Keck All Sky Precision Adaptive Optics

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ABSTRACT

We present the status and plans for the Keck All sky Precision Adaptive optics (KAPA) program. The program includes four key science projects, an upgrade to the Keck I laser guide star (LGS) adaptive optics (AO) facility to improve image quality and sky coverage, AO telemetry based point spread function (PSF) estimates for all science exposures, and an educational component focused on broadening the participation of women and underrepresented groups in instrumentation. All of these elements have pathfinder relevance for the ELTs. For the purpose of this conference we will focus on the AO facility upgrade which includes implementation of a new laser, wavefront sensor and real-time controller to support laser tomography, the laser tomography system itself, and modifications to an existing near-infrared tip-tilt sensor to support multiple natural guide star (NGS) and focus measurements.

Keywords: adaptive optics, laser tomography, near-infrared sensing, PSF reconstruction

1. INTRODUCTION

Thanks to funding from the NSF Mid-Scale Innovation Program the W.M. Keck Observatory (WMKO) has embarked on a major new five-year AO initiative as of September 2018. KAPA consists of four key science programs, an upgrade to the Keck I AO facility [1] and an education program.

The key science programs are focused on the following challenges:

1. Constraining dark matter, the Hubble constant, and dark energy via strong gravitational lensing
2. Testing General Relativity and studying supermassive black hole interactions at the Galactic Center
3. Characterizing galaxy kinematics and metallicity using rare highly magnified galaxies
4. Directly studying gas-giant protoplanets around the youngest stars

The KAPA education program has elements ranging from undergraduate to post-graduate level with an overall goal of broadening participation in instrumentation for women and underrepresented minorities.

The goal of the KAPA upgrade is to improve the image quality delivered to OSIRIS [2] over more of the sky, and to improve the quantitative science results by providing PSF estimates with each science exposure. OSIRIS is a near-infrared integral field spectrograph and imager. The elements of the KAPA upgrade are illustrated in Figure 1.

A TOPTICA/MPBC laser, identical to the laser now implemented on Keck II [3], has been ordered to replace the Keck I LMCT laser. This is being done to increase the sodium return (by a factor of 10 to allow multiple laser guide stars) and to improve the laser reliability. The new laser should be in science operation by early 2020.

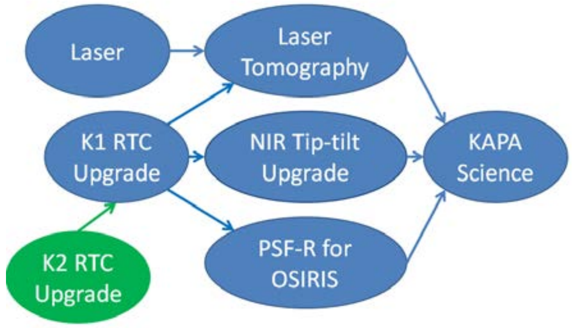

Figure 1: Technical elements of the KAPA upgrade to the Keck I AO facility

We are building on the separately NSF MRI funded Keck II real-time controller (RTC) upgrade (which completed its detailed design review in July 2019). This upgrade includes a new larger format, lower noise wavefront sensor camera (i.e. OCAM2K) that will also be implemented on Keck I for KAPA. The Keck II RTC will be duplicated for KAPA and the interfaces and algorithms needed to support multiple LGS and NGS will be added. The implementation will occur first on Keck I for KAPA.

Multiple LGS will be used to reduce the "cone" effect. The laser tomography upgrade includes three components: a modification to the laser beam transport system to produce three LGS, a modification to the wavefront sensor camera optics to sense all three LGS on the same detector, and modifications to the RTC to support three LGS and a laser tomography algorithm.

Multiple NGS are needed to determine the tip-tilt in the direction of the science object. This will be implemented with the existing Keck I near-infrared tip-tilt sensor [4].

Finally, we will be extending our NIRC2 PSF-reconstruction (PSF-R) approach to multiple LGS and OSIRIS.

The following sections follow the sequence shown in Figure 1. These sections are followed by overviews of the predicted performance, science products and the education program.

2. LASER GUIDE STAR FACILITY

KAPA includes replacing the existing LMCT solid-state laser with a TOPTICA/MPBC Raman-fiber amplifier laser for higher sodium return, higher reliability and lower maintenance. The new laser's factory acceptance test occurred in August 2019 and the new laser is planned to be in science operation in early 2020.

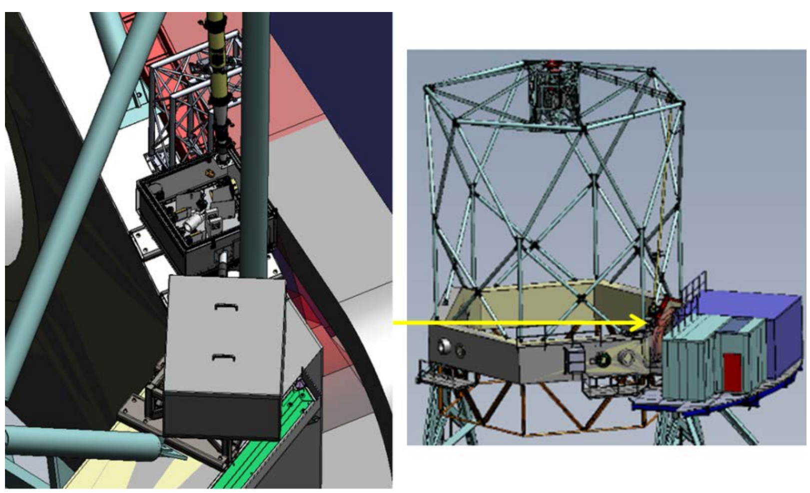

Figure 2. Left: Laser head (gray box) and laser table enclosure (transparent gray box) mounted on the telescope elevation ring. The output of the laser table enclosure connects to the existing laser beam train. The Nasmyth platform is on the right. Right: Telescope with existing laser room (light blue) on the right Nasmyth platform.

The existing laser sits in an enclosure on the telescope's right Nasmyth platform which requires a beam transport system that includes a pair of tracking mirrors to get the laser beam from the platform onto the elevation moving part of the telescope. The new laser will be mounted on the elevation ring and will interface with the existing beam transport system without the need for these tracking mirrors. The existing laser and the elevation tracking system will be removed.

3. REAL-TIME CONTROLLER

The RTC is being developed by a consortium led by Microgate. The consortium members include Swinburne University of Technology, Australian National University, and Observatoire de Paris, each specializing in their areas of expertise including hardware systems and controls, GPU computing, AO and simulations. Members were also part of the European Green Flash Consortium, working toward a common computational architecture for the ELT.

The RTC architecture is shown in Figure 3. Microgate (consortium) is responsible for delivering the interface module (IM), computational engine (CE), and telemetry recorder server (TRS). KAPA has 11 science modes requiring the RTC to be capable of interfacing with both a Shack-Hartmann sensor (SciMeasure or OCAM2K camera) and a near-infrared pyramid wavefront sensor (PWS). The IM must be backwards compatible with existing controlled hardware such as the STRAP tip-tilt sensor, Xinetics deformable mirror, and the downlink (DTT) and uplink (UTT) tip-tilt mirrors. It will also interface with a future MEMS DMs. To reduce the footprint and impact of the RTC, only the IM will be located near the AO hardware. A 10GbE fiber link transfers both the sensor data to the CE and command data from the CE. This allows the CE and the TRS to be co-located in a temperature controlled computer room.

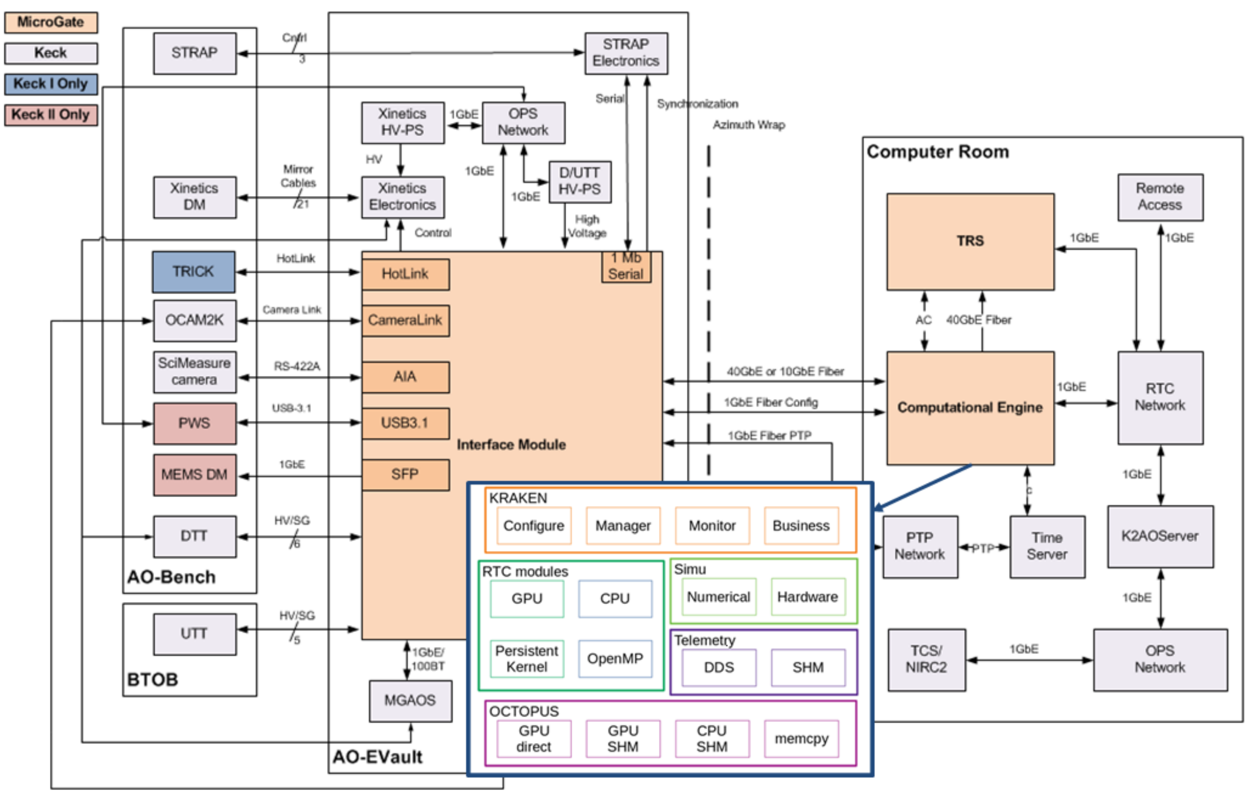

Figure 3: Real-time controller architecture. The inset box at bottom-center shows the components on the Computational Engine.

The CE is a Linux Server based on the CACAO (Compute and Control for AO) architecture of low latency, shared memories, and semaphores. The CE is based on NVidia's TESLA V100 TESLA boards with the CUDA development environment. Currently, two VT100 TESLA boards are planned for the CE; one for the real-time computer and one to support functionalities such as PSF-R, sensor fusion and predictive control. Raw and processed data are stored onto a 100TB TRS with 12 nights of capacity in the most data intensive mode.

Within the CE, the software architecture uses modules such as KRAKEN (high level sequencing and user interface) and OCTOPUS (interface to shared memory) to configure the software and pass data to the GPUs. The use of semaphores, persistent kernels, shielding and direct memory transfers of data to the GPUs provides low latency (< 250 μs) and jitter performance meeting the KAPA timing requirements. The COMPASS simulator framework is added to support simulation and analysis of the various modes.

The existing SciMeasure wavefront sensor camera (Figure 4 (left)) will be replaced with an OCAM2K camera. The reducer optics that relay the Shack-Hartmann lenslet images to the detector with the right scale (i.e. going from 200 μm lenslet spacing to 4 pixel spacing) will be replaced with new optics allowing sampling of three LGS.

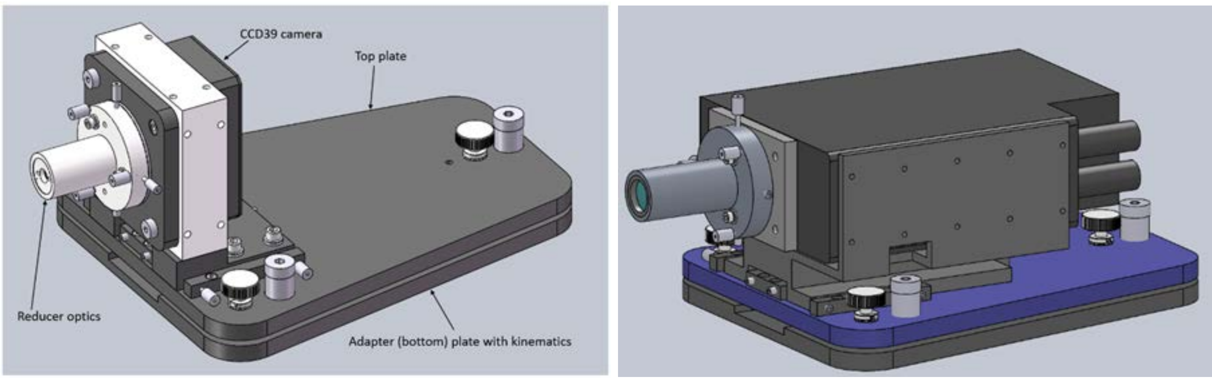

Figure 4: Current SciMeasure (left) and new OCAM2K (right) wavefront sensor camera installation.

4. LASER TOMOGRAPHY

Three LGS on an equilateral triangle with a 6.35″ radius will be used for laser tomography. This radius was selected based on a combination of simulations (see Figure 5) and what radius would fit on the OCAM2K wavefront sensor camera (see Figure 6). The wavefront sensor optics will include three field stops on the appropriate radius followed by three sets of pupil relay optics to reimage the telescope pupil on the lenslet array.

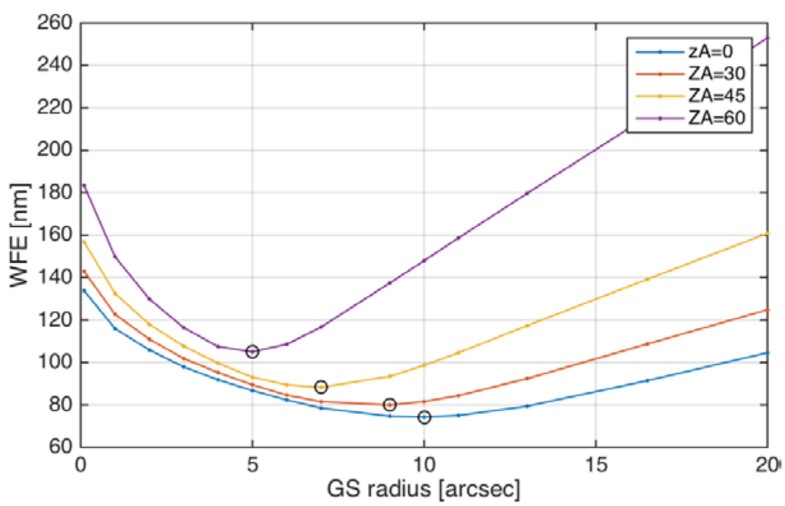

Figure 5: High order tomographic wavefront error (tip-tilt removed) for median seeing conditions as a function of guide star (GS) asterism radius and zenith angle (ZA). The minima are indicated with black circles.

Figure 7 shows the current conceptual design for producing the three LGS asterism from a single input laser beam. This system would be located in the top end of the telescope ~2 m before the laser launch telescope. The generator is mounted on a rotation stage to keep the LGS asterism fixed with respect to the LGS wavefront sensor, and on a translation stage to allow removal for single LGS operation.

A pseudo-open-loop control (POLC) approach will be used for laser tomography with KAPA. The POLC consists of two major steps: tomographic reconstruction (spatial) and control (temporal filtering). A minimum mean square error reconstructor will be used.

The system design review for the laser tomography, near-infrared tip-tilt sensing and PSF-R elements of KAPA will be held in September 2019.

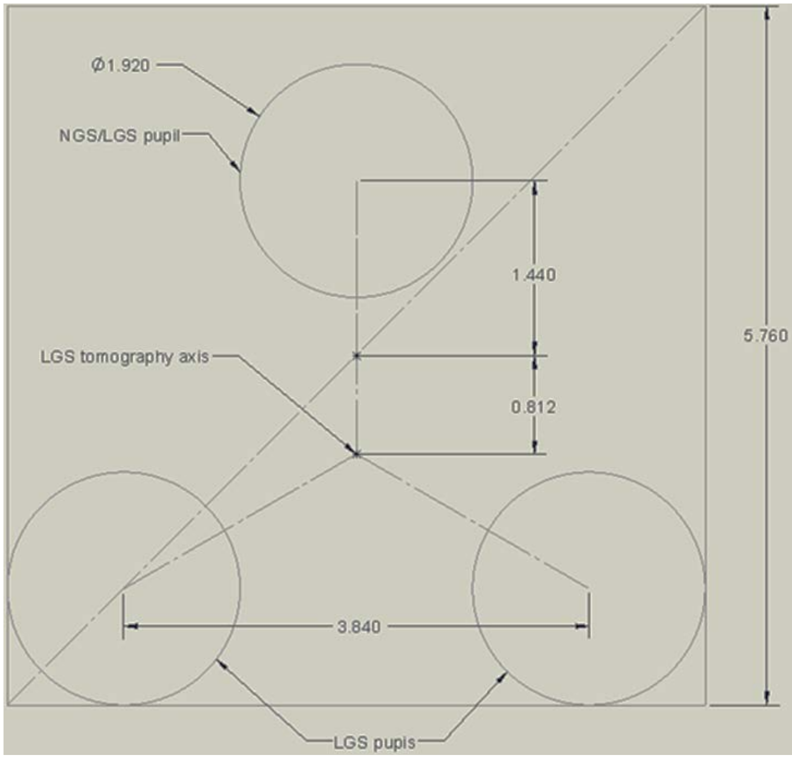

Figure 6: The location of the three LGS pupils on the on the OCAM2K detector.

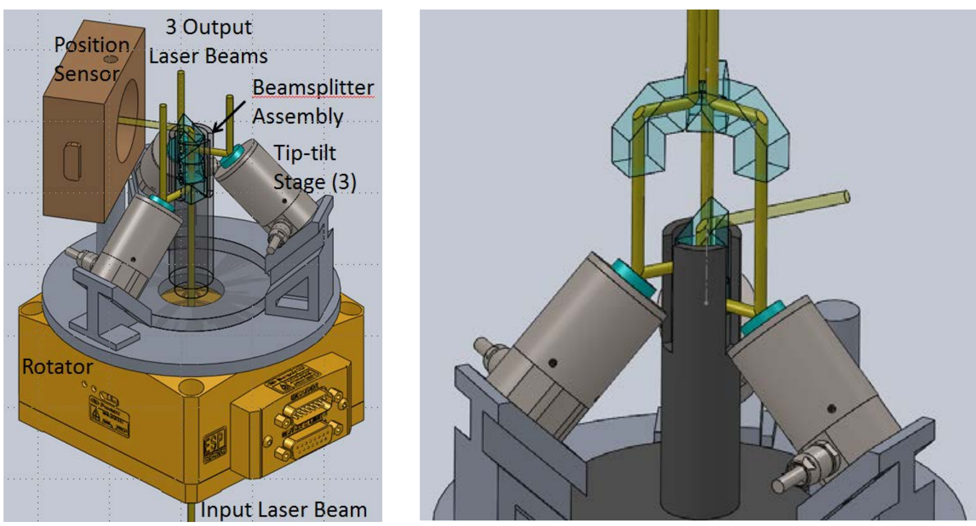

Figure 7: Potential asterism generator concept. Left: The asterism generator with the input laser beam entering at bottom and the three beams exiting at top. Right: A beam compressor (at top) used to put the three beams on a 3 mm radius.

5. NEAR-INFRARED TIP-TILT SENSOR

The existing near-infrared tip-tilt sensor is shown in Figure 8. The KAPA upgrade will include reading out up to three regions of interest centered on the NGS used for tip-tilt sensing to reduce tip-tilt anisoplanatism. We will also investigate the benefits of additionally using this sensor for slow focus measurements (e.g. [5]) and test improved tip-tilt methods (e.g. correlation).

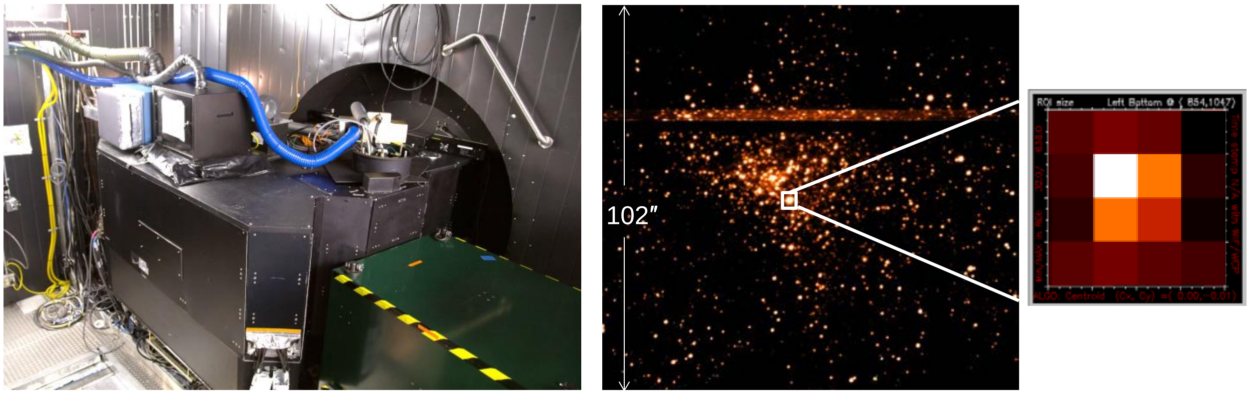

Figure 8: Left: The near-infrared tip-tilt sensor is mounted to the AO bench (blue hose goes to camera electronics) just before the OSIRIS science instrument (green). Center: An image of the Galactic Center taken with the H2RG detector. Right: Multiple reads of one or more regions of interest (a 4x4 pixel region is shown here) are used to reduce noise.

6. PSF RECONSTRUCTION

A multi-institutional PSF-R development effort has been undertaken for science with NIRC2 on Keck II [6][7]. The NIRC2 tool includes an algorithm to reconstruct the on-axis PSF based on the AO telemetry, and algorithms to generate the off-axis components based on the measured instrument off-axis aberrations and atmospheric profiler data. The PSF-R estimates have been successfully demonstrated on-sky for point sources and a science verification phase is currently underway. The nightly data will be processed by pipeline software to provide a grid of PSFs that are archived in the Keck Observatory Archive along with the science data. Some progress has been made to extend these tools for integral field spectroscopy with OSIRIS [8][9]. The impact of multiple LGS and NGS must be incorporated into both the imaging and integral field spectroscopy PSF-R estimates as part of the KAPA project.

7. PREDICTED PERFORMANCE

Detailed error budgets and PSF estimates have been developed for KAPA observations of targets representing each of the four key science programs.

For example, for the Galactic Center under median conditions and using one near-infrared tip-tilt star, KAPA is predicted to achieve a high order wavefront error of 244 nm rms with a residual tip-tilt error of 5.6 mas rms on-axis resulting in an H-band Strehl ratio of 0.36 (versus 0.12 with the current system) and an ensquared energy of ~50% in a 50 mas square integral field spectrograph aperture.

For the sample galaxy formation target the H-band Strehl ratio is predicted to be 0.42 using three near-infrared tip-tilt stars.

8. KAPA SCIENCE

Beginning in semester 2024B, subsequent to commissioning of the upgraded system, each science program will perform 20 to 42 nights of science observations spread over three to five years. A number of legacy science products will be released and point spread function (PSF) estimates will be provided for each science exposure in the Keck Observatory Archive (KOA).

To ensure that the four KAPA science programs provide the community with a valuable scientific legacy, the data sets (see Table 1) will be publicly released through the Keck Observatory Archive and the specific science products listed in Table 2 will be published.

The four science programs are led by Tommaso Treu (UCLA) for dark matter/energy; Andrea Ghez, Tuan Do and Mark Morris (UCLA) for the Galactic Center; Shelley Wright (UCSD), Tucker Jones (UCD) and Claire Max (UCSC) for galaxy evolution; and Michael Liu (UH) and Dimitri Mawet (Caltech) for gas-giant protoplanets. In addition, Jessica Lu (UCB) is the KAPA project scientist.

The second annual KAPA science workshop will be held in September 2019.

Table 1: KAPA science data available through the Keck Observatory Archive.

Science Case	Reduced Data Sets in KOA	# targets	# nights	OSIRIS	Band
Dark Matter	Gravitational imaging	20	5	Imager	H or K
	Lensed quasar flux ratios	20	10	IFU	
Dark Energy	Lensed host galaxy images	40	10	Imager	
	Stellar kinematics of stars in the deflector	40	17	IFU	
Galactic Center	Astrometric imaging (central 1″ diameter)	100	12	Imager	H,K
	Radial velocity spectroscopy (central 1″ dia.)	25	28	IFU	H,K
Galaxy Evolution	Gravitationally-lensed galaxies	40	20	IFU	J,H,K
Gas-Giant Protoplanets	First-epoch imaging	200	30	Imager	K
	Astrometric & spectroscopic followup	TBD	≥5	IFU	K

Table 2: KAPA science data products.

Science Case	Publicly Available Data Products
Dark Matter	Subhalo mass function
Dark Energy	Stellar velocity fields
Galactic Center	Kinematics catalog
	Reference frame
	Stellar spectral & photometric properties
Galaxy Evolution	Internal kinematics of lensed galaxies
	Metallicity gradients of lensed galaxies
Gas-Giant Protoplanets	Contrast curves
	List of identified candidates
	Imaging data

9. EDUCATION PROGRAM

The overall goal of the KAPA education program is to broaden participation in astronomical instrumentation to include more women and underrepresented minorities. This program (see Figure 9) includes hosting scholars through the Akamai and Keck Visiting Scholars (KVS) programs, developing a new one-week instrumentation summer school called AstroTech funded by the Heising-Simons Foundation and led by Lisa Hunter and Jessica Lu, and employing three KAPA science postdocs (a number that will grow with additional anticipated science funding) and a KAPA technology postdoc.

During the summer of 2019, the first Akamai student participated in the development of the new laser safety system, the technology postdoc began work at Keck, and an AstroTech develpoment workshop was held to prototype and design summer school activities. The first Keck Visiting Scholar will join us in October 2019 to work on PSF-R.

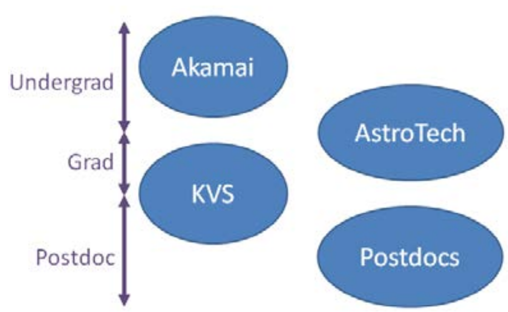

Figure 9: KAPA education program designed to broaden participation in instrumentation for women and underrepresented minorities.

10. CONCLUSION

The five year KAPA program will upgrade the Keck I AO system with a new higher return sodium-wavelength laser, a new real-time controller for higher bandwidth and increased capacity to support both KAPA and future upgrades, multiple LGS for laser tomography, multiple near-infrared tip-tilt sensing, and PSF-R for the KAPA science observations with OSIRIS. The AO correction and sky coverage are predicted to be significantly improved as a result. The resultant KAPA system will be used to carry out four key science programs as well as supporting all science observations with the Keck I AO system. The education program is in place, and has and will be integrated with KAPA technical developments where possible.

Technical progress prior to publication of this paper includes acceptance of the new laser, completion of the detailed design review for the new RTC and the system design for the rest of the system. The new laser and RTC should be in science operation on Keck I in early calendar year 2020 and 2021, respectively.

11. ACKNOWLEDGEMENTS

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