Summary

Astrophysical and cosmological observations provide overwhelming evidence for the existence of non-baryonic dark matter, yet its fundamental particle nature remains one of the most profound open questions in physics. The absence of signals in conventional GeV$/c^2$–TeV$/c^2$ WIMP searches has driven the field toward unexplored territory: low-mass dark matter candidates, including sub-GeV$/c^2$ WIMPs and light bosonic particles such as axion-like particles and dark photons. Exploring this regime demands ultra-low-threshold detectors, precise sub-keV calibration, rigorous statistical methods, and unprecedented control of backgrounds.

This thesis presents experimental and phenomenological advances that strengthen the scientific reach of low-mass dark matter searches, centered on the Super Cryogenic Dark Matter Search (SuperCDMS) program.

The first part develops a novel sub-keV energy calibration technique for SuperCDMS silicon high-voltage eV-resolution (HVeV) detectors. Using Compton steps arising from gamma-ray scattering on bound atomic electrons, distinct spectral features at known atomic binding energies provide a direct and robust mapping between deposited energy and de-

tector response at zero bias voltage. A comparison with an independent optical photon calibration under high bias reveals an approximately 30% difference in response, offering new insight into low-energy phonon production mechanisms. This improved calibration directly enhances sensitivity to light dark matter interactions and refines our understanding of detector physics at the eV scale.

The second part presents statistically rigorous searches for bosonic dark matter candidates, axion-like particles and dark photons, using SuperCDMS Soudan data. A profile likelihood ratio framework incorporating detector response modeling, background parameterization, signal efficiencies, and systematic uncertainties is employed to constrain the axion–electron coupling (g_{ae}) and dark photon kinetic mixing parameter (ϵ). The resulting limits improve upon previous SuperCDMS constraints by up to a factor of five across the mass range 40 eV$/c^2$ to 25 keV$/c^2$, advancing the exploration of light dark sectors.

The third part investigates neutrino-induced nuclear recoils as an irreducible background for low-mass WIMP searches. A detailed phenomenological study of reactor antineutrino–induced coherent elastic neutrino–nucleus scattering is performed using Monte Carlo simulations tailored to SuperCDMS-like ultra-low-threshold detectors, with reactor spectra validated against CONUS+ measurements. A profile likelihood analysis demonstrates that a gigawatt-scale nuclear reactor within approximately 10 km can substantially elevate the neutrino floor, degrading sensitivity to WIMPs below approximately 10 GeV$/c^2$. In contrast, the impact becomes negligible at baselines of order 100 km, identifying reactor proximity as a critical factor in site selection for next-generation experiments.

The fourth part addresses fast neutrons as a dominant environmental background for nuclear-recoil-based dark matter searches. EJ-301 liquid scintillation detectors are calibrated using gamma-ray and Am–Be neutron sources and modeled with detailed Geant4 simulations that incorporate optical photon production, transport, and scintillation quenching. The Birks constant is extracted from proton-recoil data, enabling the construction of a validated neutron response matrix. Unfolding of measured spectra successfully reproduces the known source distribution, establishing a robust and experimentally validated framework for fast-neutron background characterization at underground laboratories.

Together, these studies form a comprehensive framework that integrates detector calibration at the sub-keV scale, advanced statistical dark matter searches, and precise background characterization. By strengthening both experimental sensitivity and theoretical interpretation, this work enhances the discovery potential of next-generation ultra-low-threshold dark matter experiments and advances the global effort to uncover the particle nature of dark matter.