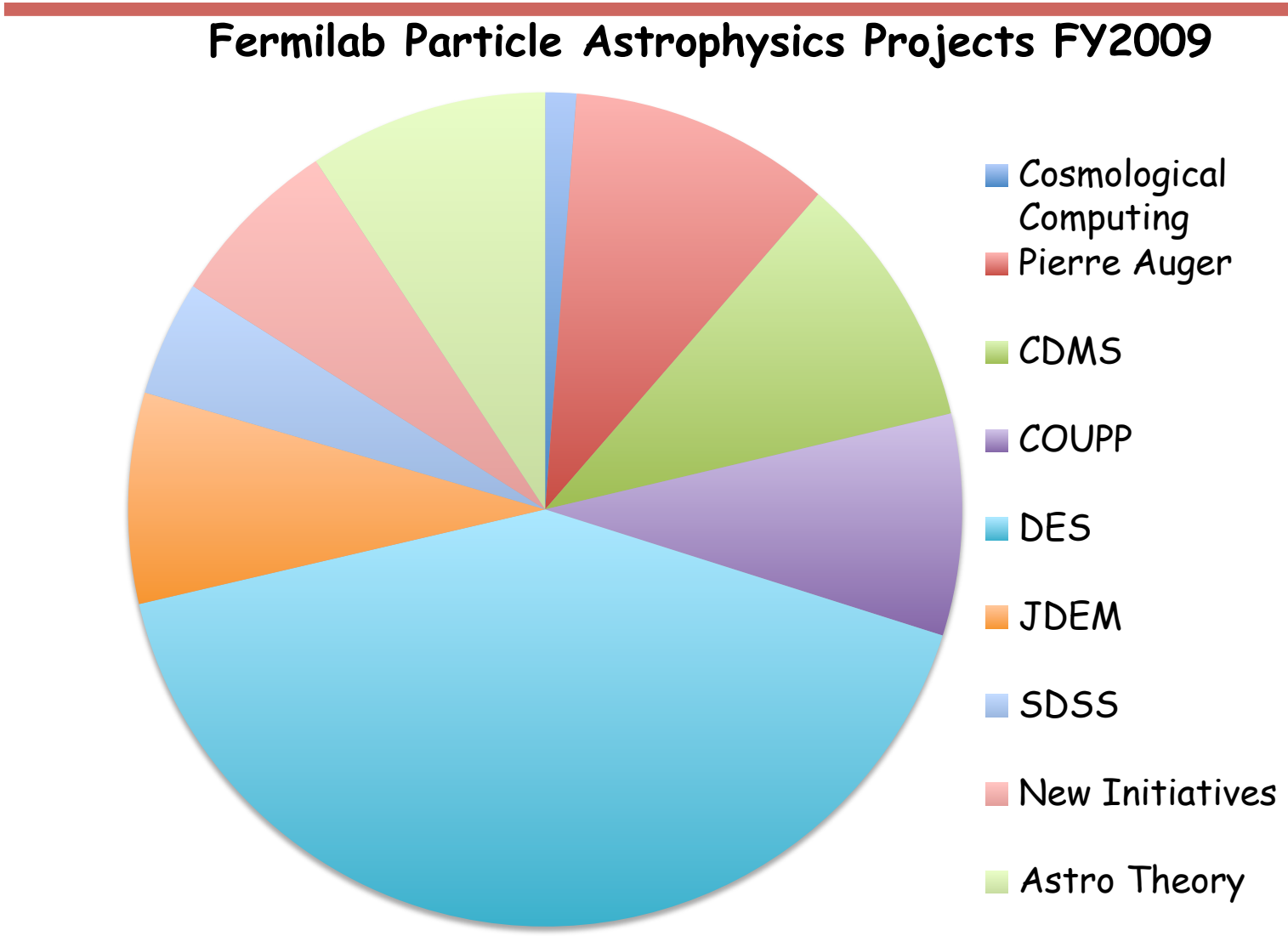
But QUIET-II is not yet funded by NSF: delay is inevitable

"Auger North addresses questions of great interest... Given its relative science priority for HEP and the funding constraints, PASAG recommends significant HEP support for the construction of Auger North in budget Scenarios C and D."

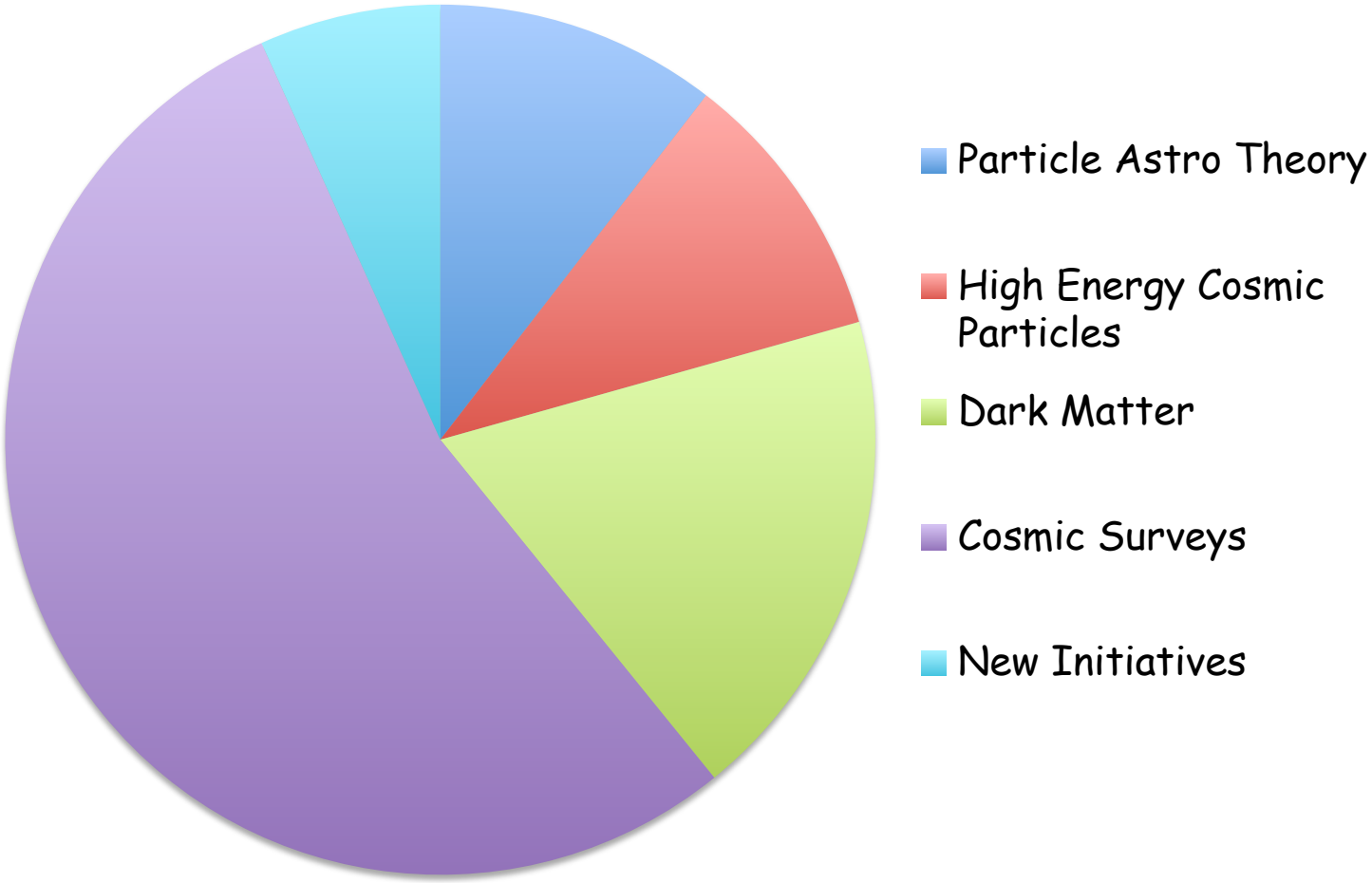
Astro 2010 recommendations

- LSST top of ground-based projects
  - Technically ready
  - Partnership with NSF; MREFC funding
  - DOE camera: SLACNL lead
- WFIRST top of space-based projects
  - Still unformed design
  - Combines Dark Energy with microlensing survey of exoplanet population
  - Possible partnership with ESA

Lab-Wide Cosmic Frontier Effort by Project



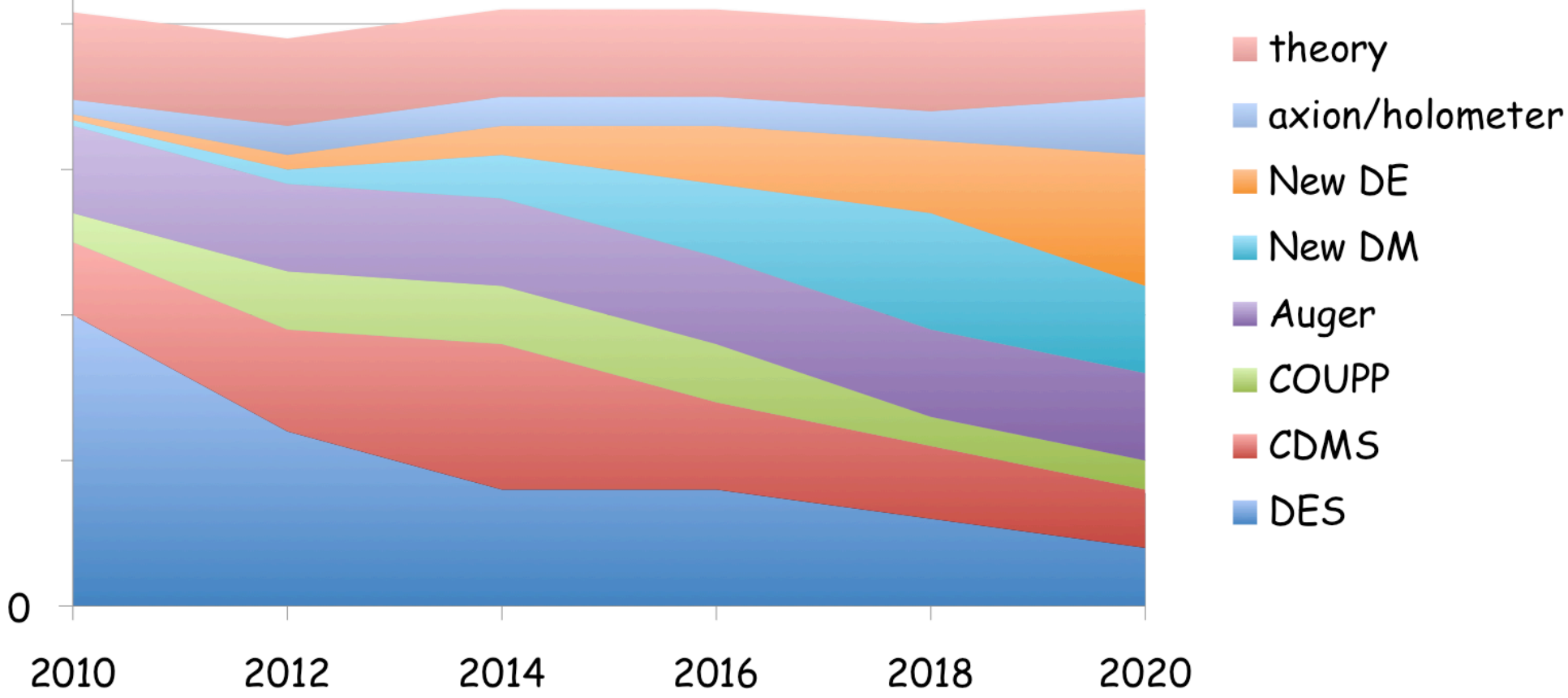
Lab-Wide Cosmic Frontier Effort by Research Area



Total particle astrophysics budget ~ $26M

Very Schematic 10 year funding Profile

A broad, substantive, evolving program fits into realistic resources



Actual program will be shaped by new discoveries!

Future Dark Matter at SNOLab, Gran Sasso, DUSEL

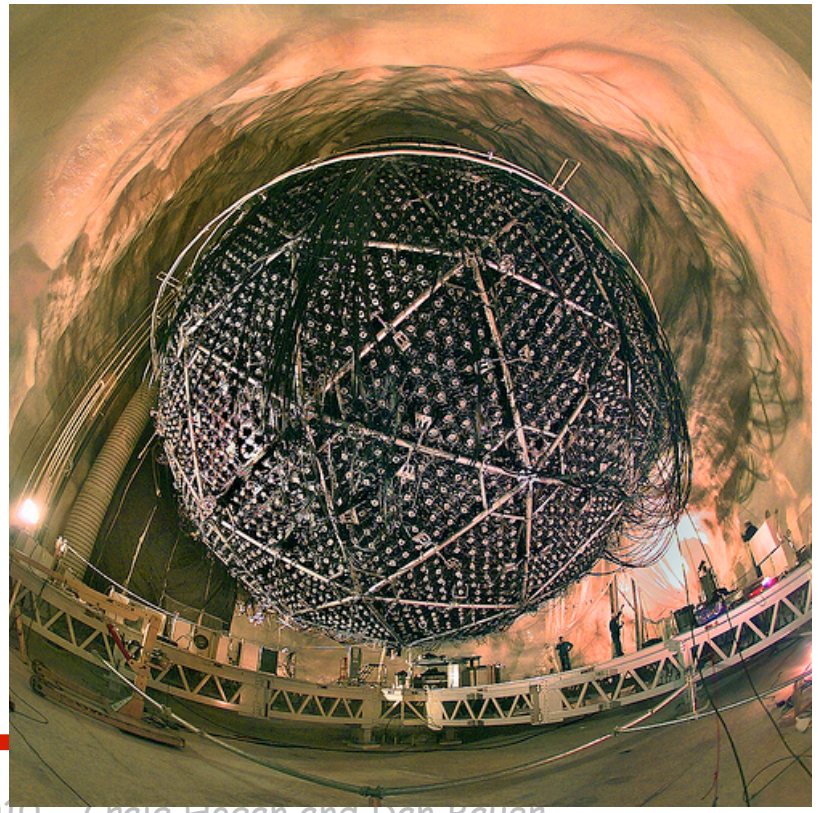
SuperCDMS: 100 kg at SNOLab

Expect CD0 this fall,MIE in FY12

COUPP: 60kg, then 500kg to deep site (SNOLab?)

Darkside: SNOLab? Gran Sasso?

Long term future at DUSEL?



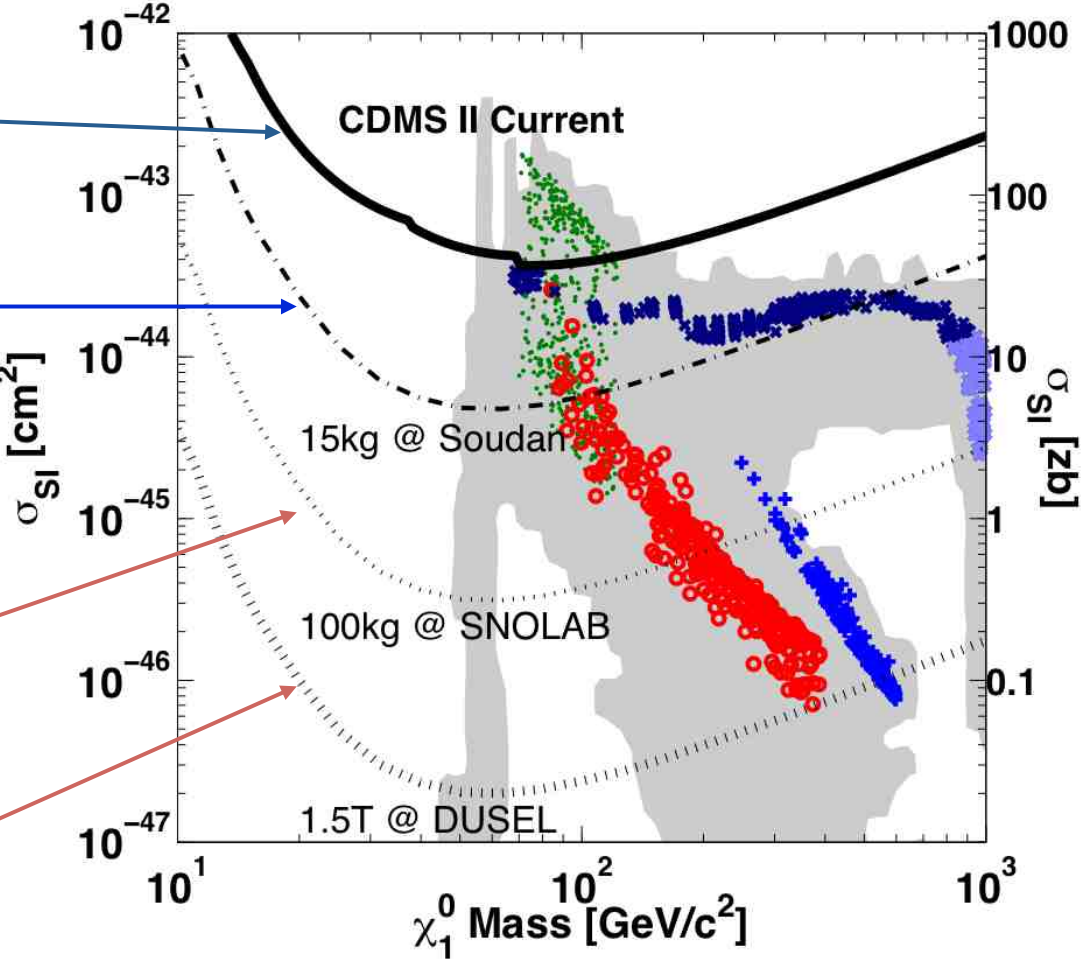
Example: CDMS Future Projections

CDMS II
4 kg Ge
~ 2 yrs operation

SuperCDMS @ Soudan
15 kg Ge
~ 2 yrs operation

SuperCDMS @ Snolab
100 kg Ge
~ 3 yrs operation

DUSEL/GEODM
1.5T



DarkSide and MAX

DarkSide Collaboration : UMass Amherst, Arizona State, Augustana College, Black Hills State, Fermilab, Houston, Notre Dame, Princeton, Temple, UCLA

- DarkSide-50 (50 kg, 10^{-45} cm^2)

DarkSide + XENON = MAX Collaboration

UMass Amherst, Arizona State, Augustana, Black Hills State, Coimbra, Columbia University, Fermilab, Houston, INAF, LNGS, MIT, Münster, Notre Dame, Princeton, Rice, Shanghai Jiao Tong, Temple, UCLA, Virginia, Waseda, Zürich

- 5t Depleted Argon and 2.5t Xe TPCs (10^{-47} cm^2)
- S4 Funded Project
- Possible change in baseline (25t DAr, 10t Xe) if DUSEL delay to 2016-2017 confirmed

adapted from C.Galbiati PAC presentation 11/09

DarkSide-50

dual-phase TPC

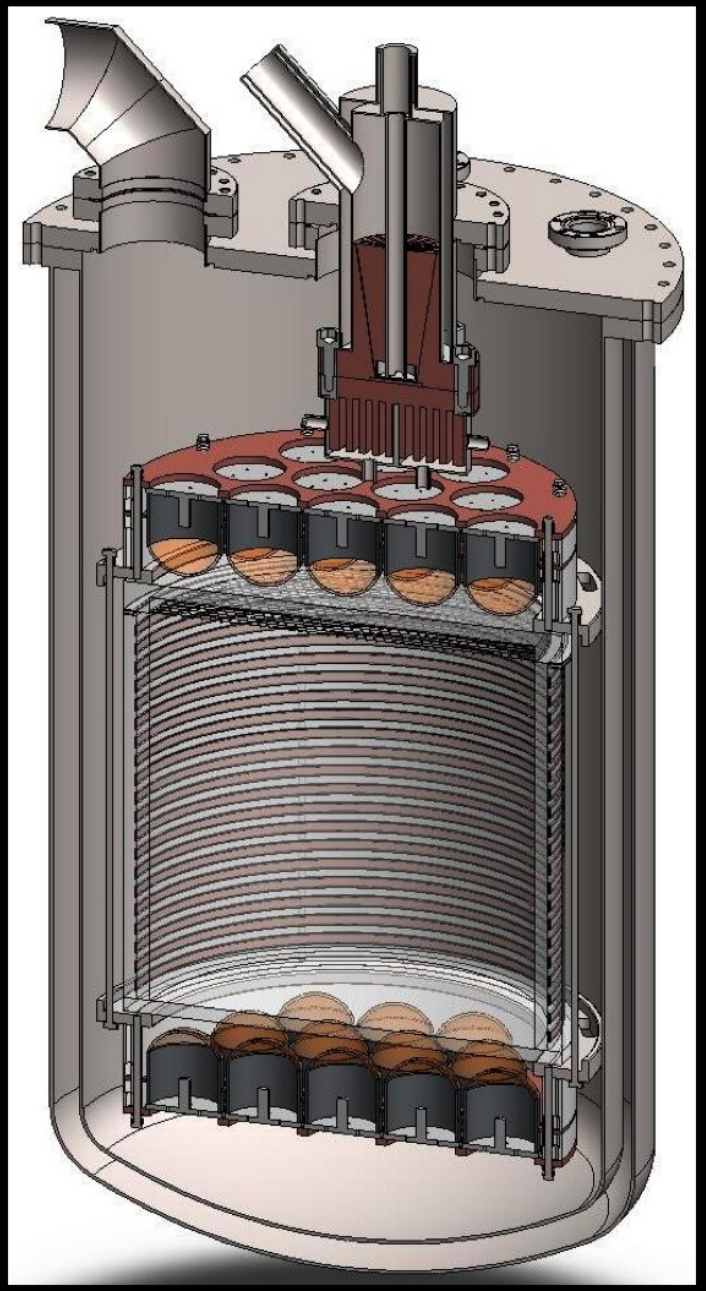
50 kg active mass

background-free for 3 yrs

sensitivity 10^{-45} cm^2

Test for three advances crucial to achieve zero background:

1) depleted argon
2) QUPIDs at LAr temp
3) active liquid scintillator neutron veto



adapted from C.Galbiati PAC presentation 11/09

Synergies at FNAL

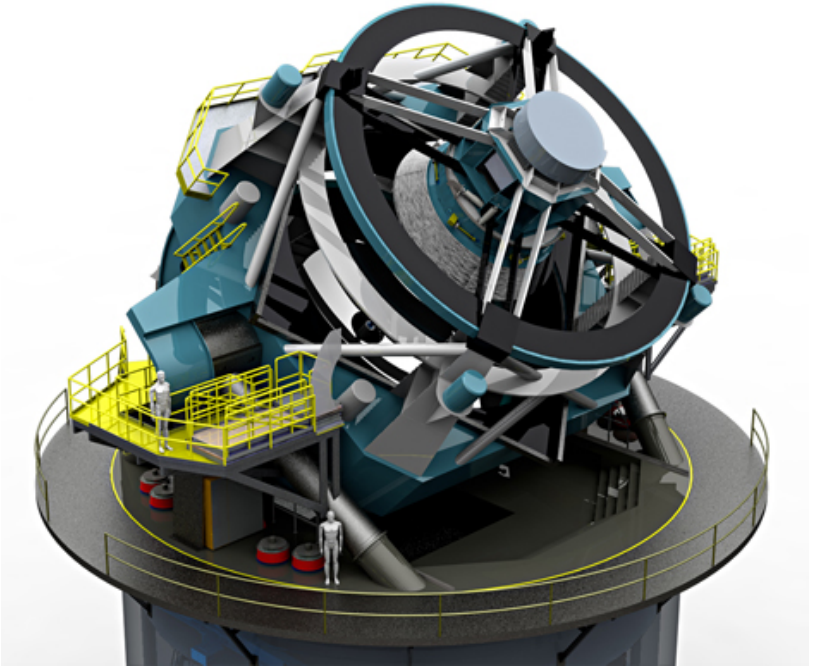
- LAr Neutrino Program (LBNE, MicroBoone, ArgoNeut)
  - Purification, DAQ, Electronics, Material Qualification, Wavelength Shifters, Optical Measurements and Simulations, Data Storage, Analysis, Electrostatics Design, HV Feedthroughs, Power and readout of QUPIDs and PMTs
- CDMS
  - Neutron Veto, Low Background Materials and Measurement, Cryogenics
- COUPP
  - Neutron Veto, Quartz Vessel

from C.Galbiati PAC presentation 11/09

Future Dark Energy: Astro2010 DOE priorities

CD-0 this fall; possible MIE in FY12

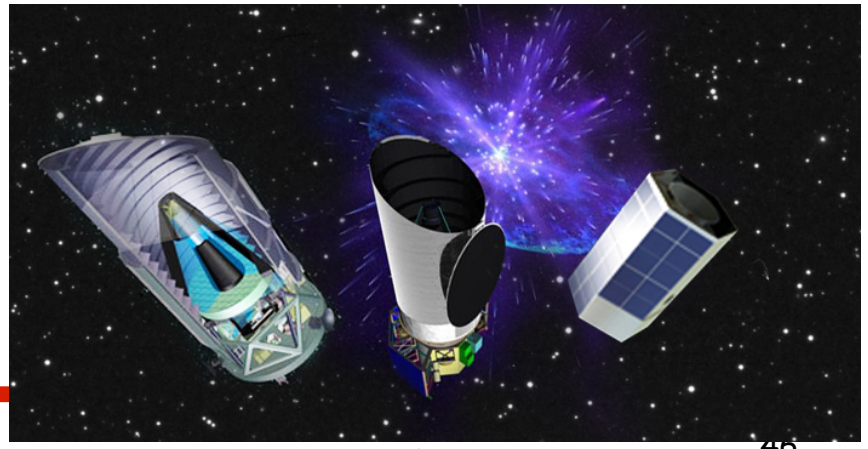
LSST: Possible Fermilab role in calibration, analysis, database, building on SDSS and DES experience



JDEM (WFIRST?): future DE satellite

Fermilab: Science Operations Center (E. Gottschalk)

Project leadership (S. Kent)



Dark Energy: other proposals

- 21cm BAO "intensity mapper"
  - Cylindrical antennas, aperture synthesis
  - Conceptual design by FNAL theorists
  - FY10: Fermilab R&D on technical feasibility
  - Technical viability validated by external review
  - Await formation of viable collaboration and funding model
- Dark Energy Camera Spectrograph (DESpec)
  - Upgrade to DECam after DES completion: new multi-fiber focal plane and spectrograph system
  - Similar to BigBoss
  - Southern hemisphere followup to DES, LSST
  - FY 11: evaluate science, develop design, costing

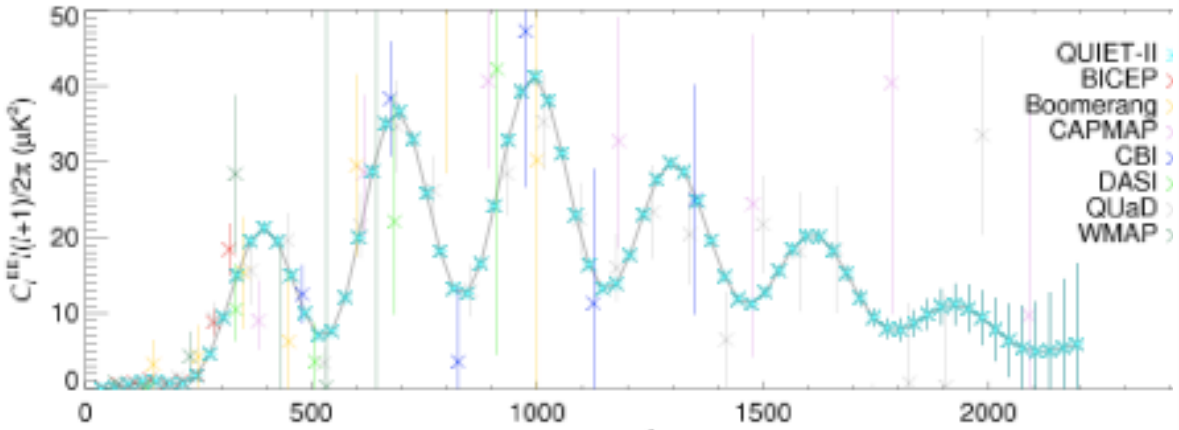
Cosmic Microwave Background : QUIET-II

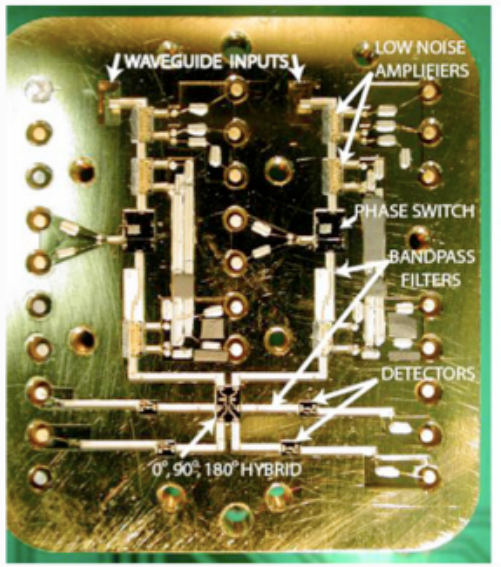
Next generation CMB polarization experiment led by B. Winstein (U Chicago)

Contingent on NSF funding; await concrete plan

Possible Fermilab roles: assembly of detector modules, focal plane elements (SiDet facility), science analysis

First Fermilab venture into experimental CMB

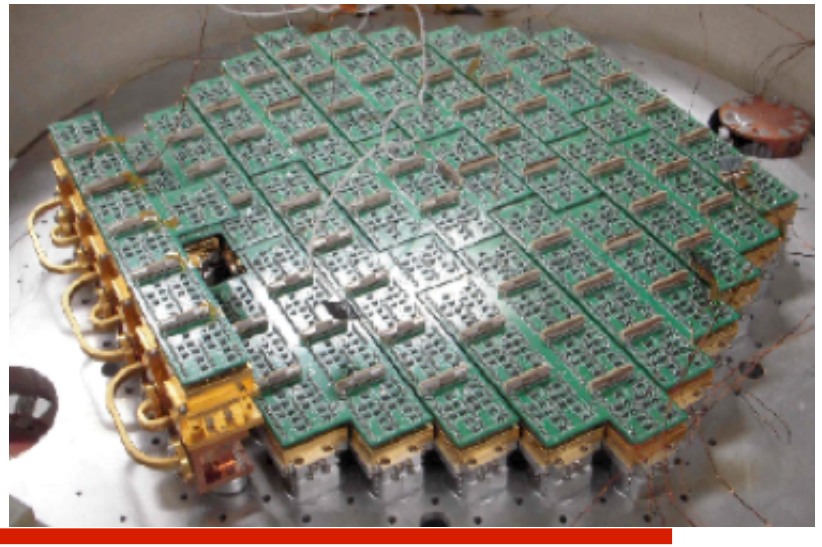




QUIET-II Activity

PASAG recommends that QUIET II be supported at the proposed scope under all budget scenarios.

- Fermilab group proposes to provide mass production and testing of 1500 MMIC modules using existing precision assembly tools at SiDet.
- Also assembly and testing of an integrated W-band receiver
- Current Fermilab effort: 1 FTE scientist
- FY11: continued R&D with emphasis on noise and cost reduction
- Future depends on NSF



New projects outside scope of PASAG, Astro2010

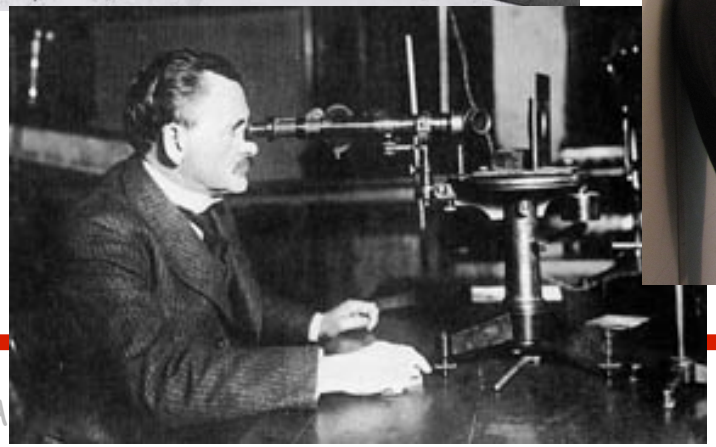
Holographic interferometer & Axion search

laser interferometer cavities: new tools for Fermilab

fundamental physics: Planck scale at modest cost

FY10/11: design and prototype construction

Albert Michelson's interferometers: Precision probes of spacetime



Holometer prototype cavity in Fermilab MP8 beamline

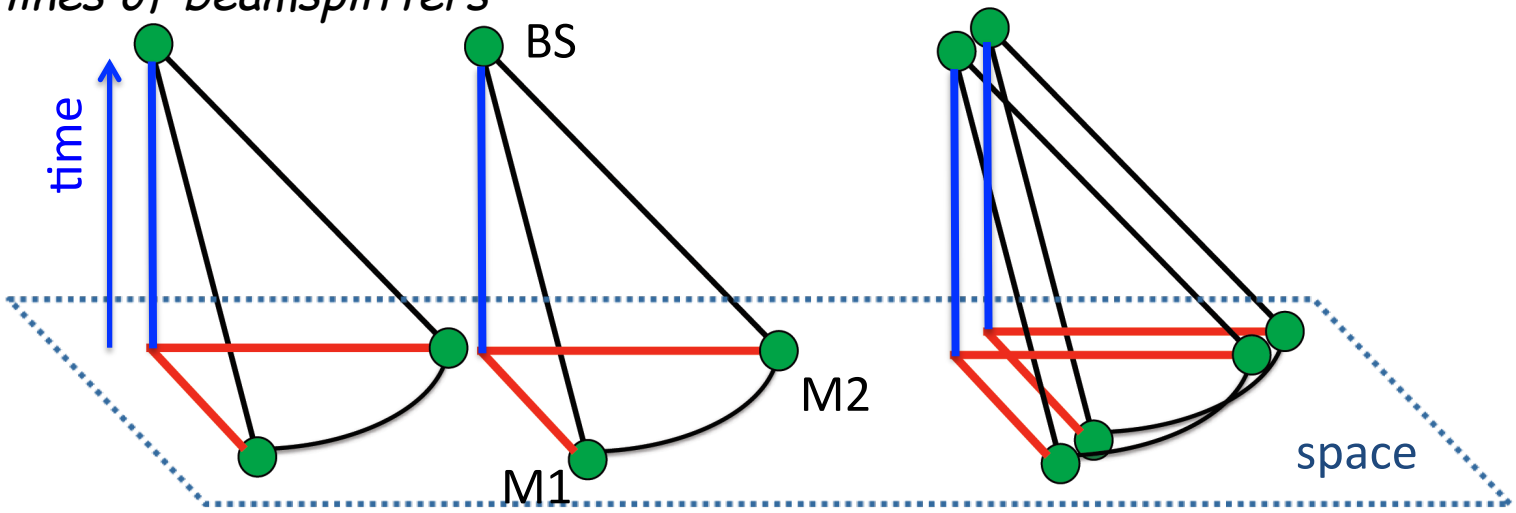
Direct probe of Planck scale: Fermilab Holometer

Correlate two high-finesse, power-recycled 40-meter Michelson interferometers at high frequency ("Megahertz microphones")

Detect or limit "holographic noise" in spacetime position: null phases in different directions random-walk apart at 10^44 Hz

Experimental team: FNAL team (Chou et al.), S. Meyer (U Chicago), LIGO experts (Weiss, Waldman, Gustafson)

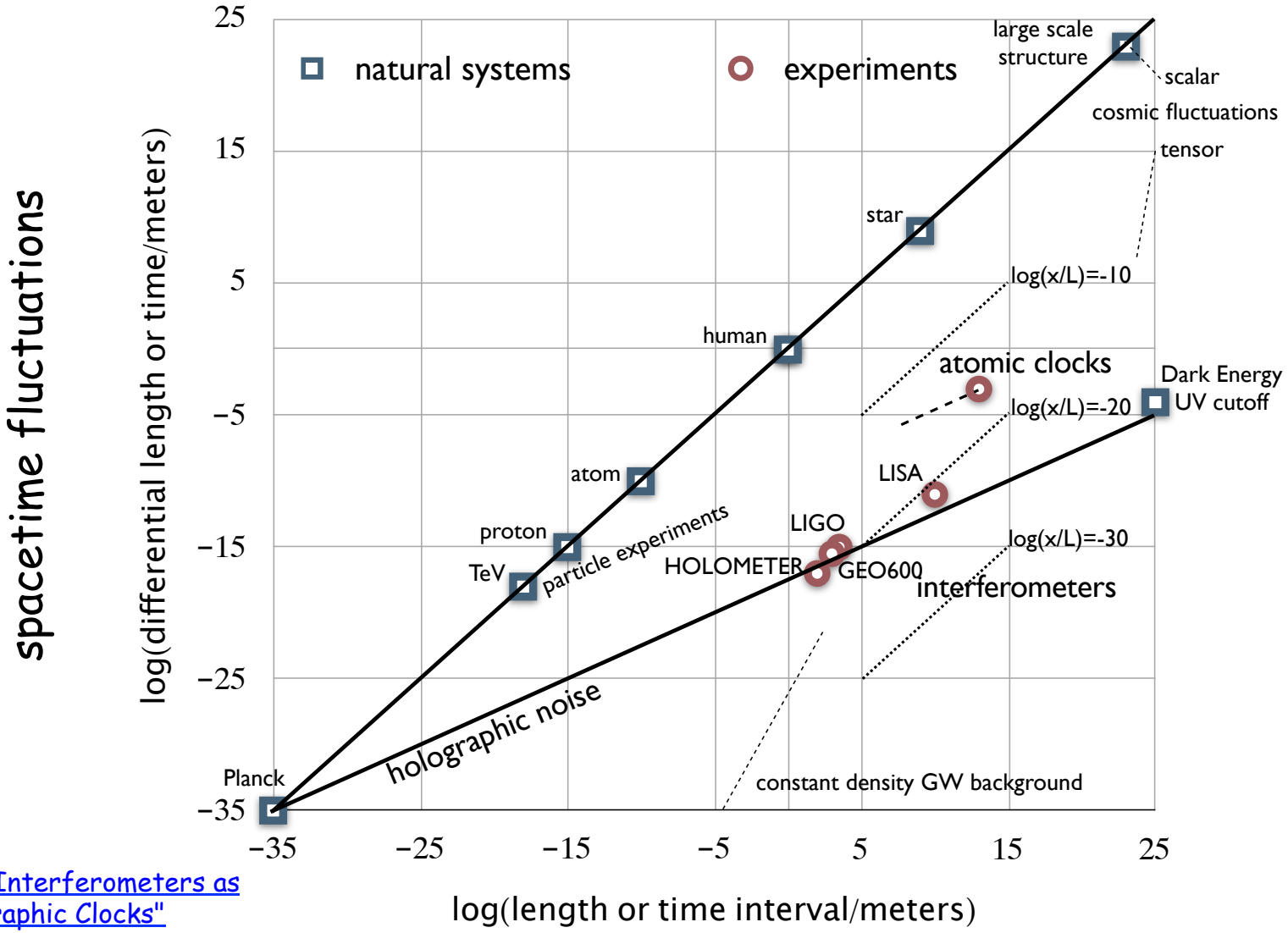
World lines of beamsplitters



Separate spacetime volumes: No correlation

Overlapping spacetime volumes: Correlated holographic noise

Interferometers as holographic clocks



CJH, "Interferometers as Holographic Clocks"

Axion-like particles: GammeV, REPR

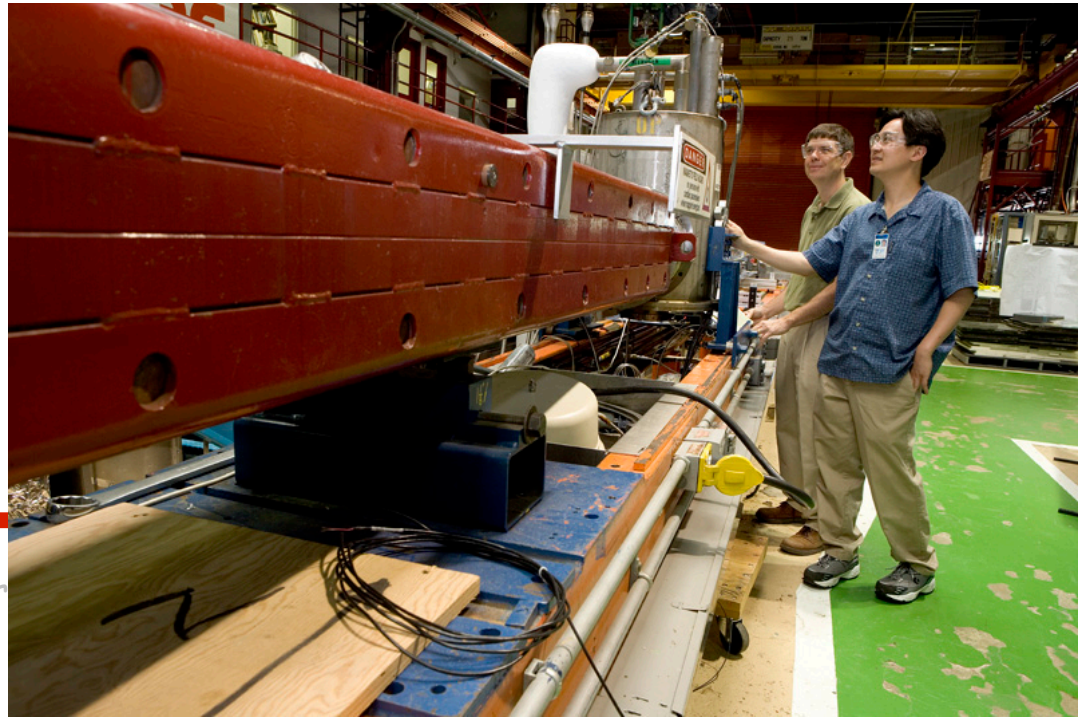
Mediate interactions of light with magnetic fields

FY 10: chameleons; trapped particle afterglow, results pending

Future: resonant regeneration, "light through a wall", laser cavities in Tevatron magnets

Reach to ~10^11 GeV scale with ~100m system

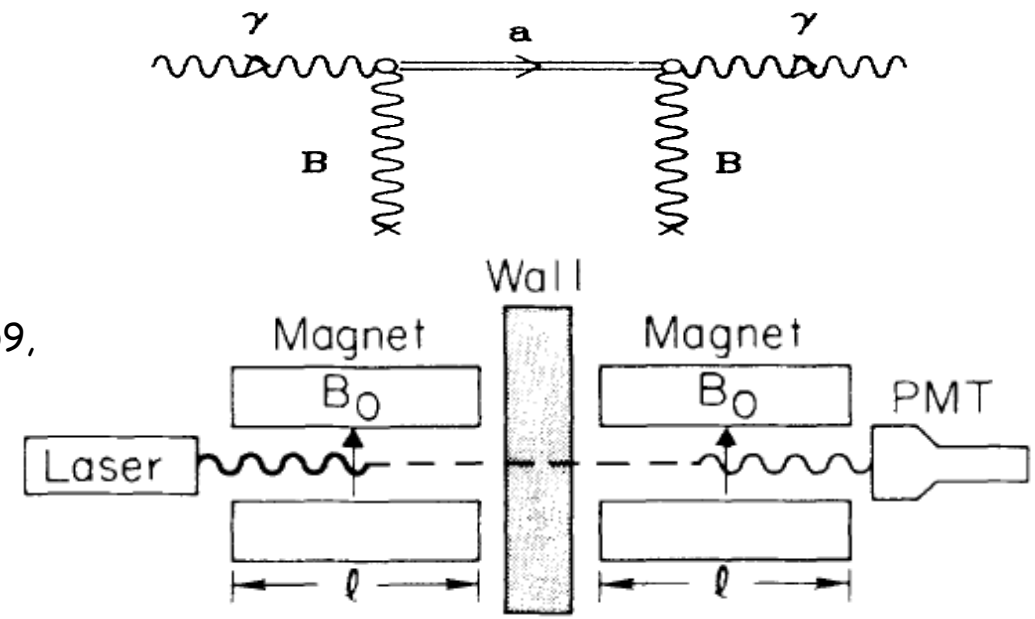
Challenge of high finesse: holometer as pathfinder



Axion search: Light shining though walls

Experimental configuration inspired by a Feynman diagram.

K. Van Bibber, et. al., PRL 59, 759 (1987)

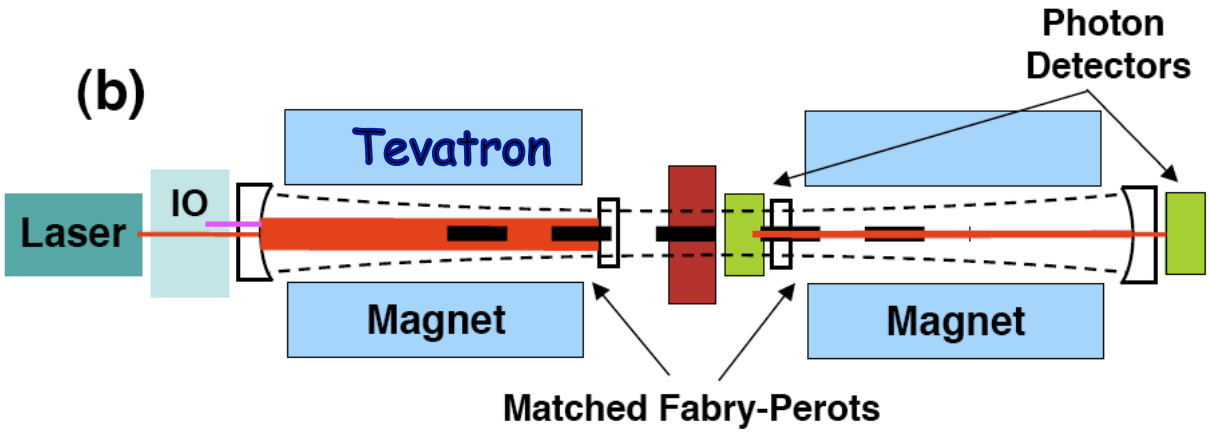


$$P_{\text{regen}} \approx \left(\frac{1}{4} g^2 B^2 L^2\right)^2$$

g=coupling constant

Cost scales linearly with sensitivity.
How to achieve orders of magnitude improvement???

Cavity-enhanced photon-axion conversion

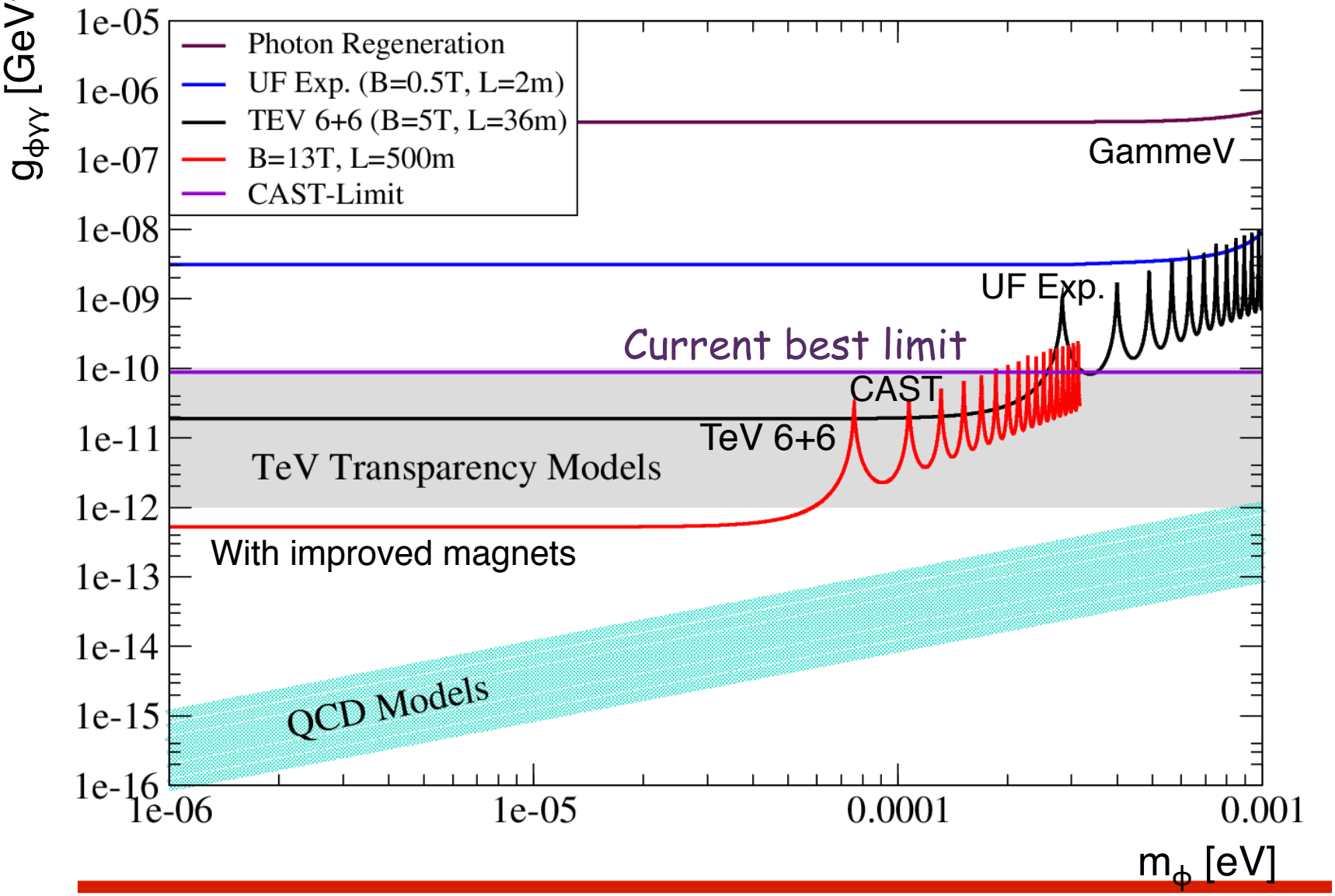


Matched Fabry-Perot cavities shape the axion beam and resonantly enhance the axion-photon transition probability. Light leaks coherently from the bright cavity into the dark cavity.

Signal rate increases as the square of cavity finesse: with 10^5 bounces, the rate increases by 10^{10} !!!

Possible to improve GammeV limit by 4 orders of magnitude using 40m long strings of **existing spare Tevatron magnets**.

Resonant regeneration discovery potential



Plan for New Activities in FY 11-12

- Expand Dark Matter experiments
- Depends on funding of FWPs (SuperCDMS SNOLab, COUPP, Darkside)
- Future Dark Energy planning
  - Dark Energy project priorities shaped by Astro2010
    - Some Fermilab role in LSST: e.g. calibration, analysis
  - Dark Energy Science Center
    - Coordinate with other labs
  - DESpec: spectroscopic followup to DES, LSST
    - Design, science impact, cost analysis underway
- CMB
  - Depends on NSF QUIET-II support; delay likely
- Holographic interferometer
  - R&D leading to FWP in FY 11 with proven technology

Budget challenges and issues

- Commissioning and operations of experiments
  - Construction budgets typically do not cover commissioning
  - Advance planning needed for operations
  - DES and SuperCDMS Soudan
- How much funding for scientists?
  - DOE-allocated budget does not cover existing effort
  - Need KA13 funding for scientists working on detector R&D
- When will projects be funded?
  - Budget stress will cause delay; how much?
  - Difficulty in planning level of scientist effort

Coming up

Experiments on the Cosmic Frontier symposium

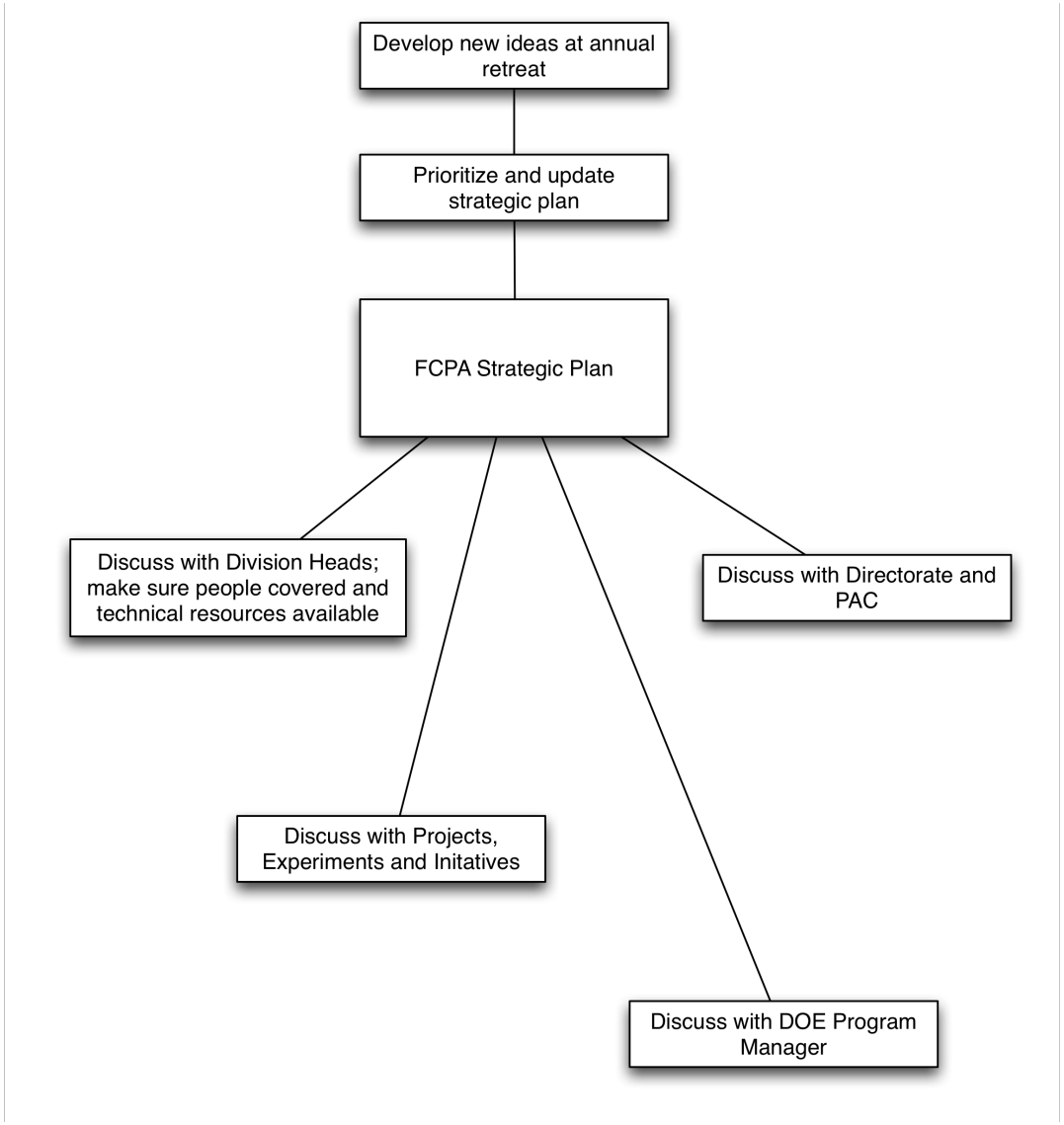
- Fermilab, March 23 to 26, 2011
- Community planning effort, post-Astro 2010
- Organized with other HEP labs and particle astro university community
- Dialog and Debate to help shape future program

Backup slides

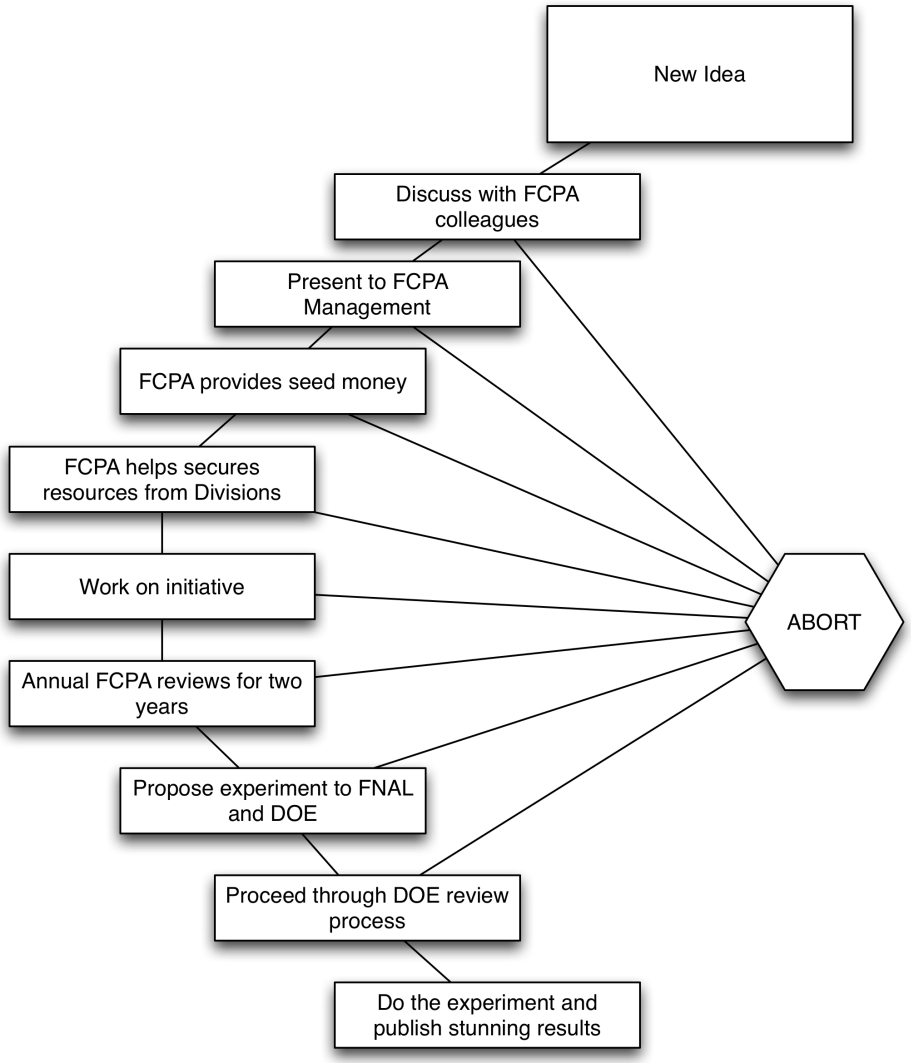
Strategic Planning, Development Process

- FCPA planning retreats
- Strategic plan document, revisited every year
- Overall criteria (PASAG)
  - Physics: matter, energy, space and time
  - Key particle community/ lab role
- Process for new initiatives
  - Alignment with long term lab, DOE program needs
  - Early development through KA15
  - internal review
  - PAC, Directorate approval
  - Field Work Proposal
  - Upon approval, graduate to KA13

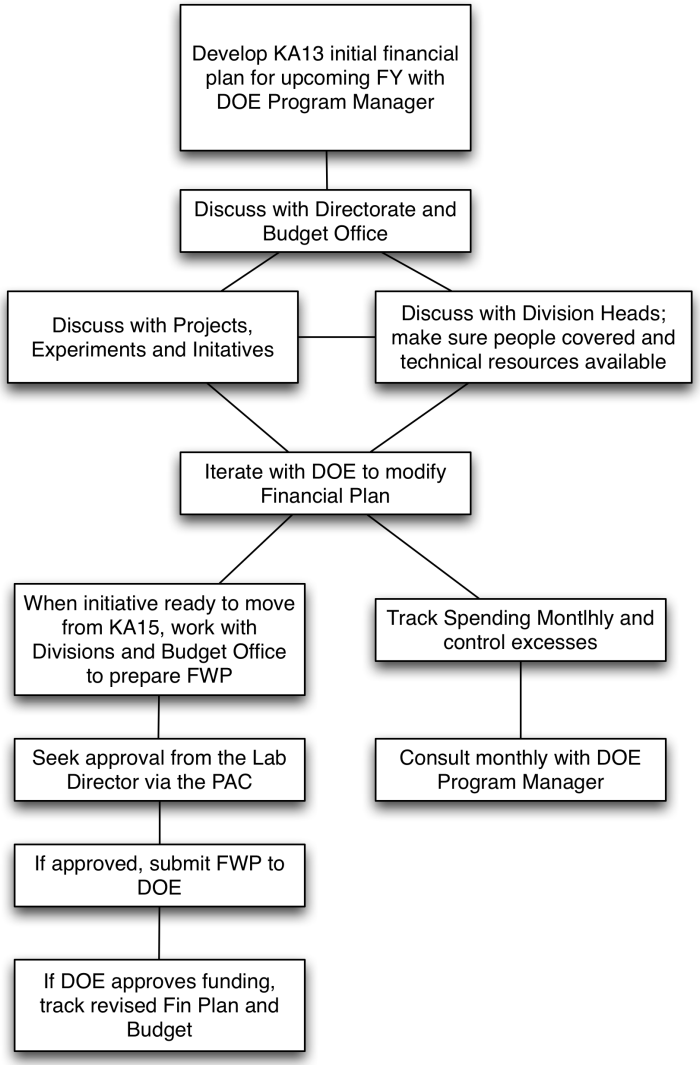
Strategic Planning Process



Project Lifecycle



Budget Process



FCPA Retreat, Nov 2007: What we are **not** doing now

- OBSERVATIONAL COSMOLOGY /DARK ENERGY
  - DES
  - ~~SDSS~~
  - ~~SNAP~~
  - ~~LSST~~
  - ~~PRIME~~
- 21 CM Radio Astronomy
  - ~~Intensity Mapping project~~
  - ~~Square Kilometer Array~~
- CMB Polarization
  - QUIET
  - ~~CMBpol~~
- DARK MATTER DIRECT DETECTION
  - CDMS
  - COUPP
  - Argon/ ~~Xenon~~ Dark Matter, DUSEL
  - Axion ~~searches~~
    - ~~ADMX~~
    - higher mass

COSMIC RAYS

- AUGER
- ~~AUGER NORTH~~
- ~~GAMMA RAYS~~
  - ~~GLAST (guest observer)~~
  - ~~AIR CERENKOV TELESCOPES~~
    - ~~AGIS~~
    - ~~DELTA~~