

1 Project Summary

1.1 Overview

This interdisciplinary NSF-BSF proposal has three objectives: 1) to search for sub-GeV hidden-sector dark matter with the SENSEI experiment, which uses the newly developed Skipper-CCDs, 2) to perform novel auxiliary measurements of the low-energy properties of silicon using Skipper-CCDs, and 3) to help advance Skipper-CCDs as a novel ultra-low-noise detector for quantum technology experiments.

Uncovering the identity of dark matter is among the most important goals of particle physics today. SENSEI ("Sub-Electron Noise Skipper-CCD Experimental Instrument") is a direct-detection experiment that will search for well-motivated Hidden-Sector dark matter particles with eV-to-keV and MeV-to-GeV masses. This proposal will maximize the science gain of SENSEI, by calibrating the silicon detector's sensitivity to dark matter events, developing a data acquisition system, estimating the radioactive and detector backgrounds, and further developing the analysis tools needed to analyze the data.

Quantum imaging has the possibility of beating the limits of classical imaging by exploiting the peculiar properties of quantum optical states, such as entanglement. Quantum imaging experiments need to count individual photons and measure their correlations. Skipper-CCDs can count single photons without charge multiplication and thus have distinct advantages over other technologies. This proposal will measure the quantum efficiency of the Skipper-CCD, which is a basic property needed for several potential applications in quantum information.

1.2 Intellectual Merit

The proposal addresses three of NSF's 10 Big Ideas: (i) "Windows to the Universe", for which we use Skipper-CCDs as an ultra-sensitive detector to search for dark matter, (ii) "Quantum Leap", for which we will advance the Skipper-CCD as a tool for the next-generation quantum-enabled science and technology for sensing, and (iii) "Growing Convergence Research", for which we merge ideas, approaches, and technologies from diverse fields of knowledge to stimulate innovation and discovery.

The proposal has six Specific Aims: 1) Measure low-energy Fano factor of silicon, 2) Measure Quantum Efficiency of Skipper-CCD, 3) Simulate radiogenic backgrounds in SENSEI-100, 4) Design data acquisition system for SENSEI-100, 5) Measure Compton spectrum between a few eV to 60 eV, and 6) Analyze SENSEI dark matter search data. The outcome will be to improve significantly the dark matter discovery potential of SENSEI; to provide crucial understanding of the low-energy behavior of silicon, including novel measurements of the Fano factor and Compton spectrum; and to open a new window for utilizing Skipper-CCDs in quantum technology applications, such as high-efficiency quantum imaging and ultra-low-noise detection of low-rate entanglement swapping in large quantum networks.

1.3 Broader Impacts

The measurement of the Fano factor and low-energy Compton spectrum are key measurements of a fundamental property of silicon, which will benefit not only the SENSEI dark matter search, but also DAMIC-M and SuperCDMS. It will also test condensed matter theory calculations that predict these properties. A measurement of the quantum efficiency of Skipper-CCDs is a crucial ingredient for having Skipper-CCDs be used as a novel tool in quantum imaging and quantum sensing.

This proposal is truly international and interdisciplinary, merging quantum information and particle physics, and fostering collaboration between researchers in the US and Israel. It will seed new collaborations between researchers of distinct disciplines, and is an ideal training ground for a new generation of scientists versed in particle physics and quantum information, and in the

emerging interdisciplinary area of using quantum imaging and sensing to develop new probes for dark matter.

We also propose to mentor and teach undergraduate women and minority students through the Stony Brook "Women in Science and Engineering" (WISE) program, mentor middle and high school women students and teachers through WISE, improve accessibility to STEM fields in Israel, give public lectures, and educate graduate students at summer schools.

NSF-BSF: The Hunt for Sub-GeV Dark Matter with SENSEI, and Skipper-CCDs for Quantum Imaging

1 Objectives and Overview

This proposal is an NSF-BSF proposal between Stony Brook University (SBU) and Tel-Aviv University (TAU) that is being submitted for joint evaluation to the “Particle Astrophysics - Experiment” and “Quantum Information Science” programs.

This proposal is interdisciplinary and has **three objectives**: 1) to search for sub-GeV hidden-sector dark matter (DM) with the SENSEI experiment, which uses the newly developed Skipper-CCDs [1], 2) to perform novel auxiliary measurements of the low-energy properties of silicon using Skipper-CCDs, and 3) to help advance Skipper-CCDs as a novel ultra-low-noise detector for quantum technology experiments.

Uncovering the identity of DM, which makes up about 85% of the matter in the Universe, is among the most important goals of particle physics today. SENSEI – the *Sub-Electron Noise Skipper-CCD Experimental Instrument* – is a direct-detection experiment that will search for well-motivated Hidden-Sector (non-WIMP) DM particles with eV-to-keV and MeV-to-GeV masses that have received increased attention in the past decade, e.g. [2, 3]. SENSEI uses silicon Charged Coupled Devices with a new, ultralow-noise readout technology (“Skipper-CCDs”), which have been designed in collaboration with the LBL Micro Systems Lab. SENSEI has demonstrated the ability to measure precisely the number of free electrons in each of the million pixels across the CCD, showing single-electron sensitivity with a large dynamical range [1]. This is a major technological breakthrough that allows for the most sensitive search to date for sub-GeV DM that either scatters off, or is absorbed by, electrons [4, 5, 6, 7].

The DM detection concept is shown in Fig. 1 (left), and SENSEI published its first DM results, made with a prototype Skipper-CCD, in 2018 [8]. The SENSEI Collaboration is procuring new Skipper-CCDs and constructing a detector consisting of ~ 100 -grams of Skipper-CCDs (“SENSEI-100”) to be deployed at SNOLAB in 2020. A 10-gram precursor detector will be constructed in 2019 (“SENSEI-10”). *The construction of SENSEI is fully funded by a grant from the Heising-Simons Foundation, and supported by Fermilab and SNOLAB.* Nevertheless, in order to maximize the science gain, there is a **critical need** to calibrate the silicon detector’s sensitivity to DM events, develop a data acquisition system, estimate the radioactive and detector backgrounds, further develop the analysis tools, and (once the data is in hand) analyze the data.

Quantum imaging is an area of quantum science that addresses the possibility of beating the limits of classical imaging by exploiting the peculiar properties of quantum optical states, such as entanglement [9, 10]. In the past few years sub-shot-noise imaging was demonstrated in [11] and sub-diffraction-limited quantum imaging was realized in [12]. Quantum imaging experiments need to count individual photons and measure their correlations. Standard CCDs cannot be used for this, since their typical readout noise is a few electrons. Instead, the usual detectors are intensified CCDs (iCCDs) [13] and Electron-Multiplying CCDs (EMCCs) [14], which are able to count single photons due to their intrinsic gain. However, these suffer from excess noise due to statistical fluctuations in their intrinsic gain mechanism. Skipper-CCDs, on the other hand, can count single photons without charge multiplication and could prove to be a revolutionary new tool for quantum technology applications such as high-efficiency quantum imaging and ultra-low-noise detection of low-rate entanglement swapping in large quantum networks. There is, however, a **critical need** to measure the quantum efficiency of the Skipper-CCD to high precision such that the device can be used for simultaneous quantum-optical-channel characterization in which the quantum correlations between the optical beams play a major role.

The co-PIs will achieve the proposal’s objectives by pursuing the following **six specific aims**:

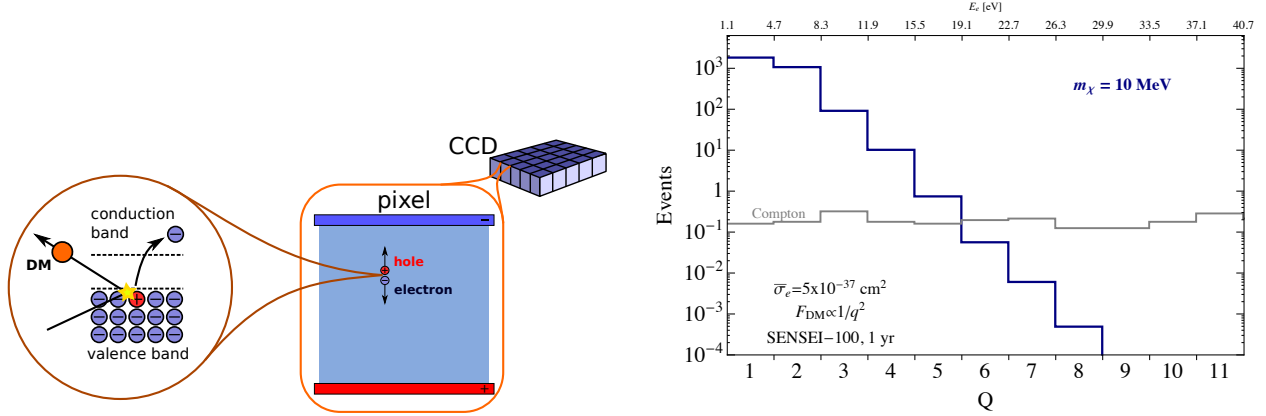


Figure 1: **Left: Detection concept for SENSEI.** Sub-GeV DM scatters off an electron, or is absorbed by an electron, in the valence band of silicon, promoting the electron to the conduction band. Depending on the recoil energy, this creates one or more free electrons, which are moved from pixel-to-pixel to one of the corners of the CCD, where they are measured with the Skipper readout. **Right:** Theoretically expected electron-recoil spectrum as a function of the electron recoil energy E_e (top axis) and the expected number of electron-hole pairs Q (bottom axis), for a 10 MeV DM particle scattering off an electron in silicon. We assume an exposure of 100-gram-years, and a cross section consistent with DM obtaining the observed relic abundance via “freeze-in” through an ultralight dark photon mediator [4, 5, 15, 16]. The outcome of **Specific Aim 1** will be to improve significantly the mapping of E_e to Q at the lowest energies. The expected outcome of **Specific Aims 3 and 5** will be the precise knowledge of the Compton background in SENSEI-100, an estimate of which is shown in light gray.

1. **Specific Aim 1: Measure Low-Energy Fano Factor of Silicon.** Extensive theory work has gone into calculating the energy spectrum of the recoiling electron from a DM-electron scattering event [4, 5, 17, 18], see Fig. 1 (right) for an example. However, experiments do not measure directly the deposited energy, E_e , but rather the the number of electron-hole pairs produced in an event, Q . Linking the two is a complicated chain of secondary scattering processes that are extremely challenging to compute and – until now – difficult to measure in the energy range of interest for DM, i.e. 1 – 50 eV. Moreover, the Q obtained for a given E_e will fluctuate around a mean value, $\langle Q \rangle$, with a variance given by σ_Q^2 (all quantities are a function of E_e). We propose to do an experiment at SBU to measure the *Fano factor* at 3 eV, defined as $F = \sigma_Q^2 / \langle Q \rangle$. We will use existing optical setups and ~ 3 eV photons from a 400 nm second harmonic generator in Figueroa’s lab, but need to procure a vacuum vessel, vacuum pump, a cryocooler, and electronics. We will use a Skipper-CCD from the SENSEI Collaboration, which has a surplus of them. The **outcome** of this work will be a crucial measurement of the Fano factor in silicon at 3 eV, which is near the lowest energy of interest for DM events. The **expected significance** is that this will provide a crucial measurement of the precise sensitivity to $\sim$ MeV-scale DM in SENSEI, DAMIC-M, SuperCDMS, and other experiments sensitive to DM-electron recoils; in addition, it will provide a crucial measurement with which to test condensed-matter-theory models of secondary interactions of electrons in silicon.
2. **Specific Aim 2: Measure Quantum Efficiency of Skipper-CCD.** Based on measurements of ordinary CCDs used in the Dark Energy Spectroscopic Instrument (DESI), which have a similar anti-reflective coating, the quantum efficiency of Skipper-CCDs is believed to be above 90%. However, in order to use Skipper-CCDs in quantum technology applications, we must characterize them fully at the quantum level. For these purposes, we will build on the experiment designed for Specific Aim 1, but use an entangled-photon source in Figueroa’s lab, to measure the quantum efficiency of the Skipper-CCD to at least $\sim 2\%$ precision. The **out-**

come of this work will be the most precise measurement to date of the quantum efficiency of the Skipper-CCD ($\sim 2\%$). The **expected significance** is that such characterization will define clear possibilities to use Skipper-CCDs in a plethora of new applications in quantum science, such as direct quantum imaging of entanglement, shot-by-shot measurement of quantum correlations among pairs of photons, and characterization of entanglement swapping in long-distance quantum communication networks.

3. **Specific Aim 3: Simulate Radiogenic Backgrounds in SENSEI-100.** Precise knowledge of the expected radiogenic backgrounds is crucial for any DM direct-detection search, not only to place limits but especially for claiming a discovery. While SENSEI Collaboration members have gained valuable experience from working on DAMIC-100 at SNOLAB [19], which has similar shielding requirements to SENSEI-100, a precise estimate is lacking for $E_e < 60$ eV, which contains most of the DM-electron scattering signal. In an effort led by TAU, we propose to simulate these backgrounds for SENSEI-100 using a detailed GEANT4 simulation and a precise detector model. The **outcome** of this work will be to provide a crucial ingredient that, together with the outcome of Specific Aim 5, will allow us to develop a precise background model for SENSEI-100. The **expected significance** is that this will help the SENSEI Collaboration to claim a DM discovery in the case we see an excess of events or otherwise allow us to place the strongest constraints possible on DM with our data.
4. **Specific Aim 4: Design Data Acquisition System for SENSEI-100.** The TAU group proposes to lead the design of the data acquisition (DAQ) system for SENSEI-100, which is significantly more involved than for SENSEI-10 given the increased amounts of data and number of channels from different boards. TAU will custom-design the DAQ, leveraging their extensive experience gained at their lab with existing detectors. The **outcome** of this work will be a DAQ system for SENSEI-100. The **expected significance** is that this will allow us to collect the complex and large amounts of data to perform the world's most sensitive search for sub-GeV DM.
5. **Specific Aim 5: Measure Compton Spectrum between a few eV to 60 eV.** Compton scattering of photons off electrons will be a small, yet dominant, background for the SENSEI DM search, see Fig. 1 (right). However, the shape of the Compton spectrum has only been measured down to ~ 60 eV (see e.g. [20], which used an ordinary CCD). Moreover, simulations of the spectrum must rely on theoretical calculations of the silicon band structure for energies below ~ 50 eV, which is less reliable than a measurement. We propose therefore to measure the Compton spectrum for the first time for energies of $\sim 1 - 60$ eV, which includes the energy range of interest for DM-electron scattering events. Funds exist at TAU to procure the needed vacuum vessel, cryocooler, vacuum pump, and electronics. This system would be distinct from the one at SBU, since it will use an x-ray source and does not require a vacuum chamber with a window. The **outcome** of this work will be to measure for the first time the shape of the Compton spectrum between a few to 60 eV, which provides the second crucial ingredient (in addition to the outcome of Specific Aim 3) to develop a precise background model for SENSEI-100. The **expected significance** is that this measurement will inform the shape of the dominant radioactive background in DM searches with electron recoils and thus benefit the search for DM with SENSEI, DAMIC-M, and SuperCDMS. It will also provide a crucial cross-check of Condensed Matter theory calculations of the Compton spectrum below 50 eV, where the silicon band structure becomes important.
6. **Specific Aim 6: Analyze SENSEI Dark Matter Search Data.** SENSEI will yield the world's most sensitive data on sub-GeV DM, which we propose to analyze in detail. The **outcome** of this work will be a careful and detailed analysis of the SENSEI DM data. The **expected**

significance is that this will provide the most stringent constraints on many DM models with masses in the MeV-to-GeV and eV-to-keV range or, possibly, a high-value discovery.

The proposed research is a collaborative effort between members of the SENSEI Collaboration: Co-PIs Figueroa and Essig at SBU, Co-PIs Barak and Volansky at TAU, and Collaborators Etzion at TAU as well as Estrada and Tiffenberg at Fermilab. Letters of Collaboration are attached.

We are requesting NSF funds for equipment, materials, and supplies as well as support for one SBU graduate student for Specific Aim 1 (Particle Astrophysics - Experiment) and Specific Aim 2 (Quantum Information Science); and 0.5-month summer salary for the SBU Co-PIs to oversee this work and take part in Specific Aim 6, with Figueroa focused more on the experimental aspects and Essig focused on the data analysis and its interpretation. From the BSF, we are requesting funds for one graduate student at TAU to work on Specific Aims 3, 5, and 6, and one postdoc at TAU to work on Specific Aims 4, 5, and 6. Travel funds from both NSF and BSF are also requested to facilitate collaboration between all Co-PIs.

We note that while the design and procurement of the equipment for the SENSEI DM search, and its deployment at SNOLAB, are fully funded by a grant from the Heising-Simons Foundation, no funds exist for the proposed research in this proposal. In particular, Specific Aims 1 (funded by NSF) and 5 (funded by BSF) propose auxiliary measurements of silicon properties with new, dedicated experiments, which are clearly distinct from the DM search, but will be crucial in order to maximize the science gain of the DM search by SENSEI, DAMIC-M, and SuperCDMS. NSF funds would further be used for Specific Aim 2, namely to measure a fundamental property of Skipper-CCDs. This would also establish a new SENSEI Quantum Characterization Facility at SBU, aimed at characterizing Skipper-CCDs as a quantum technology and, in the intermediate term, exploring their applications in Quantum Information Science, such as experiments related to highly sensitive imaging of quantum correlations and ultra-low noise measurements of entanglement rates. Specific Aims 3 and 4 are proposed activities to be based at TAU and funded by the BSF; SENSEI would benefit greatly from the TAU group's expertise and joint collaboration. Specific Aim 6 requires funding from both NSF and BSF, without which the data analysis would be severely manpower-limited.

2 Background

2.1 SENSEI and the Direct Detection of Dark Matter

Direct-detection experiments are an essential laboratory tool to identify DM. The traditional technique is to search for ~ 10 keV-scale nuclear recoils characteristic of Weakly Interacting Massive Particles (WIMPs) with masses $\gtrsim 1$ GeV scattering off nuclei in a detector [21]. Design and construction advances over the last few decades have led to many orders of magnitude improvement in sensitivity [22].

Significant advances in DM theory over the past decade have highlighted other well-motivated (non-WIMP) DM candidates, in particular Hidden-Sector DM with mass below the GeV scale. The traditional nuclear-recoil search is, however, unable to probe sub-GeV Hidden-Sector DM, which give too little energy to the nucleus (below detector thresholds). Fortunately, the last few years has also seen several ideas for detecting sub-GeV DM, see [3, 2] for recent reviews. The first paper on this topic was written in 2011 by Co-PIs of this proposal [4] and suggested a search for *low-energy electron recoils*. Significant recent technological advances by the SENSEI Collaboration using Skipper-CCDs [1, 8] and by the SuperCDMS Collaboration using a Transition-Edge-Sensor-based device [23, 24] have demonstrated sensitivity to signals as small as one electron. The implications of this for the search of sub-GeV DM are profound, since such DM typically only produces a few ionized electrons, well below the energy threshold of previous detectors.

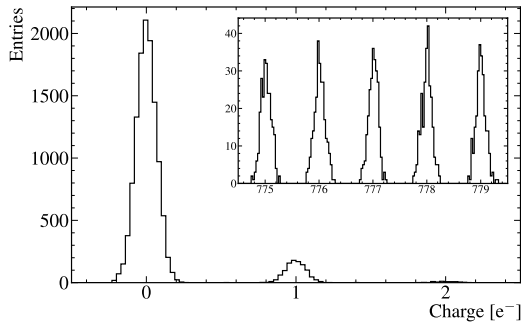


Figure 2: Single-electron charge resolution using a Skipper CCD from [1]. The measured charge per pixel is shown for low (**main**) and high (**inset**) illumination levels. Integer electron peaks can be distinctly resolved in both regimes contemporaneously. The 0 e^- peak has rms noise of 0.068 e^- rms/pixel while the 777 e^- peak has 0.086 e^- rms/pixel, demonstrating single-electron sensitivity over a large dynamical range.

The Skipper-CCDs ability to measure precisely the number of free electrons in each of the million pixels across the CCD is illustrated in Fig. 2. As discussed in §1, the SENSEI Collaboration is constructing a detector to search for DM, which consists of 100-grams of Skipper-CCDs. It will be deployed at SNOLAB (see Fig. 7 for the timeline). SENSEI will be the most sensitive dedicated direct-detection search for sub-GeV DM in the next few years. DAMIC-M is planning to put together 1-kg of Skipper-CCDs over a longer timescale (we note that the SENSEI and DAMIC-M collaboration are currently distinct collaborations with no overlapping members).

Besides the DM search, Skipper-CCDs present a remarkable new technology with other applications. Due to its intrinsic ultra-low noise and high quantum efficiency, Skipper-CCDs have intriguing prospects for their use in quantum technology applications, including quantum imaging, as discussed next.

2.2 Quantum Imaging with Skipper-CCD Cameras

Photonic entanglement has become a remarkable resource in the development of quantum technologies. Due to the energy-momentum correlations present in Einstein-Podolsky-Rosen photon pairs, it is an important goal to characterize these correlations in real time with high quantum efficiency. This will allow important quantum applications such as imaging high-dimensional entanglement and the study of generalized Bell [25, 26, 27].

Spatial characterization of such entangled states with single-photon sensitive cameras has been attempted in the past. However, most of these measurements used resource-intensive methods, such as sequential scanning or multiple standalone detectors. Early studies of entanglement imaging used an EMCCD camera with a frame readout-rate of 5 Hz. Although the EMCCD quantum efficiency was up to 90%, the noise is significantly worse than shot-noise due to Poisson statistics, which makes it an inefficient tool to measure multiple photons in the same pixel [28, 29, 30, 31].

Another approach for quantum entanglement imaging is using intensified CMOS and CCD cameras. For example, an intensified sCMOS camera was used to observe Hong-Ou-Mandel interference, where the entangled photons were collected on a 700×22 pixel area at a framing rate of 7 kHz. However, the quantum efficiency for these intensified devices is less than 10%; moreover, their noise is also larger than the shot noise [32, 33, 34, 35].

The big advantage of Skipper-CCDs compared to these other devices is that Skipper-CCDs have no intrinsic charge multiplication and are able to measure *precisely* the number of electrons in a pixel, even if the pixel contains as many as $\mathcal{O}(1000)$ electrons [1], see Fig. 2. This opens up the exciting possibility to do sub shot-noise quantum imaging with many photons per pixel. (We also note that our Fermilab Collaborators Estrada and Tiffenberg, with S. Holland from LBL, are already working on designing Skipper-CCDs with faster readout than the currently available designs.) In addition, SENSEI has measured the dark counts in prototype Skipper-CCDs, finding values as low as 3×10^{-3} electrons/pixel/day [36], several orders of magnitude lower than measured in the best EMCCDs or ICCDs. The new Skipper-CCDs procured for the SENSEI DM search are expected to have even lower DC rates. This provides ultra-low background levels that, together with the high quantum efficiency, could potentially change the landscape of quantum entanglement

imaging and characterization experiments. For example, they could be applied in twin imaging experiment aimed to characterize the quantum correlations of the entangled photons in real time.

3 Results from prior NSF Support

Co-PIs **Essig, Barak, and Volansky** have no prior NSF support.

Co-PI Figueroa has prior support: “Full Characterization of a Cavity Electromagnetically Induced Transparency Based Quantum Gate” (NSF PHY-1404398, 09/01/2014 - 08/31/2017, \$561,548), “Full Temporal Characterization of Interacting Photon Wavefunctions Using Real-Time Multi-Mode Quantum Measurements” (NSF PHY-1707919, 09/01/2017 - 08/31/2020, \$507,717) and “Icorps: Quantum hardware package for fully-secure long-distance data transfer” (NSF 1811244, 01/01/2018 - 01/01/2019, \$50,000).

Intellectual merits:

Single-photons at rubidium transitions.

Generating single-photon sources with high brightness that are compatible with atomic interaction still remains one of the bigger challenges of the quantum communication community. We have engineered a low bandwidth (MHz range), SPDC-based photon source tuned to the Rb transitions. We employ an optical-parametric amplifier (OPA) composed of a Type II collinear down-conversion crystal situated in the spatial mode of a bow-tie resonator optically pumped below threshold. The emerging SPDC-created photons are matched to the longitudinal mode of the cavity and forced to efficiently transmit through the cavity out-coupling mirrors. As a consequence, the probability that the produced quantum field interferes constructively with subsequently photon creation events is increased, and upon emission they match the bandwidth dictated by the cavity design.

Quantum imaging of entanglement.

Recently we have shown how a development from the high-energy physics community – the intensified Tpx3Cam camera – can be converted into a quantum characterization device of photonic polarization entanglement. In a collaborative experiment between SBU and Brookhaven National Laboratory, we have studied the characterization of SPDC-based quantum polarization entanglement using fast 2D imaging with a Tpx3Cam. We have imaged and time-stamped a continuous stream of entangled photons with excellent spatial and temporal resolution ($55 \times 55 \mu\text{m}^2$, 1.5 ns), providing a high signal-to-background ratio.

Broader impacts:

A robust and technologically simple single-photon source tuned to Rb atoms is useful for a wide variety of technological applications. It will also allow to test the predictions of many theoretical ideas. We have designed our setup aiming for flexibility and room temperature operation, with the capability of discrete operation (single-photons) or continuous variable (squeezed light). Further developments will lead to a next miniaturized version of the current setup. Also, using an NSF ICorps grant, the room temperature quantum technology has been tested in a program looking for possible commercialization scenarios.

4 Intellectual Merit: Proposed Research

The SBU part of the proposal will be dedicated to establishing a new “SENSEI Quantum Characterization Facility” in the SBU Dept. of Physics and Astronomy, which includes equipment already available in the Figueroa Quantum Technology laboratory and dedicated infrastructure to measure the quantum properties of the Skipper CCDs.

4.1 Specific Aim 1: Measure Low-Energy Fano Factor of Silicon

Electrons in silicon can be excited by interactions with, for example, photons or DM from the valence to the conduction band across a band gap of $E_{\text{gap}} \sim 1.1 \text{ eV}$ [37]. The resulting energy of the

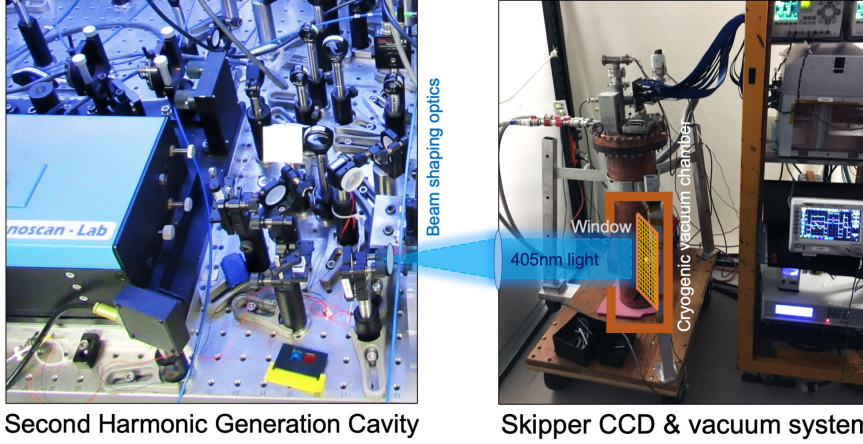


Figure 3: **Schematic experimental setup to measure Fano factor at 400 nm (~ 3 eV) for Specific Aim 1.** Shown are the master laser, second harmonic generation cavity (SHG), stabilization laser, and electronics. The blue laser is attenuated and sent to an optical setup for beam shaping and expansion. The large beam is sent to the vacuum system containing the Skipper-CCD (shown schematically).

recoiling electron, E_e , is redistributed into some number of electron-hole pairs, Q , as the recoiling electron relaxes to the bottom of the conduction band. Experiments such as SENSEI only directly measure Q , rather than the theoretically predicted E_e , so knowing the conversion from E_e to Q is a crucial step in calculating the experimental sensitivity.

The exact modeling of this conversion is extremely challenging. A phenomenological model that works well at $\mathcal{O}(\text{keV})$ (much higher than the energies of interest here) suggests that

$$\langle Q(E_e) \rangle = 1 + \lfloor (E_e - E_{\text{gap}})/\varepsilon \rfloor, \quad (1)$$

where $\lfloor x \rfloor$ rounds x down to the nearest integer, $\langle Q \rangle$ is the average Q , and $\varepsilon \simeq 3.8$ eV is the mean energy needed to create an additional electron-hole pair in silicon (as measured in high-energy recoils) [38]. Fluctuations around the average Q are captured by the Fano factor, $F \equiv \sigma_Q^2/\langle Q \rangle$. A recent measurement by the DAMIC Collaboration, using ordinary CCDs, found that $F \sim 0.13$ at $E_e \sim 5$ keV [20]. However, electron recoils from DM scattering typically have $E_e \sim 1 - 50$ eV (see Fig. 1 (right)), well below existing measurements. While there are reasons to trust the extrapolation of Eq. (1) and have constant F down to these low energies [38, 39, 5], a *measurement is necessary for a proper calibration. With the advent of the Skipper-CCD, such a measurement is now possible.*

The SBU team proposes to measure the Fano factor at ~ 3 eV, which is near the lowest energy of interest for DM events. The first part of the project will be to engineer and implement the vacuum system to host the Skipper-CCD. This vacuum chamber will have a custom design intended for maximal optical access, with anti-reflection-coated windows for wavelengths between 400 – 800 nm. The acquisition electronics of the Skipper-CCD will be procured through Fermilab Collaborators Estrada and Tiffenberg, who will also provide advice on setting up the SBU system.

The second part of the project will be to connect the Skipper-CCD setup to the optical setup. We will use as a source the existing laser system in Co-PI Figueroa’s laboratory. A tapered amplified diode laser will produce radiation at 795 nm, and a second harmonic generation cavity will frequency double the light to produce a wavelength of $\lambda = 397$ nm. This blue light will be attenuated and sent to an optical setup for beam-shaping and expansion. The resulting photons will then pass through the transparent window of the vacuum vessel to illuminate a Skipper-CCD, see Fig. 3.

We expect that the 397 nm (~ 3) eV photons impinging on the silicon of the Skipper-CCD will produce $\langle Q \rangle = 1$, but since their energy is more than $2E_{\text{gap}}$, Fano factor fluctuations could occasionally allow for $Q = 2$. The distribution of the $Q = 1$ and $Q = 2$ events will give a measurement of the Fano factor. We note that dark counts from thermal excitations of electrons will produce a Poisson-distributed background rate that can be measured independently and needs to be subtracted. Also, two photons impinging on the same pixel can also produce events with

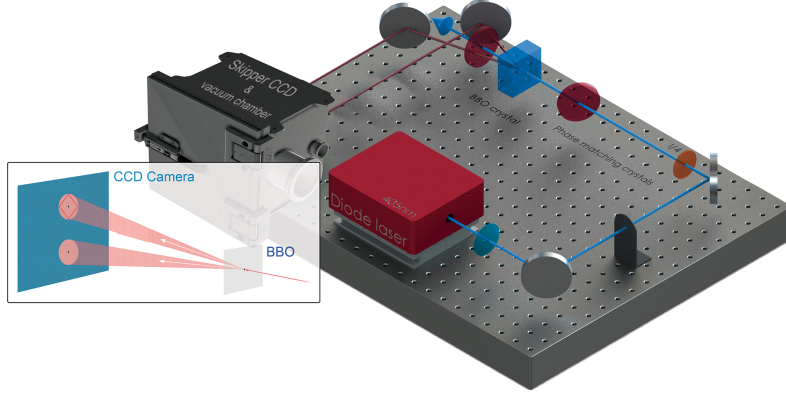


Figure 4: **Schematic experimental setup for measuring the Skipper-CCD quantum-efficiency.** The source utilizes a blue pump laser diode tuned to a wavelength of $\lambda = 405$ nm and a pair of Type I BBO crystals with optical axes perpendicular to one another to generate signal and idler photons entangled in polarization at a wavelength of $\lambda = 810$ nm; these travel without losses to a vacuum chamber with a special optical access window. **Inset:** Concept of the quantum efficiency measurement using the simultaneous imaging of photons in the Skipper-CCD.

$Q = 2$, but this “background” can be understood by keeping the illumination of the Skipper-CCD low and repeating the experiment multiple times.

The **outcome** of this work will be a crucial measurement of the Fano factor in silicon at 3 eV, which is near the lowest energy of interest for DM events. The **expected significance** is that this will provide a measurement of the precise sensitivity to $\sim$ MeV-scale DM in SENSEI, DAMIC-M, SuperCDMS, and other experiments sensitive to DM-electron recoils; in addition, it will provide a crucial measurement with which to test condensed-matter-theory models of secondary interactions of electrons in silicon.

4.2 Specific Aim 2: Measure Quantum Efficiency of Skipper-CCD

The SBU team also *proposes to build a second experiment in the SENSEI SBU Quantum Characterization Facility to measure the quantum efficiency of the Skipper-CCD to $\sim 2\%$ precision.* Its quantum efficiency has never been measured before, although we expect it to be above 90% based on measurements of DESI CCDs that have the same anti-reflective coating [40].

For the proposed experiment, the SBU team will use a polarization-entanglement source utilizing a blue pump laser diode tuned to wavelength $\lambda = 405$ nm, and a pair of Type I non-collinear BBO crystals with optical axes perpendicular to one another to generate signal and idler photons at wavelength $\lambda = 810$ nm, see Fig. 4. The first crystal optical axis and the pump beam define the vertical plane. Owing to Type I phase matching, an incoming photon that is vertically polarized gets down-converted and produces two horizontally polarized photons in the first crystal, whereas a horizontally-polarized photon going through these crystals would get down-converted in the second crystal producing two vertical photons. An additional pair of birefringent crystals will ensure maximum spatial overlap of the down-converted photons by pre- and post-compensating for differences in effective optical path lengths of signal and idler photons. The produced state has the form $|\phi^\pm\rangle = \frac{1}{\sqrt{2}}(|HH\rangle \pm |VV\rangle)$.

Both optical modes of the entanglement source will then impinge onto the Skipper-CCD, with each of the two 800 nm (1.5 eV)-photons creating a single electron-hole pair (since the photon energy is below twice the band gap, there are no Fano-factor fluctuations that create two electron-hole pairs from a single photon). Due to the entanglement properties, these two events will be located on opposite sides of a circle on the CCD. We will perform a statistical measurement where many twin detections are gathered along the circle. Due to the quantum efficiency not being unity, one of the photons in the pair will occasionally not be detected. The variance of the distribution of the number of events on opposite sides of the circle (i.e., the relative efficiency) can be shown to be directly correlated with the quantum efficiency. (Note that therefore we do *not* need to know the precise number of incoming photons to measure the quantum efficiency.)

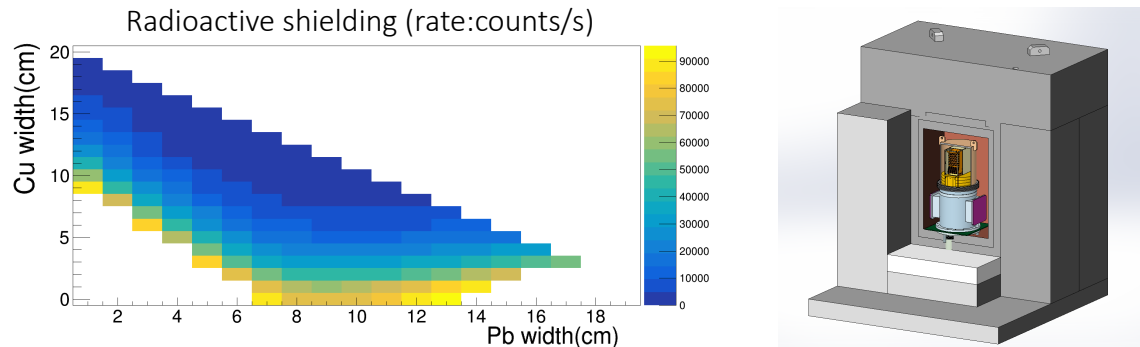


Figure 5: **Left:** Preliminary results on the background-rate simulations varying the lead and copper thicknesses. **Right:** Current model of the SENSEI-100 DM detector inside its shielding.

The **outcome** of this work will be the most precise measurement to date of the quantum efficiency of the Skipper-CCD ($\sim 2\%$). The **expected significance** is that such characterization will define clear possibilities to use Skipper-CCDs in a plethora of new applications in quantum science, such as direct quantum imaging of entanglement, shot-by-shot measurement of quantum correlations among pairs of photons, and characterization of entanglement swapping in long distance quantum communication networks. These topics are of current interest to the DoE, which could translate into important future collaborations between SBU and Fermilab or other laboratories.

4.3 Specific Aim 3: Simulate Radiogenic Backgrounds in SENSEI-100

Understanding precisely the various backgrounds, such as cosmic rays or gamma radiation from various radioactive contaminations in the shield, is essential for the search of dark matter in a “background-free” environment. Moreover, a reliable radiogenic background estimation is required in order to design an optimal shield, which for SENSEI-100 will consist of layers of copper and lead.

Based on the DAMIC measurements performed at SNOLAB, we can model the radiation rates of the expected contaminants in lead, namely U^{238} , U^{235} , Th^{232} , K^{40} , Cs^{137} , Co^{60} , and Po^{210} . We propose to determine the widths of the lead and copper shielding layers needed given the constraint from the vessel’s size (which limits the total shielding to 20 cm).

Preliminary studies by the TAU group, which do not yet take into account the precise SENSEI-100 detector setup at SNOLAB, are shown in Fig. 5 (left). They demonstrate that the lowest background rates are achieved for a mix of 6.6 cm lead and 13.4 cm copper. These results were obtained using GEANT4.

We propose to validate these preliminary results. We then propose to take into account the detailed detector setup and the various expected background sources (such as alpha radiation) and run a detailed simulation of the expected background rates and their energy distributions. We will use GEANT4 for the simulations. Fig. 5 (right) illustrates the current design of the SENSEI-100 detector at SNOLAB. The proposed work is going to be led by a graduate student at TAU.

The **outcome** of this work will be to provide a crucial ingredient that, together with the outcome of Specific Aim 5, will allow us to develop a precise background model for SENSEI-100. The **expected significance** is that this will help the SENSEI Collaboration to claim a DM discovery in the case we see an excess of events or otherwise allow us to place the strongest constraints possible on DM with our data.

4.4 Specific Aim 4: Design Data Acquisition System for SENSEI-100

A challenge in SENSEI-100 is the aggregation of the data arriving simultaneously from many distinct Skipper-CCDs. This task is simpler and will be treated efficiently in SENSEI-10 with the

data arriving in Ethernet format (using standard data protocols) from four boards, each carrying four channels connected to an FPGA. Each board will readout a single Skipper-CCD, which contains four readout nodes, and all data will be processed using a single software package.

The complexity increases significantly in SENSEI-100 where 40 boards will be needed, resulting in 160 channels in total. To process all channels in parallel and control all boards in a synchronized manner, an efficient computing environment is required. Moreover, the data read by a single image occupies 50GB of space per Skipper-CCD, totaling to 2TB per readout in SENSEI-100. As a consequence, the collected data must be processed and compressed in real time, either on the computer or the FPGA.

In an effort led by TAU, we propose to explore several manners to tackle the computing challenge, either by utilizing a single PC or by using multiple ones in conjunction with connecting the various LTAs (low-threshold acquisition) electronic systems through a bridge. The system will enable a full synchronization of the boards, parallel readout of all Skipper-CCDs, and compression of the data.

The **outcome** of this work will be a DAQ system for SENSEI-100. The **expected significance** is that this will allow us to collect the complex and large amounts of data to perform the world's most sensitive search for sub-GeV DM.

4.5 Specific Aim 5: Measure Compton Spectrum between a few eV to 60 eV

Photons from radioactivity near the SENSEI DM detector can Compton scatter off electrons in the silicon and generate an ionization signal that can mimic the DM signal. While the dominant Compton background will be at much higher energies ($> \mathcal{O}(\text{keV})$) than the signal from sub-GeV DM scattering off electrons (1–50 eV, see Fig. 1 (right)), a tail nevertheless persists down to eV energies. The normalization and shape of this Compton background can be reliably estimated using both simulations and theory at energies above ~ 50 eV, but for energies below ~ 50 eV, the band structure of silicon will play an important role. Moreover, current measurements of its shape only extend down to ~ 60 eV [20], since they were done with an ordinary CCD that has a large noise. With the advent of the Skipper-CCD, we can extend this measurement to eV scales.

The TAU group proposes to build an experiment to measure the Compton spectrum between a few eV to 60 eV. The experimental setup is shown schematically in Fig. 6: a gamma-ray source (^{241}Am) is put inside a vacuum chamber and illuminates a Skipper-CCD with high-energy photons. A thin shield is placed between the source and the Skipper-CCD to remove α -particles.

The **outcome** of this work will be to measure for the first time the shape of the Compton spectrum between a few to 60 eV, which provides the second crucial ingredient (in addition to the outcome of Specific Aim 3) to develop a precise background model for SENSEI-100. The **expected significance** is that this measurement will inform the shape of the dominant radioactive background in DM searches with electron recoils and thus benefit the search for DM with SENSEI, DAMIC-M, and SuperCDMS. It will also provide a crucial cross-check of Condensed Matter theory calculations of the Compton spectrum below 50 eV, where the silicon band structure becomes important.

4.6 Specific Aim 6: Analyze SENSEI Dark Matter Search Data

The timeline for the SENSEI DM Search is shown in Fig. 7. SENSEI will collect the world's most sensitive direct-detection data on sub-GeV DM in the next 2–3 years. The SBU and TAU teams *propose to analyze this data in detail.*

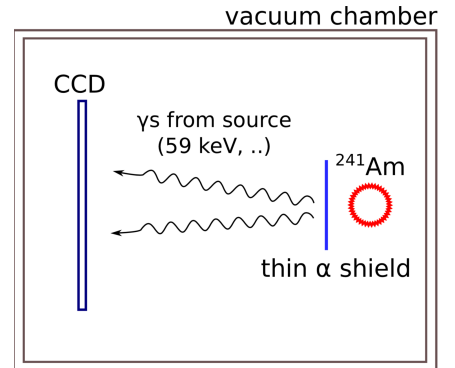


Figure 6: Schematic setup for the Compton measurement at TAU.

After validating the Skipper-CCD detectors for the SENSEI DM search, the first step will be to study the dark counts (DC) arising from thermal fluctuations. SENSEI has measured the dark counts in prototype Skipper-CCDs, recently finding values as low as 3×10^{-3} electrons/pixel/day [36]. We will measure the DC rate of the new Skipper-CCDs procured for the SENSEI DM search and study their statistical distribution, which is expected to follow a Poisson distribution. We will also need to identify localized sources of noise that can arise from, e.g., soft photon emission from the sense-node amplifier or “bad” pixels with an excess of noise due to localized impurities. Some preliminary tools to carry out such analyses have already been developed using our current prototype Skipper-CCD detector [8, 36], but a significantly improved analysis will be necessary for the quieter new detectors.

With a detailed understanding of the backgrounds, we will search for sub-GeV DM. We will investigate several models giving rise to distinct spectra, including DM-electron scattering [4, 5], DM-electron absorption [6, 7, 41], as well as bremsstrahlung [42, 43] and the Migdal effect [44] from DM-nucleus interactions. To ensure an unbiased analysis, we propose to design a blinded procedure for which the cuts will be designed on a small fraction of the data. Cuts include fiducialization due to external noise and vetoing of noisy pixels and high-energy events. With the expected DC and a minimal set of cuts we expect background-free data with a two-electron threshold.

The **outcome** of this work will be a careful and detailed analysis of the SENSEI DM data. The **expected significance** is that this will provide the most stringent constraints on many DM models with masses in the MeV-to-GeV and eV-to-keV mass range or, possibly, a high-value discovery.

5 The Co-PIs’ Roles and Benefits of the SBU-TAU Collaboration

Here we discuss the role of each of the SBU and TAU co-PIs and explain how they will collaborate together. In addition, we explain the role of the unfunded Fermilab Collaborators.

The proposed research is a collaborative effort between members of the SENSEI Collaboration. Co-PI Figueroa is a leading expert on quantum information science and has extensive experience in quantum imaging and quantum sensing. His vision is to build a new SENSEI Quantum Characterization Facility at SBU, with the long-term goal of developing novel applications of Skipper-CCDs in quantum technology for quantum imaging and sensing. Co-PIs Essig and Volansky are both particle theorists and co-spokespeople for SENSEI. They were the first to propose the search for sub-GeV DM by searching for its interactions with electrons [4], and followed up extensively on this and related topics [1, 8, 5, 6, 45, 46, 47, 48, 49, 50]. Essig has co-led several US community efforts that survey the physics case and detection ideas for sub-GeV DM and dark sectors [2, 3, 51, 52, 53]. Essig and Volansky have a long history of collaborating on experimental projects (besides SENSEI); e.g., Essig is a co-spokesperson of APEX [54] and a member of HPS [55, 56] (both of which will take new data in 2019) and LBECA [3], and Volansky is working on an experiment that aims to use color centers for DM detection [49] and has served as a short-term member of the ATLAS experiment [57, 58]. Co-PI Barak is a leading expert on experimental particle physics with extensive experience with analysis, background simulation, and data acquisition. The unfunded Collaborators on this proposal include Estrada and Tiffenberg (Fermilab), who have led the development of CCDs, and Skipper-CCDs in particular, as an ultrasensitive tool to search for DM; and Etzion, who is also a leading expert on experimental particle physics with extensive experience with detector physics, analysis, background simulation, and data acquisition. The SBU, TAU, and Fermilab groups have already collaborated closely on SENSEI and will also collaborate closely on the proposed research. Letters of Collaboration are attached.

A unique strength of this proposal is the combination of theorists and experimentalists from particle physics and quantum information. This combination is crucial due to the interdisciplinary nature of the proposal. We anticipate the following collaborations on this proposal:

- **Specific Aims 1 & 2:** These sub-projects will be based at SBU in Figueroa’s lab, with close collaboration with Estrada and Tiffenberg at Fermilab. The data analysis will be in collaboration with Essig and the TAU group, who will be developing the corresponding tools and expertise and who will be closely involved in interpreting the data.
- **Specific Aims 3 & 4:** Barak and Etzion are experts in the study of radiogenic backgrounds and in designing and building DAQ systems. These two tasks will be performed at TAU in collaboration with the Fermilab group, who have extensive experience in studying backgrounds for the DAMIC experiment [59]. Essig and Volansky will also help with providing extensive physics input to the background studies.
- **Specific Aim 5:** A dedicated lab to carry out this experiment will be built in the clean room in TAU. The design will be made in collaboration with Figueroa who will build a related setup for the Fano factor and quantum efficiency measurements, as well as with Estrada and Tiffenberg who are the world-leading experts in Skipper-CCDs and have extensive experience with the design of such a setup. Data analysis of the experiment will be done in collaboration with Essig, Figueroa, and Volansky.
- **Specific Aim 6:** This effort will be led by Essig and Volansky who have experience with data analysis and statistical studies in general, with Skipper-CCDs in particular [8, 36], and with deriving implications of the data for DM models. Barak, Etzion, Figueroa, Estrada, and Tiffenberg will collaborate closely, given their varied and extensive experience with data analysis.

Currently, the only working Skipper-CCD system is at Fermilab built by Tiffenberg and Estrada. An important goal of this proposal is to enable the development of a Skipper-CCD system at SBU and TAU, which would not only allow us to perform important auxiliary measurements that will benefit the search for sub-GeV DM by SENSEI, DAMIC-M, and SuperCDMS, but also develop other novel applications in quantum imaging and quantum sensing. Correspondingly, the Co-PIs and their groups will have frequent visits at Fermilab as well as at each other’s institutions, to gain expertise on the Skipper-CCD system and to collaborate closely on the proposed research. **The proposal will undoubtedly seed new collaborations between researchers of distinct disciplines and help train a new generation of scientists versed in particle physics and quantum information.**

6 Timeline and Resources

The timeline of the proposed research is shown in Fig. 7. In blue, we show the approximate timeline of the SENSEI DM search. The ~ 10 -gram detector (SENSEI-10) will commence operation around the second quarter of 2019, while a 100-gram detector (SENSEI-100) will commence operation about a year later. Both detectors will require commissioning and SENSEI-100 may take data for longer than one year. For SBU (orange), the first year will be spent procuring the vacuum chamber (with a transparent window), cryocooler, vacuum pump, and electronics, as well as setting up the experiment and becoming familiar with operating the Skipper-CCD. In the second year, SBU will measure the Fano factor (Specific Aim 1), which will help inform the final SENSEI-100 DM analysis. Towards the end of the second year and into the third year, SBU will measure the quantum efficiency of the Skipper-CCD (Specific Aim 2). The analysis of the data will be finalized in the few months after completing the measurement, in collaboration with TAU.

At TAU (green), the first year will be devoted by the postdoc to prepare the DAQ for SENSEI-100 and by the student to perform the background simulations to finalize the background prediction for SENSEI-100. Towards the end of the first year, a Skipper-CCD system will be set up at TAU that will be very similar to SBU (except there is no need for a transparent window), and the postdoc will get familiar with it. Then, in the middle of the second year, the postdoc, with help from the

TIMELINE FOR PROPOSED RESEARCH AT SBU, TAU, AND JOINT

	2019			2020			2021			2022			
PROPOSAL DURATION				9/1/2019 — 8/30/2022									
SENSEI Dark Matter Search		SENSEI-10			SENSEI-100								
Specific Aim 1: Low-Energy Fano Factor				Procure Equip. Set-up Exp.		Measure Fano Factor		Finalize Analysis					
Specific Aim 2: Quantum Efficiency of Skipper-CCD										Measure QE		Finalize Analysis	
Specific Aim 3: Simulations of Radiogenic Backgrounds				Simulate Backgrounds									
Specific Aim 4: Data Acquisition for SENSEI-100				DAQ									
Specific Aim 5: High-Energy Fano Factor and Low-Energy Compton Spectrum					Procure Equip. Set-up Exp		Measure Compton spectrum			Finalize Analysis			
Specific Aim 6: Data Analysis of SENSEI DM search data			Analysis of DM Data										

Figure 7: **Timeline of the proposed research.** SBU, TAU, and joint SBU-TAU activities are shown in orange, green, and purple, respectively.

student, will measure the Compton spectrum. Funds exist at TAU to procure the needed equipment (a vacuum chamber, cryocooler, vacuum pump, and electronics). However, no funds exist at TAU for a student or postdoc and traveling to SBU and Fermilab/SNOLAB.

7 Future of Skipper-CCDs in Quantum Technologies

Having performed the full quantum characterization of the properties of the Skipper-CCD will be essential to design new applications of these devices in quantum technology related tasks.

In the intermediate term, we envision that Skipper-CCD cameras can prove useful in quantum information processing tasks needing high quantum efficiency and ultra-low noise performance. They can become the detecting devices in protocols aimed at distributing entanglement over long-distance for quantum communication, as they could allow entanglement swapping procedures despite low experimental rates. The intrinsic characteristic of the Skipper-CCD cameras can also be used in experiments where Bell state characterization with high fidelity is paramount, such as teleportation between photons and quantum memories, and the study of the violation of the CHSH (Clauser-Horne-Shimony-Holt) inequality measured over long distances [60, 61].

In the long term, the Skipper-CCD technology can find a niche in applications in quantum communication needing real time measurements and feedback of photo beams in long-distance free-space quantum channels. Furthermore, the ultra-low noise and scalability of the Skipper-CCD camera makes it a very suitable candidate as a measurement device in multi-node large quantum repeater networks [62, 63].

8 Broader Impacts

There are broader impacts of the proposed research and activities by the SBU and TAU Co-PIs.

8.1 Broader Impacts from Proposed Research

- The measurement of the Fano factor is a key measurement of a fundamental property of silicon, which define the resolution and performance of silicon detectors. It will be highly valuable not only for the SENSEI DM search – where it will allow us to set more accurate limits or, in the case of a discovery, quantify the DM mass and interaction strength more accurately – but also for other DM direct-detection experiments that search for electron recoils from DM interactions in silicon detectors, including DAMIC-M, SuperCDMS, and others.
- Similarly, the proposed measurement of the Compton spectrum will be invaluable to all DM direct-detection experiments that search for electron recoils from DM interactions in silicon

detector, since it is the main radiogenic background.

- The measurement of the Fano factor and Compton spectrum will also allow the testing of condensed matter theory calculations, which will improve our understanding of the band structure of silicon as well as improve our theoretical description of time-dependent effects, including how excited electrons relax to the bottom of the conduction band. This improved theoretical understanding will also benefit our understanding of other materials.
- A measurement of the quantum efficiency of Skipper-CCDs is a crucial ingredient for having Skipper-CCDs be used as a novel tool in quantum imaging and quantum sensing.
- This proposal is truly interdisciplinary, merging quantum information, astroparticle physics, and theoretical particle physics. The proposal will undoubtedly seed new collaborations between researchers of distinct disciplines. It will also train a new generation of scientists versed in particle physics and quantum information, and in the emerging interdisciplinary area of using quantum imaging and sensing to develop new probes for DM and other new phenomena.
- This proposal is truly international and will help the exchange of ideas and foster new collaborations between the US and Israel, a primary mission of the BSF.

8.2 Broader Impacts from the Activities by the Co-PIs that Contribute to the Achievement of Societal Relevant Outcomes

A diverse, scientifically literate population is needed in order to meaningfully affect public policy and to decide how to allocate finite resources. Moreover, to help ensure a fairer and more equal society, women and minorities need to be represented much better in science, technology, engineering, and mathematics (STEM) fields, especially in high-level positions. To this end, the SBU and TAU groups plan several activities:

(1) Mentor and Teach Undergraduate Women and Minority Students. The SBU researchers will partner with the Women in Science and Engineering (WISE) program at SBU. WISE was founded in 1993 to increase the number of women in STEM fields through outreach, rigorous academics, project-based learning, leadership skills development, recruitment, and retention efforts. The sophomore undergraduate WISE students take the class “Research and Discovery in STEM” (WSE 380), in which they first receive classroom instruction that teaches them best practices in research methodology. They then choose three projects, each 11 hours long, from a menu of approximately 15 choices. At the end of their project, the students work in small groups and present their research to their peers, faculty, and mentors. WISE has a close relationship with the Physics and Astronomy program and is in need of more mentors and project leaders.

The SBU Co-PI’s will each develop and offer one project for the WSE 380 course in the WISE program. **Figueroa’s** project will be entitled “Quantum Technology”, which will offer a comprehensive introduction to the four pillars of quantum technology, including: quantum sensing, quantum simulation, quantum communication, and quantum computing. **Essig’s** project will be entitled “What makes up 85% of the Matter in Our Universe?” It will first review the main pieces of evidence for DM, focusing on those that are easily explained with the physics and math knowledge of the WISE students (e.g., Newton’s Laws are sufficient to explain the evidence for DM from rotation curves). It will then explain a few ways that we are trying to detect DM in the laboratory, including an introduction to SENSEI.

By partnering with the well-established WISE program, we ensure that the necessary resources and administrative support are available. Moreover, WISE has in place a rigorous system that evaluates the effectiveness of each course and provides feedback to the faculty and other mentors so that activities can be improved in the future. *A letter of collaboration from Ms. Doreen Aveni, WISE Honors Program Administrator, is included as a Supplementary Document.*

(2) Mentor Middle and High School Women Students and Teachers. WISE also has a middle- and high-school program that takes place in several local school districts as well as on the SBU campus. Students from underserved school districts on Long Island, New York, work with college mentors, faculty, and graduate students, exposing them to role models as well as to innovative research. **The SBU researchers** will each be one of the mentors for the WISE middle and high school program. The students who are part of this program are expected to have a high probability of attending college and majoring in a STEM discipline. Part of the mentoring program also involves working with the teachers. Since the teachers reach a large number of students throughout the year, such teacher-mentoring is able to inspire indirectly many students to go to college and follow a STEM discipline. The mentoring involves coming up with small projects for the students, answering their questions, and serving as role models.

(3) Improve accessibility to STEM fields in Israel. **The TAU researchers** are extremely proud of their involvement in advancing STEM accessibility for students, and attempts to recruit women and underrepresented minorities. The TAU lab programs success over the last years may be credited in part to its rigorous training of undergraduate researchers. Presently TAU has three undergraduate students working at the lab and many more have participated in previous years. The TAU team also participates in extensive outreach programs (e.g., CERN Research Experience for Undergraduates). They educate a large number of graduate students who routinely present at conferences and contribute to articles as authors. In addition, the TAU team participates extensively in giving lectures to high school students and lectures, as well as training, to young elementary-school girls, since we believe that the right education should start from an early age. Co-PI Volansky is further involved with promoting and aiding women and minorities (most importantly refugees in Israel) in STEM sciences as an active member in the Israeli Young Academy of Sciences.

(4) Public Lectures. The proposed research is part of the broader scientific quest to understand the fundamental laws of Nature, including its forces and matter content. This quest is inspiring to the general public and can foster in them a deeper appreciation for science. *The Co-PIs will give public talks on their research and related topics.* A natural venue for this is provided by SBU's regular "Astronomy Open Night" [64] and the "World of Physics" [65], but there are many opportunities throughout Long Island. These talks attract a large audience of people from the surrounding areas. For example, in 2018, Essig has given two public talks entitled "The Hunt for Dark Matter", one at the Montauk Observatory and one at the Astronomical Society of Long Island. Figueroa has offered several public lectures, including "Photons and atoms sharing their secrets" and "Building a quantum network on Long Island" aimed at outside of academia public. His quantum technology laboratory is a mainstay of the SBU open weekend where local Long Island families visit the campus and learn about ongoing research.

The TAU researchers take part in public open lectures given to physics teachers and high school students and take part in the TAU public lecture series, which reach a wide audience.

(5) Graduate Education at Summer Schools. Beyond mentoring and educating physics graduate students at SBU and TAU, Essig and Volansky have helped educate a wide graduate student audience at physics summer schools. In particular, Essig has lectured at "Theoretical Advanced Study Institute in Elementary Particle Physics (TASI)" (2012), "Prospects in Theoretical Physics (PiTP)" (2017), and "Mainz Institute for Theoretical Physics" (2018), and was also responsible for shaping the program and choosing the lecturers at TASI 2016 as one of two Scientific Directors. Similarly, Volansky has lectured, e.g., at the "International School of LHC Physics" (2007), "52nd Cracow School of Theoretical Physics" (2012), and "GGI Lectures on the Theory of Fundamental Interactions" (2014). The Co-PIs plan to continue similar efforts in the future.

References Cited

- [1] J. Tiffenberg, M. Sofo-Haro, A. Drlica-Wagner, R. Essig, Y. Guardincerri, S. Holland, T. Volansky, and T.-T. Yu, “Single-electron and single-photon sensitivity with a silicon Skipper CCD,” Phys. Rev. Lett., vol. 119, no. 13, p. 131802, 2017, 1706.00028.
- [2] J. Alexander et al., “Dark Sectors 2016 Workshop: Community Report,” 2016, 1608.08632.
- [3] M. Battaglieri et al., “US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report,” 2017, 1707.04591.
- [4] R. Essig, J. Mardon, and T. Volansky, “Direct Detection of Sub-GeV Dark Matter,” Phys. Rev., vol. D85, p. 076007, 2012, 1108.5383.
- [5] R. Essig, M. Fernandez-Serra, J. Mardon, A. Soto, T. Volansky, and T.-T. Yu, “Direct Detection of sub-GeV Dark Matter with Semiconductor Targets,” JHEP, vol. 05, p. 046, 2016, 1509.01598.
- [6] I. M. Bloch, R. Essig, K. Tobioka, T. Volansky, and T.-T. Yu, “Searching for Dark Absorption with Direct Detection Experiments,” JHEP, vol. 06, p. 087, 2017, 1608.02123.
- [7] Y. Hochberg, T. Lin, and K. M. Zurek, “Absorption of light dark matter in semiconductors,” Phys. Rev., vol. D95, no. 2, p. 023013, 2017, 1608.01994.
- [8] M. Crisler, R. Essig, J. Estrada, G. Fernandez, J. Tiffenberg, M. Sofo haro, T. Volansky, and T.-T. Yu, “SENSEI: First Direct-Detection Constraints on sub-GeV Dark Matter from a Surface Run,” Phys. Rev. Lett., vol. 121, no. 6, p. 061803, 2018, 1804.00088.
- [9] S. Barz and P. Walther, “Quantum imaging: Beating the classical camera,” Nature Photonics, vol. 4, pp. 199–200, Apr. 2010.
- [10] G. Lemos, V. Borish, G. D. Cole, S. Ramelow, R. Lapkiewicz, and A. Zeilinger, “Quantum Imaging with Undetected Photons,” Nature, vol. 512, pp. 409–412, 2014.
- [11] G. Brida, M. Genovese, and I. Ruo Berchera, “Experimental realization of sub-shot-noise quantum imaging,” Nature Photonics, vol. 4, pp. 227–230, Apr. 2010, 1004.1274.
- [12] M. A. Taylor, J. Janousek, V. Daria, J. Knittel, B. Hage, H.-A. Bachor, and W. P. Bowen, “Subdiffraction-limited quantum imaging within a living cell,” Phys. Rev. X, vol. 4, p. 011017, Feb 2014.
- [13] <http://www.andor.com/learning-academy/intensified-ccd-cameras-the-technology-behind-iccds>.
- [14] <https://www.oxinst.com/learning/view/article/electron-multiplying-ccd-cameras>.
- [15] X. Chu, T. Hambye, and M. H. G. Tytgat, “The Four Basic Ways of Creating Dark Matter Through a Portal,” JCAP, vol. 1205, p. 034, 2012, 1112.0493.
- [16] L. J. Hall, K. Jedamzik, J. March-Russell, and S. M. West, “Freeze-In Production of FIMP Dark Matter,” JHEP, vol. 03, p. 080, 2010, 0911.1120.
- [17] P. W. Graham, D. E. Kaplan, S. Rajendran, and M. T. Walters, “Semiconductor Probes of Light Dark Matter,” Phys. Dark Univ., vol. 1, pp. 32–49, 2012, 1203.2531.

- [18] S. K. Lee, M. Lisanti, S. Mishra-Sharma, and B. R. Safdi, “Modulation Effects in Dark Matter-Electron Scattering Experiments,” Phys. Rev., vol. D92, no. 8, p. 083517, 2015, 1508.07361.
- [19] J. R. T. de Mello Neto et al., “The DAMIC dark matter experiment,” PoS, vol. ICRC2015, p. 1221, 2016, 1510.02126.
- [20] K. Ramanathan et al., “Measurement of Low Energy Ionization Signals from Compton Scattering in a Charge-Coupled Device Dark Matter Detector,” Phys. Rev., vol. D96, no. 4, p. 042002, 2017, 1706.06053.
- [21] M. W. Goodman and E. Witten, “Detectability of Certain Dark Matter Candidates,” Phys.Rev., vol. D31, p. 3059, 1985.
- [22] P. Cushman et al., “Working Group Report: WIMP Dark Matter Direct Detection,” in Community Summer Study 2013: Snowmass on the Mississippi (CSS2013) Minneapolis, MN, USA, July 29-August 6, 2013, 2013, 1310.8327.
- [23] R. K. Romani et al., “Thermal detection of single e-h pairs in a biased silicon crystal detector,” Appl. Phys. Lett., vol. 112, p. 043501, 2018, 1710.09335.
- [24] R. Agnese et al., “First Dark Matter Constraints from a SuperCDMS Single-Charge Sensitive Detector,” Phys. Rev. Lett., vol. 121, no. 5, p. 051301, 2018, 1804.10697.
- [25] M. Reichert, X. Sun, and J. W. Fleischer, “Quality of spatial entanglement propagation,” Phys. Rev. A, vol. 95, p. 063836, Jun 2017.
- [26] R. Fickler, M. Krenn, R. Lapkiewicz, S. Ramelow, and A. Zeilinger, “Real-time imaging of quantum entanglement,” Scientific Reports, vol. 3, p. 1914, May 2013.
- [27] M. P. Edgar, D. S. Tasca, F. Izdebski, R. E. Warburton, J. Leach, M. Agnew, G. S. Buller, R. W. Boyd, and M. J. Padgett, “Imaging high-dimensional spatial entanglement with a camera,” Nature Communications, vol. 3, p. 984, Aug 2012.
- [28] A. C. Dada, J. Leach, G. S. Buller, M. J. Padgett, and E. Andersson, “Experimental high-dimensional two-photon entanglement and violations of generalized bell inequalities,” Nature Physics, vol. 7, p. 677, May 2011.
- [29] J. C. Howell, R. S. Bennink, S. J. Bentley, and R. W. Boyd, “Realization of the einstein-podolsky-rosen paradox using momentum- and position-entangled photons from spontaneous parametric down conversion,” Phys. Rev. Lett., vol. 92, p. 210403, May 2004.
- [30] S. P. Walborn, A. Salles, R. M. Gomes, F. Toscano, and P. H. Souto Ribeiro, “Revealing hidden einstein-podolsky-rosen nonlocality,” Phys. Rev. Lett., vol. 106, p. 130402, Mar 2011.
- [31] M. Reichert, H. Defienne, and J. W. Fleischer, “Massively parallel coincidence counting of high-dimensional entangled states,” 2017, arXiv:1710.01781.
- [32] A. Zhao, M. van Beuzekom, B. Bouwens, D. Byelov, I. Chakaberia, C. Cheng, E. Maddox, A. Nomerotski, P. Svihra, J. Visser, V. Vrba, and T. Weinacht, “Coincidence velocity map imaging using tpx3cam, a time stamping optical camera with 1.5 ns timing resolution,” Review of Scientific Instruments, vol. 88, p. 113104, November 2017.

- [33] T. Poikela, J. Plosila, T. Westerlund, M. Campbell, M. De Gaspari, X. Llopart, V. Gromov, R. Kluit, M. van Beuzekom, F. Zappone, et al., “Timepix3: a 65k channel hybrid pixel readout chip with simultaneous toa/tot and sparse readout,” Journal of instrumentation, vol. 9, no. 05, p. C05013, 2014.
- [34] B. van der Heijden, J. Visser, M. van Beuzekom, H. Boterenbrood, S. Kulis, B. Munneke, and F. Schreuder, “Spidr, a general-purpose readout system for pixel asics,” Journal of instrumentation, vol. 12, no. 02, p. C02040, 2017.
- [35] M. Fisher-Levine and A. Nomerotski, “Timepixcam: a fast optical imager with time-stamping,” Journal of Instrumentation, vol. 11, no. 03, p. C03016, 2016.
- [36] The SENSEI Collaboration, “SENSEI: Direct-Detection Constraints on sub-GeV Dark Matter from a Shallow Underground Run Using a Prototype Skipper-CCD,” to appear.
- [37] B. G. S. B. Streetman, “Solid state electronic devices,” Prentice Hall, 2005.
- [38] C. A. Klein, “Bandgap Dependence and Related Features of Radiation Ionization Energies in Semiconductors,” Journal of Applied Physics, vol. 39, pp. 2029–2038, Mar. 1968.
- [39] R. C. Alig, S. Bloom, and C. W. Struck, “Scattering by ionization and phonon emission in semiconductors,” Phys. Rev. B, vol. 22, pp. 5565–5582, Dec. 1980.
- [40] J. Estrada, private communication
- [41] H. An, M. Pospelov, J. Pradler, and A. Ritz, “Direct Detection Constraints on Dark Photon Dark Matter,” Phys. Lett., vol. B747, pp. 331–338, 2015, 1412.8378.
- [42] C. Kouvaris and J. Pradler, “Probing sub-GeV Dark Matter with conventional detectors,” Phys. Rev. Lett., vol. 118, no. 3, p. 031803, 2017, 1607.01789.
- [43] C. McCabe, “New constraints and discovery potential of sub-GeV dark matter with xenon detectors,” 2017, 1702.04730.
- [44] M. Ibe, W. Nakano, Y. Shoji, and K. Suzuki, “Migdal Effect in Dark Matter Direct Detection Experiments,” JHEP, vol. 03, p. 194, 2018, 1707.07258.
- [45] R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, “First Direct Detection Limits on sub-GeV Dark Matter from XENON10,” Phys. Rev. Lett., vol. 109, p. 021301, 2012, 1206.2644.
- [46] S. Derenzo, R. Essig, A. Massari, A. Soto, and T.-T. Yu, “Direct Detection of sub-GeV Dark Matter with Scintillating Targets,” 2016, 1607.01009.
- [47] R. Essig, J. Mardon, O. Slone, and T. Volansky, “Detection of sub-GeV Dark Matter and Solar Neutrinos via Chemical-Bond Breaking,” Phys. Rev., vol. D95, no. 5, p. 056011, 2017, 1608.02940.
- [48] R. Essig, T. Volansky, and T.-T. Yu, “New Constraints and Prospects for sub-GeV Dark Matter Scattering off Electrons in Xenon,” Phys. Rev., vol. D96, no. 4, p. 043017, 2017, 1703.00910.
- [49] R. Budnik, O. Chesnovsky, O. Slone, and T. Volansky, “Direct Detection of Light Dark Matter and Solar Neutrinos via Color Center Production in Crystals,” Phys. Lett., vol. B782, pp. 242–250, 2018, 1705.03016.

- [50] R. Essig, M. Sholapurkar, and T.-T. Yu, “Solar Neutrinos as a Signal and Background in Direct-Detection Experiments Searching for Sub-GeV Dark Matter With Electron Recoils,” *Phys. Rev.*, vol. D97, no. 9, p. 095029, 2018, 1801.10159.
- [51] J. L. Hewett *et al.*, “Fundamental Physics at the Intensity Frontier,” 2012, 1205.2671.
- [52] Rouven Essig, John Jaros, William Wester (conveners) + many authors, “Summary Report of the New, Light Weakly-coupled Particles subgroup for Snowmass 2013,” to appear.
- [53] Basic Research Needs Workshop on Dark Matter Small Projects New Initiatives, Oct. 15-18, 2018, <https://orau.gov/hepbrn2018/default.htm>.
- [54] S. Abrahamyan *et al.*, “Search for a New Gauge Boson in Electron-Nucleus Fixed-Target Scattering by the APEX Experiment,” *Phys. Rev. Lett.*, vol. 107, p. 191804, 2011, 1108.2750.
- [55] M. Battaglieri *et al.*, “The Heavy Photon Search Test Detector,” *Nucl. Instrum. Meth.*, vol. A777, pp. 91–101, 2015, 1406.6115.
- [56] P. H. Adrian *et al.*, “Search for a dark photon in electroproduced e^+e^- pairs with the Heavy Photon Search experiment at JLab,” *Phys. Rev.*, vol. D98, no. 9, p. 091101, 2018, 1807.11530.
- [57] G. Aad *et al.*, “Search for displaced muonic lepton jets from light Higgs boson decay in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector,” *Phys. Lett.*, vol. B721, pp. 32–50, 2013, 1210.0435.
- [58] G. Aad *et al.*, “Search for long-lived neutral particles decaying into lepton jets in proton-proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector,” *JHEP*, vol. 11, p. 088, 2014, 1409.0746.
- [59] DAMIC Collaboration, “DAMIC at SNOLAB,” *TAUP*, 2013.
- [60] W. Tittel, J. Brendel, H. Zbinden, and N. Gisin, “Violation of bell inequalities by photons more than 10 km apart,” *Phys. Rev. Lett.*, vol. 81, pp. 3563–3566, Oct 1998.
- [61] J.-W. Pan, D. Bouwmeester, H. Weinfurter, and A. Zeilinger, “Experimental entanglement swapping: Entangling photons that never interacted,” *Phys. Rev. Lett.*, vol. 80, pp. 3891–3894, May 1998.
- [62] J. F. Sherson, H. Krauter, R. K. Olsson, B. Julsgaard, K. Hammerer, I. Cirac, and E. S. Polzik, “Quantum teleportation between light and matter,” *Nature*, vol. 443, pp. 557–560, Oct 2006.
- [63] R. Ursin, F. Tiefenbacher, T. Schmitt-Manderbach, H. Weier, T. Scheidl, M. Lindenthal, B. Blauensteiner, T. Jennewein, J. Perdigues, P. Trojek, B. Omer, M. Furst, M. Meyenburg, J. Rarity, Z. Sodnik, C. Barbieri, H. Weinfurter, and A. Zeilinger, “Entanglement-based quantum communication over 144km,” *Nat Phys*, vol. 3, pp. 481–486, Jul 2007.
- [64] Astronomy Open Night Public Talks: www.astro.sunysb.edu/openight/.
- [65] World of Physics Public Talks: www.physics.sunysb.edu/Physics/WorldsOfPhysics/20162017/.