Contents

1 Scientific/Technical/Management

1.1 Introduction

Charge-coupled devices (CCDs) have long been the standard for astronomical image and data capture [19, 20, 21, 32, 24], enabling state-of-the-art measurements and precision instruments. However, as observatories and camera electronics alike have evolved and matured, typical CCD readout noise levels often represent the majority of intrinsic noise, particularly for ultra-faint or ultra-diffuse sources. Skipper CCDs are a new type of CCD architecture [37, 19] which implement an inventive floating readout gate. This allows for multiple non-destructive readouts of the charge in each pixel. The more times a pixel is read out, the lower the read noise on the measurement will be. As such, Skipper CCDs are capable of obtaining sub-electron read noise, enabling individual photon counting from zero photons to the full well of the device.

We propose to develop Skipper CCD technology and supporting technologies, including enhanced coatings for the CCDs and improved software for Skipper CCD controllers, with complex and faint astrophysical applications in mind. We are currently developing back surface passivated and coated Skipper CCDs in collaboration with several other organizations, and plan to refine this process through continued detector characterization and eventual application to astronomical observations supported by this proposal.

In our proposed project, we will implement a multi-pronged approach to testing skippers for astrophysical use. We plan to test ordinary and UV enhanced skipper CCDs with multiple readout controllers. We will test for quantum efficiency, experimenting with its dependence on processing, as well as explore the impact of sub-electron dark and read noise. Moreover, we will optimize the skipper CCD readout time for a given noise floor and characterize the relationship between readout time and noise levels. As a final step, we plan to use a skipper CCD tested in the lab for an on-sky test at a small, under-subscribed telescope we have access to. Characterizing these sub-electron noise detectors with the optimal fast readout times will allow for time sensitive, ultra-diffuse astronomical measurements, including mapping the faint circumgalactic medium (CGM). These extended CGM measurements will help to inform galaxy evolution models, which shape views of cosmology and the formation of the universe.

1.1.1 Probes of Galactic Origins

Galactic evolution is dictated by the gas and dust that compose galaxies [39]. Pristine gas inside of galaxies feeds star formation, which in turn governs the physical and observable properties of those galaxies [38]. As stars are born and gas is consumed, the gas and dust reservoirs must be replenished from external sources [16]. The majority of this material lies in the empty space between galaxies, in the intergalactic medium (IGM). As galaxies evolve through time, they accrete material from the IGM, simultaneously recycling spent gas back into the IGM [39, 29]. As material flows into and out of galaxies, it must pass through the circumgalactic medium (CGM), the gravitationally-bound reservoir of warm and hot gas immediately surrounding galaxies. The CGM holds numerous clues to the formation and evolution of galaxies [8]. As the mediating boundary between the IGM and galaxies, all inflow and outflow must pass through the CGM, driving complex and poorly understood kinematics that may vary greatly between different types of galaxies [39, 8]. Although diffuse, the CGM is thought to house the majority of the baryons in typical galaxies, and is often credited as the solution to the "missing baryon problem." [6, 40, 12, 13] However, the actual mass of baryons contained in the CGM, specifically in the different, diffuse phases (e.g., cool, warm, warm-hot, hot) is still an open question. This is in part due to how difficult it is to observe the CGM, especially in the ultraviolet [28].

In the ultraviolet (UV), the CGM emits incredibly faintly, owing mostly to its super-diffuse nature (emission is governed by the square of density, so very diffuse material emits much less than denser material) [1]. As such, direct emission observations are nearly impossible with the current technology [28, 44]. Modern UV CGM observations are dominated by absorption line studies [14, 33, 42, 43, 34]. By observing a background quasar with a known or well-modeled spectrum passing through a foreground CGM, we can extract the absorption signals from the intervening CGM, giving us an idea about the composition and mass of the CGM. Additionally, we get an idea of the kinematics along this line of sight. However, such studies only give us CGM statistics along a small pencil-beam line-of-sight, and may not represent the whole CGM, especially in the hotter phases where the gas is theorized to be more clumped with a smaller filling factor [1, 2, 43]. The majority of UV absorption line studies of nearby galaxies are dominated by UV space telescopes, such as the Hubble Space Telescope (HST) or the Far Ultraviolet Spectroscopic Explorer (FUSE). Even the most powerful telescopes, though, are unable to map the CGM in emission, highlighting the need for new telescopes enabled by optimized UV technology: specifically detectors.

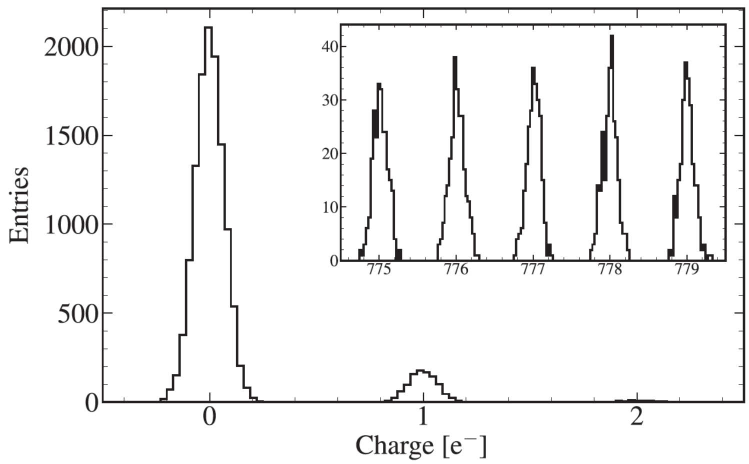

Figure 1: Figure 1 from [37]. Shown is a histogram from a Skipper CCD with sub-electron read-out noise. Individual electron peaks can be differentiated from each other, through the entire dynamic range of the Skipper.

1.1.2 Current UV Technology

Historically, charge-coupled devices (CCDs) have been used for the majority of astronomical applications, revolutionizing the field when they were introduced. However, it has only been recently that CCDs have reached the required sensitivity for UV applications [41, 4, 23, 22, 25, 36]. Instead, detectors like micro-channel plates (MCPs) had been used for decades on UV missions (HST, FUSE, GALEX, Aspera and others). More recently, electron-multiplying CCDs (EMCCDs) like those aboard FIREBall-2 have become more popular for UV missions. Despite the maturity of these two types of detectors, they present several problems for mapping the diffuse CGM in emission. MCPs have good quantum efficiencies (QE) in the UV, with low noise, but very limited dynamic range [11, 35]. Since the diffuse CGM is so faint, low QE and intrinsic detector noise makes its detection very challenging. Additionally, the voltages required to run MCPs can pose issues for their construction and implementation. EMCCDs, and other silicon-based detectors, on the other hand, have caught up in QE, and promise electron counting capabilities by amplifying the signal from single electrons [26, 30, 17]. EMCCDs benefit from the large investments in silicon fabrication across multiple industries, and are cheaper to produce. Neither device, though, has low enough noise performance to resolve single electrons/photons across the entire dynamic range, a requirement for CGM emission mapping [41, 25]. **A lack of large format, low cost, high sensitivity UV detectors with photon counting capability is holding back CGM emission mapping at UV wavelengths.** UV-enhanced Skipper CCDs promise to solve this issue.

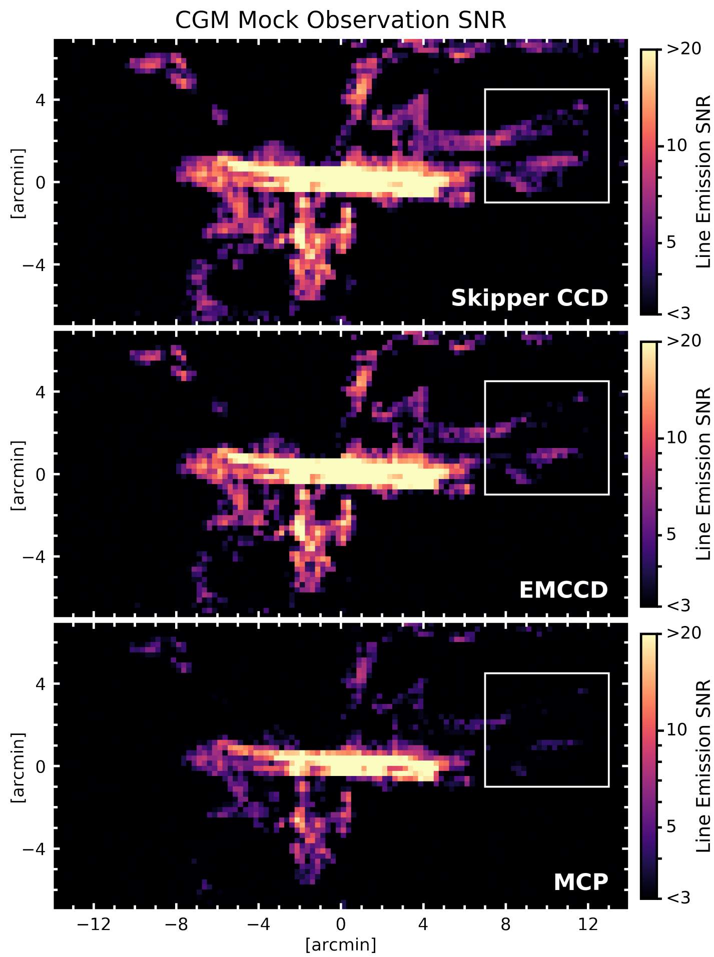

Figure 2: Simulated CGM around a Milky Way type galaxy shows faint, extended, filamentary structure. The panels show mock observations and the resulting SNR distribution (random-noise effect included) from an IFU with the simulated performance of a (Top) Skipper CCD, (Middle) EMCCD, and (Bottom) MCP. The white rectangle shows that the Skipper CCD can detect a very faint diffuse gas signal with greater fidelity compared to an EMCCD or MCP for otherwise the same conditions.

1.2 Skipper CCDs for Astrophysics

Skipper CCDs are based on typical CCD architecture with one significant change: instead of a one-time destructive readout (as is standard on all other CCDs), Skipper CCDs implement a floating gate amplifier [37]. This amplifier reads the charge out non-destructively, allowing for subsequent read outs of the same pixel. The read noise is reduced by the square root of the number of readouts, or ‘skips.’ Skipper CCDs are thus able to not only differentiate 0 or 1 electrons like EMCCDs or MCPs, they can also fully resolve individual electrons through their entire dynamic range. Figure 1 shows a histogram of pixel counts in a Skipper CCD. The 0 and 1 electron peaks can be clearly seen in the main figure, and the 775 through 779 electron peaks can be seen in the insert. For both ranges, the distributions are clearly separated. Skippers are uniquely able to do this, and have none of dynamic range issues of EMCCDs or MCPs.

Since Skippers are based on regular silicon CCD architecture, typical CCD UV processing steps to improve QE, such as thinning, back side passivation, and anti-reflection coating, is directly applicable to Skipper CCDs. These techniques have already been proven on space-ready detectors, such as the EMCCD on FIREBall-2 [23, 26]. Other CCD production techniques for mitigating spurious charge sources, such as clock-induced-charge (CIC), dark current, brighter-fatter effect, and persistence, are also easily implemented on Skipper CCDs [**?**]. Skipper CCDs pose a few unique challenges not seen in traditional CCDs; specifically, Skipper CCDs have significantly longer readout times than traditional CCDs, increasingly approximately linearly with the number of skips. Several methodologies and technologies promise to reduce the readout time to levels applicable for astronomy. Instead of transferring the charge into a storage pixel and then back into a floating gate amplifier to be read out once, the charge can instead 'skip' back and forth between two floating gate amplifiers—known as a differential amplifier—to half the read out time [9]. Similarly, increasing the number of on-chip readout amplifiers reduces the readout time linearly. (Several tests are already underway to develop Skippers with up to 64 readout amplifiers.) Another methodology involves only skipping pixels that have low charge in a 'smart readout' mode, preventing the waste of valuable readout time on pixels that have large amounts of charge [10]. Combining all of these methods make Skipper CCDs viable for astronomical applications, where time spent reading out is time lost from data collection [7, 27, 15].

Low read noise detectors, such as Skipper CCDs, hold the potential to revolutionize several areas of astronomy. Mapping the diffuse CGM in emission requires low read noise to resolve faint signals, a perfect application for Skippers with long readout times. Figure 2 shows the simulated signal-to-noise ratio of a CGM around a Milky Way like galaxy in OVI emission. With only 1024 skips, the Skipper CCD has noticeable improvements to SNR, especially in the lowest signal regions. High-contrast exoplanet imaging, where the exoplanet is orders of magnitude fainter than the star, benefits similarly from large dynamic range electron counting and low read noise detectors [18]. Skipper CCDs pave the way for new scientific instruments, such as a high resolution spectrograph; low read noise allows the light to be spread over multiple detectors without significant loss in SNR, giving spectral resolutions unobtainable with traditional CCDs. This also allows selective surface processing dependent on the wavelength of light hitting the detector, increasing not only large spectral resolution but also QE.

1.2.1 Project Overview

To develop astronomical Skipper CCDs, we will implement a four-phase iterative testing and design process. We will conduct in-depth characterization to validate performance of existing ordinary and UV optimized Skipper CCDs, along with verification of our characterization setup. This includes read noise, dark current, and quantum efficiency, and how these parameters vary with changing controller parameters. We will then modify the read out patterns and timings to find the optimal trade off between read noise and read out time for electron-counting astronomy. Next, we will collaborate with other groups to develop improved Skipper CCD architecture, including differential amplifiers, an increased number of amplifiers, and UV enhancement. We will then repeat these steps with these new batches of Skippers, iteratively improving on a rapidly maturing technology. This will be repeated with two separate CCD controllers, and their performance will be compared. Finally, we will use fully characterized Skipper CCDs to conduct emission mapping of the faint CGM, leveraging the availability of a local small telescope and existing collaboration. Comparing these observations to the existing CGM data will shine a light on new insights that can be made from low-noise maps of nearby CGMs.

1.2.2 Detector Characterization Setup

We are currently developing a vacuum dewar testing setup to measure Skipper CCD properties. An example setup is shown in Figure 3. The Skippers will be held under vacuum inside of an IRLabs dewar, as seen in gold in the center of the figure. A Sunpower cryocooler will connect to the back of the Skipper CCDs through a flexible and easily exchangeable cold chain, not visible in the picture, to mitigate dark current and allow for hot swapping of devices. The detector output will pass through a hermetic feedthrough in the side of the dewar, similar to the connection of the left-hand side of the gold dewar. Two different Skipper controllers will be attached to the outside of the dewar, in place of the Nuvu controller pictured: an Archon controller from STA and the Low Threshold Acquisition (LTA) controller used by collaborators [5, 3]. We are able to quickly switch controllers thanks to external attachments, which also helps mitigate any electrical noise. While the detectors are cooled and under vacuum, we will test both the intrinsic read noise and dark current. The dewar is sealed off to light, preventing a major source of noise in highly sensitive devices.

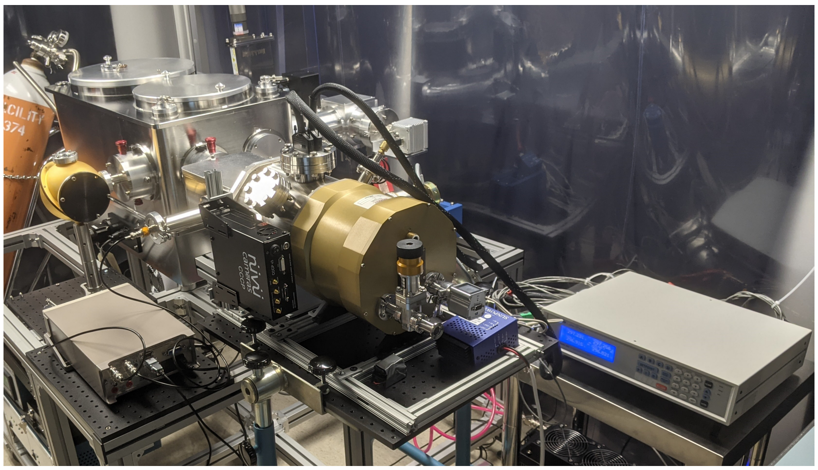

Figure 3: An example CCD test setup that our Skipper setup will mirror. On the left and center, the vacuum monochromator is connected to an IR Labs dewar housing the CCDs. The EMCCD controller, to be replaced by a Skipper CCD controller, is connected to the side of the vacuum dewar. In the foreground, the temperature control hardware and photodiode measurement devices are pictured. All of this is housed in a cleanroom to ensure both ESD and contamination protection.

We have access to a lab with a UV monochromator, the large silver enclosure pictured on the left hand side in Figure 3, enabling PTC and QE characterization. This includes a vacuum monochromator, light sources, and options to filter and collimator on the output. The entire monochromator and dewar is held under vacuum, and light from a deuterium lamp illuminates both a photodiode and the Skipper CCDs. Using such a monochromator, we will measure the Skipper CCDs' quantum efficiencies and photon transfer curves, letting us calculate the gain and another independent measure of read noise. The electron counting capability for Skippers allows a more precise calculation and calibration of the gain through the separation in the electron peaks, reproducing the results in Figure 1. Previous experiments with commercially available devices have validated the calibration of the UV monochromator, and future upgrades are planned to further improve performance.

1.2.3 Specific Goals

Throughout this project, we aim to achieve several well defined goals:

- The development and manufacturing of designs and patterns for a 4k x 4k CCD with differential Skipper readouts and 64 amplifiers per side.
- Testing and characterizing both Skipper CCDs and UV enhanced CCDs. This includes readout times, read noise per pixel for a range of sample times, dark current rates, clock induced charge, and quantum efficiency.
- On sky testing of fully characterized Skipper CCDs utilizing a local under-subscribed

telescope through existing collaborations. Previous and archival data will be compared to quantify CGM emission measurement improvements.

1.3 Applications to Future NASA Missions

Skipper CCDs, and the development of space-ready UV instrumentation, directly align with the goals put forward in the 2020 Astro Decadal. Specifically, the Decadal identifies a need for lower noise, higher QE UV detectors to map out the CGM in emission [31]. UV enhanced Skipper CCDs are prime candidates for this goal and future long-term NASA missions, such as the Habitable Worlds Observatory. Rigorous testing and characterization is required before such detectors are flight ready, but their similarity to traditional CCDs means less risk and easier integration into existing missions. Both recent and future missions—like FIREBall-2, Aspera, and UVEX—would greatly benefit from low-noise Skipper CCDs, reducing mission timelines and increasing detection limits.

1.4 Timeline/Period of Performance

Our project is separated into three distinct phases. The first stage, lasting approximately one year, involves characterization of existing Skipper CCDs. In particular, noise characterization, readout time optimization, and UV processed detector QE measurements. Over the following year to two years, we will develop and manufacture novel Skipper architecture, specifically implementing 64 or more differential amplifiers with read noise optimized electronics. This will result in science-ready Skipper CCDs with high UV QE, fast readout times, and high dynamic range electron counting capabilities. In the final year and phase, these in-house tested CCDs will be implemented onto an existing CGM emission mapping instrument equipped on a local small telescope. We will conduct an on-sky CGM emission mapping study following up well-studied nearby CGMs, likely providing marked improvements over traditional CCDs. This timeline is broken down in Figure 4.

Throughout our project, we plan to publish three separate papers, all as part of my thesis. Each paper will roughly align with the distinct development phases: the first paper will detail the characterization setup and noise properties of current Skipper CCDs, the second paper will cover the design and manufacturing of novel Skipper CCDs with corresponding noise and QE properties, and the final paper will delve into comparisons of the new Skipper CGM emission mapping program to traditional CCD observations.

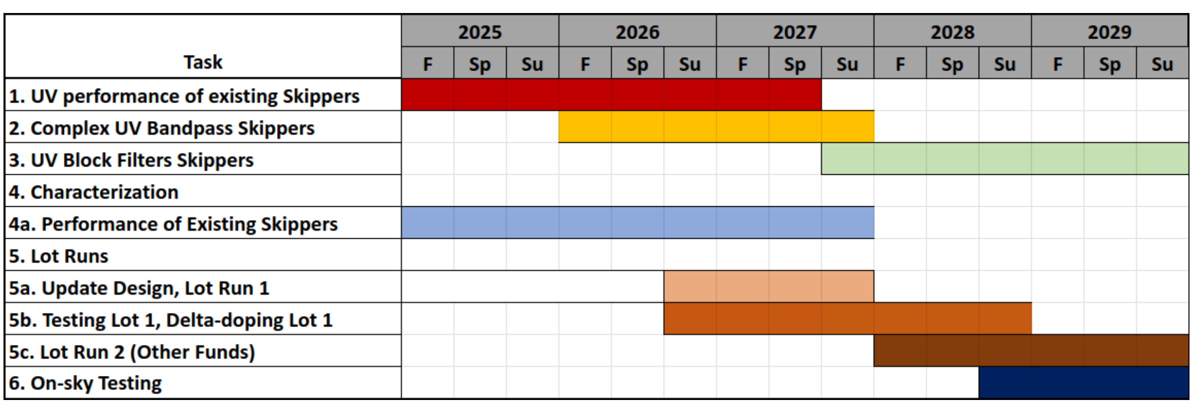

Figure 4: Timeline of completion for each phase in our project. In general, each phase will last roughly a year with a subsequent paper produced for each.

2 References and Acknowledgements

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3 Open Science and Data Management Plan

The main data product produced from this proposal is raw Skipper CCD images in standard FITS image formats. This includes calibration images such as monochromator exposures, darks, flats, and biases. All of this data will be made public via a public GitHub repository, and will likely total several gigabytes of raw data. Data taken during the final on-sky testing phase of the project will also be made available through a public data-hosting website, such as Zenodo, as a data product of the relevant paper when it is published in the same standard FITS format. This will include all raw calibration images, science exposures, and all of the fully reduced data. Everyone in our lab is intimately familiar with FITS files and standard GitHub and Zenodo procedures.

All of the data processing scripts and steps will be described and made public alongside the published papers. Software and scripts will be developed following standard Python conventions. Examples files include all Python scripts and notebooks used to reduce the data and produce the results presented in the papers. The scripts will be posted to a public GitHub repository, including all of the necessary documentation. All of the scripts will be organized into a self-contained pipeline to ensure easy duplication for everyone.

A secondary produced data product includes all of the scripts necessary to control and readout the Skipper CCDs. This includes sequence files used by both of the controllers and the scripts used to communicate with the controllers. Additionally, all of the scripts and code necessary for all of the other lab hardware will be made available on our group's website and public GitHub, including acquisition scripts used to take data. These scripts will follow the existing public documentation for the Skipper CCD controllers.

Finally, a tertiary data product produced as an intermediary step is the raw readout data produced by the Skipper CCD controllers. This data is simply the pre-processed images, and will not be made available, as it is only useful for the development and optimization of our readout sequences and very little modification is needed to produce standard FITS images.

While much of the data is not directly useful to the broader research community and is only useful to our group and others working with these specific devices, we choose to make all of the pertinent data and data processing scripts publicly available to ensure reproducibility.

4 Mentoring Plan and Agreement

This mentoring agreement has been developed together by the principal investigator (PI) and the future investigator (FI), and is applicable for both the NASA FINESST proposal and the FI's graduate program.

FI Statement of Commitment:

The FI agrees to actively participate in the mentoring process, and acknowledges and respects the PI's role there within. The FI hopes to become a well-rounded, educated, approachable, and inclusive scientist with the continued support and guidance from the PI.

PI Statement of Commitment:

The PI agrees to share guidance, advice, motivation, and the necessary technical knowledge to achieve the above stated goals. The PI will provide the FI with the knowledge, experience, and

Practically, the mentorship will follow the outline below, with a major focus on six areas.

1. **Training**:
   The PI will ensure the FI has the necessary expertise and background in order to properly develop Skipper CCDs, study the CGM, and conduct self-guided research. The PI and FI will work together closely throughout all steps of the proposal, meeting on a bi-weekly basis to discuss and evaluate research progress.

2. **Scientific Writing:**
   The PI will train the FI in proper scientific writing, both for papers and proposals. The FI will prepare numerous drafts of scientific manuscripts, and the PI will provide feedback on scientific content, writing quality, and overall storytelling.

3. **Networking and Collaborations:**
   The PI will help the FI develop professional connections and expand their scientific network. The FI will maintain connections developed by the PI, and will continue to maintain and grow their network after graduation.

4. **Conferences and Presentations:**

   The PI will encourage the FI to attend and present at relevant scientific conferences, including travel support to domestic and international conferences. The PI will also provide feedback and training regarding science talks and communication to the broader public, with concrete feedback and guidance.

5. **Science Outreach:**

   The PI will provide the FI with guidance to return support to both the local and the astronomy community. The PI will share experiences and events from previous outreach projects, and will brainstorm ideas with the FI for unique and impact ways to give back to those who need additional motivation and support.

6. **Mentoring and Teaching:**

   The PI will help the FI develop mentoring and teaching skills to enable the continued training of the next generation of scientists. The PI will share best teaching practices and beliefs, helping the FI to develop a supportive and inclusive teaching philosophy. The PI will provide feedback and guidance on teaching statements for applications.