The Fermilab Dark Matter Program

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Fermilab Institutional Review
June 6-9, 2011

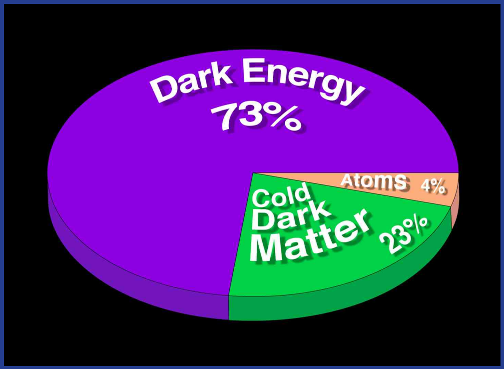
What is Dark Matter?

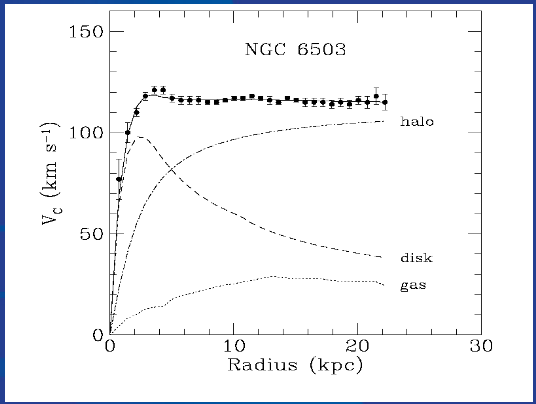
Galaxy Clusters

We know the Dark Matter is

stable / non-baryonic / non-relativistic / interacts gravitationally

Strong Lensing

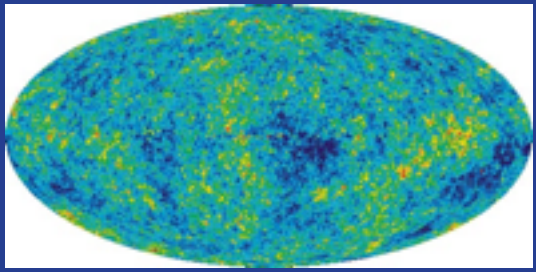




Galaxy Rotation Curves

We don't know its

mass / coupling / spin / composition / distribution in our galaxy…



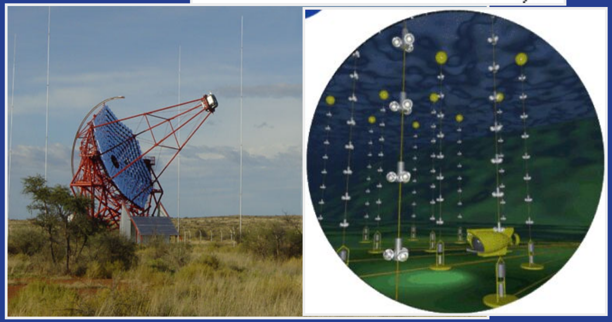
Cosmic Microwave Background

Best candidate for Dark Matter: Weakly Interacting Massive Particles (WIMPs)

Many different ways to search for WIMPs

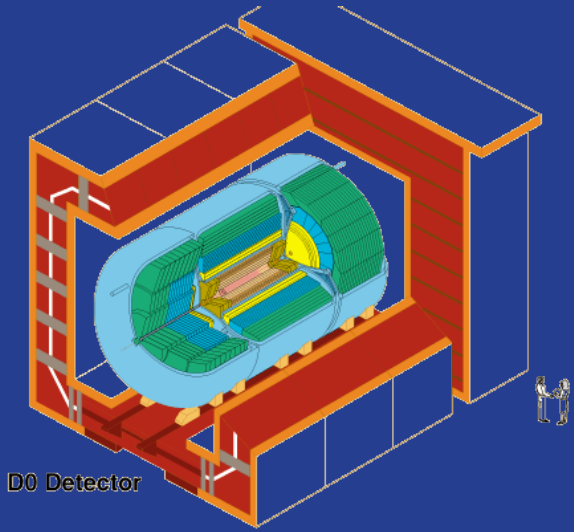
Direct Detection

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



Indirect Detection

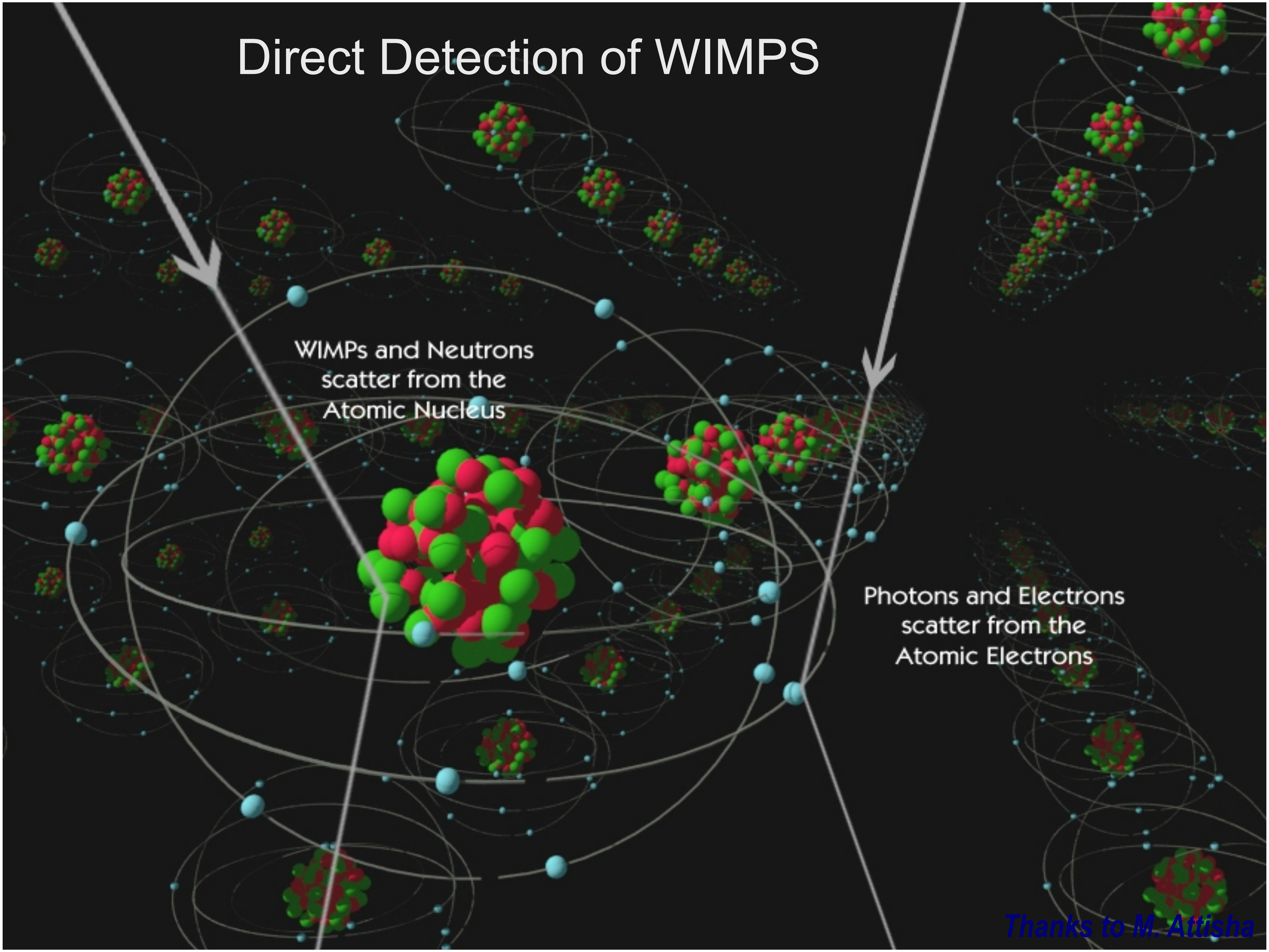
Look for evidence of WIMP annihilations to gammas, neutrinos, antiparticles occurring in our galaxy



Colliders

Try to produce WIMPS with accelerators

Direct Detection of WIMPS



The Challenge for Direct Detection Experiments

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

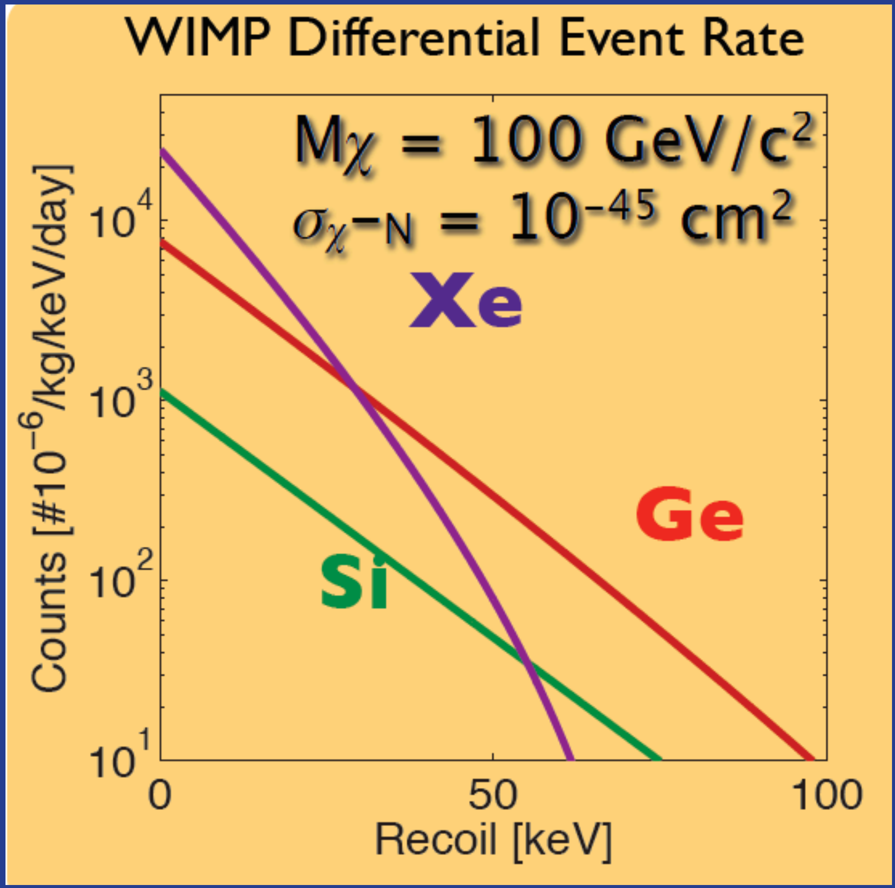
Experimental Challenges:

low energy thresholds (~10 keV)

mitigation of natural radioactive background

operation deep underground to avoid cosmics

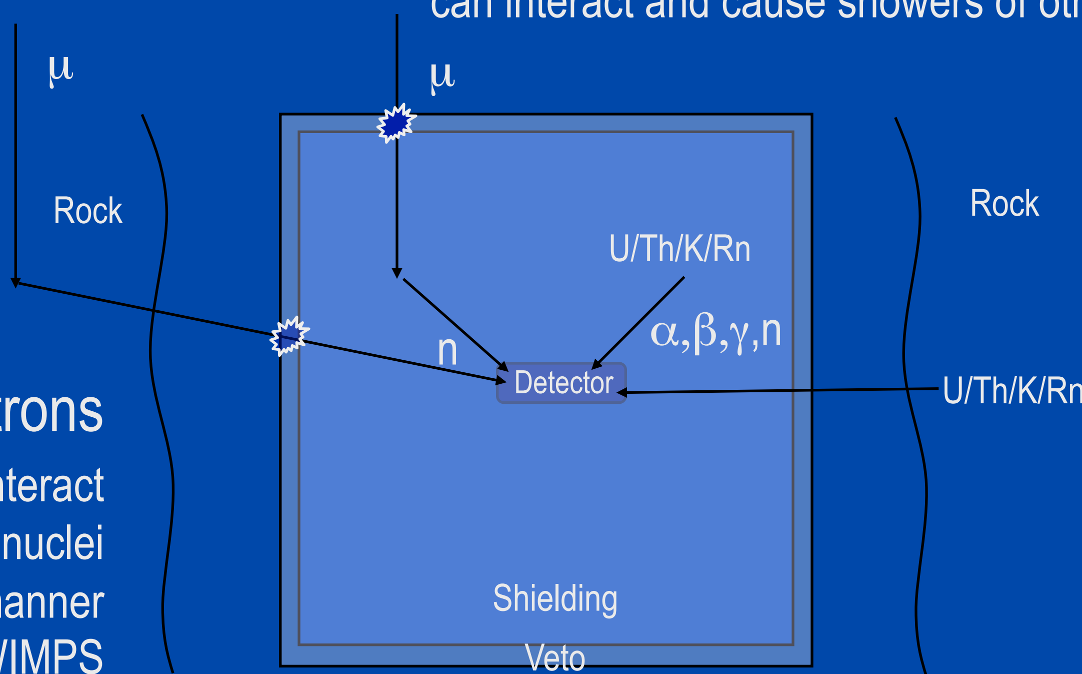
long exposures, scale to high mass



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

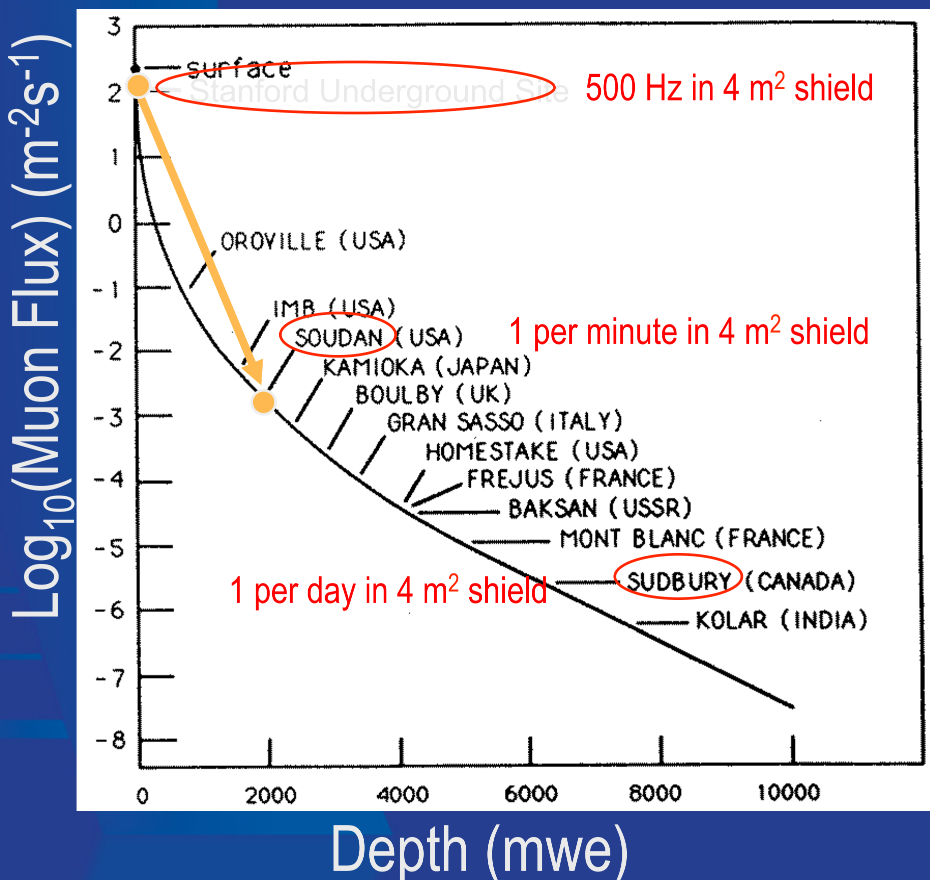
Long-lived isotopes of natural uranium, thorium, potassium produce α, β, γ, n

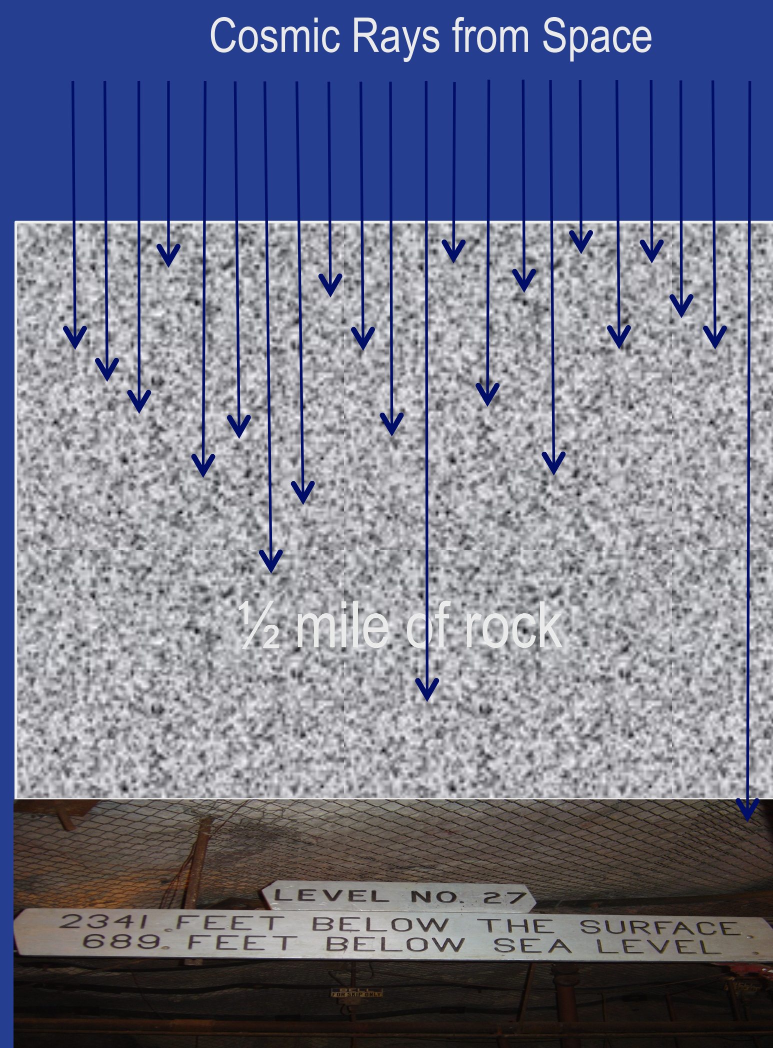
How do we guard against these backgrounds?

- 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





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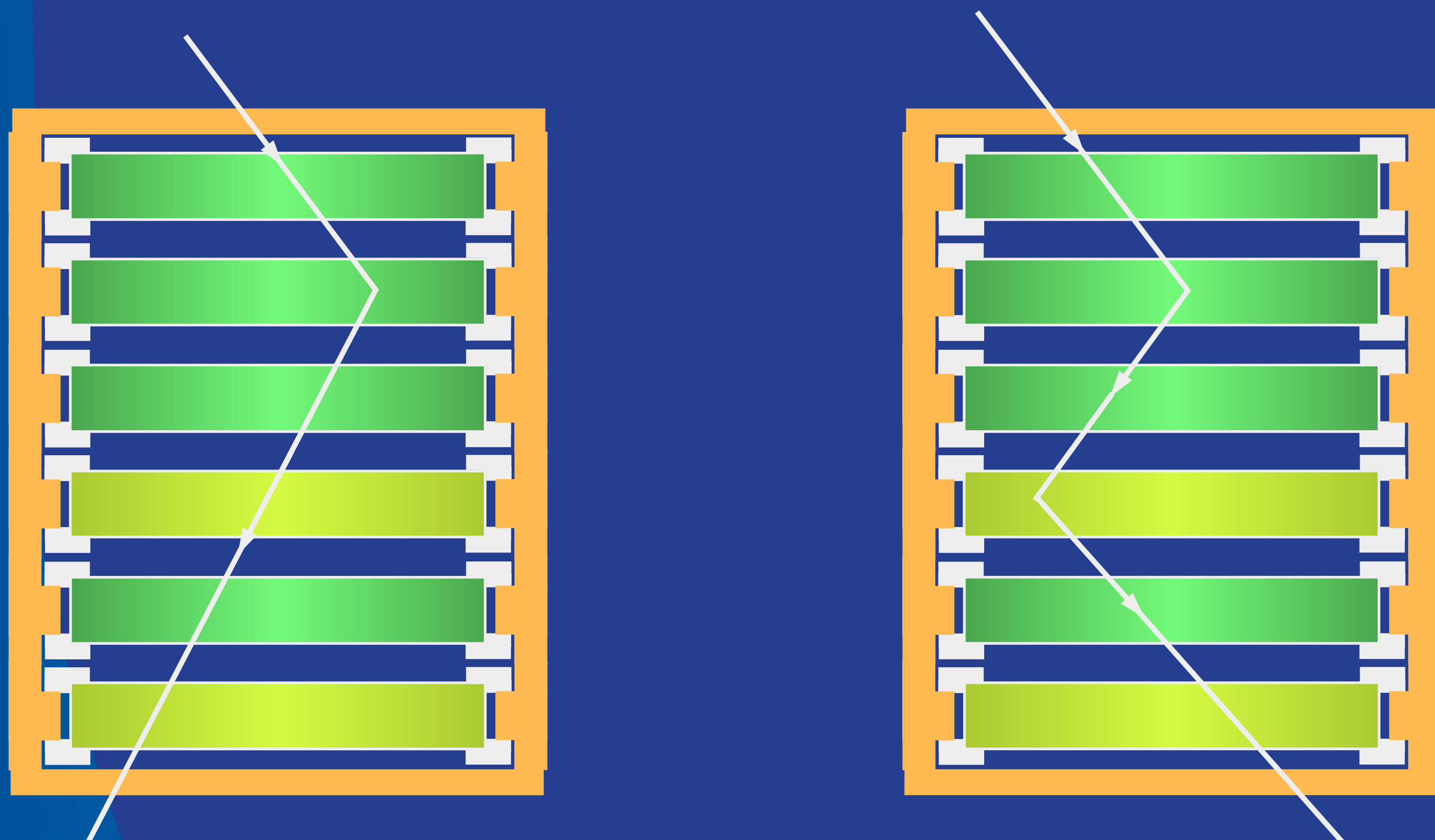
Multiple Scattering – a tool against residual neutrons



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

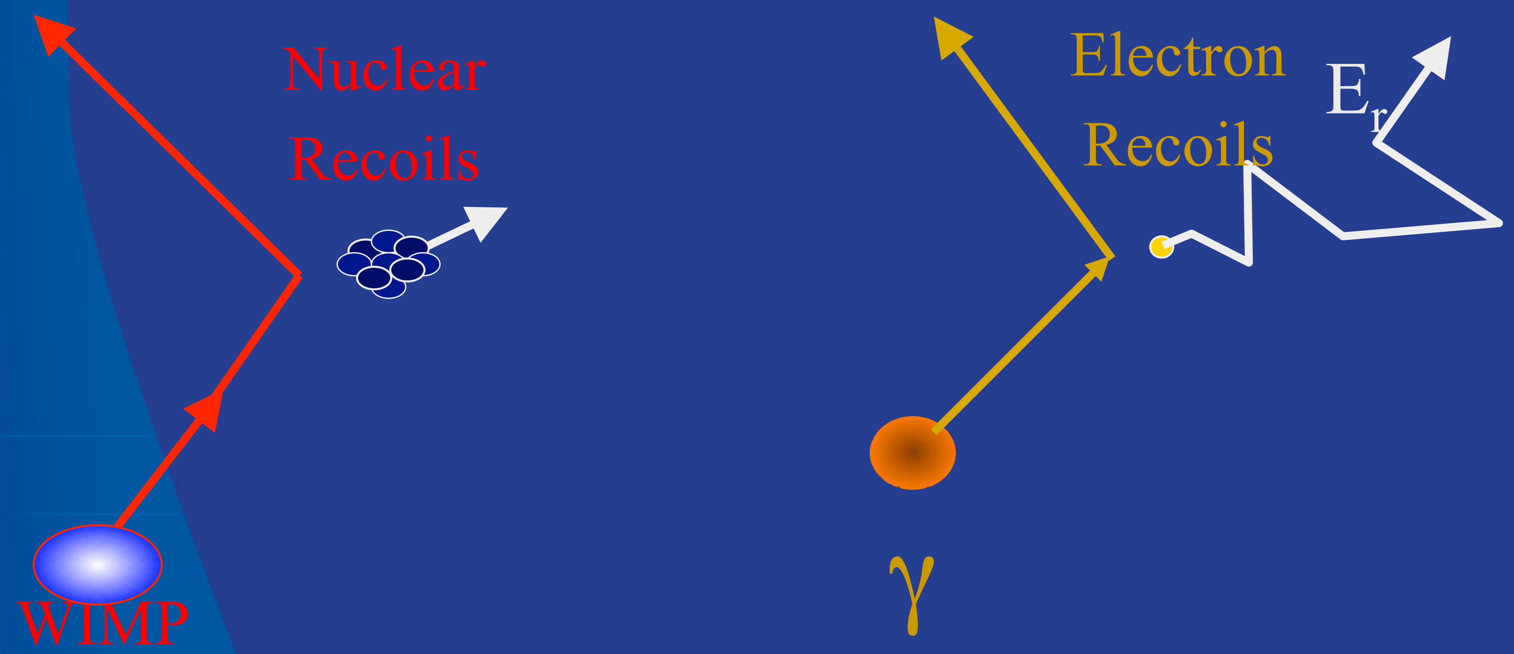
Multiple-scatter nuclear-recoils are only produced by neutrons.

Active Background Discrimination

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

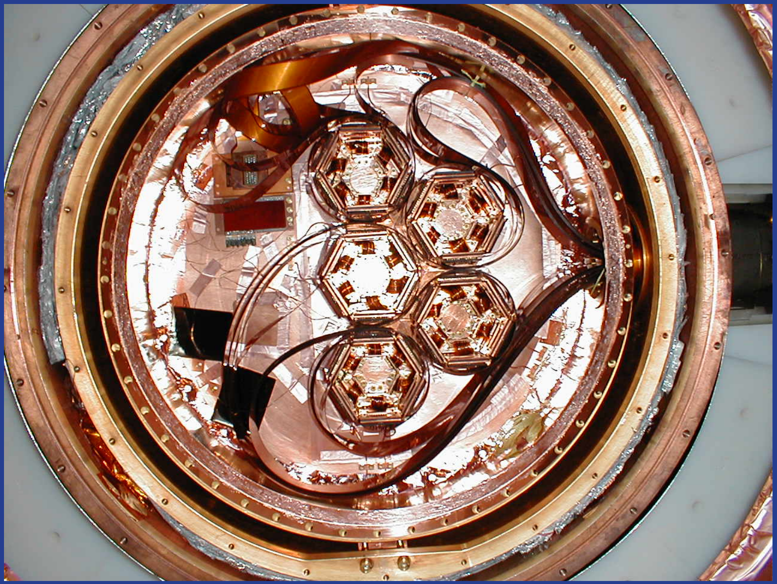
Most experiments detect particle interactions in two ways and compare (e.g. charge/phonon, charge/scintillation light, …)

Signal **Background**

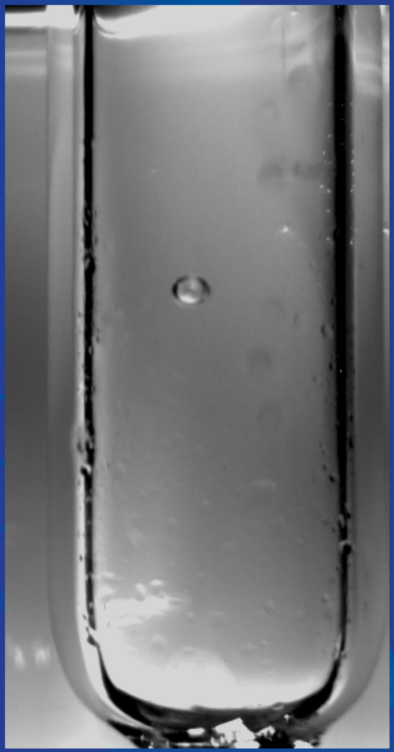


The Fermilab Direct Detection Suite

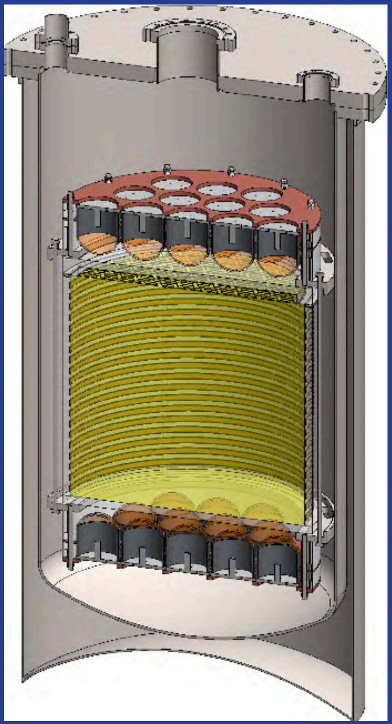
CDMS



COUPP



DarkSide



DAMIC

Cryogenic Dark Matter Search (CDMS)
Cryogenic Germanium Detectors

FNAL responsibilities include everything except the detectors

Involved since 1998. Currently 3 FTE scientist

Detectors

Pure Ge and Si crystals

Detect charge and phonon signals to provide excellent background rejection

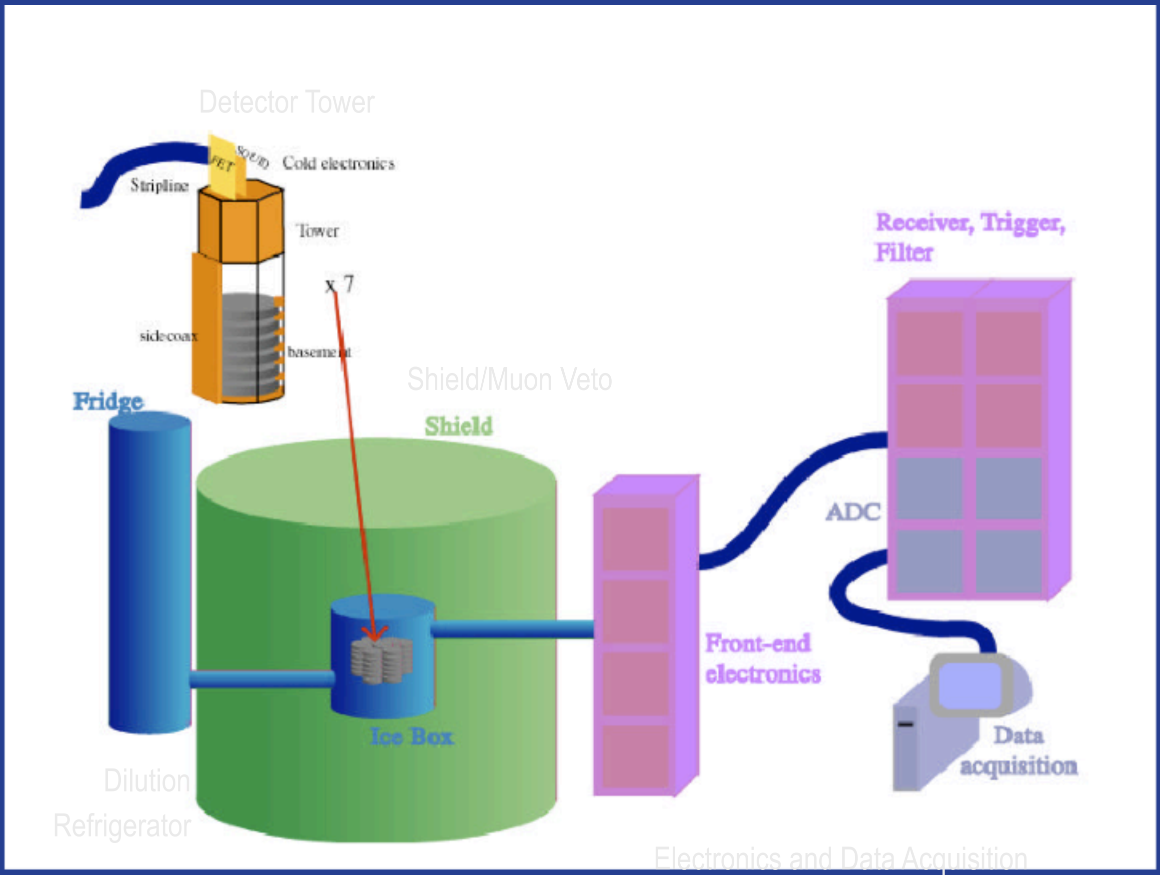
Cryogenics

Cool to near absolute zero in order to see single particles

Shielding and Veto

Reduce flux of radioactive decay particles near the detectors

Actively tag any interactions associated with cosmic rays



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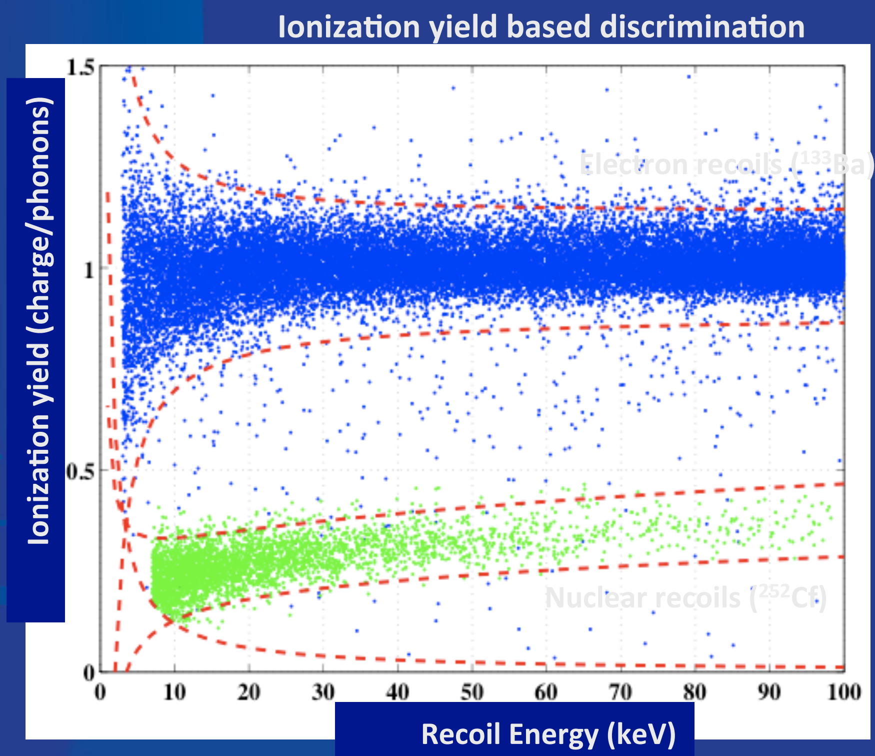
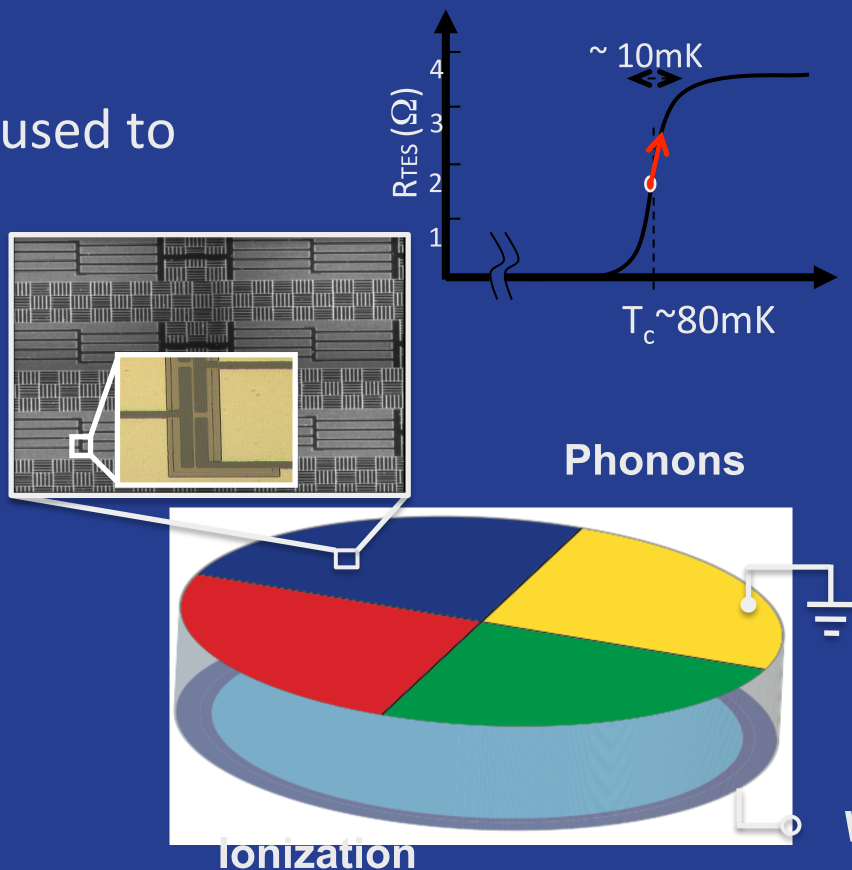
CDMS Detectors

- Measure both phonons and ionization for each particle interaction
- Ratio of ionization to recoil energy used to identify nuclear recoils





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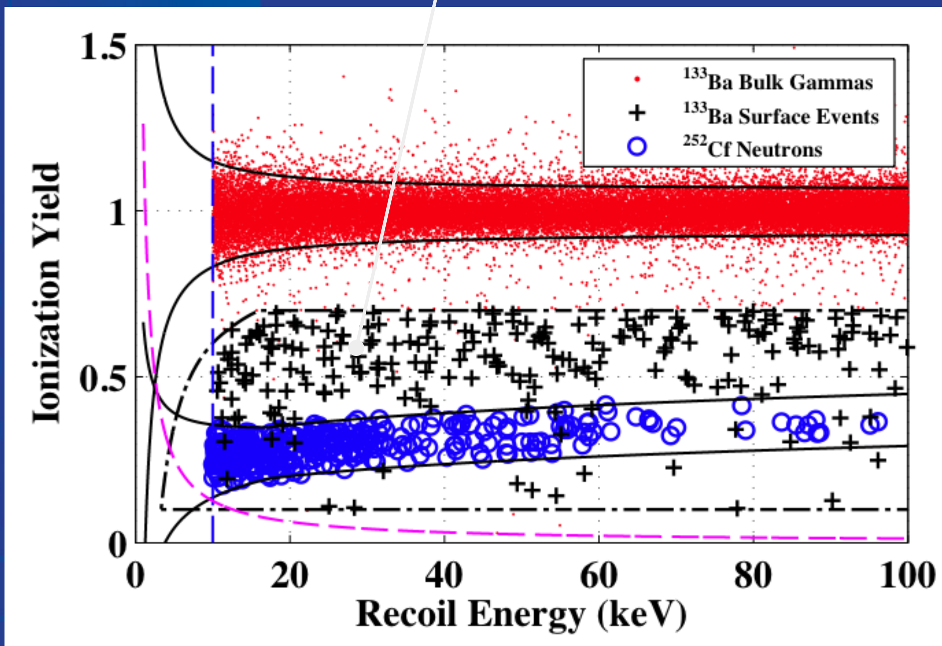
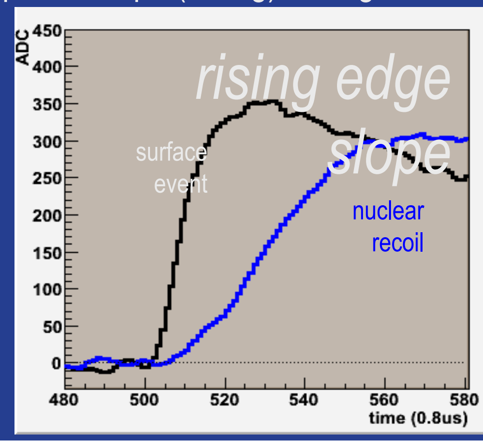
Rejection of Surface Events

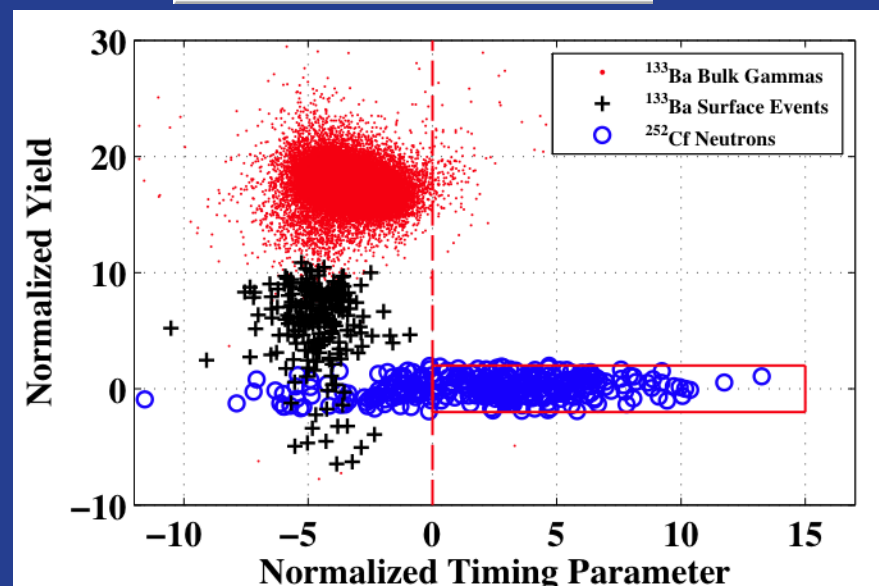
10 μm "dead layer" results in reduced ionization collection



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





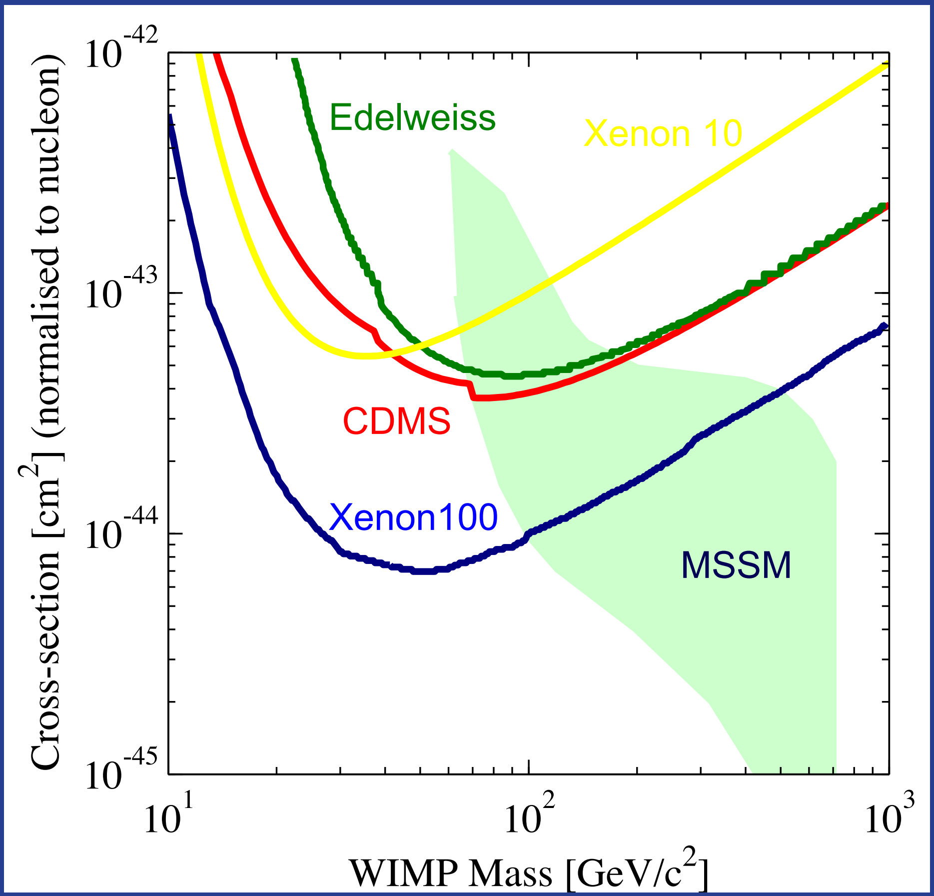
Limits on Spin-Independent WIMP Interactions

CDMS II background limited by two surface events in Dec 2010.

Still better than Xenon 10 for masses > 40 GeV. Upper limit at the 90% C.L. on the SI WIMP-nucleon cross-section is **3.8×10^{-44} cm^2**

Surpassed by March 2011 limits from Xenon100 at **7×10^{-45} cm^2.**

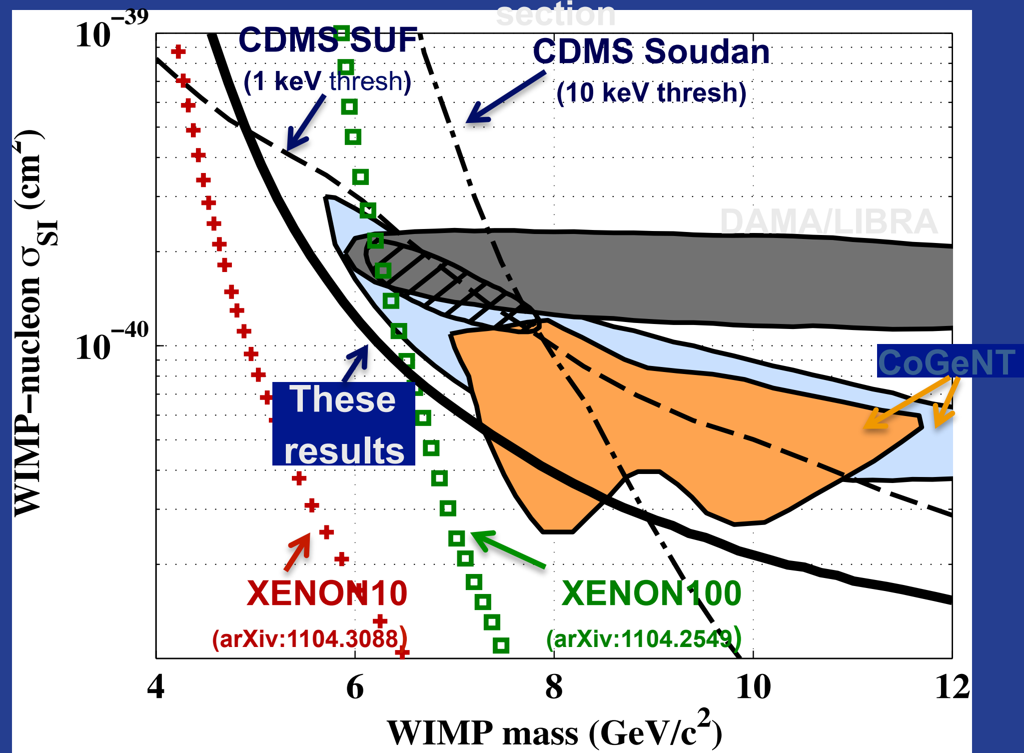
Still no sign of WIMPS, so the race continues!



Low-threshold search for low-mass WIMPs

- Threshold ~ 2 keV
  - EM background rejection not as good
  - Treat all candidates as if WIMPS even though background well understood
- For spin-independent, elastic scattering, 90% CL limits incompatible with DAMA/LIBRA and entire CoGeNT excess
- Some parameter space for CoGeNT remains if majority of excess events not due to WIMPs

90% CL upper limits on elastic scattering cross section



Ahmed et al., PRL **106**, 131302 (2011), *arXiv:1011.2482*
Akerib et al., PRD **82**, 122004 (2010), *arXiv:1010.4290*

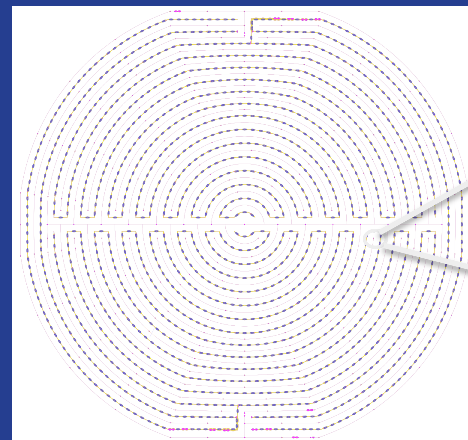
SuperCDMS – A Detector Breakthrough

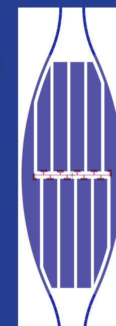
iZIP = interleavened charge and phonon channels

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

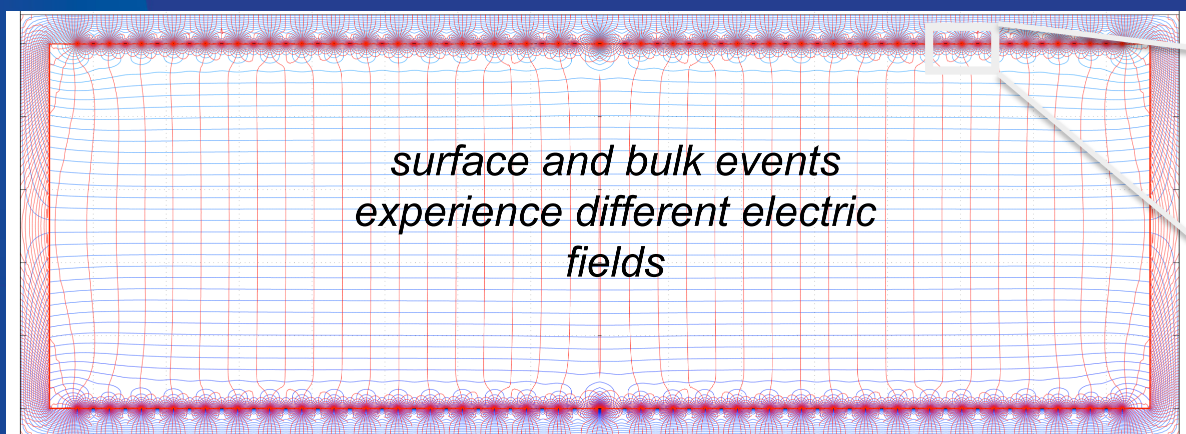
Fiducial volume x2 better than CDMS II (~80% of the crystal)

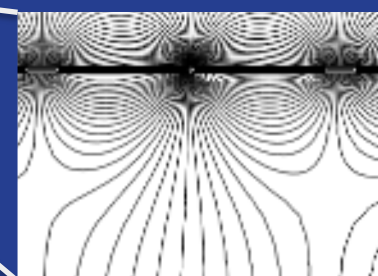
At least 3 iZIP towers will be included in SuperCDMS Soudan





Closeup of phonon sensor





Charge near surface is collected by electrodes on only one side

The Future – SuperCDMS SNOLAB

- 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

CDMS Future Projections

<u>CDMS II</u>

4 kg Ge

~ 2 yrs operation

<u>SuperCDMS @ Soudan</u>

15 kg Ge

~ 2 yrs operation

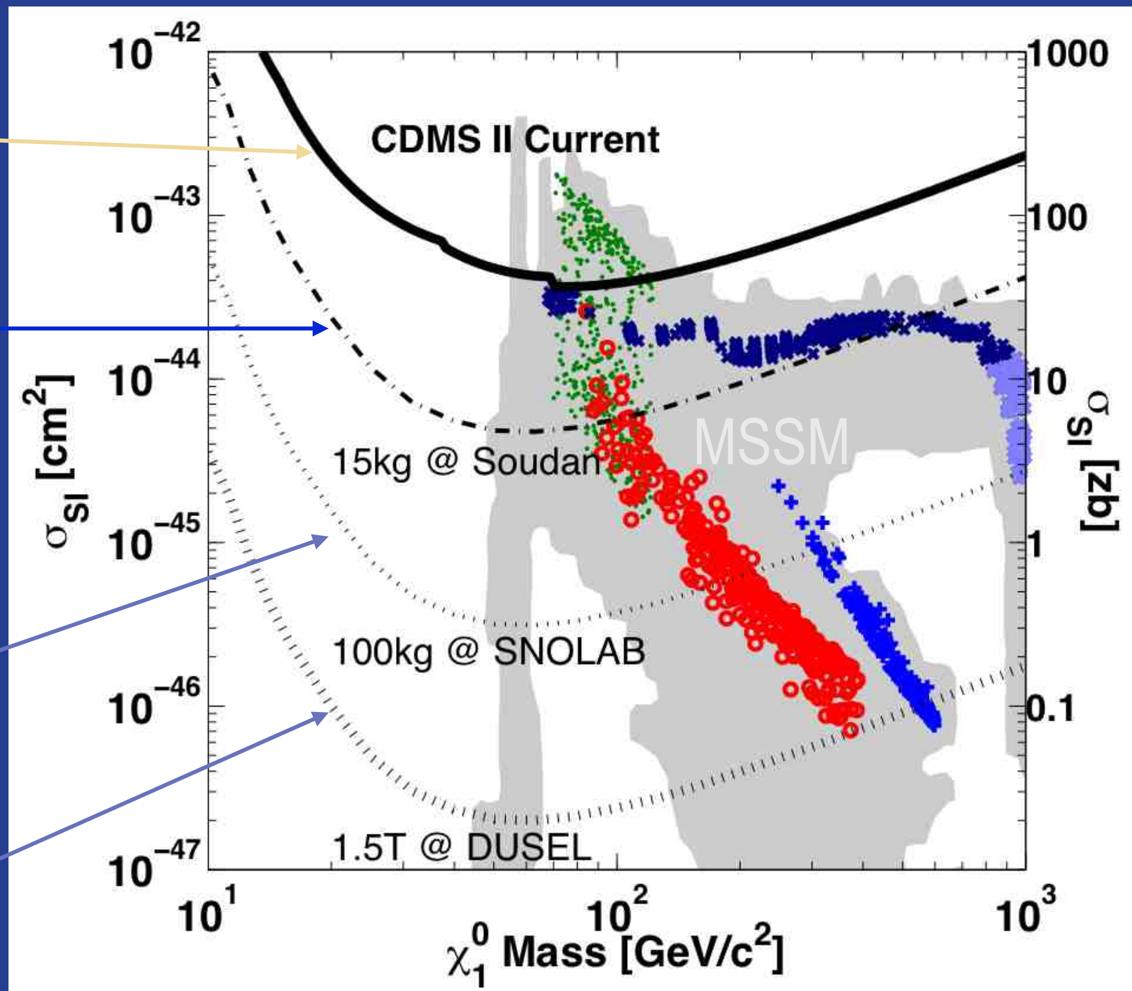
<u>SuperCDMS @ Snolab</u>

100 kg Ge

~ 2 yrs operation

<u>DUSEL/GEODM</u>

1.5T

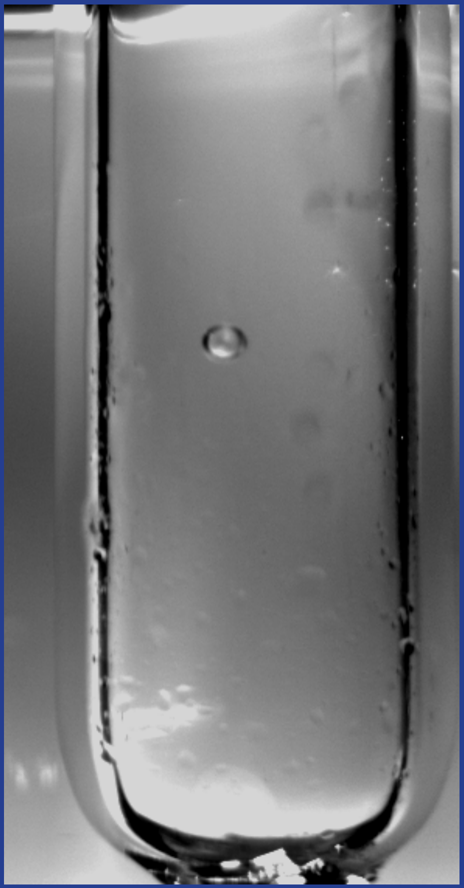


iZIPs should be good enough for ton-scale experiment!
Will need to make larger detectors (6” diameter feasible)

Chicagoland Observatory for Underground Particle Physics (COUPP)
Bubble Chambers

Fermilab Responsibilities includes everything except acoustic sensors

Involved since 2004. Currently 4 FTE scientist effort



Large target masses

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

Choice of target nuclei

"Heavy Liquids": Xe, Ne, CF_3I are good targets for both spin-dependent and spin-independent scattering

Possible to "swap" liquids to check suspicious signals

Low energy thresholds

<10 keV threshold achievable

Background Suppressions

Immune to electromagnetic backgrounds

The Technique

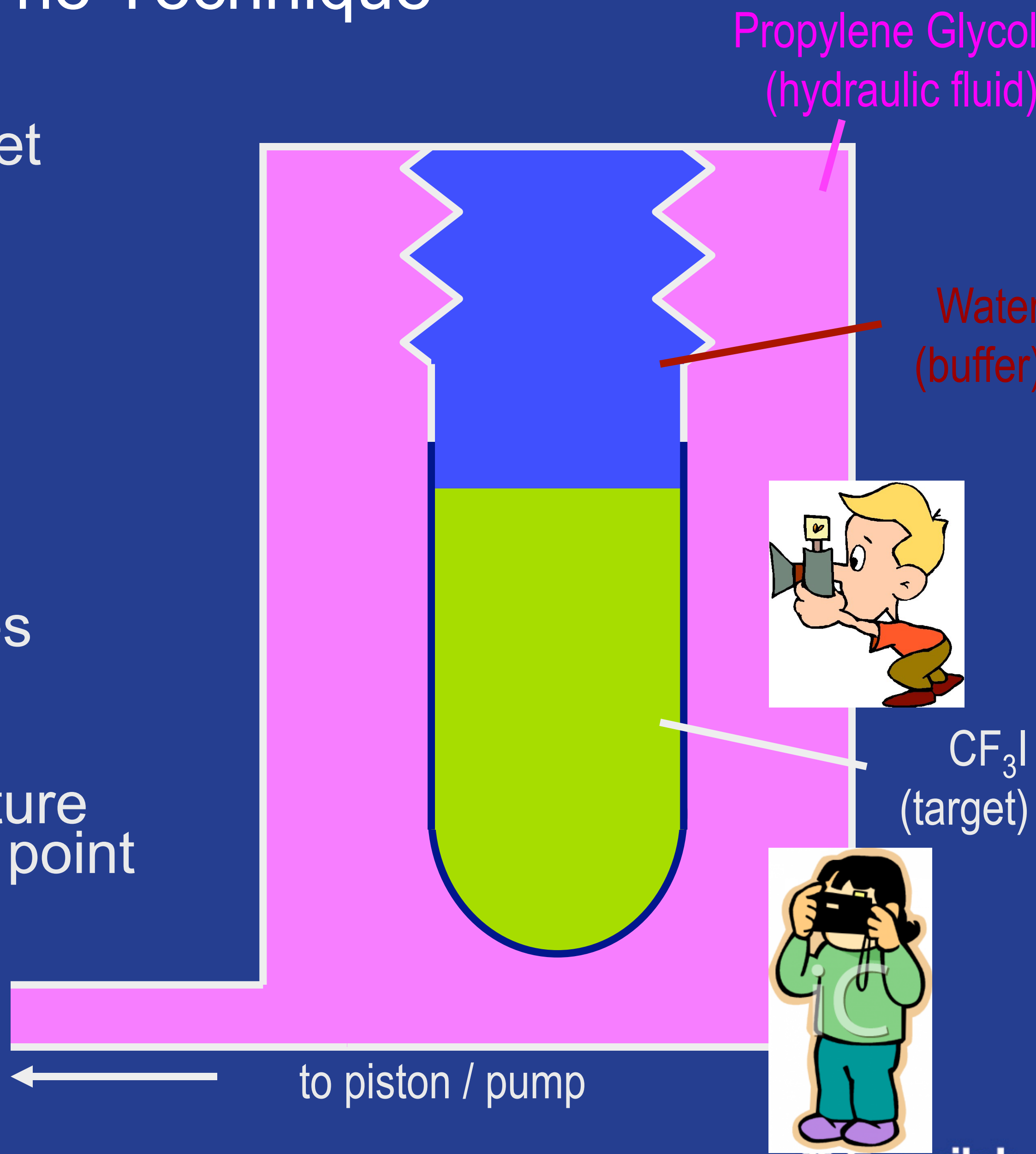
Superheated CF_3I target

Particle interactions nucleate bubbles

Cameras capture stereoscopic bubble images

Chamber recompresses after each event

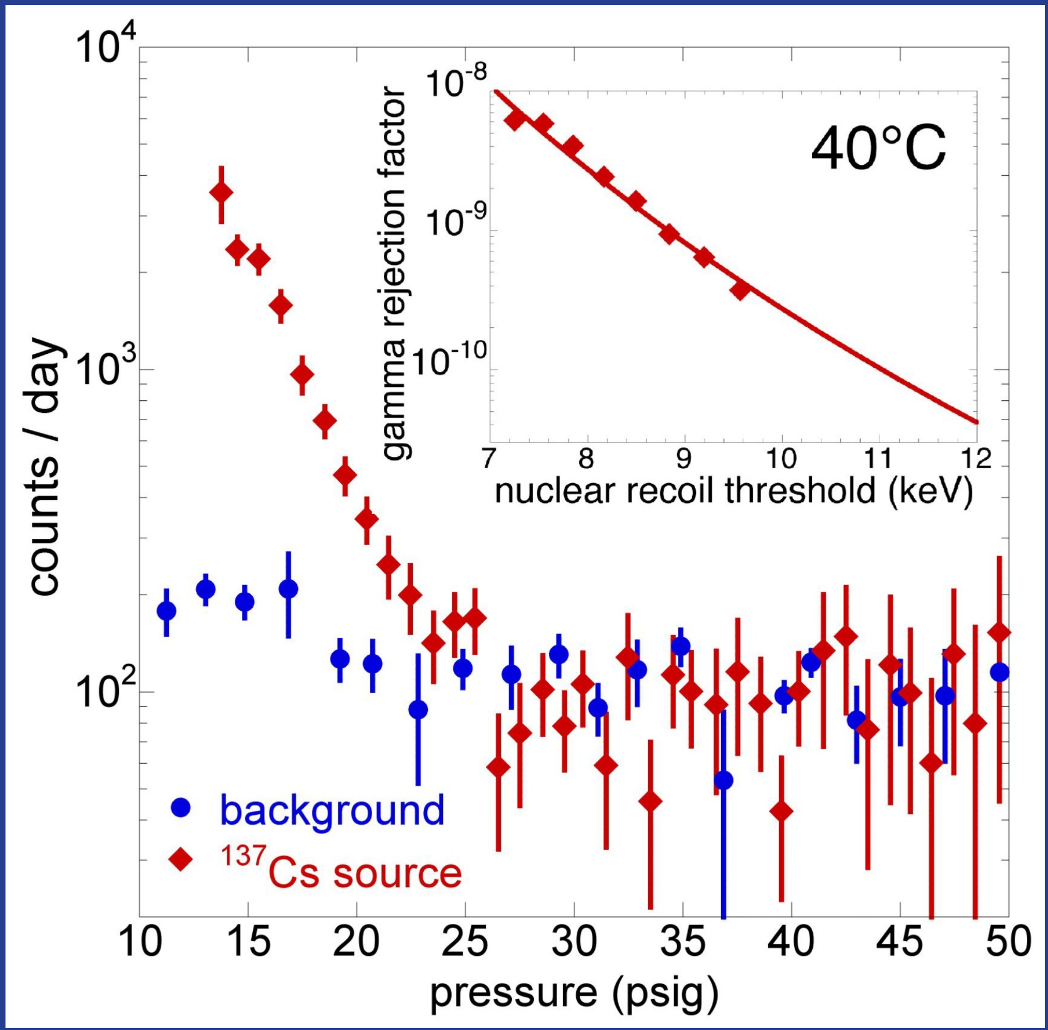
Pressure and temperature define the operating point



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 ☹



Progress in Bubble Chamber R&D

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

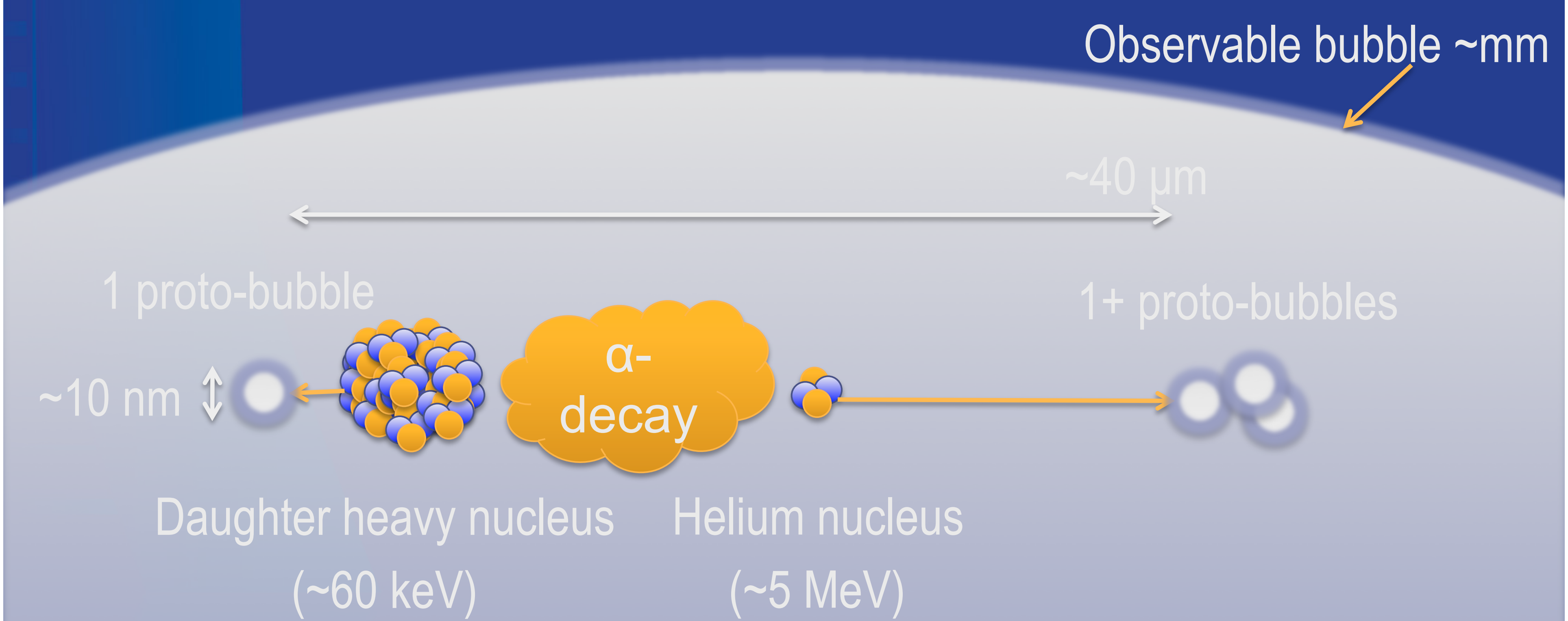
Important test bed in the NUMI underground hall

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	

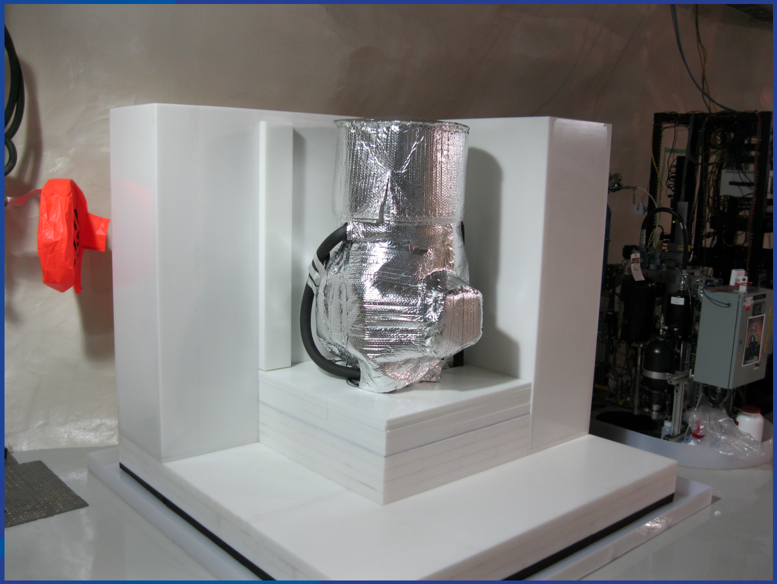
Acoustic Discrimination Against Alphas

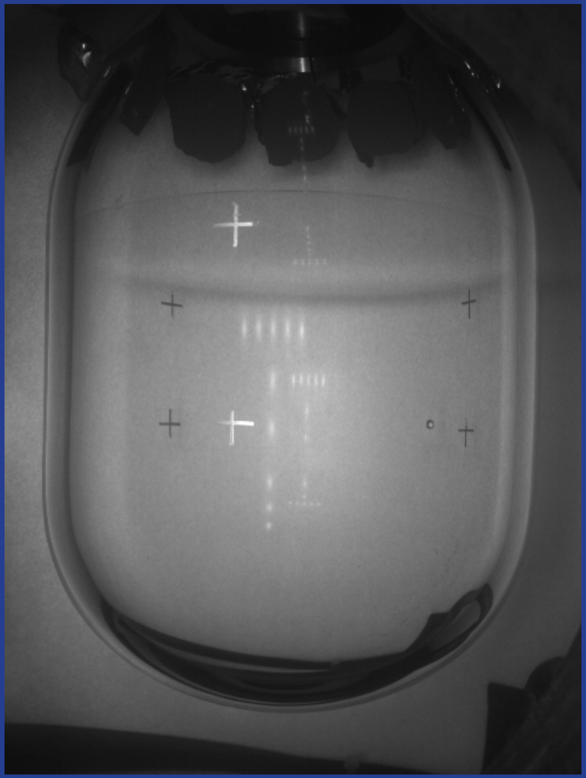
High frequency acoustic information probes smaller scales
Alpha decays produce many bubbles, louder at high frequencies



COUPP 4 kg – Installed at SNOLAB

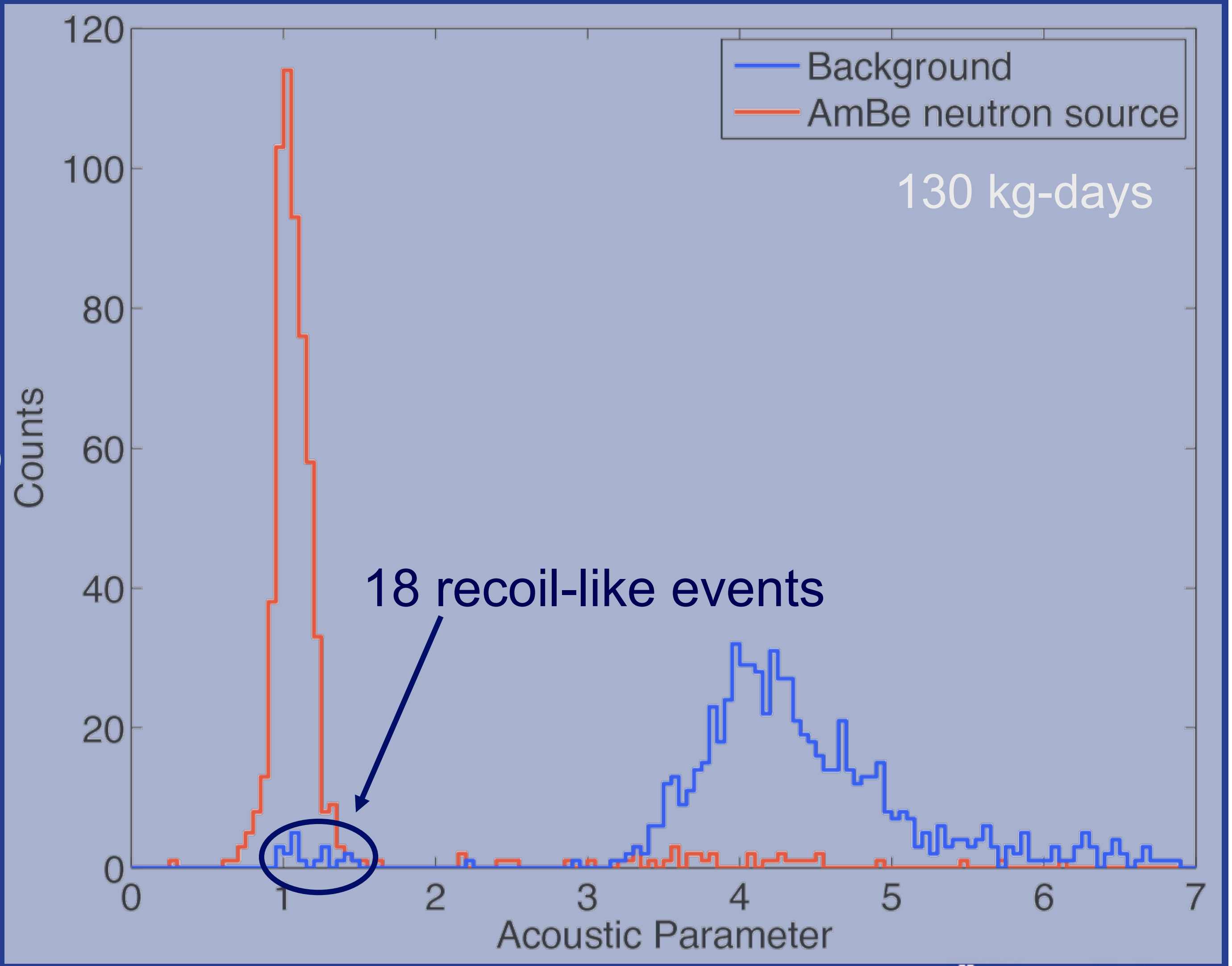
- The 4 kg chamber has recently been relocated to the deep underground SNOLAB facility
- Main goal is to measure acoustic alpha discrimination



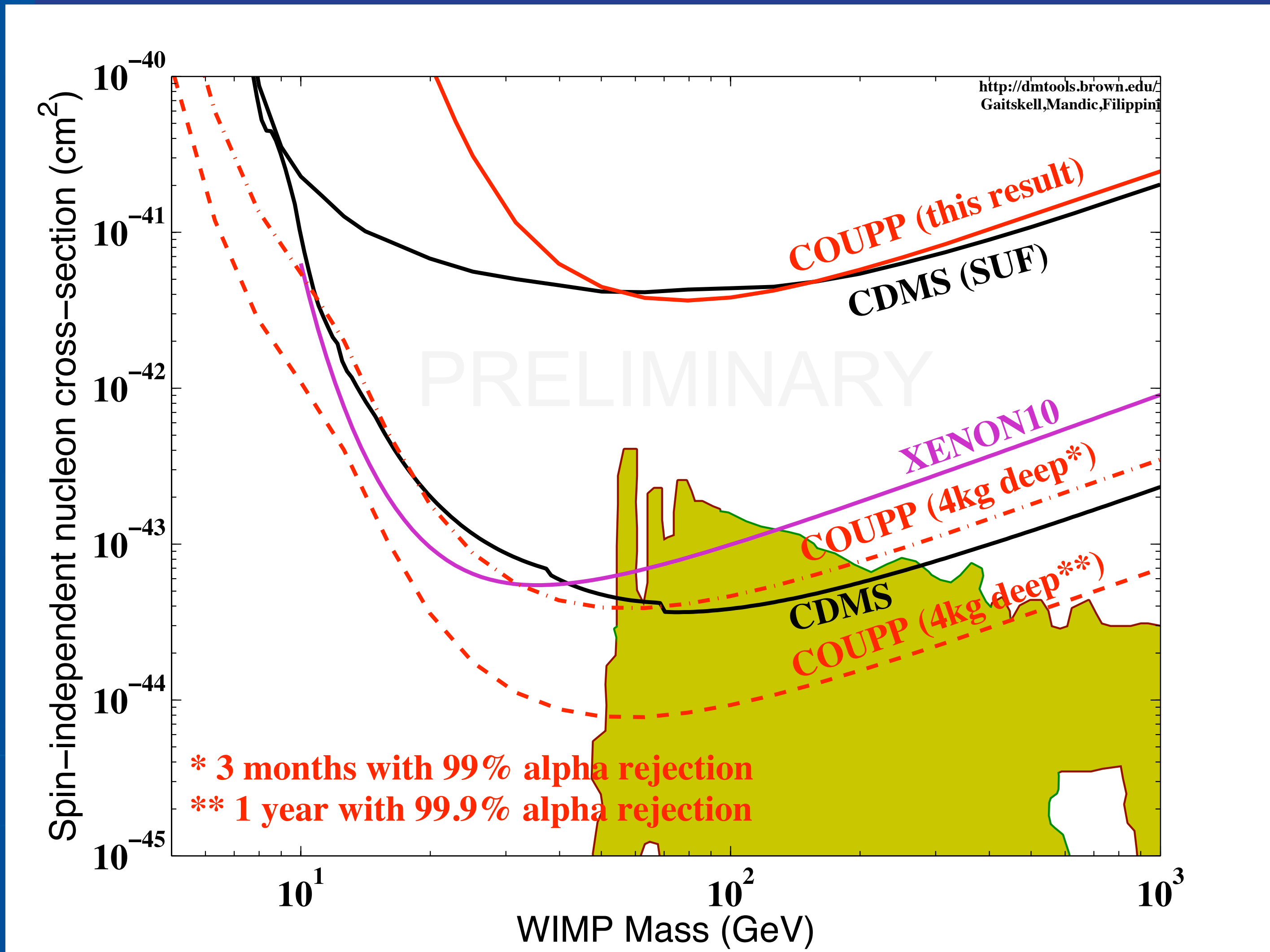


COUPP 4kg @ SNOLAB; early results

- Alpha rejection at least 98%
- Single-bubble background of ~0.05 events/kg-day from neutrons (***big*** statistical error bar)
- *O*(1) event/year expected from cosmogenic and environmental neutrons



Projected Sensitivity for a 4kg run at SNOLAB



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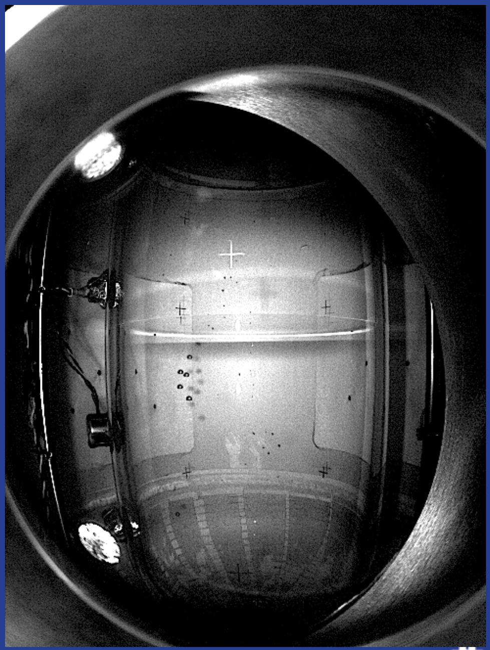
COUPP 60 kg – R&D towards a larger experiment

Data

- Several live days of operation during July and August

Milestones

- Successful commissioning of chamber and DAQ system
- Demonstration of acoustic discrimination in large chamber

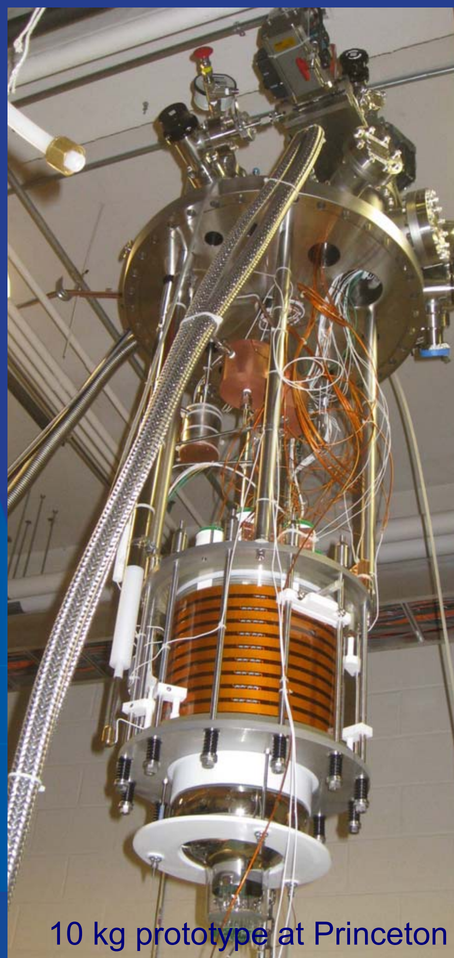


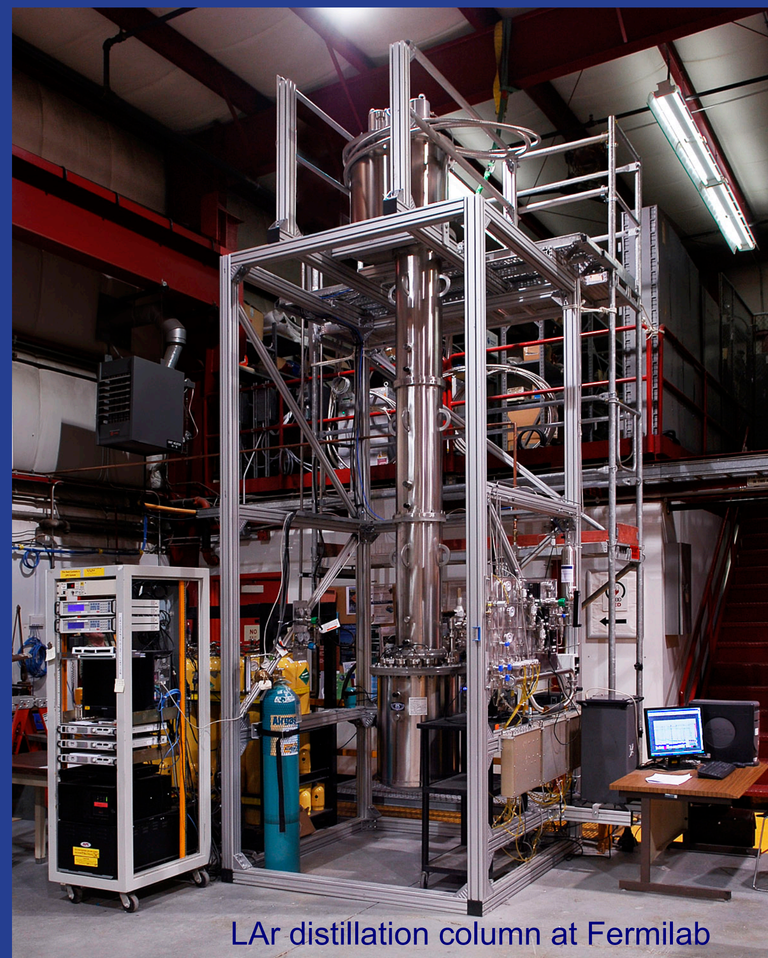
COUPP 60 Technical Issues

- Chemistry
  - CF_3I reacting with impurities or illumination
  - High bubble nucleation rate at CF_3I-H_2O interface
- Optics, Imaging
  - Higher resolution and frame-rate desired
  - More uniform illumination, lower intensity light source
- Neutron Backgrounds
  - Acoustic sensor replacement needed
  - Screening of other elements ongoing…

DarkSide: *Liquid Argon TPC*

Fermilab responsibilities include iquid argon distillation, DAQ, electronics
Involvement began in 2008; currently 0.3 FTE scientist


10 kg prototype at Princeton


LAr distillation column at Fermilab

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 $\sim 10^2$
- 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

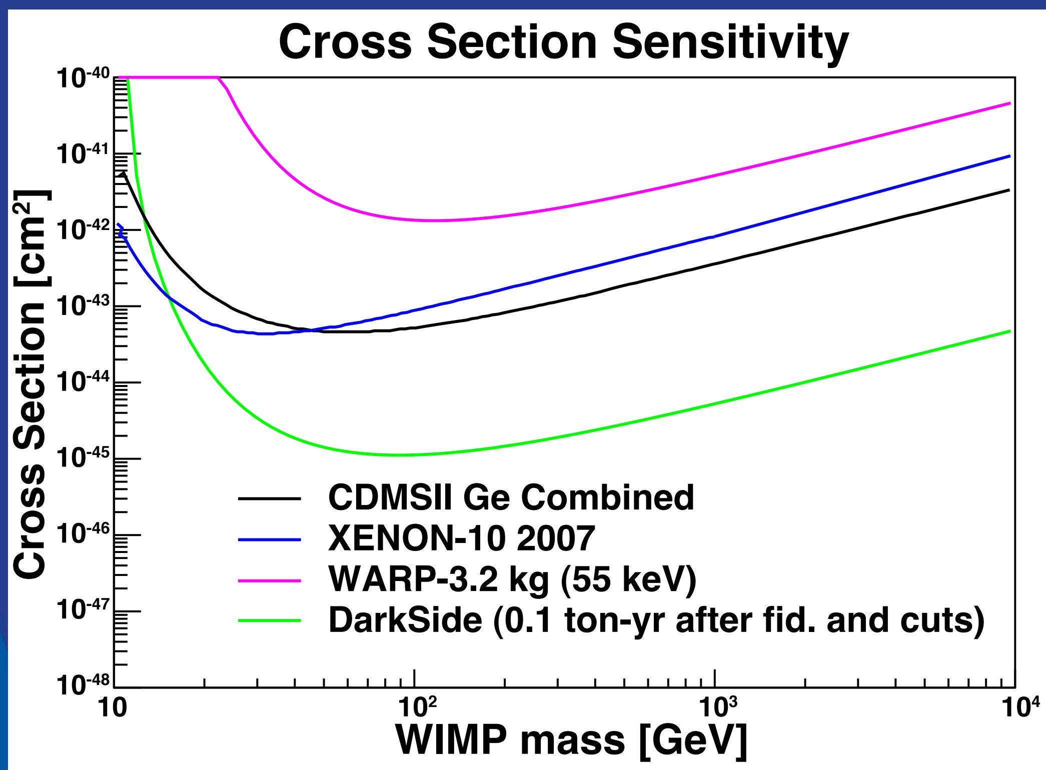
no radioactive background detected in best HpGe screener

new photocathode with 35% QE at liquid argon temperature

DarkSide Goals

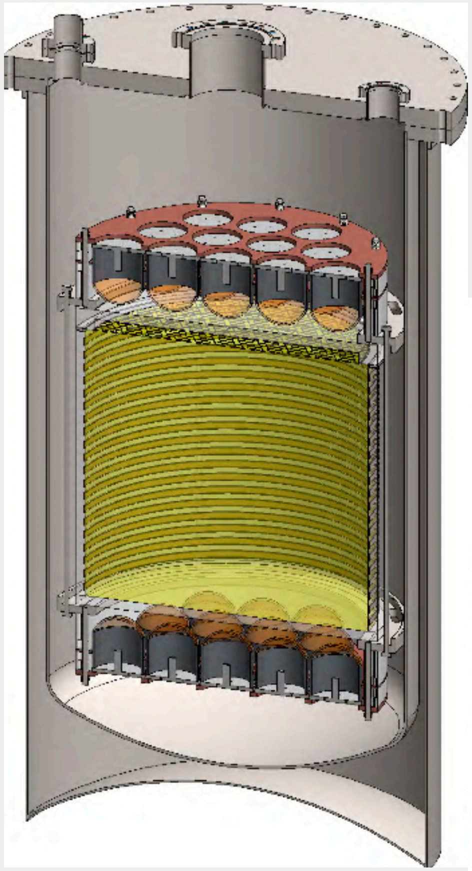
Program starts with DarkSide 50kg

Plan to install at Gran Sasso in 2012



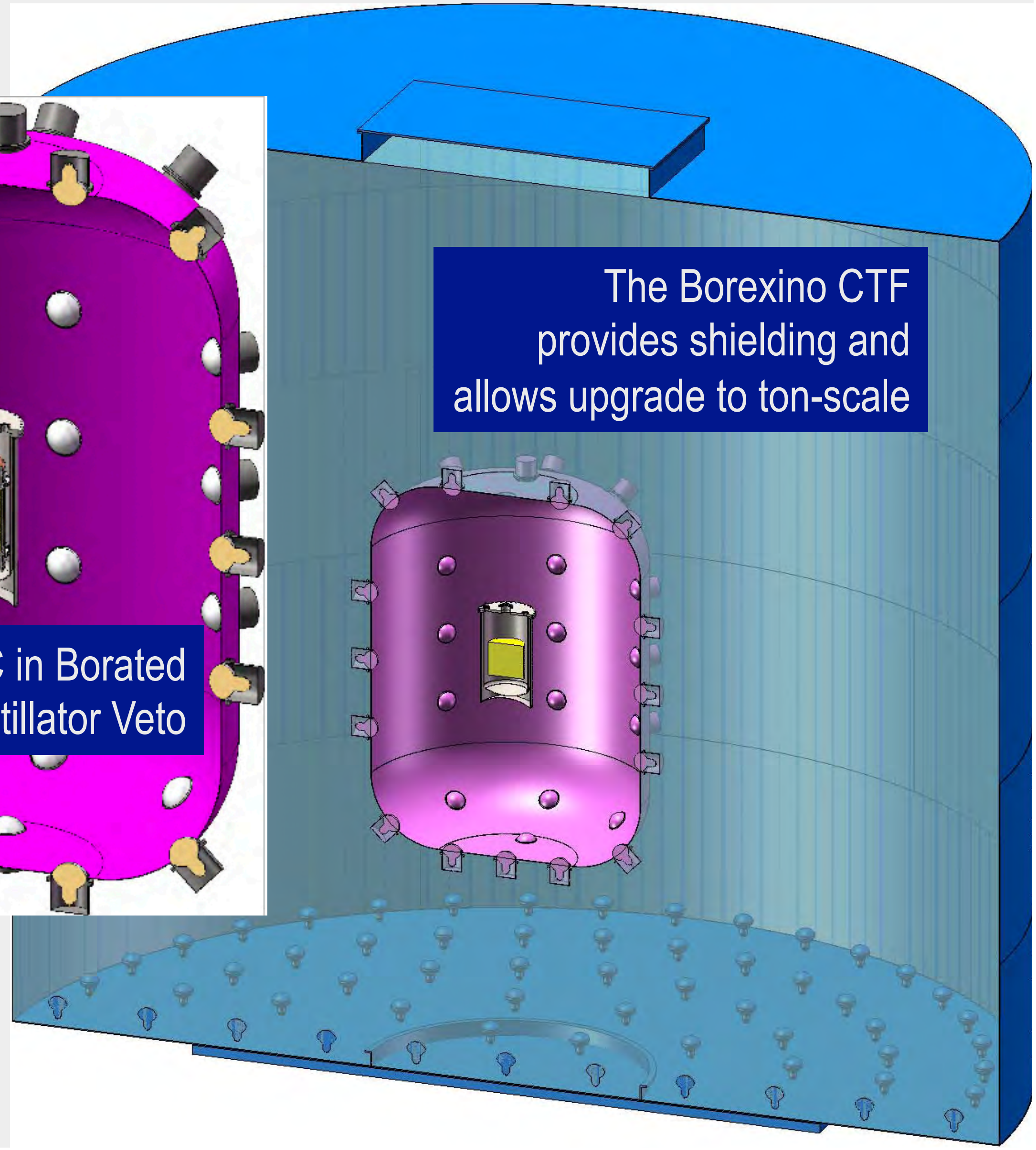
Projected Sensitivity assuming 3 years x 33 kg (fiducial) and < 0.1 event background

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



50 kg LAr TPC

DarkSide TPC in Borated Scintillator Veto

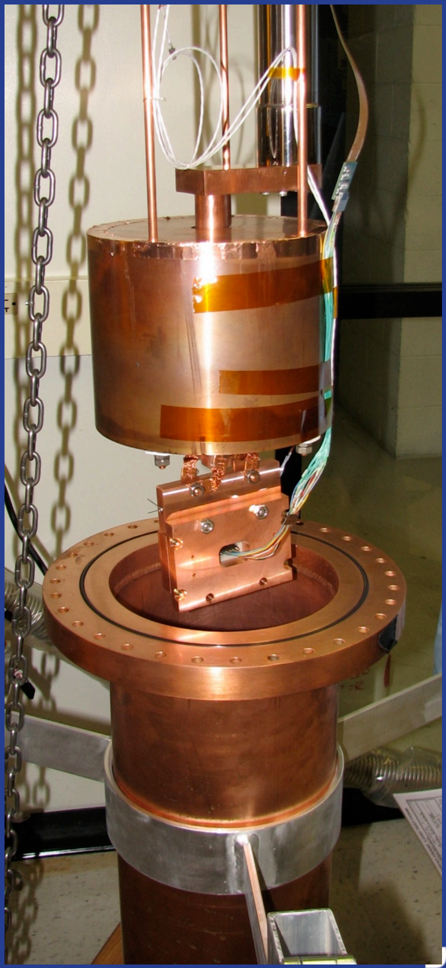


The Borexino CTF provides shielding and allows upgrade to ton-scale

DAMIC
Very low mass WIMP search with CCDs

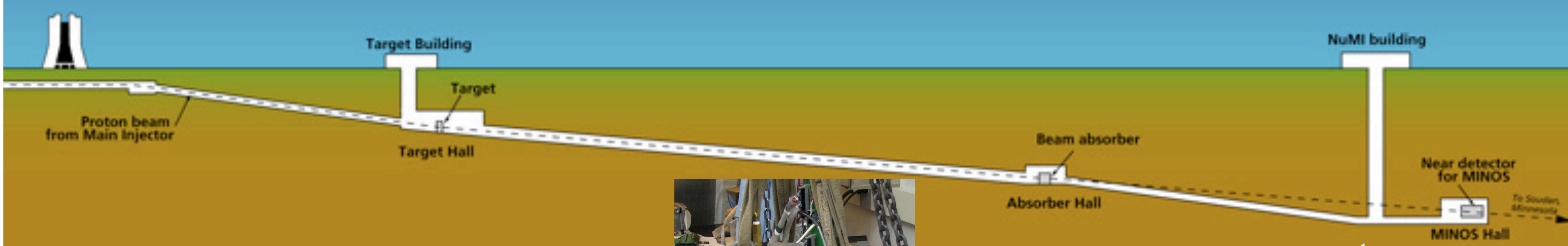
Fermilab responsibilities in all aspects of experiment.

Led by Juan Estrada (PECASE award); 0.5 FTE

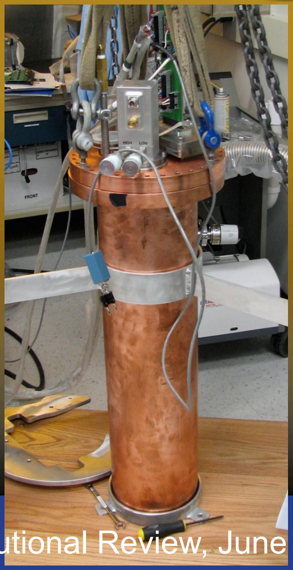


DAMIC underground test at FNAL

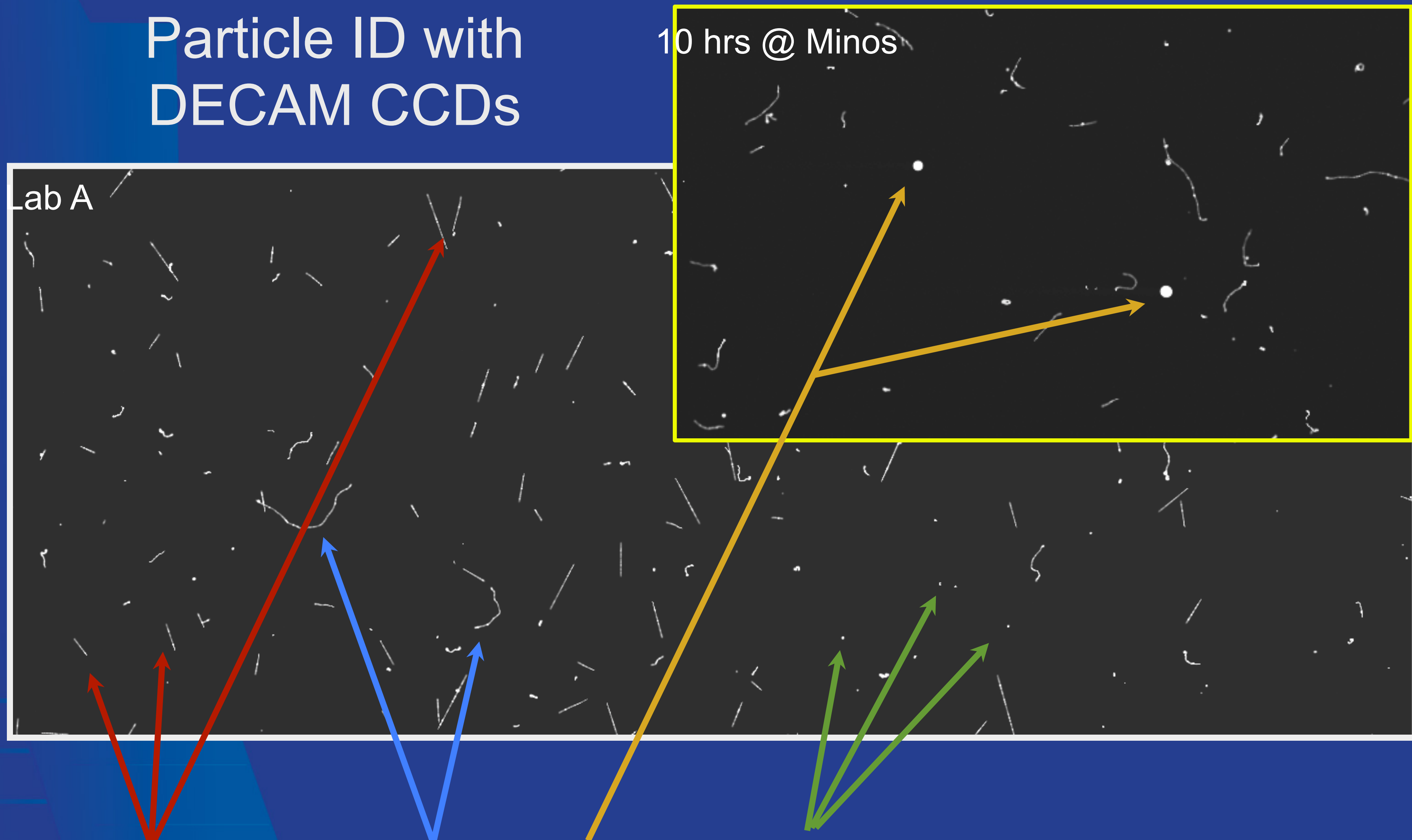
CCD operated at 350'
underground (MINOS hall)



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

Sensitivity to low Mass WIMPS

Direct Dark Matter Detection with CCDs (DAMIC) with 40 eV threshold.

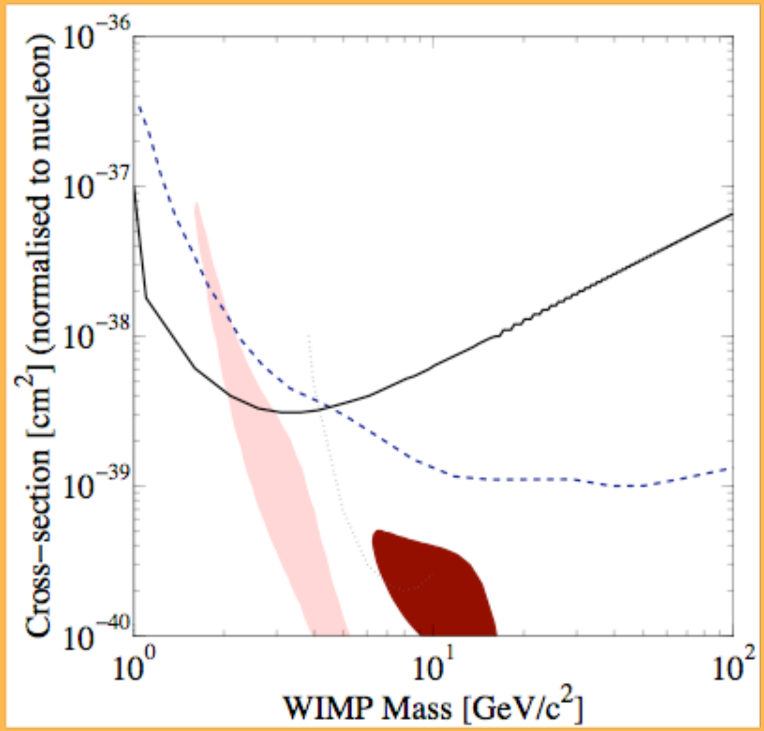


FIG. 8: Cross section upper limit with 90% C.L. for the DAMIC results (solid-black) compared to CRESST 2001 (dashed) and CoGent 2008 (dotted) results. The shaded area corresponds to the 3-sigma contour consistent with the DAMA/LIBRA annual modulation signal (dark: no ion channeling, light: ion channeling) [53].

Why are we pursuing four different experiments?

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

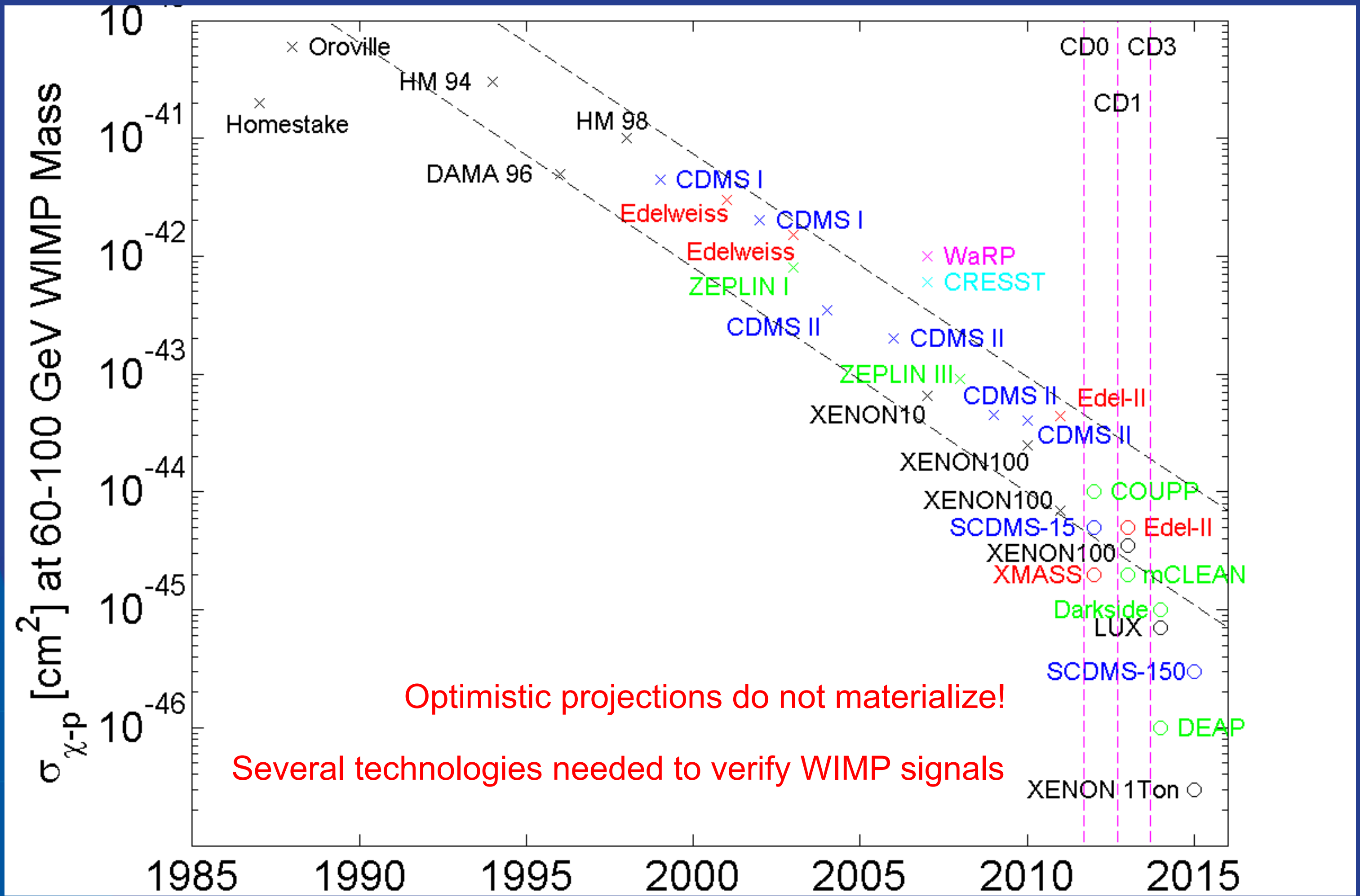
Darkside

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

DAMIC

- Best sensitivity to < 1 GeV WIMP masses

The Competitive Landscape for Dark Matter



Summary

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

Pursuit of multiple technologies assures that we will participate in both 100 kg and ton-scale experiments.

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.