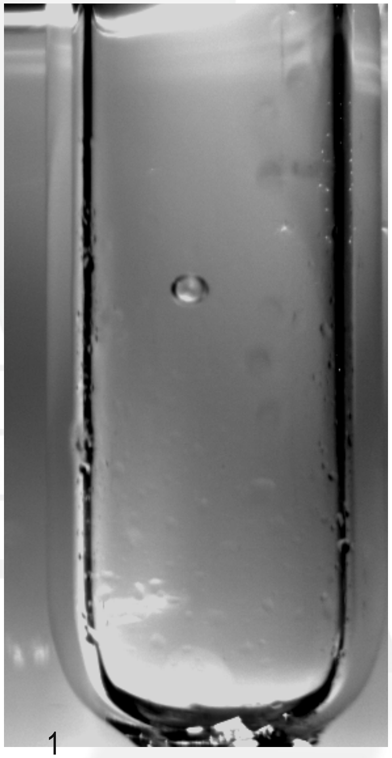
The Dark Matter Program at Fermilab

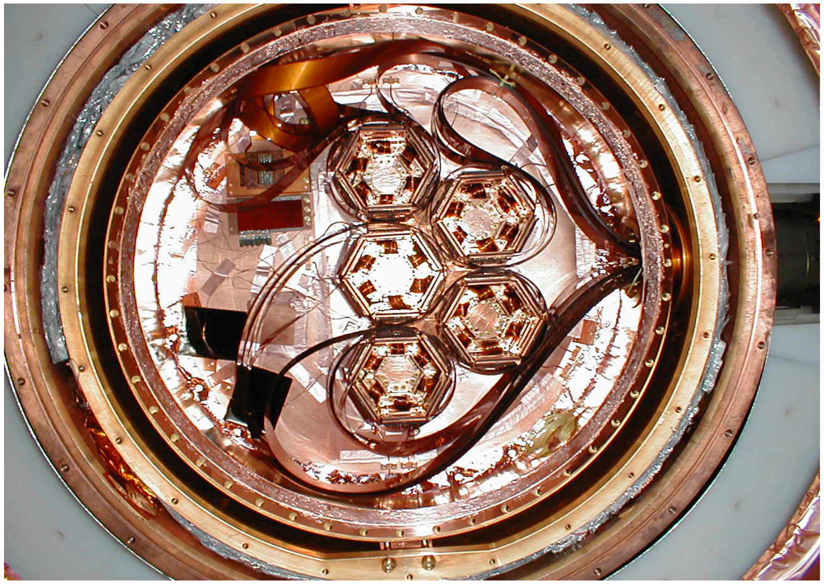
Dan Bauer, Fermilab

DOE Non-Accelerator Review, September 29, 2010

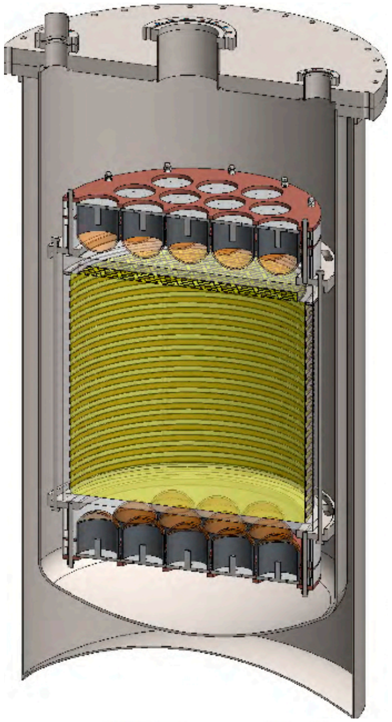
COUPP



CDMS



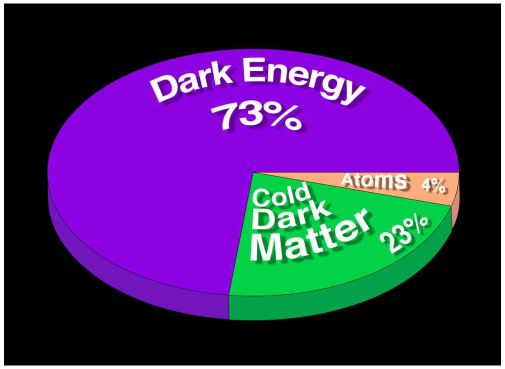
DarkSide

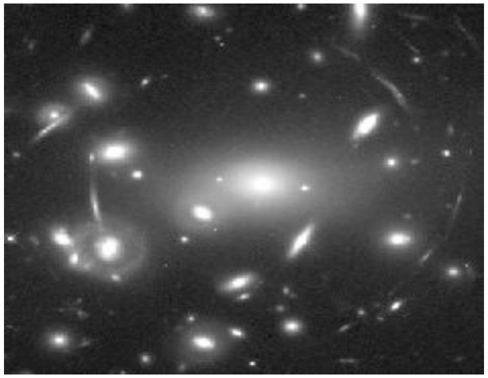


What is Dark Matter?

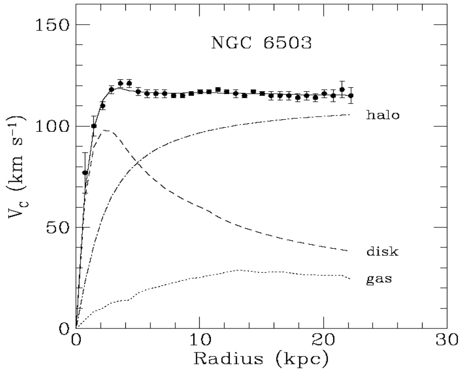
Galaxy Clusters

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



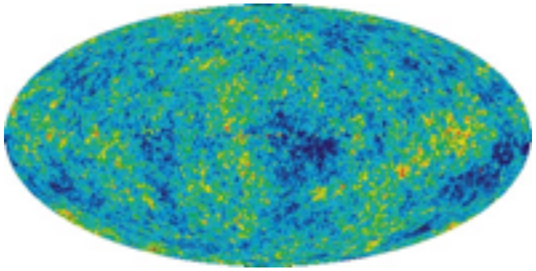


Strong Lensing



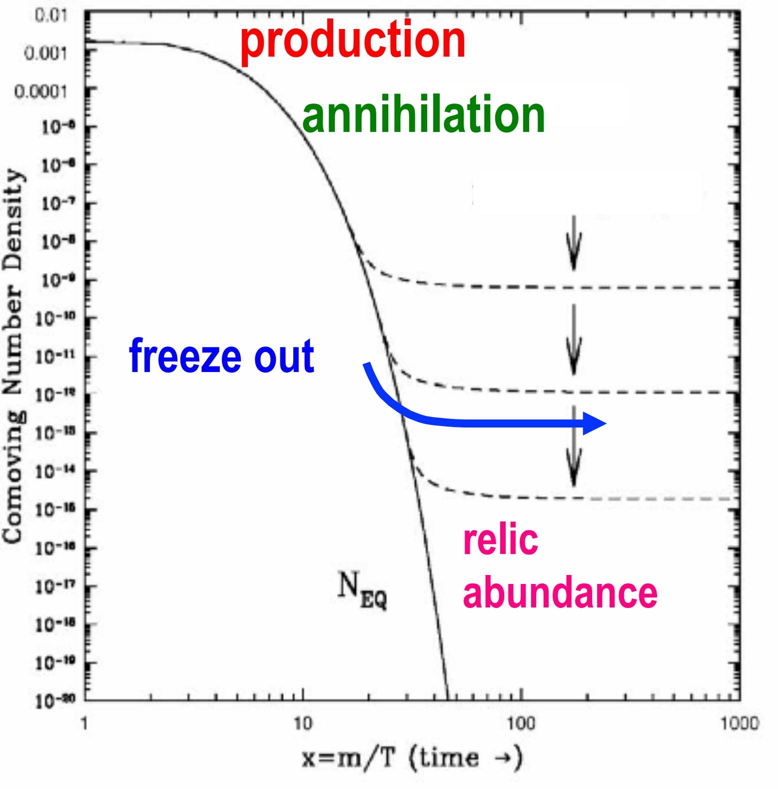
Galaxy Rotation Curves

We don't know what it actually is
mass / coupling / spin / composition / distribution in our galaxy…



Cosmic Microwave Background

A Particle Physics Explanation for Dark Matter



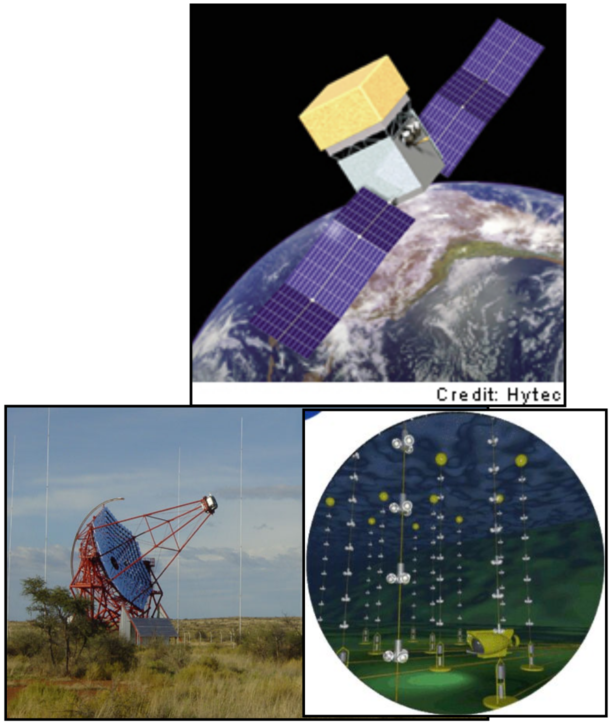
Weakly Interacting Massive Particles (WIMPs)

- 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

Many different experimental approaches!

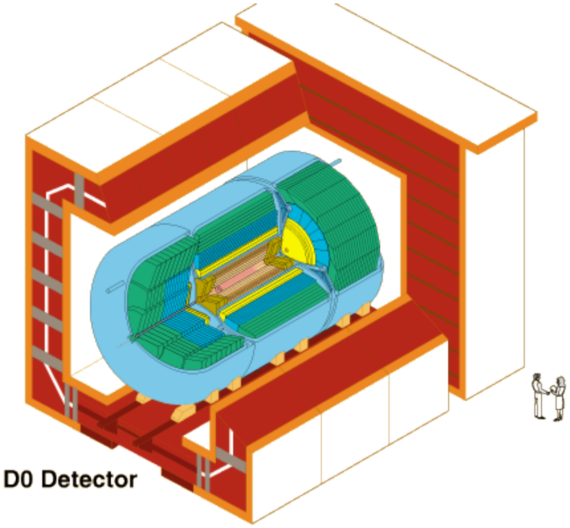
Direct Detection

Try to find WIMPS from the galactic halo passing through earthly laboratories.



Indirect Detection

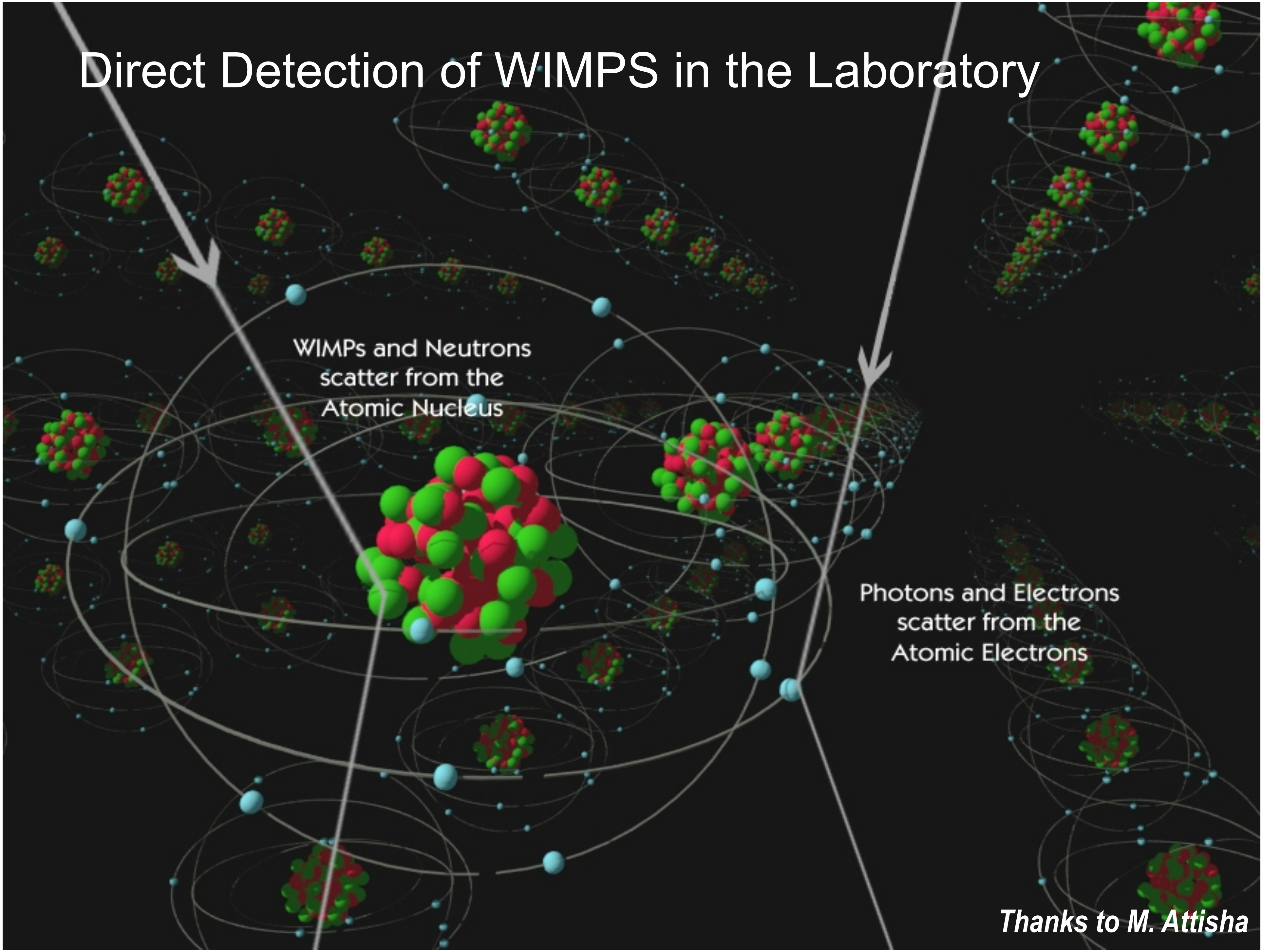
Look for evidence of WIMP annihilations to gammas, neutrinos, antiparticles occurring in our galaxy



Colliders

Try to produce WIMPS with accelerators

Direct Detection of WIMPS in the Laboratory



WIMPs and Neutrons
scatter from the
Atomic Nucleus

Photons and Electrons
scatter from the
Atomic Electrons

Thanks to M. Attisha

The Challenge of Direct Detection Experiments
Extracting Signal from Background

Expected WIMP signal:

elastic scattering from nuclei

nuclear form factors important

spin-independent cross section ~ A^2

exponential recoil spectrum ~ few 10's of keV

rates <0.1 events /kg/day

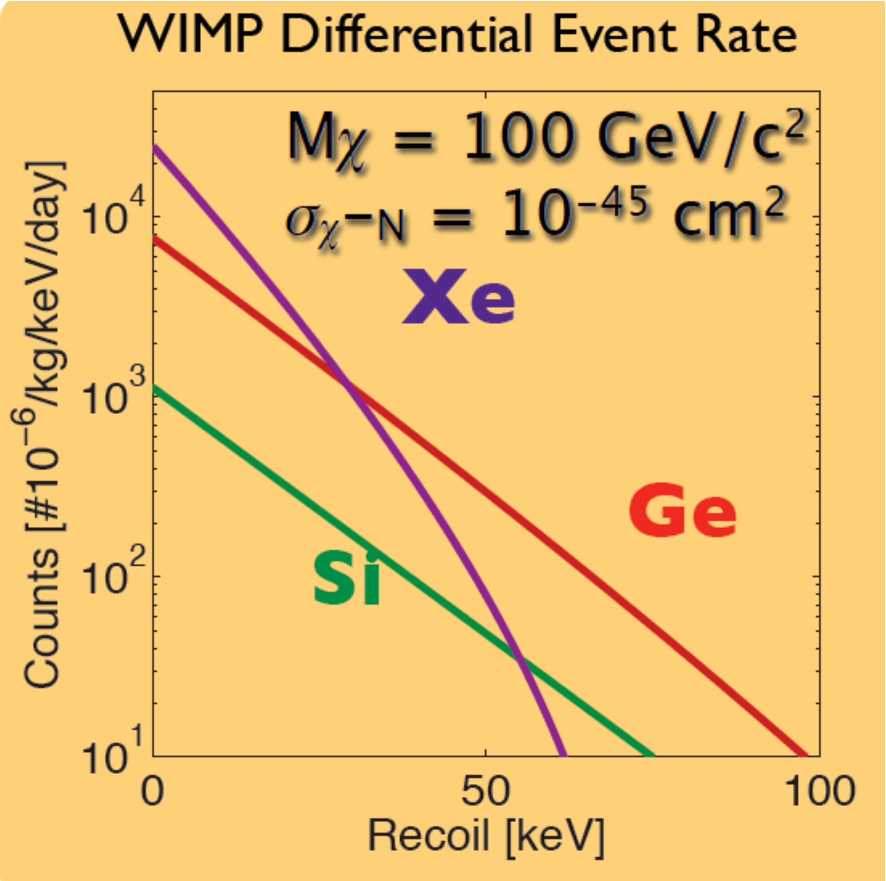
Experimental Challenges:

low energy thresholds (~10 keV)

mitigation of natural radioactive background

operation deep underground to avoid cosmics

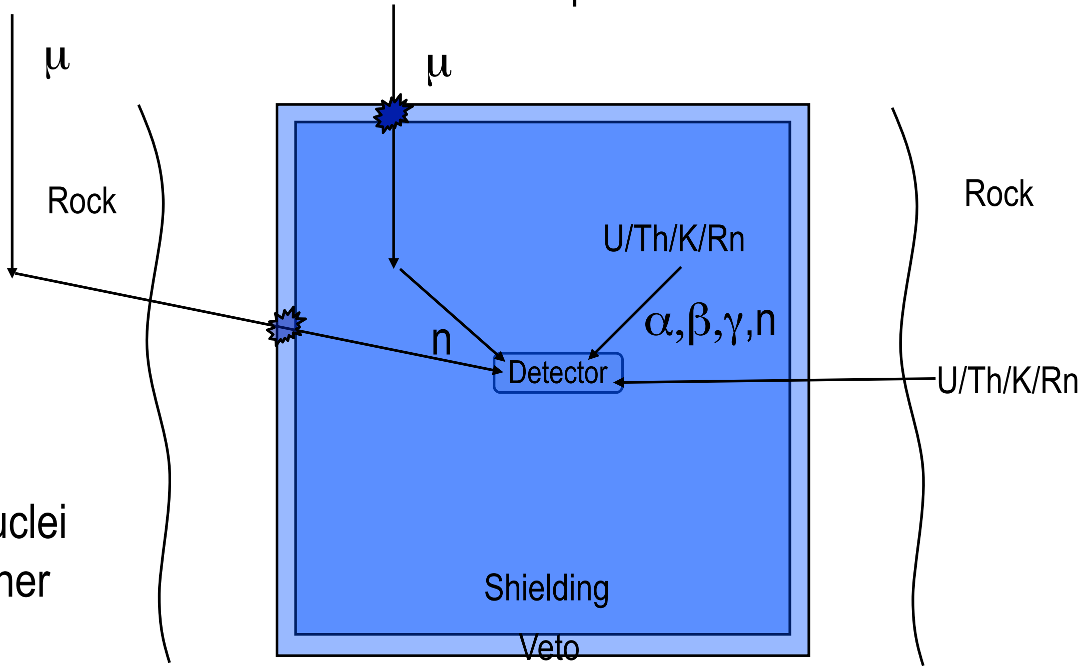
long exposures, scale to high mass



What are the backgrounds?

Cosmic rays

High energy particles from space hit the atmosphere and produce muons which can interact and cause showers of other particles



Neutrons

These interact elastically with nuclei in the same manner as WIMPS

Radioactivity

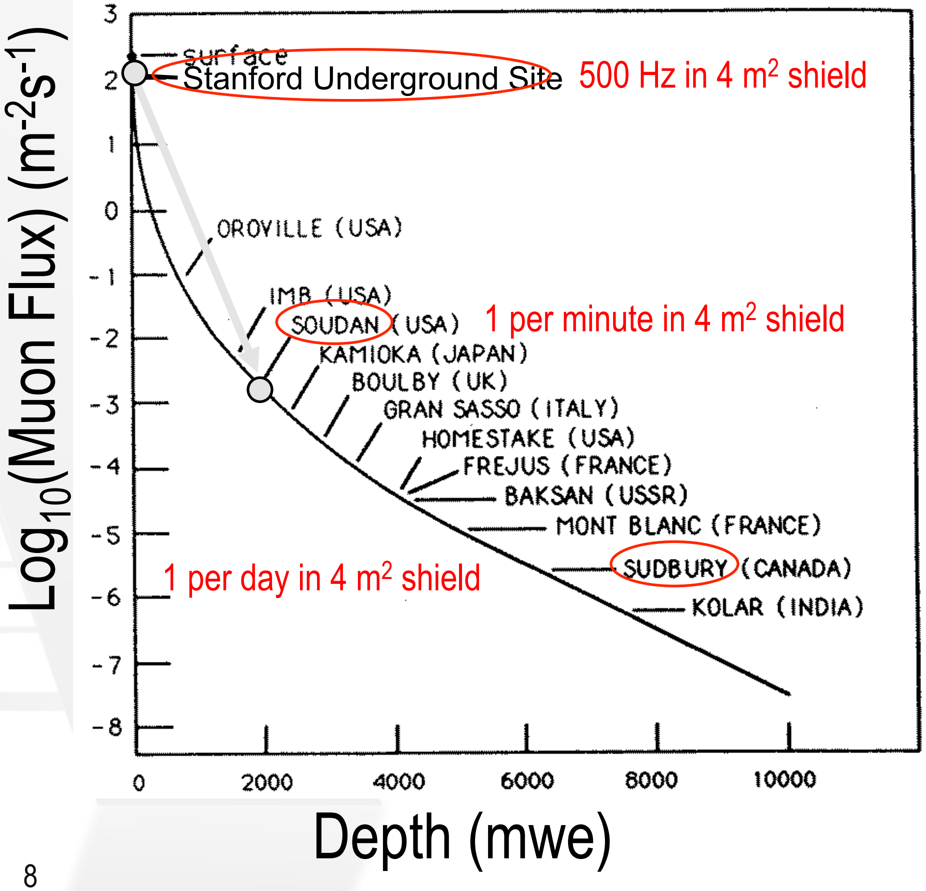
Long-lived isotopes of natural uranium, thorium, potassium produce α, β, γ, n

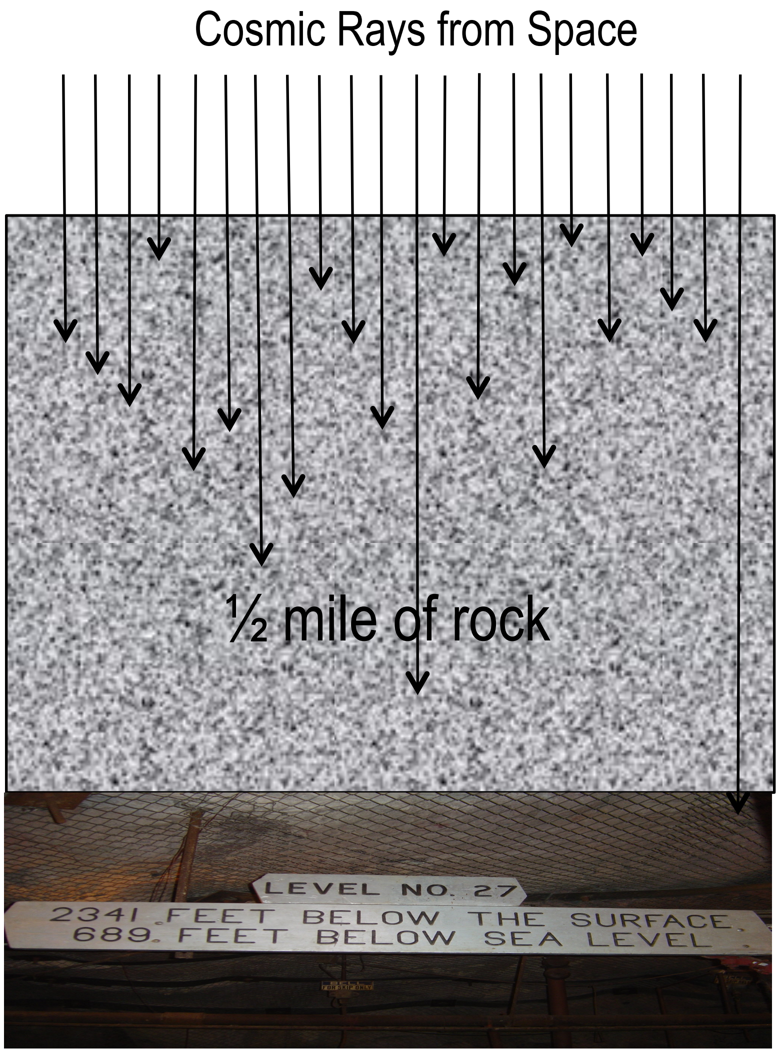
How do we guard against these backgrounds?

- Layered shielding to reduce rate of normal particles hitting detectors
- Lead, copper effective against alpha, beta, gamma rays
- Plastic and Water moderate neutrons from radioactivity
- Active veto and deep underground laboratories to reduce cosmic rays

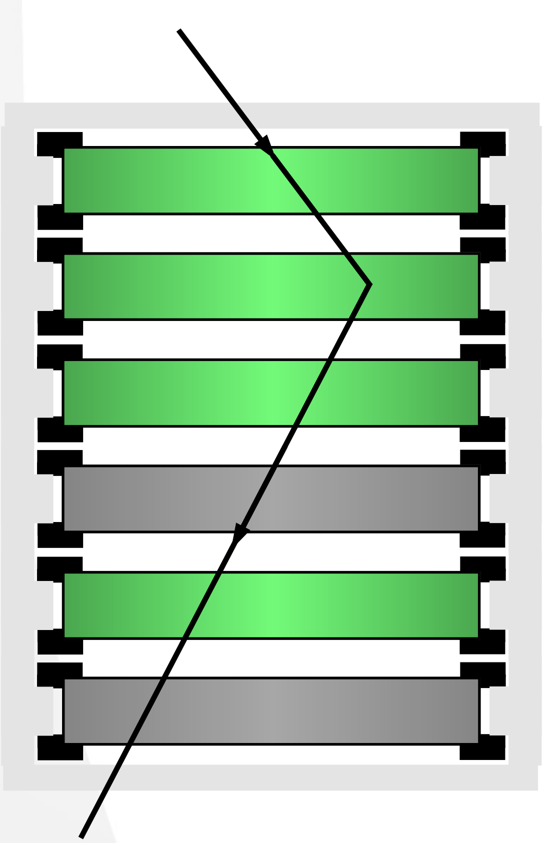
How to escape cosmic ray backgrounds - Go Deep

Cosmic ray muons in underground labs

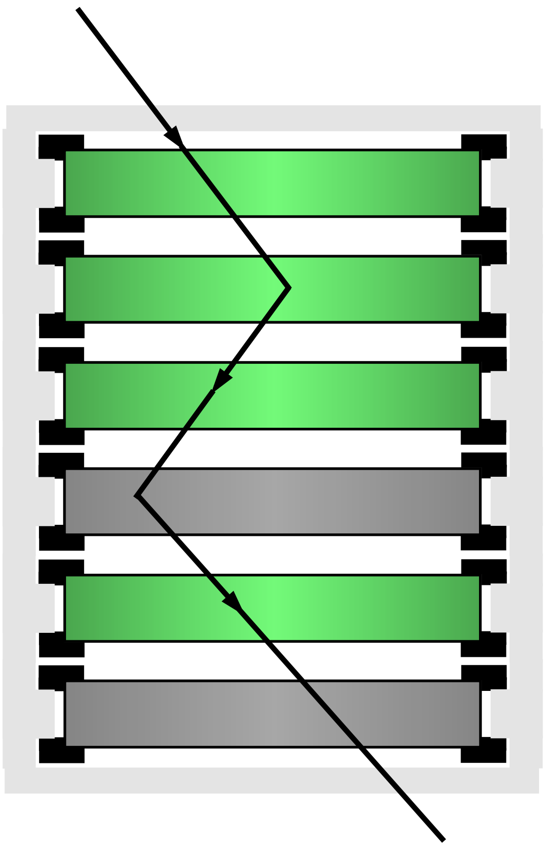




Multiple Scattering – a tool against residual neutrons



Single-scatter nuclear-recoils are produced by WIMPs or neutrons.



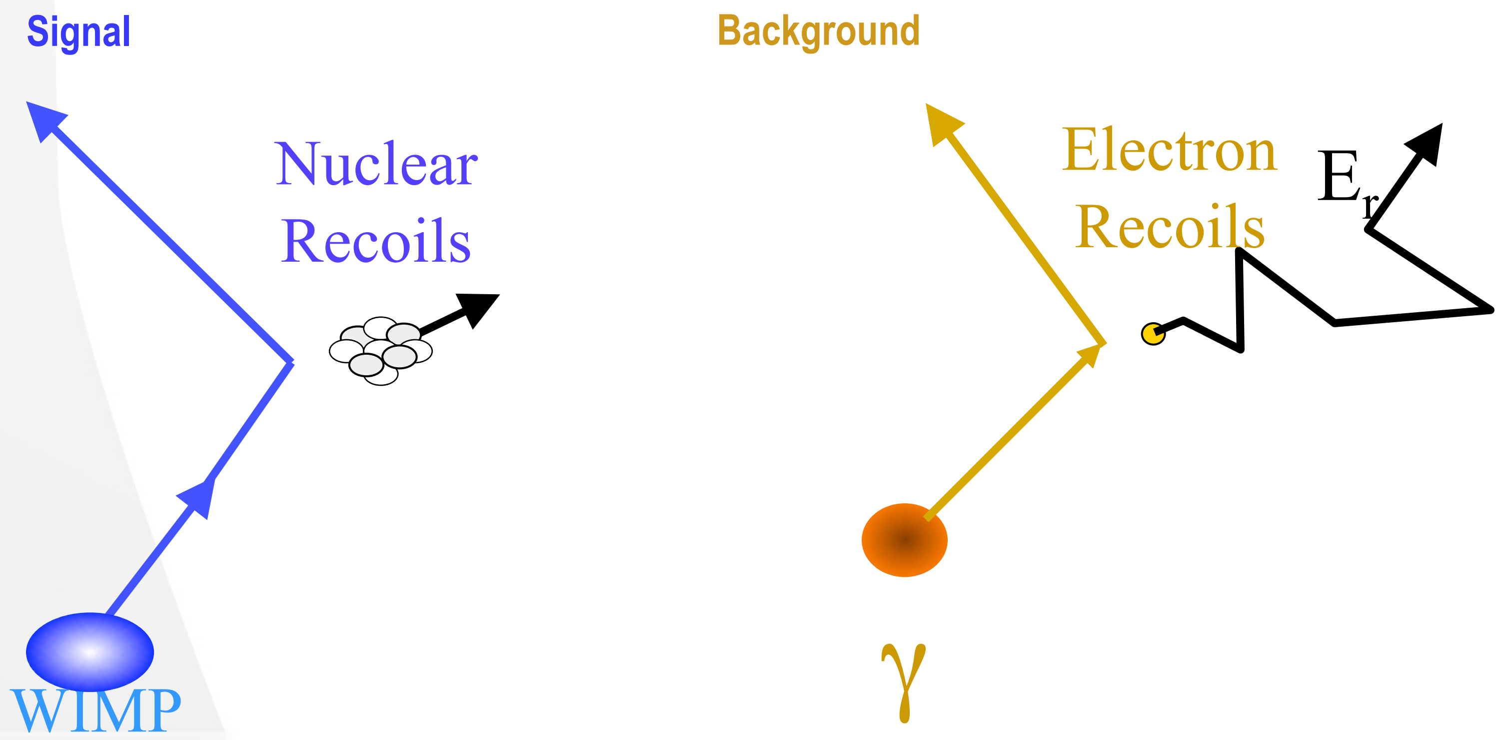
Multiple-scatter nuclear-recoils are only produced by neutrons.

In a typical experiment, ~ 1/3 of the neutrons may have detected multiple interactions

Active Background Discrimination

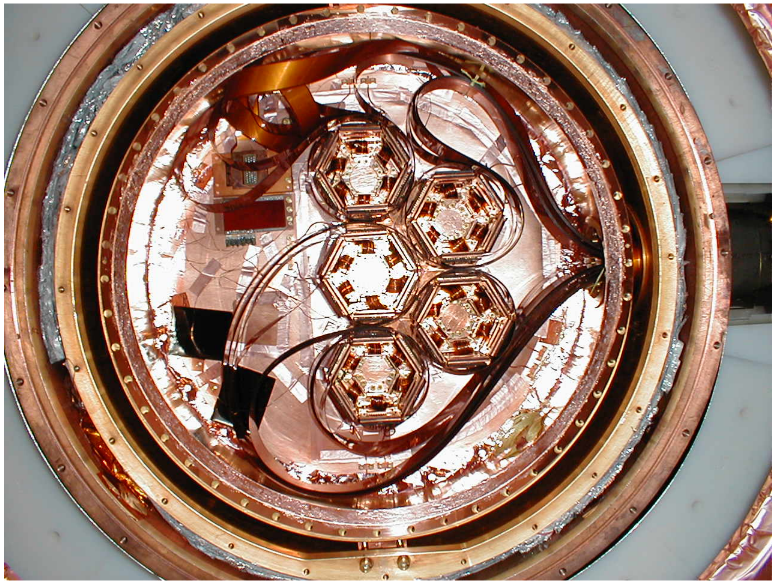
The variety in direct detection experiments comes primarily from how detectors distinguish background interactions from WIMP interactions

Most experiments detect particle interactions in two ways and compare (e.g. charge/phonon, charge/scintillation light, …)

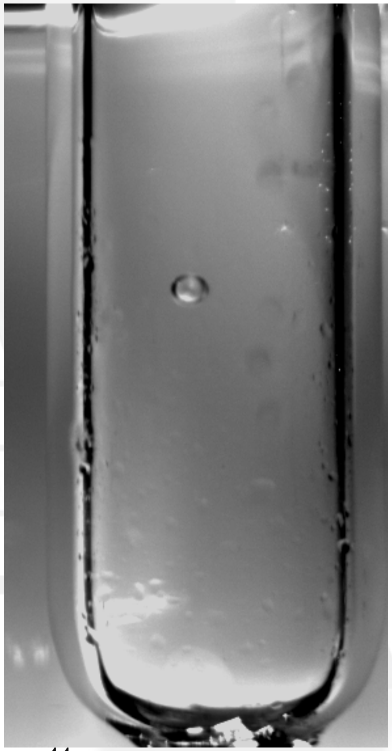


The Fermilab Direct Detection Experiments

CDMS

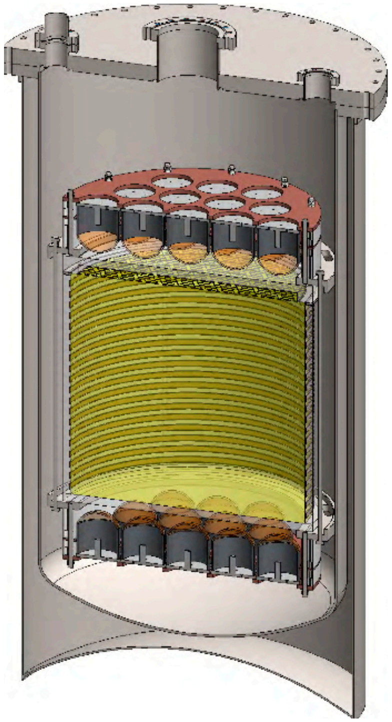


COUPP



DAMIC

DarkSide



Cryogenic Dark Matter Search (CDMS)
Low-Temperature Ge Detectors

3.7 FTEs

Fermilab Scientists and Roles

- Dan Bauer – Project and Operations Manager,
  Cryogenics, Shielding
- Jeter Hall – Electronics, Data Acquisition, Analysis
- Lauren Hsu – Software, Data Quality, Analysis
- Jonghee Yoo - Analysis
- Fritz DeJongh – Electronics
- Don Holmgren – Data Acquisition, Computing
- Erik Ramberg – Analysis

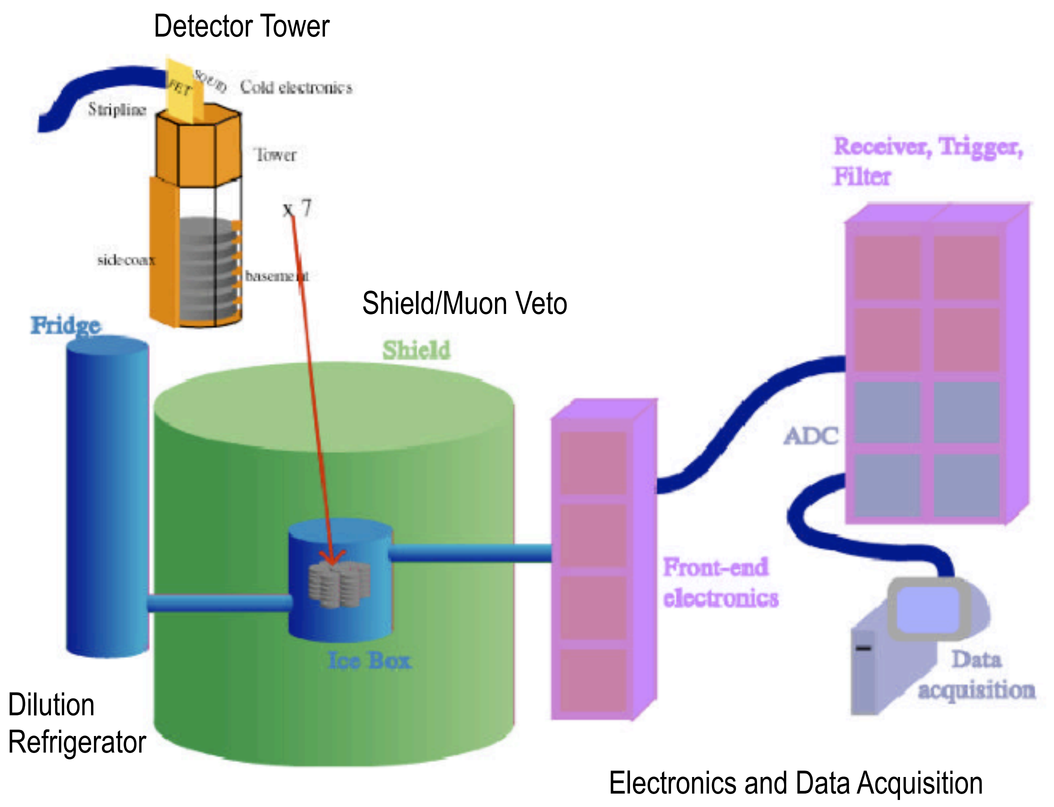
Fermilab History

- Involvement began in 1997
- Leadership role began with CDMS II at Soudan

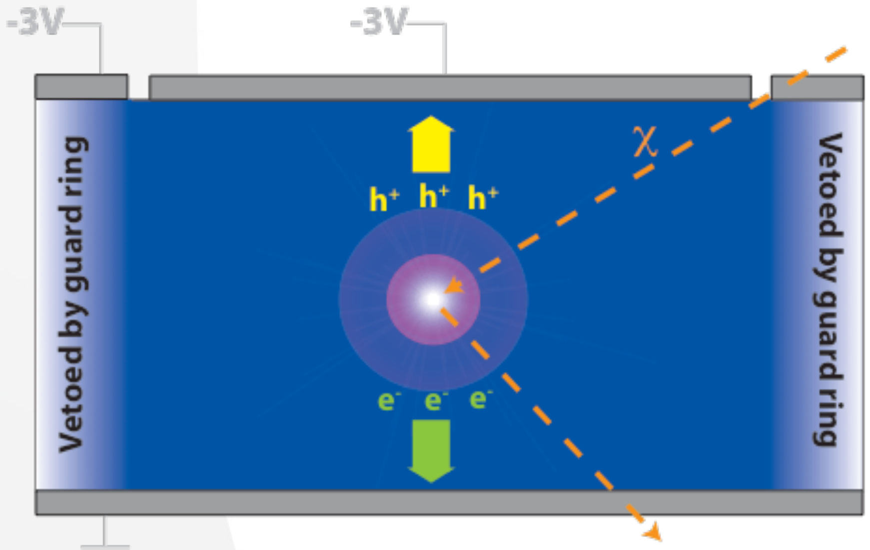
CDMS in a Nutshell

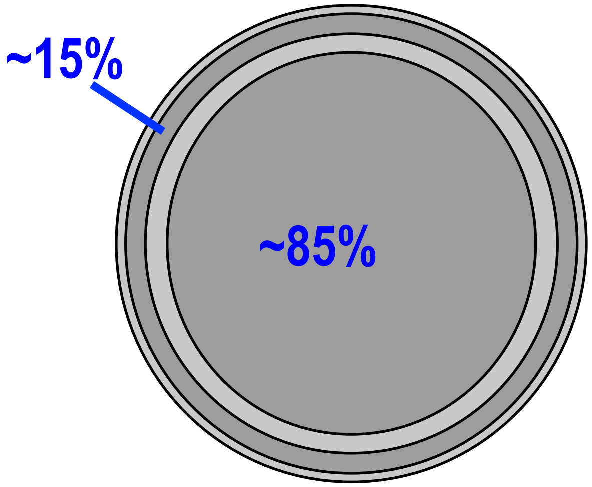
- Detectors
  - Pure Ge and Si crystals
  - Detect charge and phonon signals
  - Excellent background rejection
- Cryogenics
  - Cool to near absolute zero in order to measure single particle interactions.
- Layered Shielding and Veto
  - Reduce flux of radioactive decay particles near the detectors
  - Actively tag any interactions associated with cosmic rays

FNAL responsibilities include everything except the detectors



CDMS Detectors: Charge



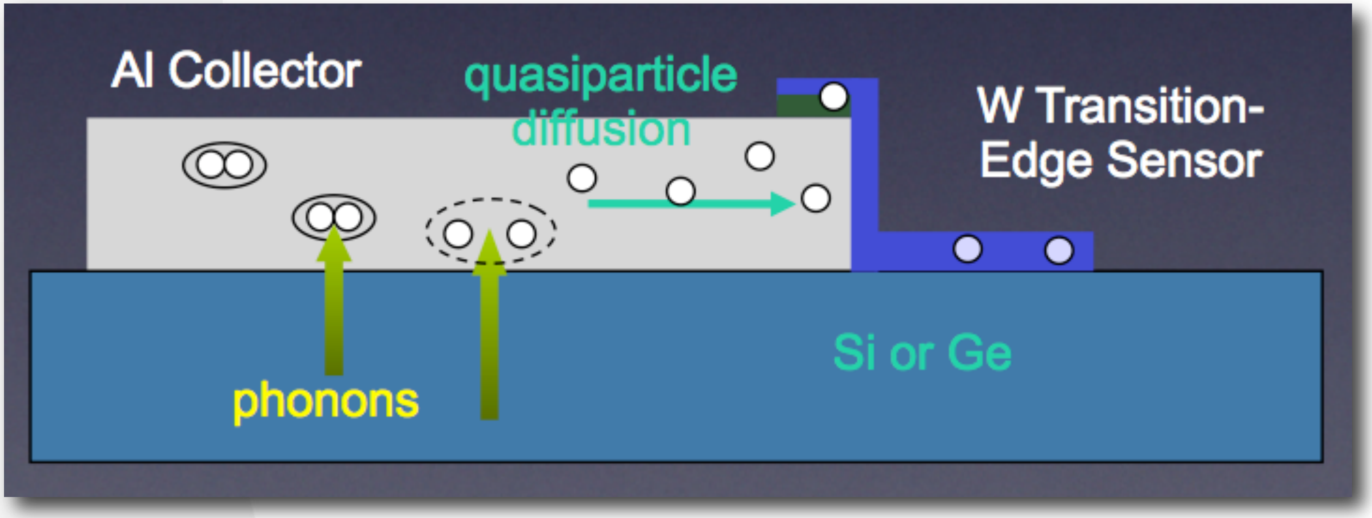


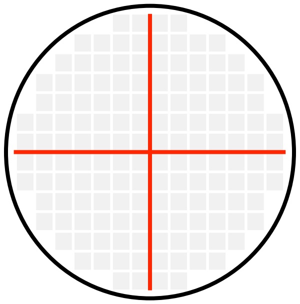
Charge electrodes on the bottom face of the Ge crystal

Inner Channel: ionization measurement

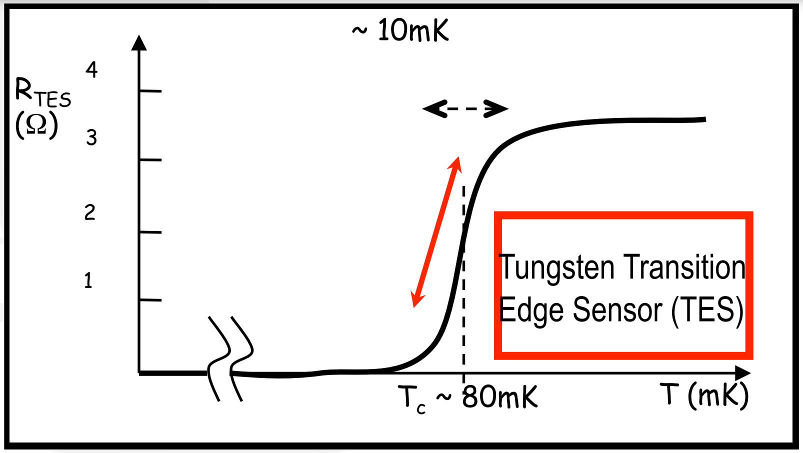
Outer Channel: fiducial volume definition

CDMS Detectors: Phonons



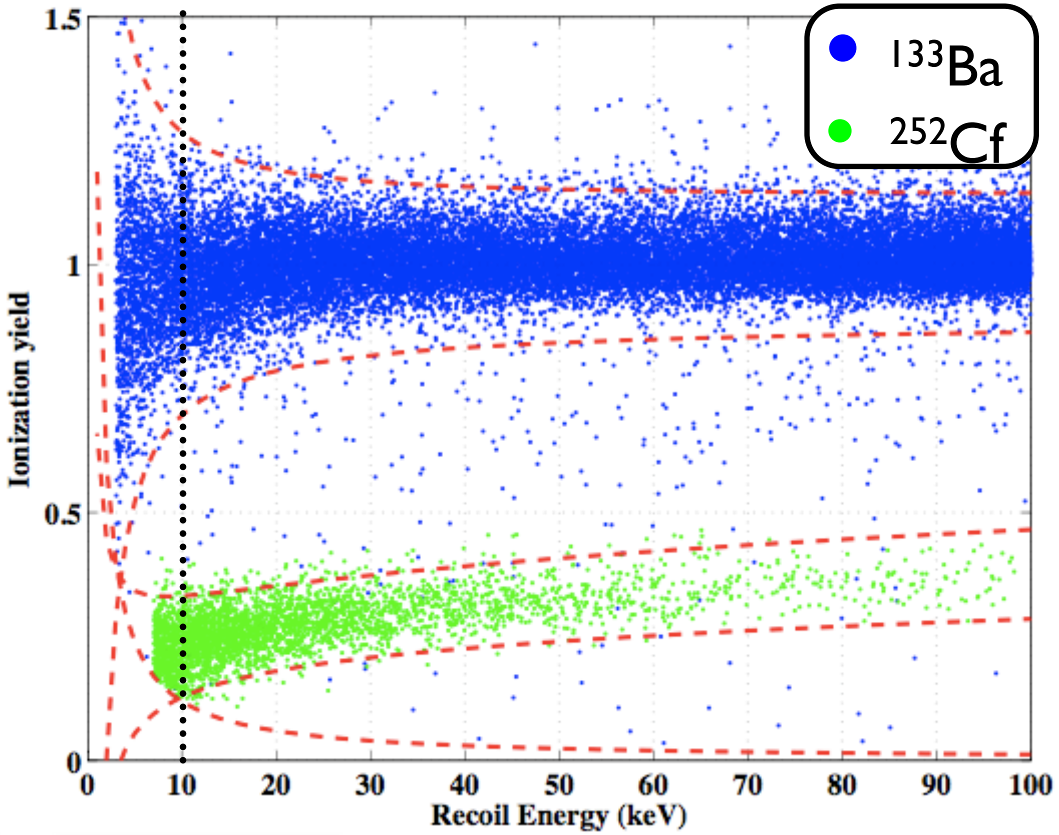


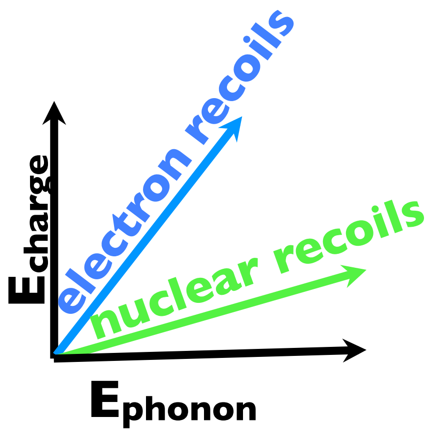
4 SQUID readout channels, each reads out 1036 TESs patterned on the bottom face of the Ge crystal



Phonons are crystal lattice vibrations (very high frequency sound), but we measure them with very sensitive thermometers.

CDMS Gamma Rejection



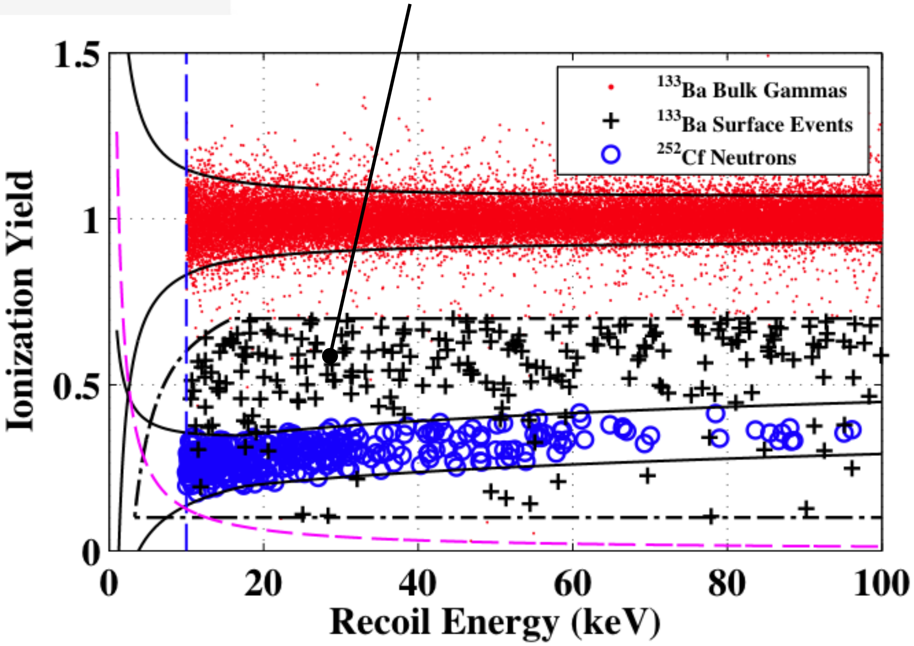


$$\text{ionization yield} = \frac{E_{charge}}{E_{phonon}}$$

BETTER THAN 1:10^4 rejection of gammas based on ionization yield alone

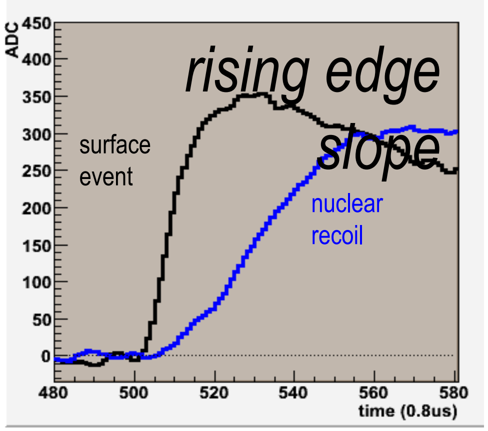
CDMS Surface Event Rejection

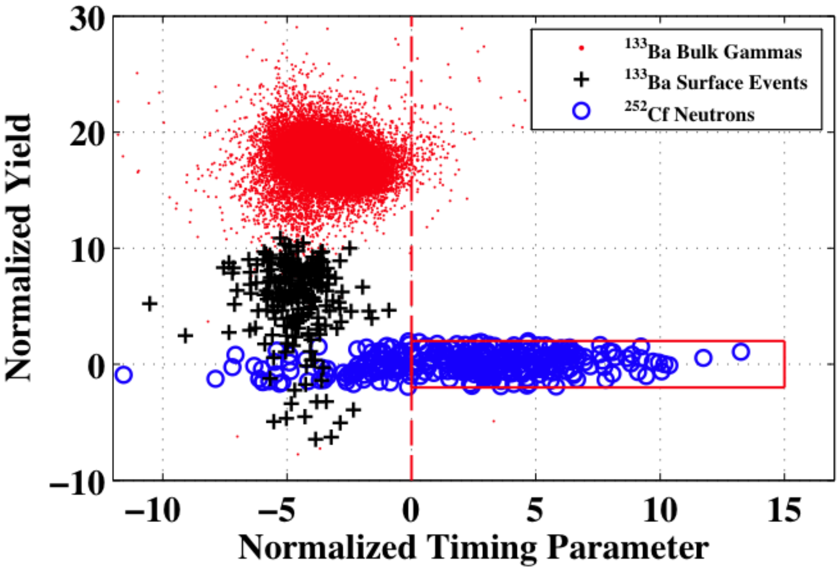
10 μm “dead layer” results in reduced ionization collection



These events are primarily due to electrons and soft x-rays originating from Radon daughters on faces of the detectors and nearby materials

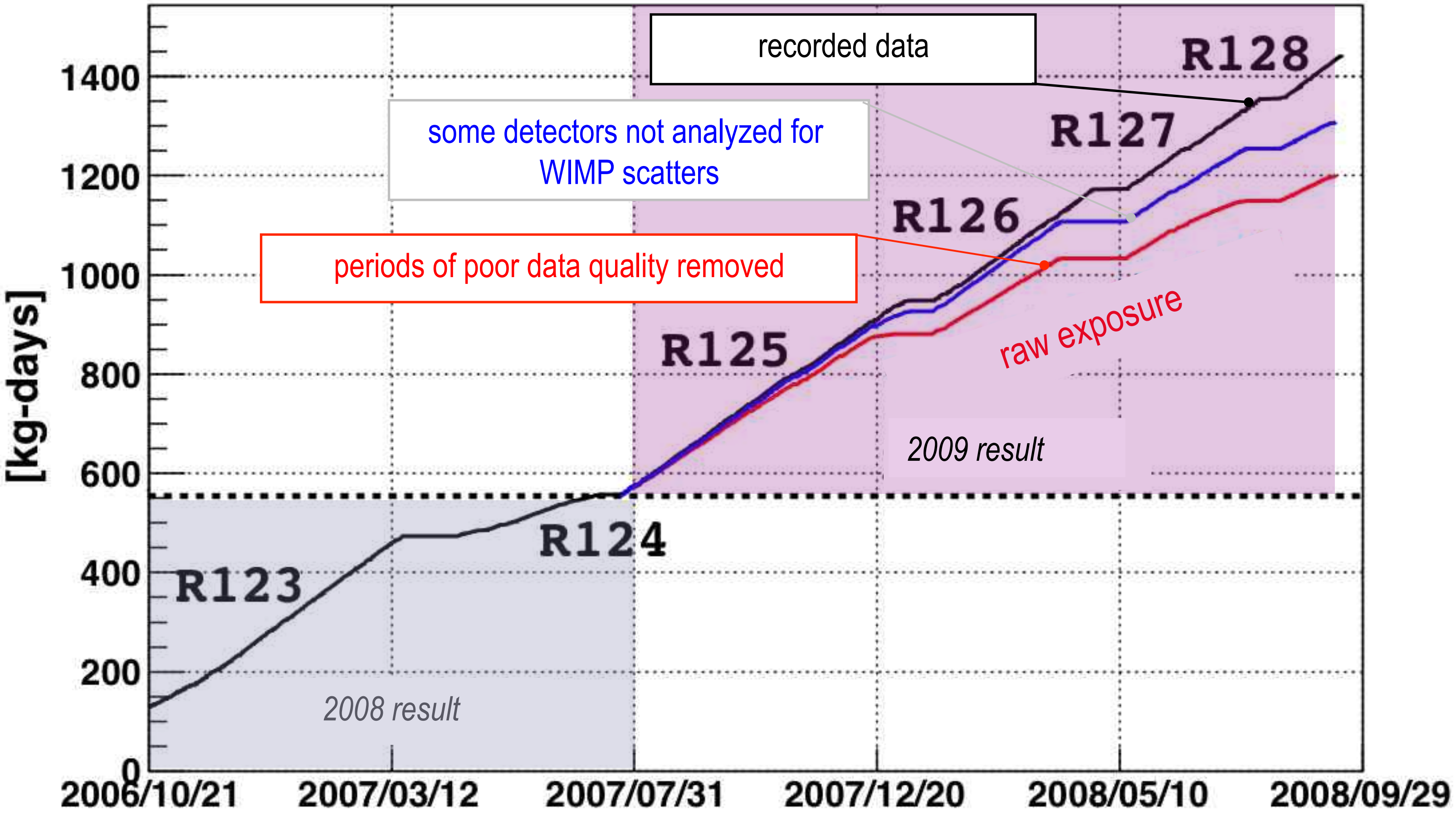
Phonon pulse shape (timing) distinguishes surface events



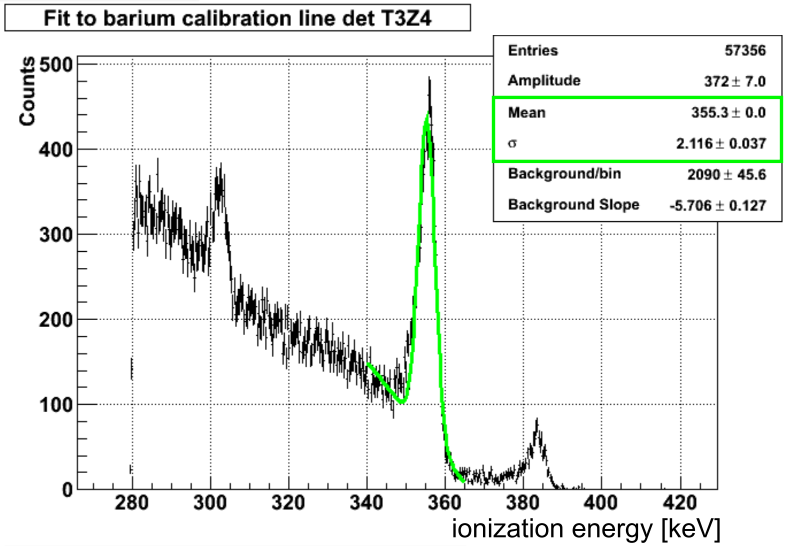


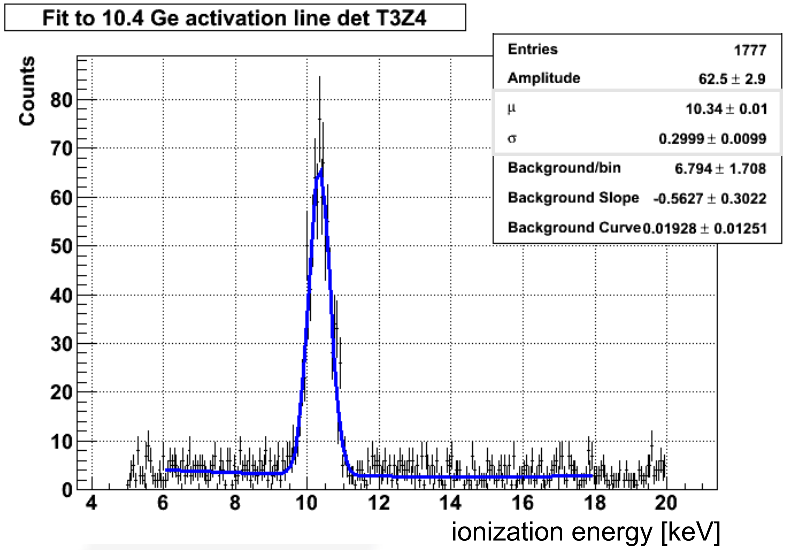
CDMS has many years of data from Soudan

Dan Bauer, Jeter Hall and Lauren Hsu lead CDMS operations, data monitoring/quality groups



‘In-situ’ calibration is key to understanding detectors





Two Sources:

^{133}Ba: γ-lines at 303, 356 & 384 keV

^{252}Cf: neutrons ~few MeV, neutron activation of Ge → 10.4 keV γ-line

Many Uses:

In-situ measurement of energy scale

resolution and linearity

position correction

set cuts & measure selection efficiencies

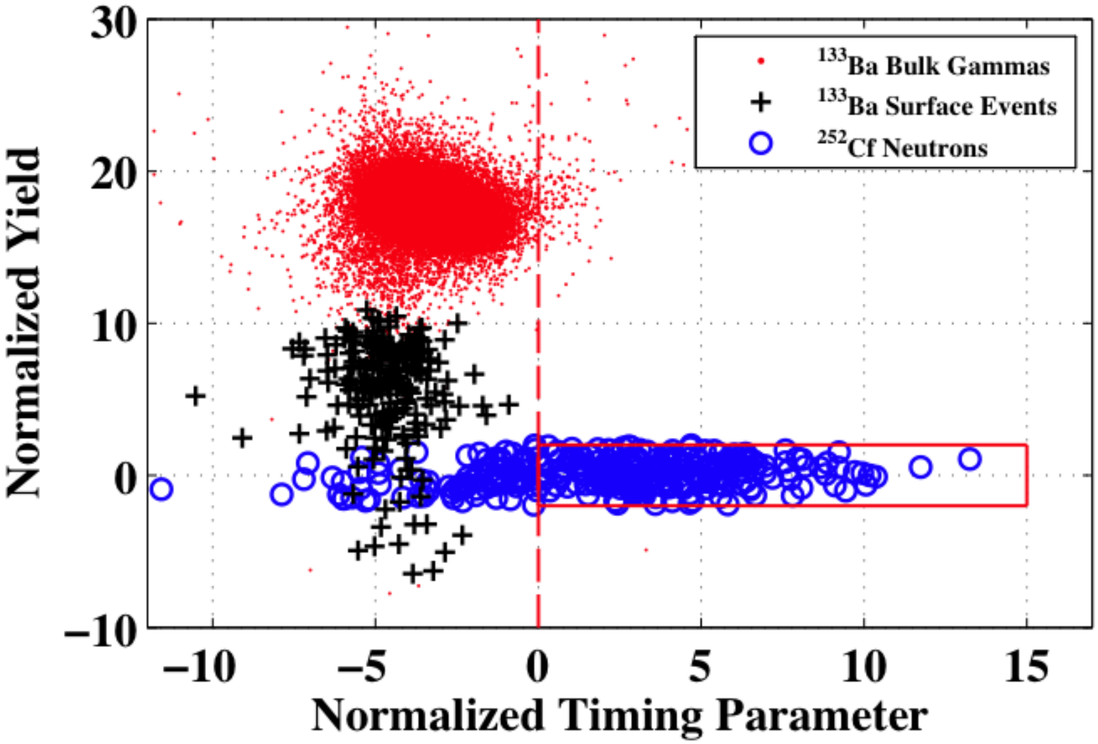
develop surface event rejection (^{133}Ba ~40X the number of WS events)

Note the really good energy resolution at 10 keV

Analysis Strategy for a Rare Event Search

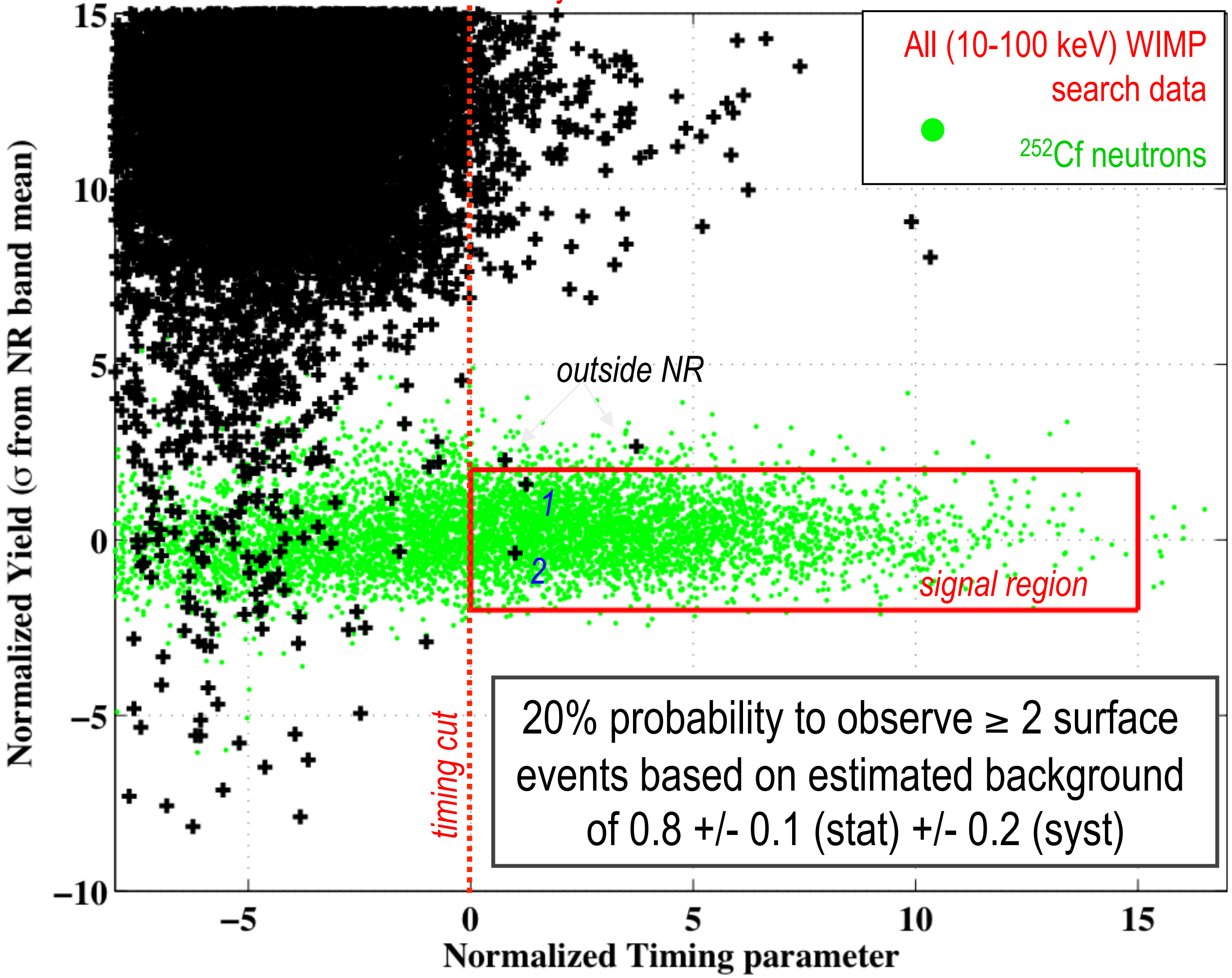
- “Blind” Analysis
  - Data quality
    - Make certain that each data set is stable and well understood
  - Event Selection
    - Determine cuts without looking in the signal region
  - Leakage Estimate
    - Predict how many background events there will be in the signal region
  - Open the box
    - Are there WIMP candidates?
- Avoids Bias
  - All rare event searches should employ blinding for credibility

^{252}Cf neutron & ^{133}Ba gamma source calibrations



Interesting New Result – Dec 18, 2009

Lauren Hsu was a leader in this analysis and announced the result at a Fermilab seminar

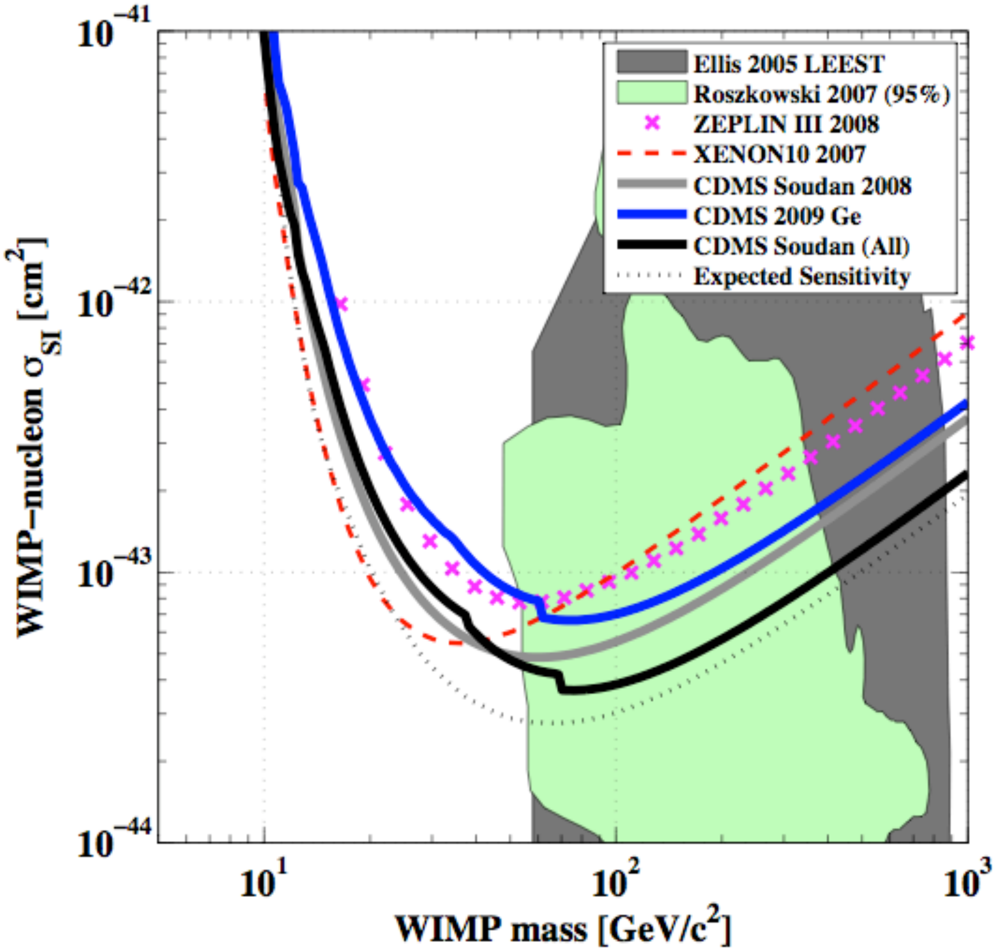


20% probability to observe ≥ 2 surface events based on estimated background of 0.8 +/- 0.1 (stat) +/- 0.2 (syst)

Limits on Spin-Dependent WIMP Interactions

Although we see 2 events with the characteristics of a WIMP scatter, we cannot interpret the results of this analysis as significant evidence for WIMP interactions.

Upper limit at the 90% C.L. on the SI WIMP-nucleon cross-section is **3.8 x 10^{-44} cm^2** for a WIMP of mass **70 GeV/c^2**



Fermilab

Recent CDMS Papers

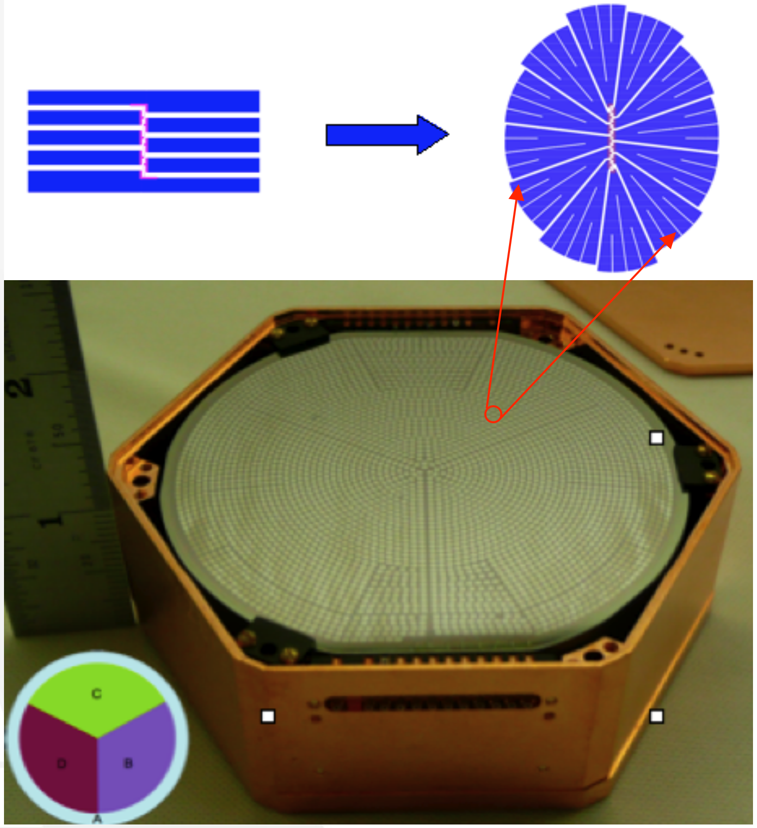
Dark Matter Search Results from the CDMS II Experiment.
Science 327:1619-1621,2010 and arXiv: 0912.3592 [astro-ph]
Limits on WIMPS and Inelastic Dark Matter models
Key FNAL contributions from Lauren Hsu, Jeter Hall

Analysis of the low-energy electron-recoil spectrum of the CDMS experiment
Phys.Rev.D81:042002,2010 and arXiv: 0907.1438 [astro-ph]
No evidence for low energy photons from decaying dark matter
Important contributions from Jonghee Yoo (FNAL)

Search for Axions with the CDMS Experiment
Phys.Rev.Lett.103:141802,2009 and arXiv:0902.4693 [hep-ex]
Rule out parameter space for axion couplings to photons (solar axions) and electrons (galactic axions)
Work led by Jonghee Yoo (FNAL)

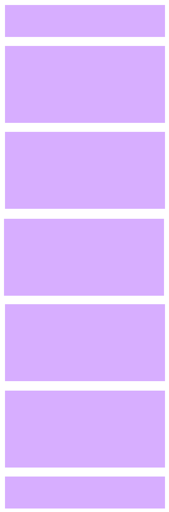
The current experiment – SuperCDMS Soudan

~10 kg fiducial mass at Soudan, arranged as 5 SuperTowers

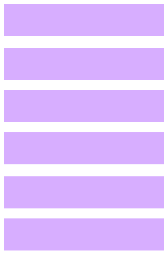


“mercedes” zip = mZIP

SuperTower



CDMSII Tower



- 2.5X thicker (1-inch) Ge crystals
- “endcap” Ge veto detectors in each tower

- modified Al fin layout, improves phonon collection efficiency
- cleaner, simplified, and streamlined production
- new phonon sensor layout, outer phonon “guard”

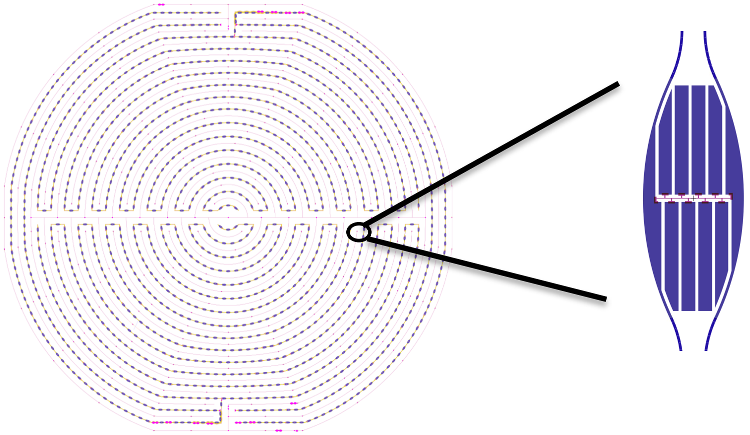
Breakthrough in CDMS Detectors - iZIPs

iZIP = interleavened charge and phonon channels

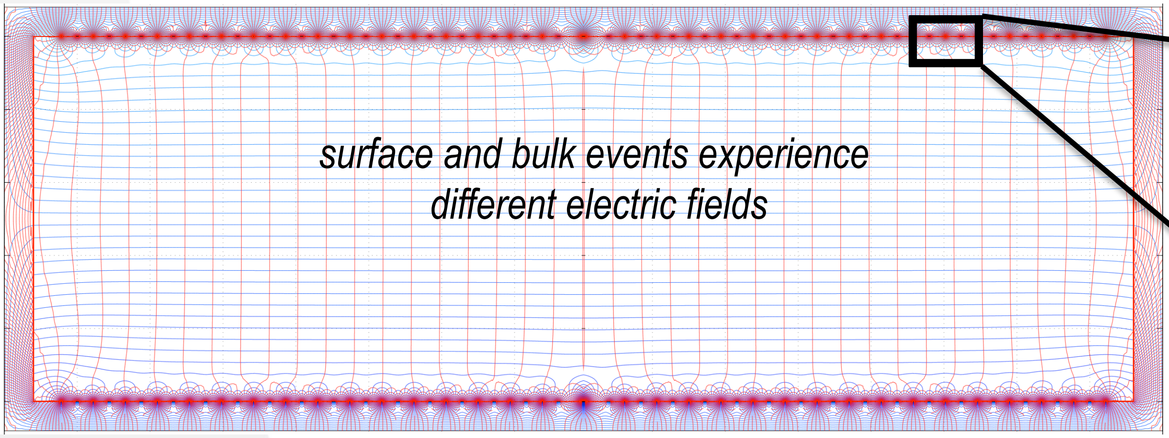
Rejection of surface events > x30 better than single-sided detectors

Fiducial volume x2 better than CDMS II (~80% of the crystal)

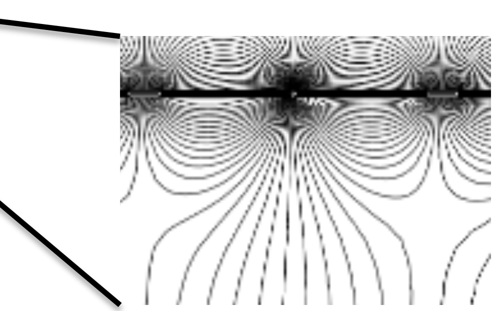
At least 3 iZIP towers will be included in SuperCDMS Soudan



Closeup of phonon sensor



surface and bulk events experience different electric fields



Charge near surface is collected by electrodes on only one side

The Future – SuperCDMS SNOLAB

Propose new experimental apparatus at SNOLAB

- x3 deeper than Soudan => no cosmogenic neutron background
- Up to 200 kg of Ge target mass in cryostat
- Reduced radioactive backgrounds due to material selection
- Larger iZIP detectors 4” diameter x 1.3” thick, 1.5 kg each
- Need ~75 detectors for 100 kg experiment
- Challenge is to keep costs down and build detectors quickly

Strong contender in the ‘generic’ dark matter CD process

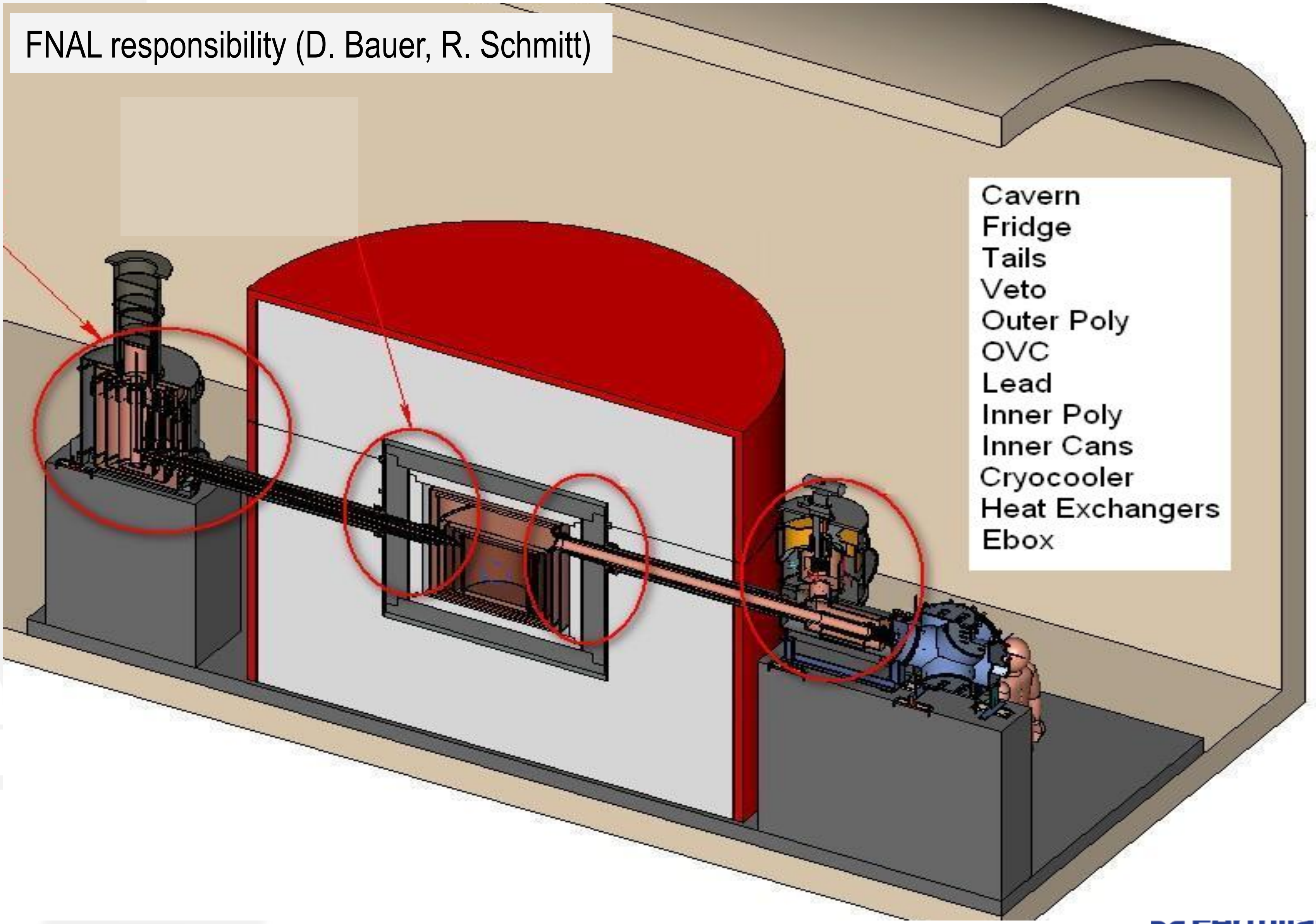
- FNAL will manage the project, and cryogenics, shielding, DAQ
- SLAC joins to lead production of the Ge towers
- Significant Canadian involvement (Queens, SNOLAB)
- DOE and NSF supported University group contributions vital

SuperCDMS SNOLAB
Our new home in Canada awaits us!

Dan Bauer, Fermilab, DOE KA13 Review

SuperCDMS SNOLAB Cryogenics and Shielding

FNAL responsibility (D. Bauer, R. Schmitt)



Cavern
Fridge
Tails
Veto
Outer Poly
OVC
Lead
Inner Poly
Inner Cans
Cryocooler
Heat Exchangers
Ebox

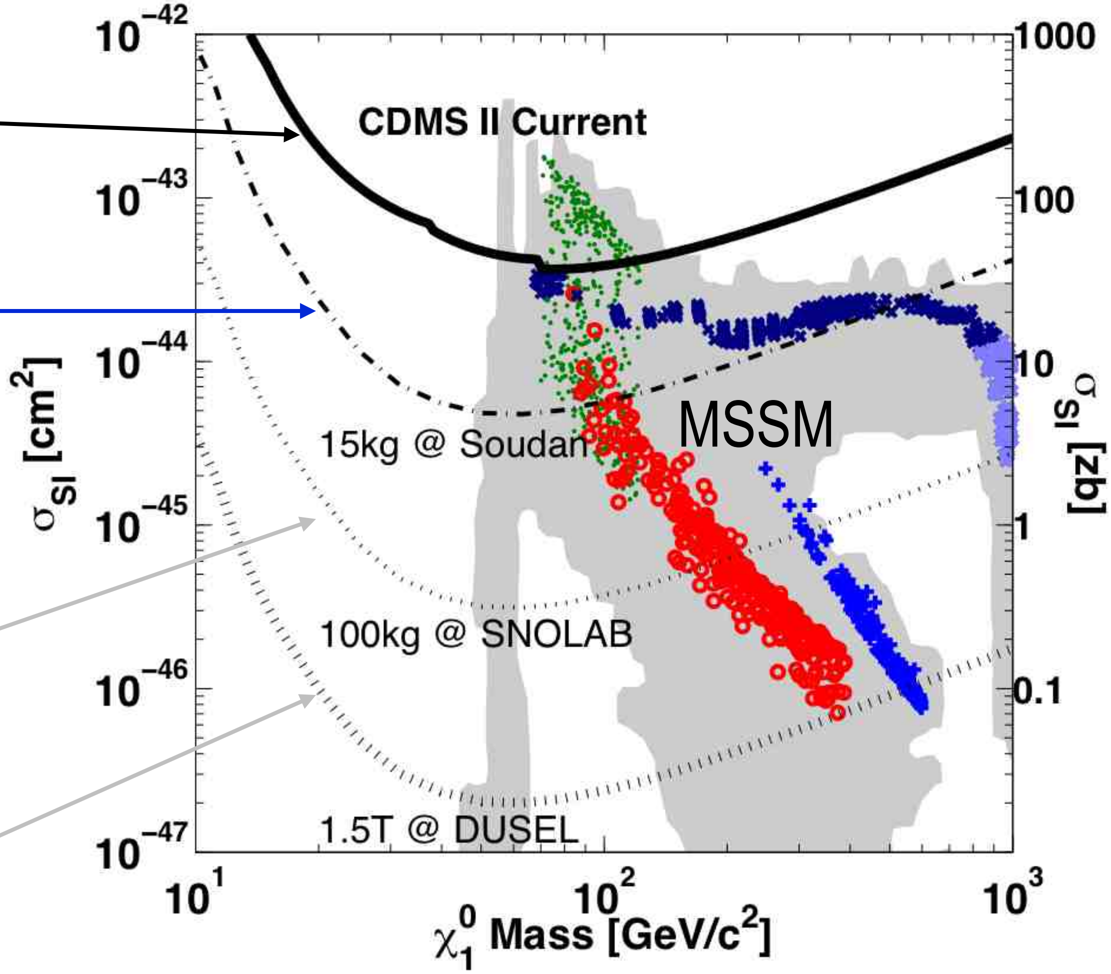
CDMS Future Projections

<u>CDMS II</u>
4 kg Ge
~ 2 yrs operation

<u>SuperCDMS @ Soudan</u>
15 kg Ge
~ 2 yrs operation

<u>SuperCDMS @ Snolab</u>
100 kg Ge
~ 2 yrs operation

<u>DUSEL/GEODM</u>
1.5T



iZIPs should be good enough for ton-scale experiment!
Will need to make larger detectors (6” diameter feasible)

The CDMS Scientists

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** new collaborators or new institutions in SuperCDMS*

Chicagoland Observatory for Underground Particle Physics (COUPP)
Bubble Chambers

Fermilab Scientists

Andrew Sonnenschein – Project Manager

Mike Crisler – 4 kg bubble chamber

Hugh Lippincott – 60 kg chamber operations, analysis

Steve Brice – 4 kg SNOLAB deployment, analysis

Peter Cooper – 60 kg chamber DAQ and analysis

Erik Ramberg – NUMI site, infrastructure, veto

Jeter Hall – 4 kg analysis, veto

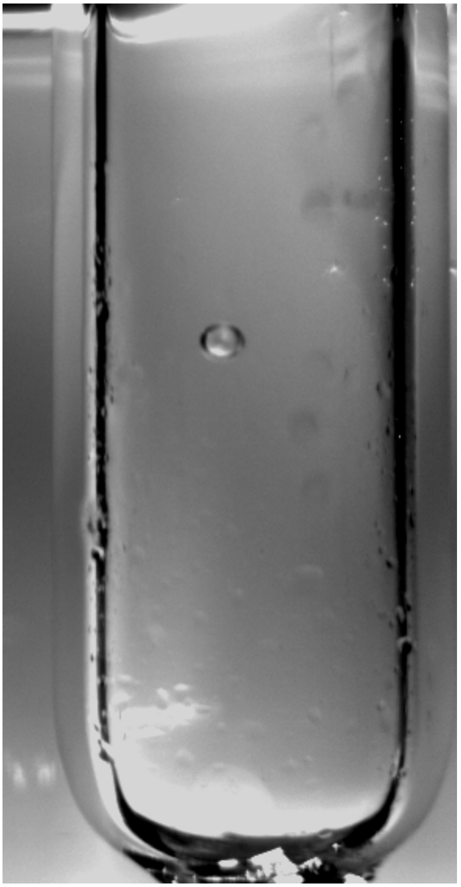
Dan Broemmelsiek – Camera, DAQ

3.2 FTEs

Fermilab History

Fermilab involvement began in 2004

Why Bubble Chambers?



1. Large target masses

   Multi ton chambers were built in the 50's- 80's.

2. Choice of target nuclei

No liquid that has been tested seriously has failed to work as a bubble chamber liquid (Glaser, 1960)

   Most common: Hydrogen, Propane

   But also "Heavy Liquids": Xe, Ne, CF_3I

   Good targets for both spin-dependent and

   spin-independent scattering

   Possible to "swap" liquids to check suspicious signals

3. Low energy thresholds

   <10 keV threshold achievable

4. Background Suppressions

   Immune to electromagnetic backgrounds

The Technique

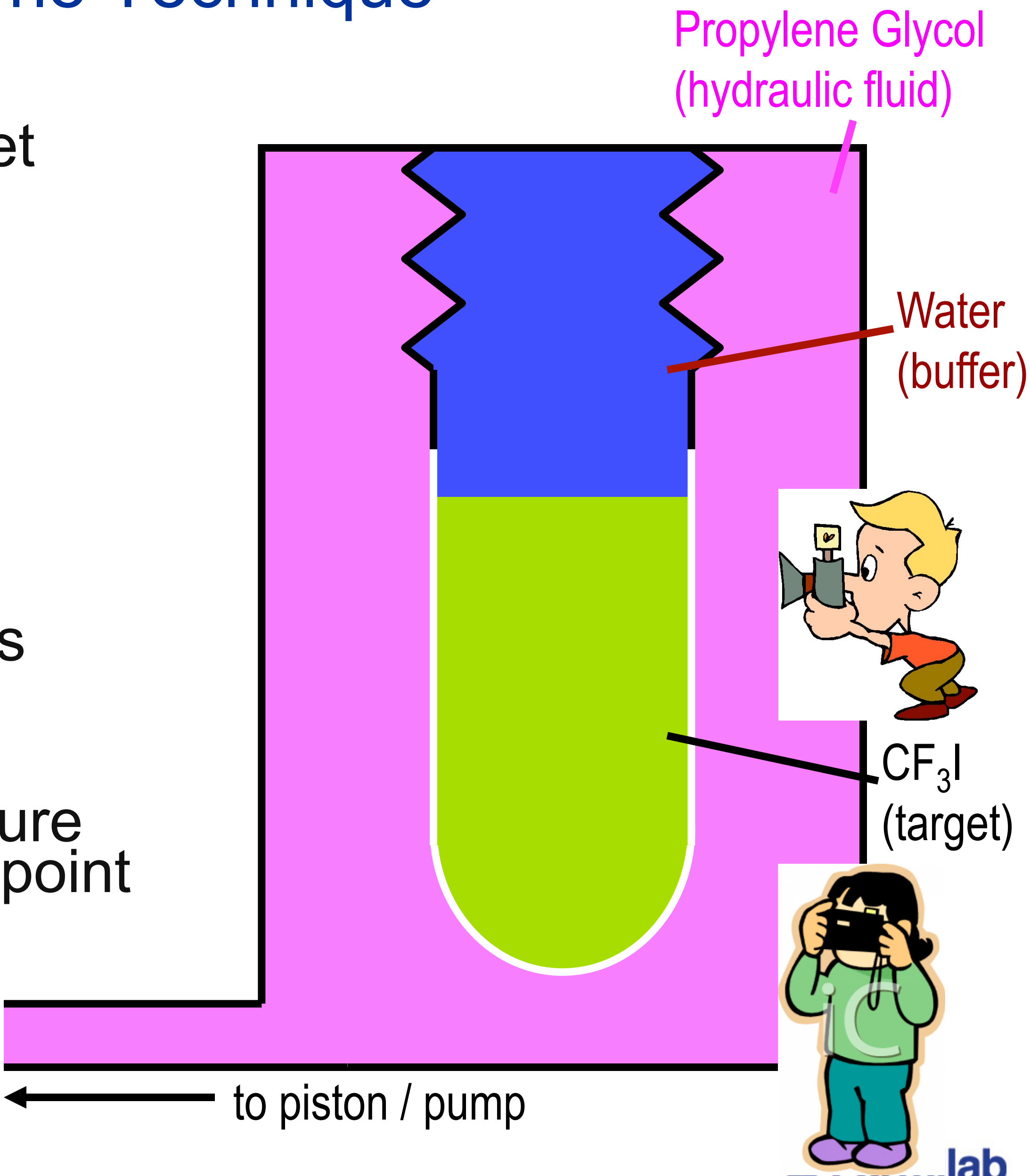
Superheated CF_3I target

Particle interactions nucleate bubbles

Cameras capture stereoscopic bubble images

Chamber recompresses after each event

Pressure and temperature define the operating point



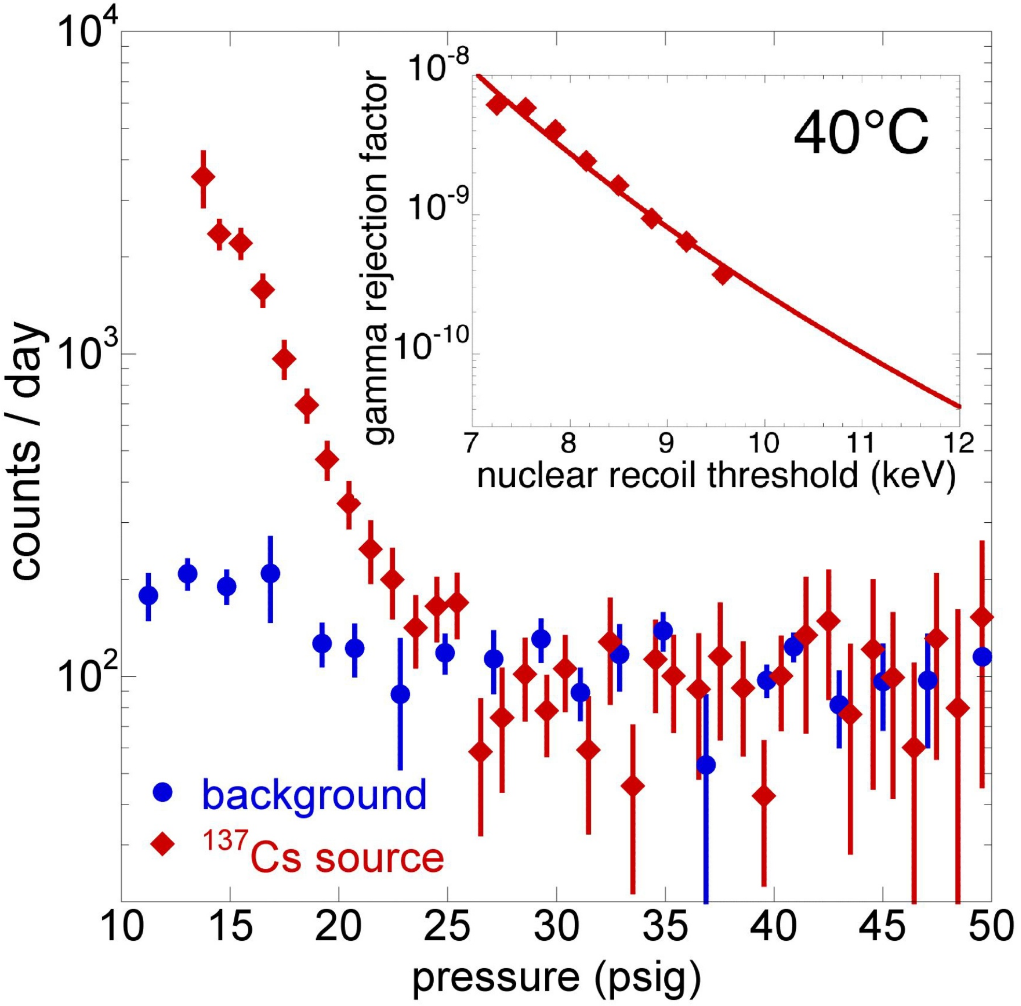
Thresholds for Bubble Nucleation

Only proto-bubbles with sufficient energy and dE/dx grow to macroscopic sizes

γ's or β's do not ☺

Nuclear recoils do ☺

α's also do ☹



Fermilab

Progress in Bubble Chamber R&D

Continuing R&D on larger, cleaner bubble chambers; science along the way!

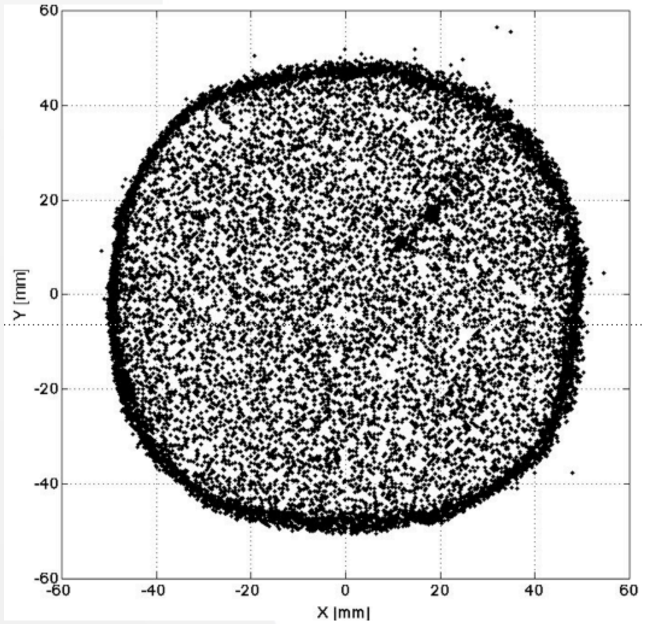
Important test bed in the NUMI underground hall

Ultimate goal is ton-scale bubble chamber

Date	**2003**	**2005**	**2007**	**2009**	**2011**
Mass (kg)	0.018	2		4	4, 60
Site	Chicago	NUMI	NUMI	NUMI	SNOLAB, NUMI
Depth (mwe)	10	300	300	300	6000
Backgrounds (/kg/day)	7000	77	7	0.7	0.1 or lower
Technical	Continuously sensitive bubble chamber	Pressure control	Metal seals, radon eliminated	Synthetic silica, high purity fluid handling	Acoustic discrimination
Publications		*Science* **319**:93(2008)		arXiv: 1008.3518	

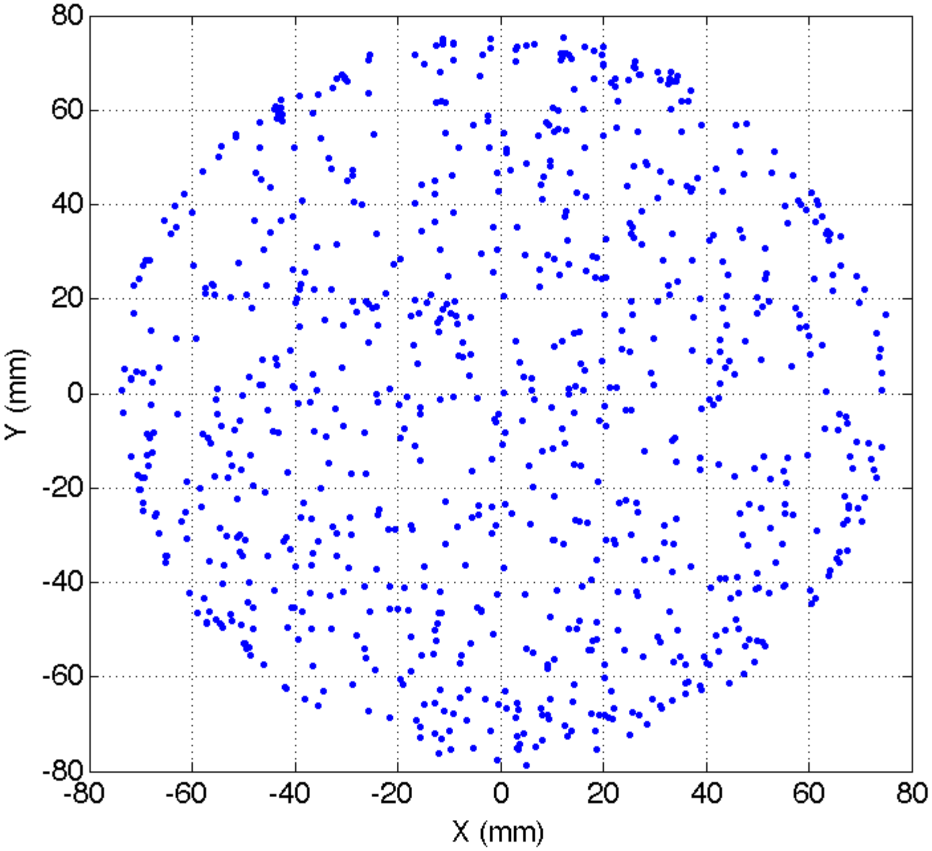
Reducing Alpha Backgrounds via Material Selection

Natural Quartz: 0.8/day/cm^2



~40 live-days
(2007-08)

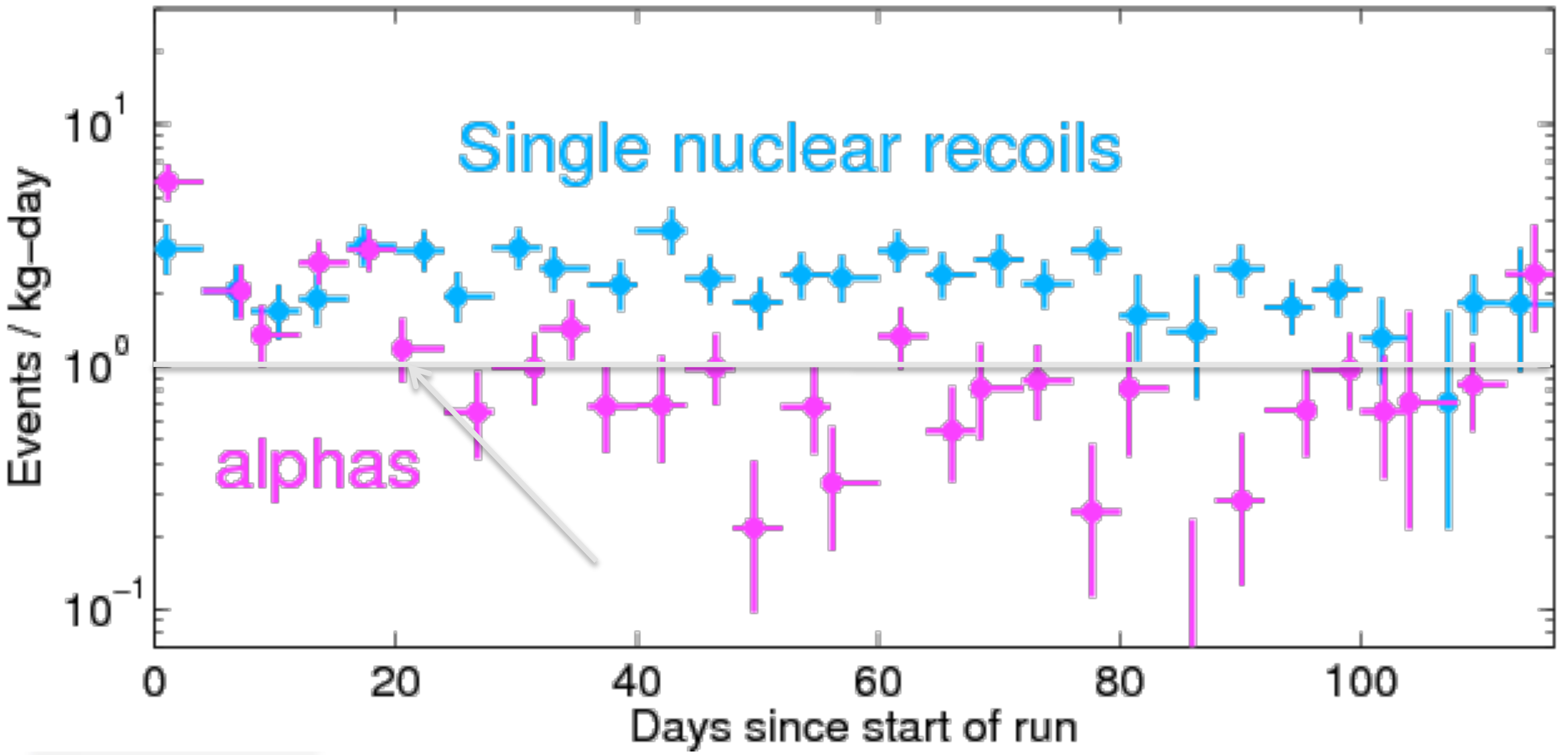
Synthetic Silica: ≤1e-2/day/cm^2



64 live-days (2009)

Alpha Rate Reduction from Radon Suppression

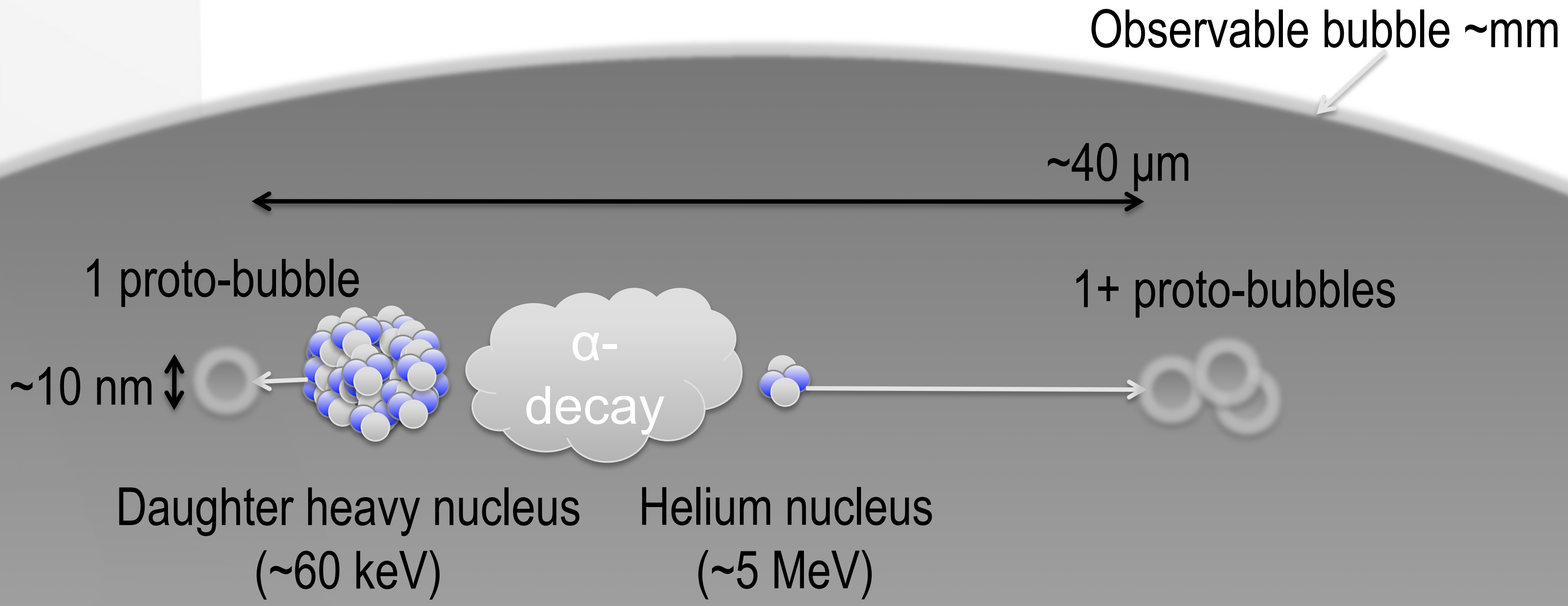
Initial Radon injection ~10X lower due to improved fluid transfer
Low enough for 60 kg chamber operation with reasonable livetime



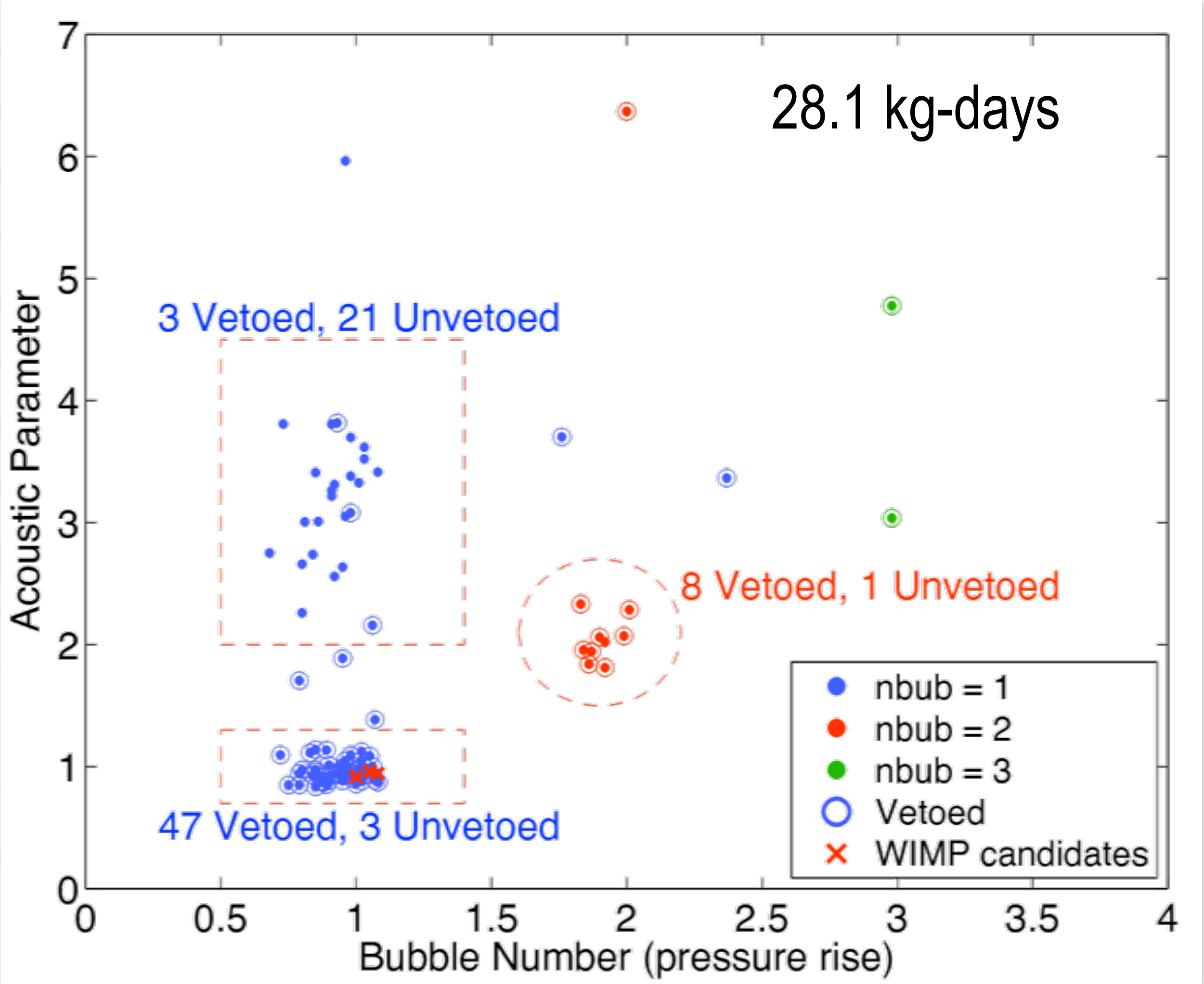
Acoustic Discrimination Against Alphas

High frequency acoustic information probes smaller scales

Alpha decays produce many bubbles, louder at high frequencies



Candidate Events in the 4kg NUMI physics run



Assume the 3 unvetoed events are alphas

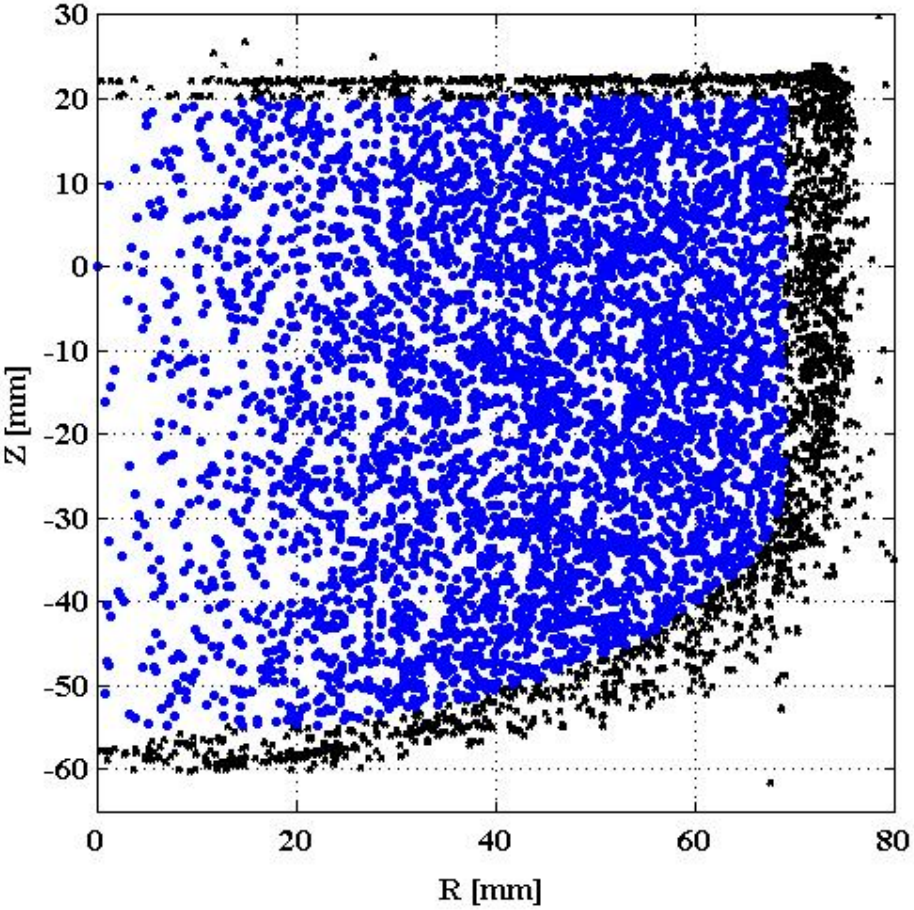
Alpha rejection >80% at 90% confidence level

Consistent with >99% alpha rejection

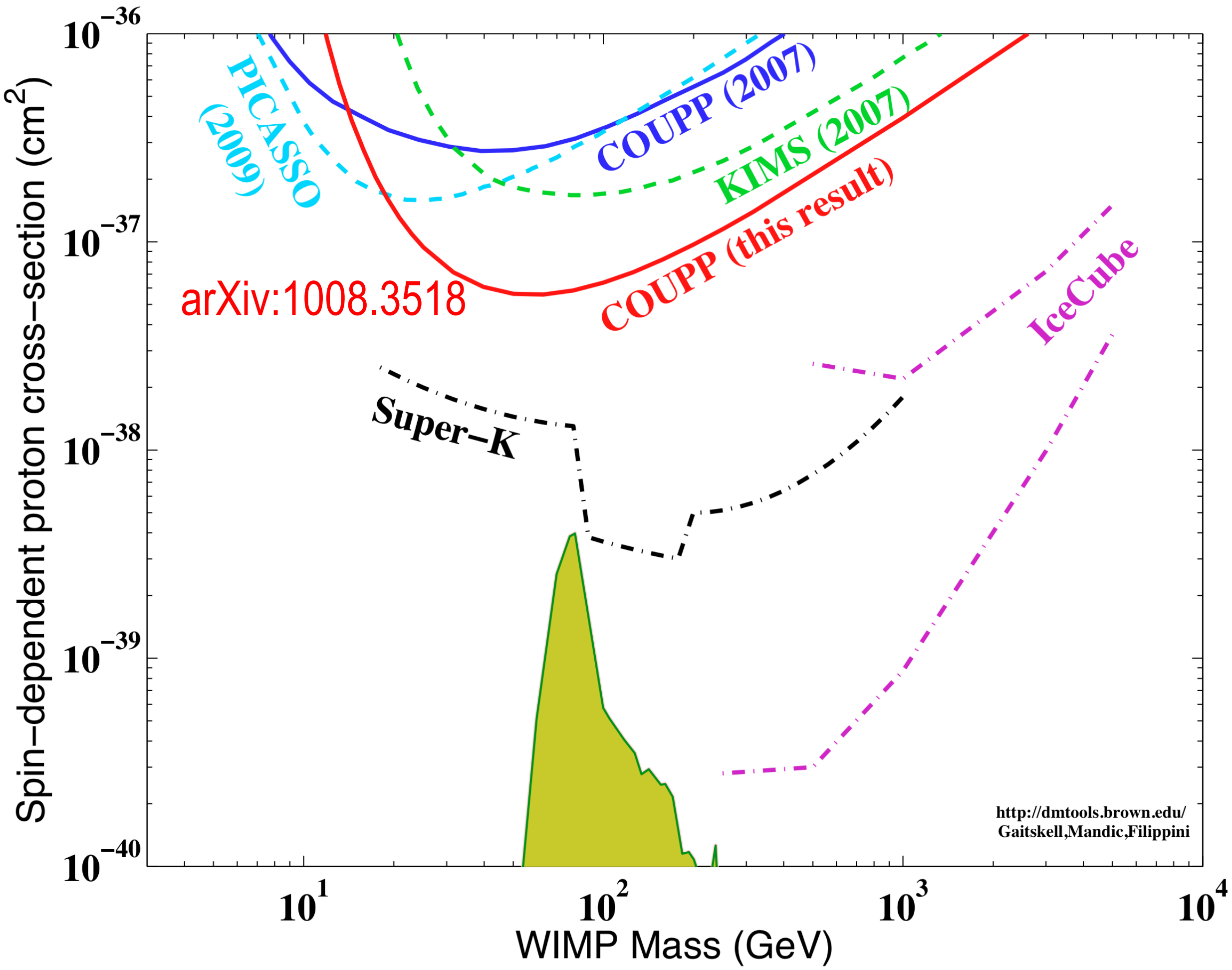
Need deep site to measure accurately

Fiducial Mass Determination in the 4 kg Bubble Chamber run at NUMI

- Acoustic discrimination worsens near glass jar
- 3 calibration datasets consistent, fiducial mass is 75% of the active volume
- 3.5 kg CF_3I total
- 2.6 kg CF_3I fiducial
  - 0.76 kg ^{19}F (SD)
  - 1.6 kg ^{127}I (SI)



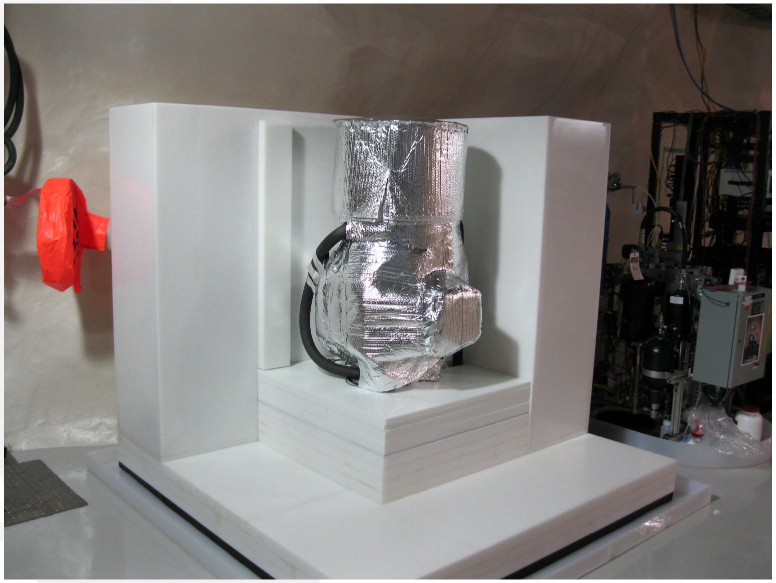
COUPP Spin-Dependent Limits from the 4kg run at NUMI

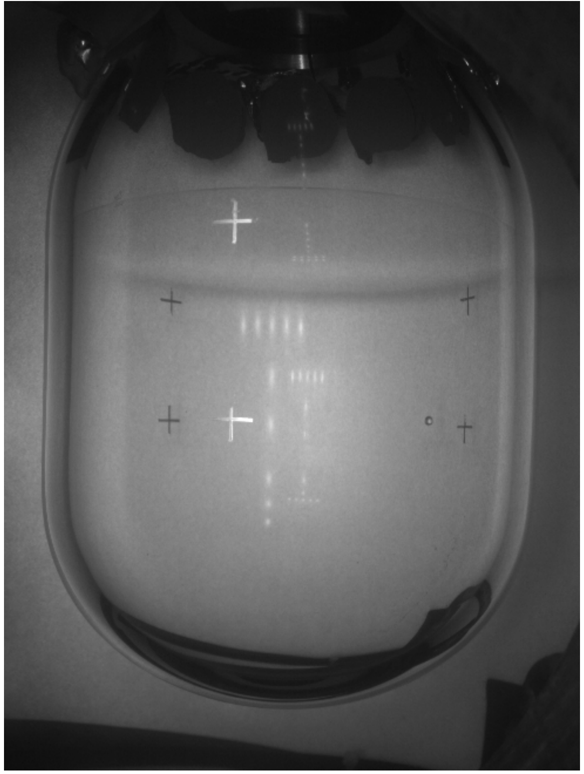


COUPP 4 kg – Installed at SNOLAB

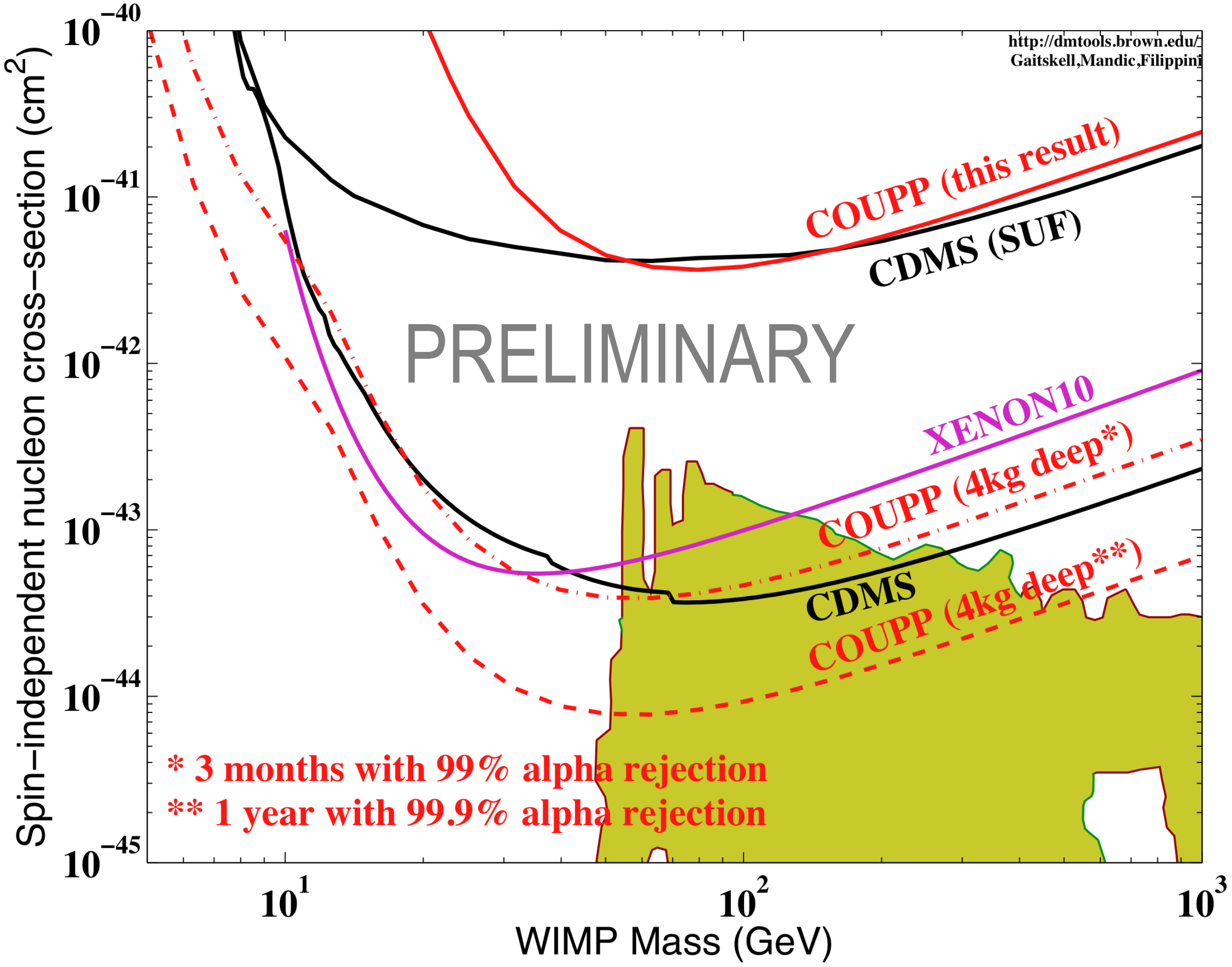
The 4 kg chamber has recently been relocated to the deep underground SNOLAB facility

Main goal is to measure acoustic alpha discrimination





Projected Sensitivity for a 4kg run at SNOLAB



COUPP 60 kg – R&D towards a larger experiment

Data

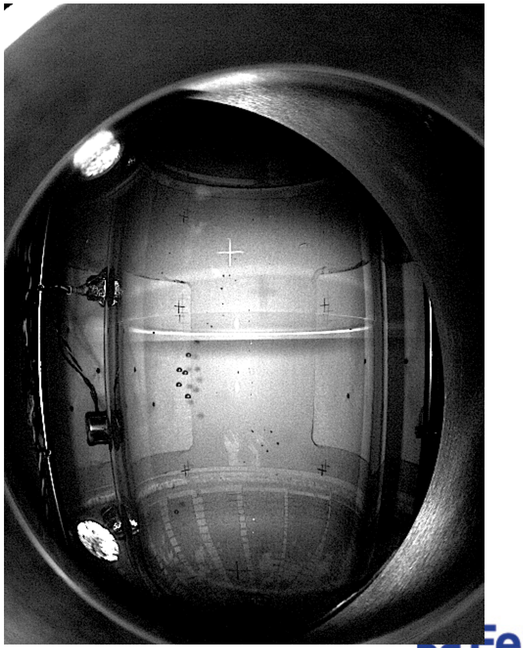
Several live days of operation during July and August

Technical Issues

High rate of meniscus events (~90% of events)

CF3I darkening (light sensitivity, chemistry?)

Stability and data quality



The COUPP Collaboration

Kavli Institute
for Cosmological Physics
AT THE UNIVERSITY OF CHICAGO

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

Indiana University South Bend
I. Levine

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

DarkSide
Liquid Argon TPC with reduced 39Ar

Fermilab Scientists

- Stephen Pordes

0.3 FTEs

Fermilab Roles

- Liquid argon distillation and measurements, shielding, veto, DAQ, electronics

Fermilab History

- Involvement began in 2008, aided by sabbatical visits from Jeff Martoff (Temple) and Cristiano Galbiati (Princeton)

Why a Liquid Argon TPC?

- Pulse shape of primary scintillation provides very powerful discrimination between nuclear and electron recoils

  Rejection factor expected to be >10^8 for > 60 photoelectrons

- Ionization to scintillation ratio is another semi-independent discrimination mechanism to extend pulse shape discrimination

  Measured rejection factor ~10^2

- Spatial resolution of a few mm allows rejection of multiple interactions and "wall events”

- Main problem is large 39Ar radioactive contamination in atmospheric Argon gas

New technology introduced in DarkSide

Depleted Argon from underground sources

< 0.04 ^{39}Ar of atmospheric argon

Borated liquid scintillator neutron veto

Estimate >99.8% rejection efficiency for radiogenic neutrons

QUPID photosensors

no radioactive background detected in best HpGe screener
new photocathode with 35% QE at liquid argon temperature

DarkSide Goals

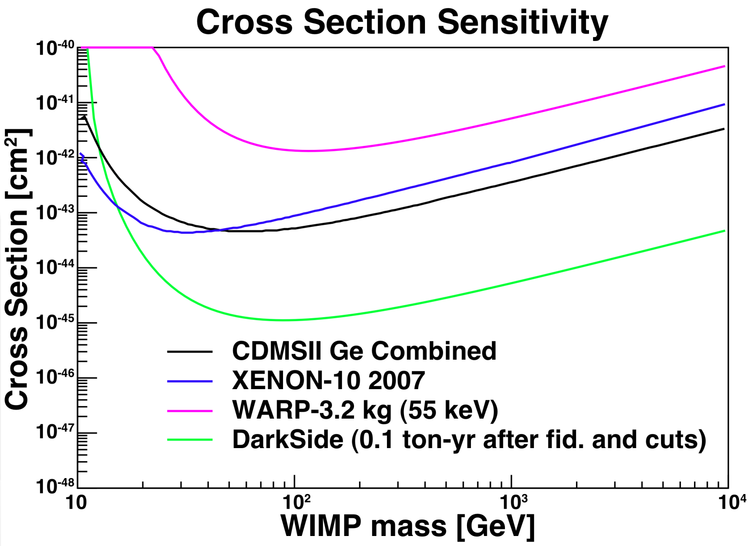
Minimize internal sources of background

Maximize background rejection down to low energies

Maximize efficiency for signal detection

Program starts with DarkSide 50kg

Plan to install at Gran Sasso in 2012



Projected Sensitivity assuming
3 years x 33 kg (fiducial) and
< 0.1 event background

DARKSIDE

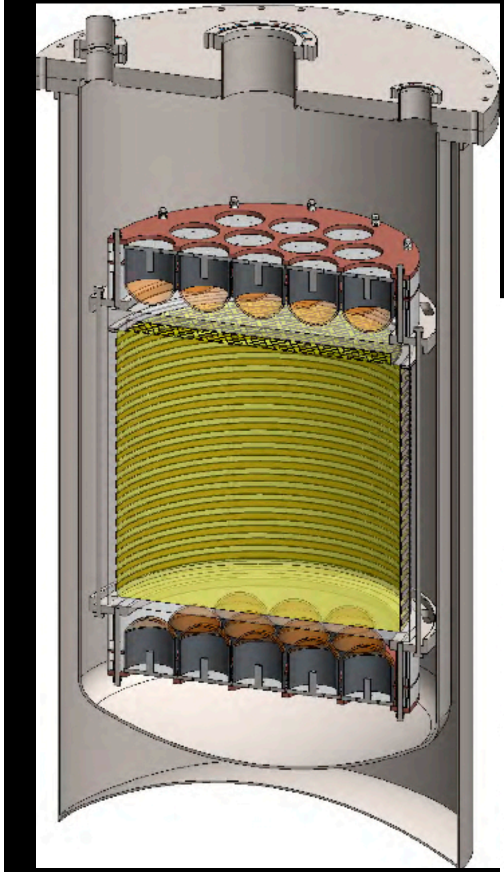

FNAL physicists and technicians helping to assemble and operate

Distillation Column at Fermilab

FNAL designed and tested HV feedthroughs and PMT bases

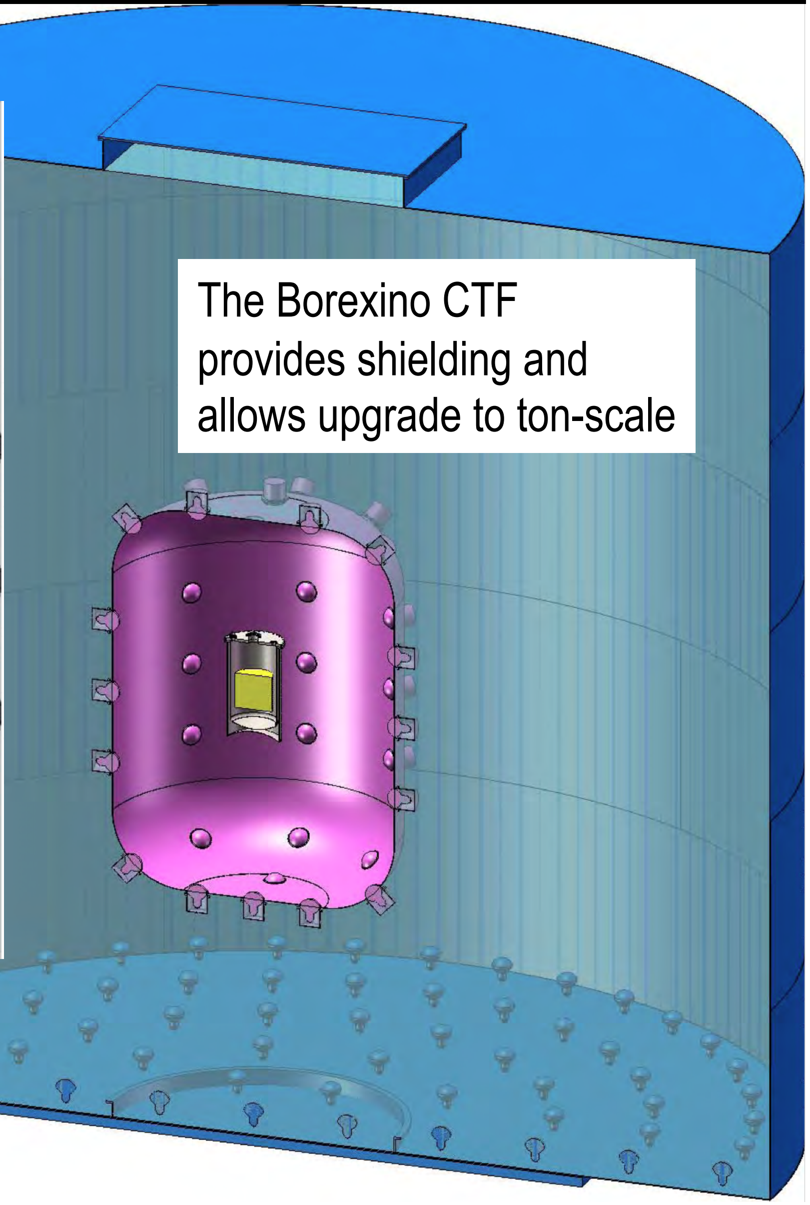
10 kg LAr detector at Princeton

DARKSIDE installation in Borexino `Counting Test Facility' at Gran Sasso



50 kg LAr TPC

DarkSide TPC in Borated Scintillator Veto



The Borexino CTF provides shielding and allows upgrade to ton-scale

DARKSIDE

Augustana College – SD, USA 🇺🇸
Black Hill State University – SD, USA 🇺🇸
Fermilab – Il, USA 🇺🇸
INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy 🇮🇹
INFN and Università degli Studi Genova, Italy 🇮🇹
INFN and Università degli Studi Milano, Italy 🇮🇹
INFN and Università degli Studi Naples, Italy 🇮🇹
INFN and Università degli Studi Perugia, Italy 🇮🇹
Joint Institute for Nuclear Research – Dubna, Russia 🇷🇺
Princeton University, USA 🇺🇸
RRC Kurchatov Institute – Moscow, Russia 🇷🇺
St. Petersburg Nuclear Physics Institute – Gatchina, Russia 🇷🇺
Temple University – PA, USA 🇺🇸
University of California, Los Angeles, USA 🇺🇸
University of Houston, USA 🇺🇸
University of Massachusetts at Amherst, USA 🇺🇸

DAMIC
R&D with low-noise DECAM CCDs towards a low mass WIMP search

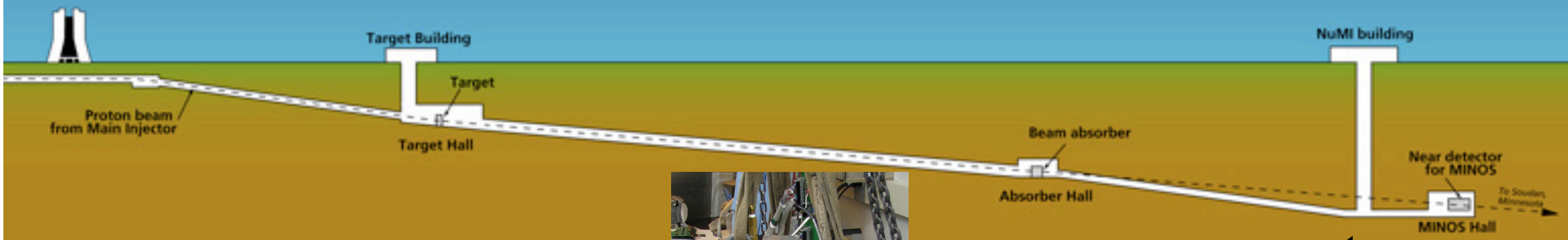
- Fermilab Scientists
  - J. Estrada, B. Kilminster

0.2 FTEs

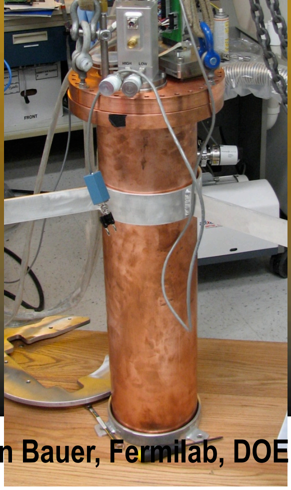
- Fermilab Roles
  - Small, home-grown effort
  - Spin-off from DECAM work
  - Tests made possible by NUMI underground hall
- Fermilab History
  - Initiated by Estrada as Wilson Fellow in 2007
  - Recently won Presidential Early Career Award for Scientists and Engineers for this work

DAMIC underground test at FNAL

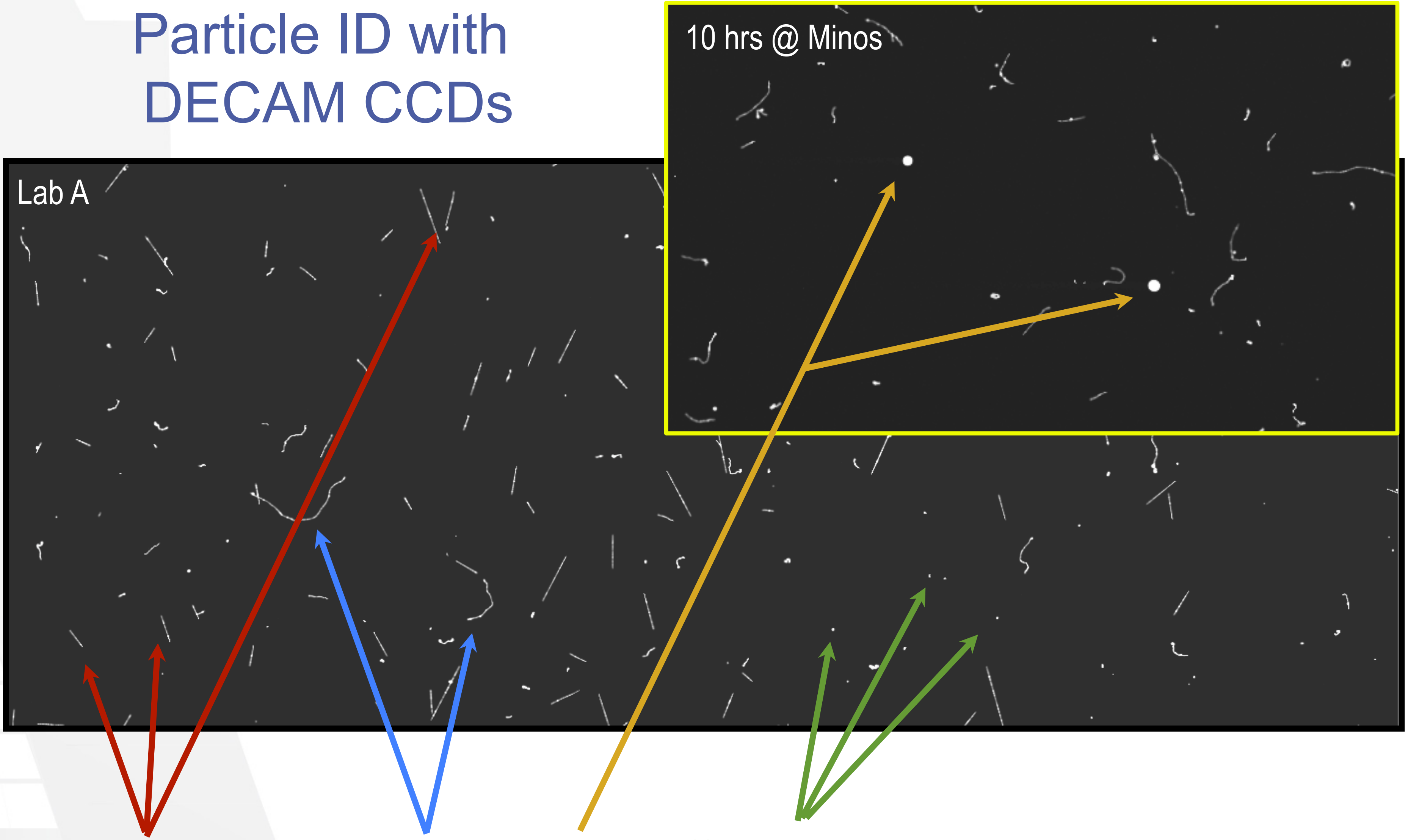
CCD operated at 350’ underground (MINOS hall)



developed a low background CCD package operated inside a Cu vessel shielded with lead.



Particle ID with DECAM CCDs



muons, electrons alphas diffusion limited hits

nuclear recoils will produce diffusion limited hits

Strengths of the FNAL Dark Matter Technologies

CDMS

- Most sensitive to spin-independent WIMP interactions
- Highest demonstrated WIMP discovery potential
- New iZIP technology continues zero background path

COUPP

- Most sensitive to spin-dependent WIMP interactions
- Competitive for spin-independent if α rejection sufficient

Darkside

- Liquid argon offers possibility of multi-ton experiment
- Excellent intrinsic discrimination achieved
- Breakthrough in reduced 39Ar contamination

DAMIC

- R&D towards unique low-mass WIMP search

Summary

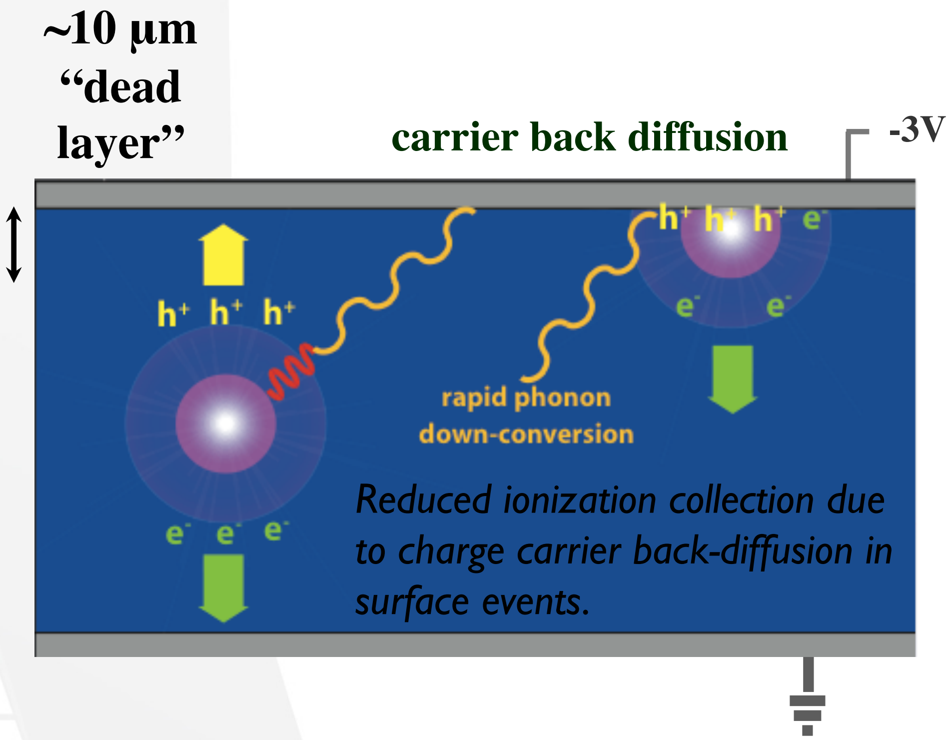
FNAL is well prepared to continue leadership in dark matter direct detection

CDMS, COUPP and DarkSide will all propose next generation experiments to advance in the 'generic' dark matter CD process at DOE

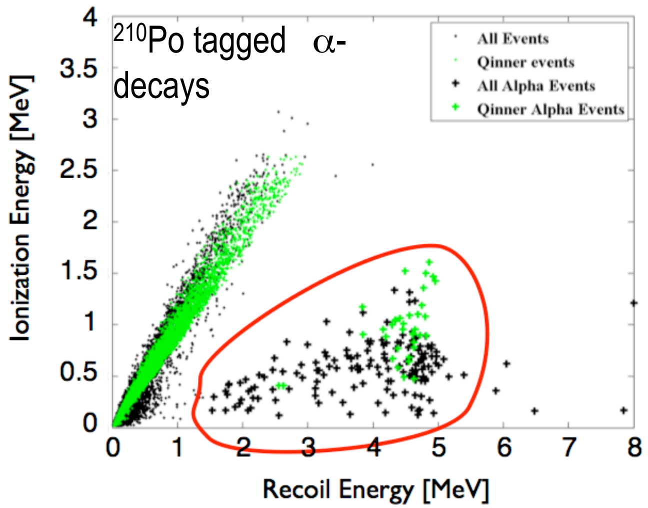
The dark matter program at FNAL is coordinated with DOE/NSF-supported University groups, and takes advantage of the strengths of the laboratory scientists, technical staff and infrastructure.

Backup Slides

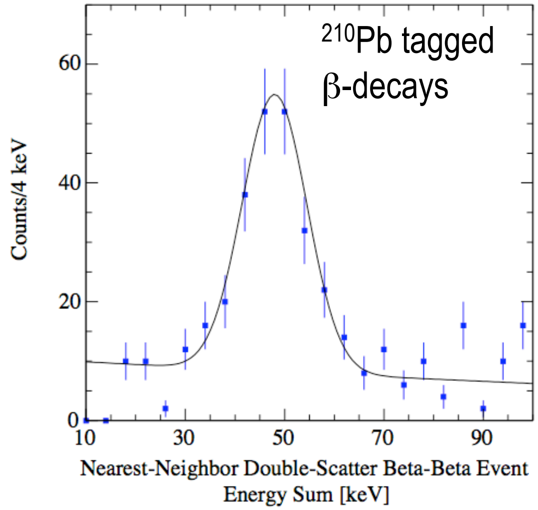
Main CDMS Problem: Surface Events



Reduced ionization collection due to charge carrier back-diffusion in surface events.

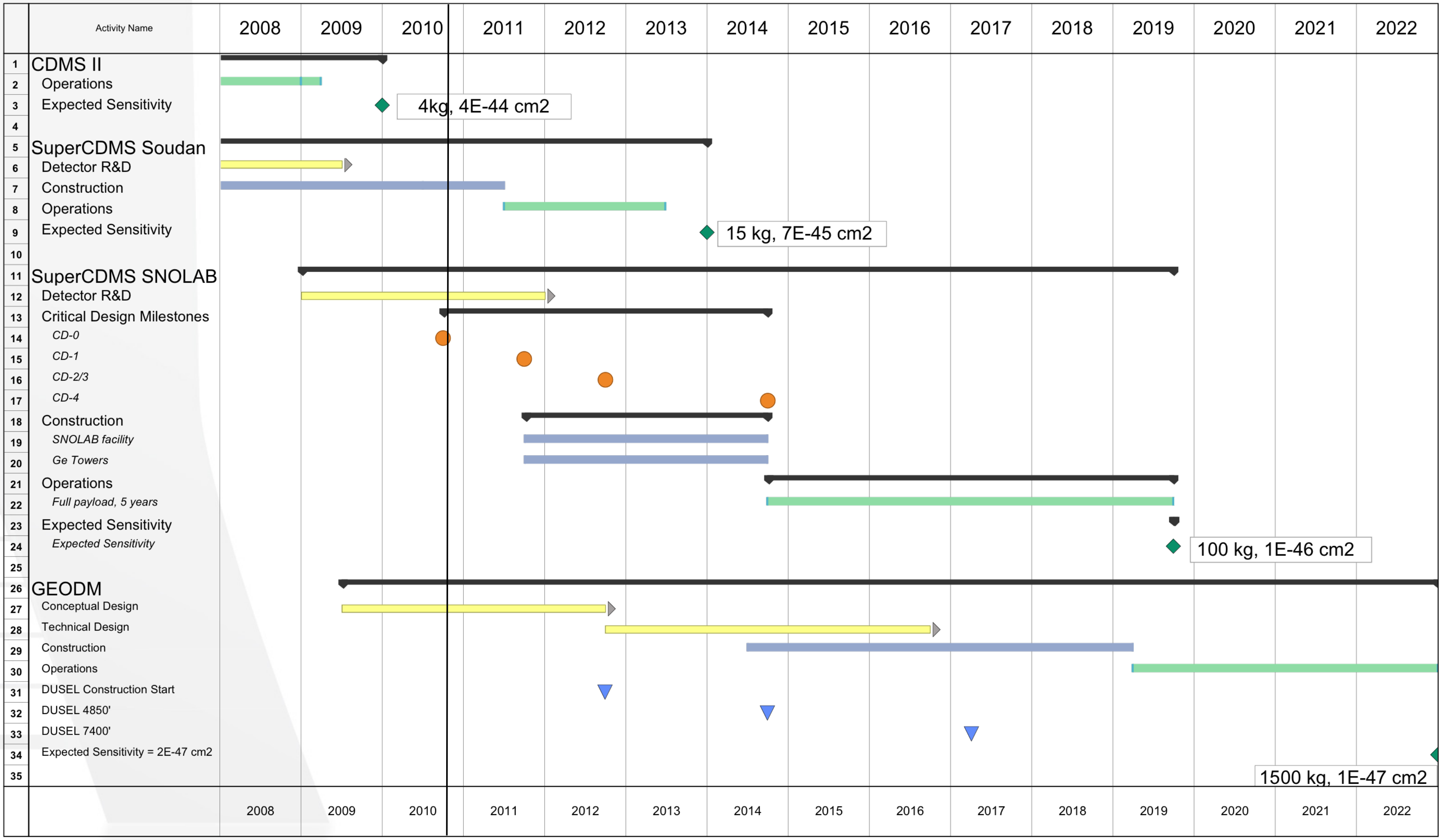


Correlations to ^{222}Rn daughter contamination observed



These events are primarily electrons and soft x-rays originating from surfaces of the detectors and surrounding materials

SuperCDMS Schedule



Alpha Discrimination in the 4 kg chamber