Title: Solid State Detectors for Low-Mass Dark Matter Searches

Speakers: Miriam Diamond

Collection: PSI 15th Anniversary Reunion

Date: June 19, 2024 - 2:00 PM

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Abstract: "We are faced with convincing evidence that approximately a quarter of the universe is composed of something whose gravitational effects can be seen in a variety of astrophysical phenomena, but which we have been unable to detect and identify in the laboratory. The majority of physicists agree that this ""dark matter"" (DM) consists of as-yet-undiscovered subatomic particle(s) that are not included in our Standard Model of particle physics; the quest to discover its exact nature is among the foremost missions in modern physics and the greatest treasure hunts in history. Direct DM searches over the past few decades have been largely focused on Weakly Interacting Massive Particles with masses much greater than that of the proton. The absence of any conclusive discovery, along with various theoretical developments and certain astrophysical observations, has recently motivated the direct detection community to broaden our experimental program to search for DM candidates in lower mass ranges. Solid-state detectors provide many advantages for such searches. This talk will summarize recent advances in phonon- and ionization-based semiconductor crystal experiments, cryogenic scintillating calorimeter experiments, and Charge-Coupled Device experiments. It will also discuss future prospects and discovery potential for solid-state detectors with respect to various low-mass DM candidates, including dark photons, axion-like particles, and lightly-ionizing particles."

Solid State Detectors for Low-Mass Dark Matter Searches




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PSI 15th Anniversary Reunion

Perimeter Institute, Waterloo ON

June 19 2024

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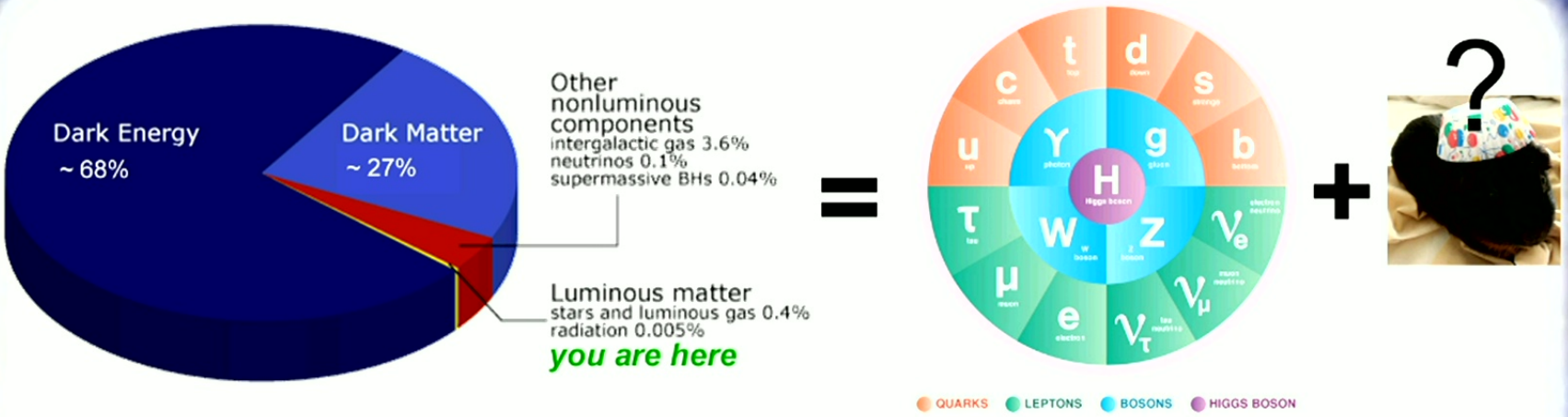
The Dark Matter Question

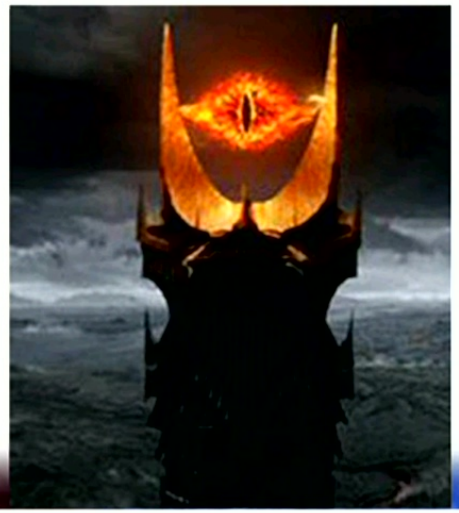


So far, evidence for existence of DM comes from astrophysics

How to look for it in particle physics experiments?

Come to the (Solid) Dark Side

- What are we looking for?
- How are we looking for it?
- The solid program of solid-state detectors
- SuperCDMS: apparatus, sensitivity, results with prototypes

"Beyond the Standard Model" Searches

DM searches → BSM particle(s) that are:

- Cold (non-relativistic)
- Stable on cosmological timescales
- Gravitationally interacting
  - Plus feeble, if any, non-gravitational interactions with each other / with luminous matter

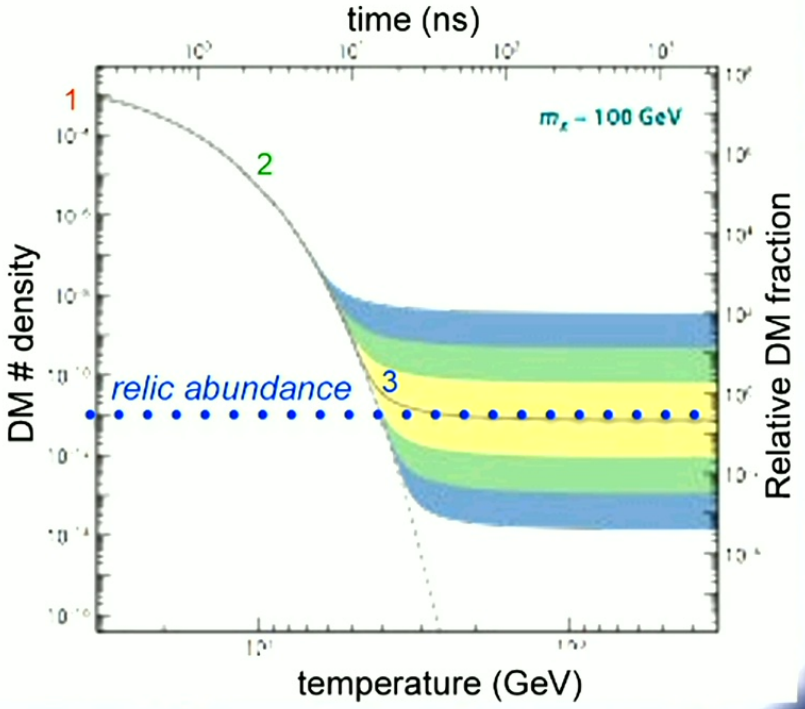
What mass scale?
What interactions with SM?
Are there "dark forces"?
How many new particle species?
…

Happy Valentine's Day courtesy of Symmetry magazine

Thermal Production of DM Particles?

A general, simple possibility for DM production in early universe:

1. DM initially in thermal equilibrium with SM, in hot "soup"
   $\chi\bar{\chi} \leftrightharpoons f\bar{f}$
2. Universe cools, SM no longer energetic enough to produce DM pairs, DM begins annihilating away
   $\chi\bar{\chi} \not\leftrightharpoons f\bar{f}$
3. Universe expands, DM stops annihilating ("freeze-out")
   $\chi\bar{\chi} \not\leftrightharpoons f\bar{f}$



WIMP Miracle?

"relic abundance" of DM particle χ

$$\Omega_\chi h^2 \simeq \frac{0.1 \text{ pb} \cdot c}{\langle \sigma v \rangle}$$

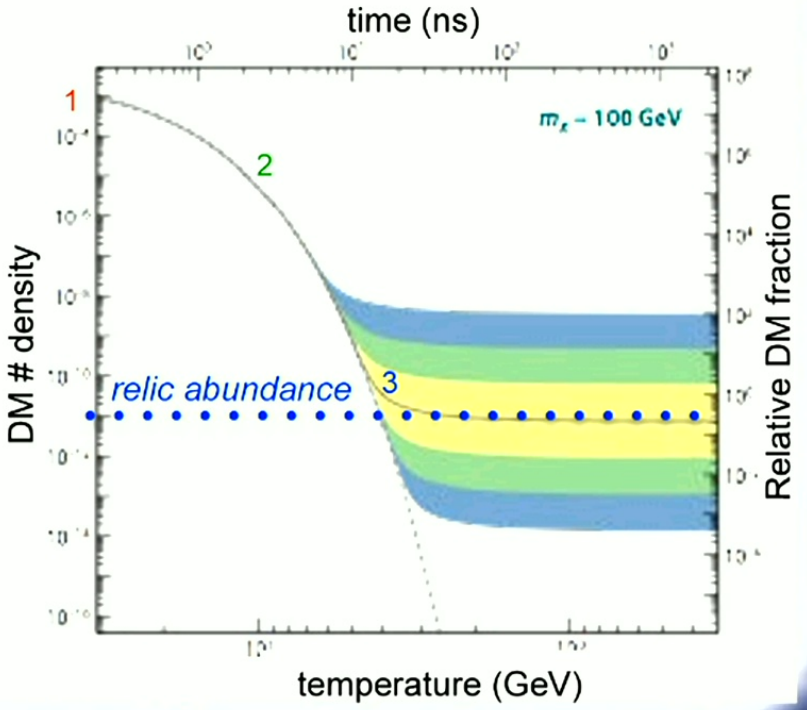
avg cross section times velocity

$$\Omega_\chi h^2 \approx 0.1 \Longrightarrow \langle \sigma v \rangle \approx 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

$$\langle \sigma v \rangle \propto \frac{m_\chi^2}{m_Z^4} \Longrightarrow m_\chi \approx 100 \text{ GeV}$$

weak scale

"Weakly Interacting Massive Particles" (WIMPs)



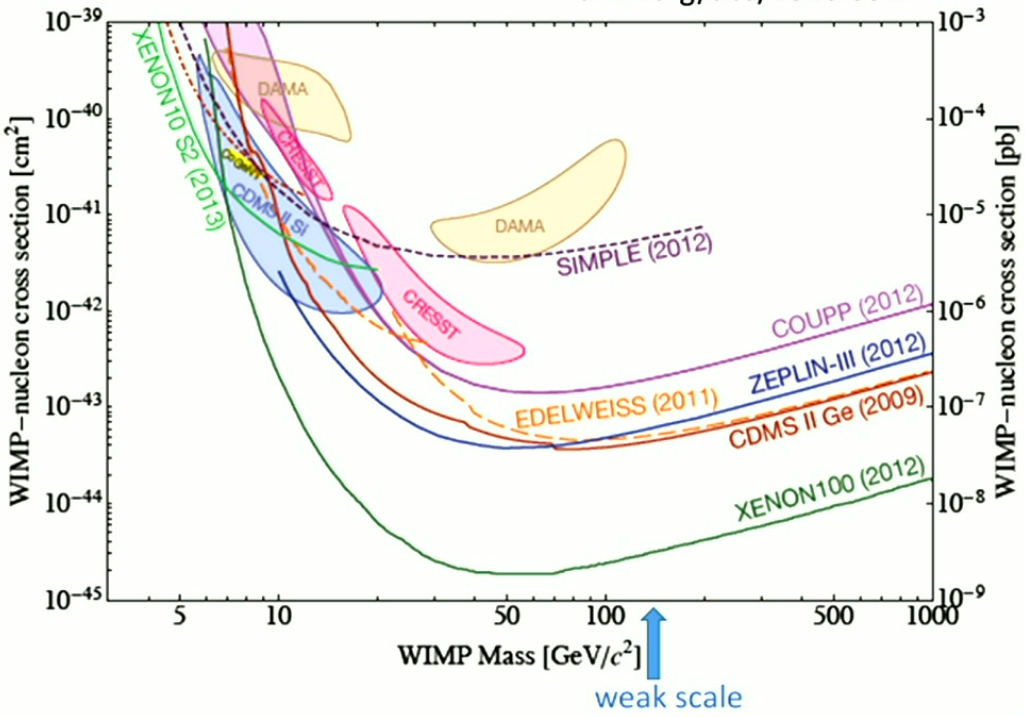
WIMPing out?

Lots of WIMPy candidates:

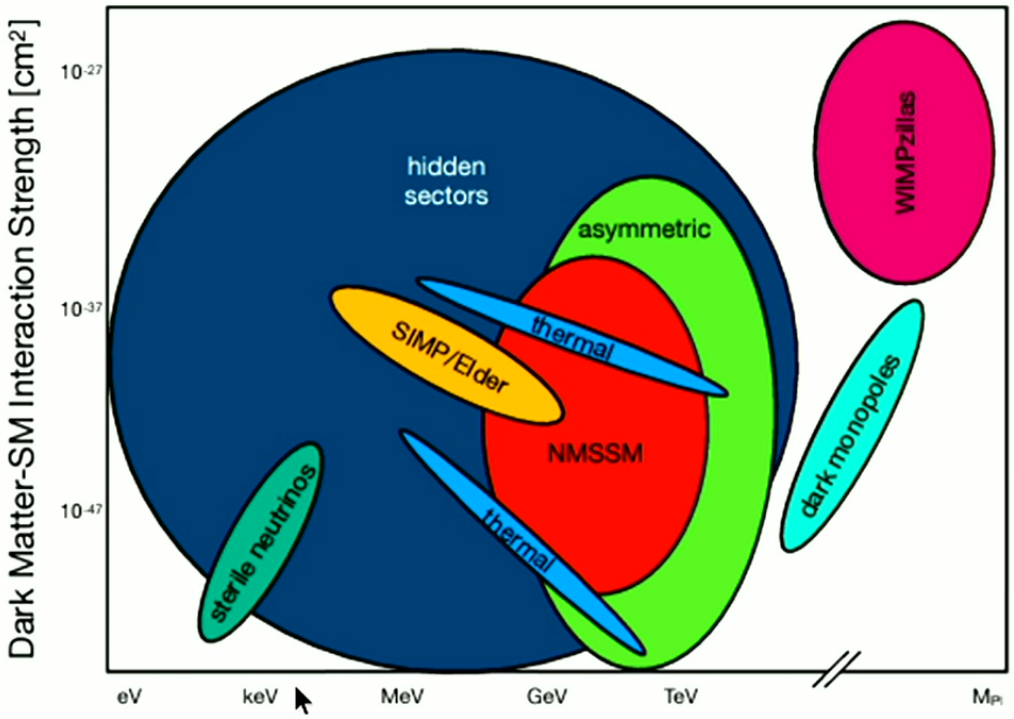
- Supersymmetric partners
- Additional Higgs bosons
- Kaluza-Klein modes
- … etc

But… searches *where we most expected to find WIMPs* haven't found them!

arxiv.org/abs/1310.8327



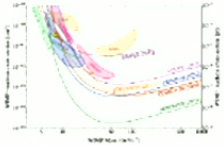
Now what?



arxiv.org/abs/2209.07426

My Favourite Park in the Particle Zoo

- Stick with thermal relic DM, it works (theoretically) at least down to $2m_e$

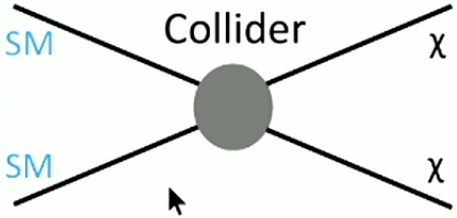


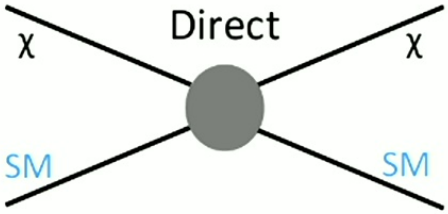
- "Light WIMP-like DM" requires new, low-mass "dark mediators" (dark force carriers)
  - e.g. "Hidden Valley" / "Mirror Universe" models with "dark photons"
- Look for the sub-GeV DM and also the mediators

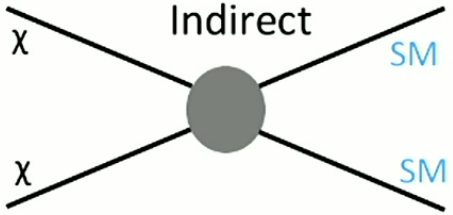
“How are we looking for it?”

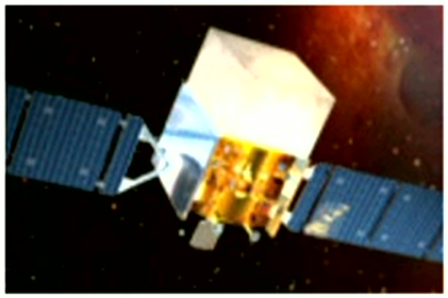
Search Strategies

Complementarity between different types of experiments



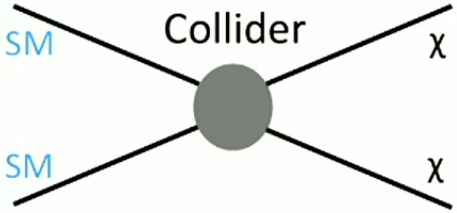


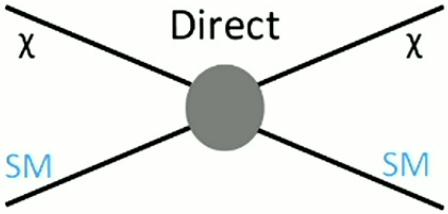


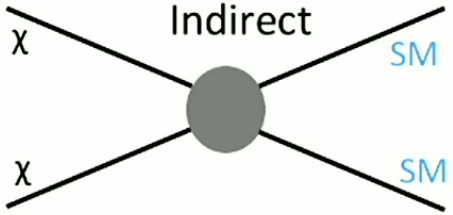


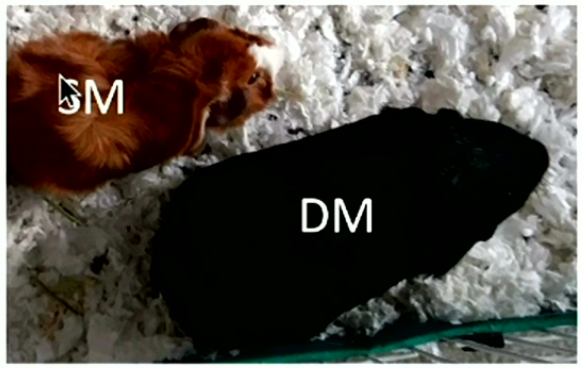
Search Strategies

Complementarity between different types of experiments

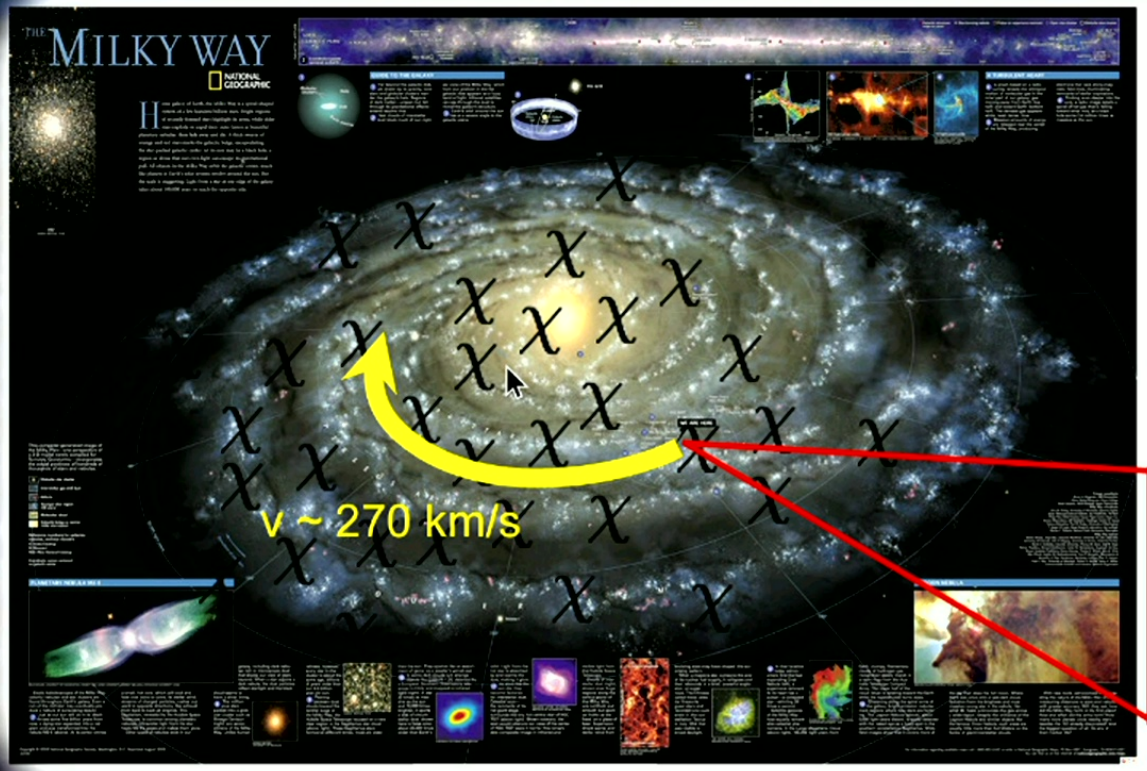








Direct Detection

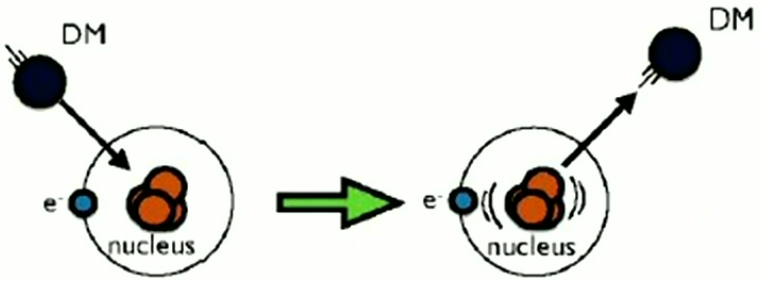


Collisions of galactic DM with SM particles in detector on Earth

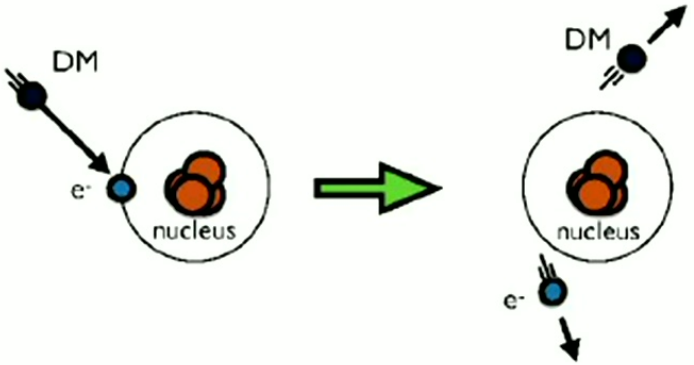
Direct Detection

DM particles collide with SM particles in detector “target” and are absorbed, or cause nuclear and/or electronic recoils

Nuclear Recoil



Electron Recoil

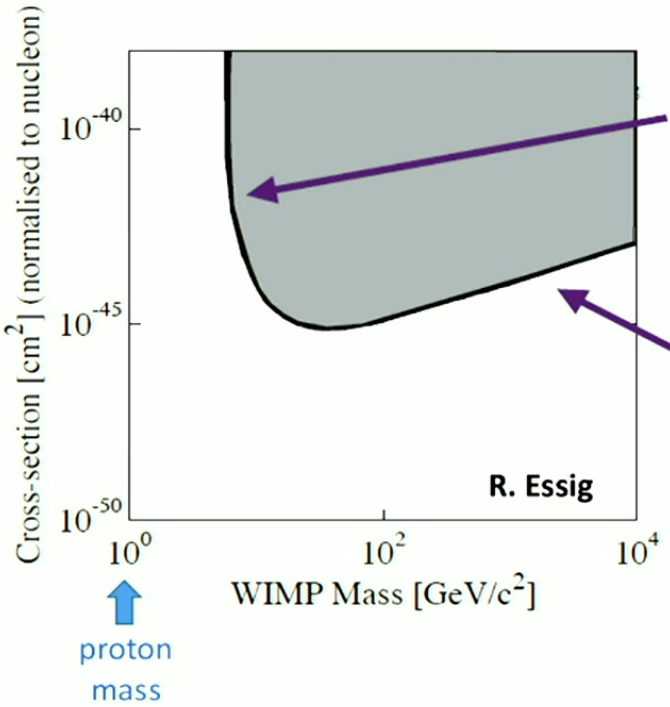


The GeV-Scale & Sub-GeV Detection Challenge

Light DM (~2m_e) stretches traditional WIMPy direct detection techniques, which rely extensively on inelastic nuclear recoil

Not enough energy transfer

Can't see recoil of nucleus



nuclear recoil energy too small

linear, since

$$\text{Rate} \propto n \propto \frac{\rho}{m}$$

$$\propto \frac{0.4\ \text{GeV/cm}^3}{m}$$

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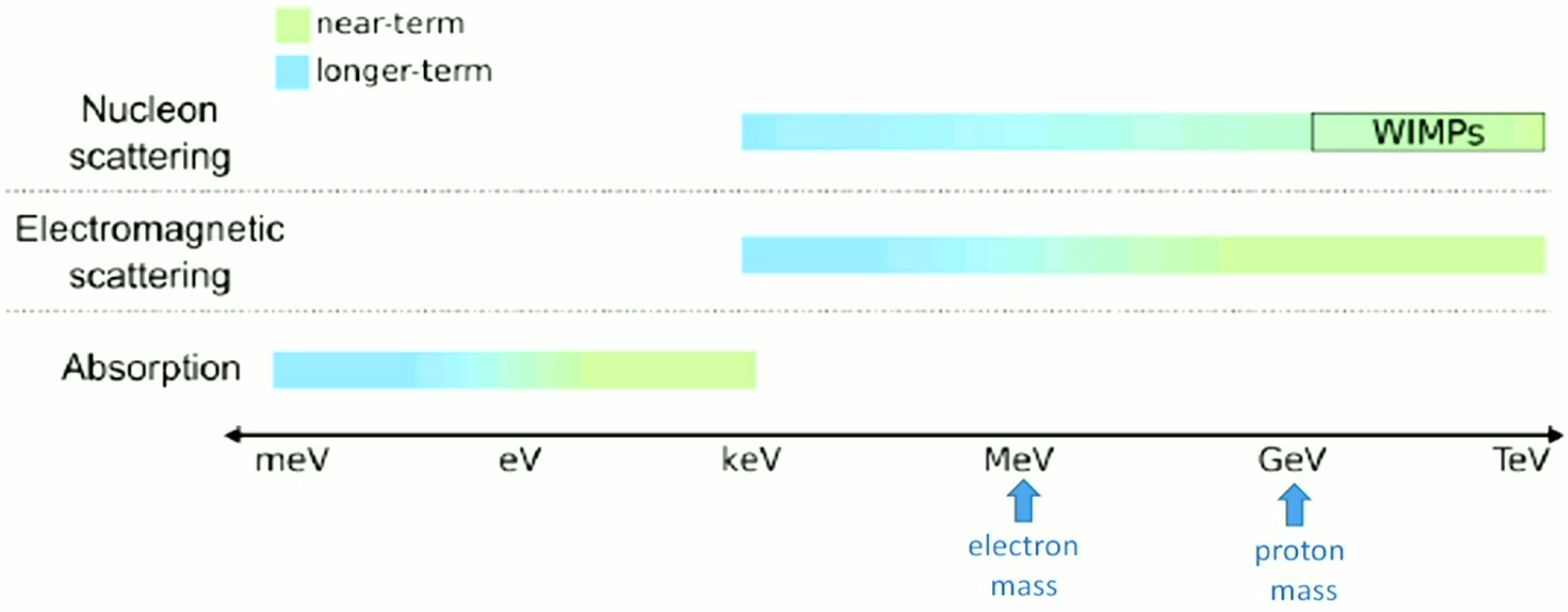
The GeV-Scale & Sub-GeV Detection Challenge

For ~meV – keV dark mediators, need absorption searches



BRN for DM Small Projects New Initiatives https://www.osti.gov/servlets/purl/1659757

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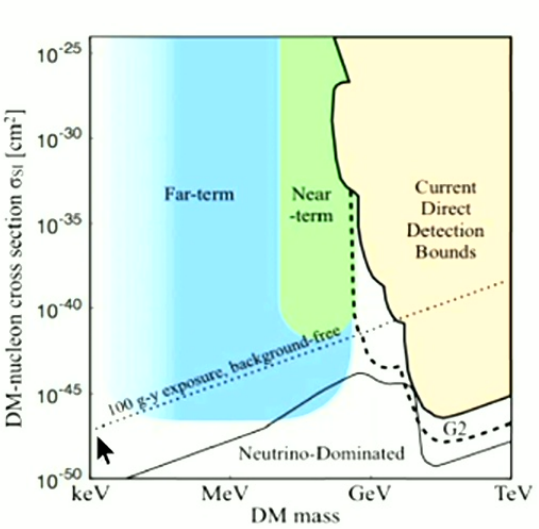
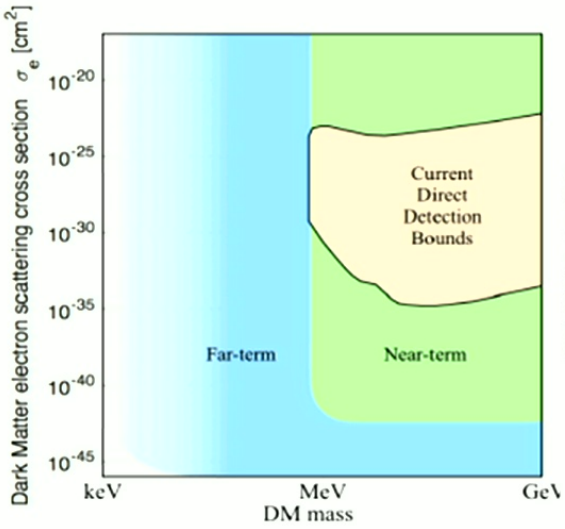
The GeV-Scale & Sub-GeV Detection Challenge

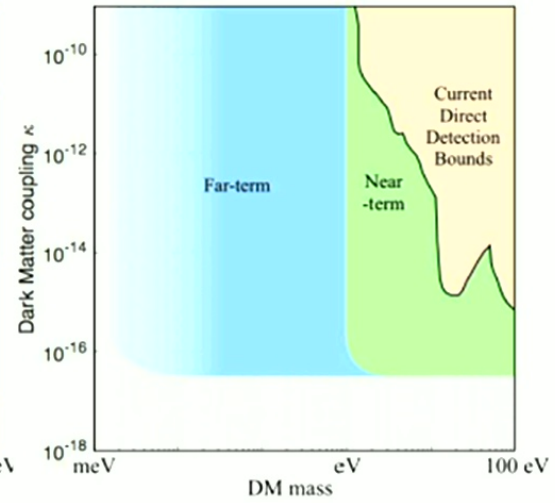
Lowering *mass* and/or *interaction* thresholds



Galactic dark matter scattering off nuclei



Galactic dark matter scattering off electrons

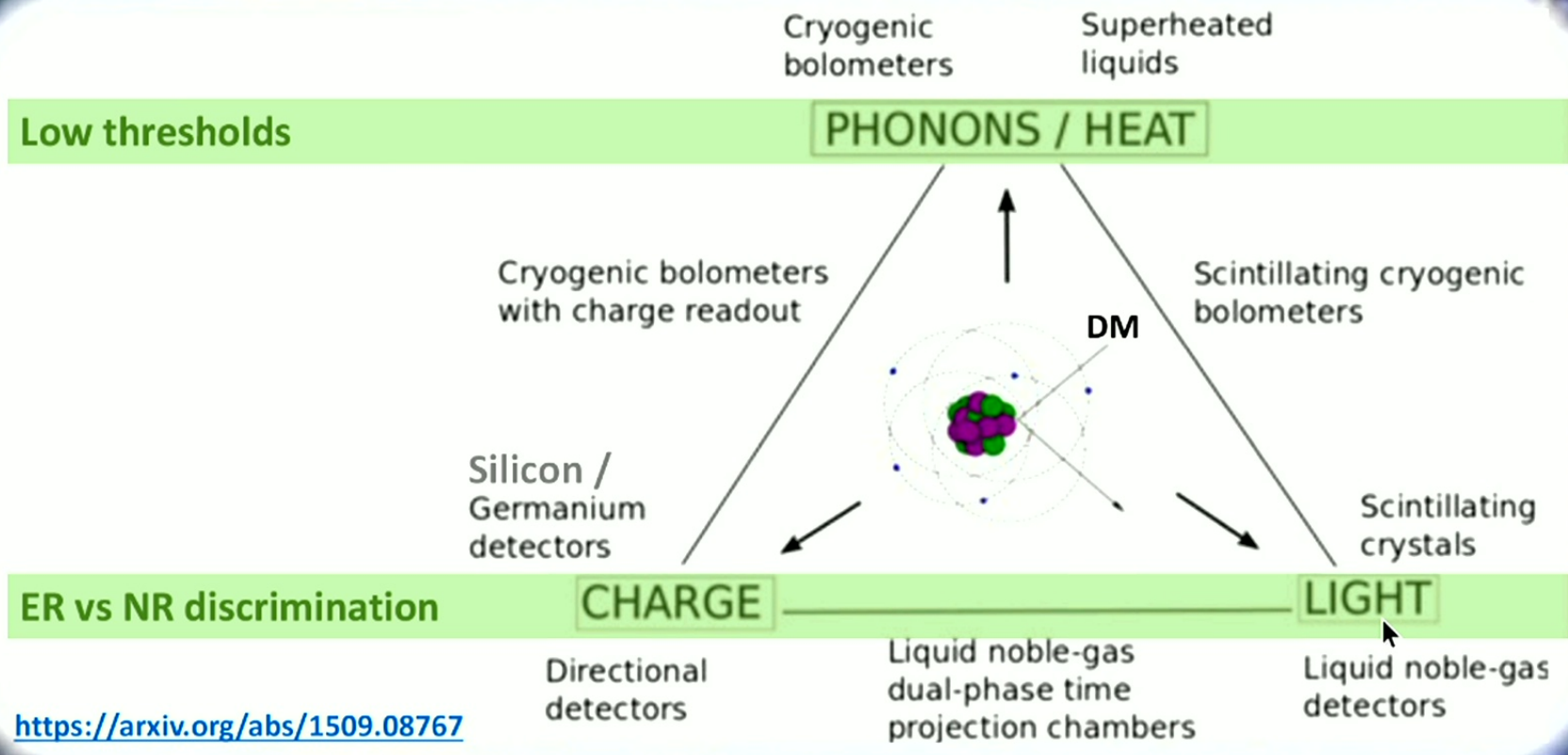


Galactic dark-photons absorbed by electrons

BRN for DM Small Projects New Initiatives https://www.osti.gov/servlets/purl/1659757

Solid-State Detectors

3 Channels for Next-Generation Detectors



https://arxiv.org/abs/1509.08767

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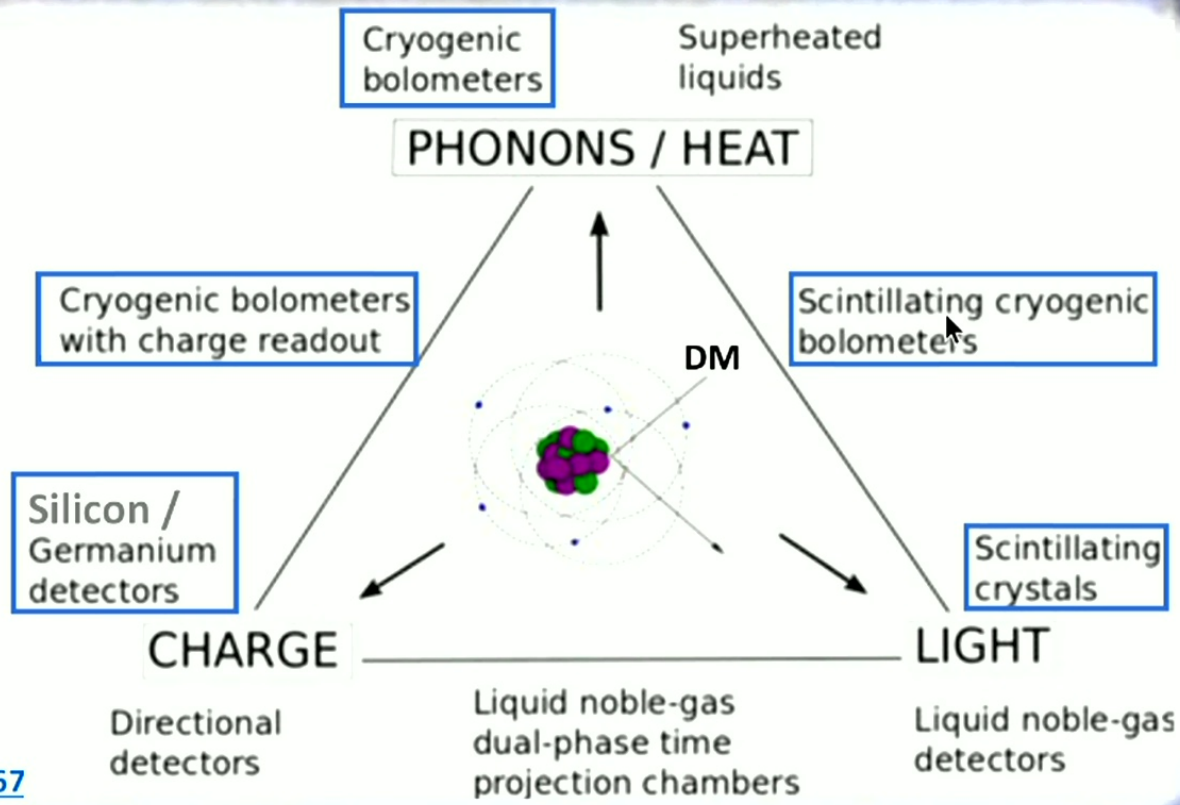
Many Next-Generation Detectors are Solid-State



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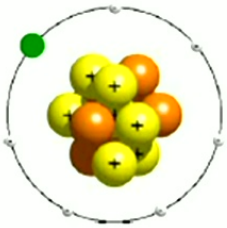
Many Next-Generation Detectors are Solid-State

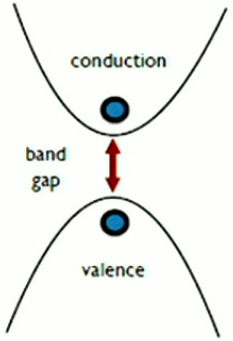
Categorized by electron recoil energy (ΔE) and m_{DM} detectable:



noble liquids

$\Delta E \sim 10$ eV

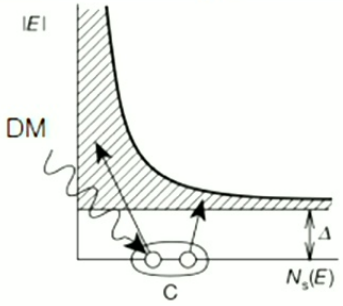
$m_{\rm DM} \sim 5$ MeV



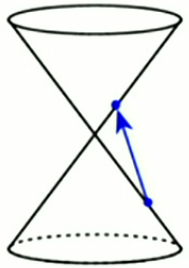
semiconductors
scintillators

$\Delta E \sim 1$ eV

$m_{\rm DM} \sim 500$ keV



superconductors
(R&D)



Dirac materials
(speculative "exotic")

$\Delta E \sim$ few meV

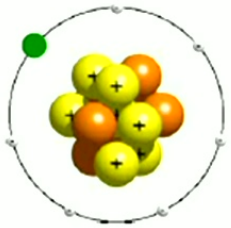
$m_{\rm DM} \sim$ keV

...

R. Essig

Many Next-Generation Detectors are Solid-State

Categorized by electron recoil energy (ΔE) and m_{DM} detectable:



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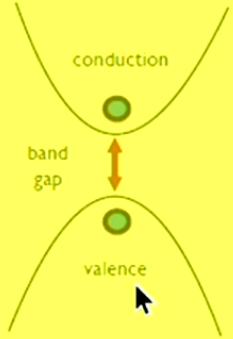

semiconductors
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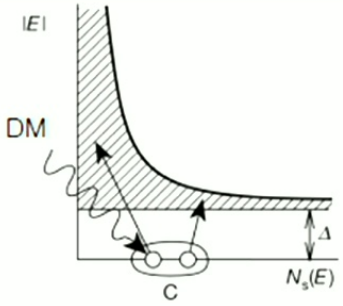

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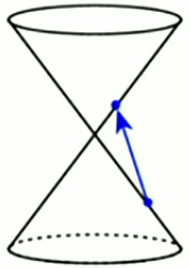

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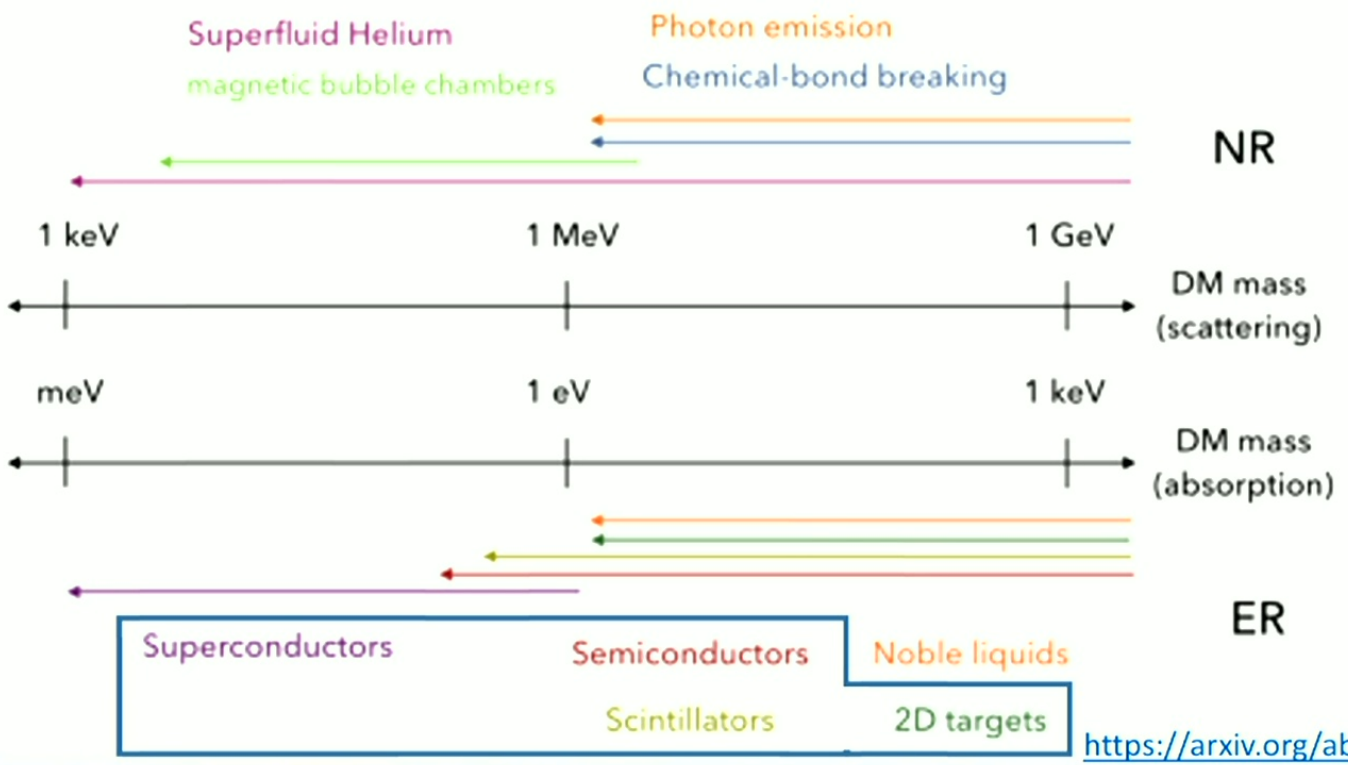
Many Next-Generation Detectors are Solid-State



https://arxiv.org/abs/1707.04591

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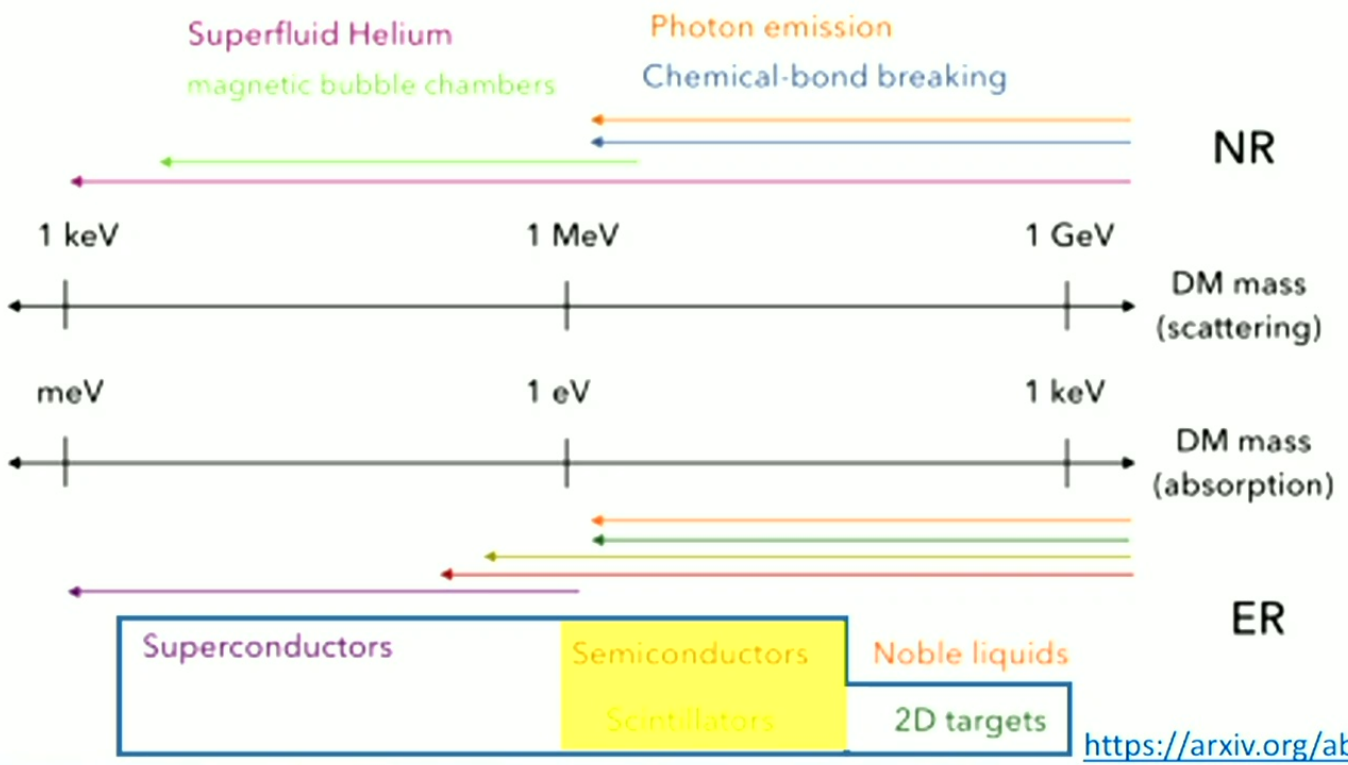
Many Next-Generation Detectors are Solid-State



https://arxiv.org/abs/1707.04591

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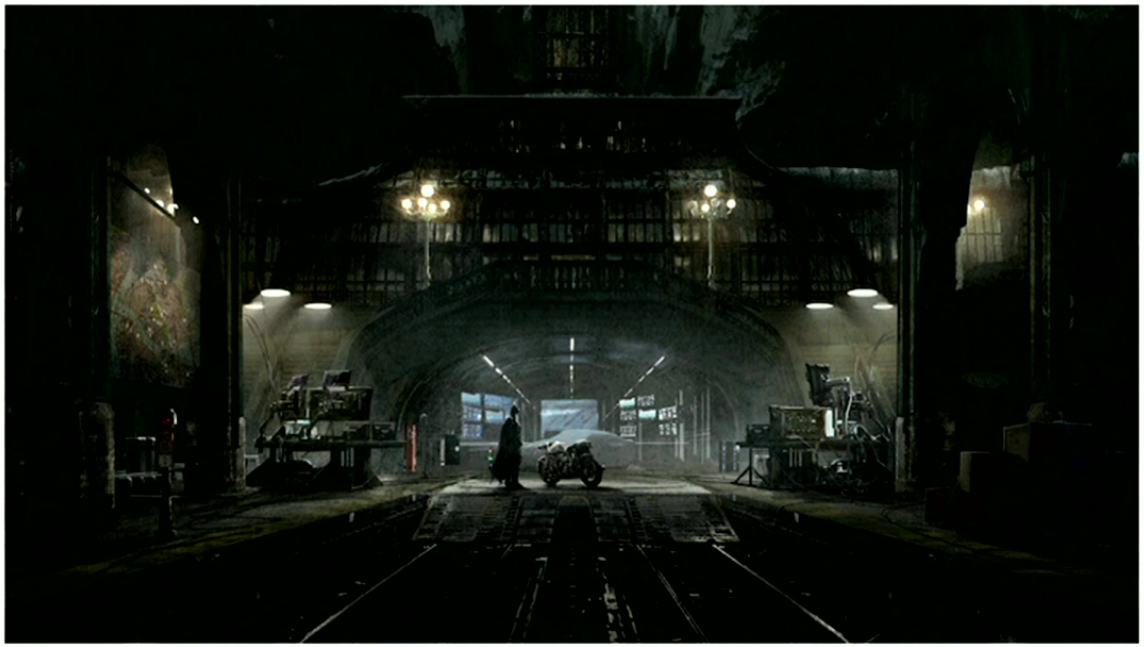
Underground Shielded Secret Lairs

Hide the detectors in shielding and bury them in an underground clean-room.

Why?



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Underground Dark Shielded Lairs

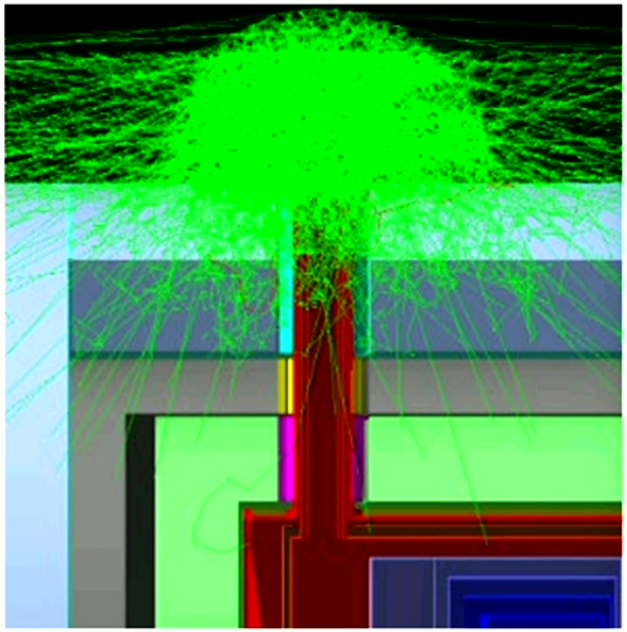
Backgrounds, backgrounds, backgrounds!

Cosmogenic

- **Cosmic ray muons**
- **Spallation neutrons**
- **Activated materials**

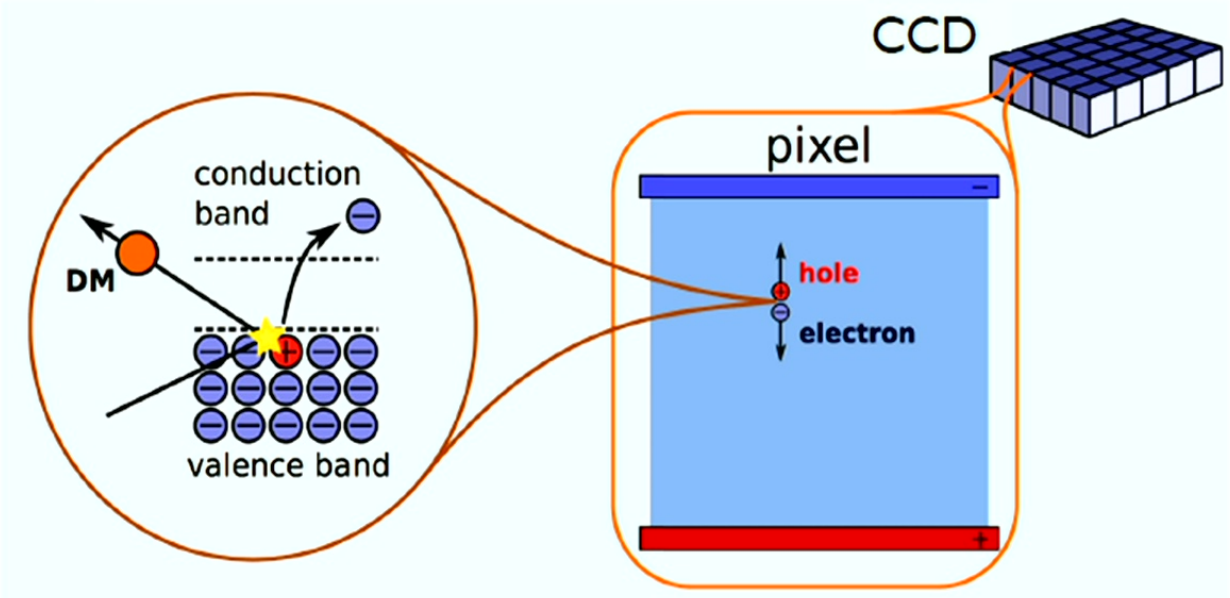
Environmental

- **Airborne radon & daughters**
- **Radio-impurities in materials**



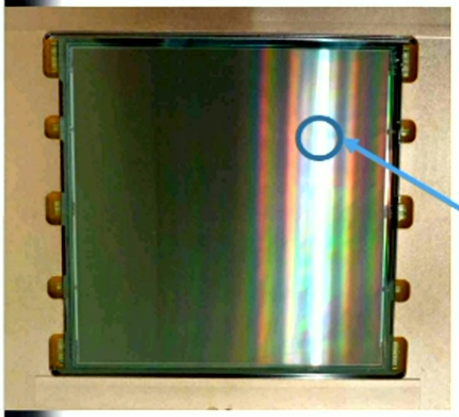
Charge-Coupled Devices (Semiconductor Pixels)

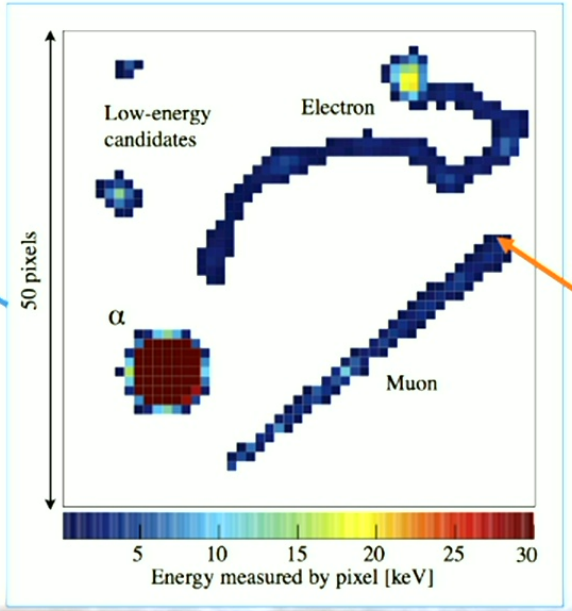
- Take a photo of DM, like with your cellphone camera!
- Ionization events induced by DM (instead of photons) in bulk Si of CCD pixels

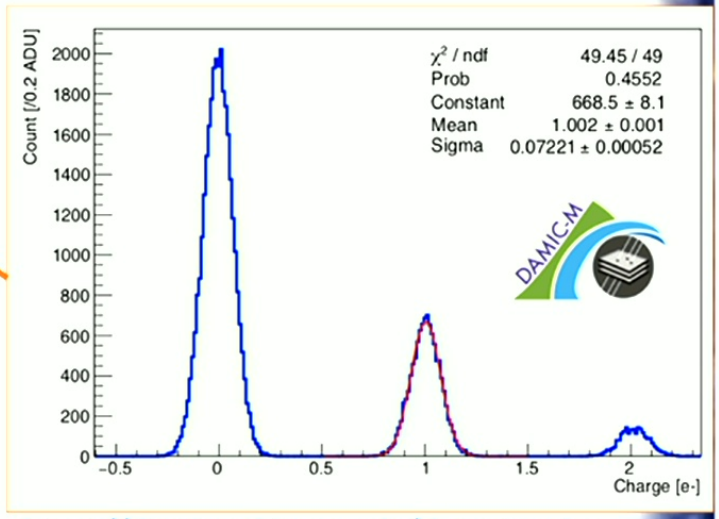


Charge-Coupled Devices (Semiconductor Pixels)

- **Pixels ~15 x 15 μm^2 , hundreds of μm thick**
- **"Skipper" CCDs reliably detect excitations as small as 1 electron in a pixel**







https://damic.uchicago.edu/detector.php

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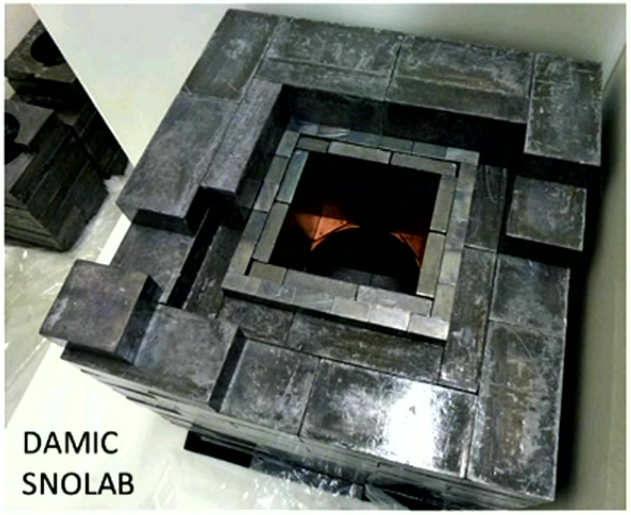
Charge-Coupled Devices (Semiconductor Pixels)

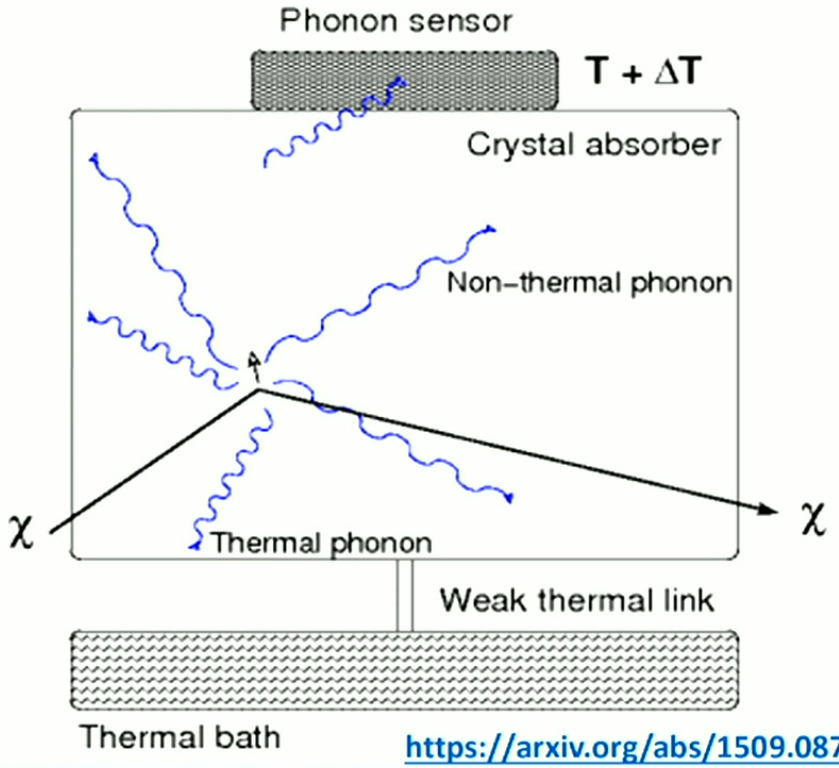
- **Liquid nitrogen temperatures**
- **Hour[s] of "exposure time" per "image"**

- DAMIC (Dark Matter in CCDs)
- SENSEI (Sub-Electron-Noise Skipper-CCD Experimental Instrument)
- OSCURA (Observatory of Skipper CCDs Unveiling Recoiling Atoms)


DAMIC
SNOLAB

Cryogenic Semiconductor Crystals

- **Collect phonons as well as electrons**
- **Calorimetry rather than tracking/imaging**
- **Operated at tens of mK**



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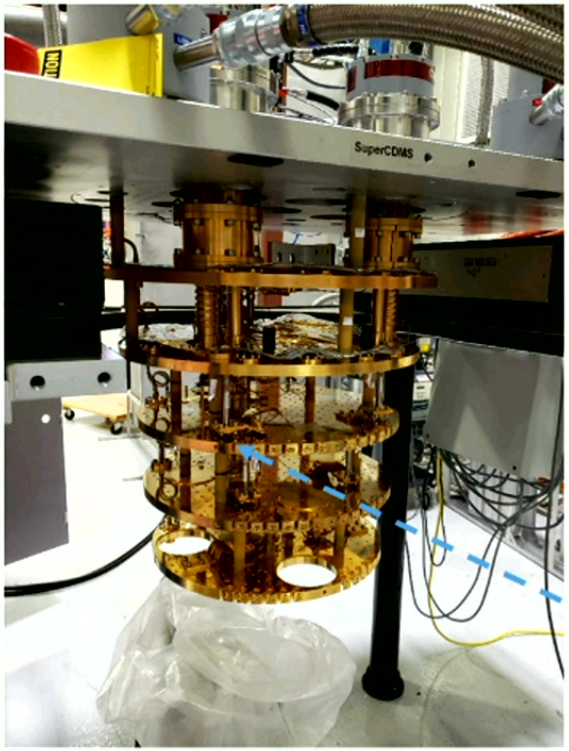
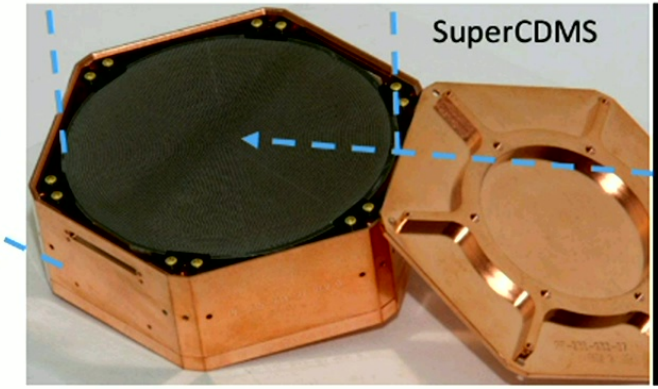
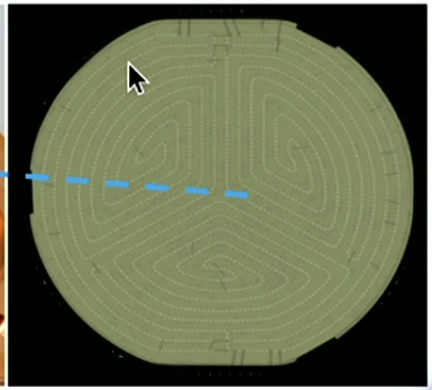
Cryogenic Semiconductor Crystals



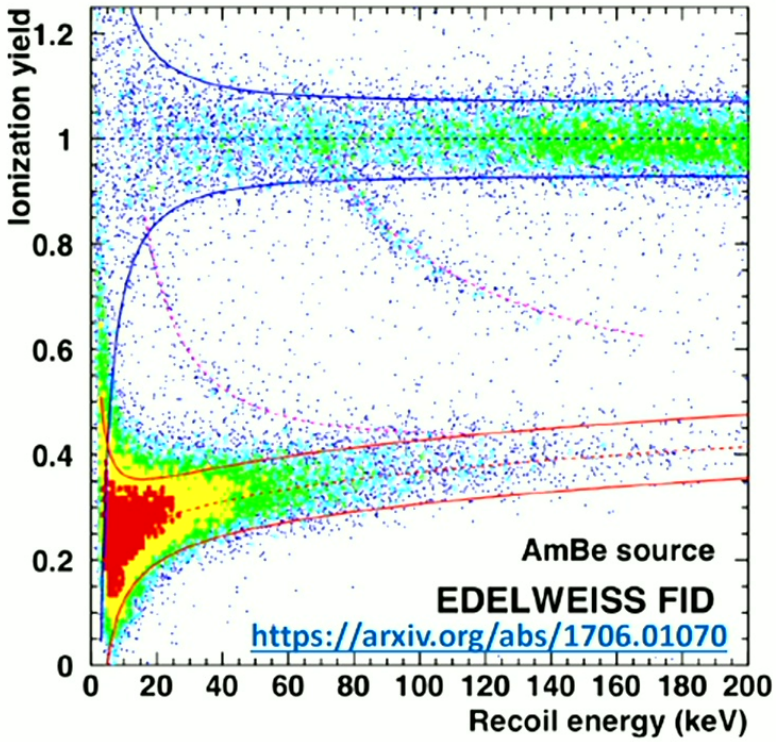




Cryogenic Semiconductor Crystals

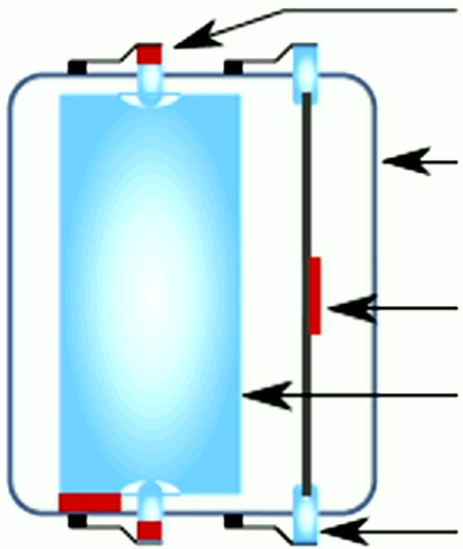
Combination of phonon and ionization channels allows NR vs ER discrimination

- EDELWEISS (Expérience pour Detecter Les WIMPs En Site Souterrain) @ Modane
- SuperCDMS



Cryogenic Scintillating Crystals

Along with phonon signal: instead of collecting electrons in semiconductor crystals, collect light in scintillating crystals, operated at ~5 mK



$CaWO_4$ iSticks
(with holding clamps & TES)

reflective and
scintillating housing

light detector (with TES)

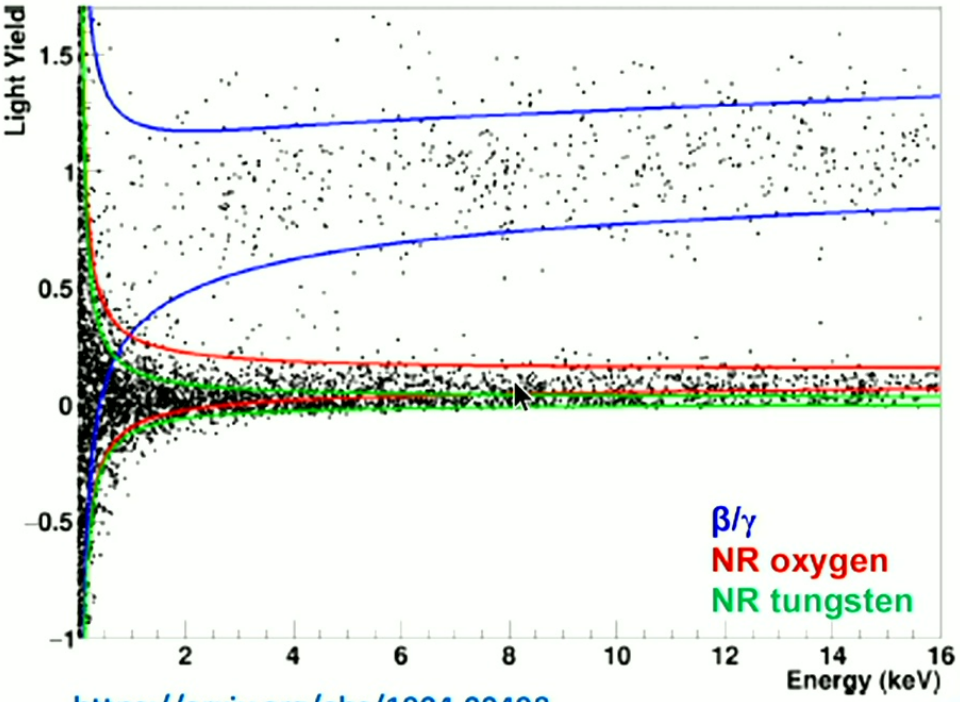
block-shaped target crystal
(with TES)

$CaWO_4$ light detector holding
sticks (with clamps)

https://arxiv.org/abs/1904.00498

Cryogenic Scintillating Crystals

Combination of phonon and light channels allows ER & gammas vs NR discrimination



- CRESST-III (Cryogenic Rare Event Search with Superconducting Thermometers) @LNGS

https://arxiv.org/abs/1904.00498

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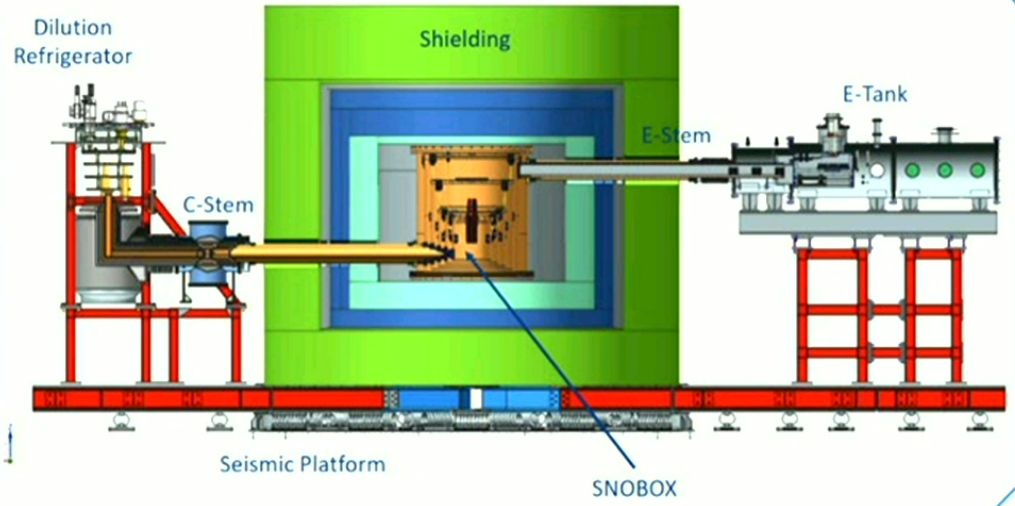
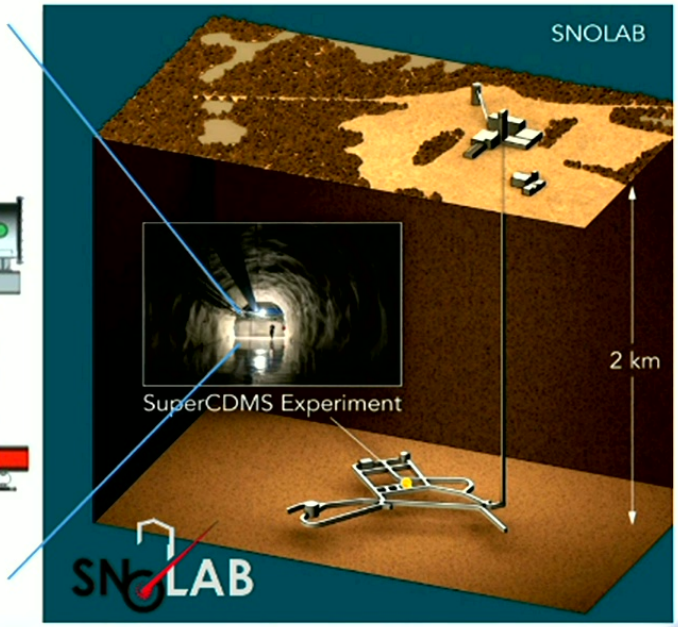
SUPER
CDMS
Cryogenic Dark Matter Search

SuperCDMS (Super Cryogenic Dark Matter Search)

Operated in a Soudan, Minnesota underground lab until 2015

More powerful version now being constructed in Canada's world-leading astroparticle physics facility, 2 km underground in the Vale Creighton Mine near Sudbury





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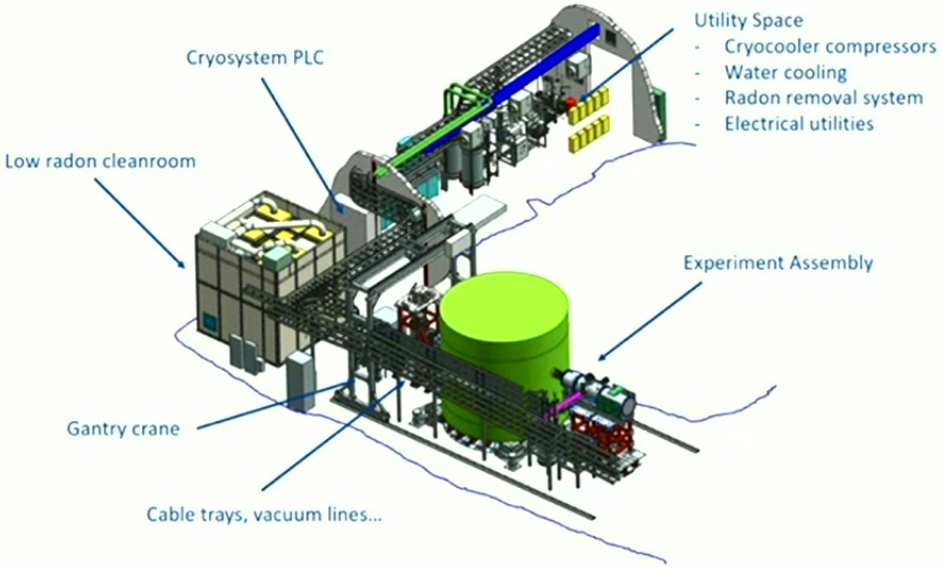
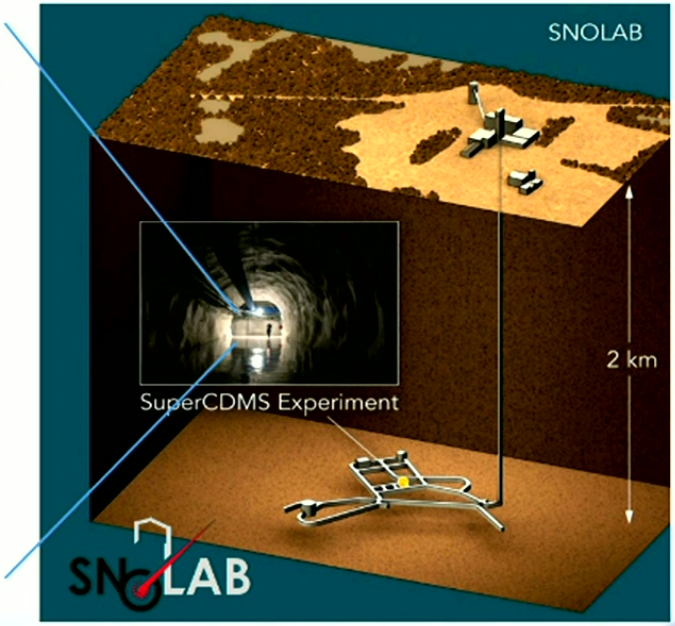
SuperCDMS (Super Cryogenic Dark Matter Search)

Operated in a Soudan, Minnesota underground lab until 2015

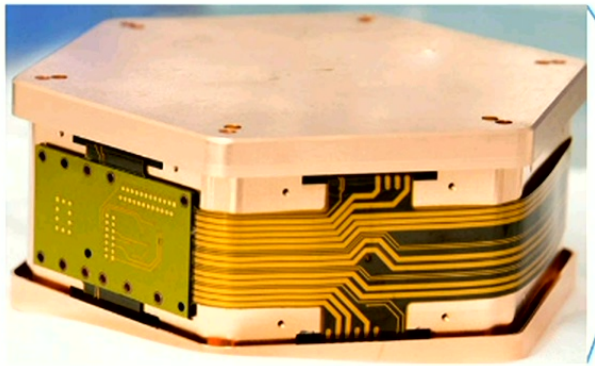
More powerful version now being constructed in Canada's world-leading astroparticle physics facility, 2 km underground in the Vale Creighton Mine near Sudbury

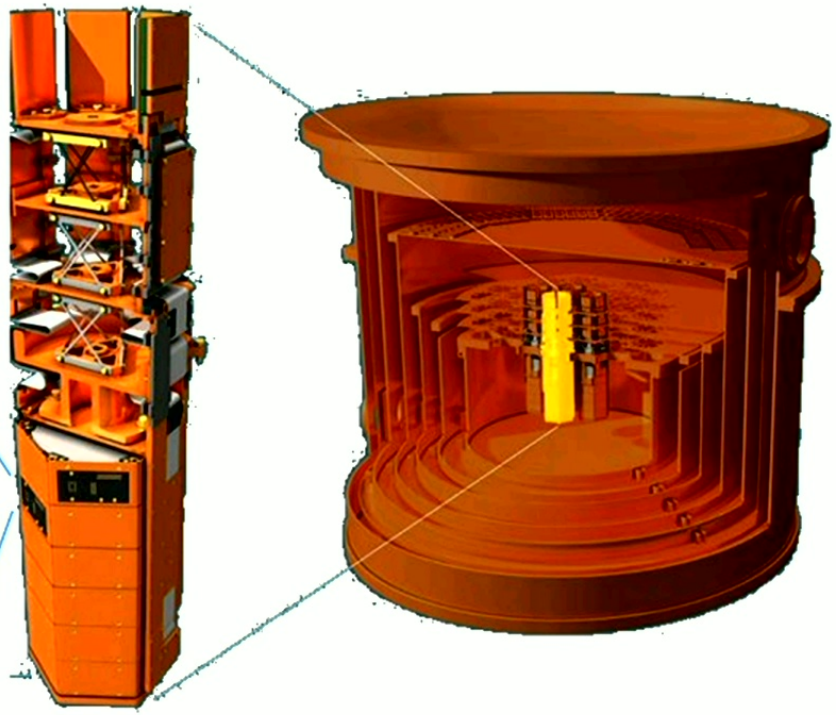




SuperCDMS@SNOLAB

- kg-scale Si and Ge detector modules
- 6 modules per “tower”, 4 “towers” in cryostat





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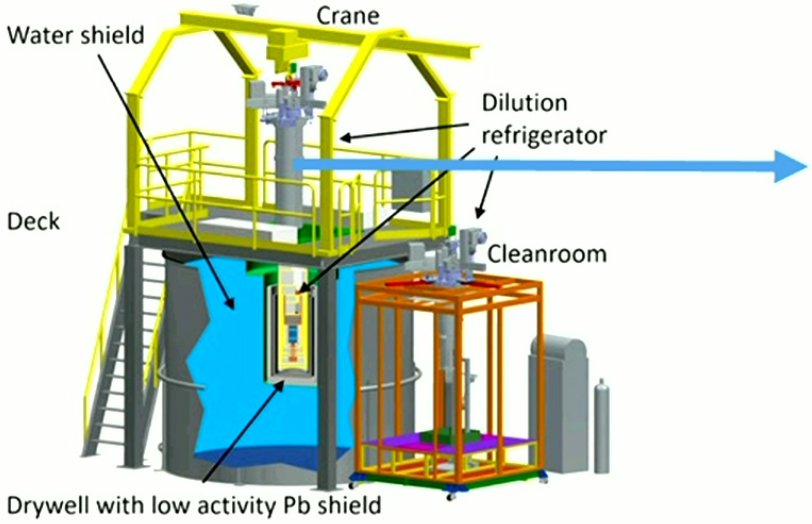
SuperCDMS@SNOLAB

- First full science run expected next year

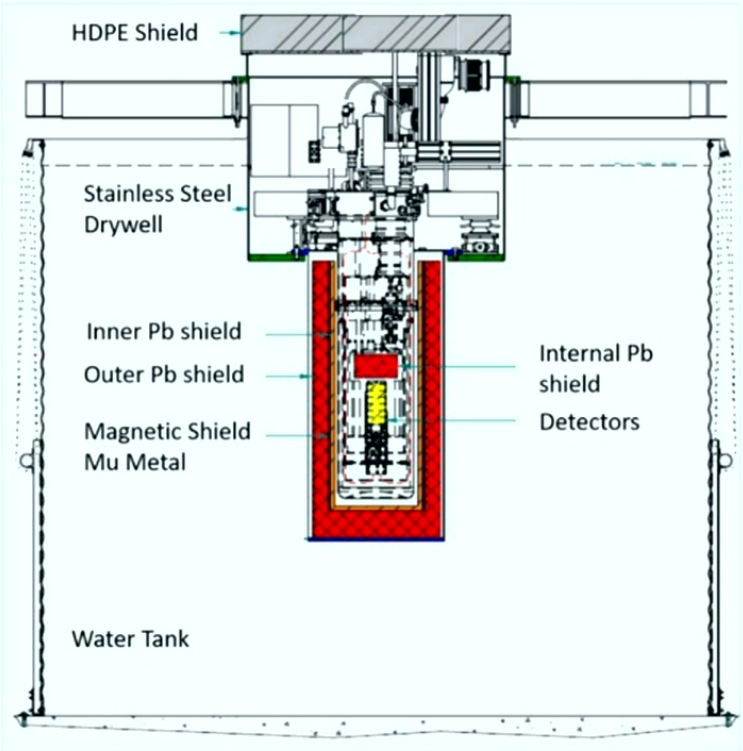
CUTE (Cryogenic Underground TEst) Facility @SNOLAB

One tower has been tested in CUTE

- Calibrations & detector response
- Background measurements
- "Early science data"!



https://arxiv.org/abs/2310.07930



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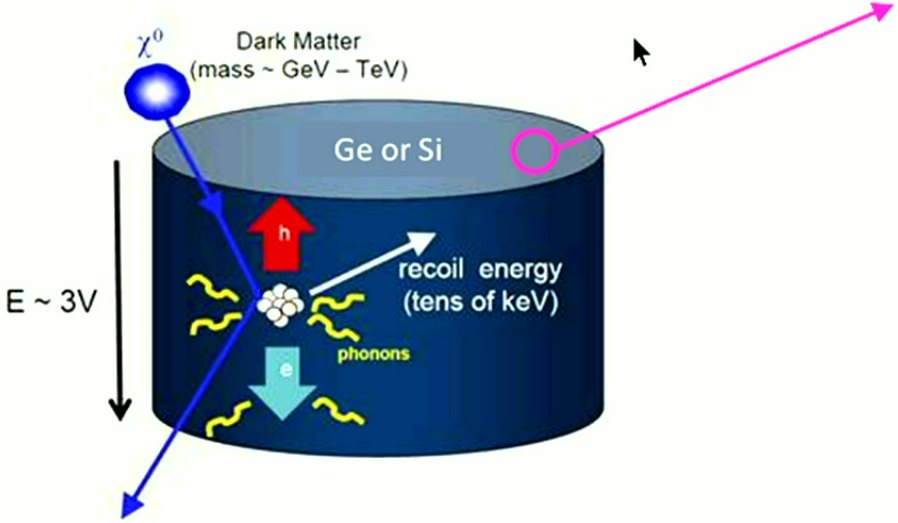
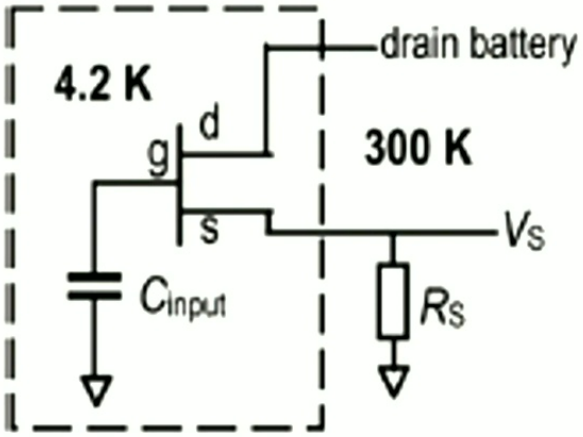
Charge Channels: High Electron Mobility Transistors

Low-noise amplifiers to read out small ionization signals





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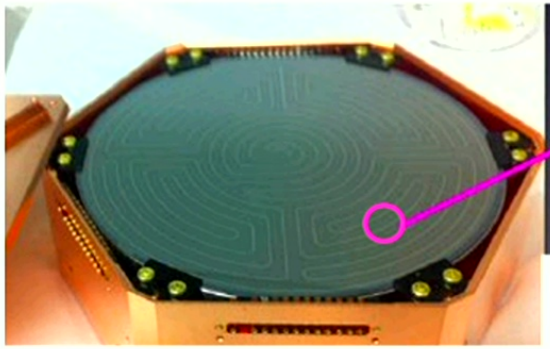
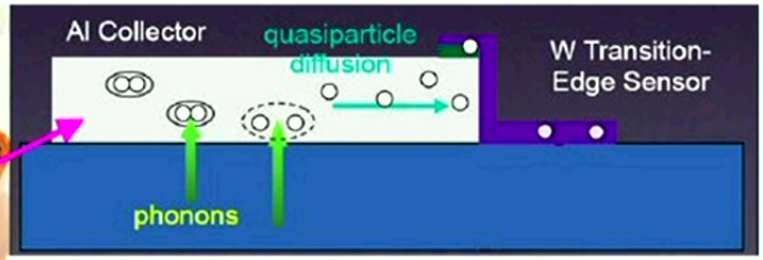
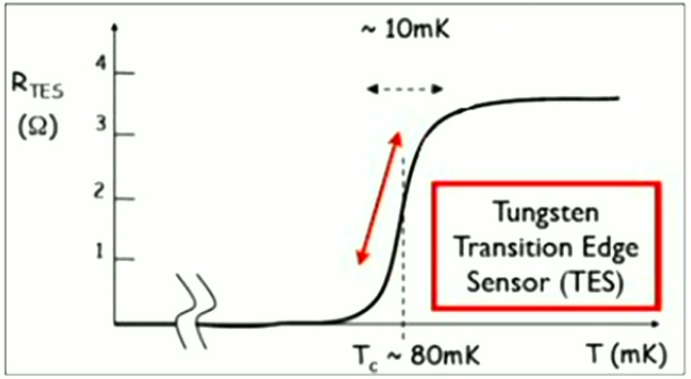
Phonon Channels: Transition Edge Sensors + SQUIDs





- **Phonon energy deposits cause TESs operated near critical temp to transition from superconducting to normal state**
- **Signal amplification by Superconducting Quantum Interference Devices**



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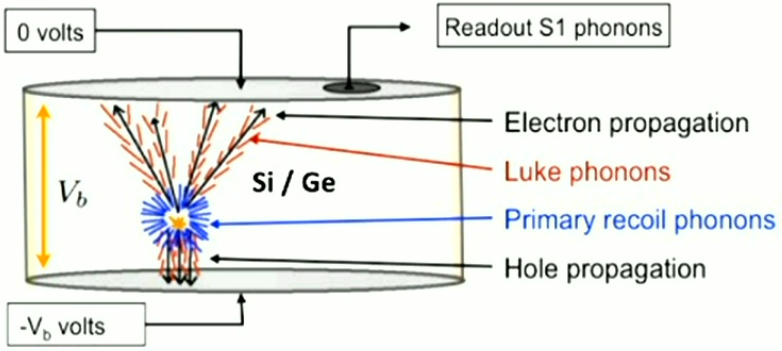
Jun 19 2:53 CA

New in SuperCDMS: Phonon Signal Amplification

- **Drifting charges across a V_b generates cascade of "Luke phonons"**
  - **Lowers recoil energy threshold**
  - **But "true calorimetry" and NR vs ER discrimination lost**



$$E_t = E_r + n_{eh} q V_b$$

Total phonon energy	Primary recoil energy	Luke phonon energy

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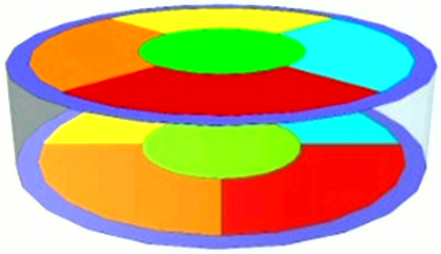
SuperCDMS Detector Types

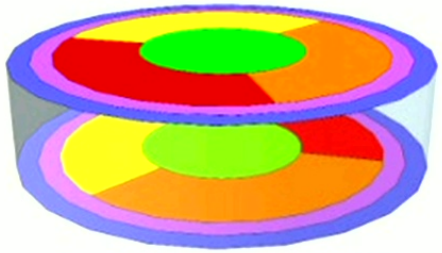
Interleaved Z-sensitive Ionization & Phonon: both HEMTs and TESs

- **ER vs NR discrimination, especially useful for background rejection**



High Voltage: only TESs

- **lower energy threshold**



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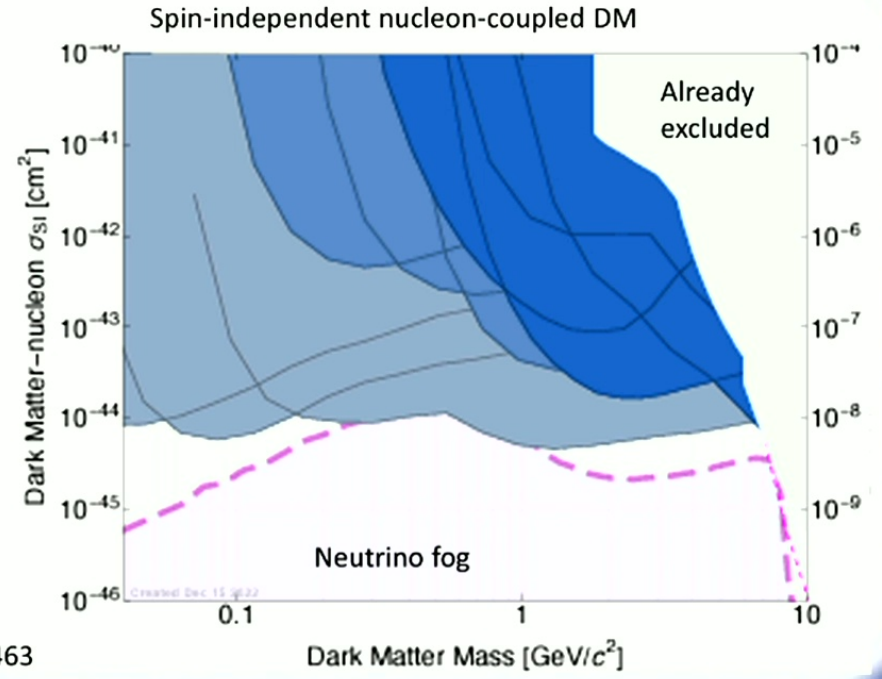
SuperCDMS@SNOLAB Sensitivity Projections

Projection for setup under construction

Possible with near-term upgrades

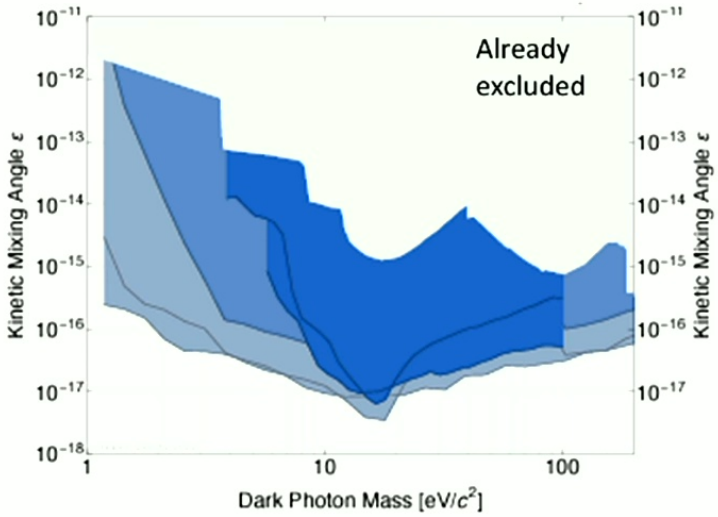
Possible with longer-term upgrades



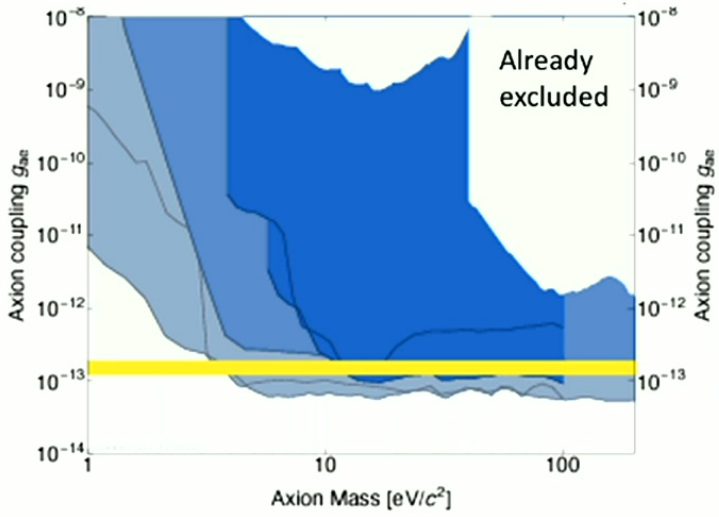
arxiv.org/abs/2203.08463

SuperCDMS@SNOLAB Sensitivity Projections

Dark Photon



Axion-Like Particle DM



arxiv.org/abs/2203.08463

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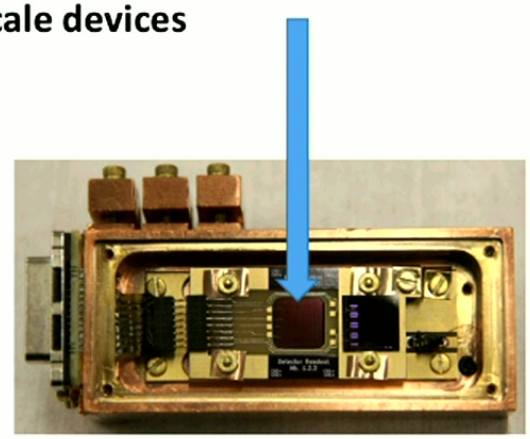
Results from Prototypes at Test Facilities are Exciting!

"HVeV", "CPD" Si prototypes: gram-scale devices



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Jun 19 2:59 CA

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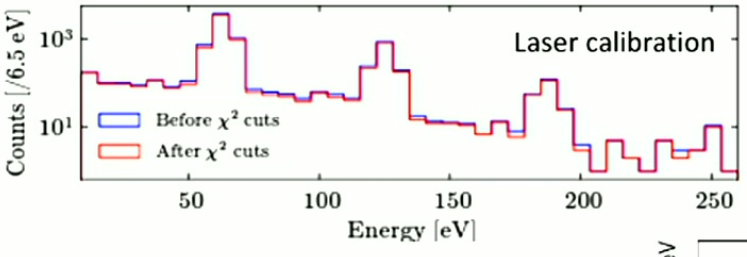
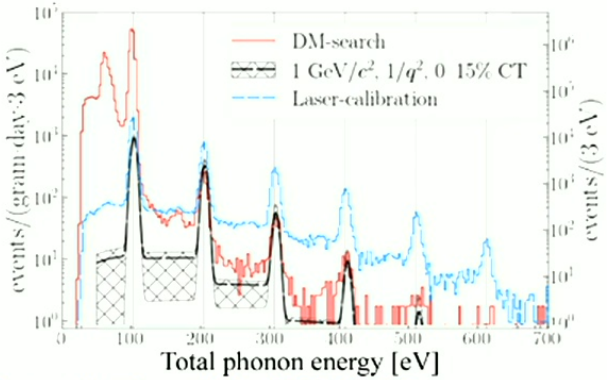
Results from Prototypes at Test Facilities are Exciting!



Few eV phonon resolution, can see single electron-hole pairs

https://arxiv.org/abs/2204.08038



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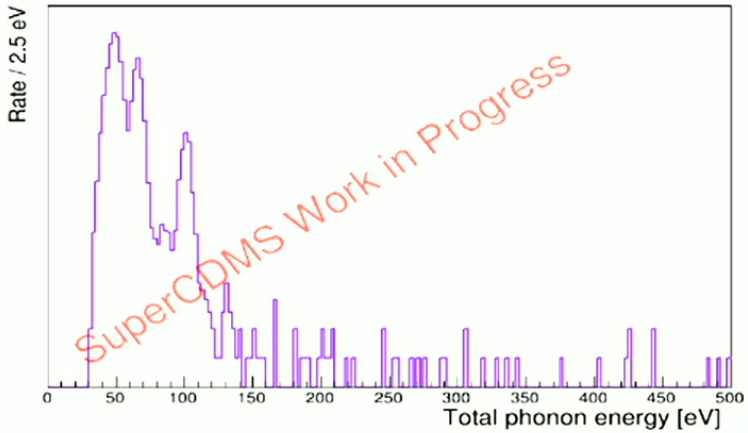

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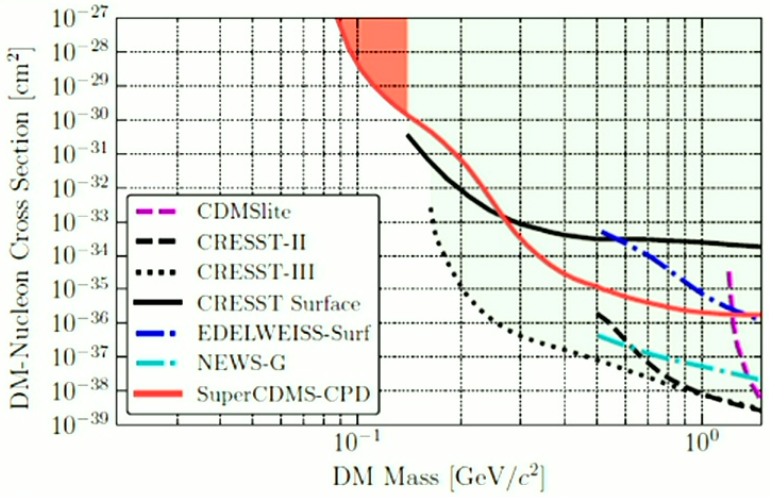
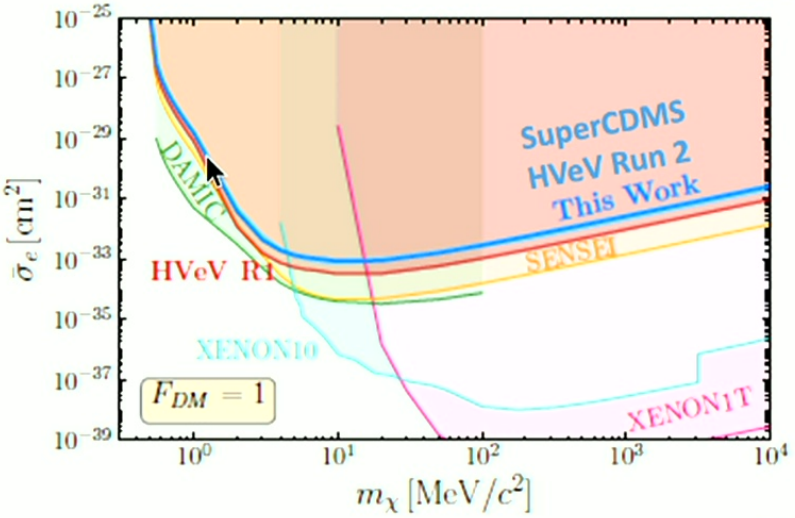
Nuclear Recoil & Electron Recoil Limits

Nuclear Recoil



https://arxiv.org/abs/2007.14289

Electron Recoil



https://arxiv.org/abs/2005.14067

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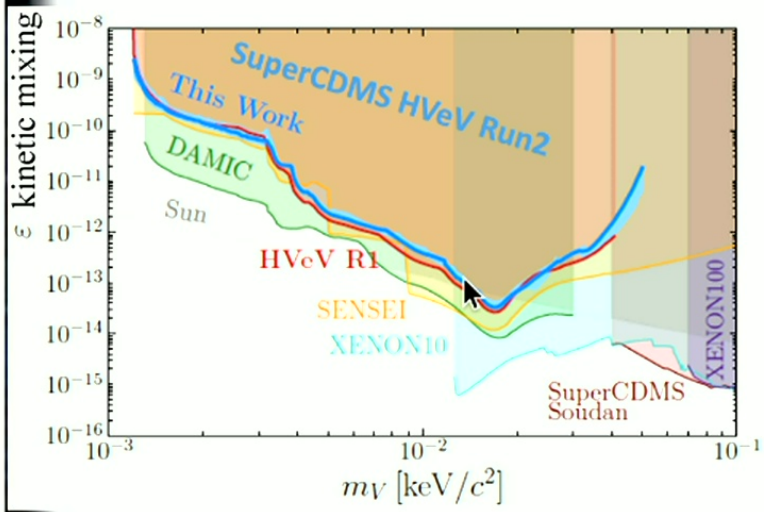
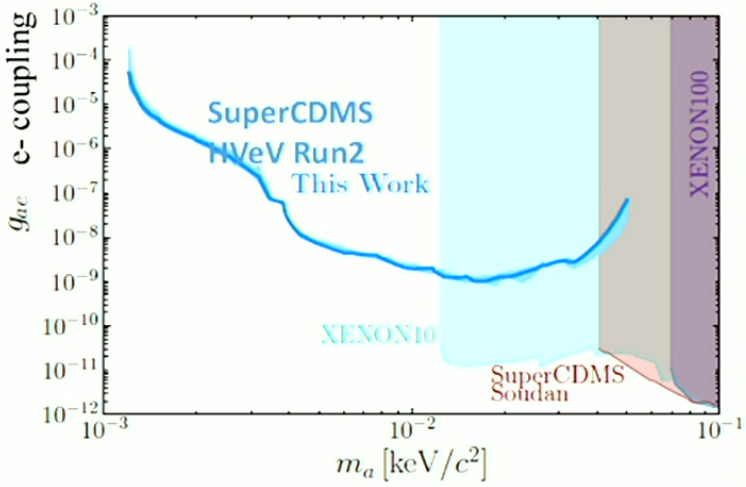
Dark Absorption: Dark Photon & Axion-Like Limits

Dark Photons



Axion-Like Particles



https://arxiv.org/abs/2005.14067

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Jun 19 3:00 CA

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@SuperCDMS

https://www.snolab.ca/experiment/supercdms/

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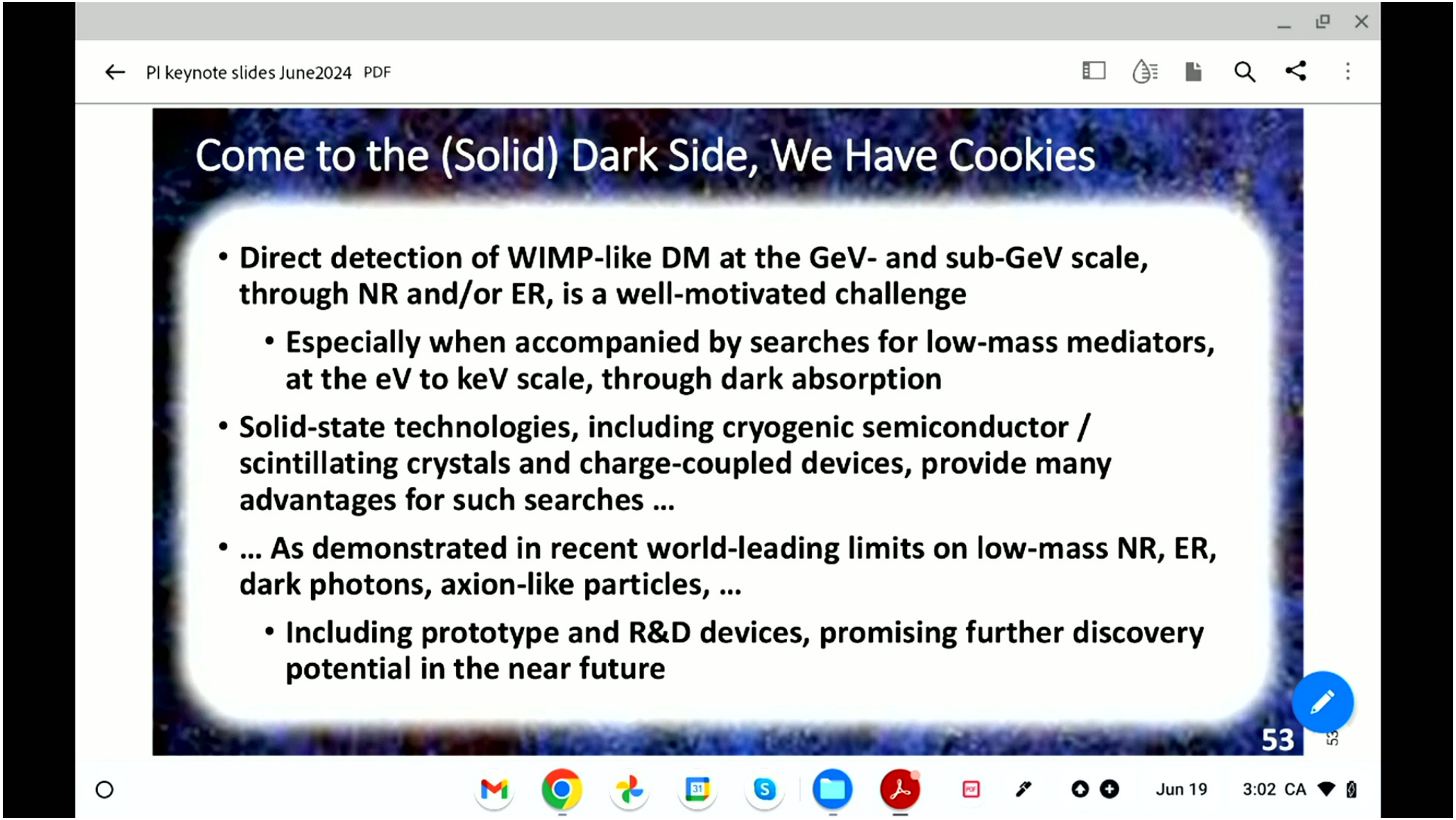
Jun 19 3:01 CA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Come to the (Solid) Dark Side, We Have Cookies
• Direct detection of WIMP-like DM at the GeV- and sub-GeV scale, through NR and/or ER, is a well-motivated challenge
• Especially when accompanied by searches for low-mass mediators, at the eV to keV scale, through dark absorption
• Solid-state technologies, including cryogenic semiconductor / scintillating crystals and charge-coupled devices, provide many advantages for such searches …
• … As demonstrated in recent world-leading limits on low-mass NR, ER, dark photons, axion-like particles, …
• Including prototype and R&D devices, promising further discovery potential in the near future
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Jun 19
3:02 CA