A Strategy for Low-Mass Dark Matter Searches with Cryogenic Detectors in the SuperCDMS SNOLAB Facility

UCLA DM 2023

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S. Golwala for the SuperCDMS Collaboration

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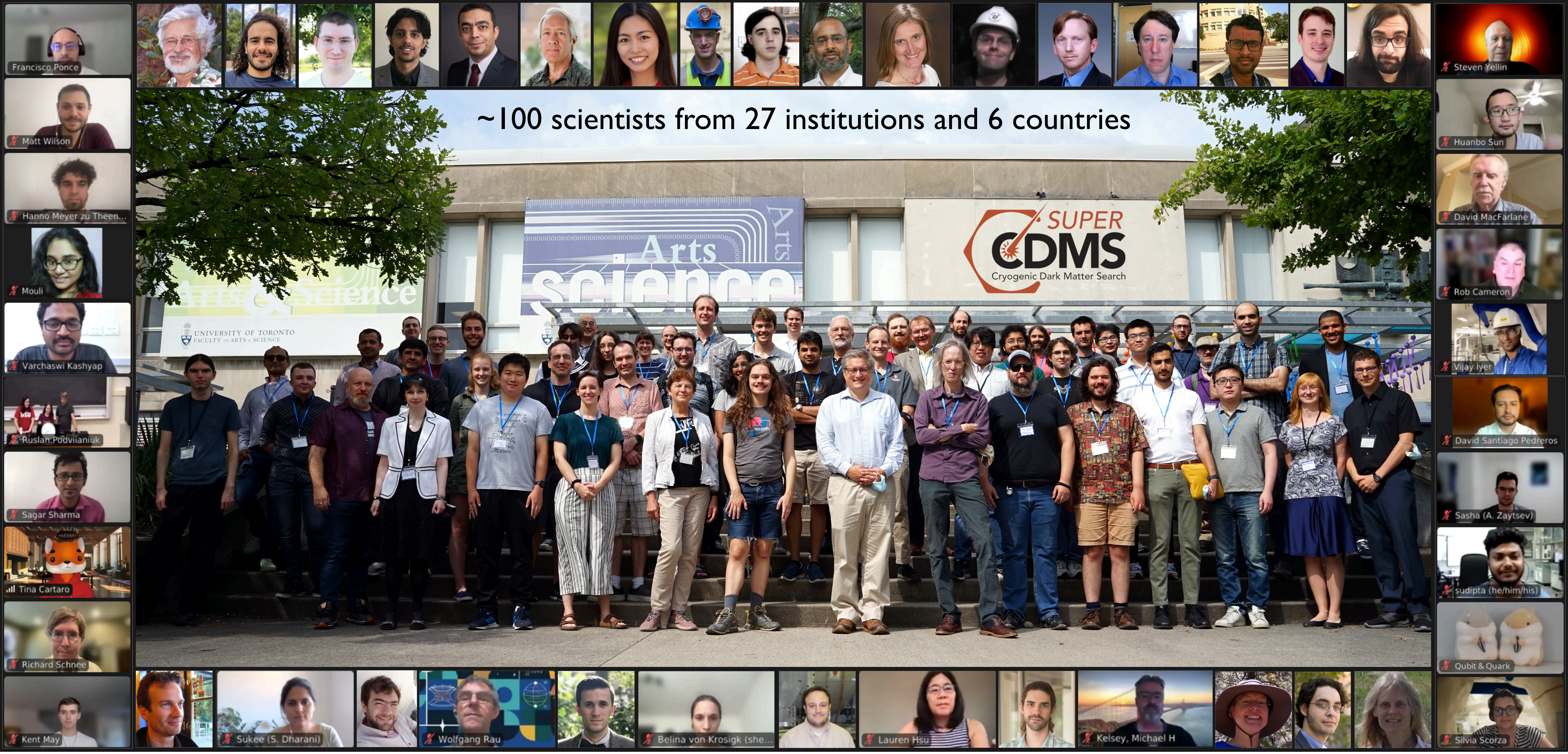

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supercdms.slac.stanford.edu

Overview

SuperCDMS SNOLAB Facility:
A venue for DM searches with sub-Kelvin detectors

SuperCDMS SNOLAB: G2 experiment sensitive to

0.5-5 GeV nucleon-scattering DM
1-100 eV dark photons and ALPs
1-100 MeV dark-photon-coupled light DM
Early science: underground at CUTE in 2023, Science Run 1 starting end 2024/start 2025
(See talk by E. Michielin, Session 12)

Only the start:

facility and technology have much more potential
DM landscape is constantly evolving

Upgrade program: (Snowmass white paper, arXiv:2203.08463)

Coherent, multi-staged, multi-prong technical R&D program →
new reach in DM parameter space,
discovery potential and constraints on DM properties

Time horizons: 5 yrs (post-current-experiment), 10 years, 15 years.

Outline

SuperCDMS SNOLAB Facility review and upgrade potential

Approach to analyzing upgrades

Science reach for:

0.5-5 GeV nucleon-scattering DM

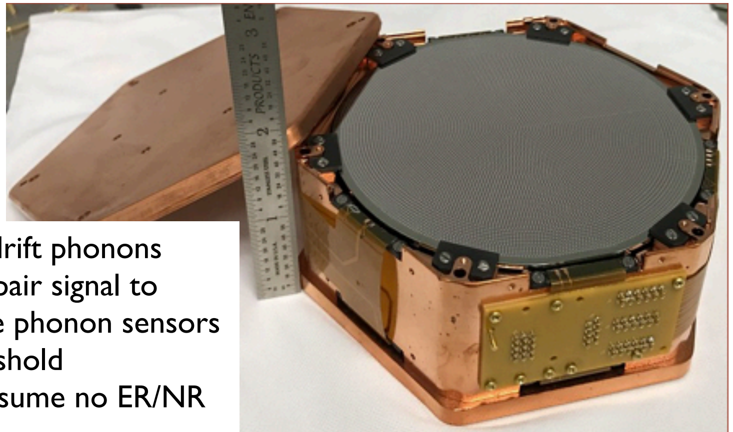
1-100 eV dark photons and ALPs

1-100 MeV dark-photon-coupled light DM

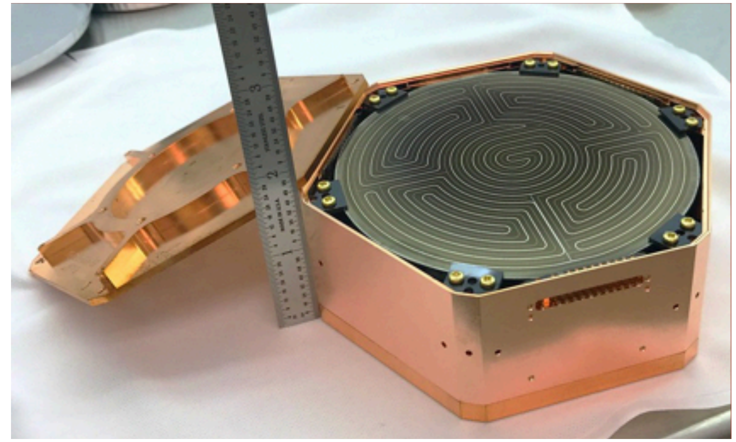
SuperCDMS SNOLAB: A joint CFI-DOE-NSF G2 dark matter experiment

SUPER CDMS Cryogenic Dark Matter Search

HV detectors: 8 Ge, 4 Si



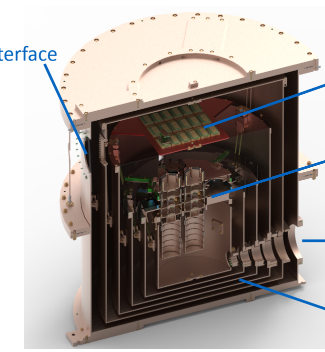
- @100V bias, drift phonons transduce eh pair signal to more sensitive phonon sensors
- ~50 eV_{ee} threshold
- projections assume no ER/NR discrimination



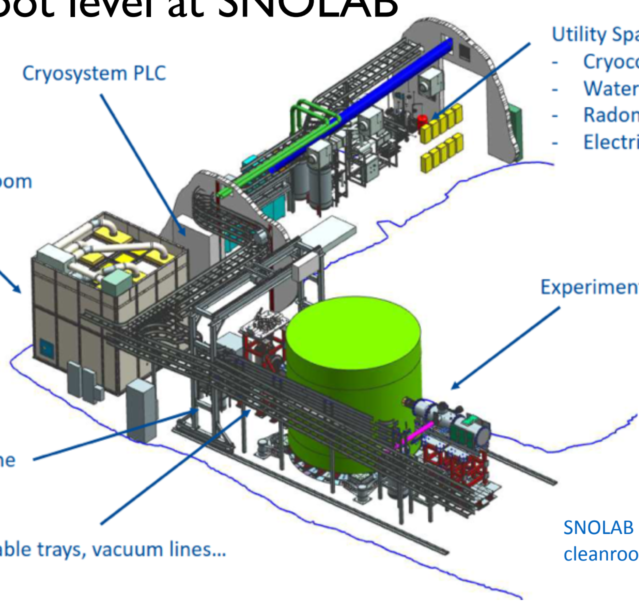
- Full ER/NR discrimination down to 1-2 keV_{nr}, limited by ionization readout noise

iZIP detectors: 10 Ge, 2 Si

Cryostat
(up to 42 detectors @ 100mm x 33mm; Ge 1.4 kg, Si 0.6 kg)

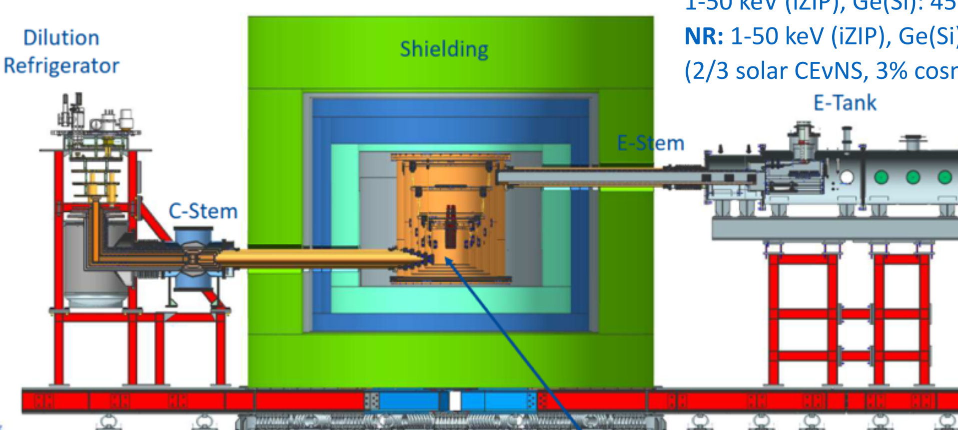


6850 foot level at SNOLAB



Expected **facility** backgrounds:
ER: (kky = kg keV yr)
0.003-2 keV (HV), Ge(Si): 25(80)/kky
1-50 keV (iZIP), Ge(Si): 45(150)/kky
NR: 1-50 keV (iZIP), Ge(Si)L 3.2(2.3)x10^{-3}/kky
(2/3 solar CEvNS, 3% cosmogenic, 9% cavern)

Cryogenics/Shield systems



SuperCDMS SNOLAB: Potential Upgrades

Change detector size, configuration, substrate; reduce cosmogenic bgnds

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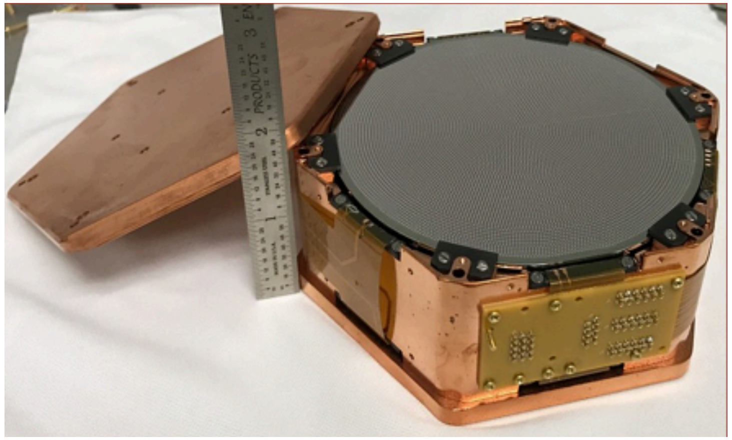

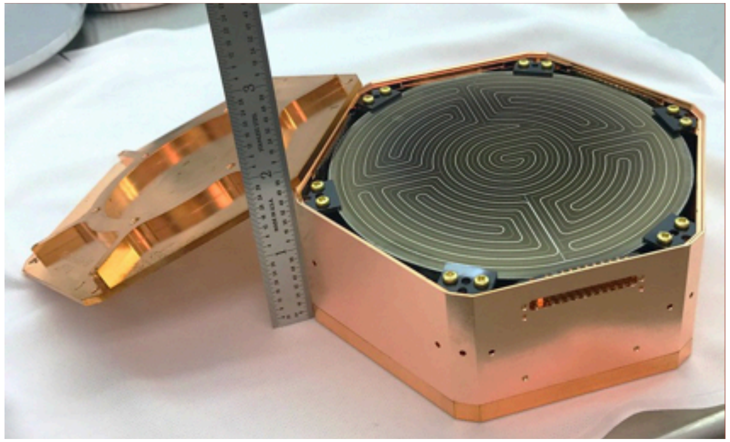

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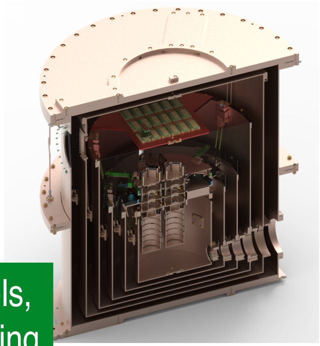

Larger cryostat, more readout channels, new dilution refrigerator, modified cooling path for lower base temp.

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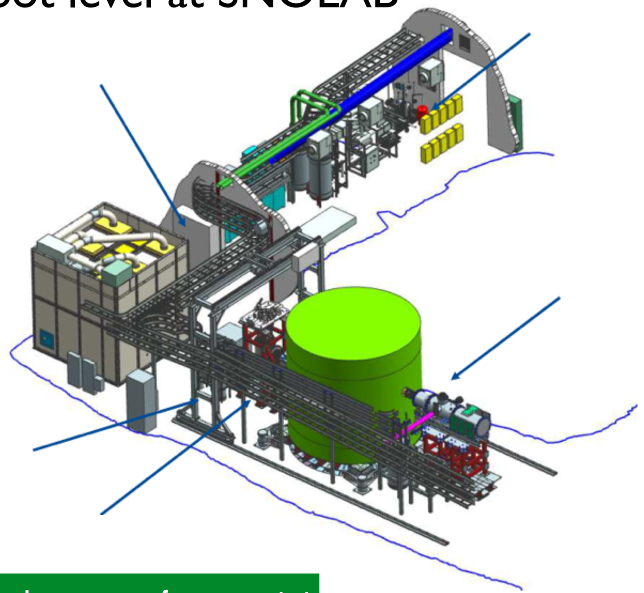

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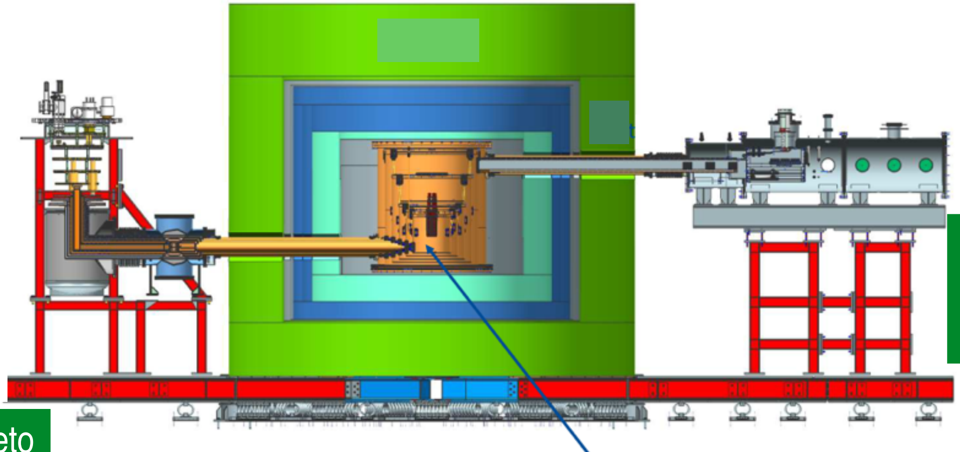

Reduced materials backgrounds

Class 100 cleanroom for cryostat

Enhanced shield and/or active veto

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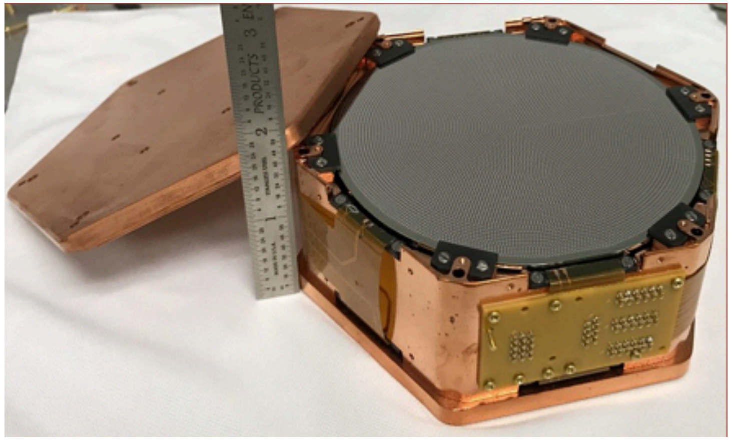

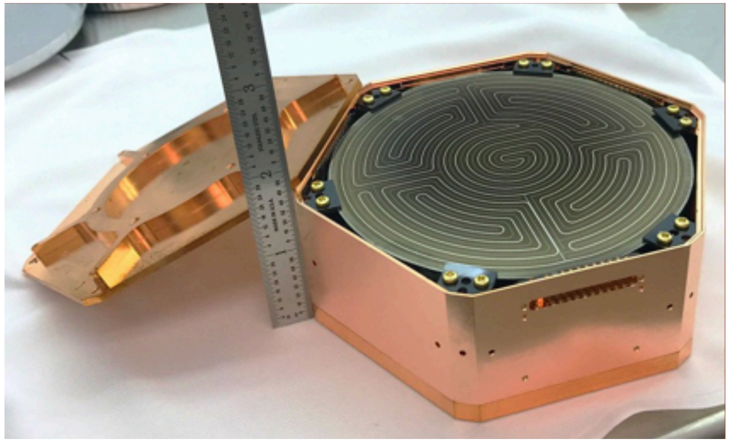

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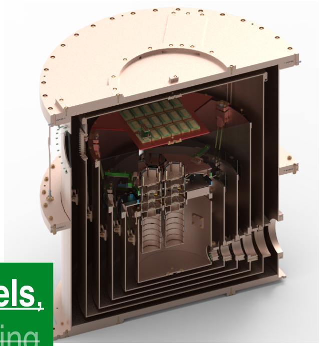

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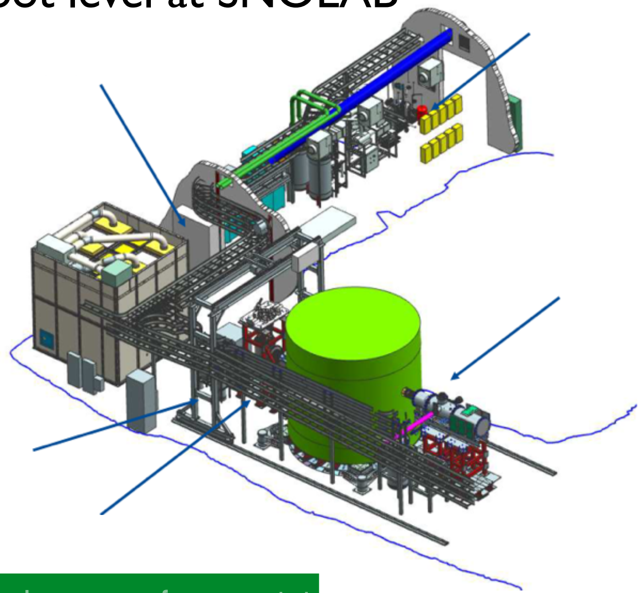

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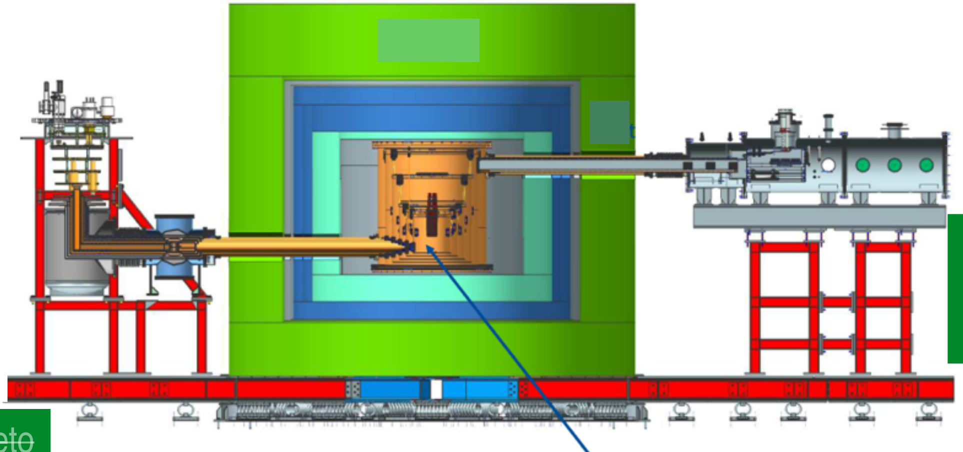

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Framework for Analyzing Upgrade Options

A range of improvements in both backgrounds and detectors possible

- Backgrounds 1/2/3, Detectors A/B/C
- 1→2→3, A→B→C: higher cost (R&D, implementation) and higher risk of failure (lower maturity)
  - Backgrounds upgrades are lower risk/higher maturity; cost dominated by implementation

Ideally, you construct a matrix →

Baseline assumptions:

- 2 towers (144 readout channels) for each option
  - 6 towers can fit (3x)
  - 2 towers allows multiple different detector types
  - Max channel count: 2880 (20x)
- 4 years exposure
- Threshold = 7 σ_{pt}

<table>
<tr><th colspan="2" rowspan="2">Science Potential</th><th colspan="3">Backgrounds (cost, risk)</th></tr>
<tr><th>1 ($, Low)</th><th>2 ($$, Med)</th><th>3 ($$$, High)</th></tr>
<tr><td rowspan="3">Detectors (cost, risk)</td><td>A ($, Low)</td><td colspan="3" rowspan="3">Fill in by forecasting sensitivity based on various assumed improvements.
Forecasts use:
• realistic MC-based background models
• spectrum-level ensemble of realizations
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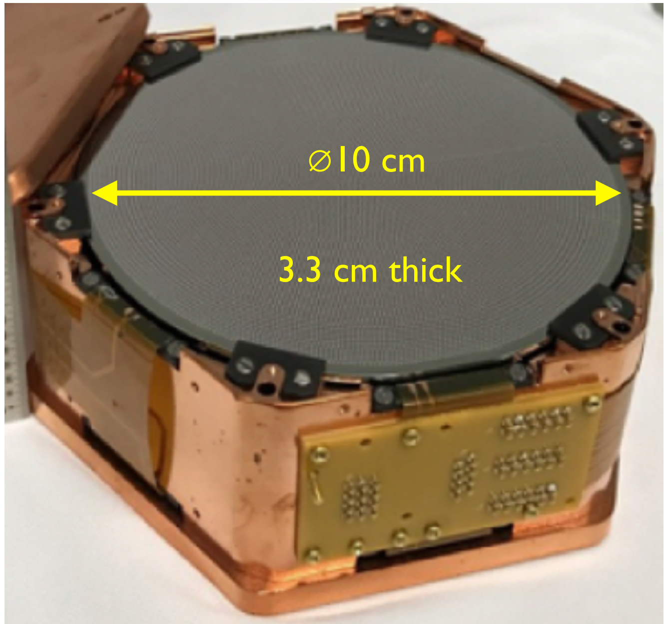
Conclusion:

Detectors A→B→C dominates: NR discrimination improves or CEνNS dominates

Backgrounds 1→2→3 provide only incremental gains

Science Potential		Backgrounds (cost, risk)		
		1 ($, Low)	2 ($$, Med)	3 ($$$, High)
Detectors (cost, risk)	A ($, Low)	Fill in by forecasting sensitivity based on various assumed improvements. Forecasts use: • realistic MC-based background models • spectrum-level ensemble of realizations • simplified profile-likelihood ratio technique		
	B ($$, Med)			
	C ($$$, High)			

Detector R&D Options: Multiple Detector Formats



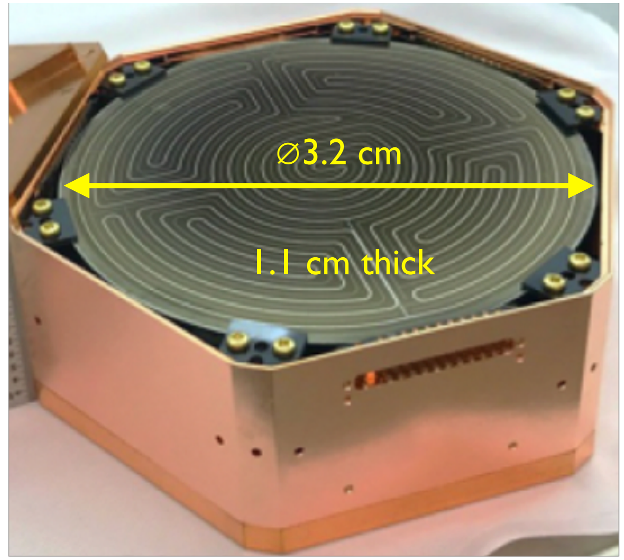
SNOLAB-sized HV:

improve phonon resolution to << eV_b (1 eh pair):

- NRs and ERs at different phonon energies due to ionization yield differences:
  $E_p = N_{eh}\, e V_b + N_{eh} / Y$
- ERs down to 2 eh pair (leakage @ 1 eh pair)

Y = electron-hole pairs created per eV of recoil energy ("classical" definition)

x3 smaller in each dimension
~x25 smaller mass

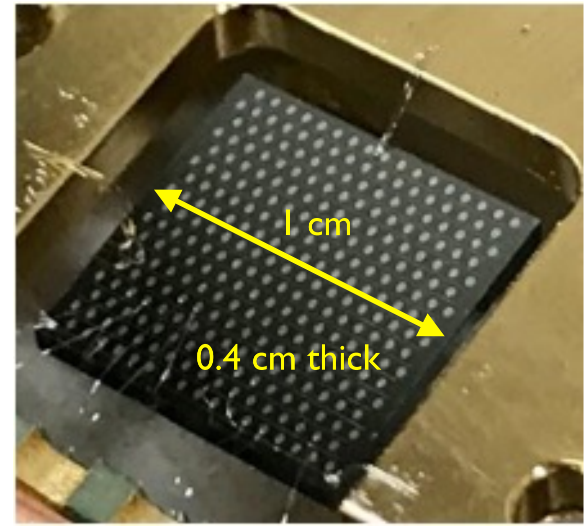


"10 cm³" iZIP and piZIP:

NR discrimination to lower mass w/ improved ionization yield (Y) measurement:

- iZIP: improve ionization resolution:
  - active reset of integrator
  - smaller C_{det}
- piZIP: improve phonon resolution, pixellize phonon sensor to *separately* measure:
  - primary phonons: E_R
  - drift phonons: N_{eh}
  - $\} \rightarrow Y$

x3² smaller in each dimension
~x25² smaller mass



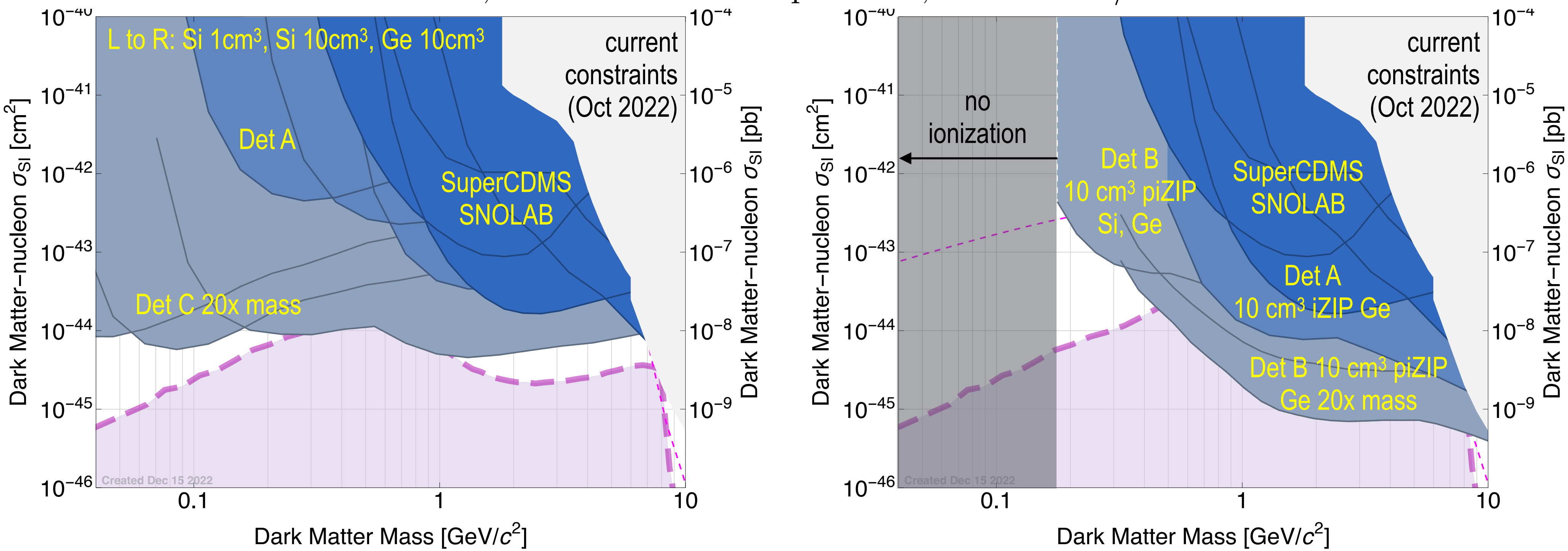
"1 cm³" 0V:

reduce size to achieve phonon resolution of $\mathcal{O}(1)$ eV → $\mathcal{O}(0.1)$ eV → $\mathcal{O}(0.01)$ eV

- Sub-GeV DM NR spectrum steeper than backgrounds including solar CEνNS
- DPDM, ALPM, DP-coupled light DM below 1 eh pair

Nucleon-Coupled DM

SG-1, SG-2: Nucleon-Coupled DM, 0.05–5 GeV/c^2



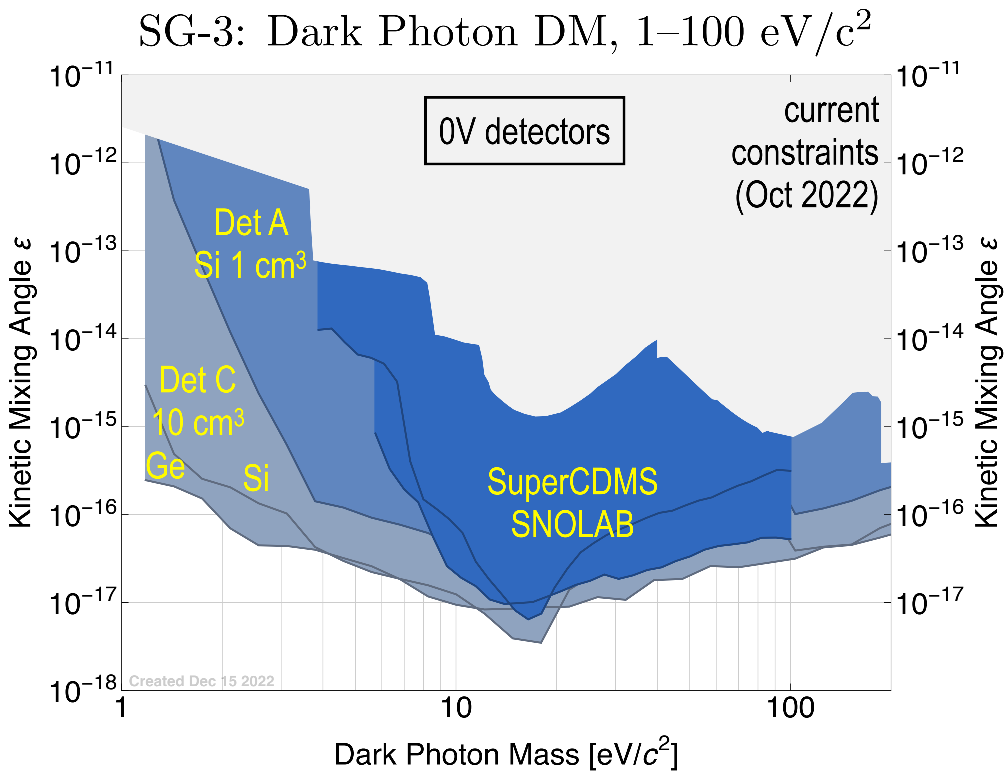
SG-1: Sub-GeV nucleon-coupled DM: Si/Ge 0V 1cm³, 10cm³

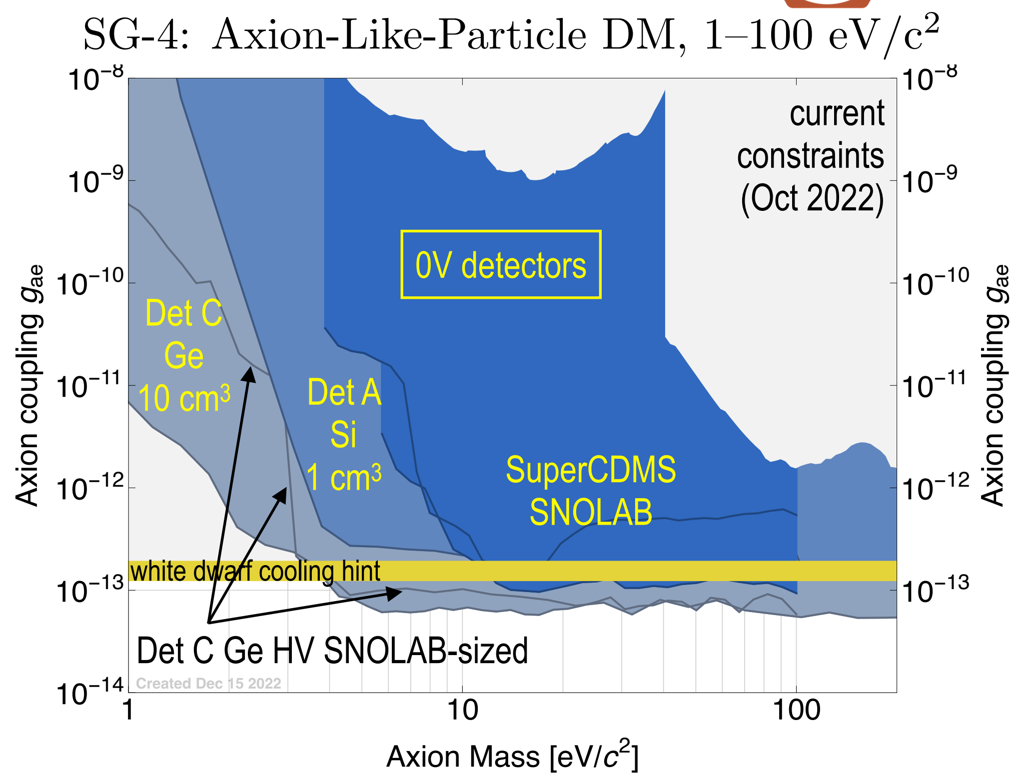
- CEνNS is dominant background; spectral discrimination enables impressive reach
- "Environmental/excess" backgrounds are largely unknown, though now being studied
  - crystal/film relaxation, vibration, RF, IR/BB photons, secondary UV/O/IR photons, ….

SG-2: 0.5-5 GeV nucleon-coupled DM: 3 options to ν fog using ionization yield Y:

- HV SNOLAB-sized: NR spectral discrimination: $E_p = N_{eh}\, e V_b + N_{eh} / Y$
- 10cm³ iZIP: improved ionization resolution → improved Y measurement
- 10cm³ piZIP: separately measure phonons from E_R and N_{eh} → Y

Dark Photon and Axion-Like Particle DM

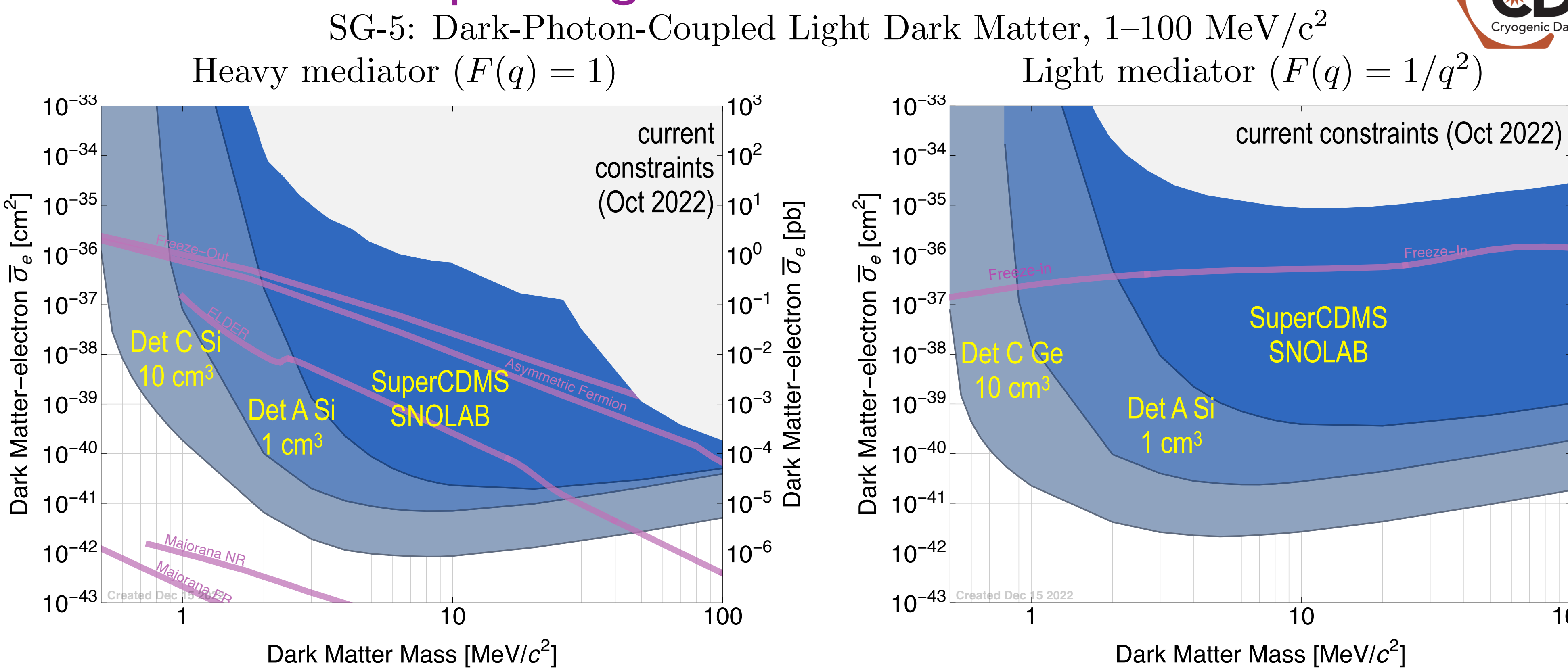




SG-3, 4: 1-100 eV DPDM, ALPDM w/large HV or 0V

- HV SNOLAB-sized reach comparable to above, but hard cutoff imposed by ionization leakage (2 eh ~ 3-4 eV)
- axion-electron coupling g_{ae}
  - exceed astro limits below 100 eV for 1st time
  - test white dwarf cooling hint in long run?

Dark-Photon-Coupled Light DM



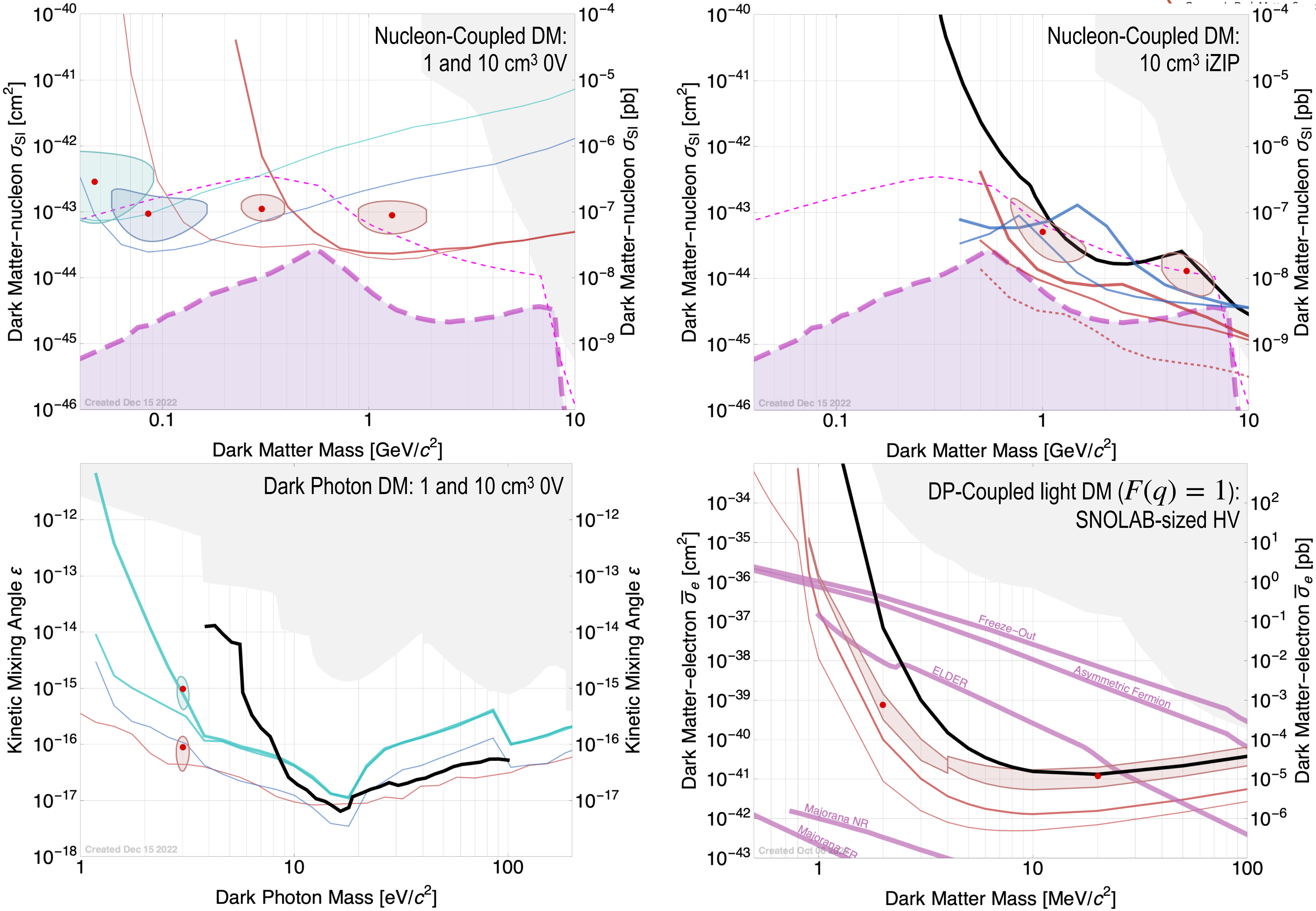
SG-5: 1-100 MeV DP-coupled LDM w/0V or SNOLAB-sized HV

HV has greater cross-section reach, cuts off in mass ~1 MeV/c^2

Can test:

- heavy mediator: Elastic Scalar, Asymmetric Fermion, ELDER, SIMP
- light mediator: Freeze-in

Discovery Potential: 3σ CL regions for ~3σ detections



Conclusions

The SuperCDMS SNOLAB facility is amenable to numerous upgrade options

Detector advances promise expanded science reach in both mass and cross-section

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⬇

SuperCDMS SNOLAB is just the start!

The evolving landscape for dark matter demands a diverse program to search exhaustively. Our technologies and facility situate us well to play a leading role to this program.

See the full Snowmass white paper, arXiv:2203.08463

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