SuperCDMS & low mass dark matter

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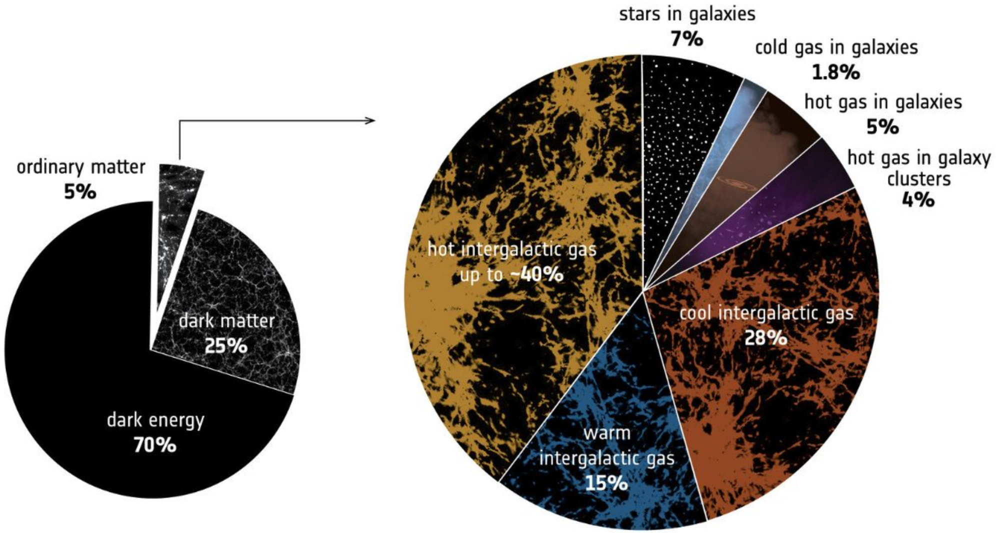
Introduction



Why dark matter (DM)?

- 25% of density in the universe [1-2]
- Strong motivation: CMB power spectrum [3], gravitational lensing [4], etc.
- Nature of DM unknown: mass? Coupling strength?

Outline

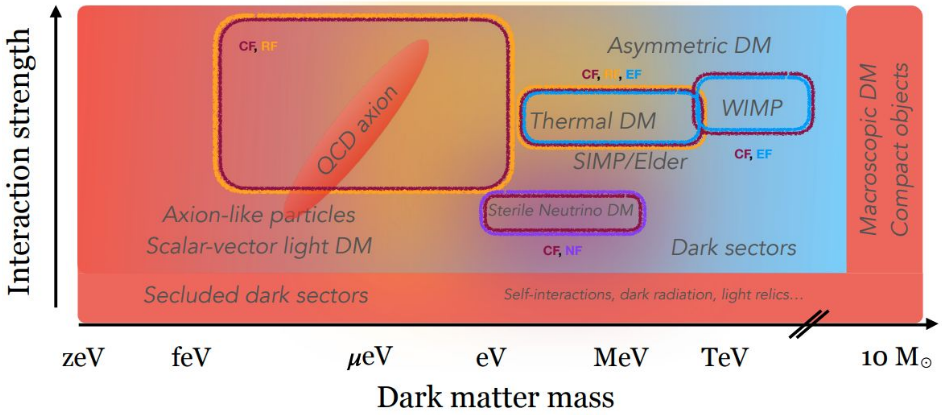
- Low mass dark matter overview
- SuperCDMS & future upgrades

Possible mass range of DM

* zeV: zepto 10^{-21}
* solar mass: 10^{66} eV

Large range DM mass possible

[Figure: snowmass]



< ~1 eV:

- Axion-like wave-like DM
- Wave detection @ different frequencies, e.g. DMRadio [5]

Particle-like DM

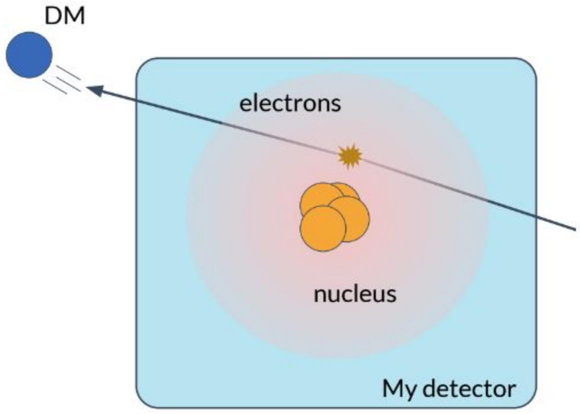
- 1 eV ~ 1 GeV: **low mass DM**
- 1 GeV ~ 100 TeV: WIMP @ e.g. liquid noble gas detectors such as LZ [7]
- > 100 TeV: ultra-heavy dark matter @ e.g. galaxy γ-rays [8]

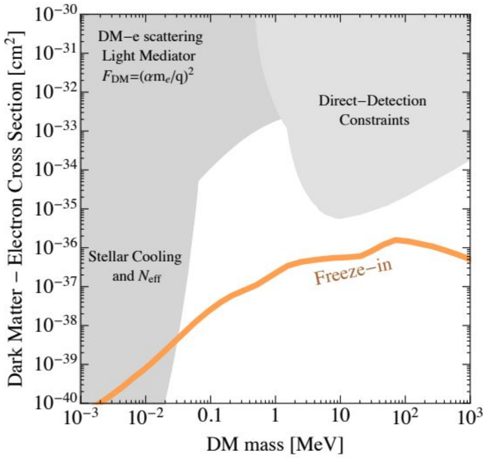
> solar mass:

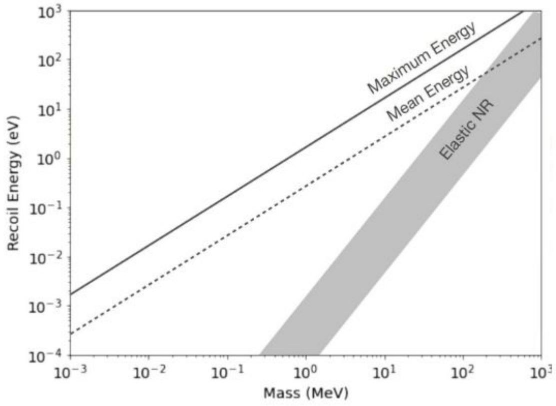
- macroscopic DM
- E.g.: black holes @ LIGO [6]

* Freeze-in model [12]

Low mass DM interactions







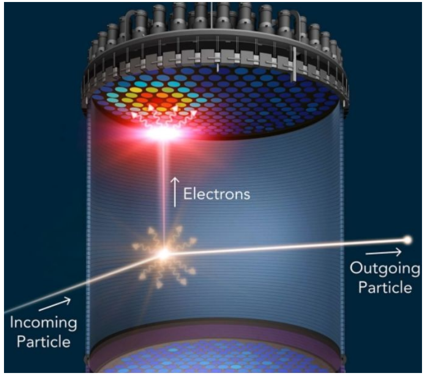
Direct interactions from dark matter halo [11]:

- **Nuclear recoil (NR):** elastic, Migdal effects [9]
- **Electron recoil (ER)**: heavy/ light mediators, electric/magnetic dipole moments, dark photon mediator [10]
- Collider constraints [13], telescope indirect constraints [14]

Low mass DM features:

- Higher flux -> smaller detector
- Lower recoil energy -> better energy resolution

Low mass DM searches

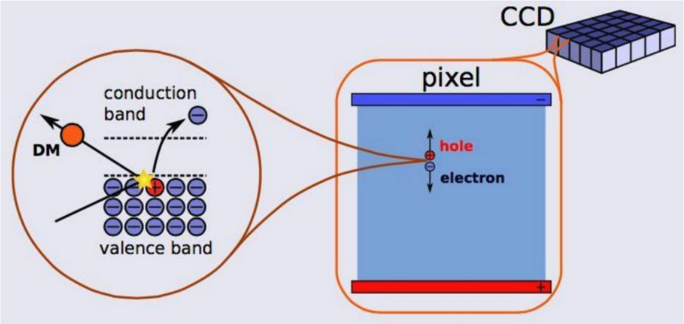


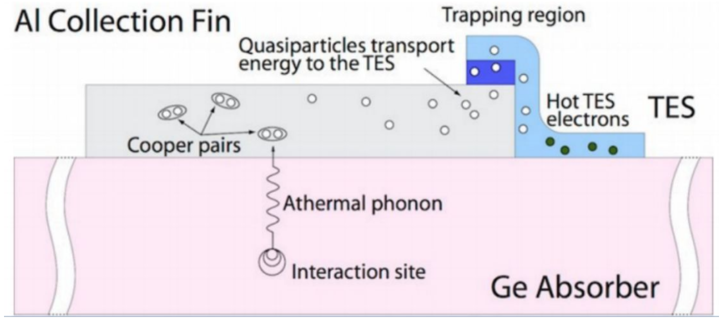
Noble liquid gas:

- Hydrox: doping with lighter nuclei

Solid state charge detectors (ER-only):

- Oscura: small bandgap Si charge-coupled device





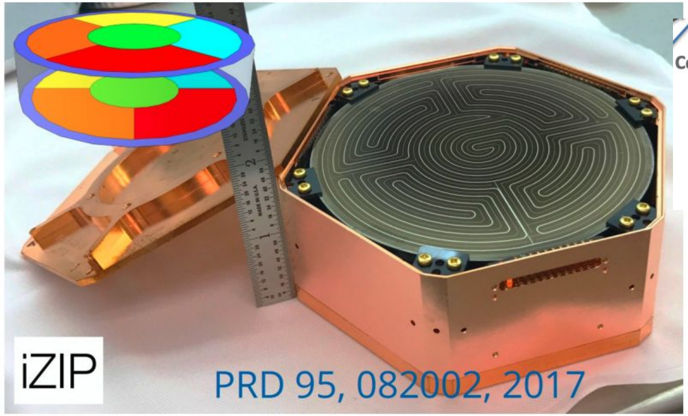
Solid state phonon detectors:

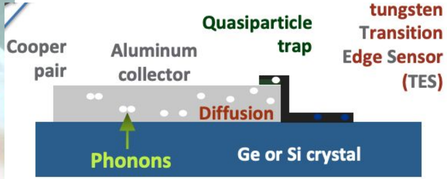
- **SuperCDMS**: Ge vibration lattice phonon signals
- More: crystal scintillators, single photon detectors [10], atom interferometers [15]

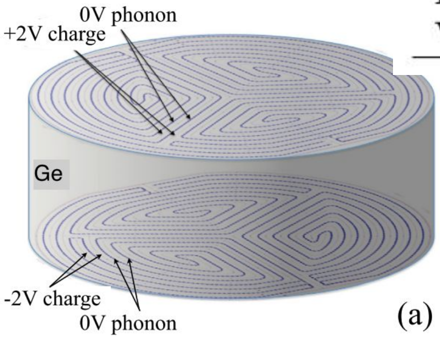
Outline

- Low mass dark matter overview
- **SuperCDMS & future upgrades**

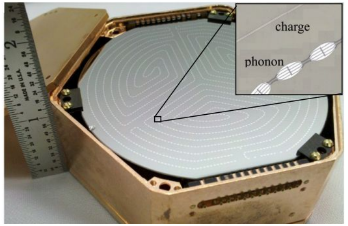
SuperCDMS (Cryogenic Dark Matter Search) detectors – iZIP







	iZIP	
	Ge	Si
Number of detectors	10	2
Total exposure [kg·yr]	45	3.9
Phonon resolution [eV]	33	19
Ionization resolution [eV_{ee}]	160	180
Voltage Bias ($V_+ - V_-$) [V]	6	8



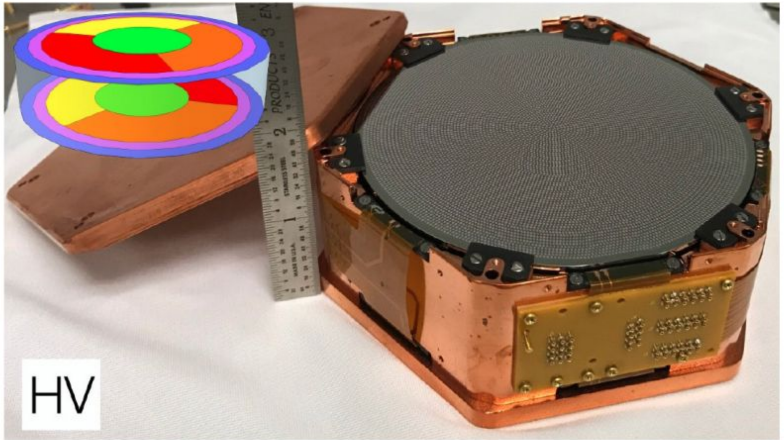
iZIP detectors (interleaved Z-dependent Ionization and Phonon**)** [16, 17]**:**

- Ge + Si
- Phonon + charge
- 6 channels on each side

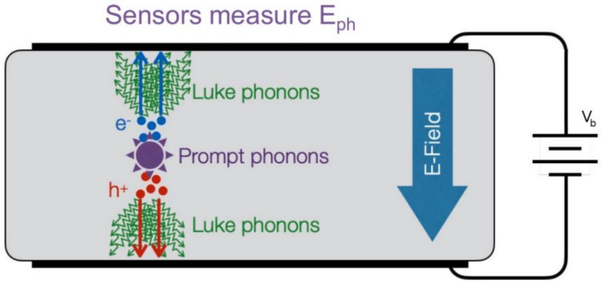
Readout

- Phonon -> phonon TES sensor + SQUID
- Charge -> ionization electrodes -> good surface electron rejections

SuperCDMS detectors – HV



	iZIP		HV	
	Ge	Si	Ge	Si
Number of detectors	10	2	8	4
Total exposure [kg·yr]	45	3.9	36	7.8
Phonon resolution [eV]	33	19	34	13
Ionization resolution [eV_{ee}]	160	180	–	–
Voltage Bias ($V_+ - V_-$) [V]	6	8	100	100

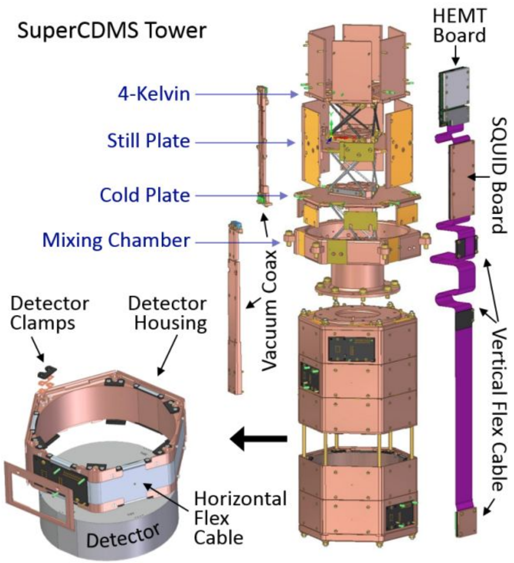


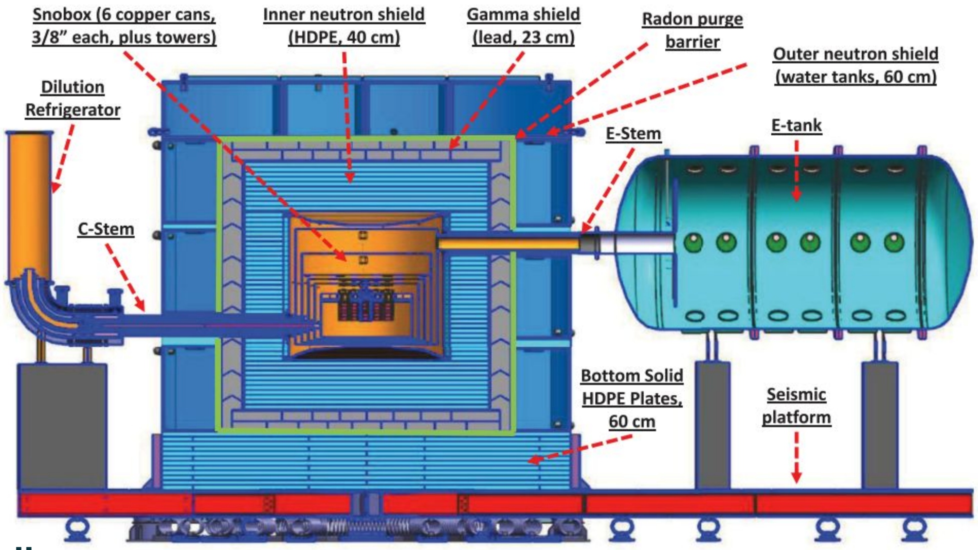
HV detector (high voltage) [18]**:**

- Ge + Si
- 6 channels on each side
- Phonon-only + HV -> Luke phonon dominant -> lower thresholds / worse surface e discrimination

SuperCDMS shielding

SNOLAB ladder lab: 2km underground





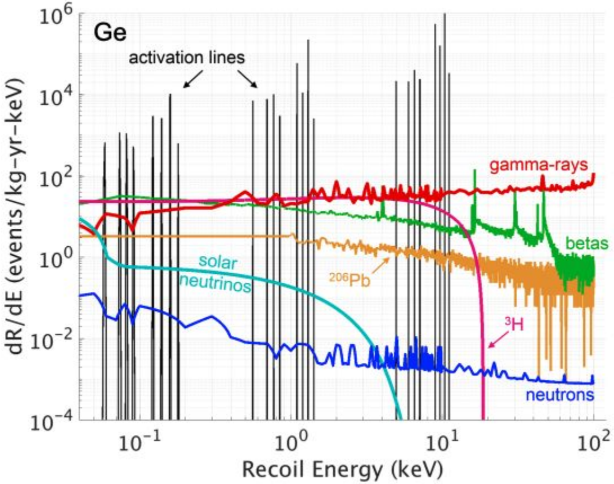
Detector tower:

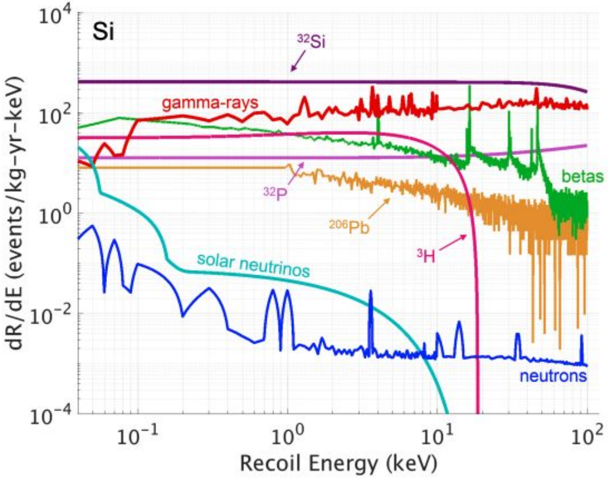
- Dilution refrigerator: 50 K - 4 K - 30 mK

Shielding:

- SNObox: cold regions
- Neutron shield: polyethylene plastic
- Gamma shield: lead
- Radon shield: aluminum
- Outer neutron shield: water + plastic
- E-stem (electronic) + C-stem (cryogenic) + seismic platform

SuperCDMS backgrounds





Dominant backgrounds [19]:

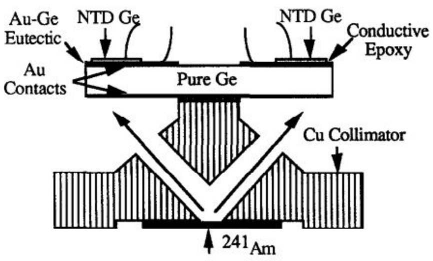
- Gamma rays from rocks (^{238}U, ^{232}Th)
- Neutrons from rocks (^{238}U, ^{232}Th)
- Betas / ^{206}Pb at detector surface from detector exposure to Rn during installation
- Solar neutrinos: coherent elastic neutrino-nucleus scattering
- ^{3}H, Ge activation lines, ^{32}Si: cosmogenically produced / naturally occurring in the detector;
- Low energy excess = PCB luminescence [20]

Simulation = GEANT4 + shielding + Sources 4c (neutron)

SuperCDMS timeline

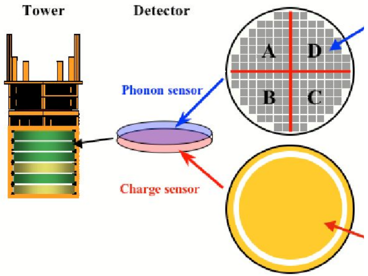
CDMS I @ Stanford 1990-2002 [21]

- Neutron transmutation doped Ge phonon sensors



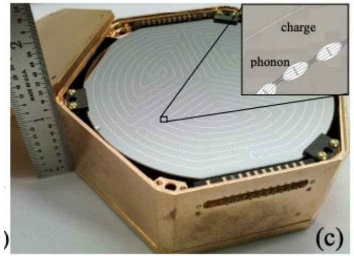
CDMS II @ Soudan 2002-2009 [22]

- ZIP: ionization + charge detector



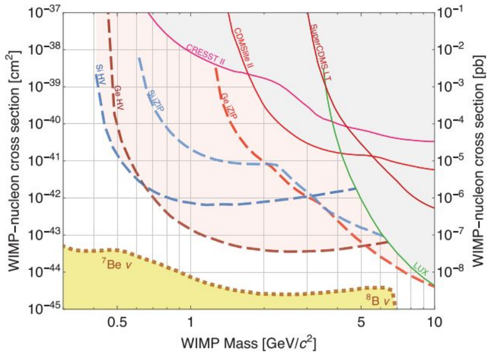
SuperCDMS / CDMSlite @ Soudan 2011-2015

- iZIP: interleaved
- Lite: HV operation



SuperCDMS @ SNOLAB 2024-2028?

- Better shielding + ~x3 larger (~30kg detector mass)

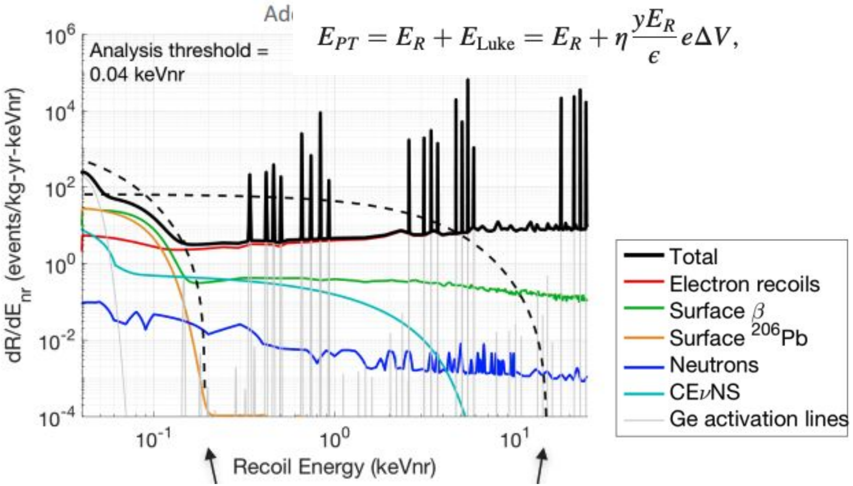


Outline

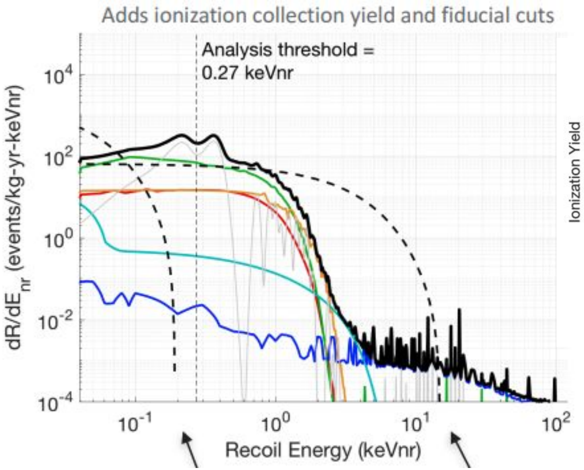
- Low mass dark matter overview
- SuperCDMS & future upgrades
  - Detectors ✅
  - **Physics**

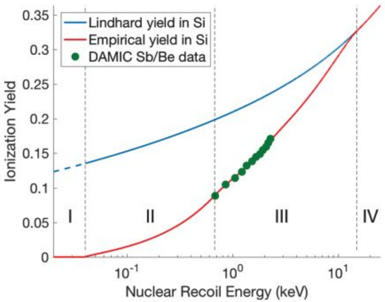
SuperCDMS data cleaning

* y: ionization yield = NR/ER ionization
* σ_{ph}: phonon sensor resolution



$$E_{PT} = E_R + E_{\text{Luke}} = E_R + \eta \frac{yE_R}{\epsilon} e\Delta V,$$





$$E_Q = \eta y E_R,$$

More voltage adjustments during commissioning!

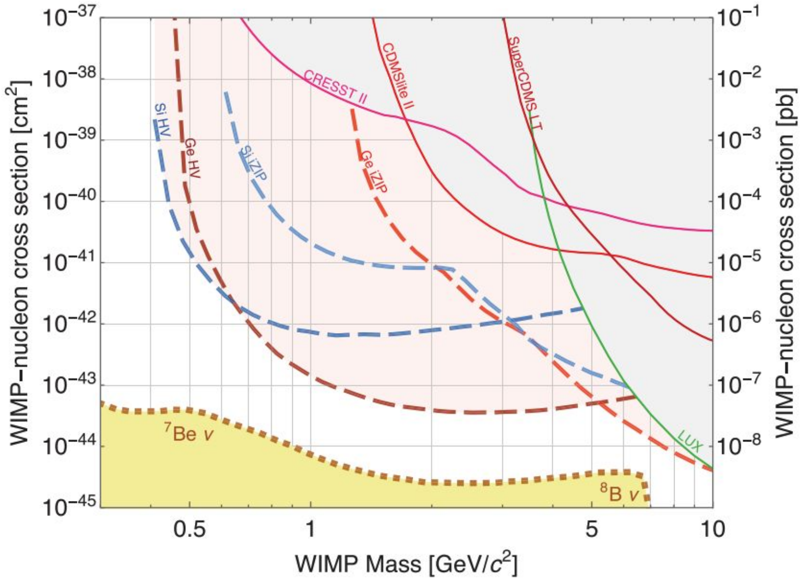
Data cleaning

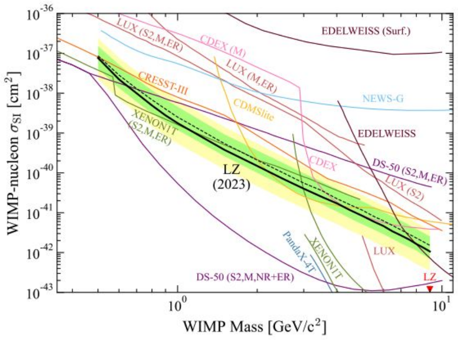
- Data quality cuts: temp fluctuations + electrical noise
- Fiducial volume cuts: outer cylinder
- iZIP ionization signal cuts: eliminate surface betas (right)
- Signal efficiency: 85% (HV), 75% (iZIP)

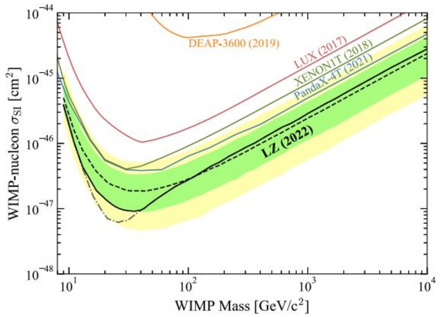
Detector	$7\sigma_{\text{Ph}}$ (eV)	$e\Delta V$ (eV)	Analysis threshold (eV) E_{Ph}	E_{nr}
Si HV	35	100	100	78
Ge HV	70	100	100	40
Si iZIP	175	8	175	166
Ge iZIP	350	6	350	272

- **HV:** lower threshold + higher recoil energy
- **iZIP:** less beta bkg

SuperCDMS sensitivity







Physics results

- Competitive < 10 GeV (WIMP-nucleon)
- Much more to explore:
  - Electron-coupled DM: dark photon, ALPs [16]
  - EFT for WIMP [23]
  - Anomaly detection [24]
  - Non WIMP physics: neutrino magnetic moment? [25]

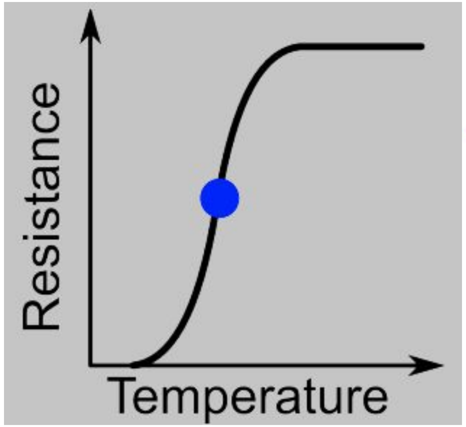
Limit setting

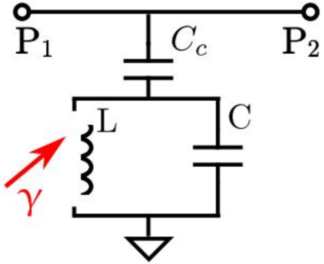
- 90% CL upper limits at each WIMP mass
- **HV**: good sensitivities <~ 1 GeV
- **Si**: iZIP better phonon resolution -> better sensitivity at low mass

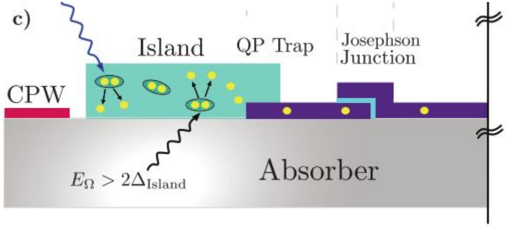
Outline

- Low mass dark matter overview
- SuperCDMS & future upgrades
  - Detectors ✅
  - Physics ✅
  - Upgrades

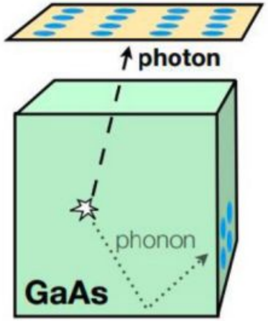
SuperCDMS upgrades / R&D







Many ideas to measure recoil energy down to meV!



Alternative sensors: fundamental threshold of Cooper pair breaking energy 0.3 meV in Al

- TES vs KID: ~eV [26]
- Qubit: quantum tunneling [27]

Alternative target materials

- GaAs: scintillation + phonon

Conclusion

- **Low mass** dark matter searches 1 eV to 1 GeV require detectors with good energy resolution.
- **SuperCDMS** iZIP + HV detectors -> leading experiment in <5 GeV regime with many potential directions.
- Many **RD** ongoing to push to meV energy resolution / keV DM searches.

References

[1] Dark matter plot: https://www.esa.int/ESA_Multimedia/Images/2018/06/The_cosmic_budget_of_ordinary_matter
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[3] Planck 2015 results: https://arxiv.org/pdf/1502.01589.pdf
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[7] Snowmass particle like dark matter: https://browse.arxiv.org/pdf/2209.07426
[8] Ultraheavy DM searches: https://arxiv.org/pdf/2203.06508.pdf
[9] Migdal effects: https://arxiv.org/pdf/2307.12952.pdf
[10] Light DM searches: https://arxiv.org/pdf/2203.08297.pdf
[11] Halo modulation: https://arxiv.org/pdf/1209.3339.pdf
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[27] Qubit detectors: https://arxiv.org/pdf/2310.01345.pdf

Backup

SuperCDMS backgrounds

"Singles" Background Rates	Electron Recoil				Nuclear Recoil	($\times 10^{-6}$)
(counts/kg/keV/year)	Ge HV	Si HV	Ge iZIP	Si iZIP	Ge iZIP	Si iZIP
Coherent Neutrinos					2300.	1600.
Detector-Bulk Contamination	21.	290.	8.5	260.		
Material Activation	1.0	2.5	1.9	15.		
Non-Line-of-Sight Surfaces	0.00	0.03	0.01	0.07	–	–
Bulk Material Contamination	5.4	14.	12.	88.	440.	660.
Cavern Environment	–	–	–	–	510.	530.
Cosmogenic Neutrons					73.	77.
Total	27.	300.	22.	370.	3300.	2900.