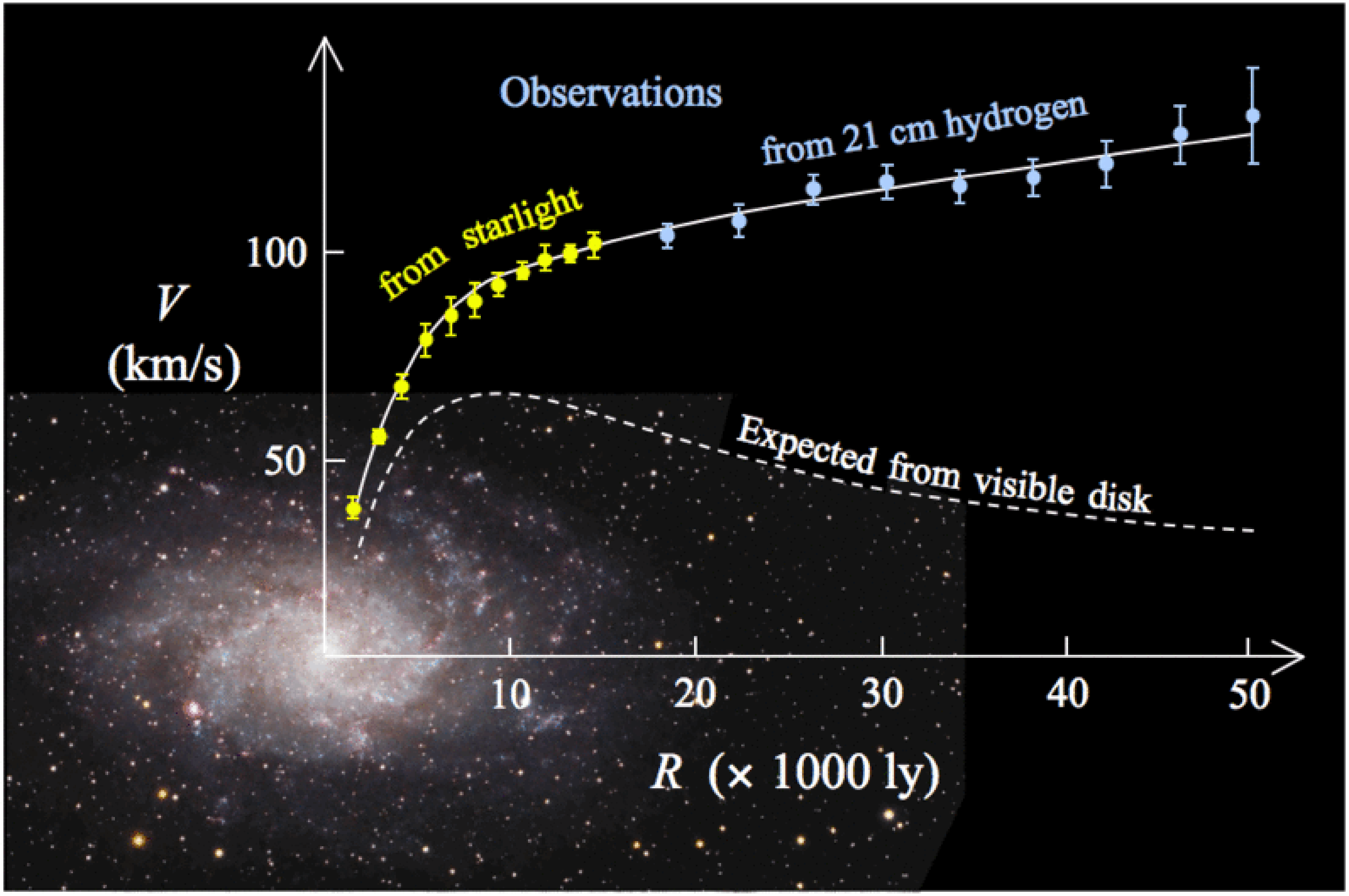
SuperCDMS: Now and Tomorrow

Ben Loer, on behalf of the SuperCDMS Collaboration
Fermilab Joint Experimental-Theoretical Seminar
2015 October 23

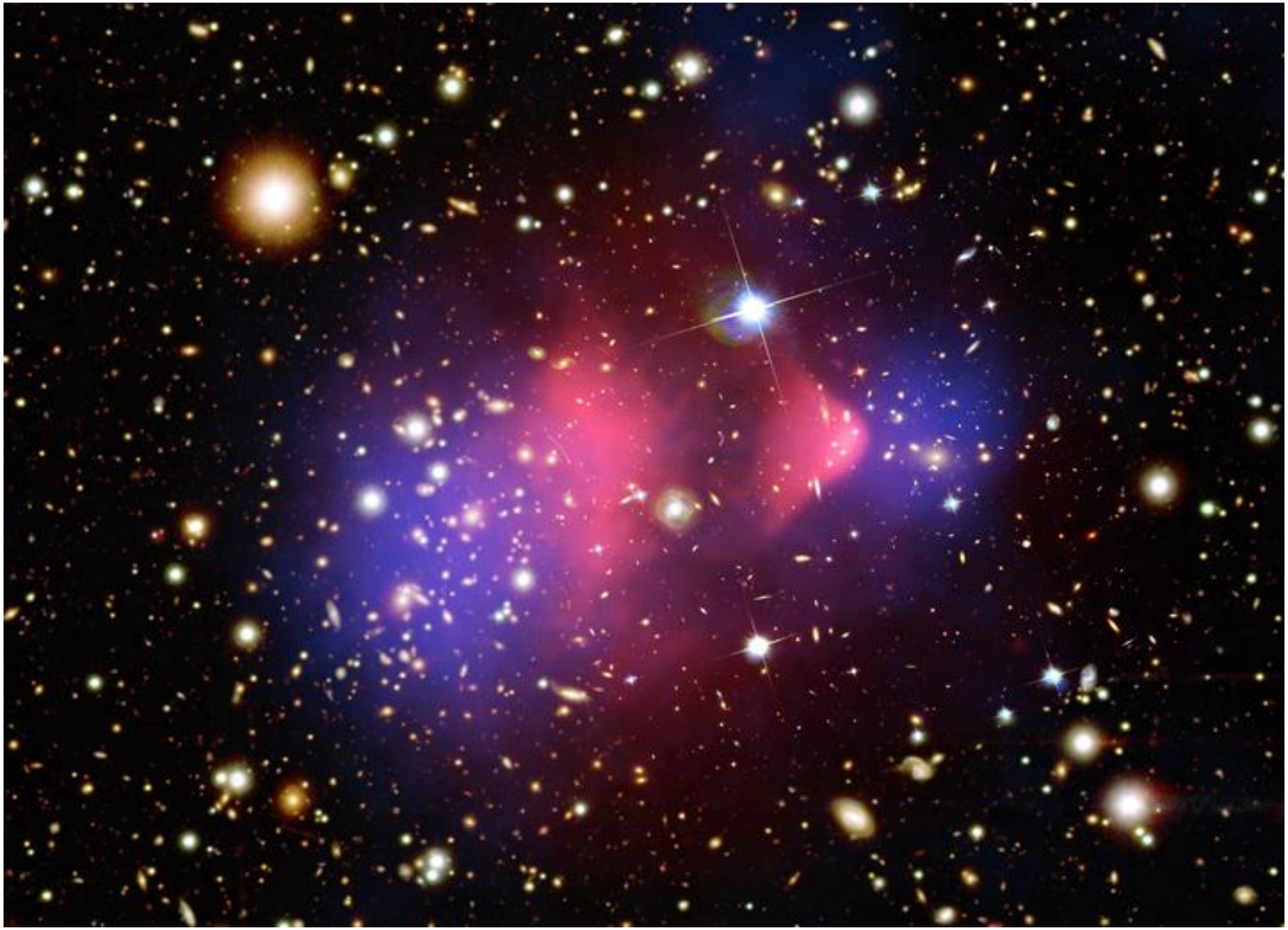
Outline

- Why look for dark matter?
- SuperCDMS Soudan overview
- CDMSlite: low ionization threshold experiment
- SuperCDMS SNOLAB

Evidence for dark matter: galactic scale



Evidence for dark matter: galaxy cluster scale



Evidence for dark matter: galaxy cluster scale

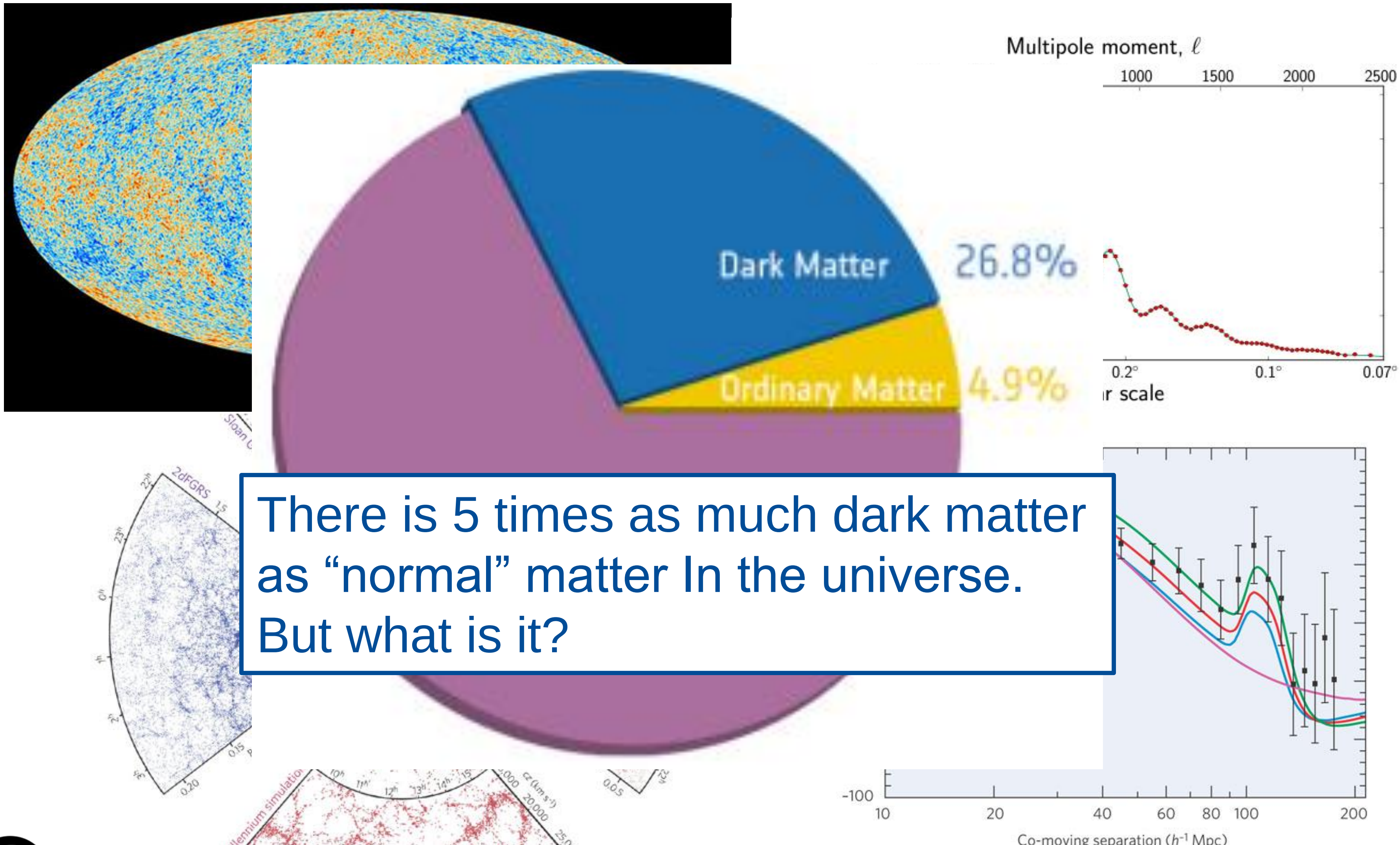
Hubble spies Big Bang frontiers

22 October 2015

Observations by the NASA/ESA Hubble Space Telescope have taken advantage of gravitational lensing to reveal the largest sample of the faintest and earliest known galaxies in the Universe. Some of these galaxies formed just 600 million years after the Big Bang and are fainter than any other galaxy yet uncovered by Hubble. The team has determined, for the first time with some confidence, that these small galaxies were vital to creating the Universe that we see today.

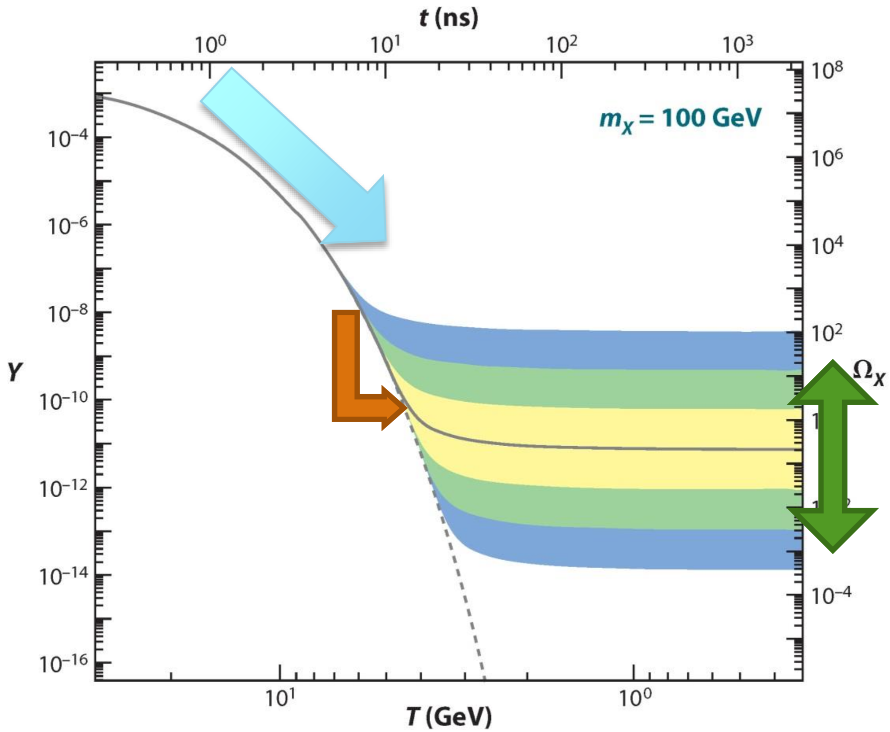
http://www.spacetelescope.org/news/heic1523/?lang

Evidence for dark matter: cosmological scale



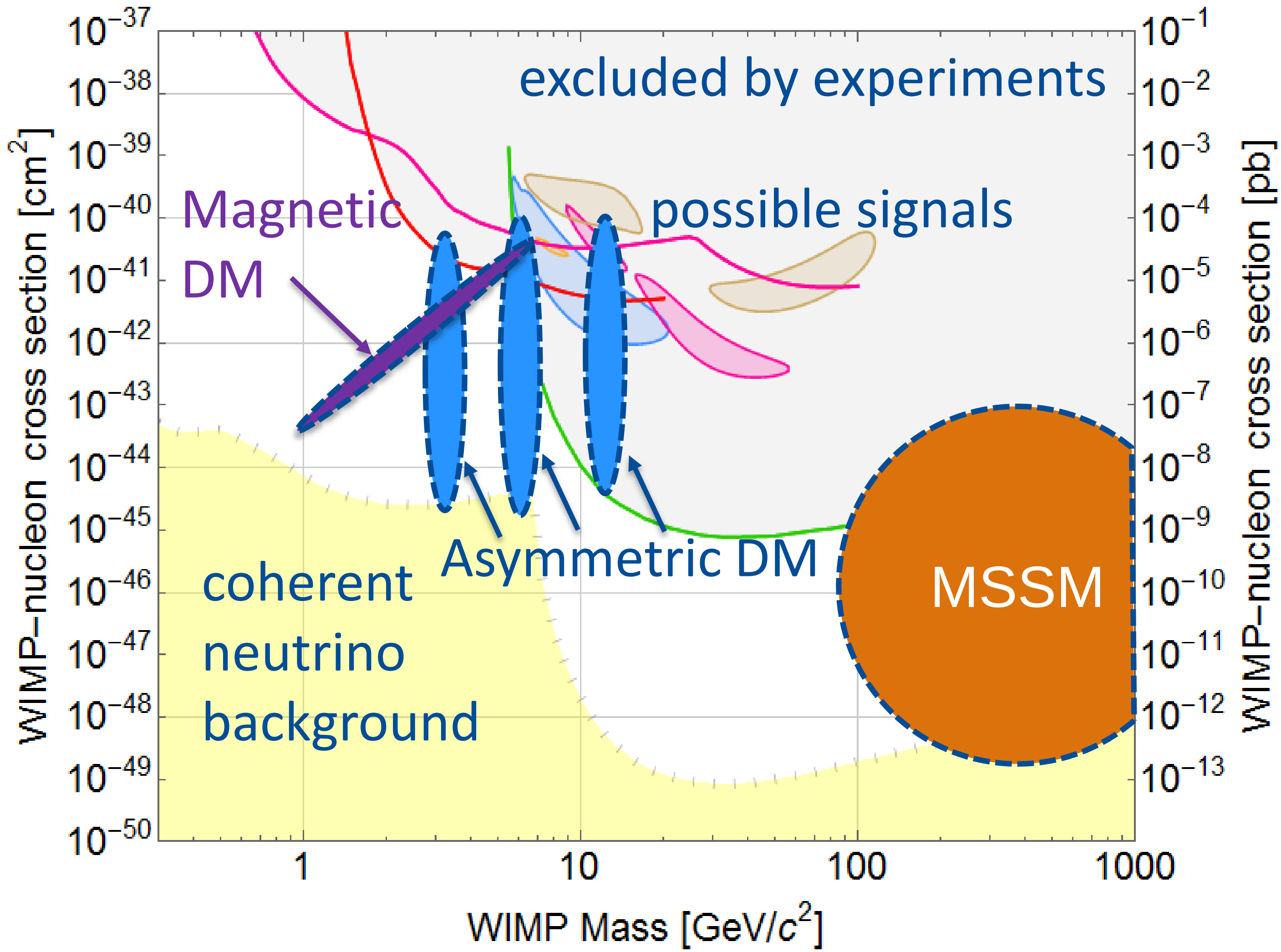
There is 5 times as much dark matter as “normal” matter In the universe. But what is it?

The “WIMP Miracle”

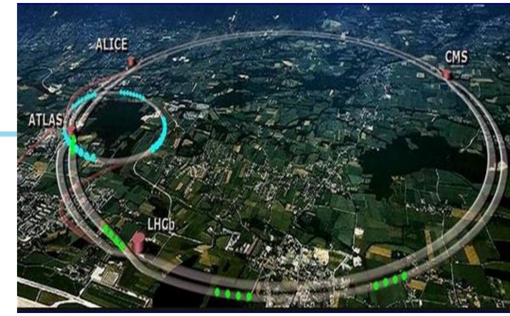


- Dark matter is in thermal equilibrium in early universe
- Density decreases as universe cools
- Eventually annihilation rate slower than expansion: “freeze out” of equilibrium
- Remaining density depends primarily on annihilation σ
- Weak-scale σ gives correct relic density
- Bonus: consistent with SUSY neutralino

Why look for light(weight) dark matter?



Observing particle dark matter



collider:
creation

direct:
scattering

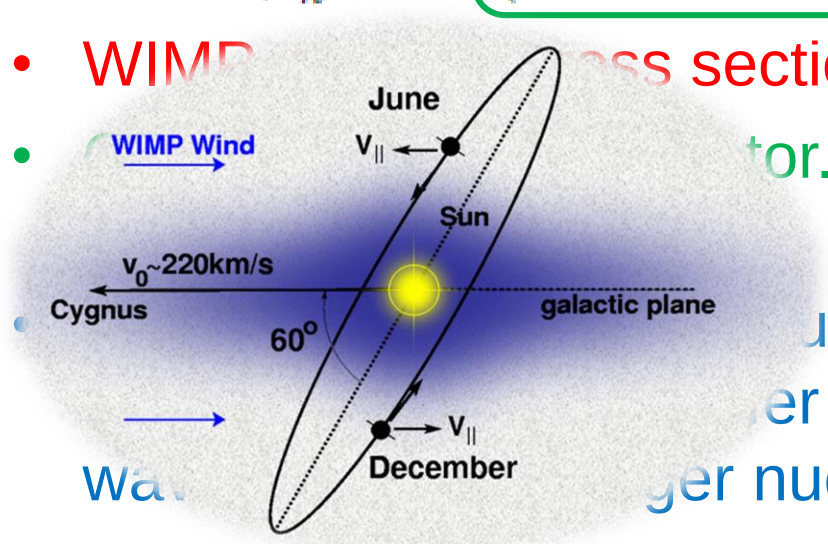
χ q

χ q

indirect:
annihilation

Expected spin-independent detector response to WIMPs

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{N_0 \sigma_n \rho_D M_T}{2 A \mu_n^2 M_D} \left(Z \frac{f_p}{f_n} + (A - Z) \right)^2 F^2(q) \int_{v_{min}}^{\infty} \frac{f(v_D, v_E, v_{esc})}{v_D} \mathrm{d}v_D$$



- WIMP ss section and local WIMP density
- tor. If fp=fn (isospin symmetry),
- unts for imperfect coherence at er (i.e. smaller propagator wa ger nucleus
- Velocity distribution function. v_E term introduces seasonal modulation. Only upper tail of velocity distribution above v_{min} can cause recoil of energy E_R

100 GeV WIMP Recoil Rates

~few counts/ton/year

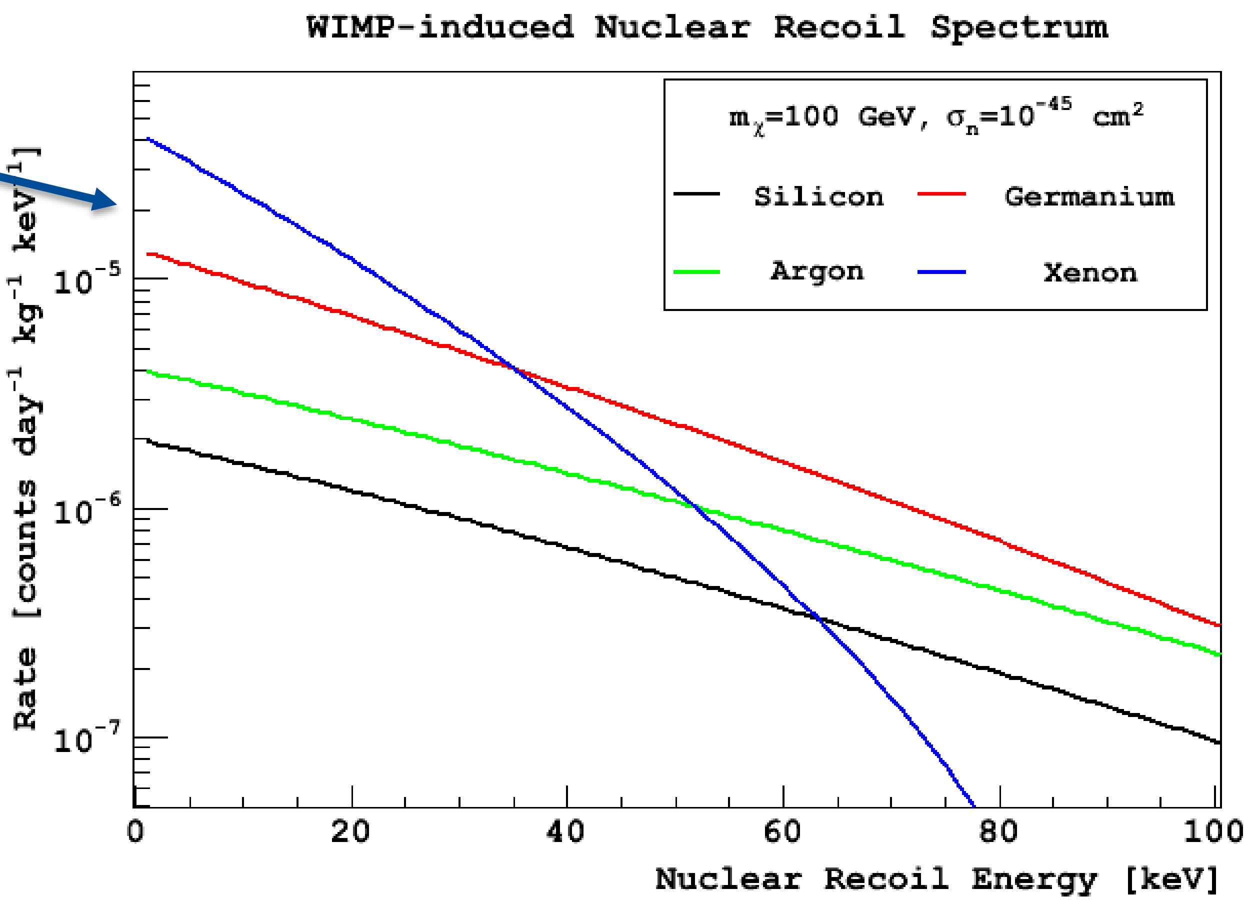
Compare to:

Clean copper:

10^7 decays/ton/year

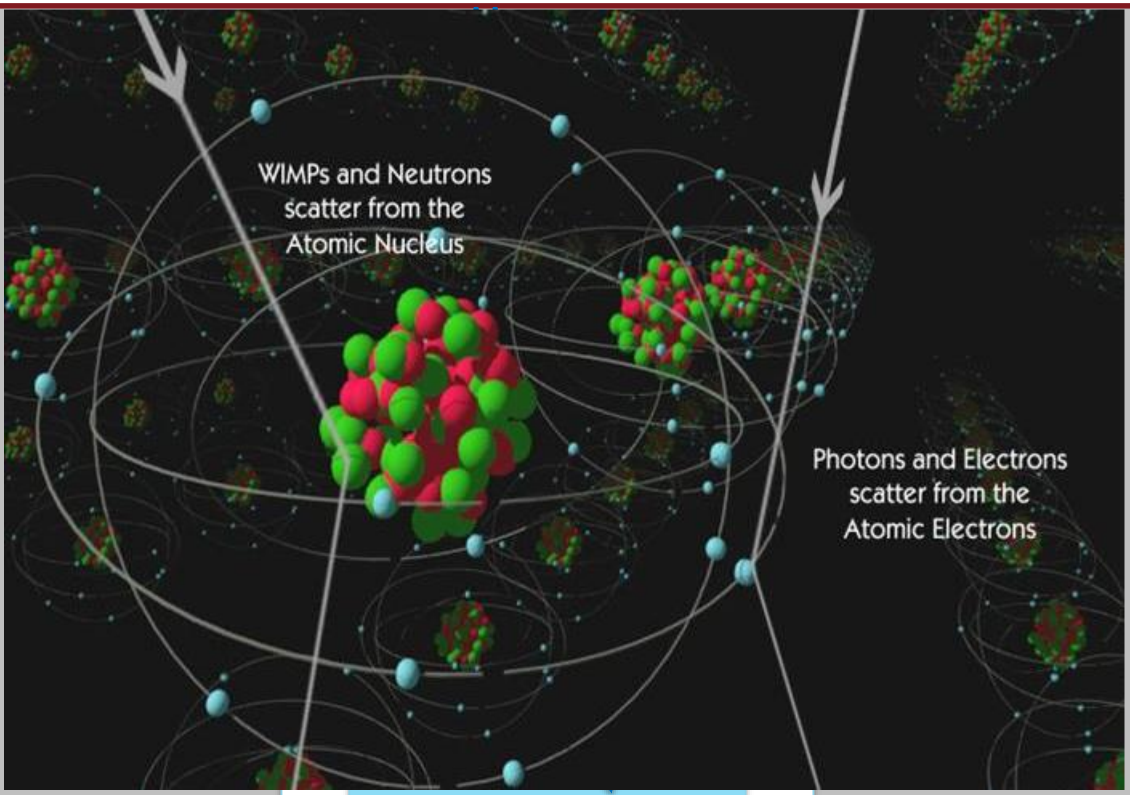
Fingerprint:

20 decays/year



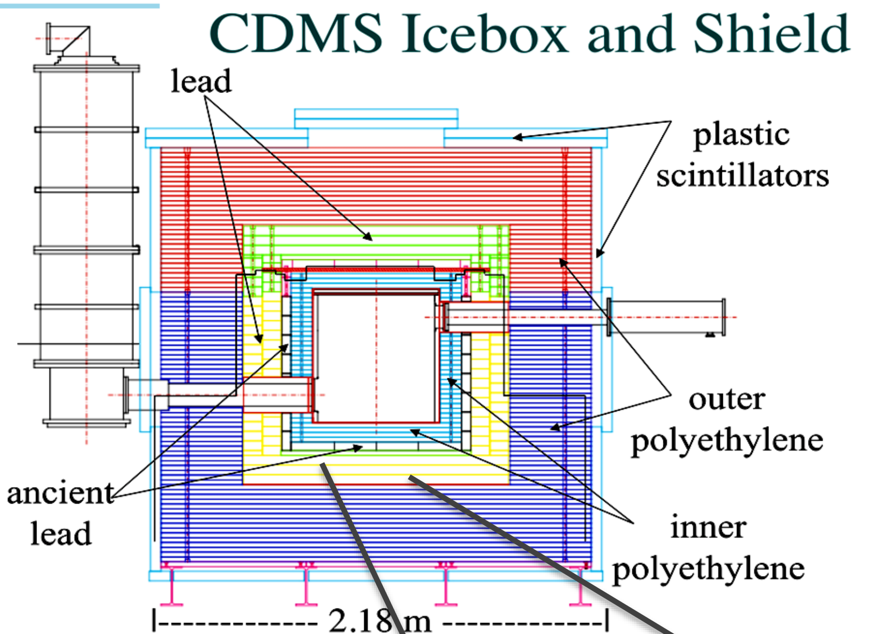
Let's build a dark matter detector!
What are the backgrounds? Pretty much everything…

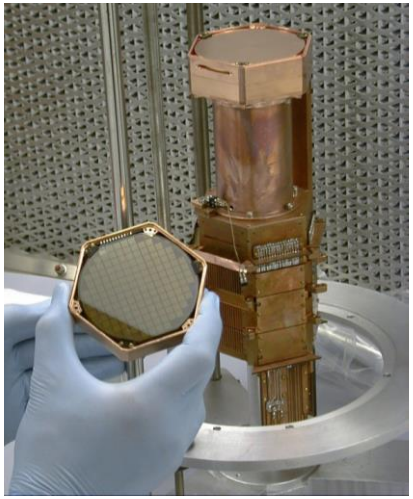
γ, n from environmental radioactivity	build a big shield
γ, n from radioactivity in shield	screen for low radioactivity materials
still more γ, n from shield	ultra-clean inner layers (ppt U,Th)
cosmogenic neutrons	go deep underground
alpha, beta, x-rays from inner surfaces	cleaning, radon reduction, fiducialization
still lots of gammas!	particle (dE/dx) discrimination



SuperCDMS Soudan at a glance

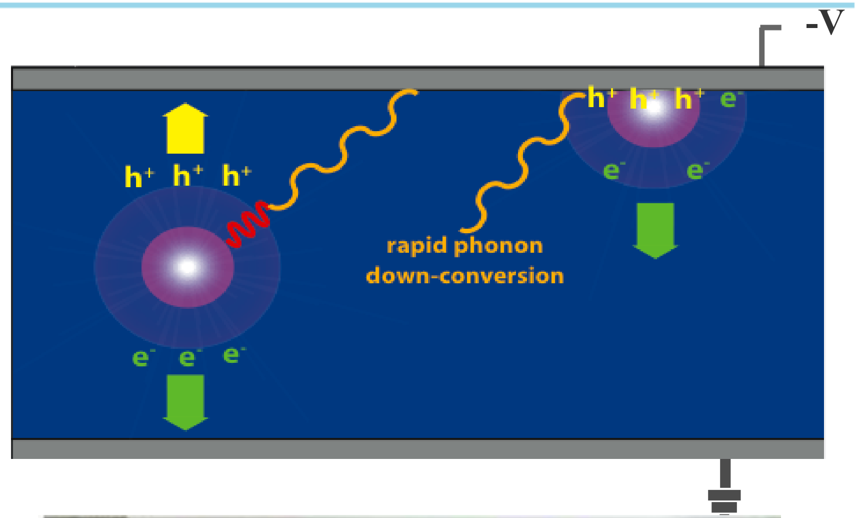
- 5 towers of 3 Ge iZIP detectors each
- 2341 ft underground at the Soudan mine (next to MINOS far detector)
- Lead and polyethylene shield with scintillator muon veto
- ~600 live days acquired since 2012

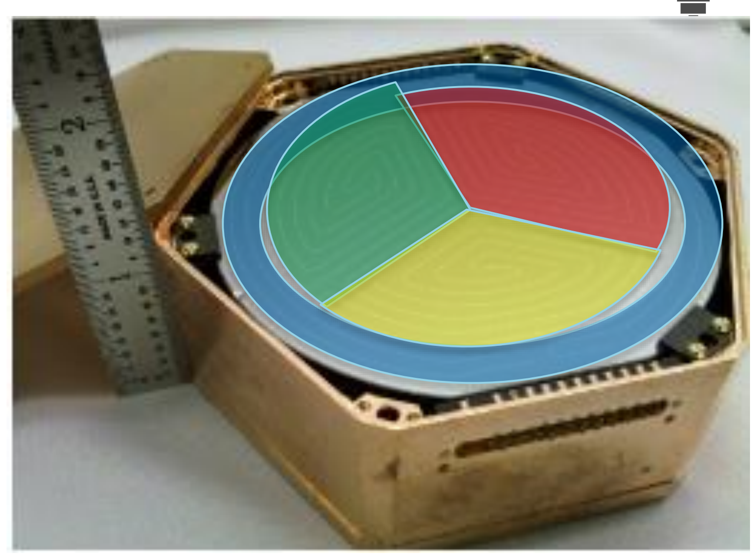




SuperCDMS iZIPs

- Ultrapure Ge crystals operated at <50 mK
- Read out athermal phonon and charge signals
- Phonons give total energy
- Ratio of charge/phonon discriminates bulk gamma and nuclear recoil events
- Outer charge and phonon rings remove outer surface events
- Interleaved 2-sided charge sensors remove face events

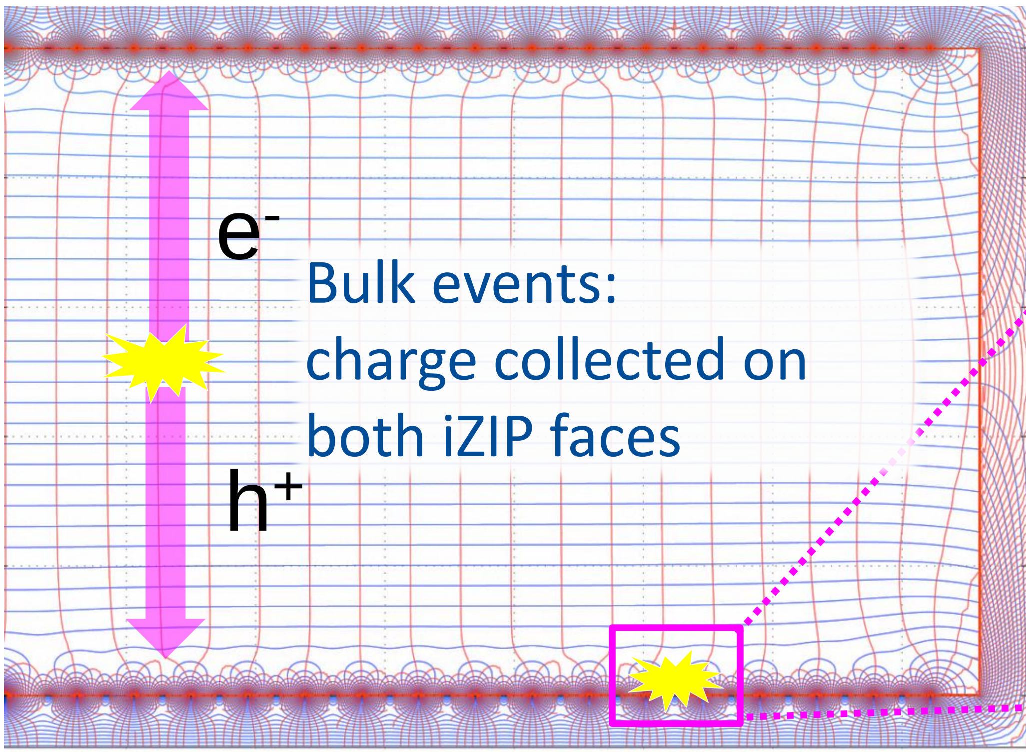




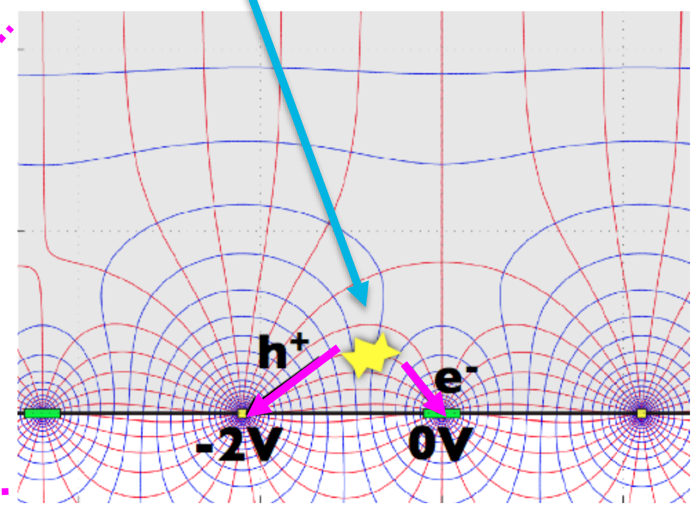
8 phonon, 4 charge channels

SuperCDMS iZIP surface rejection

iZIP: *I*nterleaved phonon and charge sensors on both sides

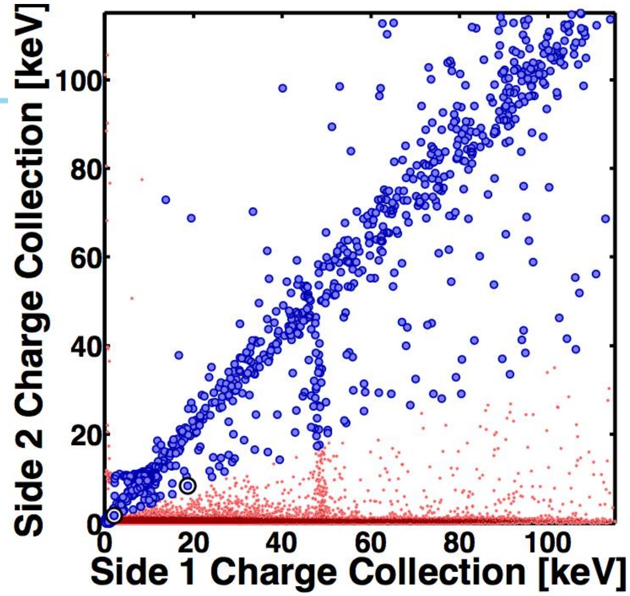


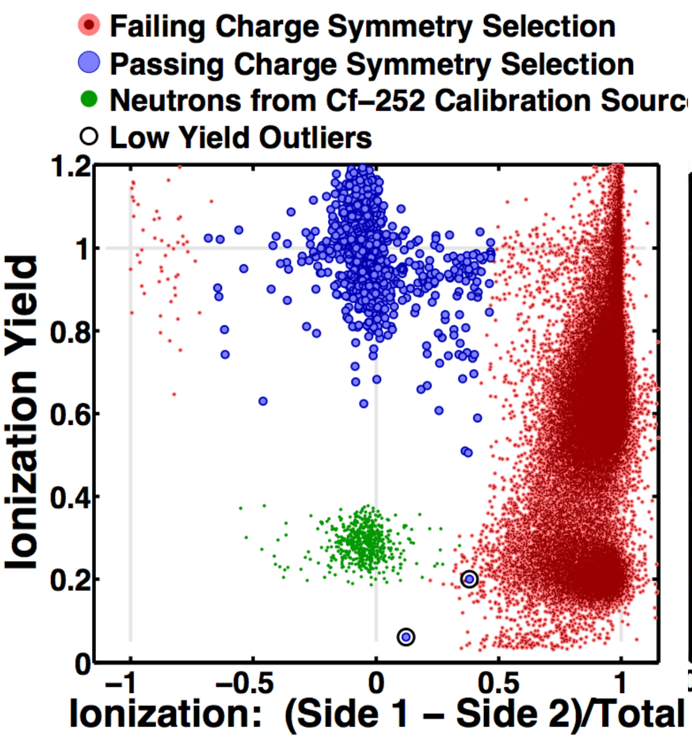
Surface events: only detect charge on one face

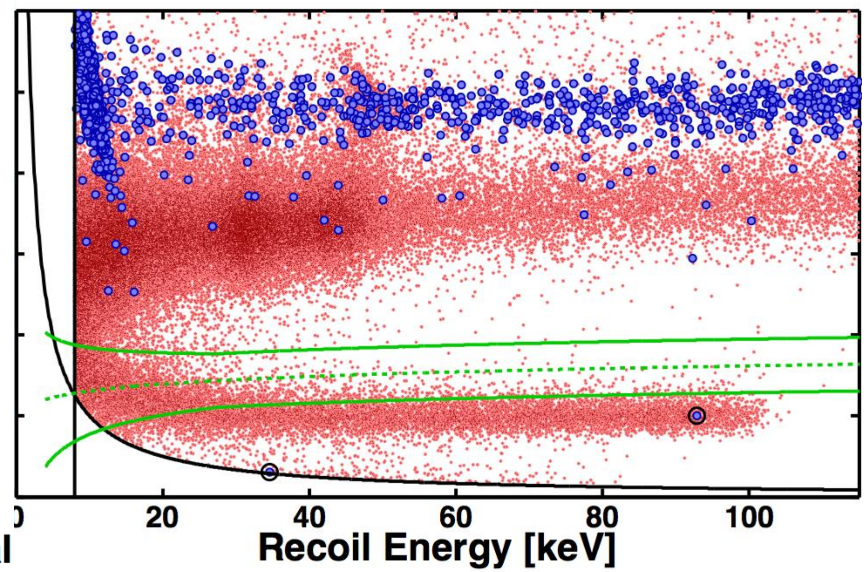


iZIP Discrimination Performance

- Surface leakage < 1.26E-5 (90% CL)
  - for ~50% signal acceptance
- Not using phonon position info

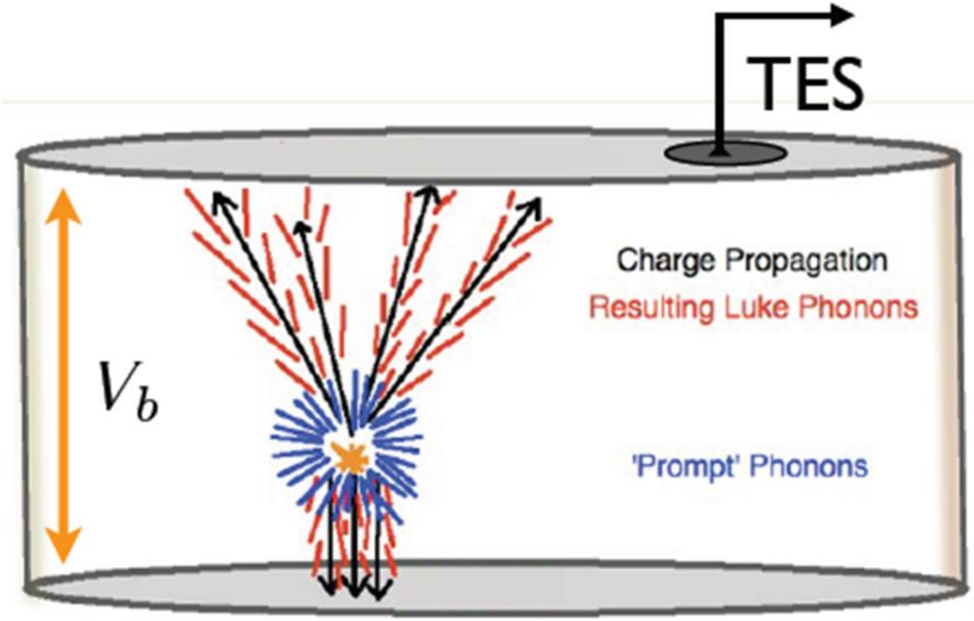






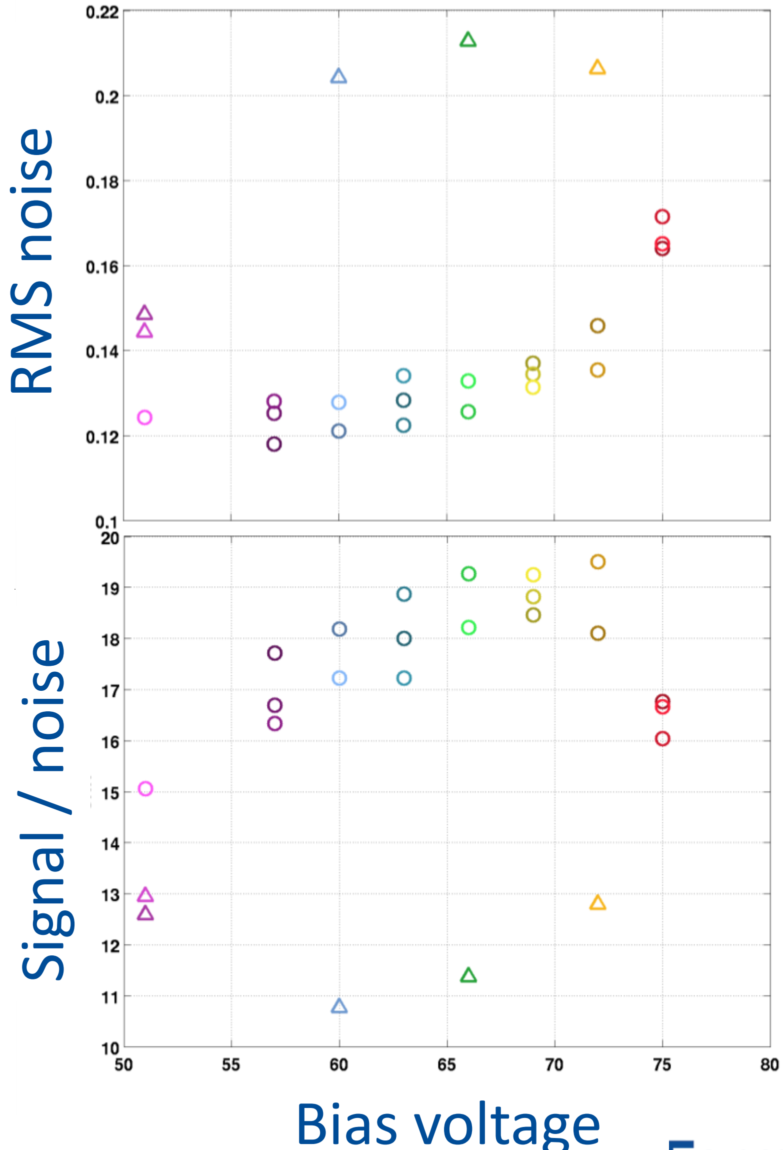
Luke-Neganov phonons

- Electrons/holes propagating in crystal reach “terminal velocity”
- Excess energy from bias field transferred to lattice as Luke phonons
- In standard iZIP mode, subtract Luke contribution out when calculating energy from phonons
- What happens if we turn the bias way up?



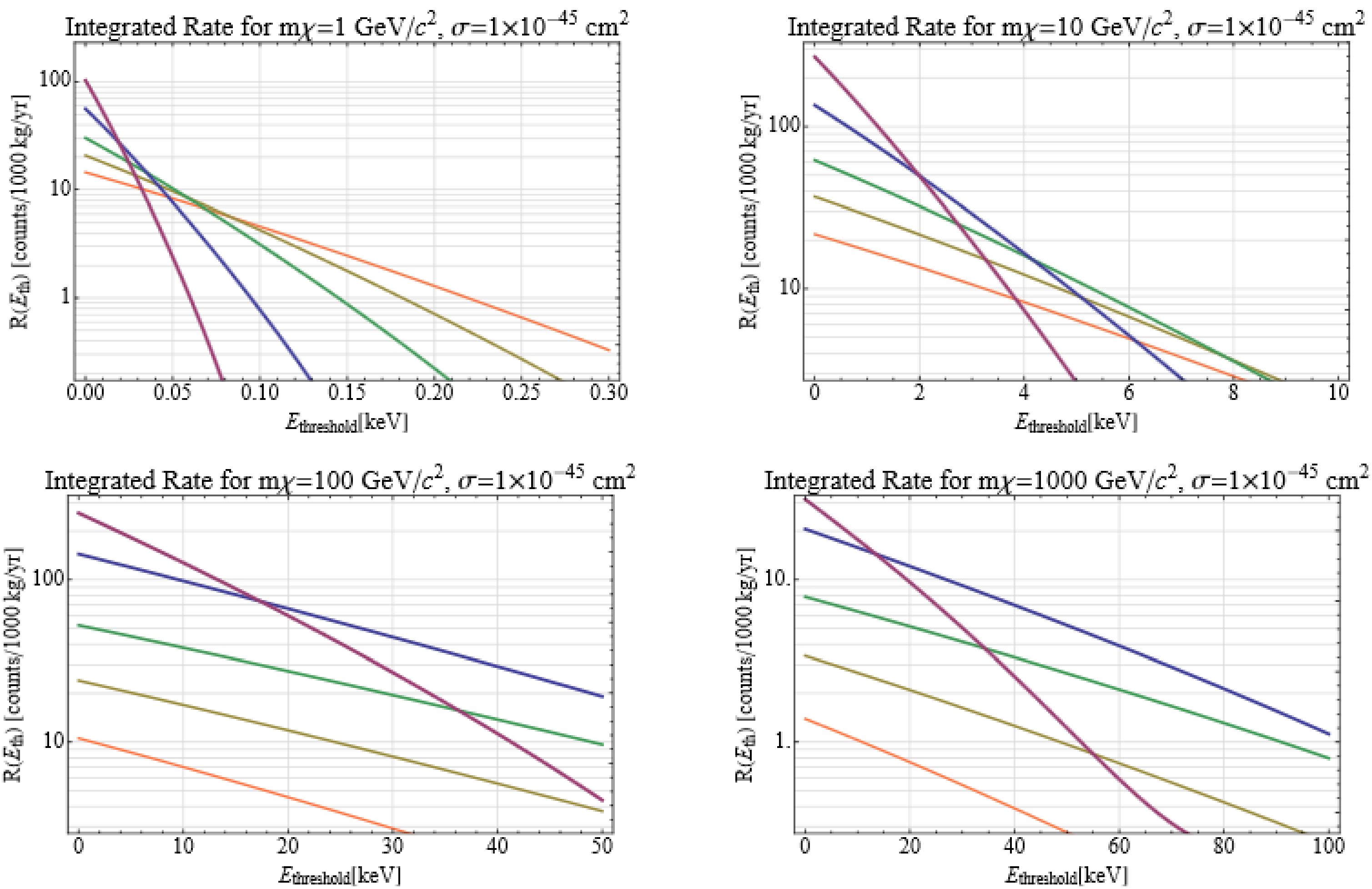
CDMSlite: charge amplification through Luke gain

- Noise is almost flat with bias until breakdown
- Large bias => high gain, low noise charge measurement through the phonon channel
- BUT: prompt phonons are drowned out
- So why sacrifice discrimination for gain?



Fermilab

Low threshold needed for light mass

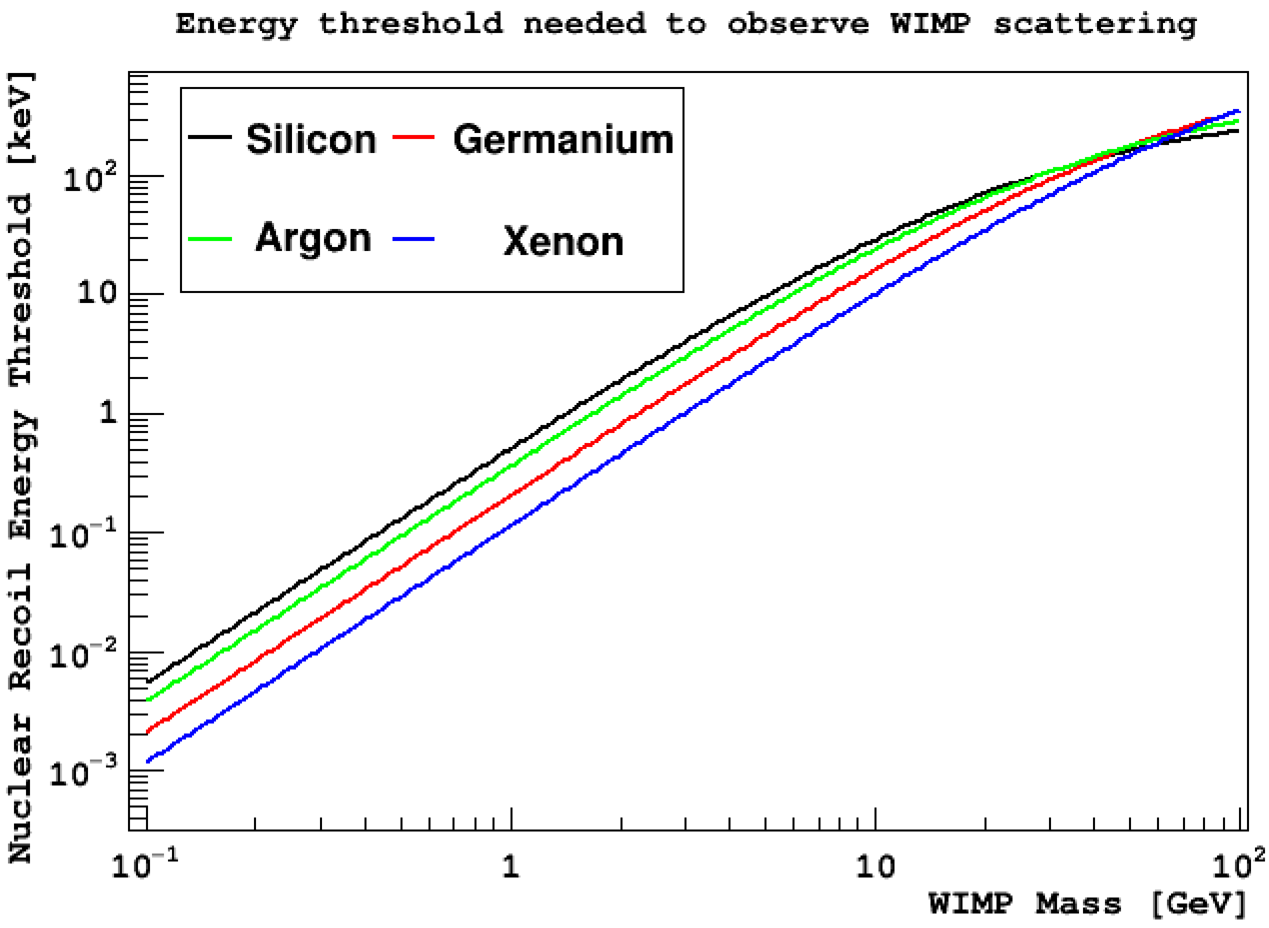


From top to bottom at y-intercept:

Xenon
Germanium
Argon
Silicon
Neon

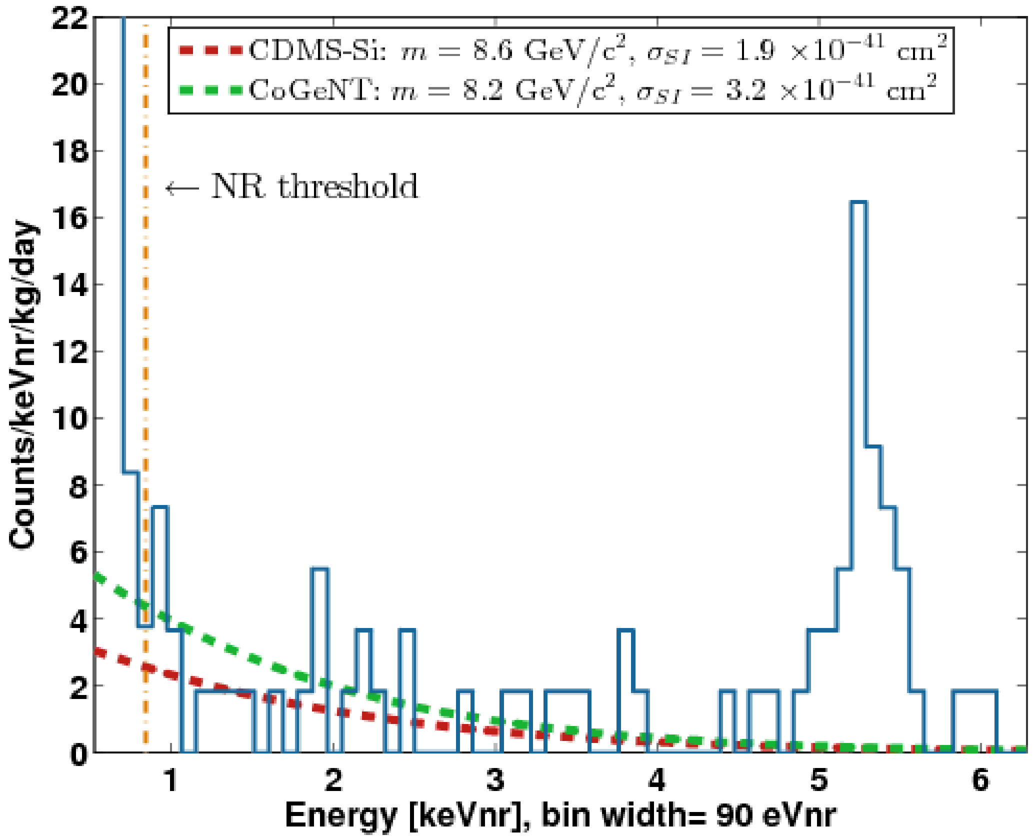
SNOWMASS CF1 Summary Report

Minimum WIMP Mass vs Detector Threshold



SuperCDMs Soudan CDMSlite Run 1

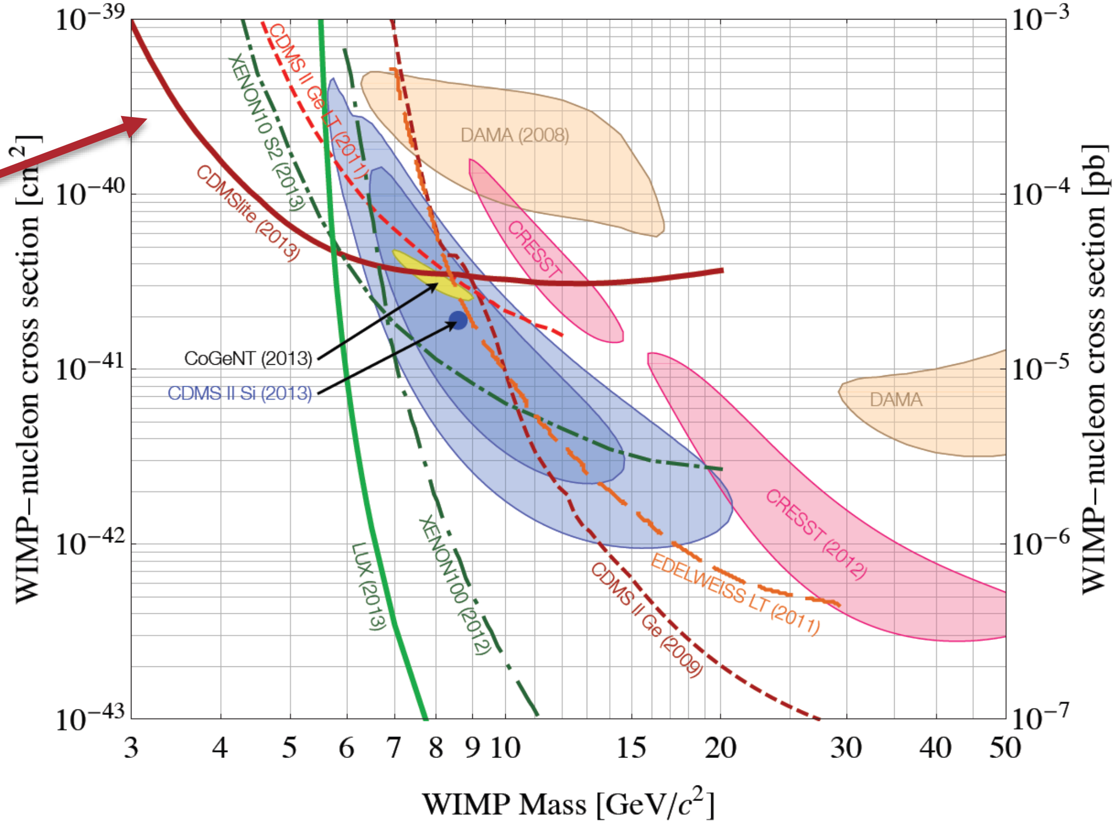
- Proof-of-concept run of 16 days in summer 2012
- 14 eVee resolution
- 170 eVee (840 eVnr) threshold (limited by vibrational noise)



Phys. Rev. Lett. **112** (2014)

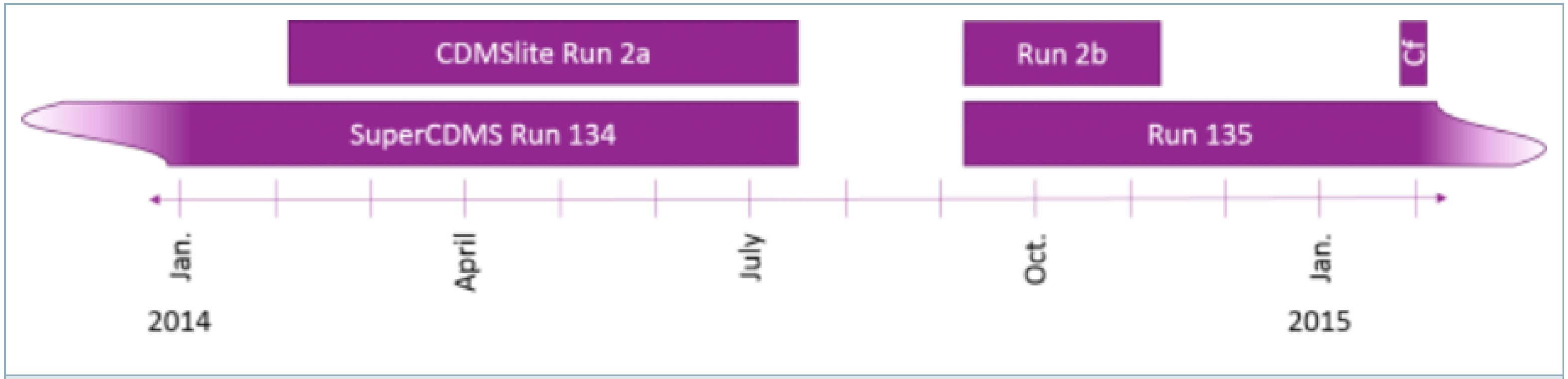
SuperCDMS Soudan CDMSlite Run 1

- 6.2 kg-day exposure
- At the time world-leading limit for WIMPs below 6 GeV



CDMSlite Run 2

- 70 kg-days acquired over most of 2014 with an interruption for long overdue fridge maintenance
- Multiple steps taken to improve data at the lowest energies:
  - Better control of HV detector bias
  - HV pre-biasing and current monitoring
  - Cryocooler noise monitoring

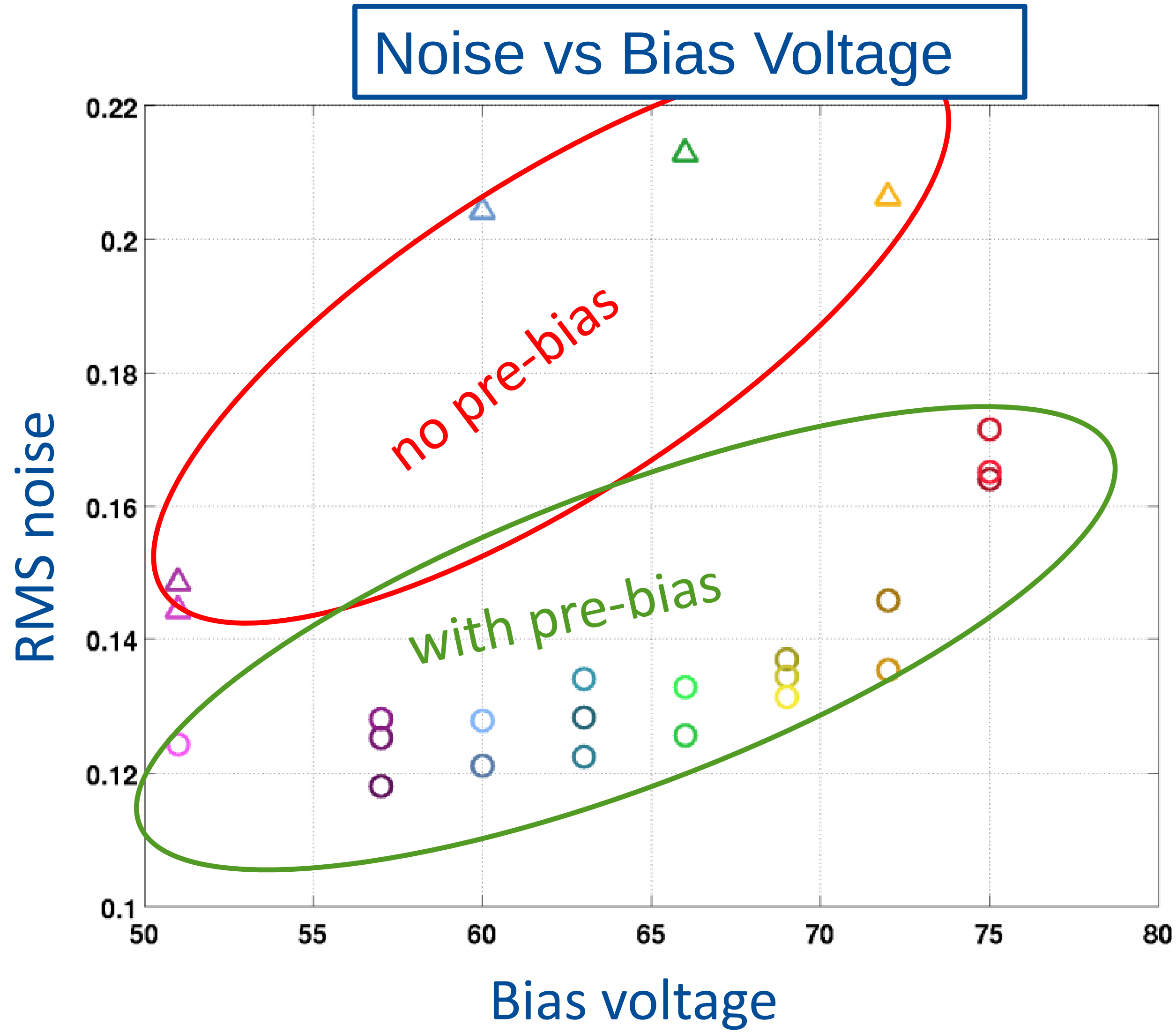


Timeline of CDMSlite Run 2 with SuperCDMS Runs.

HV Pre-biasing

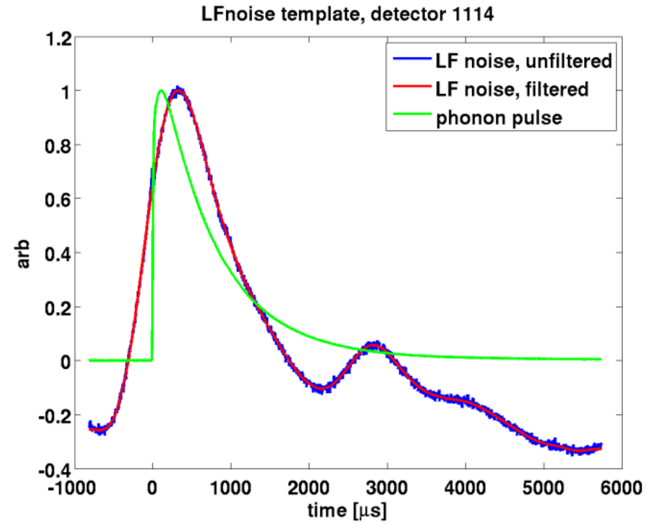
Transient currents after raising voltage induce noise

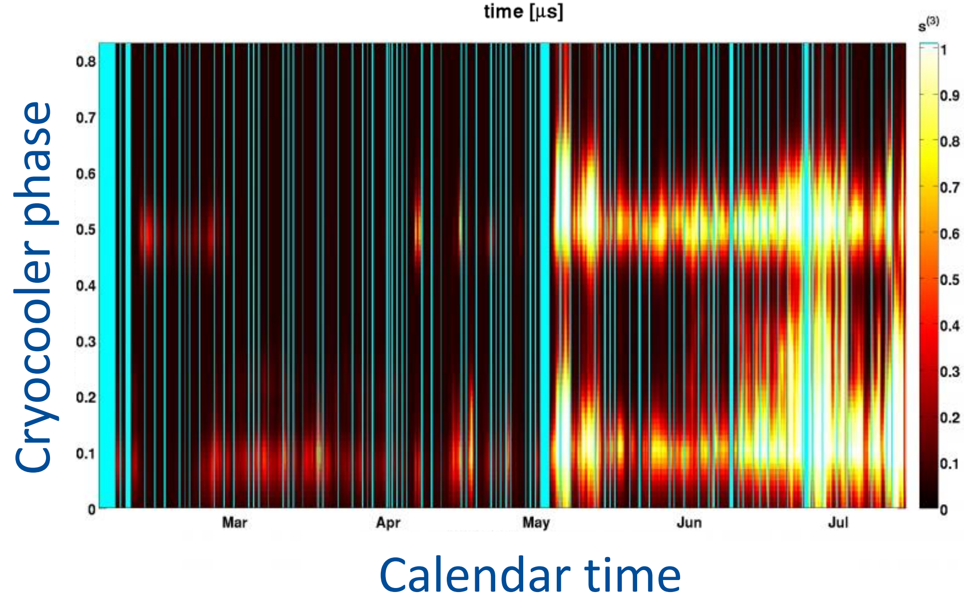
Short overvoltage period prior reduces significantly



Rejecting low-frequency noise

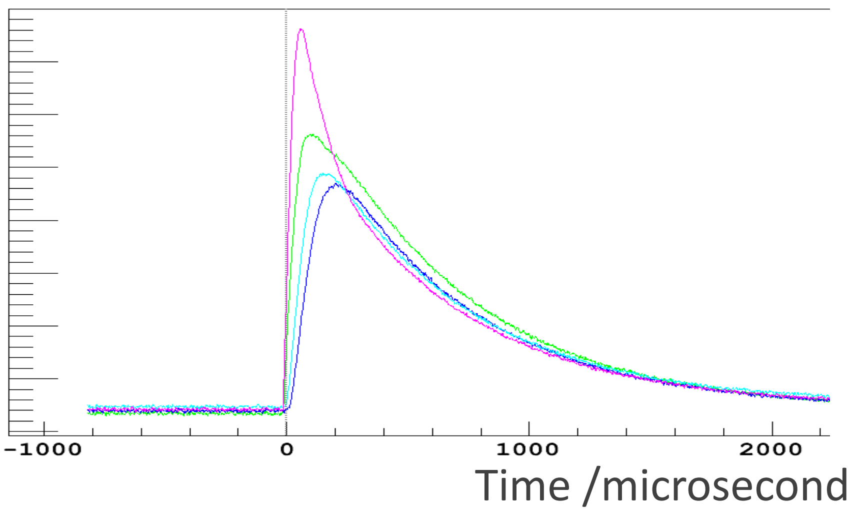
- Vibrational noise pickup mimics good pulses in phonon sensors
- Main source: cryocooler piston
- Accelerometer attached to crycooler and read by DAQ
- Used to identify and reject higher noise periods

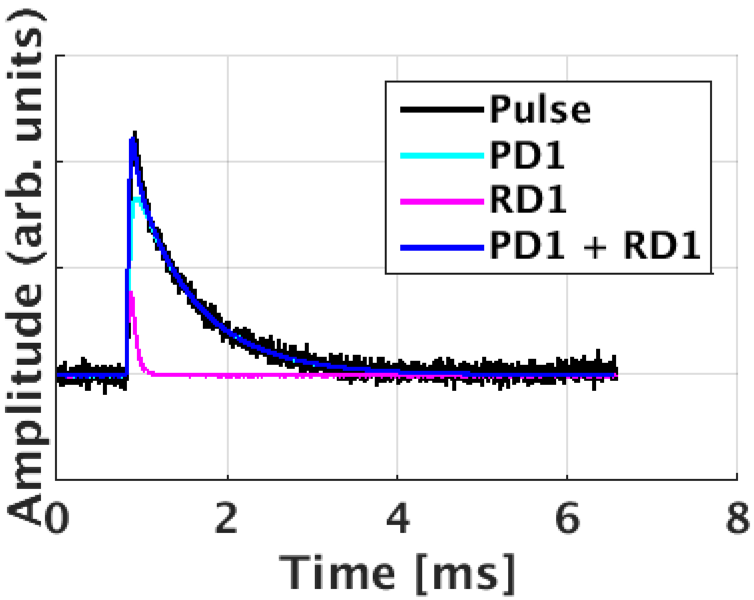




Position information from phonon pulse shapes

- Phonon pulses show separate prompt and slow components
- CDMS primary energy estimator uses a template based on summed traces, de-weights prompt part
- Works well for energy, but loses lots of position information
- Two template approach creates a second template from the averaged residual

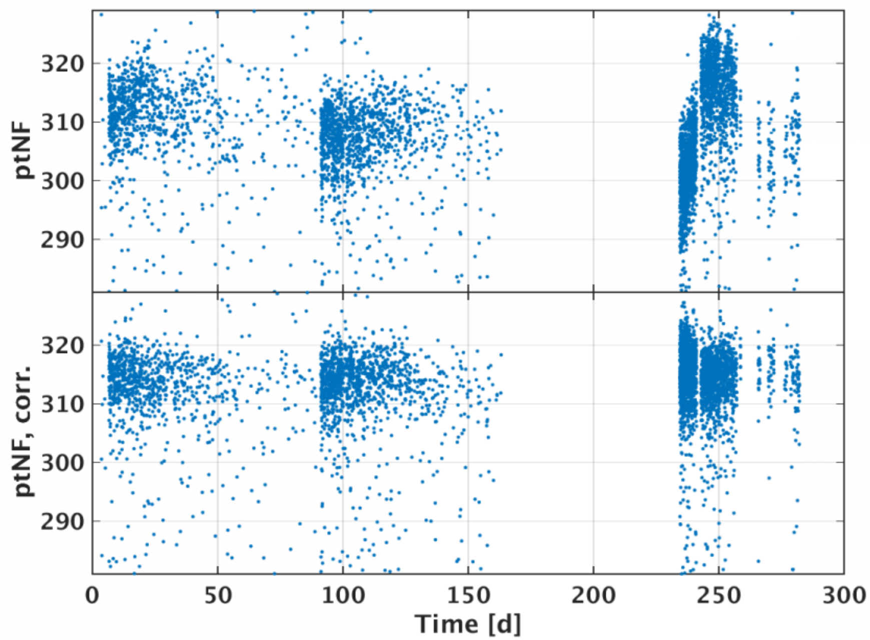




Empirical corrections to the energy scale

- Correct bias changes from variable leakage current
- Empirical fit to observed variation vs temperature
- Scale neutron activation x-ray line for jumps in Sept. and Oct. 2015
- Linear fit to observed dependence on two-template residual

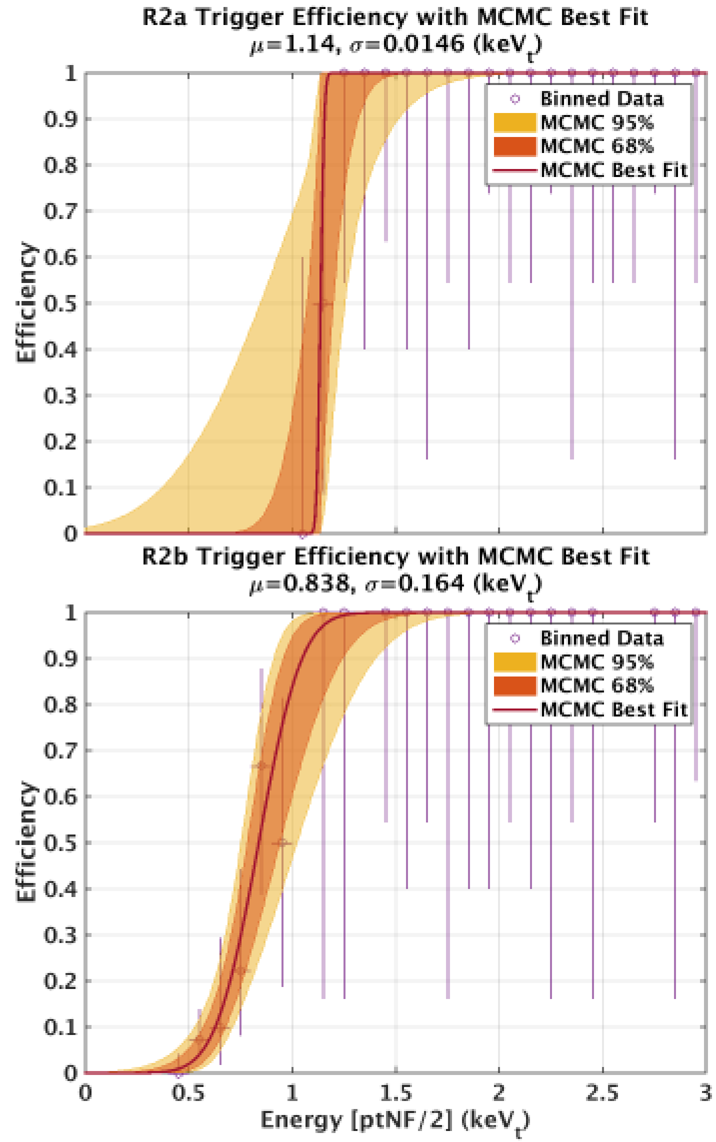
Before correction



After correction

Trigger Efficiency

- Exploit multi-detector CDMS nature
- Whole tower (3 detectors) is read on any trigger
- Test trigger efficiency on multiple scatter events
- Low statistics and fast turn-on make for large uncertainties
- 50% efficiency for electron-like events:
  - 75 eV for Run 2a
  - 56 eV for Run 2b



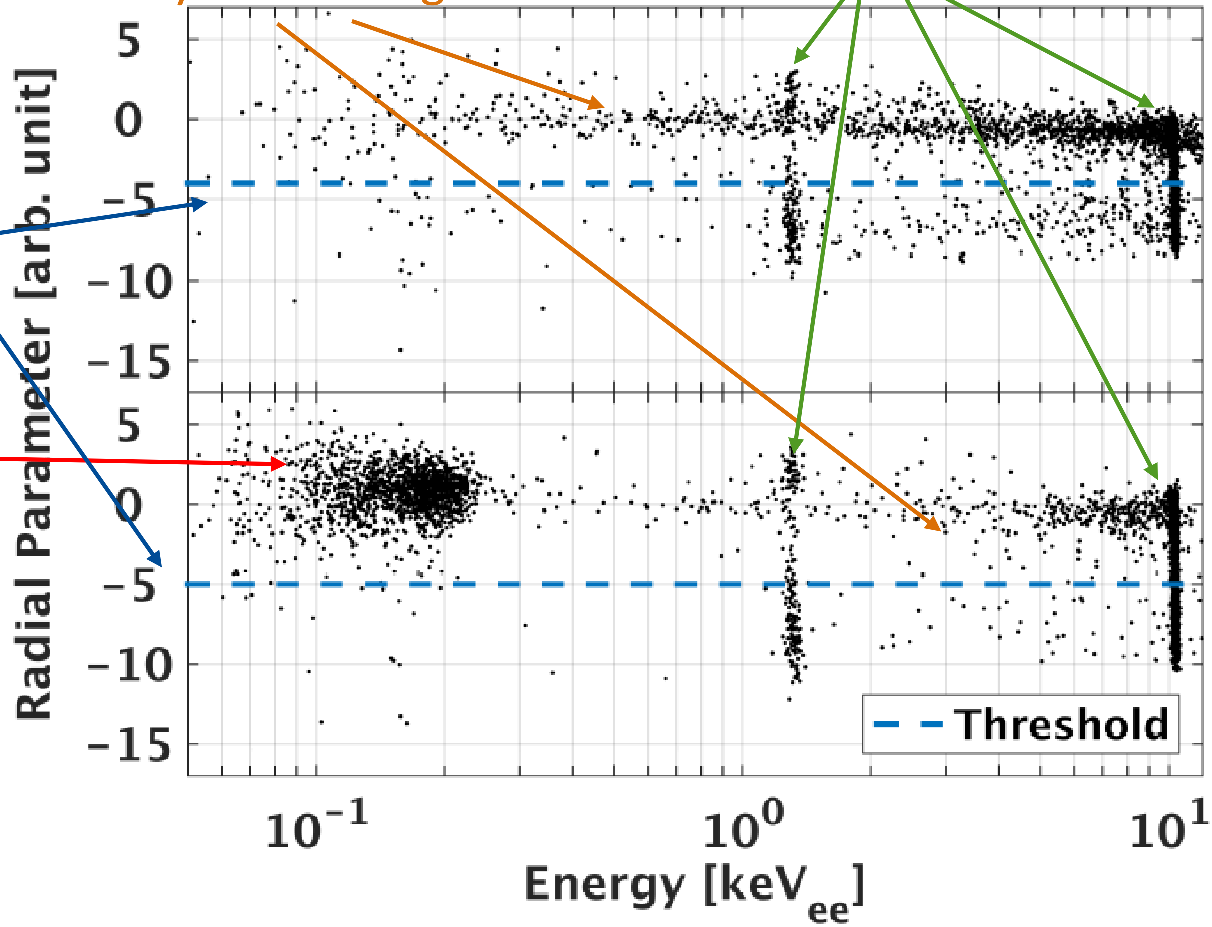
Radial fiducial volume

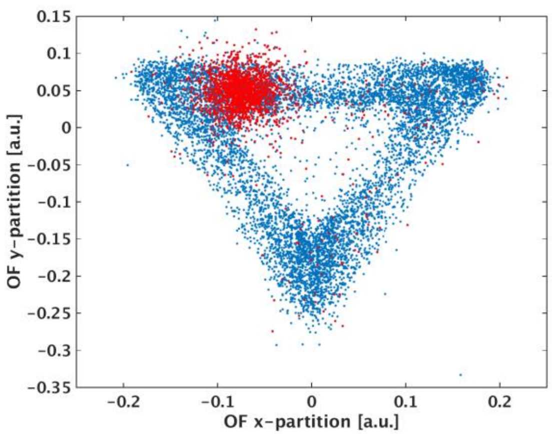
High radius events with low charge collection,
High rates from surface activity on housings

Ge-71 x-rays
(neutron capture activation)

Fiducial volume cut

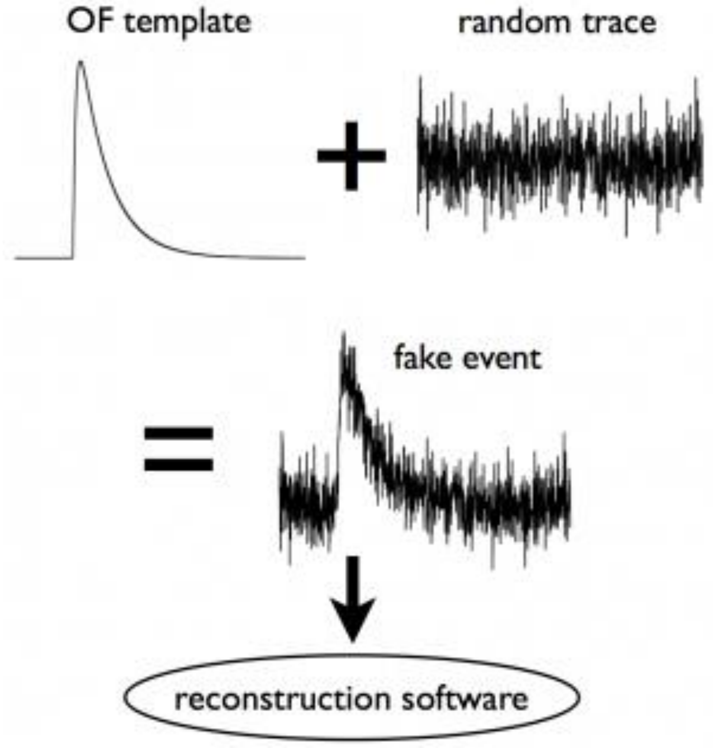
??





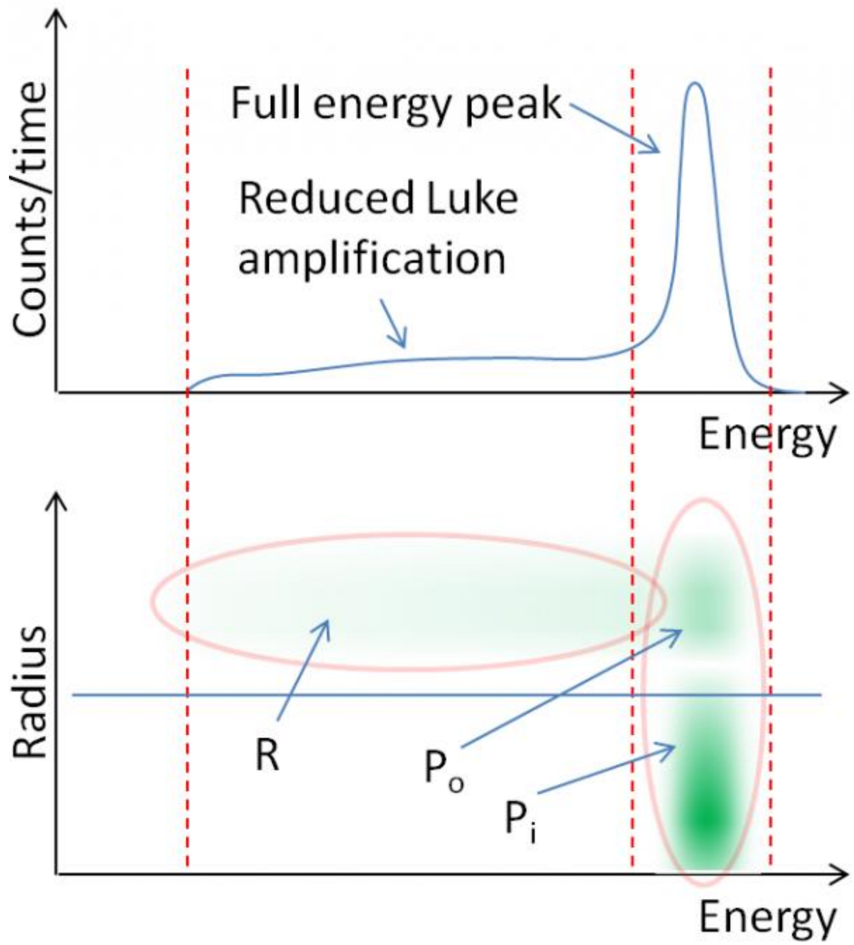
Quality cut acceptance calculations

- Use pulse simulation for energy-dependent cuts
  - Take reconstruction template or real pulses
  - scale down to low energy
  - add real noise from randoms triggers
  - run through reconstruction software
  - apply cuts and measure acceptance

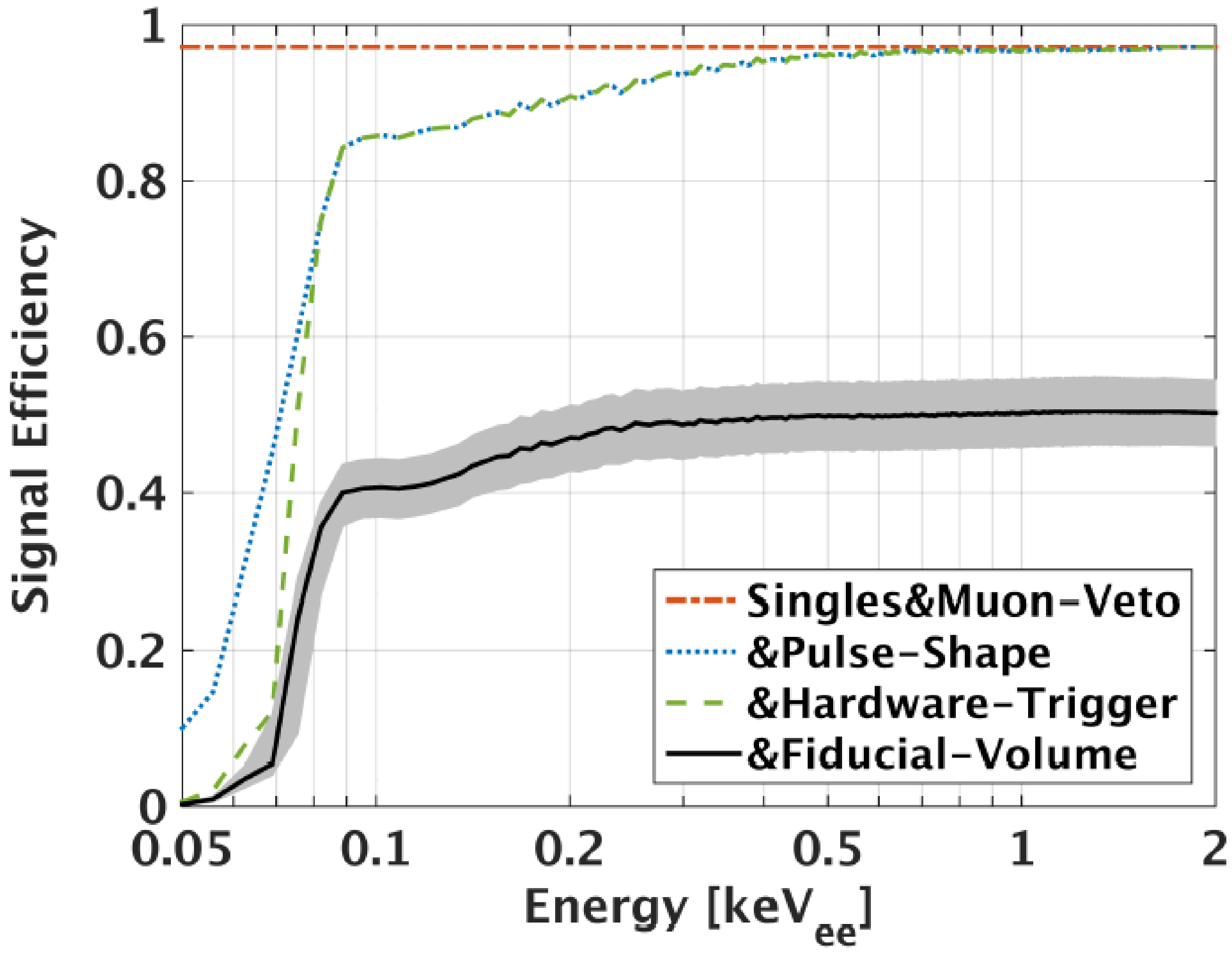


Fiducial volume efficiency calculation

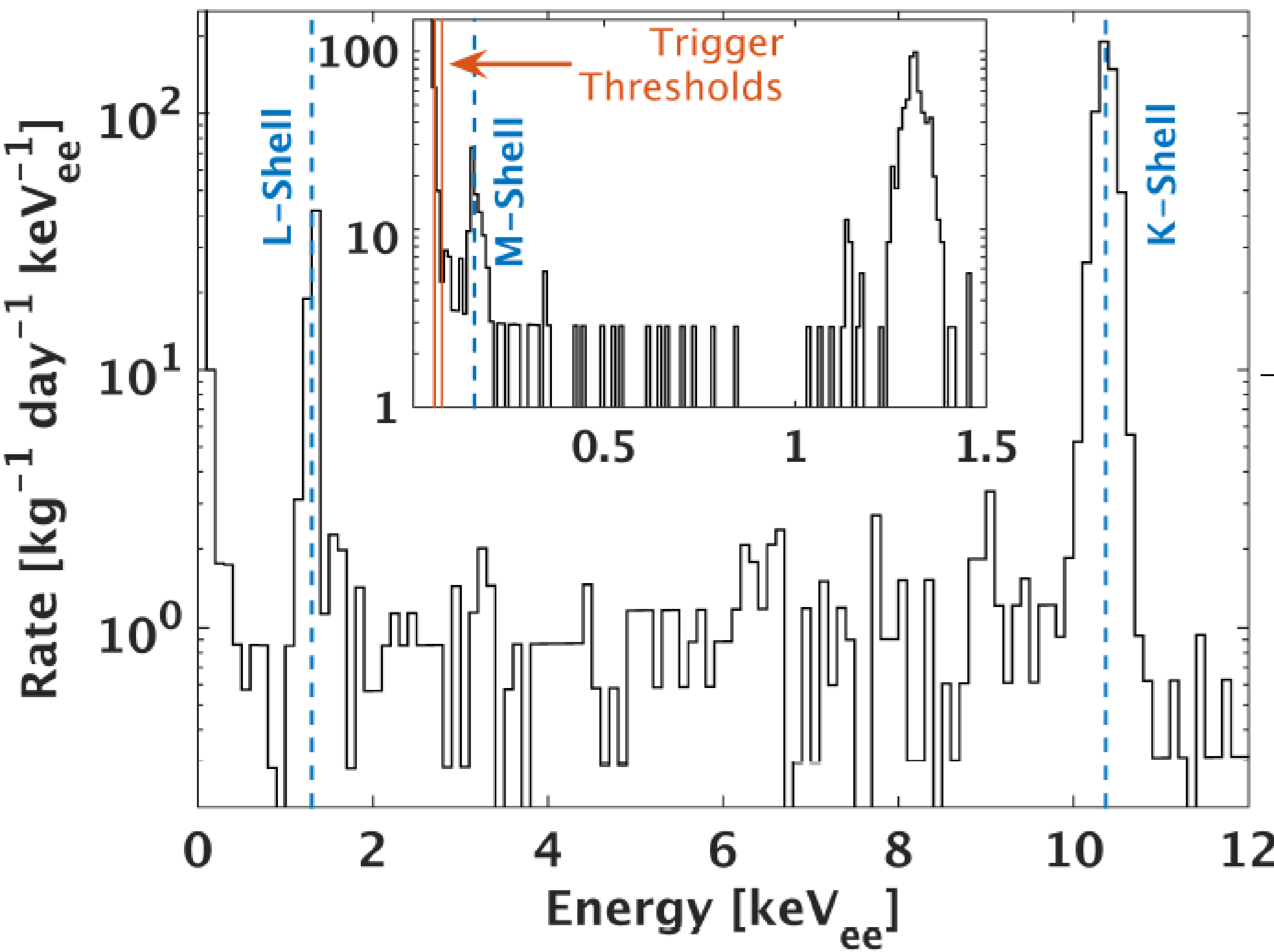
- Need to find fraction of events with degraded charge
- Should be geometrical effect, so energy independent
- Use the prominent Ge-71 x-ray lines
- Bin in radius-vs-energy and fit to a constant background + exponential with half-life of Ge-71



Cuts efficiency



Final Spectrum



Ge-71 activation peaks

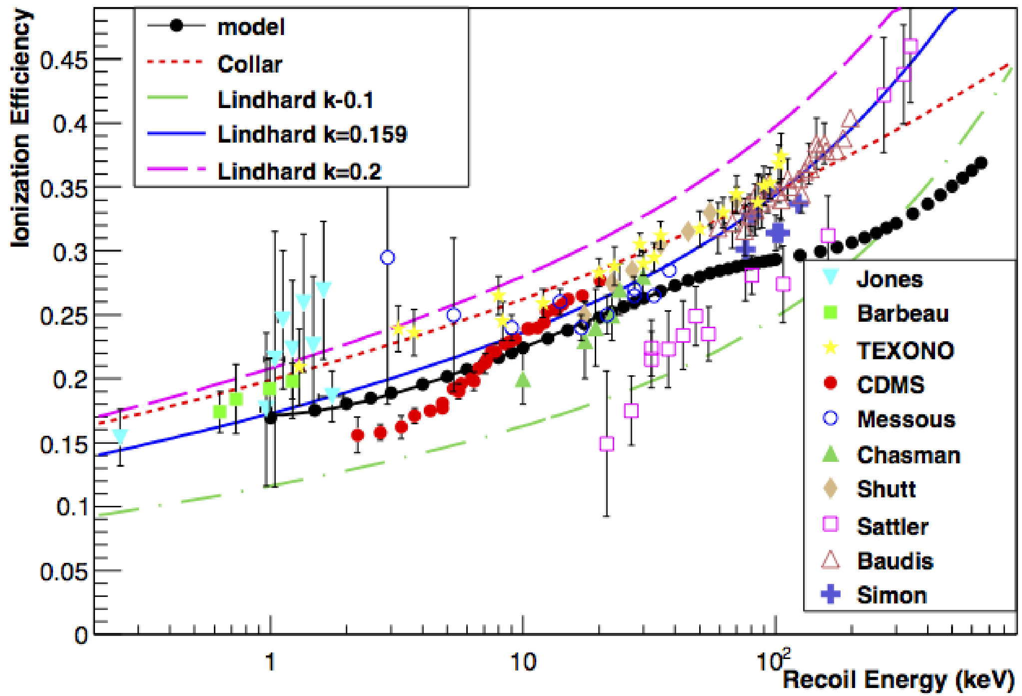
Energy [keV$_{ee}$]	Resolution [σ/μ, %]
0.16	11.4±2.8
1.30	2.36±0.15
10.37	0.974±0.009

~1 count/kg*day*keV between peaks

Converting to Nuclear Recoil energy scale

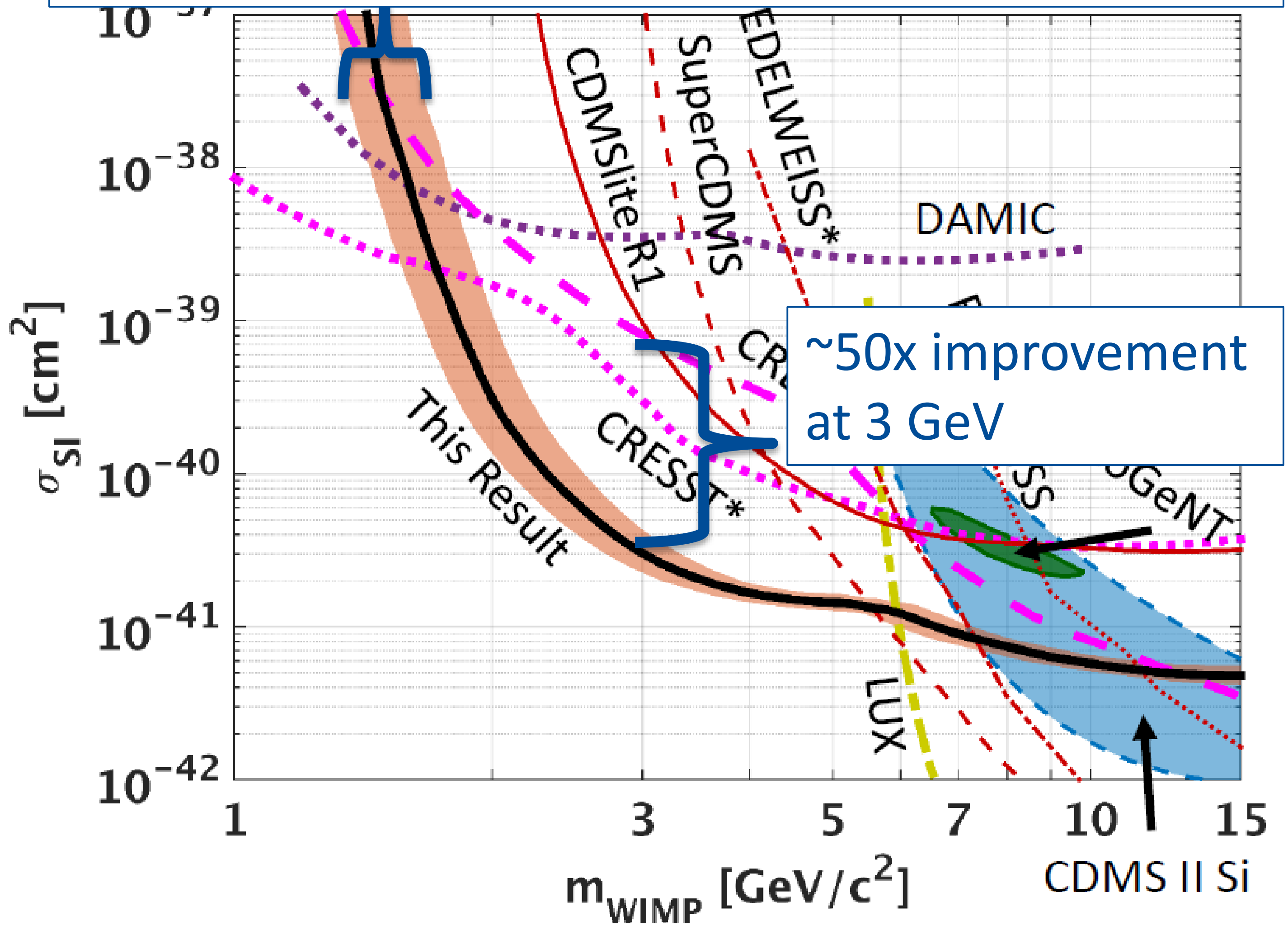
- CDMSlite measures charge signal (indirectly)
- Ionization yield needed to calculate nuclear recoil energy
- Used semi-empirical Lindhard model
- Large uncertainties and few measurements below 1 keV

Barker and Mei, Astropart Phys. **38** 2012

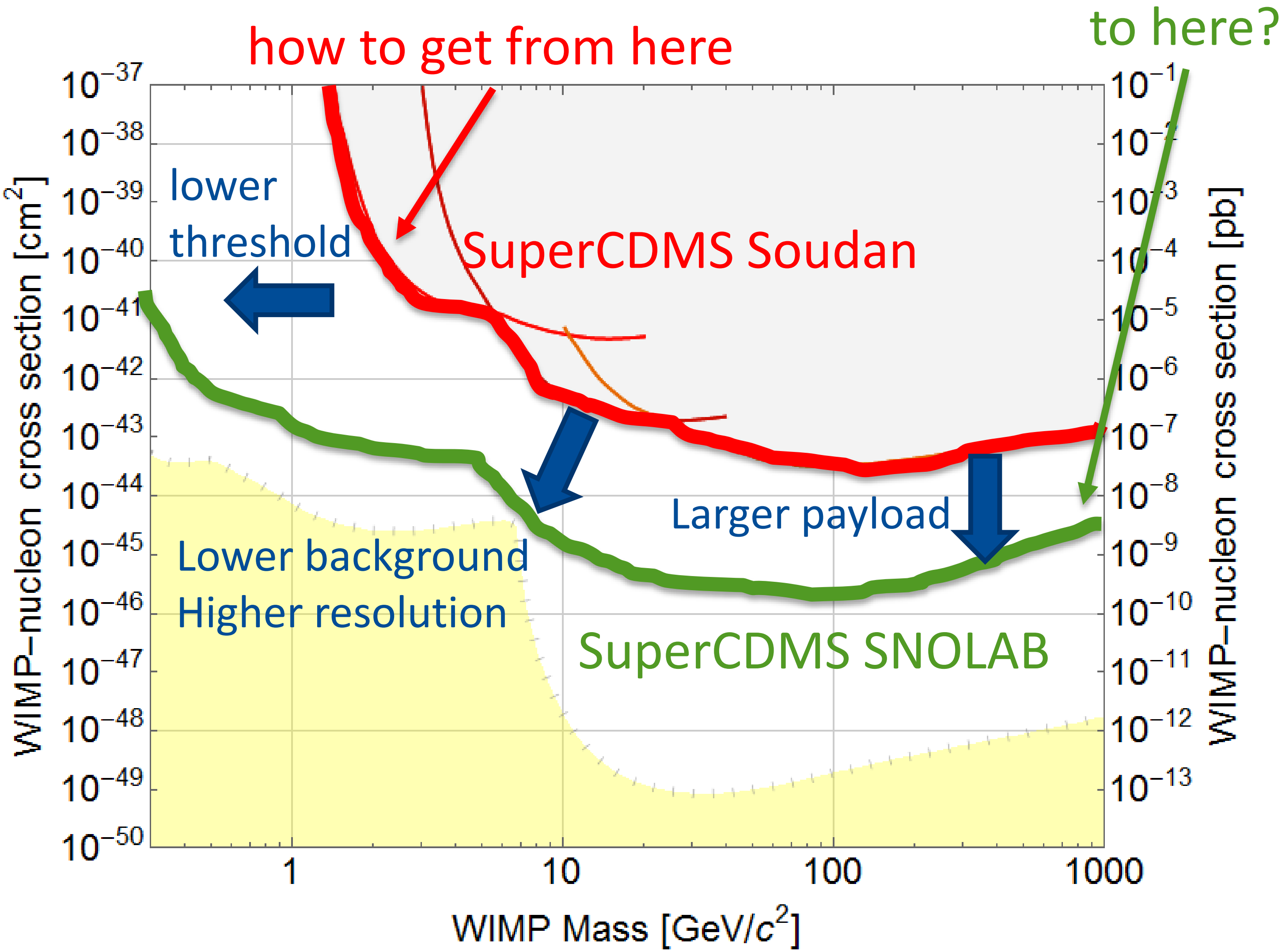


CDMSlite Run 2 Result

Width from nuclear recoil energy scale uncertainty

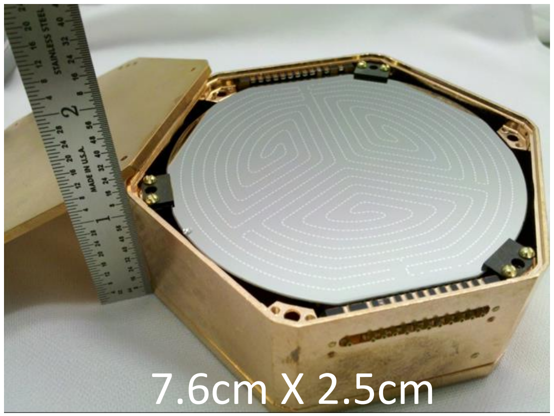


A big leap forward to SuperCDMS SNOLAB



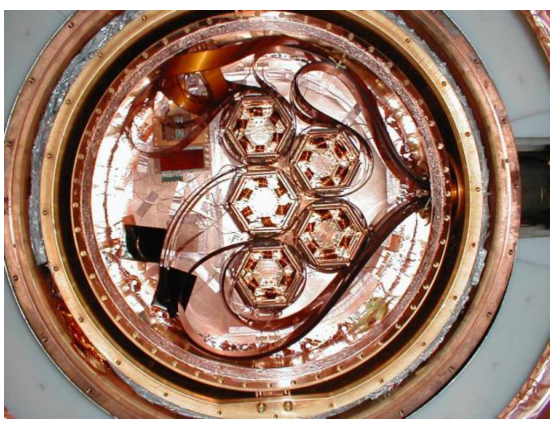
Bigger, better detectors

SuperCDMS Soudan



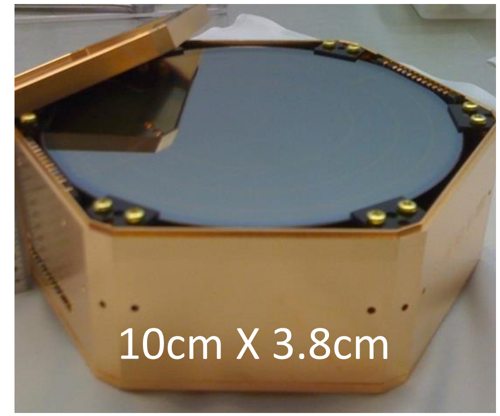
8 phonon
4 charge
channels

5 towers, 15 iZIPs
9 kg Ge



SuperCDMS SNOLAB

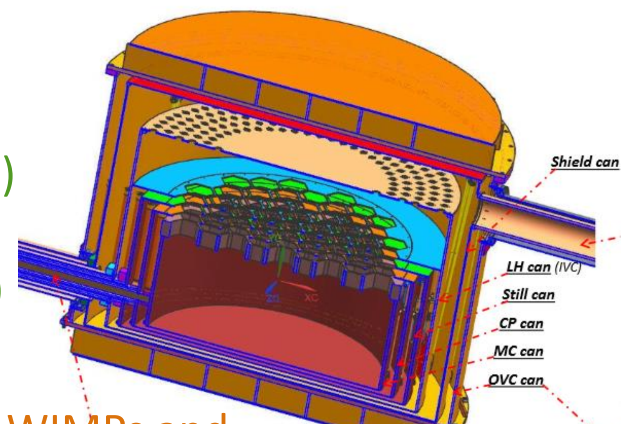
12 phonon
4 charge
channels



More channels
=
Better fiducialization

Cryostat can hold up to 260 kg

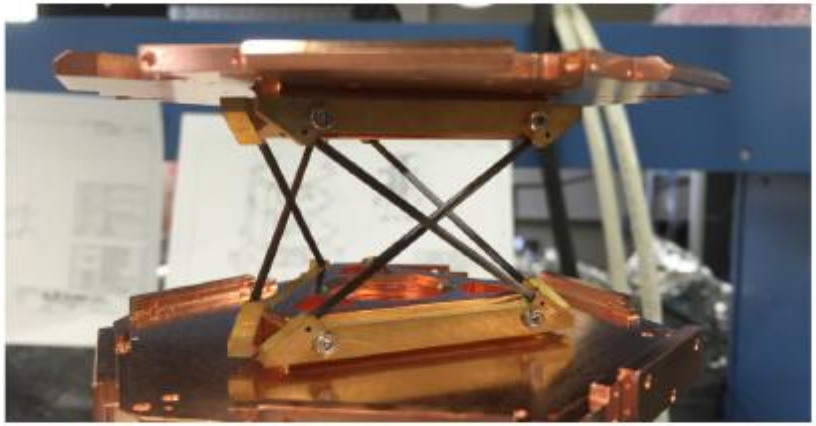
Initial payload (preliminary):
Ge: 18 iZIPs (25 kg)
4 HV (5.6 kg)
Si: 6 iZIPs (3.7 kg)
2 HV (1.2 kg)

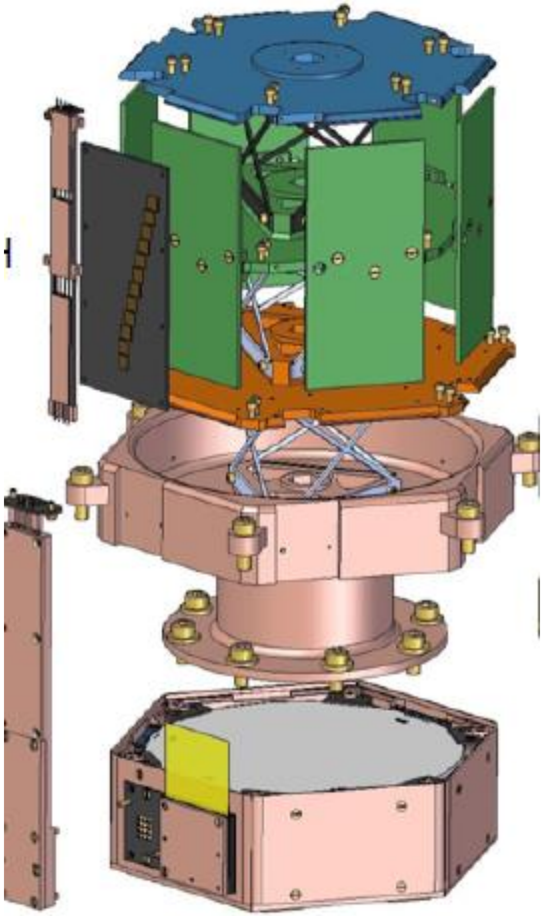


Si more sensitive to light WIMPs and gives complementary targets

New tower support system minimizes vibrations

- Ti or carbon fiber trusses between thermal stages
- Low thermal conductivity
- High resonant frequency to damp vibration transmission

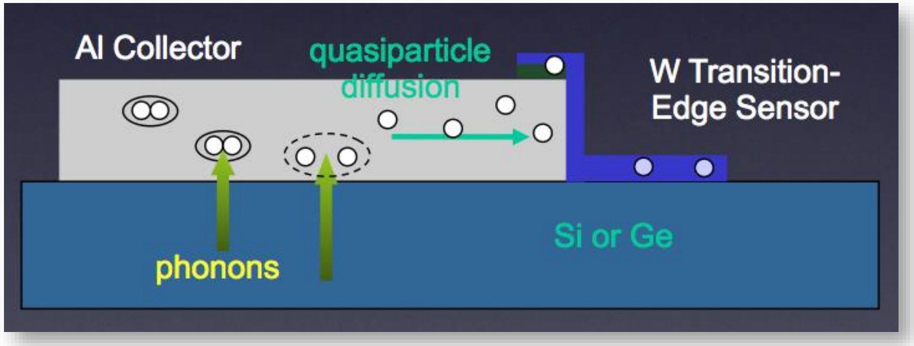


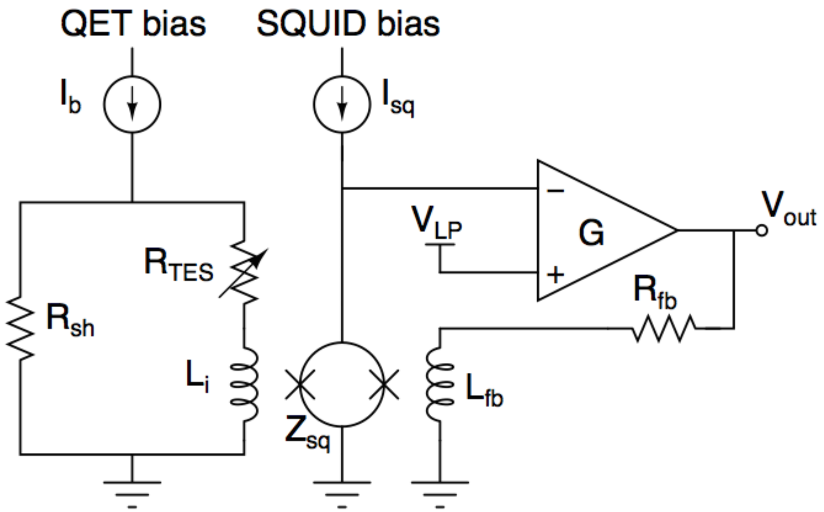


Improved Phonon and Charge Resolution

- Lower operating temp (15 mK) allows lower Tc TESs=> steeper change in resistance per phonon
- NIST standard SQUIDs with lower intrinsic noise
- Replace JFETs with HEMTs for charge readout
- 2-sided HV readout (x2 gain), higher breakdown voltage

Target 10 (50) eV phonon resolution for HV (iZIPs), 100 eV for charge



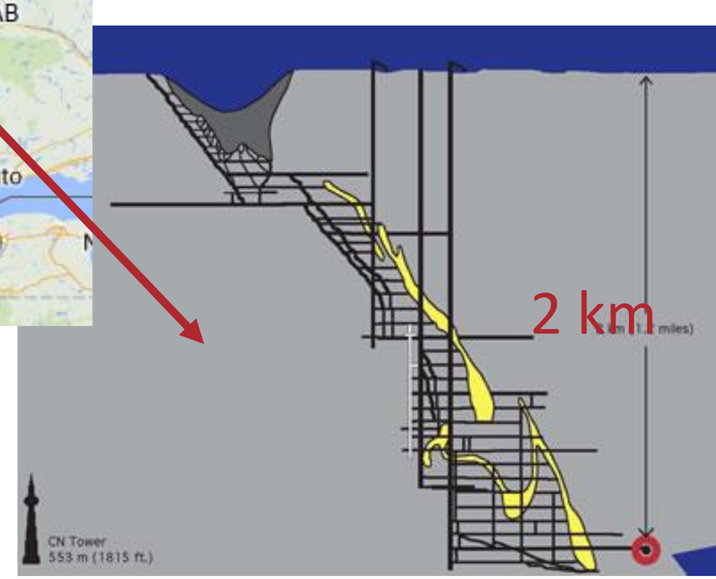


Fermilab

Background Reduction Goals

- >x50 reduction in bulk gamma rates,
  x10 reduction in bulk neutron rates
  - Bigger shield
  - Cleaner shield materials
    - Better radioactive contaminant assays
    - More stringent control of materials and handling
  - Tight radon purge barrier
  - Deeper site
- x25 reduction in copper housing surfaces
  - Radon-suppressed clean room
- Some dominant remaining backgrounds:
  - tritium from cosmic ray activation
  - neutrino coherent scattering (expect ~15 events in Ge)

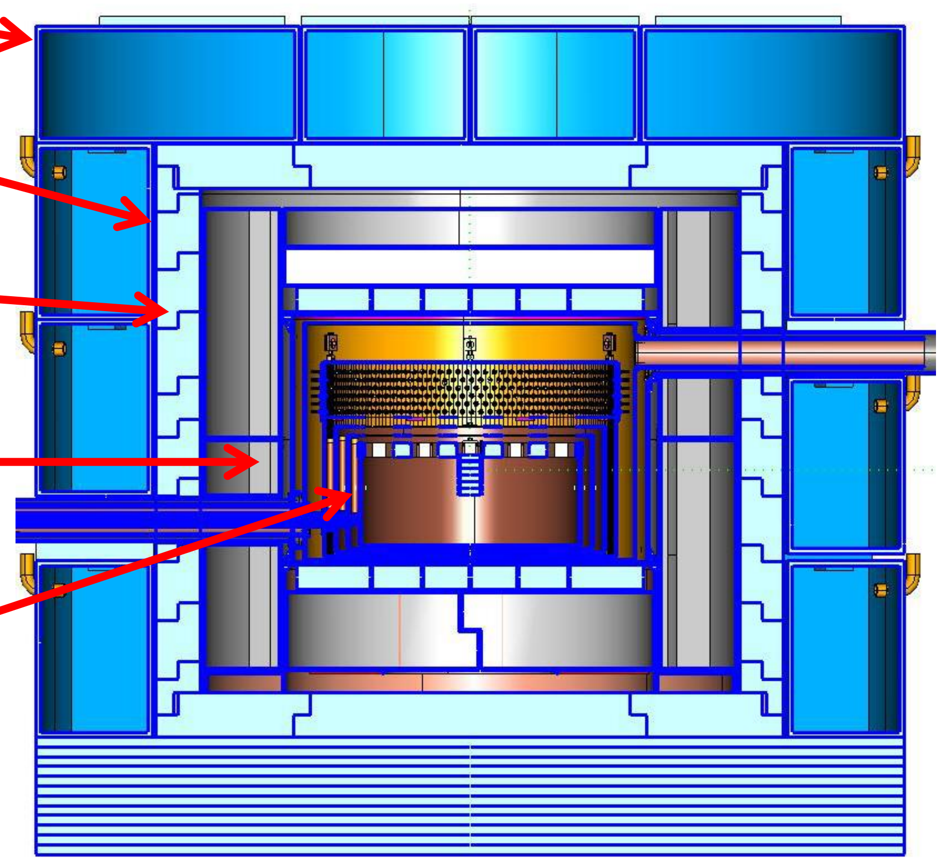
Moving down (and south) to SNOLAB



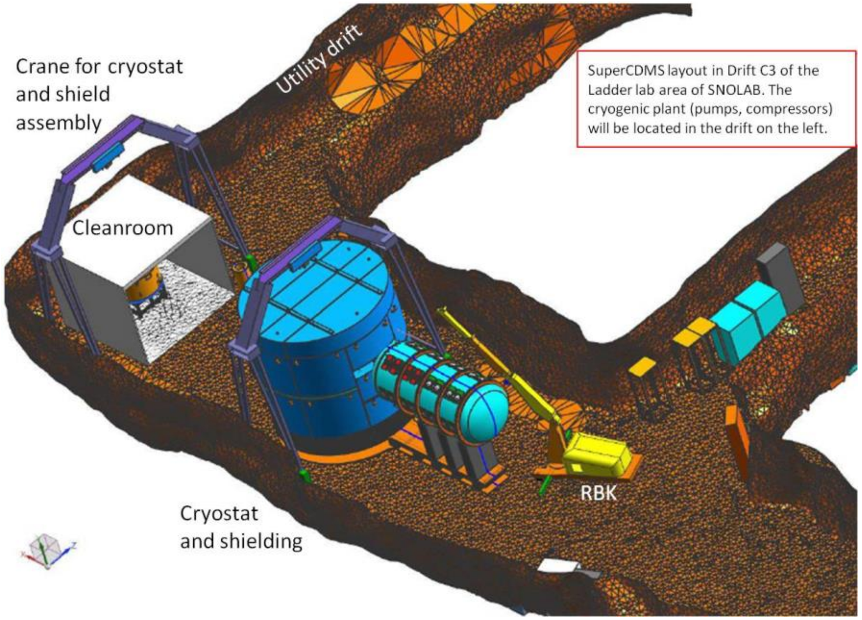
>100x reduction in muon flux at SNOLAB compared to Soudan

SuperCDMS SNOLAB Shielding

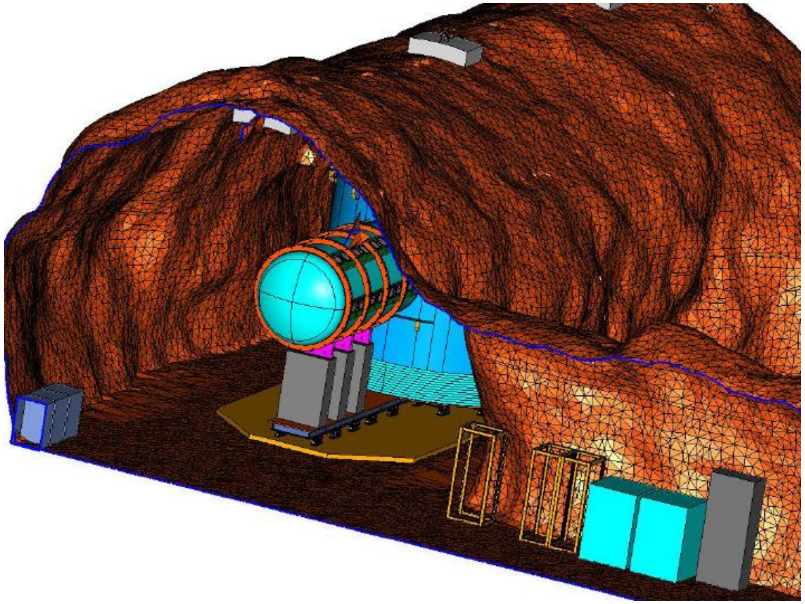
- 60 cm neutron shield:
  - water tanks + HDPE base
- Radon purge containment
- 23 cm lead gamma shield
  - Inner 1 cm “ancient” lead
- 40 cm HDPE neutron absorber
  - large enough space for possible future upgrade to active neutron veto
- Copper cryostat cans 3/8” to 1/2” thick



Efficient shielding needed for small ladder lab space!

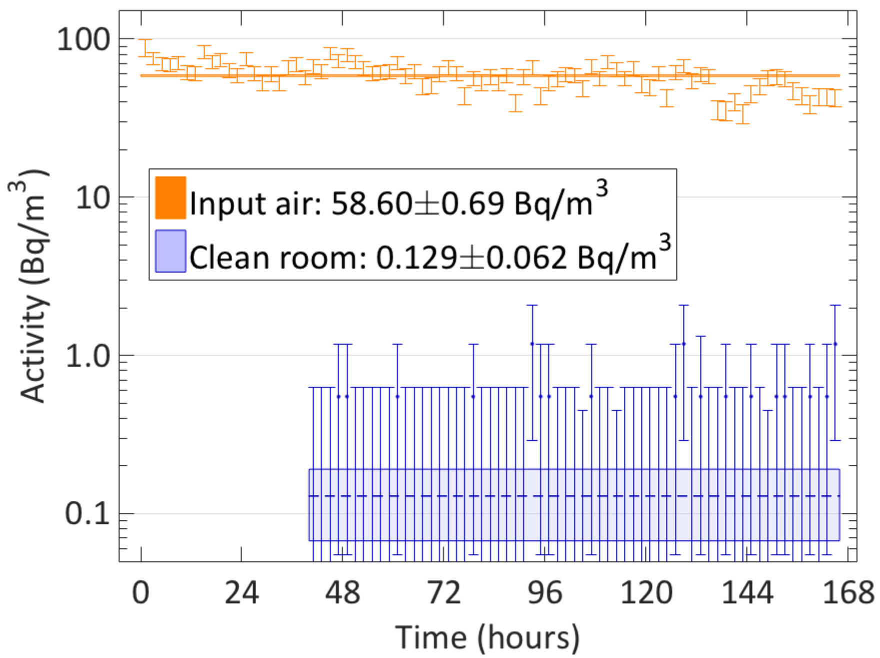


Model of the SuperCDMS shield, fridge, and “ebox” in the SNOLAB ladder lab

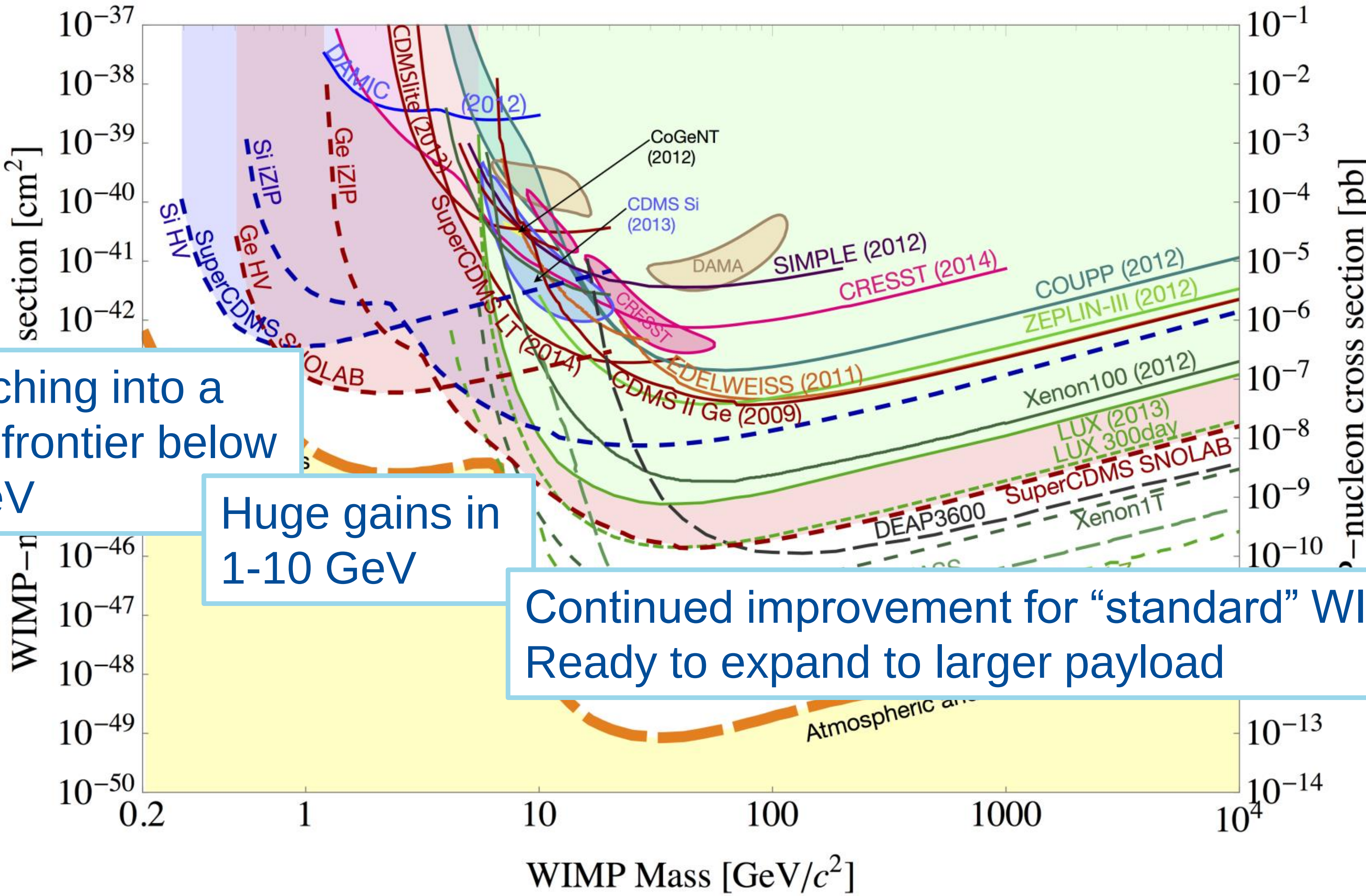


SuperCDMS shield and “ebox” nestled in 3D laser scan of cavern

Radon mitigation system: reduce surface backgrounds



The WIMP Landscape in the next decade



Reaching into a new frontier below 1 GeV

Huge gains in 1-10 GeV

Continued improvement for “standard” WIMPs
Ready to expand to larger payload

Conclusions

- Continued pushing against minimal supersymmetry models motivates a broader search for dark matter
- SuperCDMS HV detectors offer the best resolution and lowest thresholds for large (kg-scale) detectors
- CDMSlite Run 2 improves cross section limits for low mass WIMPs (~2-5 GeV) thanks to lower thresholds and larger run time
- SuperCDMS SNOLAB will extend sensitivity to below 1 GeV and significantly improve current limits for all masses below ~10 GeV
- Detector fab begins early 2016, installation 2018

Thank you!

California Inst. of Tech. | CNRS-LPN* | Durham University | FNAL | NISER

NIST* | Northwestern U. | PNNL | Queen's University | SLAC

Southern Methodist U. | Santa Clara U. | South Dakota SM&T | Stanford University | Texas A&M University | U. British Columbia

U. California, Berkeley | U. Colorado Denver | U. Evansville | U. Florida | U. Minnesota | U. South Dakota

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