Cosmic Frontier at Fermilab

Overview

Craig Hogan
June 5, 2012
FCPA/KICP/ANL joint retreat

Welcome to Fermilab

Today: exploration of initiatives of Fermilab, Argonne, and the new KICP Physics Frontier Center

Fermilab Center for Particle Astrophysics

- Represents the Cosmic Frontier at Fermilab
- Coordinates with DOE and Fermilab divisions
- Workshops, retreats, initiatives, postdocs
- Visitors, seminars, strategic planning, reviews

Cosmic Frontier Science at Fermilab

- Experiments: design, build, operate, discover
- Detector R&D
- Fermilab Theoretical Astrophysics Group
  - Particle astrophysics, cosmology, simulation

Fermilab

Cosmic Frontier Experiments at Fermilab

Dark Energy

Deep, precise surveys of the universe: map history of expansion and growth of structure to understand physics of cosmic acceleration

Dark Matter

Direct detection of WIMP dark matter particles

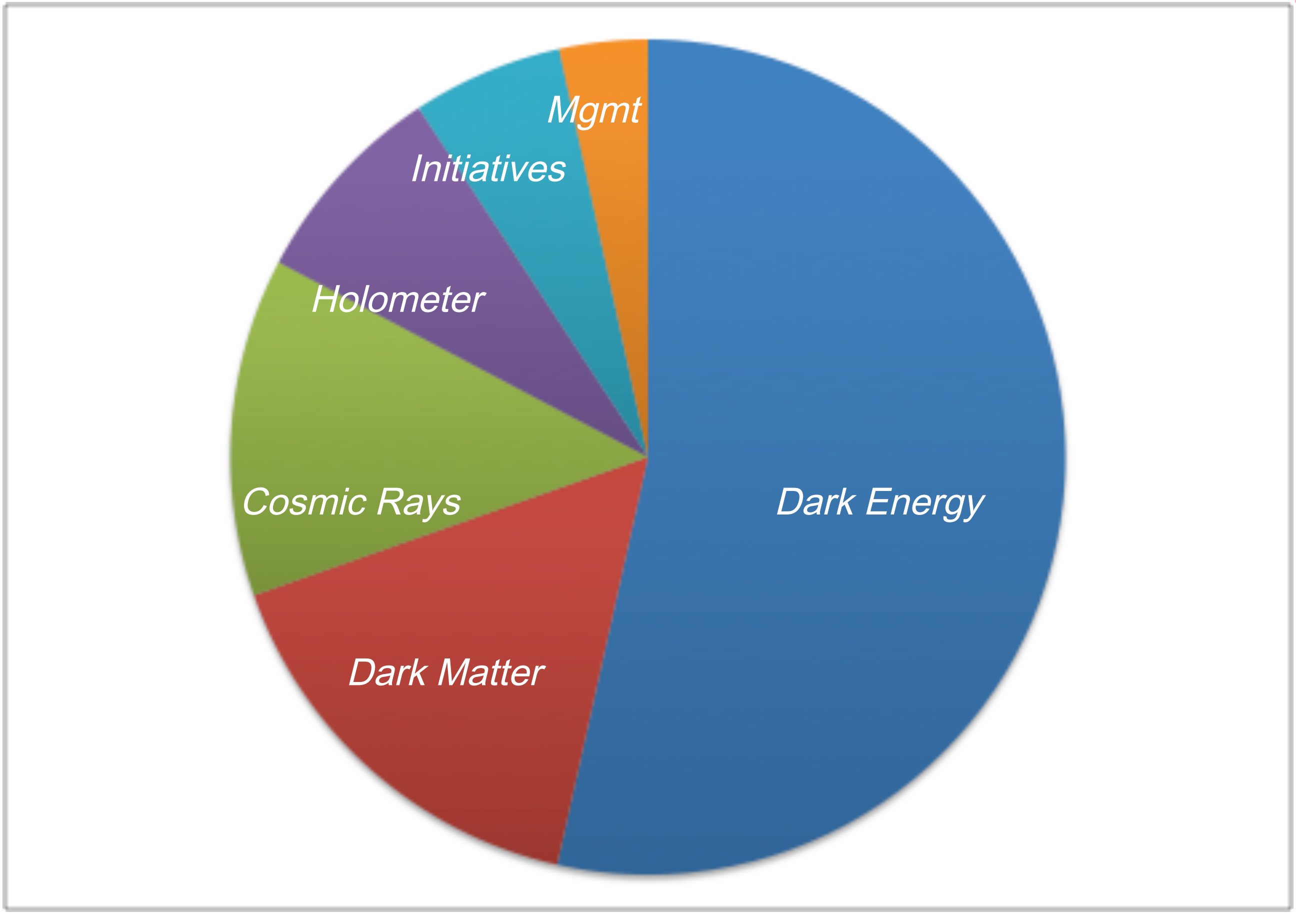
Highest Energy Cosmic Rays

Detailed study of rarest, largest cosmic ray showers

Quantum Spacetime and Unification

Measurement of Planckian position fluctuations

Cosmic Frontier Experimental Effort



42 scientists (counting 8 postdocs), 32 FTEs
Plus astro theory group (5 scientists, 4 postdocs)

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Dark Energy

Dark Energy Survey (2012-2017)

Will soon extend ultra wide, precision imaging to Hubble distance for the first time; factor ~5 improvement in Dark Energy measurements

Dark Energy Spectrometer/BigBoss (~2018-2022)

Obtain ~10^7 spectra for DES-imaged objects to improve Dark Energy measurement. At Fermilab, build on SDSS/DES

Large Synoptic Survey Telescope (2022-2032)

The ultimate in wide, fast, deep imaging. Fermilab roles in camera, data management, LSST Dark Energy Science Collaboration

Dark Energy Survey

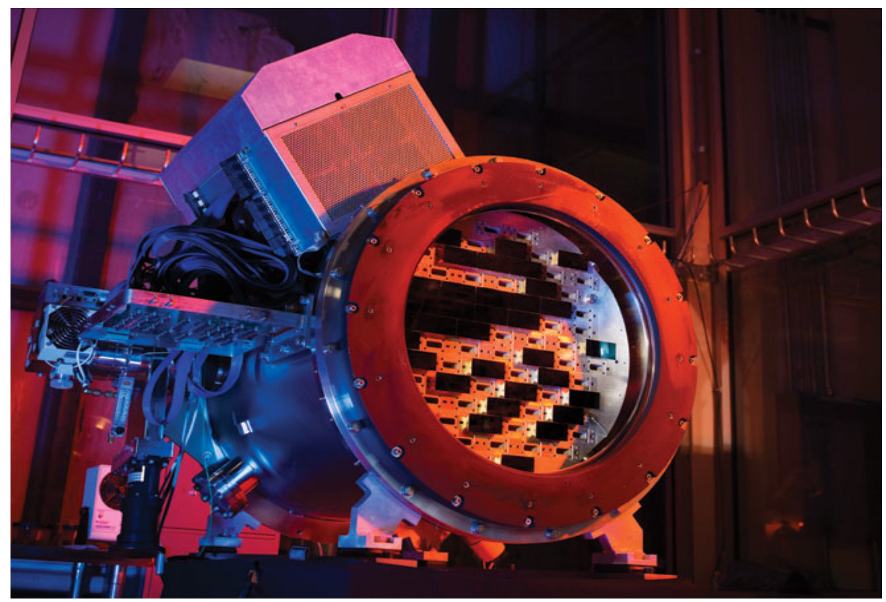
Next big step in cosmic surveys

Wide, Deep (z>1), Precise

DE Camera construction at Fermilab

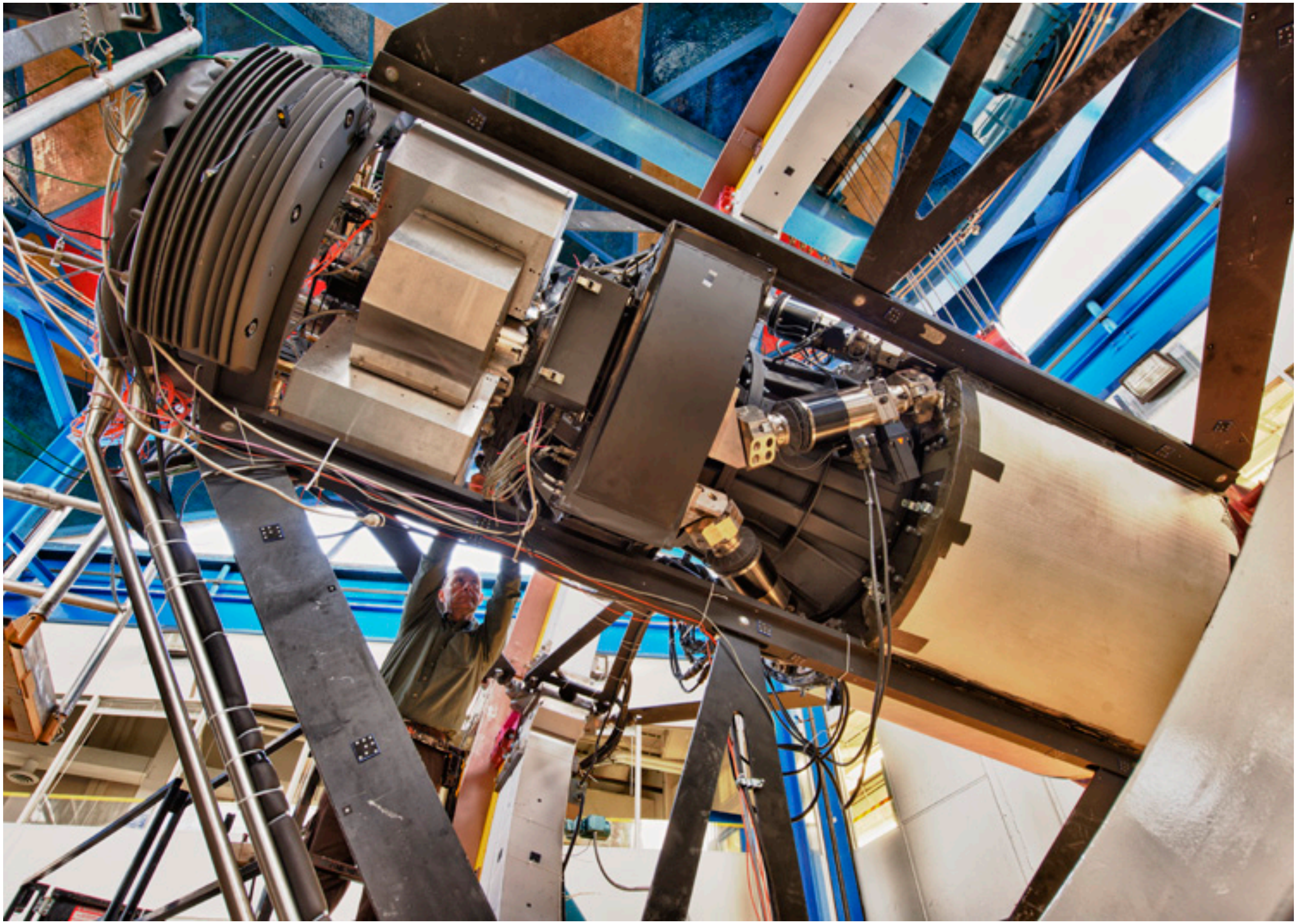
Survey starts in 2012, then runs 5 years

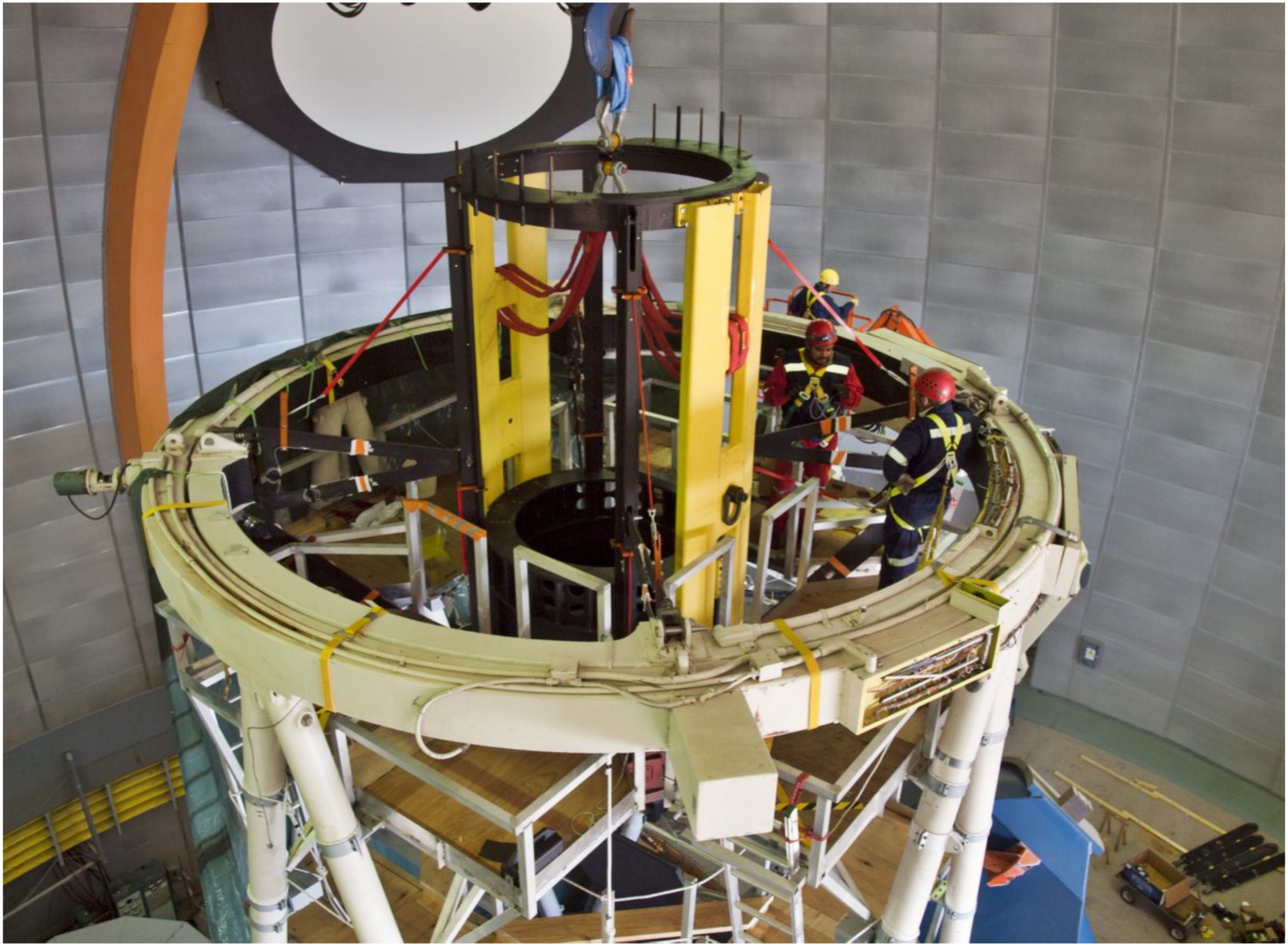
DECam under construction at Fermilab



Fermilab

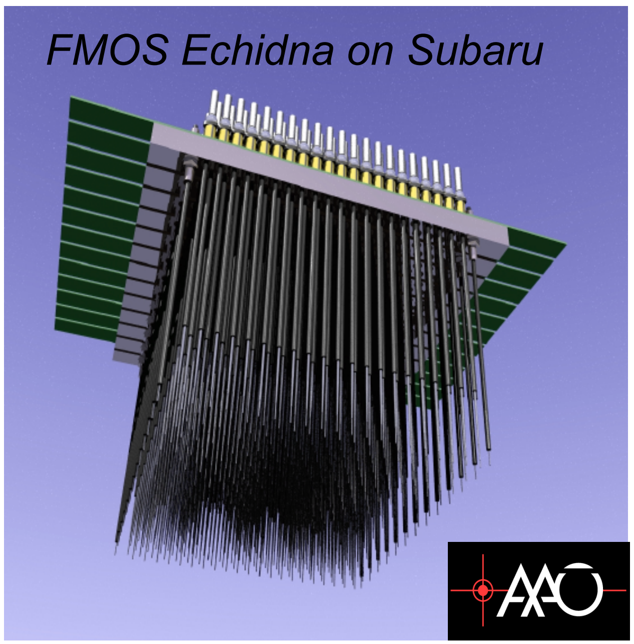
DECam at Fermilab

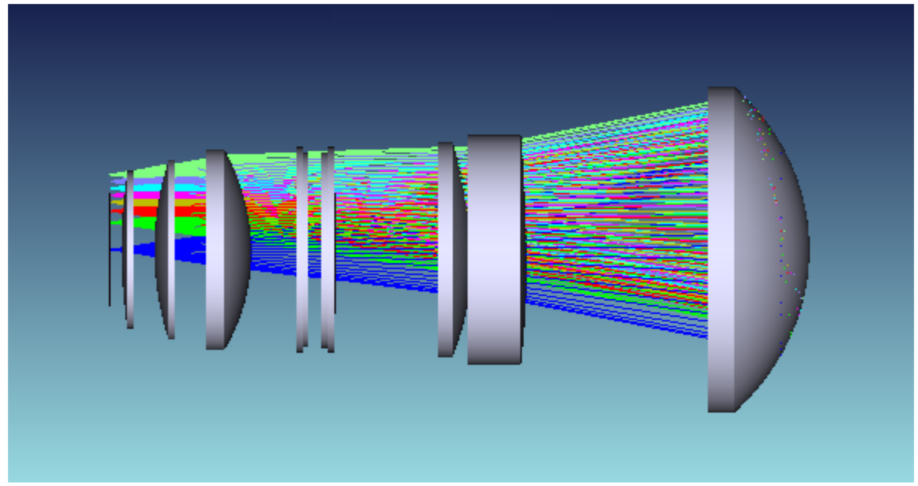


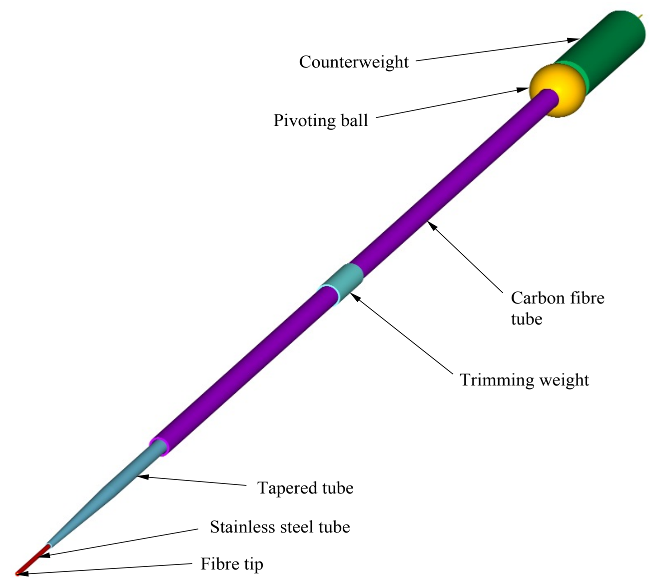


Dark Energy Spectrometer (DESpec)

DESpec concept: build a new focal plane module with robotic optical fiber positioners, for simultaneous spectroscopy of ~4000 galaxies







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

Advances require larger detector masses with zero background

Detectors now have sensitivity to expect a discovery

Mass and detailed interactions of particles are unknown; pursue multiple technologies now, downselect later

WIMP Dark Matter at Fermilab

CDMS: Cryogenic Ge detectors have demonstrated background rejection and have excellent sensitivity to low-mass WIMPs

G1: 10 kg, Soudan G2: 100 kg, SNOLAB G3: 1500 kg, ??

COUPP: Bubble chambers promise best spin-dependent WIMP discovery potential

G1: 60kg, SNOLAB G2: 500 kg, SNOLAB G3: ??, ??

Darkside: Liquid argon has best intrinsic background rejection and may be the right path towards high-mass WIMP discovery

G1: 50 kg (Gran Sasso) G2: 1000 kg, Gran Sasso G3: 10000 kg, ??

DAMIC: CCDs applied to low mass WIMP detection

Generation 2 experiments reach the middle of the theoretical range expected for "standard WIMPs"

Highest Energy Cosmic Rays – Pierre Auger

- World's leading experiment on the highest energy particles, fully operational since 2008
- Fermilab is 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? Comparison with LHC: Auger center of mass collision energies up to ~100 TeV

Pierre Auger Observatory

Observatory: installed over a 3000 km^2 site in Argentina – data taking started in 2004
24 fluorescence telescopes;
1600 surface Cherenkov detectors;
Enhancements: 3 high elevation fluorescence telescopes, 60 infill detectors, muon counter array.

Collaboration & Partnership: Large international collaboration of 19 institutions, 463 people. Fermilab hosts the Project Office.

Quantum spacetime and unification

Laboratory experiments address new fundamental physics (matter, energy, space and time), far beyond the TeV scale

Fermilab Holometer will probe Planck-scale noncommutative quantum geometry

Dual, correlated 40-meter Michelson interterferometers now under construction, first results expected next year

Future experiments may explore new interactions of axion-like particles

Fermilab E-990: Holometer

Science: Planck scale microphysics of space-time

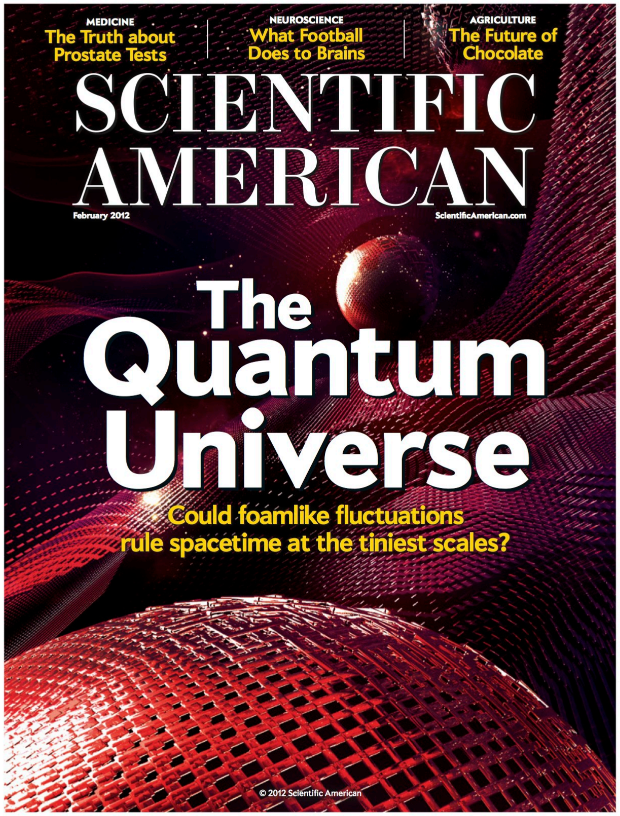
- Holographic noise motivated by black hole entropy bound
- Exotic position noise predicted to grow with propagation distance
  - → Needs large apparatus to detect

Basic experimental setup:
Two neighboring 40m Michelson interferometers measure correlated beamsplitter position jitter at 10^{-20} m/rtHz (Planckian spectral density)

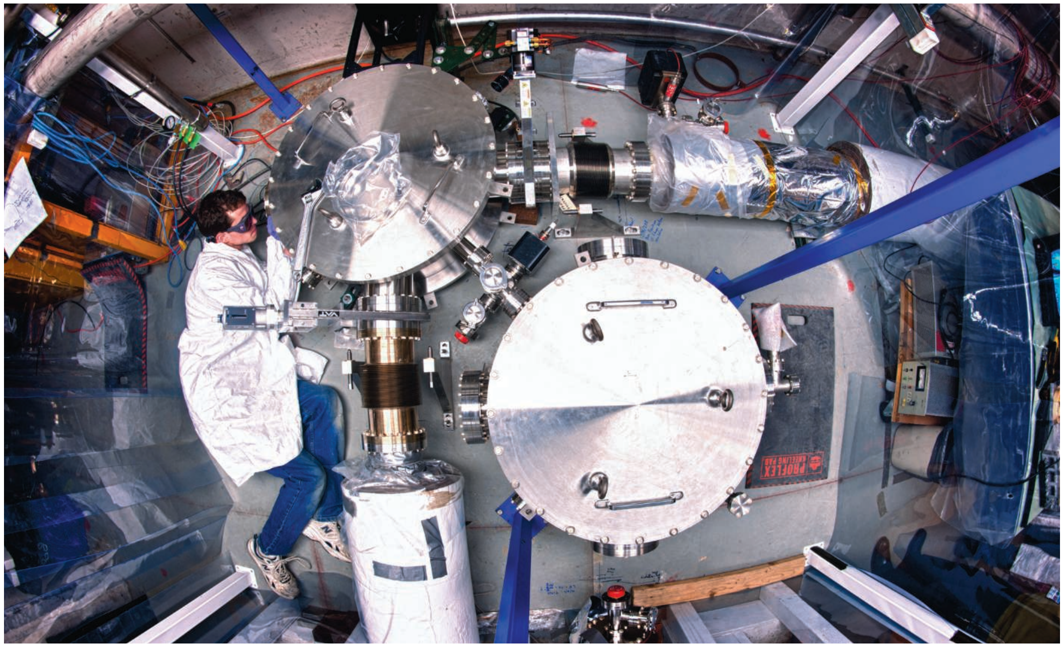
Collaboration:
20 scientists/students from 5 institutions

Funding: DOE, NASA, NSF,
A. Chou DOE Early Career Award

Status: Vacuum system complete.
First interferometer operational.
Commissioning digital control system.
Beginning RF noise-hunting.



Not a test of the holographic principle!
Drives theorists nuts!



Hands-on. Student Benjamin Brubaker tinkers with the Fermilab holometer.

PHYSICS

Sparks Fly Over Shoestring Test Of 'Holographic Principle'

A team of physicists says it can use lasers to see whether the universe stores information like a hologram. But some key theorists think the test won't fly

BATAVIA, ILLINOIS—The experiment looks like a do-it-yourself project, the scientific equivalent of rebuilding a 1983 Corvette in your garage. In a dimly lit, disused tunnel here at Fermi National Accelerator Laboratory (Fermilab), a small team of physicists is constructing an optical instrument that looks like water pipes bolted to the floor.

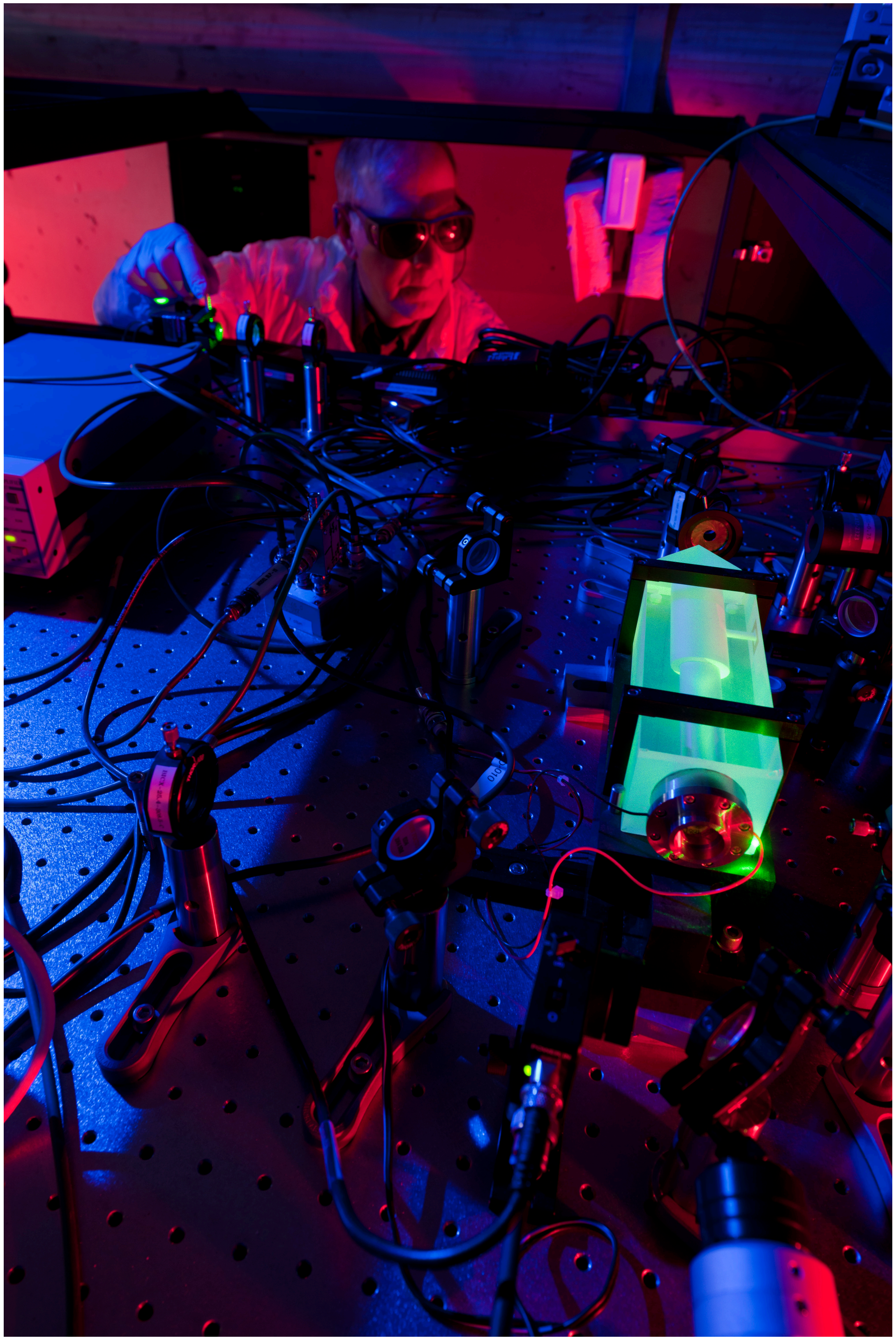
in a room increases with the room's volume, not the area of its walls. If the holographic principle holds, then the universe is a bit like a hologram, a two-dimensional structure that only appears to be three-dimensional. Proving that would be a big step toward formulating a quantum theory of spacetime and gravity—perhaps the single biggest chal-

Not everyone cheers the effort, however. In fact, Leonard Susskind, a theorist at Stanford University in Palo Alto, California, and co-inventor of the holographic principle, says the experiment has nothing to do with his brainchild. "The idea that this tests anything of interest is silly," he says, before refusing to elaborate and abruptly hanging up the phone. Others say they worry that the experiment will give quantum-gravity research a bad name.

Black holes and causal diamonds

To understand the holographic principle, it helps to view spacetime the way it's portrayed in Einstein's special theory of relativity. Imagine a particle coasting through space, and draw its "world line" on a graph with time on the vertical axis and position plotted horizontally (see top figure, p. 148). From the particle's viewpoint, it is always right "here," so the line is vertical. Now mark two points or events on the line. From the earlier one, imagine that light rays go out in all directions to form a cone on the graph. Nothing travels faster than light, so the interior of the "light cone" contains all of spacetime that the first event can affect.

Similarly, imagine all the light rays that can converge on the later event. They define another cone that contains all the spacetime that can influence the second event. The cones fence in a three-dimensional, diamond-

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Future of Fermilab's Cosmic Frontier

Dark Energy: precise imaging of billions of galaxies; comprehensive map of large scale cosmic web over its whole history

Dark Matter: grow detectors in scale up to ~10 tons; detect or rule out "standard WIMPs"; explore new technologies

Highest Energy Particles: follow up on anisotropy and composition; FNAL may participate in new technologies

Holometry/Axions: will continue; depends on what we find at Planckian sensitivity

Other new things: CMB possible if a suitable Fermilab/DOE role emerges

Dark Energy Survey (DES)

Science: probe dark energy using 4 methods:

- Galaxy Clusters
- Weak Lensing
- Large-scale structure including Baryon Acoustic Oscillations
- Type Ia Supernovae

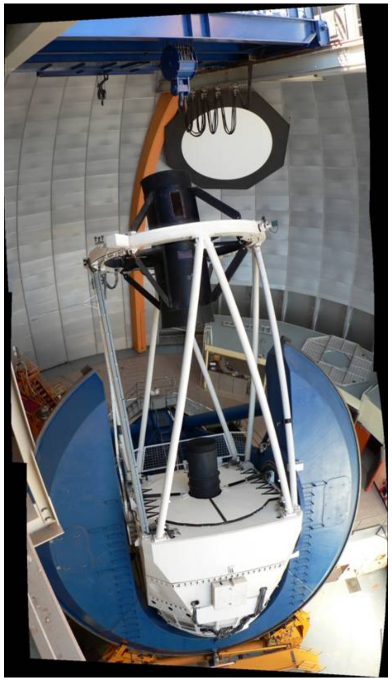
Experimental set-up:
570-Megapixel, 3 sq-deg FoV optical/NIR camera with 5-element optical corrector, to be mounted on the existing Blanco telescope at Cerro Tololo Inter-American Observatory (CTIO) in Chile

DES will measure photometric redshifts and shapes for 300 million galaxies over 5000 sq-deg and 4000 SNe Ia to redshift z~1, largest digital survey to date

Roughly an order of magnitude advance over previous imaging; "Stage III" Dark Energy experiment

Collaboration: ~200 scientists from 5 countries

Partnership: US: DOE & NSF-AST, with contributions from Spain, UK, Brazil, Germany, and participating institutions



Dark Energy Survey (DES)

Current Status:

All hardware delivered to the mountain, checked out & ready for installation

Telescope shutdown for installation started Feb. 20

Plan for future:

- First light for camera on the sky expected Aug. 2012
- DECam Commissioning Aug.-Sept. 2012
- Science Verification observations Oct. 2012
- Survey operations ~Nov. 2012-late 2017 (525 nights over 5 years)
- Initial science results 2013-2014

DECam imager at CTIO

Cleaning of DECam C1 lens at CTIO

DESpec Concept

- Multi-object prime focus spectrograph for the Blanco 4m, ***interchangeable with DECam imager***, 3.8 sq. deg. FOV
- Use DECam infrastructure (cage, barrel, hexapod, most optics, shutter, 20 spare CCDs,…): substantial cost saving
- 10 low-cost spectrographs, 4000 robotically positioned fibers
- Two 30-minute exposure critically sample all linear cosmic structure to z~1.5
- Redshifts for ~7 million DES galaxies (in ~270 nights), ~20 million from DES+LSST (~800 nights)
- Enhance Dark Energy science reach of DES by factor ~several, especially testing DE vs. modified gravity: Stage IV DETF
- Enhance DE science reach of Stage IV LSST
- Uniquely synergize with DES and LSST: power of third dimension, `same sky’
- White paper with science case and conceptual design in final draft; workshop at KICP, May 30-31

CDMS – Cryogenic Dark Matter Search

Science: Direct Detection of Weakly Interacting Massive Particles (WIMPs) that may make up Dark Matter

- ‘Conventional’ WIMP candidates (MSSM, Kaluza-Klein)
- ‘Dark sector’ particles (low-mass WIMPs)
- Axions from the sun and/or the galaxy
- Lightly-ionizing particles

Basic experimental setup: Ge crystals with charge and phonon sensors, operated at cryogenic temperatures, surrounded by layered shielding in a deep underground laboratory

- DOE provided the Soudan infrastructure, cryogenics, shielding and much of the detector payload

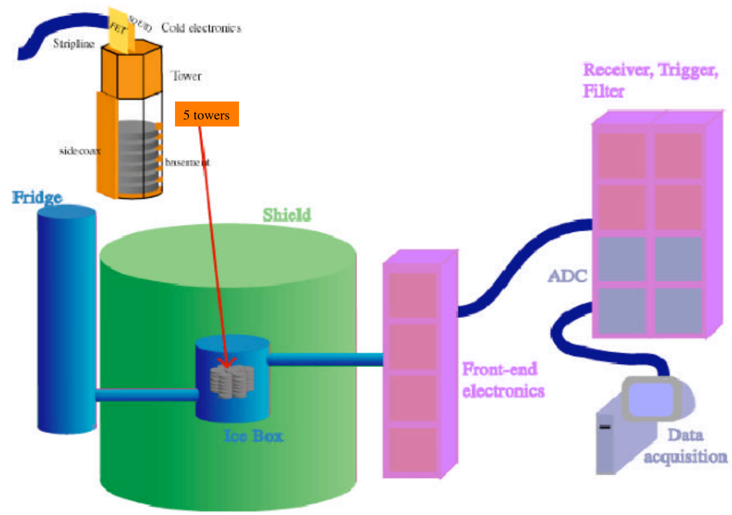
Collaboration: 80 scientists from the US and Canada

Partnership: US (DOE, NSF) with contributions from Canada

Current Status:
CDMS II operated at Soudan from 2004-2009 with 4 kg payload
SuperCDMS Soudan will operate with 10 kg 2012-2013
FNAL manages operations with DOE funding

Recent News:
New results on low-mass WIMPS and annual modulation

Plan for future:
SuperCDMS SNOLAB 100 kg will be proposed in G2 process



Schematic of the CDMS experiment

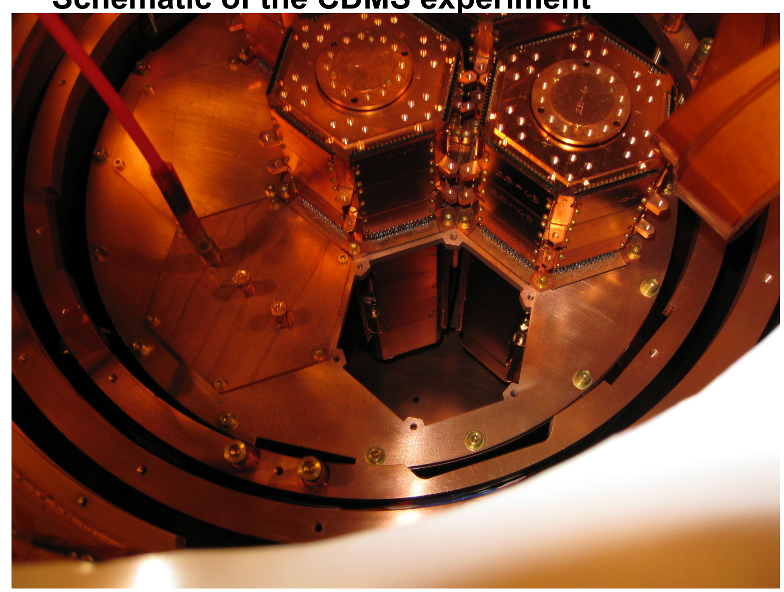


Photo showing iZIP tower installation at Soudan

CDMS – Cryogenic Dark Matter Search

Science status & recent results:

Continuing to extract interesting science from CDMS-II data, especially concerning low-mass WIMPS

2011 Highlights:

Analysis of data between trigger threshold and previous analysis threshold allowed greatly improved limits on low-mass WIMPs

Rule out DAMA/LIBRA and CoGeNT WIMP signals

Statistical analysis of CDMS rates revealed no significant annual modulation, again in conflict with purported WIMP signals from DAMA/LIBRA and CoGeNT

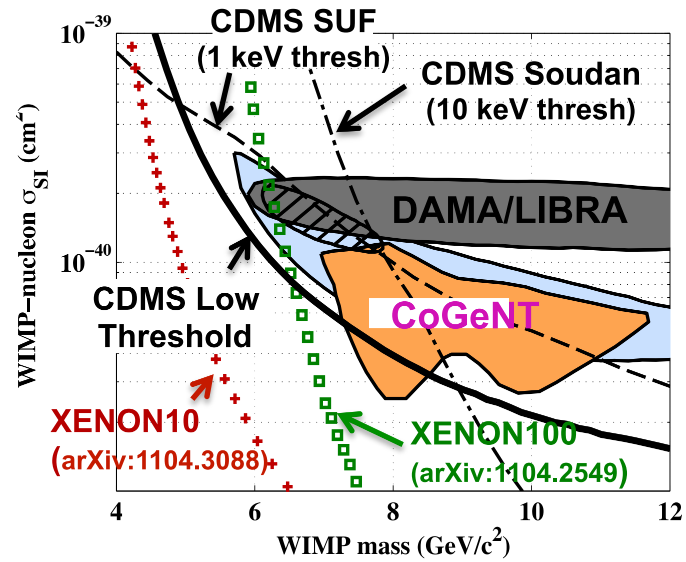
2012 Plan:

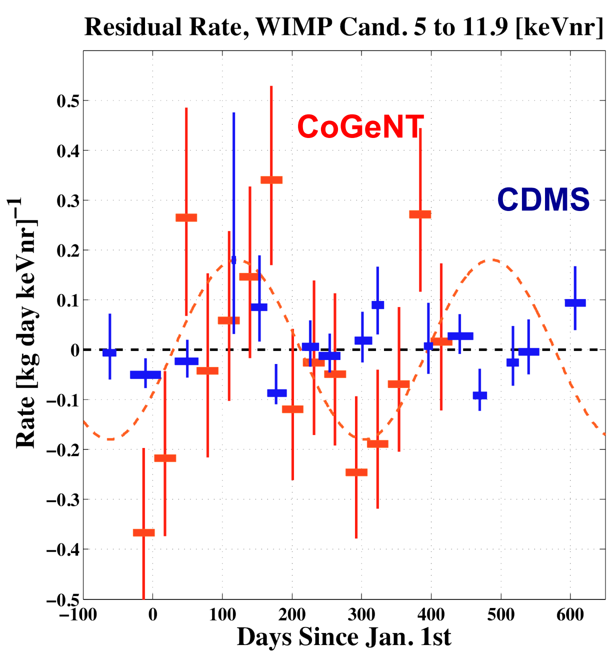
Analysis of first data from SuperCDMS Soudan to determine background rejection power of new iZIP detectors

Future Plans:

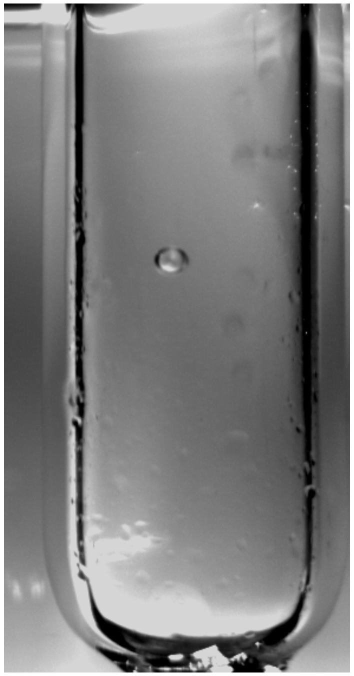
Two year data set from SuperCDMS Soudan will yield x5 improvement in WIMP sensitivity compared with CDMS II

SuperCDMS SNOLAB will provide another order of magnitude improvement in WIMP sensitivity





COUPP- Chicagoland Observatory for Underground Particle Physics



Detection of WIMP dark matter particles with bubble chambers. Thermodynamic conditions for bubble nucleation are manipulated to make chambers insensitive to gamma backgrounds.

COUPP-4kg: Currently operating deep underground at SNOLAB. First results announced in 2011.

COUPP-60kg: Installation in 2012.

Collaboration: 20 scientists from University of Chicago, Fermilab, Indiana University, SNOLAB, Virginia Tech.

Partnership: DOE, NSF, SNOLAB (Canada). DOE providing management and most construction resources.

Plan for future: Proposed COUPP-500 would increase target mass and sensitivity by an order of magnitude. R&D funded by NSF-S4.

COUPP- Chicagoland Observatory for Underground Particle Physics

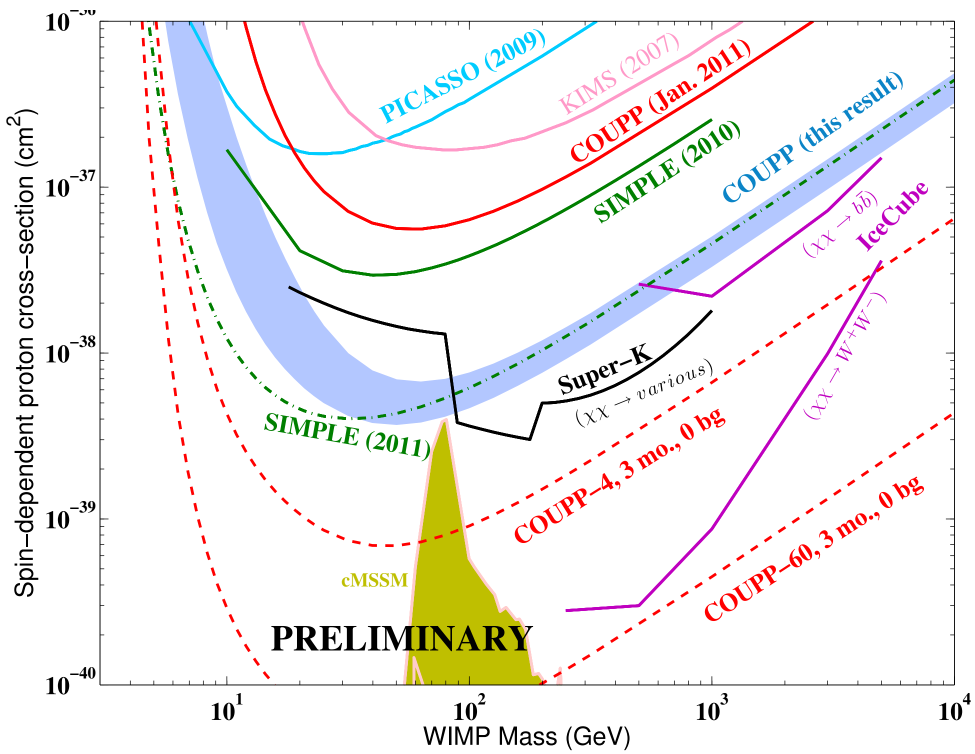
First results from COUPP-4 at SNOLAB

- In 553 kg-day exposure: 20 single-bubble nuclear recoil candidate events and 3 multiple bubble events from neutrons.
- New acoustic measurement technique rejected backgrounds due to alpha particles at >99% level.
- World's best cross section limits for spin-dependent WIMP-proton scattering above 20 GeV.

2012 plan

- Increase sensitivity of COUPP-4 by replacing neutron-emitting components.
- Improved calibrations to reduce efficiency uncertainties.
- COUPP-60 to begin operation at SNOLab.

Spin-dependent WIMP Limits



DarkSide-50 (FNAL E-1000)

Science Search for Dark Matter in the form of Weakly Interacting Massive Particles

Experiment setup:

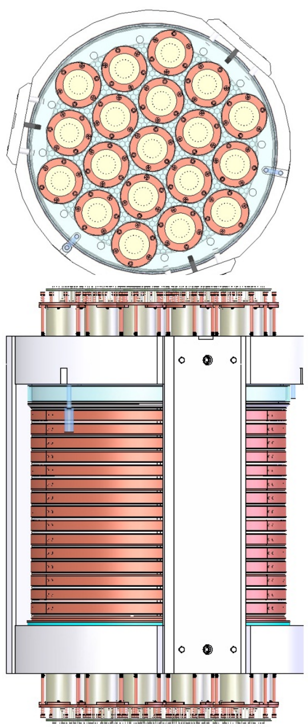
50 kg low radioactivity liquid Argon dual-phase TPC (left below) inside a 4m spherical Neutron Scintillator Veto (left center) inside an existing 10 m high and 11 m diameter cylindrical Water Tank (right center) under a mountain (right) at the Laboratori Nazionali del Gran Sasso (LNGS), Italy. **Key features** are the use **of low radioactivity Argon, low radioactivity photosensors**, and a highly efficient **Neutron veto using boron-loaded scintillator**.

DOE funds the Argon detector, the Argon system, management, and PMTs for the Neutron Veto.

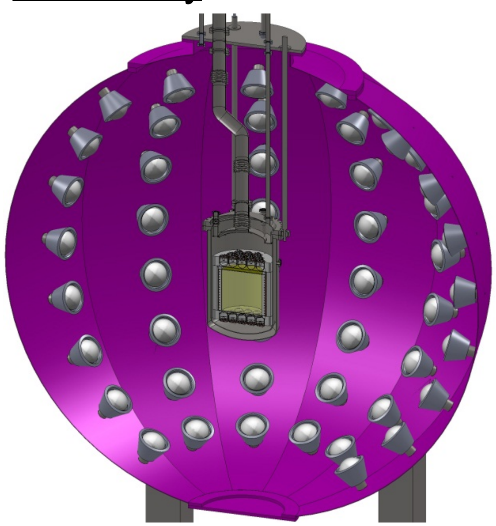
Collaboration: 60 scientists from China, Italy, Russia and the U.S.A.

Partnerships: US (DOE, NSF) with major contributions from I.N.F.N.

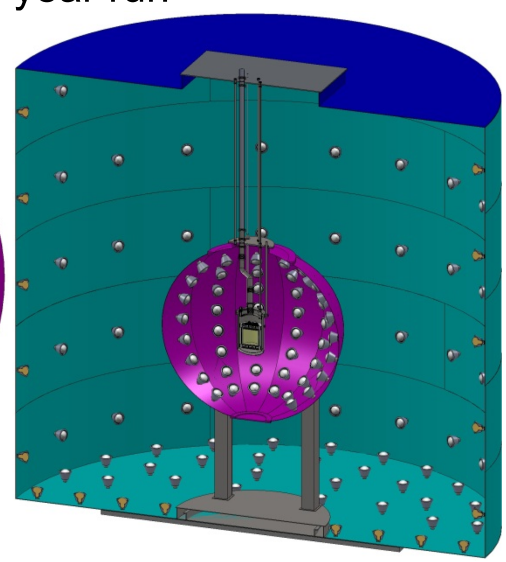
Sensitivity: 10^{-45} cm^2 in 3 year run



Dual-Phase TPC



4 m diameter Neutron Veto



10 m x 11 m Water Tank

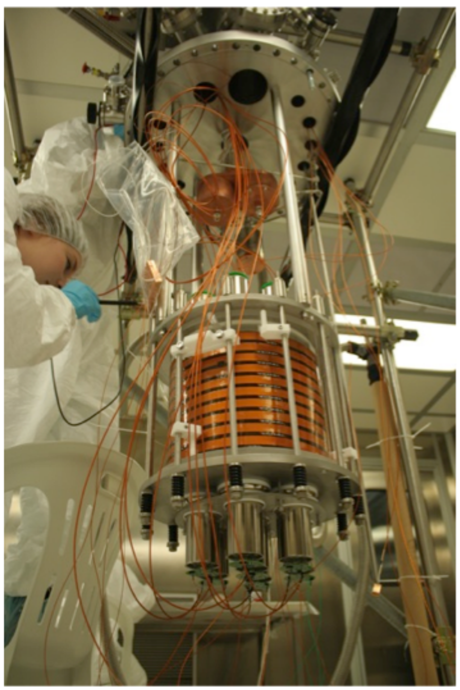
4000 m Mountain

DarkSide-50 (FNAL E-1000)

Current Status: .
Final design and construction of components ongoing in Italy and the U.S.
Prototype - DarkSide-10 - operating at L.N.G.S. since 6/2011

Purification of argon by distillation to >99.95% (At FNAL)

Schedule: Start commissioning at end of 2012.

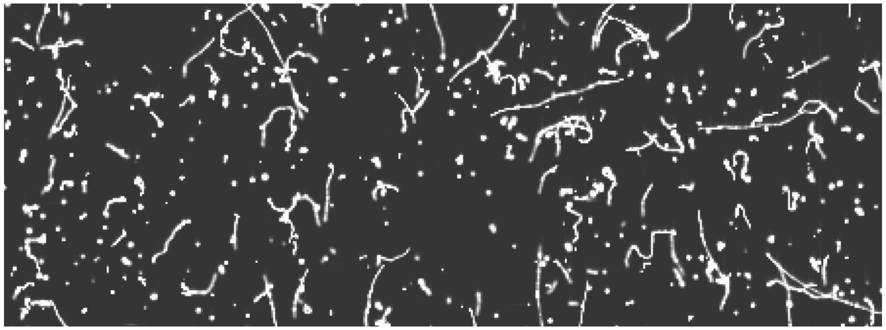


DS-10 Assembly at LNGS

DS-10 Cryostat in water shield at LNGS

Argon Purification plant at Fermilab

DAMIC: Dark Matter with CCDs



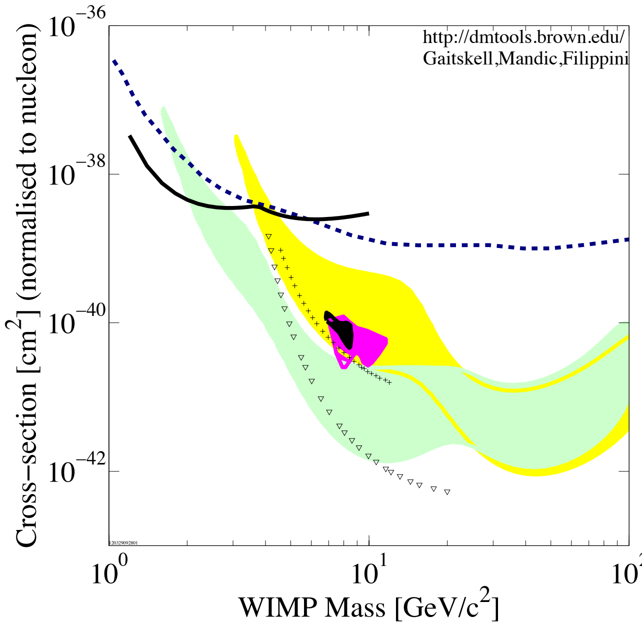


FIG. 13: Cross section upper limit at 90% C.L. for the DAMIC results (solid black) compared to CRESST 2001 (dashed blue), XENON10 [40] (triangles) and CDMS [41] (crosses). The shaded areas correspond to the 5-sigma contour consistent with the DAMA/LIBRA annual modulation signal (yellow: no ion channeling, green: ion channeling) [39]. The magenta contour corresponds to the DM interpretation of the CoGent observed excess and the black contour is the region of interest for the CoGent annual modulation signal [4].

Juan Estrada's PECASE project: use DECam CCDs as state of the art detectors for low mass WIMPs

Pierre Auger Observatory

Upcoming results and plans

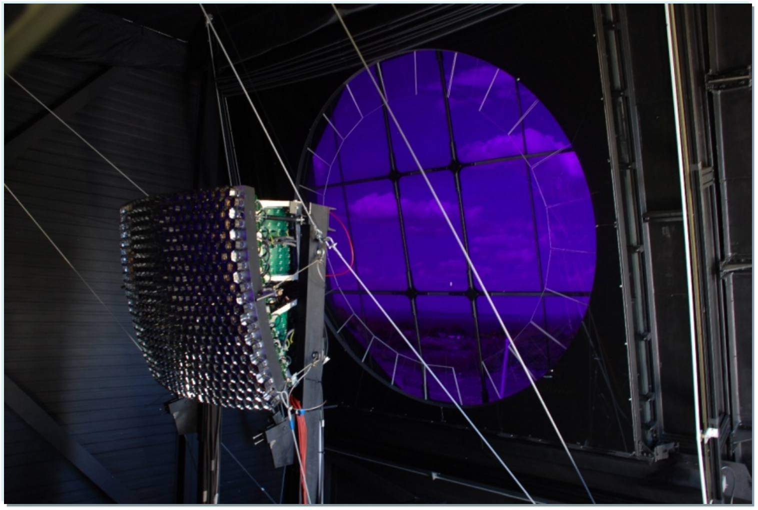
Proton-air cross section: with larger statistics, measurement at higher energy is possible.

Hadronic interaction models at high energies: data from the LHC and unexplained muon excess strongly indicates the need to revise current interaction models. This may also illuminate the composition/ anisotropy conundrum.

Composition: the apparent transition from light-to-heavy composition is being studied. Papers on SD asymmetry and muon numbers from inclined showers are in preparation.

Energy spectrum: details of the spectrum will provide constraints on models for the production and propagation of cosmic rays. Paper of the lower energy spectrum measured with the infill array is in preparation.

Photon limit: larger statistics will exclude further top-down models and start to have sensitivity to GZK photons. Paper on directional photon limits is in preparation.

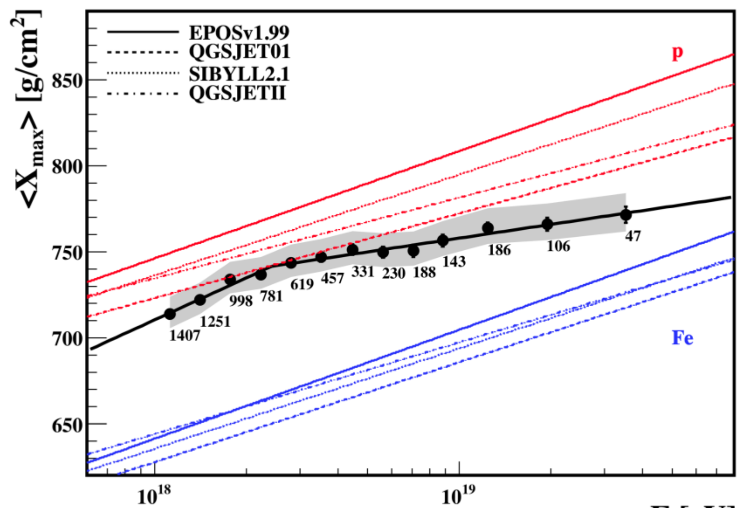


Neutrino limit: will be able to rule out some SUSY models; sensitivity to GZK neutrinos is expected by 2015. Paper on sensitivity to point-like neutrino source is in preparation.

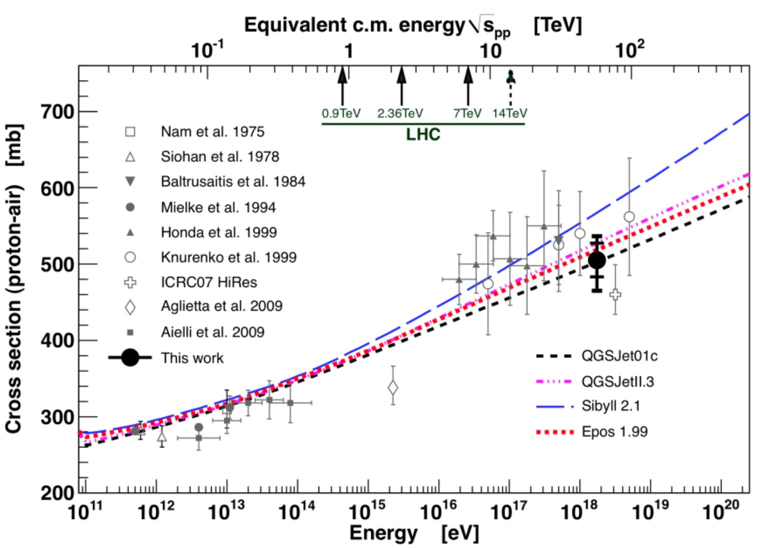
Anisotropy: search for dipole anisotropy is on-going.

Radio R&D: self-trigger of the radio array and polarization signals will be reported in forthcoming publication.

Pierre Auger Observatory
http://www.auger.org/



Composition of UHECRs show a light-to-heavy transition (2010).



Proton-air cross section measured at center-of-mass 57 TeV (2011).

Science Highlights

2007: UHECRs above 55 EeV were found to be correlated with near by Active Galactic Nuclei. AIP, Nature, Science magazine ranked as one of the top ten physics stories. The long format paper is the most cited paper in Astroparticle Physics (APP) journal.

2008: Sharp decrease in the number of cosmic rays at energies above 40 EeV. This feature is consistent with the GZK suppression.

2008: Tau-neutrino flux limit. Most stringent limit above 5 EeV.

2009: Photon search ruled out top-down scenarios, e.g. superheavy dark matter and Z-bursts, down to 1 EeV. 7th most cited paper in APP.

2010: Energy spectrum measurement is the most precise amongst UHECR experiments.

2010: Composition measurement via behavior of shower parameter Xmax suggests a light-to-heavy transition of the cosmic ray mass.

2011: Proton-air cross section measurement at center-of-mass = 57 TeV, highest energy measurement available.

Fermilab E-990: Holometer

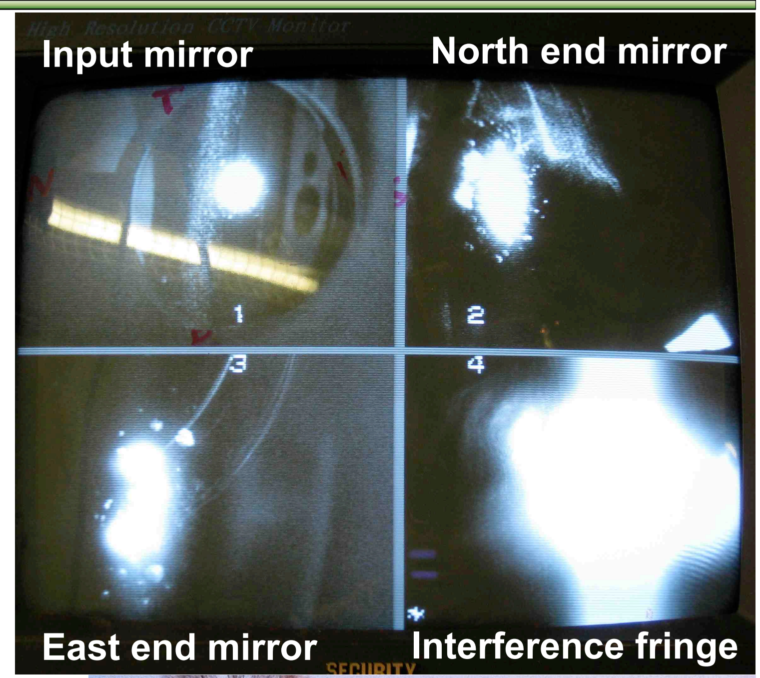
<u>Science status & recent noteworthy results:</u>

100W power-recycled interferometer demonstrated.

<u>2011-12 Highlights:</u>
June: Early Career grant funding arrives
November: Civil construction complete
December: UHV vacuum for 3 arms deployed
February: First light in interferometer

<u>2012 plan</u>
Operate two interferometers in nested configuration.
Begin a completely new and unique probe of spacetime in a never-before-tested regime.

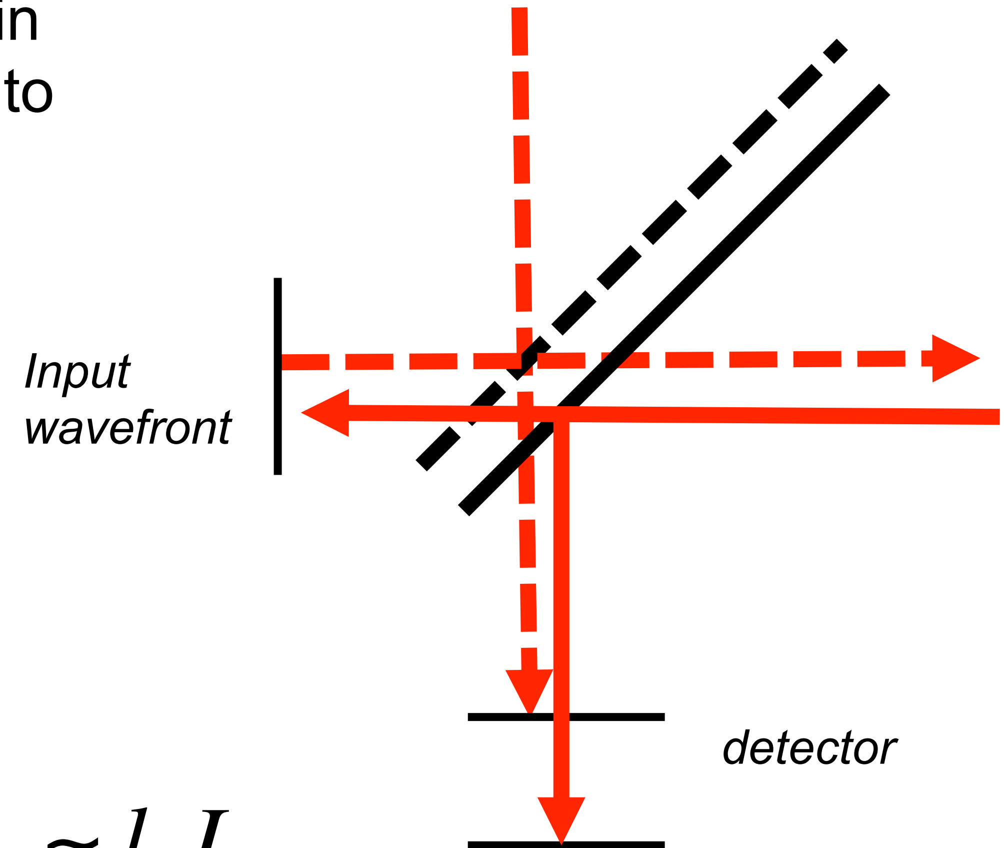
<u>In future:</u>
If non-conventional noise detected, test consistency with the holographic noise model
-- Check predicted spectral features.
-- Use back-to-back configuration to null the signal.
-- Check predicted scaling with interferometer length.



Backup Slides

Holographic noise in a Michelson interferometer

Quantum-geometric “jitter” in beamsplitter position leads to fluctuations between reflections in different directions



Range of jitter depends on arm length:

$$\Delta x_1 \Delta x_2 \approx l_P L$$

this is a new Planckian effect predicted with no parameters

Experiment Concept

Measurement of the correlated optical phase fluctuations in a pair of isolated but collocated power recycled Michelson interferometers

exploit the spatial correlation of the holographic noise

measure at high frequencies (MHz) where other correlated noise is small