Direct dark matter detection with SuperCDMS in 10 Minutes

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Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Cluster of Excellence Quantum Universe

UNIVERSITY OF TORONTO

Dark Matter (DM)

- From astrophysical observations, **85% of all matter is dark!**
- Measurements of dark matter can be made via:
  - Indirect methods (galaxy rotation curves, collision of galaxy clusters, etc)
  - DM production (colliders)
  - **Direct methods (direct interactions of DM with detectors)**

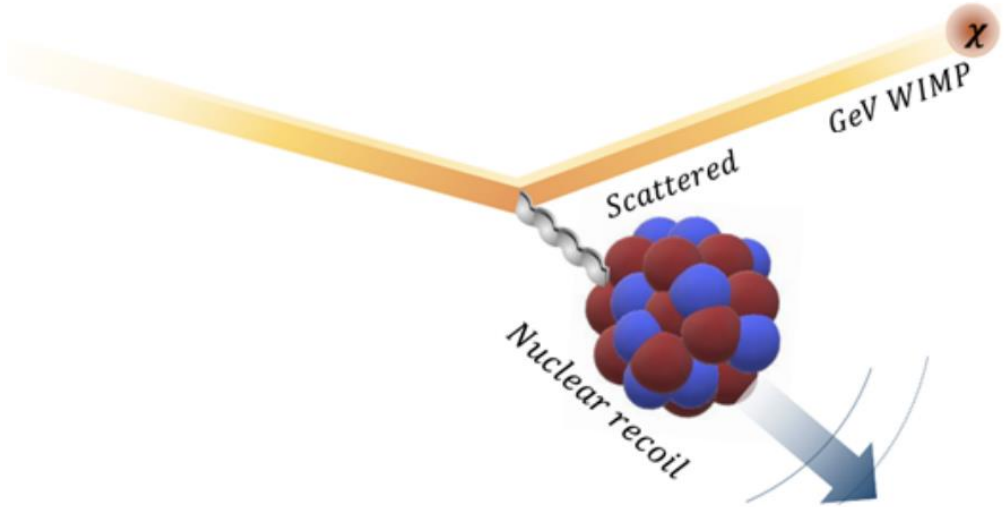
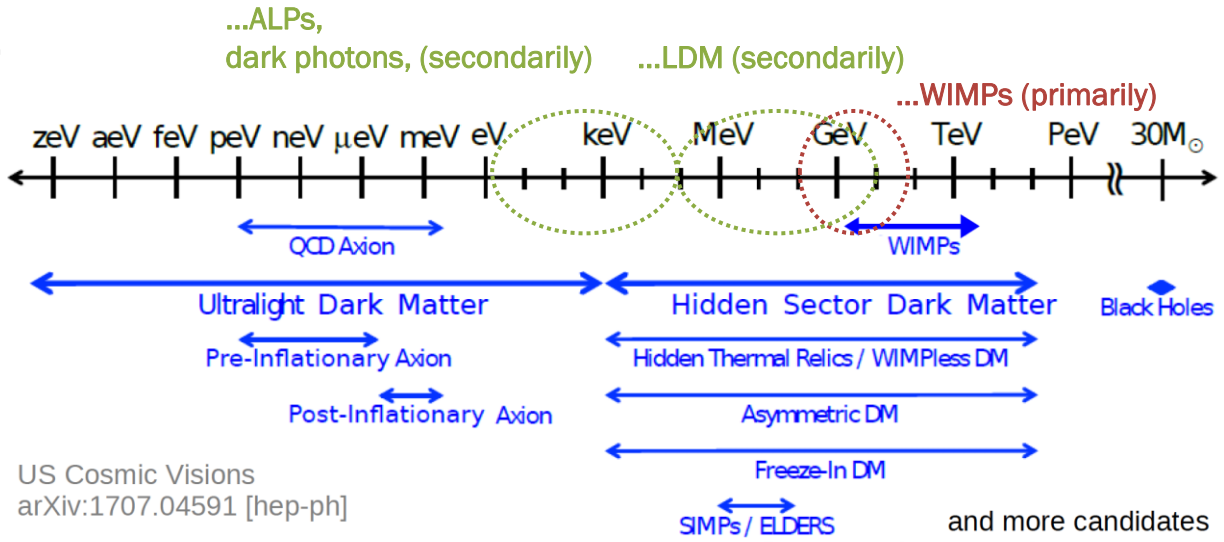


Figure: Stefano Davini

SuperCDMS searches for:...



US Cosmic Visions
arXiv:1707.04591 [hep-ph]

WIMP = Weakly-Interacting Massive Particle
ALP = Axion-Like Particle
LDM = Light Dark Matter

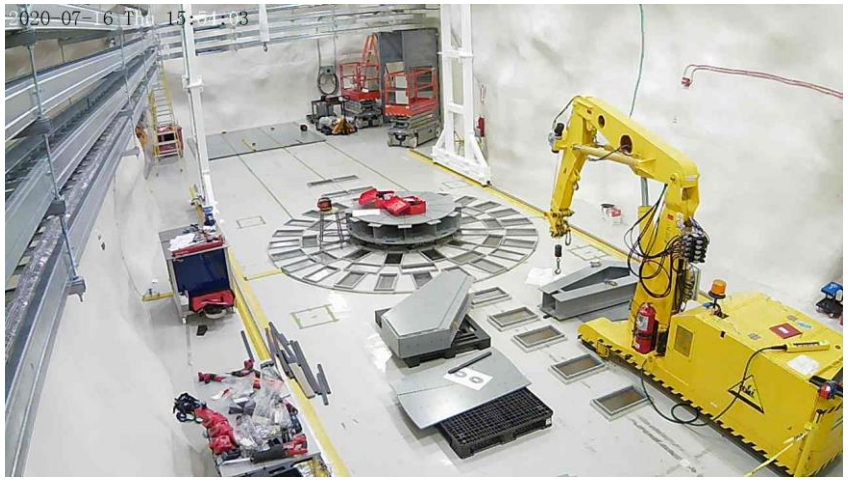
Our collaboration

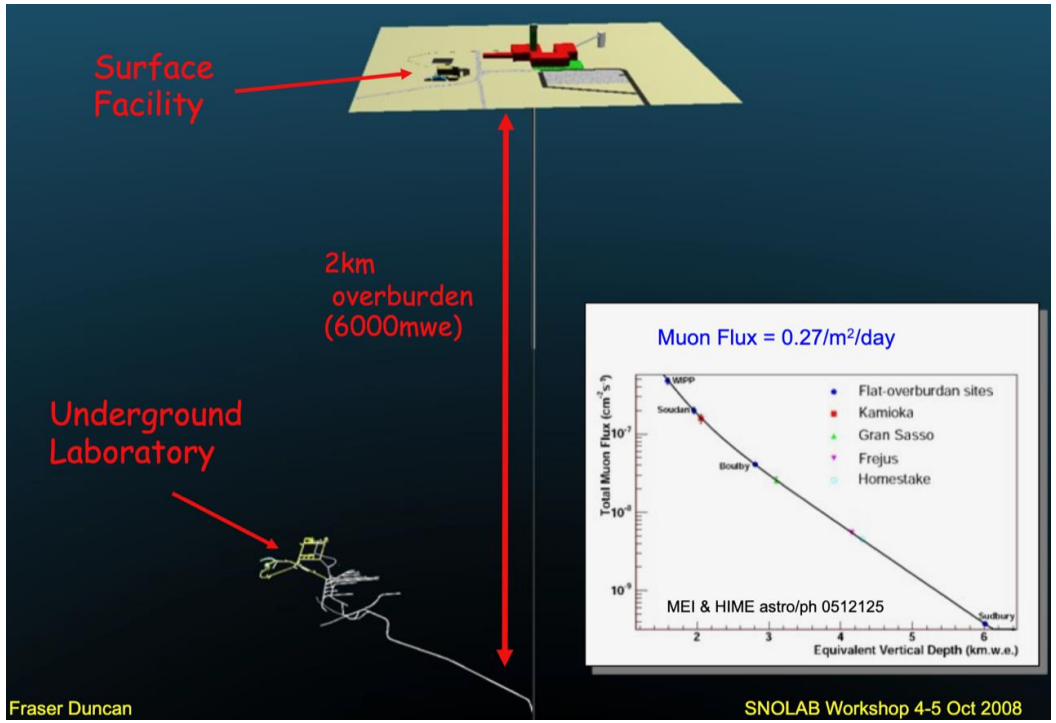
California Inst. of Tech
C2N*
Durham University
FNAL
NISER
NIST*
Northwestern
PNNL
Queen's University
Santa Clara University
SLAC
South Dakota SM&T
SMU
SNOLAB
Stanford University
Texas A&M University
TRIUMF
U. British Columbia
U. California, Berkeley
U. Colorado Denver
U. Florida
U. Hamburg
U. Montréal
U. Minnesota
U. South Dakota
U. Toronto

* Associate Members

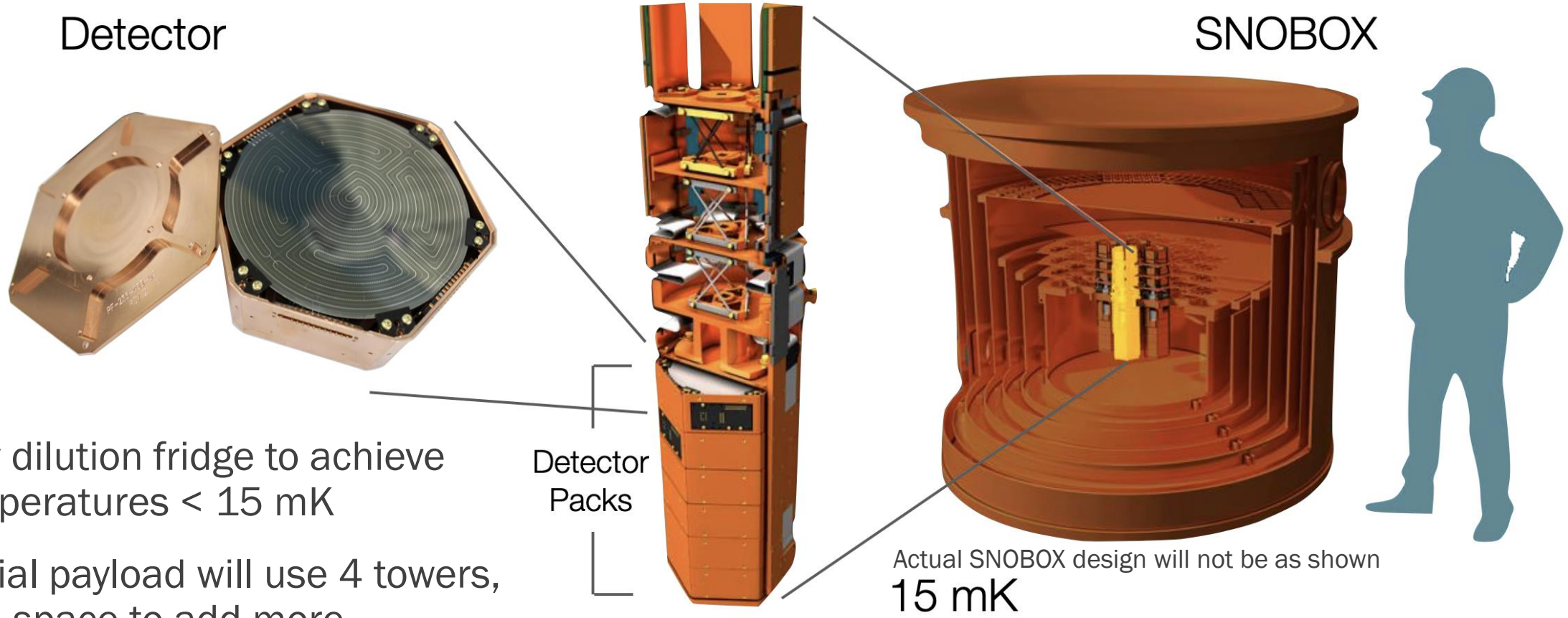
SuperCDMS at SNOLAB (Sudbury, Canada)

- ~2 km deep underground in an active mine (~6000 m.w.e.)
  - 0.27 muons per m^2/day
- Cleanroom class 2000
- Home to ~10 low background experiments





SuperCDMS detector setup



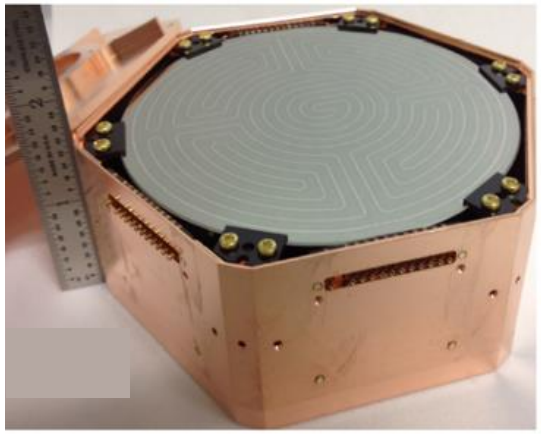
- Dry dilution fridge to achieve temperatures < 15 mK
- Initial payload will use 4 towers, with space to add more
- 6 detectors per tower

Commissioning starts late 2021!

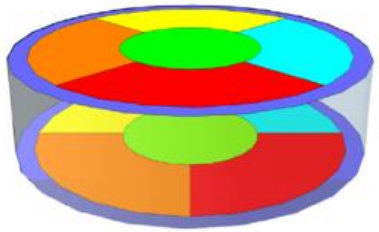
SuperCDMS detectors

- Made of silicon and germanium crystals
- Particles that interact with the detectors are measured via:
  - **Phonons** (i.e. heat/lattice vibrations)
  - **Electron-hole pairs** (ionization)

iZIP



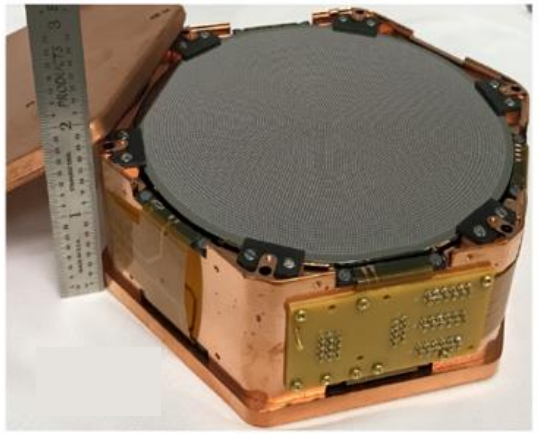
Phonon channels



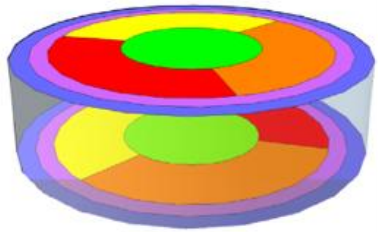
interleaved with charge channels

Phonon and charge channels allows for efficient nuclear recoil (NR) to electron recoil (ER) discrimination

HV



Phonon channels

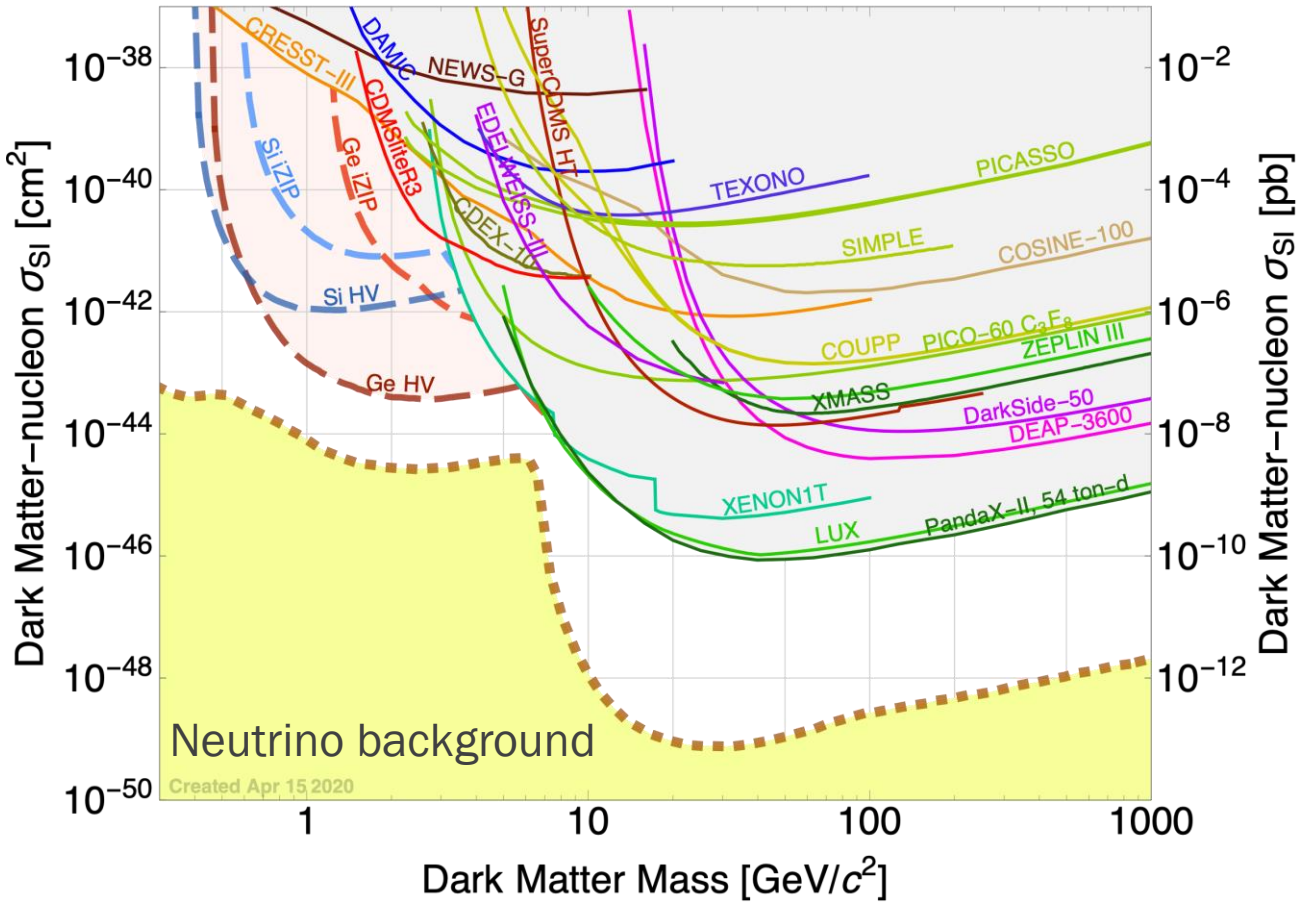


Phonon amplification allows for strongly reduced energy thresholds

SuperCDMS projections (WIMPs)

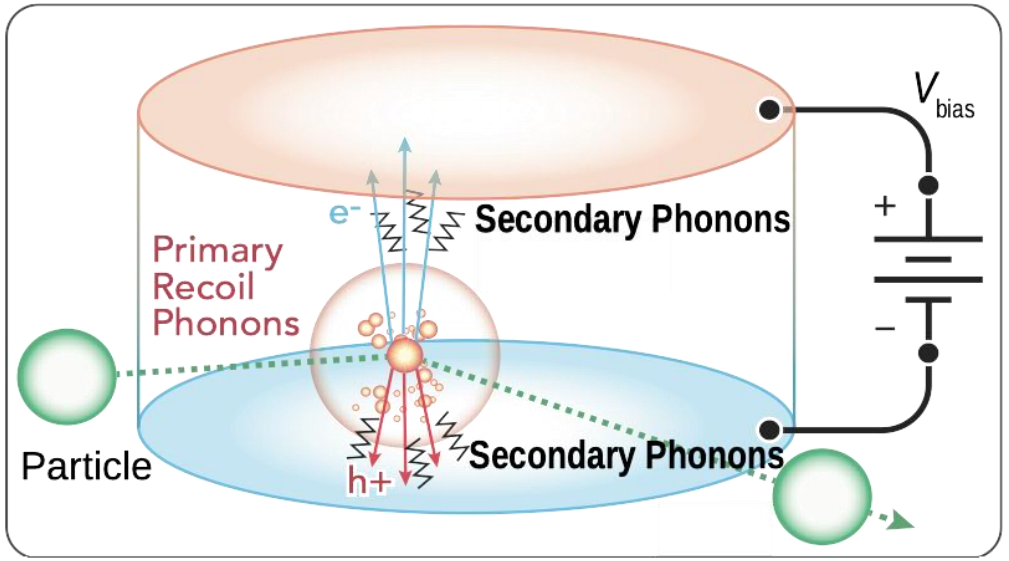
Project goals for initial payload (2022-2027)…

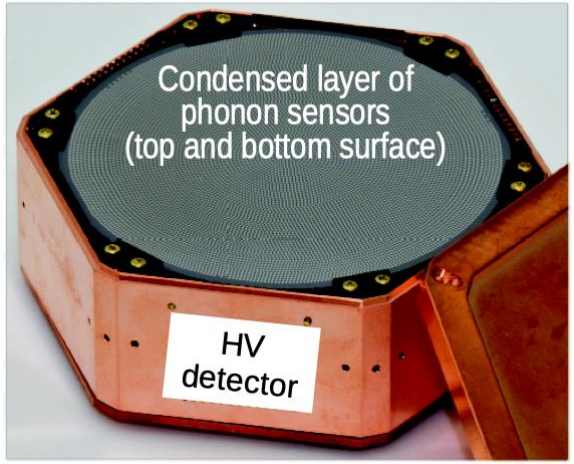
Lower energy thresholds in HV detectors lead to sensitivity to lower DM masses!



Phonon amplification of ionization signal

- As electrons and holes drift through the detector, secondary phonons are produced via Neganov-Trofimov-Luke amplification
- $V_{\text{bias}} \sim 100$ V

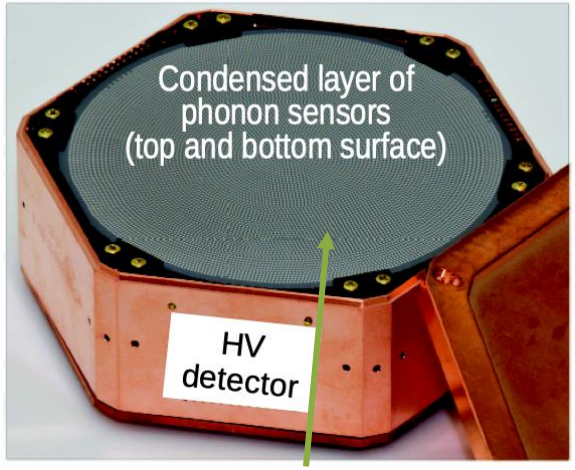




R&D high-voltage detectors (HVeV)

SuperCDMS HV

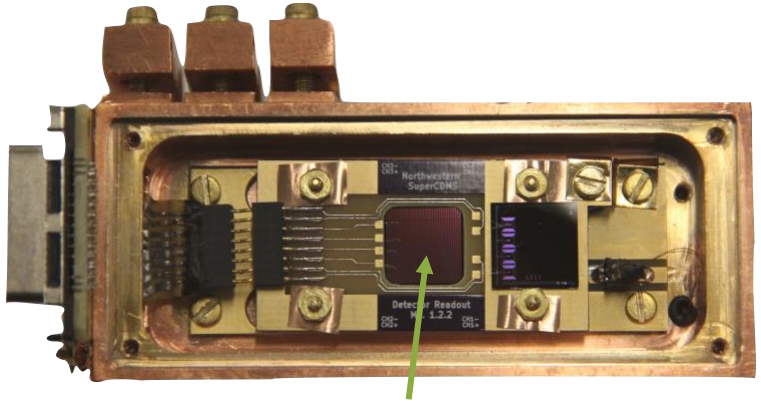
- Phonon channels only
- Phonon amplification of ionization signal
- Low threshold



SNOLAB HV detector (Si(Ge) crystal, 0.61(1.39) kg, 10 cm diameter x 3.33 cm thickness)

R&D HVeV

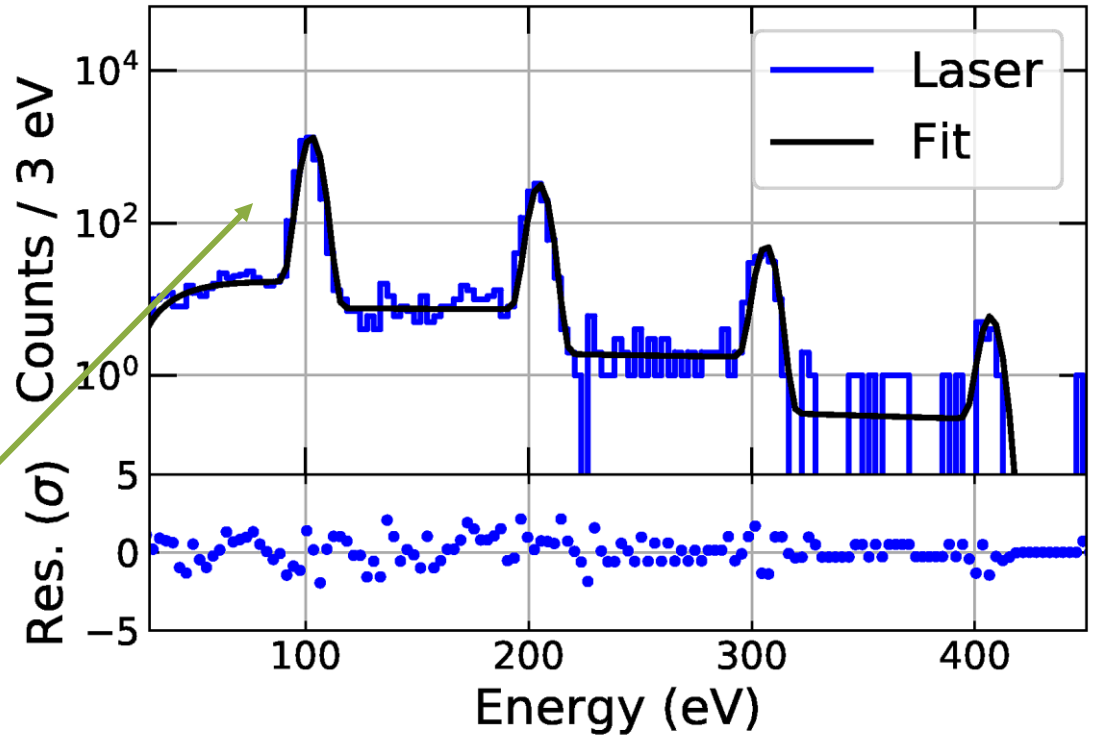
- Phonon channels only
- Phonon amplification of ionization signal
- **Ultra-low threshold (band-gap)**
- **Single electron-hole pair resolution**



HVeV detector (Si crystal, 0.93 g, 1 x 1 x 0.4 cm^3)

Quantized peaks with HVeV detectors

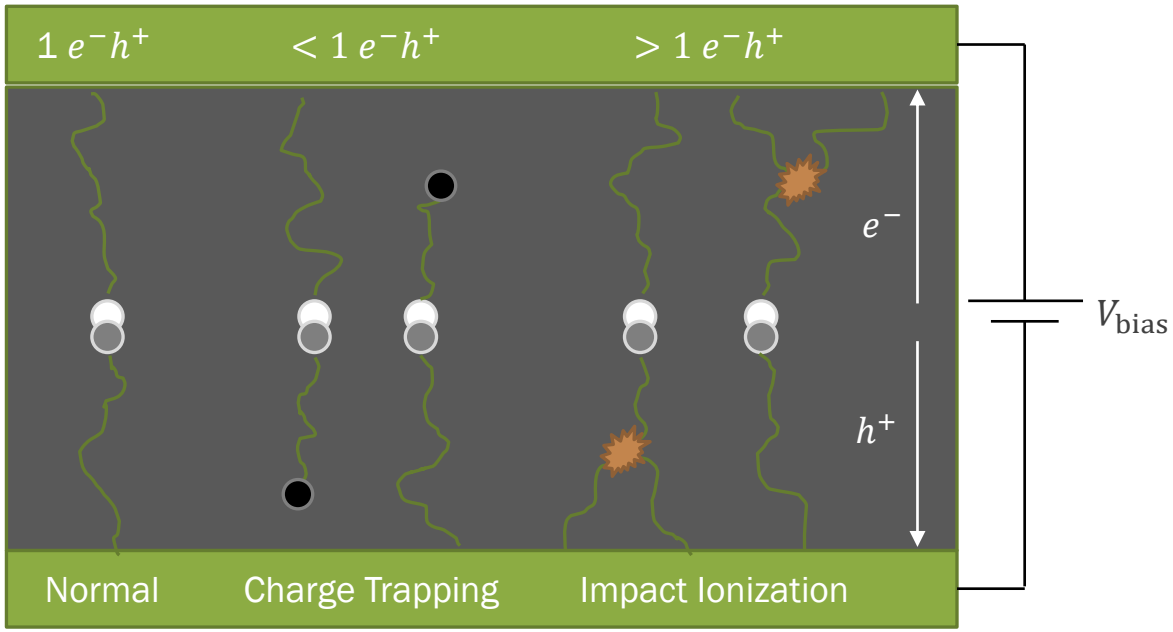
Test data from 1.95 eV laser pulses (λ~1 photon per pulse) generates quantized $e^{-}h^{+}$-pair peaks

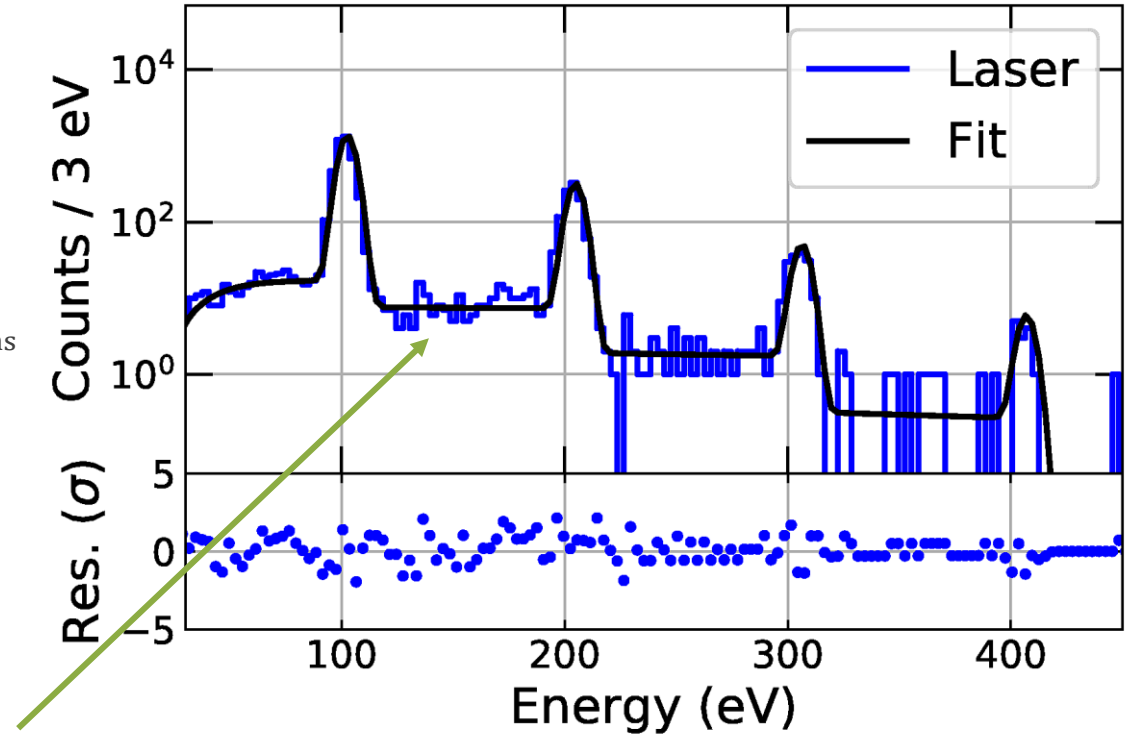


With a bias voltage of 100 V, the single $e^{-}h^{+}$-pair peak is measured at 100 eV

Charge propagation effects

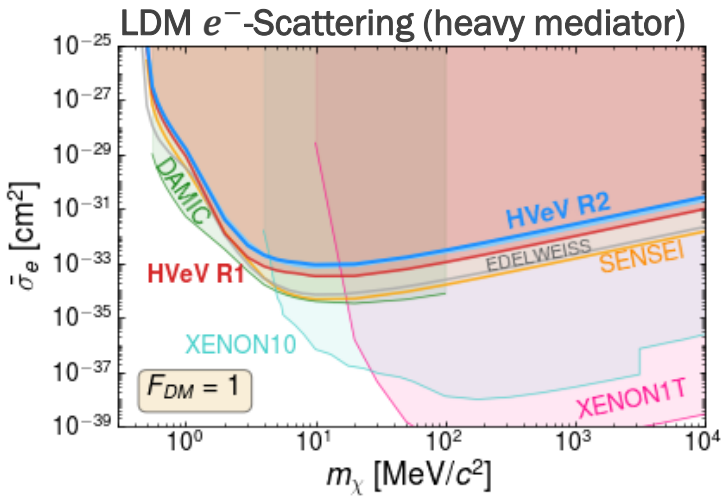
With the extremely high resolution of HVeV detectors, we can look at charge propagation effects in the detector (charge trapping and impact ionization)

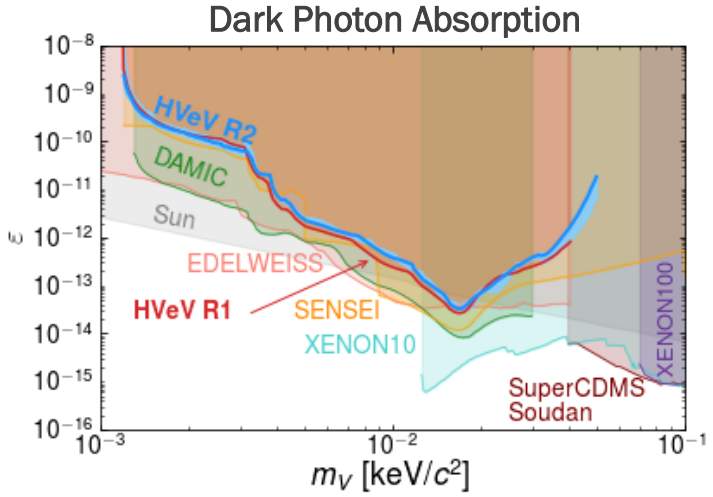


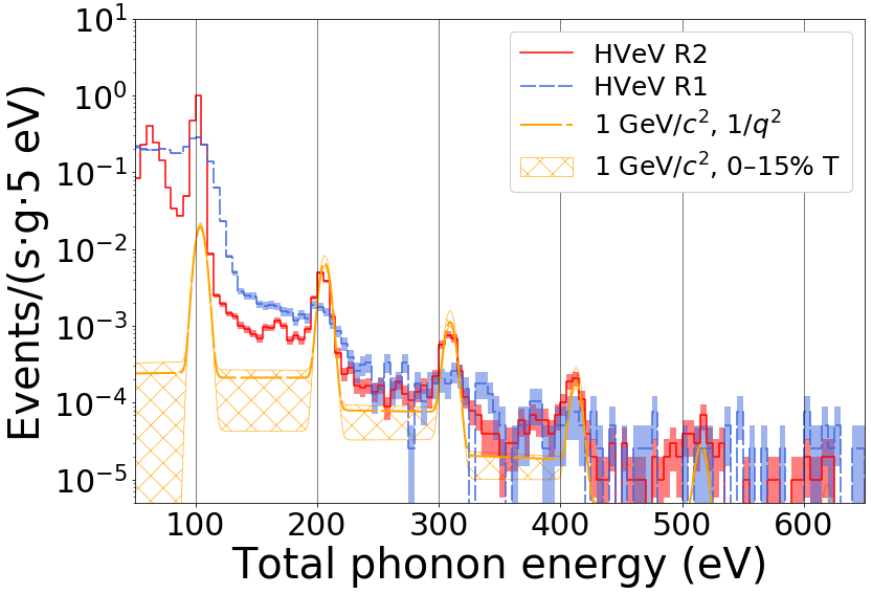


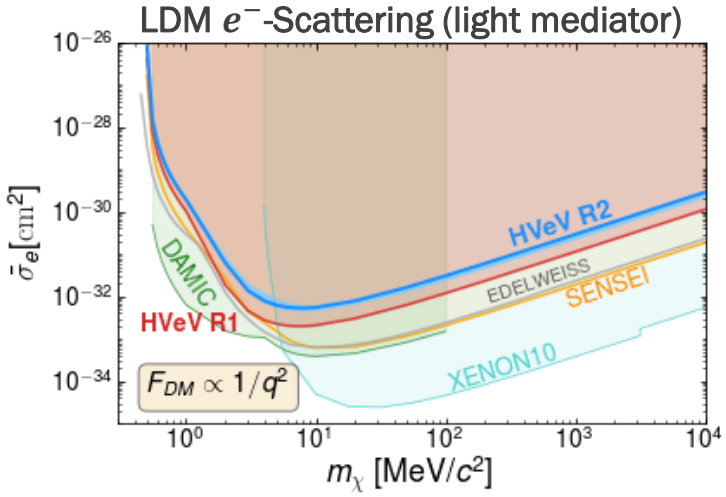
Charge trapping and impact ionization cause events to appear between the e^-h^+ pair peaks

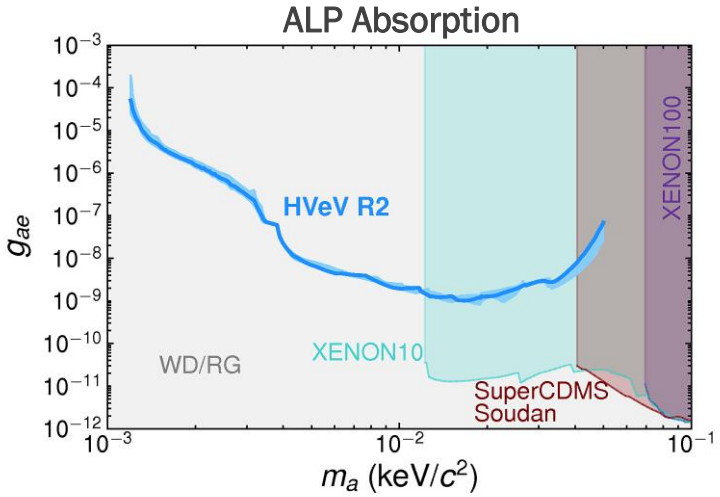
HVeV dark matter results (LDM, ALPs, dark photons)











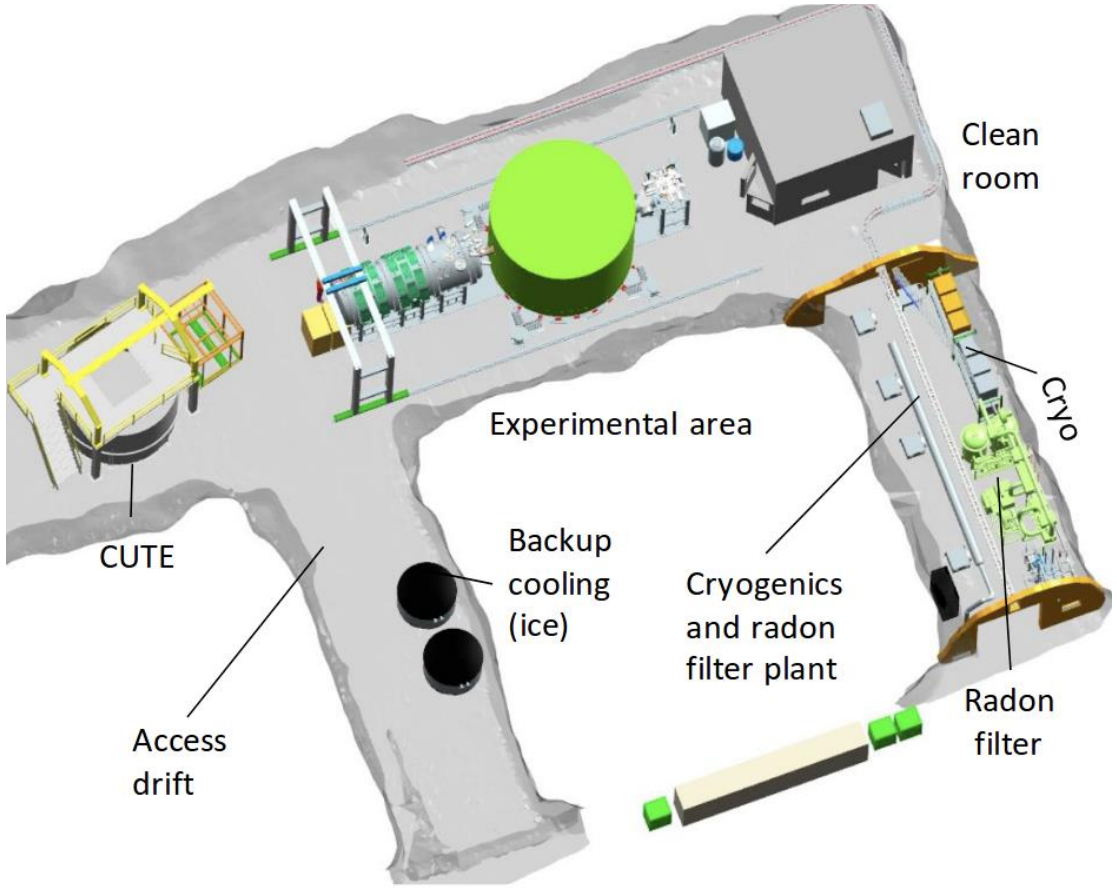
- Ongoing work being done to understand the origin of these events!
- Greater sensitivity can be achieved by utilizing the between-peak regions in limit setting!

PRL 121, 051301 (2018), arXiv:2005.14067 (2020) [hep-ex]

Extra Slides

Status of SuperCDMS and CUTE

- Installation of SuperCDMS ongoing
- R&D program ongoing, first ionization yield analysis ongoing
- Commissioning of CUTE and first data taken with prototype detector in 2019
- Early science with CUTE in 2020
- Commissioning of SuperCDMS in late 2021
- Initial payload run starting in 2022



SuperCDMS detector projections

	iZIP		HV	
	Ge	Si	Ge	Si
Number of detectors	10	2	8	4
Total exposure (kg·yr)	56	4.8	44	9.6
Phonon resolution (eV)	50	25	10	5
Ionization resolution (eV)	100	110	–	–
Voltage Bias (V)	6	8	100	100

	$7\sigma_{Ph}$	$e\Delta V$	Analysis threshold (eV)	
Detector	(eV)	(eV)	E_{Ph}	E_{nr}
Si HV	35	100	100	78
Ge HV	70	100	100	40
Si iZIP	175	8	175	166
Ge iZIP	350	6	350	272

PRD 95, 082002 (2017)

Nuclear vs. electron recoil event class

- Nuclear Recoil:
  - Mostly primary phonons
  - NR event class is primary class for SuperCDMS searches (iZIP, HV)
  - Elastic WIMP-nucleon scattering, …
- Electron Recoil:
  - Mostly electron-hole pairs
  - ER event class is particularly interesting for HV/HVeV detectors
  - Light DM–electron scattering, absorption of ALPs, absorption of dark photons, …

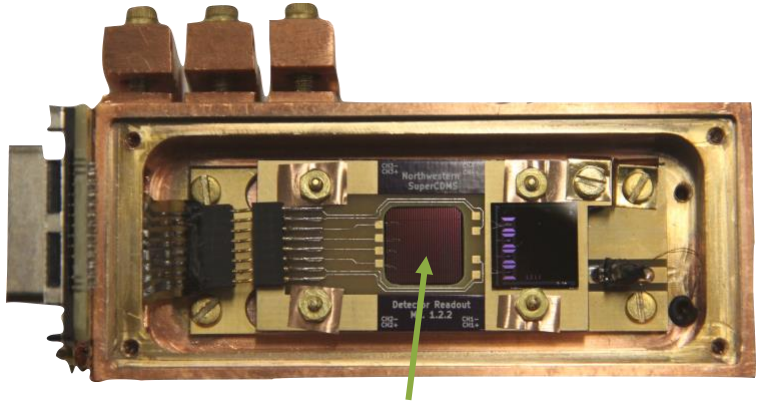
R&D high-voltage detectors (HVeV)

SuperCDMS HV

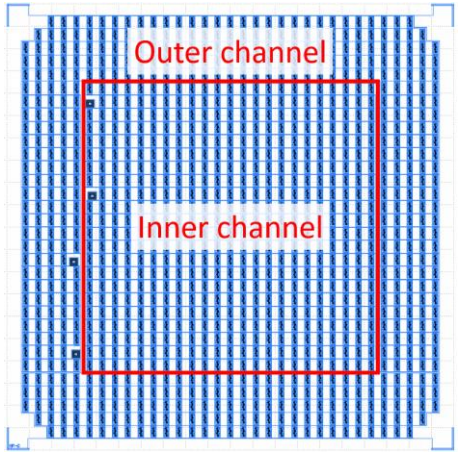
- Phonon channels only
- Phonon amplification of ionization signal
- Low threshold

R&D HVeV

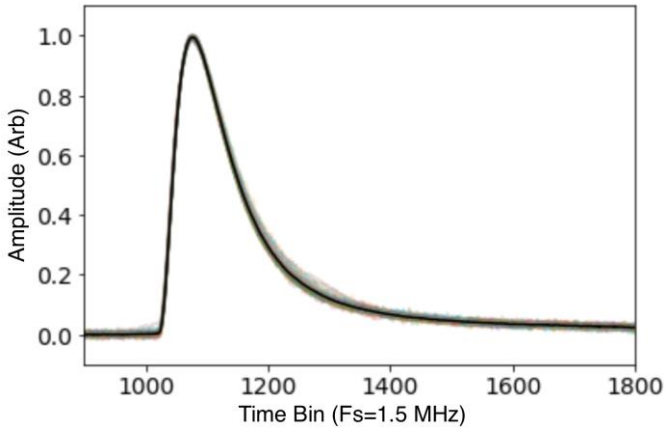
- Phonon channels only
- Phonon amplification of ionization signal
- **Ultra-low threshold (band-gap)**
- **Single electron-hole pair resolution**



HVeV detector (Si crystal, 0.93 g, 1 x 1 x 0.4 cm^3)



Phonon sensor layout

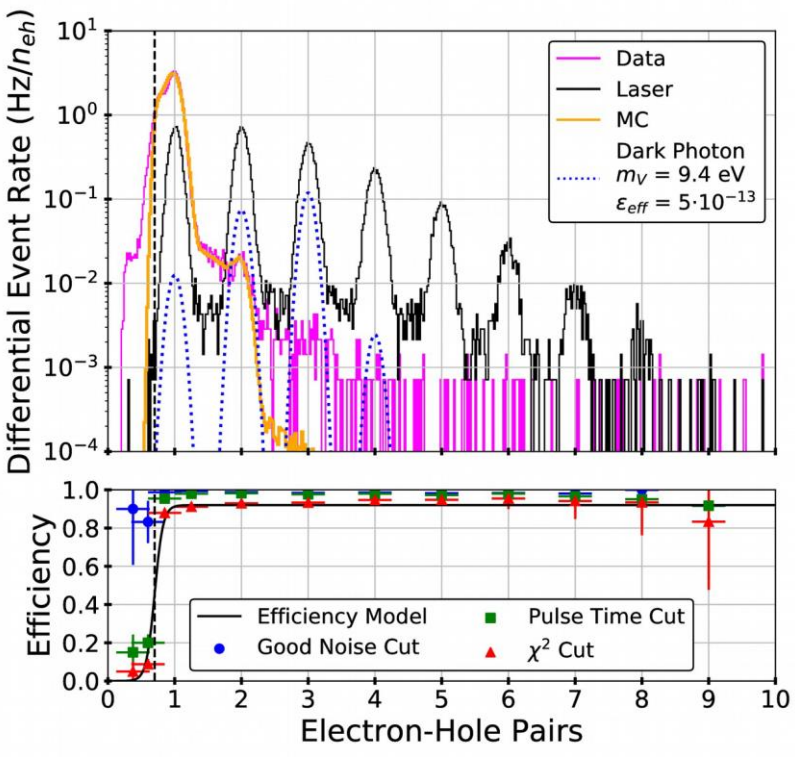


Phonon signal pulse template

HVeV Science Runs

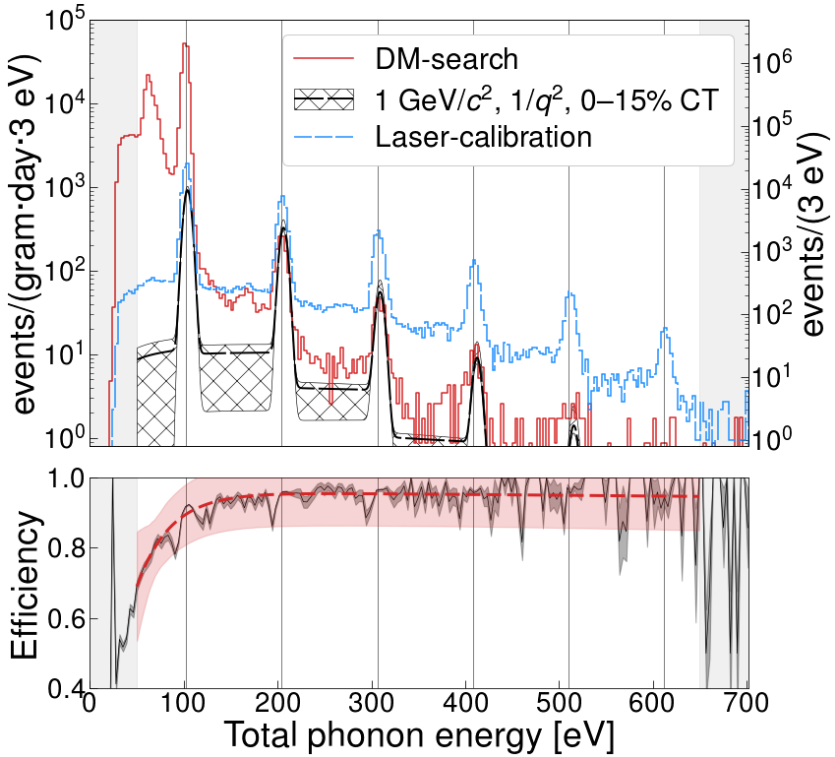
HVeV Run 1

- 0.49 g-day exposure at surface laboratory, 2018
- ~14 eV resolution
- PRL 121, 051301 (2018)

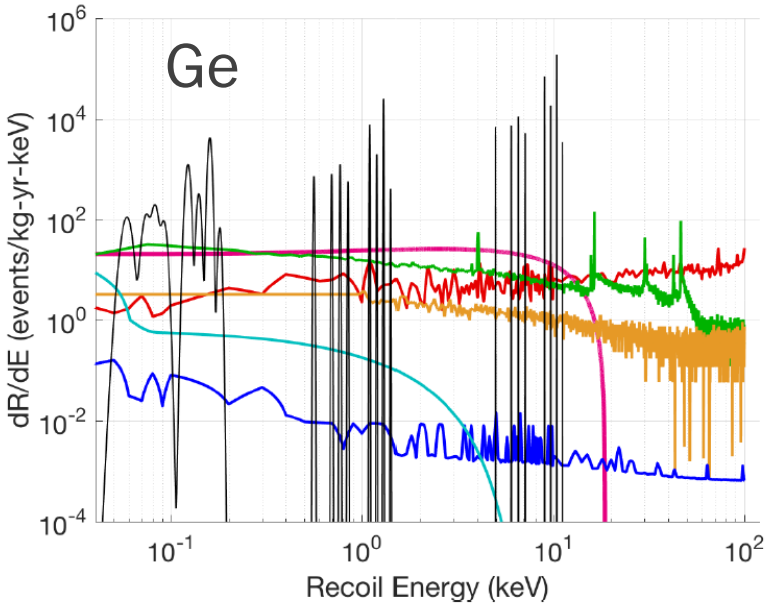


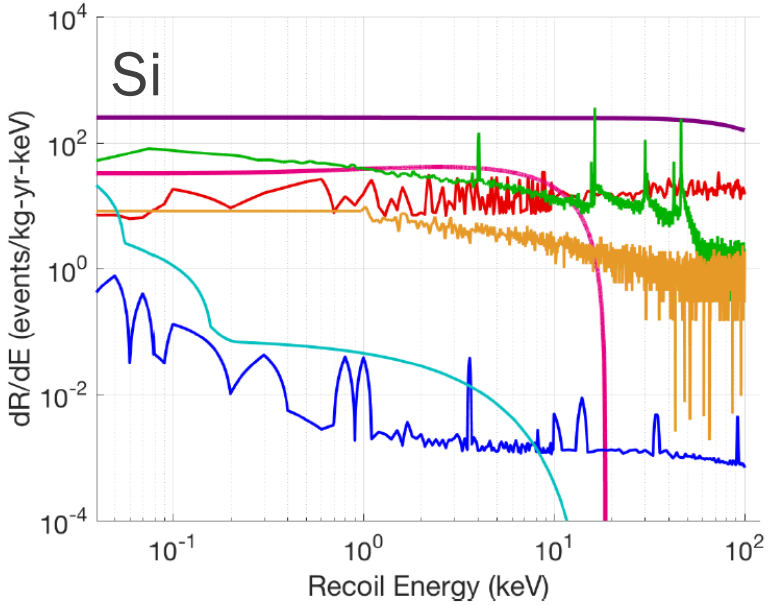
HVeV Run 2

- 1.2 g-day exposure at surface laboratory, 2019
- ~3 eV resolution
- arXiv:2005.14067 (2020) [hep-ex]



SNOLAB Backgrounds





"Singles" Background Rates (counts/kg/keV/year)	Electron Recoil				Nuclear Recoil ($\times 10^{-6}$)	
	Ge HV	Si HV	Ge iZIP	Si iZIP	Ge iZIP	Si iZIP
Coherent Neutrinos					2300.	1600.
Detector-Bulk Contamination	21.	290.	8.5	260.		
Material Activation	1.0	2.5	1.9	15.		
Non-Line-of-Sight Surfaces	0.00	0.03	0.01	0.07	–	–
Bulk Material Contamination	5.4	14.	12.	88.	440.	660.
Cavern Environment	–	–	–	–	510.	530.
Cosmogenic Neutrons					73.	77.
Total	27.	300.	22.	370.	3300.	2900.

PRD 95, 082002 (2017)

WIMP-nucleon scattering

Expected interaction rate		Particle theory	Local properties of DM halo	Nuclear structure

$$\frac{dR}{dE_R} = \frac{\sigma_n}{m_{\mathrm{DM}}} \frac{\rho_{\mathrm{DM}} T(E_R)}{v_{\mathrm{DM}}\sqrt{\pi}} \frac{F^2(E_R)}{\mu_n^2}$$

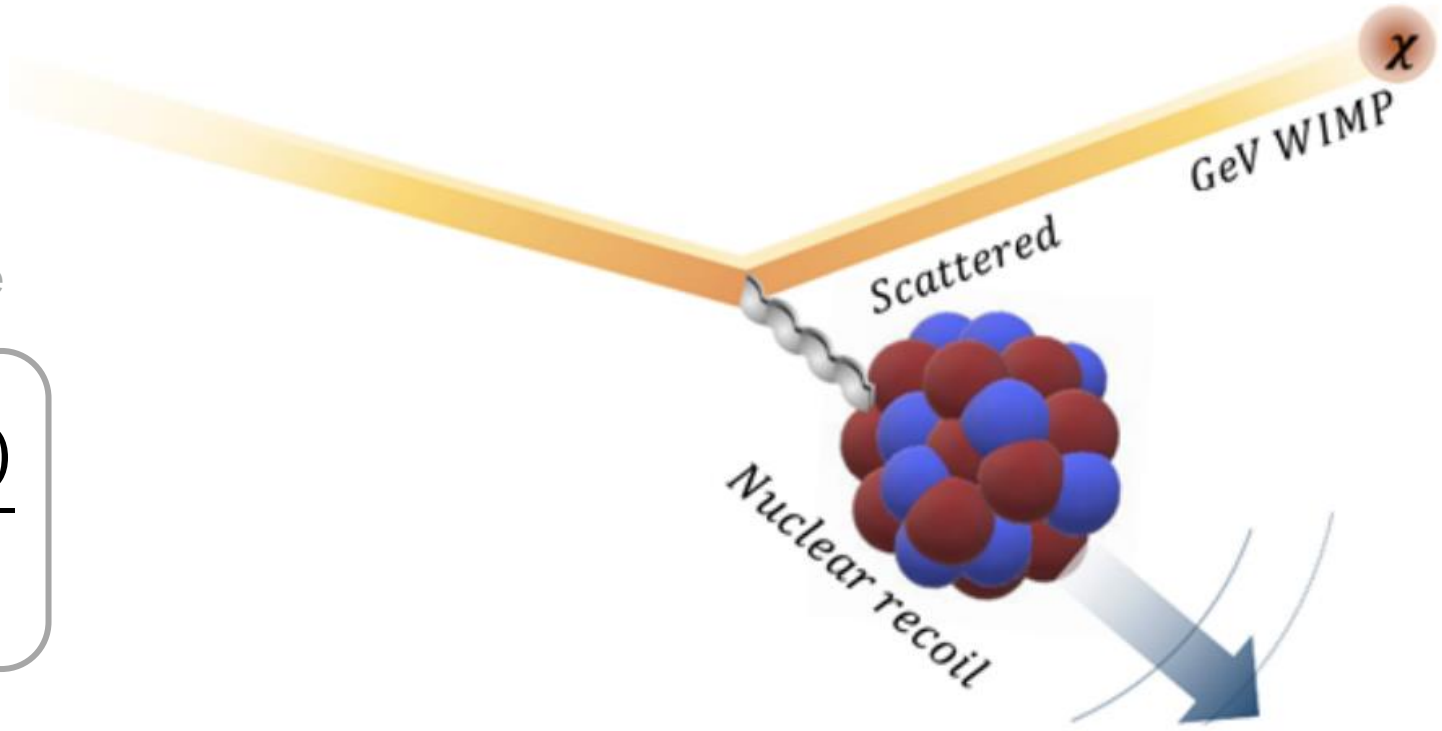
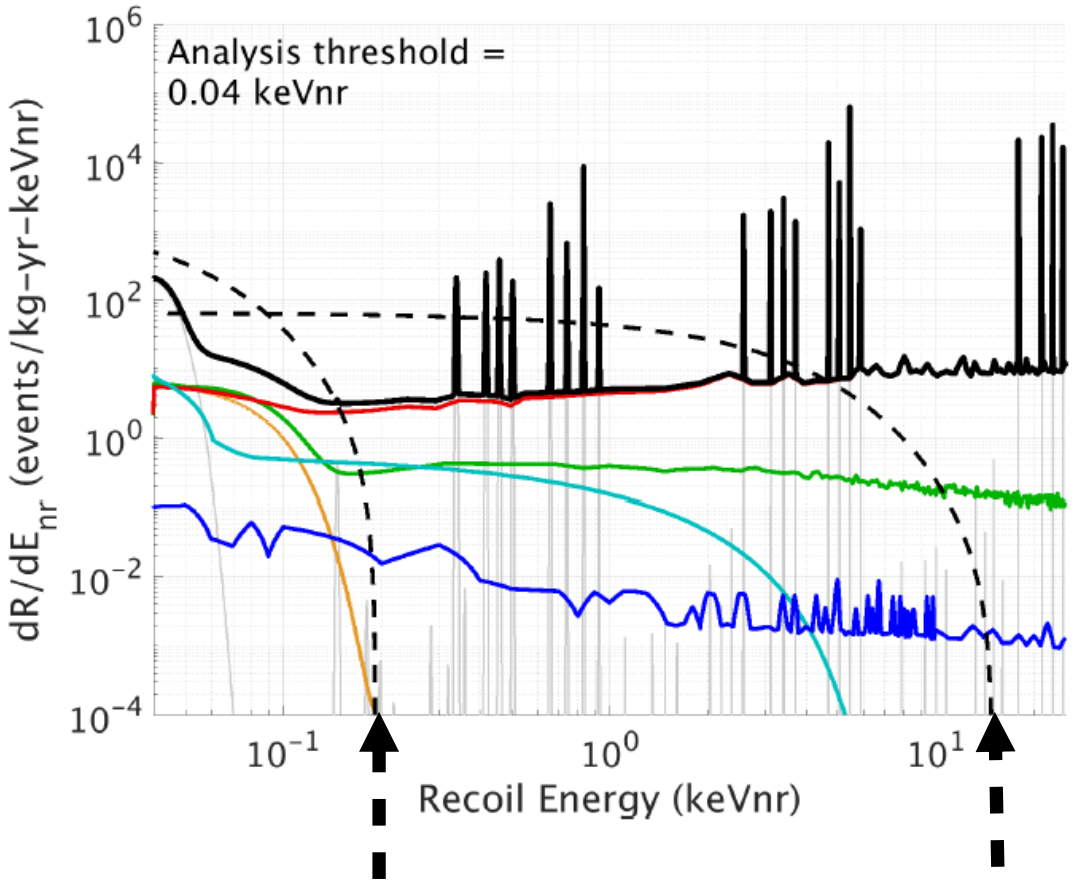


Figure: Stefano Davini

WIMP-nucleon scattering

Prediction in Ge HV detectors after fiducial cuts:



Total
^{3}H and Comptons
Ge activation
Surface betas
Surface ^{206}Pb
Coherent neutrinos
Neutrons

1 GeV/c^2 WIMP

10 GeV/c^2 WIMP with $\sigma = 10^{-42}$ cm^2

Backgrounds from PRD 95, 082002 (2017)

LDM-electron scattering

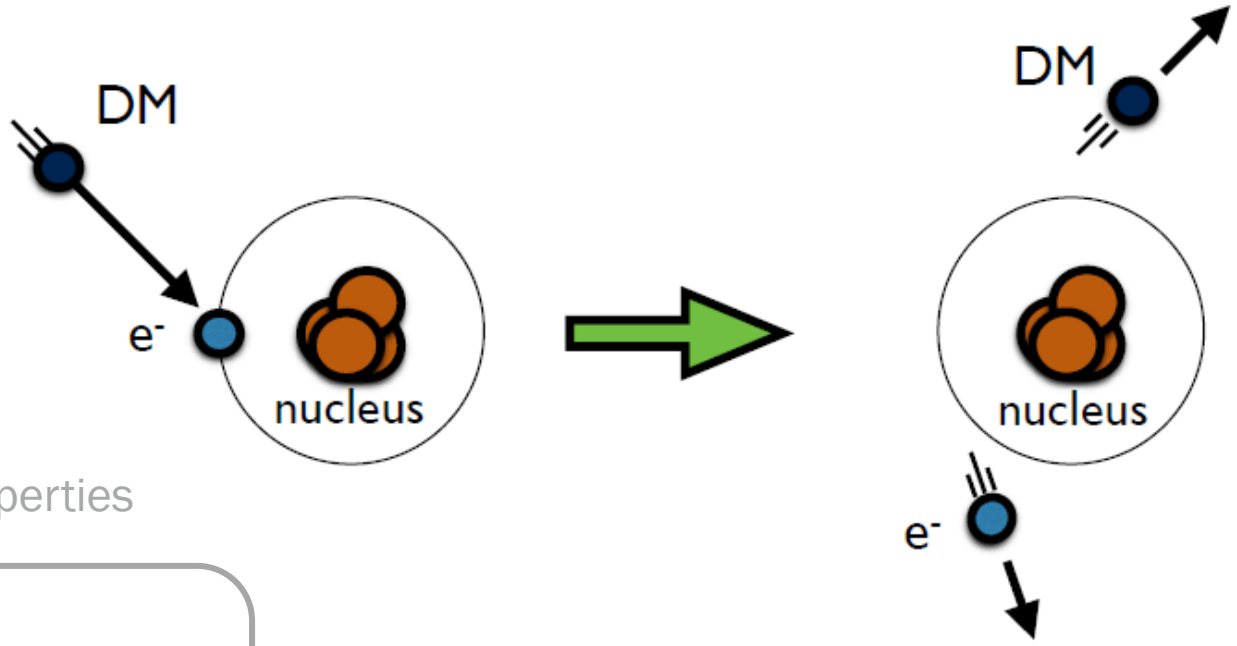


Figure: Rouven Essig

Expected interaction rate

Particle theory

Local properties of DM halo etc

Crystal properties

$$\frac{dR}{d\ln E_R} = \frac{\overline{\sigma}_e}{m_{\mathrm{DM}}} \rho_{\mathrm{DM}} \alpha \frac{m_e^2}{\mu_{\mathrm{DM}}^2} V_{\mathrm{det}} \frac{\rho_{\mathrm{Si}}}{2m_{\mathrm{Si}}} I_{\mathrm{crystal}}(E_e; F_{\mathrm{DM}})$$

Beyond the WIMP

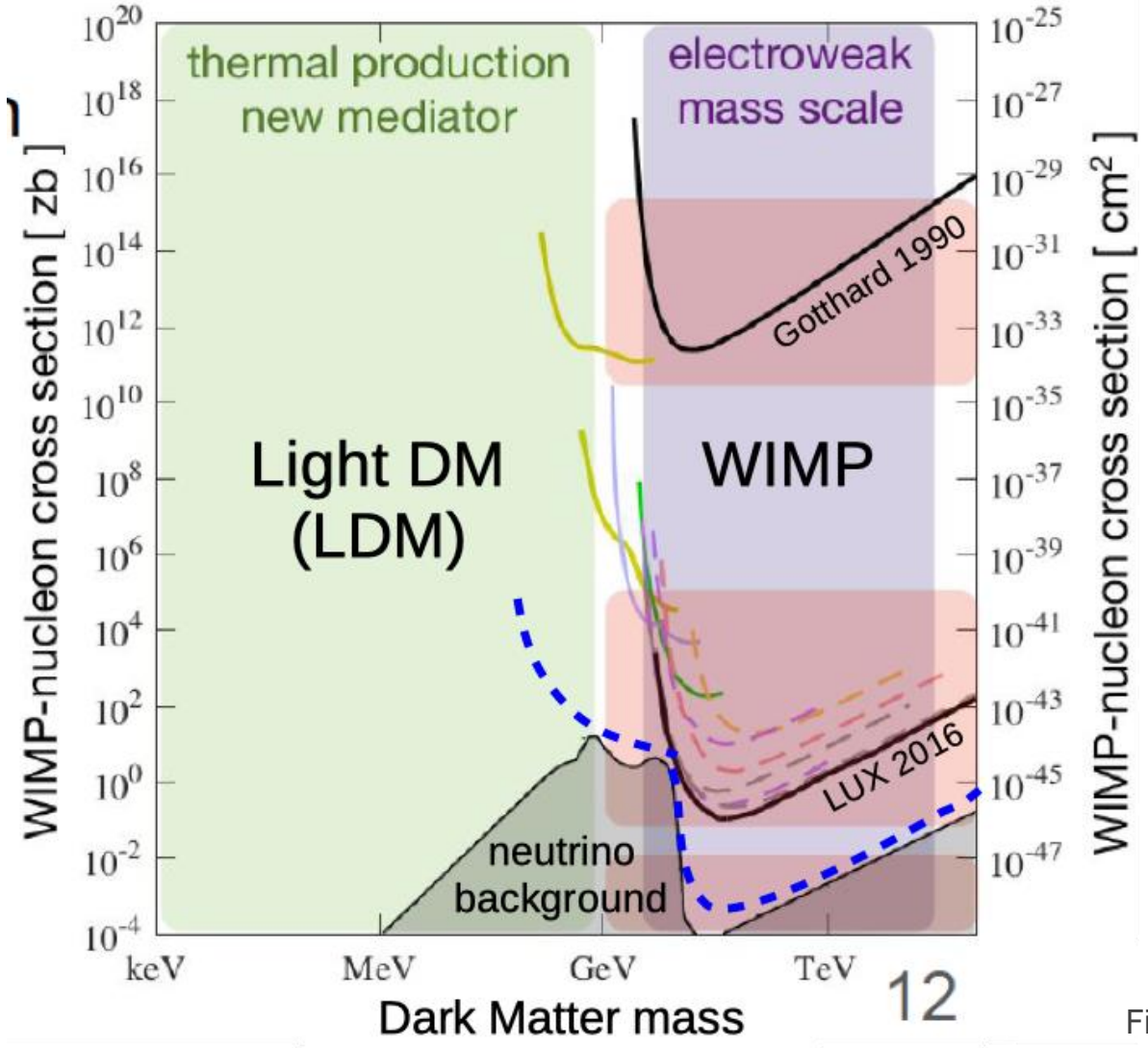


Figure: Vetri Velan