Next-generation dark matter searches with SuperCDMS

Lauren Hsu

Fermilab Particle Astrophysics Seminar

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Motivation

An old puzzle…

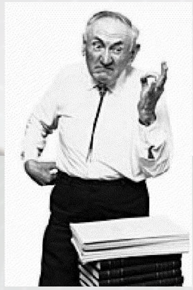
1933:

Fritz Zwicky analyzes velocity dispersion in Coma Cluster

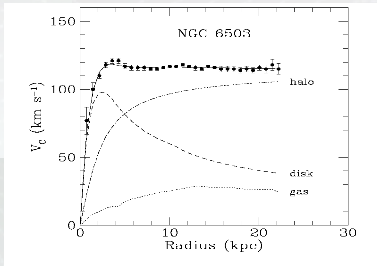
Individual galaxies move too fast for a bound system…

was the cluster more massive than deduced from luminous material?

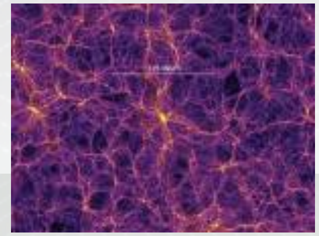
…becomes an established problem



Zwicky discovers missing mass in Coma Cluster



Galactic rotation curves measured with 21cm suggest dark matter on galactic scales

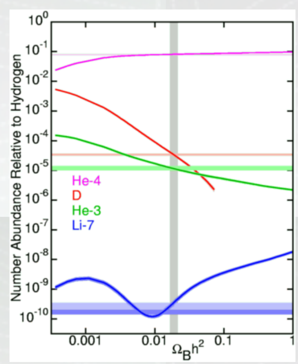


N-body simulations reproduce large scale structure if DM is cold

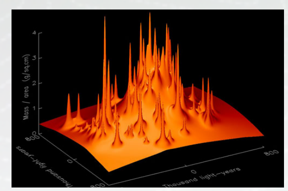
Bullet Cluster shows separation btwn baryonic matter and center of gravity

1933 — ~1970 — ~1975 — ~1980 — ~1990 — 2006 — TODAY

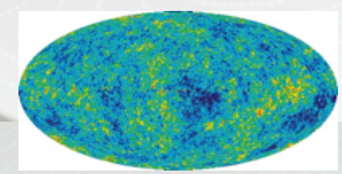
Astrophysical data tell us much about dark matter but we still don't know its fundamental properties !



BBN sets bound on baryonic matter content of the universe

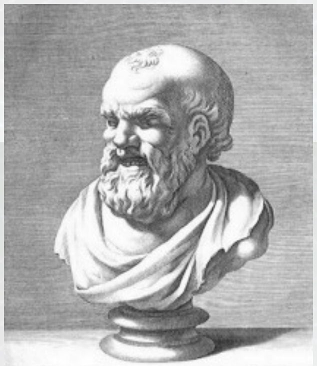


Gravitational lensing tomography supports existence of DM



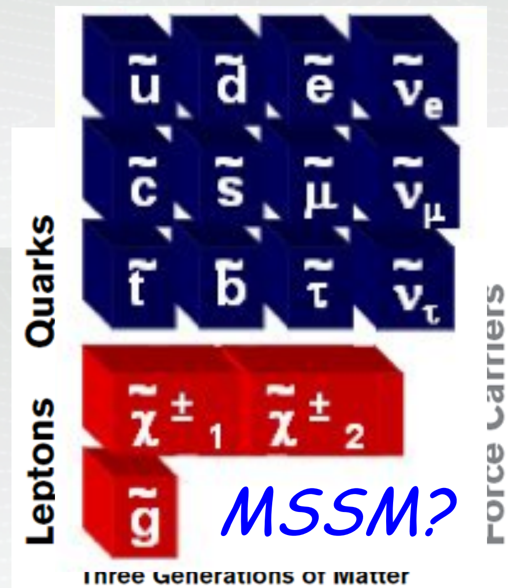
CMB tells us that DM is ~85% of all matter in the Universe, and Ω_{CDM} = 23%

What we know about matter



We believe all matter is built from fundamental components and described by a single powerful theory

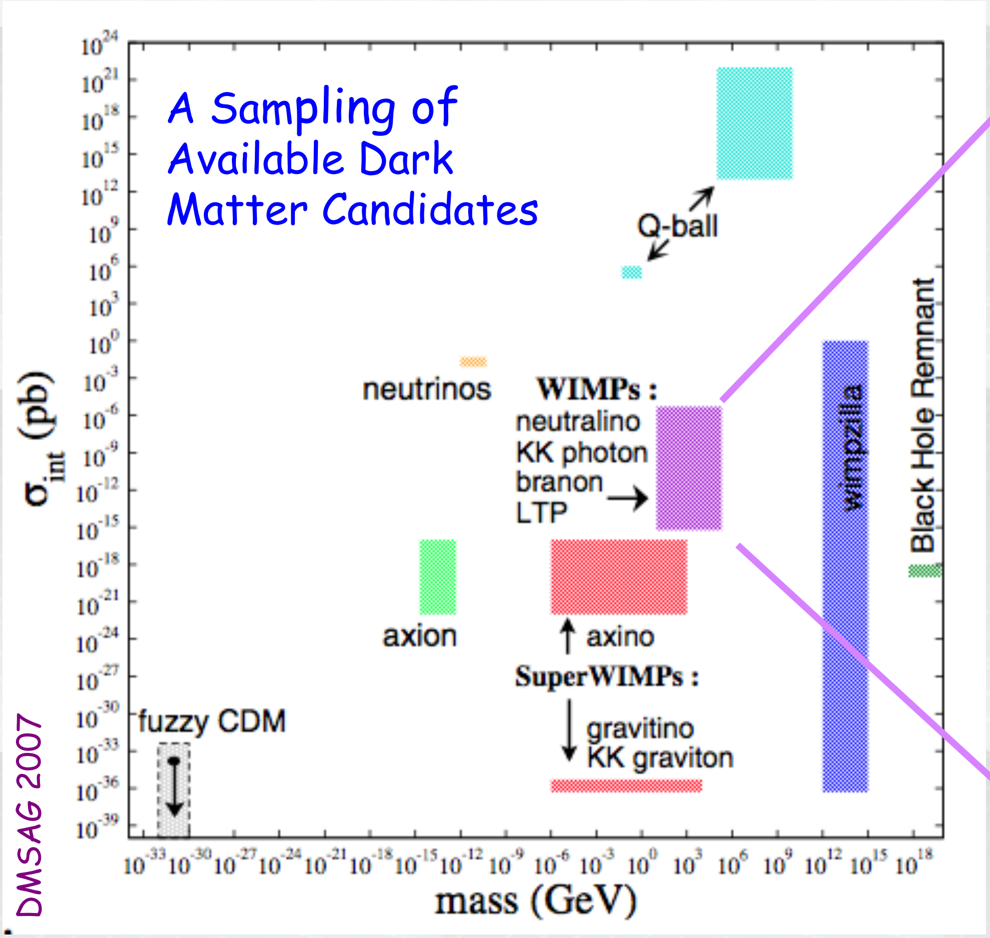
So far this has seems true for all matter we can study in the laboratory…



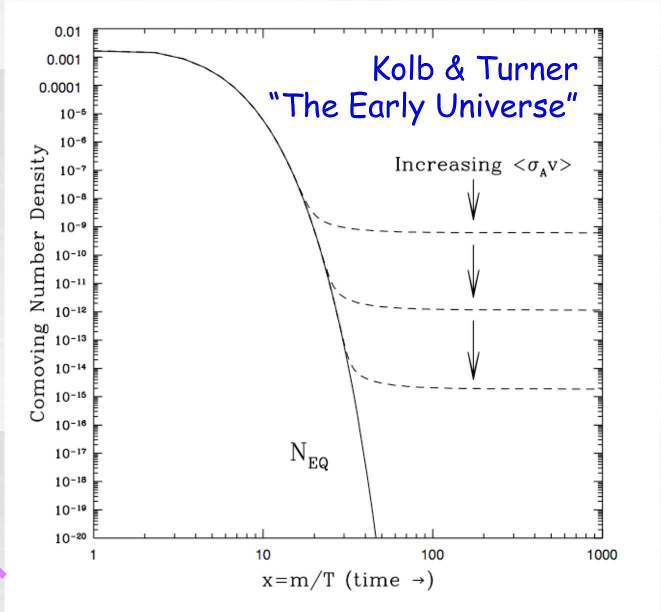
…but the Standard Model of particle physics is far from a complete description (hierarchy problem, unification problem, neutrino masses, strong cp problem ….)

Solutions to remaining Standard Model problems also provide candidates for dark matter!

The Weakly Interacting Massive Particle

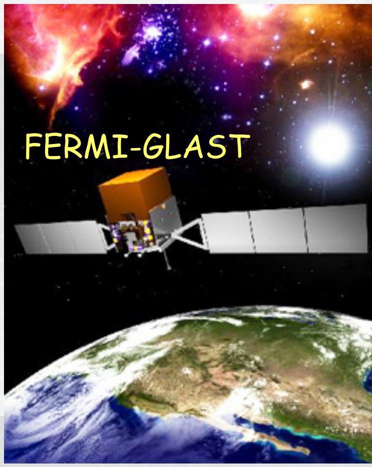


Particles with mass and couplings at the weak scale yield cross sections that correspond to ~correct relic density of CDM



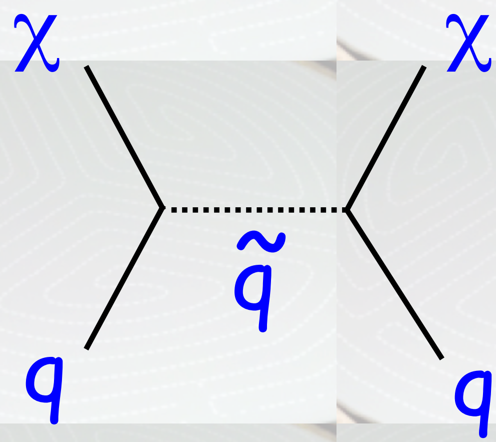

Direct Detection

How to detect WIMPs



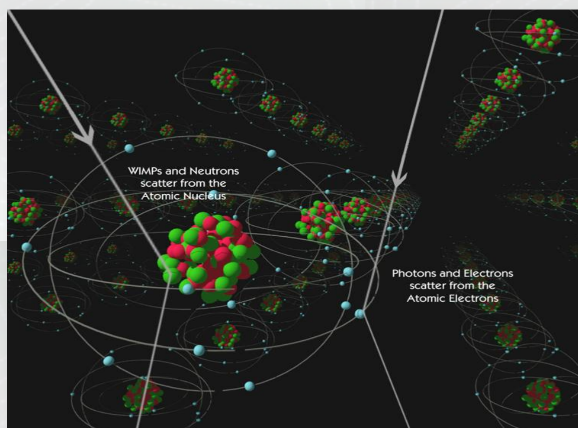
Relic annihilation in the cosmos

INDIRECT DETECTION



man-made COLLIDER production

M. Attisha



Relic WIMP-nucleon elastic scattering

DIRECT DETECTION

WIMP-nucleon scattering 101

General WIMP-nucleus elastic scattering cross section (for $q^2 = 0$):

$$\sigma_0 = \frac{4\mu^2}{\pi}\left[f_p N_p + f_n N_n\right]^2 + \frac{32G_F^2\mu^2}{\pi}\frac{(J+1)}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

scattering adds coherently with A^2 enhancement! (A = atomic mass)

Spin-dependent term: small for most Ge isotopes

What about kinematic factors? Full expression: $\frac{d\sigma}{dq^2} = \sigma_0 F^2(q^2)$ Form Factor

Roughly speaking, the form factor parameterizes coherence. So if:

$$E_{recoil} > \frac{2X10^4}{A^{5/3}}\ keV$$

~ tens of keV for Ge

...then coherence is lost - In other words, a big target nucleus only helps up to a certain point!

The relic WIMP distribution

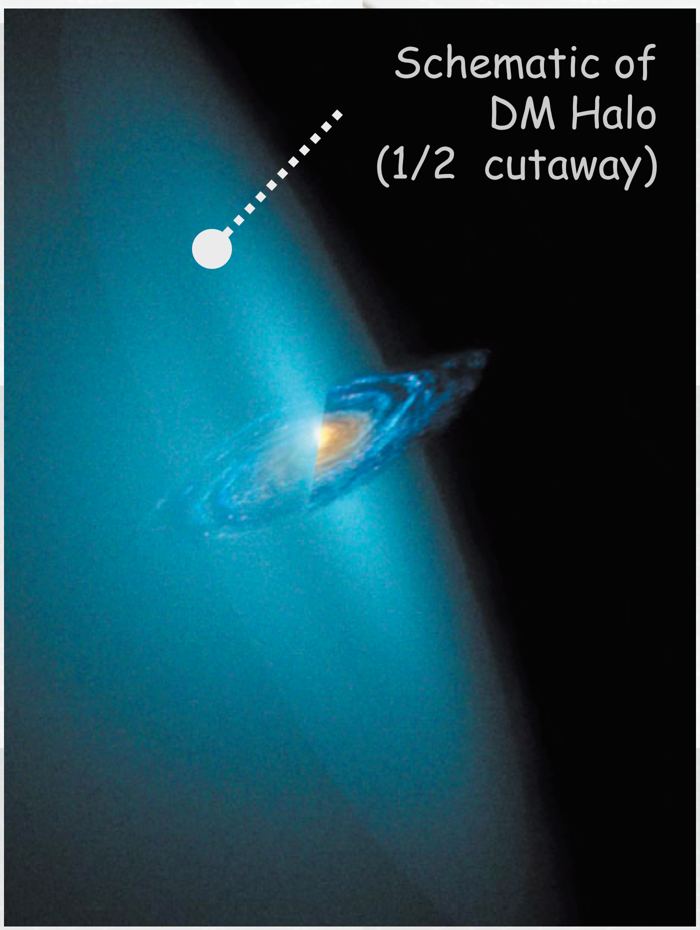
Observed energy spectrum & rate depend on WIMP distribution in dark matter halo

- WIMPs distributed in spherical halo

$$\rho \sim \rho_0 (r/r_s)^{-1}(1+r/r_s)^{-2}$$

- Assume isothermal Maxwell-Boltzmann velocity distribution **(width = 220 km/s)**
- **Ve ~ 245 km/s** - WIMP velocity relative to Earth
- Local density of WIMPs **= 0.3 GeV/cm^3**

If WIMPs are 100 GeV/c^2 particles, then ~10 million pass through your hand each second!



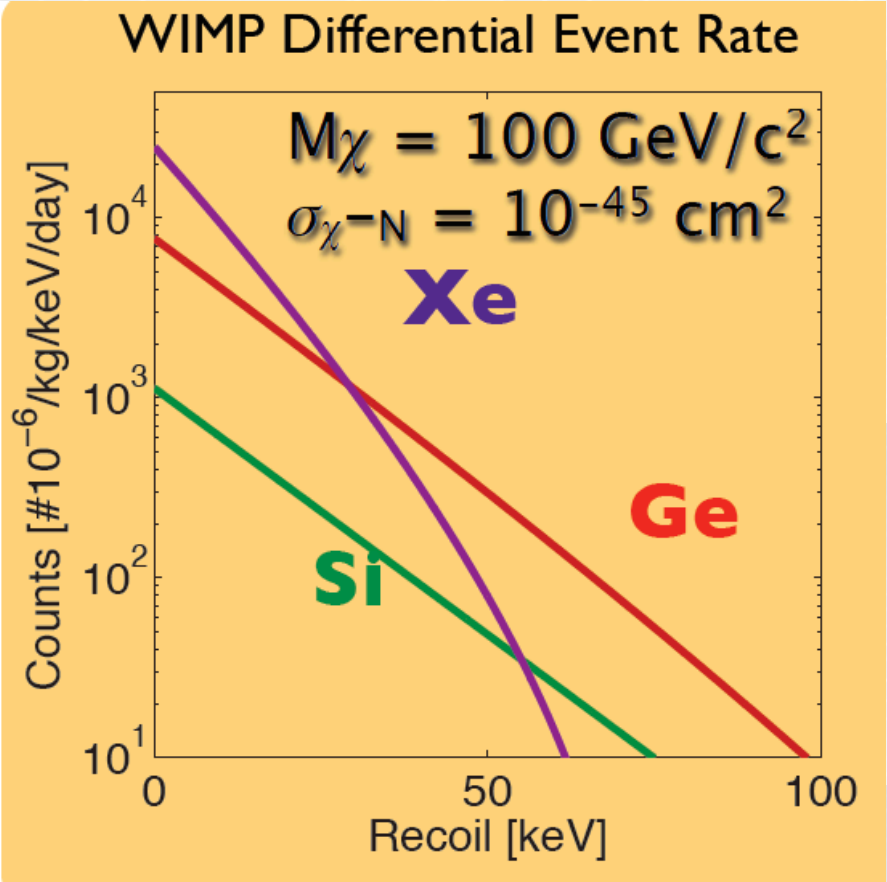
Putting it all together

Expected signal:

- nuclear recoil
- signal at ~ few 10's of keV
- rates <0.1 events /kg/day

Challenges:

- low energy thresholds (~10 keV)
- mitigation of natural radioactivity
- operation deep underground

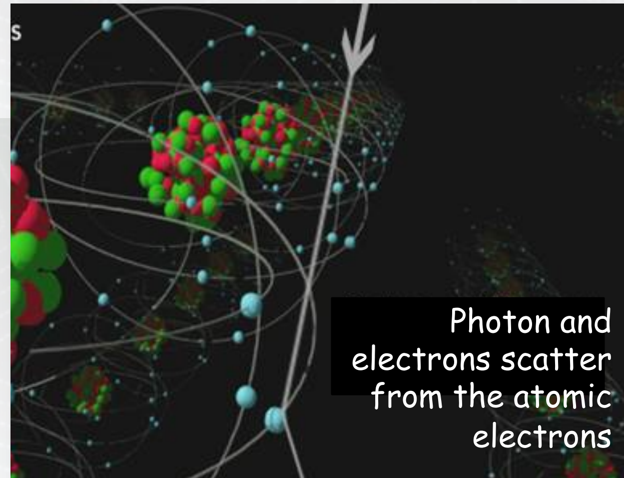


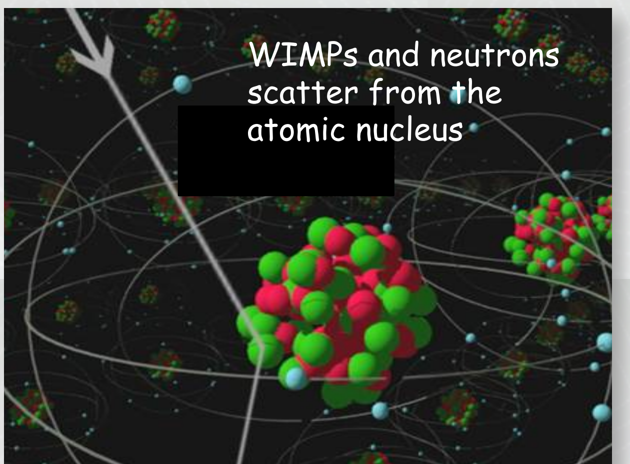
Its all about backgrounds

ELECTRON RECOILS

Gamma – most prevalent background

Beta – "surface events" in CDMS





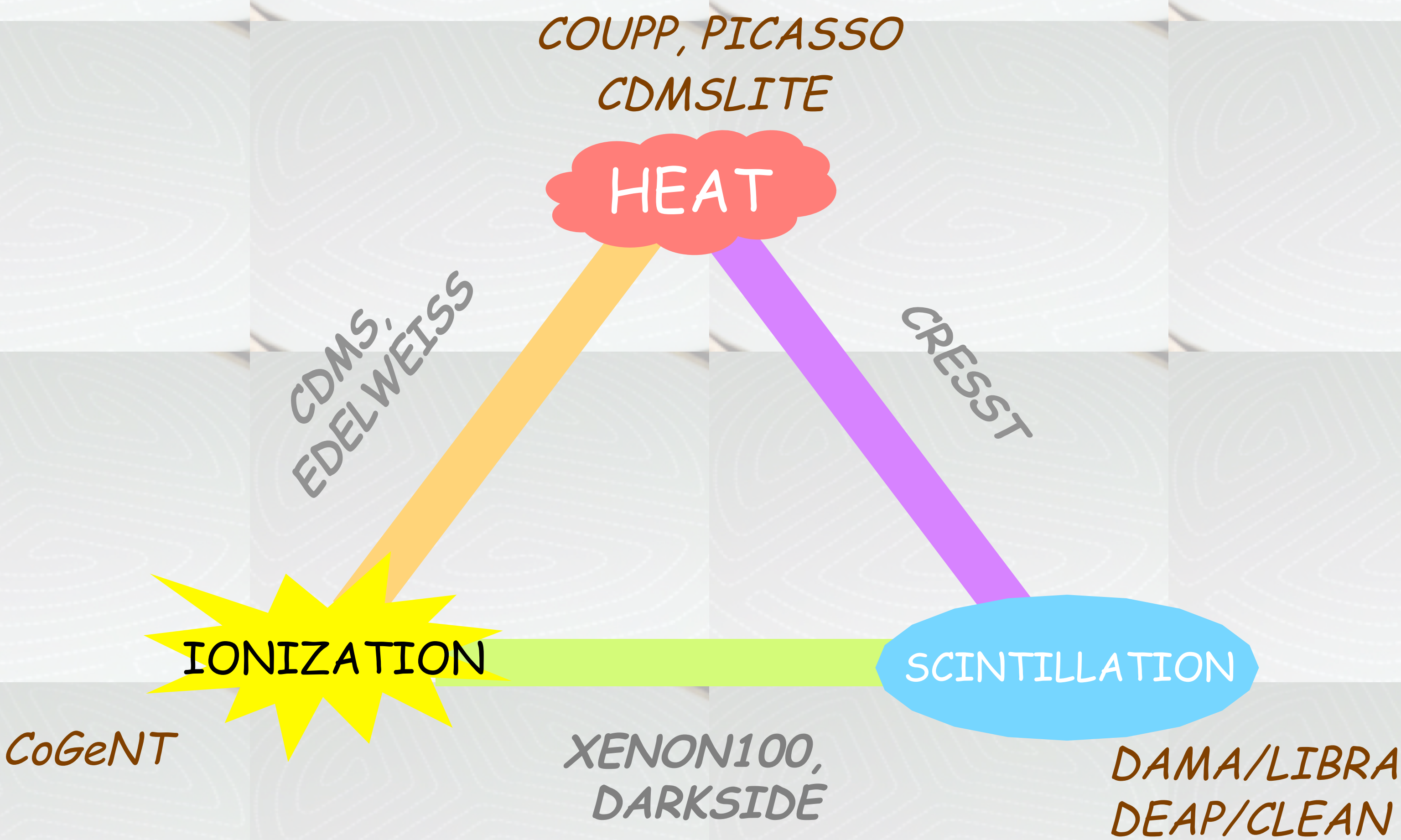
NUCLEAR RECOILS

Neutron – *rare but NOT distinguishable from WIMP signal*

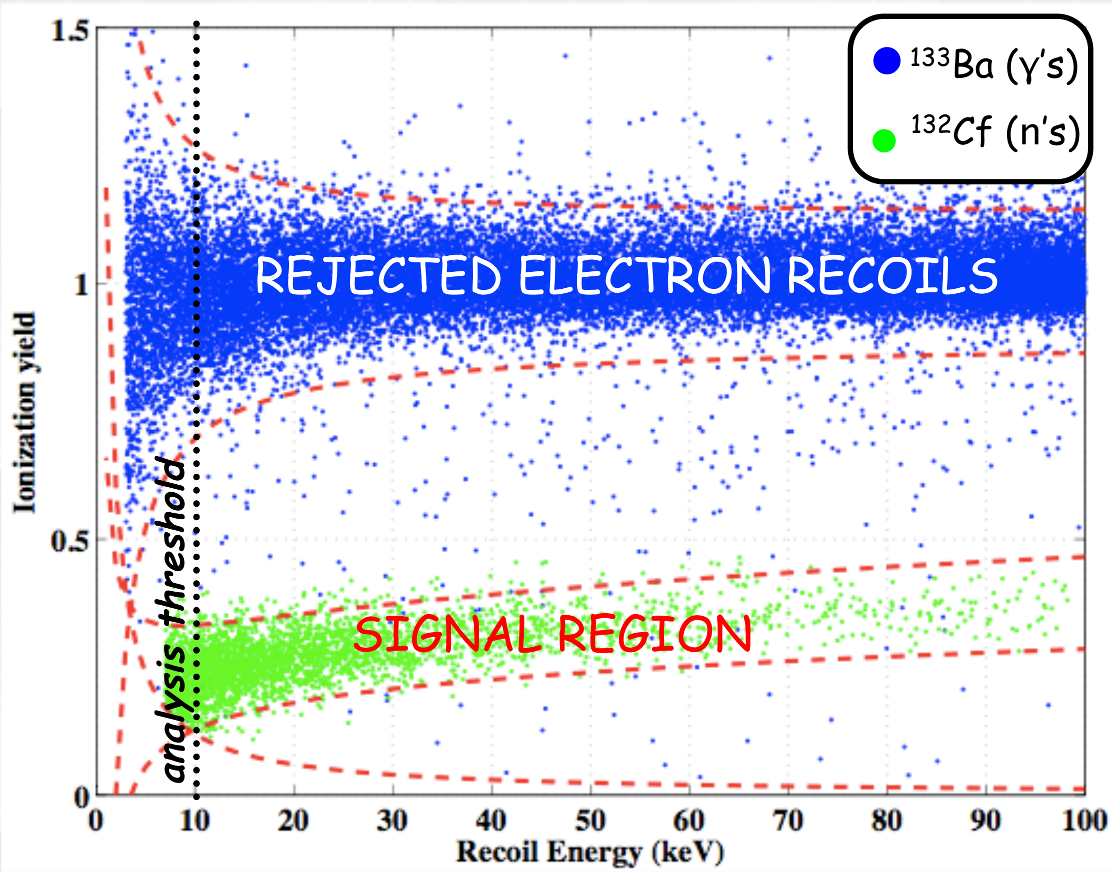
Alpha/recoiling parent – *not a background for most experiments*

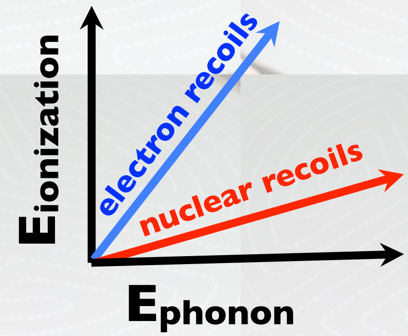
~~WIMP detection~~ techniques

Background rejection



How it works for CDMS



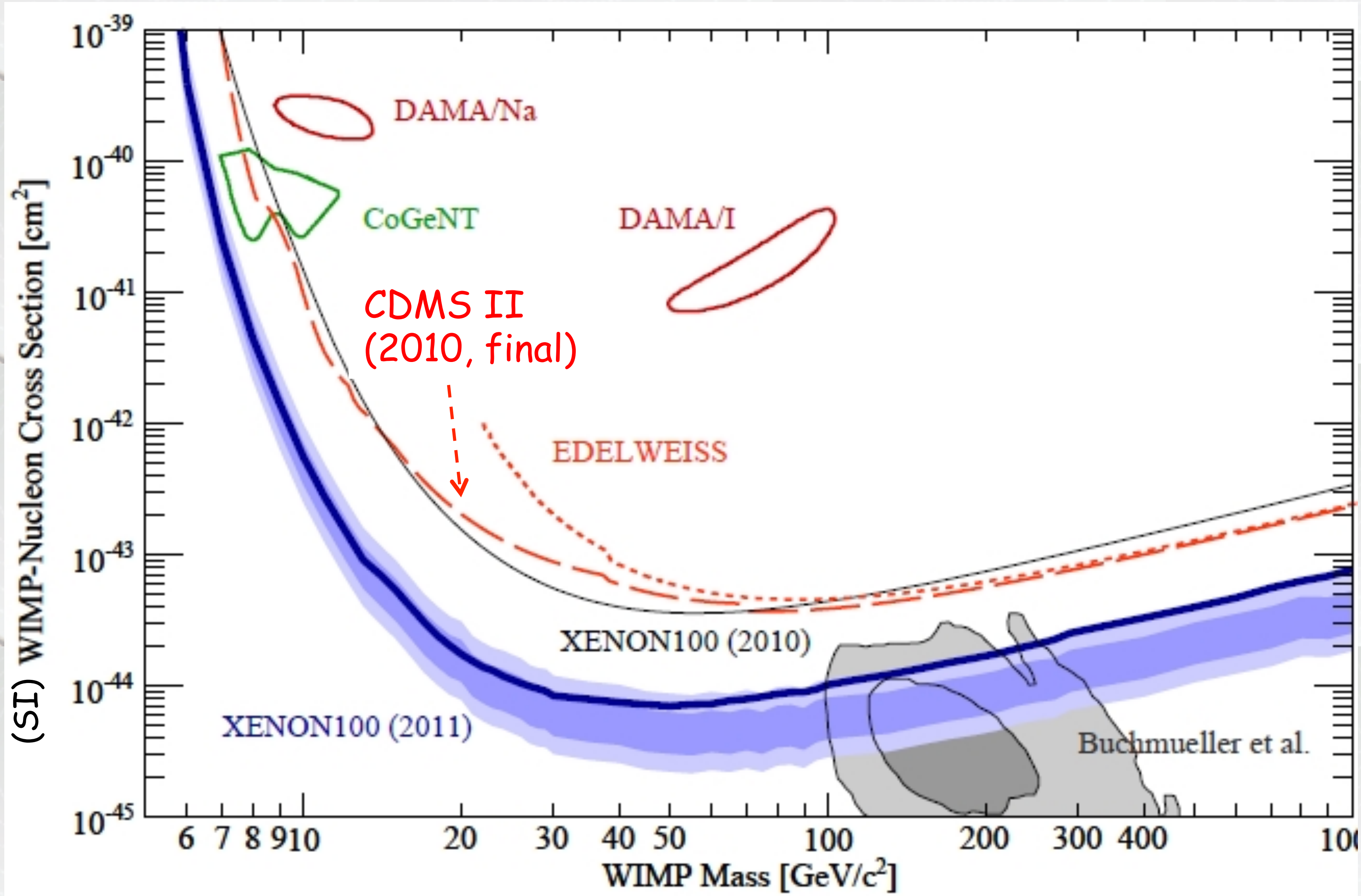


$$\text{ionization yield} = \frac{E_{ionization}}{E_{phonon}}$$

$1:10^4$ rejection of gammas based on ionization yield alone...

BETTER THAN $1:10^6$ rejection of gammas and betas w/ phonon pulse shape (in CDMSII)

Where we are (minus caveats)



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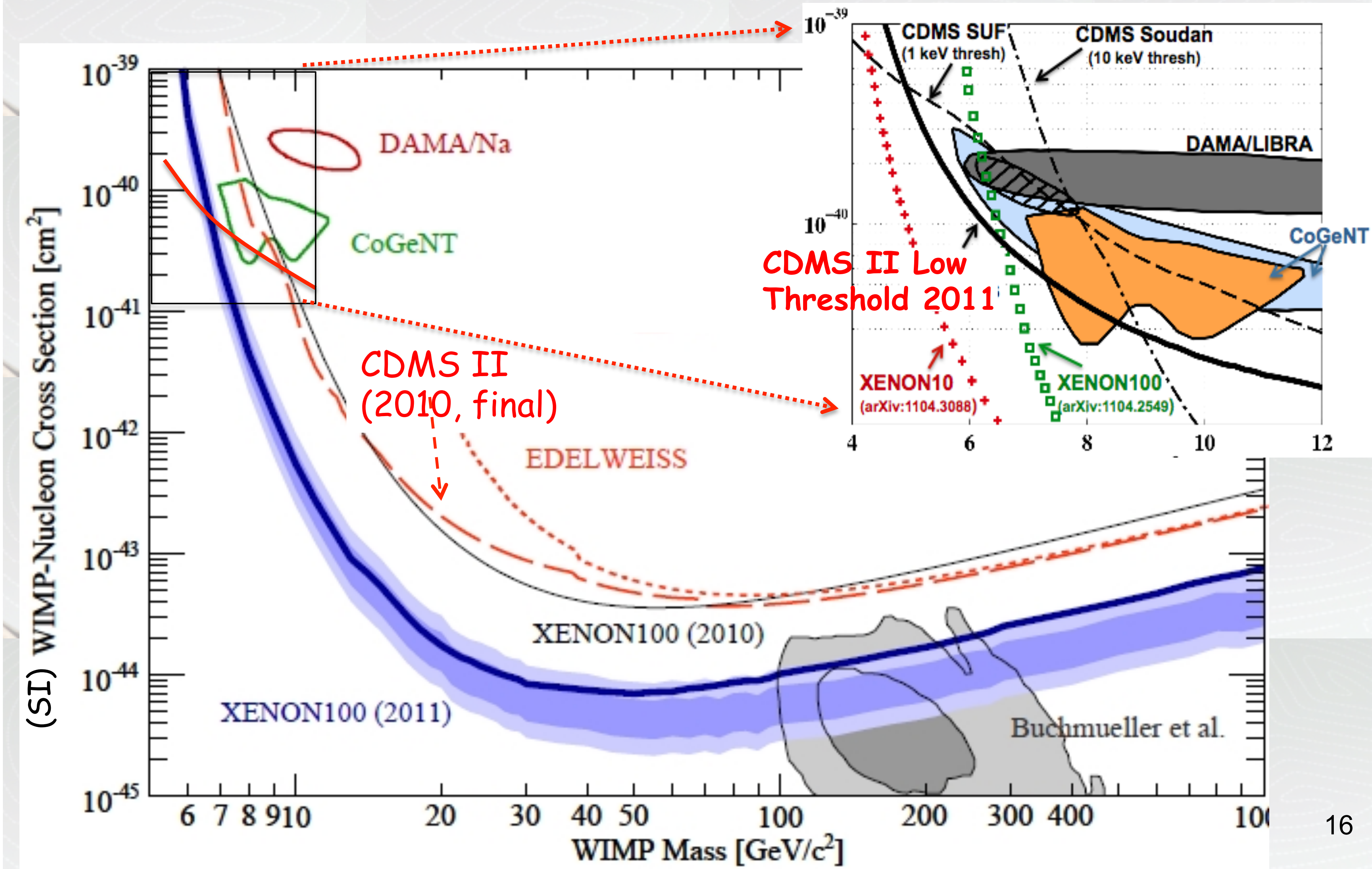


Where we want to go

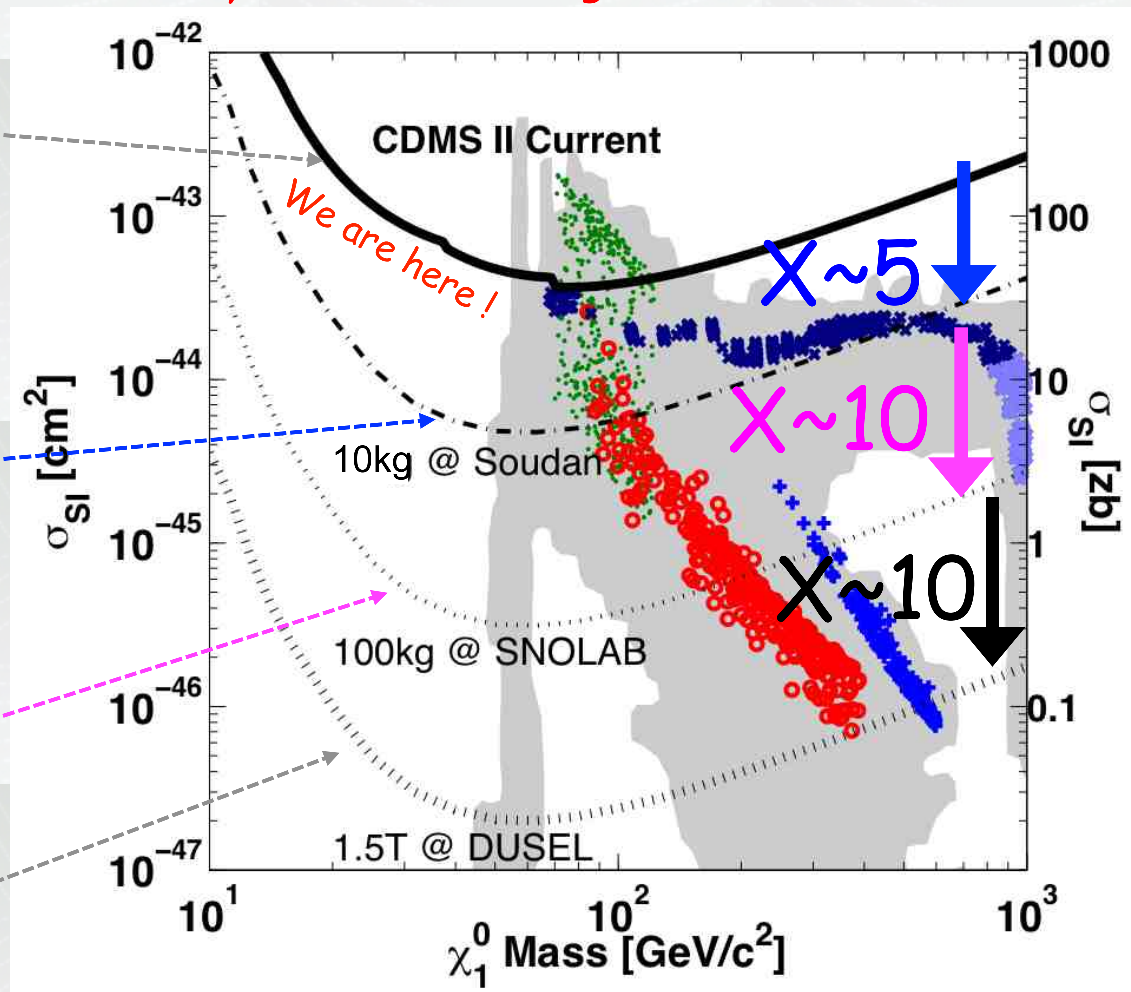
SuperCDMS constitutes phose I and II of a 3 step program to deeply probe MSSM OR study a dark matter signal

CDMS II (completed)
4 kg Ge
$3.8\times10^{-44}cm^2$ at 90% CL
(for 70 GeV/c^2 WIMP)

SuperCDMS @ Soudan
10 kg Ge
~ 2 yrs operation

SuperCDMS @ SNOLAB
O(100) kg Ge
~ 3 yrs operation

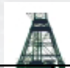
GEODM
O(1) ton Ge



SuperCDMS at Soudan

Soudan setup

Surface

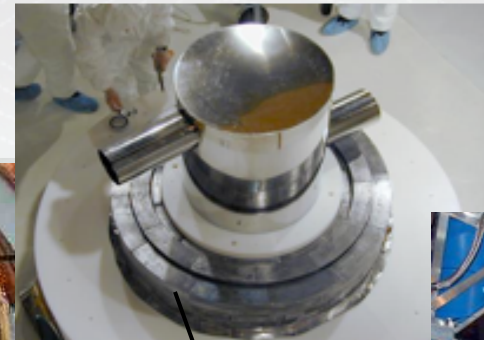


WIMP detectors were completely replaced. All other infrastructure is being reused.

Deep underground site significantly reduces cosmogenic background

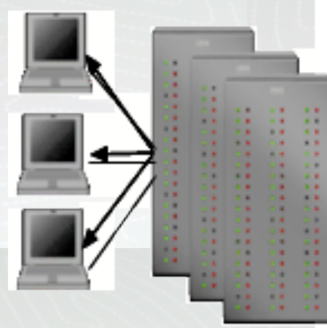
780m (2090mwe)

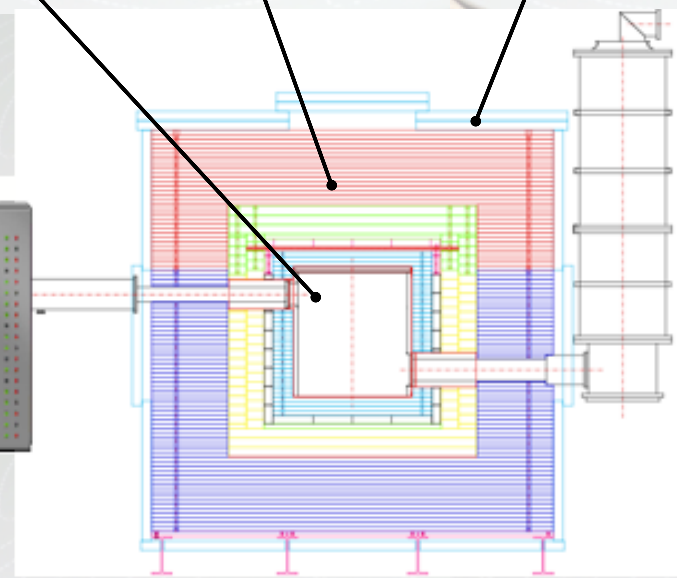
Array of 15 Ge detectors reside in the "icebox"



Lead, poly and scintillator provide additional shielding

DAQ



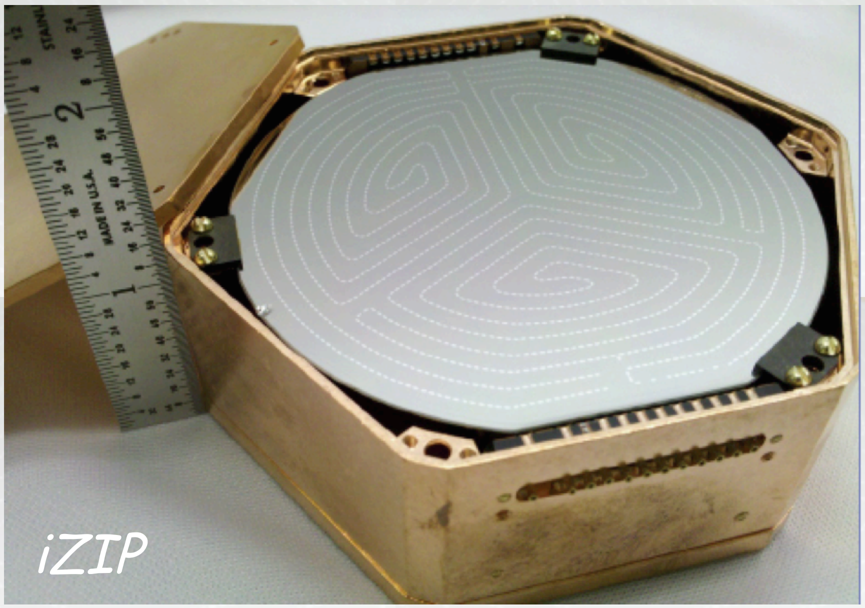


Cryogenic system cools detectors to ~50 mK, needed for phonon detection

SuperCDMS Soudan

10 kg of Ge arranged in 5 towers

iZIP = "interleaved Z-sensitive Ionization and Phonon" detector



CDMSII ZIP profile

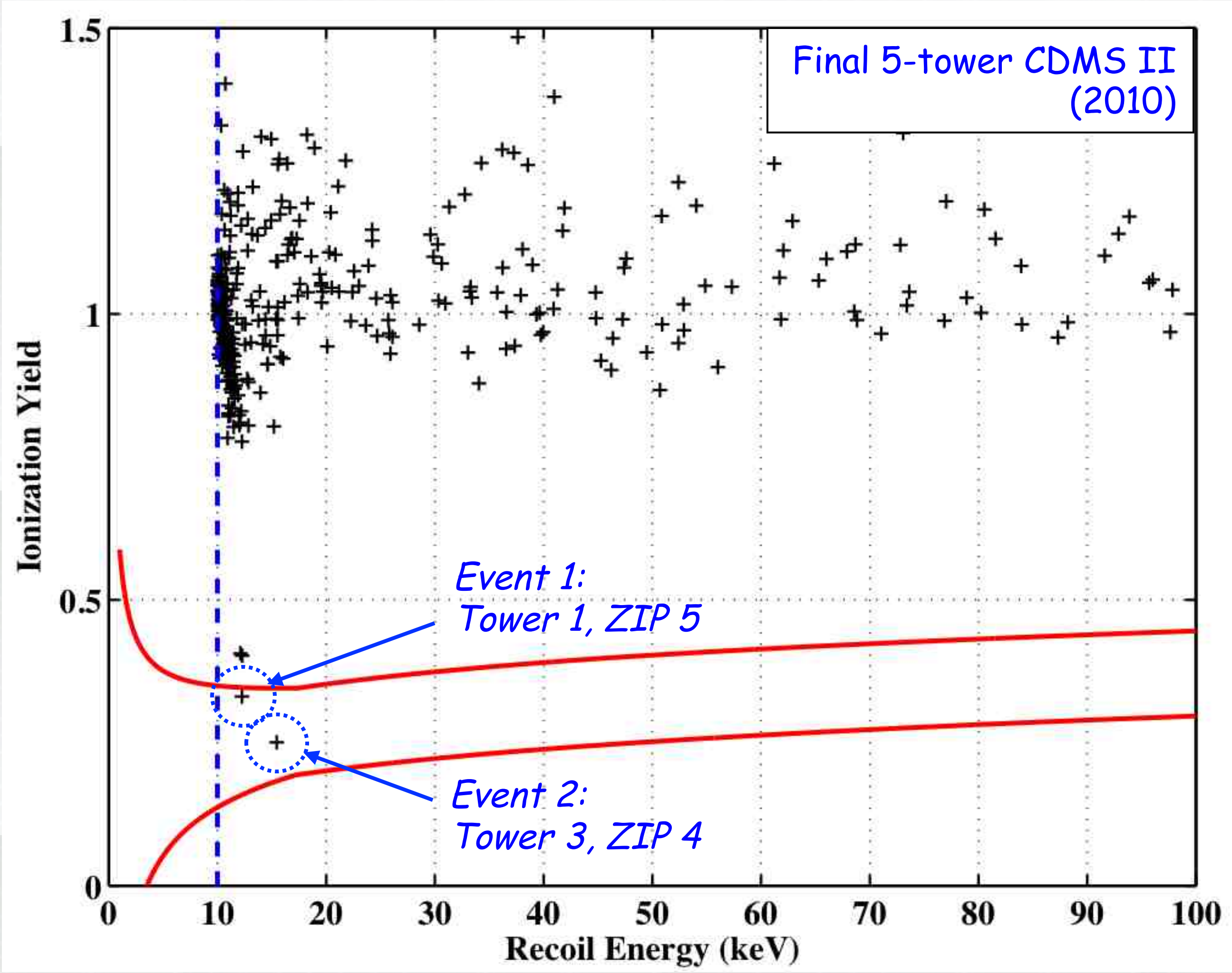
iZIP profile

1cm ➔2.5 cm (thickness of Ge crystals)

0.25 kg ➔ 0.6 kg per detector

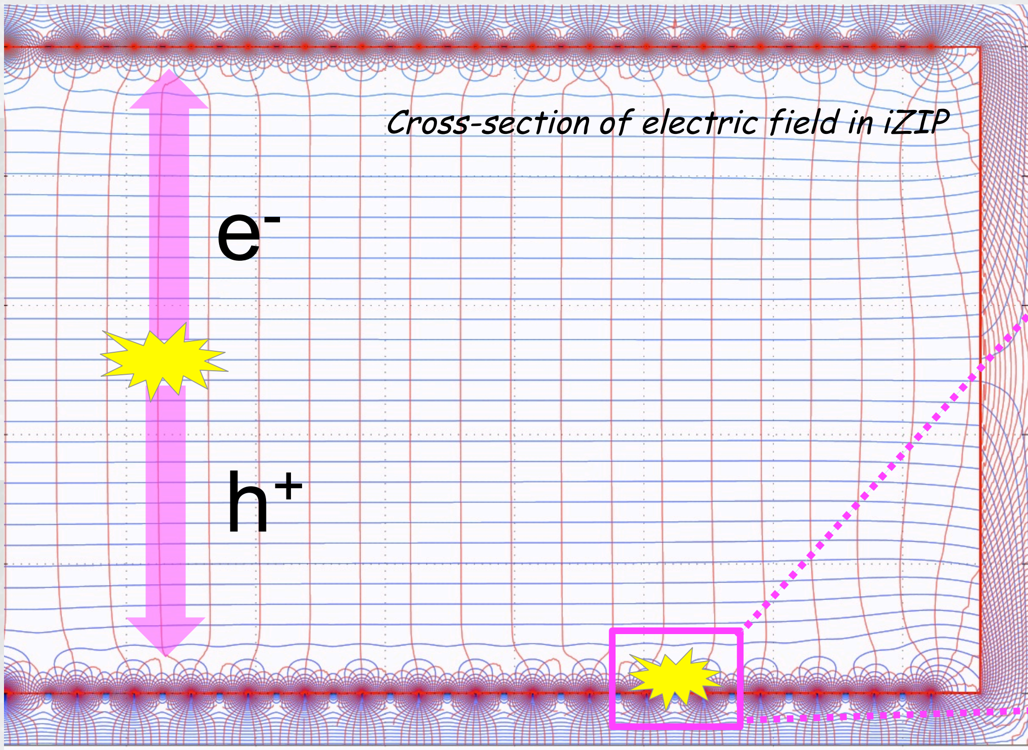
iZIP: 2.5-cm thick, double-sided phonon and charge sensors – the design for the future

Hint of WIMPs or hint of background?

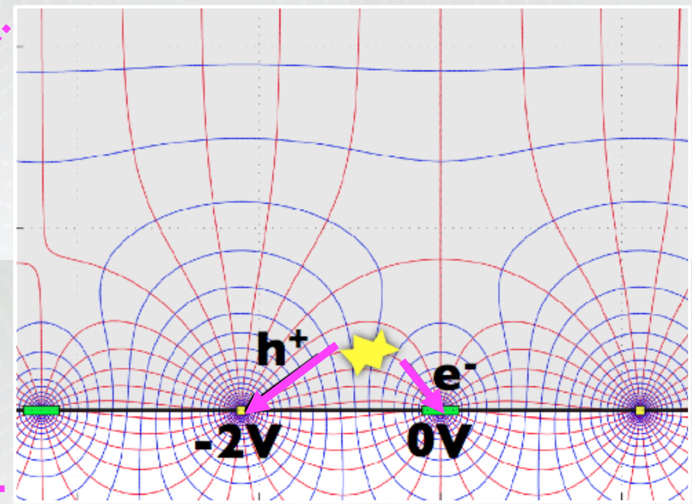


Final exposure of CDMS II yielded 2 events in signal region (w/ 0.9 expected bg)

Surface events a thing of the past?



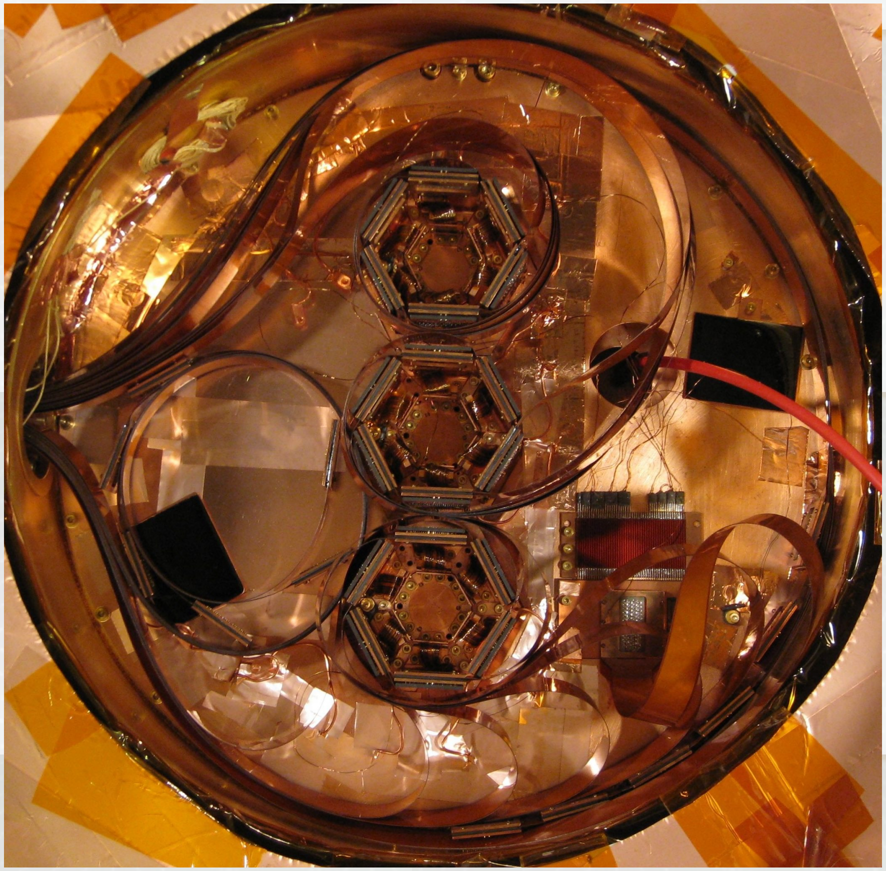
iZIP have > 30X better surface event rejection w/ 50% better efficiency to WIMPs



Measurements limited by neutron background at (above ground) test facility. Full potential must be explored at Soudan…

True rejection expected to be far greater – enough for 10-kg and likely a 100 kg experiment as well!

2011: iZIP engineering run



First iZIP tower fabricated, installed and running in 2010

In 2011, planned to study background rejection of iZIPs at deep site, w/ implanted beta-source

BUT…

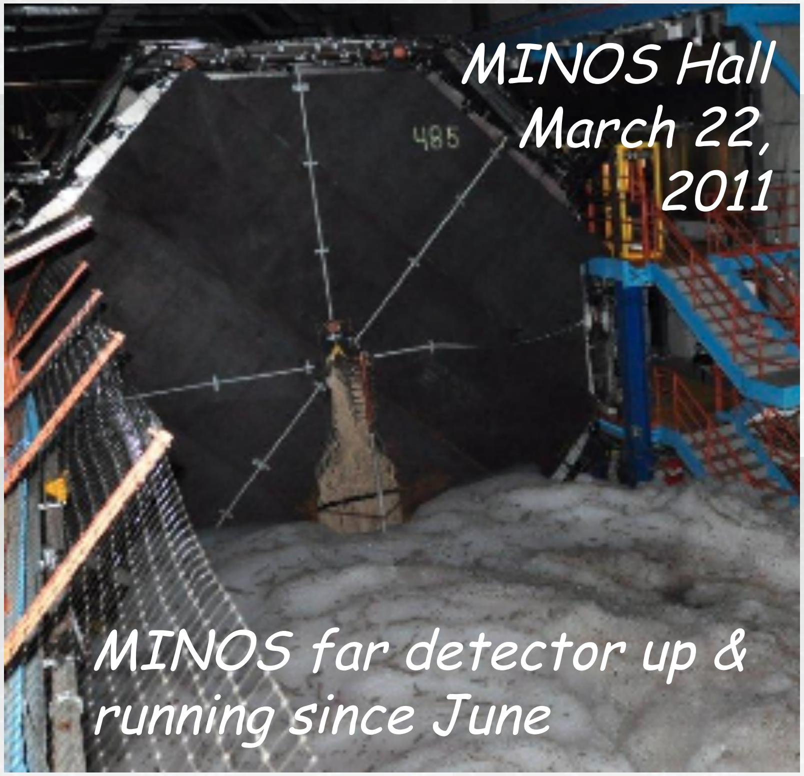
Unexpected end to the run

9pm March 17, fire in Soudan shaft ends the engineering run

- No one injured
- Fire out on March 20
- 50,000 gallons foam pumped down the shaft and into the lab

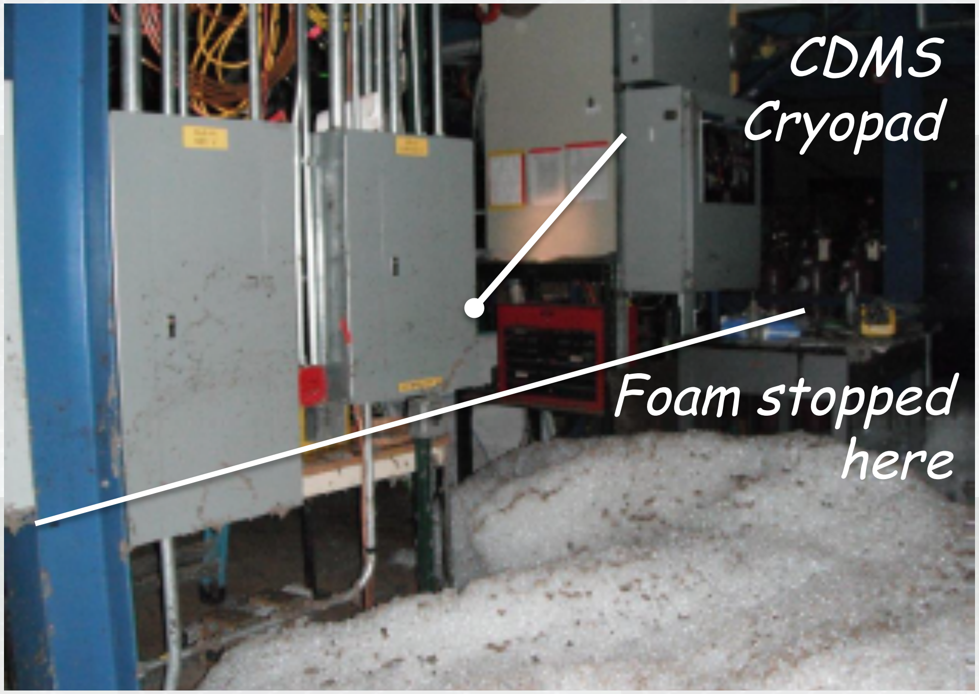
Soudan Cage

Recovery

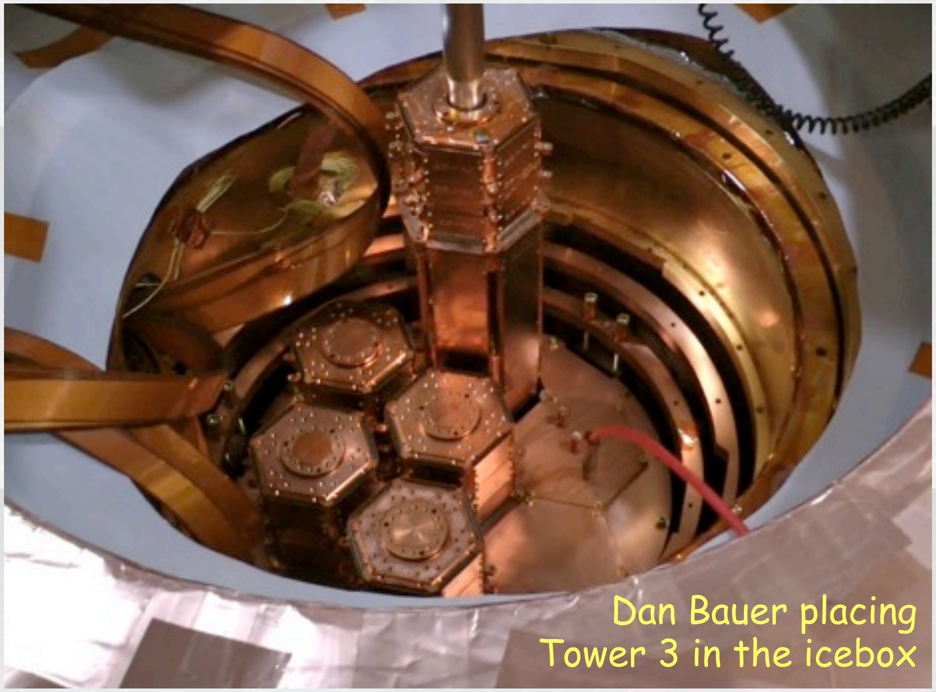


CDMS is unharmed!

Laboratory now open after several months of cleanup, safety reassessment and mine shaft repair



SuperCDMS 5-Tower installation



OCTOBER/
NOVEMBER:

10-kg payload installed and cooled to base temperature

Currently in the last phases of commissioning…

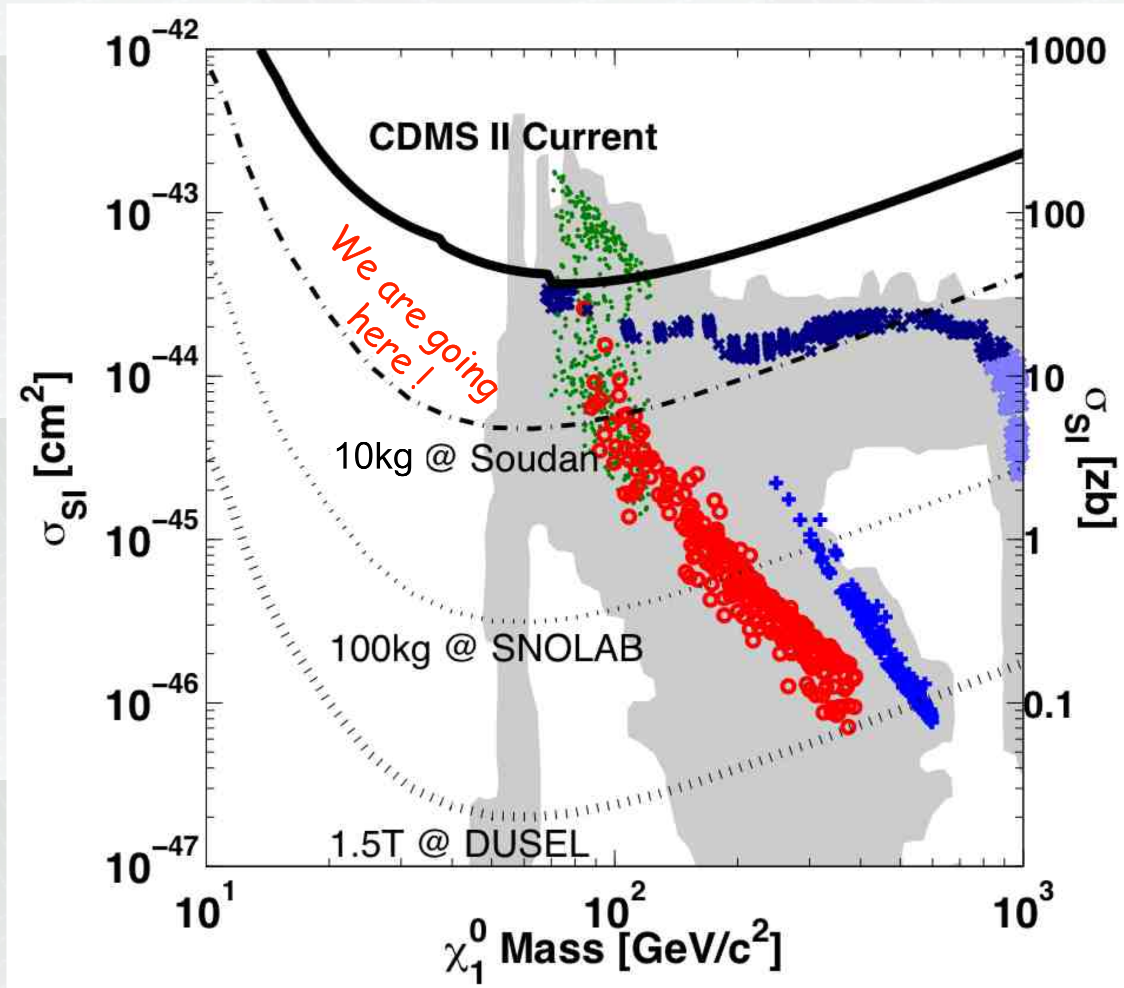
Goals for the Soudan dataset

On to science running !

Search for WIMPs down to sensitivity of ~few x 10^{-45}

Explore low-mass region of parameter space (low threshold, CDMSLITE, annual modulation)

Measure intrinsic background rejection of iZIPs for 10 and 100 kg experiment



Goals for the ~~Soudan dataset~~ Analysis Coordinator

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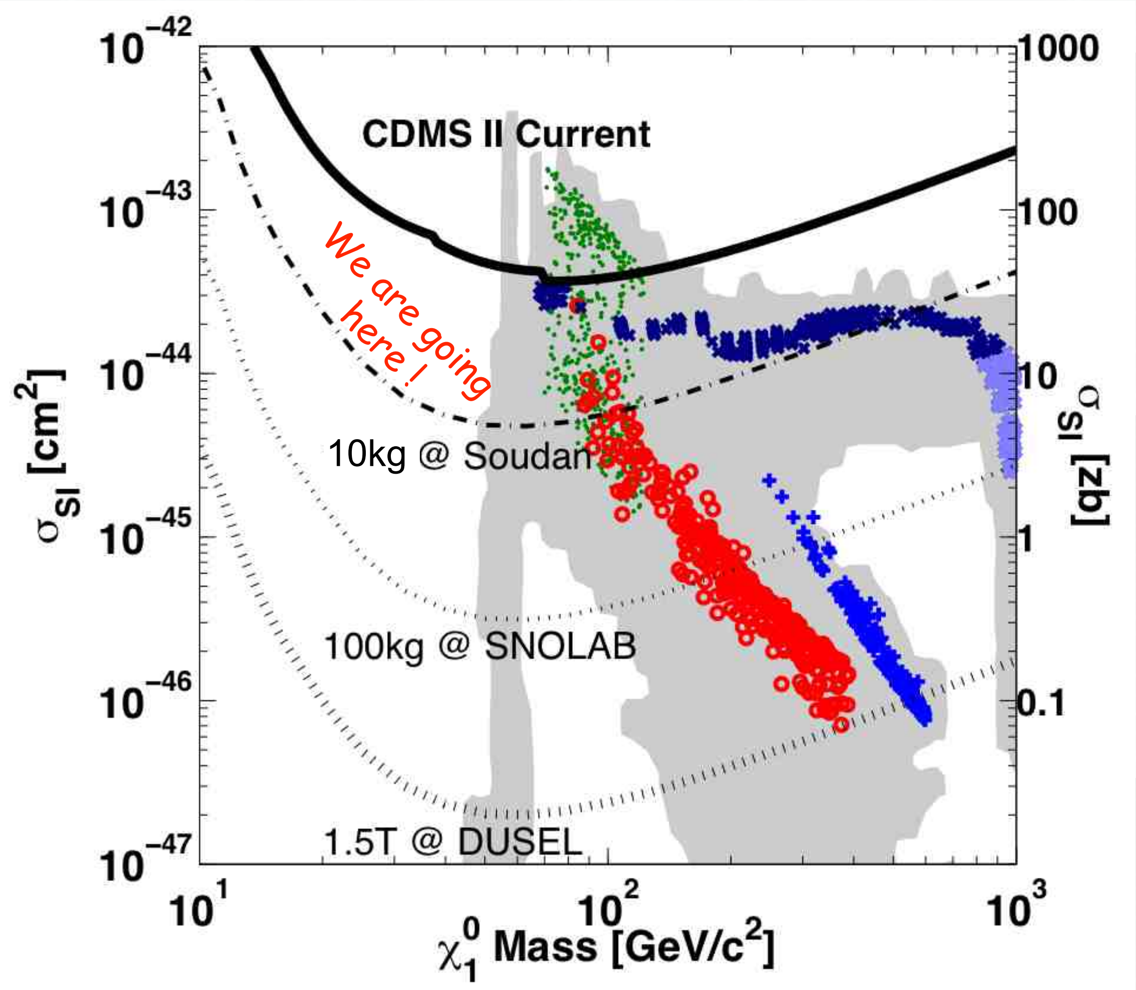


Live time matters

Although backgrounds are under control, SuperCDMS has a small target mass compared to competing experiments

Gaining 2 weeks of physics-quality data in a year is equivalent to adding another iZIP

Data frequently lost due to detector stability issues, DAQ malfunction, shifter mistakes, hardware failures, etc.

A system that helps to quickly identify and diagnose correctable problems is critical

We are commissioning a brand new system for SuperCDMS that is doing just this!

A sophisticated data checking tool

Lets try a live demo: http://cdmsmini.cdms-soudan.org:8080/DQDiagnostics.jsp

Summary Page Search Tool

Data Summary Table - Hover Over A Cell For More Info

Series	Run	Type	Dets	Events	Run Time	Process Status	Operator Selection	Trig. Rate OK?	Phonons OK?	Veto On?	Comments	DQ Diagnosis
01120208_1034	133	Test	15	NA	02:41	waiting t...	?	✘	✘	✔	1V Ba...	☠
01120208_0836	133	Test	3	141744	01:39	done	✔	✔	✔	✔	2V bia...	☺
01120207_1436	133	Test	13	6624	00:04	done	✘	✔	✔	✔	DAQ t...	☠
01120207_1259	133	Test	13	0	00:40	NA	✘	✔	✔	✔	EB ne...	☠
01120207_1138	133	Test	13	74052	01:08	done	✔	✔	✘	✔	2V bia...	☺
01120207_1106	133	Test	13	4642	00:11	done	✔	✔	✘	✔	2V bia...	☠
01120207_0938	133	Test	13	127351	01:17	done	¿	✔	✔	✔	2V bia...	?
01120206_2034	133	Test	13	172957	12:21	done	✔	✔	✘	✔	2V bia...	☠
01120206_1544	133	Test	15	25844	00:19	done	✔	✔	✘	✔	mislab...	☠
01120206_1457	133	Test	15	21673	00:33	done	✘	✔	✘	✔	2V bia...	☠
01120206_0728	133	Test	15	155284	04:05	done	¿	✔	✘	✔	1V bia...	☠
01120205_1733	133	Test	15	79443	00:46	done	¿	✔	✘	✔	1V bia...	☠
01120205_1726	133	Test	15	606	00:01	failed	✘	?	✔	✔	1V bia...	☠
01120205_1550	133	Test	3	121686	01:24	done	✔	✔	✔	✔	2V bia...	☺
01120205_1401	133	Test	2	117806	01:43	done	✔	✔	✔	✔	2V bia...	☺
01120205_1214	133	Test	3	175415	01:43	done	¿	✔	✔	✔	2V bia...	?

Number Of Rows To Display: 15 Number Of Recent Series To Fetch: 20 Get Most Recent Series ☑ Suppress DAQ Tests Renew My Last Query

SuperCDMS at SNOLAB

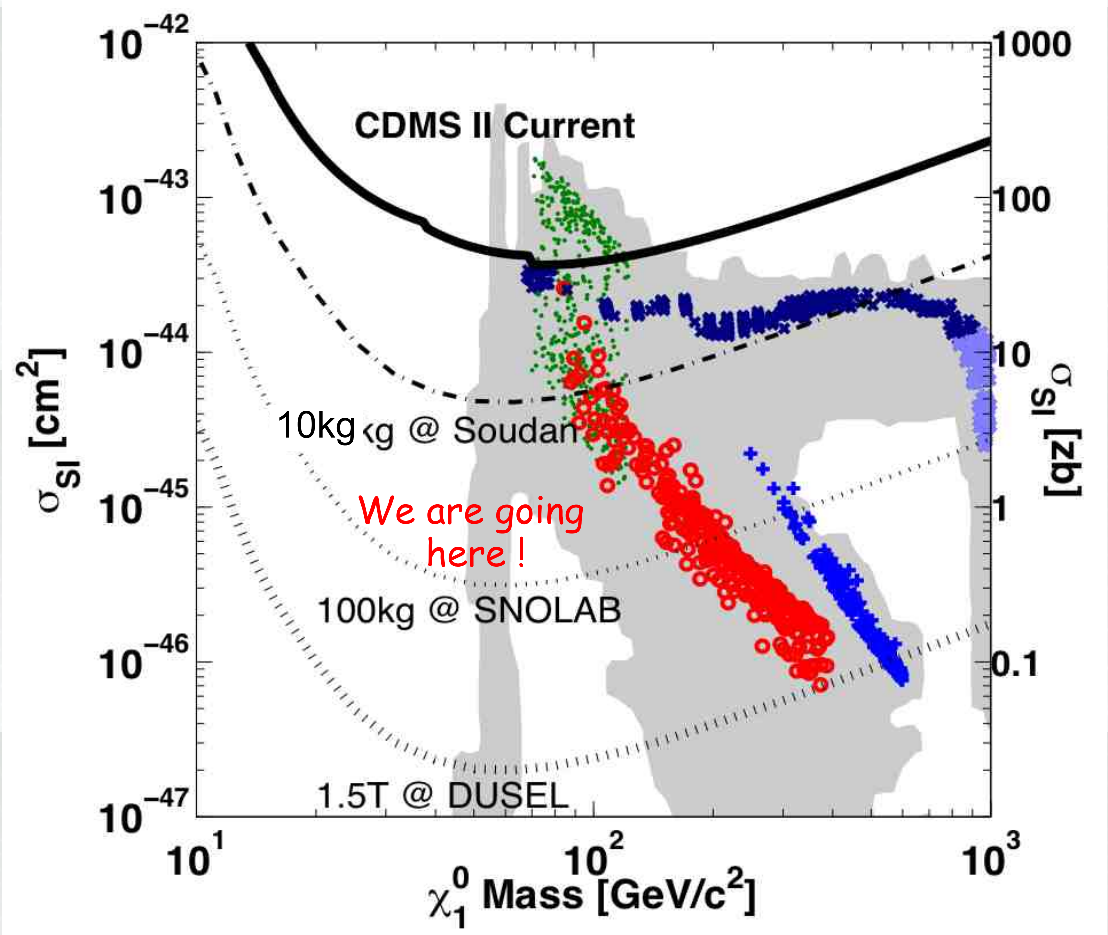
SuperCDMS SNOLAB

Move to North America's deepest underground lab for >100X reduction in cosmogenic neutron backgrounds

Science reach for SNOLAB

10X better sensitivity than 10-kg phase with full control over backgrounds

- σ_{SI} < few x 10^{-46}cm at 60 GeV/c^2
- ~100 kg payload, *all Ge*
- iZIP sensor layout w/ bigger detectors to reduce fabrication costs

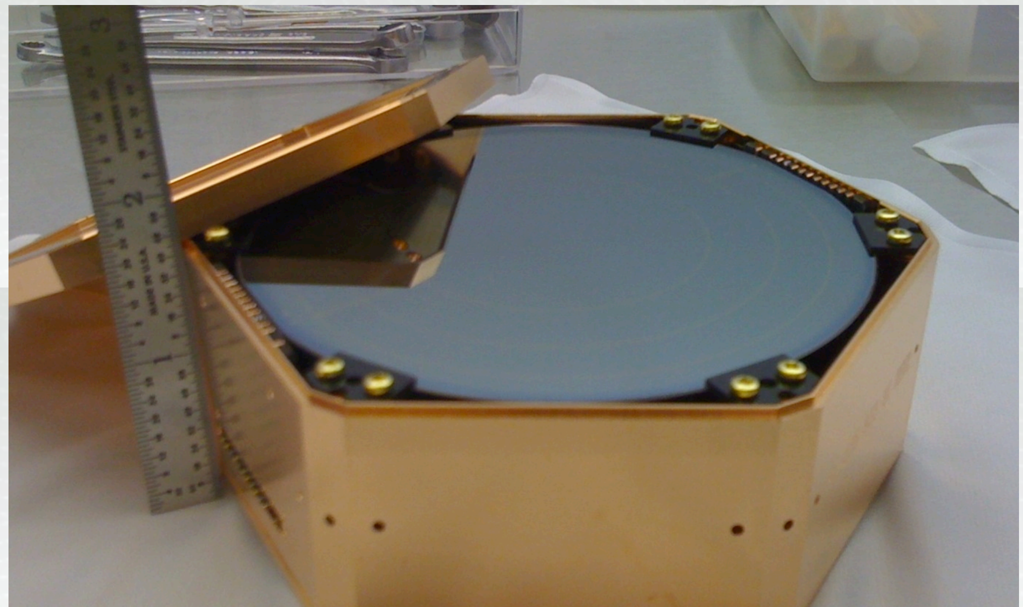


Aiming to start construction by 2014

Significant R&D funds for 2011/12

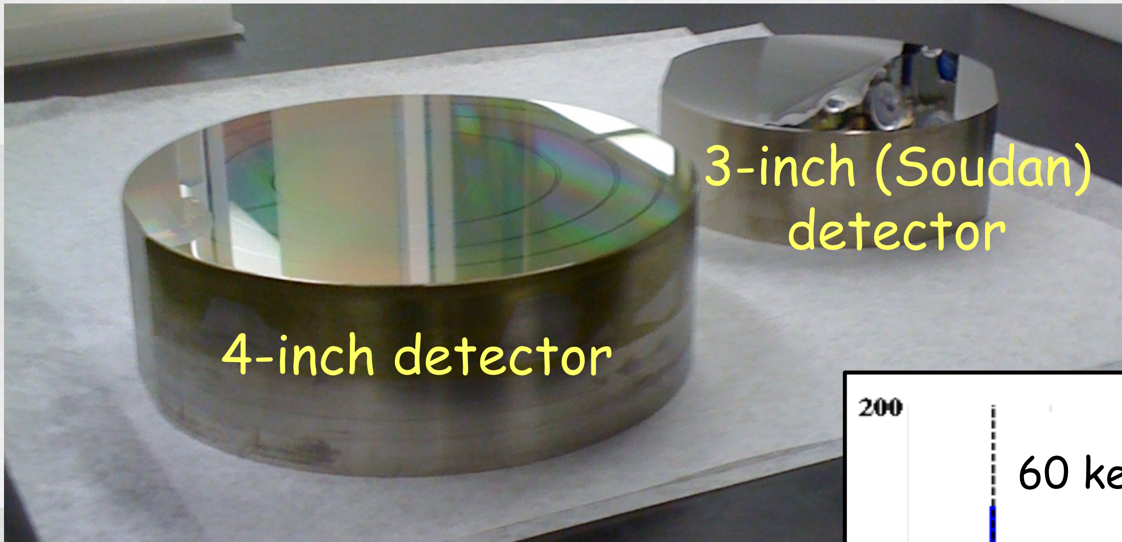
- Develop 4"x1.5" iZIP
- Streamline fabrication, Texas A&M fab facility coming online
- Cold hardware redesign
- "tower engineering model" being developed
- Shielding and cryo design

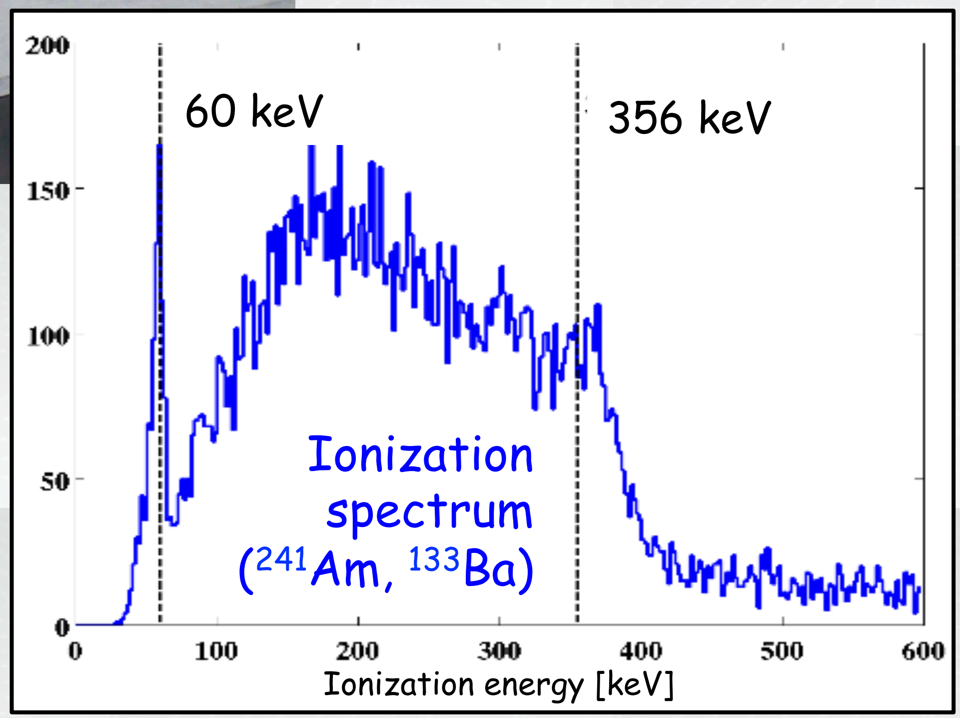
DOE proposal for G2 funding due this spring *- must demonstrate that iZIPs at Soudan are working well !*



4-inch X 1.5-inch Ge crystal (~1.4 kg)

First demo of 4-inch detector





Two 4-inch detectors fabricated at Stanford/SLAC with ionization sensors (2010)

First results from UMN test facility are promising, but work continues.

Neutron backgrounds

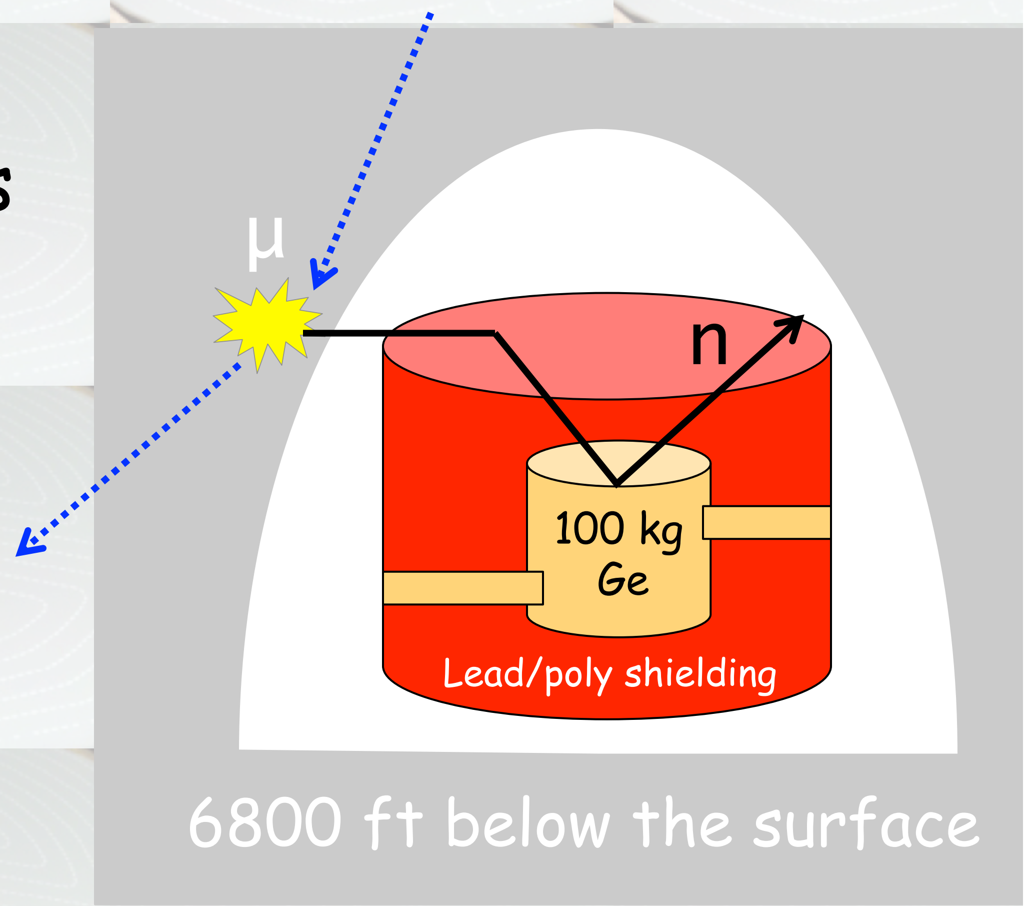
For maximum discovery potential we will aim for < 1 event total background in the full SNOLAB exposure

3 categories of neutron background:

I. Cosmogenic neutrons

- From unvetod muons interacting in the cavern walls
- SNOLAB depth makes this rate very low
- *< 0.1 events remain in 2-year exposure (at SNOLAB)*

Not a concern!



Neutron backgrounds

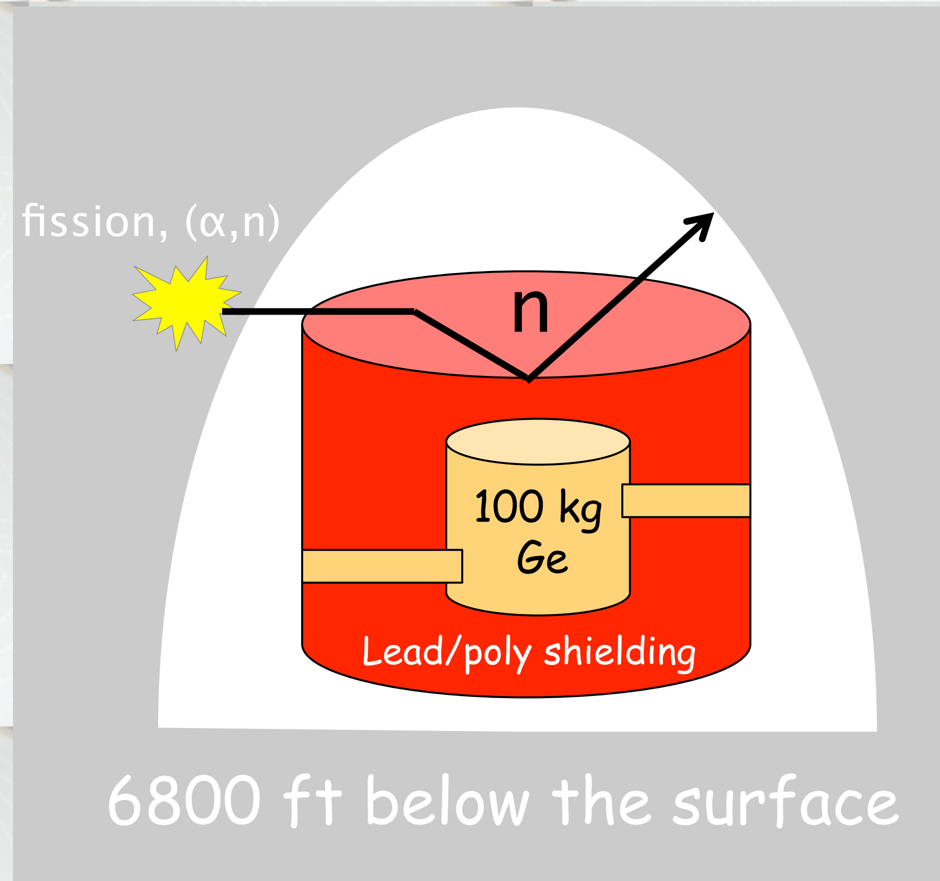
For maximum discovery potential we will aim for < 1 event total background in the full SNOLAB exposure

3 categories of neutron background:

II. Cavern neutrons

- From radiactive decay (fission & α,n) in rock walls
- Shielding will moderate most below our analysis threshold
- *Negligible contribution to background*

Not a concern!



Neutron backgrounds

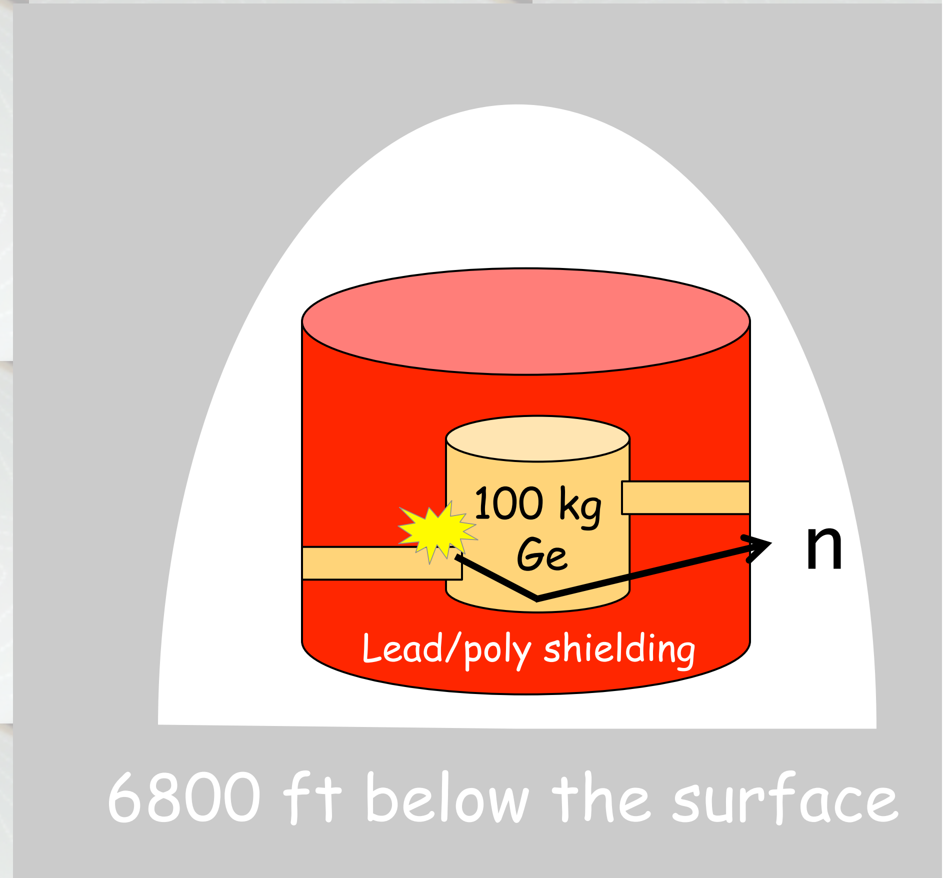
For maximum discovery potential we will aim for < 1 event total background in the full SNOLAB exposure

3 categories of neutron background:

III. Internal neutrons

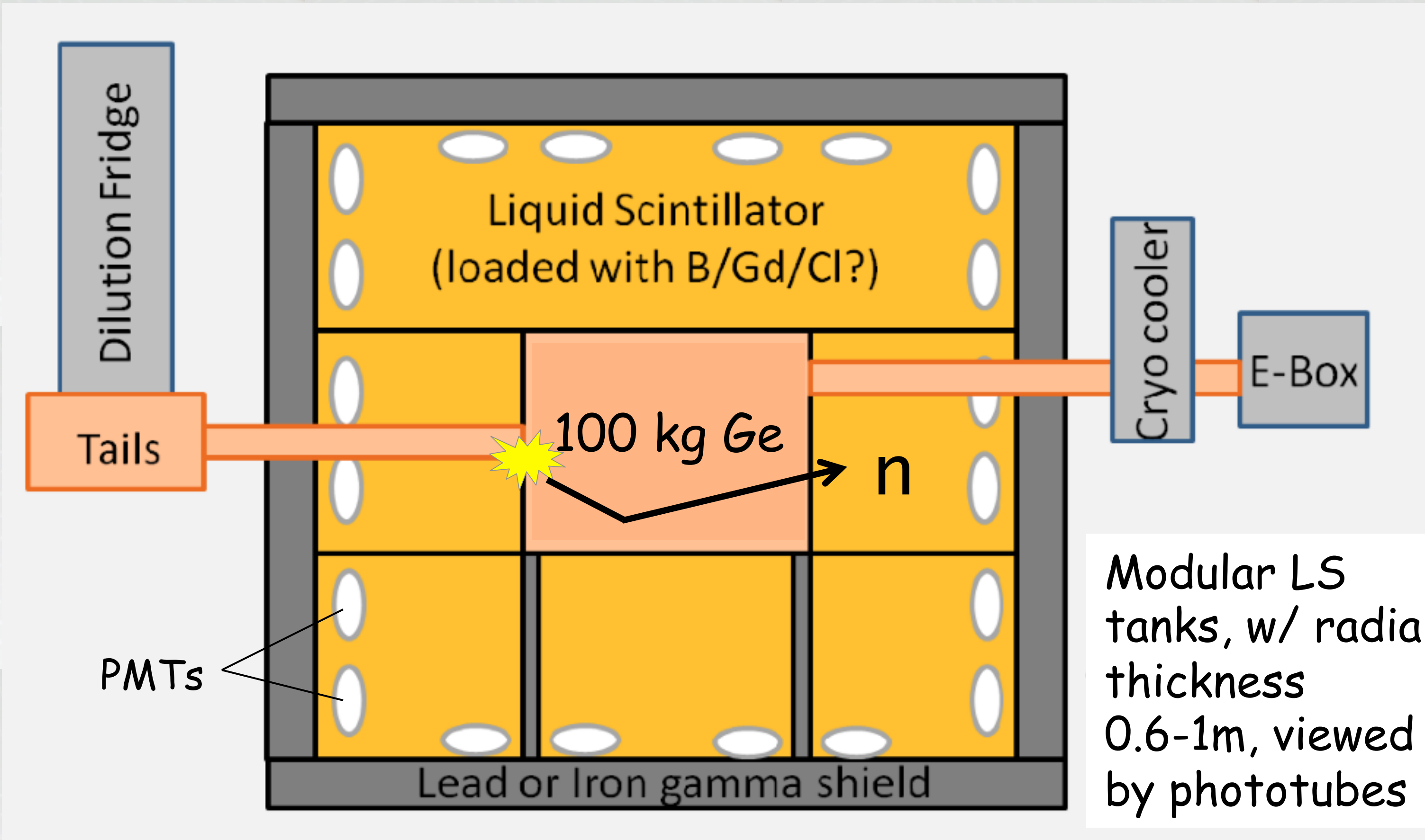
- From radiactive decay (fission & α,n) in material near iZIPs
- Will produce nuclear recoils in iZIPs
- *Naïve scale-up from CDMSII yields several events per year*

This is the major concern



A neutron veto for SuperCDMS

Surround the cryostat with a high efficiency neutron detector to tag neutrons that would otherwise produce nuclear recoils in the iZIP



Modular LS tanks, w/ radial thickness 0.6-1m, viewed by phototubes

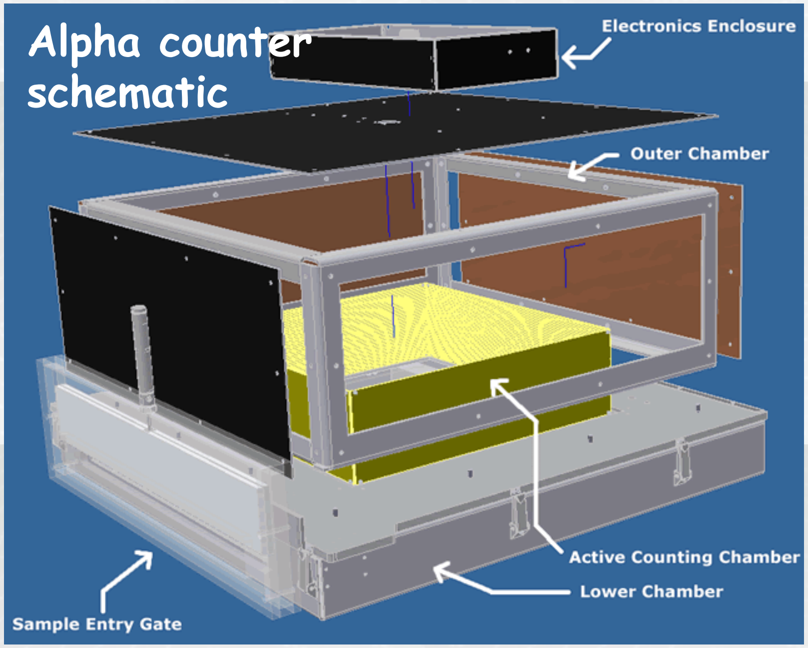
Neutron veto R&D

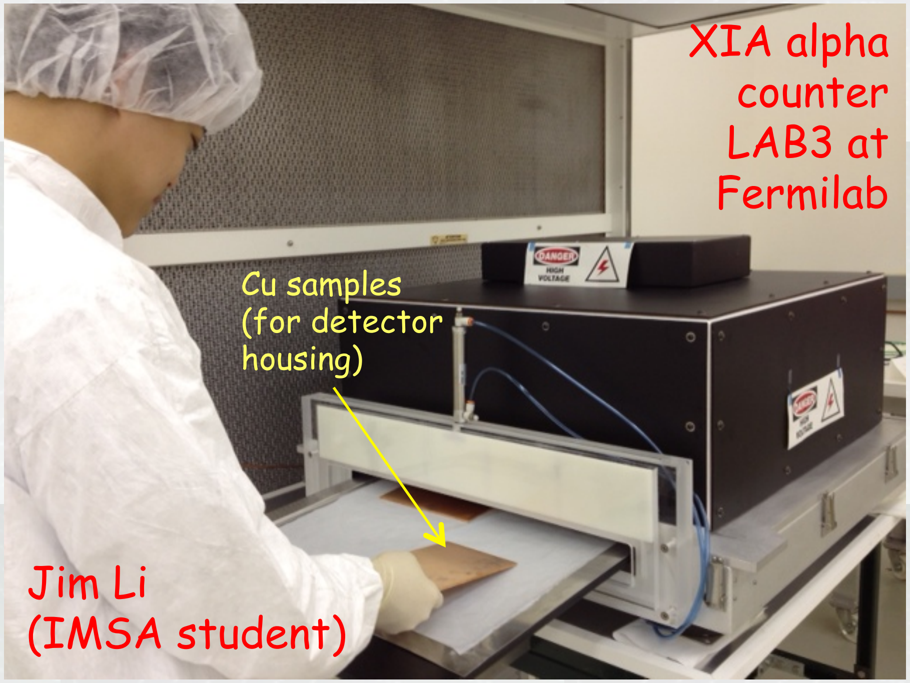
- Working group has been organized. Charged with demonstrating the need for a neutron veto by late Spring (for G2 review)
- In the process, we are evaluating effectiveness of various veto designs
- Geant4 simulations underway using new SNOLAB MC framework (designed by SLAC). Offshoot of this R&D is rapid development of MC for SNOLAB
- Much overlap with passive shielding design and understanding intrinsic contamination in shielding, cryostat and detector housing materials

Alpha screening for SuperCDMS

Remember, its all about backgrounds

Materials used in *shielding, detector housing and fabrication* all must be screened for trace radioactivity





The counter at Fermilab is a prototype, high-sensitivity alpha counter (drift chamber)

Rates of 0.004 alphas/cm^2/day achieved. Ready for screening!

Summary

CDMS has been a long-time leader in the field of direct searches for dark matter

New iZIP design vastly improves background rejection, paving the way for 10^{-45} and 10^{-46} cm^2 sensitivity to spin-independent WIMP-nucleon scattering

10-kg SuperCDMS Soudan has begun and is now collecting data

R&D for the SNOLAB phase is actively underway, aiming for construction in 2014

Stay tuned!

Thank You!

Z. Ahmed,[19] D.S. Akerib,[2] S. Arrenberg,[18] C.N. Bailey,[2] D. Balakishiyeva,[16] L. Baudis,[18] D.A. Bauer,[3] P.L. Brink,[10] T. Bruch,[18] R. Bunker,[14] B. Cabrera,[10] D.O. Caldwell,[14] J. Cooley,[9] P. Cushman,[17] M. Daal,[13] F. DeJongh,[3] M.R. Dragowsky,[2] L. Duong,[17] S. Fallows,[17] E. Figueroa-Feliciano,[5] J. Filippini,[19] M. Fritts,[17] S.R. Golwala,[19] D.R. Grant,[2] J. Hall,[3] R. Hennings-Yeomans,[2] S.A. Hertel,[5] D. Holmgren,[3] L. Hsu,[3] M.E. Huber,[15] O. Kamaev,[17] M. Kiveni,[11] M. Kos,[11] S.W. Leman,[5] R. Mahapatra,[12] V. Mandic,[17] K.A. McCarthy,[5] N. Mirabolfathi,[13] D. Moore,[19] H. Nelson,[14] R.W. Ogburn,[10] A. Phipps,[13] M. Pyle,[10] X. Qiu,[17] E. Ramberg,[3] W. Rau,[6] A. Reisetter,[17,7] T. Saab,[16] B. Sadoulet,[4,13] J. Sander,[14] R.W. Schnee,[11] D.N. Seitz,[13] B. Serfass,[13] K.M. Sundqvist,[13] M. Tarka,[18] P. Wikus,[5] S. Yellin,[10,14] J. Yoo,[3] B.A. Young,[8] and J. Zhang[17]
(CDMS Collaboration)