Stefan Zatschler

University of Toronto, LPSC Grenoble

Shedding light on Dark Matter with SuperCDMS at SNOLAB

Postdoc seminar // LPSC, January 25th 2024

Personal introduction

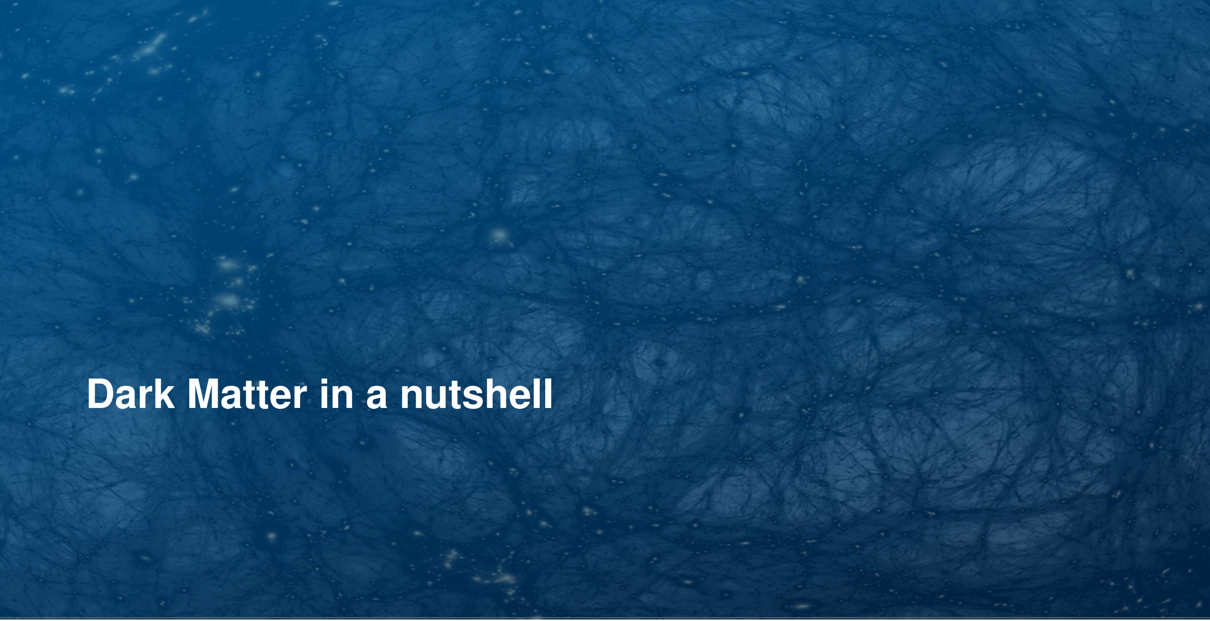
- PhD in Neutrino group at IKTP, TU Dresden, Germany
  "Pulse-shape studies with coplanar grid CdZnTe detectors and searches for rare nuclear decays with the COBRA experiment"

Postdoctoral research

- **SuperCDMS** (University of Toronto, Canada) → **today!**
  - Searching for low-mass Dark Matter particles with cryogenic Si and Ge detectors at SNOLAB
- **Ricochet** (LPSC, Neutrino group)
  - High-precision measurement of CEνNS reactor ν-spectrum
  - Located at ILL research reactor in Grenoble

Outline

- Dark Matter in a nutshell
- SuperCDMS at SNOLAB
- Summary & Takeaways
- Bonus: Ricochet at ILL

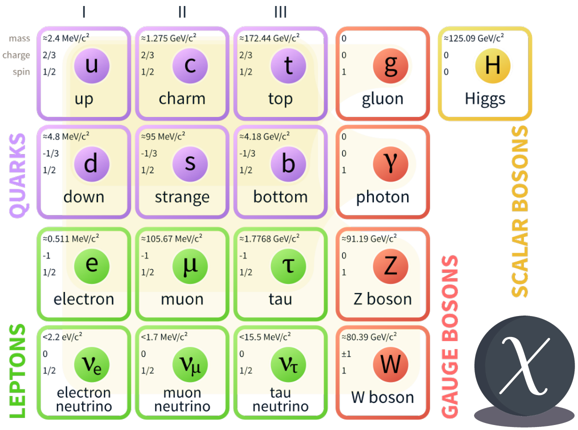


Dark Matter in a nutshell

What do we know about Dark Matter?

The true nature of Dark Matter (DM) remains a mystery to the present day!

- **DM is (likely) not ordinary matter**
  - Atoms, known particles, black holes[a], etc.
- **DM is (almost) invisible** → "dark"
  - Does not interact via electromagnetism
  - New elusive particle(s)? Dark sector?
- **Best guess: ΛCDM model of cosmology**
  - Non-baryonic = no "known" particle
  - Cold = non-relativistic velocity distribution
  - Collisionless = interaction mainly via gravity (and possible weak force)
- **Alternatives to ΛCDM?**
  - Modified Newtonian Dynamics (MOND)



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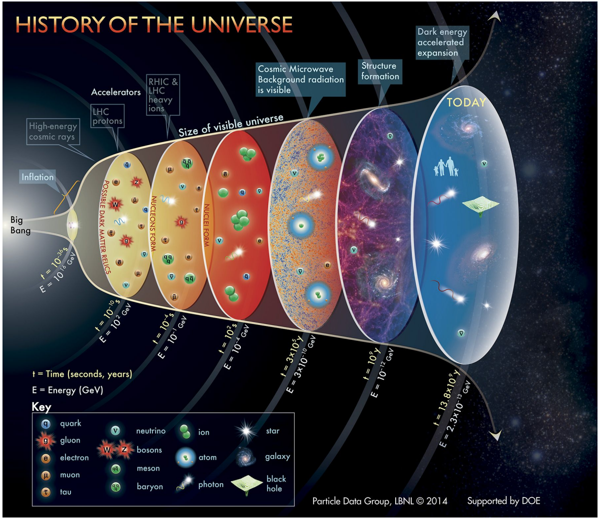
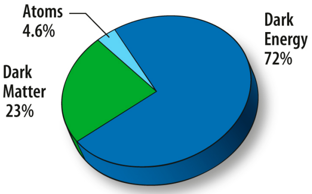
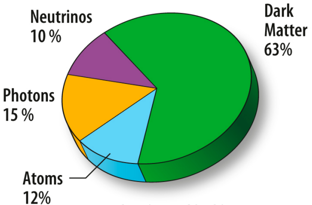
[a] except for (hypothetical) primordial black holes

ΛCDM cosmology in a nutshell





TODAY

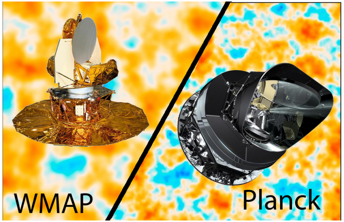


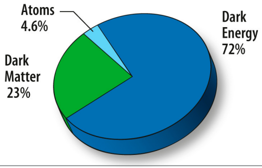
13.7 BILLION YEARS AGO
(Universe 380,000 years old)

Cosmological evidence for Dark Matter

Astrophysical observations provide strong evidence for Dark Matter (DM).

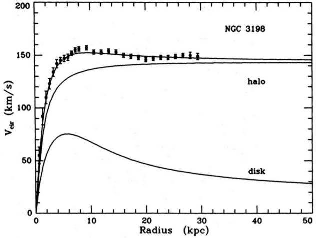
CMB surveys





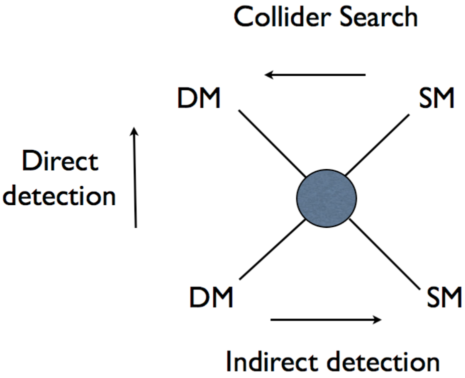
Large-scale structures

Galaxy rotation curves



And many more... But no direct detection (yet)!

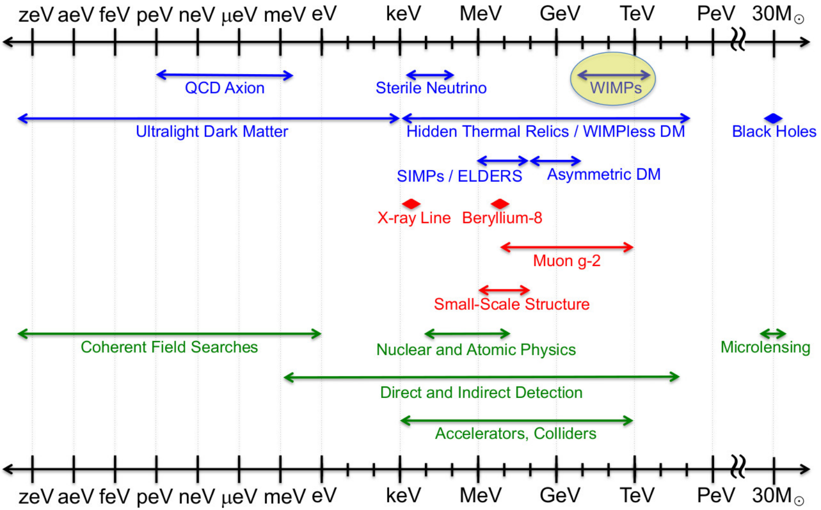
How to search for Dark Matter?



Three ways to look for DM

- **Collider search**
  - DM production in SM interactions
  - Signal: "missing" momentum (p_T, E_T)
- **Indirect detection**
  - DM annihilation into SM particles
  - Signal: Excess in cosmic rays (e^+, p, γ-rays)
- **Direct detection** $\rightarrow$ today's topic!
  - DM scattering off of target (atoms)
  - Signal: recoiling nucleus / e^-
  - Challenge: $\mathcal{O}$(eV–keV) of energy deposit

DM candidates, anomalies & detection methods



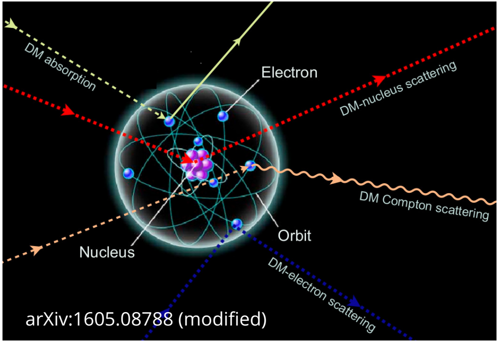
US Cosmic Visions: New Ideas in Dark Matter 2017 – Community Report

Dark Matter direct detection

Dark Matter direct detection

Principal idea: DM is made of **particles** which **interact** with atoms in different ways.

- **Any observable interaction counts!**
  - NR = nuclear recoil
  - ER = electronic recoil

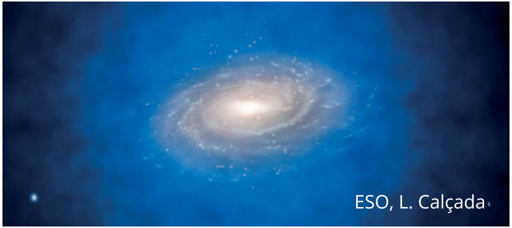


arXiv:1605.08788 (modified)

Estimate of DM flux on Earth

→ **110 000 DM particles per cm^2 per s**

- DM Density: 0.3 GeV/cm^3
- DM Mass: 60 GeV
- Relative velocity: 220 km/s



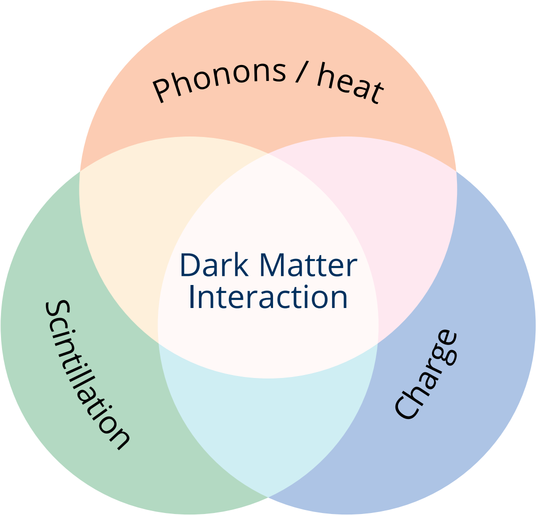
ESO, L. Calçada

Dark Matter detection techniques

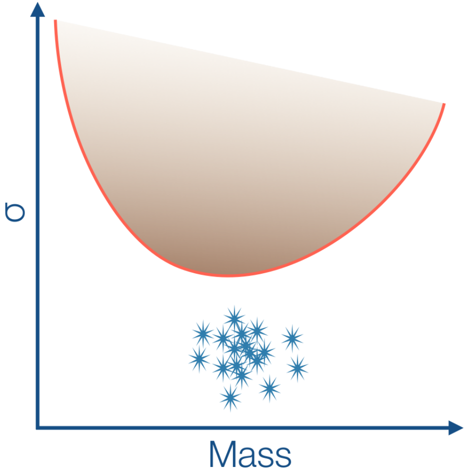
DM interactions fall into two categories:

- **Nuclear recoils (NR)**
  - Interaction with atomic nucleus
  - Traditional WIMP channel
  - Neutron and neutrino backgrounds
- **Electron recoils (ER)**
  - Interaction with atomic electron
  - Light DM interactions and absorption
  - Most background sources (γ, e^-)
- **Experimental requirements**
  - Ultra sensitive detectors
  - Low backgrounds
  - Long exposure

SuperCDMS uses Phonon-only ("HV")
as well as Phonon + Charge devices ("iZIP")



Evolution of DM exclusion curves



Credits: T. Saab (UF)

- **Typical DM exclusion curve**
  - DM-SM cross-section vs. DM mass
  - Parameter space above curve is excluded at a certain confidence level
- For more than two decades, DM exclusion curves were **quasi time-invariant**
  - Limits get lower but so do **theory predictions** (mainly driven by MSSM models)
- **Neutrino floor** as definite target
  - Time for more nuanced treatment of ν-BG!
- Beyond SUSY theories expand parameter space to **lower DM masses**
  - To be covered by next-generation experiments with ultra-low thresholds!

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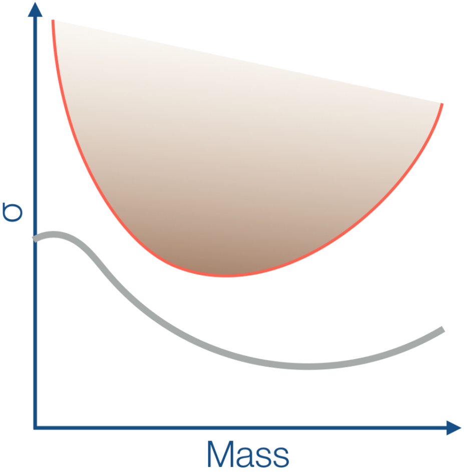

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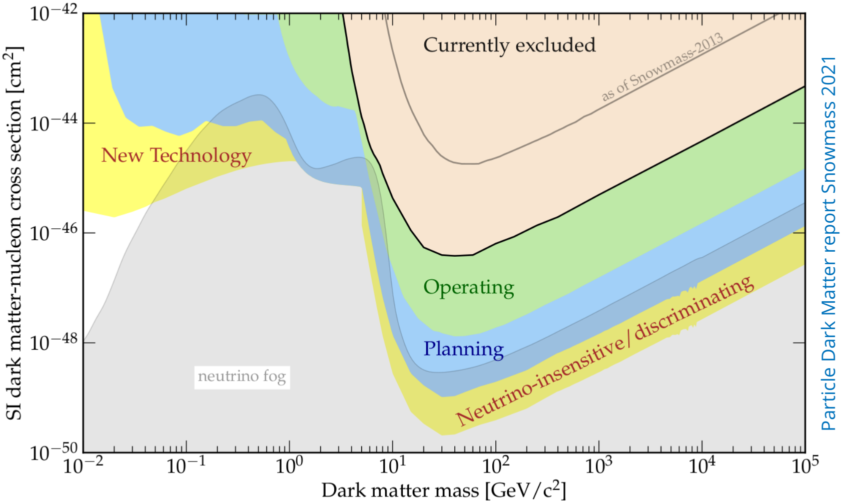
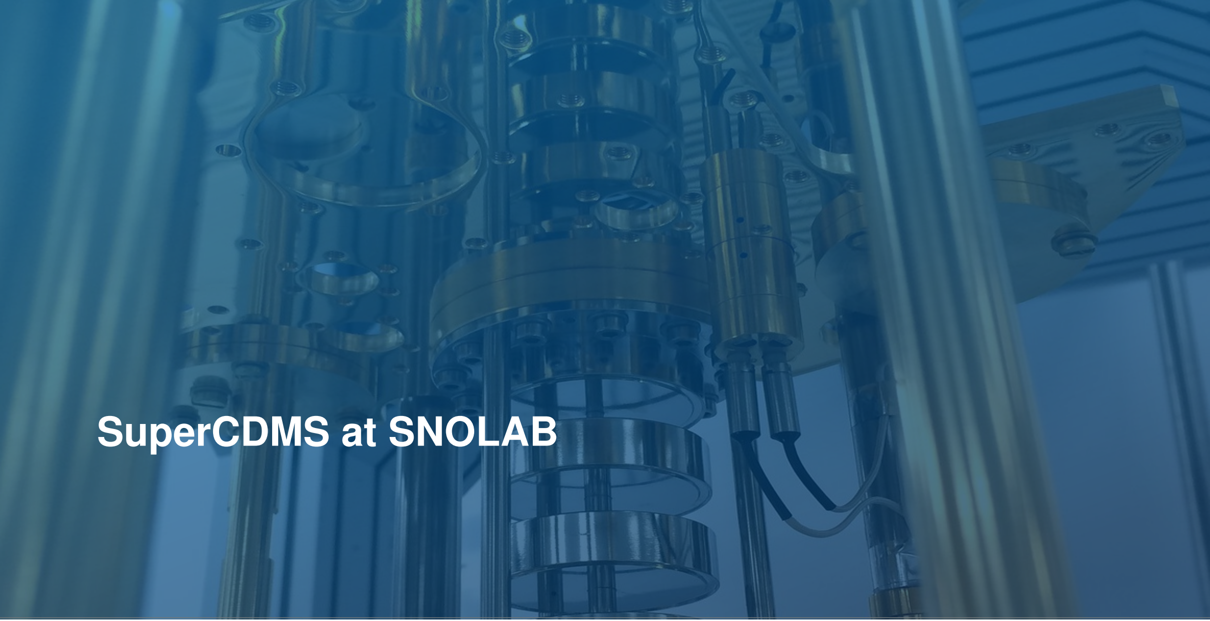
The "Big Picture"



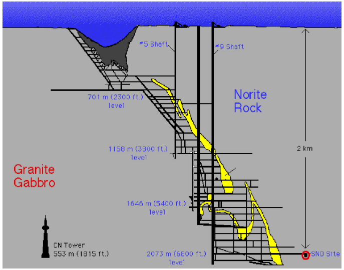


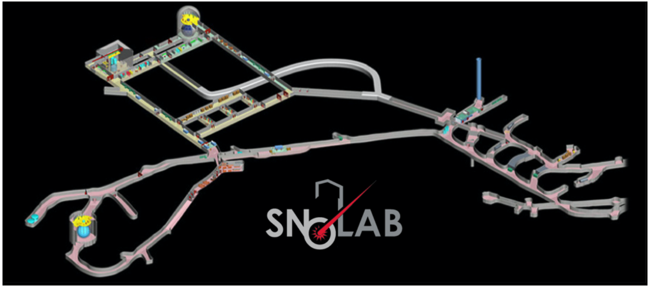
SuperCDMS at SNOLAB

SNOLAB infrastructure

Let's do a virtual visit at SNOLAB!

- Rock overburden of 2 km (6000 m.w.e.)
  - Cosmic muon flux reduced by 50 millions
- Large lab space ($\sim$ 5000 m^2)
  - Cleanroom (class 2000 or better)
  - Surface facilities with support staff (>100)

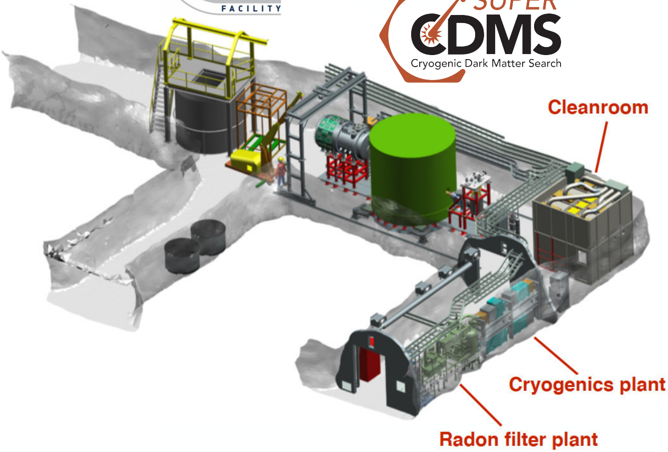




SuperCDMS at SNOLAB

- **Dilution refrigerator** with a closed-loop cryogenics system
- **Initial payload:** 24 detectors
  - iZIP towers: 10 Ge + 2 Si crystals
  - HV towers: 8 Ge + 4 Si crystals
  - Complementary science reach!
- Collaboration with **CUTE**
  - **C**ryogenic **U**nderground **TE**st facility
  - Full-scale tower 3 testing under way right now!

SuperCDMS infrastructure is under construction!



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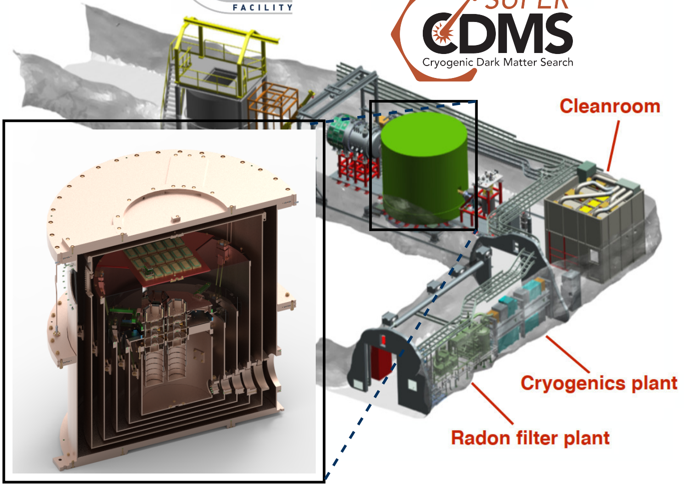

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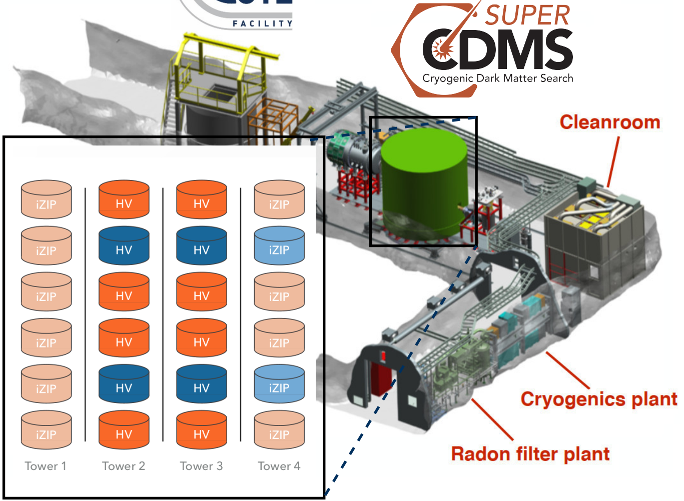
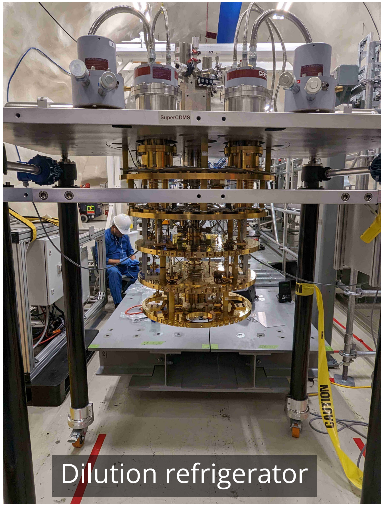
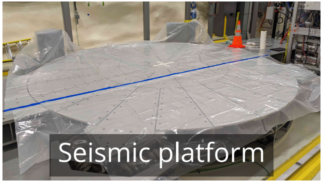
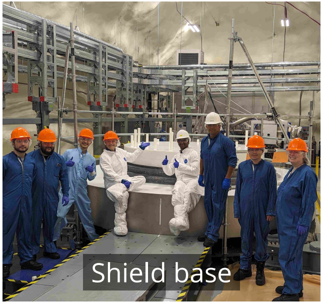


Status of Construction

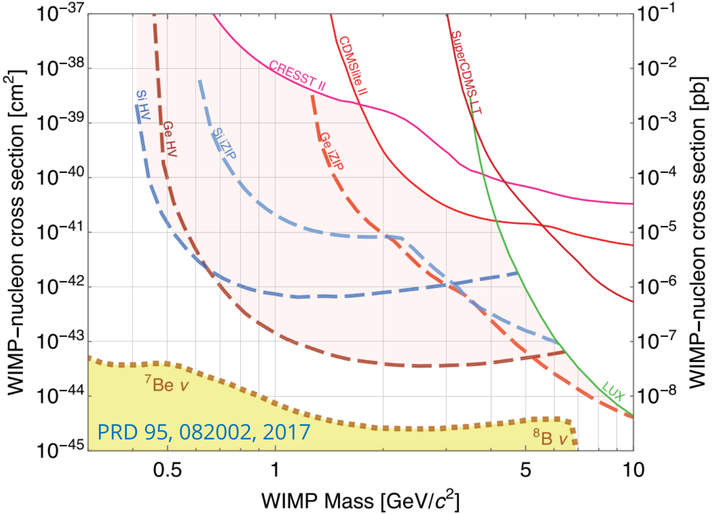

Dilution refrigerator


Detector tower


Seismic platform


Shield base

SuperCDMS science reach



PRD 95, 082002, 2017

- Aiming for **world-leading sensitivity** to low-mass WIMPs
- **Unique approach** with complementary detector designs
  - **Ge/Si iZIP & HV detectors**
  - **iZIP:** NR/ER discrimination → background studies
  - **HV:** low-threshold → low-mass sensitivity

Challenges

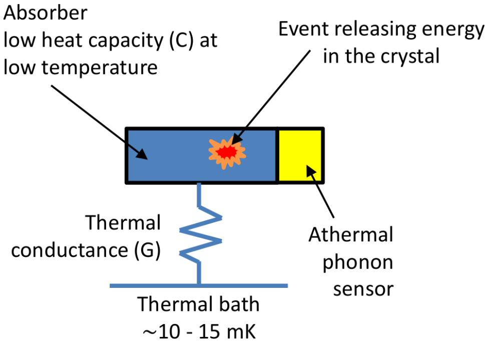
- Understanding detector response down to semiconductor bandgap
  - Dominating backgrounds
  - Low-energy calibration
  - Detector response modeling

SuperCDMS detector technology

How to measure Dark Matter interactions?

Setting: Low-energy deposit of DM particle recoiling on detector lattice

- Cryogenic calorimeters at temperatures $\sim$ 10 – 15 mK
- Athermal phonon sensors – Transition Edge Sensors (TES)



Signal formation

- Energy deposit creates e^-/h^+ pairs and prompt phonons in crystal
- Charges drift in external electric field
- Drifting charges emit Luke phonons
  - Signal amplification
  - Sensitivity to single e^-/h^+ pairs
- Phonon collection with TES
  - Pulse reconstruction
  - Measure of energy deposit

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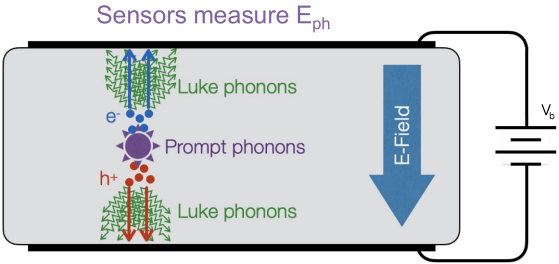

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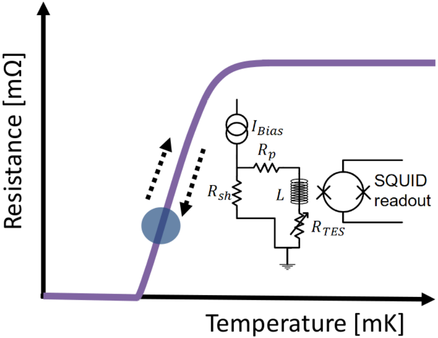

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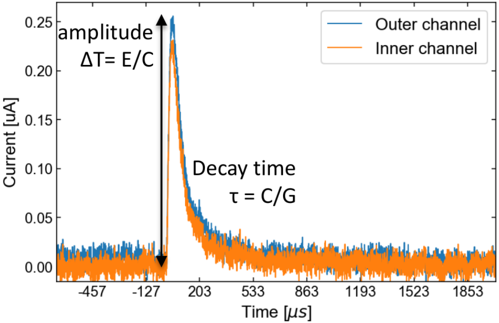

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SuperCDMS detectors

HV detector → low threshold

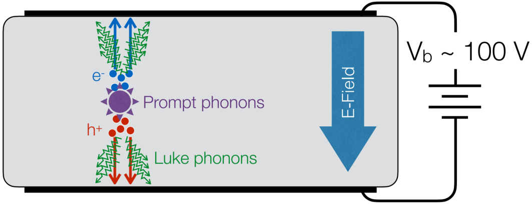
- Drifting charge carriers (e^-/h^+) across a potential (V_b) generates a large number of Luke phonons (NTL effect)
- Trade-off: no NR/ER discrimination

$$\underbrace{E_t}_{\text{total phonon energy}} = \underbrace{E_r}_{\text{primary recoil energy}} + \underbrace{(N_{eh} \cdot e \cdot V_b)}_{\text{Luke phonon energy}}$$

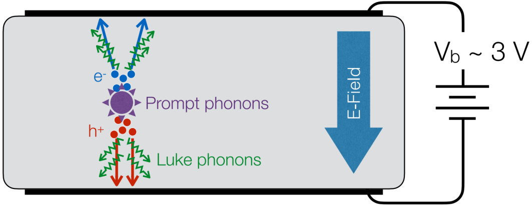
iZIP detector → low background

- **I**nterleaved **Z**-sensitive **I**onization and **P**honon detector
- Prompt phonon and ionization signals allow for NR/ER event discrimination

Sensors measure E_t



Sensors measure E_t and N_{eh}



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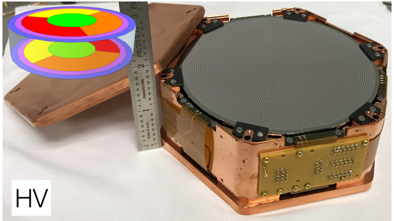

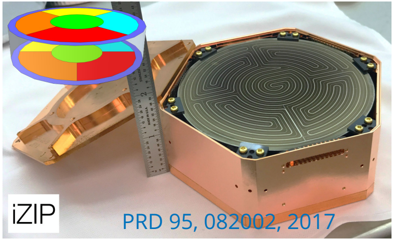

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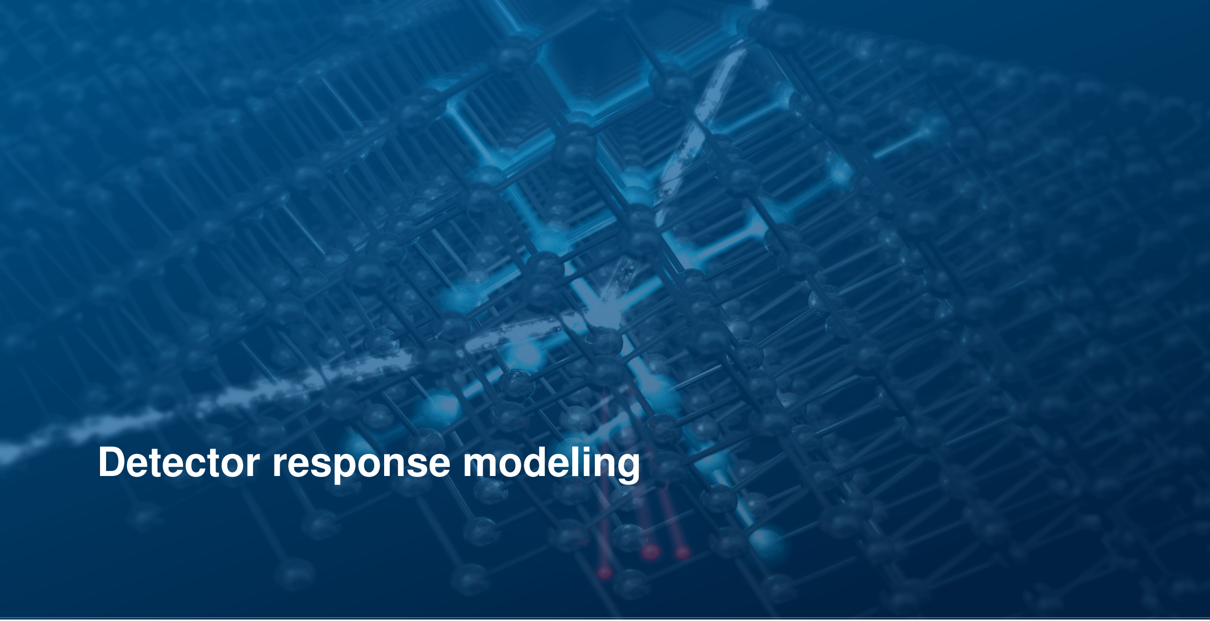
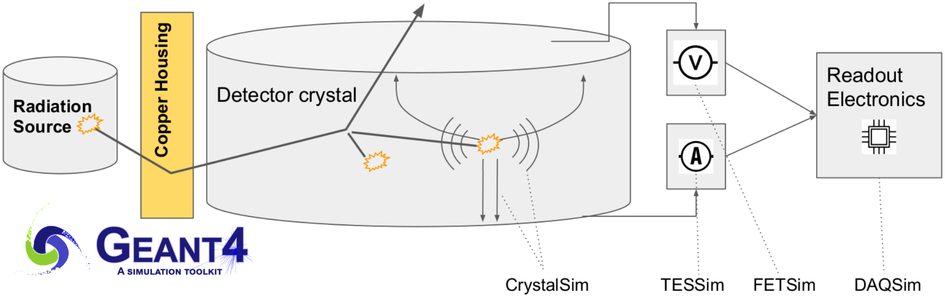


Detector response modeling

SuperCDMS phonon sensor – QET

QET – **Q**uasiparticle trap assisted **E**lectrothermal feedback **T**ransition edge sensor



- **Sophisticated GEANT4-based framework** to model crystal and sensor response
  - **Crystal dynamics:** lattice definition, charge and phonon scattering → **G4CMP!**
  - **Impurity effects:** Charge Trapping, Impact Ionization
  - **TES configuration:** physical layout, circuitry and electro-thermodynamics
  - **Goal:** same reconstruction path for real and simulated data!

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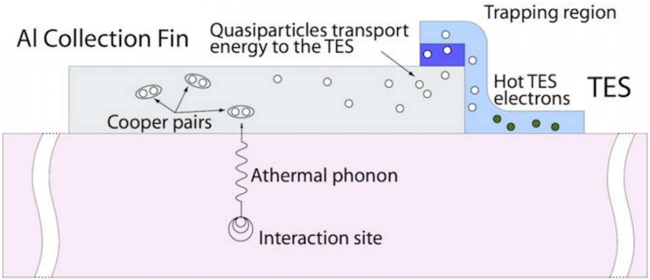
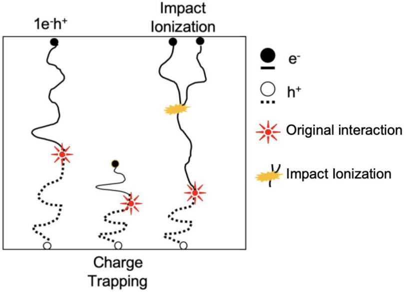


https://figueroa.physics.northwestern.edu



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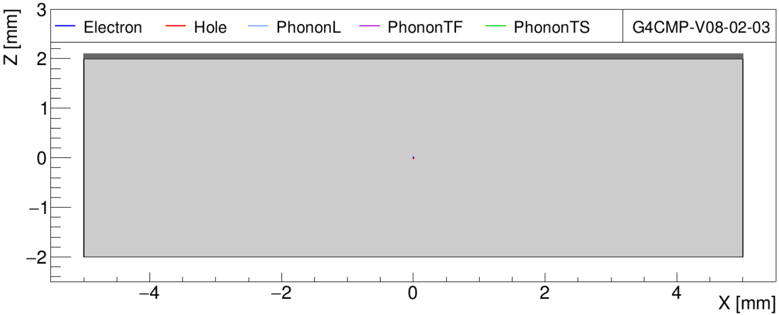
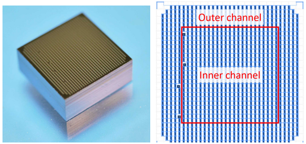
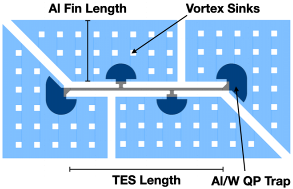
SuperCDMS Si-HVeV prototype modeling



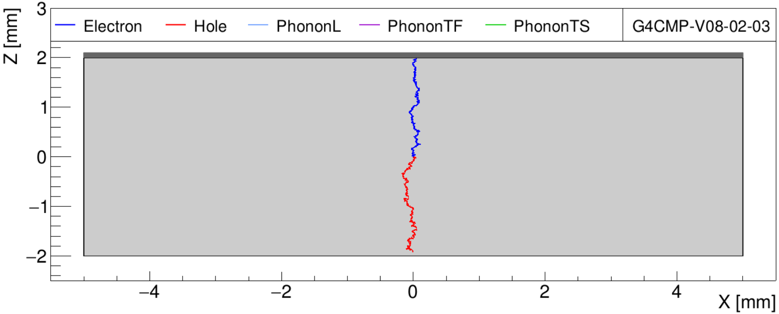


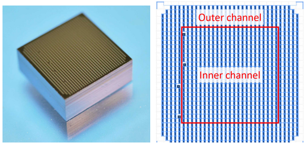
PRD 104, 032010 (2021)



- **Si-HVeV** = prototype HV detector with eV-scale resolution (one-sided QET readout)
- **Tracking of single e^-/h^+ pair** created at center in electric field of $\mathcal{O}(10)$ V/cm
  - About ∼5-10k steps for charge tracks in this configuration (mainly Luke scattering)
  - About ∼50k phonon tracks with $\mathcal{O}(100) - \mathcal{O}(1000)$ steps each (mainly surface reflections)

SuperCDMS Si-HVeV prototype modeling





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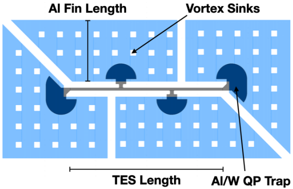

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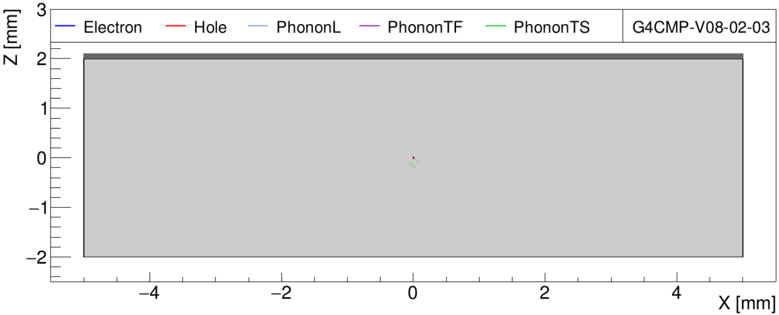
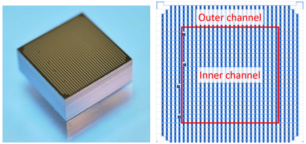
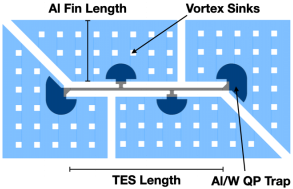




PRD 104, 032010 (2021)



- **Si-HVeV** = prototype HV detector with eV-scale resolution (one-sided QET readout)
- **Tracking of single e^-/h^+ pair** created at center in electric field of $\mathcal{O}(10)$ V/cm
  - About ∼5-10k steps for charge tracks in this configuration (mainly Luke scattering)
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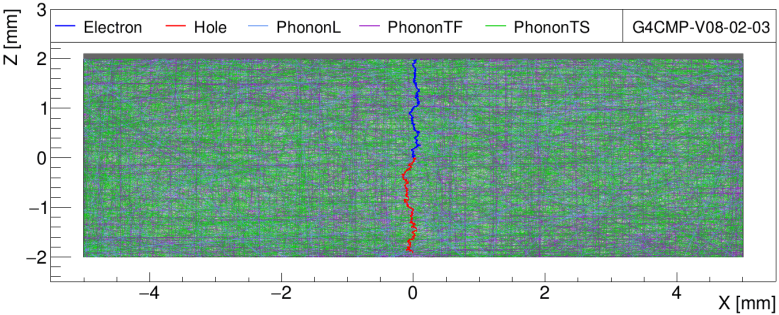
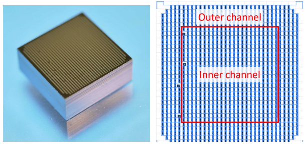
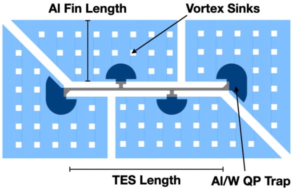




PRD 104, 032010 (2021)



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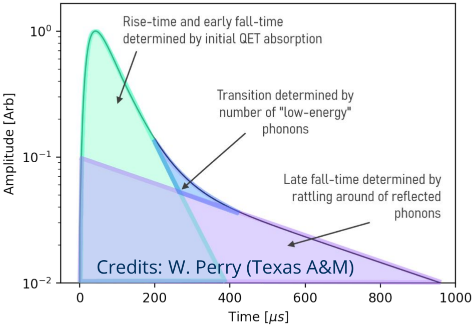
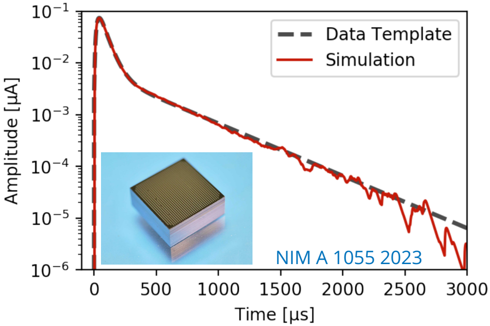
G4DMC parameter tuning for Si-HVeV



Credits: W. Perry (Texas A&M)

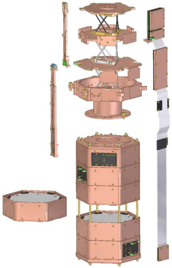


NIM A 1055 2023

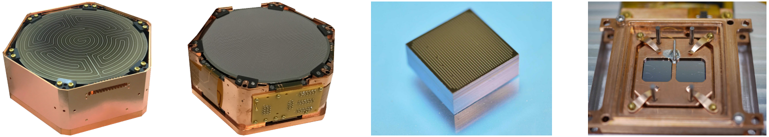
- **Goal:** Match experimental phonon pulse template with G4DMC simulation
- Multi-dimensional parameter tuning of *CrystalSim* + *TESSim*
  - TES characteristics (T_C, T_W, circuitry), impurity densities, etc.
- Ongoing data-taking at cryogenic test facilities (CUTE, NEXUS)
  - It is about time to see first light with SuperCDMS detectors... stay tuned!

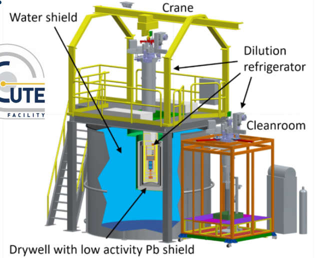
Summary

Summary & Takeaways



- **SuperCDMS is well-suited for sub-GeV DM searches**
  - Complementary detector technology (iZIP, HV)
  - Infrastructure at SNOLAB under construction
- **SuperCDMS full-tower testing underway at CUTE and SLAC**
  - Detector performance, reconstruction, simulation validation
- **Very successful HVeV R&D detector program**
  - Moving underground – HVeV run in CUTE at SNOLAB in 2024!

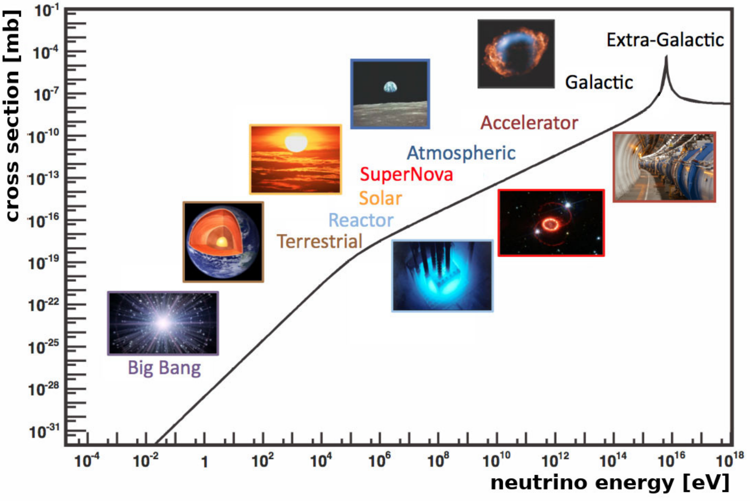




Bonus: Ricochet at ILL

Shedding light on the "neutrino fog"

- **ν-fog** is composed of:
  - Solar neutrinos
  - Geo + reactor neutrinos
  - Diffuse SN neutrinos
  - Atmospheric neutrinos
- **ν-floor** defined as $n_\nu \geq 2$
- Uncertainties in σ_ν
  - Nuclear form factors
  - Neutrino physics
- **Takeaway message:** ν-floor is not the limit!
- New technologies needed to discriminate NR types (neutrons, νs, WIMPs)



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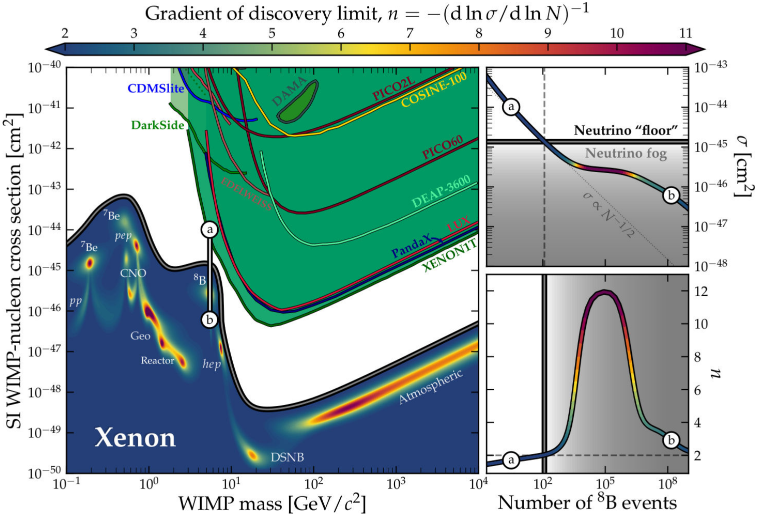
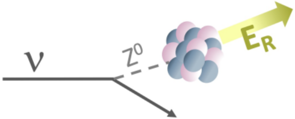


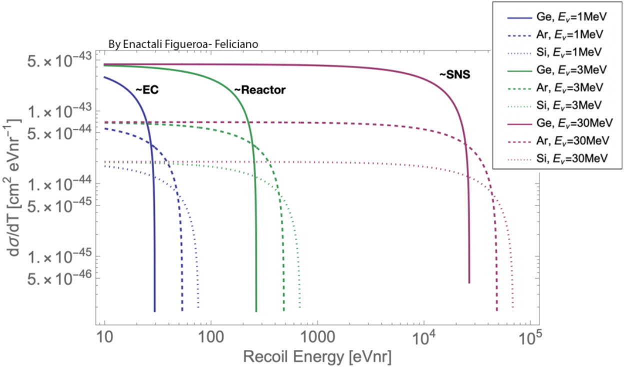
Coherent Elastic ν-Nucleus Scattering – CEνNS

CEνNS in a nutshell

- Well-understood process in SM (weak interaction)
- First observed by COHERENT at SNS (Science, Vol 357, 6356, 2017)

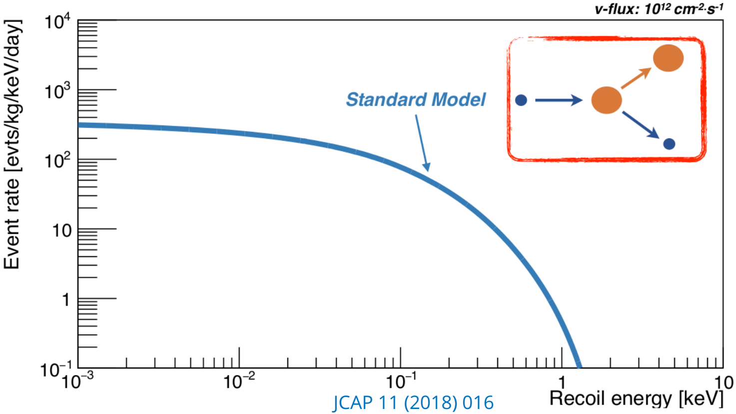


- **"Coherent"** when momentum transfer is small
  $2E_\nu < 1/r_N$ with $r_N \approx \frac{\sqrt[3]{A}}{200\,\text{MeV}}$
- Recoil energy can be calculated exactly like Compton scattering
  $E_r = \frac{E_\nu^2(1-\cos\vartheta)}{M_N+E_\nu(1-\cos\vartheta)}$
- **Trade-off between**
  $\sigma_\nu \sim N^2 E_\nu^2$ and $E_r^{max} \approx \frac{2E_\nu^2}{M_N}$


By Enactali Figueroa- Feliciano

CEνNS at reactors – New Physics potential

- **Lower E_ν at reactor** compared to SNS
  - Almost purely coherent (no form factor required)
- **Higher sensitivity to New Physics**
  - Neutrino magnetic moment
  - BSM light mediators
  - Sterile neutrino oscillations
- **But:** more backgrounds...
  - Muons, γ-rays, neutrons



JCAP 11 (2018) 016

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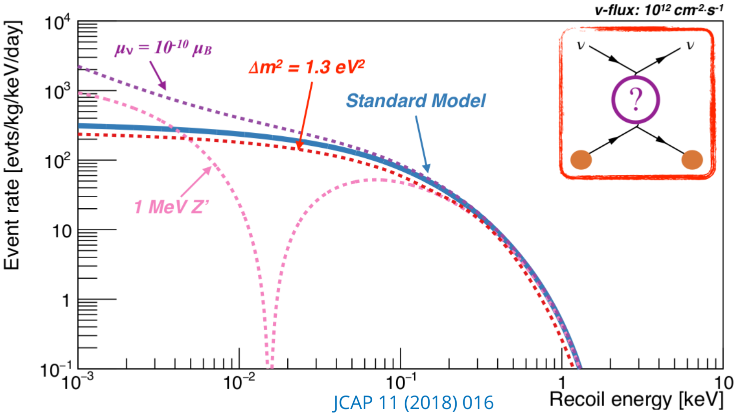

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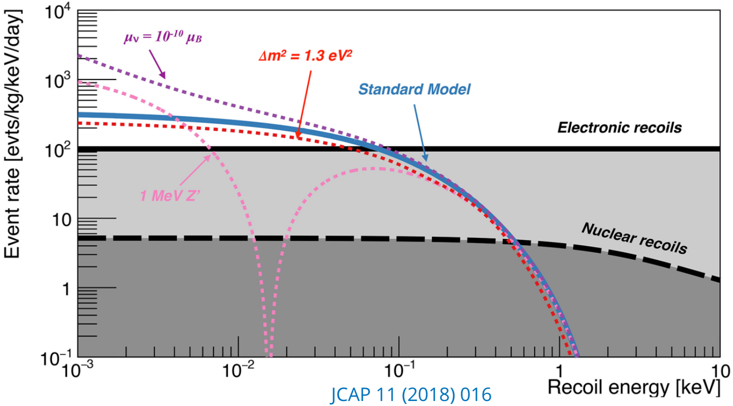
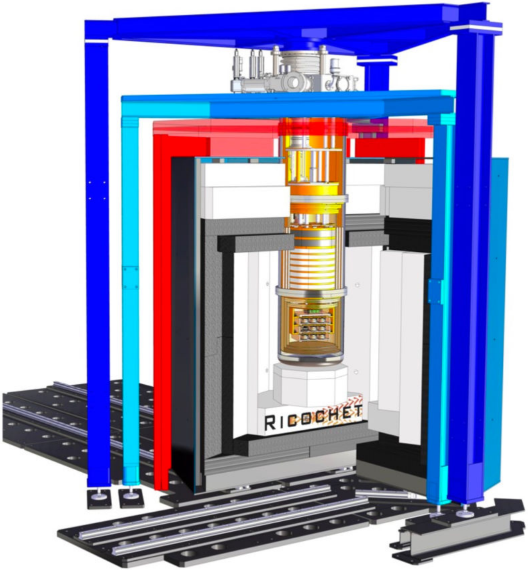


JCAP 11 (2018) 016

Ricochet at ILL

- Low-energy reactor neutrino observatory at the ILL reactor in Grenoble, France
- **Cryogenic detector payload**
  - Modular kg-scale detector
  - **CryoCube** (Ge crystals)
  - **Q-Array** (superconducting crystals)
- **Complementary technologies** with ER / NR discrimination
- Challenging radiation environment (reactorgenics, radiogenics, cosmics)
- First phase of data-taking in 2024!
- Active R&D for TESSERACT DM program



Appendix

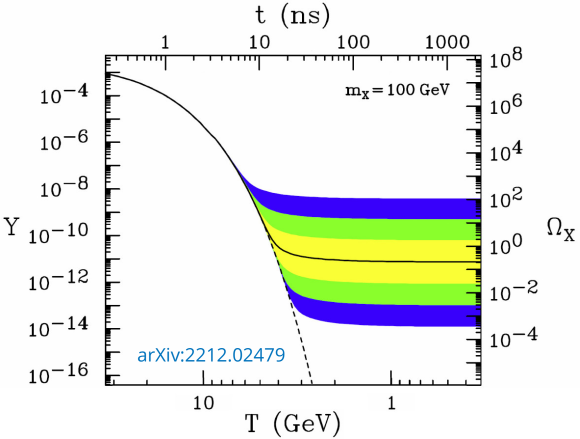
SuperCDMS Collaboration

@SuperCDMS

supercdms.slac.stanford.edu

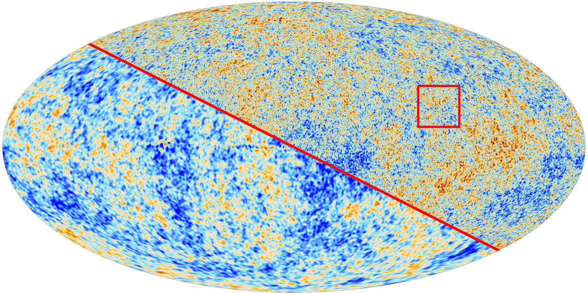
The famous "WIMP miracle"

- **Thermal equilibrium** in early universe
  $\chi + \chi \longleftrightarrow \mathrm{SM} + \mathrm{SM}$
- **Boltzmann equation**
  $\frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle \left(n^2 - n_{eq}^2\right)$
  - DM "gas" becomes dilute as universe expands and cools down
  - DM "freezes out" when $n \langle \sigma_A v \rangle \approx H$
- **Miracle:** freeze-out happens "naturally" around the weak scale with the required relic density of $\Omega_{DM} \approx 0.23$
  - Mass $m_\chi \sim \mathcal{O}(100)$ GeV – $\mathcal{O}(1)$ TeV

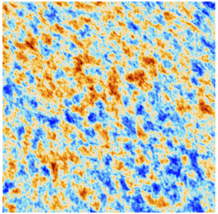


arXiv:2212.02479

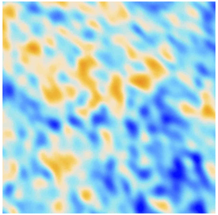
CMB – Cosmic Microwave Background



Planck



WMAP



- **Precisely studied by satellite missions (WMAP, Planck)**
  - Consistency in observed patterns and features!
- Fluctuations around $\langle T \rangle \approx 2.7\,\mathrm{K}$ can be expressed in form of **power spectrum** (to be fit with ΛCDM model)
- **Build your own universe** with planckapps on the web :)

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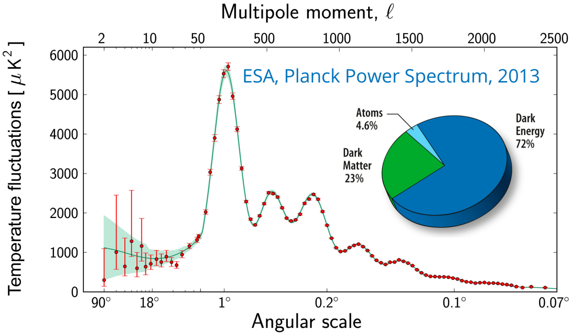

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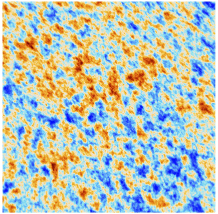

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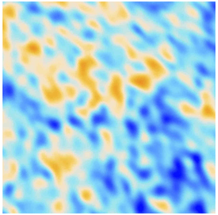
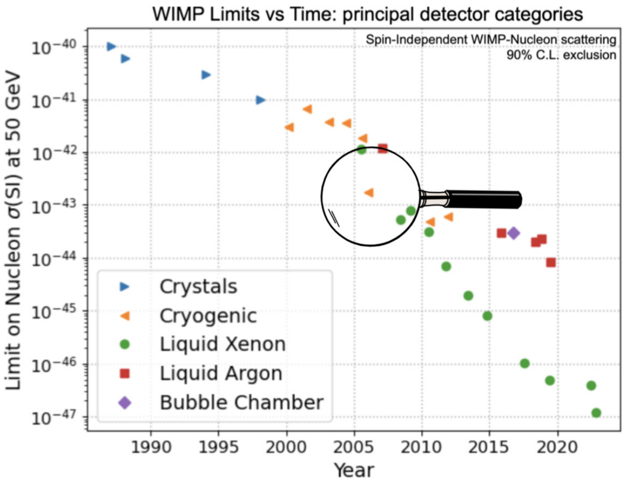


History of direct DM searches

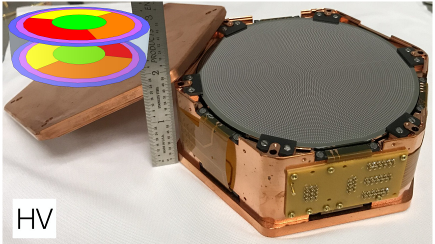


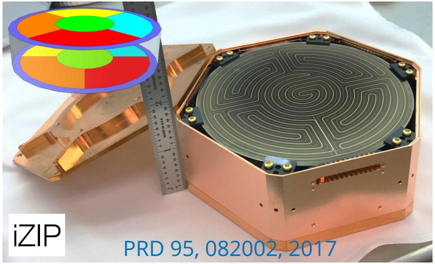
Credits: K. Schäffner, TAUP 2023

- **Crystal and cryogenic detectors** started the "WIMP hunt" more than 30 years ago
  - NaI: DAMA (DM modulation claim)
  - Ge/Si: CDMS, SuperCDMS
  - Ge: Edelweiss, CDMS-II, CDMSlite
- **Breakthrough:** particle discrimination in cryogenic detectors
  - Combine detection channels (e.g. charge + heat, light + heat)
  - Powerful background suppression
- **Up-scaling of target mass**
  - Xe: XENON-1T, LZ
  - Ar: DarkSide, DEAP

SuperCDMS detectors: Ge/Si HV & iZIP

- **Made of high-purity Ge and Si crystals**
  - **Si detectors** (0.6 kg each) provide sensitivity to **lower DM masses**
  - **Ge detectors** (1.4 kg each) provide sensitivity to **lower DM cross-sections**
- **Low operation temperature: ∼ 15 mK**
  - Phonon measurement with TESs (HV, iZIP)
  - Ionization measurement with HEMTs (iZIP)
- **Two-sided readout** with multiple channels to identify **event position**





PRD 95, 082002, 2017

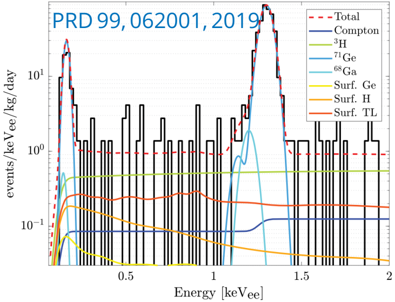
Low-threshold vs. low-background modes

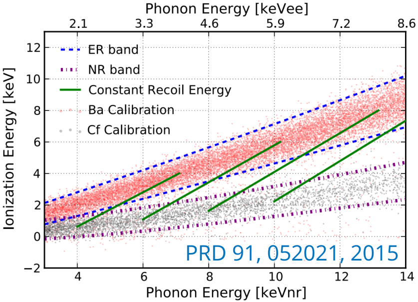
HV detectors – low threshold

- High resolution total phonon measurement
- No yield or surface discrimination
- Typical thresholds below 0.1 keV (4 eV_{ee})!

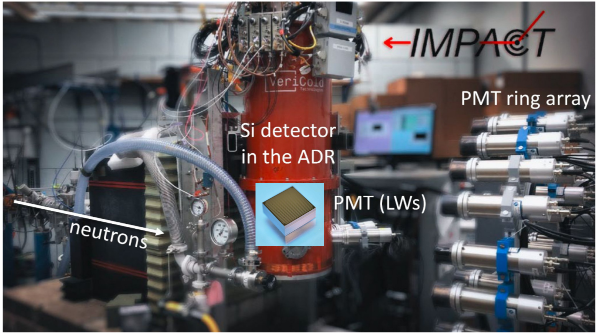
iZIP detectors – low background

- High resolution phonon and charge readout
- Discrimination of surface and ER backgrounds from NR signal region

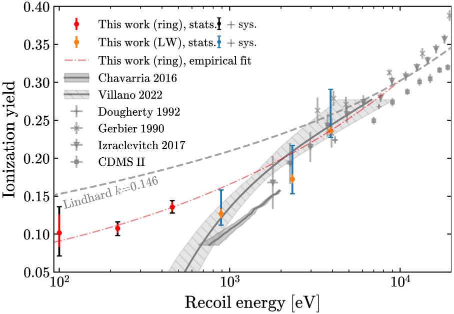

PRD 99, 062001, 2019


PRD 91, 052021, 2015

Nuclear recoil ionization yield measurement



PRL 131, 091801, 2023

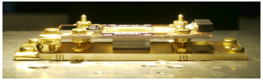


- Ionization yield (*Y*) measurement down to 100 eV with Si-HVeV prototype detector in a neutron beam
  - HVeV = HV prototype detector with eV-scale resolution
  - No indication for ionization threshold in Si!
- Ge yield measurement in preparation

Total phonon energy and yield

$$\begin{aligned} E_t &= E_r + (N_{eh} \cdot e \cdot V_b) \\ &= E_r \cdot (1 + e \cdot V_b / \varepsilon_{\text{pair}} \cdot Y(E_r)) \end{aligned}$$

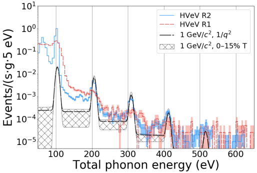
Highlights of HVeV R&D detector program

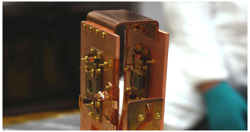


PRD 102, 091101(R), 2020

HVeV Run 2

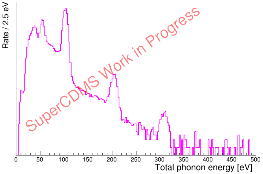
- Detection and study of 1 e^-/h^+ burst events
- Hypothesis: originate in PCB holder

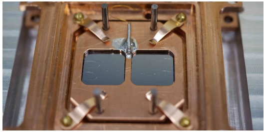




HVeV Run 3

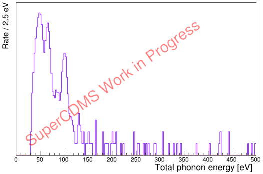
- Coincidence measurement with HVeVs
- Confirmed external origin of burst events





HVeV Run 4

- Replaced PCB + coincidence measurement
- Elimination of higher-order e^-/h^+ peaks

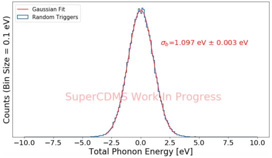


Stay tuned!

Latest performance

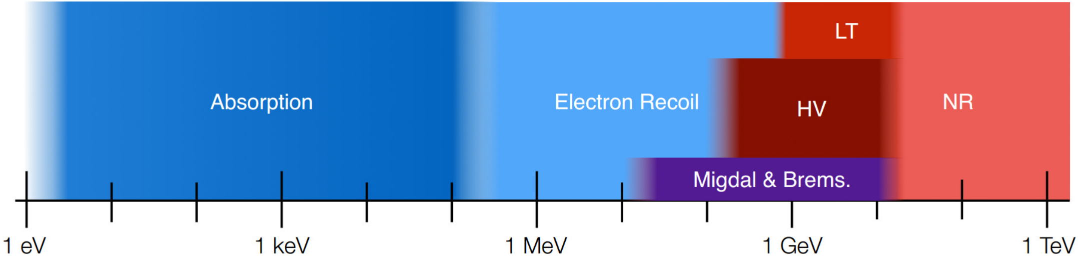
- V3 of HVeV detectors
- Achieved lowest baseline resolution in class!

$\rightarrow$ $\sigma_b = 1.097 \pm 0.003\,\text{eV}$



SuperCDMS: A broadband DM search

Absorption (Dark Photon, ALP):	$\sim$ 1 eV – 0.5 MeV	peak search (HV)
Electron Recoil:	$\sim$ 0.5 MeV – 10 GeV	no NR/ER discrim. (HV)
Migdal & Bremsstrahlung:	$\sim$ 0.01 – 10 GeV	no NR/ER discrim. (HV + iZIP)
HV Detectors:	$\sim$ 0.3 – 10 GeV	no NR/ER discrim. (HV)
Low Threshold (LT):	$\gtrsim$ 1 GeV	limited NR/ER discrim. (iZIP)
Traditional Nuclear Recoil:	$\gtrsim$ 5 GeV	full NR/ER discrim. (iZIP)



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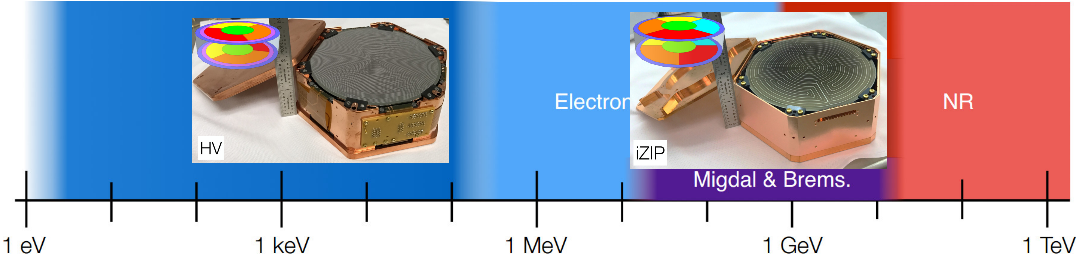


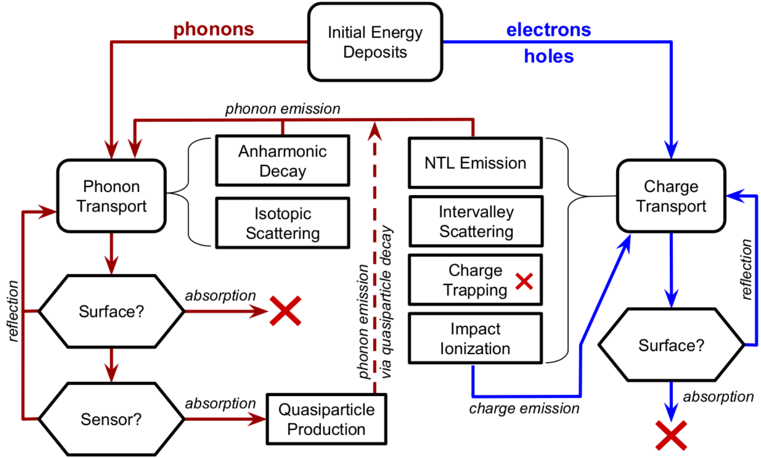
G4CMP – "in-house" physics library

G4CMP – **C**ondensed **M**atter **P**hysics library for GEANT4

1) **Production of e^-/h^+ pairs and phonons from $\mathcal{O}$(keV) GEANT4 energy deposits**
2) **Transport** of **eV-scale** (conduction band) **electrons and holes** in crystals
    - Anisotropic transport of electrons
    - Scattering, phonon emission (NTL), charge trapping, impact ionization
3) **Transport** of **meV-scale** (acoustic) **phonons** in deeply cryogenic crystals
    - Mode-specific relationship between wave vector and group velocity
    - Impurity scattering (mode mixing), anharmonic decays
4) **Sensor modeling** (SuperCDMS example: QET)
    - User application implements phonon collection
    - Phonons incident on QET trigger thin-film simulation (*G4CMPKaplanQP*)

More details: NIM A 1055, 168473, 2023 (arXiv:2302.05998)
Source code: https://github.com/kelseymh/G4CMP

G4CMP – Event processing flow



arXiv:2302.05998