Projected Sensitivities for Future Upgrade Scenarios of SuperCDMS SNOLAB

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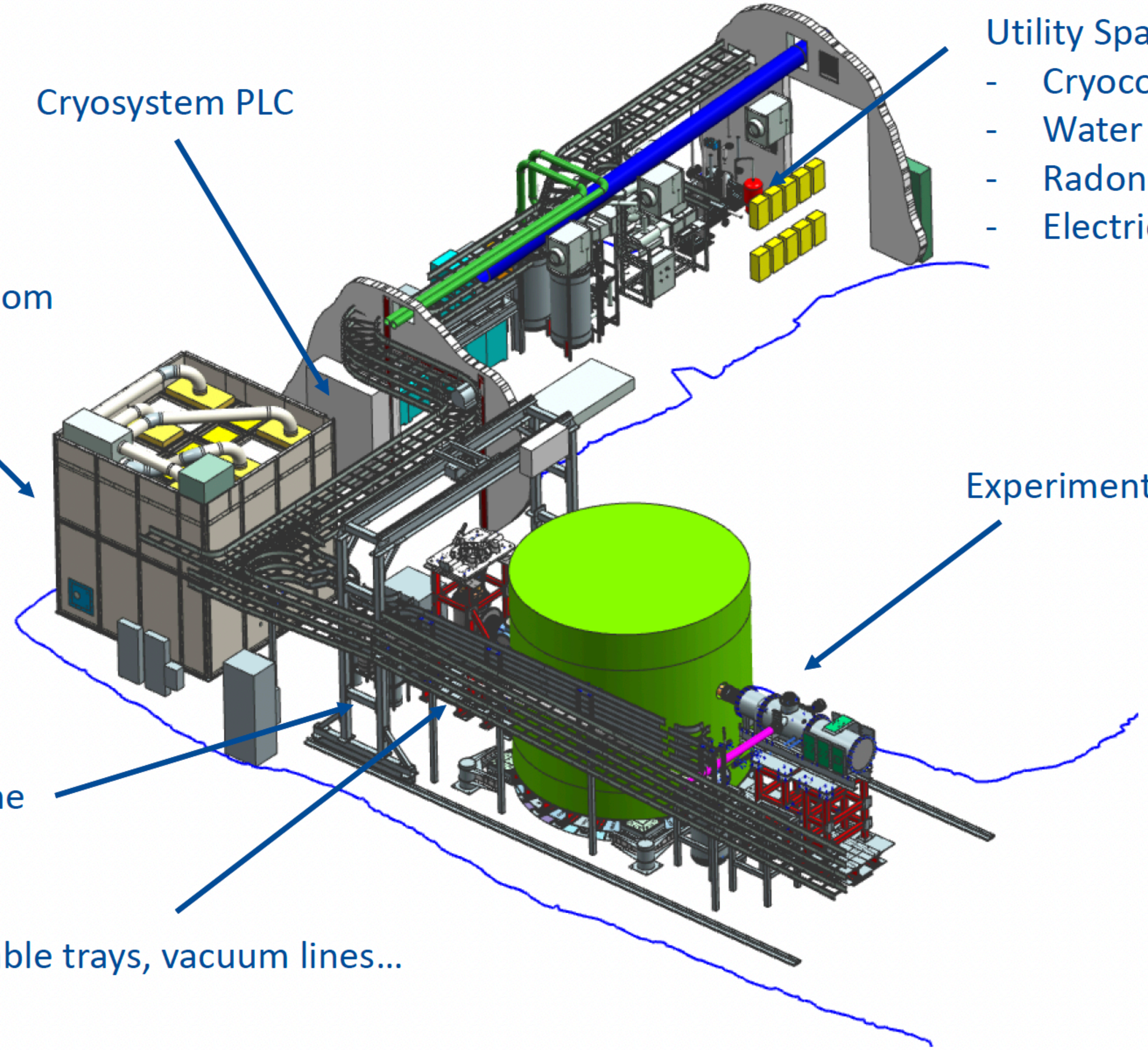
Overview

- SuperCDMS SNOLAB under construction, expected to start operation in 2024
- Updated sensitivity calculations from 2016 paper (doi.org/10.1103/PhysRevD.95.082002)
  - Background and facility adjustments, including in cryostat capacity
  - Includes instrumental background (leakage current)
- **Calculated the expected science reach for different future upgrade scenarios**
- Results are described in SNOWMASS white paper, *A Strategy for Low-Mass Dark Matter Searches with Cryogenic Detectors in the SuperCDMS SNOLAB Facility,* *arXiv* 2203.08463

SuperCDMS SNOLAB

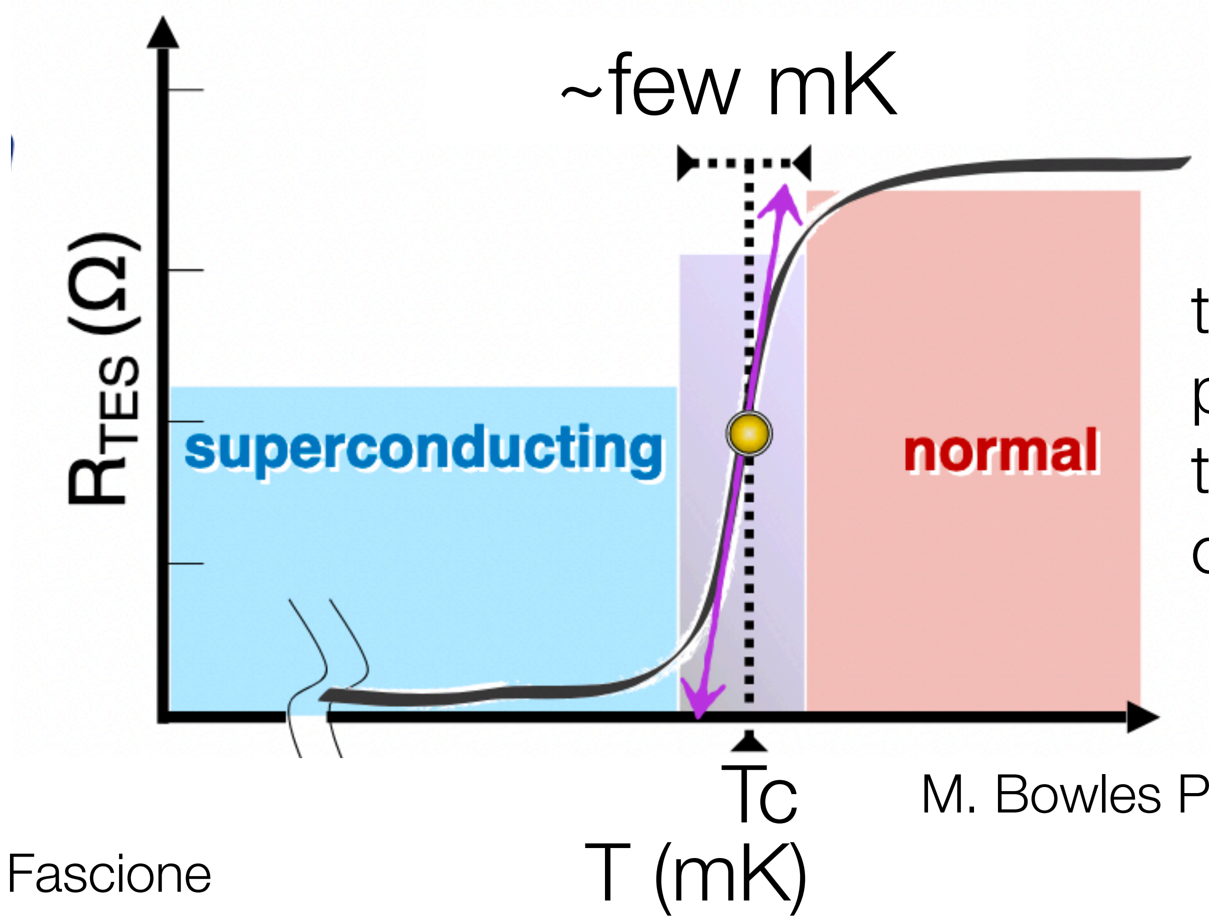
Figure 4 from 2203.08463

- Use cryogenic detectors to search for dark matter interactions with standard model matter
- Next generation under construction at SNOLAB
- 7 tower capacity, 6 detectors per tower
- Commissioning planned for 2022
- First run with 4 towers



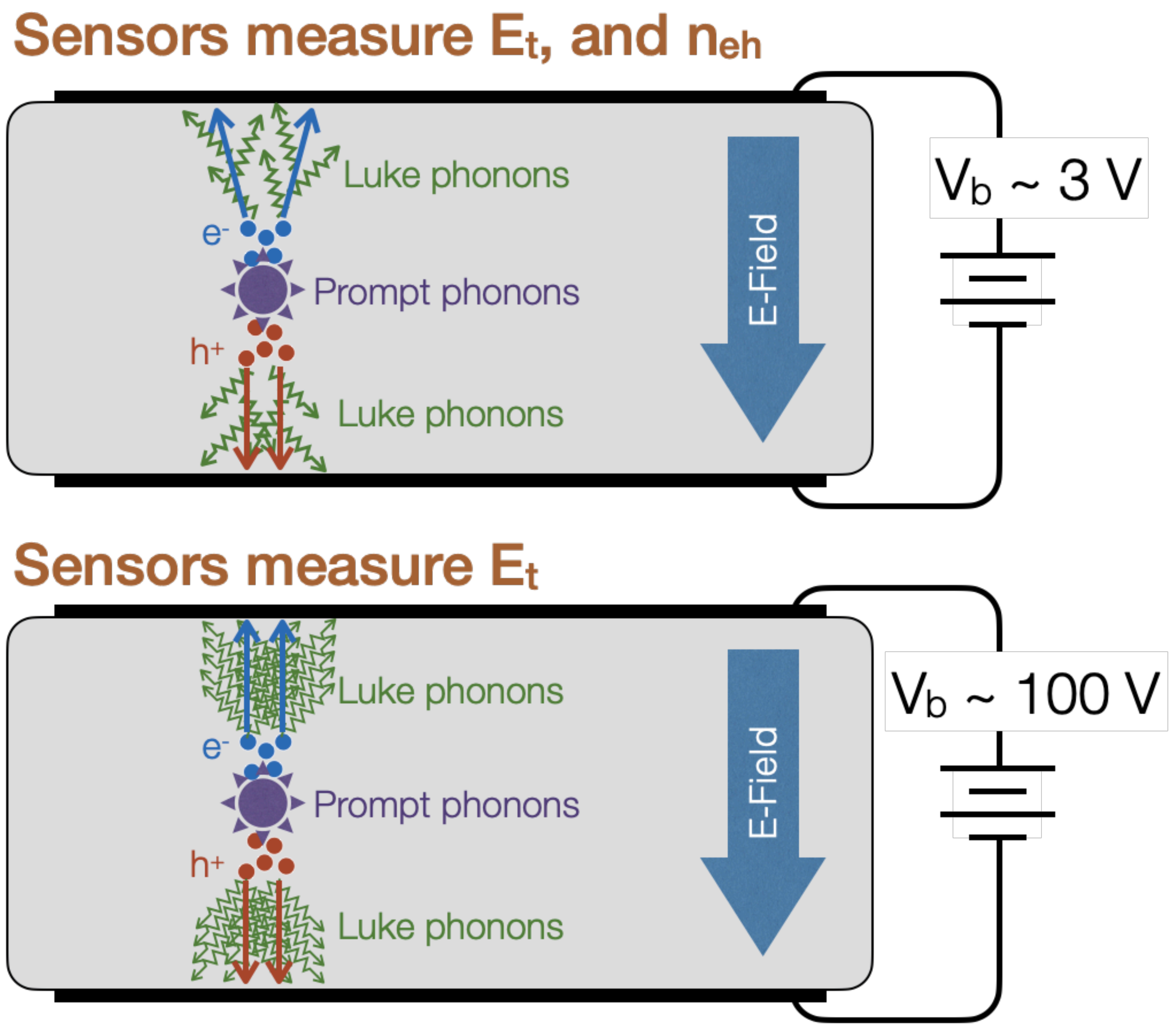
Neganov-Trofimov-Luke (NTL) Effect and Phonon Readout

- Charges in the crystal lattice drifting across an applied potential will produce additional phonons called NTL phonons
- Energy in NTL phonons is proportional to applied voltage across the detector
- Results in sensitivity to much lower energies
- Phonons are measured via transition edge sensors (TESs)



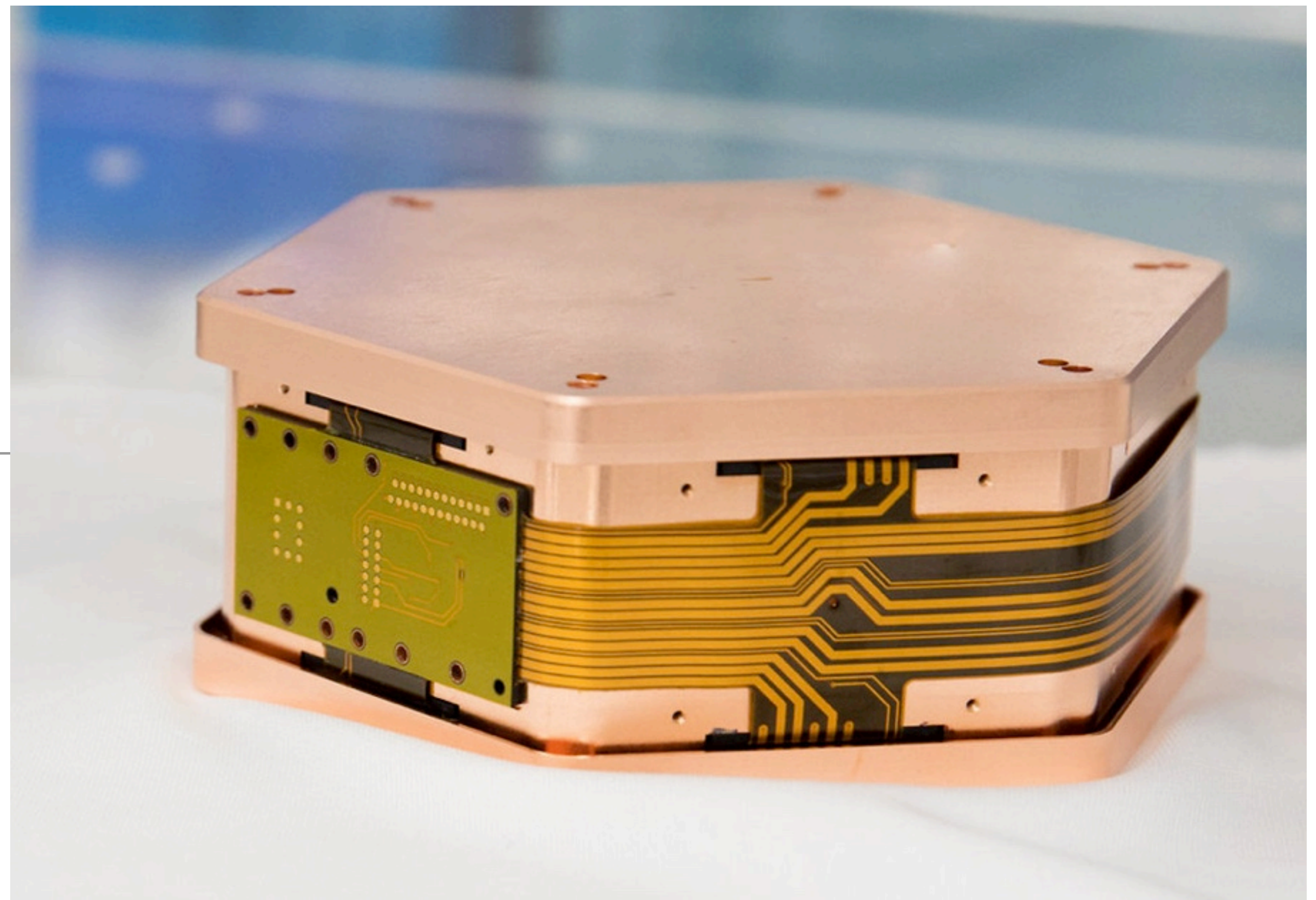
transition edge sensor principle: small change in temperature leads to large change in resistance

M. Bowles PhD thesis



SuperCDMS SNOLAB Detectors

Figure 2 from 2203.08463



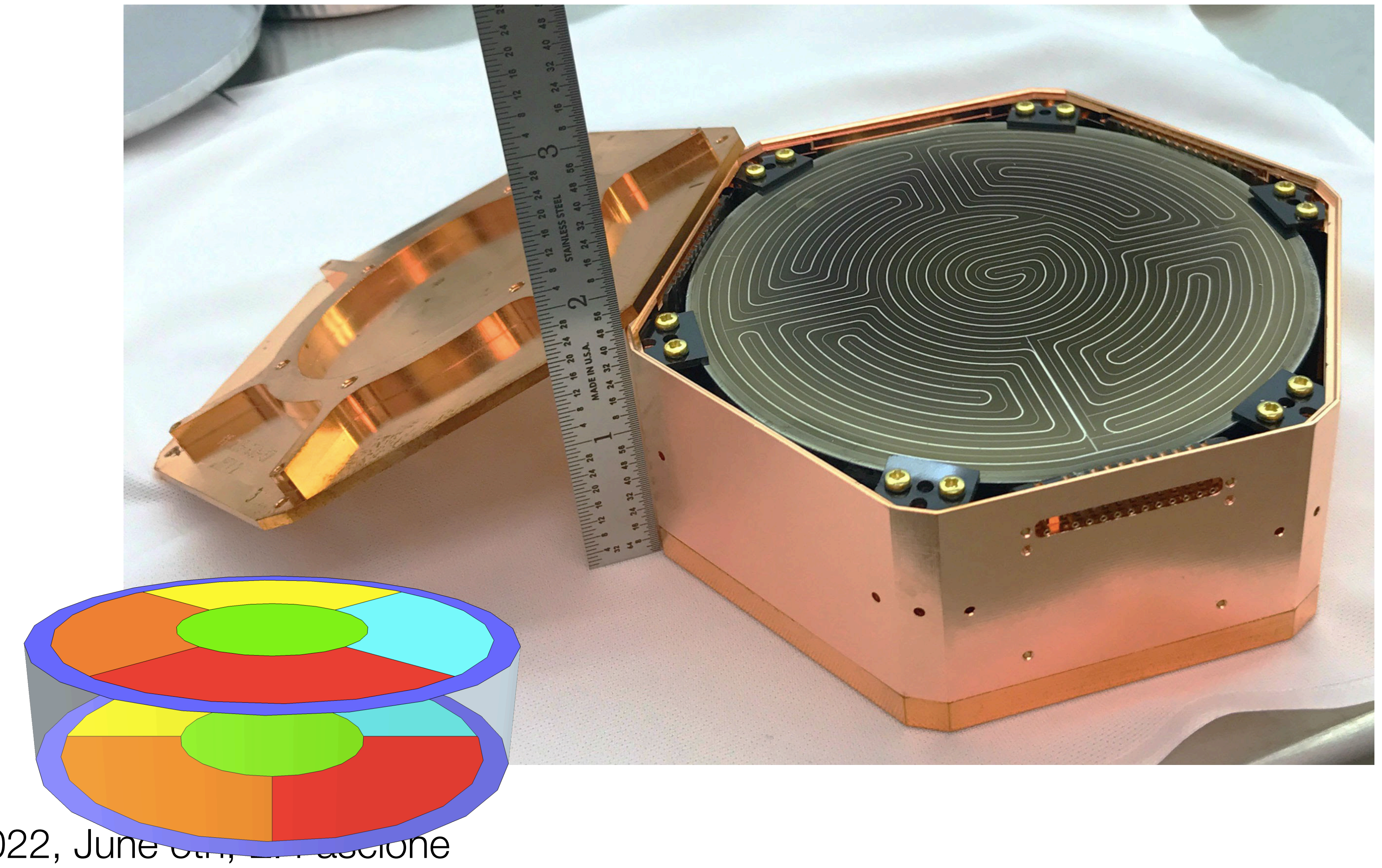
iZIP and HV detectors with new sensor layout in two materials:

- Ge - sensitivity to lower DM cross sections
- Si - sensitivity to lower DM masses

Larger than Soudan detectors (100 mm diameter, 33 mm thick)

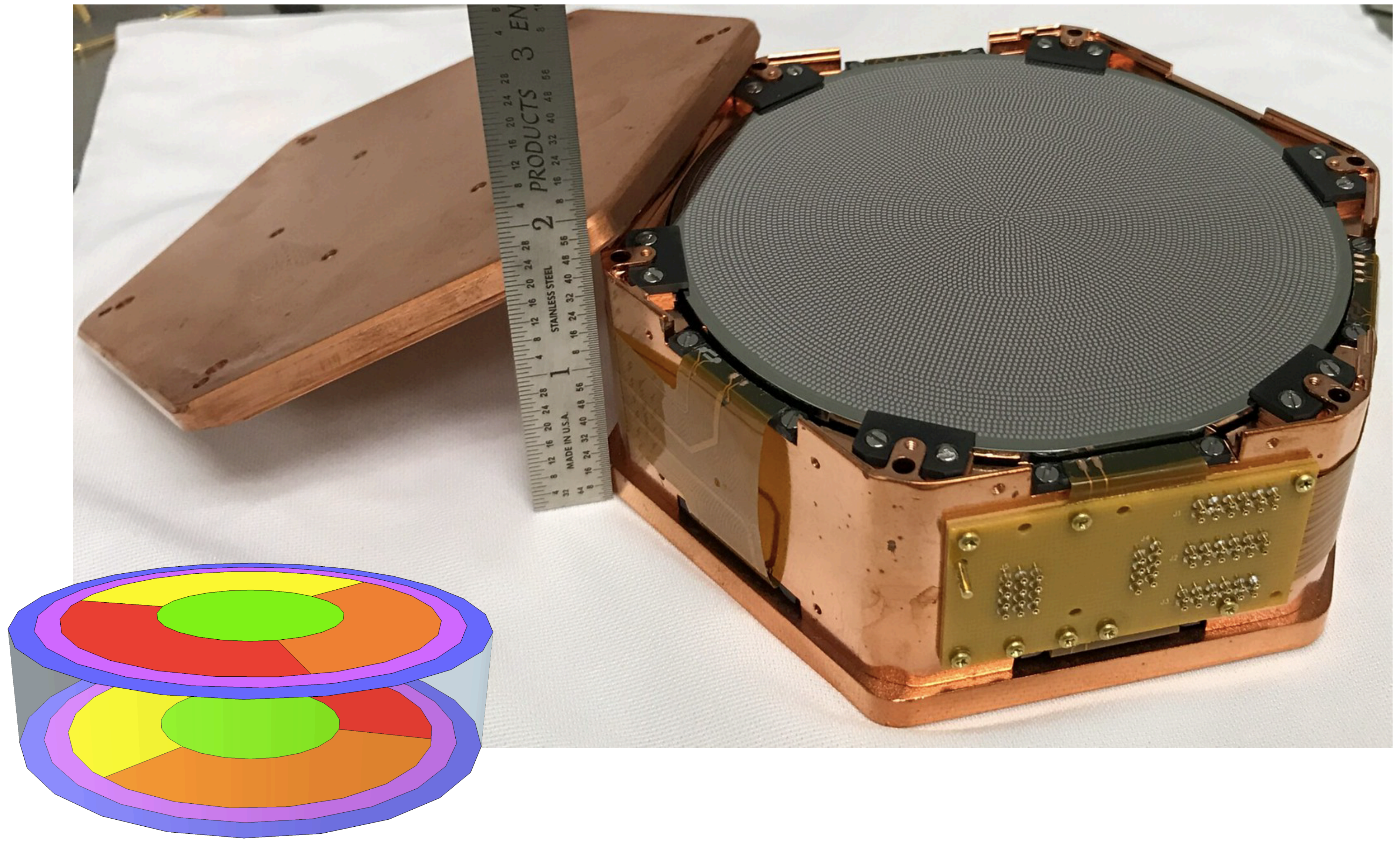
iZIP

- 6-8 V bias (minimal NTL phonon contribution)
- NR/ER discrimination
- Surface event removal



High Voltage (HV)

- 100 V bias (NTL phonons dominate)
- Much lower threshold
- No event-by-event background discrimination



Future Upgrade Scenarios

Science Goals

- We consider five different science goals enabled by the upgrade scenarios
  - SG-1: Nucleon couplings of sub-GeV-scale (0.05-0.5 GeV) DM
  - SG-2: Nucleon couplings of GeV-scale (0.5-5 GeV) DM down to the neutrino fog
  - SG-3: Electron couplings of kinetically mixed eV-scale (1-100 eV) dark photon DM (DPDM)
  - SG-4: Electron couplings of eV-scale (1-100 eV) axion and axion-like particle DM
  - SG-5: Dark-photon-mediated couplings of MeV-scale (1-100 MeV) light DM (LDM)

Upgrades Considered: Background Improvements

- Several upgrades are close at hand, but too late for SuperCDMS SNOLAB; refer to these improvements as Bkg 1 scenario
  - Reduction of bulk ER background from U/Th in Kapton and Cirlex in material used in cabling near detectors and detector clamps
  - Reduction of neutron background from magnetic shielding
  - Reduction of backgrounds from radon daughters on detector surfaces
- More aggressive and costly background scenarios with ^{32}Si reduction and all-underground detector life-cycle were considered, but found unnecessary

Upgrades Considered: Detector Improvements

- Alternative detector sizes (current size: ⌀10 cm, 3.3 cm high)
  - Smaller detectors with improved phonon energy resolution
  - 1 cm^3: 1 x 1 x 0.4 cm^3
  - 10 cm^3 : 3 x 3 x 1.2 cm^3

Detector Type	Detector Size	Dimensions	mass [kg] Ge	mass [kg] Si	number of Detectors	raw exposure [kg·yr] Ge	raw exposure [kg·yr] Si
SNOLAB	HV/iZIP	⌀10 cm × 3.3 cm	1.4	0.61	12	54	23
	piZIP				6	27	12
10 cm^3	HV	$3 \times 3 \times 1.2$ cm^3	0.057	0.025	36	6.6	2.9
	iZIP				24	4.4	1.9
	piZIP				12	2.2	1.0
	0V				144	26	12
1 cm^3	0V	$1 \times 1 \times 0.4$ cm^3	0.0021	0.00093	144	1.0	0.42

Table 3: Detector masses, exposures, and channel counts assuming 4 years of data, 80% duty cycle, and two tower capacity

- Alternative detector types
  - phonon iZIP (piZIP) : iZIP electric field configuration, measures ionization yield by separating primary and NTL phonon components
  - 0V : simplified design, 1 phonon sensor, ideal for sub-GeV nucelon-coupled DM
- Improved detector performance
  - 3 upgrade scenarios with increasing maturity, Det A, Det B, Det C (see following slide)

Detector Upgrades

Quantity	Detector		Detector Upgrade Scenario					
			A		B		C	
	Type	Size	Si	Ge	Si	Ge	Si	Ge
phonon energy resolution [eV]	0V	1 cm^3	0.5		0.13	0.28	0.013	
		10 cm^3	2.5	4.5	0.7	1.5	0.07	0.14
	HV	10 cm^3	3.3	4.5				
		SNOLAB-sized	12.	21.	4.	6.	0.6	0.7
	iZIP	10 cm^3	2.5	4.5	0.7	1.5		
		SNOLAB-sized	12.	21.	3.4	6.		
	piZIP	10 cm^3	3.3	4.5	1.2	1.5	0.19	0.21
		SNOLAB-sized	12.	21.	4.	6.	0.6	0.7
ionization energy resolution [eV_{ee}]	iZIP	10 cm^3	50.	60.	17.	17.		
	piZIP	10 cm^3	8.	11.	3.	6.	0.5	0.5
		SNOLAB-sized	30.	53.	10.	15.	1.5	1.8
ionization leakage current [Hz/gm]	HV		1.0		0.1		0.01	
impact ionization probability	HV		0.02		0.01		0.01	
charge trapping probability	HV		0.01		0.01		0.001	

Table 2 from 2203.08463: Quantitative improvements for each detector type and background scenario

- Staged plan for achieving improved phonon resolution
  - Energy resolution scales with T_C^3. Reduction in TES T_C to 40, 30, and 20 mK for scenarios Det A, Det B, and Det C, respectively
  - Phonon energy collection probability improvements could be possible with alternative fabrication
- Staged improvement to charge transport performance

Forecasting

Forecasting Process

Forecasts assume 4 year exposure with 2 tower capacity, up to 144 channels

- Backgrounds and signal spectra are simulated
- Simplified models to account for analysis cuts
- Generate many realizations of event spectra and determine exclusion sensitivity at upper 90% CL using profile likelihood ratio (PLR) method

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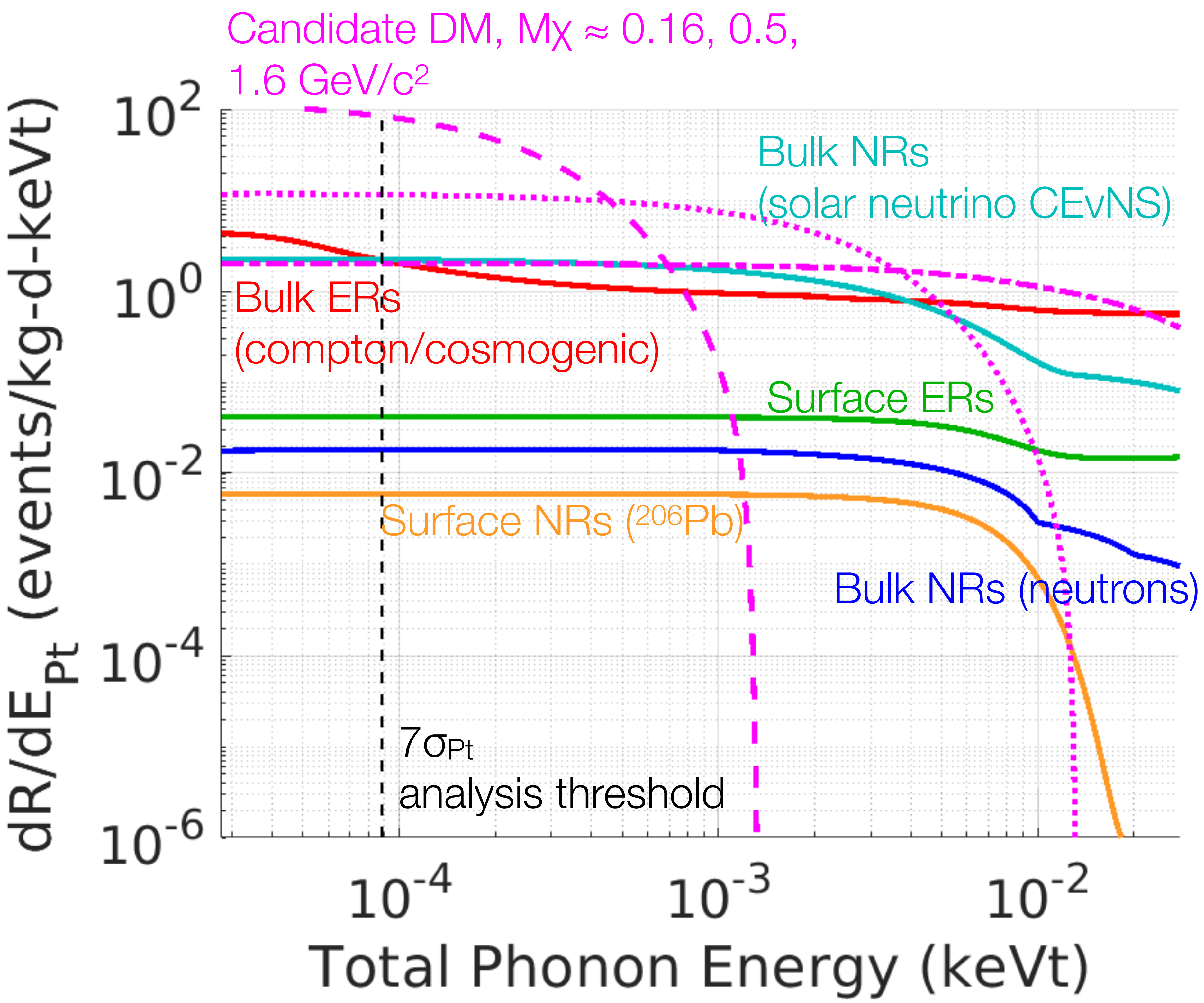
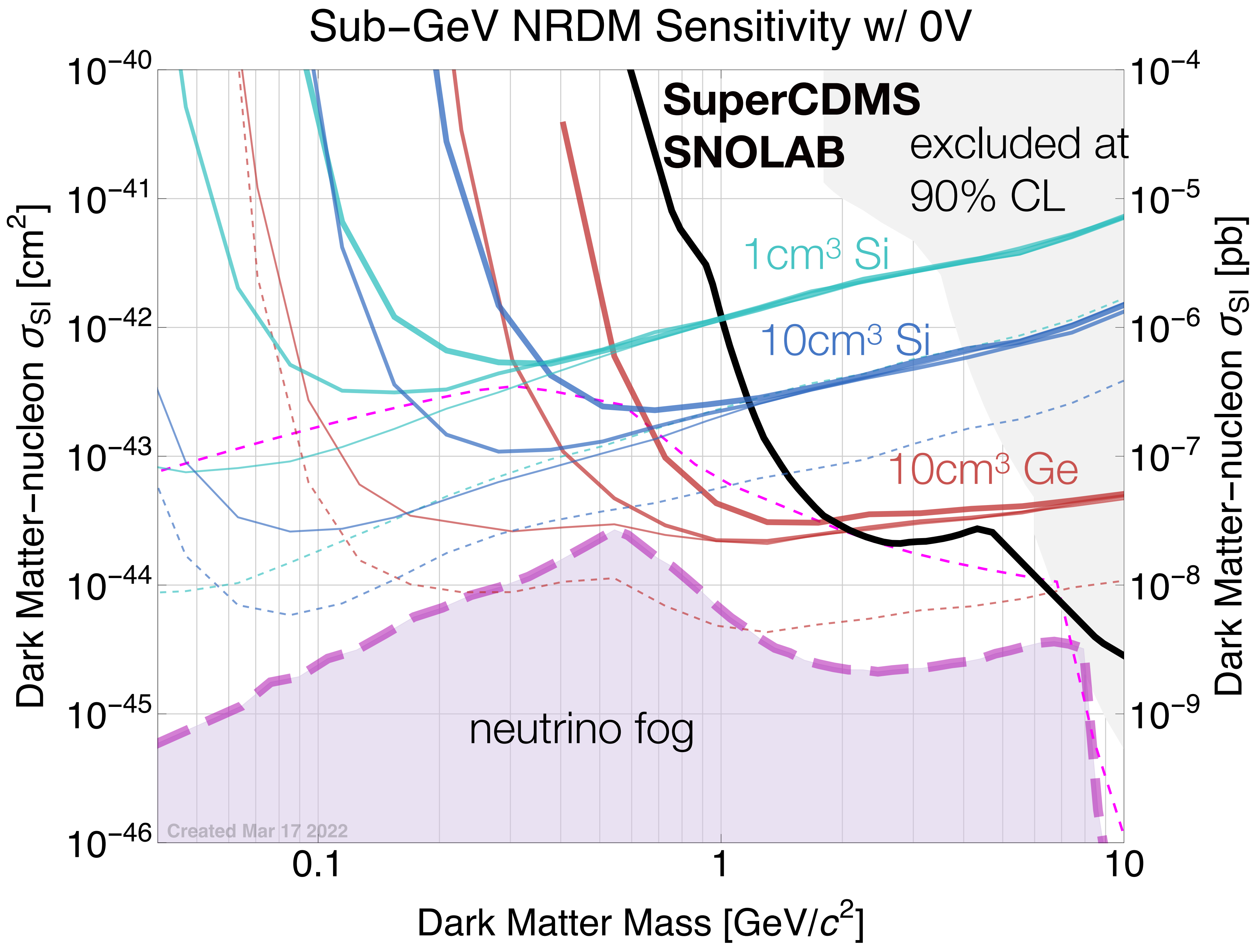
Forecasting Process and Results: NRDM 0V 10 cm³ and 1 cm³

Figure 9 from 2203.08463

Expected background contributions
Si 0V 1 cm³ Bkg 1 Det C





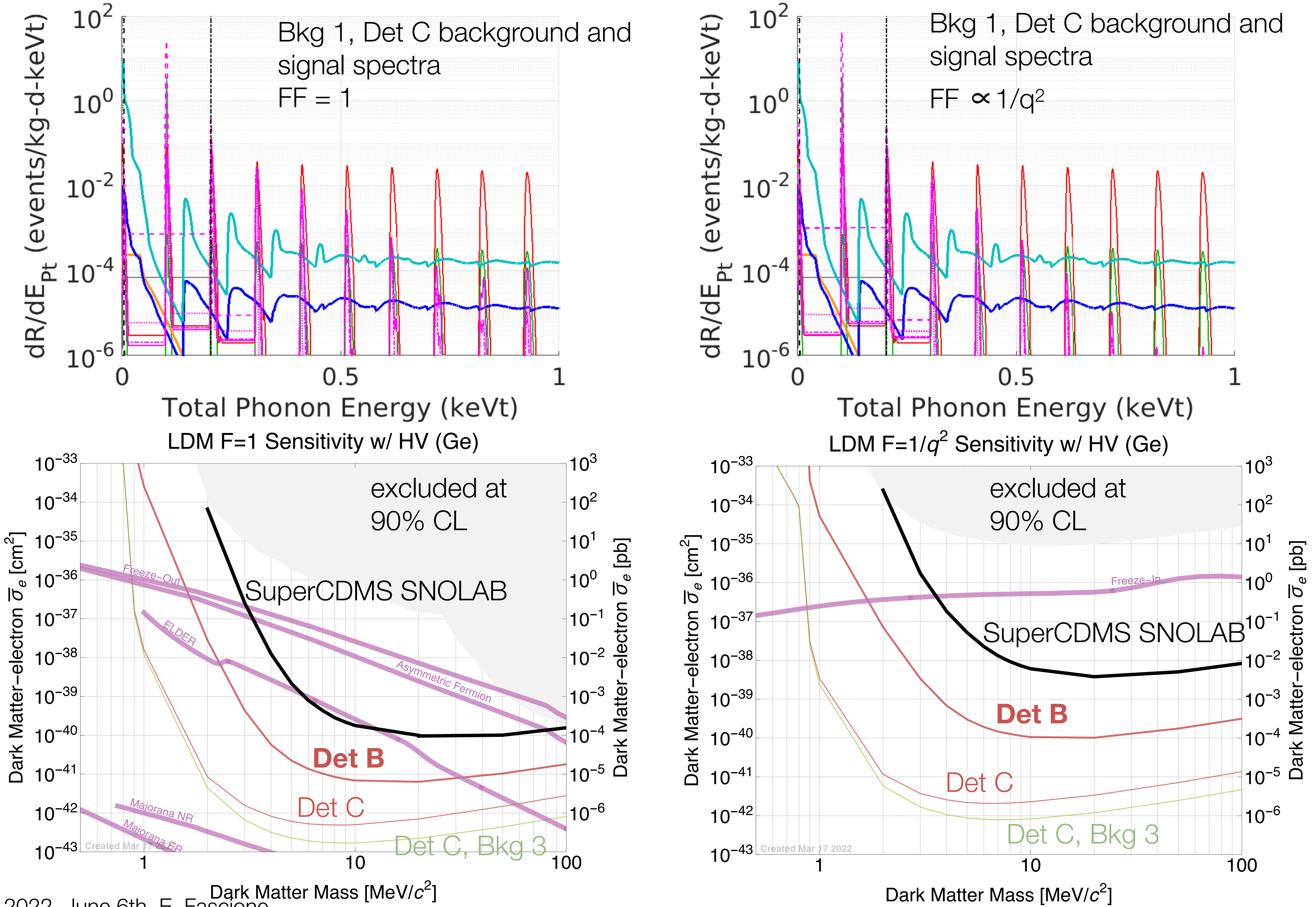
single neutrino sensitivity
Line thickness indicates upgrade scenario (**Det A**, Det B, Det C)

Dotted lines: Det C, 20x payload

- Bulk ERs and neutrinos dominate backgrounds
- Mass reach improves with decreasing phonon resolution
- Cross section reach improves with increasing exposure
- Det C x20 payload demonstrates these scenarios are exposure limited

Forecasting Process and Results: LDM SNOLAB-sized HV

Figure 16 from 2203.08463



$7\sigma_{Pt}$ analysis threshold
Bulk ERs (compton/cosmogenic)
Surface ERs
Surface NRs (^{206}Pb)
Bulk NRs (neutrons)
Bulk NRs (solar neutrino CEvNS)
Candidate DM, $M\chi \approx$ 1, 3, 10, 30 MeV/c²

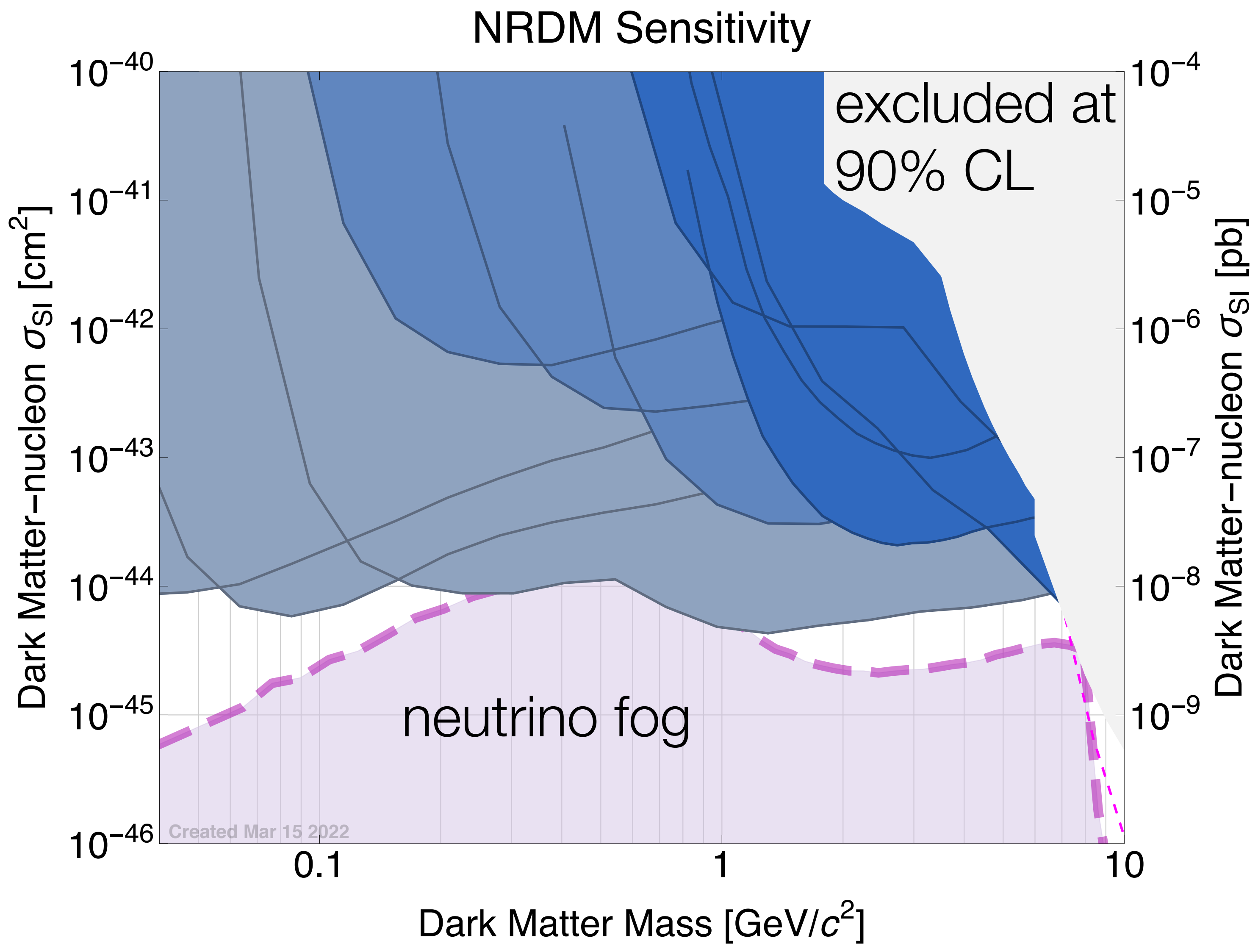
SuperCDMS SNOLAB envelope
HV SNOLAB-sized Ge.
Line thickness indicates upgrade scenario (**Det B**, Det C)
Det C, Bkg 3

Science targets from 2017 Cosmic Visions Report

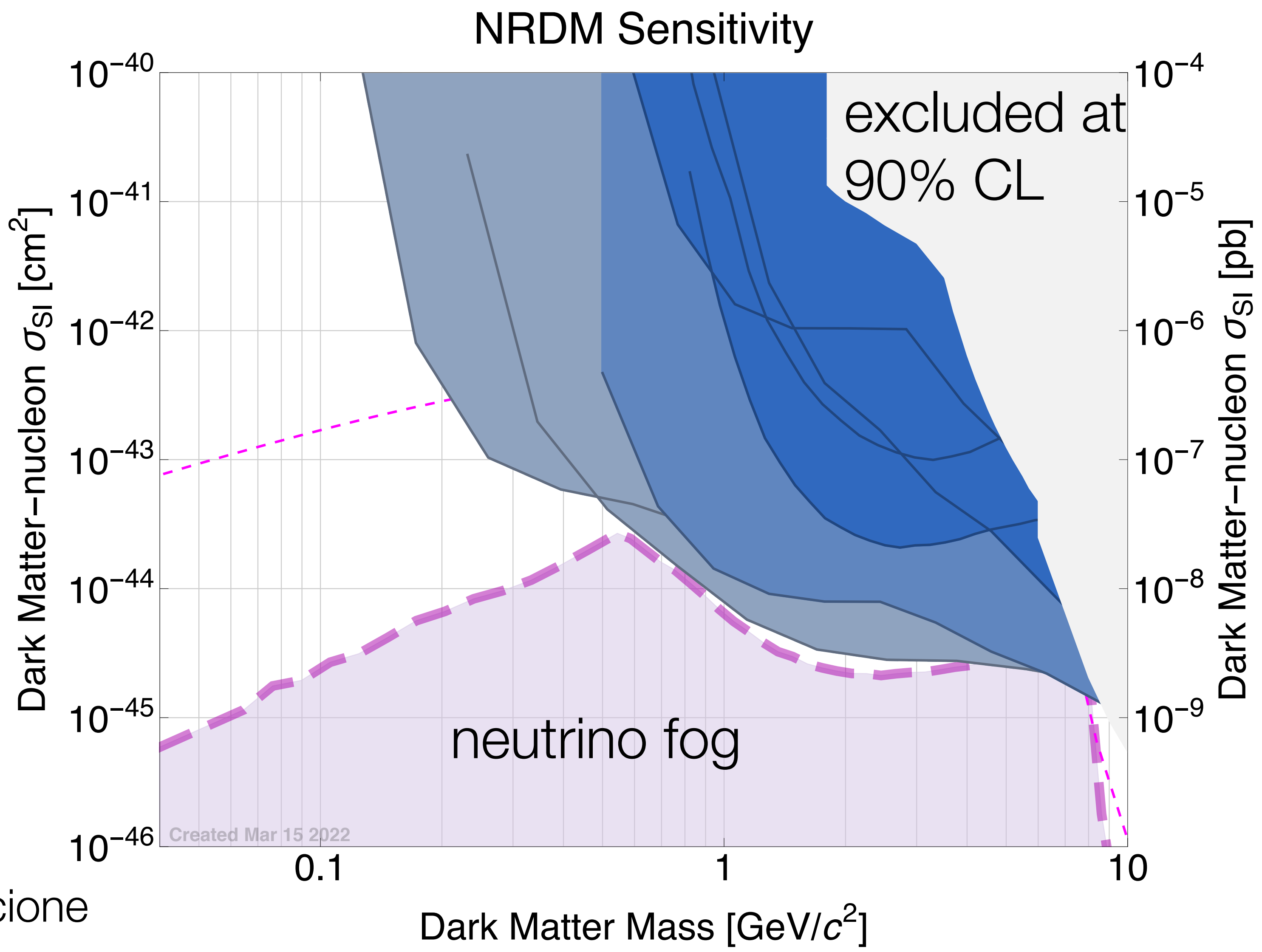
Not shown for plot clarity: Si SNOLAB-sized HV (very similar to Ge)

Summary Results: SG-1 and SG-2

Low mass sensitivity from 0V 1 cm³ and 0V 10 cm³



Cross section reach from SNOLAB-sized HV and iZIP/piZIP 10 cm³



- SG-1: Nucleon couplings of sub-GeV-scale (0.05-0.5 GeV) DM
- SG-2: Nucleon couplings of GeV-scale (0.5-5 GeV) DM down to the neutrino fog

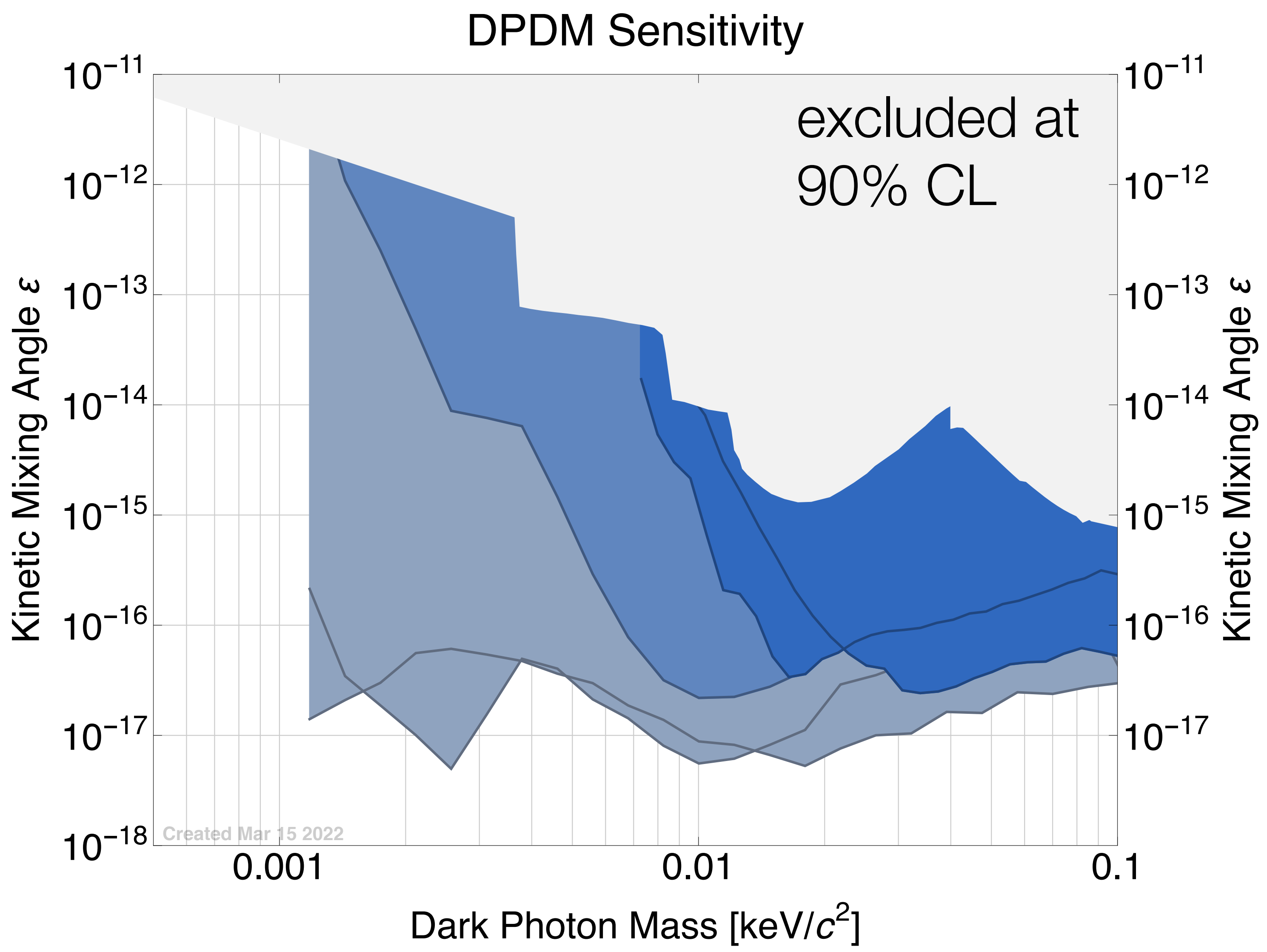
Summary of future science reach

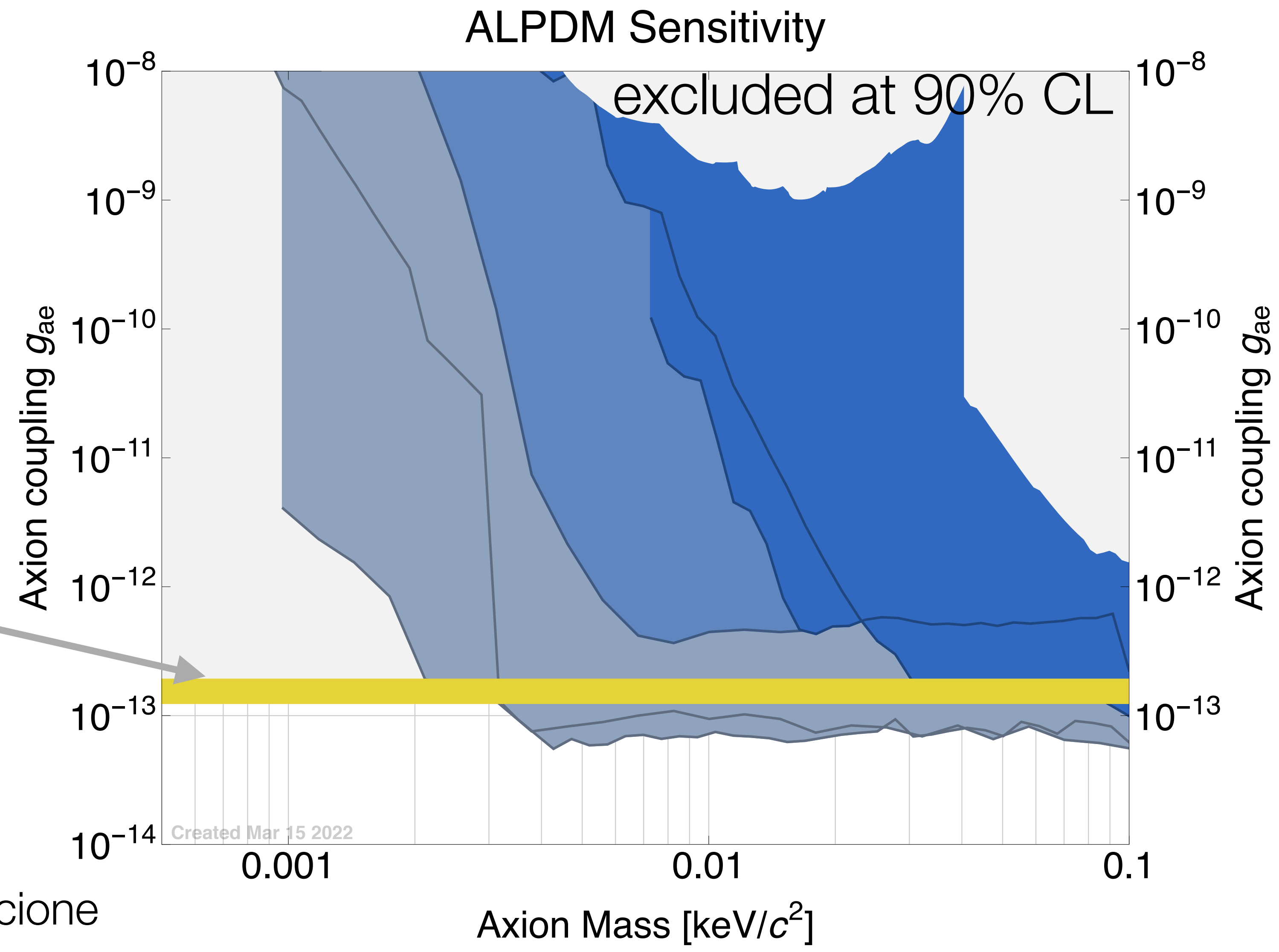
Figure 1 from 2203.08463

- Expected reach of SuperCDMS SNOLAB
- Scenarios with in-hand performance (Det A) and backgrounds
- Scenarios exploiting full reach of current facility (Det C)

Summary Results: SG-3 and SG-4

Sensitivity from 0V 1 cm^3 and 0V 10 cm^3, avoids leakage from HV detectors





Parameter space consistent with hint from stellar cooling

- SG-3: Electron couplings of kinetically mixed eV-scale (1-100 eV) dark photon DM (DPDM)
- SG-4: Electron couplings of eV-scale (1-100 eV) axion and axion-like particle DM

Summary of future science reach

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- Expected reach of SuperCDMS SNOLAB
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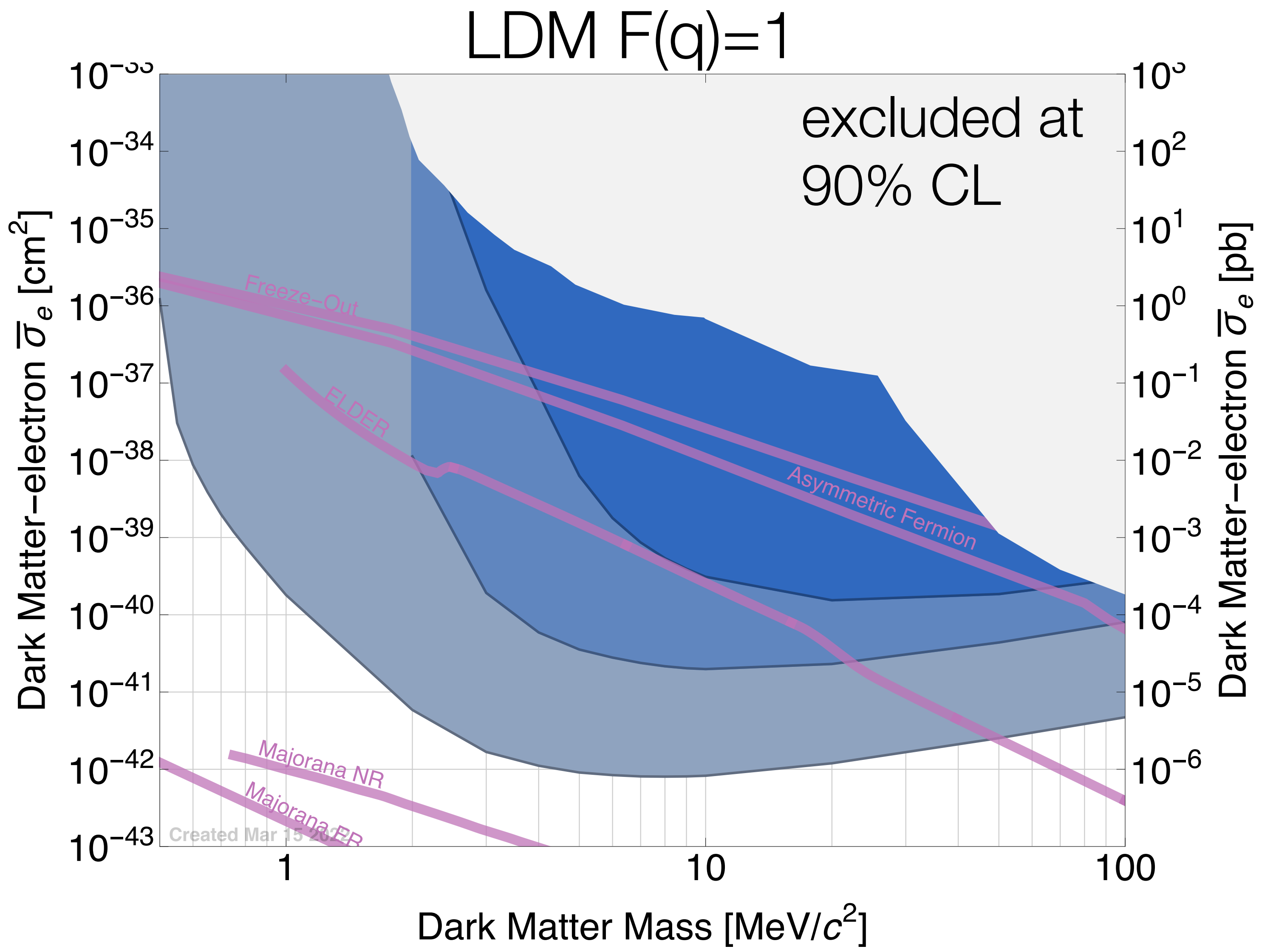
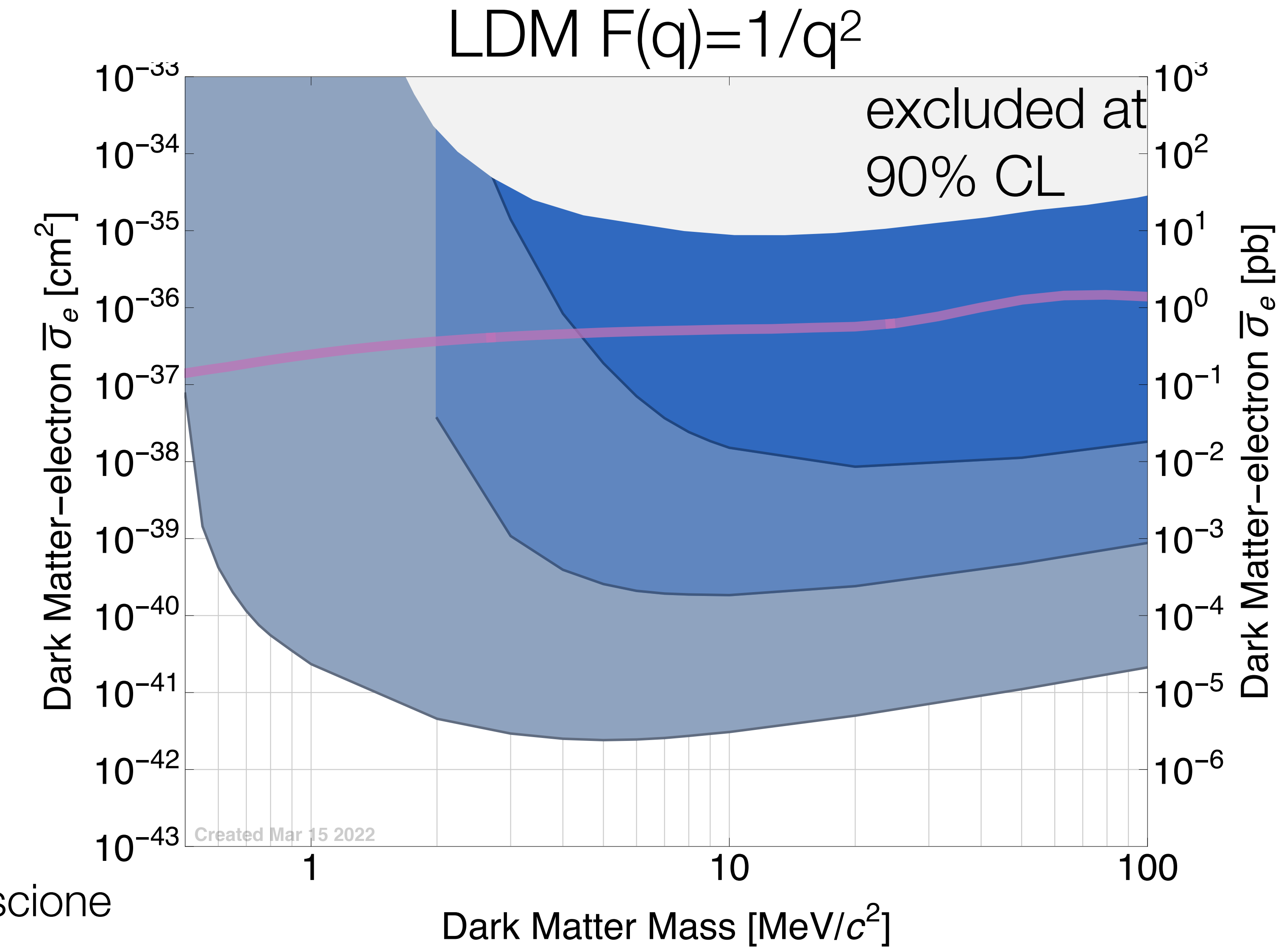
- Scenarios exploiting full reach of current facility (Det C)

Summary Results: SG-5

Sensitivity from 0V 1 cm³ and 0V 10 cm³, avoids leakage from HV detectors





- SG-5: Dark-photon-mediated couplings of MeV-scale (1-100 MeV) light DM (LDM)

Summary of future science reach

Figure 1 from 2203.08463

- Expected reach of SuperCDMS SNOLAB
- Scenarios with in-hand performance (Det A) and backgrounds
- Scenarios exploiting full reach of current facility (Det C)
- Science targets from 2017 Cosmic Visions Report

Science Goal Forecasting Summary

Detector		Science Goals Accessible with Detector Upgrade Scenario					
		A		B		C	
Type	Size	Si	Ge	Si	Ge	Si	Ge
0V	1 cm^3	1, 3, 4, **5**	4	1, 3, 4, **5**	3, **4**	1	
	10 cm^3	1, 4	1, 4	1, 3, 4, **5**	1, 3, 4	1, 3, 4	1, 3, **4**
HV	10 cm^3	2	2				
	SNOLAB-sized	3, 4, **5**	3, 4, **5**	2, 3, 4, **5**	2, 3, 4, **5**	3, 4, **5**	3, **4**, **5**
iZIP	10 cm^3		2		2		
	SNOLAB-sized				2		
piZIP	10 cm^3	2	2	2	2	2	2
	SNOLAB-sized	2	2	2	2	2	2

Table 4 from 2203.08463: Relevance of various detector types, sizes, and upgrade scenarios to science goals.

- Colour indicates maturity (e.g. bright green = already demonstrated)
- Numbers indicate science goals
  - 1: sub-GeV NRDM
  - 2: GeV scale NRDM
  - 3: DP DM
  - 4: ALP DM
  - 5: LDM
- iZIP and piZIP detectors only address GeV scale NRDM

Conclusion

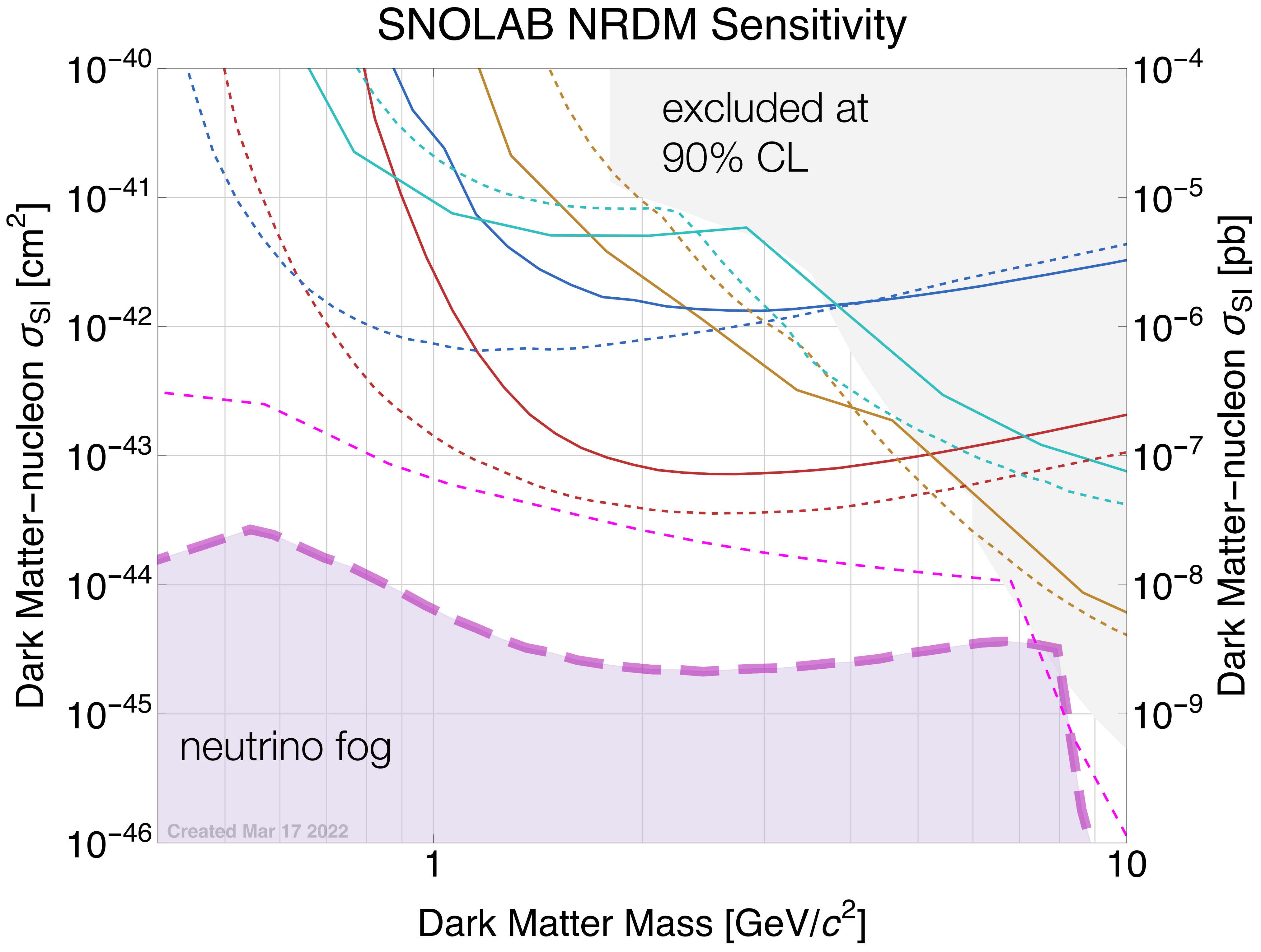
- Improvements in detector performance obviate significant (and expensive) reductions in background levels beyond current expectations for SuperCDMS SNOLAB
  - NRDM 0.05-5 GeV with sensitivity down to the neutrino fog in most of the regime
    - Low mass: 0V 1 cm^3 and 10 cm^3
    - High mass: SNOLAB-sized HV, 10 cm^3 piZIP and iZIP
  - Dark photon and ALP DM in 1-100 eV range
    - 0V 1 cm^3 and 10 cm^3, SNOLAB-sized HV
  - LDM (DP mediated couplings) 1-100 MeV extends current reach by 1-3 orders of magnitude
    - 0V 1 cm^3 and 10 cm^3
- We do not currently account for the low energy excess seen by SuperCDMS and others

Backup

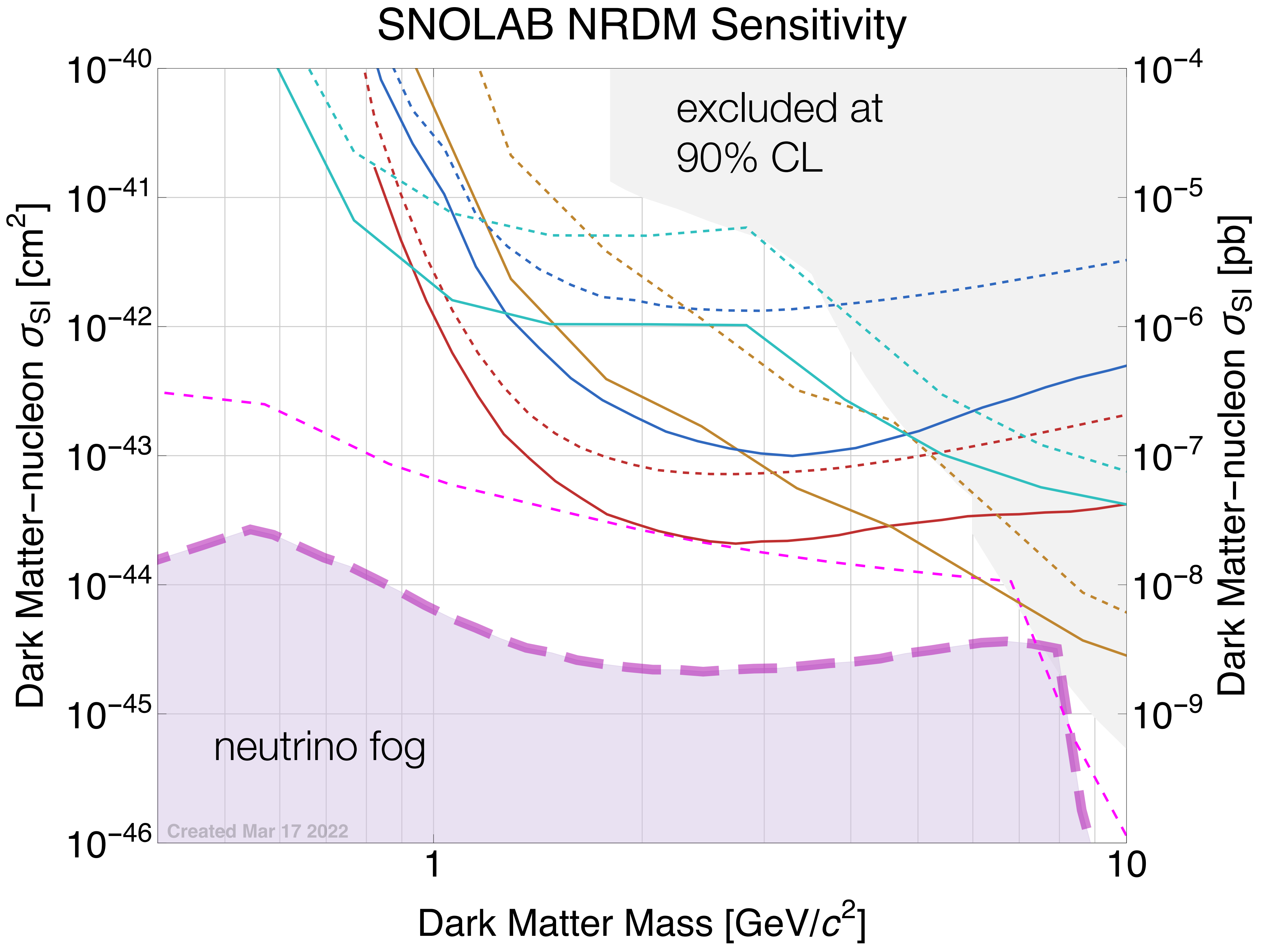
Updates From Original Forecasting Paper

Figure 5 (left and right) from 2203.08463

Dashed - OI from doi.org/10.1103/PhysRevD.95.082002
Solid - Current OI Limits



Dashed - Updated OI Limits
Solid - profile likelihood ratio (PLR) Limits



iZIP Si
iZIP Ge
HV Si
HV Ge

single neutrino sensitivity

Summary Results

Figure 1 from 2203.08463