Institute of High Energy Physics
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SuperEM: a Sub-meV Threshold Cryogenic Detector for Neutrino and Dark Matter Searches

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IHEP

EPD Seminar 2026.09.03

本人研究背景介绍

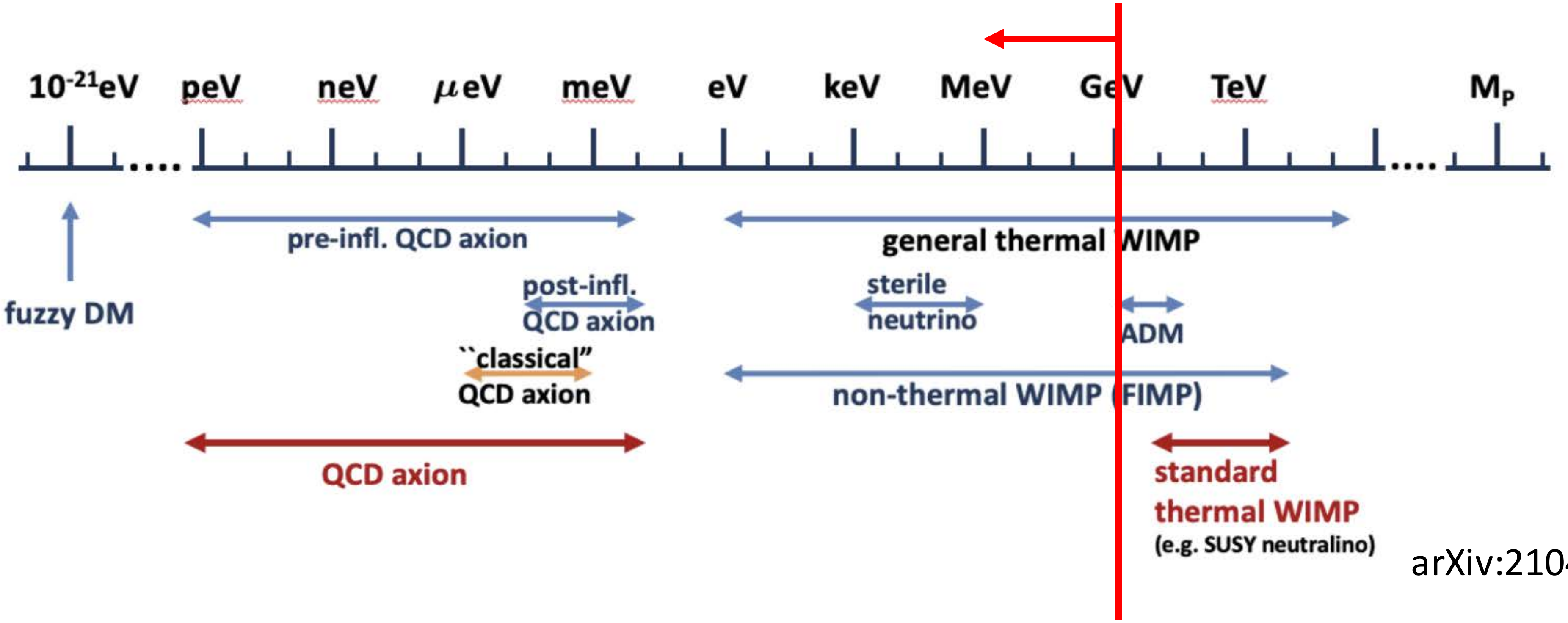
- **HERD，5面灵敏3D成像量能器方案共同提出人和原型完成人，2029.03发射** Talk by X.L. Sun at CALOR 2010; Paper by X.L. Sun et al. 2011 J. Phys.: Conf. Ser. 293 012038; PhD thesis of X.L. Sun 2011.
- **Dark Matter, 暗物质探测双发光晶体方案提出人和原型完成人** Talk by X.L. Sun at IHEP-INFN Meeting 2014; Paper by X. Zhang, X.L. Sun, J.G, Lu et al. RDTM 2, 15 (2018).
- **GECAM, SiPM+LaBr$_3$ 空间伽马射线探测器方案提出人和原型完成人，2020.12发射，在轨运行** Talk by X.L. Sun at PISA Meeting 2018; Paper by P. Lv, S.L. Xiong, X.L. Sun et al. 2018 JINST 13 P08014.
- **CEvNS, 低温CsI+SiPM+TPB探测器方案提出人和原型完成人** Talk by X.L Sun at CEvNS 2024; Paper by L. Wang, G.D. Li, X.L. Sun et al. Eur. Phys. J. C 84, 440 (2024).
- **JUNO, 2万吨超纯液闪混制任务负责人，2025.08完成，运行取数** Poster by X.L. Sun at Neutrino 2024; Paper by J.Y. Shao, W.J. Li, X.L. Sun et al. RDTM (2026), doi.org/10.1007/s41605-026-00708-y.
- **Gamma/Neutron，重点研发课题超高能量分辨率及多模辐射探测器研制负责人，2025.10完成，** 中国辐射防护学会科学技术奖-特等奖， 吴云涛，孙希磊等2024-FM-T-02-R7；国家标准，孙希磊等 GB/T 46609-2025.
- **SuperEM, sub-meV超低阈值超导体耦合半导体探测器方案提出人** Talk by X.L. Sun at NDIP 2026, CHEP2026; Paper by A.Q. Gao, X.L. Sun et al. arXiv:2509.11954.

Outline

- Motivation
- The SuperEM Proposal
- Principle Calculation and Simulation
- Characterization of SiPM at 10 mK
- Physics Impact (DM, CvB, CEvNS)
- Other Potential Applications
- Summary

Dark Matter Searches

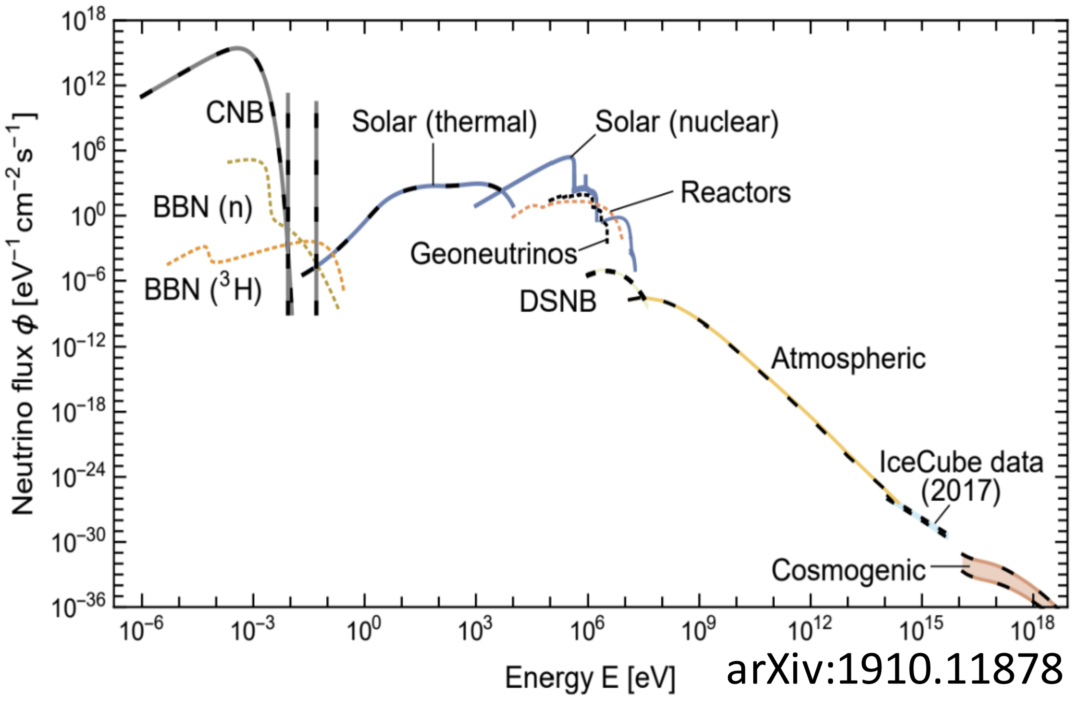
- **The Sub-GeV Frontier:** Exploring Light Dark Matter (LDM) requires strictly sub-meV energy thresholds.
- **The Scalability Challenge:** Future observatories demand massively multiplexed detector arrays with large target masses.



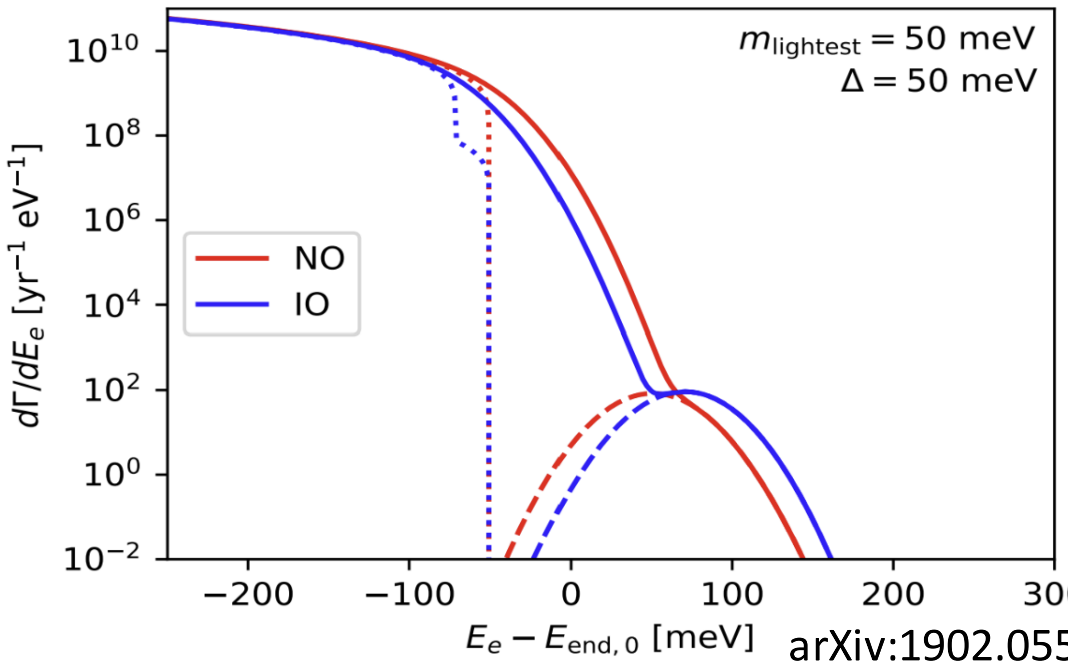
arXiv:2104.07634

Cosmic Neutrino Background Searches

- **Absolute Energy Resolution:** ≤50 meV FWHM is required to resolve CvB and neutrino mass orderings.
- **The Pile-Up Issue:** Requires nanosecond-scale readout to survive the massive tritium beta-decay flux without signal overlap.



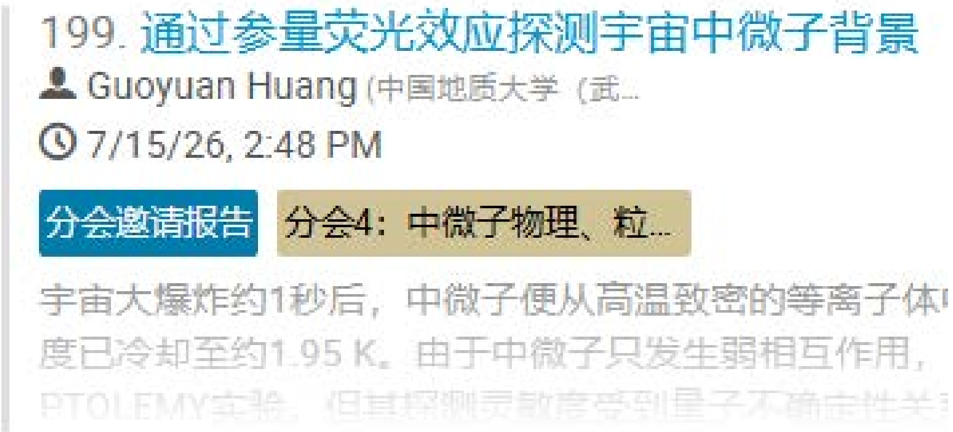
arXiv:1910.11878

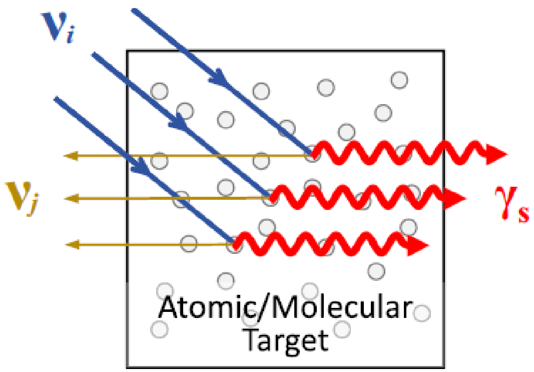


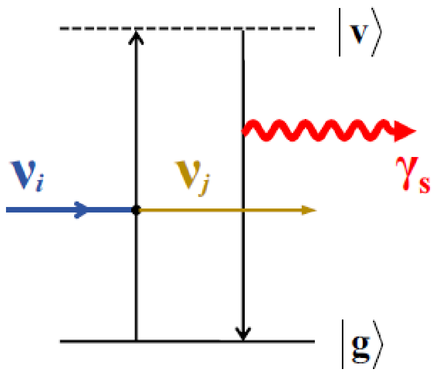
arXiv:1902.05508

Cosmic Neutrino Background Searches

- **Parametric Fluorescence proposal:** 10 meV sensitivity is required to resolve CvB.







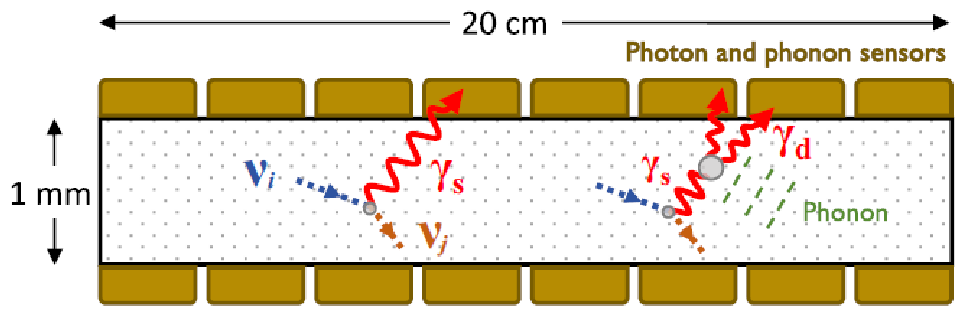
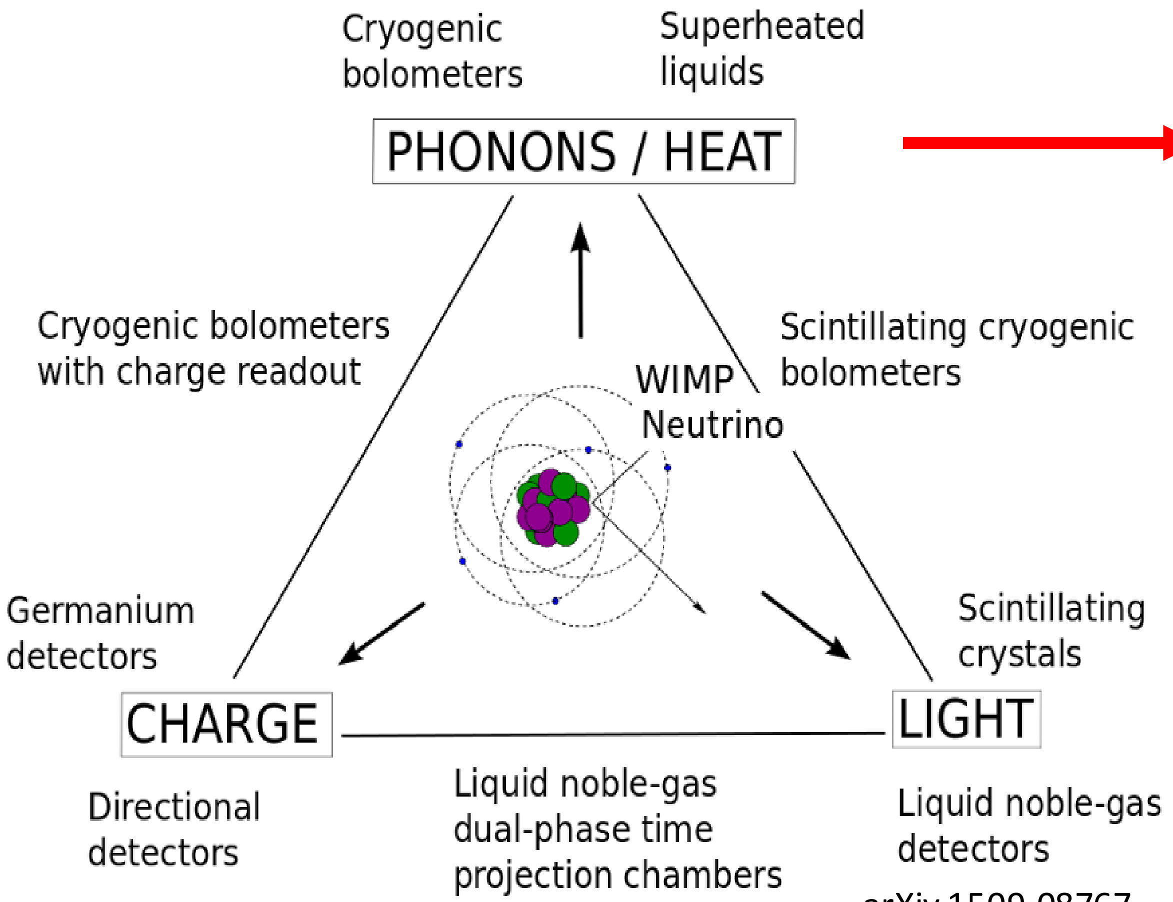


FIG. 3. A schematic plot of the experimental setup for detecting parameter fluorescence. The target is a solid film with dimensions 20 cm × 20 cm × 1 mm. Its surface is covered with superconducting photon and phonon sensors featuring $\mathcal{O}(10\ \mathrm{meV})$ sensitivities. Two types of signals can arise, depending on whether the initial photon is absorbed by the medium before reaching the sensors. Similar geometry may be found in experiments searching for light dark matters [71,72].

Phys. Rev. Lett. **136**, 081003 (2026)

How to Reach meV Threshold?

- **Atomic energy gap, eV level threshold, Charge and Light**
- **Cooper pair energy gap, sub-meV, Phonon**



arXiv.1509.08767

- Superconducting Tunnel Junctions (STJs)
- Kinetic Inductance Detectors (KIDs / MKIDs)
- Transition Edge Sensors (TES)
- Nanowire Single-Photon Detectors (SNSPDs)
- Qubit-Based Sensors (QPD/QCD)

Table 1: The performance landscape of current mainstream detection architectures.

Detector Architecture	**Representative Project**	**Energy Threshold**	**Reading Complexity & Scalability**	**Temporal Response**
High-Purity Germanium (HPGe)	CONUS [14]	~100 eV	Moderate	Nanoseconds
Skipper-CCD	SENSEI [15], Oscura [16], [17]	~1 eV	High (Precision multi-sampling)	Milliseconds to Hours
Transition Edge Sensor (TES)	PTOLEMY [3], Al-iCPT [12]	~100 meV	Extremely High (SQUID multiplexing)	Microseconds to Milliseconds
Kinetic Inductance Detector (KID)	CCAT-prime [18]	~1 eV	Moderate (Frequency multiplexing)	Microseconds
Superconducting Nanowire (SNSPD)	QROCODILE [19]	~100 meV	Low	Picoseconds
Superconducting Tunnel Junction (STJ)	^{7}Be Nuclear Recoil [13]	~10 eV	Moderate to High	Nanoseconds

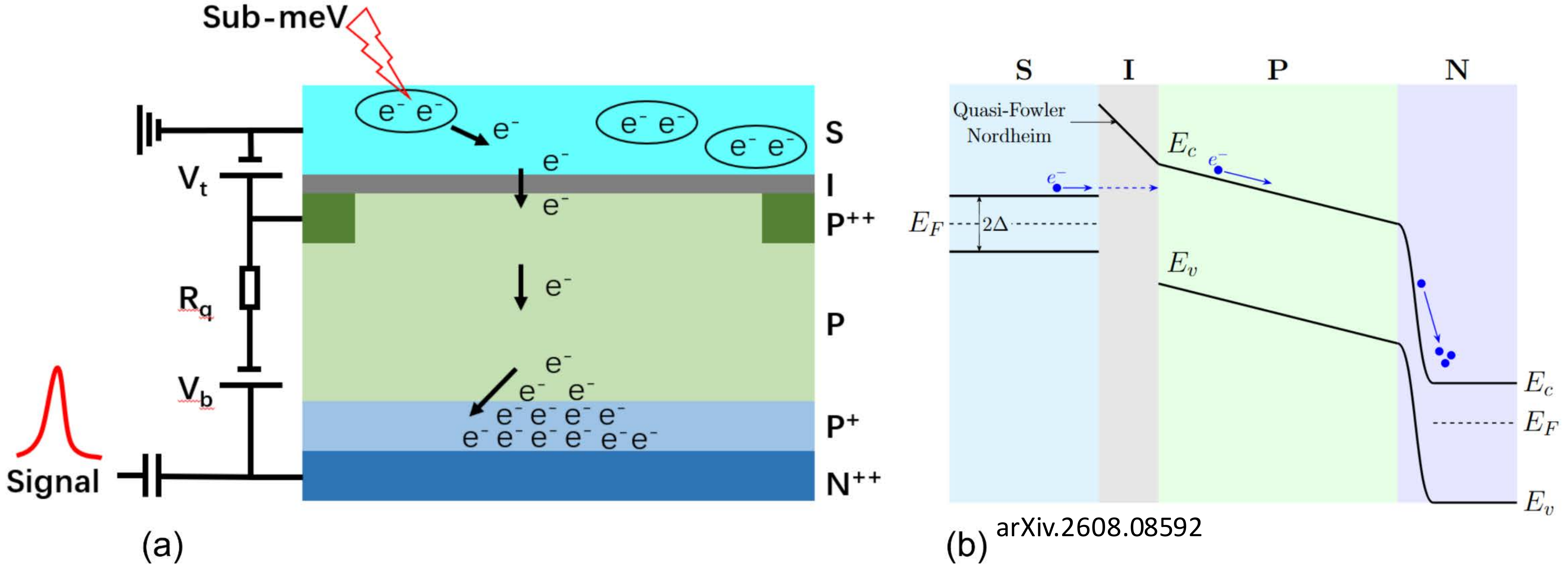
arXiv.2608.08592

impossible triangle

Sub-meV, ns, and scalability

SuperEM Proposal

- **Superconductor-Coupled Semiconductor Electron-Multiplying Detector**



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Architectural Framework (S-I-P-N):

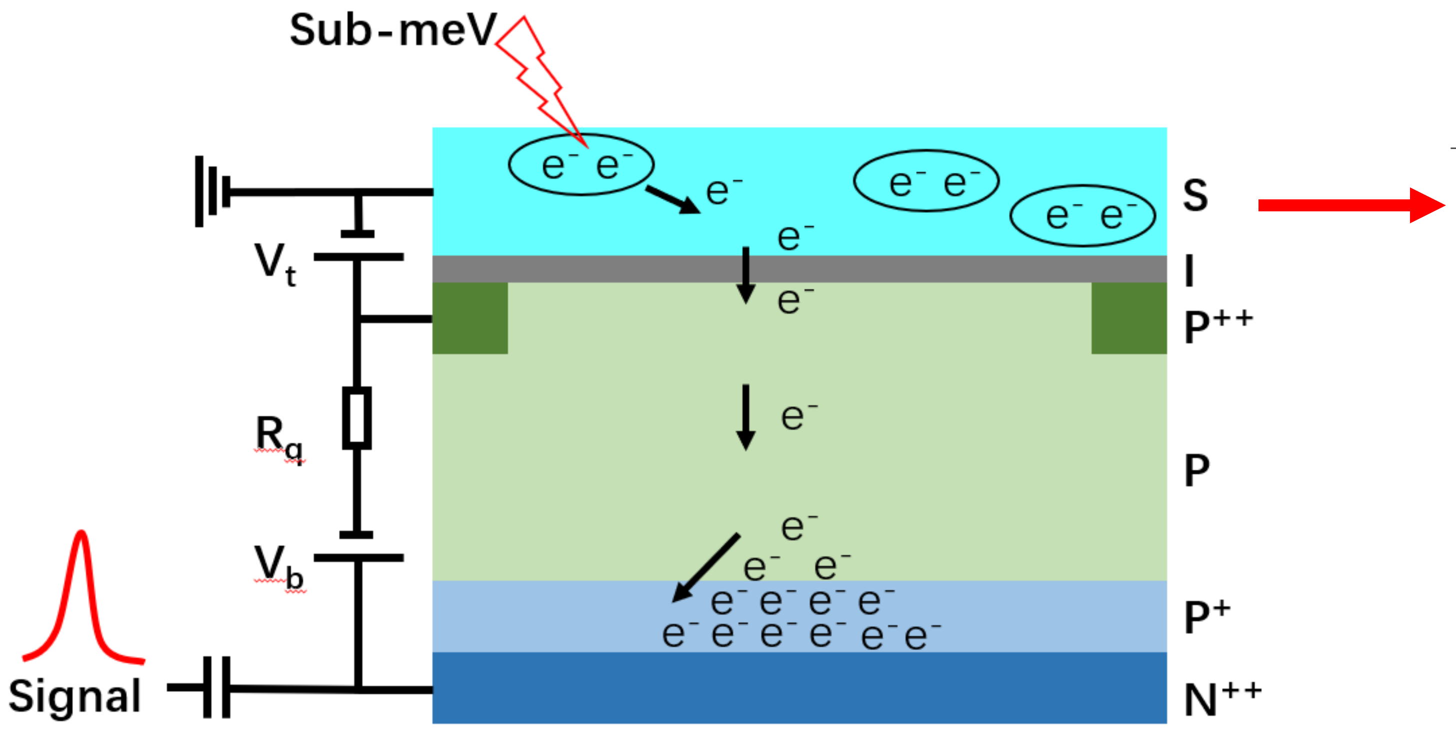
- Superconducting Absorber (S-Layer)
- Quantum Tunneling Barrier (I-Layer)
- Charge Multiplication Region (P-N Junction)

Key Features:

- Sub-meV threshold and high gain
- Nanosecond level Response, non-thermal equilibrium
- Good Scalability, Compatible with semiconductor processes
- Tunable Quantum Gating via I-Layer bias V

SuperEM Superconductor Materials

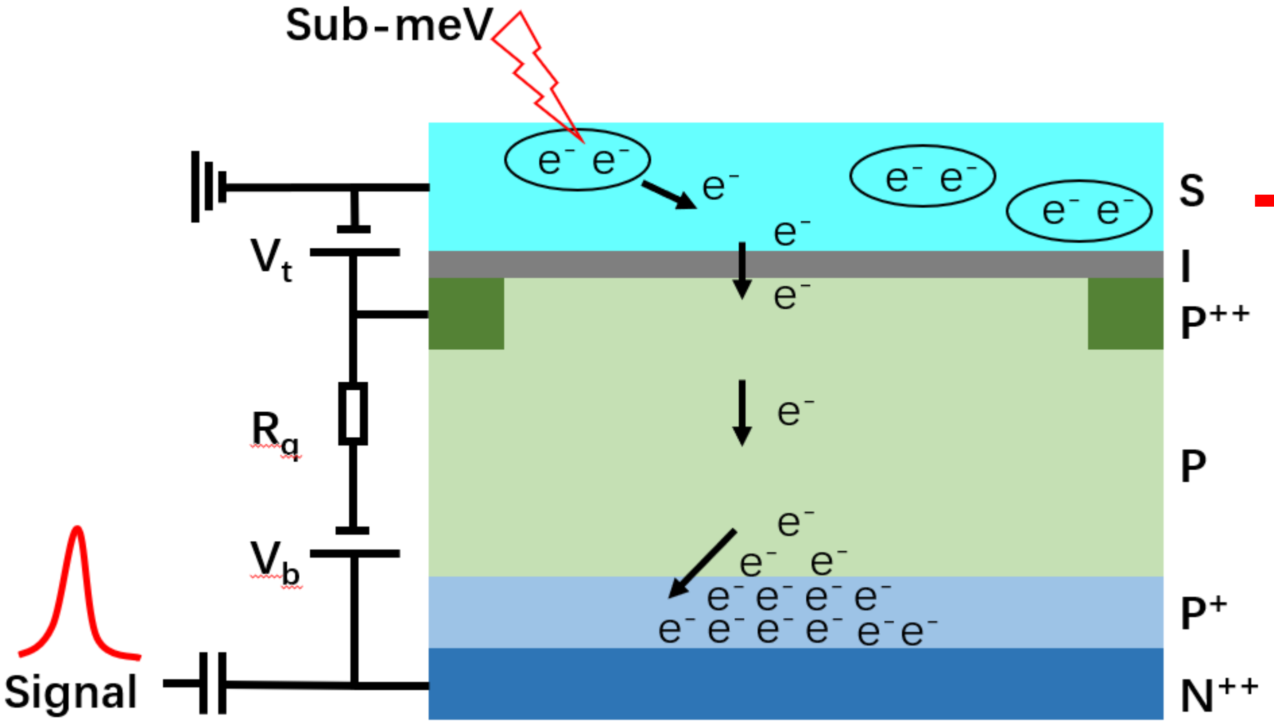
- **Superconductor Materials offers a variety of options with energy gaps ranging from 0.005 meV to 5.8 meV.**

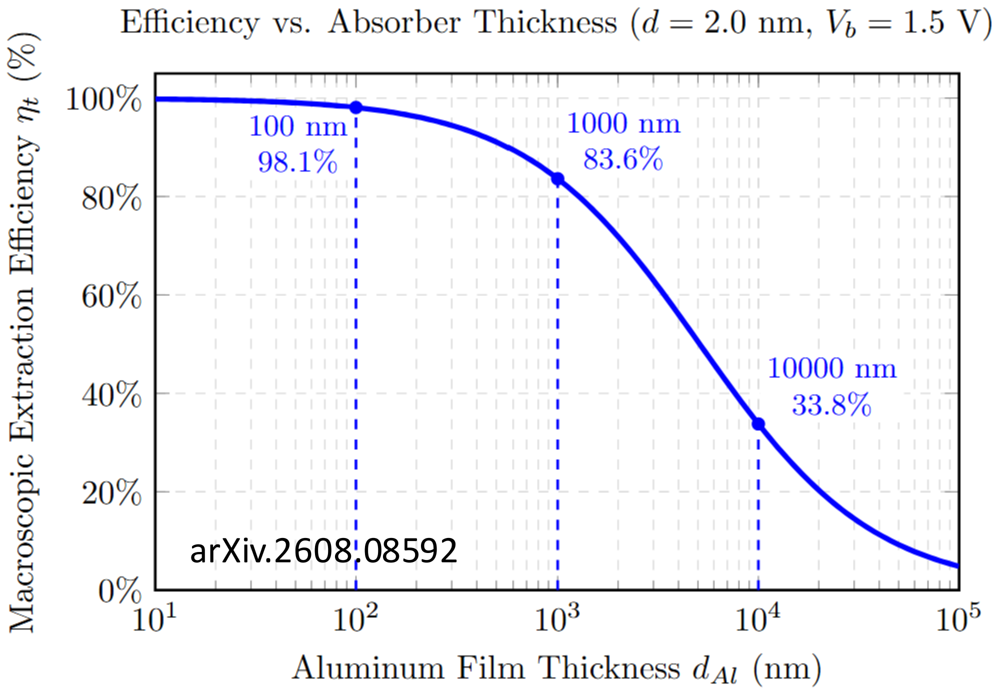


Superconducting Film	Critical Temperature (T_c)	Cooper Pair Bandgap (2Δ)	Typical Detector Application
Tungsten (W - α phase)	$\approx$ 0.015 K	$\approx$ 0.005 meV	Deep sub-mK TES (SuperCDMS)
Hafnium (Hf)	$\approx$ 0.1 K	$\approx$ 0.03 meV	Ultra-low threshold TES
Mo/Au or Mo/Cu (Bilayer)	Tunable (0.05–0.2 K)	0.015–0.06 meV	Precision tunable TES arrays
Titanium (Ti)	$\approx$ 0.4 K	$\approx$ 0.12 meV	MKIDs, low-threshold TES
Molybdenum (Mo)	$\approx$ 0.9 K	$\approx$ 0.27 meV	Bilayer bases, STJs
Aluminum (Al)	$\approx$ 1.2 K	$\approx$ 0.34 meV	MKIDs, Qubits, Phonon trapping
Tantalum (Ta)	$\approx$ 4.4 K	$\approx$ 1.4 meV	STJs, Qubit resonators
Niobium (Nb)	$\approx$ 9.2 K	$\approx$ 3.05 meV	SQUIDs, STJs, SNSPDs
Niobium Nitride (NbN)	$\approx$ 16.0 K	$\approx$ 5.8 meV	High-speed SNSPDs

SuperEM Extraction Efficiency

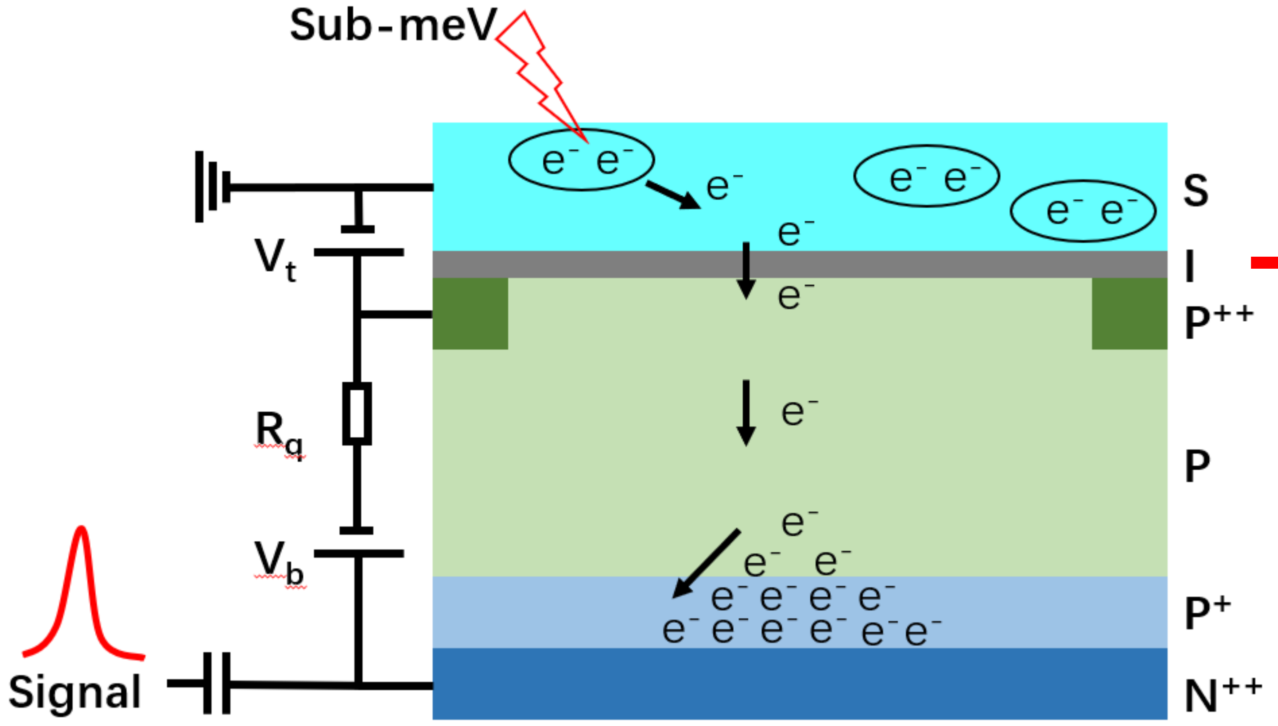
- **Thinning the superconducting aluminum absorber to 100 nm yields an excellent macroscopic extraction efficiency of 98.1%**

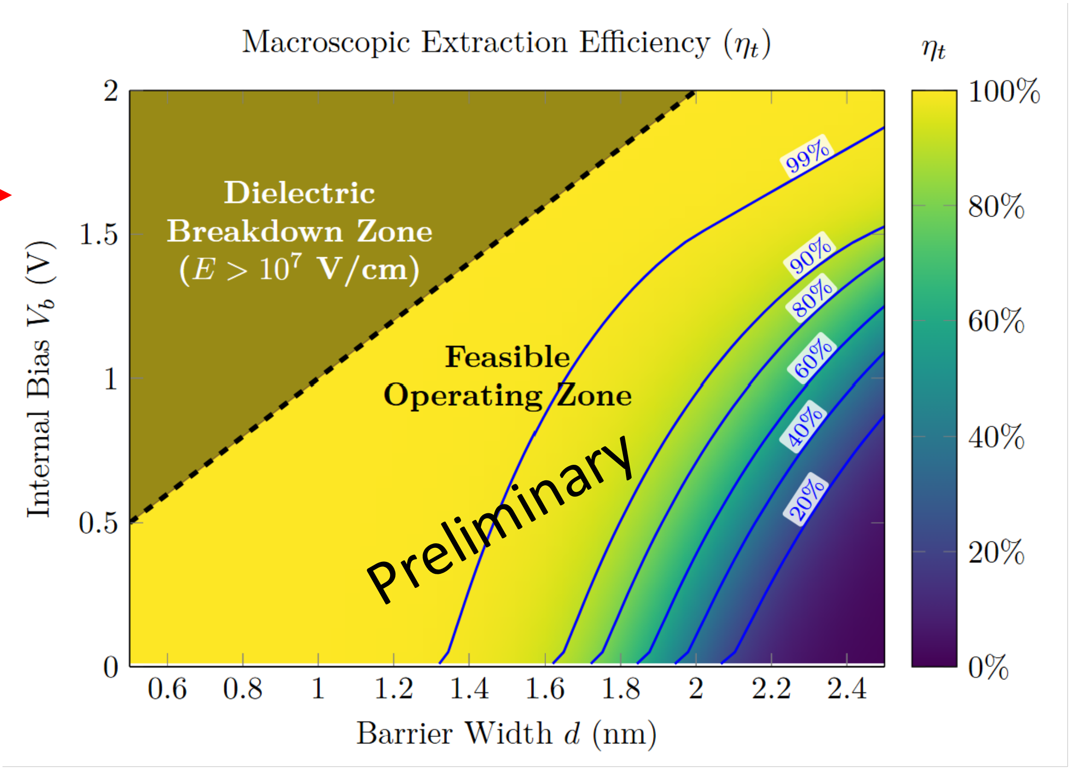




SuperEM Extraction Efficiency

- **Furthermore, tuning the internal bias and barrier width reveals a broad, feasible operating zone that avoids dielectric breakdown while maintaining efficiency**





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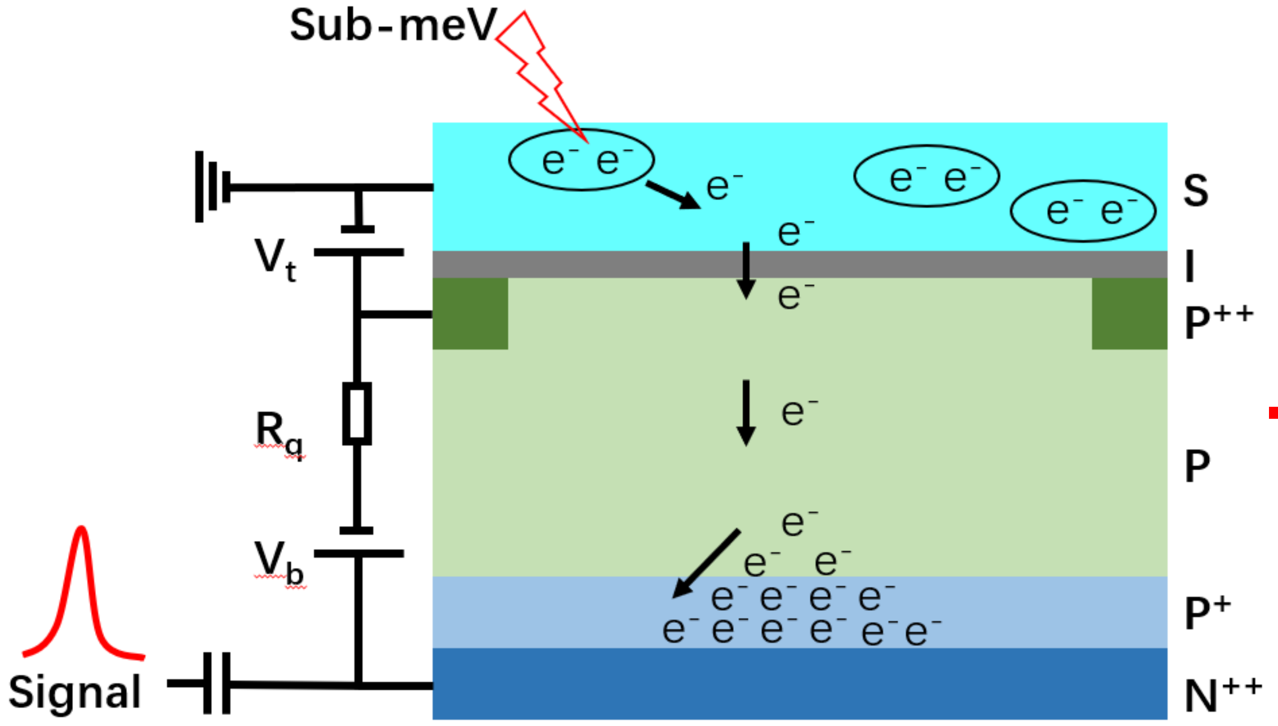
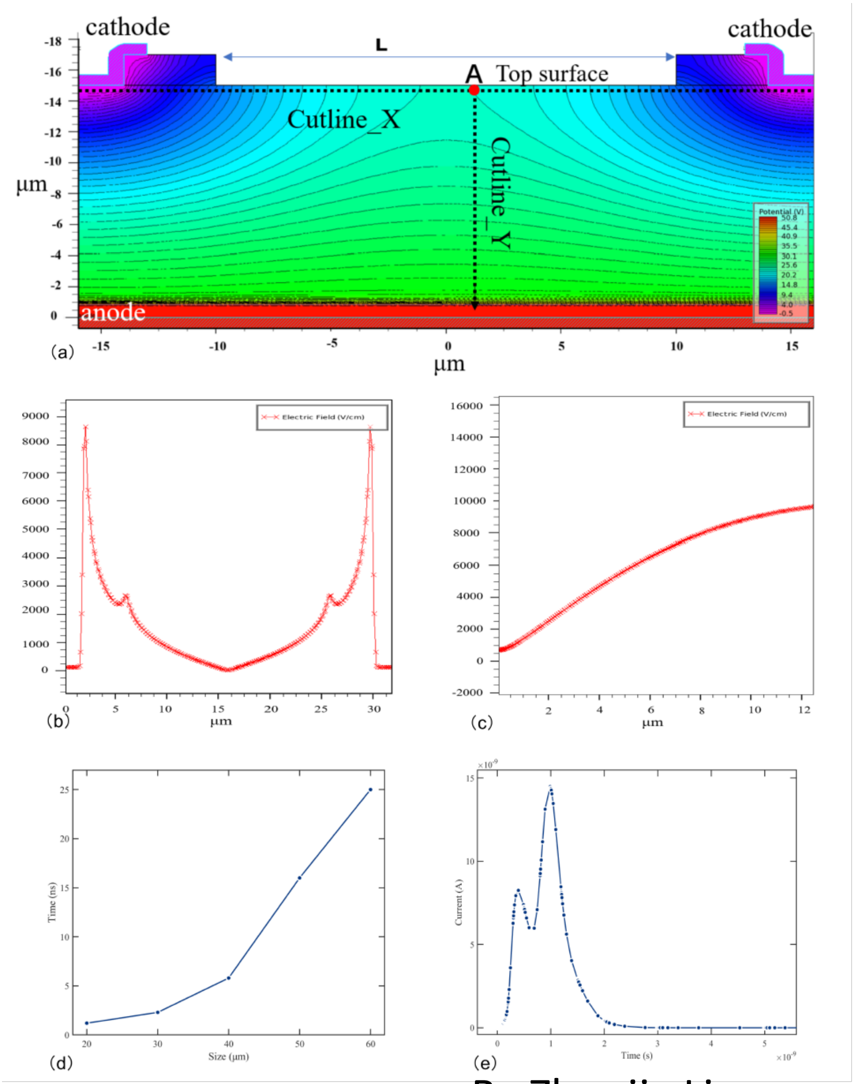
TCAD Signal Transport & Drift Simulation

- **Undoped Interface & High Field:** Immediately forces electrons into vertical drift preventing lateral diffusion, ≥95% Drift Survival.





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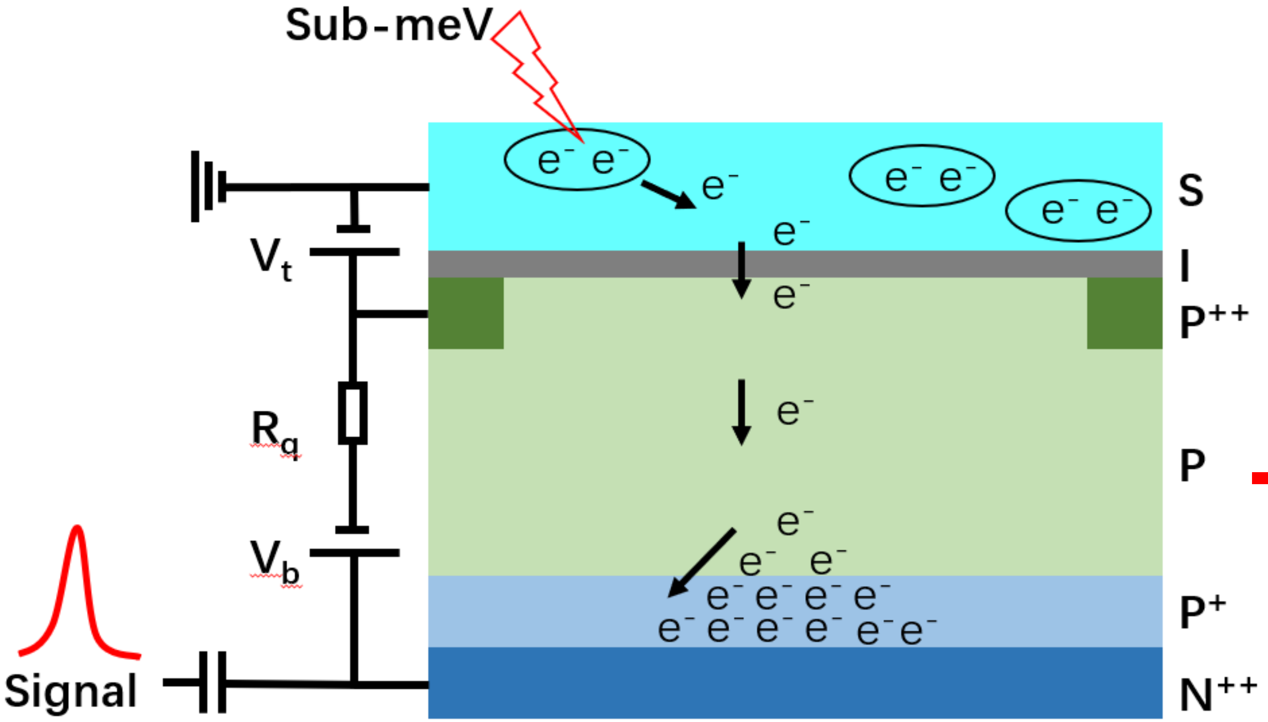
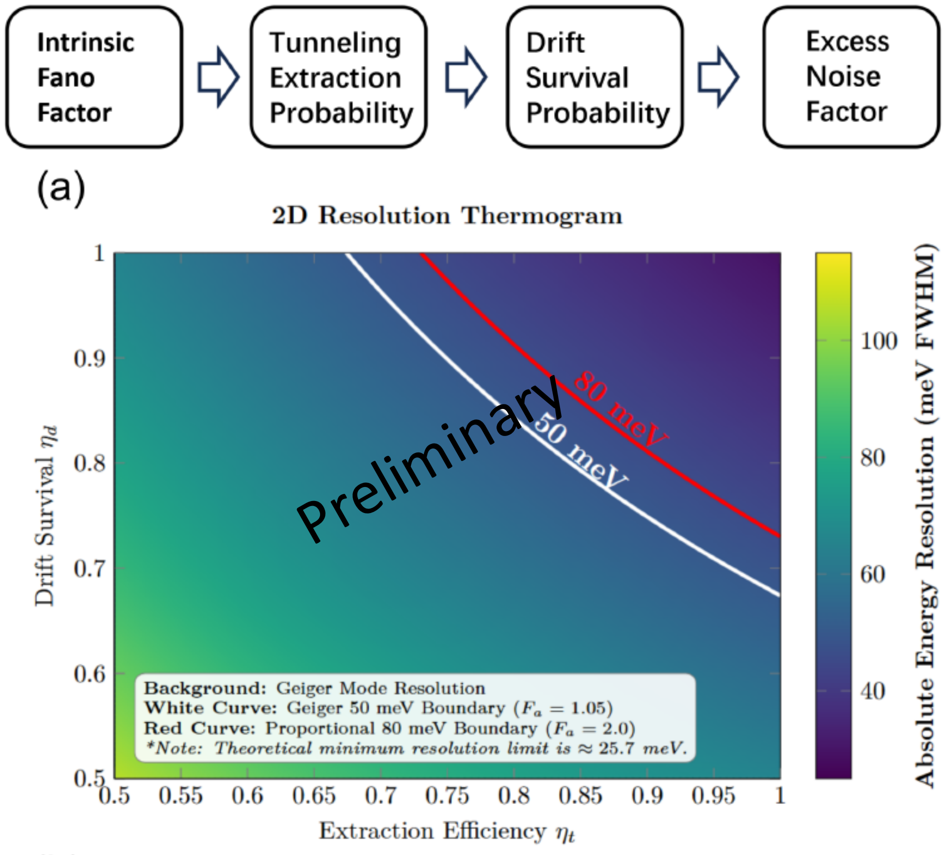
By Zhenjie Li

SuperEM Energy Resolution

- **Furthermore, tuning the internal bias and barrier width reveals a broad, feasible operating zone that avoids dielectric breakdown while maintaining efficiency**





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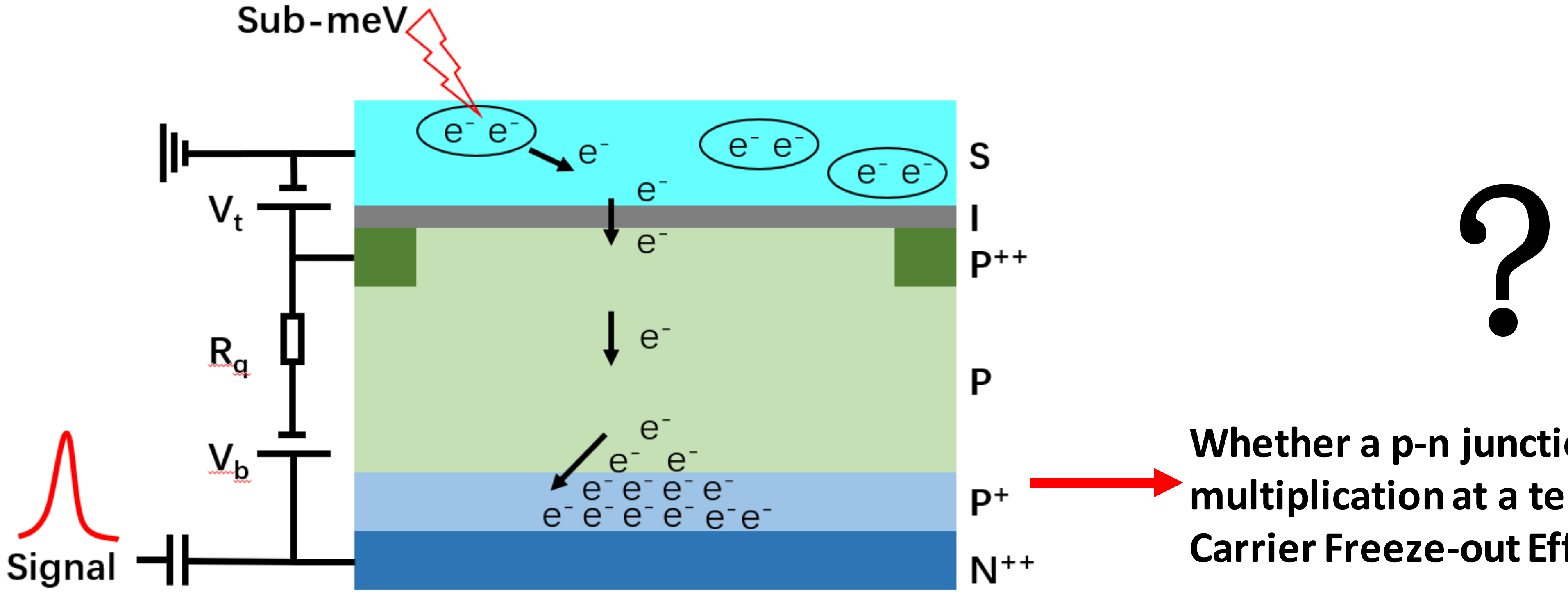
Electron-Multiplying or Carrier Freeze-out

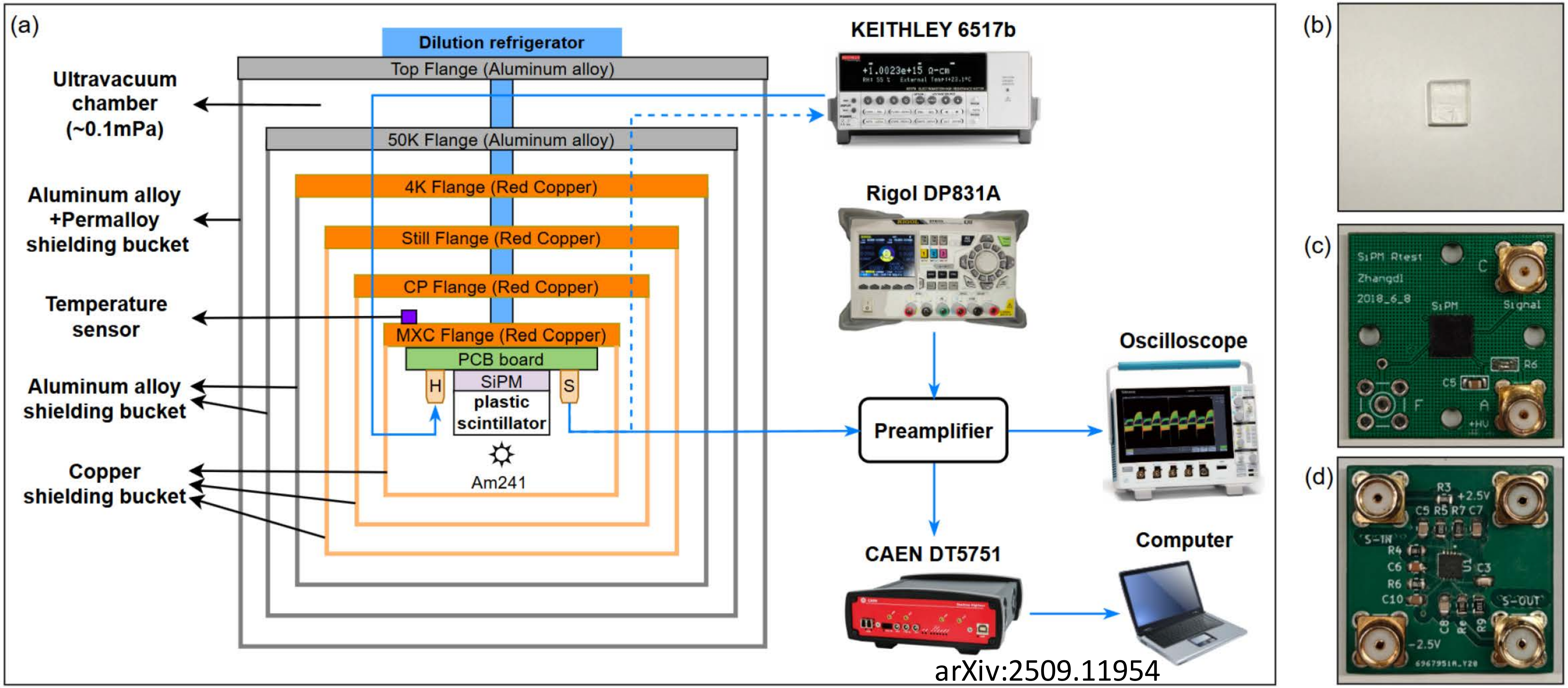
- **One of the big questions to answer is whether electrons can drift and multiply within a semiconductor at a temperature of 10 mK**



Whether a p-n junction can achieve electron multiplication at a temperature of 10 mK???
Carrier Freeze-out Effect

Characterization of SiPM at 10 mK

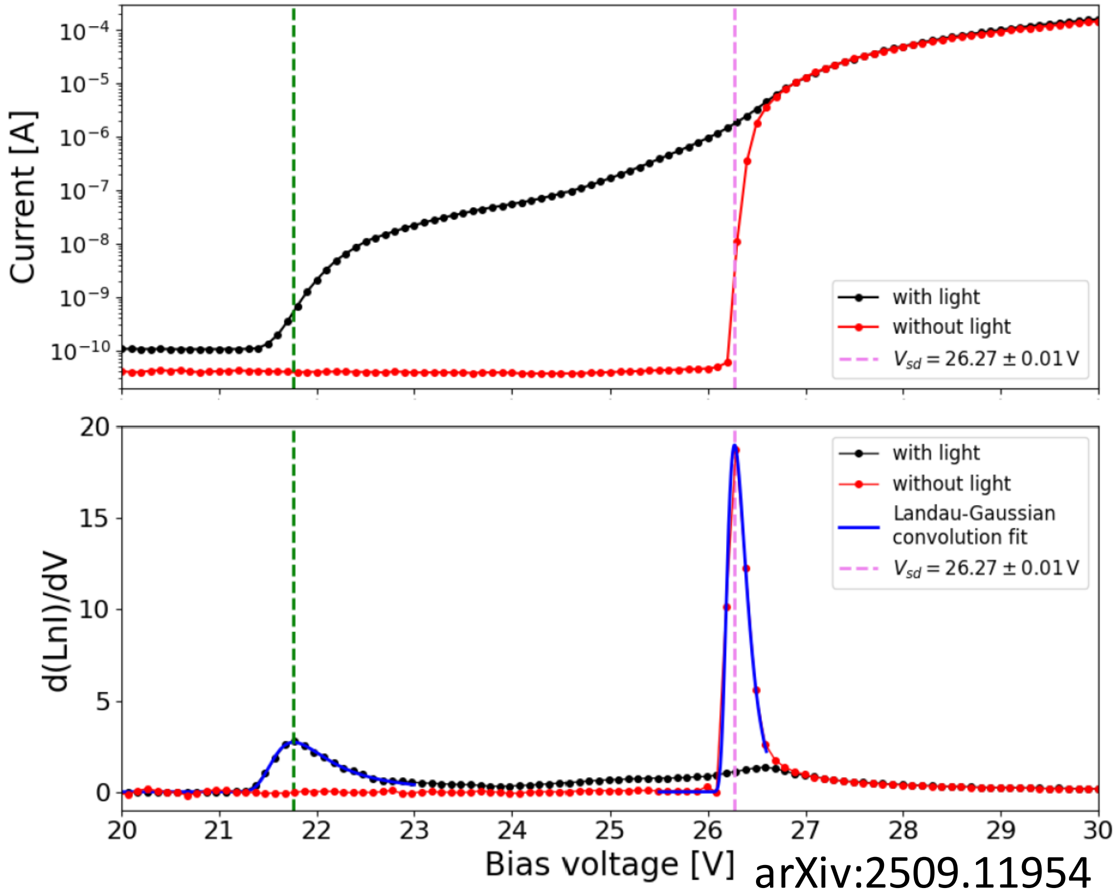
- **A dilution refrigerator test platform, PS+^{241}Am as light source, SensL J 6 mm SiPM**



arXiv:2509.11954

I-V curve and Breakdown Voltage at 10 mK

- **The breakdown voltage displays a non-linear temperature dependence, there is an inflection point at 50 K, followed by a slow rise.**



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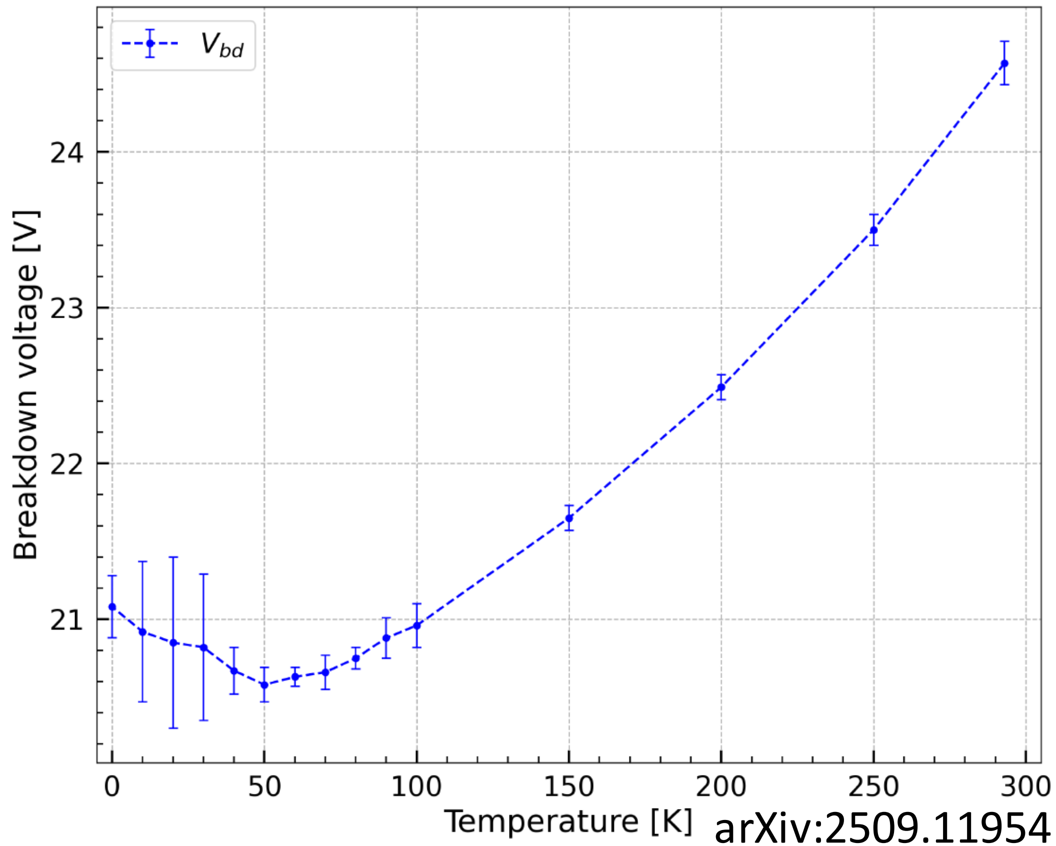
IV curves and their differential curves of the SiPM at 10 mK



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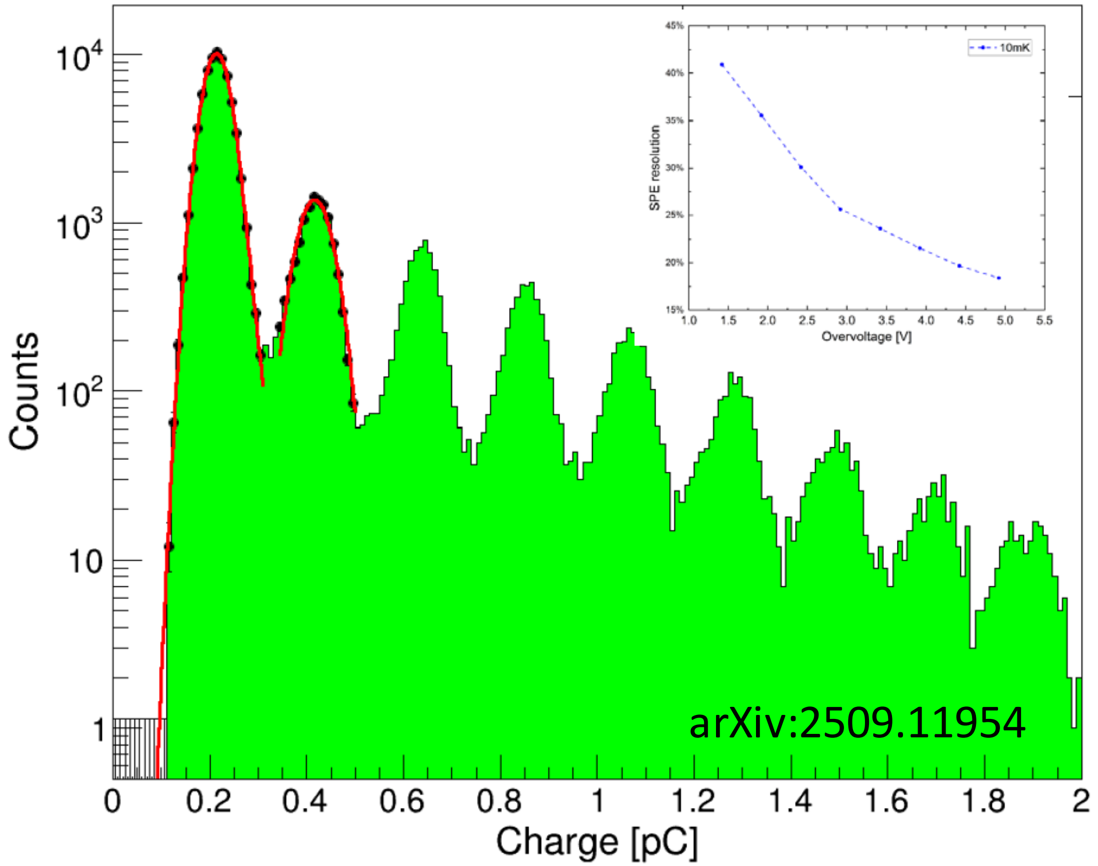
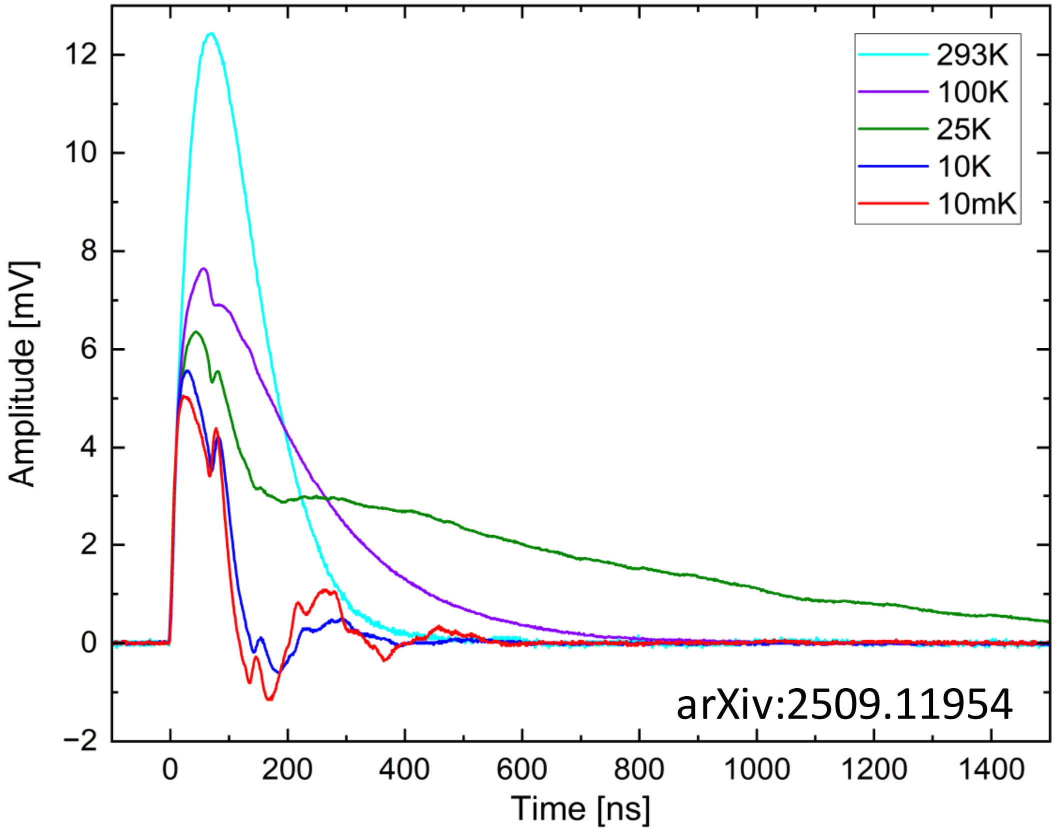
Temperature dependence of Vbd over the temperature range from 300 K to 10 mK.

Single p.e. Waveform and Resolution at 10 mK

- **At 10 mK, the SiPM maintains good single photoelectron (SPE) resolution.**
- **Pulse width undergoes a significant change: as the temperature decreases, it first widens and then narrows.**



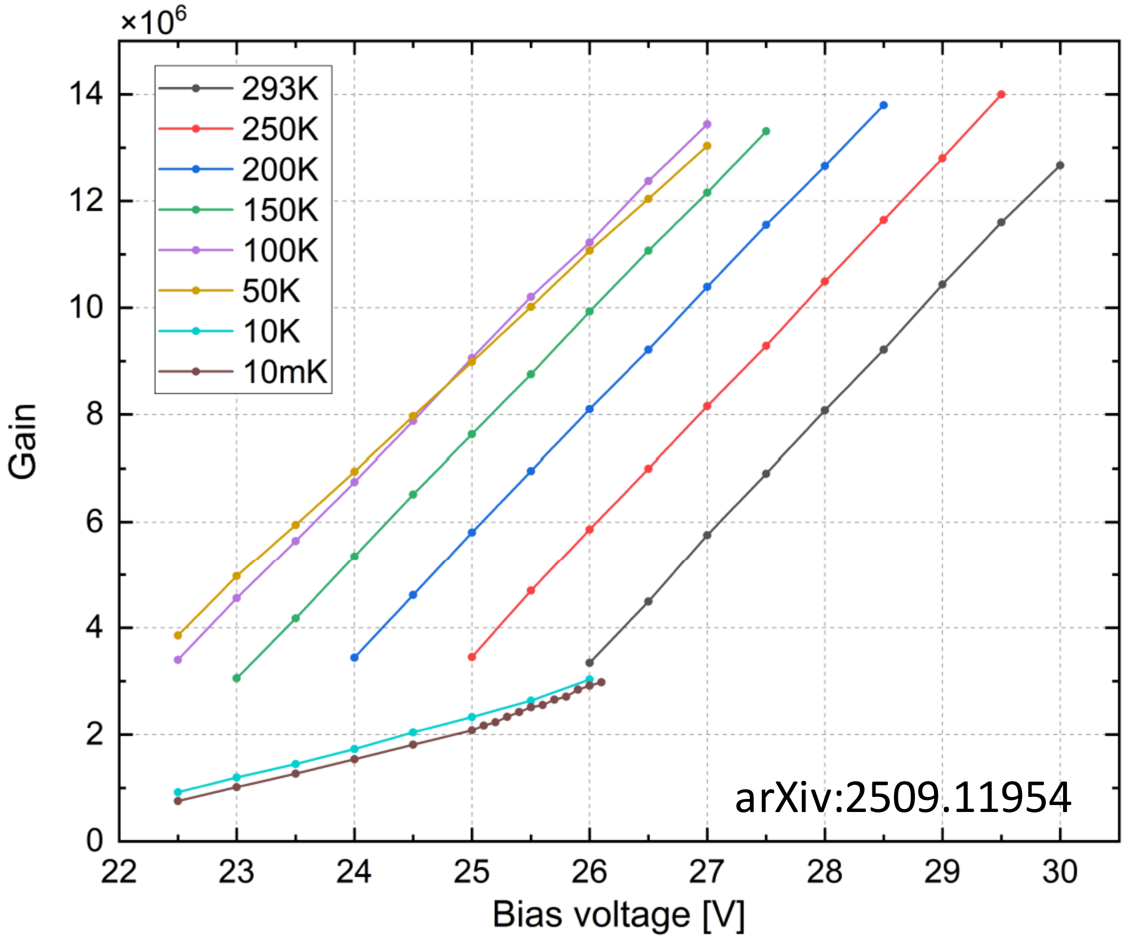
Single p.e. resolution 10 mK



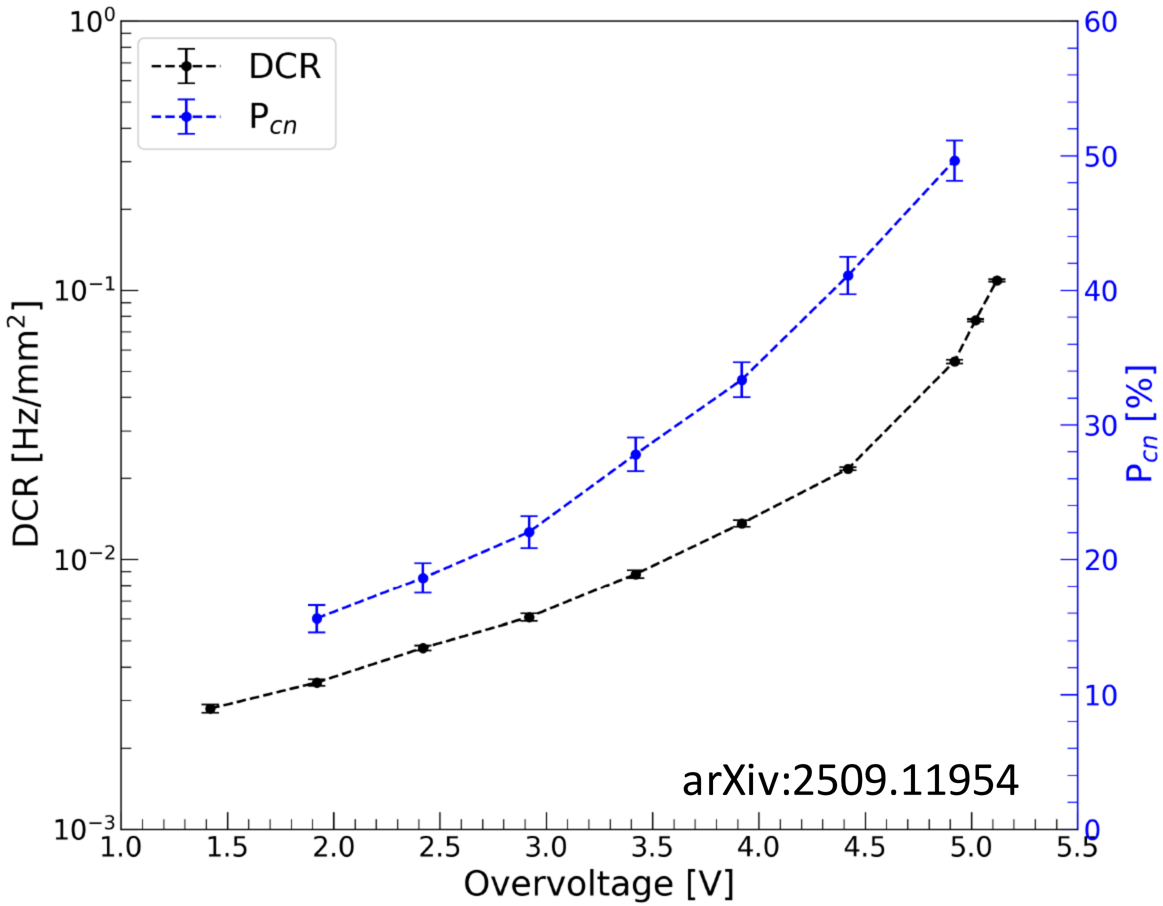
SiPM single p.e. waveform signals at different temperatures

Gain and DCR at 10 mK

- **Linear relationship between gain and bias voltage remains from room temperature down to 10 mK, DCR down to 10^{-3} Hz/mm^2 at 10 mK, important for rare event search**



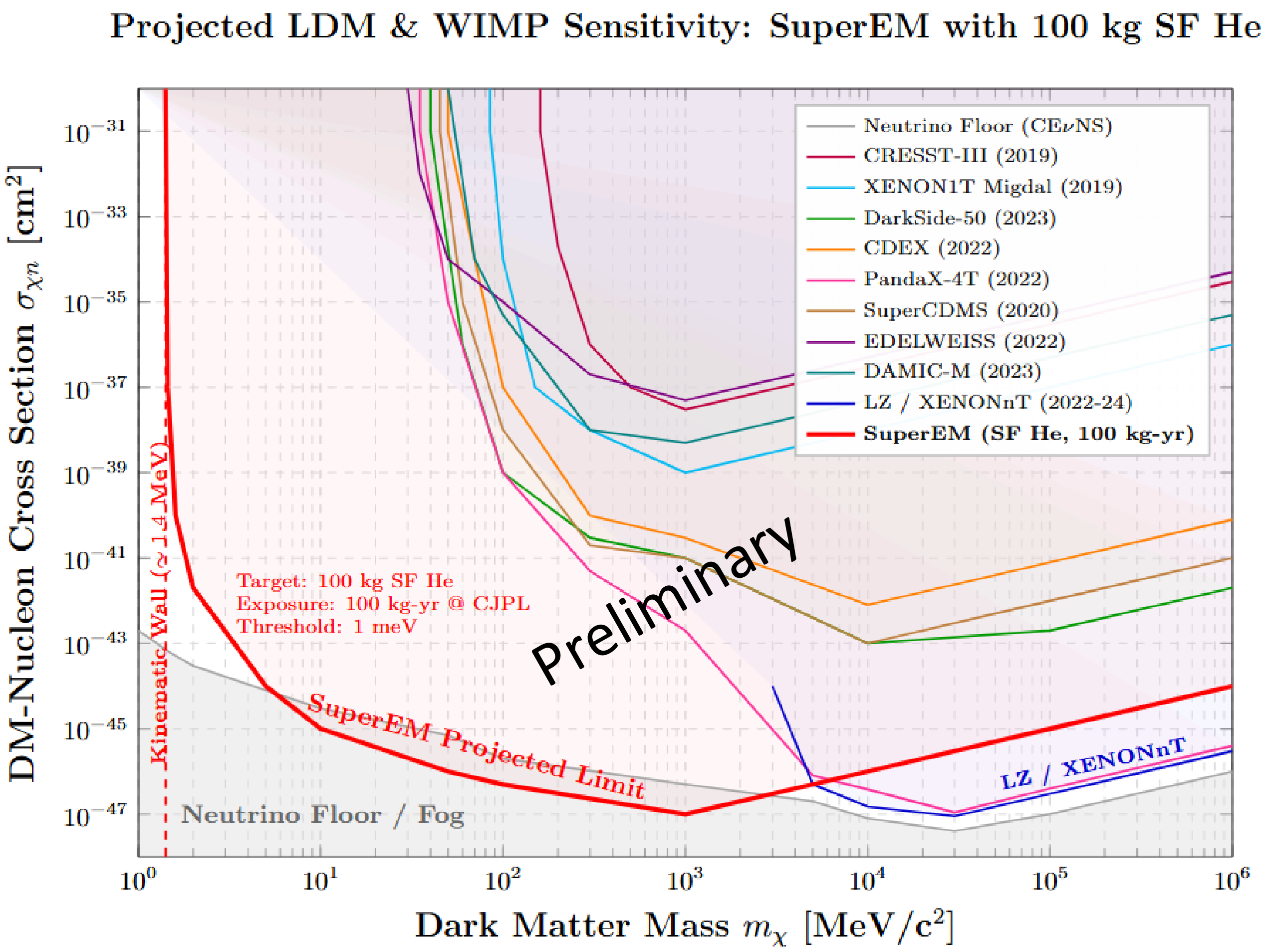
SiPM gain versus bias voltage from 293 K to 10 mK



DCR and CT as a function of overvoltage at 10 mK

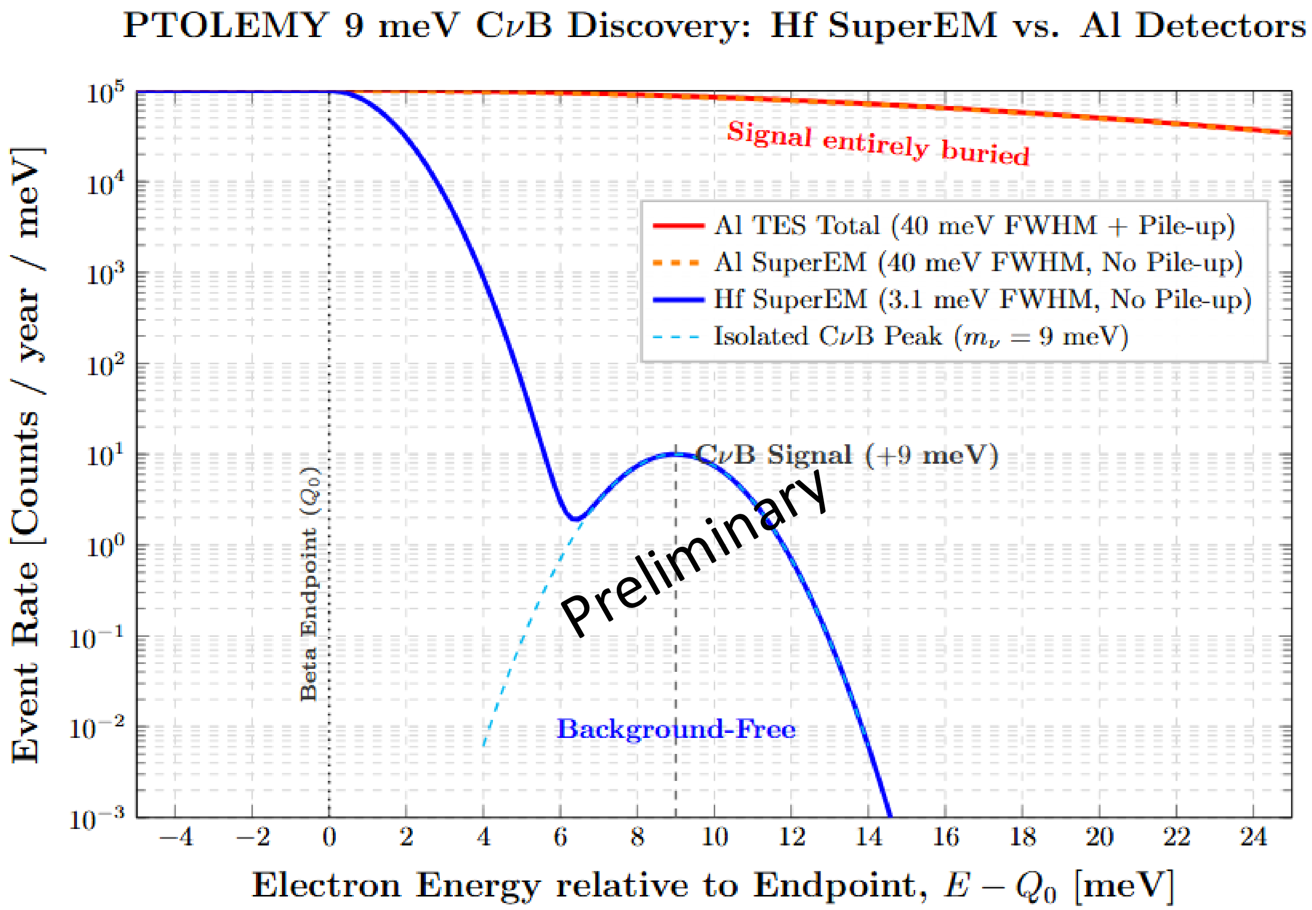
Projected LDM & WIMP Sensitivity

- **Target: 100 kg Superfluid Helium.**
- **1 meV threshold will push DM sensitivity down to the 1 MeV limit.**



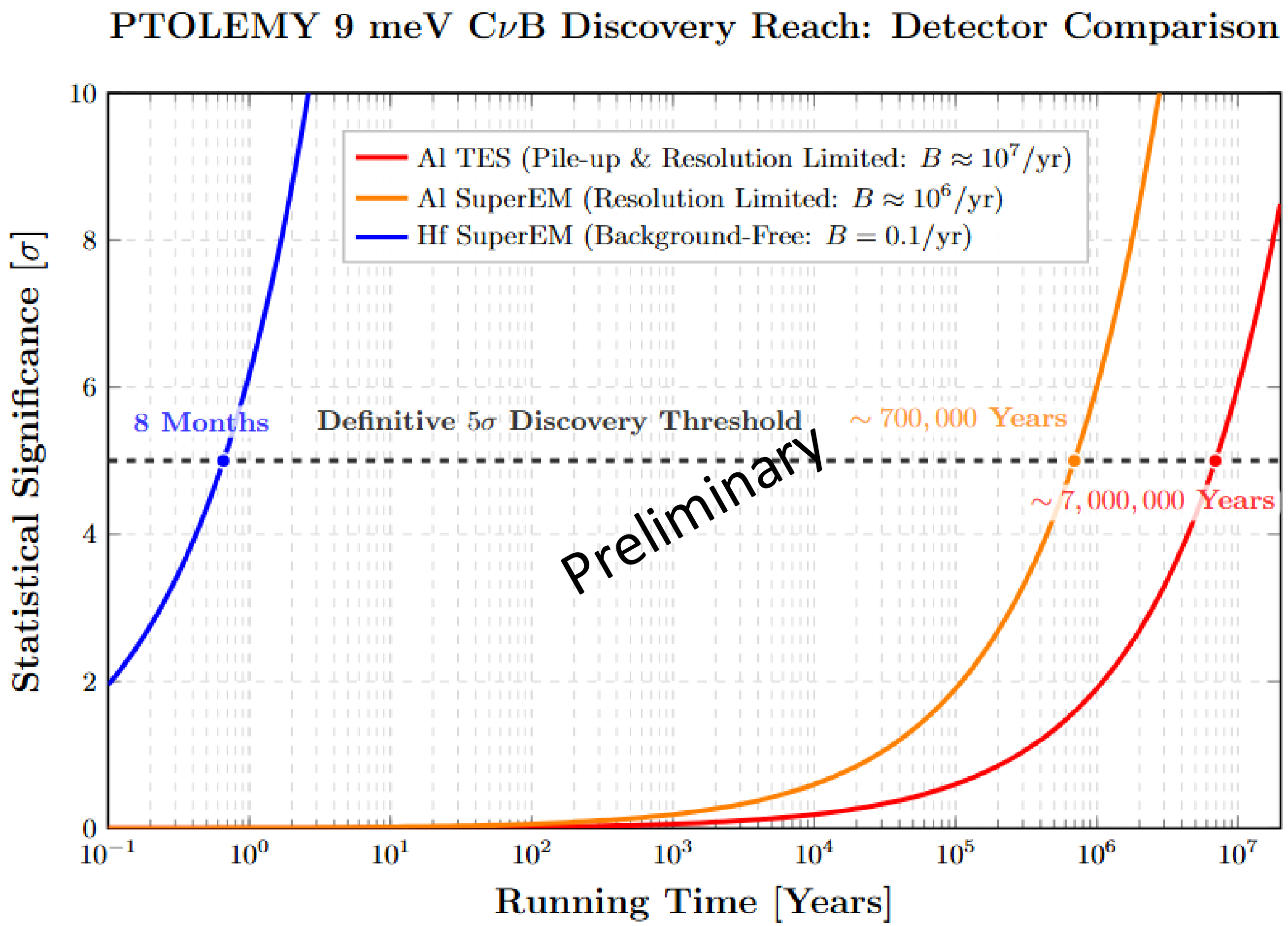
PTOLEMY 9 meV Discovery (Normal Ordering)

- **Hafnium (Hf) SuperEM:** Ultra-low gap (0.02 meV) yields a sharp 3.1 meV FWHM resolution at 100 meV.
- **Zero Pile-up:** Nanosecond response isolate the CvB signal from the beta-decay endpoint.



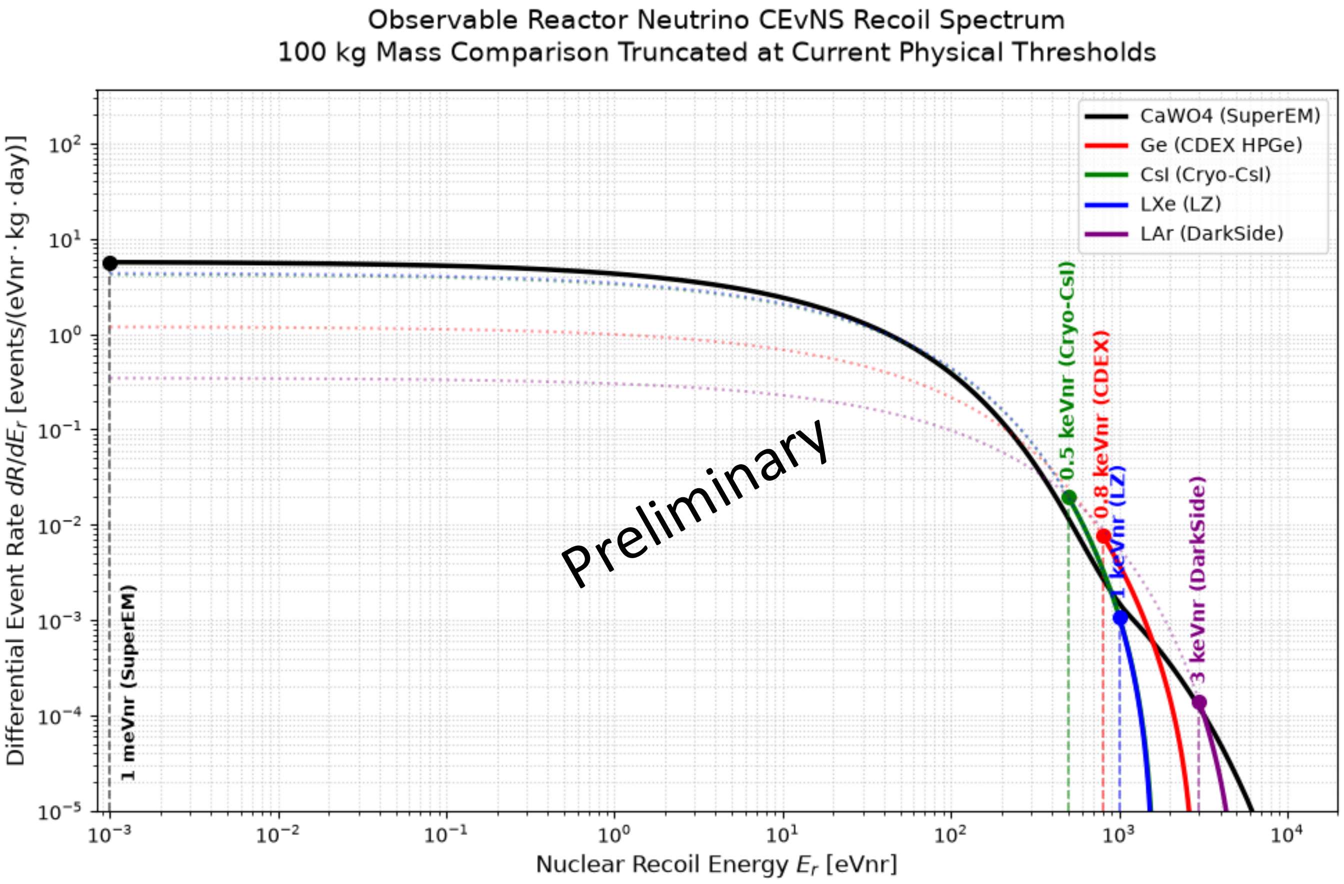
PTOLEMY CvB Discovery Sensitivity

- **Background-free performance accelerates the CvB discovery timeline.**
- **5 sigma Discovery: Achieved in just 8 months.**



Reactor CEvNS Detection

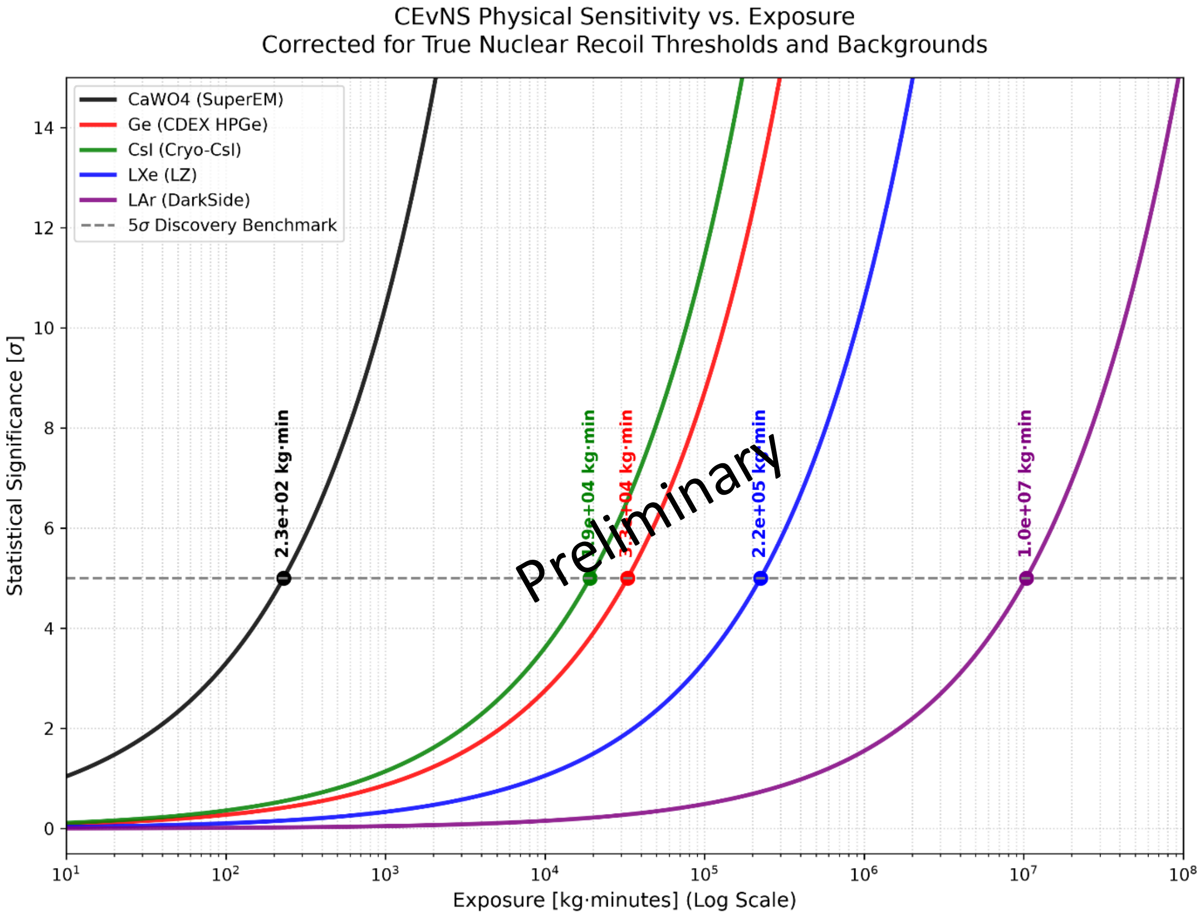
- **Unlocks access to observable signals orders of magnitude larger than current detectors.**



True Nuclear Recoil (NR) Threshold References (Accounting for Quenching):
[1] Ge (0.8 keVnr): Derived from 160 eVee ionization threshold. H. Jiang et al. (CDEX), Phys. Rev. Lett. 120, 241301 (2018).
[2] CsI (0.5 keVnr): Cryogenic scintillation readout threshold. Eur. Phys. J. C (2024) 84:440.
[3] LXe (~1 keVnr): J. Aalbers et al. (LZ Collaboration), Phys. Rev. Lett. 129, 161801 (2022).
[4] LAr (~3 keVnr): Derived from 0.6 keVee. P. Agnes et al. (DarkSide Collaboration), Phys. Rev. Lett. 121, 081307 (2018).

Reactor CEvNS Sensitivity

- **Enables a 10 kg•min scale CEvNS detector.**



Radioactive Background References (Integrated ROI):
[1] CaWO4 (~0.15 ev/kg/d): A. Münster et al. (CRESST Collaboration), JCAP 05, 018 (2014).
[2] Ge (~2.5 ev/kg/d): H. Jiang et al. (CDEX Collaboration), Phys. Rev. Lett. 120, 241301 (2018).
[3] CsI (~2.5 ev/kg/d): Background derived from KIMS. S. C. Kim et al. (KIMS Collaboration), Phys. Rev. Lett. 108, 181301 (2012).
[4] LXe (~0.001 ev/kg/d): J. Aalbers et al. (LZ Collaboration), Phys. Rev. Lett. 129, 161801 (2022).
[5] LAr (~1.5 ev/kg/d): P. Agnes et al. (DarkSide Collaboration), Phys. Rev. Lett. 121, 081307 (2018).

Reactor CEvNS Sensitivity

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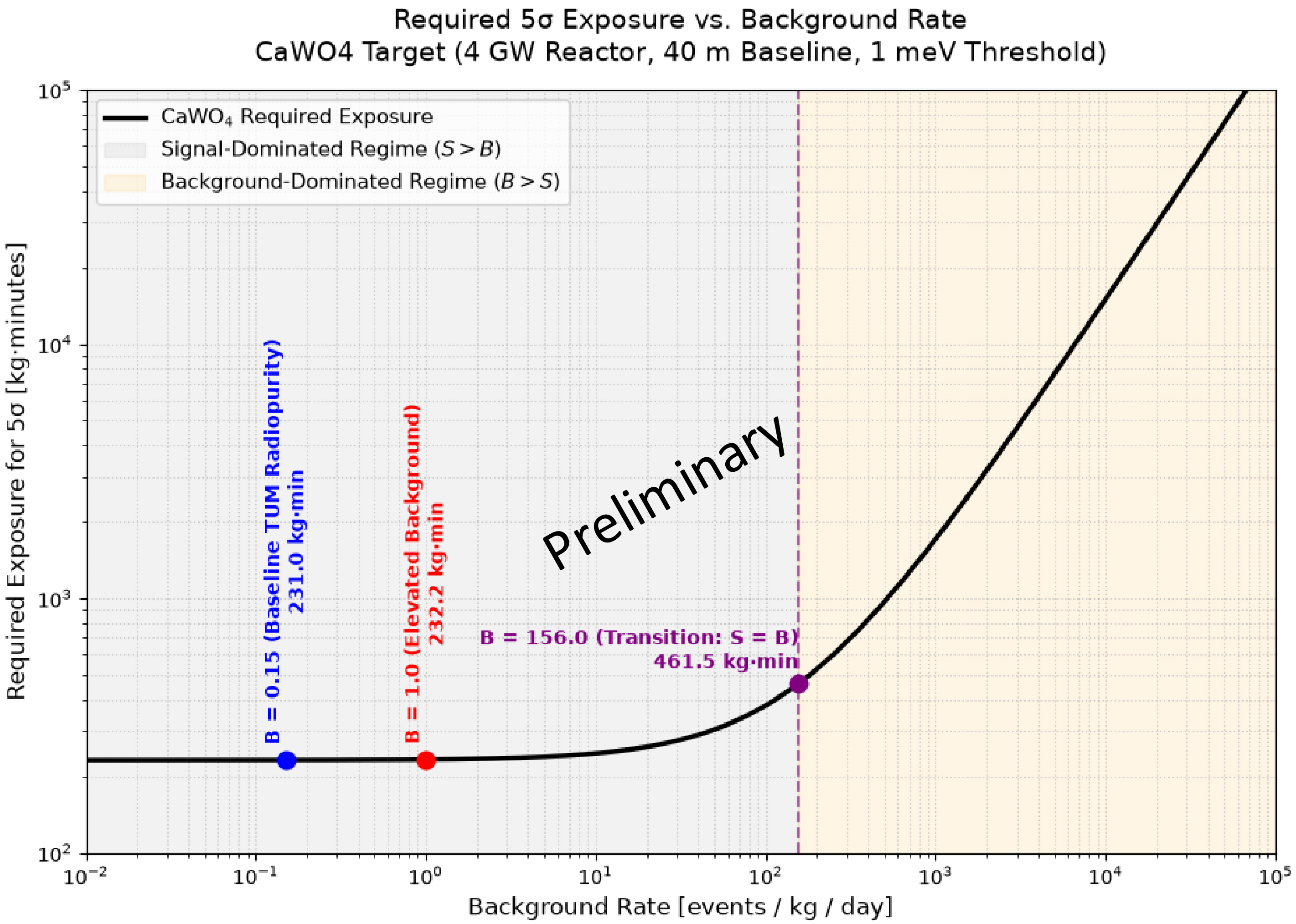

Other Potential Applications

- **CMB-B mode searches, photon counting mode**
  - 160 GHz~0.66 meV,
  - 0.01 Hz/mm^2~10^{-23} W/Hz^{-2}
  - 150–170 GHz, ~227 photons/ns/cm^2
- **THz photon detector**
  - 1 THz~4.1 meV
- **Quantum computing real-time error correction**
  - ns response, anticoincidence detector

Summary

- **The SuperEM Architecture:** A novel detector featuring sub-meV thresholds, nanosecond response times, and massive scalability.
- **Theoretical framework:** Detector mechanism analysis and simulation show that the detector architecture is feasible.
- **Empirical Milestone:** SiPM avalanche amplification has been successfully verified at 10 mK.
- **Physics Impact:** Redefine the limits of Dark Matter, CvB, CEvNS experiments and have other potential applications.
- **Current Status:** A fully integrated SuperEM prototype is in design for fabrication.

Acknowledgements

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Thank you for your attention!