Cosmic Frontier at Fermilab

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Fermilab PAC
June 2011

Cosmic Frontier Research at Fermilab

- Core Program
  - Historical context
  - Main Thrusts:
    - Theory
    - Dark Energy
    - Dark Matter
    - High Energy Particles
- Future
  - Extensions of core program
  - New initiatives: spacetime, axion-like particles
  - Community dialog: Cosmic Frontier symposium

History of Particle Astrophysics at Fermilab

Theoretical Astrophysics Group (1983)

Sloan Digital Sky Survey (1990)

Pierre Auger Observatory (1994)

Cryogenic Dark Matter Search (1997)

Dark Energy Survey (2003)

Chicagoland Observatory for Underground Particle Physics (2004)

Laser experiments (2008)

Fermilab Center for Particle Astrophysics

Established in 2007 by DOE/FRA contract

- To unify and lead a program aligned with DOE goals, science opportunities, university research

Builds on science talent of Fermilab

- Mostly particle physicists
- Wilson Fellows (Sonnenschein, Chou, Estrada, Yoo)
- Presidential Early Career Award (Estrada)
- DOE Outstanding Junior Investigator, Early Career Awards (Chou)

Sloan Digital Sky Survey at Fermilab

World's first digital survey of the universe

Highest-impact observatory of the decade

Foundation of precision cosmology (with CMB etc.)

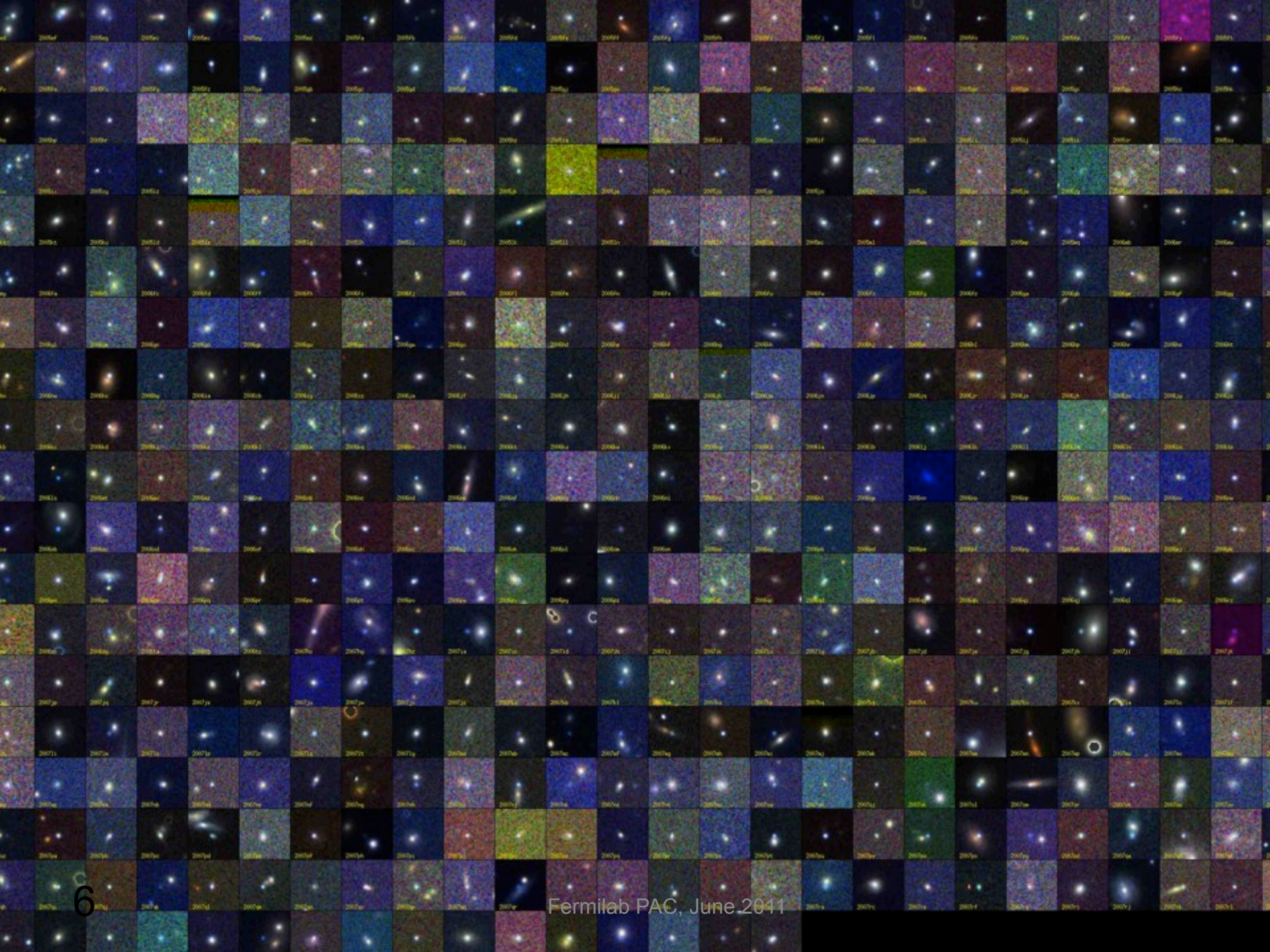
Many discoveries including BAO, ISW effects

Fermilab: anchor institution for technical infrastructure, operations, computing

Directors from FNAL: J. Peoples, R. Kron

Science ongoing: SDSS Supernova Survey, galaxy clusters

Scientists in transition to Dark Energy Survey



Core program: anchor laboratory for world-leading experiments

- Dark Energy
  - Dark Energy Survey (DES)
- Dark Matter
  - Cryogenic Dark Matter Search (SuperCDMS)
  - Chicagoland Observatory for Underground Particle Physics (COUPP)
- Ultra high energy cosmic rays
  - Pierre Auger Observatory (PAO)

Dark Energy Survey

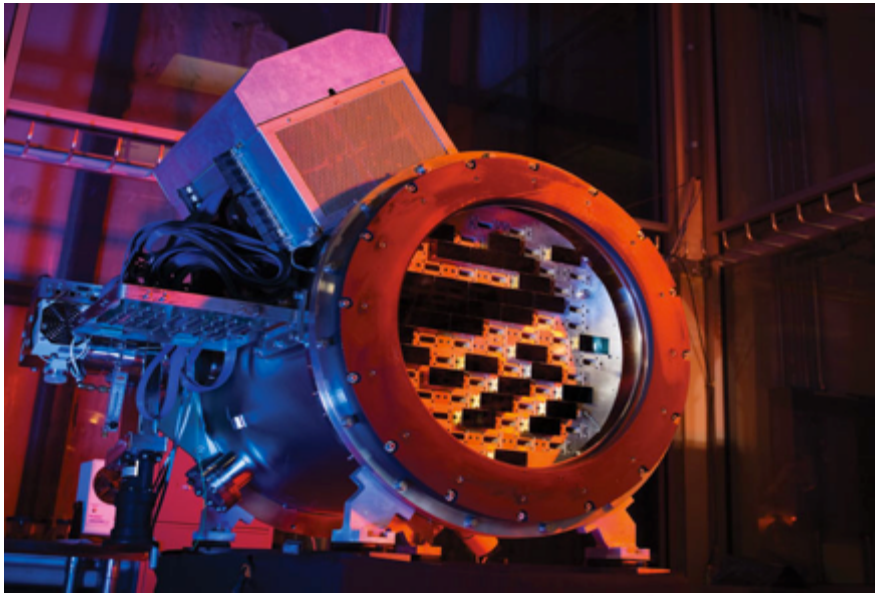
Next big step in cosmic surveys after SDSS

Wide and deep (~Hubble distance)

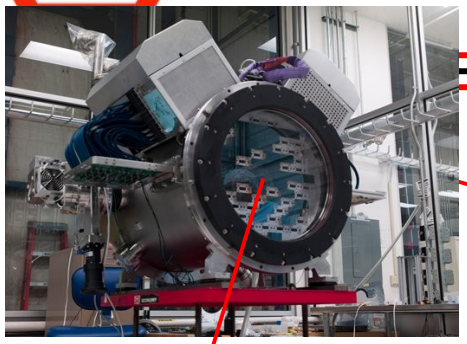
Led by Fermilab scientists

Survey starts in 2012, then runs 5 years

DECam under construction at Fermilab

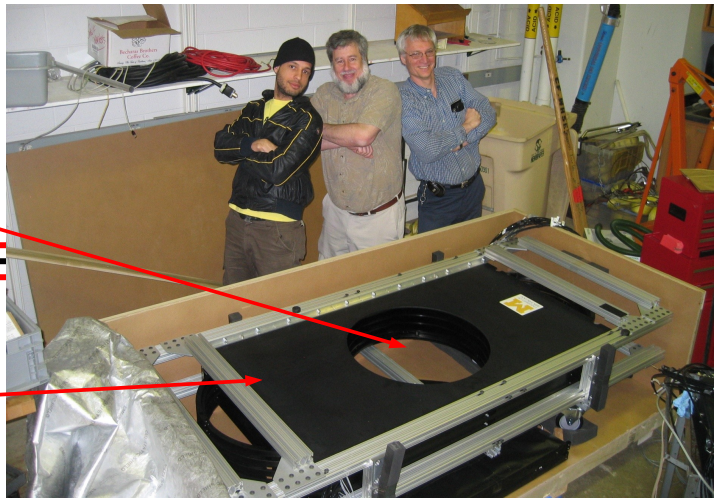


DECam System

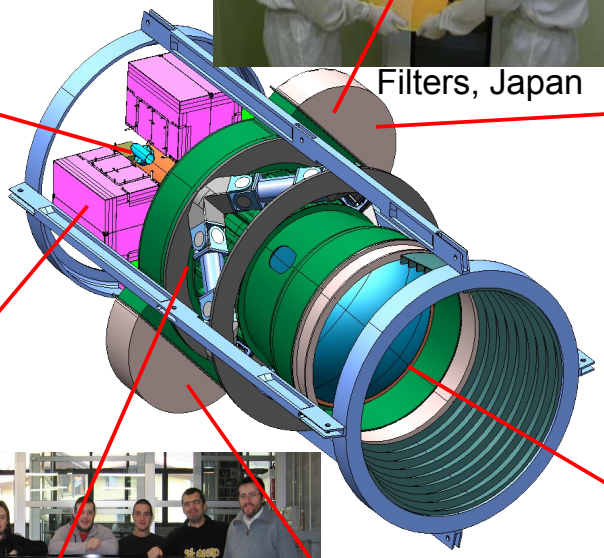


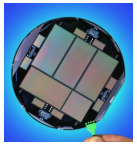
Imager, FNAL

Filters, Japan

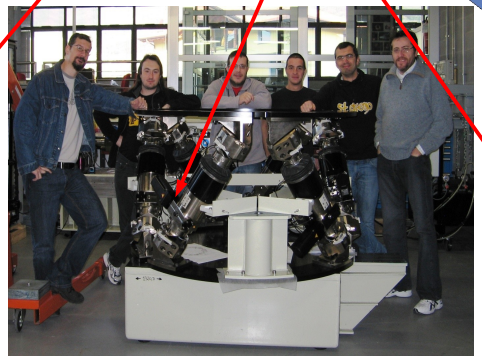


Filter changer, Univ. of Michigan

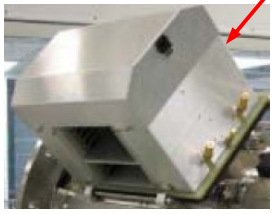




CCDs, wafer from LBNL, packaged at FNAL

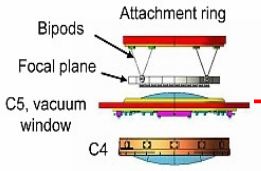


Hexapod, Italy

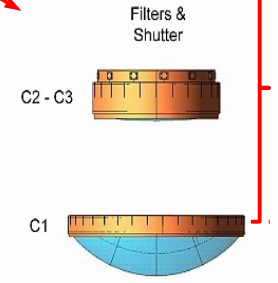


Electronics, Spain and FNAL

Optics



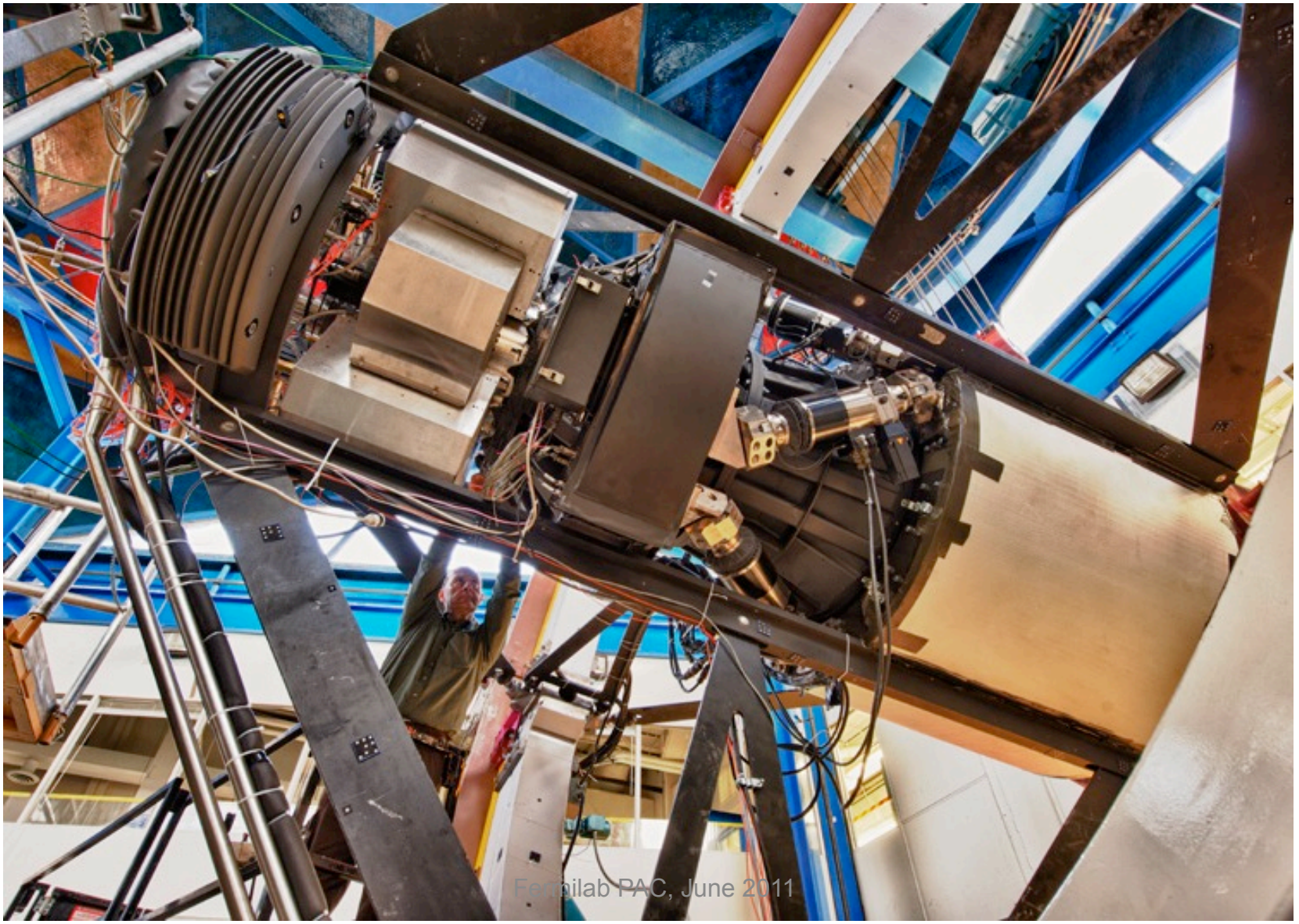
ANL/FNAL



UCL@ UK

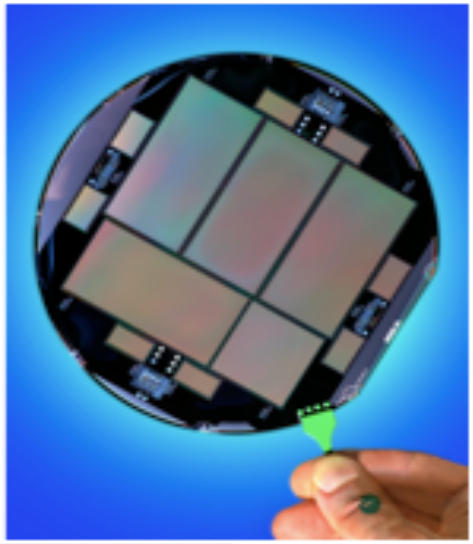
Shutter, Germany

DECam at Fermilab's SiDet

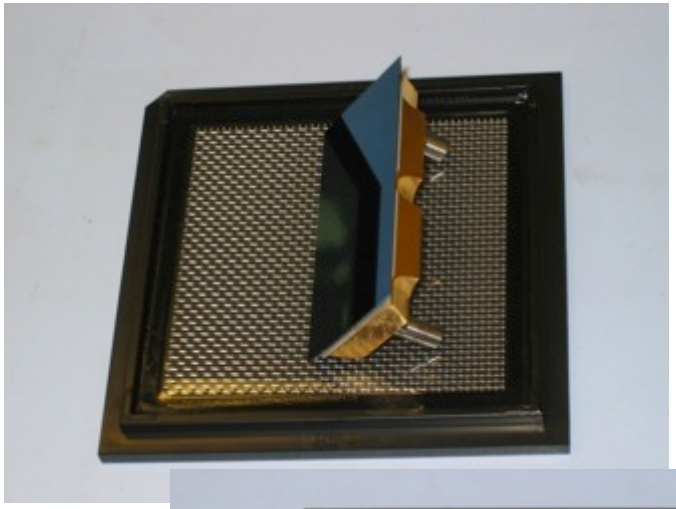


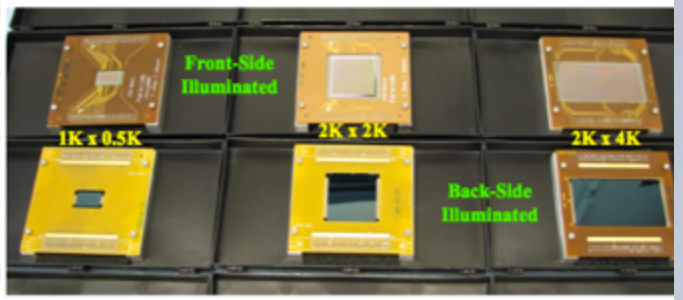
Fermilab's silicon detector technology

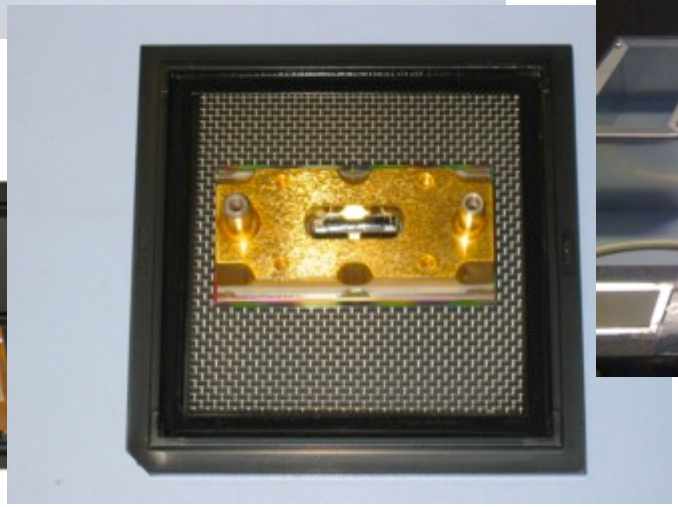
DECam wafer



DECam detector developed with LBNL

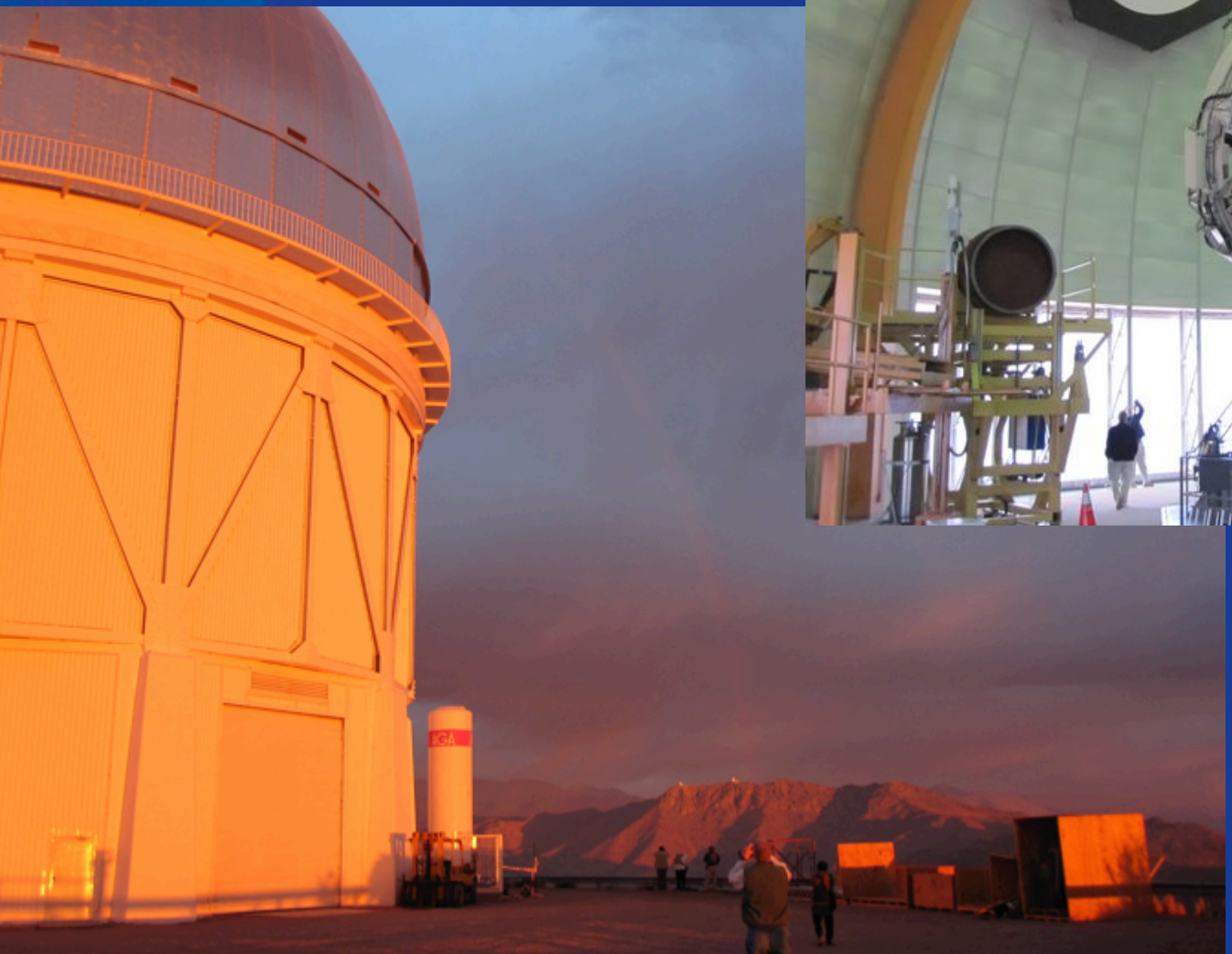






Fermilab's expertise in building silicon trackers has transferred to the design and fabrication of these CCDs

DECam's destination: 4 meter Blanco telescope at Cerro Tololo InterAmerican Observatory



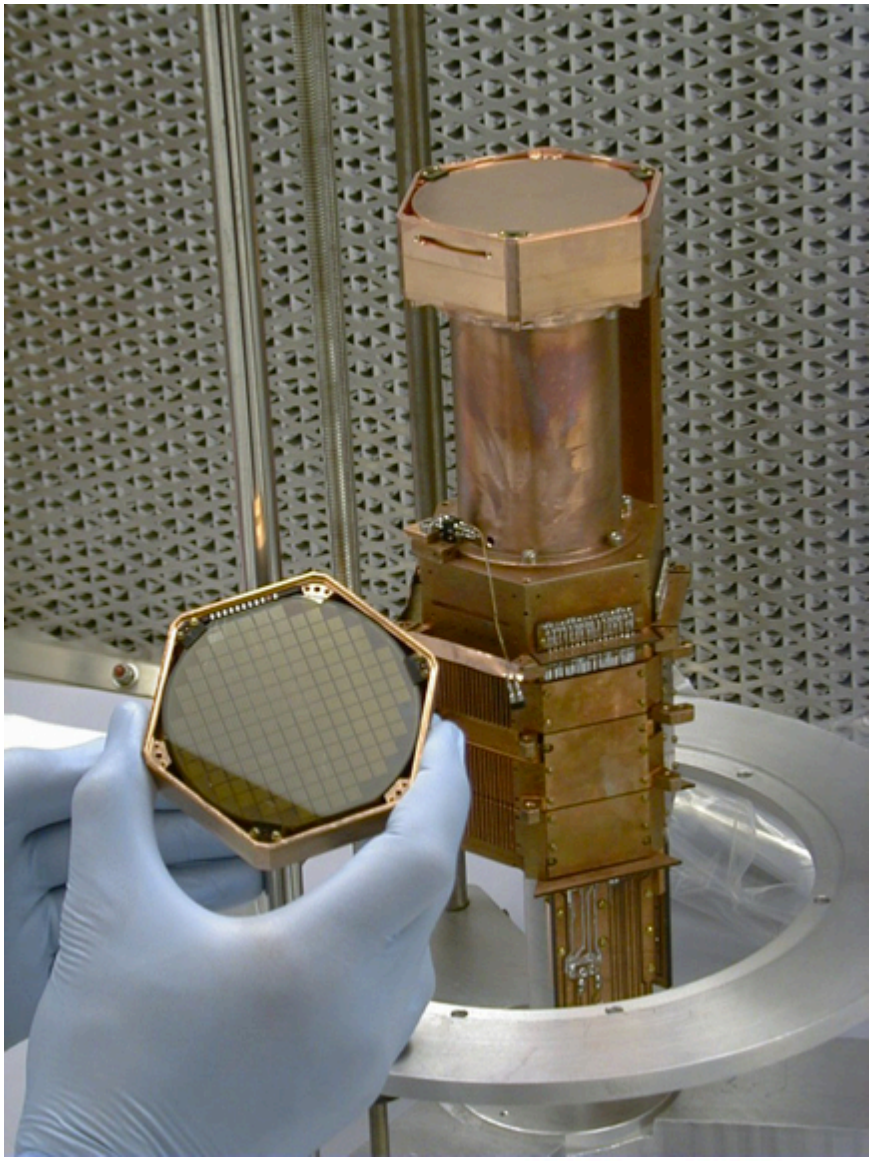
Fermilab

Dark Matter with Cryogenic Crystals: CDMS

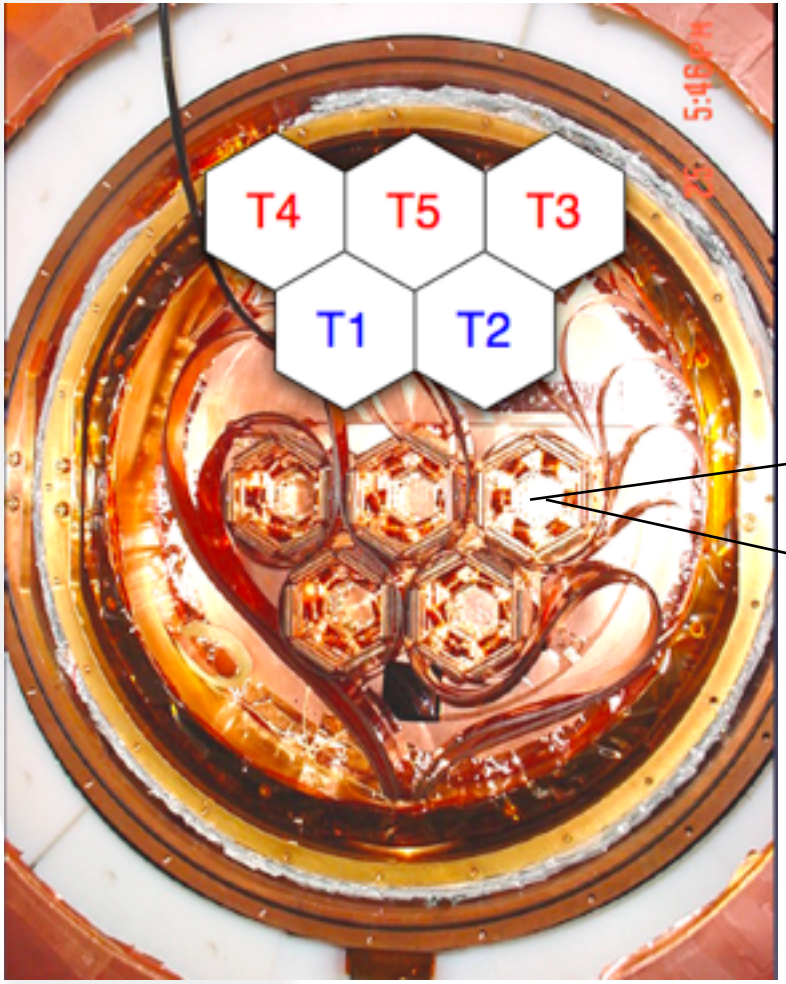
Search for rare collisions of Galactic halo WIMP dark matter particles with nuclei

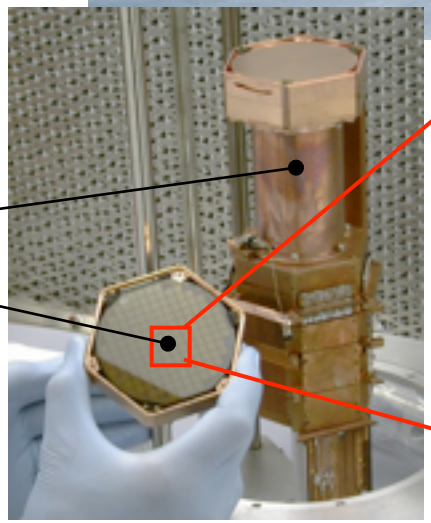
State of the art in direct detection and background rejection

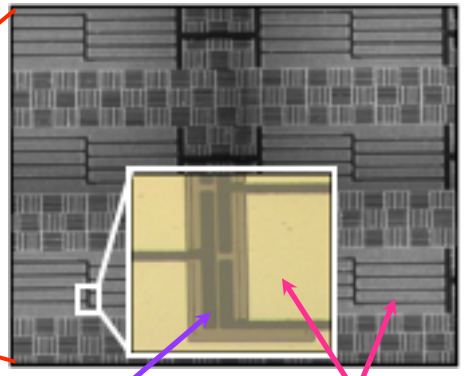
This year: 15kg at Soudan with better detectors, background rejection



CDMS-II at Soudan







Z-sensitive Ionization and Phonon detectors

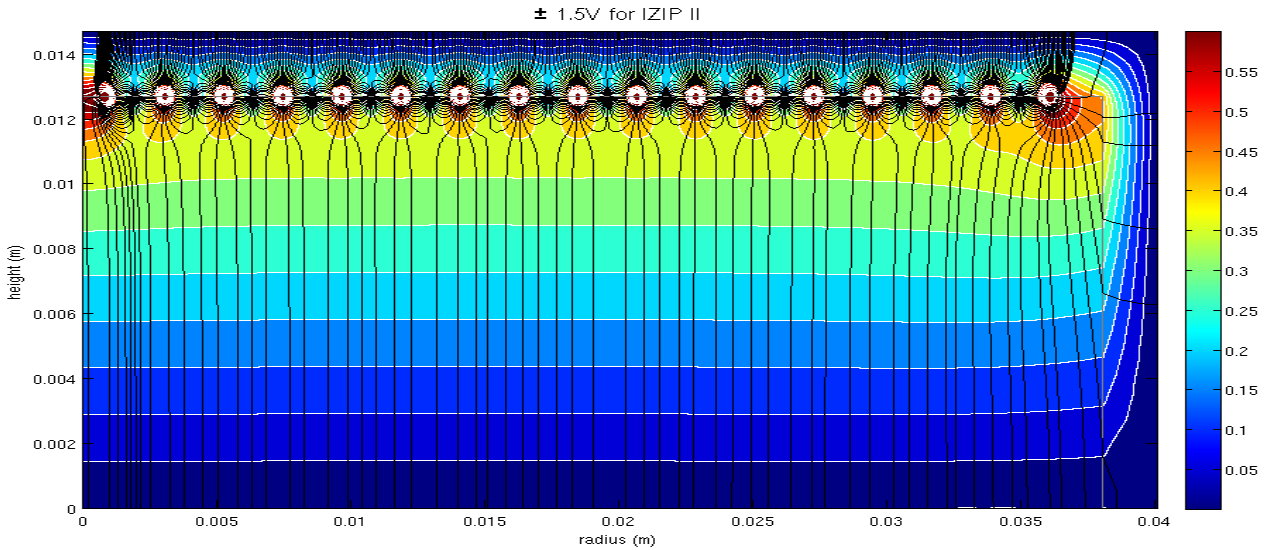
Fermilab

SuperCDMS: Technology Breakthrough

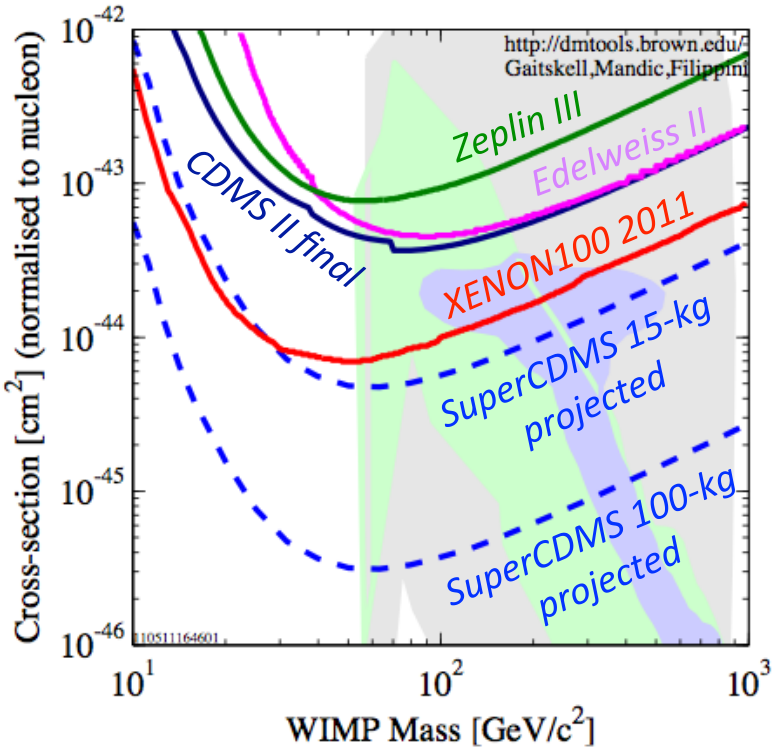
New symmetric detectors (iZIP) improve background rejection by more than an order of magnitude

Ton scale CDMS style experiment now feasible

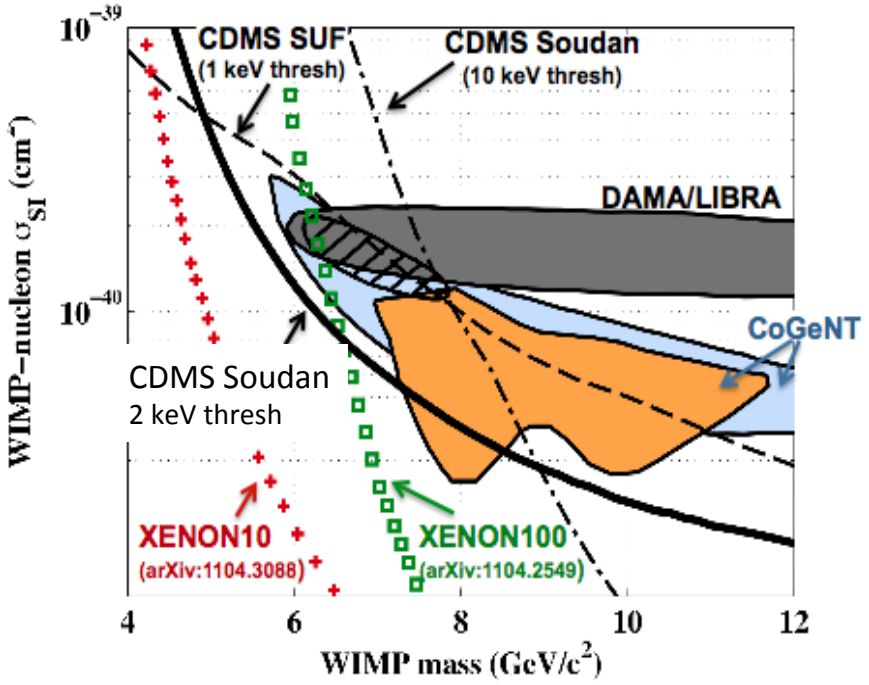
- iZIP now installed at Soudan facility
- Science run begins this summer
- Major funding needed for SuperCDMS at SNOLab



Current state of WIMP direct detection



Spin-Independent scattering above 10 GeV/c² WIMP masses



Spin-Independent scattering below 10 GeV/c² WIMP masses

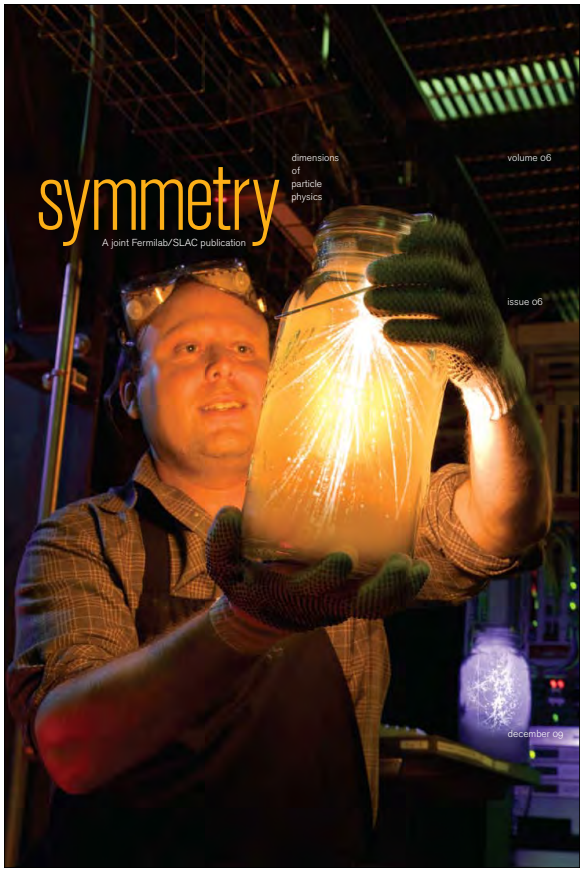
Dark Matter with Bubble Chambers: COUPP

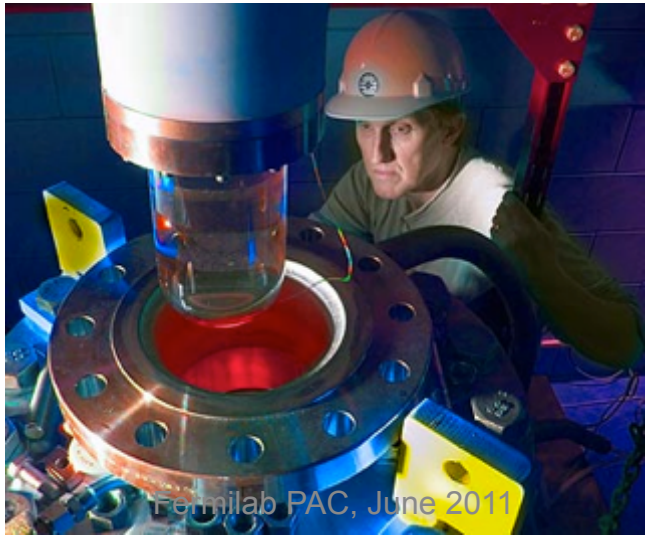
Old technique applied with stunning early success

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

Now: 4kg at SNOLab, 60kg at FNAL

Future: 60kg to SNOLab, then 500 kg





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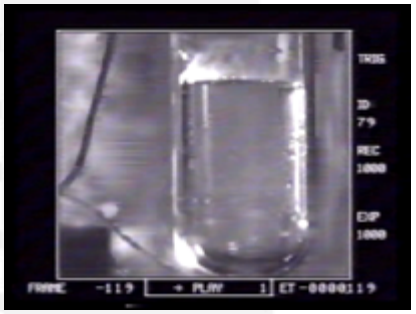
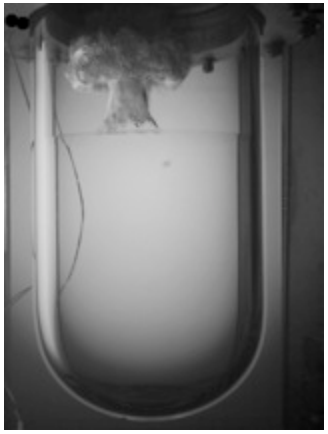
COUPP Bubble Chamber Program

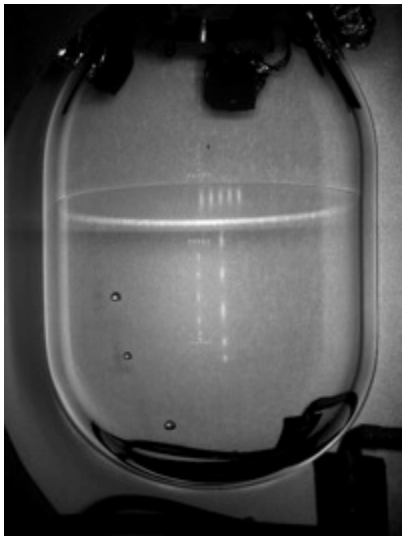
smaller chambers lead R&D for larger chambers



Test tube
(U Chicago)

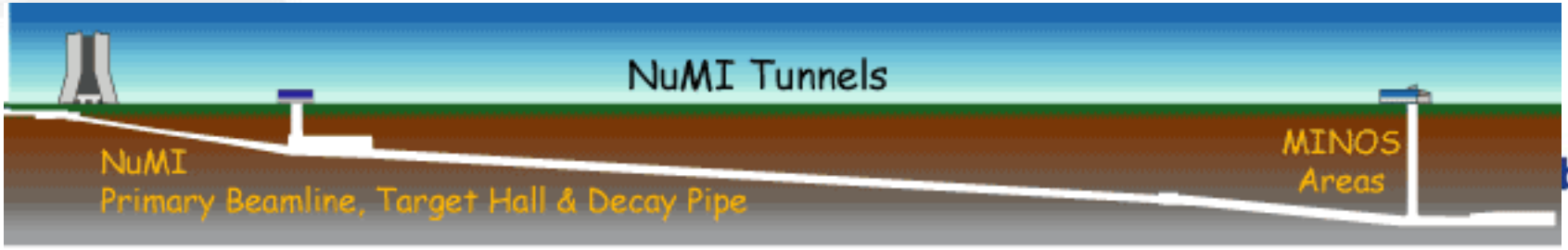


COUPP 2kg



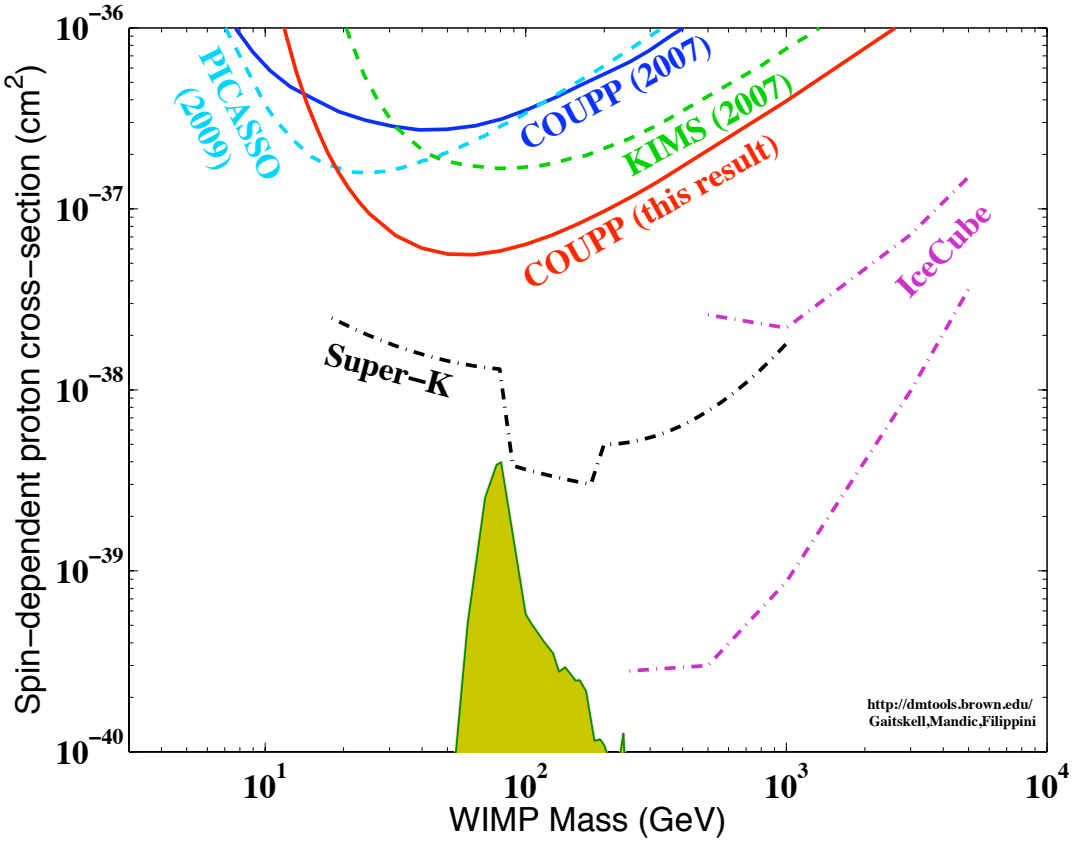
COUPP 4kg

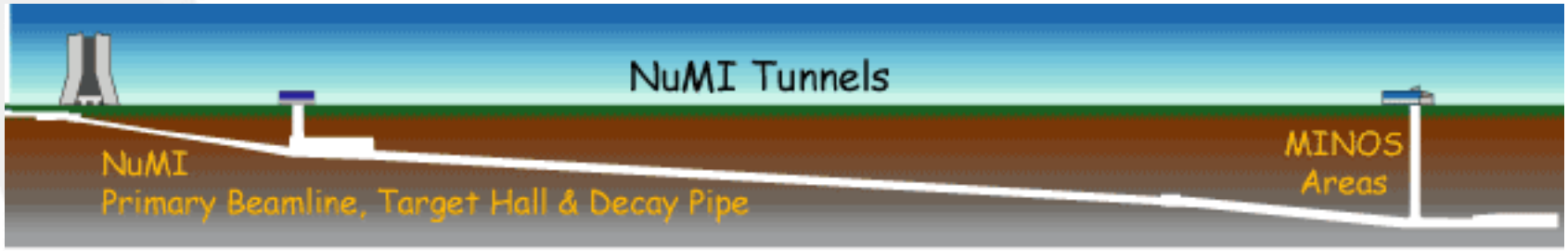
COUPP 60kg



Best direct limits on spin-dependent WIMPs

- Blue line –*Science* **319**:933-936 (2008)
- Red line – latest result (2010)
- Latest results limited by cosmic radiation in the NUMI tunnel, 350 foot depth

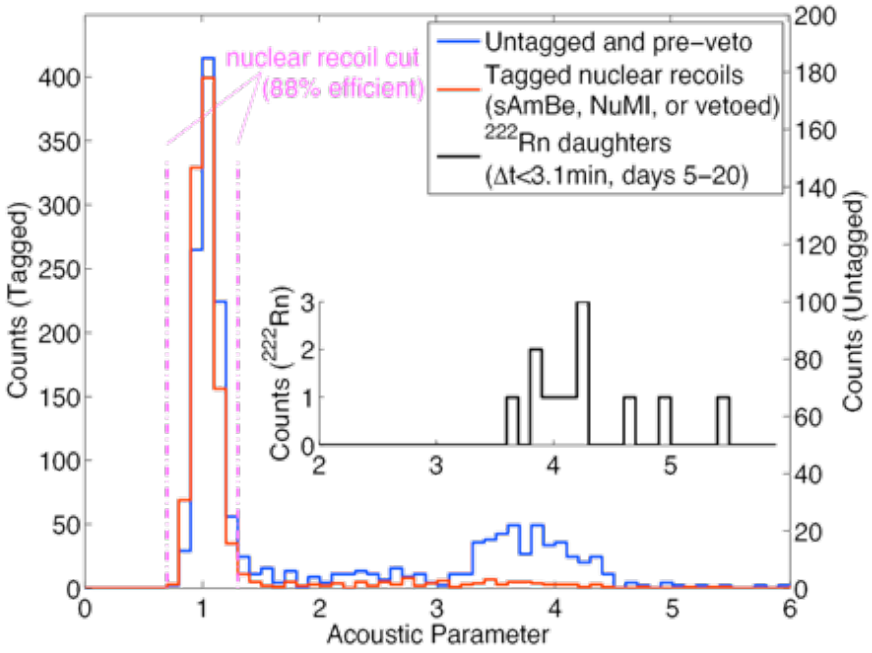


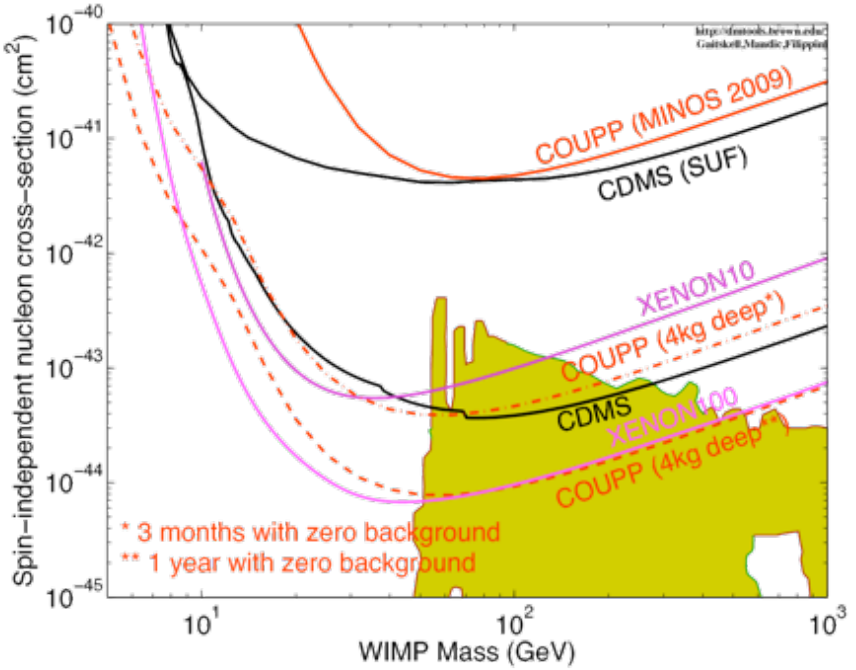


Fermilab

COUPP acoustic background rejection technique

- Demonstration of acoustic rejection against alphas, a previously limiting background
- Paper published in January, 2011 - PRL, 106, 021303



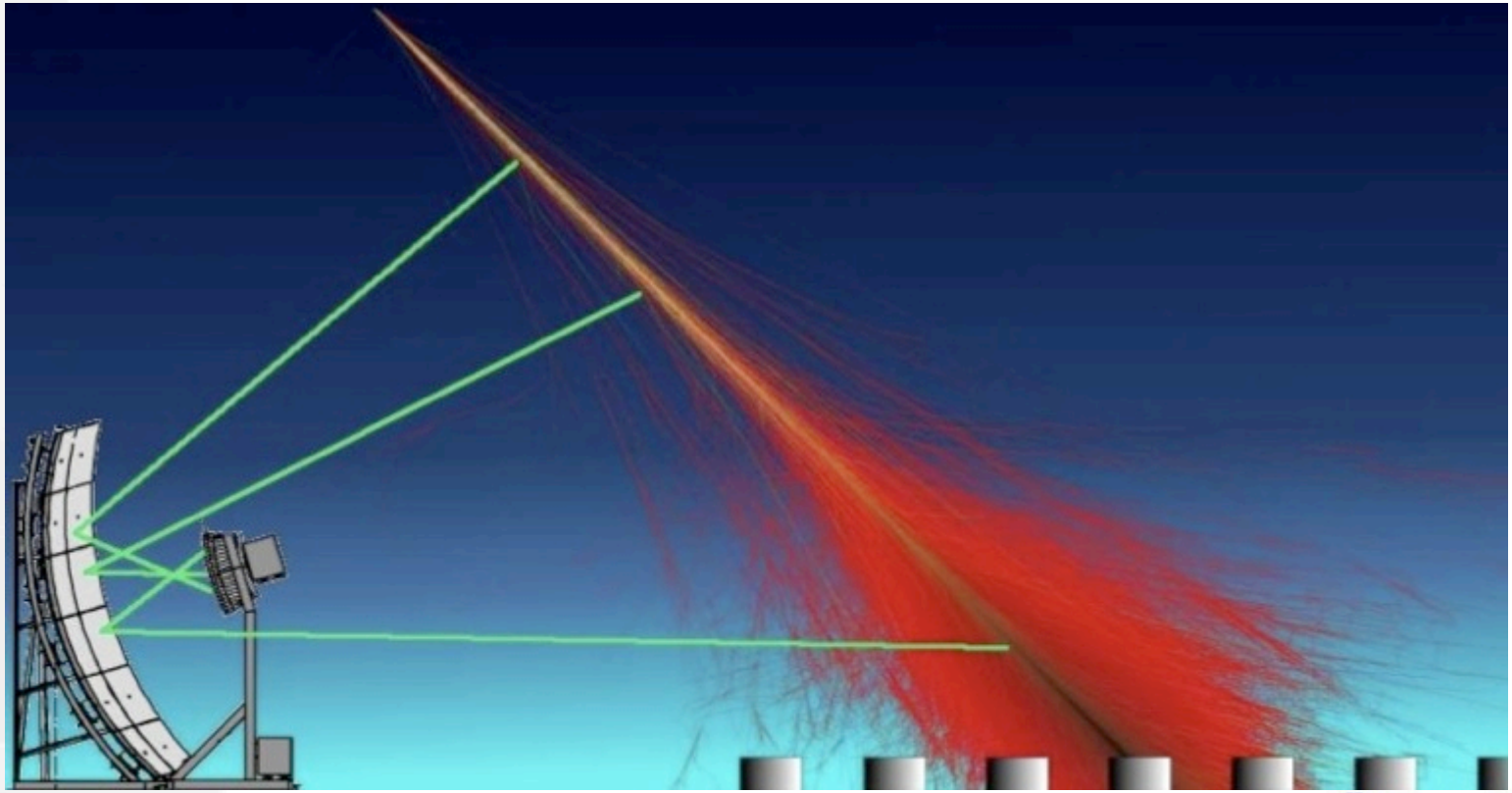


COUPP-4 is now running at SNOLab with these sensors

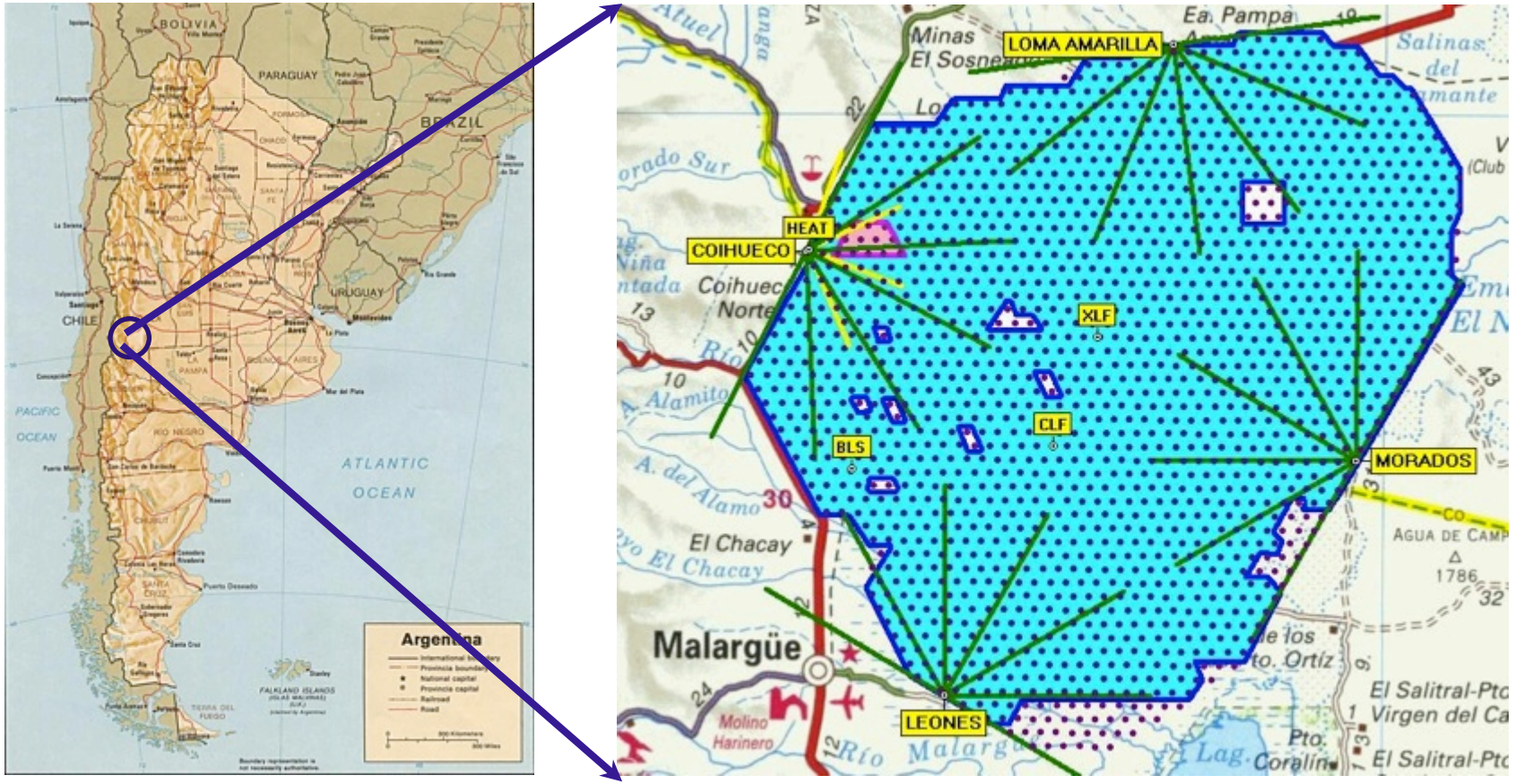
Pierre Auger Observatory

World's leading observatory for highest energy particles

Discoveries: high energy spectral cutoff from CMB interactions, anisotropy from sources, new composition puzzle

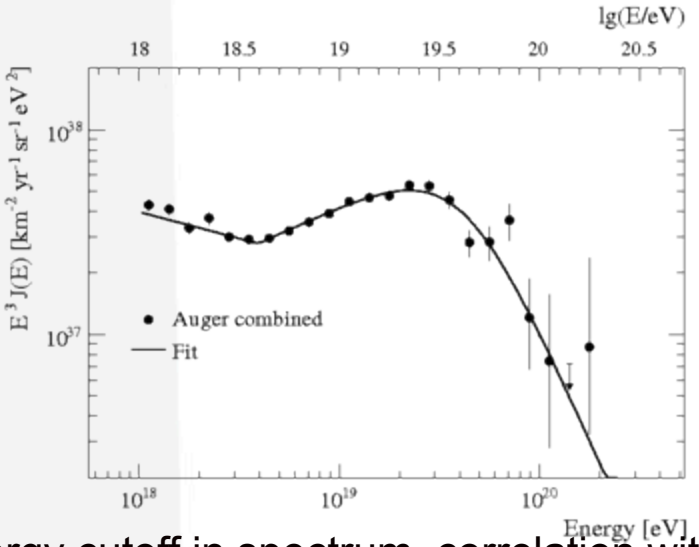


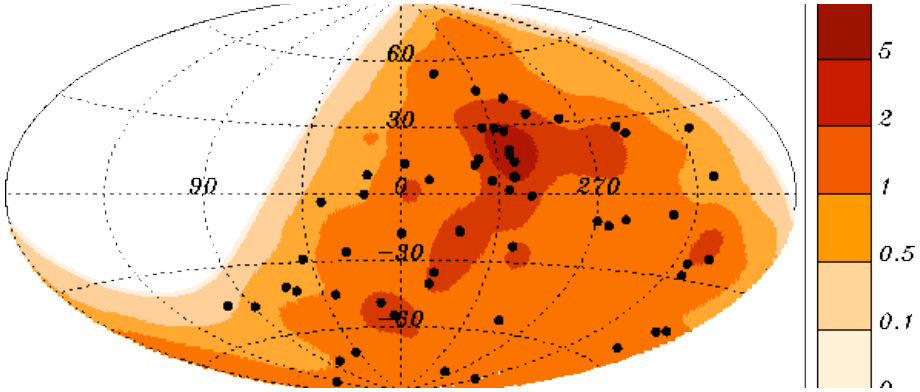
Pierre Auger Observatory Site



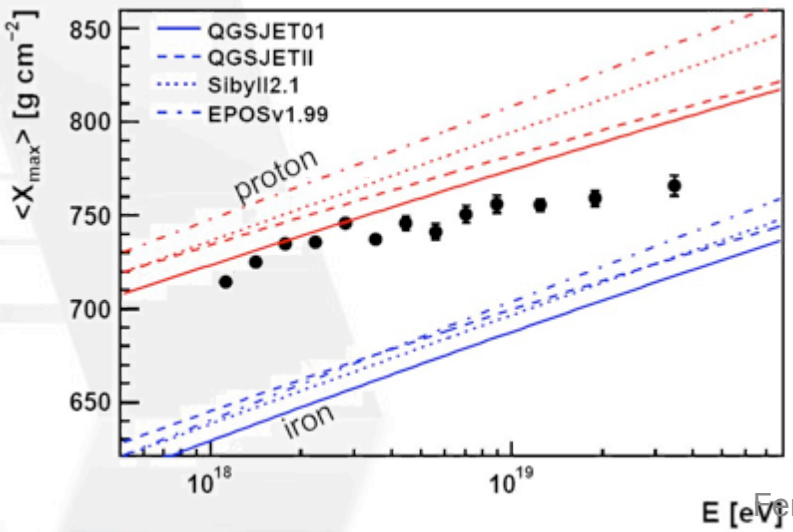
[Pierre Auger Collaboration]

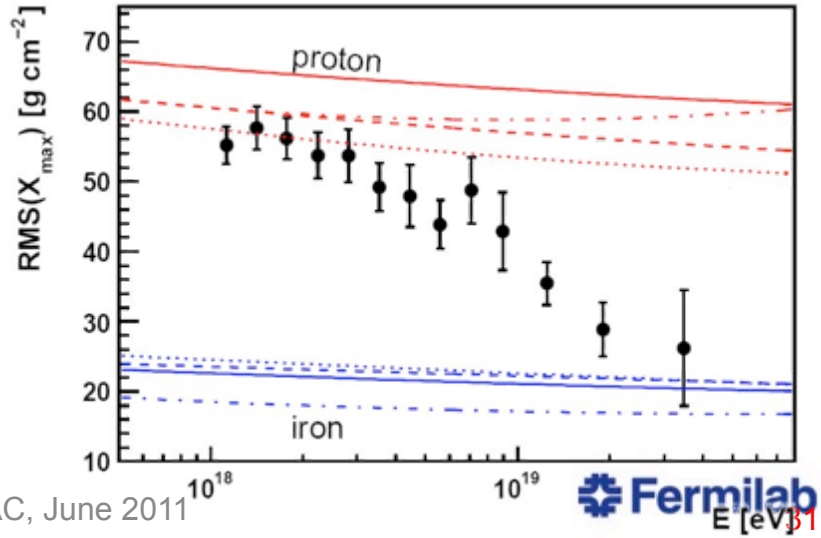
Auger results and puzzles





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.

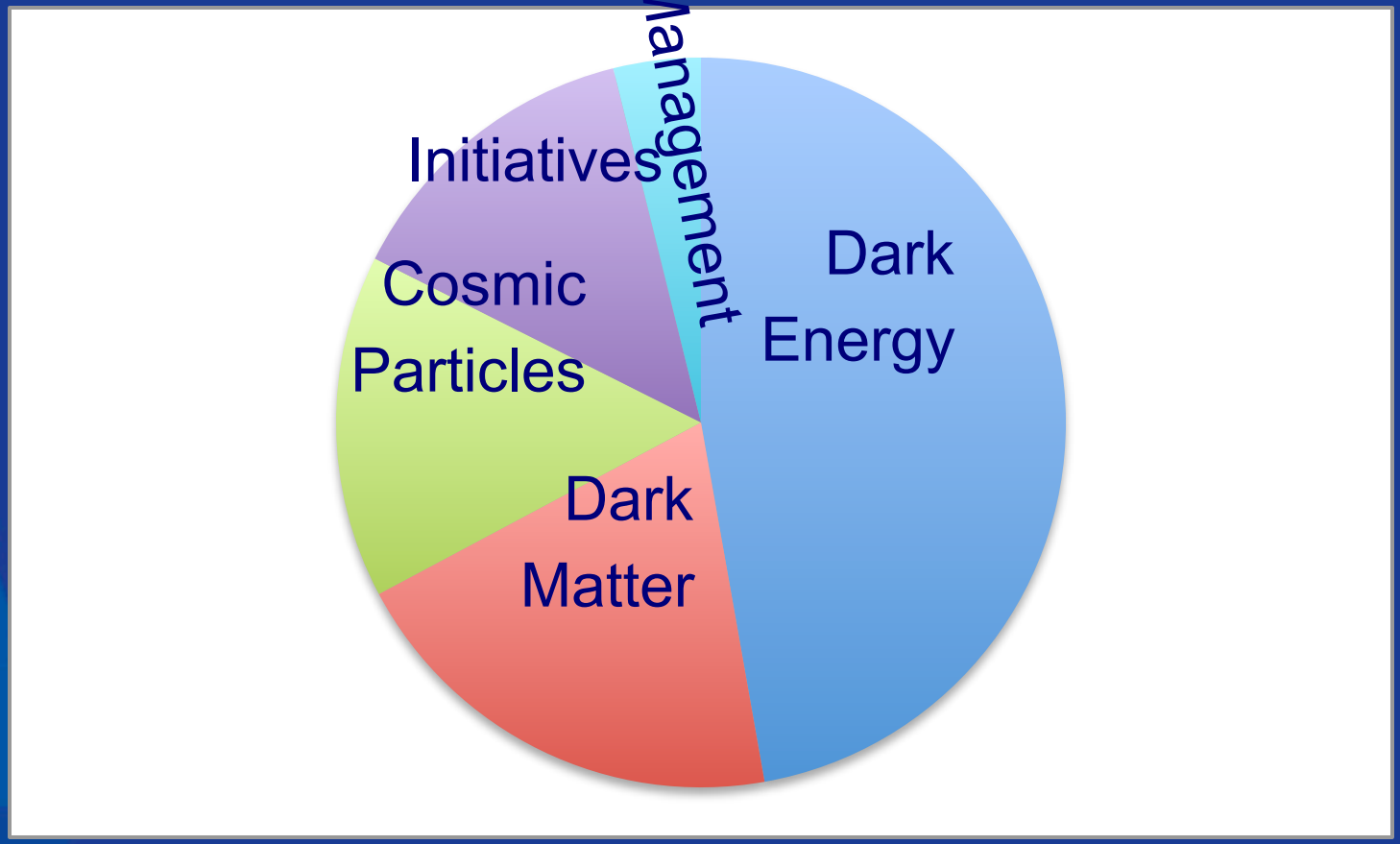




FCPA Scientific Effort – FY2011

26 Scientist FTE (from ~41 'heads') and 9 postdocs

Does not include theory (5 staff, 4 postdocs)



Program Planning

Align with DOE/HEP

- Choices based on science opportunities, community priorities, lab capabilities
- Priorities from HEPAP/P5/PASAG/Astro2010
- Size of program regulated by DOE (KA13)

KA13 Program Review (Sept. 2010)

- Overall program reviewed well
- Response to budget shortfall:
  - 21cm BAO: retire FNAL involvement
  - QUIET-II: further involvement contingent on NSF
  - PAO: scale back FTE staffing

HEPAP Particle Astrophysics Scientific Assessment Group (2009): Concise summary

"Dark matter and dark energy remain extremely high priorities."

"Dark energy funding, which receives the largest budget portion, should not significantly compromise U.S. leadership in dark matter, where a discovery could be imminent."

"Dark energy and dark matter funding together should not completely zero out other important activities in the particle astrophysics program."

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 aims to establish a multimodal WIMP program

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

Fermilab will participate in QUIET-II if it is funded by NSF

"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."

Fermilab is concentrating on Pierre Auger South

Future Program

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

This core program extends for the next ~5 years

Future projects within core thrusts:

Planning and R&D for Dark Energy after DES

Fermilab will participate in LSST, R&D on spectroscopic surveys

Next Generation Dark Matter: add Liquid Argon (Darkside)

Explore multiple modalities for direct WIMP detection

Small exploratory initiatives:

Cosmic Microwave Background Polarization (QUIET-II)

Contingent on NSF funding

Planck scale spacetime measurement (Holometer)

Axion-Like Particles (REAPR)

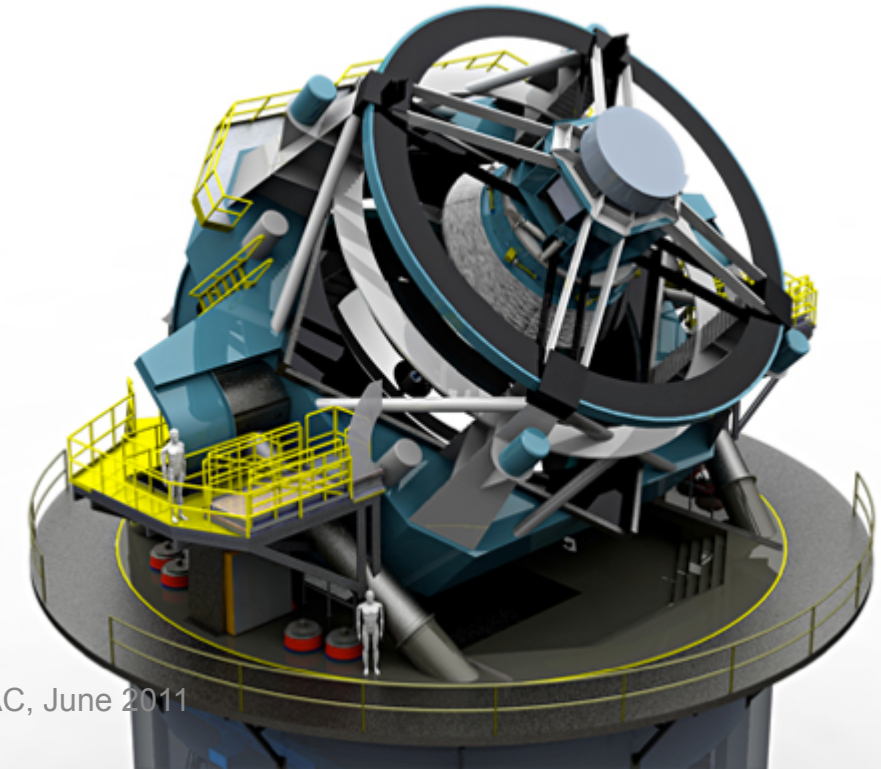
Low-cost but potentially transformative experiments

Dark Energy after DES: Large Synoptic Survey Telescope

Possible Fermilab roles in calibration, data access, database architecture, analysis, camera

Fermilab now a member of LSST Corporation (2011)

Build on SDSS & DES experience, CMS capabilities, NCSA partnership



Precision Cosmology at Fermilab: a 40 year experimental campaign

SDSS (1990- 2010)

- Advent of precision cosmology; many first measurements/ breakthroughs (ISW, BAO, SNe…)

DES (2011-2018)

- Extends reach of wide imaging to the Hubble length for the first time; factor of ~5 improvement in Dark Energy parameter measurement

LSST (2018-2030)

- Deeper, wider, longer; close to physical limits
- Faces major funding decisions in the next year

Astro 2010: LSST on top for DOE

"The top rank of LSST is a result of its capacity to address so many of the identified science goals and its advanced state of technical readiness."

"DOE is a minor partner in the two largest projects that the survey committee has recommended—LSST and WFIRST—and it is likely that the phasing will involve choices by NSF and NASA, respectively. Other considerations being equal, **the recommended priority order is to collaborate first on LSST because DOE will have a larger fractional participation in that project, and its technical contribution is thought to be relatively more critical**."

LSST is the top priority for DOE

WFIRST is the top priority for NASA

DOE no longer a partner agency in funding the mission

Medium-scale program also recommended, at lower priority for DOE

Future Dark Energy: multiplex spectroscopy

Big Boss

Collaboration led by LBNL

FNAL contributes to telescope interface

Dark Energy Camera Spectrograph (DESpec)

Upgrade to DECam after DES completion (2018): add new multi-fiber focal plane and spectrographs

Southern hemisphere followup to DES, LSST

Conceptual design and costing underway

Both greatly extend the Dark Energy sensitivity of photometric surveys

Both medium scale, not yet funded, pre-CD-0

Future Dark Matter

SuperCDMS: 100 kg at SNOLab

Aim for MIE in FY13

COUPP: 60kg, then 500kg to SNOLab

Darkside: Liquid argon; 50kg in Borexino tank, Gran Sasso

Farther future: ton-scale, but not in all techniques

Darkside at Fermilab

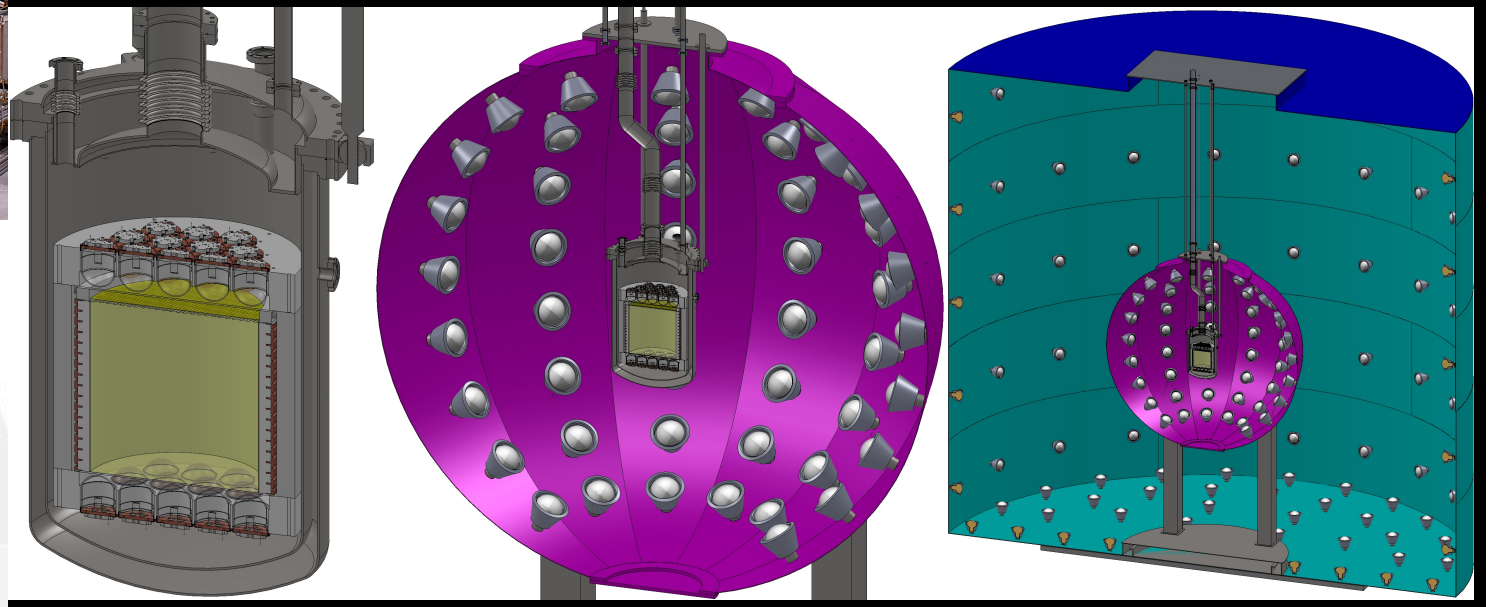
noble liquid distillation column at Fermilab

Synergy with LAr neutrino program (LBNE, MicroBoone, ArgoNeut)

DARKSIDE

DarkSide 50 at LNGS

DARKSIDE

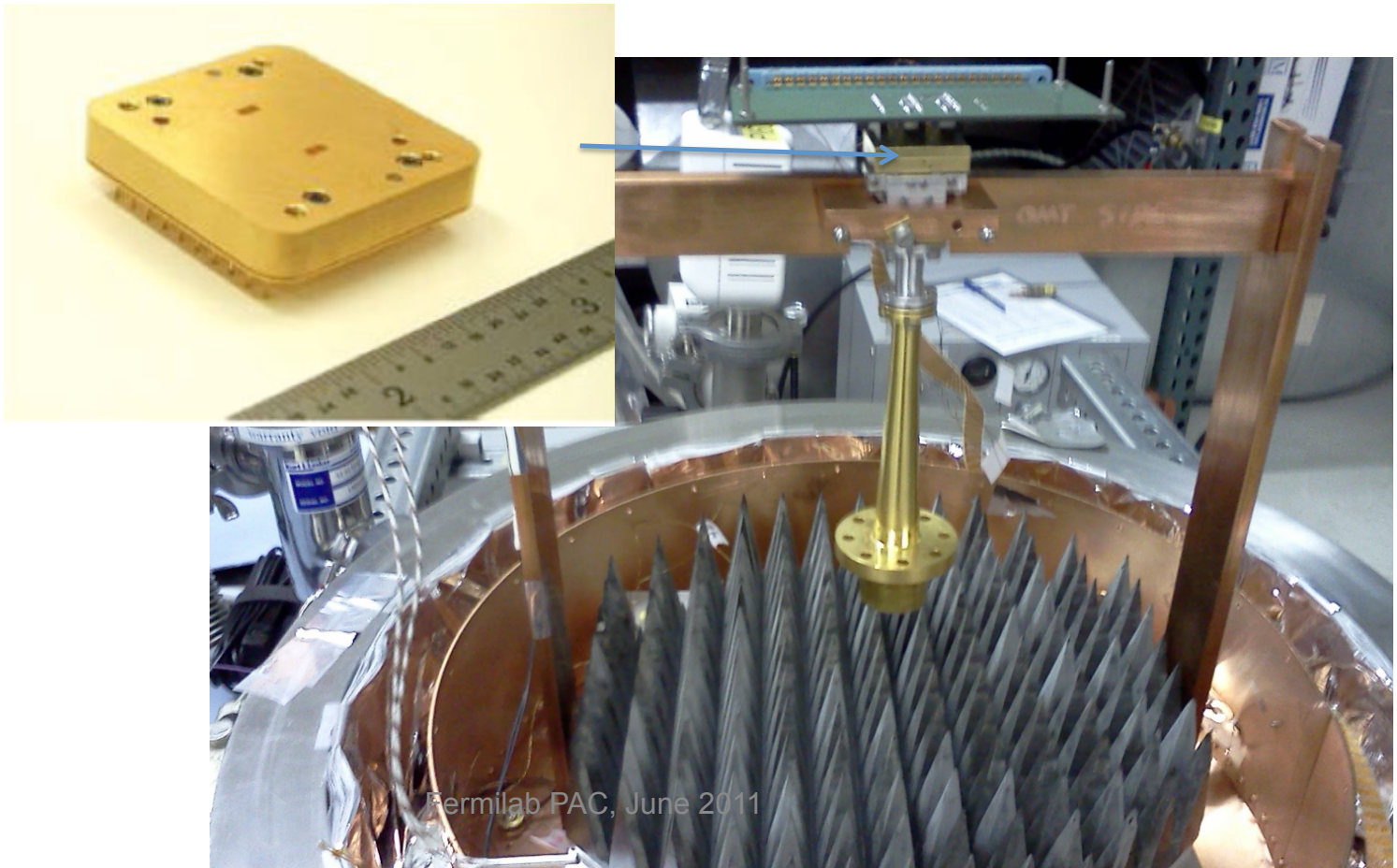


DS-50 with QUPIDs | in Scintillator Veto | in Borexino Water Tank

Quiet-II: HEMT-based CMB polarization experiment, probe of inflaton physics

Small future Fermilab effort contingent on NSF funding, collaboration plans, R&D results

QUIET 1 Module in Cryostat at Lab 3



Laboratory probes beyond the Terascale

Non-accelerator laboratory experiments can address new fundamental physics (matter, energy, space and time), far beyond the TeV scale

Fermilab program uses laser cavities and interferometers

Responsive to high-level PASAG criteria:

Addresses fundamental physics
compelling result
discovery space, possible important surprises
DOE lab leadership and critical role
small projects, high science per dollar

Recent boost: Early Career Award to Aaron Chou

Axion-like particle searches: GammeV

Mediate interactions of light with magnetic fields

Published limits at the state of the art

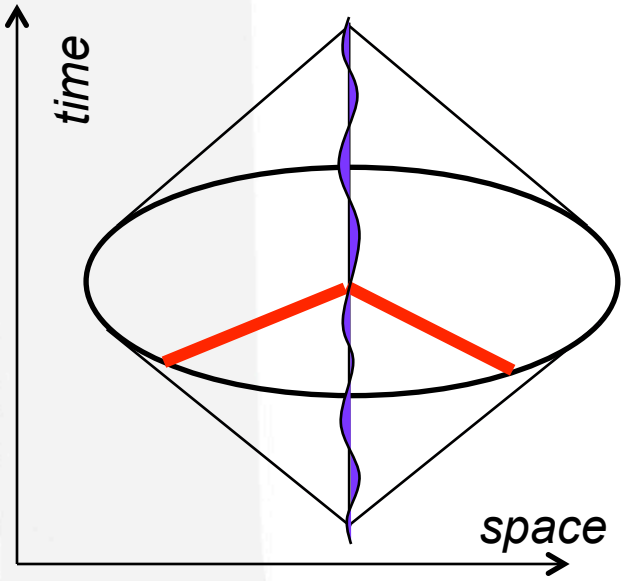
This year: CHASE, trapped chameleon afterglow

Future: laser cavities in Tevatron magnets

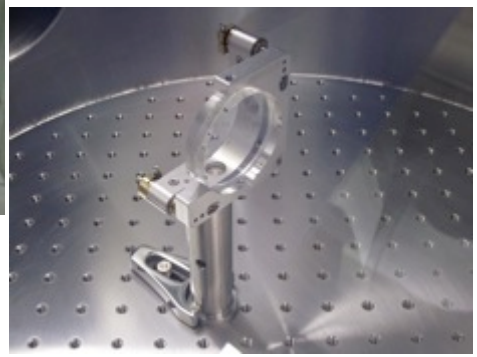
Reach to ~10^11 GeV scale in the lab

Requires development of high Q optical cavity technology

Holometer: Planck scale physics in the laboratory



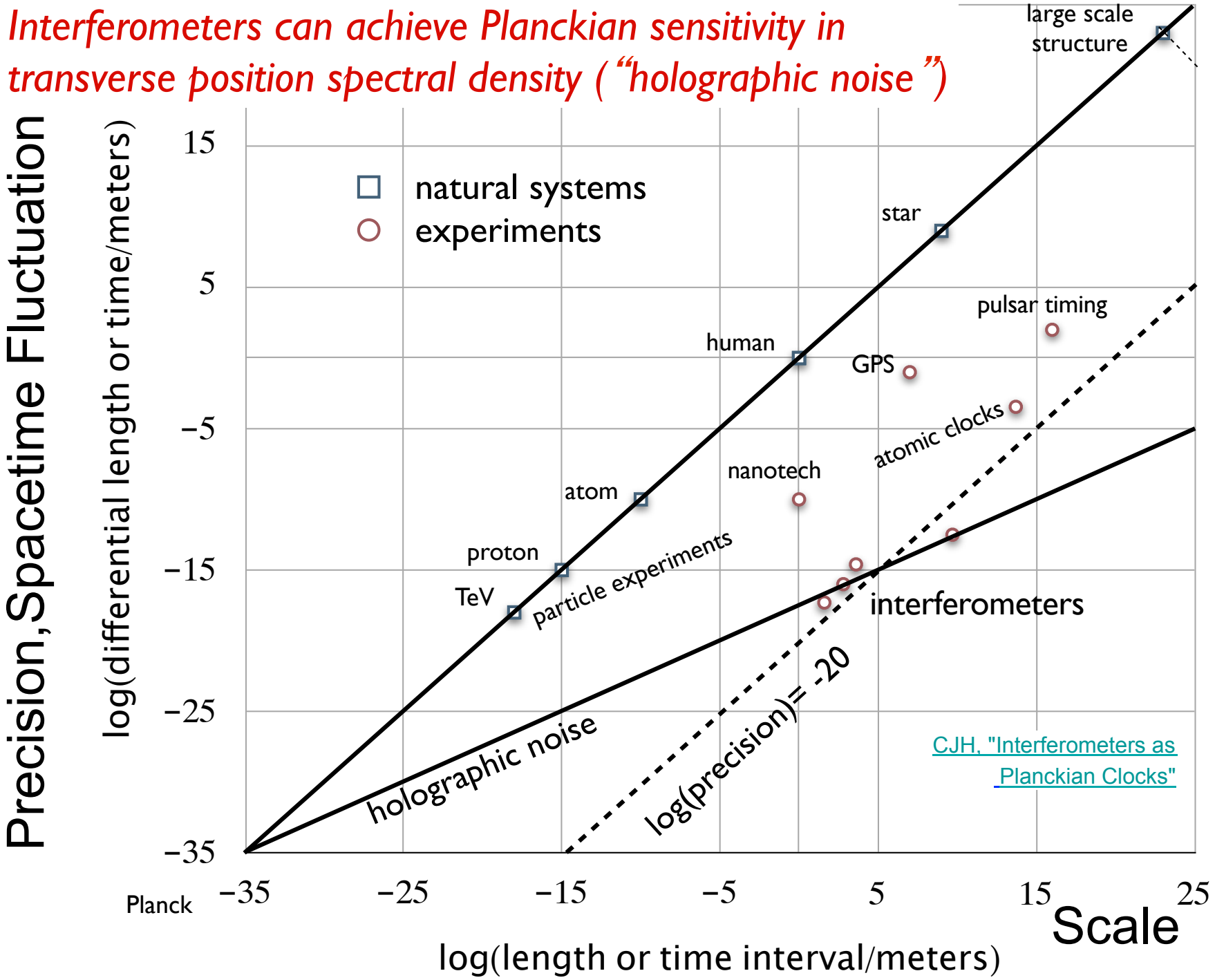
Holometer R&D cavity in Fermilab MP8 beamline



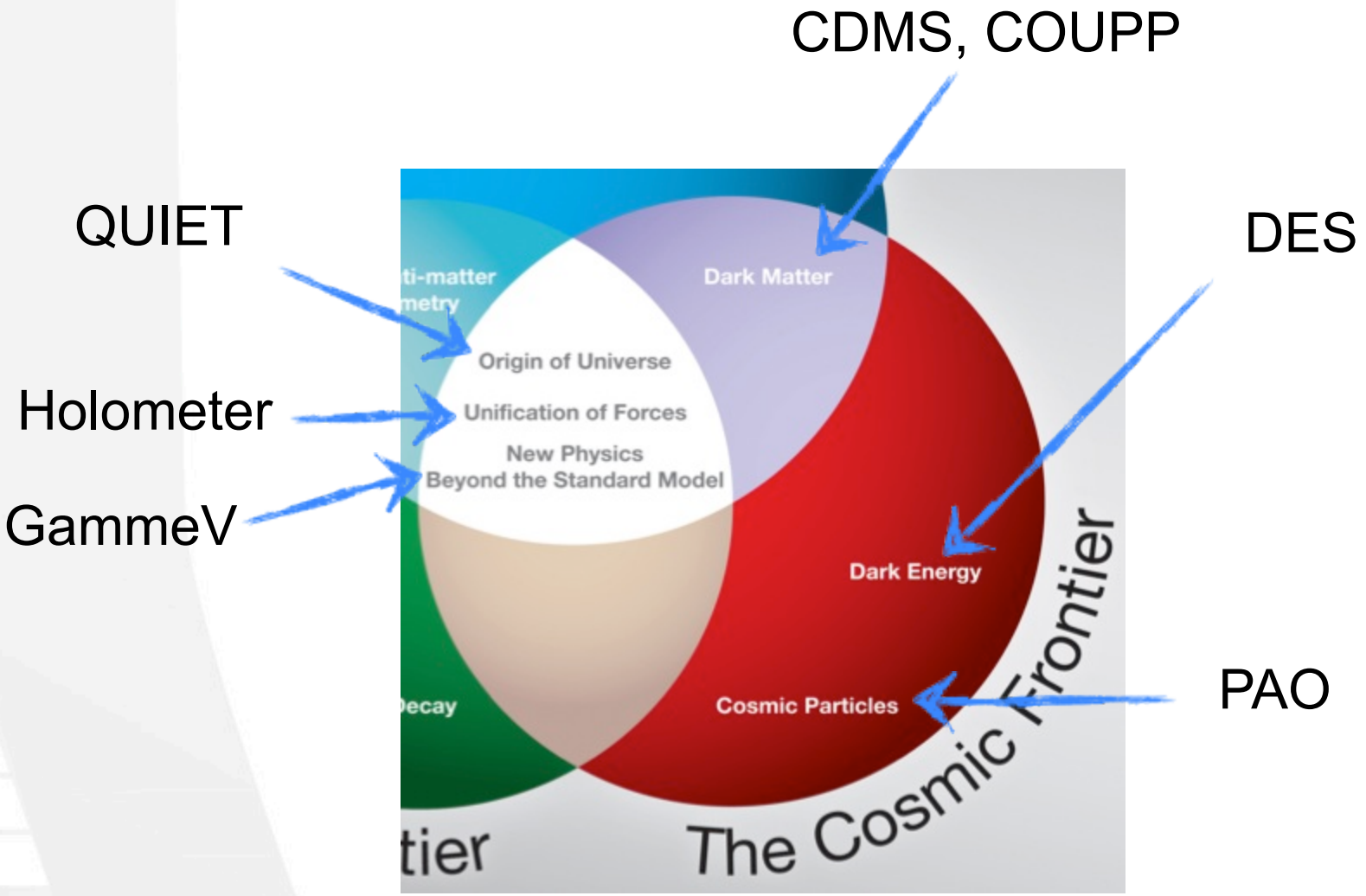
Fermilab Holometer will attain Planckian sensitivity to transverse position noise with Michelson interferometers

Probes quantum spacetime geometry

Interferometers can achieve Planckian sensitivity in transverse position spectral density ("holographic noise")



Fermilab Cosmic Frontier Experiments



Summary: Future Cosmic Frontier Experiments

- Core program extensions
  - Dark Energy: DES then LSST
  - R&D on spectroscopic surveys
  - Dark Matter: Direct WIMP Detection aligned with national program
  - Cosmic Particles: Auger South extensions
- New experiments
  - Laser interferometers and cavities probe quantum spacetime and new axion-like particles
  - Other technologies in R&D

Fermilab Cosmic Frontier Symposium

- ~160 participants, March 23-26
- See conference website for more information
- Agenda includes links to presentation slides
- See also summary by organizers
- Aimed to

"provide an opportunity for members of the particle astrophysics community to assess the long-term opportunities for advances in our understanding of the cosmos and coordinate their plans for future experiments."

The Cosmic Frontier

Dark Matter:

Pioneer era:	WIMP idea developed
Farmer era:	Candidates: SUSY, UED, …
Capitalist era:	Large direct/indirect experiments underway, LHC, …

Dark Energy:

Pioneer era:	High-z, Supernova Cosmology Project
Farmer era:	BAO, clusters, weak lensing, …
Capitalist era:	JDEM, LSST yet to start

Inflation:

Pioneer era:	Old & new inflation, theories for $\delta\rho/\rho$
Farmer era:	COBE, WMAP, Boomerang, …
Capitalist era:	Search for B-modes just starting

Dark Energy

- Currently planned projects (DES, LSST) are the right things to do
- Execution will be challenging
- Worries on systematics (esp. weak lensing)
- Familiar motivation for satellite
- Strong motivation for spectroscopic followup
- Strong motivation for related gravity and laboratory experiments
- Small followup workshop on DE laboratory options planned at FNAL in October

Dark Matter

- Multi-modal approach to WIMPs is right for now
- Too early now for downselect between technologies
- Controversy about need for DUSEL
  - SNOLab sufficient to 1 ton as is
  - More cost effective for 10 tons
  - 10 ton is the end of the line anyway
- Strong interest in axion searches
- Followup workshop at FNAL in planning stage

High Energy Particles

- Wealth of new results from FGST, ACT's (VERITAS, MAGIC, HESS), Auger, Milagro, …..
- Field set to continue on productive path, e.g. HAWC, Auger upgrades, CTA, ICECUBE
- Many new astrophysics discoveries: pulsars, particle acceleration, sources,….
- "Fundamental" physics value yet to be proven
  - Greatest success so far: atmospheric neutrinos
  - Dark Matter value depends on DM particle properties
- Sources of US funding?
  - NSF and DOE both needed
  - DOE/HEP not committed to CTA

Spacetime physics, CMB, and new experimental directions

- CMB looks to DOE lab partnerships
  - Science value, lab value added are there
  - Long-term DOE commitment is not
- Interferometry and fundamental physics
  - Holometry: Planck scale within reach
  - Gravitational waves as dark sector probe
  - Resonant cavities and magnets for axion-like particles
- “Guest speaker”: Anton Zeilinger
  - Review of fundamental quantum experiments
  - Issues of nonlocality possibly relevant to Dark Energy
- Dinner speaker: “BJ” Bjorken
  - Theme: negative impact of dismissiveness
  - Cautionary tale of Wegener and continental drift
  - Lesson for Dark Energy problem

From Joe Lykken:
1. Everything theorists tell you is wrong

- The true DM story both richer and weirder than current models
- “Dark energy” is just a placeholder, like “the ether” or “the vault of the heavens”
- “Inflation” is a dynamical process yet to be embedded in a comprehensive physical framework (who is the inflaton?)
- All theories of modified GR are physically inconsistent

2. All cosmologists are Catholics

If you believe in inflation, then you believe that there are quantum scalar fields whose vacuum energy acts as an effective cosmological constant that drives accelerated cosmic expansion

If you believe that dark energy is a cosmological constant, then you believe that the vacuum energy of quantum fields does not drive cosmic expansion, and that something else (as yet unidentified) does

When you don't have a coherent theoretical framework that relates different phenomena that ought to be related, you are lost

3. String theory will not rescue theoretical cosmology

- String theory is not a theory, it is an algorithm to generate models that are consistent with certain physical principles and assumptions
- While it is possible to make string models that make contact with inflation and string models that make contact with particle physics at the LHC, this is not the same as connecting these
- The string landscape is not a theory of anything, nor is it derived from a theory of anything (not even strings)
- Holography is a powerful idea, but it is derived from black holes, and its explicit implementation in string theory does not seem to generalize

Some Connections

- Dark matter
- Dark energy
- Inflation
- (Atoms
- Origin of the Universe

- New particle of nature
- Energy of the vacuum or breakdown of GR
- Galaxies and LSS from quantum fluctuations
- Particle interactions in the Early Universe)
- Origin of Space/time

The pieces on the table

- Dark matter
- Inflation
- Dark Energy
- Baryon asymmetry
- Eternal inflation/ multiverse
- The mix

- Standard model, gravity
- Unified gauge theory
- "Stringy ideas"*
- Holography
- Duality, extra dims
- Landscape
- Emergence

* The collection of powerful ideas formerly known as String Theory

NB: probably some missing pieces

My personal reaction to the symposium

- The particle astrophysics community is a community unified by physics culture and science goals, in spite of many different experimental approaches
- Facing deep mysteries, there is science benefit to maintaining this broad connection
- The national labs can serve this community in many ways, including symposia like this
- Thank you to PAC for suggesting it!