Exploring the Unexplored: Searching for 10meV-6GeV Dark Matter with Solid State Detectors

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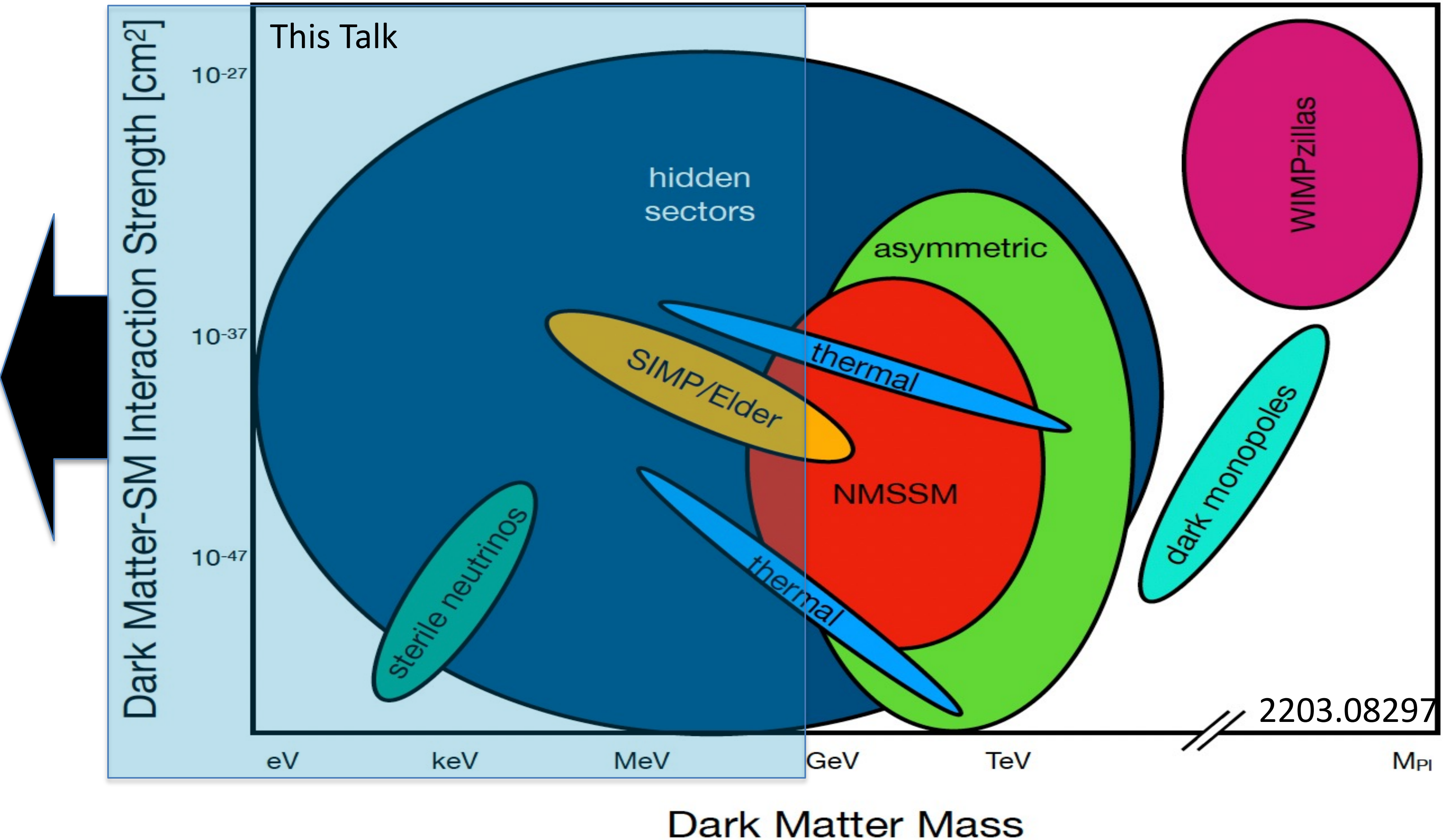
P5 2/22/23

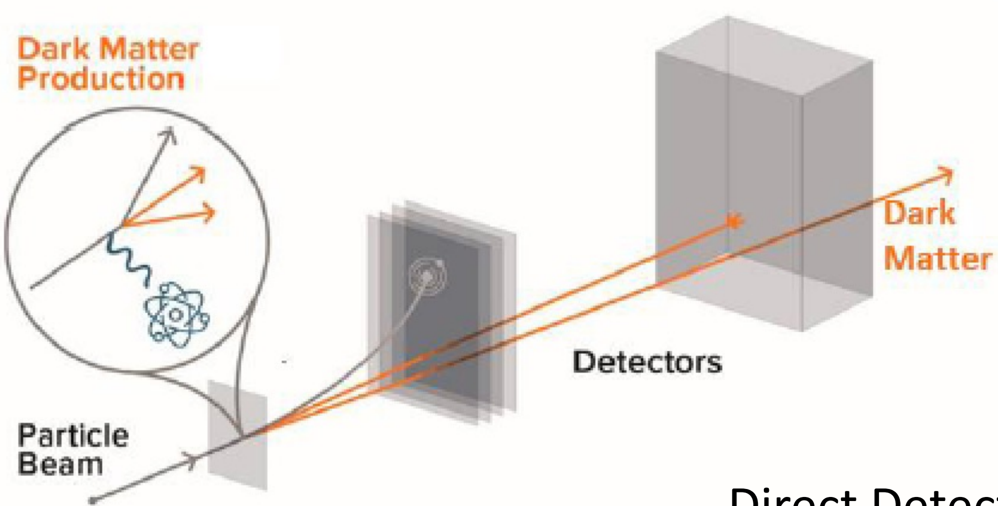
Well motivated theoretical models throughout 10meV<M_{DM}<6GeV



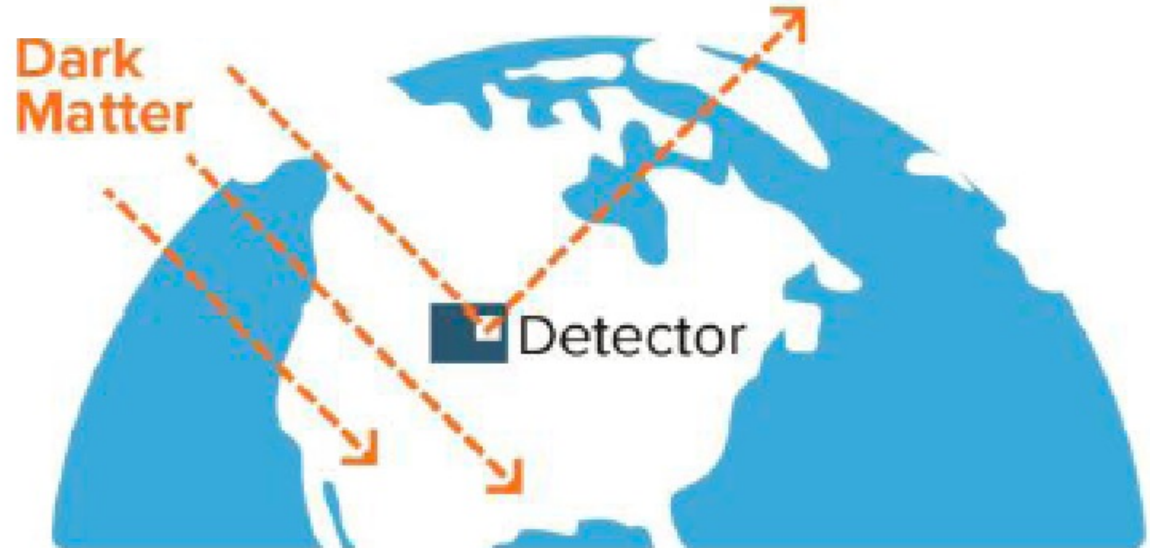
Cosmic Visions 1707.04591, NIDM BRN, and SNOWMASS 2203.08297

Detection Strategies

Production at Accelerators

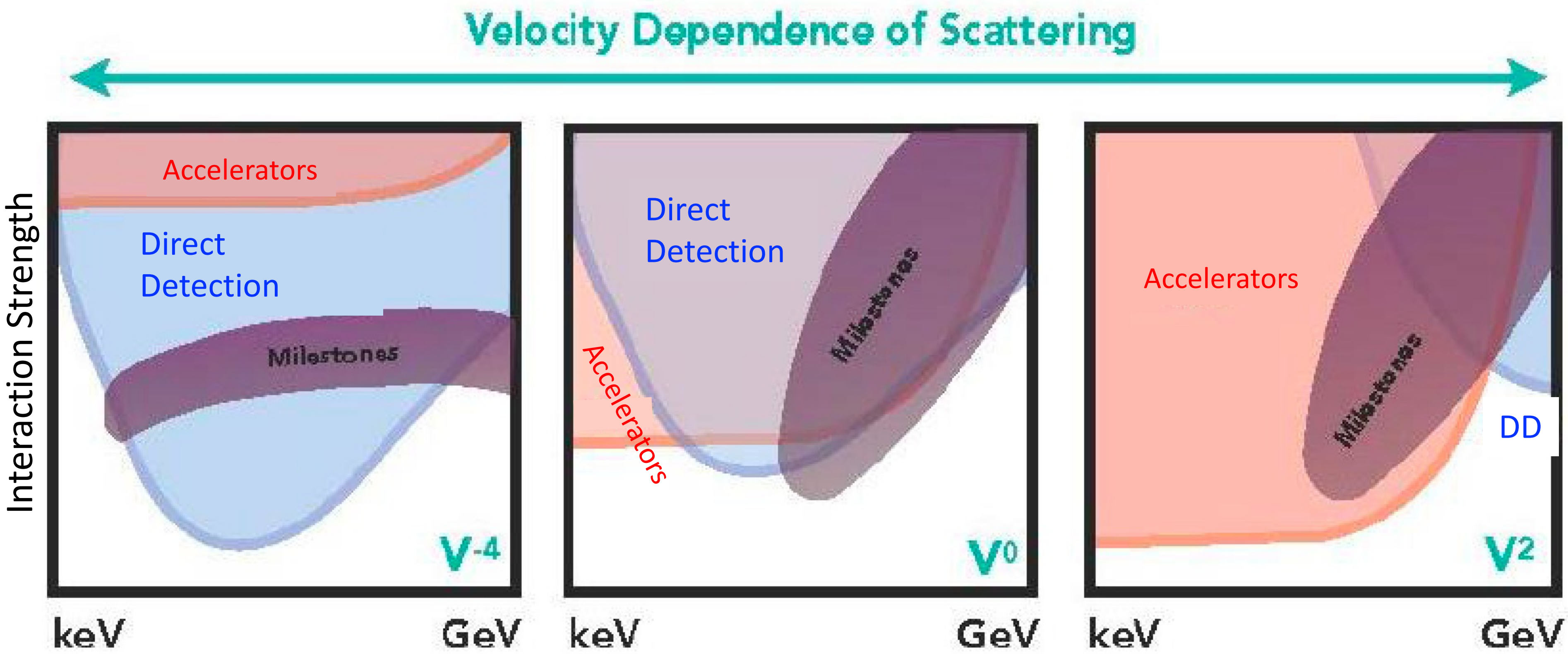


Direct Detection of Galactic Dark Matter



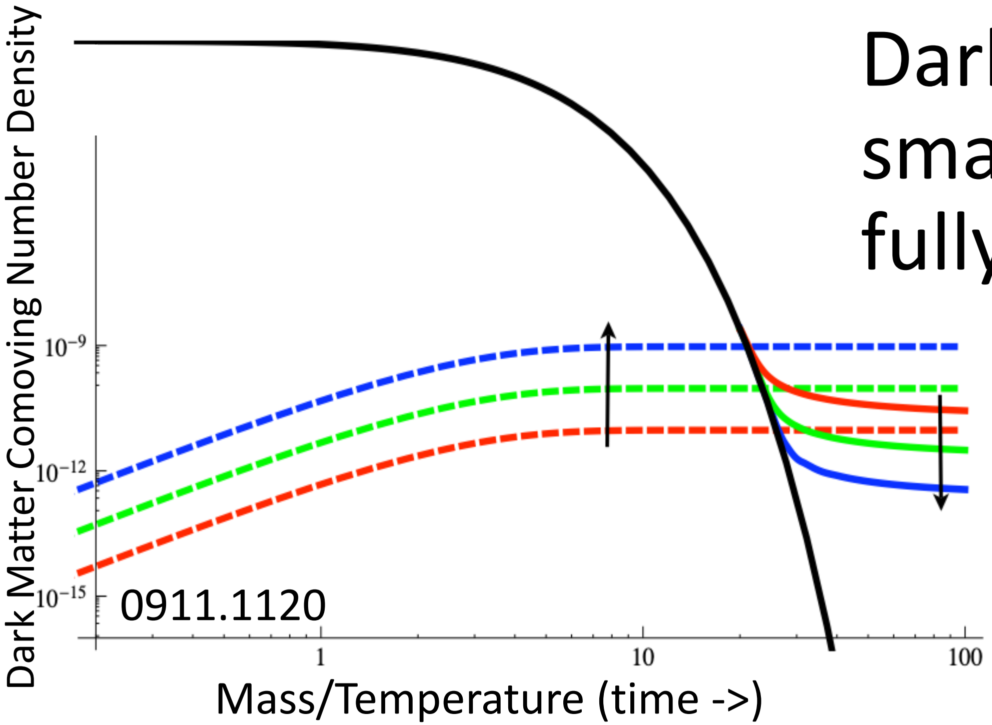
BRN: Dark Matter Small Projects New Initiatives

Complementarity with Accelerators

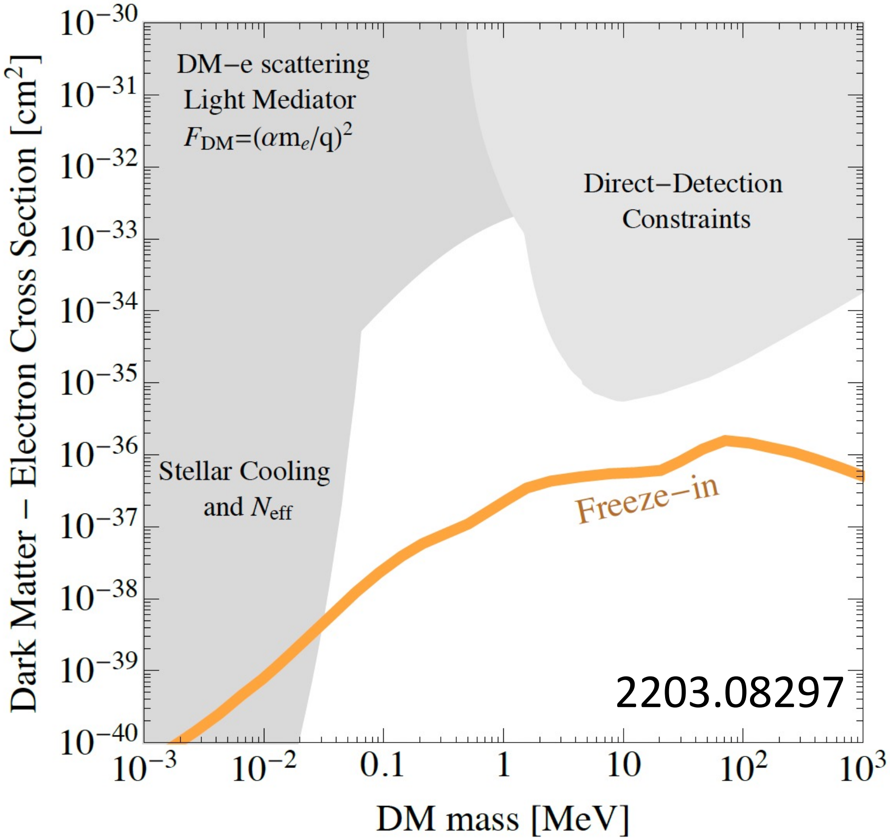


Freeze-In Dark Matter

Dark sector couplings are so small that DM never comes fully into thermal equilibrium

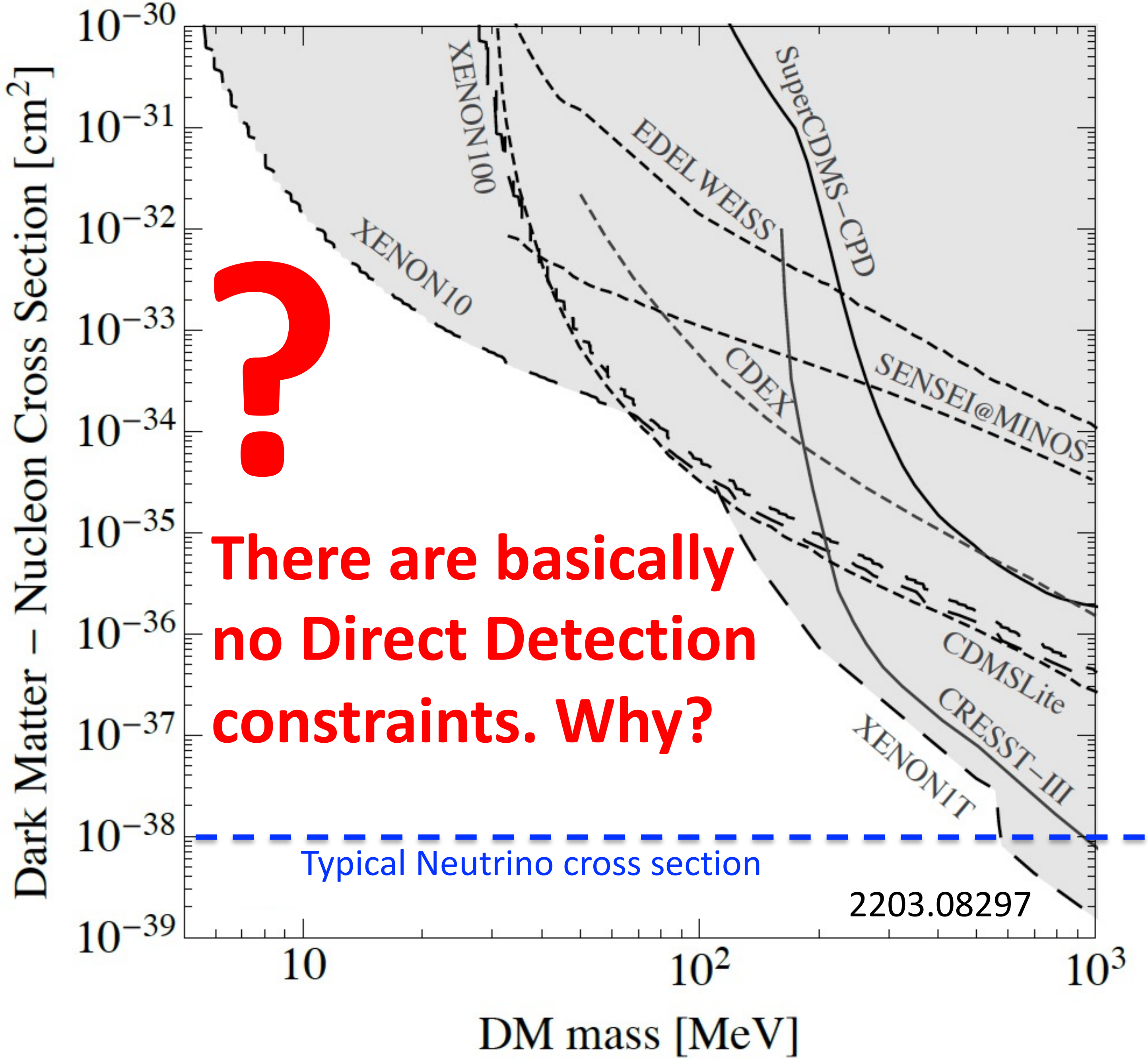


- The $\sigma \propto 1/q^2$ for this class of models, means Direct Detection is the likely discovery technique.



Light Mass DM Direct Detection
Design Drivers

Light Mass DM: Nuclear Recoil Direct Detection Constraints



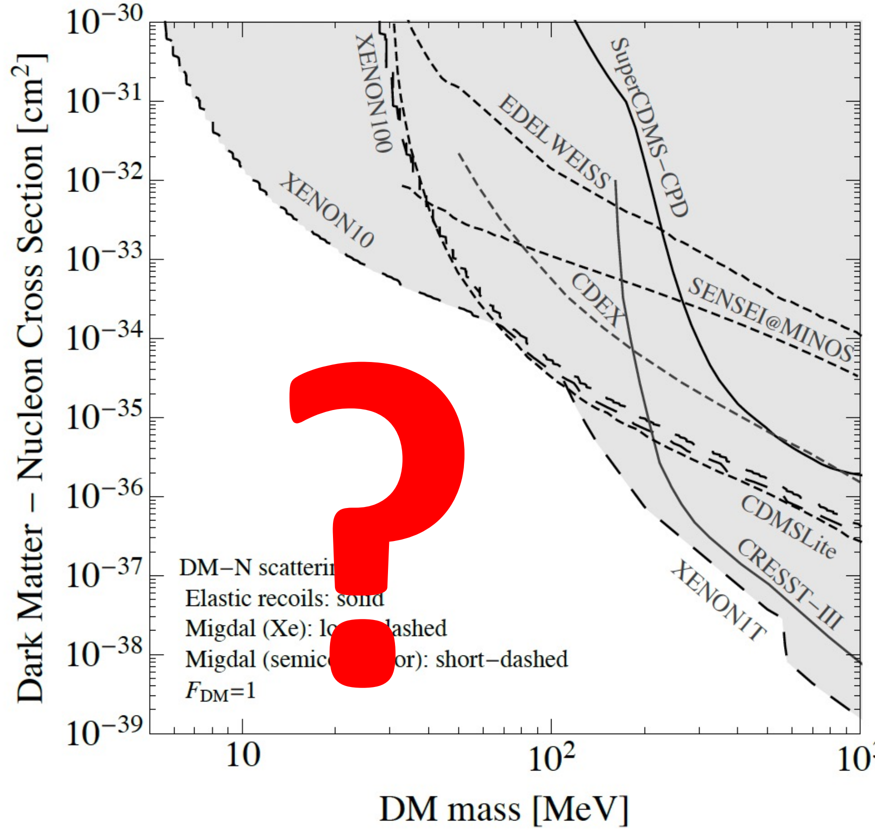
Light Mass DM Design Drivers: ~~Exposure~~

$$R = \sigma n_{DM} v_{DM} N_{exp}$$

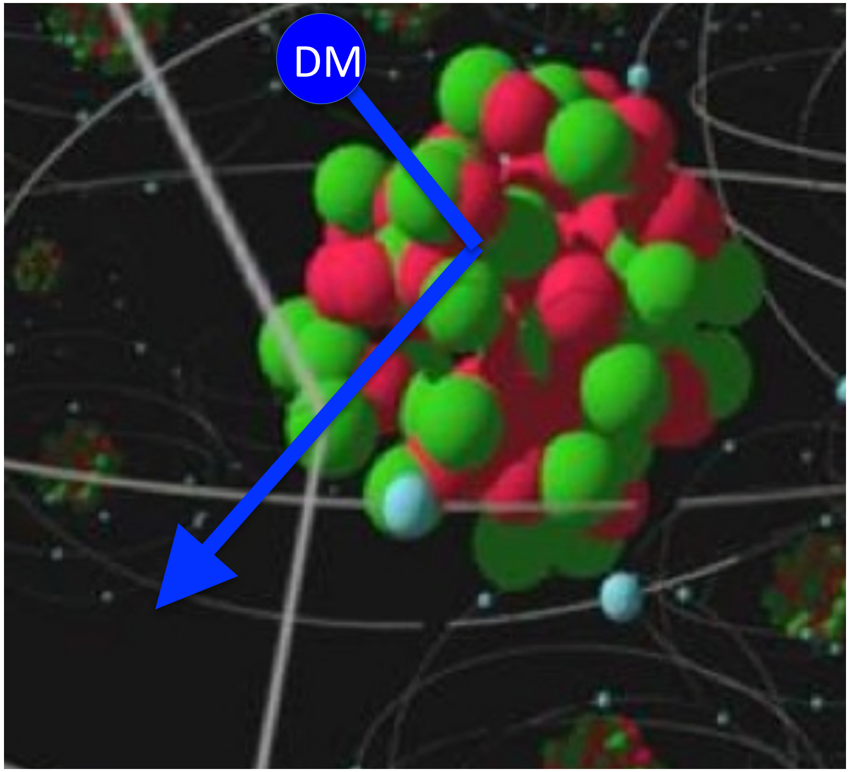
$$= \sigma \frac{\rho_{DM}}{M_{DM}} v_{esc} N_{exp}$$

Interaction Rate scales with $1/M_{DM}$

Light Mass Dark Matter Search experiments are tabletop and have small project cost scales: <10M



Kinematics: 2 Body Elastic Nuclear Scattering



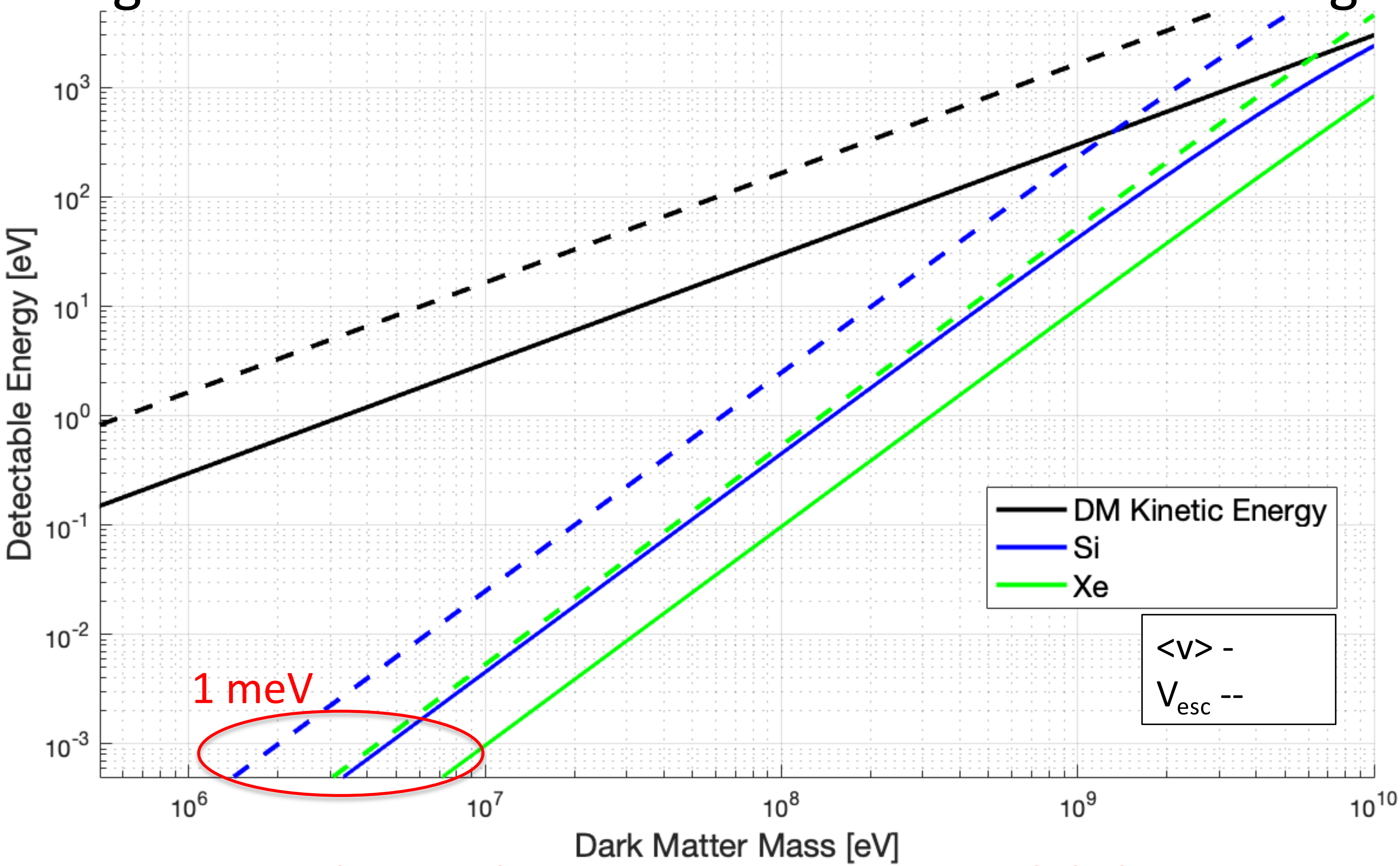
$$K_n = \frac{\mu^2 v_{DMo}^2}{M_n}(1 - \cos(\theta))$$

When $M_n >> M_{DM}$

$$\sim \frac{2M_{DM}^2 v_{DMo}^2}{M_n} = \frac{(2P_{DMo})^2}{2M_n}$$

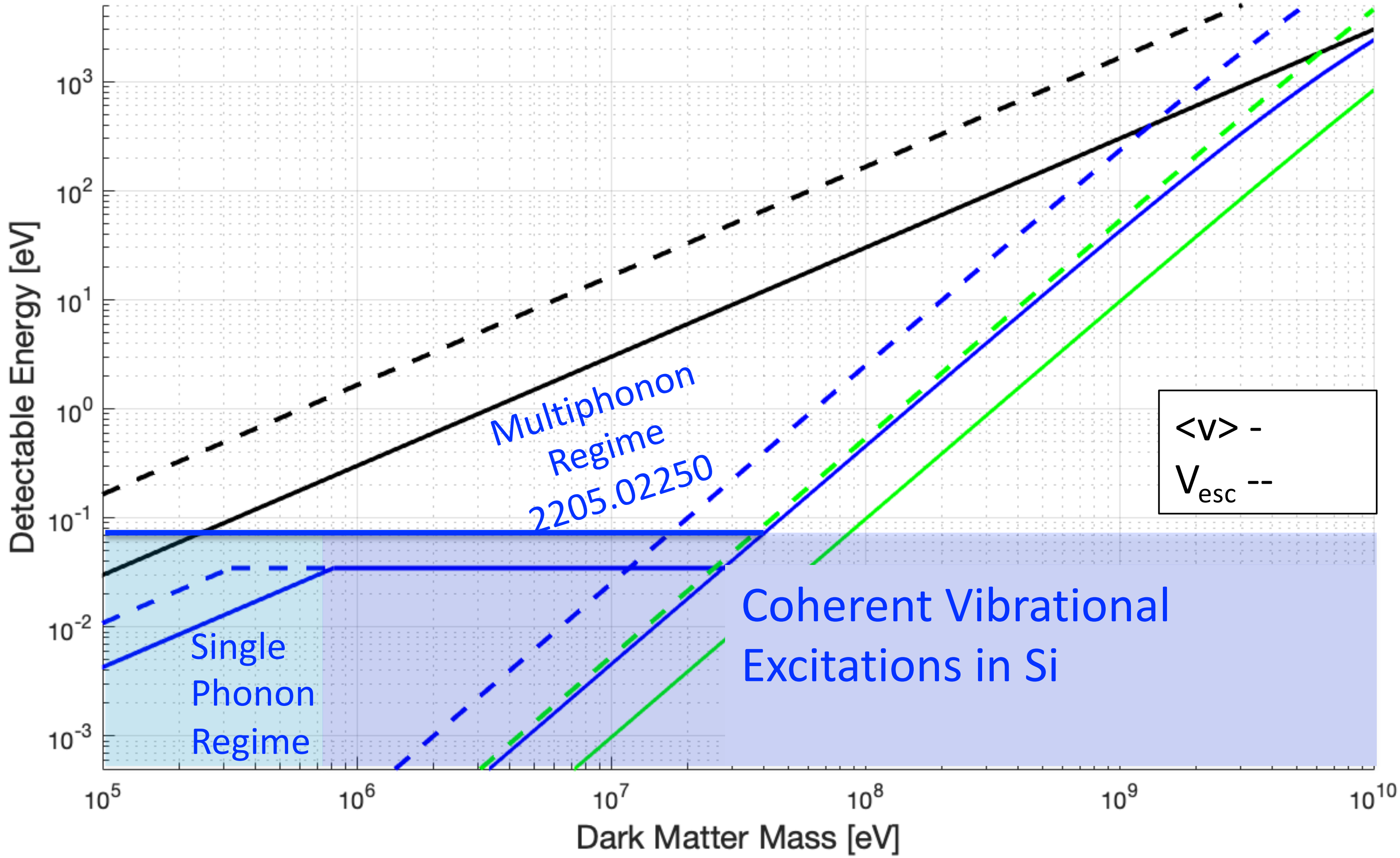
- Transfer of DM kinetic energy to nucleus is really inefficient for elastic 2 Body Scatters when $M_n >> M_{DM}$

Light Mass Dark Matter: Elastic Nuclear Scattering



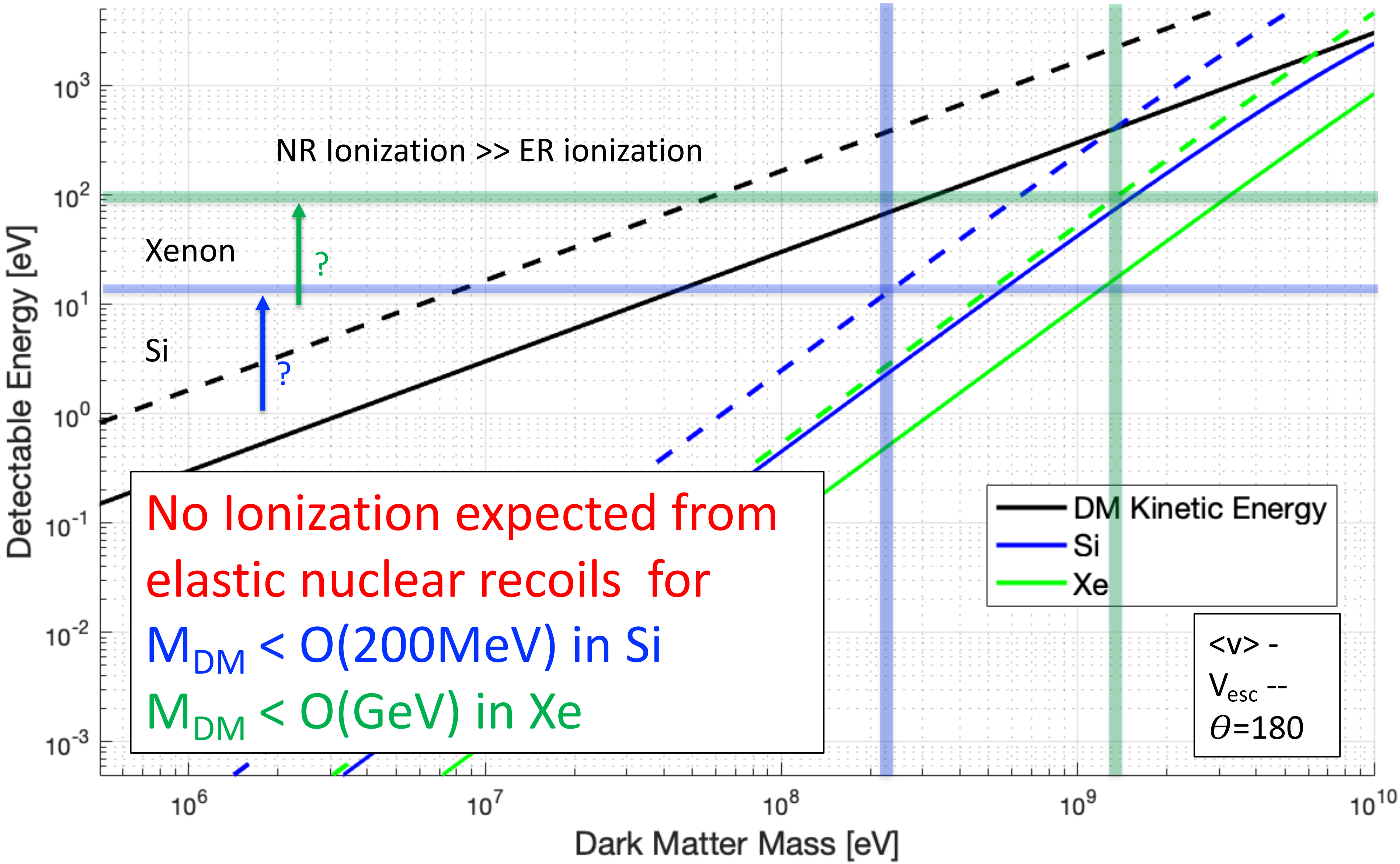
Design Driver #1: Energy Sensitivity

DM- Coherent Vibrational Interactions



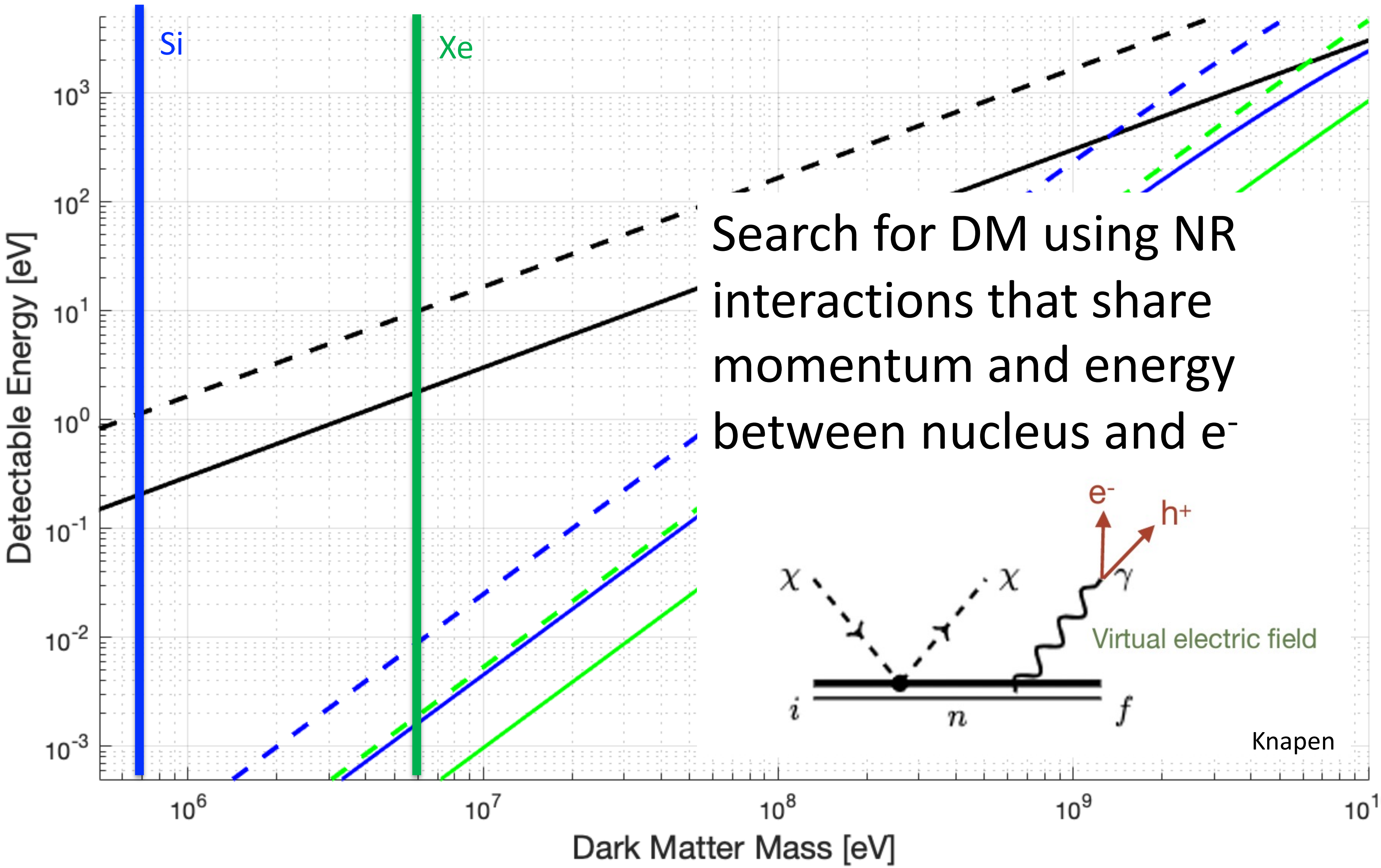
For DM interactions with small momentum and energy transfers, we need to start thinking about DM interactions producing coherent crystal excitations!

Ionization Production in eV Scale Nuclear Recoils



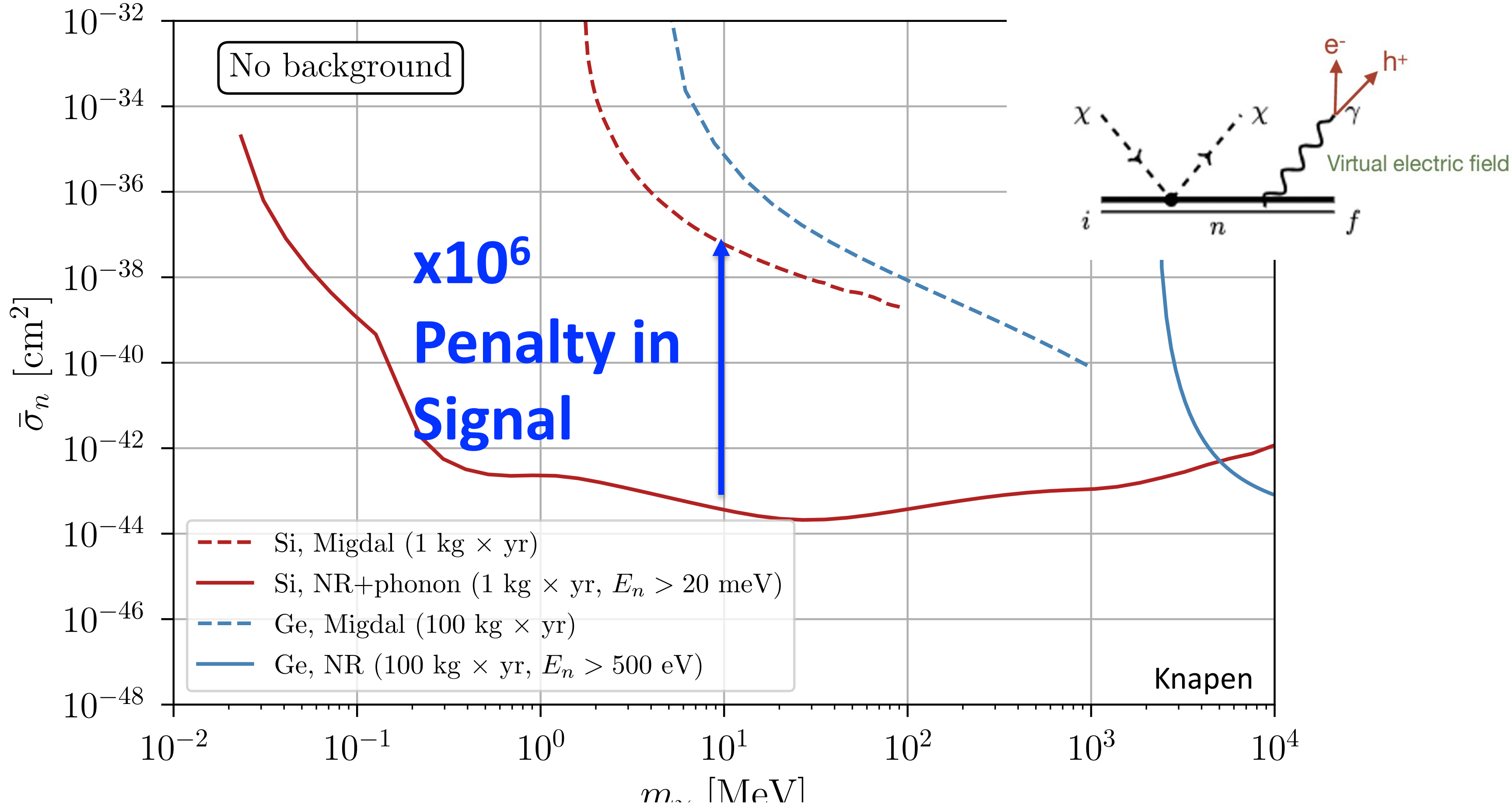
Midgal Ionization

Search for DM using NR interactions that share momentum and energy between nucleus and e⁻



Knapen

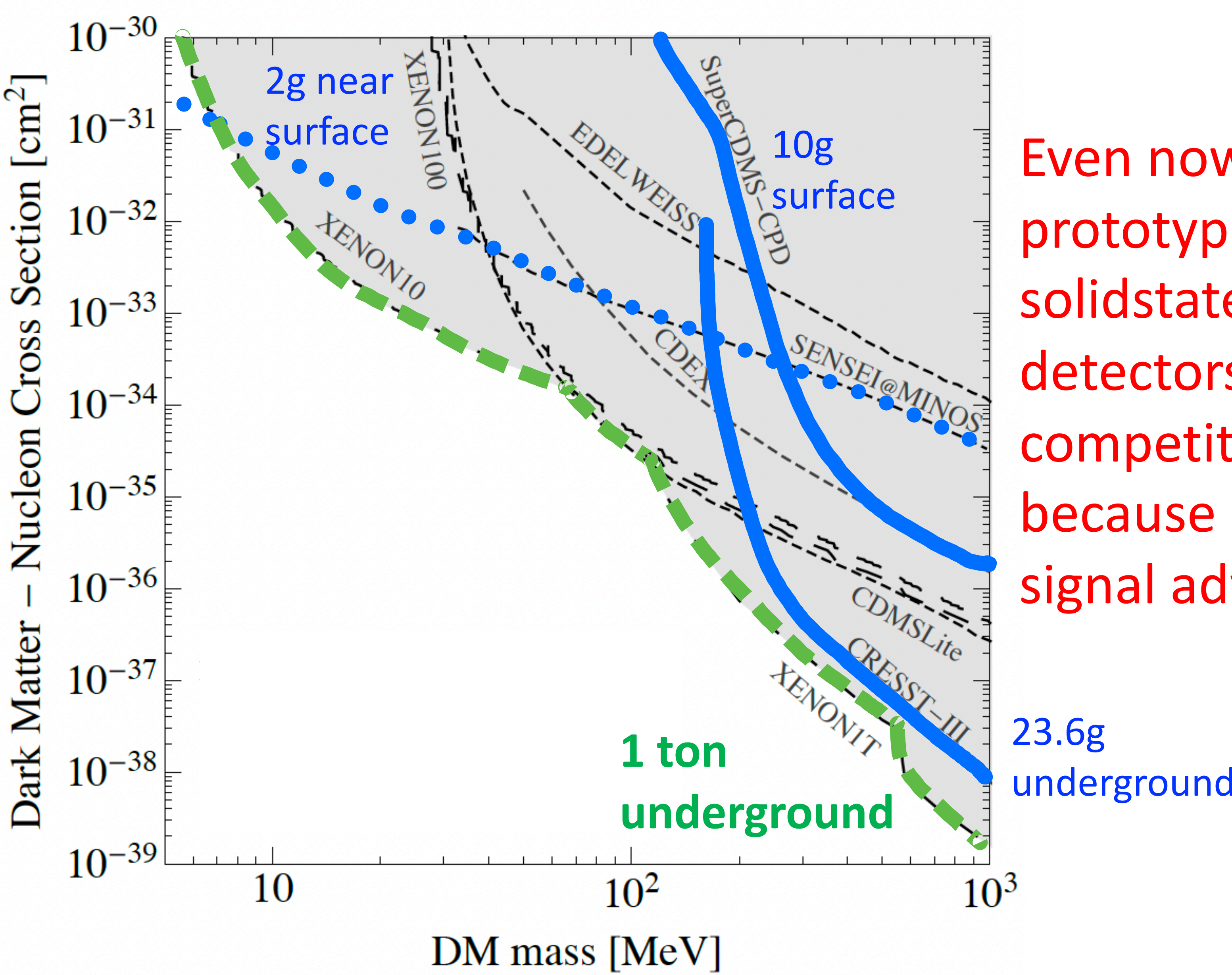
Midgal Ionization: Signal Suppression



Midgal, like all processes with off-shell particles, will have significantly suppressed signal rates

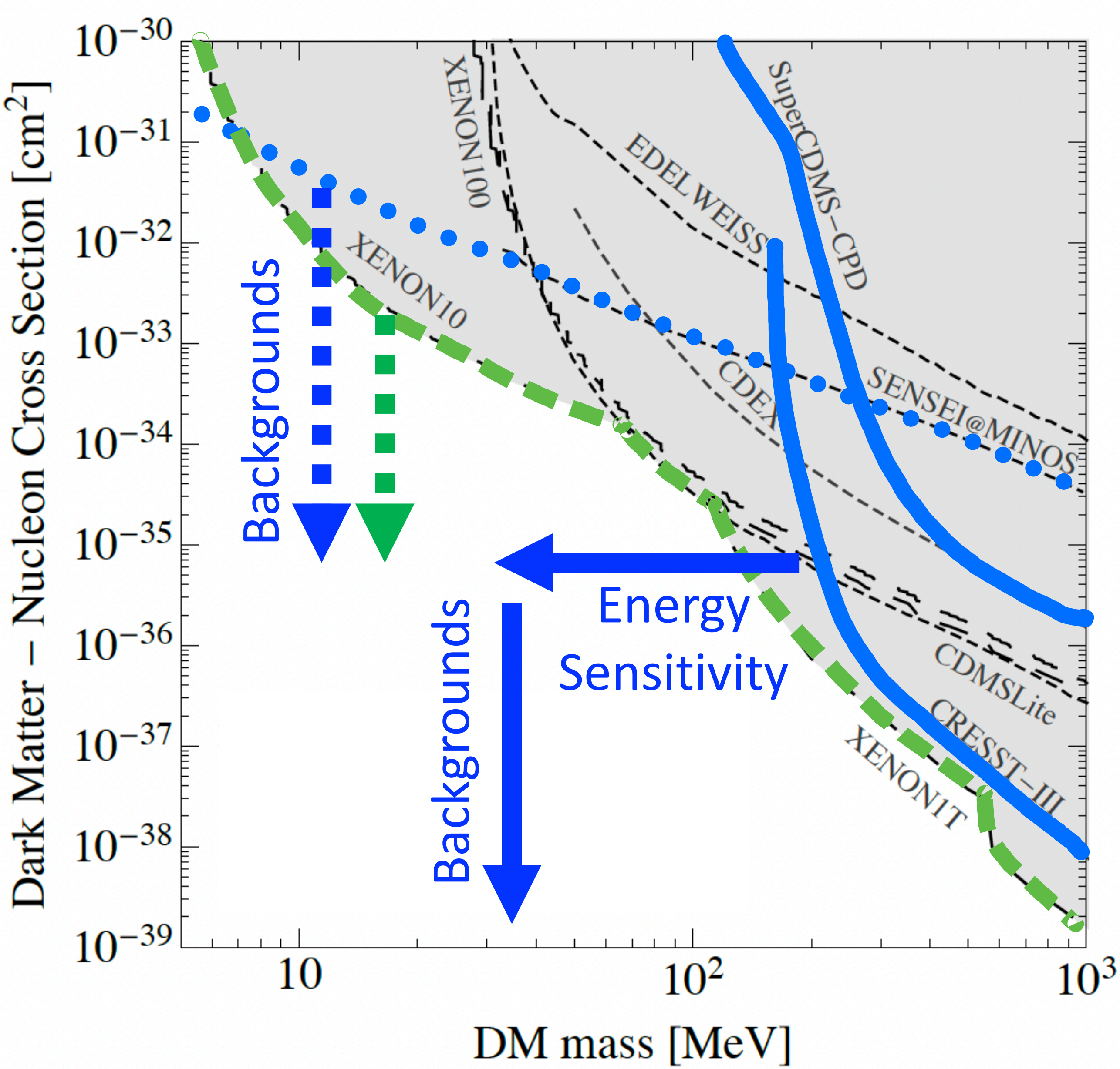
- x10^6 greater exposure needed if exposure limited
- x10^6 less backgrounds needed if background limited

Nucleonic Interactions: Current Status



Even now, small prototype solidstate detectors offer competitive reach because of these signal advantages

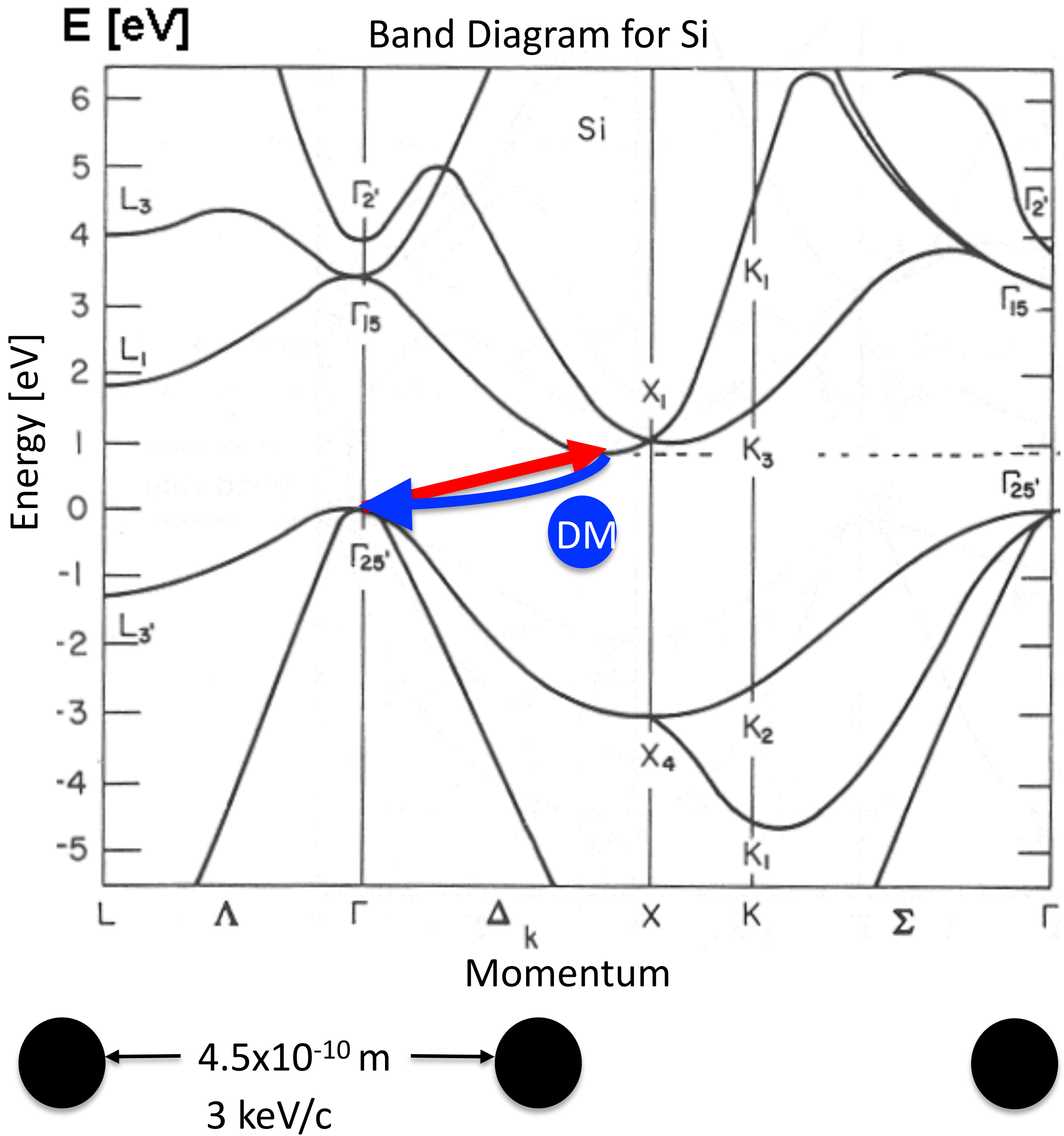
Nucleonic Interactions: Future



Design Driver #2: Backgrounds

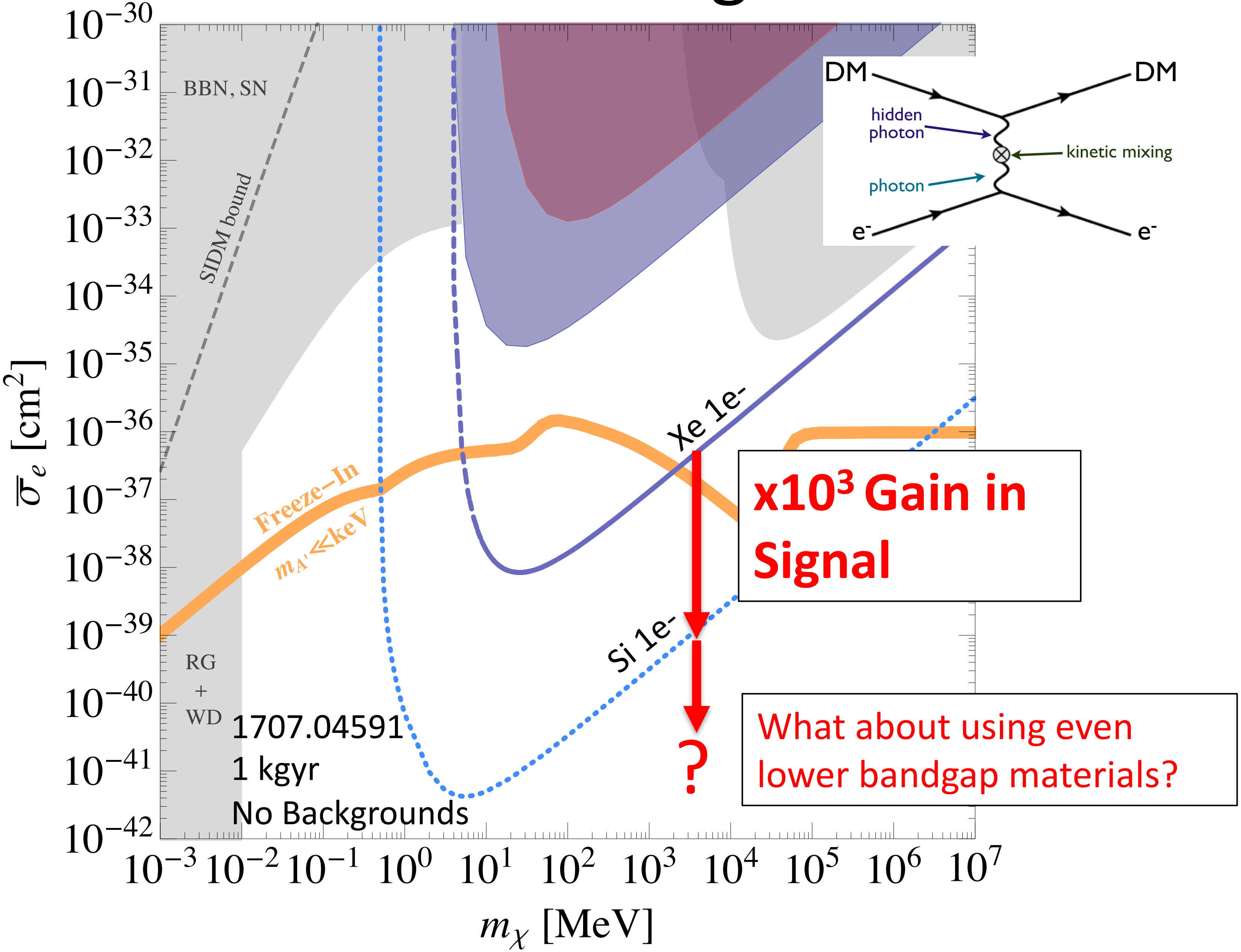
- Midgal Ionization Detectors must decrease backgrounds
- Solid State Phonon Detectors must increase sensitivity and decrease backgrounds

Inelastic e^- Recoils in Semiconductors

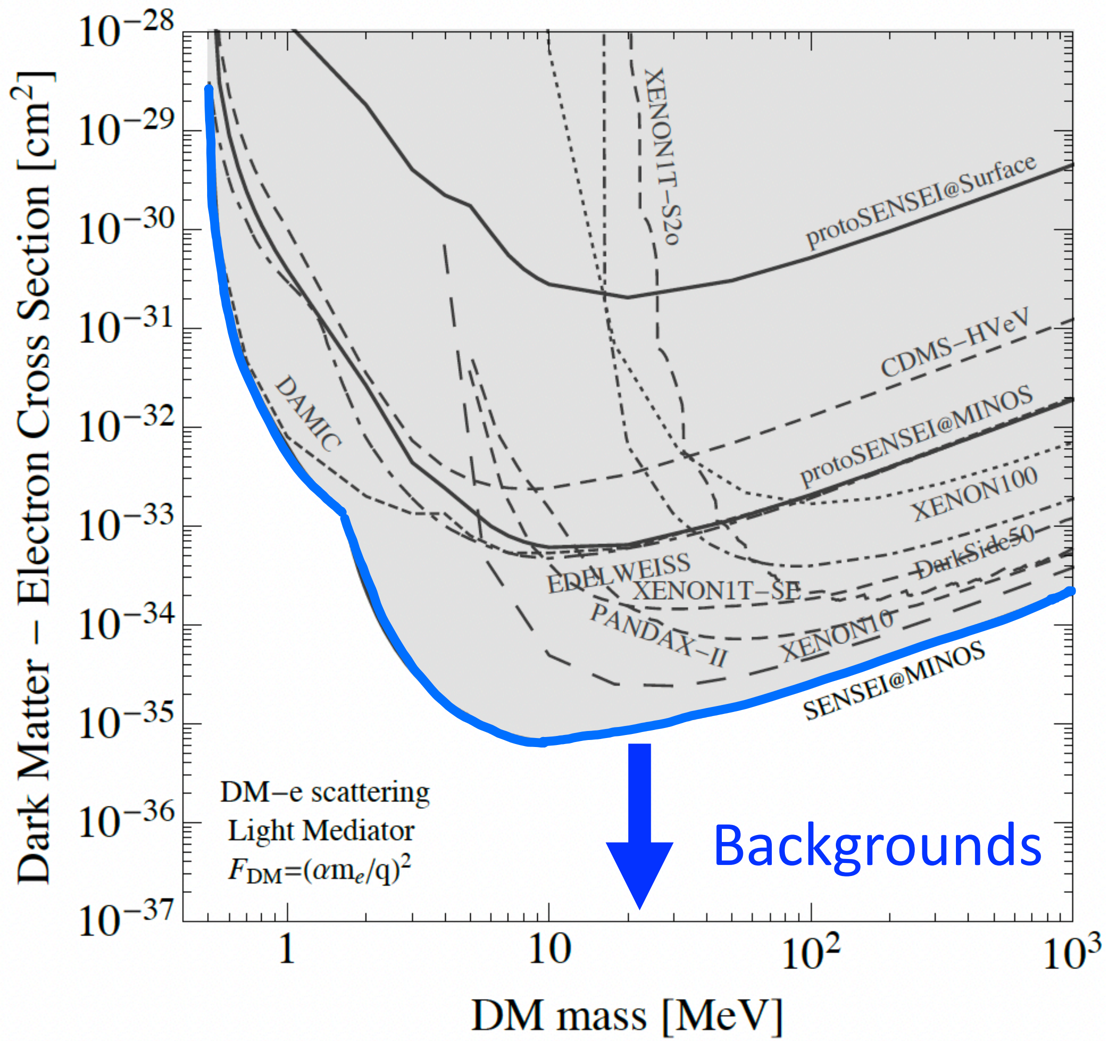


Crystal e- Momentum and Energy Scales Match MeV DM perfectly

Smaller Excitation Energies are Better



Electronic Interactions: Current Status and Future



Future sensitivity improvements depend solely on background mitigation (Design Driver #2)

Light Mass DM Design Driver Summary

0. Absorbers with small energy excitations

1. Sensitivity to Excitations

2. Backgrounds

OSCURA: 10kg Si Skipper CCDs

Current Status: DOE NIDM Pre-project Phase

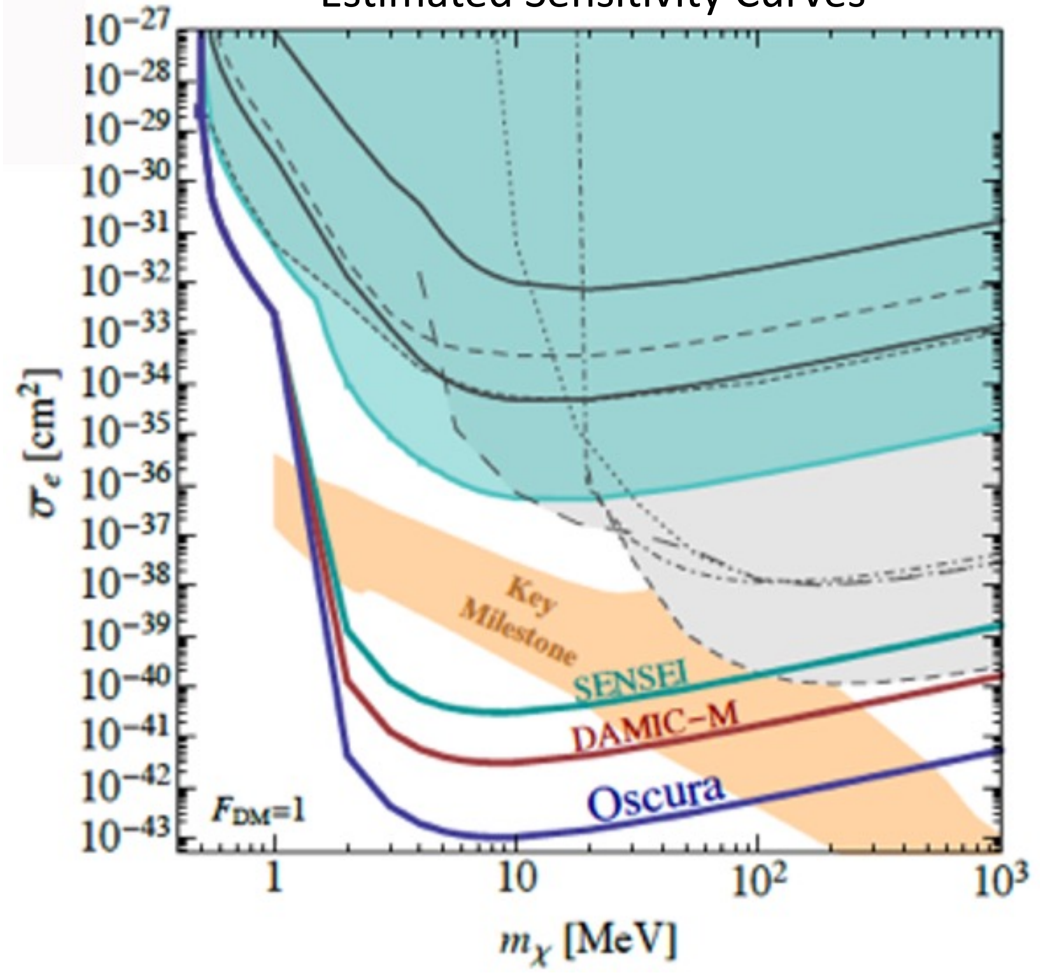
OSCURA Cost:

- Pre-Project: 4M
- Project: 10M

Timescale:

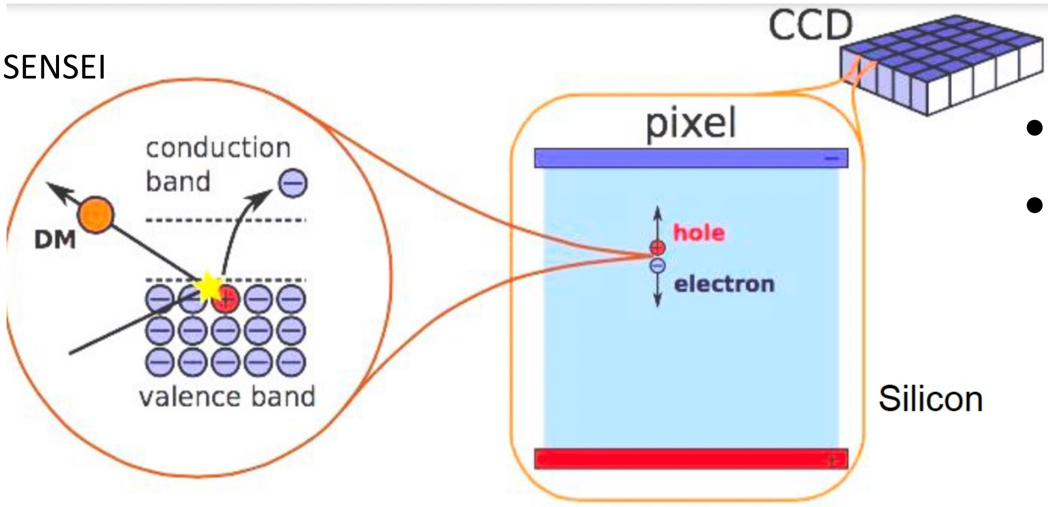
- 100g SENSEI SNOLAB: now – FY26
- 1kg DAMIC-M: FY24-FY29
- 10kg OSCURA: First Science FY26

Estimated Sensitivity Curves



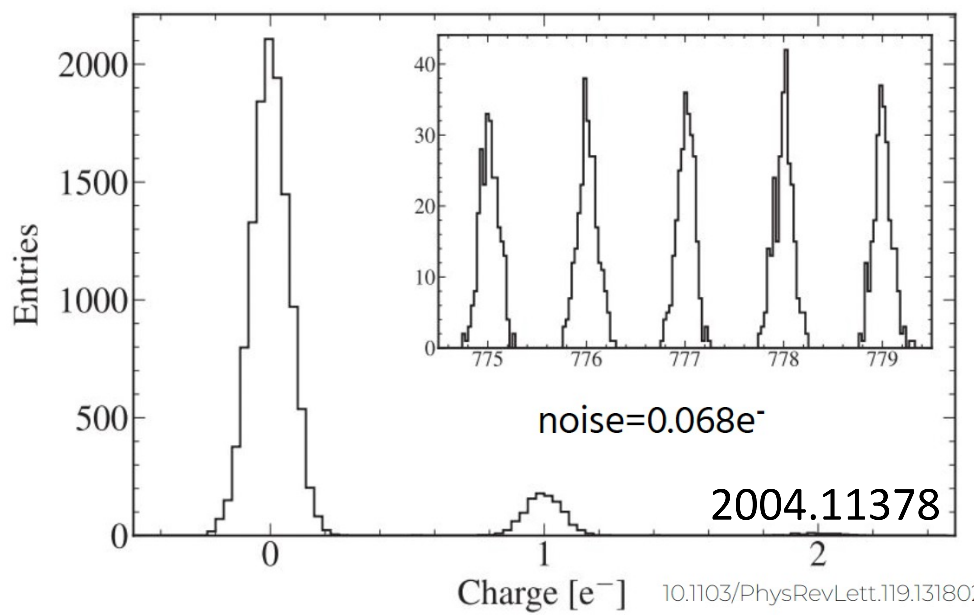
x10^7 planned improvement in DM sensitivity!

OSCURA: Skipper CCD

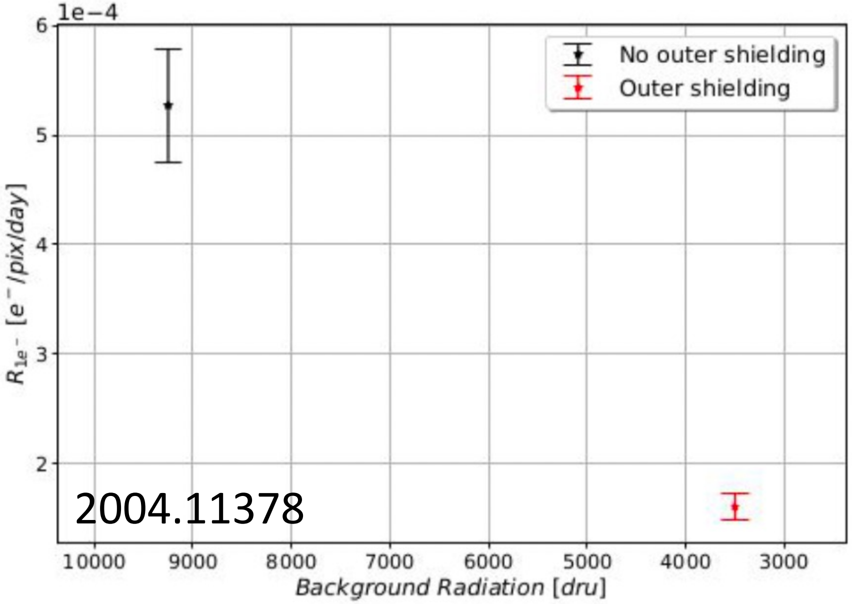


- Pixel = 15um x15um x675um
- 5.5Mpixels per 2g device

- "Skipper" CCD readout suppresses 1/f noise by having multiple short time scale measurements of ionization moving the charge off and on the sensing pixel
- σ_q = 0.068 e$^-$ (rms)
- Design Driver #1: Single Ionization Sensitivity Achieved!

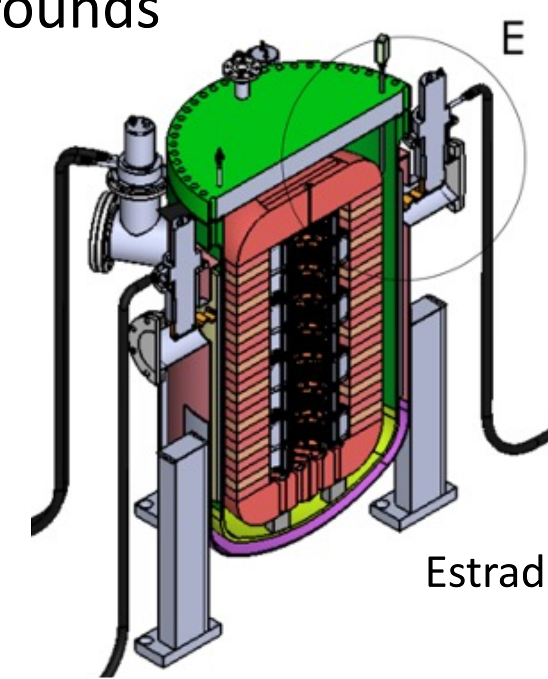


OSCURA: Backgrounds



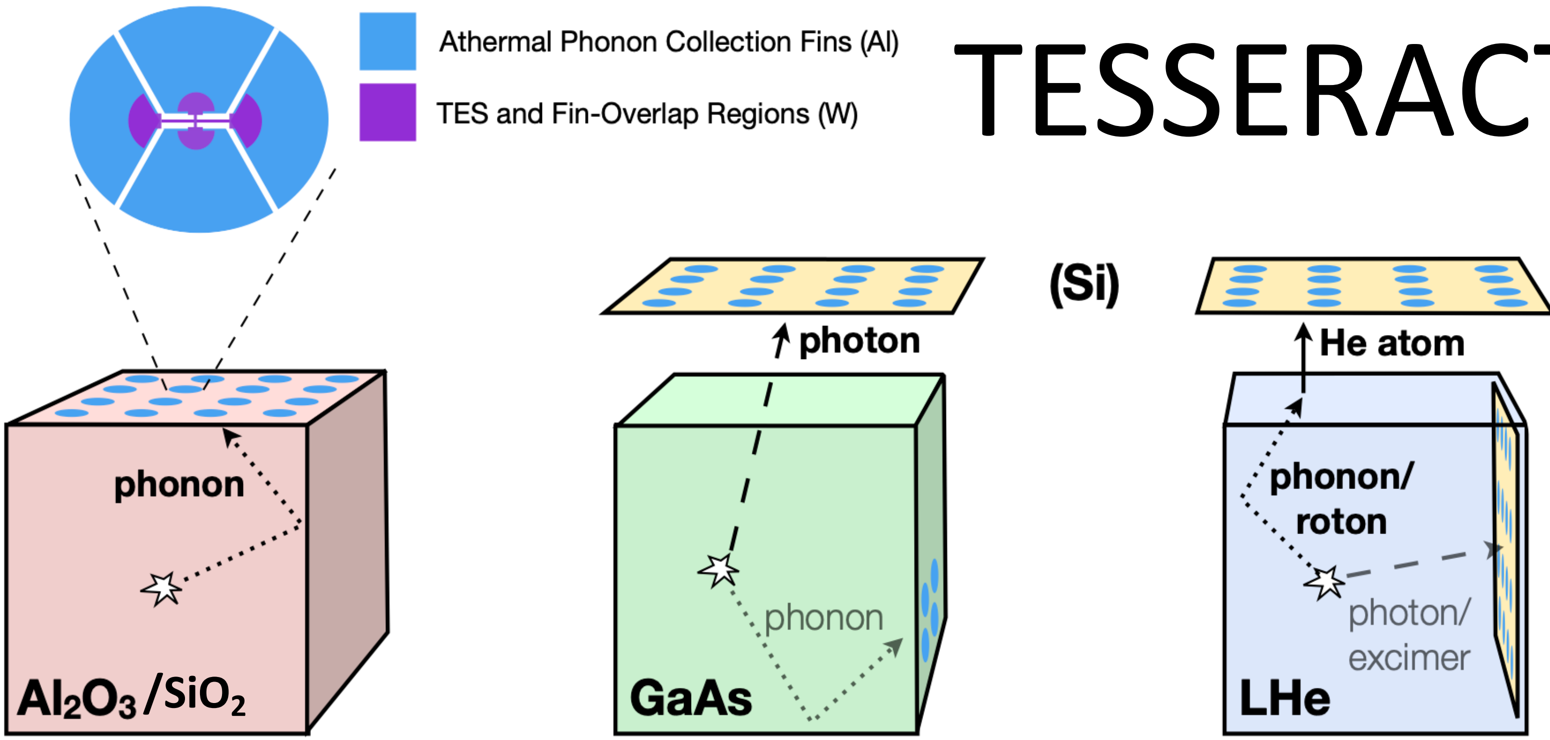
- SENSEI @MINOS: 3500 evt/(keVkgd) shielding
- Single e- background rate seen to strongly correlate with background radiation
- 2011.13939 predicts backgrounds around this level from near gap photon secondaries from high energy backgrounds

- OSCURA solution: Better shielding!
  - SENSEI SNOLAB: 5 evt/(keVkgd)
  - DAMIC M 0.1 evt/(keVkgd)
  - OSCURA 0.01 evt/(keVkgd) (the world's best cryostat)
- Design Driver #2: Plan in place to suppress backgrounds by x10^7



Estrada

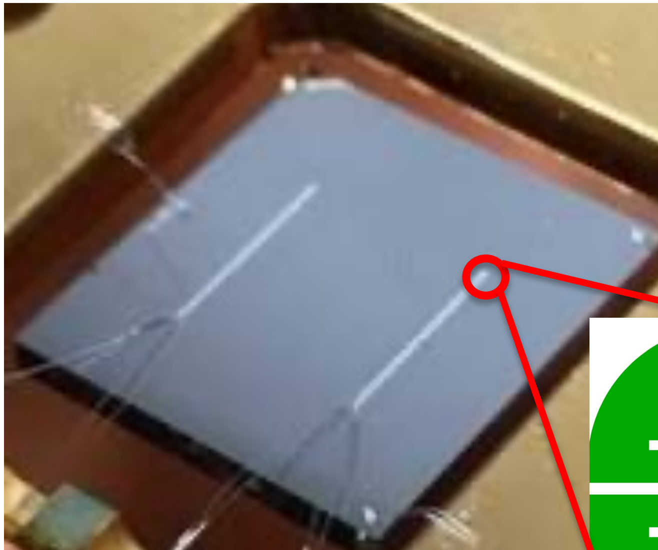
TESSERACT

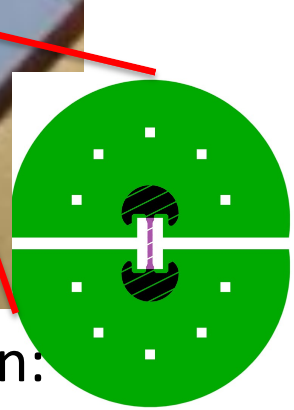


- Multiple Targets with Complementary DM Science readout by identical athermal phonon sensor technology

Status	Cost	Timescale
DOE NIDM Pre-project (Delayed 2 years due to funding)	R&D: 2.8M Project: 9.2M (mostly cryostats)	Early Science before FY25 Pre-Project ends FY25 Project complete FY28

TESSERACT: Energy Sensitivity





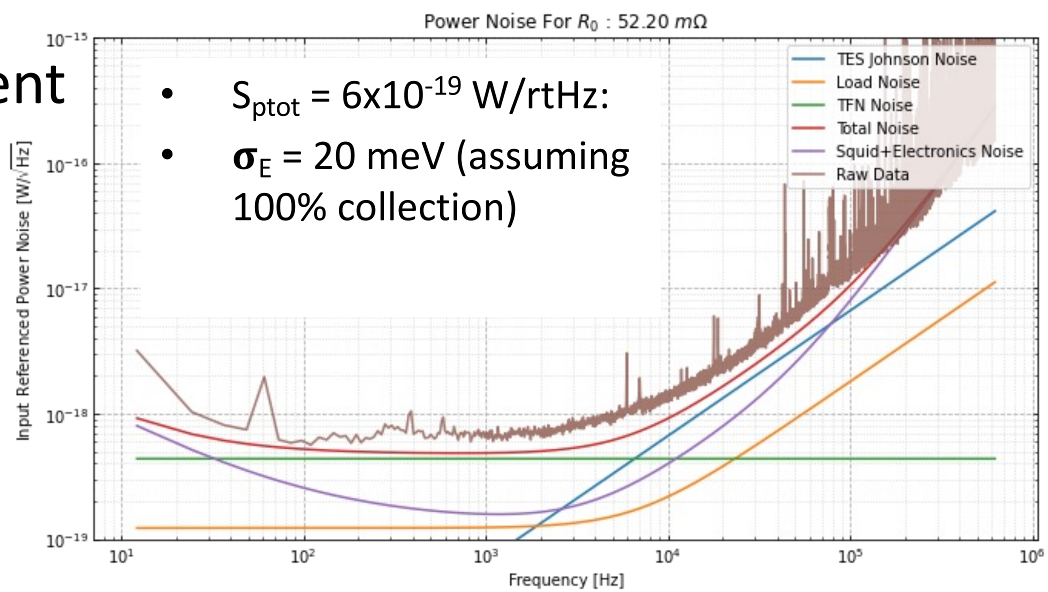
$$\sigma_E \sim \frac{\sqrt{4k_b T_c^2 G(\tau_{collect} + \tau_{sensor})}}{\epsilon_{collect}\epsilon_{sensor}}$$

$$\propto \sqrt{T_c^6 N_{tes} V_{tes}}$$

Energy Sensitivity Plan:

1. Lower Tc: 60mK -> 15mK
   - x4^3 sensitivity improvement
   - Done
2. Decrease IR and EMI backgrounds by x4^6
   - Ongoing

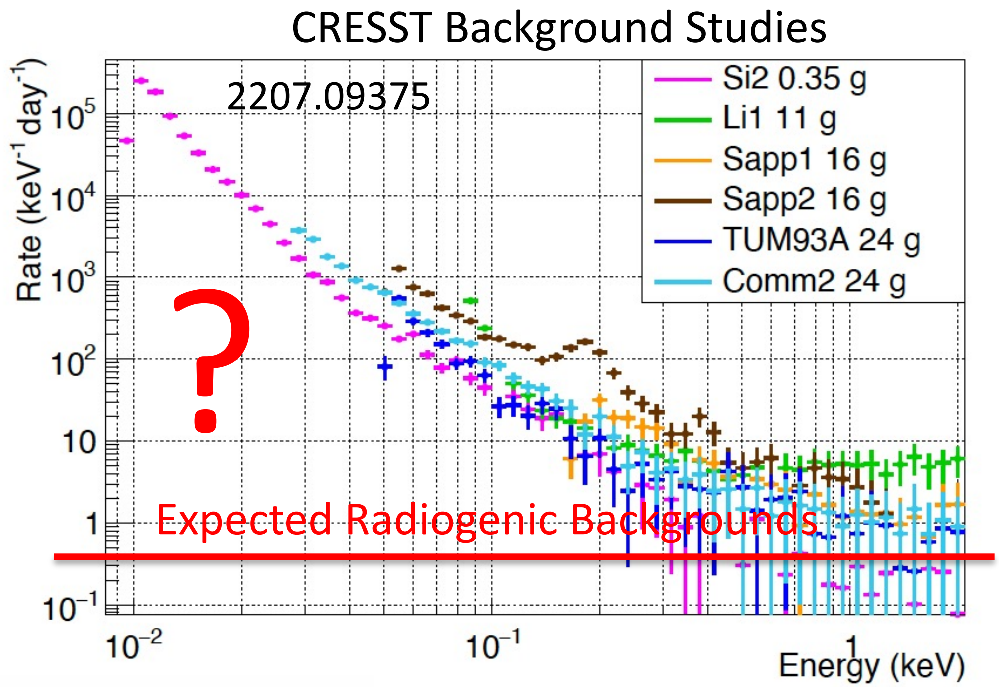
Design Driver #1: Plan and Significant Progress

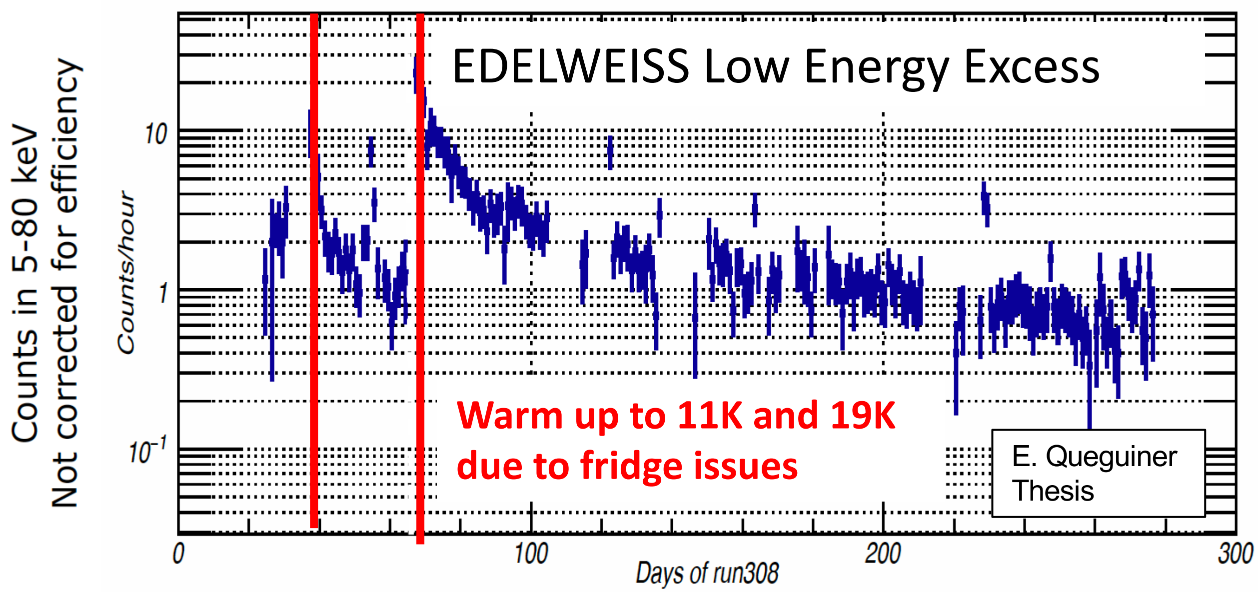


- S_{ptot} = 6x10^{-19} W/rtHz:
- $\boldsymbol{\sigma}_E$ = 20 meV (assuming 100% collection)

Phonon Detector Backgrounds

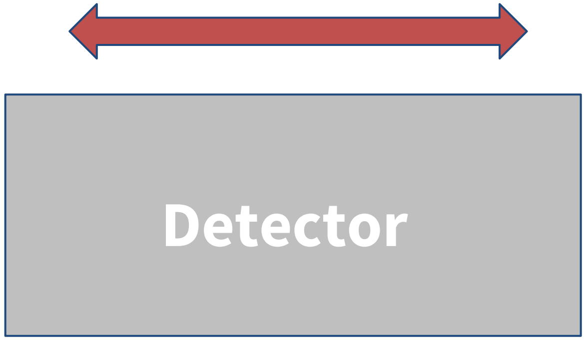
Mysterious monotonically increasing background rate at low energies



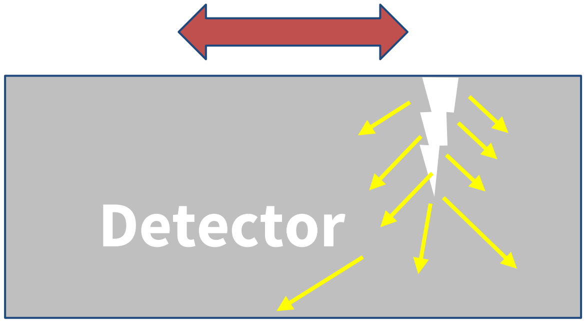


- Background varies with time/time since cooldown
- Background produces no ionization
- Scales with surface or sensor area

Stress Induced Microfractures?

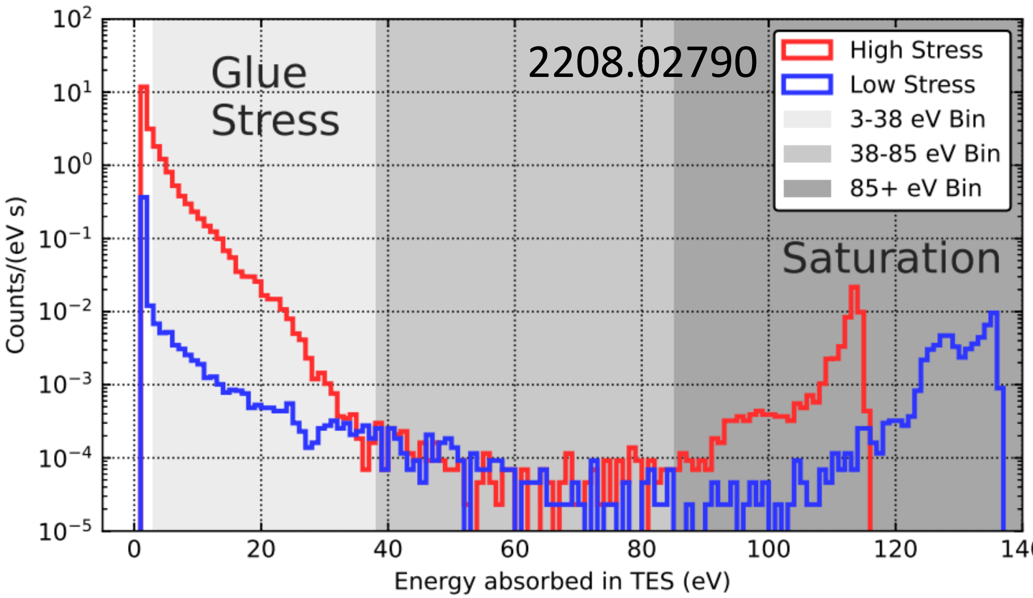


Detector under stress due to thermal contraction,manufacturing, etc.



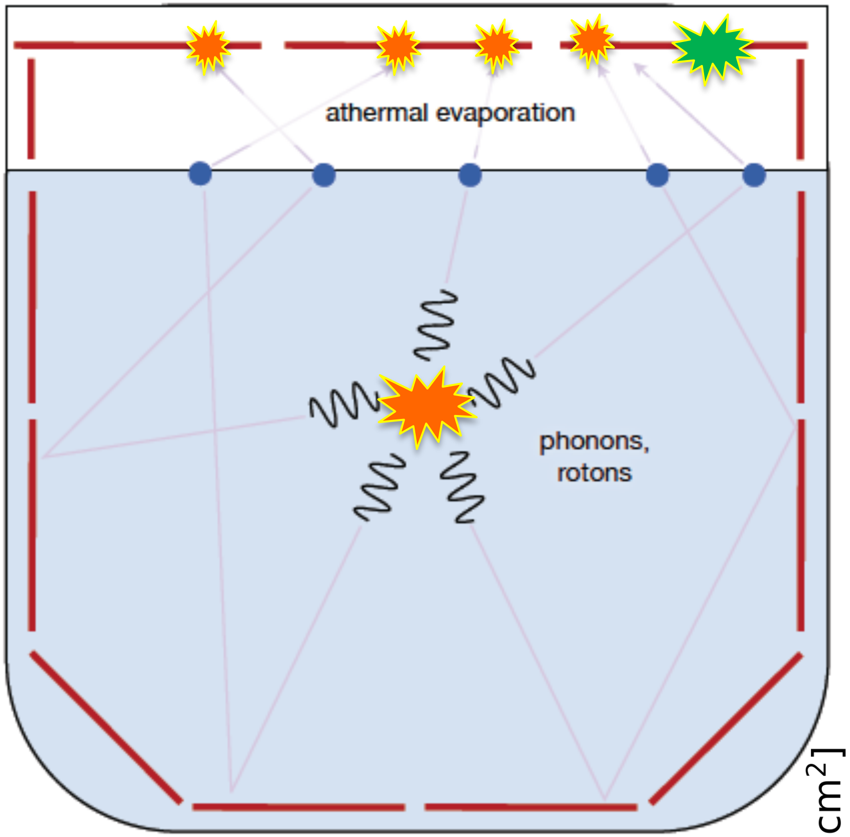
Detector relaxes releasing phonon energy

- Evidence: Using glue with high thermal contraction stress can increase low energy event rate by x10^2
- Mitigation Plan: Decrease residual stress everywhere in detector



Discriminating between DM Signals and Backgrounds

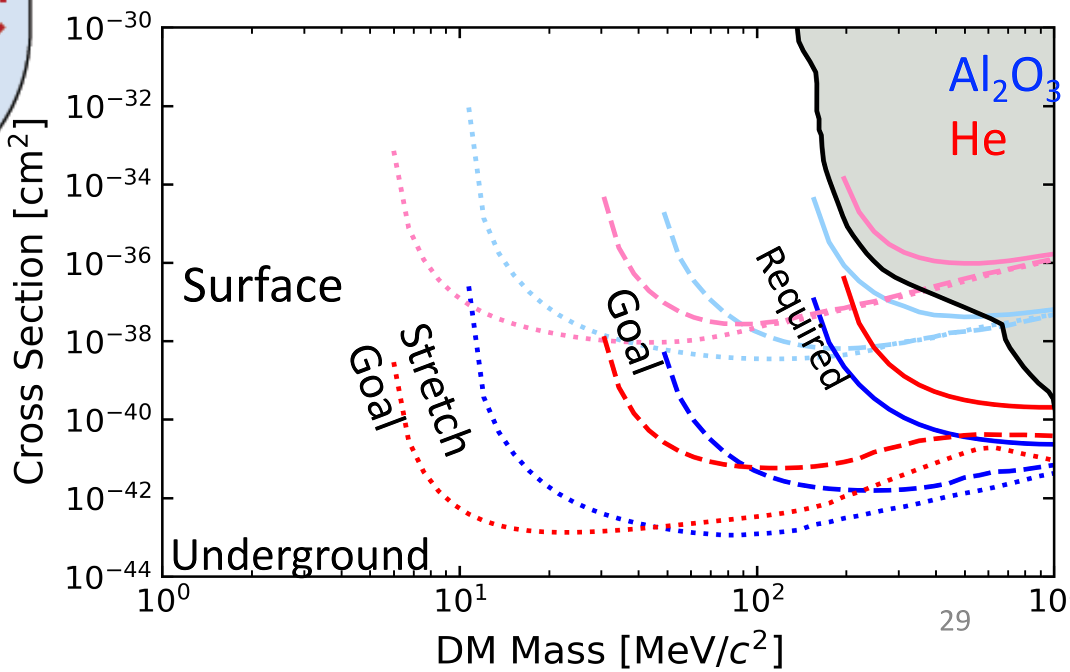
TESSERACT Discrimination: Superfluid Helium



- Superfluid Helium: it's a liquid … no stress microfractures
- Multiple Pixel Coincidence for He DM events discriminates DM from pixel microfractures
- Pulse Shape Discrimination: Helium is slow!

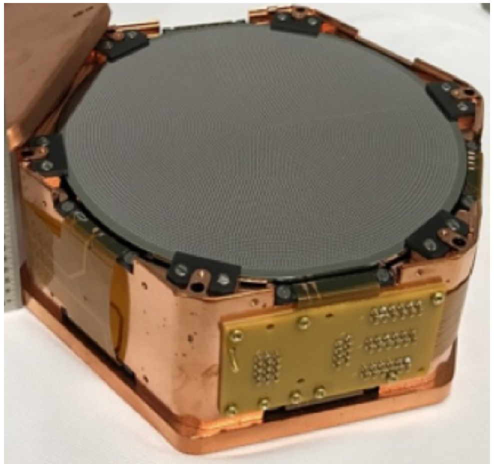
Design Driver #2:

- **Mitigation plan**
- **Discrimination plan**

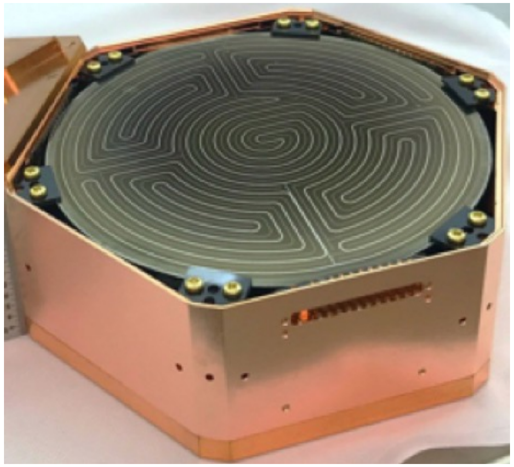


SuperCDMS Upgrades G2+

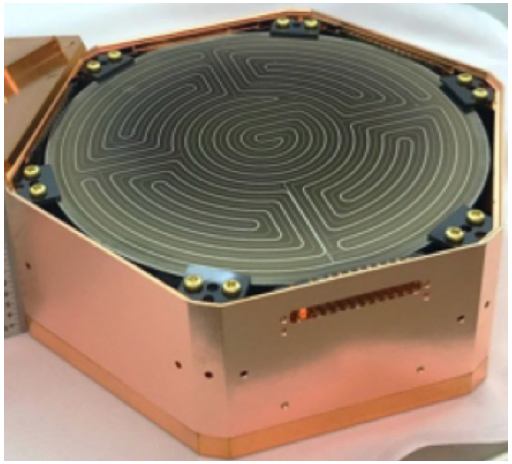
Next Generation HV



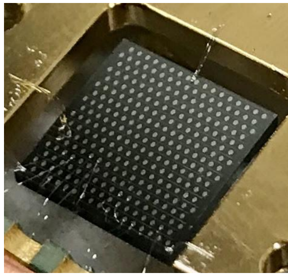
Small Volume iZIP
259cm^3 -> 11cm^3



Phonon Only iZIP
259cm^3 -> 11cm^3



0V 1cm^3

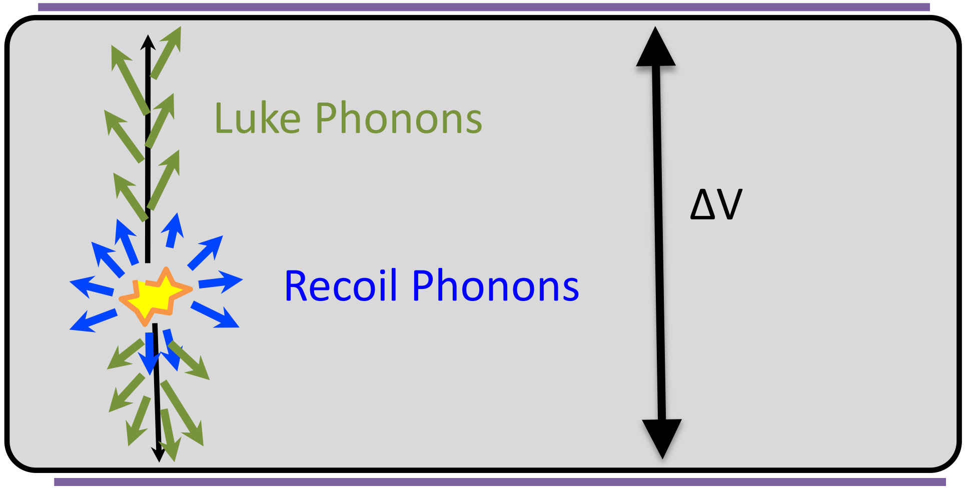


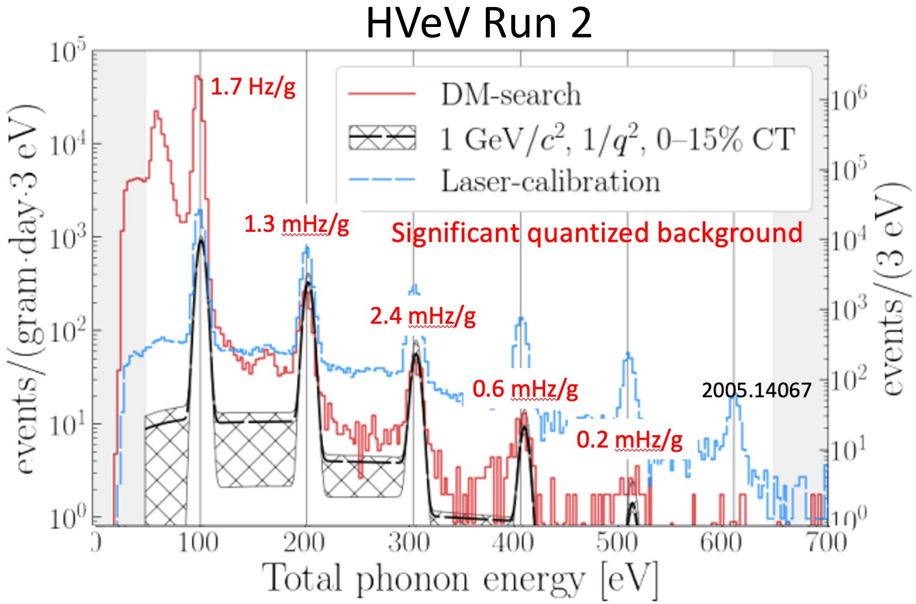
All concepts discussed in 2203.08463

Status	Cost	Timescale
Concept Development	Cryostat exists **<10M R&D + Project**	• Early Science upgrade prototypes @ CUTE FY25 • Full Deployment in SNOLAB cryostat in FY29

SuperCDMS G2: Excitation Sensitivity

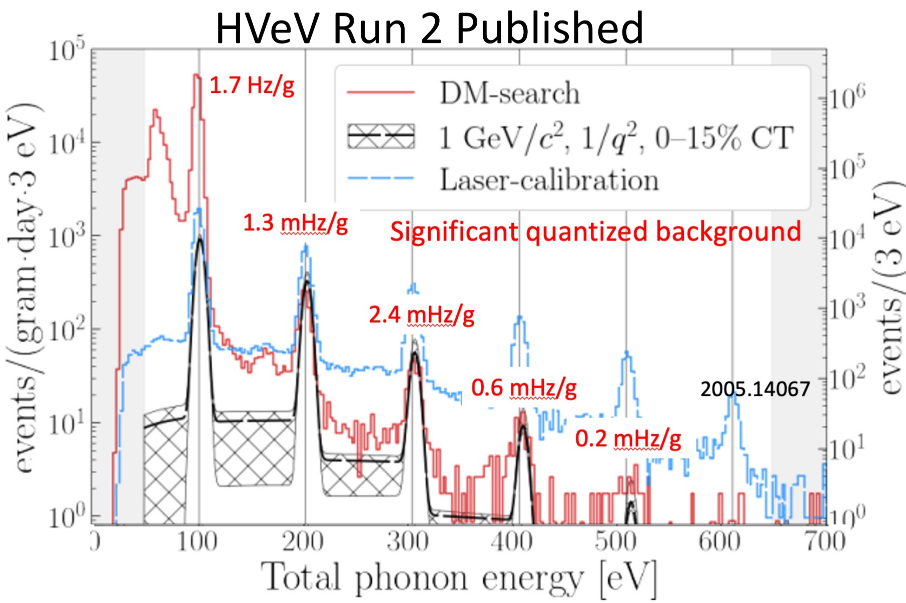
- Drifting charges release kinetic energy via NTL Phonon Production
- $$E_{total} = E_{recoil} + E_{NTL}$$
  $$= E_{recoil} + n_{eh} e \Delta V$$
- $$\lim_{\Delta V \to \infty} E_{total} \propto Q$$

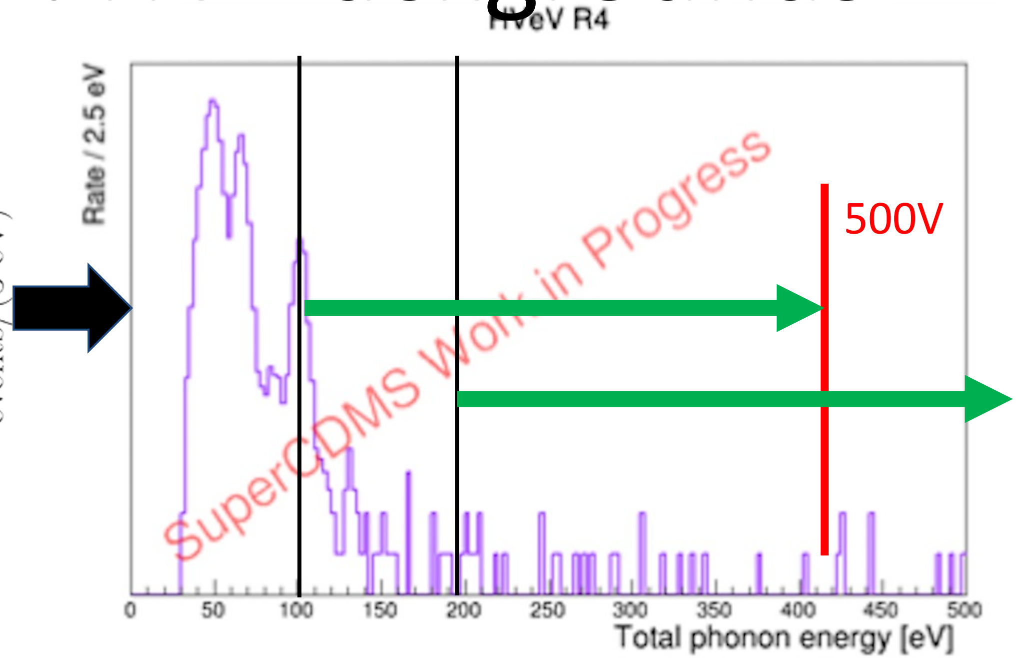




Design Driver #1:
- Single charge sensitivity achieved
- Brute phonon sensitivity - plan
- Direct charge -plan

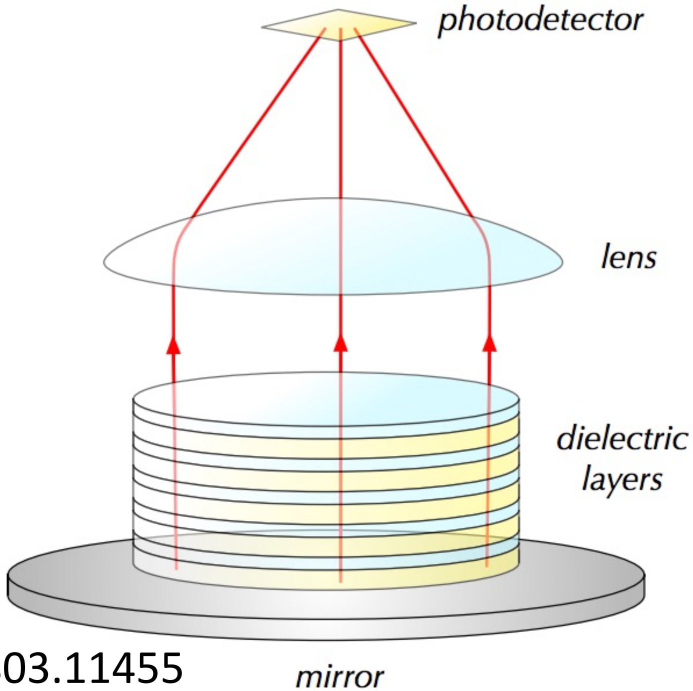
SuperCDMS G2+: HV Backgrounds





- Run 2 >= $2e^-/h^+$ quantized backgrounds dominated by scintillation production in FR4 support structure
- Run 4: Primarily limited by 0QLEE just like all phonon detectors
- Design Driver #2 (Backgrounds):
  - Mitigate 0QLEE
  - Go to 500V to separate 2 e-/h+ from 0QLEE

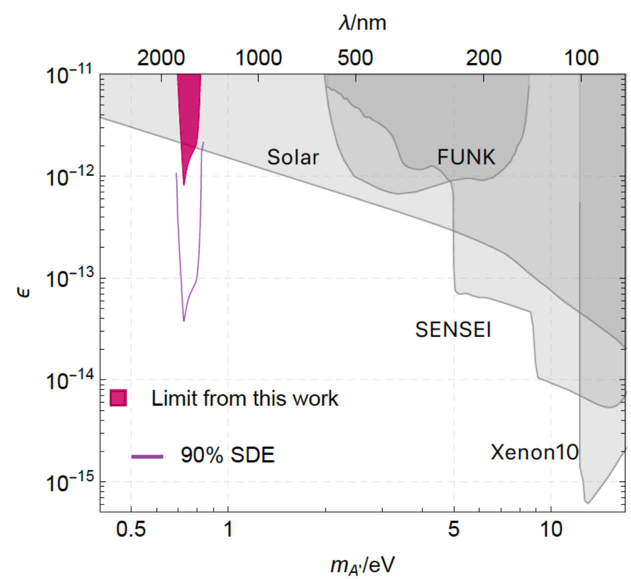
LAMPOST:Optical/IR Haloscope



1803.11455

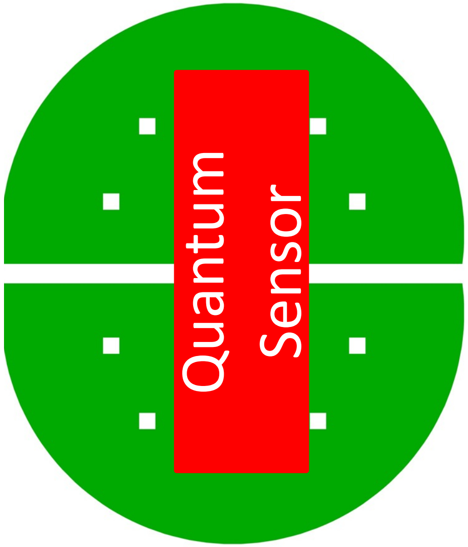
- Not currently funded by DOE
- 1709.05354,1803.11455,2110.01582
- 4 Momentum matching via multilayer stack
- Can do axions and dark photons

- Design Driver #1: Single Photon Sensitivity seen in SNSPDs, TES, MKIDs
- Design Driver #2:
  - Singles rate in SNSPDs is 6x10-6 Hz



… and so much more

NIDM funded	New Ideas
TESSERACT: GaAs	Implementation of new Quantum Sensing Technologies
TESSERACT: Polar	SNSPD readout of scintillating crystals
	Small gap semiconductor detectors
	SuperCDMS 0V $1cm^3$, iZIP, and piZIP concepts
	Liquid Noble TPCs optimized for low leakage
	Scintillating Bubble Chamber
	…



It's an exciting time!

Conclusions I

- Light Mass DM Design Drivers

  0. Small excitation energies: motivation for solid state

  1. Excitation Sensitivity: motivation for integration of quantum sensing

  2. Backgrounds: lots of viable plans to decrease by many orders of magnitude

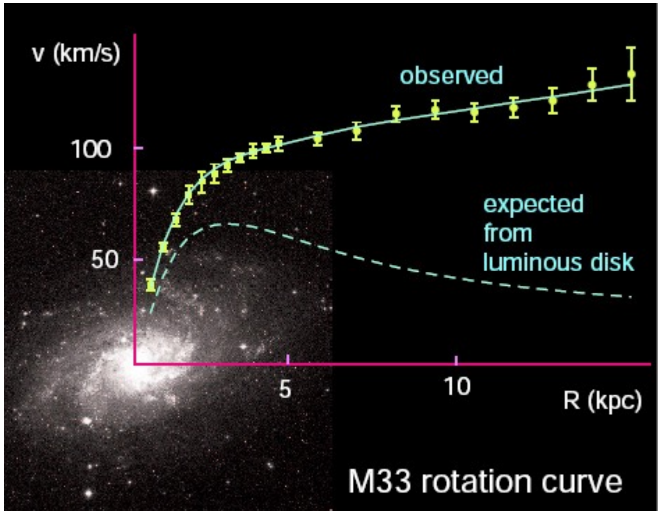
Conclusions II

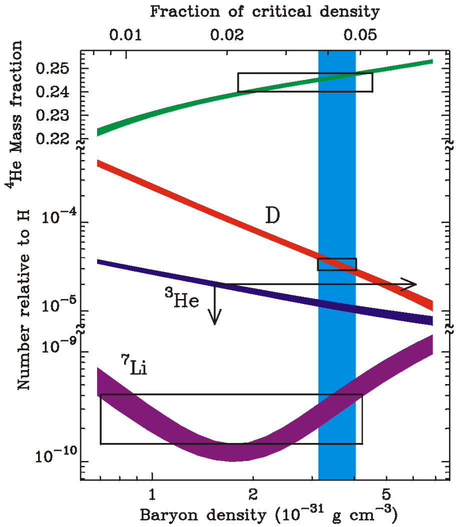
- High Science/$: O(1M) R&D, <10M project
- Lots of excitement and new ideas … field is changing so fast
- New Initiatives in Dark Matter Program
  - Absolutely critical, but underfunding has hampered the program
  - Lots of exciting, viable new concepts could really succeed and warrant a significant expansion of the program in $ and cadence (only NIDM and G2 funding calls in the last decade)
  - NIDM should be structured to expect failure.
    - more pre-project/R&D awards, fewer project awards
  - R&D/science boundary is fuzzy. World leading results can occur with 1g detectors at surface. NIDM pre-projects
    - should have science funding
    - expectation of real science from successful prototypes

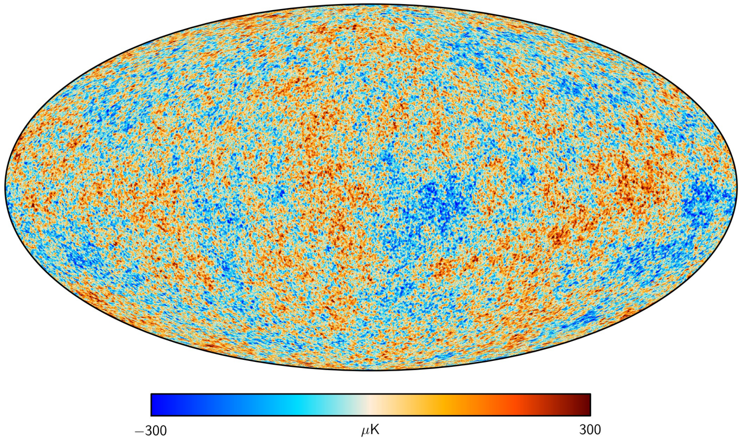
Backup

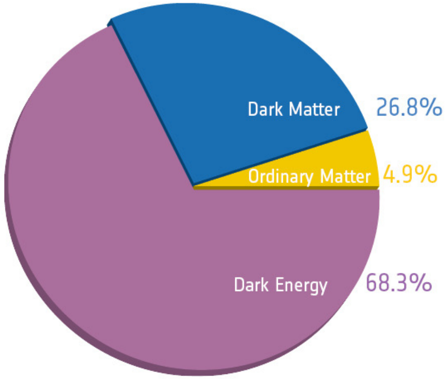
Motivation

Observational Evidence for Dark Matter



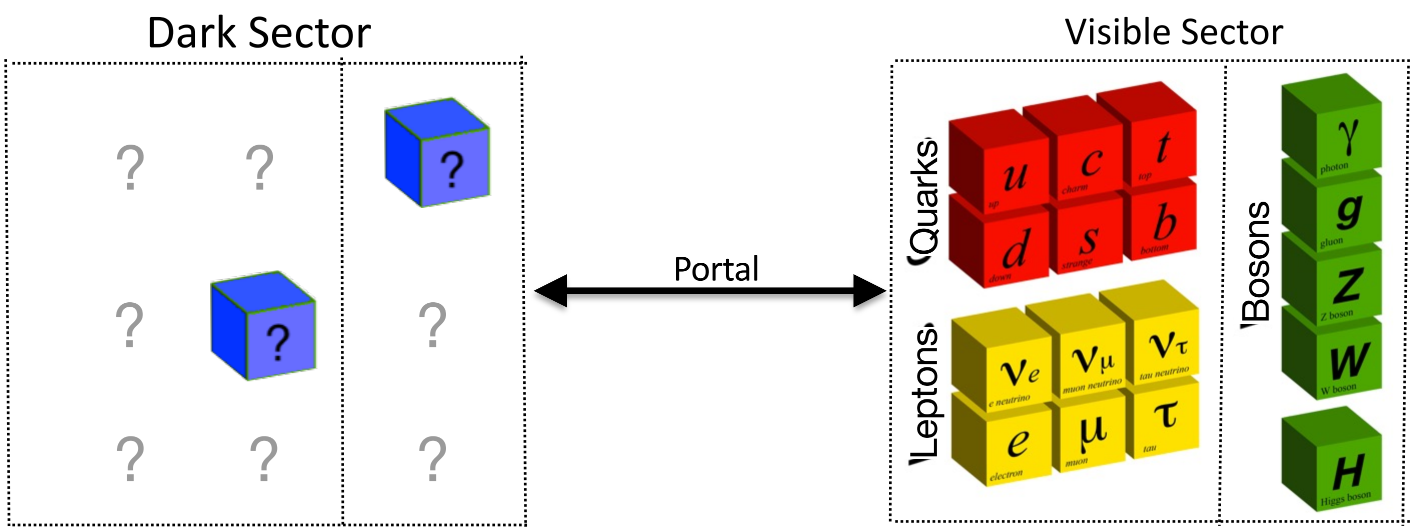






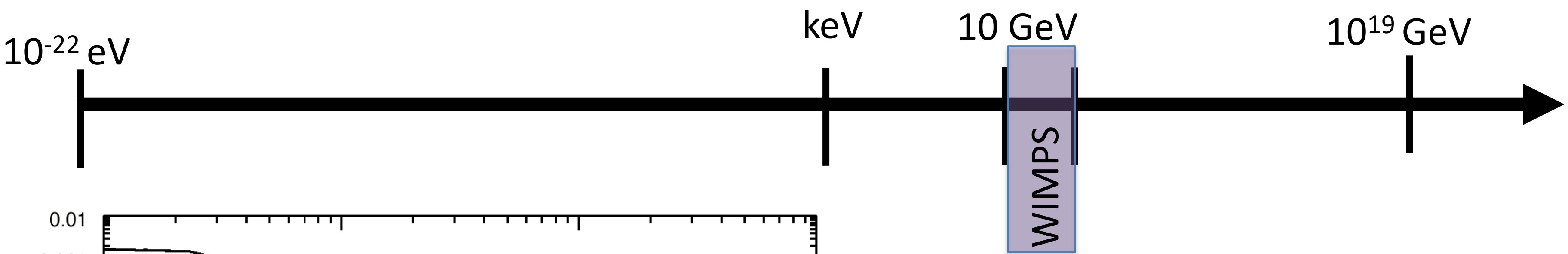
Dark Matter & Particle Physics

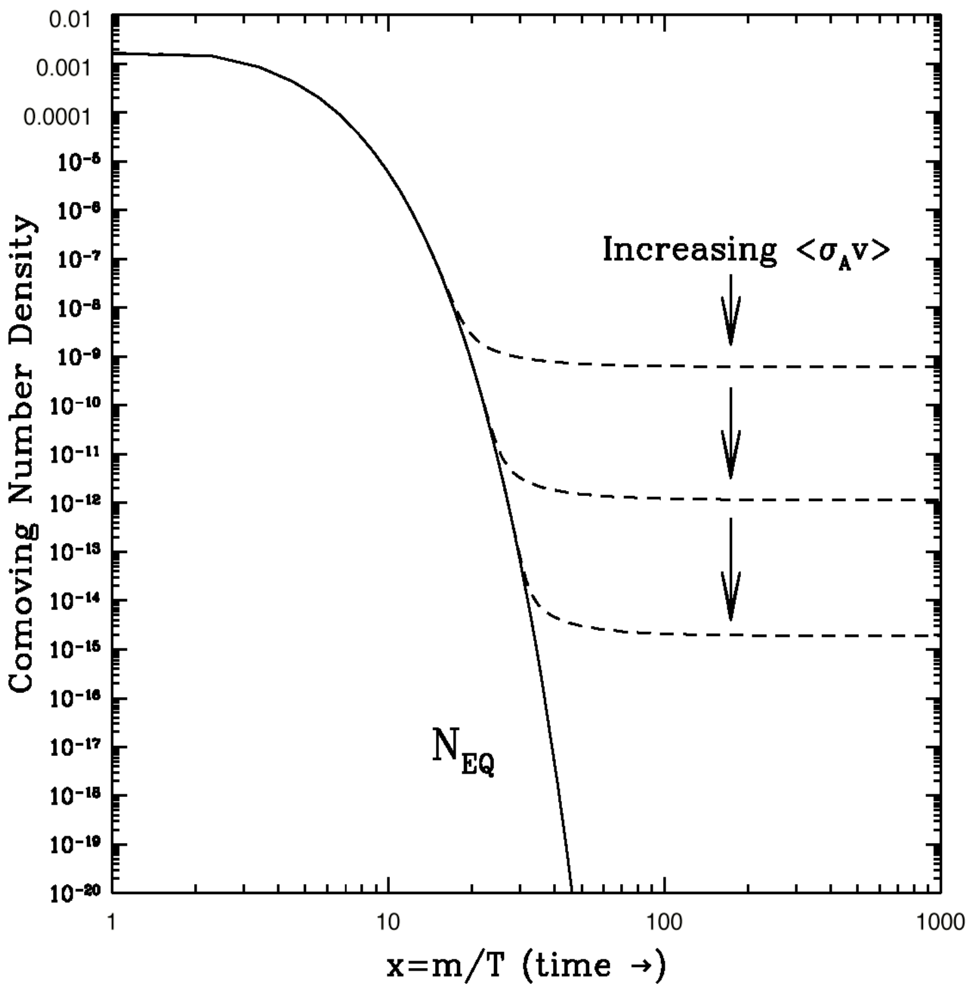
- What are its properties?
  - mass
  - Is it charged under a new force(s)?
  - How was it generated?
- Can this knowledge help us understand the laws of physics at high energies?



US Cosmic Visions: New Ideas in Dark Matter: 1707.04591

Past 35 years: A Focus on WIMPs *



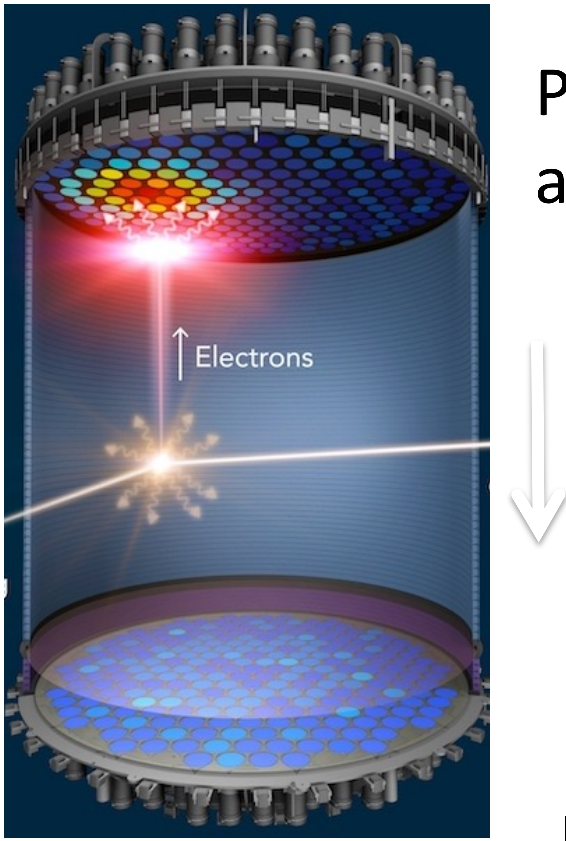


- Relic DM density suggests weak-scale cross sections
- New physics (and particles) at the weak scale could solve the hierarchy problem

* With the exception of ADMX (an experiment before its time)

Backgrounds

Problem #2: Detector Backgrounds in TPCs / PMTs



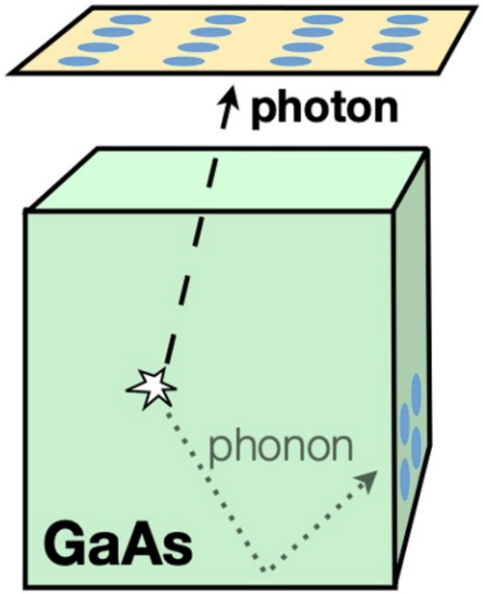
1110.3056

PMT, TPCs, SiPMs, SuperCDMS HV
all have dark currents / dark counts …

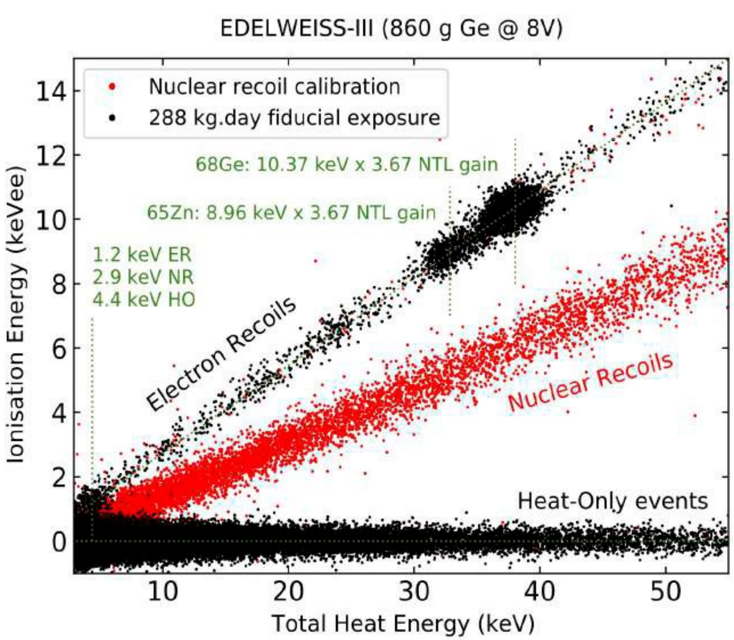
Hope: If we just get rid of the E-field …

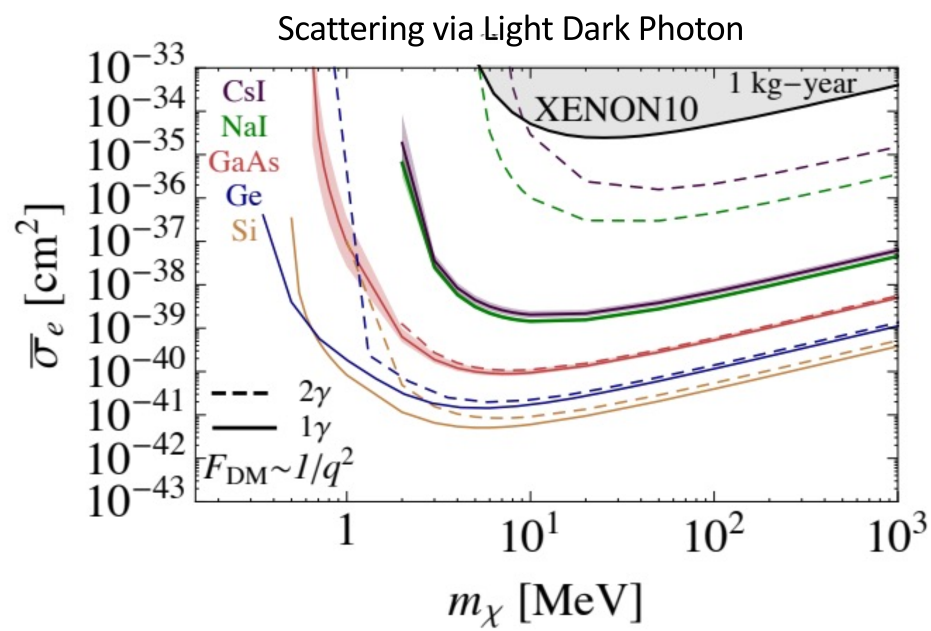
TESSERACT

TESSERACT Discrimination: GaAs

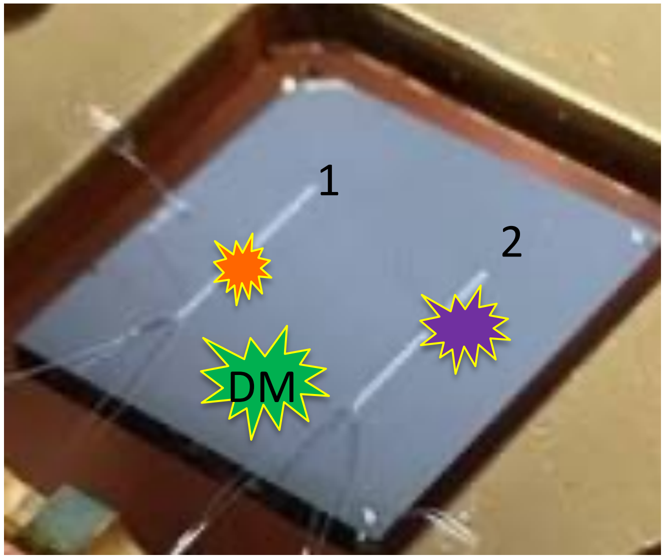


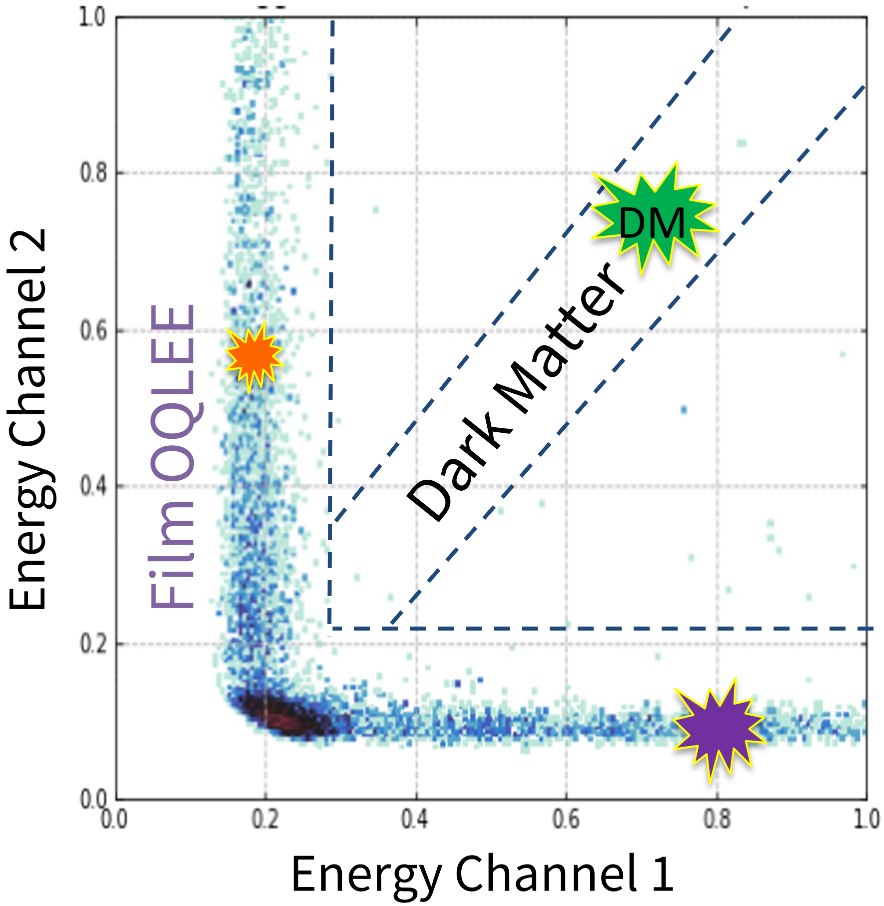
- To discriminate zero charge phonon only events in GaAs ER DM detector, one can require photon+phonon coincidence
- Design Driver #2 (Backgrounds)
  - Mitigation Plan
  - Discrimination Plan





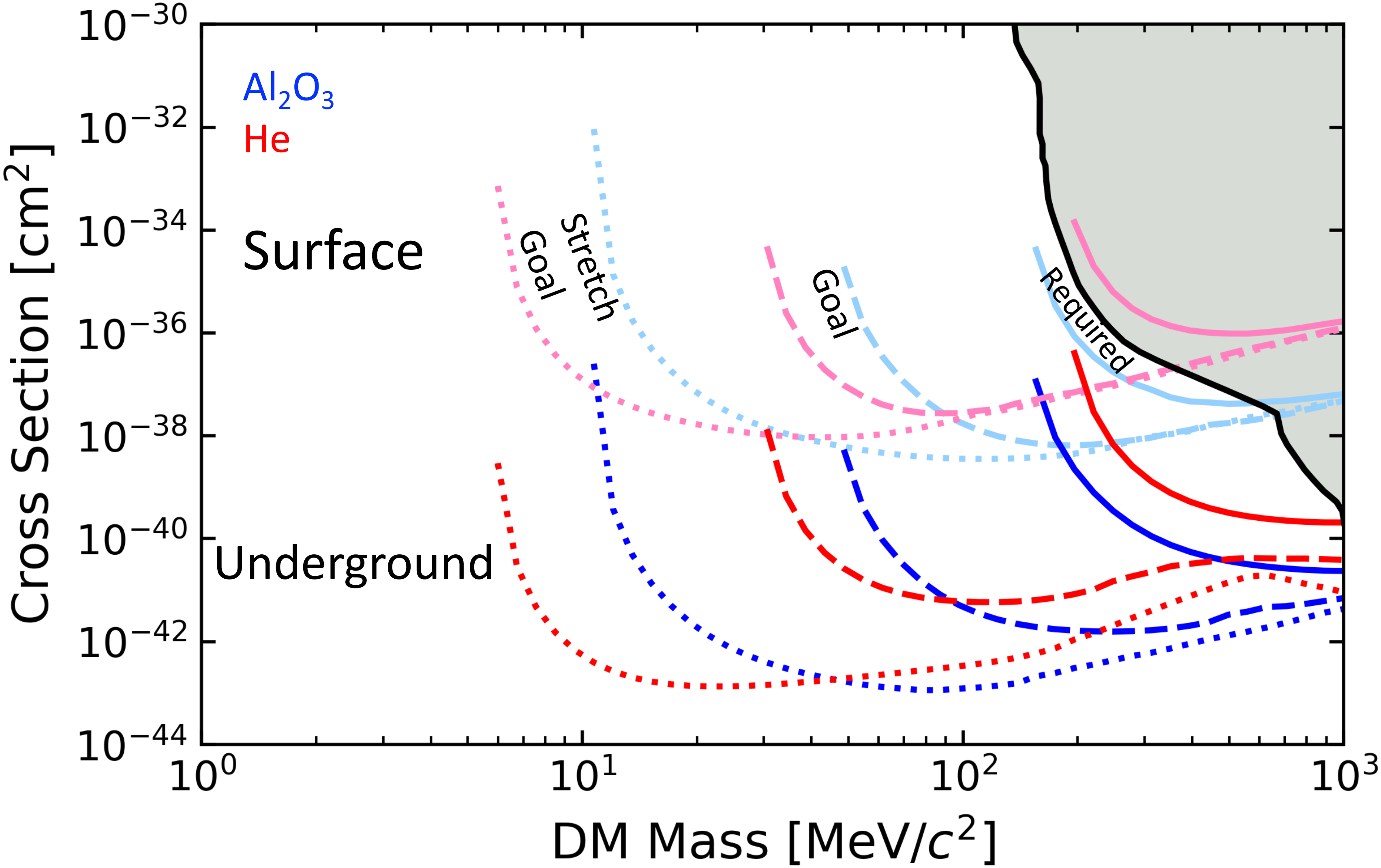
TESSERACT Discrimination: Polar Crystal





- If stress is occurring in phonon sensor films, energy will preferentially deposited in a single channel
- Design Driver 2 (Backgrounds)
  - Plan to mitigate
  - Plan to discriminate

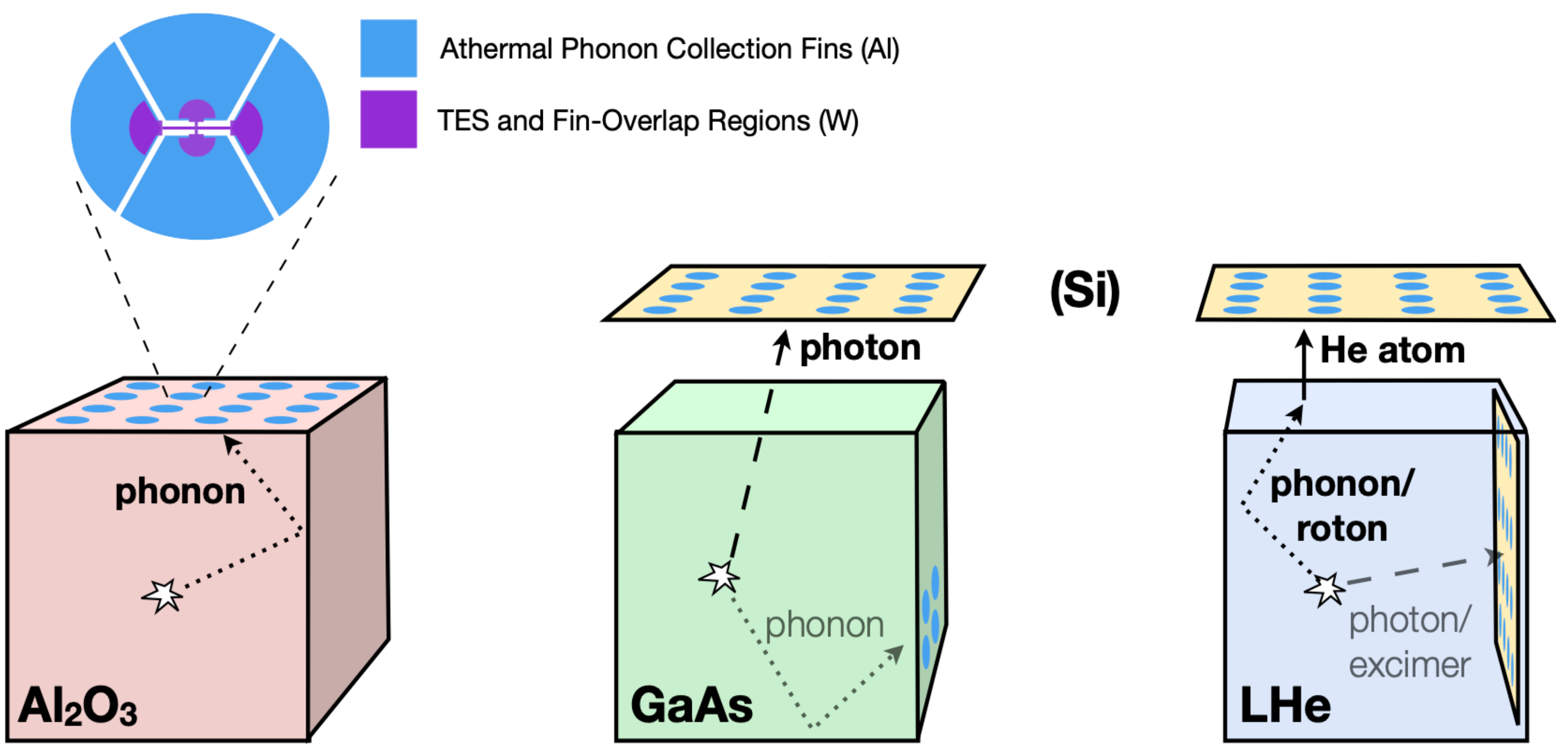
NRDM Search Sensitivity @ Surface



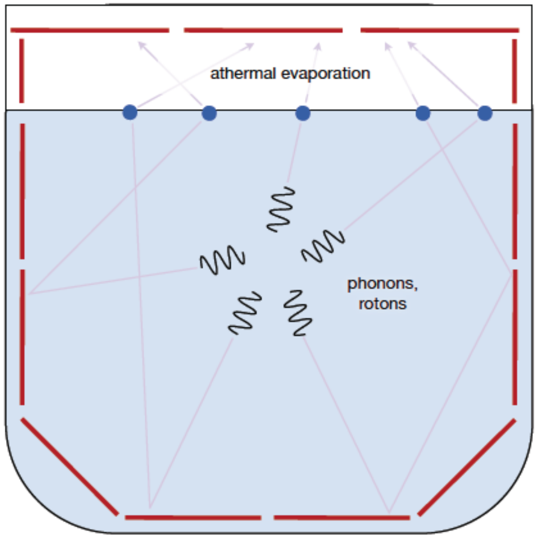
Achieving pre-project energy threshold goals leads to world leading science @ surface

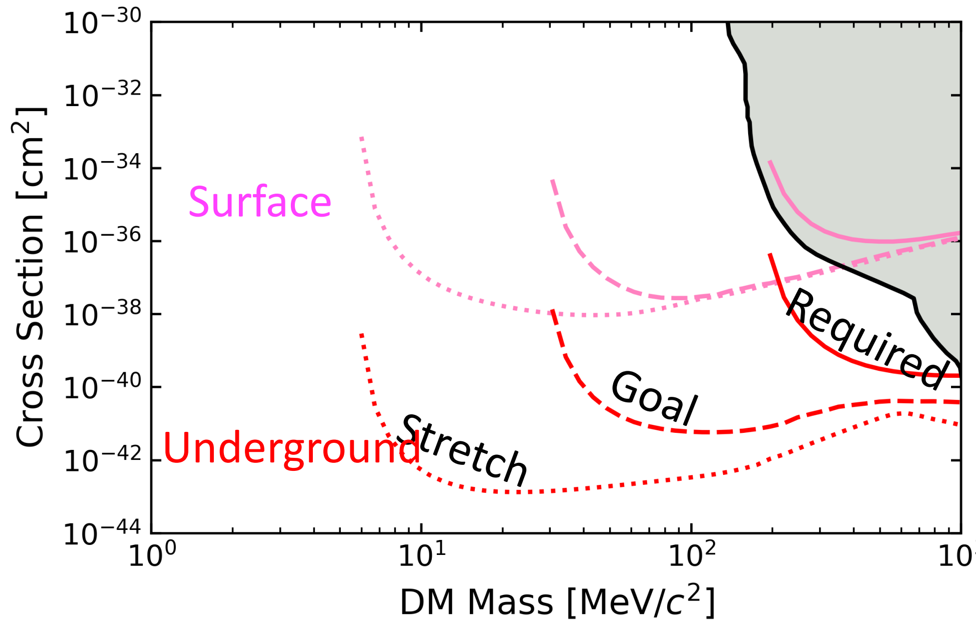
Nearly everything the same

- Having multiple targets with complementary DM science (NRDM, ERDM, Absorption) and orthogonal risks doesn't increase cost (time & money) significantly since almost everything is identical (phonon sensor development, wiring, electronics, DAQ, data handling, processing, and analysis software) except the substrate.



1) **HeRALD**:**He**lium **R**oton **A**pparatus for **L**ight **D**ark matter



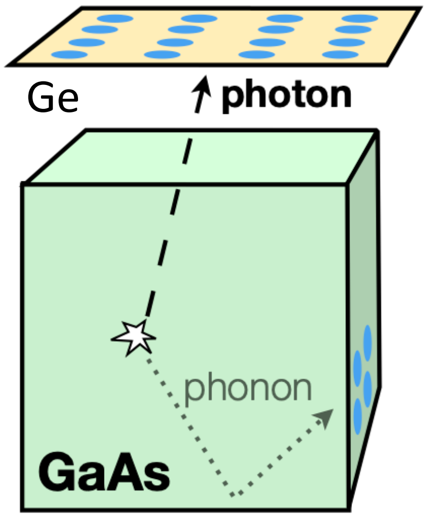


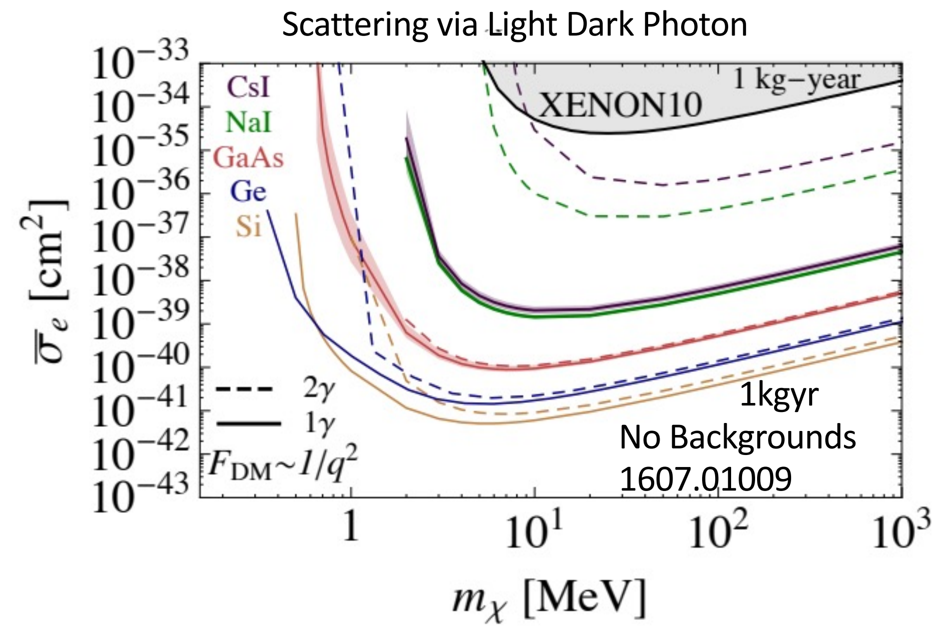
	Required Threshold	Goal Threshold	Stretch Goal Threshold
Si 4cmx4cm	6.7eV	900 meV	12 meV
He	21 eV	570 meV	24meV

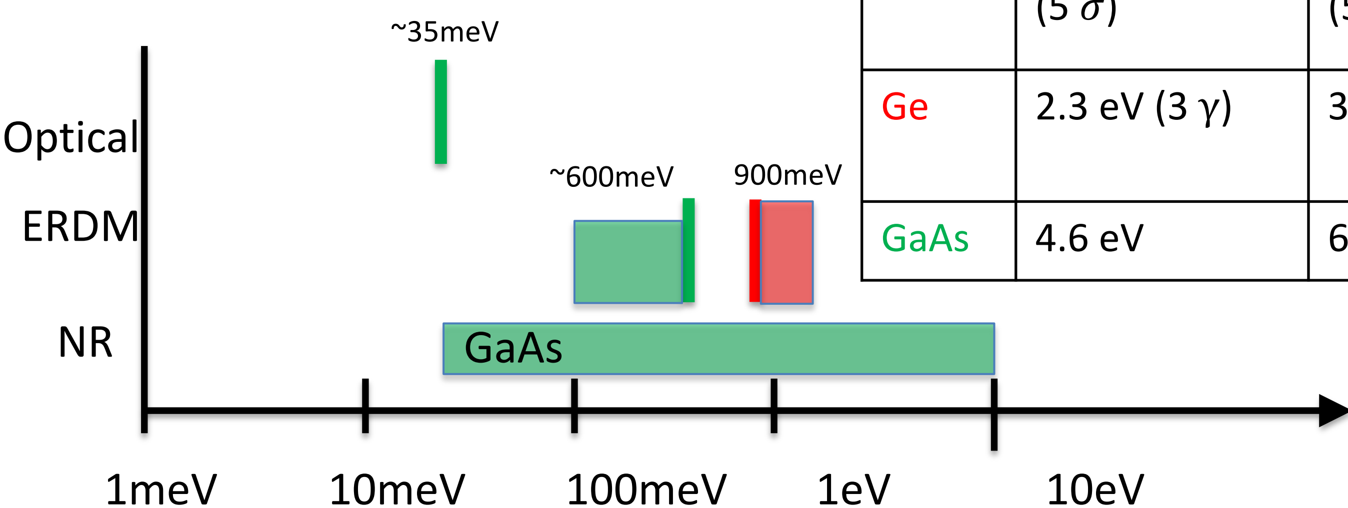
#1 Design Driver for Light Mass Dark Matter Searches: Energy Sensitivity

2) SPICE: GaAs ERDM

"CRESST for ERDM"



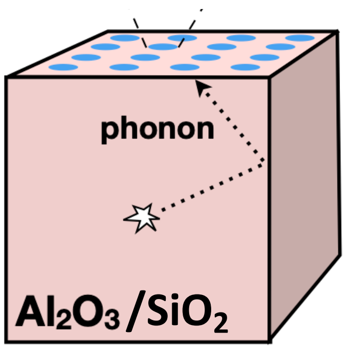


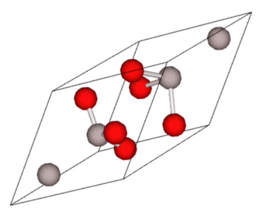


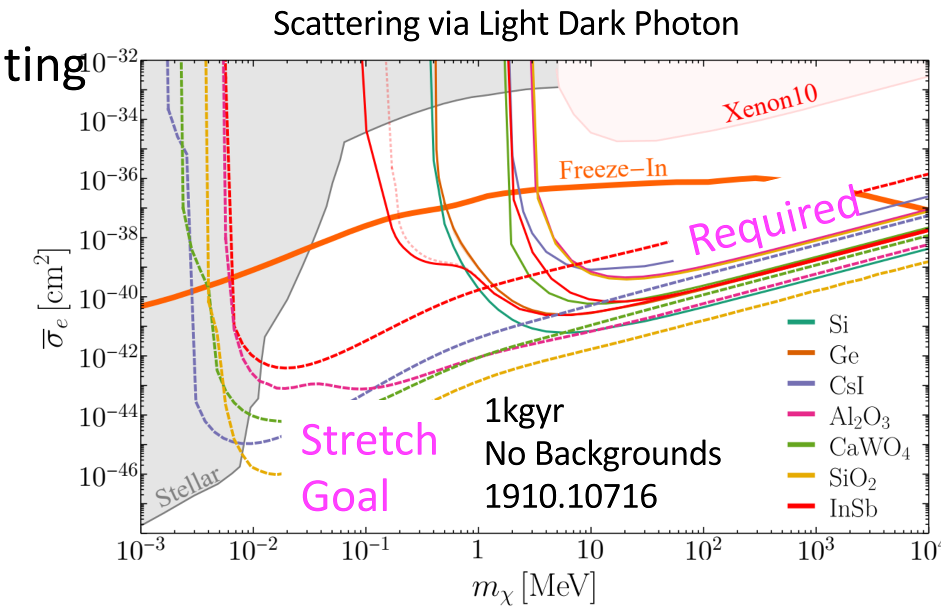
	Required (5 σ)	Goal (5 σ)	Stretch Goal (5 σ)
Ge	2.3 eV (3 γ)	300 meV (1 γ)	12 meV
GaAs	4.6 eV	600 meV	24meV

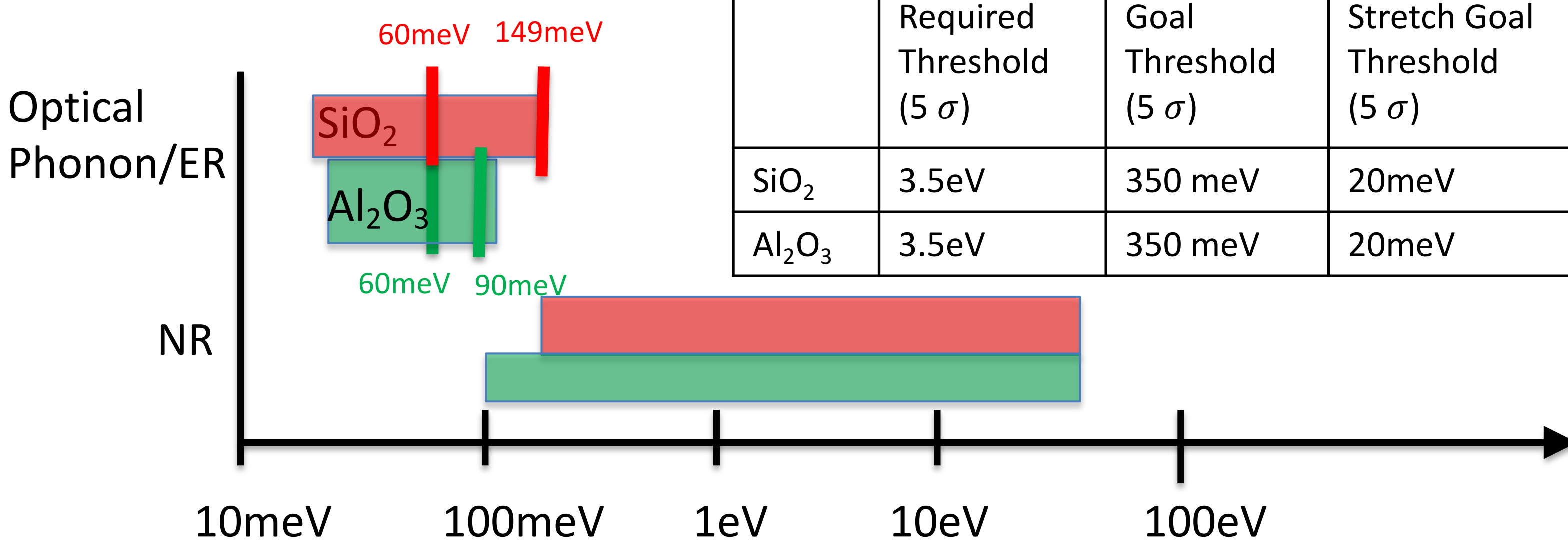
3) SPICE: Sub-ev Polar Interactions Cryogenic Experiment

In ionic crystals, optical phonons are oscillating electric dipoles! Couple strongly to dark photons!





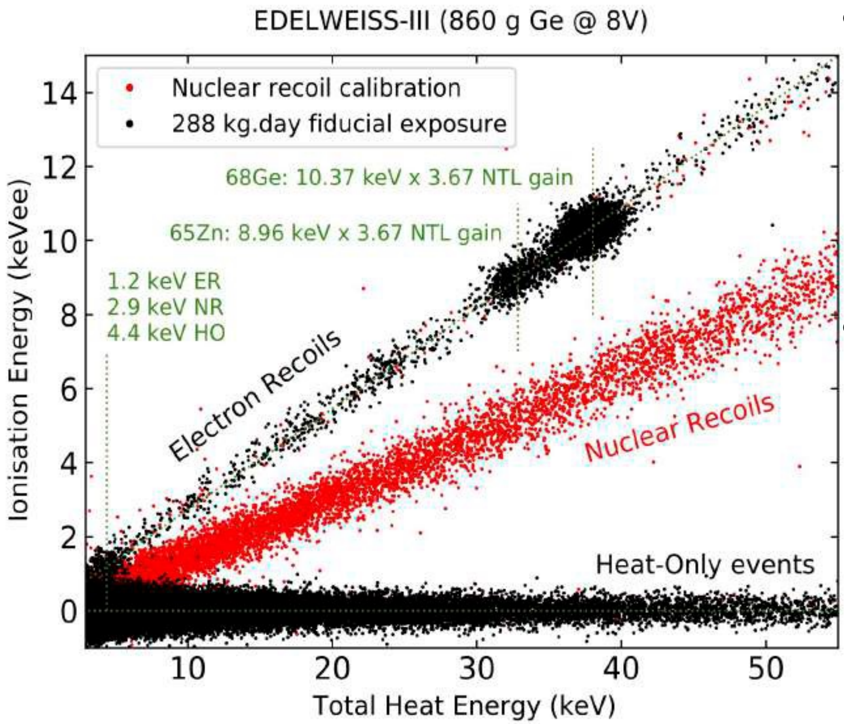




	Required Threshold (5 σ)	Goal Threshold (5 σ)	Stretch Goal Threshold (5 σ)
SiO_2	3.5eV	350 meV	20meV
Al_2O_3	3.5eV	350 meV	20meV

SuperCDMS

SuperCDMS G2+ iZIP: Backgrounds



- To discriminate zero charge phonon only events from nuclear recoils, one needs to independently measure ionization and phonon energy
- Improve ionization sensitivity with improved HEMT charge amplifier and smaller detector [σ_q =50eVee, 17 eVee]

- Design Driver #2 (Backgrounds)
  - Mitigation Plan
  - Discrimination Plan