Searching for Light Dark Matter with Narrow-Gap Semiconductors: The SPLENDOR Experiment

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on behalf of the SPLENDOR Collaboration

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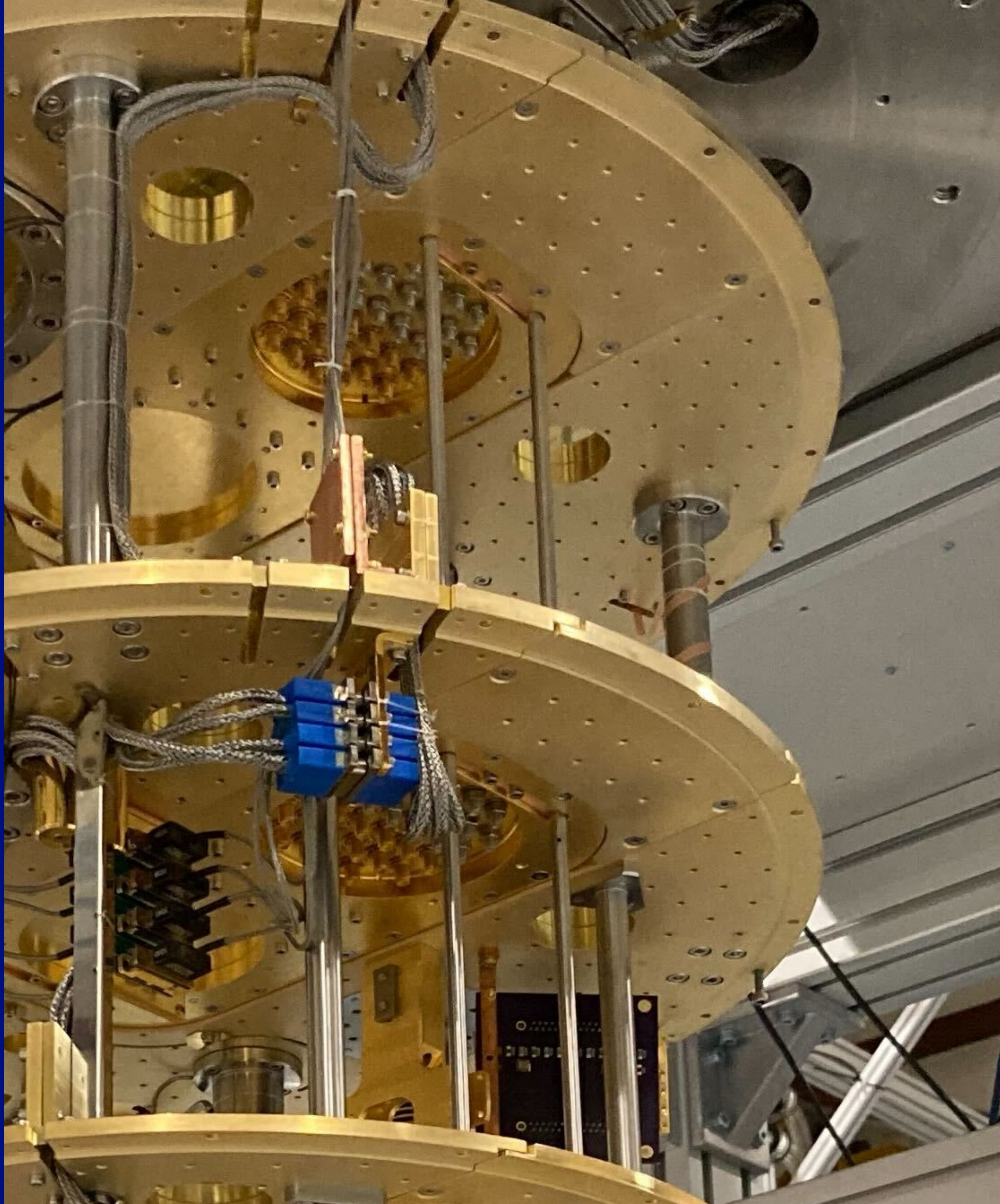
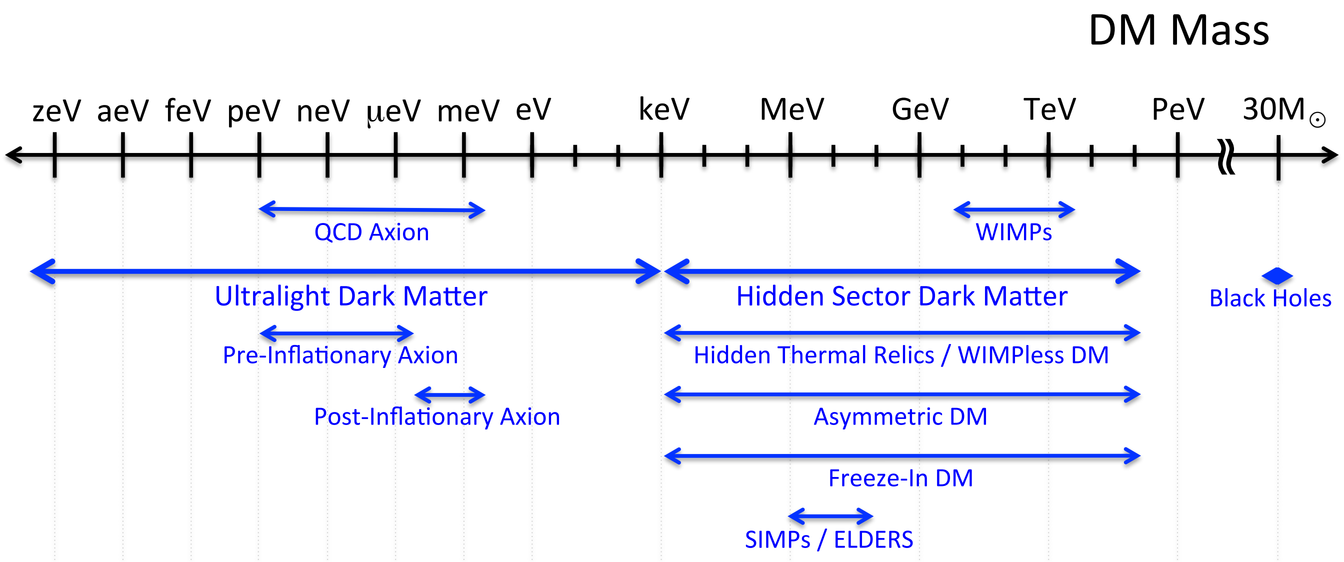
IDM 2024

LA-UR-24-26824



Light Dark Matter Candidates

- Plenty of DM candidates below the GeV scale (and the classic WIMP)
- Fermionic dark matter in the sub-MeV regime is largely unexplored
  - Inelastic recoil with an electron
- Bosonic dark matter in the sub-eV regime is largely unexplored
  - Absorption of the DM particle at energy equal to the DM mass

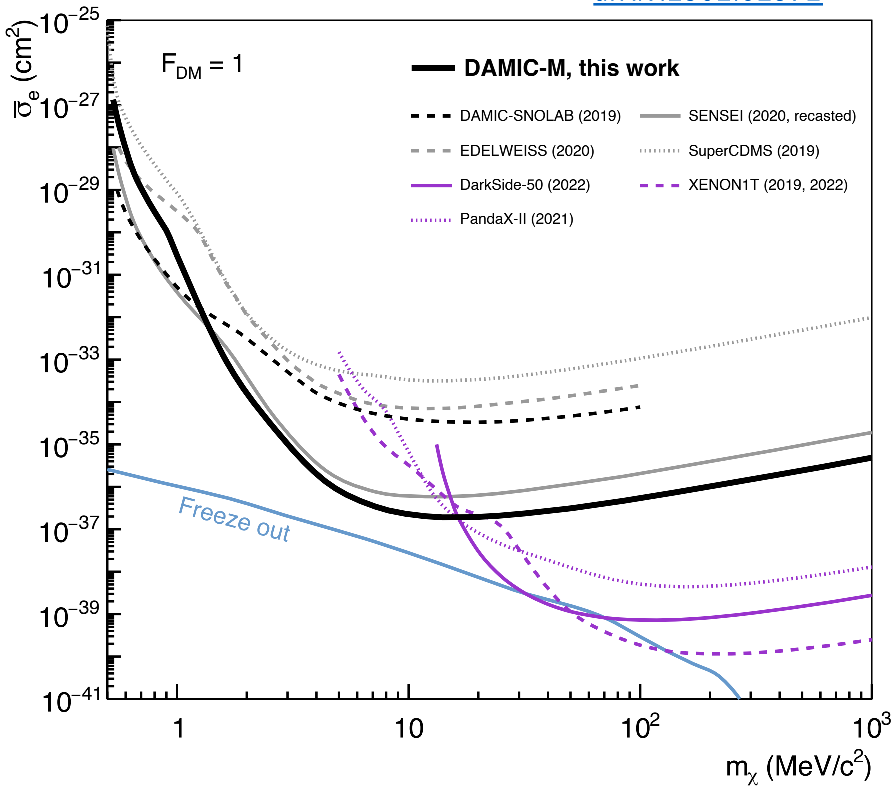


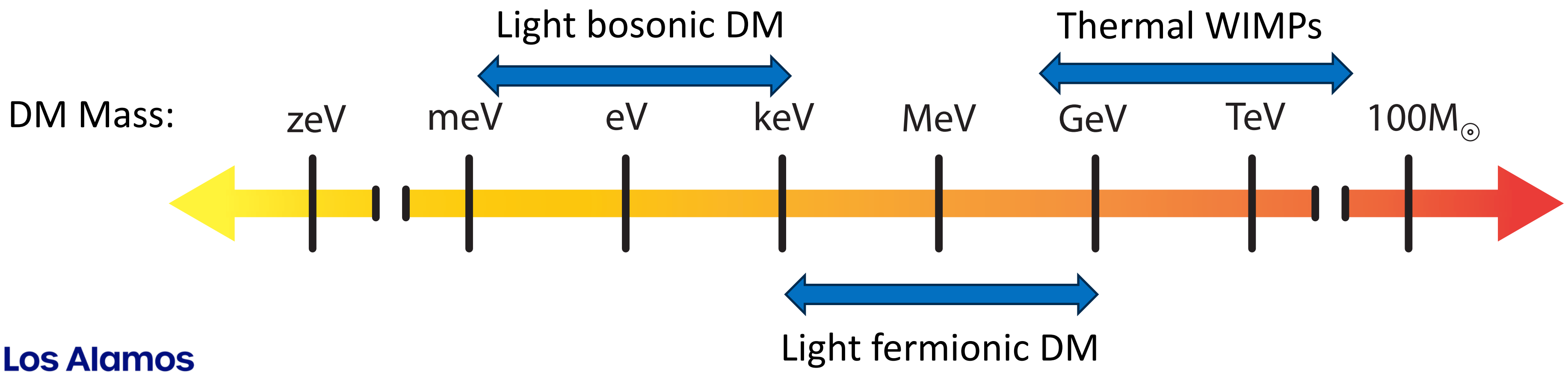
arXiv:1707.04591

DM-Electron Scattering

- Inelastic processes allows for probing of lower DM masses
- Many experiments are using semiconducting detectors for DM currently
  - Down to the MeV-scale for fermionic DM
  - Down to the eV-scale for bosonic DM

arXiv:2302.02372

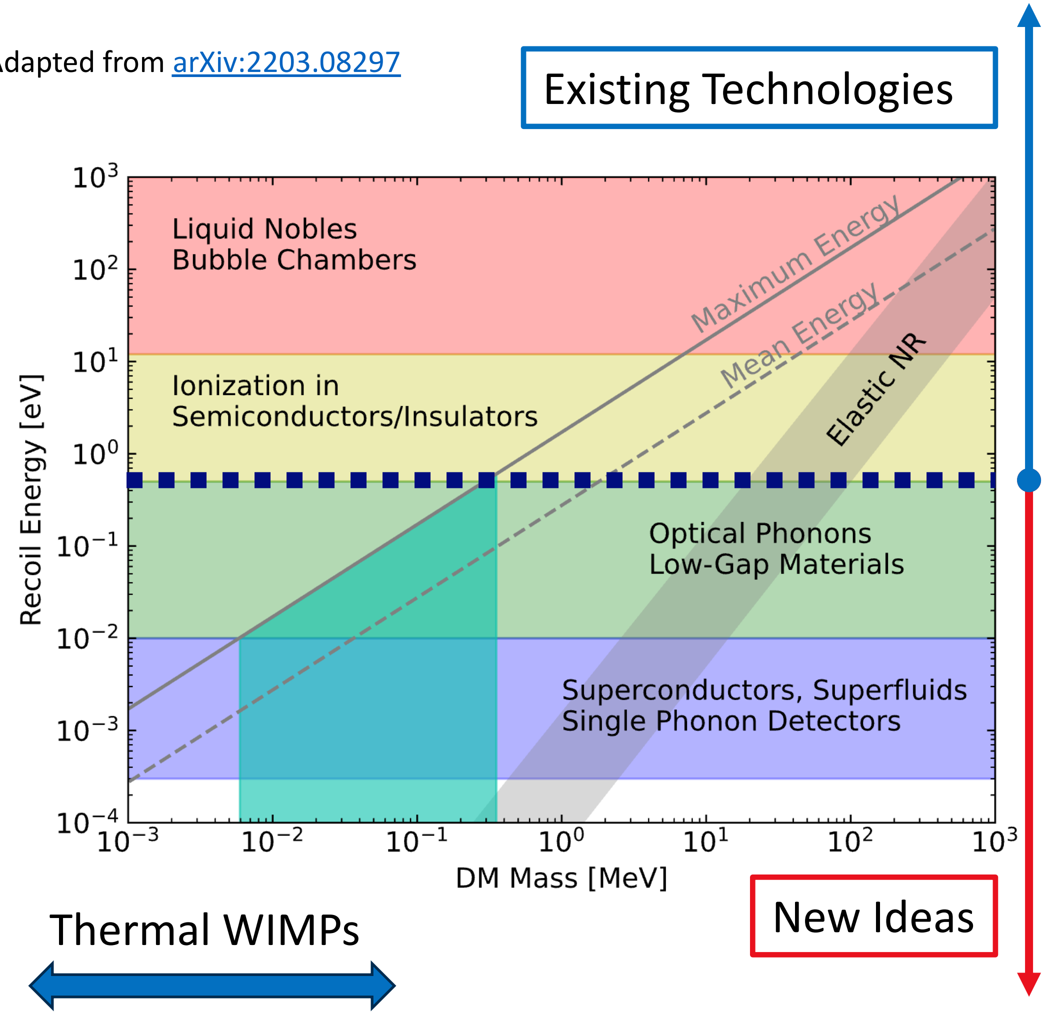


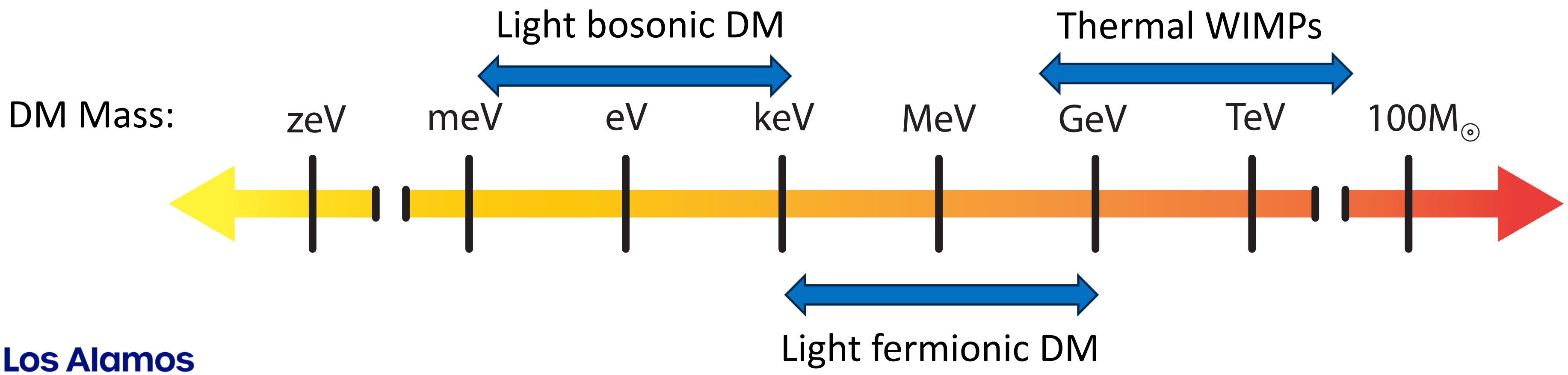


Light Dark Matter Kinematics

- Low kinetic energy of DM requires targets sensitive to very small energy depositions
- Existing detection technologies have O(eV) thresholds
- Probing fermionic DM with masses below O(MeV) requires new detection techniques

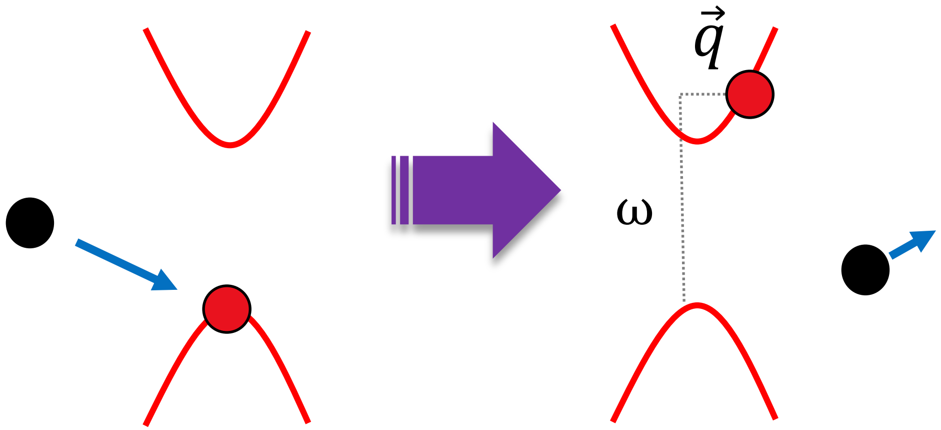
Adapted from arXiv:2203.08297

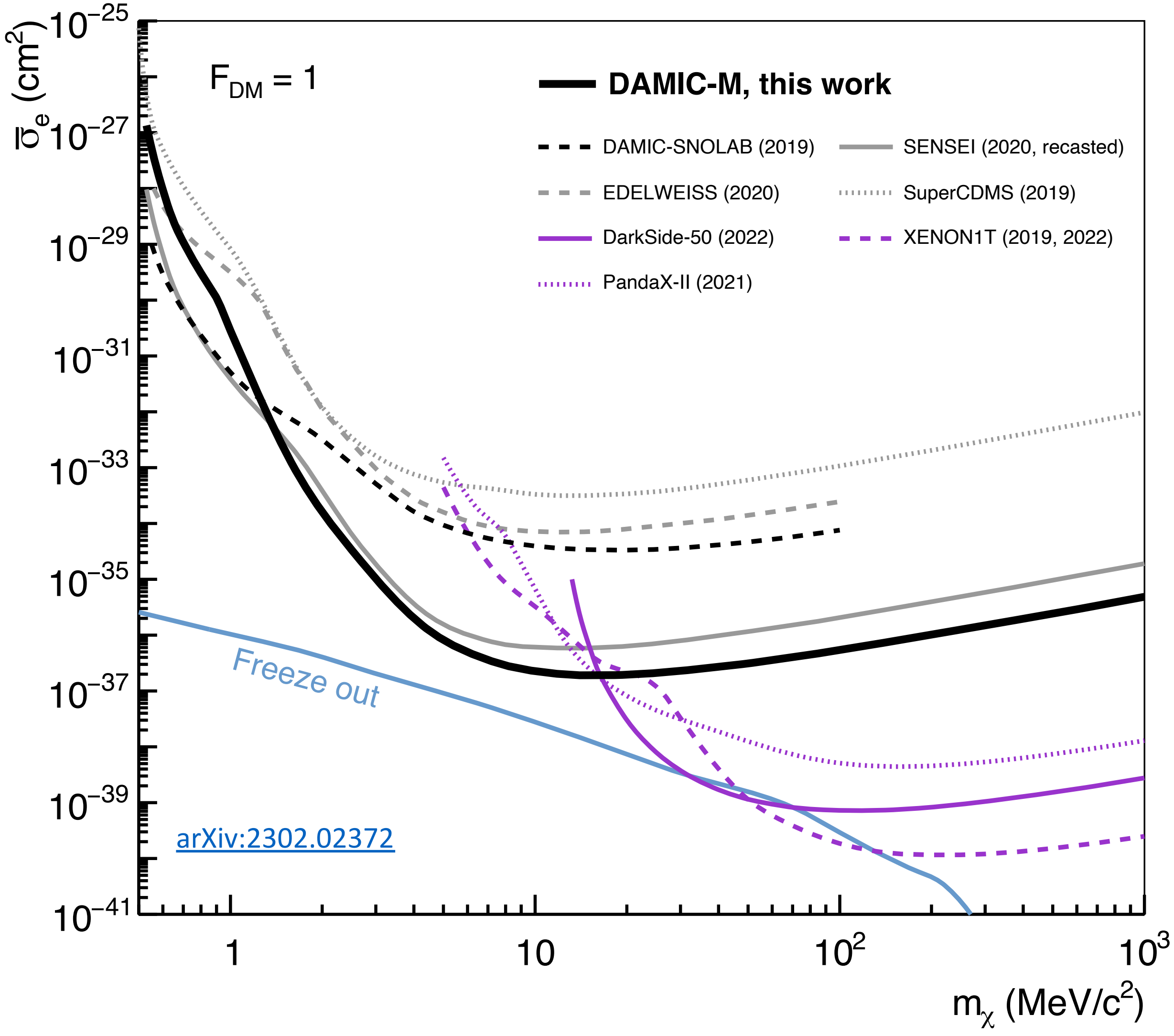




Ionization Detection with Intrinsic Semiconductors

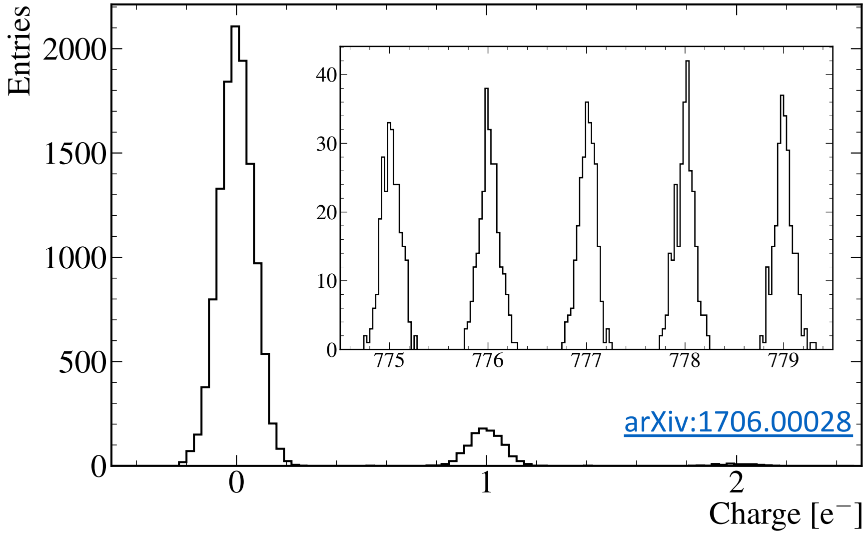
- Various existing technologies being used:
  - Charge-Coupled Devices (CCDs)
  - High-Purity Germanium (HPGe) detectors
  - Phonon detectors based on Neganov-Trofimov-Luke (NTL) gain
- All sensitive to electron recoils to varying degrees



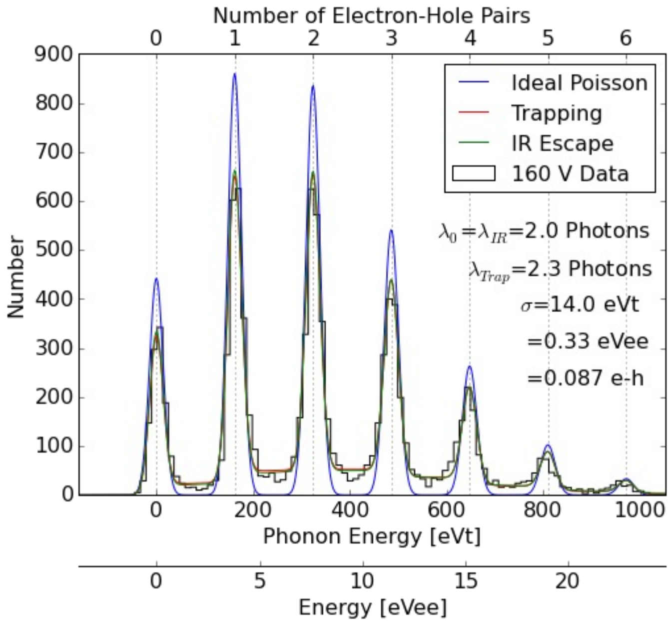


Dark Rates

- Need to reduce the backgrounds
- Sources include:
  - Cosmogenic activation
  - Isotopic contamination of electronics
  - External backgrounds
- Need:
  - High purity materials
  - Excellent shielding



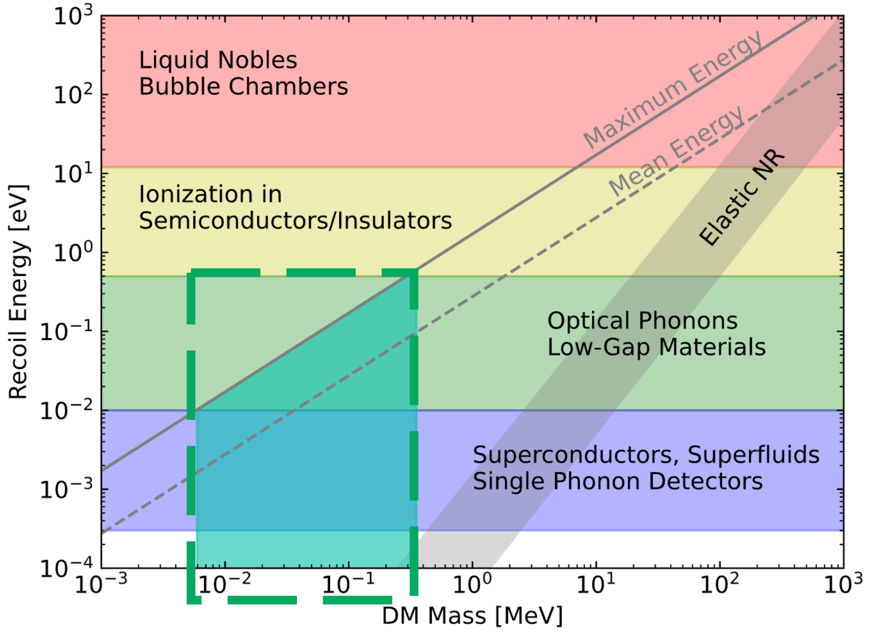
arXiv:1706.00028

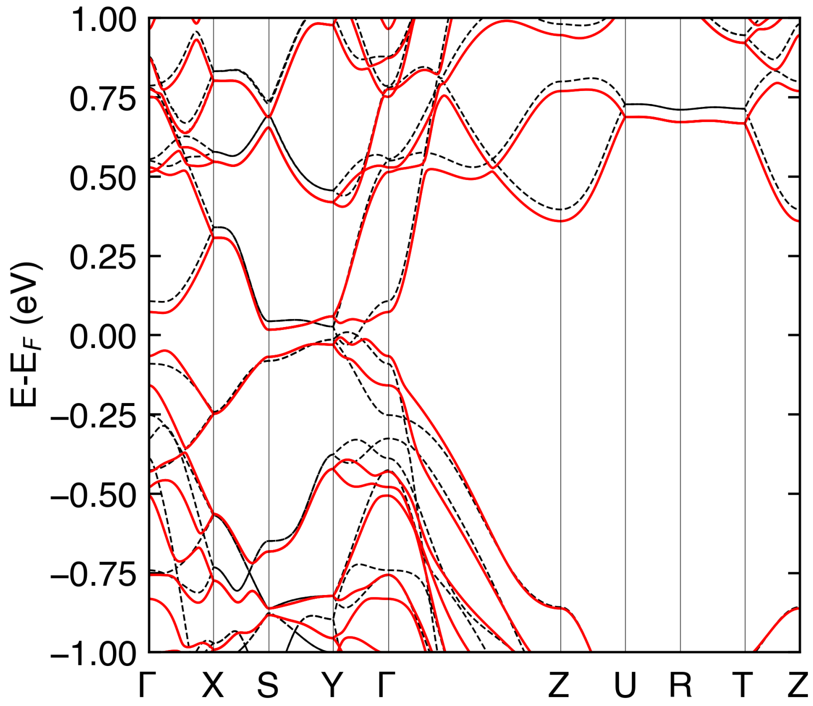


arXiv:1710.09335

Narrow-Gap Semiconductors in SPLENDOR

- Search for Particles of Light Dark Matter with Narrow-Gap Semiconductors
  - One R&D path to sensitivity to lower DM masses
- Candidate materials with O(1-100 meV) gaps developed at LANL:
  - $Eu_5In_2Sb_6$, $La_3Cd_2As_6$, EuP_2Zn_2

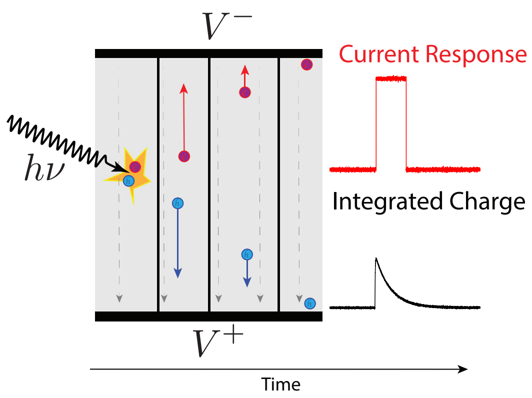




Calculated band structure of $Eu_5In_2Sb_6$

Charge Collection in SPLENDOR

- Dark current should scale with voltage bias
- The full collection regime is conservative approach
  - Optimizes charge collection
  - Minimizes dark current



Intermediate E-Field

- Field strong enough to separate excitons
- Drift charges full length of detector

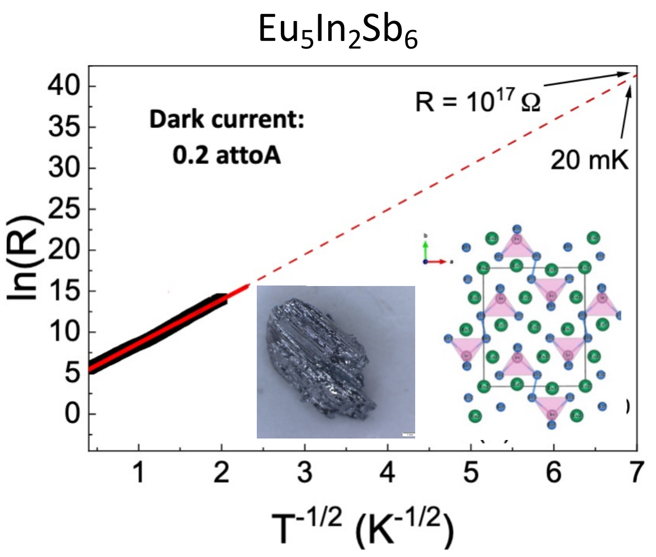
Full Collection

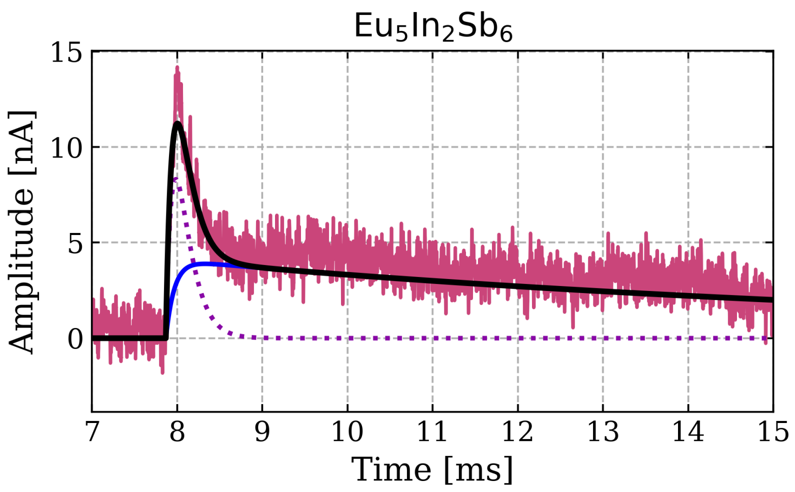
- Avalanche mode could create a large increase in dark current
- Sacrifices ability to reconstruct event energies

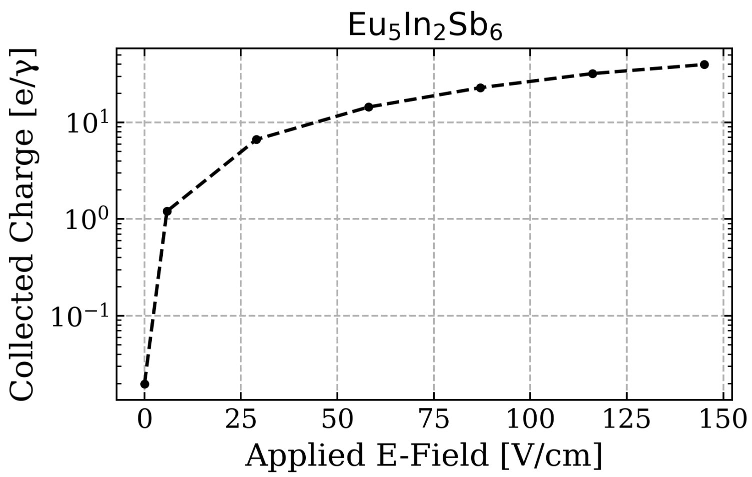
Materials Response

$$\rho(T) = A\exp[(T_0/T)^\beta]$$

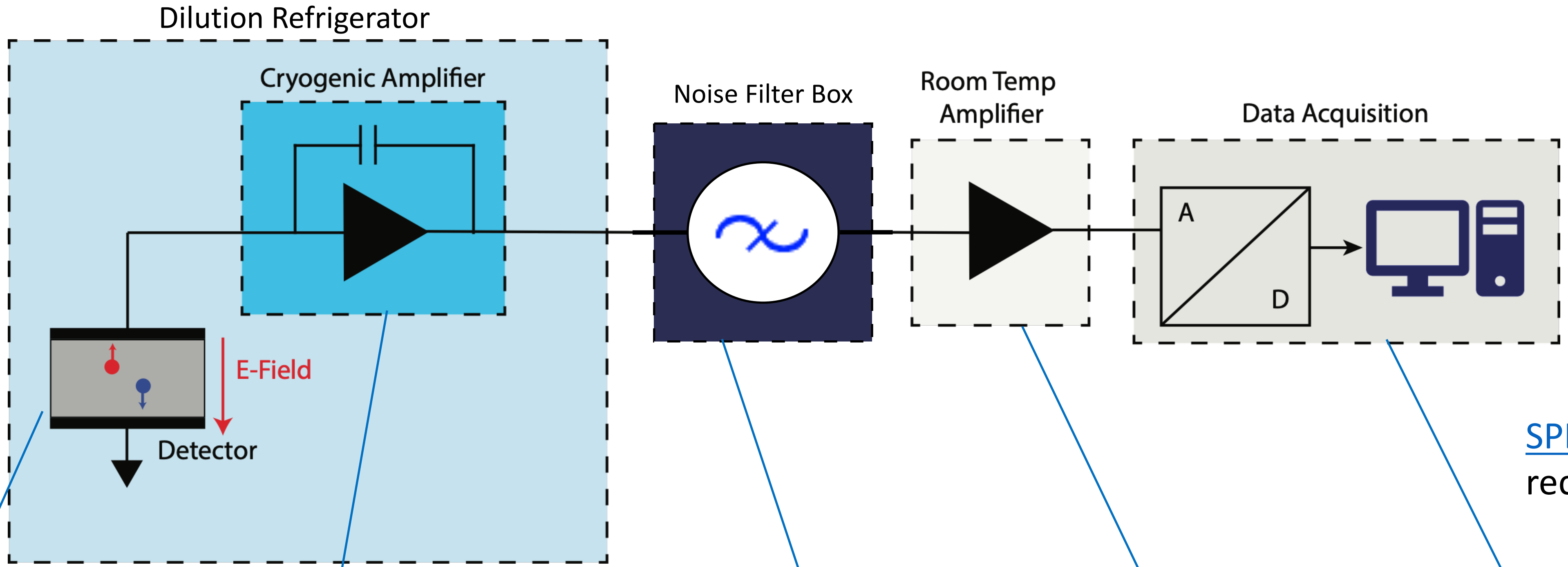
- Initial resistivity measurements indicate activated behavior with band gaps of O(1-100 meV)
  - Indicates sub attoAmps dark rates at mK temperatures
- Materials have photoresponse to IR light
- Beginning to show signs of full charge collection
  - Ongoing studies at lower temperatures





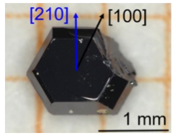


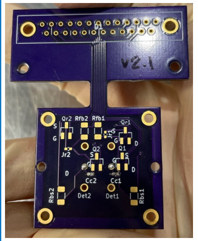
SPLENDOR's detection scheme utilizes a mix of in-house and commercial technologies



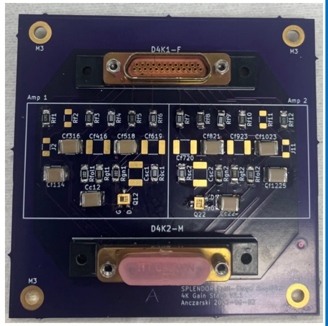
[SPLENDAQ](#) for event reconstruction

$EuZn_2P_2$ $Eu_5In_2Sb_6$





10mK



4K

SPLENDOR

SPLENDOR

SR 560

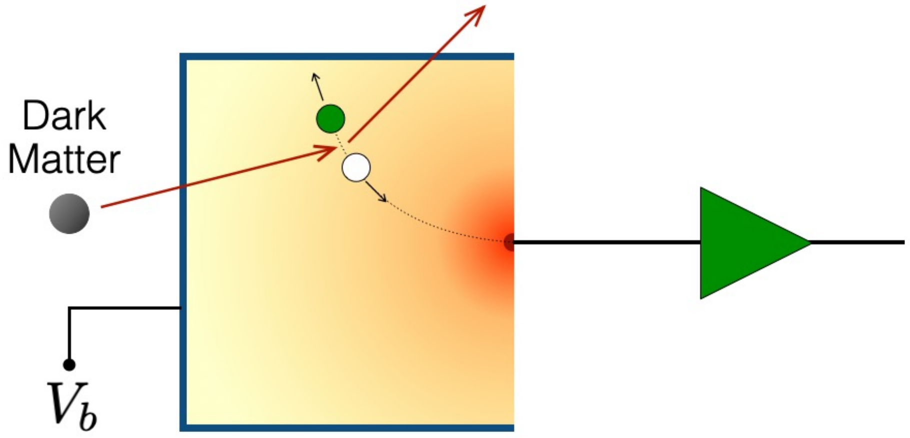
Credit: SRS

Moku:Pro

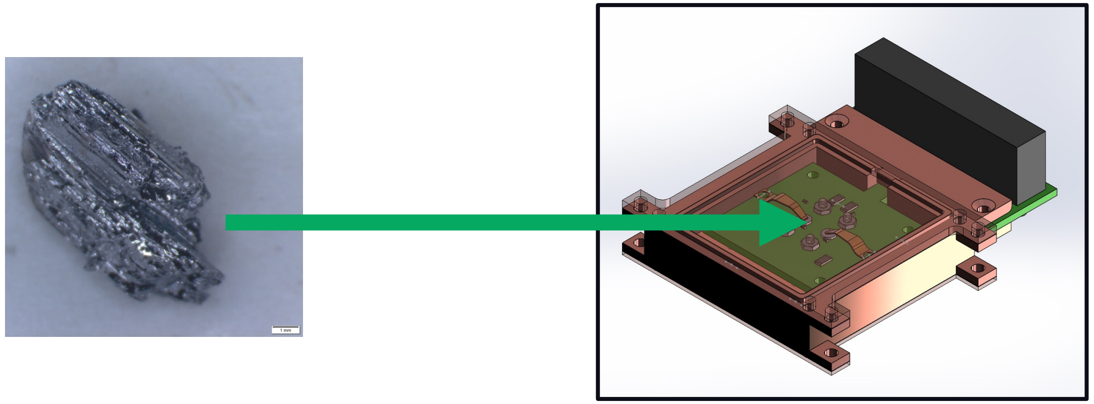
Credit: Liquid Instruments

Detector Style

- Start with well-known point contact design
  - i.e. similar to HPGe detectors



- Detector housing
  - Minimize capacitance by placing detector material as close to 10 mK board as possible
  - Can easily switch between substrates

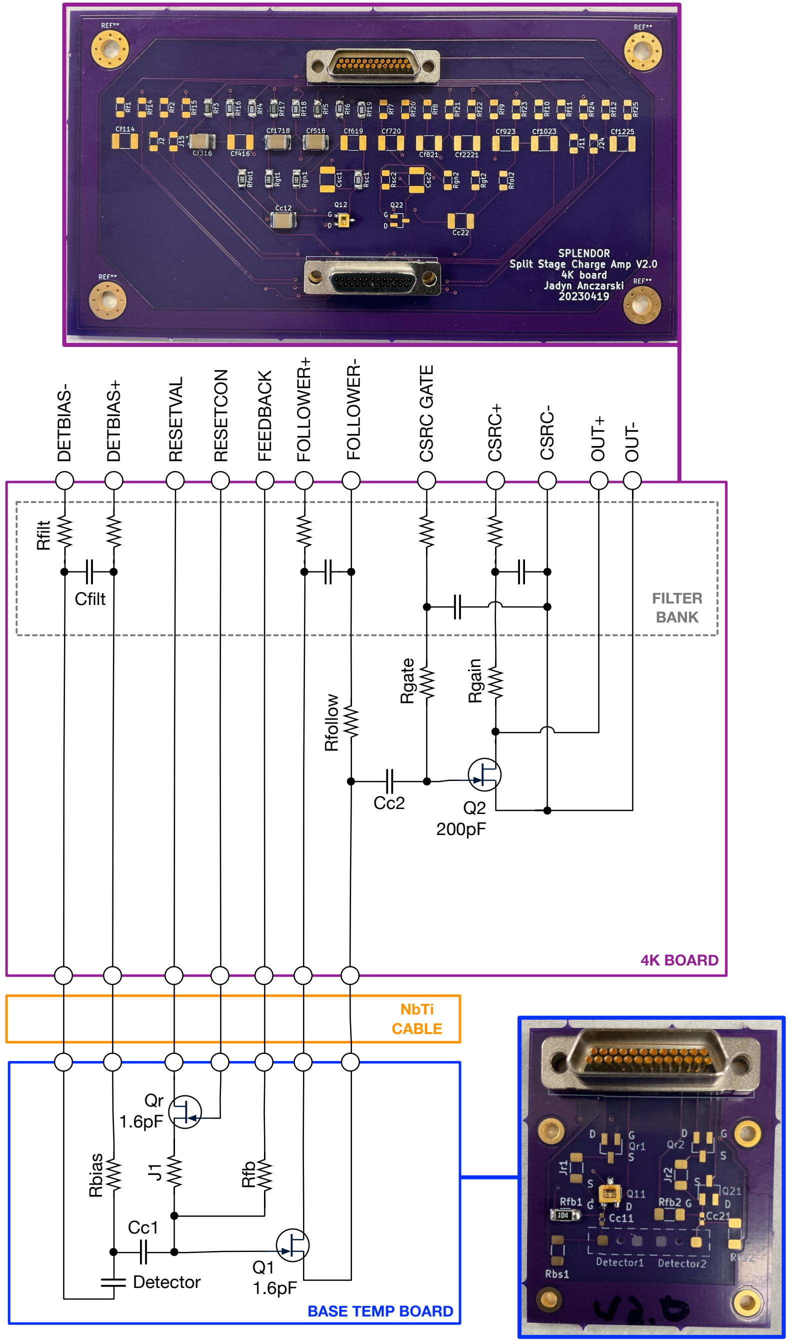


$$\sigma_E \sim E_{gap} \times \underbrace{\sigma_V \times (C_{detector} + C_{input} + C_{parasitic})}_{\text{charge resolution (goal: } \sigma_{e^-} \sim O(1)\, e^-\text{)}}$$

Cryogenic Charge Amplifier

- Use fully cryogenic amplifier technology
  - Low thermal noise
- Use High Electron Mobility Transistors
  - Essentially a JFET that works at cryogenic temperatures
- Split-stage cryogenic HEMT-based amplifier
  - 4 K gain stage with 200 pF HEMT
  - 10 mK buffer stage with 1.6 pF HEMT (buffers the upstream capacitance)

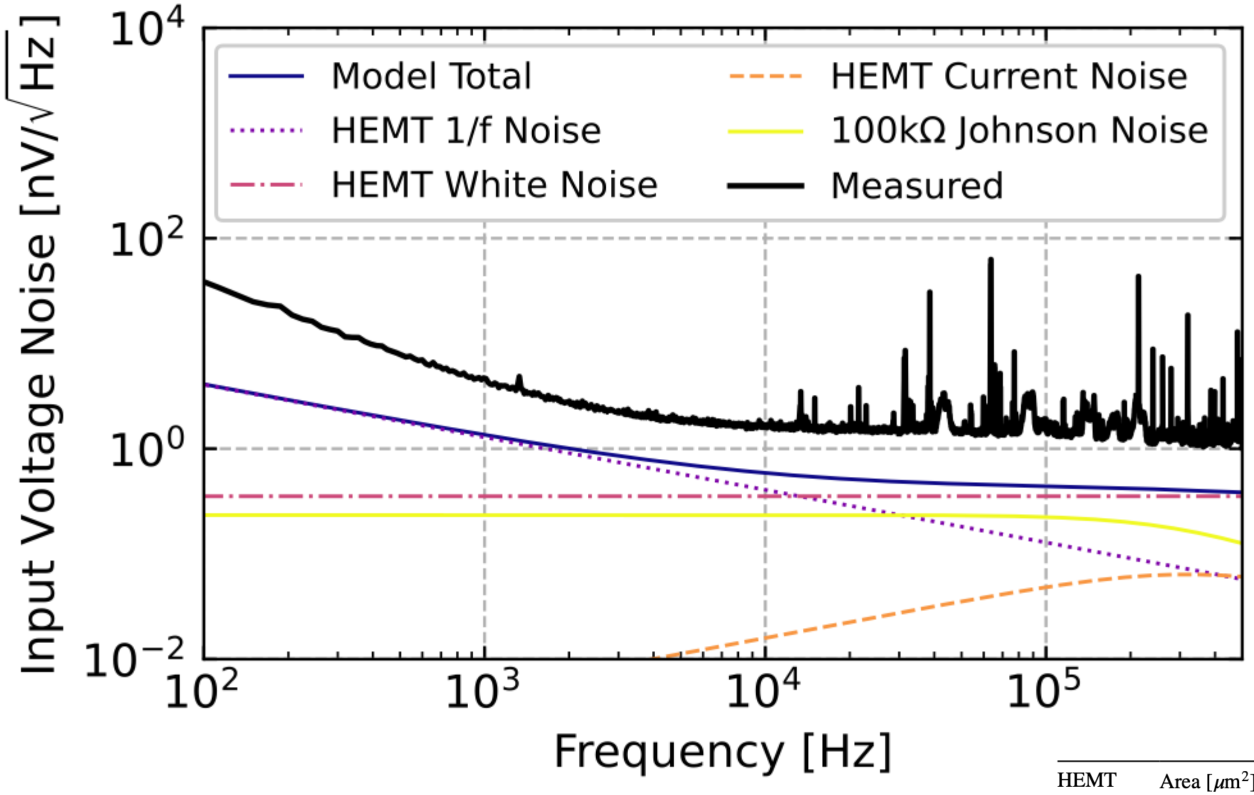
$$\sigma_E \sim E_{gap} \times \underbrace{\sigma_V \times (C_{detector} + C_{input} + C_{parasitic})}_{\text{charge resolution (goal: } \sigma_{e^-} \sim O(1)\, e^-\text{)}}$$



Los Alamos NATIONAL LABORATORY

Charge Amplifier Preliminary Performance

- Two-stage amp prototype has achieved a $5e^-$ charge resolution!

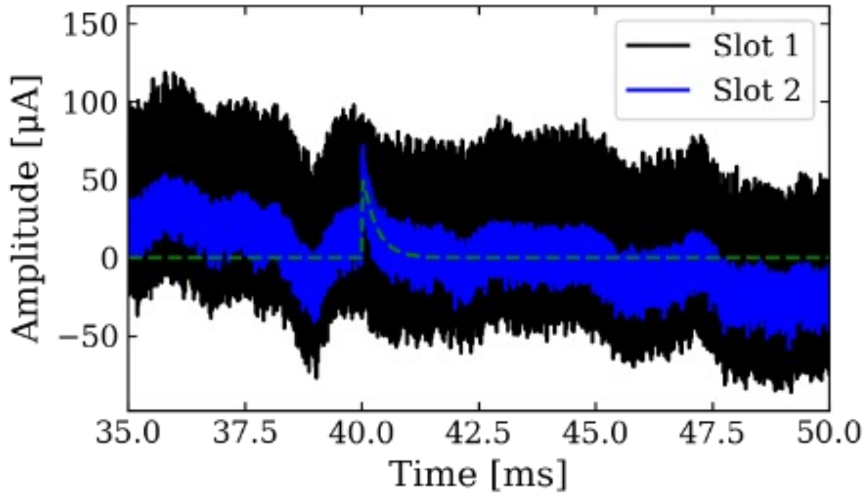


Anczarski *et al*, 2024 doi.org/10.1007/s10909-023-03046-1

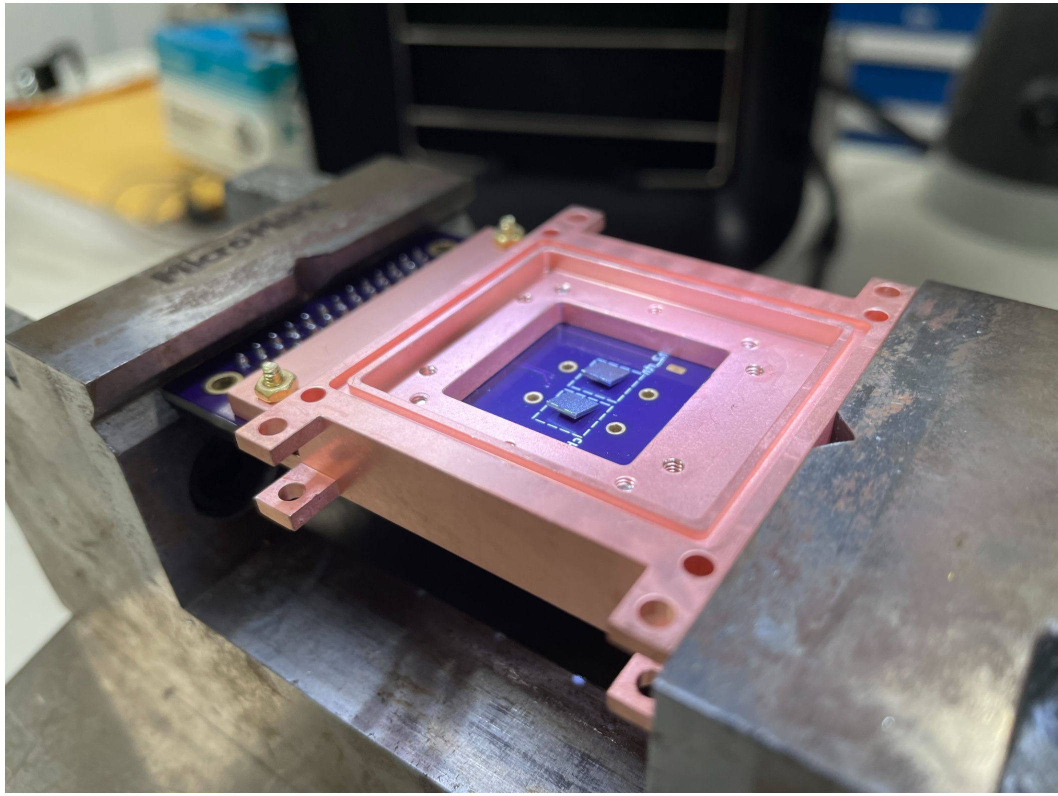
HEMT	Area [μm^2]	C_{gs} [pF]	C_{gd} [pF]	T [K]	V_{ds} [mV]	I_{ds} [μA]	Power [μW]
Q1	5.0×10^2	1.6	0.8	0.01	25	50	1.3
Q2	1.5×10^5	236	8.9	4	89	940	83.7

Running with Silicon

- Signals are apparent with a Si test substrate

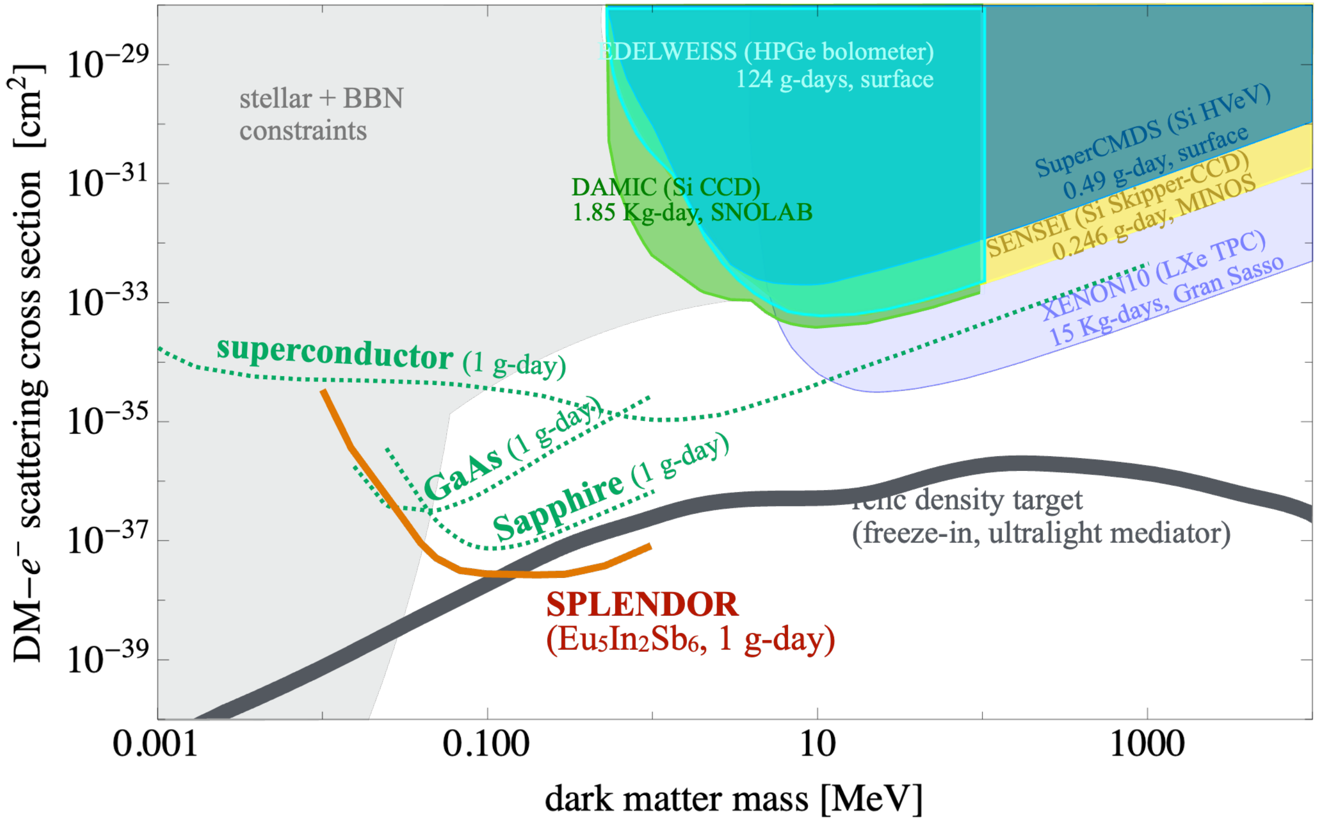


- Now running with $Eu_5In_2Sb_6$
  - Stay tuned!



DM Sensitivity

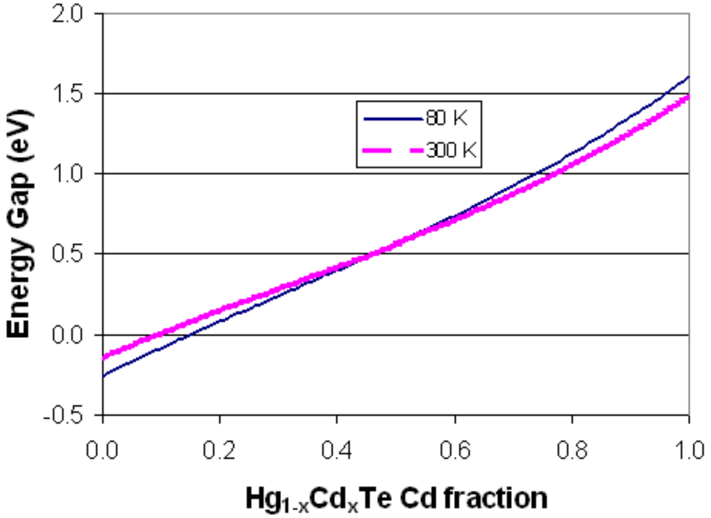
- Narrow bandgap materials can significantly expand our low-mass DM reach
  - Using tried-and-true detection techniques
- Near-term goals of SPLENDOR:
  - Continued optimization of HEMT operating conditions
  - Hunting noise sources
  - Surface DM search dataset expected later this year with prototype detector



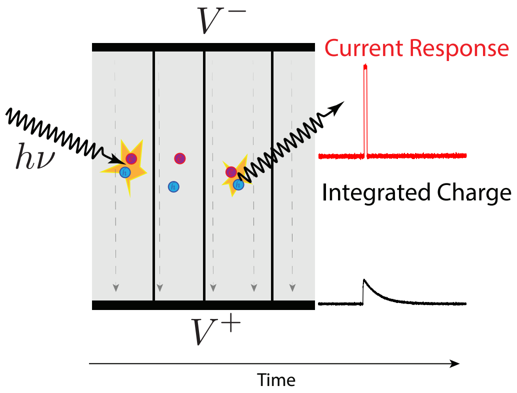
Backup

Some Known Detector Materials with Narrower Gaps

- InSb
  - Band gap of 170 meV
- $Hg_{1-x}Cd_xTe$
  - Tunable to have a gap between 0 and 1.5 eV based on doping
- Highly doped Si
  - Tunable to have a gap between 0 and 1.1 eV
- Problem:
  - Each have high dark rates and lower mean free paths
  - **Need new, scalable materials with narrow band gaps *and* low dark rates**



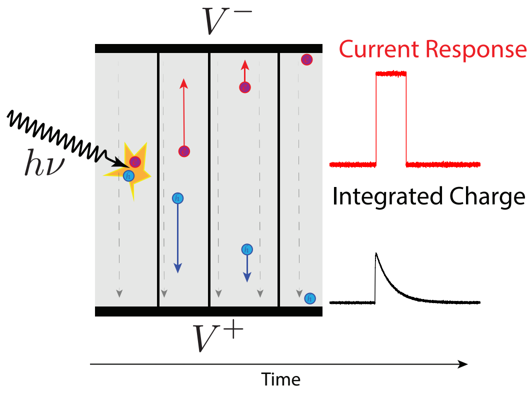
Charge Collection In Ionization Detectors



Low E-Field

- Field too low to separate electron-hole pair excitons
- Small to no signal response

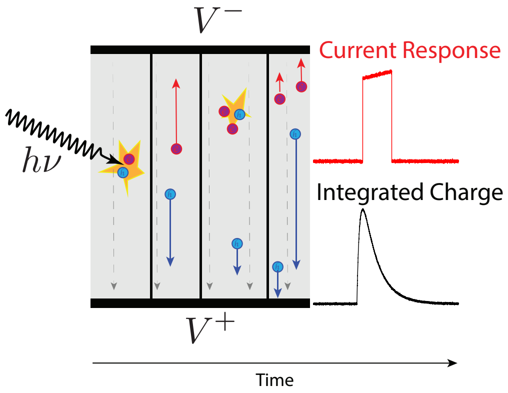
Incomplete Collection



Intermediate E-Field

- Field strong enough to separate excitons
- Drift charges full length of detector

Full Collection



High E-Field

- Drifted charges have enough kinetic energy to create new excitons – "impact ionization"
- Can create chain reaction of charges

Avalanche mode