The Fermilab Program for Direct Detection of Dark Matter

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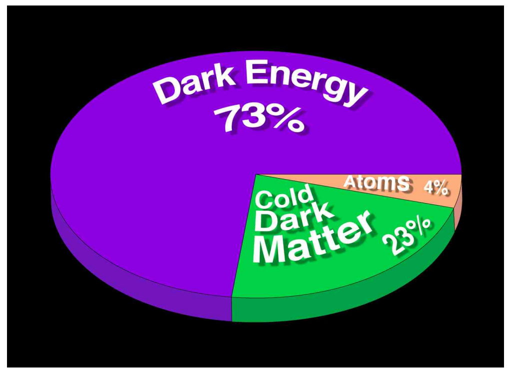
Cosmic Frontier DOE Laboratory Review
September 17, 2013

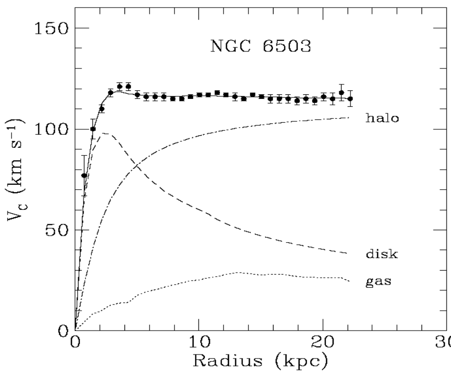
Evidence for Dark Matter

Galaxy Clusters

We know the Dark Matter is
stable / non-baryonic / non-relativistic / interacts gravitationally

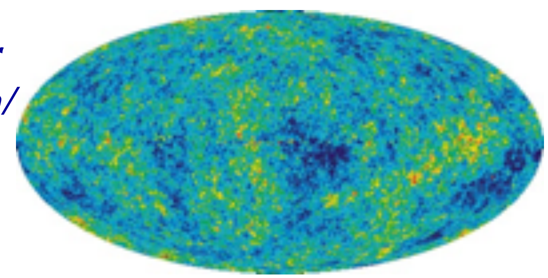


Strong Lensing



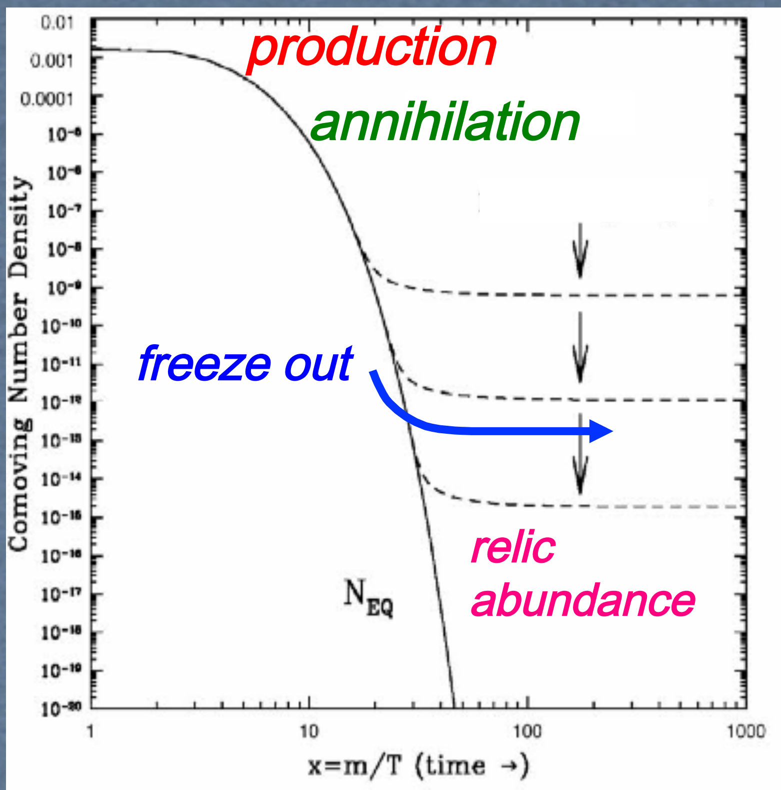
Galaxy Rotation Curves

We don't know the Dark Matter
mass / coupling / spin / composition/ distribution in our galaxy



Cosmic Microwave Background

WIMPs – The Dark Matter Connection with Particle Physics



Weakly Interacting Massive Particles (WIMPs)

- *New stable, massive particle produced thermally in the early universe*
- *~Weak-scale cross-section gives observed relic density*
- *Most theories beyond the standard model have candidates*
  - *Supersymmetry – Neutralino*
  - *Extra-Dimensions – Lightest KK*

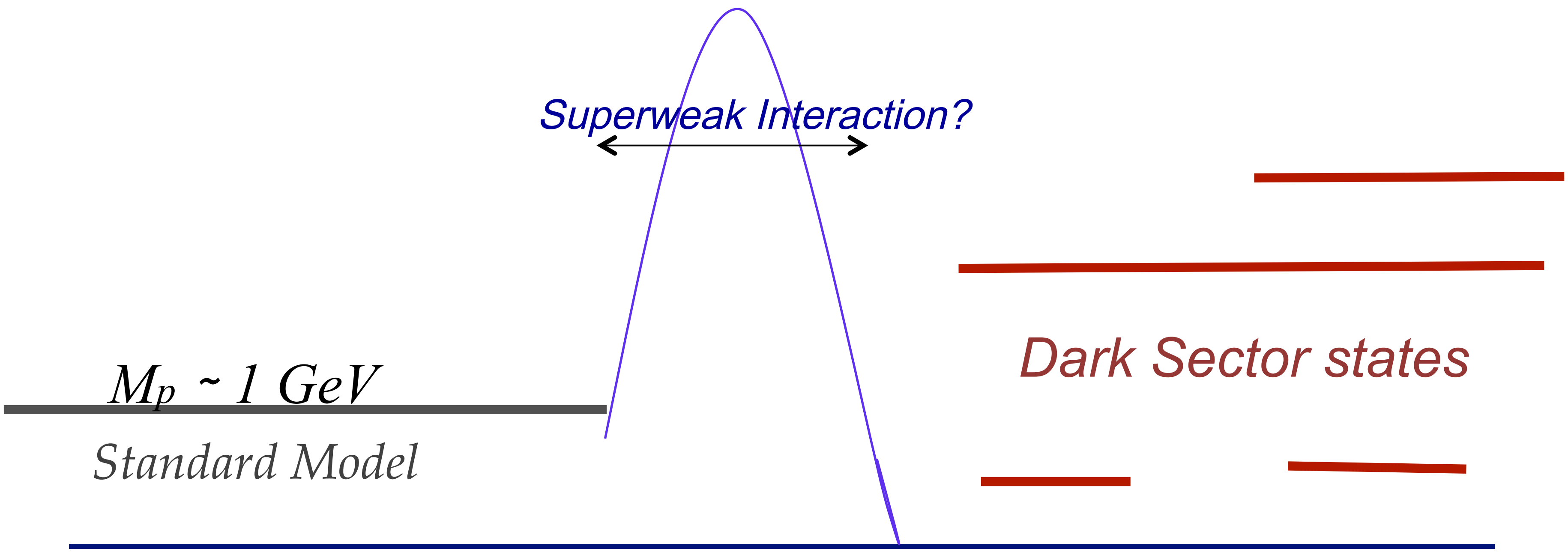
Dark Matter WIMPs

Supersymmetry provides a "natural" WIMP candidate: the neutralino

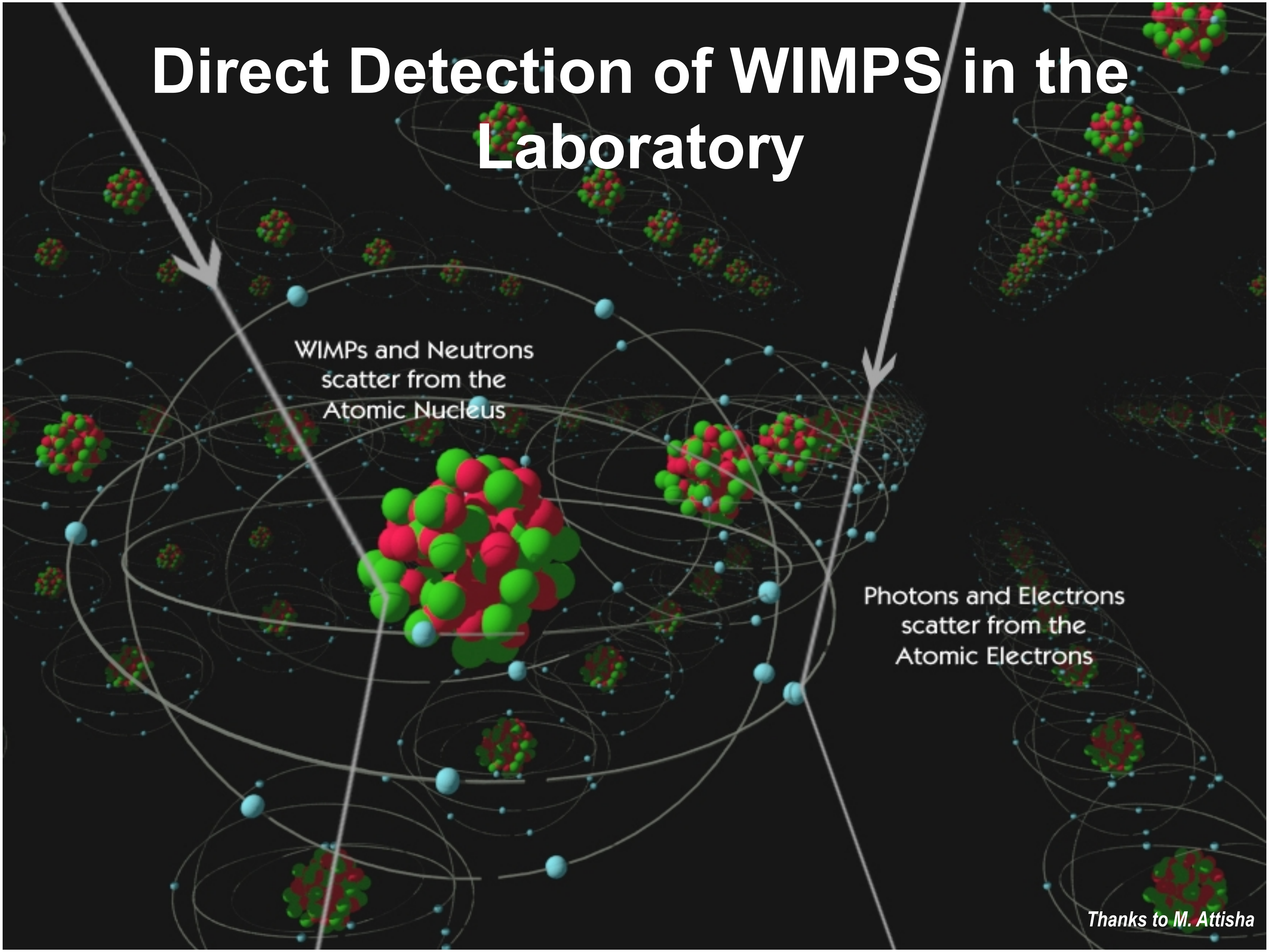
But no evidence yet for SUSY, and there are many other possibilities

Dark matter may have as complicated a particle structure as normal matter

Could be a "dark sector" of particles, with unknown couplings to normal matter



Direct Detection of WIMPS in the Laboratory

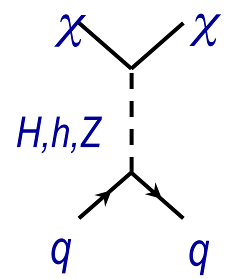


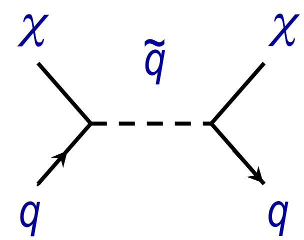
WIMP Direct Detection Basics

Detection rate $R \propto N \frac{\sigma_{\chi N}}{m_\chi} \rho_\chi \int_{v_{\min}}^{v_{esc}} \frac{f(v)dv}{v}$

Particle Physics:

WIMPs elastically scatter off nuclei in targets but we don't know the form of the interaction



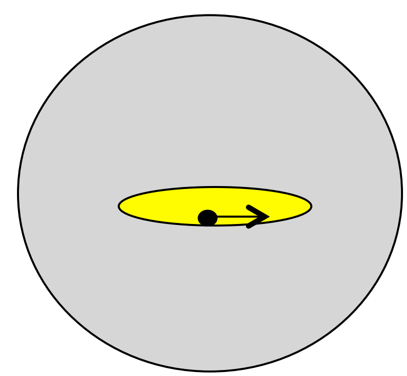


(a) Spin-independent interaction ~A^2
(large λ_{dB} ➔ coherent interaction)
(b) Spin-dependent needs target with net spin

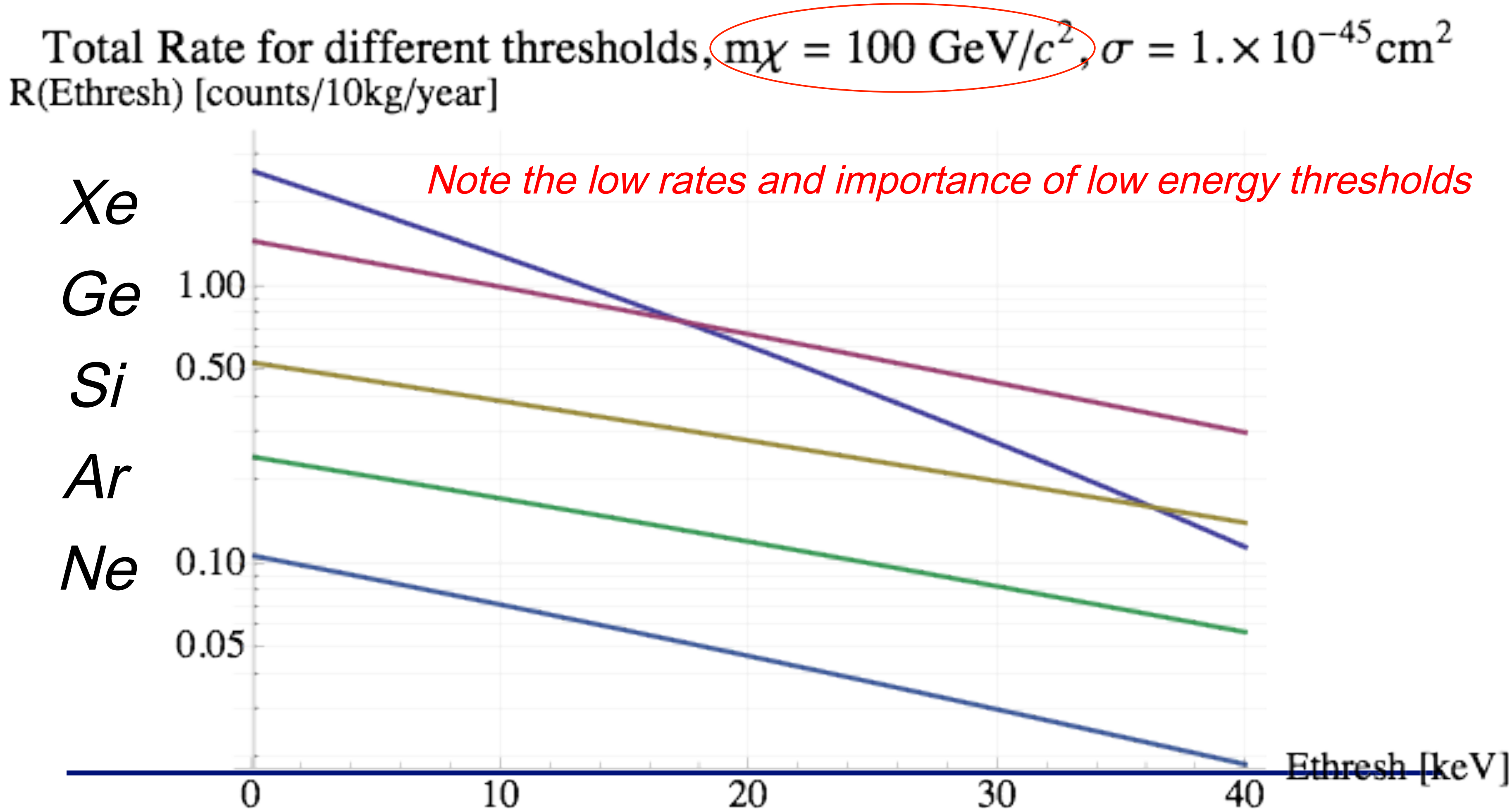
Astrophysics:

Dark matter distributed as a roughly spherical halo surrounding the visible galaxy

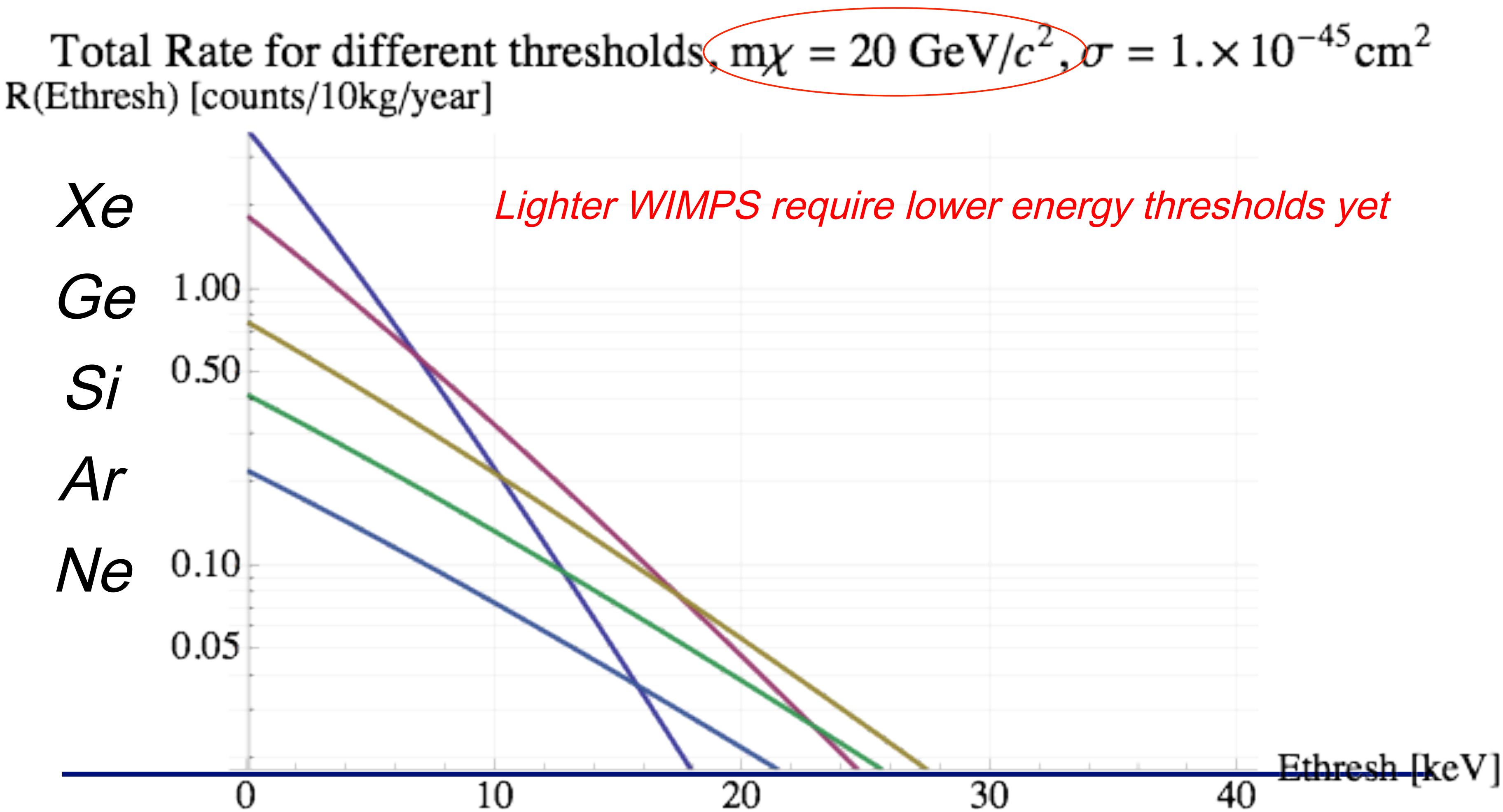
Assume isothermal, with WIMP velocities in the lab determined by motion of solar system through this halo



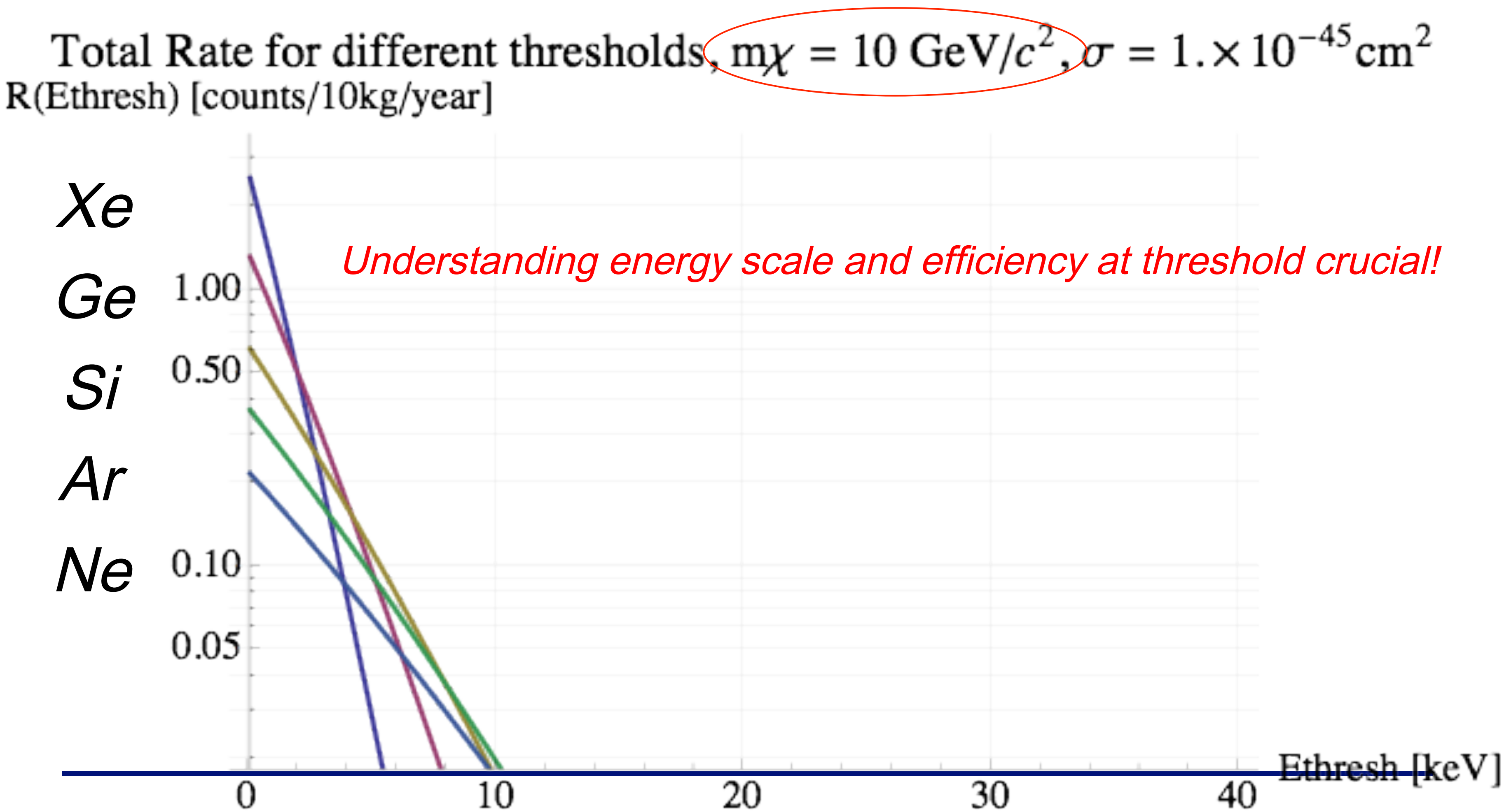
Direct Detection Rates



Direct Detection Rates



Direct Detection Rates

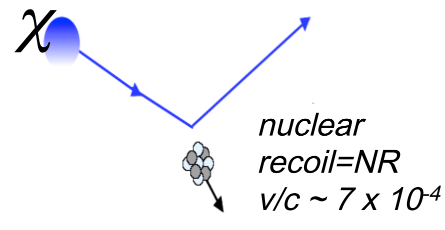


Detecting a WIMP signal

Counting

Eliminate conventional sources of nuclear recoils; count any that remain as WIMPs

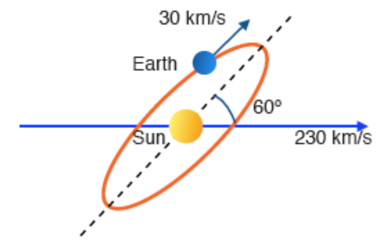
Already down to < 1/keV/100kg/year!



Annual Modulation

Rate varies slightly due to earth velocity relative to solar system through halo

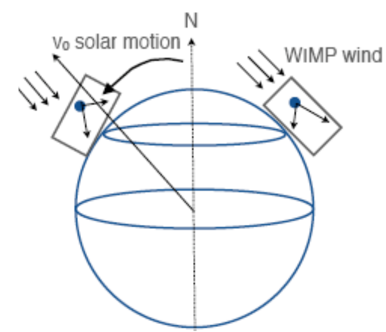
Requires precise control of experimental variations over years of operation



Diurnal Modulation

Rate varies daily with earth's rotation

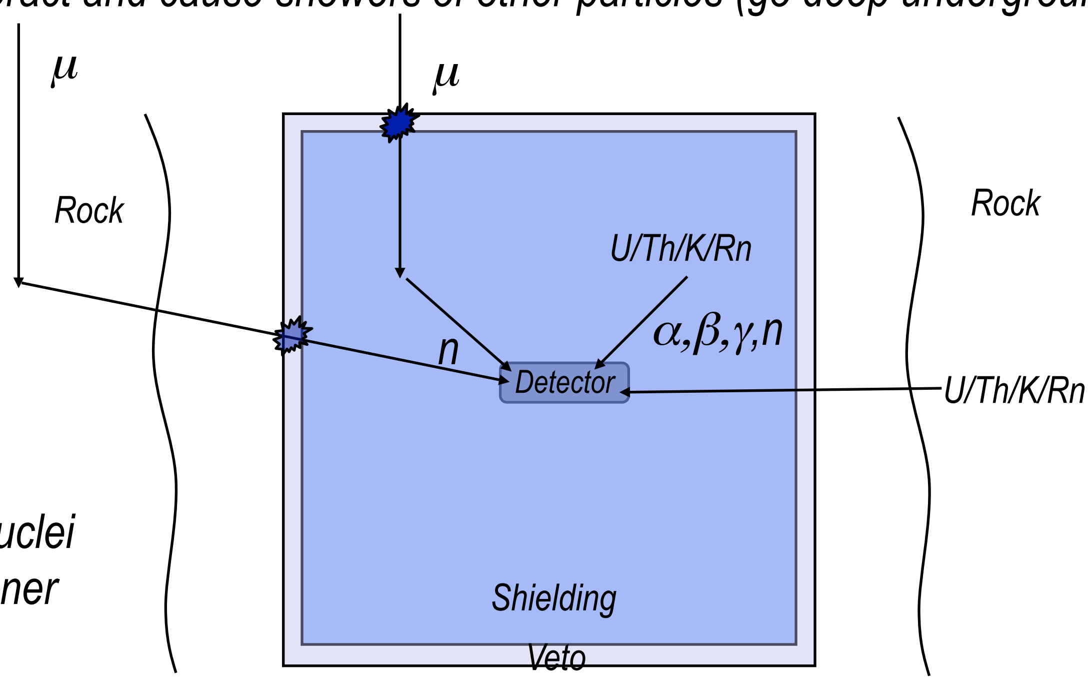
Need directional detectors to interpret as dark matter



Those nasty backgrounds

Cosmic rays

High energy particles from space hit the atmosphere and produce muons which can interact and cause showers of other particles (go deep underground to avoid)



Neutrons

These interact elastically with nuclei in the same manner as WIMPS

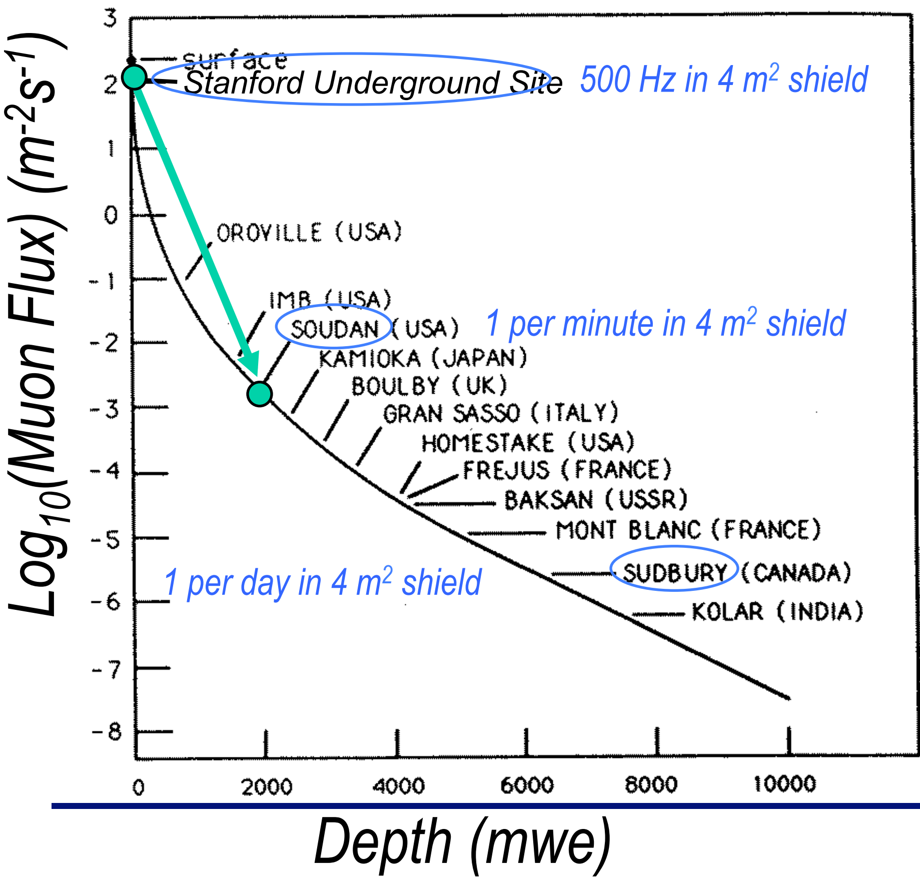
Radioactivity

Long-lived isotopes of natural uranium, thorium, potassium produce α, β, γ, n

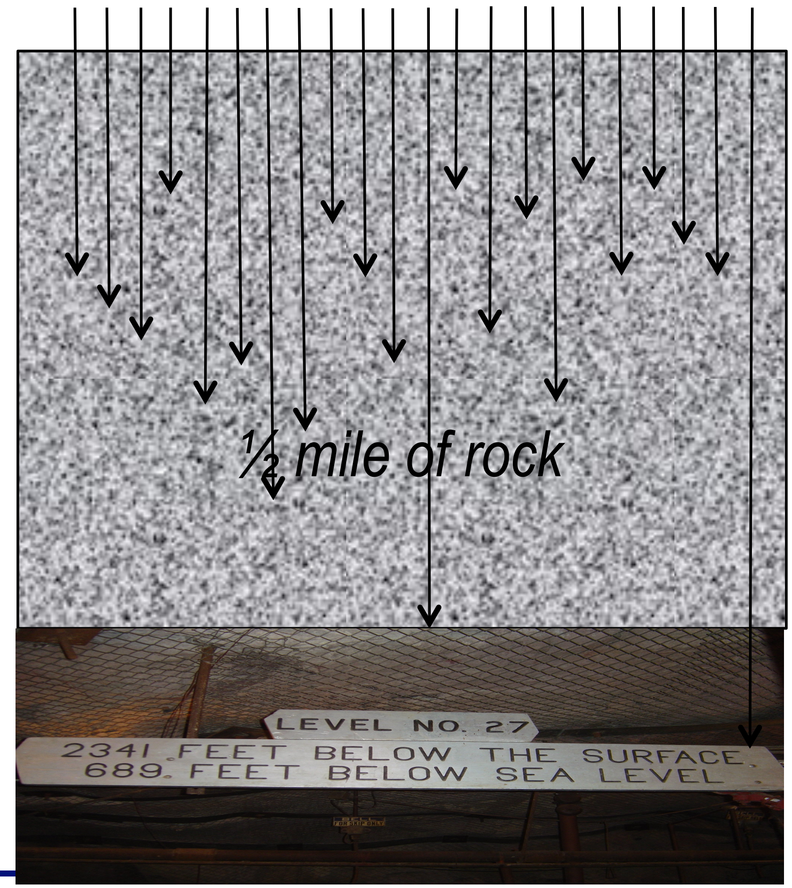
Neutrons from radioactivity most likely to be the limiting backgrounds

Go deep to escape cosmic rays

Cosmic ray muons in underground labs



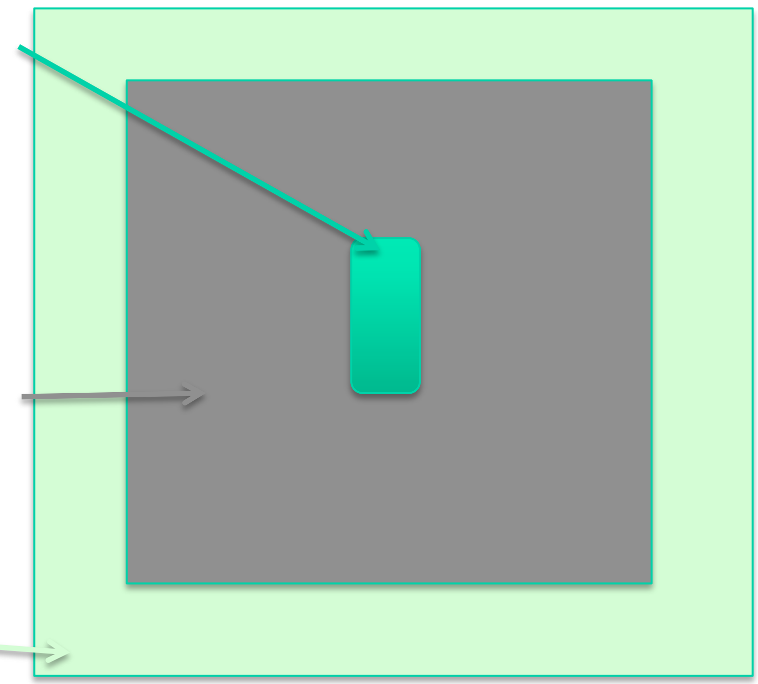
Cosmic Rays absorbed by rock



Direct Detection Experiments

Active Detection Material
Radiopure, produces detectable response to nuclear recoils, active rejection of electron recoils, high A or nuclear spin
Typical materials: Ge, Si, Xe, Ar, F, I

Passive Shielding
Radiopure, efficiently block external gammas and moderates neutrons
Typical materials: Cu, Pb, Polyethylene, Water



Active Shielding
Efficiently veto external neutrons and cosmic ray muons
Typical detectors: Water Cherenkov, Scintillator

Residual Backgrounds

- Experiments strive to be "background free"
  - Really means <0.5 event in the expected exposure with optimized nuclear recoil acceptance
- But they usually fall short of that goal
  - Conservative option is to count all remaining events as WIMPs and set limit based on that
  - IF one understands the background very well, can subtract it
    - But systematics then dominate limit and improvement goes like √(time) or worse.
- Convincing the community of a WIMP signal likely requires "background free" detection with multiple technologies

The Fermilab Direct Detection Experimental Program

- We are the lead lab for multiple projects, all of which fit our scientists interests, use unique lab capabilities and have substantial university research involvement
  - Cryogenic Dark Matter Search (CDMS)
    - FNAL joined in 1998 to manage CDMS II, bringing HEP experience, cryogenics, electronics, mechanical design
  - Chicagoland Observatory for Underground Physics (COUPP)
    - FNAL joined in 2004 to provide underground testing, mechanical design, electronics (enabled by Wilson Fellowship)
  - DarkSide
    - FNAL joined in 2009 to provide liquid argon expertise
- Detector R&D program also spawns new efforts
  - Dark Matter in CCDS (DAMIC)
    - Develop low-noise readout of DECam CCDs for low-mass WIMPs

SNOWMASS Roadmap for Dark Matter Direct Detection

Discovery

Search for WIMPS over a wide mass range (1 GeV to 100 TeV), with at least an order of magnitude improvement in sensitivity in each generation, until we encounter the coherent neutrino scattering signal that will arise from solar, atmospheric and supernova neutrinos

Confirmation

Check any evidence for WIMP signals using experiments with complementary technologies, and also with an experiment using the original target material, but having better sensitivity

Study

If a signal is confirmed, study it with multiple technologies in order to extract maximal information about WIMP properties

R&D

Maintain a robust detector R&D program on technologies that can enable discovery, confirmation and study of WIMPs

SNOWMASS Criteria for Next Generation DM Experiments

1. Provide at least an order of magnitude improvement in cross section sensitivity for some range of WIMP masses and interaction types
2. Demonstrate the capability to confirm or deny an indication of a WIMP signal from another experiment

Fermilab's suite of next generation experiments all meet these criteria:

- SuperCDMS SNOLAB
  - Expect world-leading low-mass sensitivity and at least x10 better high-mass reach
- COUPP/PICO 250l
  - Expect world-leading spin-dependent sensitivity and at least x10 better high-mass reach
- DarkSide G2
  - Excellent sensitivity to high-mass WIMPS
- DAMIC – 100
  - Unique reach for very low WIMP masses

The US G2 dark matter program

- DOE has declared "mission need" (CD-0) for next generation dark matter program, with five groups having received FY2013 R&D funding:
  - ➢ SuperCDMS SNOLAB (FNAL lead, substantial SLAC role, PNNL joined)
    - o Next generation cryogenic solid-state experiment at SNOLAB
  - ➢ COUPP-500 (FNAL lead, PNNL joined)
    - o Larger bubble chambers at SNOLAB
  - ➢ Darkside – G2 (FNAL lead, SLAC participating)
    - o Larger LAr TPC within present facility at LNGS (Gran Sasso)
  - ➢ LZ (LBNL lead, SLAC participating)
    - o Larger version of LUX, currently sited at Homestake
  - ➢ ADMX (Univ. Washington lead)
    - o Only experiment doing direct detection of axions (viable dark matter candidate)
- NSF also has a "next generation dark matter" solicitation
  - ▪ Proposals to DOE and NSF due on November 26
  - ▪ Intent is to coordinate with DOE on the G2 'five"
  - ▪ They have already approved and funded XENON1T for Gran Sasso
- Substantial funding in FY14, DOE project funding in FY15-17
- Results from this G2 process will shape the future FNAL program
  - ▪ Expect a portfolio of complementary projects to emerge

Cryogenic Dark Matter Search

Detectors

Pure Ge and Si crystals

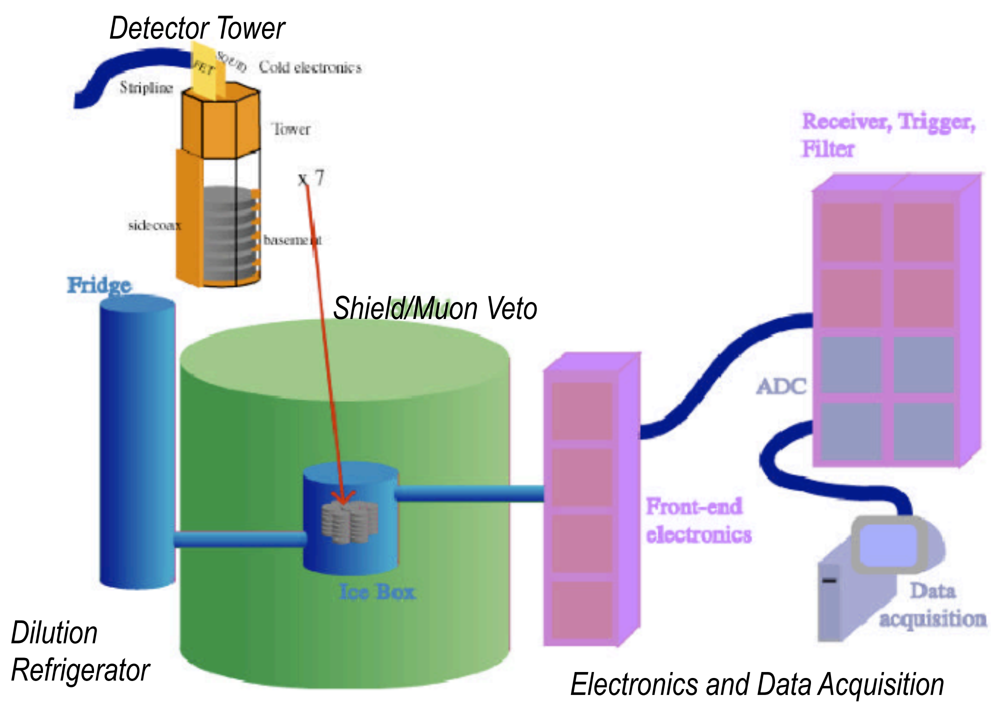
Cryogenics

Cool to near absolute zero in order to measure charge and phonons from single particle interactions. Provides excellent rejection of backgrounds

Shielding and Veto

Reduce flux of radioactive decay particles near the detectors

Actively tag any interactions associated with residual cosmic ray flux



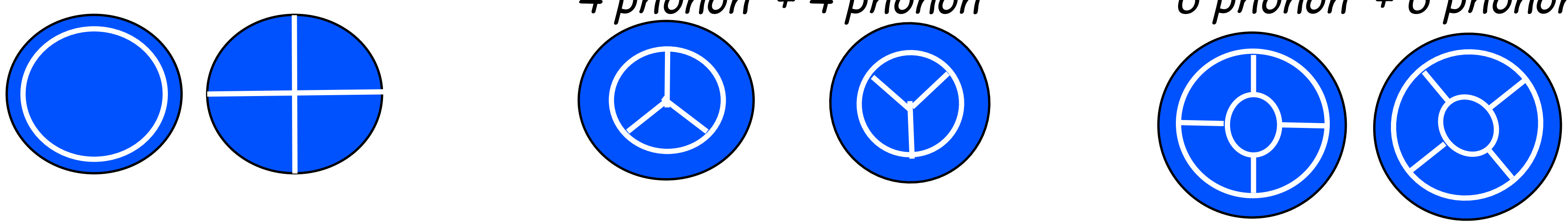
Evolution of CDMS Detectors

CDMS II: Single-sided 1 cm thick,7.6 cm diameter, 250 g Ge → *SuperCDMS Soudan: Double-sided 2.5 cm thick 7.6 cm"diameter, 620 g Ge* → *SuperCDMS SNOLAB: Double-sided 3.3 cm thick, 10 cm diameter, 1.38 kg Ge*

2 charge + 4 phonon

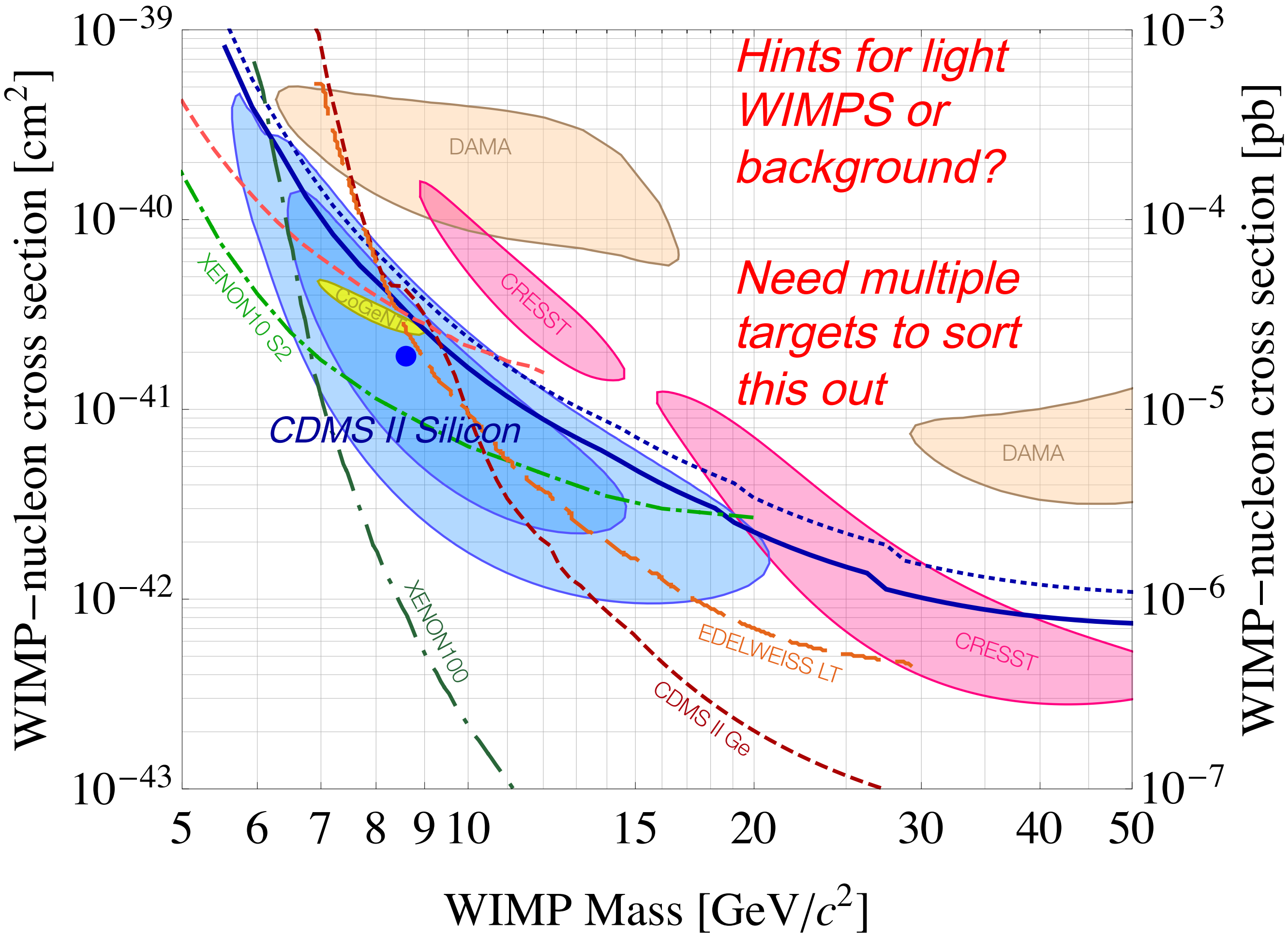
2 charge + 2 charge
4 phonon + 4 phonon

2 charge + 2 charge
6 phonon + 6 phonon

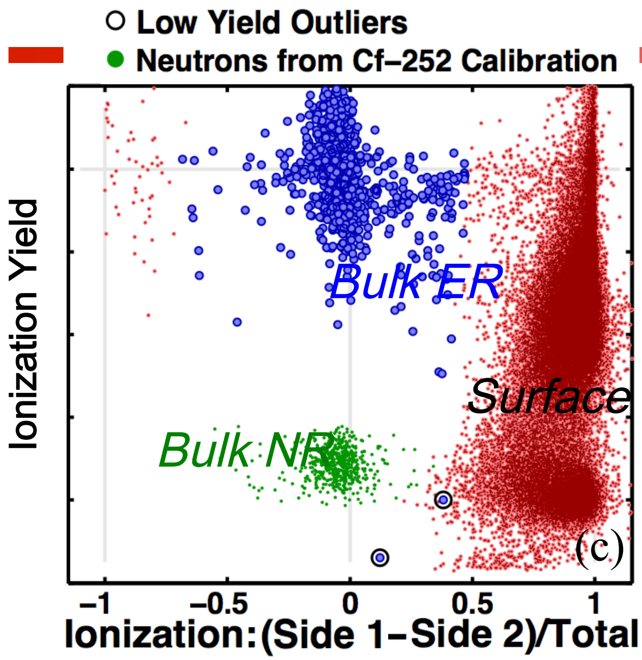


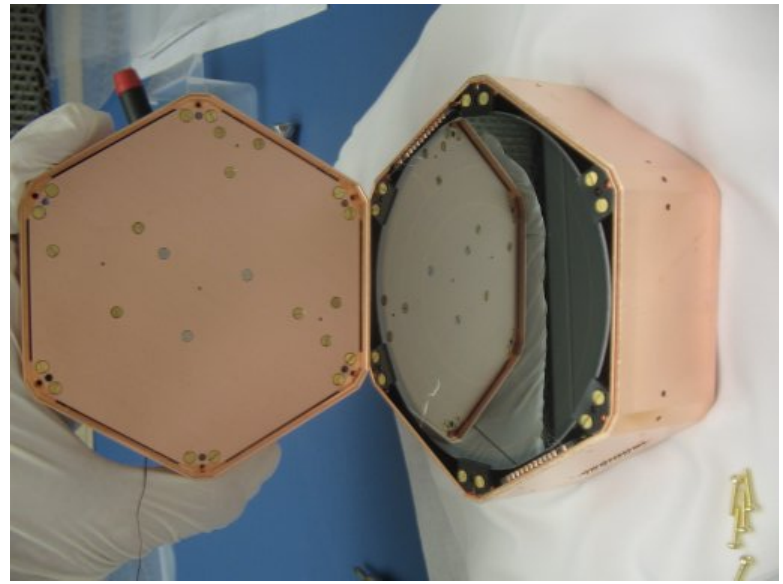
Experiment	Net Exposure	Cosmo neutrons	Shield neutrons	Surface events	Fiducial Volume
CDMS-I SUF	28 kg-d	18	---	2	---
CDMS-II Soudan	1 kg-y	.01	.07	1.2	37%
SuperCDMS Soudan	6 kg-y	.07	.34	.005	50%
SuperCDMS SNOLAB	*385 kg-y*	*.03*	*.1*	*<.24*	*73%*

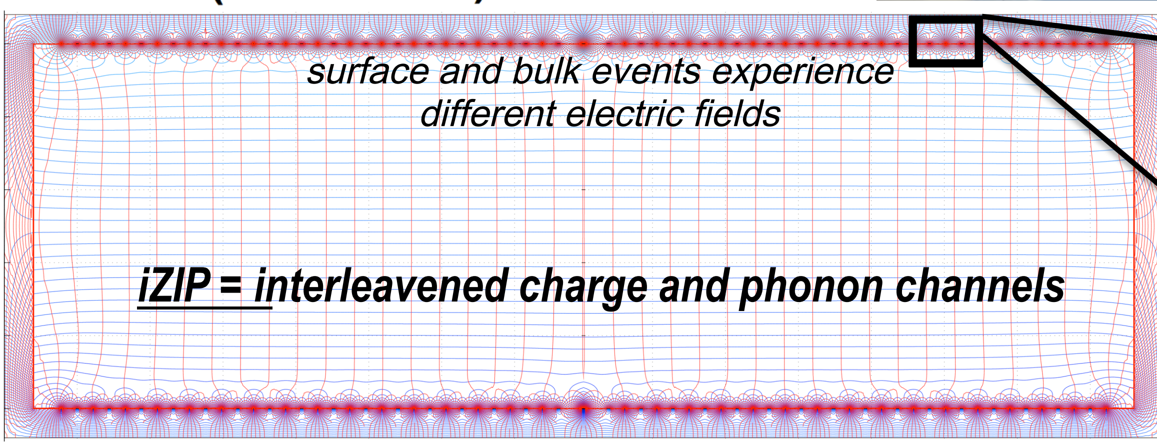
Recent Results: CDMS II Silicon

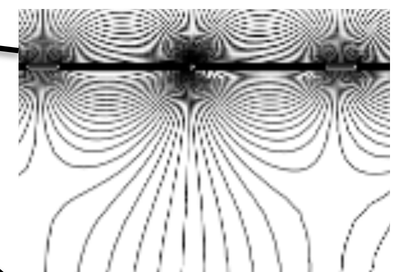


SuperCDMS iZIPs – A Detector Breakthrough



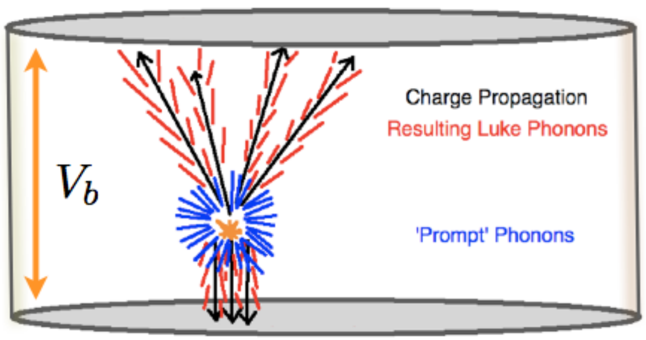






Charge near surface is collected by electrodes on only one side

Low Ionization Threshold Experiment: CDMSlite



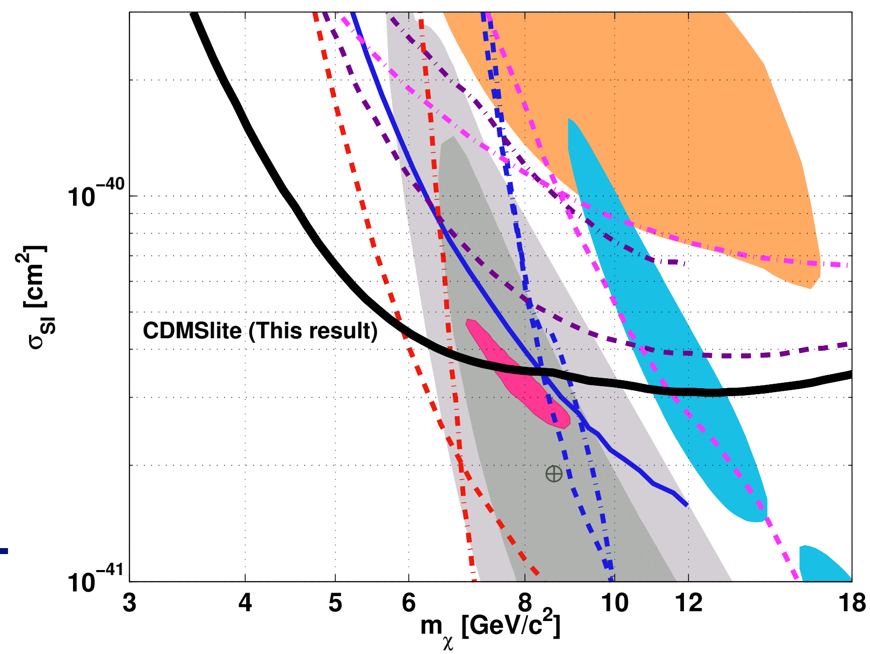
Achieved energy threshold = 170 eVee!

Consider all events as WIMP candidates (no background subtraction)

Use "optimum interval" method to derive new limits on < 6 GeV WIMPs

Apply large potential across crystal (69 V)

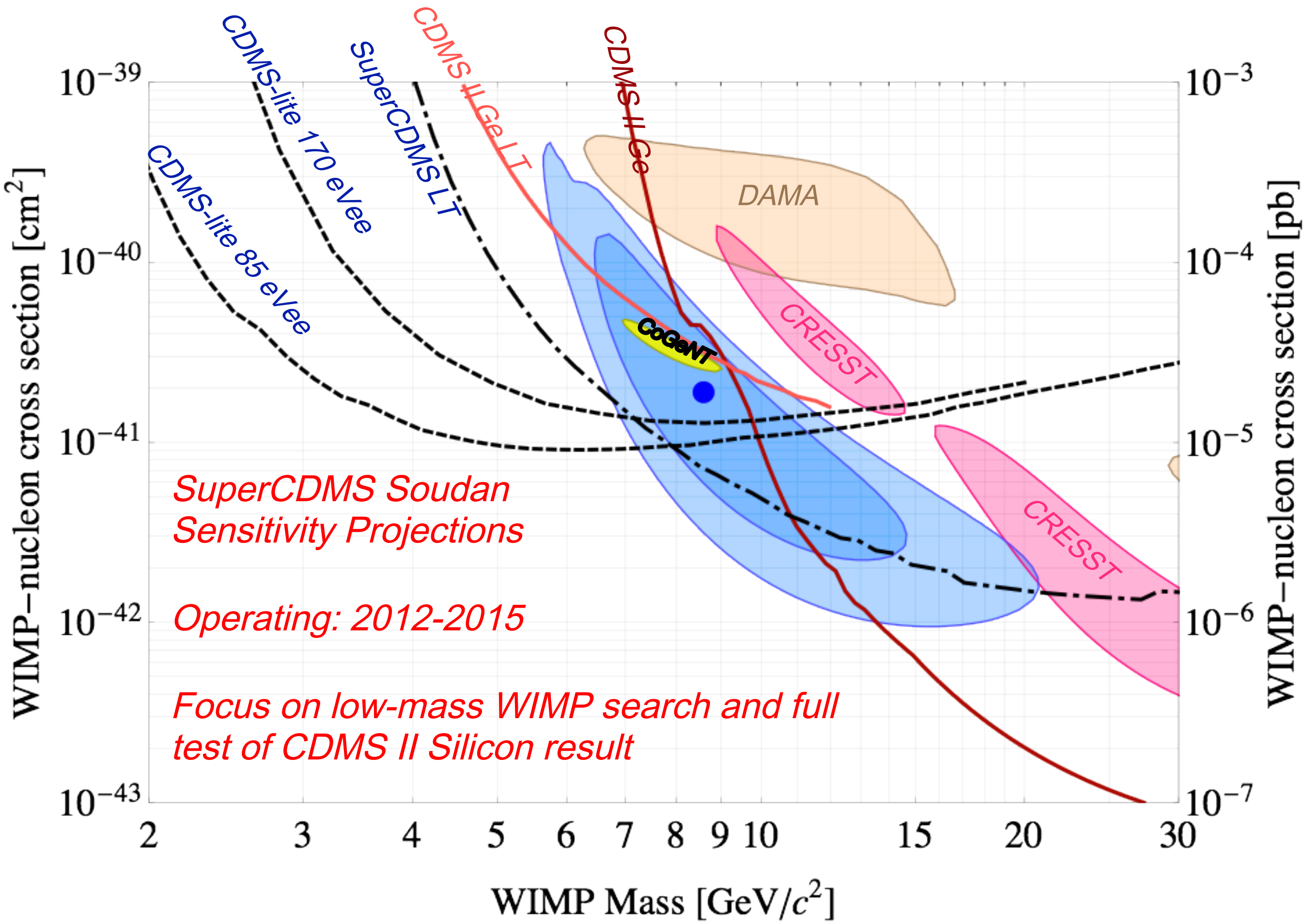
Collect much larger phonon signal without increase in noise (but lose most of the discrimination provided by independent charge signal)



SuperCDMS Soudan

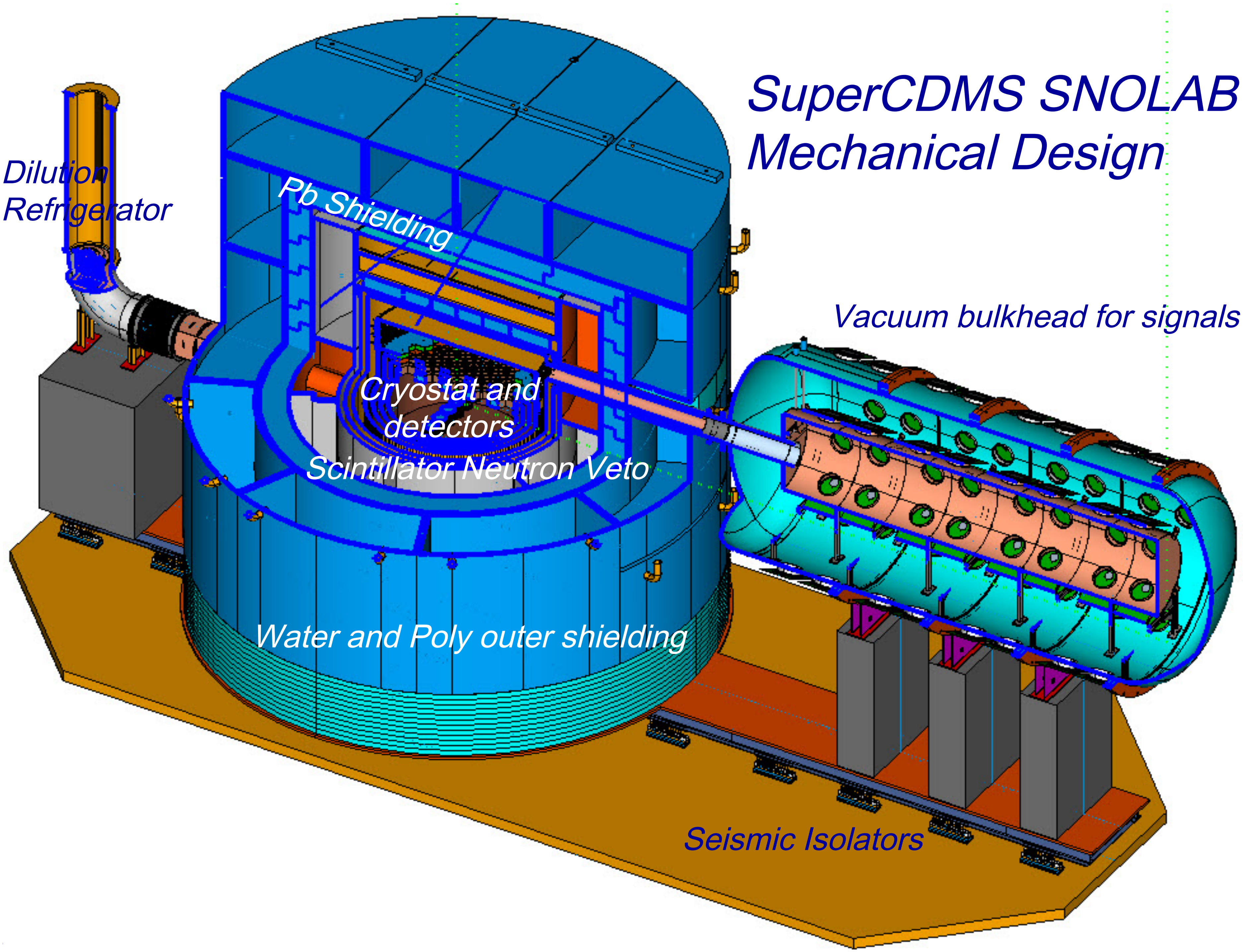
- Commissioned in fall 2011-spring 2012
- Operating since March 2012
  - 1.5 years at cryogenics temperatures (~50 mK!)
- Demonstrate iZIP background performance
  - ^{210}Pb sources supply surface events on 2 iZIPs
  - Paper on arXiv (http://arxiv.org/abs/1305.2405)
- Explore new low-mass WIMP territory
  - Check "hints" from CDMS II Silicon and other experiments
  - First CDMSlite result announced at TAUP2013 and on arXiv
- Check Xenon100 results for high-mass WIMPs
- Explore new parameter space for solar/galactic axions, lightly-ionizing particles,…

SuperCDMS Soudan
Search for low-mass WIMPs



SuperCDMS SNOLAB (G2)

- Next-generation direct detection experiment with complementary reach for high-mass WIMPs and world-class low mass WIMP sensitivity
  - 200 kg Ge target mass composed of 100mm x 33mm iZIP detectors (also considering inclusion of Si detectors)
  - Cryogenics system designed for up to 400 kg of detectors at <40 mK (probably 20-30 mK)
  - Active neutron veto and passive shielding to achieve < 0.1 event background in 4 years of operation
  - Location at 6000 mwe depth in SNOLAB ladder lab


SuperCDMS SNOLAB
Mechanical Design
Dilution
Refrigerator
Pb Shielding
Vacuum bulkhead for signals
Cryostat and
detectors
Scintillator Neutron Veto
Water and Poly outer shielding
Seismic Isolators

SuperCDMS Milestones

- Recent results from continuing analysis of CDMS II data include Silicon WIMP search (2013), Annual Modulation Search (2012) and Low-Mass WIMP search with Germanium (2011)
- Upgraded Soudan experiment with improved power backup and helium reliquefier systems; installed and commissioned 9 kg of new iZIPs
- 1.5 years of continuous operation at cryogenic temperatures
- Developed and commissioned near real-time remote monitoring for SuperCDMS Soudan data
- First results from SuperCDMS Soudan (CDMSlite)
- Multiple data processing runs of 100 TB datasets using FermiGrid
- Proposed and received approval for Canadian (CFI) and DOE R&D funding for SuperCDMS SNOLAB
- Significant progress towards cryogenic and mechanical design, as well as active scintillator neutron veto, for SuperCDMS SNOLAB
- Working prototype of electronics to be used for SuperCDMS SNOLAB

Fermilab Roles in SuperCDMS

2.5 FTE scientists

- Project and Operations Management (Bauer)
  - 13 years working underground at Soudan
- Cryogenics and Mechanical Design (Bauer)
  - Design and fabrication of the Soudan experiment
  - Using "lessons learned" to design improved SNOLAB setup
- Backgrounds and Neutron Veto (Loer)
  - Extensive experience in understanding backgrounds
  - Exploring a B or Gd loaded scintillator veto to make sure we can identify possible radiogenic neutron backgrounds at SNOLAB
- Electronics (Hall -> new)
  - Have condensed entire 9U chain on to single card, powered and read out over Ethernet
- Analysis coordination, data processing and archiving (Hsu)
  - UIUC graduate student (Ritoban Basu Thakur) resident at Fermilab for PhD work on CDMSlite
- Full-time engineer, extensive use of FNAL technical labor
  - These are on R&D funding, not research

COUPP: Bubble Chambers for Dark Matter

Superheated target liquid
- (CF3I, C3F8,…)
- Fluorine provides net spin to probe spin-dependent WIMP interactions

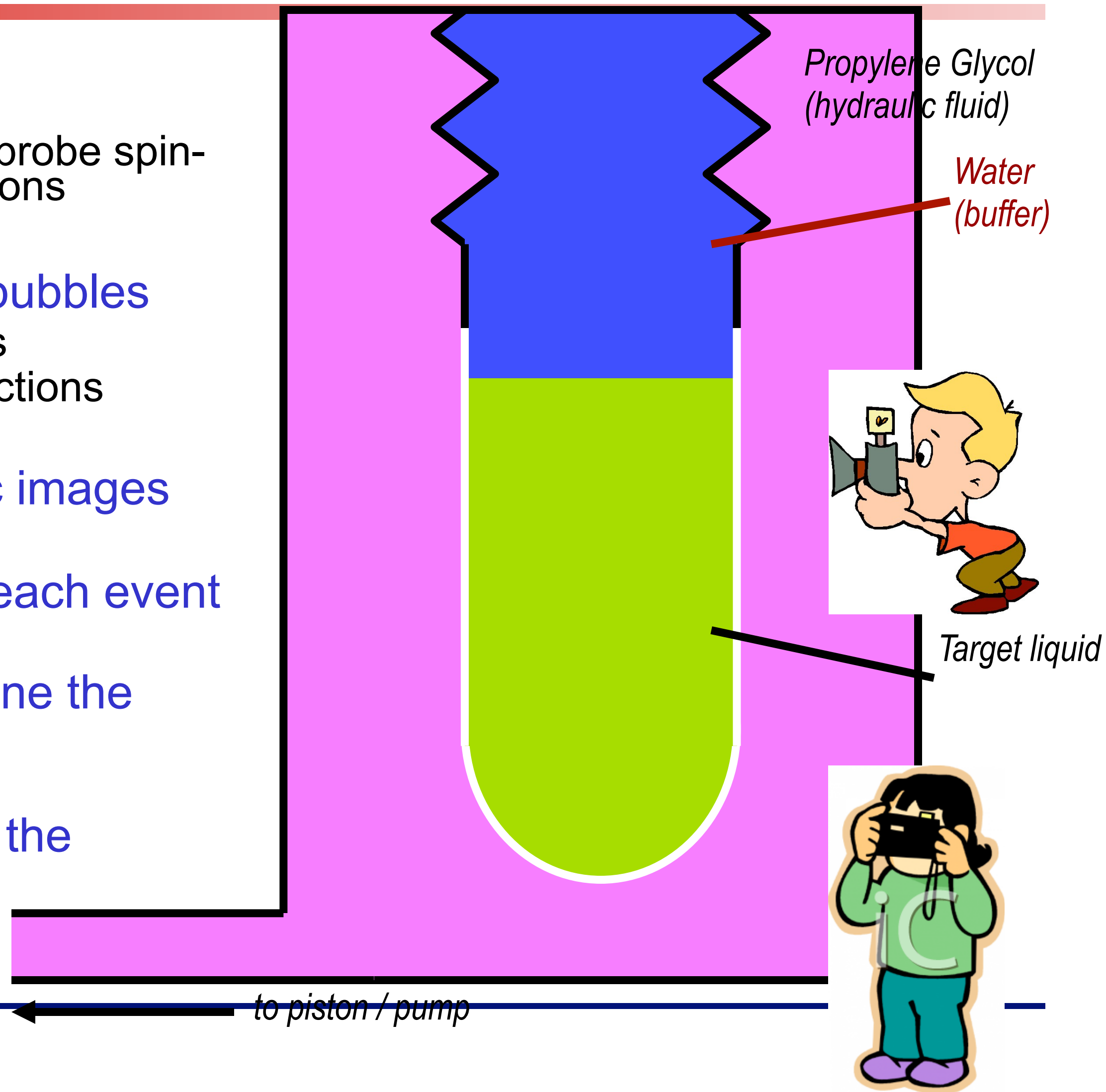
Particle interactions nucleate bubbles
- But only heavily-ionizing ones
- Insensitive to most EM interactions

Cameras capture stereoscopic images

Chamber recompresses after each event

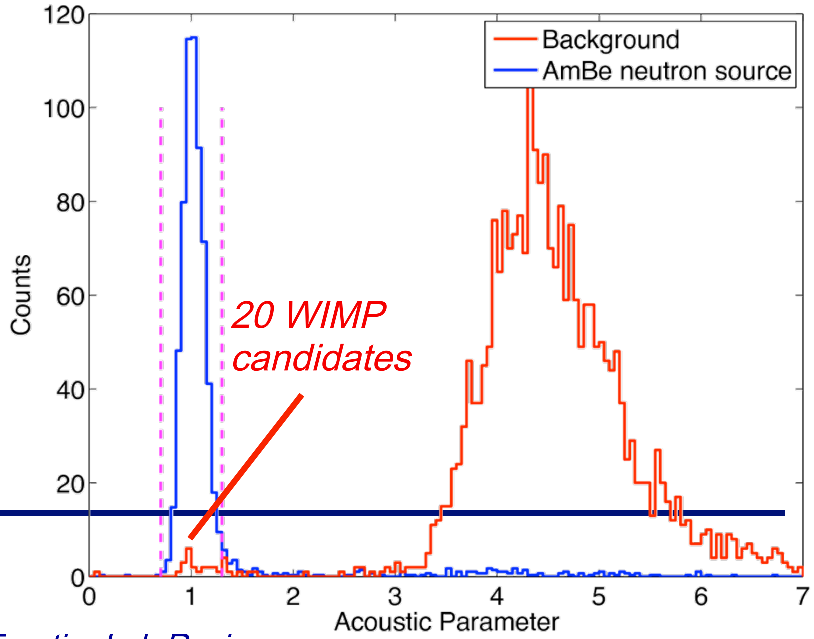
Pressure and temperature define the operating point

Acoustic transducers "listen to the bubbles
- Nuclear recoils sound different than alpha particles



COUPP 4kg

- 2L bubble chamber operated at SNOLAB in 2011-2012.
- Demonstrated excellent rejection of alpha backgrounds in CF_3I (> 99.3% 15 keV data)
- Sensitivity from CF_3I was limited by backgrounds
  - Neutrons
  - Anomalous time-correlated singles. Not yet understood.

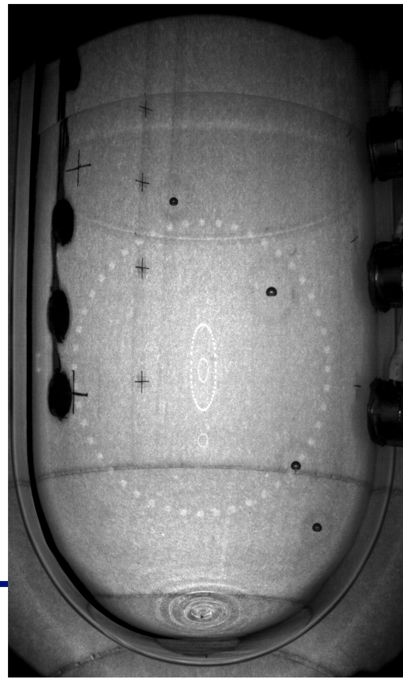


COUPP - 60kg

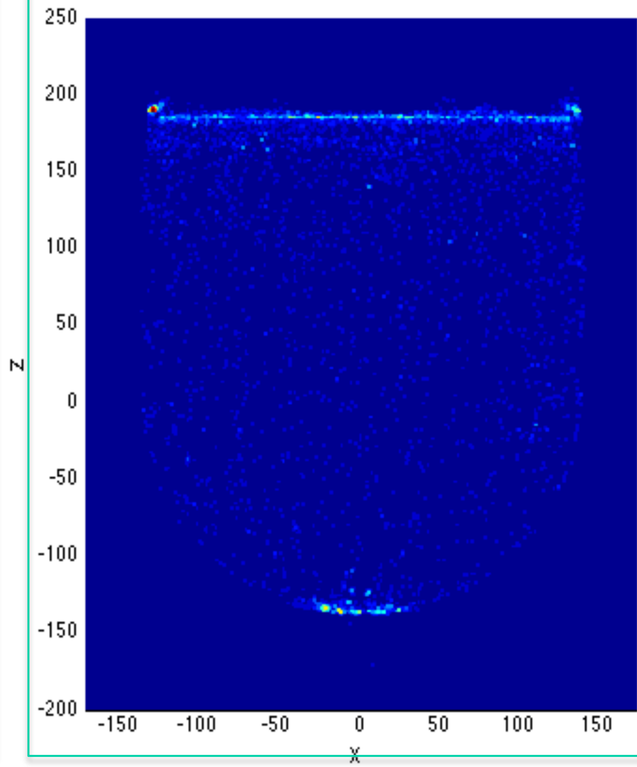
- *Larger bubble chamber now installed at SNOLAB*
- *Commissioning underway and expect WIMP search to start this fall*
- *Goal is world-leading spin-dependent WIMP sensitivity, demonstration of spin-independent sensitivity*

Inner Vessel Installation

Four- bubble neutron calibration event

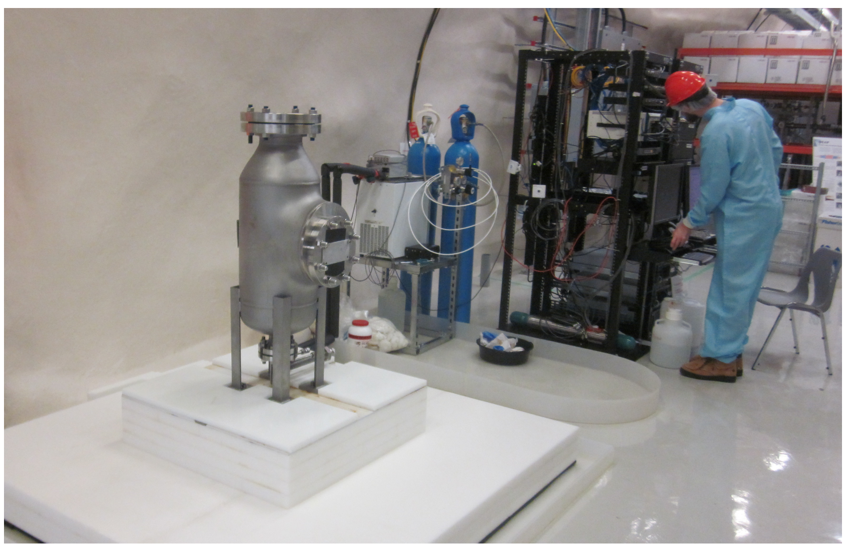


Spatial distribution from June-July Run, minimal cuts

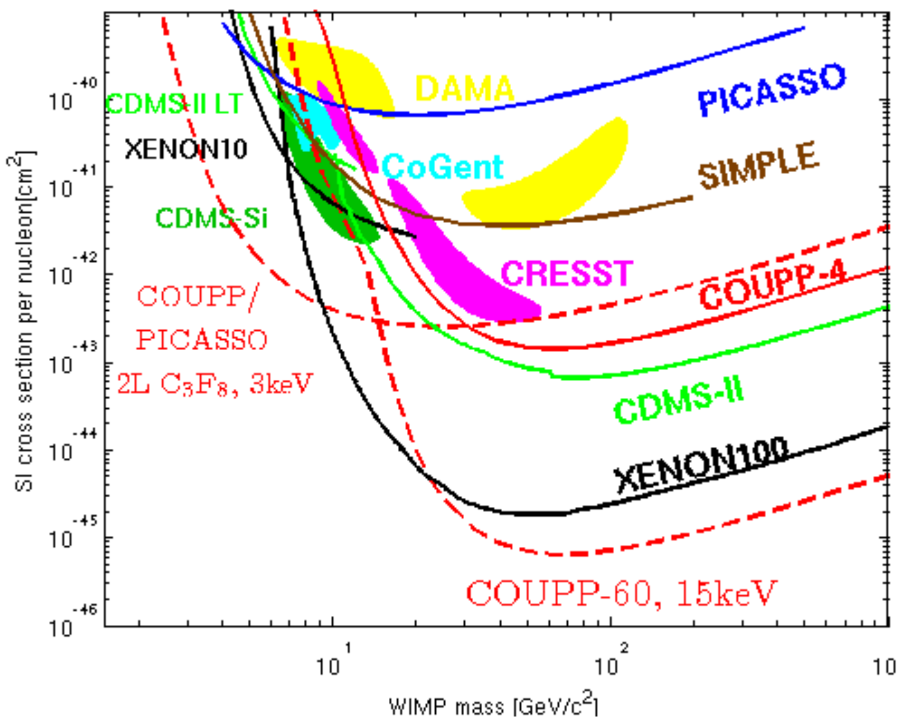


Searching for Light WIMPs with COUPP/PICO-2L

- Two liter experiment with C_3F_8 target liquid.
- Chamber built at Fermilab, reusing some COUPP-4kg parts.
- Optimized for low threshold (<3 keV) and light WIMPs (~10 GeV).
- Should test low-mass WIMP “hints”

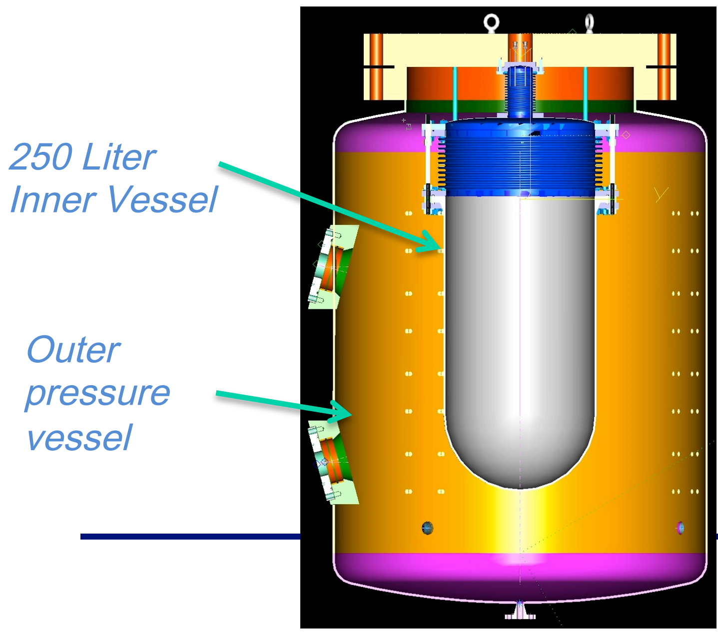


SNOLAB Installation, Sept. 2013

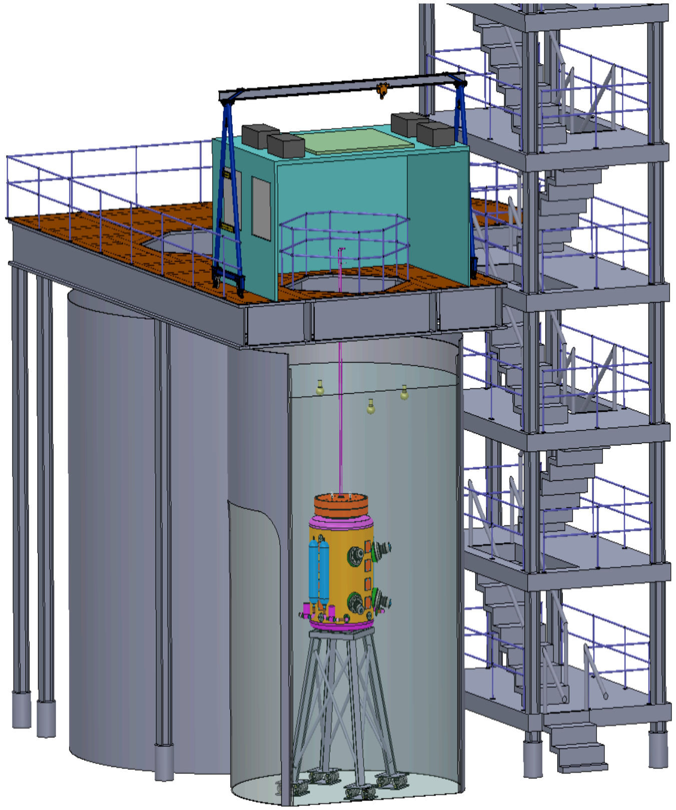


G2 Dark Matter Project: PICO-250L

- *Extrapolation of COUPP design to 250 Liters (500 kg CF_3I or 400 kg C_3F_8).*
- *Design underway at Fermilab since 2012. Progress in many areas.*
- *Initial support (FY12) from NSF, with subcontract to Fermilab for design work from U. Chicago. Received DOE G2 dark matter grant for R&D in FY13.*
- *Preparing proposals for NSF and DOE G2 Dark Matter in the fall.*



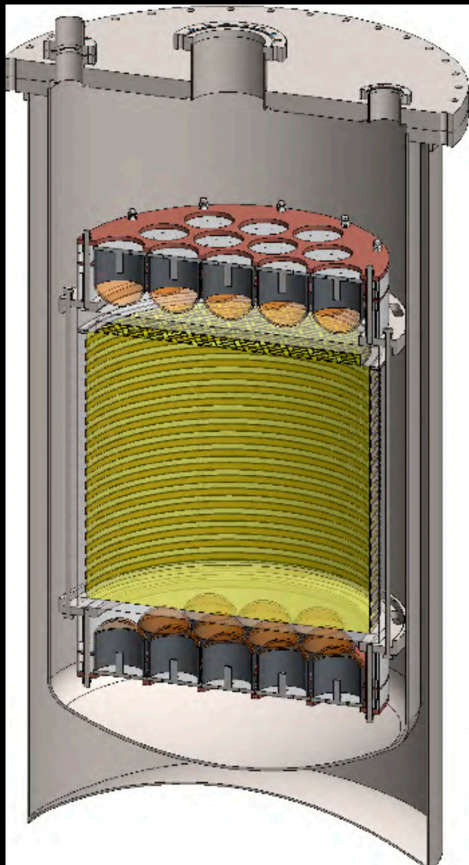
Shield Based on Existing SNOLAB Design



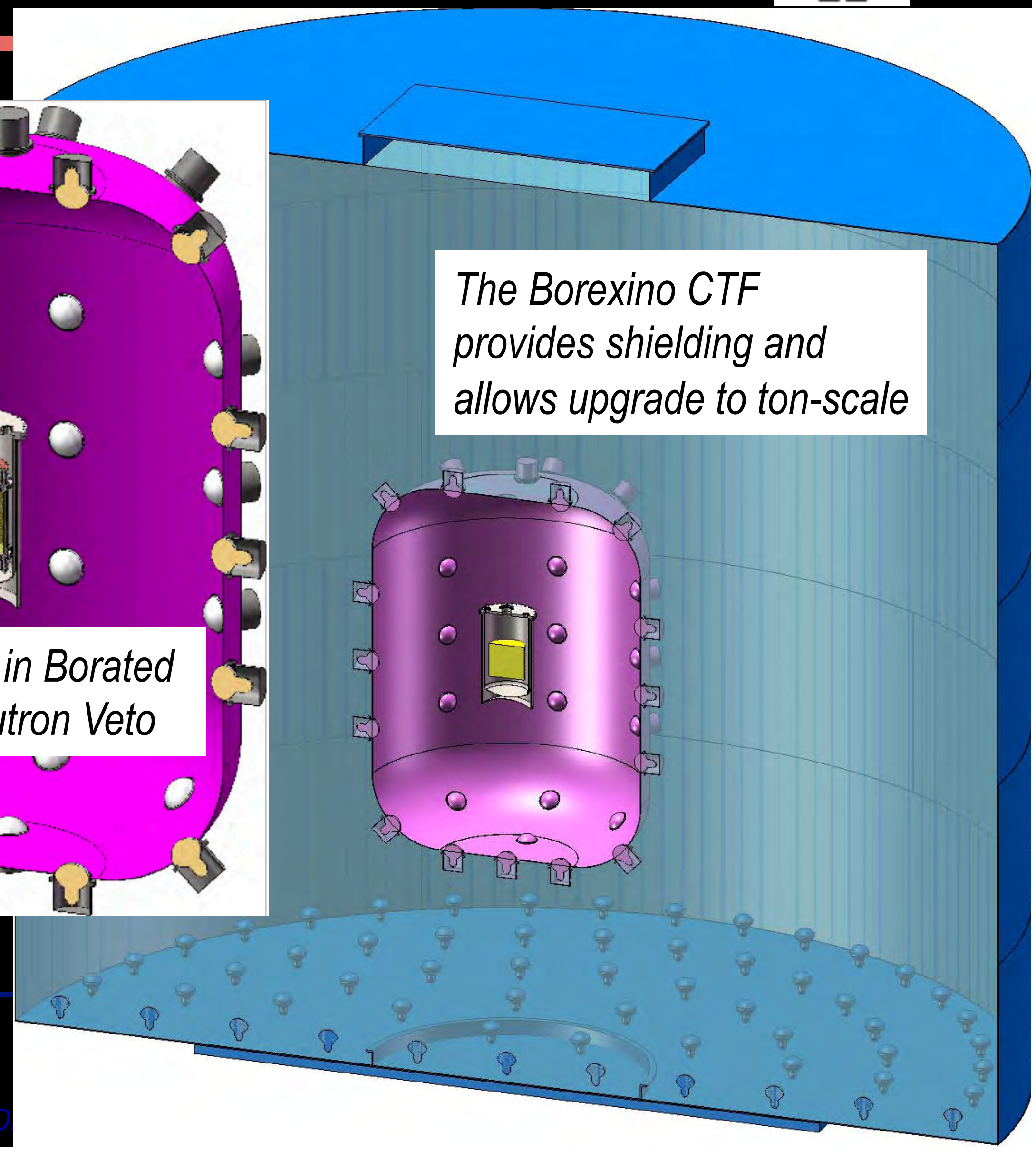
Fermilab Responsibilities for COUPP/ PICO

- Fermilab is the host lab and the center of detector design, construction, project management and data analysis.
- COUPP is in the process of merging with PICASSO, a formerly competing group. The new collaboration will be called PICO and have 60 faculty, scientists and students at 13 institutions.
- Fermilab research participation: 3 scientist FTEs (Dahl, Sonnenschein, Crisler, Ramberg, Brice, Cooper), and 1 postdoc (Lippincott).

DarkSide 50



50 kg LAr TPC



DarkSide: Zero-background liquid argon technology

- Pulse Shape Discrimination (PSD) of Primary Scintillation, S1, (rejects e/gamma) (unique to Argon - atomic physics of Argon dimer)
- Ionization:Scintillation Ratio, S2/S1 (rejects e/gamma - not unique to Argon)
- Sub-cm Spatial Resolution (identify surface bkgs) (advantage of two-phase)
- Underground argon (avoid event pile-up from ^{39}Ar)
- Neutron Veto (identify neutrons with high efficiency in finite volume)
- Water shield (identify muons and avoid cosmogenic neutrons)
- Screen and select all detector materials for minimum radioactivity

DarkSide Recent Milestones

- Completed operation of DarkSide-10 - 1 year (LY > 7 p.e./keV)
- Constructed as part of DarkSide-50:
  - 1,000 tonne water Cerenkov muon veto
  - 30 tonne organic liquid scintillator neutron veto
  - Two Rn-free clean rooms for final preparation of detector
  - Argon recirculation and purification systems

All facilities sized and built to house DarkSide-G2

April 2013 DarkSide-50 TPC assembled at LNGS

June 2013 First DarkSide-50 TPC Commissioning Run completed

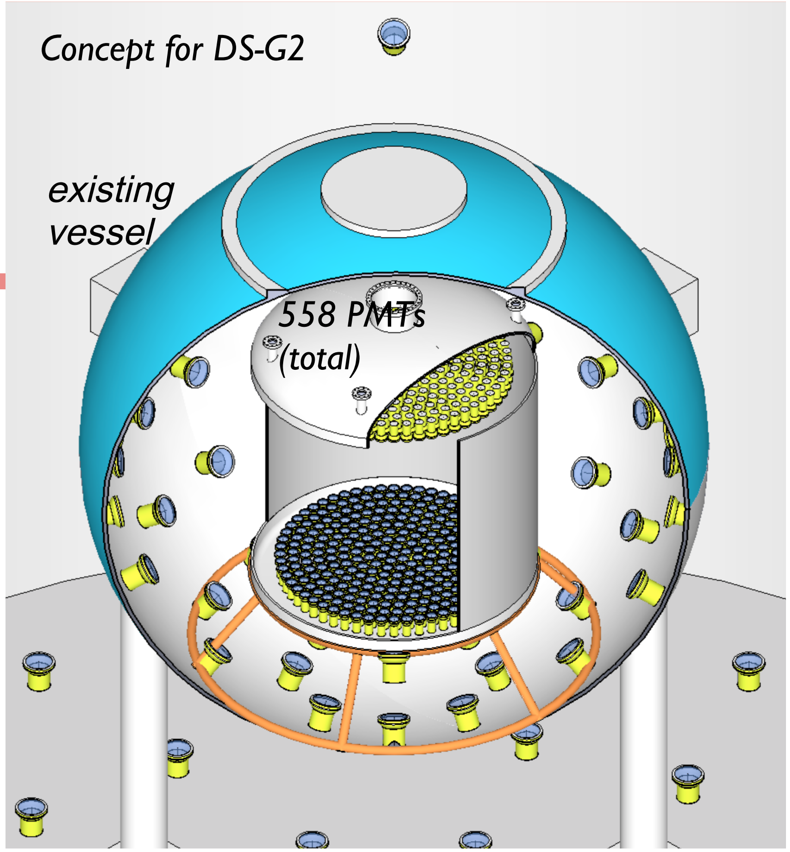
DarkSide -50 Commissioning

- *1st TPC commissioning run ended June*
  - *Replace bad PMTs* ✓
  - *Instrument all PMT bases with in-liquid pre-amps* ✓
  - *Install super-low radioactivity silica windows* ✓
  - *Fix weak points in the HV system* ✓
  - *Fix some heat leaks in the argon transfer lines* ✓
  - *Continuing improvements to the Trigger and DAQ* ✓
- *2nd TPC run starting in September*
- *Fill Neutron Veto and Water Tank by mid October*

=> *Data with complete apparatus, concentrating on background rejection performance*

- *Low radioactivity argon towards end of year*

DarkSide – G2



5 tonnes argon total, 3.3 tonnes fiducial:

Muon Veto System – built

Neutron Veto System - built

Argon Handling System – built except for recovery system

TPC - size defined by existing infrastructure

Argon – intense R & D activity to increase production & purification capability

Photosensors – program with Hamamatsu to reduce radioactivity and to make new 4 inch PMTs (presently 3” largest)

TPC mechanical design – issued contract to BNL

DAQ – baseline concept using SLAC `RCE’ module and ArtDaq

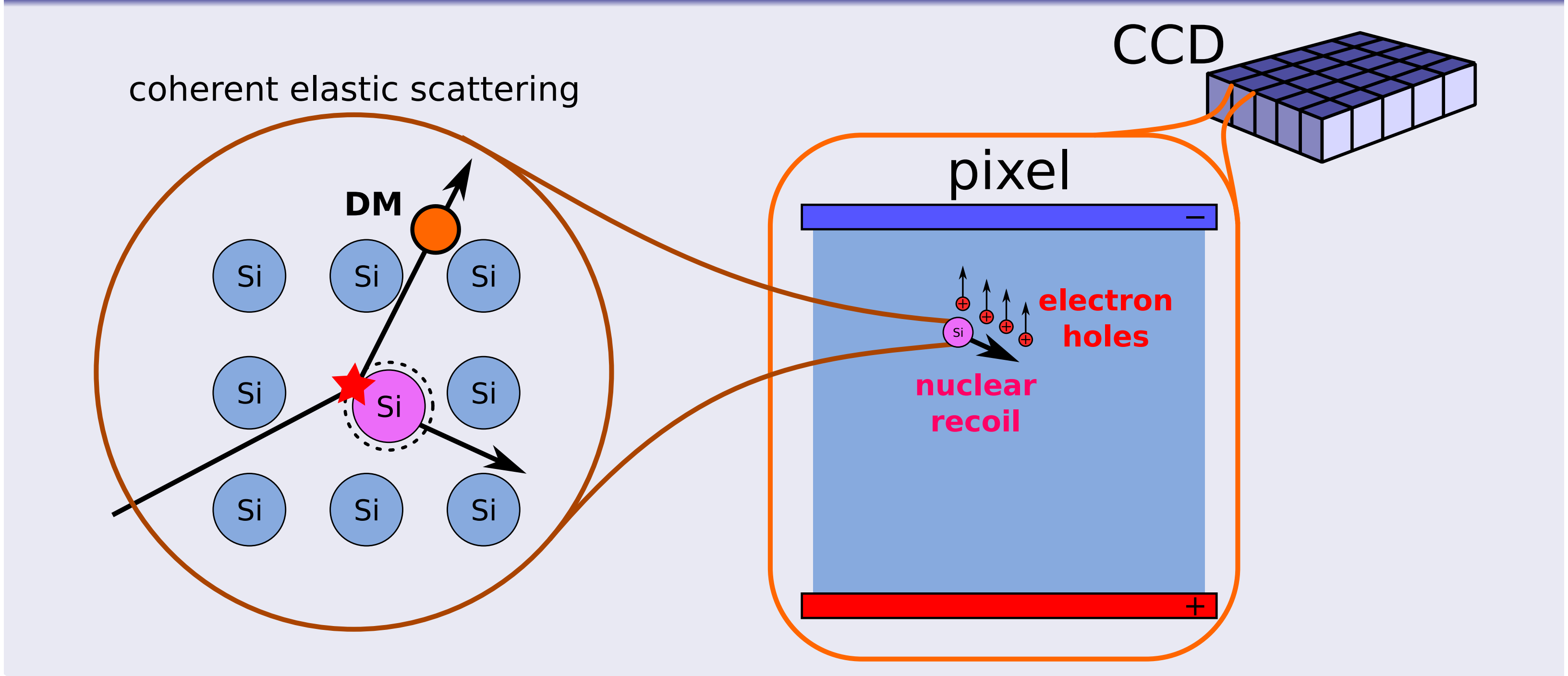
Expect to expand collaboration with new DOE institutions for G2 proposal

Fermilab Roles in DarkSide - 50

- *Underground Argon Purification (with Princeton)*
- *Argon handling system (with Princeton & UCLA)*
- *TPC Data Acquisition System (with LNGS)*
- *Trigger*
- *PMT Bases*
- *Data Storage & Analysis system*
- *Calibration of LAr nuclear recoil response (SCENE)*
- *Project management & DOE funds co-ordination*
- *1.5 FTE scientists (Pordes, Yoo) on the research budget*
- *Extensive use of technical labor from R&D and operations funding*

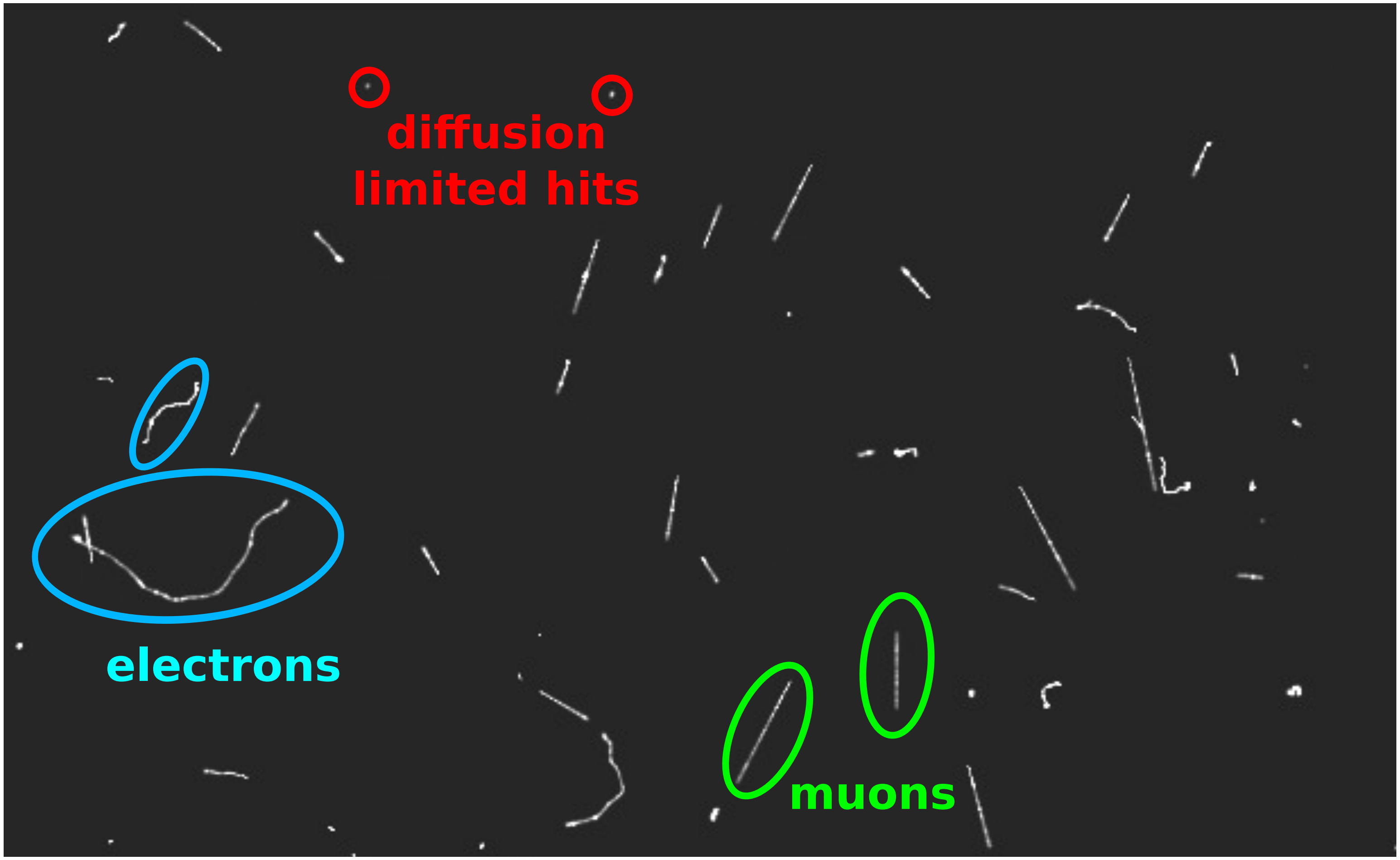
DAMIC

Idea: use CCDs as target and record the ionization produced in Si



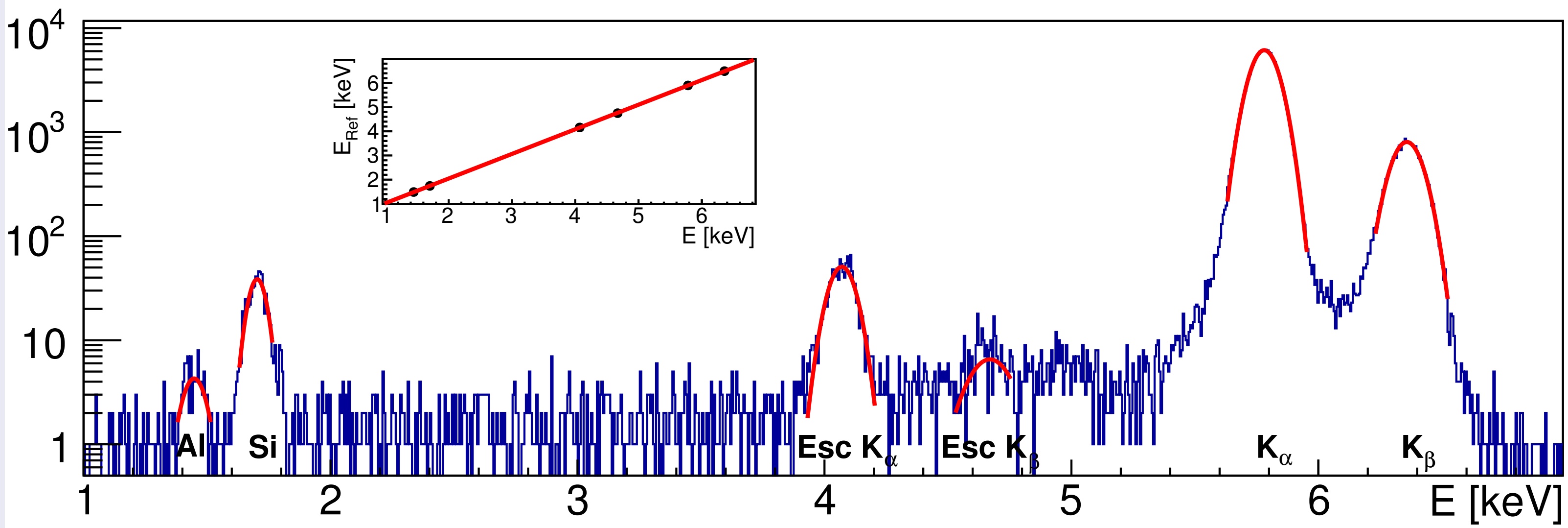
A tool for detecting low energy nuclear recoils…

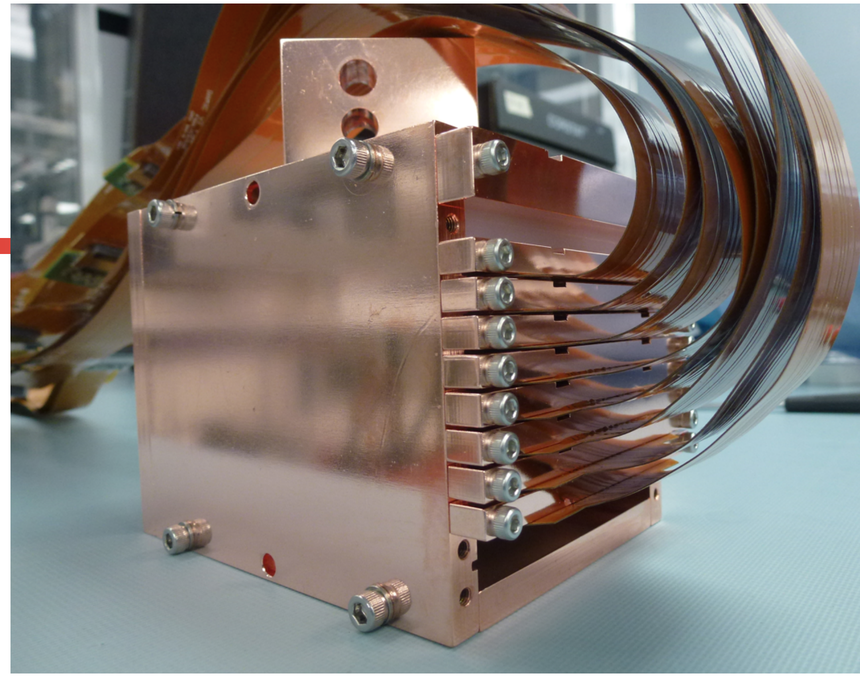
Particle ID with DAMIC

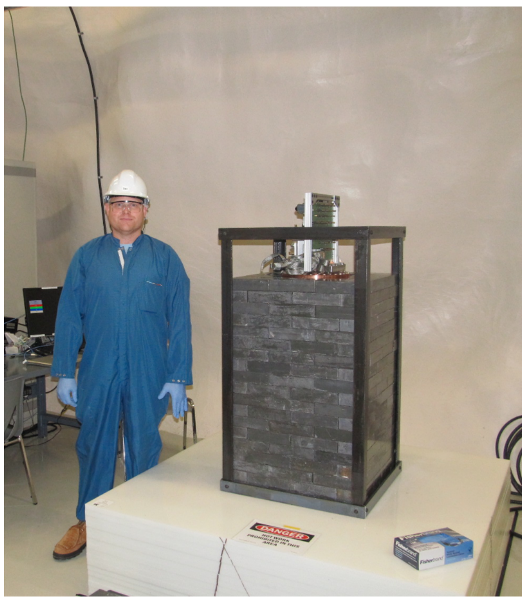


Low Energy Threshold and Excellent Resolution

Energy calibration using a ^{55}Fe source







DAMIC -10g installed at SNOLAB inside a copper vessel cooled at -150C. With a lead and poly shield.

DAMIC – 100 g

- *Our current CCDs have 1g of active mass each. We want to upgrade to detectors with 5.4g of active mass. This will allow us to achieve a total mass for DAMIC of ~100g with 18 detectors.*
- *18 detectors fit inside our current vacuum vessel and shield. We already have the electronics.*
- *We started the procurement process for the fabrication of the new sensors. In addition to having a larger mass, the new CCDs will have no optical coating. This optical coating is needed only for astronomy, and has the potential of becoming the next dominant background.*

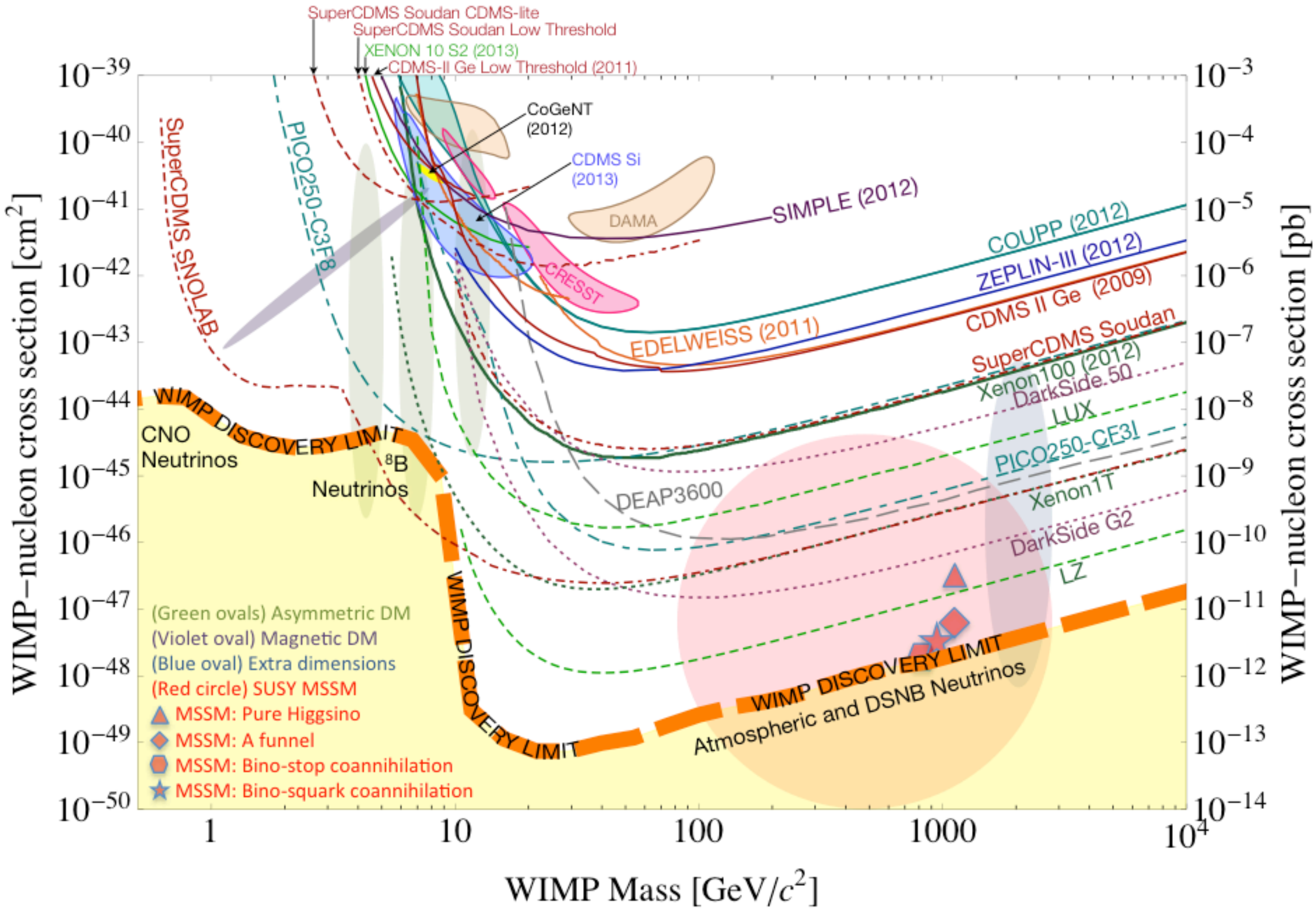
Fermilab Responsibilities for DAMIC

- Juan Estrada (Scientist)
  - Spokesperson for the experiment, advisor for postdoc and Ph.D students
- Javier Tiffenberg (Research Assoc)
  - Lead the operations of the experiment since its installation at SNOLAB
  - Developed suite of software tools to collect and analyze the data from SNOLAB and has made this available to all the other groups working on DAMIC
- Small fractions of time from:
  - Gustavo Cancelo – Low-noise CCD readout
  - Tom Diehl - CCD expertise
  - Brenna Flaugher - CCD expertise
  - Andrew Sonneschein – Initial contact with SNOLAB and DM expertise
  - Gaston Gutierrez – low energy nuclear recoil calibration experiment
  - Vic Scarpine – low energy nuclear recoil calibration experiment
- Hardware:
  - All the hardware currently at SNOLAB comes from FNAL. It was either from prototypes for another experiment, general detector R&D components or from PECASE award. For the coming upgrade we have significant contributions from collaborators.

R&D for future experiments

- DMIce
  - Plan to check the DAMA/LIBRA annual modulation result in the Antarctic ice (co-located with IceCube)
    - Interest at Fermilab in simulations and electronics for the NaI PMT bases
- Directional WIMP detectors
  - Detect the recoiling nucleus direction, infer WIMP direction
    - Interest at Fermilab in new approaches to directional detection, especially those that may allow lower energy thresholds
    - Low-pressure gas detector with low-noise readout (D-cubed)
    - High pressure gas detectors (NEXT)
      - Both of these efforts already have LBNL involvement

Probing for WIMPS down to the neutrino background



Summary

- Direct detection of dark matter WIMPS remains one of the best ways to spot evidence for something beyond the standard model, as well as providing an explanation for what most of the mass of the universe actually is.
- For the next generation, Fermilab's suite of direct detection experiments provides complementary cross section sensitivity across the whole accessible mass range with multiple target materials.
- We shouldn't lose sight of the fact that we might actually detect WIMPS soon, and must be well prepared to follow up on any signals with a range of different technologies!

Backup

The SuperCDMS Collaboration

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Universitat Politècnica de València — M. Ardid, M. Bou-Cabo

Pacific Northwest National Laboratory — D. Asner, J. Hall

Northwestern University — D. Baxter, C.E. Dahl, M. Jin

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Czech Technical University in Prague — R. Filgas, S. Pospisil, I. Stekl

University of Alberta — S. Gagnebin, C. Krauss, D. Marlisov, P. Mitra

Virginia Tech — D. Maurya, S. Priya

SNOLAB, Mining for Knowledge, Creuser pour trouver... l'excellence — I. Lawson, E. Vázquez Jáuregui

DarkSide Collaboration

Augustana College, USA
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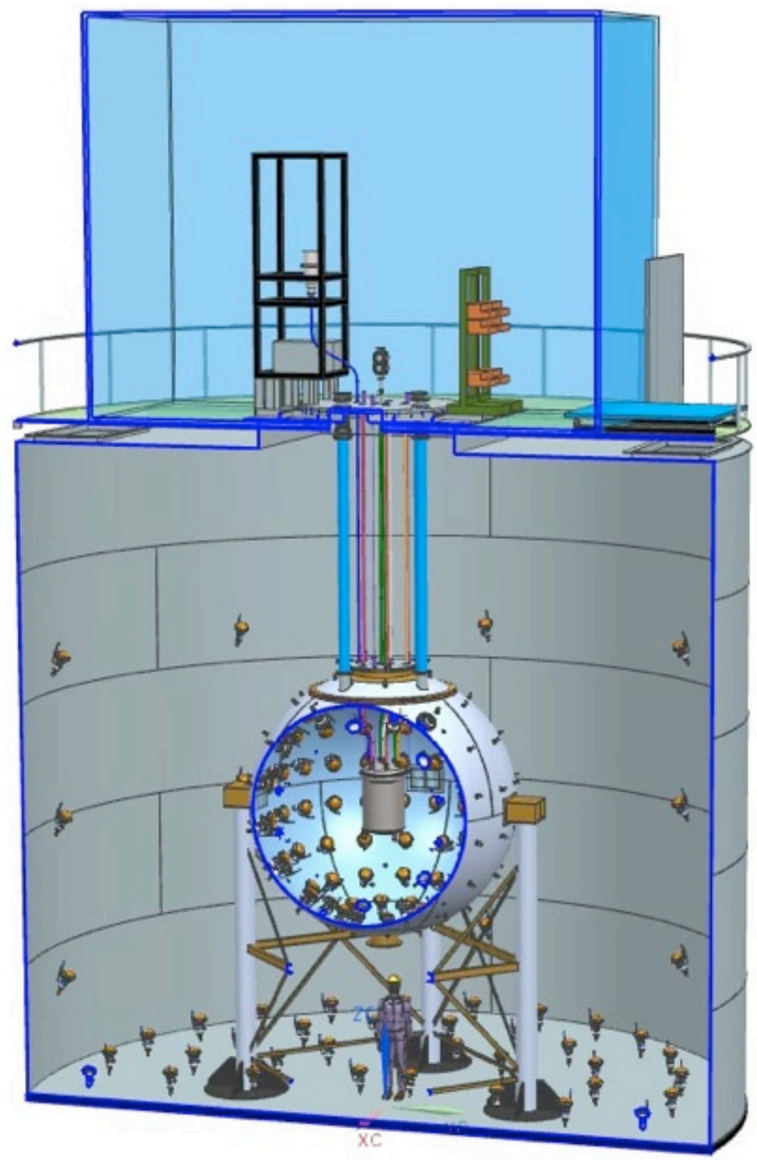
Black Hills State University, USA
Fermilab, USA
IHEP, China
INFN Laboratori Nazionali del Gran Sasso, Italy
INFN and Università degli Studi Genova, Italy
INFN and Università degli Studi Milano, Italy
INFN and Università degli Studi Napoli, Italy
INFN and Università degli Studi Perugia, Italy
INFN and Università degli Studi Roma 3, Italy
IPHC Strasbourg, France
Jagiellonian University, Poland
Joint Institute for Nuclear Research, Russia
Princeton University, USA
RRC Kurchatov Institute, Russia
SLAC National Laboratory, USA
St. Petersburg Nuclear Physics Institute, Russia
Temple University, USA
University College London, UK
University of Arkansas, USA
University of California at Los Angeles, USA
University of Chicago, USA
University of Hawaii, USA
University of Houston, USA
University of Massachusetts at Amherst, USA



DAMIC Collaboration

Fermi National Accelerator Laboratory, Universidad Autonoma de Mexico, Universidad Nacional de Asuncion, University of Chicago, University of Michigan, University of Zurich

10 faculty, 2 postdocs, 5 graduate students, undergraduate students