# Paving the Way to New Discoveries in Particle Physics: The Dark Matter Experimental Landscape

Stephen Sekula[1,2,3]

[1]SNOLAB, Lively, ON, Canada
[2]Queen's University, Kingston, ON, Canada
[3]Laurentian University, Sudbury, ON, Canada

February 5, 2026

# Table of Contents




PICO collaborators stand inside the freshly welded and completed PICO-500 pressure vessel at SNOLAB.

# What is the goal?

## What are my goals for this talk?

- I will focus on **direct detection of particle-like interactions**.
- Production by colliders [1, 2], detection through astronomy [3, 4], and direct detection of wave-like candidates (e.g., axions) [5, 6]* **are all important**.
- A discovery in any one broad area will necessarily lead to measurements and ideas across all approaches†. All of us must be ready.

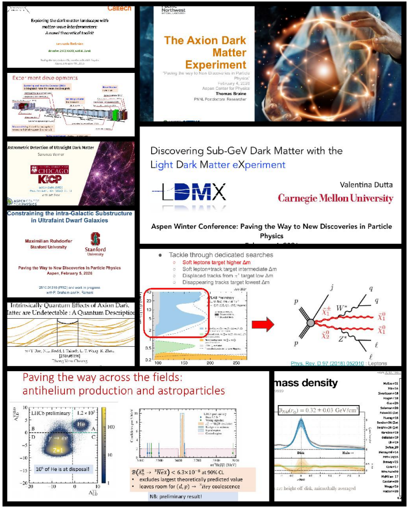
---

*If you're curious about perspectives on wave-like searches, ask me at the end.

†For example, the AMS-02 Helium and LHCb $\Lambda_b$ business shown by Lesya [7]

# What are my goals for this talk?

- I will focus on **direct detection of particle-like interactions**.
- Production by colliders [1, 2], detection through astronomy [3, 4], and direct detection of wave-like candidates (e.g., axions) [5, 6]* **are all important**.
- A discovery in any one broad area will necessarily lead to measurements and ideas across all approaches†. All of us must be ready.

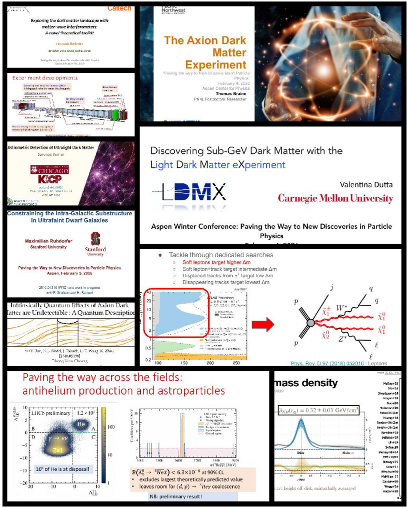



*If you're curious about perspectives on wave-like searches, ask me at the end.

†For example, the AMS-02 Helium and LHCb $\Lambda_b$ business shown by Lesya [7]

# What are my goals for this talk?

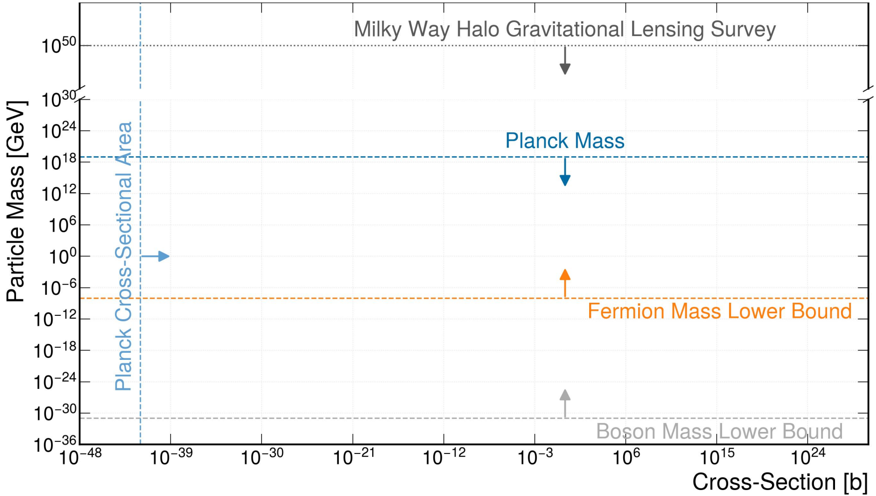
- I will focus on **direct detection of particle-like interactions**.
- Production by colliders [1, 2], detection through astronomy [3, 4], and direct detection of wave-like candidates (e.g., axions) [5, 6]* **are all important**.
- A discovery in any one broad area will necessarily lead to measurements and ideas across all approaches†. All of us must be ready.




*If you're curious about perspectives on wave-like searches, ask me at the end.

†For example, the AMS-02 Helium and LHCb $\Lambda_b$ business shown by Lesya [7]

# What are the edges of the map?

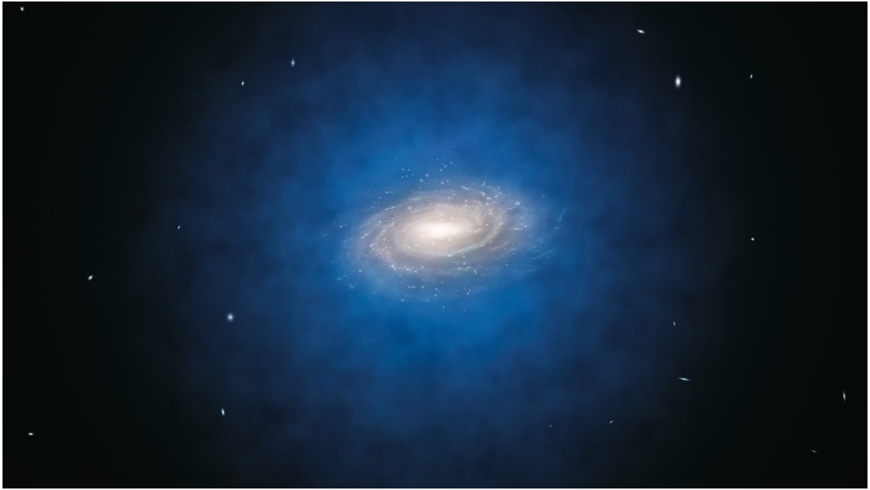



The map ignores (on purpose) constraints from freeze-in/freeze-out* and progress in direct detection searches (we'll circle back to those in a bit).

The focus here is on external constraints that are "safe" in the sense that they are motivated by simple(-ish) principles or independent astronomical interpretations.

*Feel free to ask me why later.

## Dark matter particles should be all around us

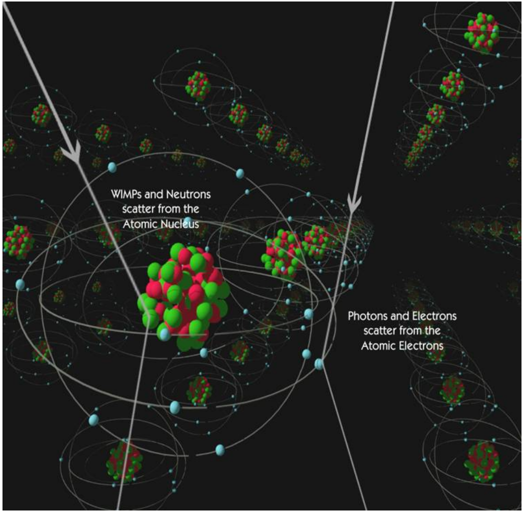


The local density is estimated to be about $0.3-0.6\ \mathrm{GeV\,cm^{-3}}$.*

The average speed of dark matter is estimated from solar motion through the galaxy ($v \approx 240\ \mathrm{km/s}$).

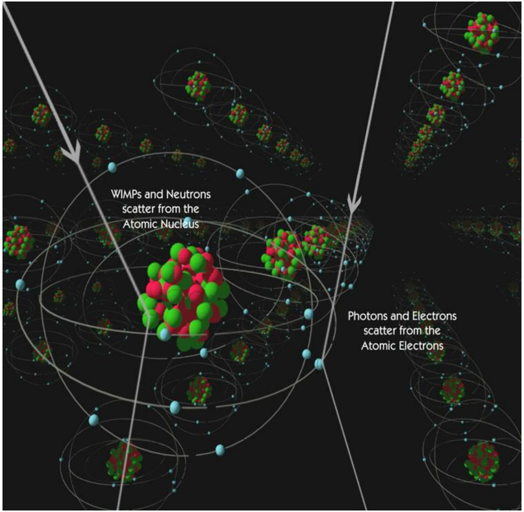
*e.g. $\rho_{\odot} = (0.44 \pm 0.13)\ \mathrm{GeV\,cm^{-3}}$ from a recent analysis of Gaia DR3 K-type dwarf star data [8] and $(0.32 \pm 0.03)\ \mathrm{GeV\,cm^{-3}}$ from the work David Shih shared yesterday [3].

## Direct detection has some core principles



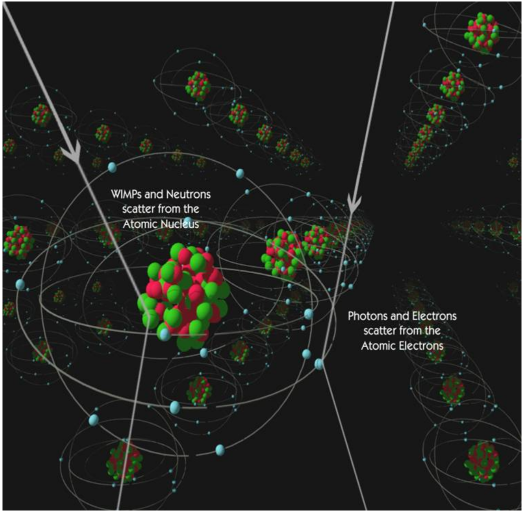

- Dark matter and standard model matter have some coupling besides gravitation by which they can interact.
- Atomic matter will respond in some way that results in the release of energy: ionization, scintillation, phonons (heat), etc.
- The interactions can be elastic or inelastic. The sensitivity to elastic collisions is optimal when $m_\chi \approx m_{\text{target}}$. Inelastic collisions relax that constraint but are more challenging to detect/interpret.

## Direct detection has some core principles



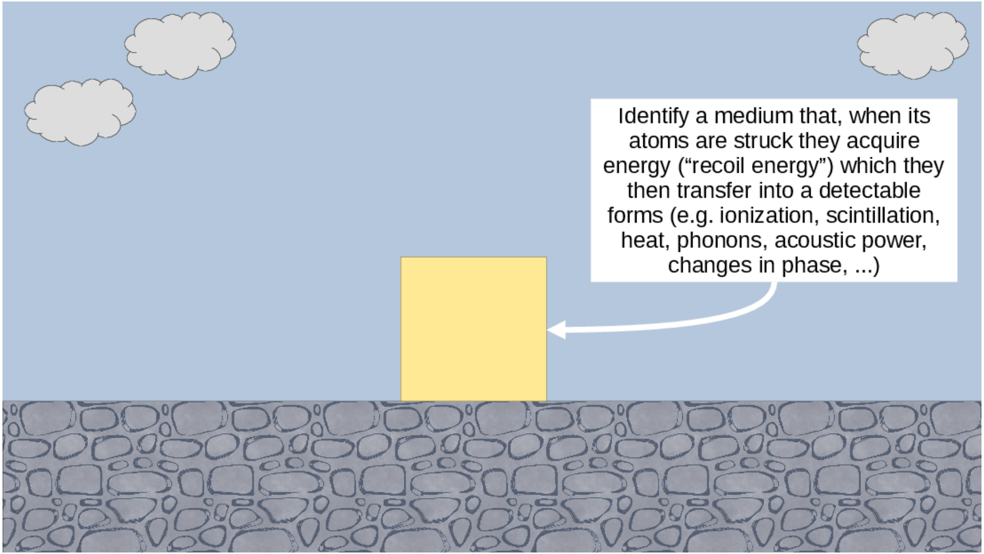

- Dark matter and standard model matter have some coupling besides gravitation by which they can interact.
- Atomic matter will respond in some way that results in the release of energy: ionization, scintillation, phonons (heat), etc.
- The interactions can be elastic or inelastic. The sensitivity to elastic collisions is optimal when $m_\chi \approx m_{\mathrm{target}}$. Inelastic collisions relax that constraint but are more challenging to detect/interpret.

# Direct detection has some core principles

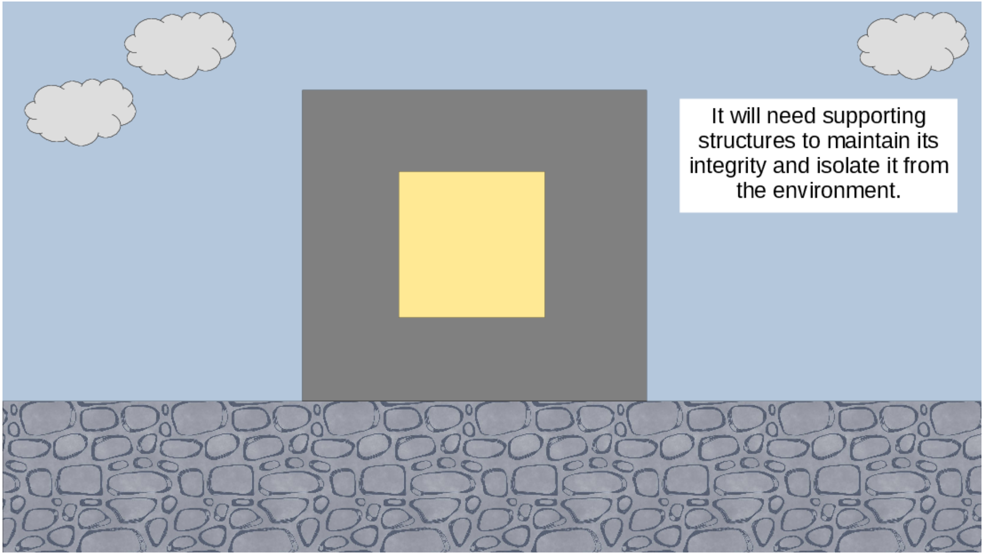



- Dark matter and standard model matter have some coupling besides gravitation by which they can interact.
- Atomic matter will respond in some way that results in the release of energy: ionization, scintillation, phonons (heat), etc.
- The interactions can be elastic or inelastic. The sensitivity to elastic collisions is optimal when $m_\chi \approx m_{\rm target}$. Inelastic collisions relax that constraint but are more challenging to detect/interpret.

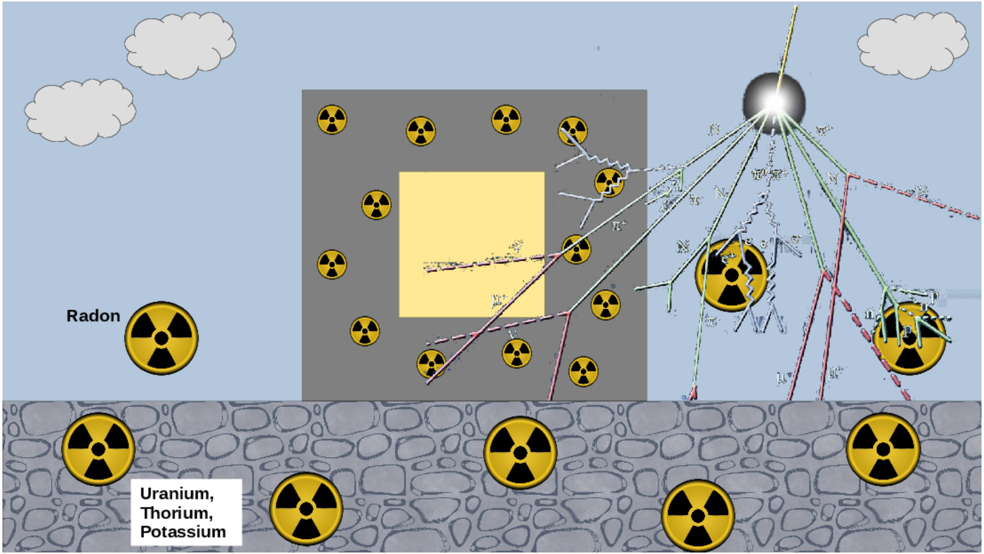
# So you want to build a dark matter detector. . .



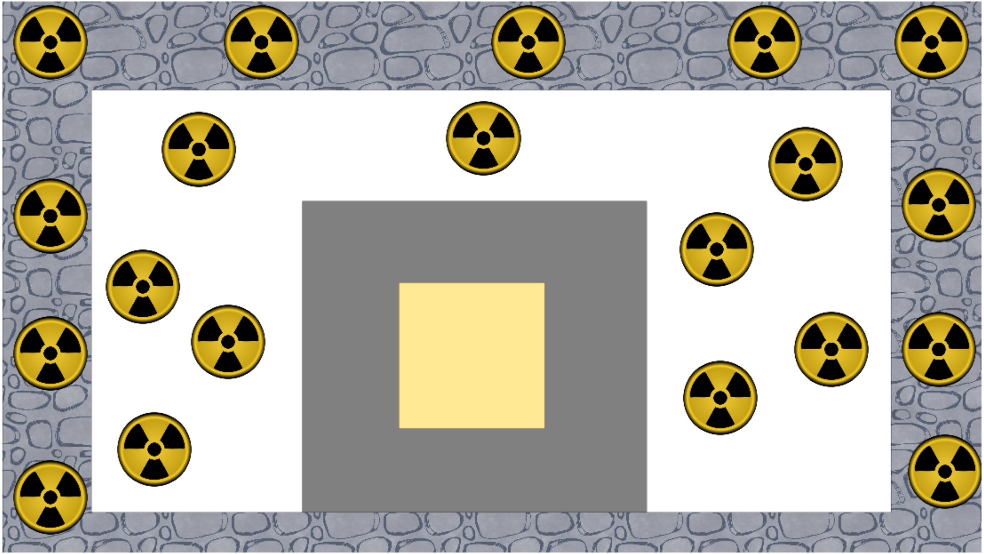
# So you want to build a dark matter detector. . .



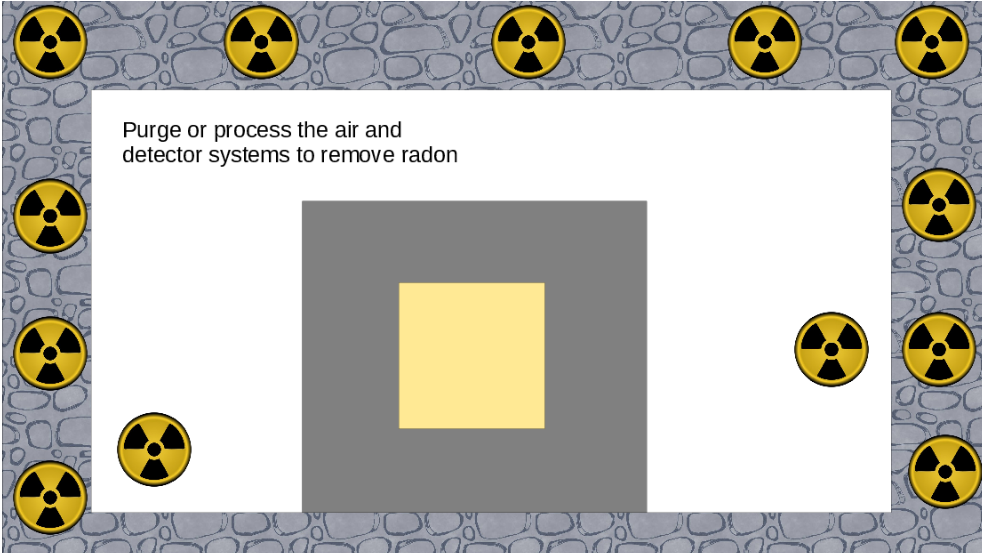
# So you want to build a dark matter detector. . .



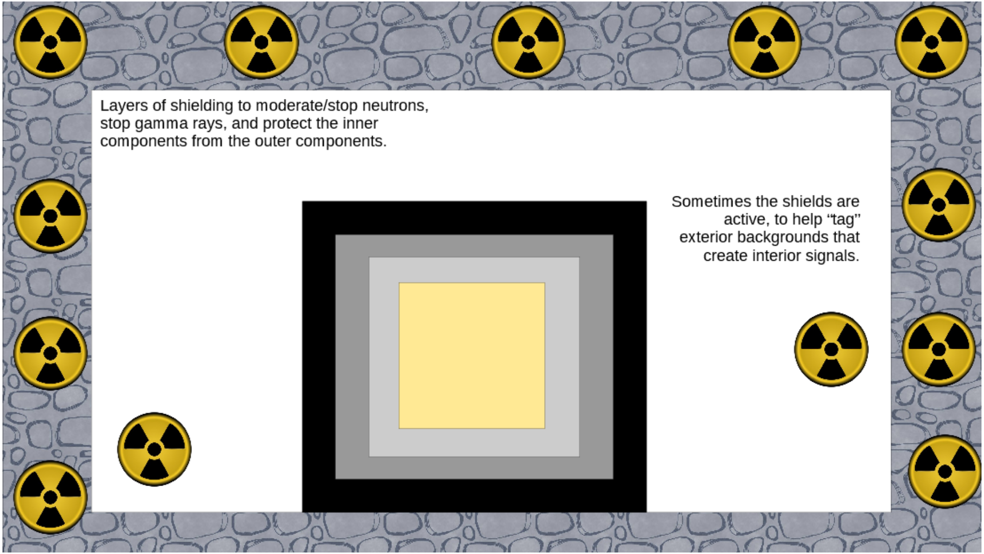
## So you want to build a dark matter detector. . .

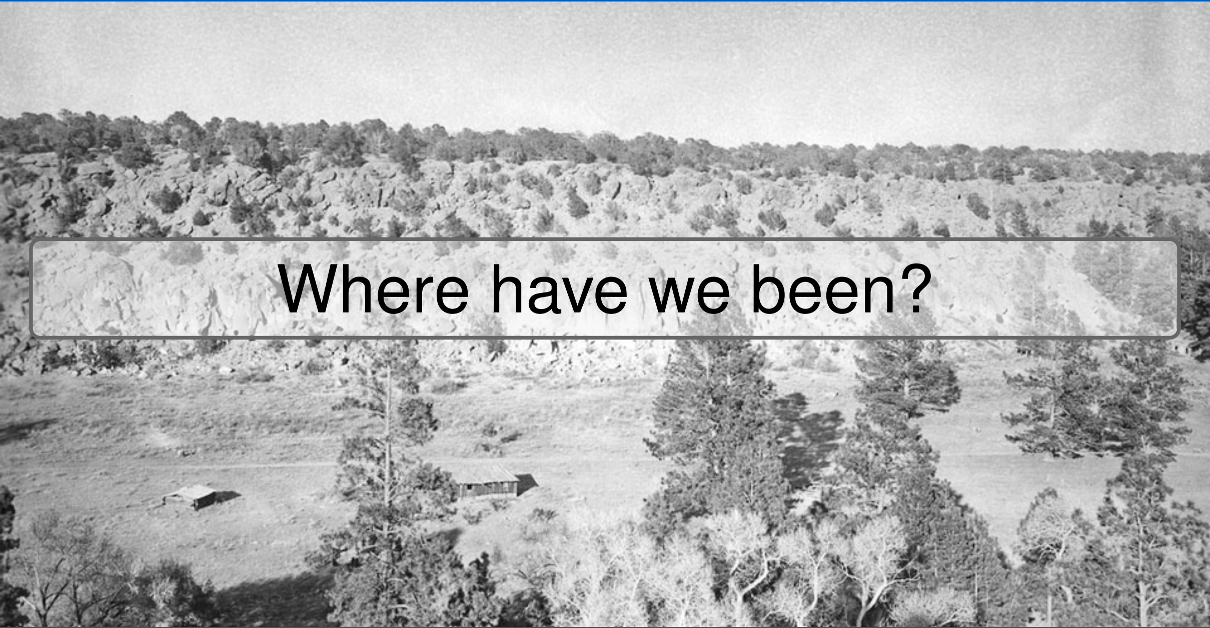


## So you want to build a dark matter detector. . .



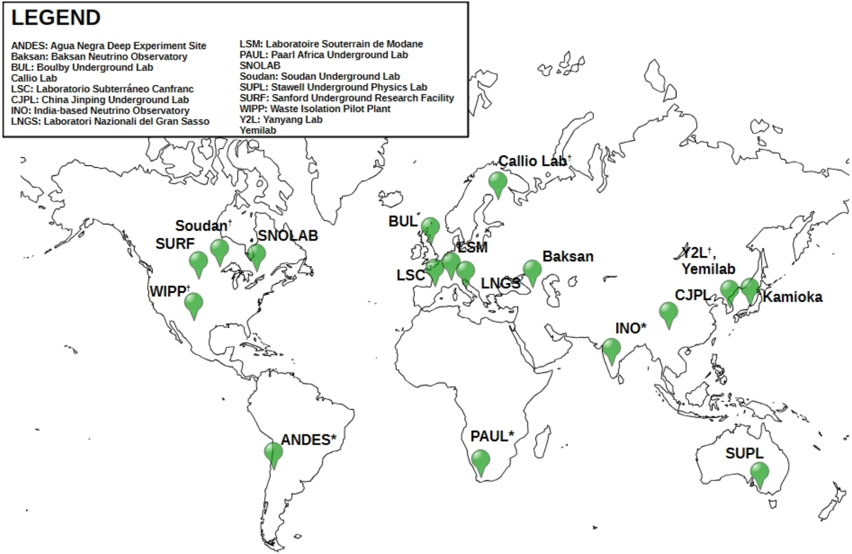
# So you want to build a dark matter detector. . .





# Where have we been?

# Underground Laboratories



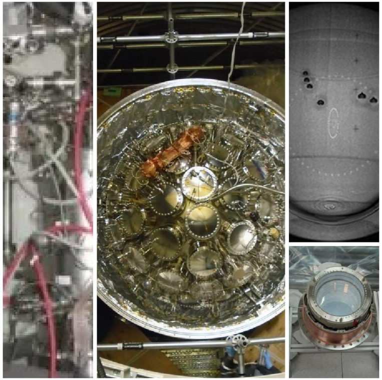

A map with markers showing underground facilities and the intensity of muons vs. depth. The symbols ⋆ and † indicate a conceptual lab and a lab that formerly hosted experiments, respectively.

# Common technologies for target design

## Solid

Ionization, phonons, scintillation

## Liquid

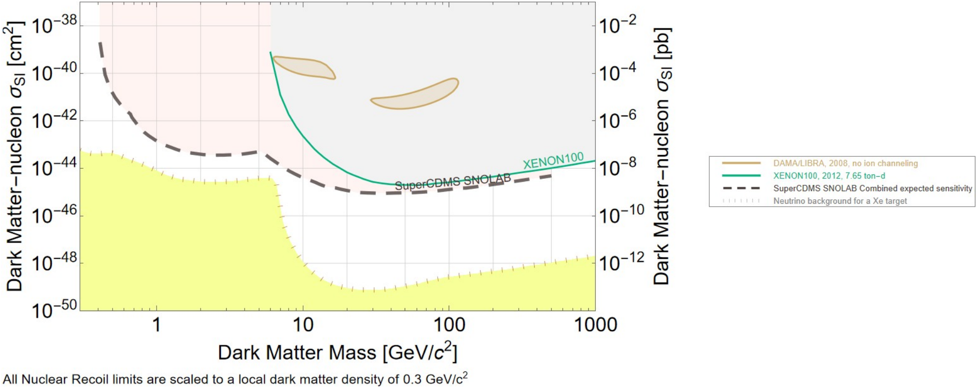


Heat, ionization, scintillation, vibration

## Gas

Ionization

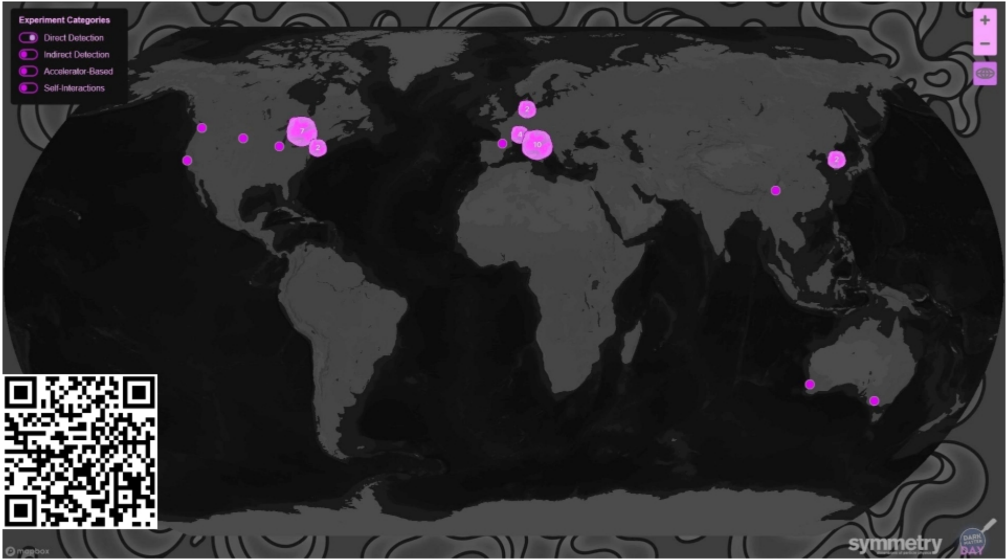
# Interpretations of detector scattering observations: cross-section and mass sensitivity [9, 10]



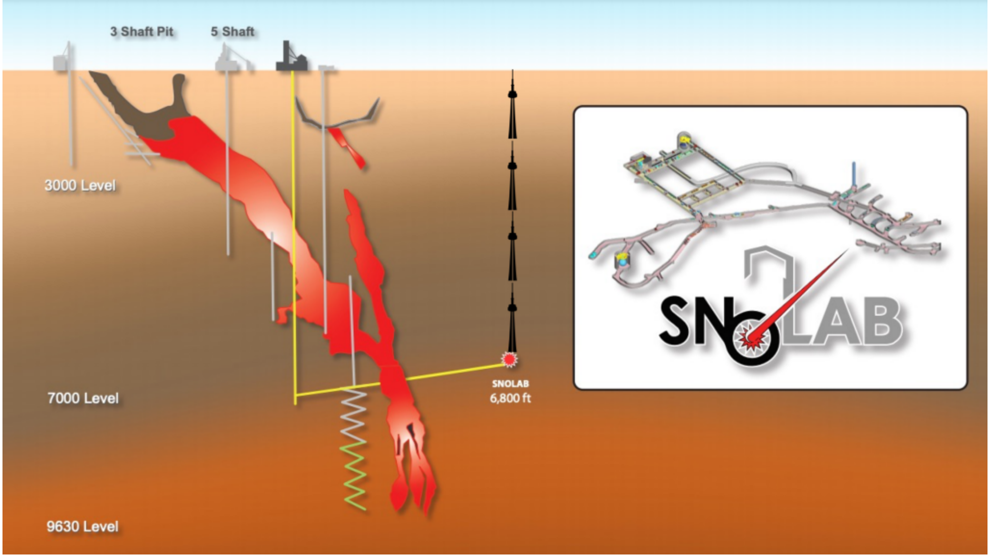

The state of constraints on particle-like dark matter for Snowmass 2013. A few example experiments are used: DAMA/LIBRA, XENON100, and a projection of SuperCDMS-SNOLAB from that era.

# Where are we now?

# A Map of Current Dark Matter Direct Detection Experiments (Axions Included)



# Example: SNOLAB in Sudbury, Ontario, Canada



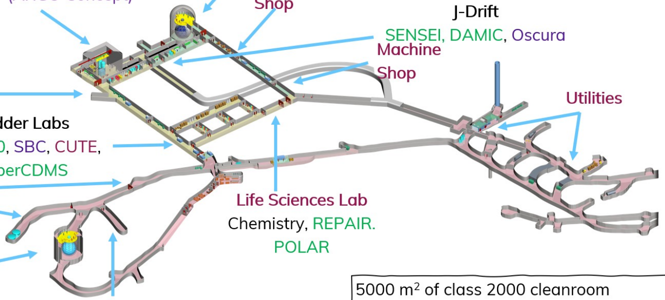
## Walking the Mine Drift

## Walking inside SNOLAB

# A busy, multidisciplinary underground laboratory

## SNOLAB – At a Glance

Current Experiments
Future Experiments
Laboratory Facilities
Experiment Areas



**Cube Hall**
DEAP-3600, PICO500, NEWS-G
(ARGO Concept)

**Cryopit**
(nEXO2.0/XLZD Concept)

**Electrical Shop**

**J-Drift**
SENSEI, DAMIC, Oscura

**Machine Shop**

**Utilities**

**Halo Stub**
HALO
potential breakthrough for
**Future Expansion**
(Theia Concept)

**Ladder Labs**
PICO40, SBC, CUTE, SuperCDMS

**Plants**
UPW, Scintillator, Te Diol, TeA, LN2

**SNO Cavern**
SNO+, SNO+ Te
Potential for large project after 2035

**Low Background Lab**
HPGe assay/screening, XRF, Radon Boards, XIA, CTBT Dual HPGe, IceCube DOM Testing

**Life Sciences Lab**
Chemistry, REPAIR. POLAR

5000 $m^2$ of class 2000 cleanroom underground.
<2000 particles >0.5 μm in diameter per $ft^3$
arXiv:2006.12746

# Current-generation dark matter experiments

**Gas:** NEWS-G;

**Liquid/Argon:** DarkSide-50, DEAP-3600;

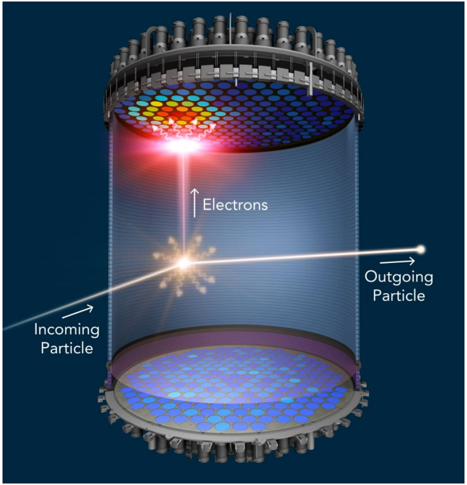
**Liquid/Superheated:** PICO-40L, SBC;

**Liquid/Xenon:** LZ, PandaX-4T, XENONnT;

**Solid/Crystal:** ANAIS, COSINE-100, DAMA/LIBRA, SABRE, SuperCDMS-SNOLAB;

**Solid/CCD:** DAMIC, DAMIC-M, SENSEI.

# Example: LUX-ZEPLIN (LZ) Detector and Backgrounds [11, 12]




LZ concept (graphic from SLAC)

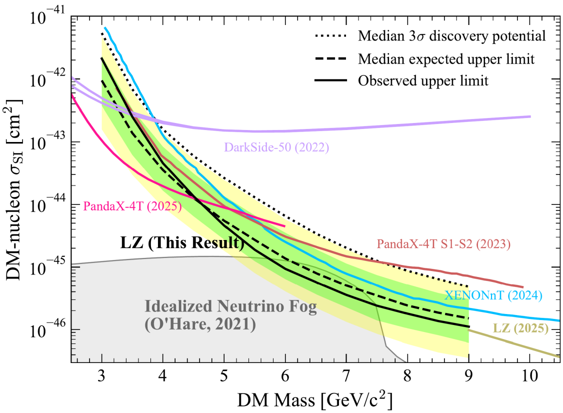
Vital stats: 7 T ($\approx 78\%$ fiducial), dual-phase liquid Xe TPC

Light Dark Matter Backgrounds and Signals:

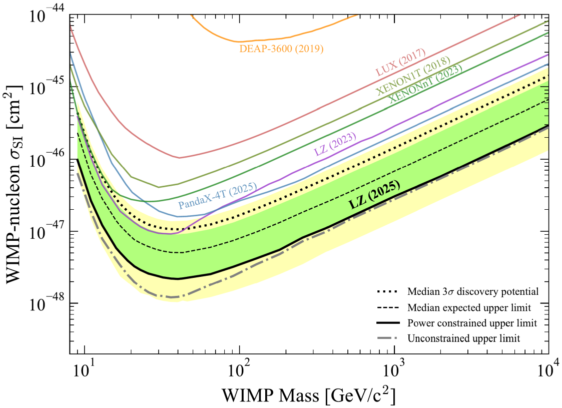
| Components | Expectation | 3 GeV/$c^2$ Fit | $^8$B CE$\nu$NS Unconstrained Fit |
|---|---|---|---|
| SI DM | - | $0.4^{+5.4}_{-0.4}$ | - |
| $^8$B CE$\nu$NS | $20.6^{+8.9}_{-6.8}$ | $14.7^{+3.0}_{-2.8}$ | $12.3^{+7.0}_{-5.4}$ |
| Accidental coinc. | $6.6 \pm 0.3$ | $6.5 \pm 0.3$ | $6.6 \pm 0.3$ |
| Detector neutrons | $0.04^{+0.25}_{-0.04}$ | $0.1^{+0.2}_{-0.1}$ | $0.1^{+0.2}_{-0.1}$ |
| Total | $27.2^{+10.1}_{-7.3}$ | $21.7^{+6.2}_{-2.8}$ | $18.9^{+7.0}_{-5.5}$ |
| $\sigma_{\text{eff}}$ | $0 \pm 1$ | $-0.86^{+0.63}_{-0.71}$ | $0 \pm 1$ |

Key radionuclide contaminants are (in order from dominant to subdominant): $^{214}\mathrm{Pb}$, $^{85}\mathrm{Kr}$, $^{39}\mathrm{Ar}$, $^{212}\mathrm{Pb}$, $^{218}\mathrm{Po}$, $^{3}\mathrm{H}$, $^{13}\mathrm{C}$, $^{136}\mathrm{Xe}$, $^{124}\mathrm{Xe}$, $^{127}\mathrm{Xe}$

# LUX-ZEPLIN: Recent Results in Heavy and Light DM [12, 11]




Light Dark Matter

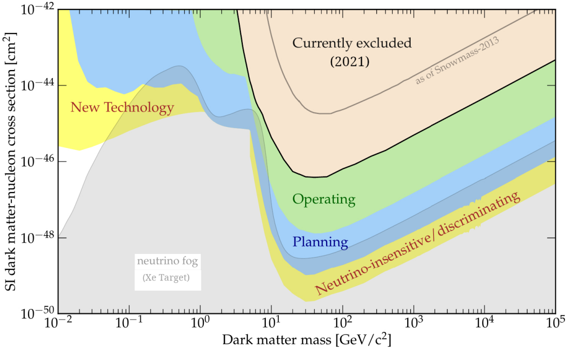



Heavy Dark Matter

## Spin-Independent Elastic Scattering Constraints

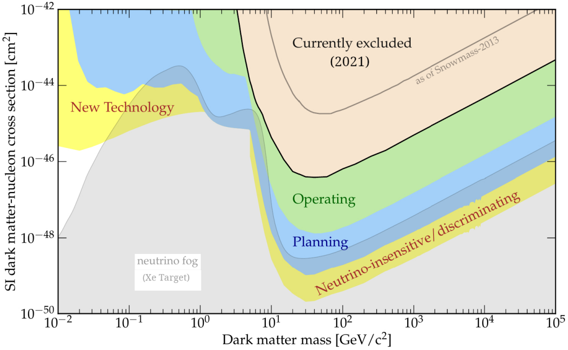
# Where are we going?

# We must confront neutrino physics

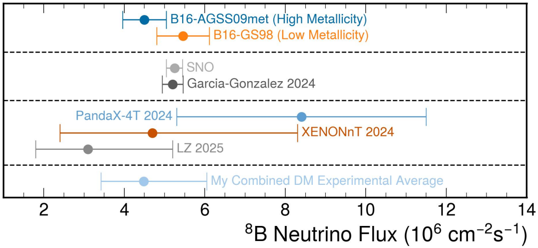



In 2021–2022 [13], "Operating" experiments included LZ, XENONnT, PandaX-4T, SuperCDMS-SNOLAB, and the Scintillating Bubble Chamber. "Planned" were SuperCDMS, DarkSide-LowMass, SBC, a 1000 tonne-year liquid Xe detector, and ARGO.

# We must confront neutrino physics

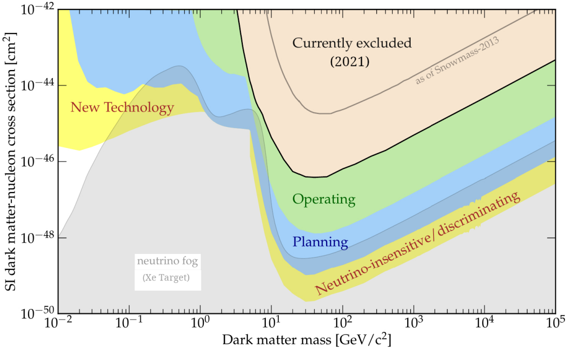



In 2021–2022 [13], "Operating" experiments included LZ, XENONnT, PandaX-4T, SuperCDMS-SNOLAB, and the Scintillating Bubble Chamber. "Planned" were SuperCDMS, DarkSide-LowMass, SBC, a 1000 tonne-year liquid Xe detector, and ARGO.

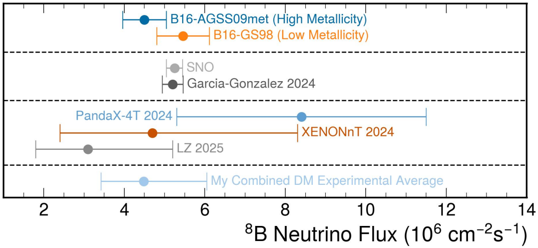



$^8$B CE$\nu$NS theory predictions (low- and high-metallicity stars) [14], SNO [15] and multi-experiment combined measurements [16], DM experiment measurements [17, 18, 12], and a naive combination of DM experiments. LZ rejects the 0-CE$\nu$NS hypothesis at $4.5\sigma$.

# We must confront neutrino physics



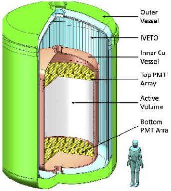

In 2021–2022 [13], "Operating" experiments included LZ, XENONnT, PandaX-4T, SuperCDMS-SNOLAB, and the Scintillating Bubble Chamber. "Planned" were SuperCDMS, DarkSide-LowMass, SBC, a 1000 tonne-year liquid Xe detector, and ARGO.

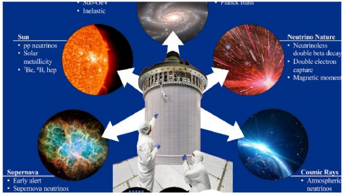


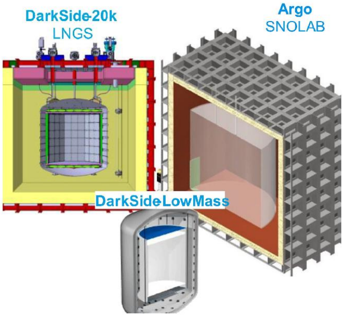

$^8$B CE$\nu$NS theory predictions (low- and high-metallicity stars) [14], SNO [15] and multi-experiment combined measurements [16], DM experiment measurements [17, 18, 12], and a naive combination of DM experiments. LZ rejects the 0-CE$\nu$NS hypothesis at $4.5\sigma$.

**We are in an era where these instruments are absolutely confirmed to be weakly interacting (somewhat) massive particle detectors.**

# Large Scale Technologies

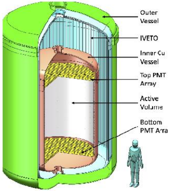


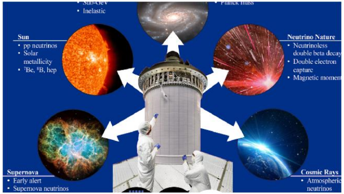



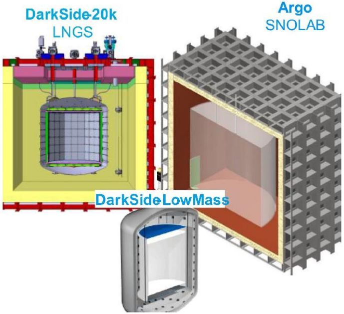




- The liquid noble technology has essentially shown it knows how to scale. Experiments are generally joining together into large collaborations behind xenon (XLZD) and Argon (DarkSide-20k and then ARGO) concepts. The PandaX collaboration has pitched PandaX-xT. All of these are $O(10-100)$ tonne detectors.
- Bubble chambers are currently scaling-limited by the size of the vessel that holds the target fluid (low-background fused silica quartz glass). Beyond PICO-500, it's not clear how (or whether) to scale up this technology...
- ...but maybe the latter doesn't need to scale, just get more clever. The Scintillating Bubble Chamber (SBC)uses cryogenic superheated argon and gets bubble images and sound **plus** scintillation light, for enhanced background rejection.

# Large Scale Technologies

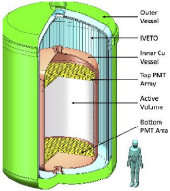


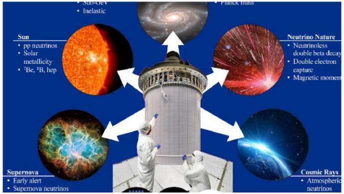



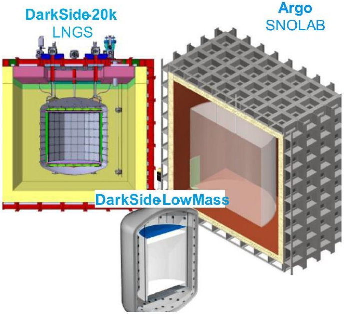




- The liquid noble technology has essentially shown it knows how to scale. Experiments are generally joining together into large collaborations behind xenon (XLZD) and Argon (DarkSide-20k and then ARGO) concepts. The PandaX collaboration has pitched PandaX-xT. All of these are $O(10-100)$ tonne detectors.
- Bubble chambers are currently scaling-limited by the size of the vessel that holds the target fluid (low-background fused silica quartz glass). Beyond PICO-500, it's not clear how (or whether) to scale up this technology. . .
- . . . but maybe the latter doesn't need to scale, just get more clever. The Scintillating Bubble Chamber (SBC)uses cryogenic superheated argon and gets bubble images and sound **plus** scintillation light, for enhanced background rejection.

# Large Scale Technologies

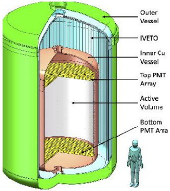


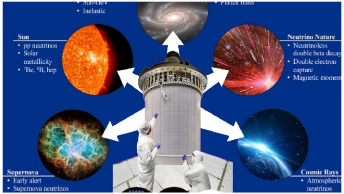



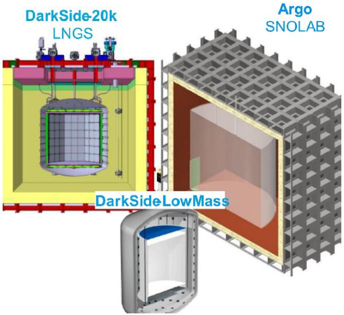




- The liquid noble technology has essentially shown it knows how to scale. Experiments are generally joining together into large collaborations behind xenon (XLZD) and Argon (DarkSide-20k and then ARGO) concepts. The PandaX collaboration has pitched PandaX-xT. All of these are $O(10-100)$ tonne detectors.
- Bubble chambers are currently scaling-limited by the size of the vessel that holds the target fluid (low-background fused silica quartz glass). Beyond PICO-500, it's not clear how (or whether) to scale up this technology. . .
- . . . but maybe the latter doesn't need to scale, just get more clever. The Scintillating Bubble Chamber (SBC)uses cryogenic superheated argon and gets bubble images and sound **plus** scintillation light, for enhanced background rejection.

# Large Scale Technologies




- The liquid noble technology has essentially shown it knows how to scale. Experiments are generally joining together into large collaborations behind xenon (XLZD) and Argon (DarkSide-20k and then ARGO) concepts. The PandaX collaboration has pitched PandaX-xT. All of these are $O(10-100)$ tonne detectors.
- Bubble chambers are currently scaling-limited by the size of the vessel that holds the target fluid (low-background fused silica quartz glass). Beyond PICO-500, it's not clear how (or whether) to scale up this technology. . .
- . . . but maybe the latter doesn't need to scale, just get more clever. The Scintillating Bubble Chamber (SBC)uses cryogenic superheated argon and gets bubble images and sound **plus** scintillation light, for enhanced background rejection.

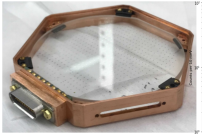
# A Broad Spectrum Search Means All Physics on Deck [20, 21, 22, 23, 24, 25, 26]

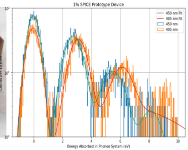
| Target | Reaction processes | Typical gap | Elastic or inelastic? | DM Mass Range |
|---|---|---|---|---|
| Atom | Ionization | 10 eV | Inelastic | $\gtrsim$ 10 MeV–GeV |
| Semiconductor | Excitation across band gap | $\sim$ 1 eV | Inelastic | MeV–GeV |
| Superconductor | Cooper pair breaking | $\sim$ 1 meV | Approximately elastic[a] | $\gtrsim$ 1 keV–GeV |
| Graphene | Electron ejection | $\sim$ 1 eV | Inelastic | $\gtrsim$ 1 MeV–GeV |
| Dirac material | Excitation across band gap | $\sim$ 0–1 meV | Inelastic | keV–GeV |
| Heavy fermion material | Excitation across band gap | $\sim$ 10 meV | Inelastic | 10 keV–GeV |

# A Broad Spectrum Search Means All Physics on Deck [20, 21, 22, 23, 24, 25, 26]

| Target | Reaction processes | Typical gap | Elastic or inelastic? | DM Mass Range |
|---|---|---|---|---|
| Atom | Ionization | 10 eV | Inelastic | $\gtrsim$ 10 MeV–GeV |
| Semiconductor | Excitation across band gap | $\sim$ 1 eV | Inelastic | MeV–GeV |
| Superconductor | Cooper pair breaking | $\sim$ 1 meV | Approximately elastic[a] | $\gtrsim$ 1 keV–GeV |
| Graphene | Electron ejection | $\sim$ 1 eV | Inelastic | $\gtrsim$ 1 MeV–GeV |
| Dirac material | Excitation across band gap | $\sim$ 0–1 meV | Inelastic | keV–GeV |
| Heavy fermion material | Excitation across band gap | $\sim$ 10 meV | Inelastic | 10 keV–GeV |

EXAMPLE: Polar Crystals in TESSARACT/SPICE:



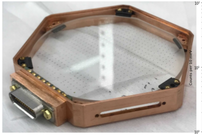


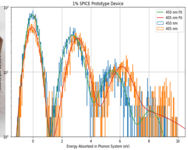

TESSARACT is sited for construction at Laboratoire Souterrain de Modane (LSM)

# A Broad Spectrum Search Means All Physics on Deck [20, 21, 22, 23, 24, 25, 26]

| Target | Reaction processes | Typical gap | Elastic or inelastic? | DM Mass Range |
|---|---|---|---|---|
| Atom | Ionization | 10 eV | Inelastic | $\gtrsim$ 10 MeV–GeV |
| Semiconductor | Excitation across band gap | $\sim$ 1 eV | Inelastic | MeV–GeV |
| Superconductor | Cooper pair breaking | $\sim$ 1 meV | Approximately elastic[a] | $\gtrsim$ 1 keV–GeV |
| Graphene | Electron ejection | $\sim$ 1 eV | Inelastic | $\gtrsim$ 1 MeV–GeV |
| Dirac material | Excitation across band gap | $\sim$ 0–1 meV | Inelastic | keV–GeV |
| Heavy fermion material | Excitation across band gap | $\sim$ 10 meV | Inelastic | 10 keV–GeV |

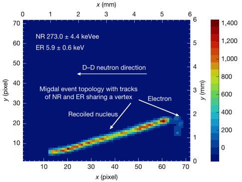
EXAMPLE: Polar Crystals in TESSARACT/SPICE:






TESSARACT is sited for construction at Laboratoire Souterrain de Modane (LSM)

EXAMPLE: Migdal effect observed [19]

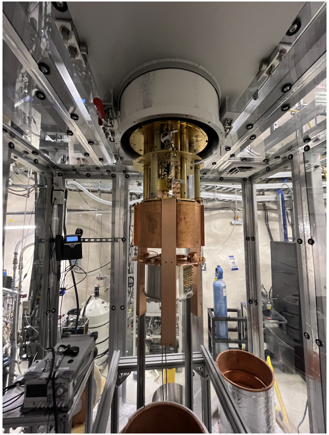



First observation with $\sigma_{\mathrm{Migdal}}/\sigma_{\mathrm{recoil}} = 4.9^{+2.6}_{-1.9} \times 10^{-5}$!

# A Broad Spectrum Search Means All Physics on Deck [20, 21, 22, 23, 24, 25, 26]

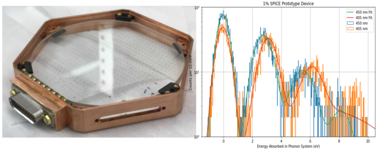
| Target | Reaction processes | Typical gap | Elastic or inelastic? | DM Mass Range |
|---|---|---|---|---|
| Atom | Ionization | 10 eV | Inelastic | $\gtrsim$ 10 MeV–GeV |
| Semiconductor | Excitation across band gap | $\sim$ 1 eV | Inelastic | MeV–GeV |
| Superconductor | Cooper pair breaking | $\sim$ 1 meV | Approximately elastic[a] | $\gtrsim$ 1 keV–GeV |
| Graphene | Electron ejection | $\sim$ 1 eV | Inelastic | $\gtrsim$ 1 MeV–GeV |
| Dirac material | Excitation across band gap | $\sim$ 0–1 meV | Inelastic | keV–GeV |
| Heavy fermion material | Excitation across band gap | $\sim$ 10 meV | Inelastic | 10 keV–GeV |

EXAMPLE: superconducting qubits



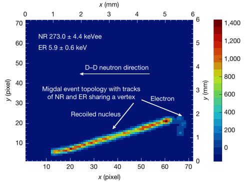
Qubits installed and operating at the Cryogenic Underground TEst (CUTE) facility at SNOLAB

EXAMPLE: Polar Crystals in TESSARACT/SPICE:




TESSARACT is sited for construction at Laboratoire Souterrain de Modane (LSM)

EXAMPLE: Migdal effect observed [19]




First observation with $\sigma_{\text{Migdal}}/\sigma_{\text{recoil}} = 4.9^{+2.6}_{-1.9} \times 10^{-5}$!

# Preparing Facilities for Future Needs

## Scenarios: Major Components

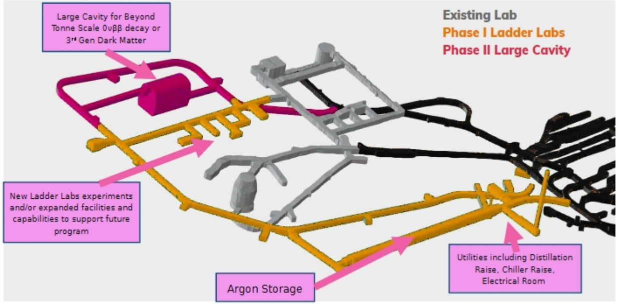
**New Surface Building**

All Scenarios:
- Located outside industrial control zone
- Large auditorium space to accommodate current staff and programs
- New spaces for training and laboratory work

Scenario 2:
- 50% more lab space and two more floors of office/collaboration space
- Visitor Centre
- Dedicated warehouse

Scenario 3:
- Daycare, Cafeteria, Hostel
- Materials fabrication lab

**Underground Laboratory**
- Scenario 1: Refurbishment and Enhanced Capabilities
- Scenarios 2 and 3: Additional laboratory expansion




41

In 2024, the Canada Foundation for Innovation requested 15-year plans from several major facilities in three scenarios: (1) Maintaining the current level of operations; (2) fully supporting the needs of the Canadian research community; and (3) increasing global competitiveness.

SURF (US) and SNOLAB (Canada) have visions or plans for growth to meet community needs. Jinping (China) has already completed an expansion and Boulby's expansion (UK) is underway.

# Preparing Facilities for Future Needs

## Scenarios: Major Components

### New Surface Building

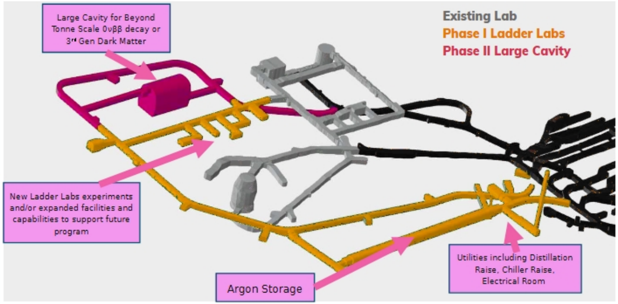
All Scenarios:
- Located outside industrial control zone
- Large auditorium space to accommodate current staff and programs
- New spaces for training and laboratory work

Scenario 2:
- 50% more lab space and two more floors of office/collaboration space
- Visitor Centre
- Dedicated warehouse

Scenario 3:
- Daycare, Cafeteria, Hostel
- Materials fabrication lab

### Underground Laboratory

- Scenario 1: Refurbishment and Enhanced Capabilities
- Scenarios 2 and 3: Additional laboratory expansion




41

In 2024, the Canada Foundation for Innovation requested 15-year plans from several major facilities in three scenarios: (1) Maintaining the current level of operations; (2) fully supporting the needs of the Canadian research community; and (3) increasing global competitiveness.

SURF (US) and SNOLAB (Canada) have visions or plans for growth to meet community needs. Jinping (China) has already completed an expansion and Boulby's expansion (UK) is underway.

# Closing thoughts

## Try to take the long view on this problem

*"We apologize to experimentalists for having no idea what is the mass of the Higgs boson…and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson …" (Ellis, Gaillard, Nanopololous. 1976) [27]*

*"We also apologize to both theorists and experimentalists for having no idea what is the mass of the constituents of dark matter. We, too, apologize for not being sure of its couplings to other particles, except that they might be non-existent, or very small, or even, consistent with the data, at the scale of strong nuclear interactions. For these reasons, **we strongly encourage big experimental and theoretical searches for the constituents of dark matter**. It is by scientific work that we will eliminate our confusion." (Cooley, SS. 2024)[28]*

## Try to take the long view on this problem

*"We apologize to experimentalists for having no idea what is the mass of the Higgs boson. . . and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson . . . " (Ellis, Gaillard, Nanopololous. 1976) [27]*

*"We also apologize to both theorists and experimentalists for having no idea what is the mass of the constituents of dark matter. We, too, apologize for not being sure of its couplings to other particles, except that they might be non-existent, or very small, or even, consistent with the data, at the scale of strong nuclear interactions. For these reasons, **we strongly encourage big experimental and theoretical searches for the constituents of dark matter**. It is by scientific work that we will eliminate our confusion." (Cooley, SS. 2024)[28]*

## Try to take the long view on this problem

*"We apologize to experimentalists for having no idea what is the mass of the Higgs boson. . . and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson . . . " (Ellis, Gaillard, Nanopololous. 1976) [27]*

*"We also apologize to both theorists and experimentalists for having no idea what is the mass of the constituents of dark matter. We, too, apologize for not being sure of its couplings to other particles, except that they might be non-existent, or very small, or even, consistent with the data, at the scale of strong nuclear interactions. For these reasons,* ***we strongly encourage big experimental and theoretical searches for the constituents of dark matter****. It is by scientific work that we will eliminate our confusion." (Cooley, SS. 2024)[28]*

# THANK YOU! (And join us for research and learning at SNOLAB)

SNOLAB is now running an annual light-weight summer academic program, the **SNOLAB Underground Science Institute (SuSi) lecture program**, over 8 weeks (June 8 – August 14, 2026).

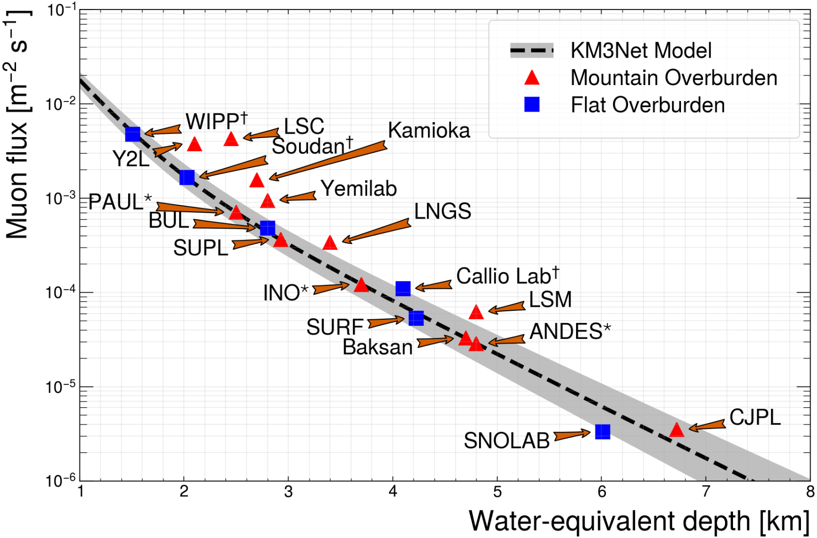
Information about SuSi 2026, including the *Application of Interest*, is available: `https://indico.snolab.ca/e/susi2026`.

- Aimed toward graduate students and post-docs
- 2–3 lectures per week, lecturers/topics change every 2 weeks
- $> 70\%$ of your time free to engage in your research.
- We have hosted both experimental and theoretical participants.

Sudbury has great natural beauty, good and varied restaurants, and a vibrant cultural arts scene.

# Appendix

# Cosmic Ray Muon Flux

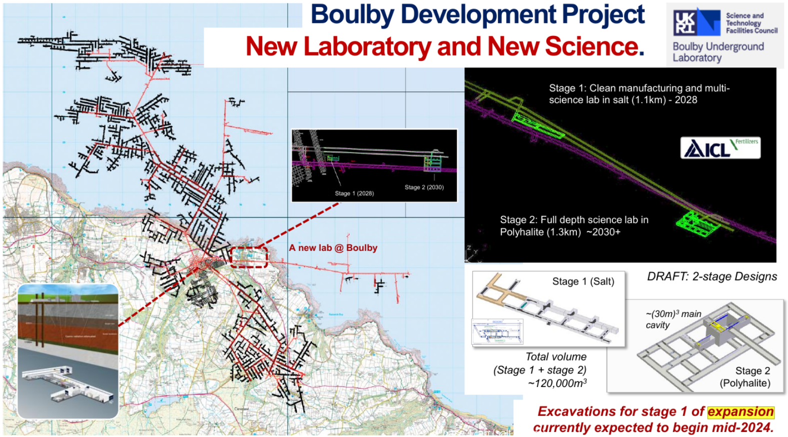



The symbols * and † indicate a conceptual lab and a lab that formerly hosted experiments, respectively.

Flux data from Refs. [29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40] and muon flux model from Ref. [41].

Labs quote their vertical depth in metres-water-equivalent. Straight vertically up is the deepest point for a mountain lab and the shallowest point for a "flat overburden" lab.

# Preparing Facilities for Future Needs




Boulby expansion [42]

Standing in the extension drift at SURF where future expansion could proceed.

Standing in the extension drift at

## Scattering Concepts for Dark Matter Detectors

### Dark Matter Detection Equations

$$E_R^{lab} = \left(\frac{m_\chi m_N}{m_\chi + m_N}\right)^2 \frac{v^2}{m_N}(1 - \cos\theta_R) \quad (1)$$

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v_{min}}^{v_{esc}} v f(\vec{v}) \frac{d\sigma_{\chi N}}{dE_R} d^3\vec{v} \quad (2)$$

Observed energy (e.g., photoelectron-related energy) may not map directly onto recoil energy (e.g., *the* nuclear recoil). This requires *quenching factors*, *QF*, that must be calculated or measured, $E_{NR} = QF\, E_{ee}$.

# Effective Field Theory for Dark Matter Scattering Interpretation

$$\mathcal{O}_1 = 1_\chi 1_N$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left[\frac{\vec{q}}{m_N} \times \vec{v}^\perp\right]$$

$$\mathcal{O}_6 = \left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right] \cdot \left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_7 = \vec{S}_N \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left[\vec{S}_N \times \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left[\vec{S}_N \times \vec{v}^\perp\right]$$

$$\mathcal{O}_{13} = i\left[\vec{S}_\chi \cdot \vec{v}^\perp\right]\left[\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right]$$

$$\mathcal{O}_{14} = i\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\vec{S}_N \cdot \vec{v}^\perp\right]$$

$$\mathcal{O}_{15} = -\left[\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right]\left[\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \frac{\vec{q}}{m_N}\right]$$

## XENONnT: Detector and Backgrounds

Credit: XENON Collaboration

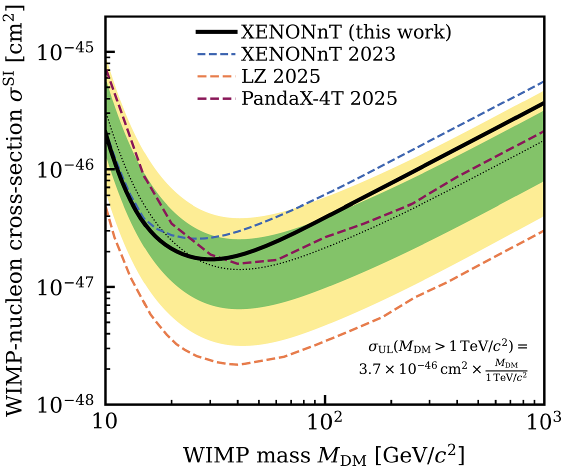
Vital stats: 8.5 T ($\approx 50$–$70\%$ fiducial), dual-phase liquid Xe TPC

Major backgrounds:

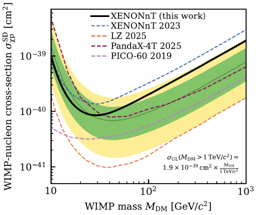
| Low Mass | High Mass |
|---|---|
| Cathode radioactivity | $\beta$ and $\gamma$ recoil events from radionuclide decay |
| Accidental electrons (pileup of single electrons) | Accidental coincidences of S1 and S2 (subdominant) |
| Delayed electrons | Neutrons |
| $^{8}$B CE$\nu$NS | Atmospheric $\nu$ nuclear recoils |
| | Solar $\nu$ electron recoils |

Key radionuclide contaminants are (in order from dominant to subdominant): $^{214}$Pb, $^{3}$H, $^{85}$Kr, $^{37}$Ar, $^{136}$Xe

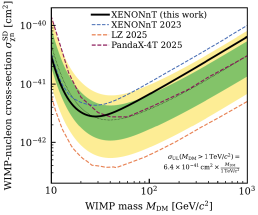
# XENONnT: Recent Results in Heavy DM [43]




Spin-Independent Constraints

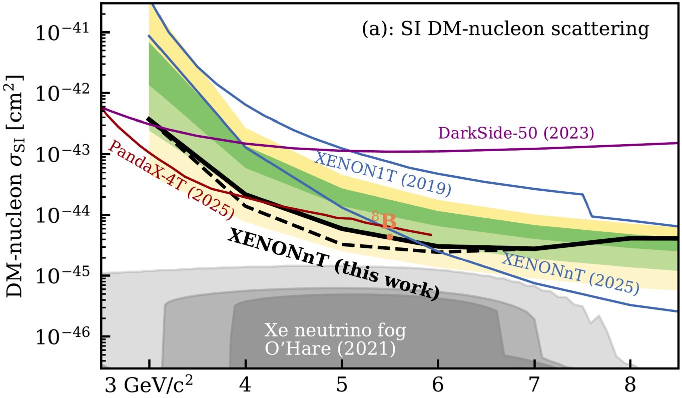



Spin-Dependent (proton) Constraints

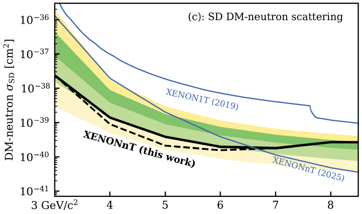



Spin-Dependent (neutron) Constraints

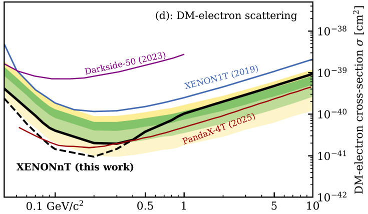
# XENONnT: Recent Results in Light DM [44]




Spin-Independent Constraints

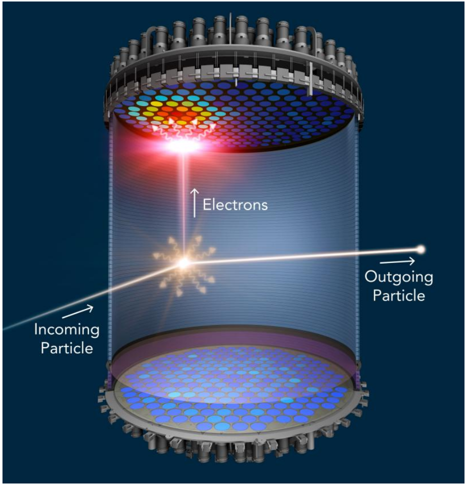



Spin-Dependent (neutron) Constraints




DM-electron Constraints

# LUX-ZEPLIN: Detector and Backgrounds [11, 12]




LZ concept (graphic from SLAC)

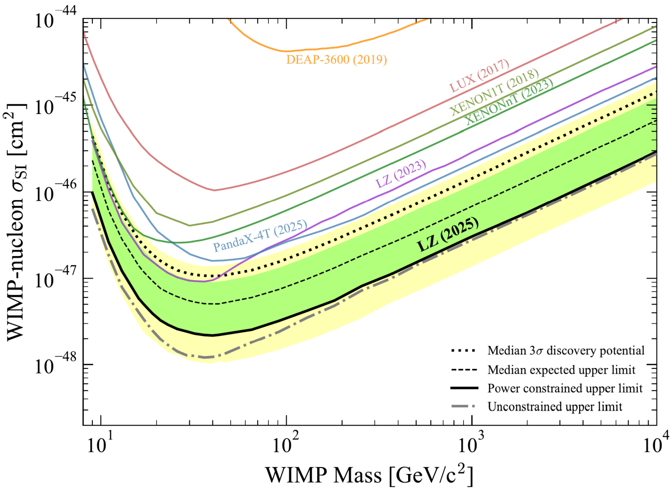
Vital stats: 7 T ($\approx 78\%$ fiducial), dual-phase liquid Xe TPC

Major backgrounds:

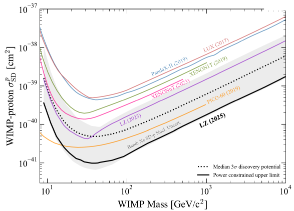
| Low Mass | High Mass |
|---|---|
| ▶ $^{8}$B CE$\nu$NS<br>▶ Accidental coincidences of S1 and S2<br>▶ Neutrons (subdominant) | ▶ $\beta$ and $\gamma$ events from radionuclide decay<br>▶ Solar $\nu$ electron recoils<br>▶ Accidental coincidences of S1 and S2 (subdominant)<br>▶ Atmospheric $\nu$ nuclear recoils<br>▶ $^{8}$B and hep $\nu$ nuclear recoils<br>▶ Neutrons |

Key radionuclide contaminants are (in order from dominant to subdominant): $^{214}$Pb, $^{85}$Kr, $^{39}$Ar, $^{212}$Pb, $^{218}$Po, $^{3}$H, $^{13}$C, $^{136}$Xe, $^{124}$Xe, $^{127}$Xe

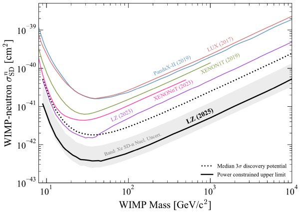
# LUX-ZEPLIN: Recent Results in Heavy DM [11]




Spin-Independent Constraints

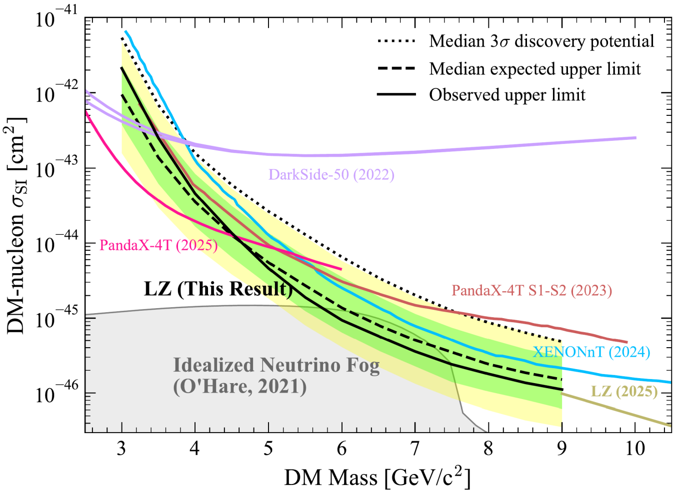



Spin-Dependent (proton) Constraints

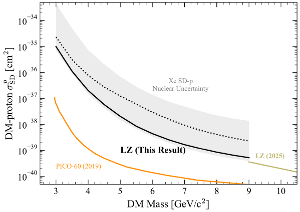



Spin-Dependent (neutron) Constraints

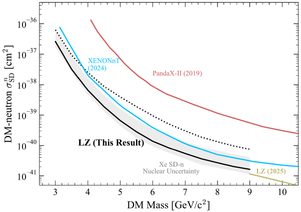
# LUX-ZEPLIN: Recent Results in Light DM [12]




Spin-Independent Constraints

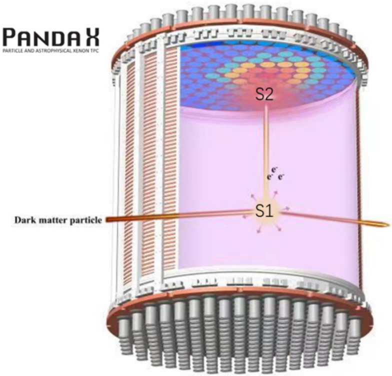



Spin-Dependent (proton) Constraints




Spin-Dependent (neutron) Constraints

# PandaX-4T: Detector and Backgrounds [46, 18, 47, 45]




PandaX-4T concept [45]

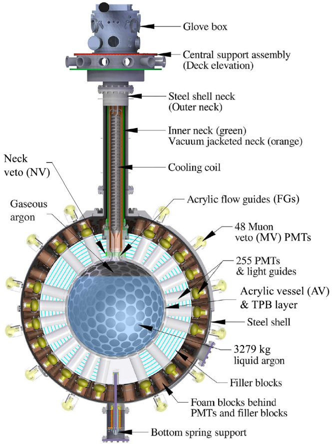
Vital stats: 3.7 T ($\approx (60–75)\%$ fiducial), dual-phase liquid Xe TPC

Major backgrounds:

| Low Mass | High Mass |
|---|---|
| ▶ $^{8}$B CE$\nu$NS<br>▶ Accidental coincidences of S1 and S2<br>▶ Neutrons,$\gamma/\beta$ ERs, surface backgrounds (subdominant) | ▶ Accidental coincidences of S1 and S2 (subdominant)<br>▶ Radon progeny (radionuclides)<br>▶ Tritium<br>▶ Neutrons<br>▶ Surface backgrounds<br>▶ Xenon radionuclides<br>▶ Neutrons |

Key radionuclide contaminants are (in order from dominant to subdominant): $^{214}\mathrm{Pb}$, $^{3}\mathrm{H}$, $^{85}\mathrm{Kr}$, $^{212}\mathrm{Pb}$, $^{136}\mathrm{Xe}$, $^{127}\mathrm{Xe}$, $^{124}\mathrm{Xe}$. $^{3}\mathrm{H}$ largely addressed after Run0 using cryogenic distillation.

# DEAP-3600: Detector and Backgrounds [48]




DEAP-3600 schematic

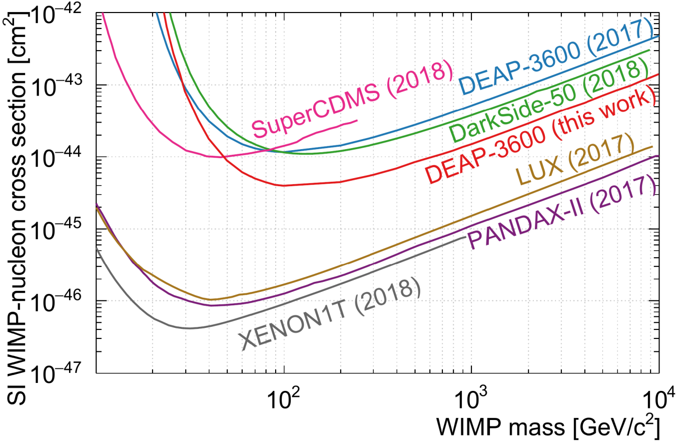
Vital stats: 3.3 T ($\approx 25\%$ fiducial), single-phase liquid atmospheric Ar

Major backgrounds (High-Mass only):

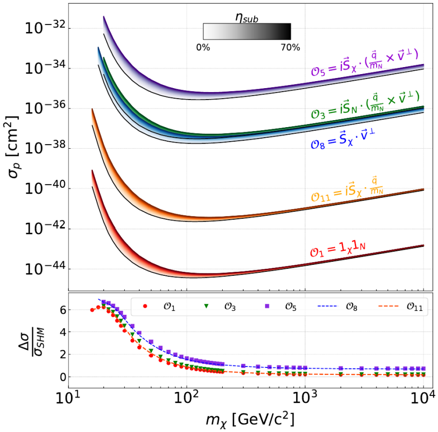
- $\alpha$ events in the neck region (should be addressed by recent upgrades)
- Radiogenic and cosmogenic neutrons
- $\beta/\gamma$ electron recoils (subdominant)
- Surface backgrounds

DEAP-3600 tuned the selection to achieve $< 1$ background event in 231 live-days. Key radionuclide contaminants that produce radiogenic neutron backgrounds are: $^{238}\mathrm{U}$, $^{235}\mathrm{U}$, $^{232}\mathrm{Th}$. These derive primarily from polyethylene filler blocks and PMT glass.

# DEAP-3600: Results in Heavy DM [48, 50]

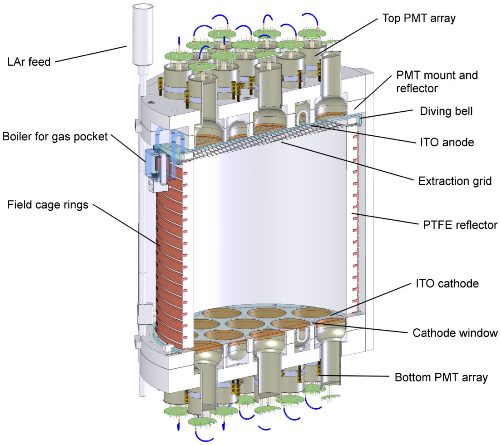



Spin-Independent Constraints




Effective Field Theory constraints using Gaia Sausage inputs [49]

# DarkSide-50: Detector and Backgrounds [51]




DarkSide-50 schematic

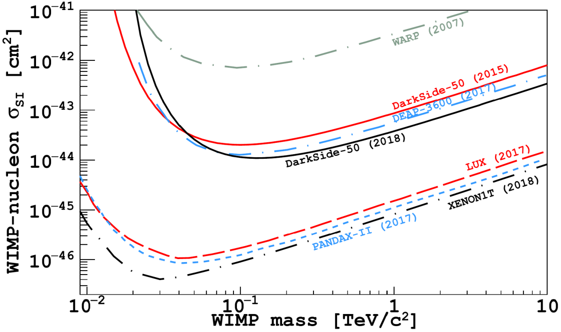
Vital stats: 50 kg ($\approx 63\%$ fiducial), dual-phase liquid underground Ar

Major backgrounds (High-Mass only):

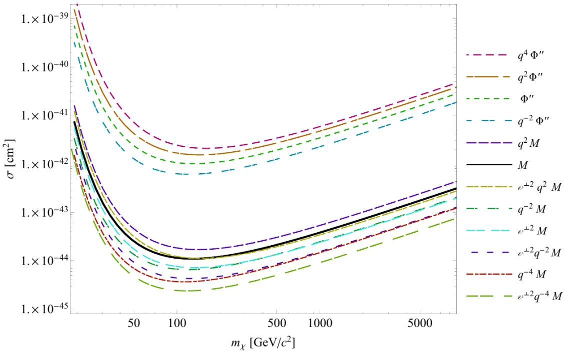
- Electron recoils (scintillation and Cherenkov events)
- Surface background (primarily real S2 induced by surface event in the liquid)
- Radiogenic and cosmogenic neutrons

DarkSide-50 achieved far less than 1 background event. Key radionuclide contaminants that produce radiogenic neutron backgrounds are: $^{238}\mathrm{U}$, $^{235}\mathrm{U}$, $^{232}\mathrm{Th}$. These arise dominantly from the PMTs and a viton o-ring. The dominant electron recoils are induced by Compton scatters of $\gamma$s from the TPC and cryostat, not radioisotope contamination of the UAr.

# DarkSide-50: Results in Heavy DM [51, 52]

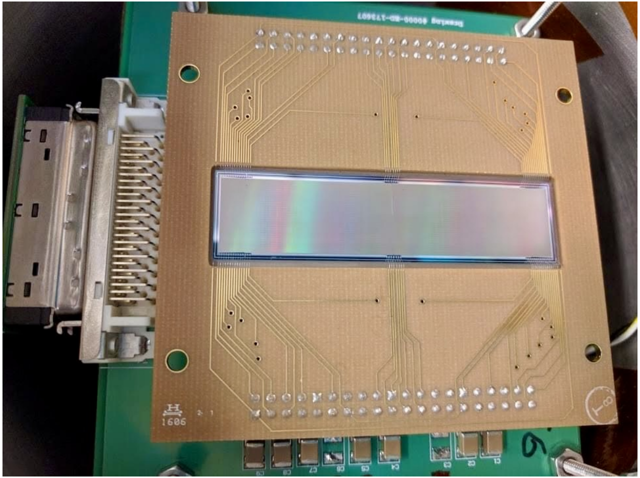



Spin-Independent Constraints

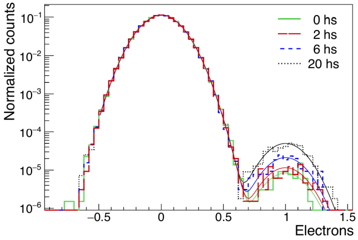



Effective Field Theory constraints using Standard Halo Model

# CCD Detectors: Status and Overview [53, 54, 55]



Vital stats: three experiments — DAMIC (SNOLAB, FNAL), DAMIC-M (LSM), and SENSEI (SNOLAB) — using (Skipper) CCD technology with sensitivity to even **single-electron displacement**. Total masses: 18 g (DAMIC), 26 g (DAMIC-M), and 48 g (SENSEI).



# CCD Detectors: Recent Results

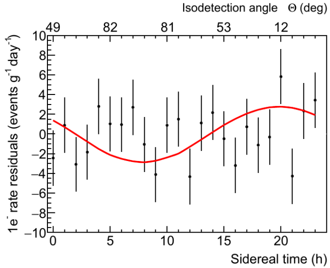
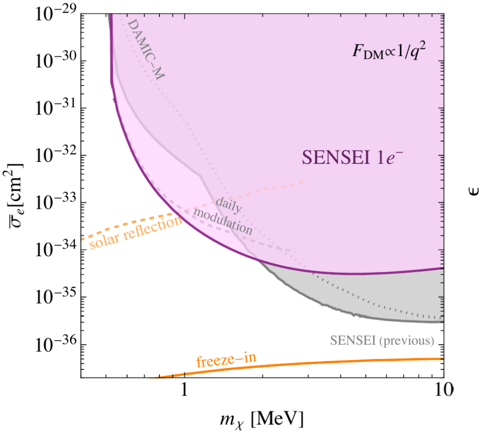


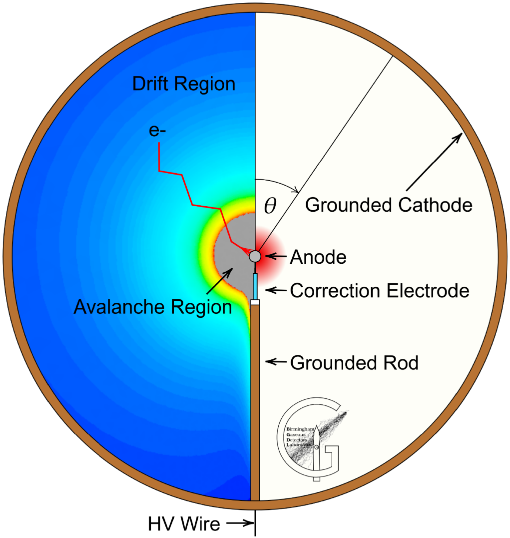

FIG. 4. Residuals after the subtraction of the best-fit background-only model to the total rate, binned as a function of local apparent sidereal time. As a reference, the upper x-axis gives the isodetection angle $\Theta(t)$ for the first day of data taking. Each data point is obtained from the average of 50 images. The red line shows the expected signal (minus its time average) for a DM particle of mass 1 MeV/c$^2$, $\bar{\sigma}_e = 10^{-33}\text{cm}^2$ interacting via an ultralight dark photon mediator.



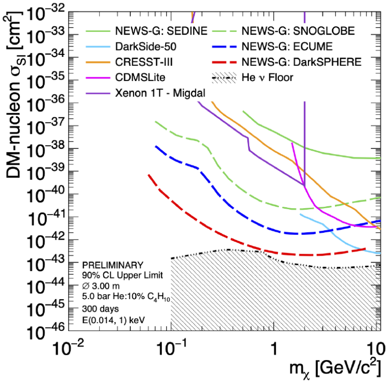

DAMIC-M diurnal modulation search [54]

Impact of single-electron event sensitivity on existing SENSEI capability

# NEWS-G: Detector and Sensitivity

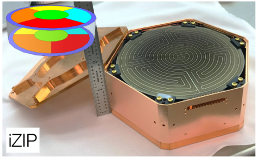


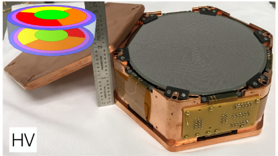

Vital Stats: spherical proportional counter capable of holding different target gases such as methane. Program operated at LSM (60 cm diameter) and now at SNOLAB (140 cm). Target low-mass DM candidates.



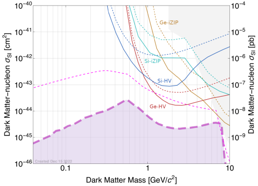
# SuperCDMS-SNOLAB: Status and Reach [56, 57]

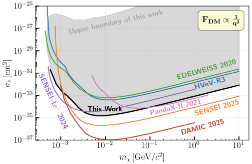

Vital Stats: SuperCDMS-SNOLAB completed primary construction in 2025 and is now in operations (commissioning, then science running). Germanium and silicon crystals cryogenically cooled to mK temperatures, sensitive to phonons and ionization. Initial $\sim 30\ \mathrm{kg}$ deployment. Emphasis on low-mass (1–10 GeV) region.



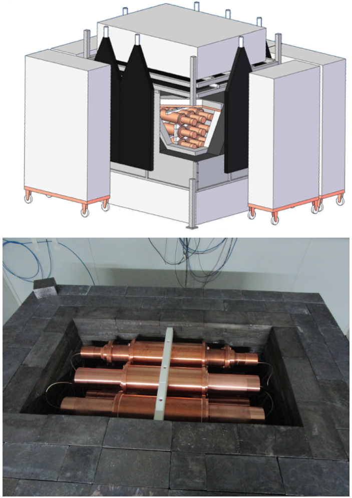

Compare various detectors and optimal inverval (dashed) and profile likelihood ratio (solid) projections:




Above-right constraints use just $6\ \mathrm{g} \cdot \mathrm{days}$ of HVeV data!

# ANAIS: Detector and Recent Results [59, 60]

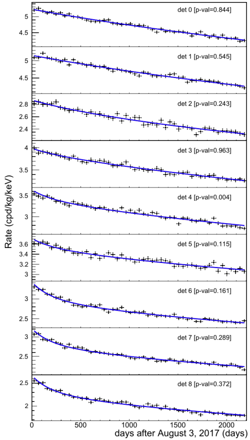


ANAIS-112 [58]

Vital stats: Nine 12.5 kg NaI(Tl) crystals (112.5 kg total), screened for radiopurity. Six-year results presented in 2025.

No evidence for annual modulation of scintillation yield in 3 years of data. Incompatible with DAMA/LIBRA claim at $4.0\sigma$ ($3.5\sigma$) including (excluding) the lowest energy region. ANAIS reports $2.8\sigma$ ($3.9\sigma$) sensitivity to DAMA/LIBRA in those respective energy regions.

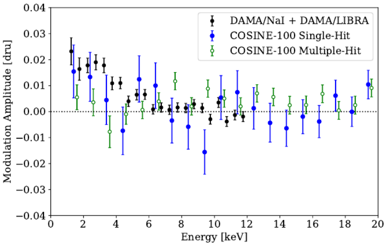
The collaboration notes that improved knowledge of quenching factors for sodium and iodine recoils and non-proportional light yield in the material is needed to reduce systematic errors.



# COSINE: Recent Results [61]

COSINE-100 detector (Credit: Chang Hyon Ha)

Vital stats: Eight NaI(Tl) crystals totaling 106 kg, screened for radiopurity. Immersed in liquid scintillator. Last results from 2019.




| Component | Average Activity (dru) |
|---|---|
| Total | $(2.74 \pm 0.23) \times 10^{0}$ |
| $^{3}$H | $(1.41 \pm 0.18) \times 10^{0}$ |
| $^{210}$Pb | $(1.12 \pm 0.15) \times 10^{0}$ |
| Flat | $(1.35 \pm 0.08) \times 10^{-1}$ |
| $^{109}$Cd | $(4.13 \pm 0.39) \times 10^{-2}$ |
| $^{113}$Sn | $(1.55 \pm 0.16) \times 10^{-2}$ |
| $^{127}$Te | $(6.59 \pm 0.52) \times 10^{-3}$ |
| $^{22}$Na | $(5.88 \pm 1.34) \times 10^{-3}$ |
| $^{121m}$Te | $(1.50 \pm 0.16) \times 10^{-3}$ |
| $^{121}$Te | $(5.07 \pm 1.23) \times 10^{-4}$ |

COSINE-200 was to be deployed in the new Yemilab complex in South Korea and was in preparation in 2025.

# Combination of ANAIS-112 and COSINE-100 Data [62]

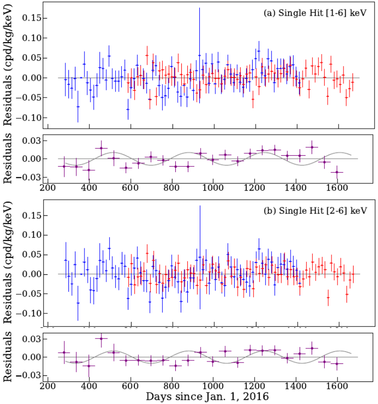



FIG. 1. The background subtracted residuals for COSINE-100 (blue) and ANAIS-112 (red),for a total exposure of 485 kg·yr in energy ranges of (a) 1–6 and (b) 2–6 keV. The subplots show their combined data in time bins of 2 months (purple) where a grey curve is drawn to visually compare the DAMA modulation signal.

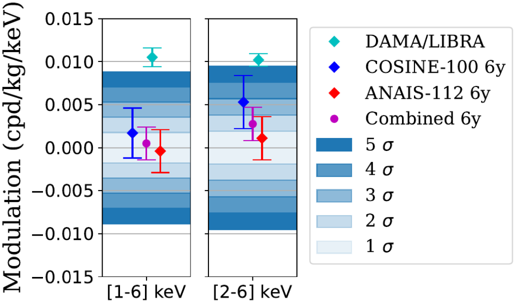


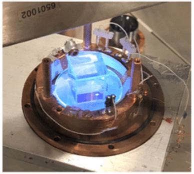

FIG. 4. Simple combination results of the COSINE-100 full dataset [18] and ANAIS-112 6-year [17] annual modulation searches. The colored bands show the sensitivity region for 6-year data from both experiments combined in 1$\sigma$ (lightest blue) to 5$\sigma$ (darkest blue).

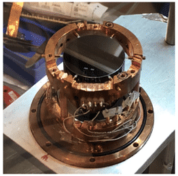
Combined exclusion of DAMA/LIBRA explanation at $4.7\sigma$

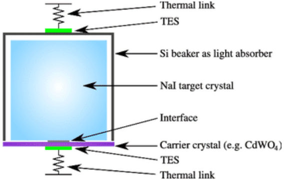
# COSINUS: Overview [63, 64, 65]


COSINUS cryostat installation

Vital stats: Phased deployment of NaI crystals in cryogenic environment at Laboratori Nazionali del Gran Sasso (LNGS). Begin with 272 g of material and scaleable to 2.8 kg. “Background free” NaI concept using transition edge sensors with a special means to attach them to the hygroscopic NaI crystal (RemoTES). Signal: scintillation + phonons.

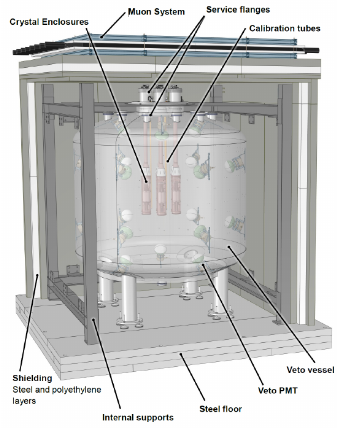






# SABRE: Detector Concept and Status [66, 37]

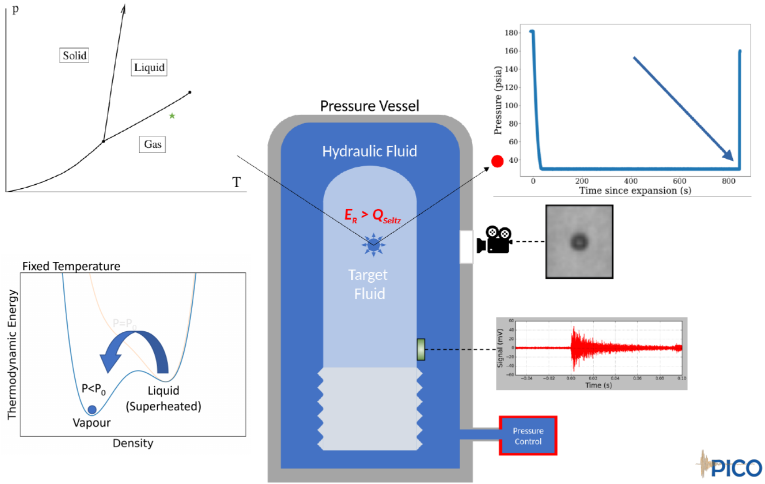
Vital stats: Total mass goal is $\approx 50$ kg of NaI(Tl) crystals, screened for radiopurity. Active liquid scintillator veto using coincidence. Two sites: LNGS (North) and SUPL (South). Any cosmic-ray-modulated effects have opposite seasonal phases in northern and southern hemisphere.




SABRE-South concept

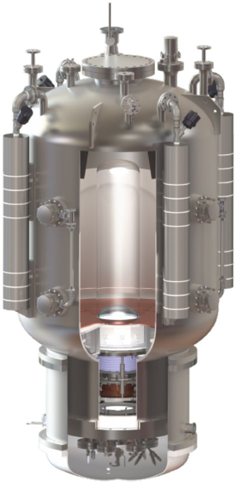

SABRE-North

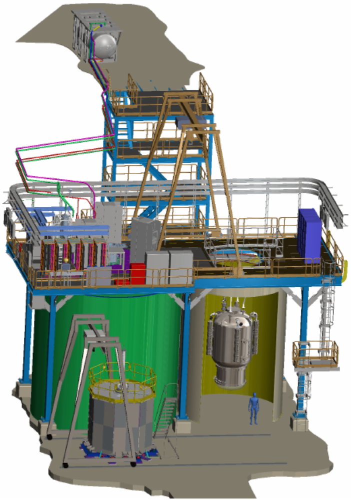
# PICO: Detector Concept and Status

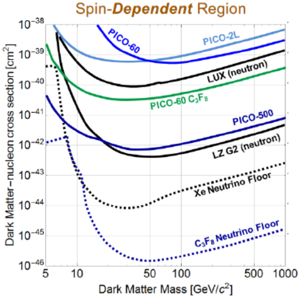



Slide by Colin Moore

# PICO-500: Spin-Dependent Scattering Sensitivity



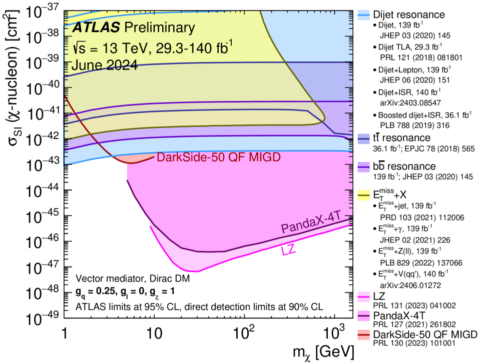


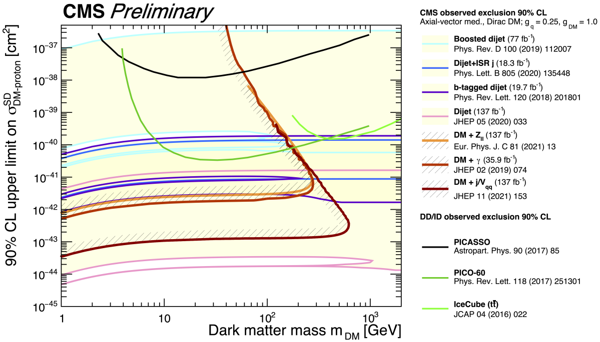



PICO

Slide by Colin Moore

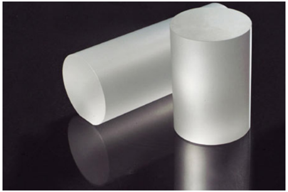
# Collider Constraints on Spin-Independent DM-nucleon scattering




Summary plots from the ATLAS and LHC experiments on interpretations of searches as theory-model-dependent constraints on DM-nucleon spin-independent scattering.

# Novel Material Approaches: Dirac Materials [67, 68, 69]



Promising candidate materials:

- Sapphire ($Al_2O_3$, left)
- Calcium Tungstate ($CaWO_4$, right)

Interactions with materials have a directional anisotropy, with response

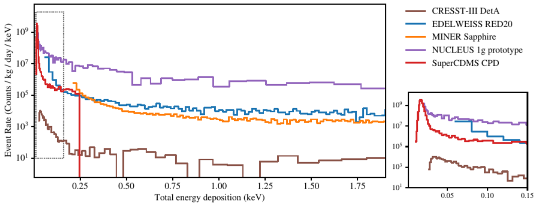
$$E_k^{\pm} = \pm\sqrt{v_F^2 \vec{k} \cdot \vec{k} + \Delta^2}$$

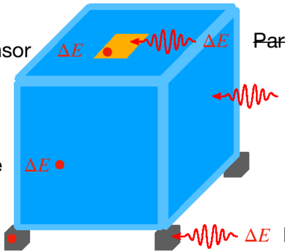
- $\vec{k}$ is the direction of the crystal lattice momentum (wave number of electrons in stationary states),
- $v_F$ is the Fermi velocity and takes the place of the speed of light in the traditional Dirac equation,
- $2\Delta$ is the bandgap energy and replaces the mass term.

Should permit modulation measurement as dark matter wind changes angle to material axes.

# The "Low-Energy Excess" (LEE) [70]

## What causes the EXCESS?




Relaxation of the sensor

~~Particles in the sensor~~

~~Particles in the absorber/substrate~~

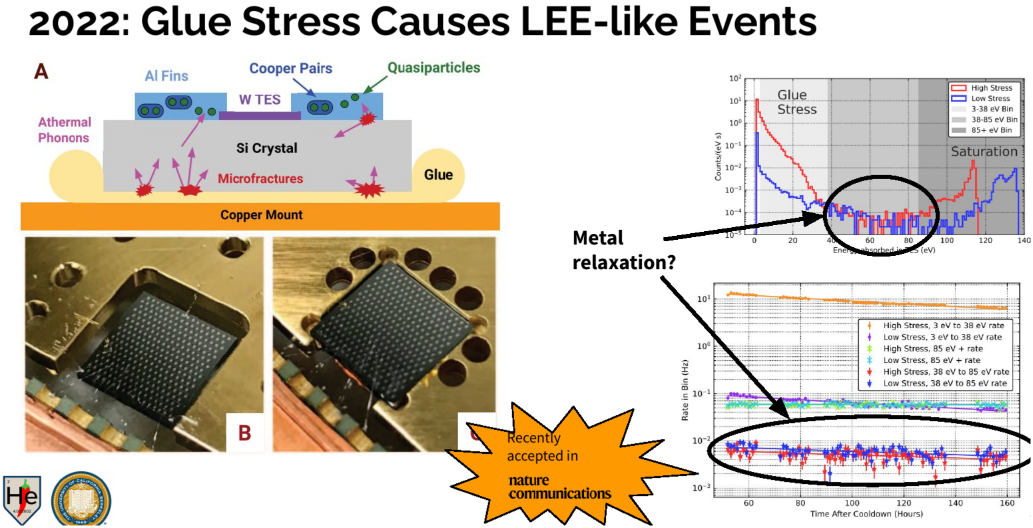
Relaxation of absorber/substrate

Relaxation of supports

Particles in inert material (e.g. supports)

Energy stored in interfaces

# One Insight: Glue Stress on Solid Detectors [71, 72]



# References I

[1] V. Dutta, “Discovering sub-gev dark matter with the light dark matter experiment.” https://indico.cern.ch/event/1562147/contributions/6857708, 2026. [Online; accessed 5-February-2026].

[2] M. Hank, “Susy searches at the lhc.” https://indico.cern.ch/event/1562147/contributions/6857703, 2026. [Online; accessed 5-February-2026].

[3] D. Shih, “A particle theorists perspective on ml for fundamental physics.” https://indico.cern.ch/event/1562147/contributions/6857678, 2026. [Online; accessed 5-February-2026].

[4] S. Verner, “Astrometric direct detection of ultralight dark matter.” https://indico.cern.ch/event/1562147/contributions/6869949, 2026. [Online; accessed 5-February-2026].

# References II


[5] T. Braine, "The axion dark matter experiment." https://indico.cern.ch/event/1562147/contributions/6869931, 2026. [Online; accessed 5-February-2026].

[6] D. Yeon, "A quantum description of axion dark matter detection." https://indico.cern.ch/event/1562147/contributions/6901850, 2026. [Online; accessed 5-February-2026].

[7] L. Shchutska, "Highlghts from lhcb and ship status." https://indico.cern.ch/event/1562147/contributions/6857532, 2026. [Online; accessed 5-February-2026].

[8] L. Söding, R. L. Bartel, and P. Mertsch, "Local dark matter density from Gaia DR3 K-dwarfs using Gaussian processes," *Mon. Not. Roy. Astron. Soc.* **542** (2025) no. 4, 2987–2997, arXiv:2506.02956 [astro-ph.GA].

[9] P. Cushman *et al.*, "Working Group Report: WIMP Dark Matter Direct Detection," in *Snowmass 2013: Snowmass on the Mississippi*. 10, 2013. arXiv:1310.8327 [hep-ex].

# References III


[10] Tarek Saab, Enectali Figueroa, "Dark Matter Limit Plotter." HTTPS://SUPERCDMS.SLAC.STANFORD.EDU/SCIENCE-RESULTS/DARK-MATTER-LIMIT-PLOTTER, 2024. Last accessed: Feb 3, 2026.

[11] **LZ** Collaboration, J. Aalbers *et al.*, "Dark Matter Search Results from 4.2 Tonne-Years of Exposure of the LUX-ZEPLIN (LZ) Experiment," *Phys. Rev. Lett.* **135** (2025) no. 1, 011802, arXiv:2410.17036 [hep-ex].

[12] **LZ** Collaboration, D. S. Akerib *et al.*, "Searches for Light Dark Matter and Evidence of Coherent Elastic Neutrino-Nucleus Scattering of Solar Neutrinos with the LUX-ZEPLIN (LZ) Experiment," arXiv:2512.08065 [hep-ex].

[13] J. Cooley *et al.*, "Report of the Topical Group on Particle Dark Matter for Snowmass 2021," arXiv:2209.07426 [hep-ph].

[14] N. Vinyoles, A. M. Serenelli, F. L. Villante, S. Basu, J. Bergström, M. C. Gonzalez-Garcia, M. Maltoni, C. Peña-Garay, and N. Song, "A new Generation of Standard Solar Models," *Astrophys. J.* **835** (2017) no. 2, 202, arXiv:1611.09867 [astro-ph.SR].

# References IV


[15] **SNO** Collaboration, B. Aharmim *et al.*, "Combined Analysis of all Three Phases of Solar Neutrino Data from the Sudbury Neutrino Observatory," *Phys. Rev. C* **88** (2013) 025501, arXiv:1109.0763 [nucl-ex].

[16] M. C. Gonzalez-Garcia, M. Maltoni, J. P. Pinheiro, and A. M. Serenelli, "Status of direct determination of solar neutrino fluxes after Borexino," *JHEP* **02** (2024) 064, arXiv:2311.16226 [hep-ph].

[17] **XENON** Collaboration, E. Aprile *et al.*, "First Indication of Solar B8 Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT," *Phys. Rev. Lett.* **133** (2024) no. 19, 191002, arXiv:2408.02877 [nucl-ex].

[18] **PandaX** Collaboration, Z. Bo *et al.*, "First Indication of Solar B8 Neutrinos through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T," *Phys. Rev. Lett.* **133** (2024) no. 19, 191001, arXiv:2407.10892 [hep-ex].

[19] D. Yi *et al.*, "Direct observation of the Migdal effect induced by neutron bombardment," *Nature* **649** (2026) no. 8097, 580–583.

# References V


[20] Y. Hochberg, Y. Kahn, M. Lisanti, K. M. Zurek, A. G. Grushin, R. Ilan, S. M. Griffin, Z.-F. Liu, S. F. Weber, and J. B. Neaton, "Detection of sub-MeV Dark Matter with Three-Dimensional Dirac Materials," *Phys. Rev. D* **97** (2018) no. 1, 015004, `arXiv:1708.08929 [hep-ph]`.

[21] A. Arvanitaki, S. Dimopoulos, and K. Van Tilburg, "Resonant absorption of bosonic dark matter in molecules," *Phys. Rev. X* **8** (2018) no. 4, 041001, `arXiv:1709.05354 [hep-ph]`.

[22] K. M. Zurek, "Dark Matter Candidates of a Very Low Mass," *Ann. Rev. Nucl. Part. Sci.* **74** (2024) 287–319, `arXiv:2401.03025 [hep-ph]`.

[23] S. Chen, H. Fukuda, T. Inada, T. Moroi, T. Nitta, and T. Sichanugrist, "Quantum Enhancement in Dark Matter Detection with Quantum Computation," `arXiv:2311.10413 [hep-ph]`.

[24] R. Moretti *et al.*, "Design and Simulation of a Transmon Qubit Chip for Axion Detection," *IEEE Trans. Appl. Supercond.* **34** (2024) no. 3, 1700705, `arXiv:2310.05238 [quant-ph]`.

[25] A. Das, N. Kurinsky, and R. K. Leane, "Dark Matter Induced Power in Quantum Devices," *Phys. Rev. Lett.* **132** (2024) no. 12, 121801, `arXiv:2210.09313 [hep-ph]`.

# References VI


[26] F. Ponce, J. L. Orrell, and Z. Wang, "Radiation-induced secondary emissions in solid-state devices as a possible contribution to quasiparticle poisoning of superconducting circuits," arXiv:2301.08239 [physics.app-ph].

[27] J. Ellis, M. K. Gaillard, and D. Nanopoulos, "A phenomenological profile of the higgs boson," in *The Standard Model Higgs Boson*, M. EINHORN, ed., vol. 8 of *Current PhysicsSources and Comments*, pp. 24–72. Elsevier, 1991. https://www.sciencedirect.com/science/article/pii/B9780444888075500662.

[28] J. Cooley and S. J. Sekula, *The Dark Matter Discoverer's Guidebook*. YBK Publishers, 2024.

[29] L. Baudis, J. Hall, K. T. Lesko, and J. L. Orrell, "Snowmass 2021 Underground Facilities and Infrastructure Overview Topical Report," arXiv:2212.07037 [hep-ex].

[30] N. K. Mondal, "India-Based Neutrino Observatory (INO)," *Eur. Phys. J. Plus* **127** (2012) 106.

[31] **COSINE-100** Collaboration, H. Prihtiadi *et al.*, "Measurement of the cosmic muon annual and diurnal flux variation with the COSINE-100 detector," *JCAP* **02** (2021) 013, arXiv:2005.13672 [physics.ins-det].

# References VII


[32] **JNE** Collaboration, Z. Guo *et al.*, "Muon flux measurement at China Jinping Underground Laboratory," *Chin. Phys. C* **45** (2021) no. 2, 025001, `arXiv:2007.15925 [physics.ins-det]`.

[33] C. O. Dib, "Andes: An underground laboratory in south america," *Physics Procedia* **61** (2015) 534–541. `https://www.sciencedirect.com/science/article/pii/S1875389214007317`. 13th International Conference on Topics in Astroparticle and Underground Physics, TAUP 2013.

[34] L. B. Bezrukov *et al.*, "New Low-Background Laboratory in the Pyhäsalmi Mine, Finland," *Phys. Part. Nucl.* **49** (2018) no. 4, 769–773.

[35] W. H. Trzaska *et al.*, "Cosmic-ray muon flux at Canfranc Underground Laboratory," *Eur. Phys. J. C* **79** (2019) no. 8, 721, `arXiv:1902.00868 [physics.ins-det]`.

[36] C. Zhang and D. M. Mei, "Measuring Muon-Induced Neutrons with Liquid Scintillation Detector at Soudan Mine," *Phys. Rev. D* **90** (2014) no. 12, 122003, `arXiv:1407.3246 [physics.ins-det]`.

[37] **The SABRE South** Collaboration, K. J. Rule, "The SABRE South Experiment at The Stawell Underground Physics Laboratory," *PoS* **EPS-HEP2025** (2026) 119.

# References VIII


[38] R. Adam *et al.*, "Paarl Africa Underground Laboratory (PAUL)," `arXiv:2306.12083 [hep-ex]`.

[39] E.-I. Esch, T. J. Bowles, A. Hime, A. Pichlmaier, R. Reifarth, and H. Wollnik, "The Cosmic ray muon flux at WIPP," *Nucl. Instrum. Meth. A* **538** (2005) 516–525, `arXiv:astro-ph/0408486`.

[40] W. Woodley, A. Fedynitch, and M.-C. Piro, "Cosmic ray muons in laboratories deep underground," *Phys. Rev. D* **110** (2024) no. 6, 063006, `arXiv:2406.10339 [hep-ph]`.

[41] **KM3NeT** Collaboration, M. Ageron *et al.*, "Dependence of atmospheric muon flux on seawater depth measured with the first KM3NeT detection units: The KM3NeT Collaboration," *Eur. Phys. J. C* **80** (2020) no. 2, 99, `arXiv:1906.02704 [physics.ins-det]`.

[42] S. Paling, "Dulio-bio workshop opening remarks." `https://indico.stfc.ac.uk/event/1058/contributions/6716`, 2024. [Online; accessed 5-February-2026].

[43] **XENON** Collaboration, E. Aprile *et al.*, "WIMP Dark Matter Search Using a 3.1 Tonne-Year Exposure of the XENONnT Experiment," *Phys. Rev. Lett.* **135** (2025) no. 22, 221003, `arXiv:2502.18005 [hep-ex]`.

# References IX


[44] **XENON** Collaboration, E. Aprile *et al.*, "Light Dark Matter Search with 7.8 Tonne-Year of Ionization-Only Data in XENONnT," arXiv:2601.11296 [hep-ex].

[45] Z. Qian *et al.*, "Position reconstruction and surface background model for the PandaX-4T detector," *Nucl. Instrum. Meth. A* **1077** (2025) 170548, arXiv:2502.07317 [physics.ins-det].

[46] **PandaX-4T** Collaboration, Y. Meng *et al.*, "Dark Matter Search Results from the PandaX-4T Commissioning Run," *Phys. Rev. Lett.* **127** (2021) no. 26, 261802, arXiv:2107.13438 [hep-ex].

[47] **PandaX** Collaboration, Z. Bo *et al.*, "Dark Matter Search Results from 1.54 Tonne·Year Exposure of PandaX-4T," *Phys. Rev. Lett.* **134** (2025) no. 1, 011805, arXiv:2408.00664 [hep-ex].

[48] **DEAP** Collaboration, R. Ajaj *et al.*, "Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB," *Phys. Rev. D* **100** (2019) no. 2, 022004, arXiv:1902.04048 [astro-ph.CO].

[49] L. Necib, M. Lisanti, and V. Belokurov, "Inferred Evidence For Dark Matter Kinematic Substructure with SDSS-Gaia," arXiv:1807.02519 [astro-ph.GA].

# References X


[50] **DEAP** Collaboration, P. Adhikari *et al.*, "Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the DEAP-3600 detector," *Phys. Rev. D* **102** (2020) no. 8, 082001, arXiv:2005.14667 [astro-ph.CO]. [Erratum: Phys.Rev.D 105, 029901 (2022)].

[51] **DarkSide** Collaboration, P. Agnes *et al.*, "DarkSide-50 532-day Dark Matter Search with Low-Radioactivity Argon," *Phys. Rev. D* **98** (2018) no. 10, 102006, arXiv:1802.07198 [astro-ph.CO].

[52] **DarkSide-50** Collaboration, P. Agnes *et al.*, "Effective field theory interactions for liquid argon target in DarkSide-50 experiment," *Phys. Rev. D* **101** (2020) no. 6, 062002, arXiv:2002.07794 [hep-ex].

[53] **SENSEI, DAMIC-M, DAMIC** Collaboration, A. Aguilar-Arevalo *et al.*, "Confirmation of the spectral excess in DAMIC at SNOLAB with skipper CCDs," *Phys. Rev. D* **109** (2024) no. 6, 062007, arXiv:2306.01717 [astro-ph.CO].

[54] **DAMIC-M** Collaboration, K. Aggarwal *et al.*, "Daily Modulation Constraints on Light Dark Matter with DAMIC-M," arXiv:2511.13962 [hep-ex].

# References XI


[55] **SENSEI** Collaboration, I. M. Bloch *et al.*, "SENSEI at SNOLAB: Single-Electron Event Rate and Implications for Dark Matter," *Phys. Rev. Lett.* **134** (2025) no. 16, 161002, `arXiv:2410.18716 [astro-ph.CO]`.

[56] **SuperCDMS** Collaboration, S. Zatschler, "Status and prospects of the SuperCDMS Dark Matter experiment at SNOLAB," *PoS* **TAUP2023** (2024) 076.

[57] **SuperCDMS** Collaboration, M. F. Albakry *et al.*, "Search for low-mass electron-recoil dark matter using a single-charge sensitive SuperCDMS-HVeV Detector," `arXiv:2509.03608 [hep-ex]`.

[58] J. Amaré *et al.*, "Performance of ANAIS-112 experiment after the first year of data taking," *Eur. Phys. J. C* **79** (2019) no. 3, 228, `arXiv:1812.01472 [astro-ph.IM]`.

[59] J. Amare *et al.*, "Annual modulation results from three-year exposure of ANAIS-112," *Phys. Rev. D* **103** (2021) no. 10, 102005, `arXiv:2103.01175 [astro-ph.IM]`.

[60] J. Amaré *et al.*, "Towards a Robust Model-Independent Test of the DAMA/LIBRA Dark Matter Signal: ANAIS-112 Results with Six Years of Data," *Phys. Rev. Lett.* **135** (2025) no. 5, 051001, `arXiv:2502.01542 [astro-ph.IM]`.

# References XII


[61] **COSINE-100** Collaboration, G. Adhikari *et al.*, "Three-year annual modulation search with COSINE-100," *Phys. Rev. D* **106** (2022) no. 5, 052005, arXiv:2111.08863 [hep-ex].

[62] **ANAIS-112, COSINE-100** Collaboration, N. Carlin *et al.*, "Combined Annual Modulation Dark Matter Search with COSINE-100 and ANAIS-112," *Phys. Rev. Lett.* **135** (2025) no. 12, 121002, arXiv:2503.19559 [astro-ph.IM].

[63] G. Angloher *et al.*, "The COSINUS project - perspectives of a NaI scintillating calorimeter for dark matter search," *Eur. Phys. J. C* **76** (2016) no. 8, 441, arXiv:1603.02214 [physics.ins-det].

[64] F. Kahlhoefer, F. Reindl, K. Schäffner, K. Schmidt-Hoberg, and S. Wild, "Model-independent comparison of annual modulation and total rate with direct detection experiments," *JCAP* **05** (2018) 074, arXiv:1802.10175 [hep-ph].

[65] G. Angloher *et al.*, "COSINUS: Cryogenic Calorimeters for the Direct Dark Matter Search with NaI Crystals," *J. Low Temp. Phys.* **200** (2020) no. 5-6, 428–436.

[66] **SABRE** Collaboration, M. Antonello *et al.*, "The SABRE project and the SABRE Proof-of-Principle," *Eur. Phys. J. C* **79** (2019) no. 4, 363, arXiv:1806.09340 [physics.ins-det].

# References XIII


[67] C. Blanco, Y. Kahn, B. Lillard, and S. D. McDermott, "Dark Matter Daily Modulation With Anisotropic Organic Crystals," *Phys. Rev. D* **104** (2021) 036011, arXiv:2103.08601 [hep-ph].

[68] A. Coskuner, A. Mitridate, A. Olivares, and K. M. Zurek, "Directional Dark Matter Detection in Anisotropic Dirac Materials," *Phys. Rev. D* **103** (2021) no. 1, 016006, arXiv:1909.09170 [hep-ph].

[69] A. Coskuner, T. Trickle, Z. Zhang, and K. M. Zurek, "Directional detectability of dark matter with single phonon excitations: Target comparison," *Phys. Rev. D* **105** (2022) no. 1, 015010, arXiv:2102.09567 [hep-ph].

[70] M. Vignati, "Welcome and introduction." https://agenda.infn.it/event/39007/contributions/235289, 2024. [Online; accessed 5-February-2026].

[71] R. Anthony-Petersen *et al.*, "A stress-induced source of phonon bursts and quasiparticle poisoning," *Nature Commun.* **15** (2024) no. 1, 6444, arXiv:2208.02790 [physics.ins-det].

# References XIV

[72] R. Romani, “Single and shared lee backgrounds in spice detectors.” https://agenda.infn.it/event/39007/contributions/235281, 2024. [Online; accessed 5-February-2026].