Keck 2035

The W. M. Keck Observatory Strategic Plan

Executive Summary

Ho'okahi ka 'ilau like ana – Wield the paddles together

Over the last three decades, W. M. Keck Observatory (WMKO) has transitioned from 'the impossible machine' to the premiere facility for discovery on the ground today. Astronomers using Keck have made fundamental and transformational discoveries across every aspect of the discipline, from the first few minutes of the universe to planets orbiting other stars. WMKO science remains the most impactful in the ground-based optical and infrared (OIR), with hundreds of highly-cited papers per year, national and international public interest, and critical contributions to two Nobel Prize-winning studies. Our leadership is a direct result of a scientific community that believes strongly that WMKO is their observatory, not just a tool. Our staff provide nimble, world-class support and service, and WMKO is a strong member of the local community. Nevertheless, each aspect of the environment the Observatory operates in has evolved since operations began. The facility is entering middle age, the world of work has changed, and our role in the community must evolve. We present in this document, *Keck 2035: The W. M. Keck Observatory Strategic Plan*. The year 2035 to scope the plan is chosen for many reasons. First, by 2035, a new lease for the observatory to operate on Maunakea will need to have been successfully negotiated. Second, on this timescale, significant changes in WMKO staffing across the Observatory will have occurred at every level. Finally, by 2035, the landscape of astronomical capabilities will be radically different both on the ground and in space.

Figure 1: The three core elements of the Keck 2035 Strategic Plan

Although this is a forward looking document, it remains grounded in our mission: to advance the frontiers of astronomy and share our discoveries, inspiring the imagination of all. We structure the document around the three core elements displayed in Figure 1 and briefly describe them below. Each are critical to the successful execution of our mission, and none of these elements exists alone. They are deeply intertwined and interdependent, and as we implement the plans laid out in this document in both the coming years and over decades, we allocate our resources under the guiding principle that our future success requires deliberate consideration of each theme. We build the document outwards towards the end goals of our mission, beginning with our organization and staff, growing to discuss our relationships in Hawaiʻi, and finishing with our plan to continue to enable strong leadership science. Across the document, we remain both ambitious and grounded in reality. Implementation of the recommendations in this plan requires varying combinations of significant new investment, new thinking, dedication, and resolve, but none are beyond our abilities to execute.

Organizational Health

WMKO's core asset is its people. Investing in our staff, where and how they work, and creating opportunities for professional growth drive our organizational strategic thinking. To help meet our mission, this plan sets four organizational goals: *1) Positioning WMKO as an employer of choice amongst U.S. astronomical observatories, 2) Achieving best in class organizational health, 3) Ensuring sustainable operations,* and 4) *Building tomorrow's workforce*.

To achieve our position as an employer of choice amongst U.S. astronomical observatories and within our community, we strive to provide competitive compensation and benefits. We also seek to expand career growth and development opportunities, and to assist our staff in balancing personal and professional lives through flexible work options.

Best in class organizational health will require a focus on diversity, equity, inclusion, and accessibility (DEIA) and effective communication throughout the organization. Further, we must invest in our staff through training, mentoring, and building leadership capabilities. Our organizational health will also improve through the elimination or reduction of barriers that prevent our staff from working as effectively as possible.

Sustainable long-term operations require a model in which we deploy our resources in an efficient manner that enhances our overall effectiveness. We seek to ensure sustainable, long-term operations through focus on economic, technical, and environmental sustainability. Economic sustainability will require aligning our staffing with our core mission and competencies within our financial means. Technical sustainability necessitates a comprehensive review of facility and staff succession planning needs. Finally, environmental sustainability recognizes our responsibility to our staff, community, and beyond to ensure our operations are aligned with environmental best practices for long term stability.

Lastly, in conjunction with our community strategy, we must build a strong workforce in our areas of critical need. Our efforts will include strengthening partnerships with Hawaiʻi educational institutions, enhancing our internship and apprenticeship opportunities, and reaching out to Hawaiʻi's youth to ensure they know their opportunities at home to pursue STEM careers.

Hawaiʻi Community Relations

Astronomy in Hawaiʻi stands at a turning point, with its vibrancy and legitimacy on the line. In our plans for community relations in Hawaiʻi, we discuss how WMKO must evolve its leadership as an agent for positive change within the astronomical community, and critically, how it becomes a strong reciprocal partner in the place we live and work. Recent years have offered significant challenges, but have set the stage for a transformation in how we approach our place in the community, and how we can thrive in and with it.

We begin by discussing how we have arrived at our position in time today, and how we can transition our mindset from a hierarchical to one, to one grounded in networks. We expand our concept of community beyond our walls or immediate geography to all of those who connect with us. We build on our strengths in outreach in STEM, and use the input from our staff and others to chart how we can move from a transactional community relationship to a lasting reciprocal one.

With this backdrop framework established, we define six strategic foundations: *Reciprocal Relationships, Maunakea Governance, Environmental Stewardship, Hawaiʻi-Grounded, Leadership, and Science Engagement*.These foundations then thematically flow into multiple, often interconnected, initiatives in the near term (and with some already underway) that each play an impactful role in our evolution as a community partner. Each initiative carries with it a commitment that must be resourced, but not always monetarily. We must invest in our community success to both enable our mission of scientific discovery and also our collective responsibility to Hawaiʻi as stewards, partners, and friends.

Science

While many of the core questions in astronomy will remain the same, the way we will explore them will undergo significant evolution in the coming decades. Transformative new capabilities are slated to come online on the ground with the onset of the ~30-meter aperture era, the rise of robust multi-messenger facilities, and large aperture synoptic capabilities yielding millions of transient events per night along with massive increases in statistical grasp across every type of astronomical object. Likewise, a new multi wavelength fleet of space missions from cubesats to flagships will arrive, offering powerful new capabilities to change and refine our view of the universe. Finally, the data tsunami is arriving, and along with it, new community expectations around how it is produced, used, and shared. Each of these changes represent immense opportunities for WMKO to continue to lead, should it rise to the challenge.

With this backdrop in mind, the science strategic plan is thematically anchored in three main themes. In the first theme, *Leveraging the Current and Future Landscape,* we explore how WMKO stands ready to augment its current capabilities with near-term additions to the instrument suite, powerful enhancements to existing instrumentation and adaptive optics, and a transformation in how data is created, managed, and archived. In the second theme, *Growing Scientific Leadership,* we describe the need for WMKO's suite of instrumentation to become faster, wider, deeper, and smarter, and how to evolve our capabilities into ecosystems of instrumentation where the impact is greater and more efficient than the sum of its parts. In the third theme, *Harvesting innovation,* we motivate an evolution in how WMKO can partner across the astronomical landscape to mature and benefit from new technologies, and how to drive and resource innovation to meet our scientific goals and increase productivity.

The strategic themes then map onto 6 key strategic goals, from which we present a suite of instrumentation and adaptive optics capabilities that meet these goals and serve to maintain WMKO's status as a premier observatory and partner. These capabilities bring not only new tools, but also significant increases in efficiency, with many capabilities being unmatched, even by the telescopes on the horizon. This portfolio is ambitious, but realizable with the appropriate investments and partnerships, and the continued deep shared sense of ownership across our scientific community.

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Keck 2035: The Scientific Strategic Plan

Since first light nearly three decades ago, data from WMKO has led the world in astronomical discovery from the ground and has been a powerful partner to facilities in space. To date, astronomers using WMKO have published over 6,500 refereed publications, with over 12,000 unique authors, garnering nearly half a million citations. The foundations of WMKO's success in maintaining leadership lie in three main areas: 1) the collecting area and spatial resolution of the telescope and its leveraging of the pristine viewing conditions of Maunakea; 2) the power and versatility of the WMKO's instrumentation and Adaptive Optics (AO) combined with the nimbleness and efficiency of WMKO operations; and 3) the strength, creativity, and innovation of the WMKO community of astronomers, instrument builders, staff, and supporters. These foundations remain at the core of the strategies that WMKO will implement as it enters the ELT era and beyond to maintain and grow its leadership.

The Keck 2035 Science strategy is grounded in three main motivational themes: *Leveraging the Current and Future Landscape, Growing Scientific Leadership, and Harvesting innovation*. These themes emerged from nearly two years of input from the Keck community as detailed in the Supporting Materials. The themes then flow into six strategic goals, and a set of recommendations on new and upgraded capabilities to meet those goals. The recommendations in this document represent the consensus view of the Keck Science Steering Committee (SSC) and WMKO leadership, and are endorsed by the CARA Board.

Leveraging the Current and Future Landscape

The next fifteen years will see a transformative change in capability across astronomy. Powerful new facilities will come online on the ground and in space, dramatically altering our ability to both survey the sky and look ever deeper into it. More and more, non-electromagnetic observations will join with traditional ones to probe the most extreme environments in the cosmos. Exoplanet studies will continue to transition from discovery to characterization, to deep exploration as new high-contrast capabilities emerge, and the search for life in the universe becomes viable. Figure 2 shows many of these new facilities, and their notional first light dates; here we note a few key examples. Already, JWST is providing its first exciting results, some of which potentially challenge the established models of galaxy formation and evolution. Every image from JWST will effectively be a deep field, requiring significant follow-up capabilities to reach their full potential. If the early science is any indication, JWST will be an immensely powerful new asset in the fleet of great space observatories for the next two decades. By mid-decade, the Roman and Rubin observatories will bring immense new capacity to wide field imaging surveys. Rubin will usher in the era of millions of transients per night, while Roman will provide Hubble quality images with 100 times the field of view. Both facilities will need an efficient and powerful partner on the ground to realize their full potential. Gravitational wave facilities will continue to increase in sensitivity and localization accuracy, opening up significant opportunities for new follow-up science. And finally, to close out the decade and start the next, the new era of large-aperture telescopes at the ~30-meter ELT scale will begin, providing the deepest looks ever from the ground, and promising to create new avenues for science that cannot be realized today.

How does WMKO best leverage its position within this landscape prior to the onset of operations of the ELTs? In the coming years, significant capabilities are already planned and underway to become available to maintain scientific excellence. For exoplanet science, a powerful trifecta of new instrumentation—KPF, plus SCALES and HISPEC coupled with HAKA's high order AO—will significantly expand WMKO's capabilities and build upon the foundations set by HIRES, NIRC2, and NIRSPEC. KAPA will provide significant improvements to AO capabilities on Keck I with OSIRIS. KCWI, with the integration of KCRM will offer full optical wavelength coverage to this premier integral field spectrograph, significantly increasing its utility for extragalactic science, and making it a powerful tool for transient follow-up. Finally, the Data Services Initiative will have transformed the end-to end process of how data flows at WMKO, culminating in DRP-processed data available to astronomers for each instrument in near real-time.

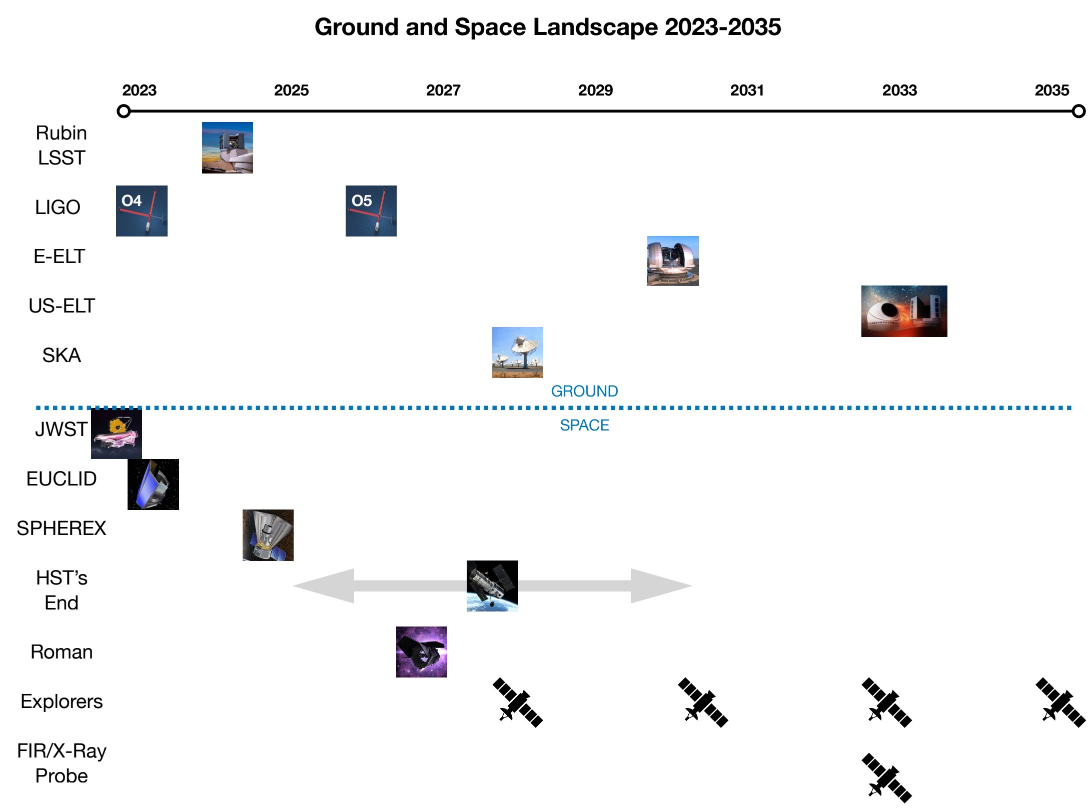

Figure 2: The Facilities landscape through 2035

Looking further forward, WMKO has significant opportunities to expand scientific leadership up to and through the start of the ELT era. These opportunities will be most successful when they maximize scientific productivity through the combination of new instrumentation <u>and</u> increases in efficiency. For example, a replacement of the workhorse LRIS instrument yields greater throughput when it is designed from the start to be compatible with an adaptive secondary mirror (ASM) and ground layer adaptive optics (GLAO). Likewise, MOSFIRE can be upgraded to benefit from the ASM + GLAO. Another example is KPF, which when expanded to include a second fiber feed from Keck II and operated via cadence scheduled observing can make significant gains in efficiency over its current baseline. Even current instrumentation can see large gains in efficiency through software that more effectively plans a sequence of observations and configures and calibrates the instrument faster and more reliably with each state change, while maintaining the classical nature of observing. Finally, expanding and optimizing the suite of instrumentation that is always available for rapid response to transient phenomena, coupled with fast, reliable DRPs allows WMKO to be first and best to target.

Growing Scientific Leadership

In the 2030s, WMKO will continue to evolve as it enters the ELT era as a powerful partner and counterpart. This same period of time will see a new probe-class mission come online in space, and the architecture and capabilities of the next flagship space observatory after Roman defined and construction underway. This new environment represents a critical change: aperture superiority for WMKO will be no longer. To maintain and grow leadership, WMKO must evolve its core strengths and create new ones to create a facility which is faster, wider, deeper, and smarter on the sky than it is today:

- ***Faster**:* WMKO can make significant strides in yielding science as fast as the transient universe demands. These include developing and deploying extremely efficient instrumentation coupled with swift, robust data processing and the ability to be always available during the night. Additionally, intelligent algorithms can assess the full facility (telescope, dome, instrument, AO, data processing, atmospheric conditions) to minimize losses and get faster and more robustly and fully-configured on target.

- ***Wider**:* To best partner with Rubin, Roman, and poorly localized, faint transient events, WMKO will take one of its core capabilities, faint and multi-object spectroscopy, to the next level by increasing both the instantaneous field of view, and the number of targets accessible within that field. In parallel, WMKO will create a new strength: wide field, high throughput imaging. Both of these capabilities will maximize coverage of the bluest wavelengths with the uniqueness of the Maunakea site, providing a capability no current or planned facility on the ground can rival.

- ***Deeper**:* While the ELTs will dominate studies of individual faint objects in the 2030s, they will do so typically at the expense of total wavelength coverage and field of view. By deploying powerful instrumentation that uses GLAO and the unique site characteristics of Maunakea, WMKO can be deeper in grasp for many science investigations than facilities of similar or larger size, especially in the first decade of their operation. Furthermore, WMKO will be a critical partner to the ELTs as it localizes and discriminates amongst faint transient sources for further study, a capability that cannot occur with today's 1-4m class facilities.

- ***Smarter**:* As the science requires, WMKO will evolve not just the instrumentation, but the entire process of observation to yield the best science. Cadence observation can extend beyond exoplanet radial velocity surveys with KPF to other instruments and science challenges. Target of Opportunity observations will evolve to incorporate event brokering and other algorithms to deal with the onslaught of transients beginning with the start of Rubin and Roman observations and the continued evolution of multi-messenger observations. Data platforms at WMKO and in the cloud can yield not only science-ready data faster, but also analyze that data to inform rapid decision making, and in some cases, algorithmic target selection and instrument reconfiguration.

Beyond individual new capabilities, WMKO can compete and lead by developing connected ecosystems of instrumentation. For example, deep imaging, intelligent targeting algorithms, and rapidly configurable multi-object spectroscopy can be combined to execute science programs in a single night which previously would have taken multiple observing cycles, if not years. Extending the ecosystem further, when the imaging capabilities are wide field, and the spectroscopic capabilities highly multiplexed, the targeting algorithm can select objects to serve the science needs of multiple independent investigators at the same time, providing a tremendous gain in efficiency for the Observatory. Similar ecosystem linkages can apply to exoplanet and transient/multi-messenger instrumentation. Likewise, WMKO data itself can be an ecosystem whereby well characterized and calibrated archival data from the Keck Observatory Archive (KOA) can serve as inputs into algorithmic targeting systems, or as parts of a discoverable whole across multiple archives from multiple observatories.

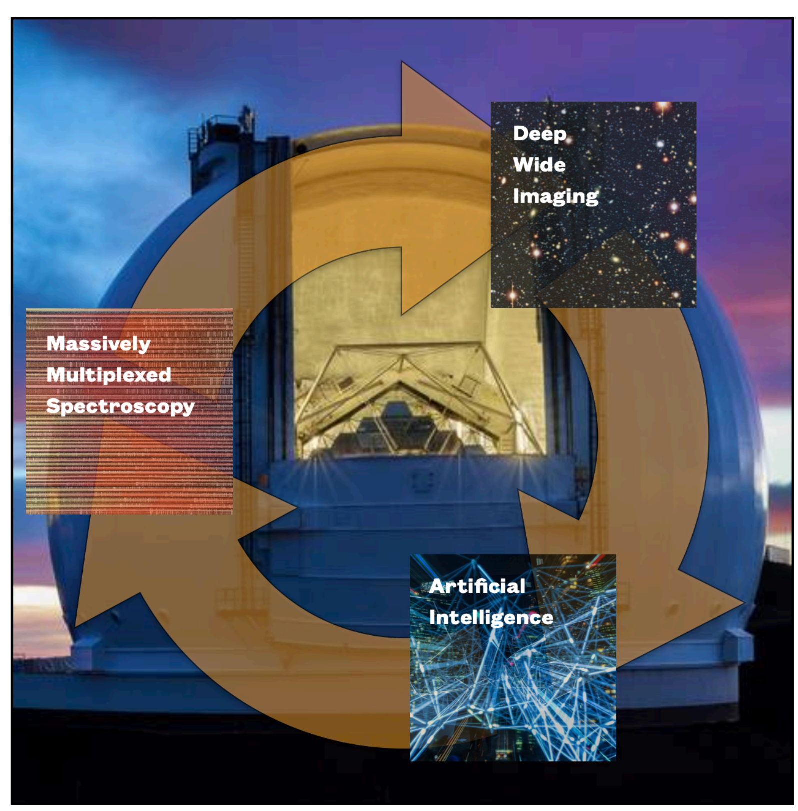

Figure 3: Example of an instrument ecosystem: imaging, spectroscopy, and algorithmic target selection combined

With the end of Hubble's mission likely within this decade, and with the next OIR space flagship of a size in the 6+ meter range nearly two decades away, the push towards the bluest wavelengths for near diffraction limited and diffraction limited capabilities via optical wavelength AO represents an immense opportunity for WMKO science and leadership. New instrumentation will need to match new AO capabilities, focused on imaging and integral field spectroscopy. Moving towards optical AO represents a substantial investment for WMKO, and will require a staged path of evolution in capabilities, with decision points along the way based on resources, the science needs of the community, technological innovations, and the external landscape. To shepherd the movement down this path, WMKO will continue to rely on and invest in the AO Future Studies Group as we advance this key strategic priority, beginning with the deployment of the ASMs, HAKA, and technologies stemming from the ORbiting Configurable Artificial Star (ORCAS) partnership between WMKO and NASA Goddard Spaceflight Center.

As WMKO develops and deploys new instrumentation and capabilities, it will continue to pursue an instrument development program guided by its community, and grounded in a balance between highly capable multi-purpose instrumentation and smaller, more focused instruments that meet more specific science needs. It is this balance that will continue to enable WMKO to powerfully engage the science that is known today, and the as of yet unknown science of tomorrow.

Harvesting Innovation

How WMKO maintains continued scientific excellence throughout the next two decades depends critically on its community's ability to maintain, expand, and harvest innovation.

For AO, significant opportunities arise by developing and deploying a new bench. This new development bench will include multiple ports for both instrumentation and technology maturation experiments. By providing this new facility, nightly scheduled AO science operations become decoupled from development, increasing operational stability, and minimizing the time required to switch to and recover from development activities. As Nasmyth deck space is limited, deploying this new bench will require retirement of some existing capabilities, as discussed below.

A major strategic push in innovation will be expanding WMKOs partnership with NASA. This expansion can take multiple roles. First, WMKO can act as a key testbed facility for new technologies and science methodologies to advance and inform architectures for future NASA strategic missions. In particular, Astro2020's recommendation of a new flagship capable of surveying dozens of Earth-like candidates around Sun-like stars will require significant advances in large, segmented-aperture wavefront control and coronagraph development, and new detector technologies. Many of these advances can be proven at WMKO, simultaneously adding new science capabilities. Additionally, future flagship and probe-class architectures can be informed by dedicated precursor science programs at WMKO. Second, new opportunities like the partnership with the ORCAS mission concept can open up significant new capabilities in the push towards optical wavelength adaptive optics, both by providing a new, configurable on the sky guide star capability and by advancing key components of the AO bench. Third, missions selected in the next decade to advance time-domain and multi-messenger astronomy will require new innovations on the ground for rapid, robust response to meet the prime mission goals. Fourth, the next generation of Solar System missions envisioned by the 2022 Planetary Decadal survey can drive innovations in observing modes like cadence, twilight, and daytime observing at WMKO to provide a constant eye on the Jovian, Saturnian, Ice Giant, and small body systems to both inform mission architectures and planning in the nearer term, and in-mission support once they fly. Finally, the increase in capabilities and breadth of NASA mission archives will motivate a commensurate increase for KOA to make the data maximally discoverable and useful in the heavily intertwined future ground/space ecosystem.

The volume and complexity of WMKO data will continue to increase, along with the interconnectedness between instruments and AO. These new complexities open the door for innovation in intelligent algorithms (Artificial Intelligence and Machine Learning) to analyze and optimize the processes of target selection, observing, data reduction, and verification of scientific viability of a data set to inform future observations. WMKO will assess then deploy those intelligent algorithms that meet our strategic needs of increasing efficiency and scientific yield. These algorithms will also play a key role in continuous monitoring of our instrumentation and facilities to optimize preventative maintenance and to highlight issues before they rise to the level where they require major servicing missions.

Palomar and Lick have been critical partners in developing technologies for WMKO through their strategic plans and the CARA partnership. As the ELT era approaches, WMKO will position itself in a similar fashion to support development of technologies in partnership with the ELTs, while simultaneously advancing our community's scientific interests. Many of the instruments in our future portfolio such as Liger and HISPEC already serve this purpose, retiring significant risks for the IRIS and MODHIS instruments at TMT, respectively. Additional ports and development facilities at WMKO will be made available to advance critical technologies.

Finally, and critically, new innovations in instrumentation and other capabilities will require significant, sustained monetary investment to match pace with facilities like ESO/VLT that plan significant resource allocations to instrumentation and technology in the coming decade. The portfolio envisioned for WMKO, both in cost and in timing relative to the astronomical ecosystem, cannot be achieved without growth in investment in our instrument and AO development programs. Many, if not most of the instruments in the coming years have notional budgets that exceed the ability for individual grants from federal or philanthropic partners to meet. The pressure is additionally acute given the annual uncertainty in the federal budgetary cycle and the volatility inherent in the stock market and other investments. As such, the stability of an instrument development program, both for the Observatory and for its community of developers is of equal importance to its funding top line. Based on history and lessons learned from other facilities and industries, WMKO adopts a value of 10-15% of the total cost of an instrument or AO capability needed to advance that project to a level where the cost, schedule, and contingency can be set with some confidence, usually coincident with the project's preliminary design review (PDR). With the envisioned portfolio of instruments and AO capabilities, we estimate a need of a stable \$3M/yr (\$2M for instrumentation, \$1M for AO) to advance projects from initial concept through to PDR, and to maintain the project teams across the uncertainty-laden periods of obtaining full-scale development funding across the spectrum of federal investment and philanthropy. These investments represent a significant increase in both the amount and funding stability WMKO has today.

The Strategic Goals

With the thematic motivation for how WMKO moves into the 2030s established, a core set of strategic goals emerge. These goals are outlined in Table 3, and set the parameters for the portfolio of new and upgraded capabilities between now and 2035, along with their prioritization. We discuss the individual goals and how they flow down to recommendations. Descriptions of each instrument or new capability are given in the supplemental materials. For brevity, we describe a new initiative only once in the discussion that follows, even though those initiatives span multiple strategic goals.

The Scientific Strategic Goals

Strategic Goal	Description
1	**Continue to support a broad OIR science portfolio with a diverse set of highly sensitive imaging, spectroscopy, and high spatial resolution capabilities**
2	**Enhance the WMKO community's competitive advantages in cadence, time domain, and large sample programs for precision spectroscopy, astrometry, and photometry**
3	**Sharpen our view of the universe with near diffraction-limited capabilities at visible wavelengths**
4	**Make maximal use of the unique capabilities of the Maunakea observing site including excellent seeing, UV sensitivity, and northern hemisphere access**
5	**Provide cutting edge science opportunities to the Keck community by hosting technology demonstrations for ELTs and space missions**
6	**Increase science yield with improved efficiency from instrument upgrades, state of the art seeing management, innovative operations improvements, excellent instrument calibration and characterization, and data reduction pipelines**

Table 3: The main scientific strategic goals

Goal 1: ***Support a broad OIR science portfolio***
Keck will remain one of the largest-aperture OIR telescopes until the onset of ELT operations, and will continue to be in high demand for many decades to come. As a result, WMKO will continue to provide state of the art instrumentation with a broad range of capabilities. In advance of and in parallel to the ELTs, WMKO will remain a scientific leader in the areas of planetary science, exoplanets, stellar astrophysics, galaxy evolution, and time-domain astrophysics, among many other fields. To maintain WMKO's core capabilities, new highly efficient instrumentation must replace the aging workhorse portfolio including:

- LRIS-2 + GLAO for blue-sensitive, single-object and multi-object spectroscopy

- Liger for near-infrared, AO-fed integral field spectroscopy and imaging.
- Investigate a high-resolution spectrometer operating over (at least) the L- and M-bands with long-slit capability for observations of extended objects.
- Develop a new capability with FOBOS for massively multiplexed, UV-sensitive spectroscopy over a wild field.
- Develop a world-leading wide-field imager with high UV sensitivity with KWFI
- Explore science cases and conceptual design for a new highly-multiplexed near-IR spectrometer
- Establish an annual instrument development fund of at least $2 million per year focused on bringing instruments to principal design review level, and enabling successful proposals for full funding.

Goal 2: *Enhance the WMKO community's competitive advantages*

As new facilities enter the landscape, WMKO's advantages will shift to those scientific endeavors that require more extensive telescope access. These would include large programs that require many repeat observations to sample time-domain phenomena (e.g. EPRV observations for exoplanets or astrometry for black hole orbits), fast response to rapid phenomena (e.g. follow up of high importance supernovae or gravitational wave events), or large samples of objects (e.g. spectroscopy of populations of stars or galaxies). While cadence work will occur on facilities like JWST or the ELTs, it will likely be very limited in the early years of operations. Fast response will always be difficult for JWST, and a challenge for ELTs in their early years. WMKO will continue to be suited for large samples over large areas or at higher spectral resolution than will be available in space or in first-generation ELT instrumentation. With these advantages in mind, the following capabilities rise to the fore:

- Support of flexible observing modes to enable rapid follow-up of targets of opportunity, cadence observing for multiple science cases, and others as the science demands.
- Develop an "always ready" capability for optical and near-IR spectroscopic observations of transit and time-variable sources. This can involve new instrumentation, augmentation of current instrumentation and software, or both.
- A KPF fiber injection unit on Keck II to provide better cadence opportunities and balance demand across the facility.

Goal 3: *Sharpen our view of the universe*

WMKO can remain competitive into the ELT era by delivering high spatial resolution at optical wavelengths using AO. Optical AO systems are easier and more cost-effective to build at smaller apertures, delaying their development on the ELT scale until later generations of instrumentation on those facilities. The ELTs will focus on near infrared AO capabilities in their first generation instrumentation. WMKO can be unique on the ground at the bluest wavelengths, providing ~15 milli-arcsecond resolution at optical wavelengths to complement the IR observations at similar spatial resolution to the ELTs. With the end of the Hubble Space Telescope mission on the horizon, the need for this capability becomes acute. Realizing these capabilities will require:

- Development of a visible and IR AO capability with high (40%) sky coverage and high (< 15 milli-arcseconds at 500nm) spatial resolution over 30 to 60 arc second diameter fields of view.
- Development of high Strehl (>0.8) visible AO at high resolution(< 15 milli-arcseconds at 500nm) over 1 arc second fields of view.
- Development of AO-fed imaging and integral field spectroscopy to take advantage of diffraction-limited resolution at visible wavelengths.
- Establish an annual adaptive optics development fund of at least $1 million per year focused on bringing instruments to principal design review level, and enabling successful proposals for full funding.

Goal 4: *Make maximal use of the unique capabilities of the Maunakea site*

WMKO operates its facilities on one of the best astronomical sites in the world. In particular, Maunakea provides an environment of exceptionally good seeing, located mostly at the ground layer, which can lead to excellent adaptive optics correction. Maunakea's high altitude, cold ambient temperature, and low precipitable water vapor provide unparalleled UV and IR atmospheric transmission and lower thermal background compared to any other developed site for large telescopes. As mentioned previously, instruments like FOBOS and KWFI are highly optimized to maximally leverage the superior conditions on Maunakea. Development of adaptive optics systems that best leverage the site conditions are also recommended (see in particular Goal #6), along with exploration of how the stable seeing for the hours following sunrise may allow for AO operations into daytime.

Goal 5: *Host technologies for the ELTs and space missions*

Looking forward to the ELT era, certain high-impact science cases are best performed with those facilities to leverage their significantly larger apertures. For example, in high-contrast imaging of exoplanets, the planet detectability scales as the diameter to the fourth power. High-contrast instrumentation for the ELTs will be expensive and challenging to develop. In this and other fields, WMKO will likely shift to become an on-sky test bed for state of the art technologies needed for next generation ELT instrumentation. As the demand for WMKO time will remain highly competitive for the next decade and beyond, technology demonstrations must be chosen strategically to deliver both novel instrumentation for future facilities and impactful science at WMKO in the present. A similar situation arises in space, where large, segmented aperture telescopes such as the

Habitable Worlds Explorer will need to mature high-contrast capabilities to search for Earth-Sun exoplanetary system analogues, and WMKO can serve to advance these and other technologies in partnership with NASA and industry. Potential technologies include novel wavefront sensing and control systems, sensors based on innovative low-noise fast-read detectors, hybrid wavefront sensors and high contrast science focal planes, coronagraphs, injection into photonics devices, and many others.

Goal 6: *Increase science yield through enhanced efficiency*
WMKO will continue to deliver excellent science return for its investments in instrumentation and other capabilities to maintain scientific leadership. An extremely impactful way to increase scientific return is through instrument and facility upgrades to improve efficiency. These upgrades must be weighed against priorities for long term projects and the increased risk and maintenance cost of older hardware. In the coming decade, a key capability for WMKO to increase efficiency is to improve seeing for a suite of instruments through ground-layer adaptive optics upgrades and adaptive secondary mirrors on both telescopes. Technological improvements and risk reductions in ASMs make this a timely investment that can improve sensitivity by factors of two to three. Specific initiatives to increase efficiency include

- Development of an ASM to implement GLAO on Keck I to provide enhanced seeing for LRIS-2, and an upgraded MOSFIRE, followed by an ASM for Keck II for high-contrast and other AO initiatives, along with enhanced seeing capabilities for FOBOS.
- Enabling efficient pathways from observations to science by supporting data reduction pipelines for all facility-class instruments and efficient data discovery and accessibility through KOA, along with observer tools for observation planning and execution that are user-friendly, flexible, and maximize the utility of archival data through the Data Services Initiative.
- Enable efficient communications and information flow between WMKO and the user community.
- Deploy systems for real-time monitoring of sky conditions such as seeing, sky brightness, atmospheric extinction, water vapor, and satellite trails.
- Develop a process (led by WMKO and the SSC) to review the instrument portfolio and make recommendations for instrument decommissioning.

Prioritization of the Recommendations

The top priorities for new and upgraded capabilities, as determined by the SSC, are grouped into three categories set by the scale of the investments. The Large scale initiatives are those with a notional cost of $15 million or greater and are presented in Table 4. The Medium scale initiatives are those with notional costs in the $5 to $15 million dollar range, and are presented in Table 5. The Small scale initiatives are those with a notional cost at $5 million dollars or less, and are presented in Table 6. In each category, we map how the recommendations enable the set of strategic goals from Table 3. The cost and schedule estimates for these initiatives are at different levels of fidelity, with some projects at the conceptual phase, and others, such as LIGER, able to begin immediate construction.

Large Scale Projects

Priority	Name	Strategic Goal Mapping
A	Keck 1 ASM for GLAO & Visible MCAO	1,2,3,4,5,6
	Liger	1,2,3
B	FOBOS	1,2,4
	GLAO on K1 for LRIS & MOSFIRE	1,2,4
	KWFI	1,2,4
	Visible AO on K1	1,3,4,5
C	GLAO on K2	1,3,4
	K2 ASM	1,4,5,6
	Visible AO IFU for K1	1,3,4

Table 4: Recommendations for large-scale projects. Projects are unranked within each priority and are listed alphabetically.

The Medium and Large scale priorities are likely only to be realized through a combination of philanthropic and federal funding. These projects will also benefit the most from the Instrument and Adaptive optics development funding lines, which are essential to bringing these projects to the design fidelity needed before making a full construction funding proposal. In the case of the Medium and Large scale projects, bringing a project to preliminary design level will require up to millions of dollars and multiple years of work.

Medium Scale Projects

Priority	Name	Strategic Goal Mapping
A	HISPEC	1,2,3,4,5
	Instrumentation Development Fund	1,2,3,4,6
	LRIS2	1,2,4
B	Visible AO imager	1,3,4

Table 5: Recommendations for medium-scale projects. Projects are unranked within each priority and are listed alphabetically.

Small Scale Projects

Priority	Name	Strategic Goal Mapping
A	AO Development Fund	1,3,4,5,6
	DEIMOS+	1,2,6
	HAKA	1,3,4,5
	KPF K2 FIU	1,2,4,5
B	High Contrast Technology Development	1,5
	MOSFIRE + GLAO	1,2,4,6

Table 6: Recommendations for small-scale projects. Projects are unranked within each priority and are listed alphabetically.

In Figure 4 we present notional schedules for development of the proposed portfolio, assuming that the recommendations in Tables 4, 5, and 6 are realized. Smaller initiatives are not shown on the figure for simplicity. The visible wavelength AO-fed instrumentation are grouped in the adaptive optics timeline. These timelines should be viewed in the context of two key elements: the larger portfolio of facilities coming online prior to 2035, and the specific notional first light dates for the European ELT and US-ELT as identified by Astro2020, as shown previously in Figure 2. In total, this portfolio represents over $300 million in new investments if realized in full between now and 2035.

In addition to the portfolio of recommendations above, a number of initiatives have been identified for further exploration and development up to a conceptual design level. These include:

- A "NIRSPEC 2" long-slit spectrograph, optimized for L and M band spectroscopy, with a focus on solar system observations
- A highly-multiplexed spectrograph with FOBOS-like capabilities but in the infrared
- A "Time Domain Astronomy Machine" spectrograph providing moderate resolution, always-on capability across the OIR
- The next generation of the Data Services Initiative, including deep archive interoperability, AI and ML assisted target selection, and science platforms.

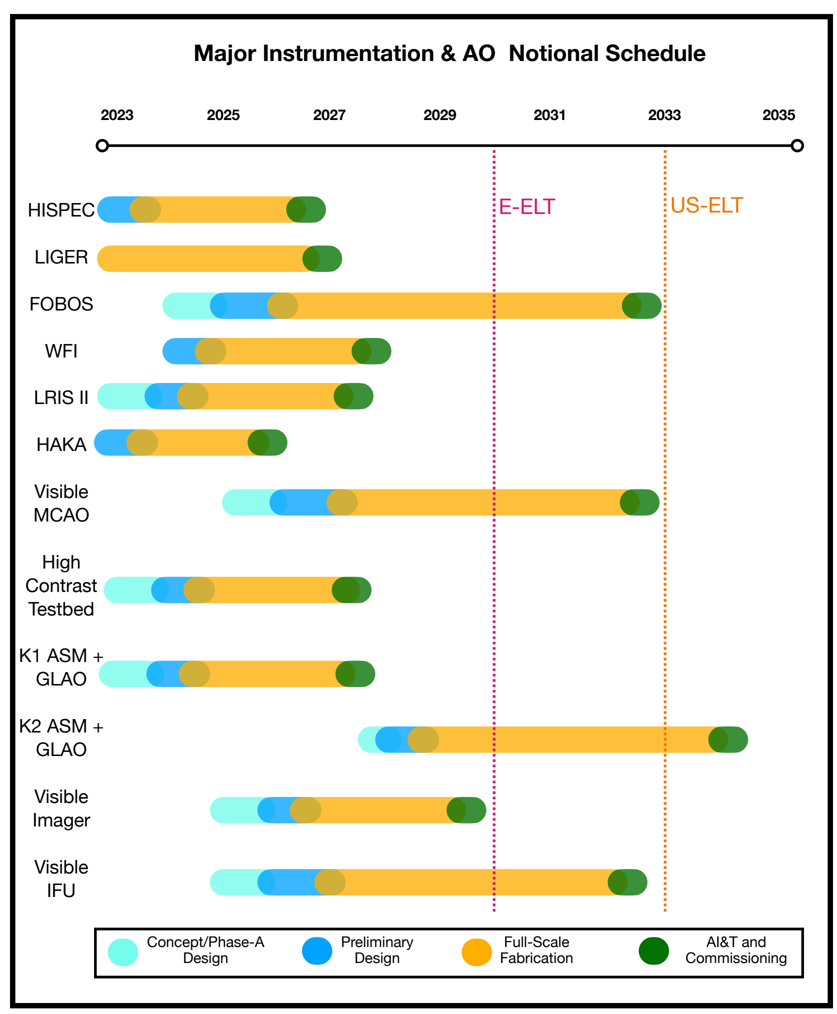

Figure 4: Instrumentation and AO timeline

Appendix B: Science

Description of Instrumentation, AO, and Initiatives [add occasional graphic]

Instrumentation

DEIMOS+: Upgrade to increase the throughput of the DEIMOS instrument via new CCDs with better QE in both blue/visual and red, along with a new flexure compensation system implemented using a hexapod-mounted detector cryostat.

FOBOS: Fiber Optic Broadband Optical Spectrograph. Multi-object fiber fed spectrograph flexible acquisition system that will position 1800 individual fibers or 45 fiber-bundle IFUs over a 20-arcminute diameter FOV, full optical band (0.31-1 µm), moderate spectral resolution (R = 3500). The current scope involves 3 spectrographs, each serving 600 fibers; each spectrograph is divided into 3 wavelength channels.

HIghly-Multiplexed NIR spectrograph: Placeholder for possible massively multiplexed (architecture TBD) near-IR (0.9-2.4 micron) spectroscopy. In the near term, there is a need for a feasibility/trade study of possible options and development of basic science requirements.

HISPEC: High-resolution near-Infrared SPectrograph optimized for forefront Exoplanet atmospheric Characterization. Single object near-IR (0.9-2.4 microns simultaneously) AO Fiber fed high resolution (R>100,000) spectrograph optimized for precision radial velocity (< 30 cm/s) and high-contrast high-resolution spectroscopy.

Instrument Development Fund: A proposed fund, incremented by ~$2M/yr, intended for use in advancing the design of facility instrument concepts to the PDR level, thereby allowing the early phases of instrument development to proceed on a much shorter timescale. The source of these funds is TBD, but would likely involve a new partner or increased share for an existing partner in exchange for new funds.

KPF : Keck Planet Finder. Fiber-fed, single object, high-resolution (R = 90,000) optical spectrometer covering 445-870 nm and is specifically designed to measure precise radial velocities (RVs) with a precision of 50 cm/s or better.

KWFI: Keck Wide Field Imager. Prime focus, 1 degree field of view imager covering 300-1000 nm, highly optimized for UV and blue. Deployable secondary mirror (DM2) as part of the design to enable multiple instrument operations in a night and to allow permanent mounting of the instrument with no need for top-end changes.

Liger: Second Generation IR integral field spectrograph, intended to replace OSIRIS. Configurable spectral resolutions (R=4000-10000) and a variety of IFU plate scales/sampling: 0.4-90 square arcseconds FOV using lenset arrays for fine scales and slicers for larger plate scales, wavelength coverage from the optical through the near infrared (0.84-2.4 µm). Simultaneous imaging with a FoV of 20".

LRIS-2: Second generation Low Resolution Imaging Spectrometer, with improved throughput, stability, and image quality. Maintains LRIS broad range of core capabilities (imaging, long slit spectroscopy, multi-object spectroscopy, FoV 10' x 5' on-axis, , 2 wavelength-optimized channels. 310-1050 nm, R~1000-5000) with technological advances that optimize its use with the GLAO system enabled by the Keck 1 ASM.

MOSFIRE + GLAO: Once the K1 ASM+GLAO system is realized, MOSFIRE (mounted at the Keck 1 Cass focus when LRIS-2 is not) can be optimized to take advantage of significant improvements in image quality over the full 6.1' x 6.1' FoV for imaging or multi-object spectroscopy in the 0.95-2.40 micron range, allowing significant reductions in slit widths, providing higher spectral resolution and, by virtue of the reduced background, improved sensitivity. The upgrade may involve replacement of the current H2RG detector with a H4RG with smaller pixels (0.1" spatial sampling rather than 0.18"), providing spectral resolving power up to R~10,000.

NIRSPEC 2 (or high-resolution mid-IR spectrograph): Placeholder for Long-slit (>15") , high-resolution (R>30,000) infrared spectrograph with focus on mid-IR (3-5 micron) capabilities. Long slit to enable observations of solar system targets. Intended as a replacement for NIRSPEC (TBD).

SCALES : Slicer Combined with Array of Lenslets for Exoplanet Spectroscopy. Integral field spectrograph and imager, wavelengths 2−5 µm, configurable 0.13-4.5 square arcsecond FOV and resolutions (R=50--7000). Imaging 13 arcsecond FOV.

TDA Machine: Placeholder for a Target of Opportunity dedicated instrument or combination of instruments that would be available on any observing night for simultaneous UV/optical/NIR spectroscopy of single targets over the range 310-1000 nm or 310-2400 nm, with resolving power R~2000-4000 (all TBD).

Visible AO Imager Imager (possibly multi-channel) paired with an adaptive optics system optimized for shorter wavelengths. (500nm-1 µm). Field of view from a few to a few tens of arcsec (TBD). The proposed VIPER concept is a candidate for this capability.

Visible AO Integral Field Spectrograph Placeholder spectrograph with contiguous field of view of TBD arcseconds, behind Visible AO, optimized for 500-1000 nm, R~1000-10000 (TBD).

AO Capabilities

AO Development Fund: A proposed fund, incremented with ~$1M/yr, to fund design, development, and upgrades of facility AO systems. The source of funds is not yet identified, but possibilities are a) trade of observing nights for additional funding from current or new partners b) similar arrangement with federal funding agencies c) foundations or individual donors.

GLAO: Ground-Layer Adaptive Optics: Use of multiple wavefront sensing systems over a wide (~10') FoV, to correct low-lying turbulence, leading to significantly enhanced image quality over large fields, and thus "enhanced seeing" for all OIR instruments. An ASM will provide the wavefront correction.

HAKA (High-Order All Sky Keck Adaptive optics): High order deformable mirror system (~3000 actuator DM) and associated upgrades for Keck II adaptive optics enabled instrumentation (e.g, NIRC2, NIRSPEC-AO, and, eventually, SCALES and HISPEC)

KAPA: Keck All-sky Precision Adaptive-optics. (in progress) Upgrades the KI LGSAO system with a new laser divided into three laser guide stars for more complete atmospheric correction, upgraded hardware for real-time wavefront corrections, and the camera that measures the atmospheric turbulence. Improves performance for OSIRIS in the near term, and possibly Liger and VisAO in the future.

Keck 1 ASM: Adaptive Secondary Mirror, a facility upgrade that would become part of a facility GLAO system, and that will work as an integral component of future facility diffraction-limited AO systems such as Visible MCAO. Envisioned as a replacement for current fixed secondary, enabling throughput and sensitivity improvements for all current and future instruments at Cass or Nasmyth locations.

Keck 2 ASM: The requirements for a Keck 2 ASM may include being deployable, in order to allow for switching between a prime focus instrument (i.e., KWFI) and instruments requiring the f/15 secondary.
As on K1, a K2 ASM would be a replacement for a fixed secondary, and would facilitate GLAO and possibly future diffraction-limited AO systems, with emphasis on "extreme AO" at IR wavelengths.

Visible MCAO: Visible wavelength multi-conjugate adaptive optics combining multiple high-performance deformable mirrors (high actuator density and rapidity) and multiple high-power laser beacons on the sky. The Keck 1 ASM may be a major component of the system.

Other Capabilities and Initiatives

The Data Services Initiative (DSI): Refinement of the end-to-end processing of data at Keck, inclusive of observation planning and execution, data reduction pipelines, and archiving.

DSI 2.0 (AI & ML): Extension of DSI to include opportunities enabled by AI and ML (artificial intelligence and machine learning) techniques to enhance telescope scheduling, instrument operations, target selection, and data analysis, potentially with components in the cloud.

ORCAS: A collaboration with NASA-Goddard to launch an ORbiting Configurable Artificial Star to be used as the guide star for science observations with Keck AO. ORCAS is intended to support AO correction at visible wavelengths when combined with appropriate Keck AO upgrades (e.g. HAKA).

Real-time monitoring of sky conditions: Concept proposed in a strategic planning white paper to implement systems for continuous monitoring of sky brightness, atmospheric extinction, seeing, precipitable water vapor, and satellite trails in the sky region that each telescope is pointed toward. Full implementation would likely require a small telescope co-mounted with each Keck telescope.