# Evolution of Adaptive Optics at Keck

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## I. Executive Summary

Keck adaptive optics (AO) will continue to play a critical and competitive scientific role in the era of new ground and space-based facilities. We emphasize three areas for strategic AO development: improving the Strehl ratio and sky coverage of the Keck II laser guide star (LGS) AO system; equipping the Keck II AO system with cutting-edge science instruments; and providing seeing-improvements through ground-layer AO with optical and near-infrared multi-object spectrographs. Our analysis is based on ten AO science cases and the AO recommendations of the other strategic planning task groups. The resulting recommendations are divided into mid-term projects, mid-term planning and long term projects.

- Key mid-term (< 5 years) projects in priority order:
    - In order to provide higher Strehl ratios in the near-infrared (IR), and AO capability at shorter wavelengths, with high sky coverage implement the already proposed Keck II LGS AO upgrades (e.g. KAPA – Keck All sky Precision Adaptive optics NSF MSIP proposal) coupled with planned instrument upgrades.
    - Develop & implement Point Spread Function (PSF) Reconstruction facility for all Keck AO science observations and incorporate with the Keck Observatory Archive (KOA).
    - Further develop unique high contrast AO capabilities on Keck II (e.g. NIRSPEC fiber injection, near-IR pyramid wavefront sensor)
    - Support time domain astronomy (TDA) with Keck II AO (i.e. laser usable & LGS acquisition < 5 min; switching between instruments < 2 min; flexible scheduling for monitoring).
    - Develop a new operational strategy for maintaining and supporting the OSIRIS data reduction pipeline.
    - Continue to maintain Keck I AO (without major upgrades).
- Recommended planning during mid-term (< 5 years) in priority order:
    - Perform a conceptual design study for ground layer AO (GLAO) with DEIMOS, LRIS & MOSFIRE on either Keck I or II. This study should include science case, technical evaluation for the instruments and an adaptive secondary mirror (ASM) feasibility study.
    - Determine what new AO science instrument(s) is needed and perform a design study (e.g. a next generation integral field unit (IFU) that extends into the visible, an L-band IFU, a multi-object IFU, a visible imager, a new or upgraded IR imager, R=100k spectrograph) & produce a Preliminary Design. In particular evaluate utilizing IRIS IFU

design heritage for Keck with an emphasis on shorter wavelengths (e.g. H alpha accretion studies in star forming regions).
    - Perform design for further steps towards high Strehl & high sky coverage on Keck II LGS AO (i.e. to support science at 800 nm), and determine future of Keck I AO after KAPA upgrade.
- Long-term (5-15 years):
    - If GLAO is deemed technically feasible and high priority then implement an ASM and wavefront sensors for the selected instrument(s), required lasers and real-time control system.
    - Deliver a new science instrument(s) to take advantage of Keck II AO.
    - Continue on a path to a higher Strehl ratio, high sky coverage Keck II LGS AO system (e.g. continued upgrades or Next Generation AO, NGAO-like system).

# II. Science Opportunities

## A. Current State of the Art

Table 1 provides an overview of the AO facilities currently in science operation or undergoing commissioning. The science productivity for these facilities, as judged by refereed science papers published in 2013, is shown in Figure 1. Gemini, Keck, Subaru and VLT were responsible for 15%, 38%, 6% and 35% of these papers, respectively.

**Table 1: AO facilities in science operations (black font) or undergoing commissioning (gray).**

| Telescope | System Type | GS Type | Adaptive Secondary | Science Instruments | Science Capabilities | Performance (R=14 GS) |
|---|---|---|---|---|---|---|
| Gemini-N 8m | SCAO | Sodium | No | NIRI, NIFS | NIR Imaging, Spect., IFS | SR=20% at K; 0.065" FWHM |
| Gemini-S 8m | MCAO | 5x Sodium | No | GSAOI | NIR Imaging | SR=50% at K over 2' |
| | SCAO | NGS | No | NICI | NIR Coronagr. Imager | SR=20% at H |
| | xAO | bright NGS | No | GPI | hi-con NIR Imaging, IFS | 3" FOV, 5-σ <1e-6 at 0.5" |
| Keck I 10m | SCAO | Sodium | No | OSIRIS | NIR IFS, Imaging | SR=35% at K; 0.05" |
| Keck II 10m | SCAO | Sodium | No | NIRC2, NIRSPEC | NIR Imaging, Spect. | SR=35% at K; 0.05" |
| LBT 8m | SCAO | NGS | Yes | CLIO | NIR imaging | |
| | GLAO | 6x Rayleigh | Yes | LUCIFER 1 & 2 | NIR Imaging, Spect., MOS | 0.2" |
| Lick 3m | SCAO | Sodium | No | ShARCS | Imaging, Spectrosc. | SR=55% at J |
| Magellan 6.5m | SCAO | NGS | Yes | CCD, MIRAC | visible/MIR imaging | SR~10%@0.85μm SR>96%@10μm |
| MMT 6.5m | SCAO | NGS | Yes | ARIES, CLIO | NIR Imaging, Spectrosc. | |
| | GLAO | 5x Rayleigh | Yes | ARIES | NIR Imaging, Spectrosc. | 0.2" |
| Palomar 6.5m | SCAO | NGS | No | P1640, SWIFT | Coronagraph, IFS | |
| RoboAO 1.5m | SCAO | Rayleigh | No | CCD | Visible imaging | SR=4-26% at i' |
| Subaru 8m | SCAO | Sodium | No | IRCS, HiCIAO (PI-mode) | NIR Imaging, Spectrosc. | SR=20-40% at K; 0.075" |
| | xAO | bright NGS | No | CCD,HiCIAO | hi-con NIR Imaging | Phase1: 1-σ <1e-6 at 0.5" |
| VLT 8m | xAO | bright NGS | No | IRDIS, IFS, ZIMPOL | hi-con NIR IFS,Polarimetry | 5-σ < ~5e-6 at 0.5" |
| | GLAO | 4x Sodium | Yes | GRAAL - HAWK-I | NIR Imaging | x1.7 EE in 0.2" over 7.5' |
| | SCAO | | | | NIR Imaging | SR=80% in K; narrow field |
| | GLAO | | | GALACSI - MUSE | 24 Vis IFS | x2 EE in 0.2" over 1' |
| | LTAO | | | | 1 Vis IFS | SR>5% at 0.65mm over 7.5" |
| SOAR 4m | GLAO | Rayleigh | No | CCD | Vis Imaging | 0.25" at I |

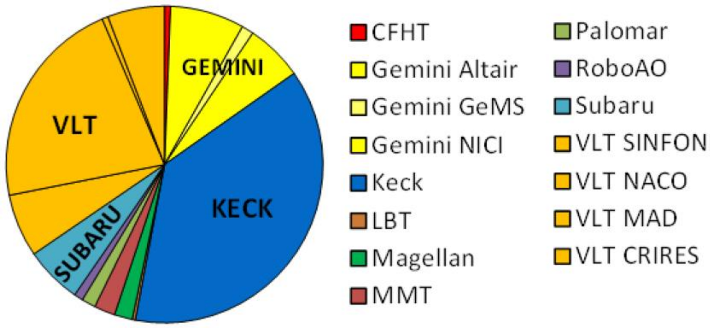


**Figure 1: Refereed science papers using NGS or LGS AO data published in 2013 in the journals A&A, AJ, ApJ, Icarus and MNRAS (interferometer papers are excluded). Gemini and VLT are each shown in a single color with dividing lines between the various AO systems.**

The science productivity of the Keck AO systems as of 2012 is described in a paper by Wizinowich (PASP 125: 798, 2013). Through 2015 a total of 633 refereed science papers have been published using data from the Keck AO systems. Keck has been responsible for 66% of the refereed science papers published worldwide using LGS AO as shown in Figure 2.

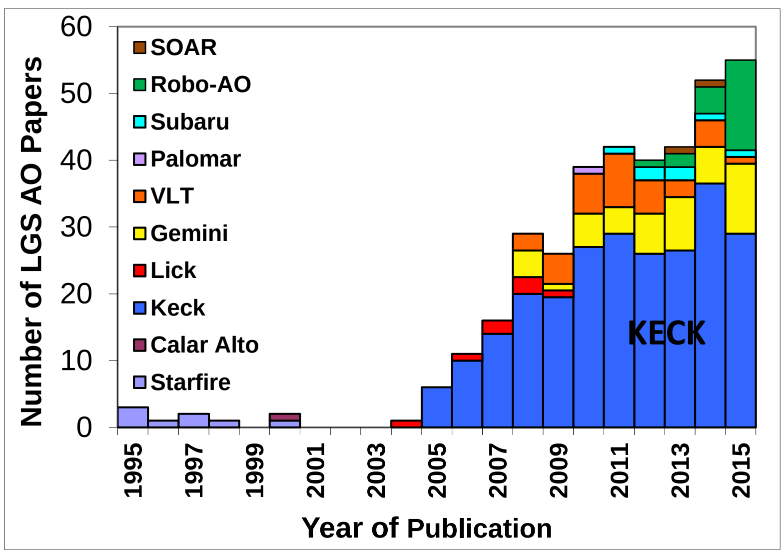


**Figure 2: Refereed science papers using LGS AO by year and Observatory.**

## B. Mid-Term Opportunities and Long Term Goals

Nine science cases are discussed in this section, along with the resultant AO and instrument requirements and the uniqueness that Keck offers.

## i. First light Galaxies

Understanding first light galaxies and the nature of the early universe ($z > 6$) is one of the most outstanding problems in astrophysics and is one of the prime science drivers for JWST and ELTs. Currently HST programs and deep spectroscopic campaigns at VLT and Keck have been pushing heavily on the current sensitivities and capabilities of today's instruments. Recent MOSFIRE results have shown that there is steep transition in the opacity of the intergalactic and circum-galactic media between $z \sim 6$

to z ~ 8 (300 Myr), that signals the epoch of reionization and the expected number density of Ly-alpha emission at these redshift (Treu et al. 2014). If the optical depth is considerably higher than we predict at z = 8, then an alternative line would be CIII (190.9 nm) that is redder and has shown to be strong in a few high-z galaxy samples.

While the majority of first light galaxy studies have been performed with non-AO studies, their surface brightness profiles have typical half-light radii of 0.4 – 0.8 kpc (0.08 – 0.15" at z = 7.5) and redshifted UV lines into the near-infrared make them highly suitable for AO follow-up studies. Therefore to resolve the internal structure of first light galaxies it is necessary to have high angular resolution and sensitivity to observe the velocity structure and widths of Ly-alpha with follow-up instruments. The faintest first light galaxies from JWST will likely have to use JWST NIRspec for redshift confirmation and studies, but even then NIRspec will not have the angular resolution needed for resolved studies of first light galaxies. The brightest first light galaxies discovered from JWST would be natural targets for an efficient narrow-field AO with an IFU study from Keck. Note that the current limits of MOSFIRE 10-sigma limit on Lyman-alpha dropouts is $6x10^{-18}$ erg $s^{-1}$ $cm^2$. Pushing down to these flux levels will be easily possible with TMT, but it is not out of the reach with a more sensitive Keck AO system with an IFU. Resolved spectroscopy would provide critical results on kinematics and surface brightness distributions of these early star forming galaxies.

In addition to spectroscopy, near-IR imaging with narrow-band filters (1%) could be utilized with a more sensitive AO system with near-IR imaging, but this could be competitive with other facilities on JWST and particular TMT where there's a gain in angular resolution. Lastly, an additional capability would be for Keck to target gravitational lensed first light galaxies with large clusters. A wide field near-IR imager (e.g., 2'x'2) fed by a moderate Strehl ratio AO system could be extremely advantageous for first light galaxies with a system that boosts sensitivity.

**AO/instrument Requirements:**

- Narrow-field AO with high Strehl ratio or enclosed energy to maximize signal-to-noise
  - Fine plate scales (e.g., 0.01-0.03") to resolve the surface brightness distribution of first light galaxies
  - Narrowband imaging (1%) filters
  - Integral field spectroscopy
- Moderate Strehl ratio to feed high sensitivity slit-based spectrograph
  - Use increased sensitivity with AO observations to boost sensitivity on first light galaxy follow-ups (aka, GLAO with MOSFIRE) with slit-based spectroscopy in particular on gravitational lensed sources

**Synergies and Competition with other Facilities:**

- JWST will discover many new first light candidates. The brightest of these sources could be well-suited for a more sensitive AO + instrument combination. This is still well-timed *before* TMT/ELTs come online.

**Keck Uniqueness:**

- Largest aperture for increased sensitivity and resolution before ELTs
- LGS facilities and expertise

- Outstanding faint-object spectrographs (MOSFIRE, LRIS, DEIMOS) that will benefit from GLAO

## ii. High-Redshift Galaxies & AGN

Studies of high-redshift galaxies and active galactic nuclei (AGN) with Keck span a wide range of investigations into the rate of galactic mass assembly over cosmological time in the field and in clusters, the nature of star formation within galaxies, the density and chemical enrichment of the intergalactic medium, measurements of fundamental cosmological parameters, etc. A common feature of these observational programs is that sources are faint (V > 18), red at higher redshifts, and compact relative to low-redshift sources (< 1”). Many ongoing Keck programs take advantage of the high sky densities of interesting targets with Keck’s sensitive optical and IR multi-object spectrographs; others utilize AO+IFU observations of individual galaxies. Most high-redshift studies can be summarized by the following list of measurement classes:

- Resolved internal kinematics of AGN host galaxies at redshifts $0.5 < z < 2$
- Color and stellar populations analyses of QSO host galaxies at $z > 1$
- Redshift surveys of field galaxies, galaxy cluster members, high redshift candidates, and other interesting populations
- Metallicities and line ratios for galaxy subpopulations with MOS, probing mechanisms of chemical enrichment over time
- Resolved metallicities and line ratios for individual galaxies
- Probing nature of gas clouds and IGM along QSO sight lines with high spectral resolution NIR spectroscopy of rest-frame optical lines (S IV, C IV, etc)
- Support of strong lensing studies in galaxy clusters with redshift surveys of field members, resolved metallicities and kinematics of lensed arcs
- Studies of dark matter halos of individual galaxies using resolved metallicities and kinematics of galaxy-galaxy lensing pairs

**AO/instrument Requirements:**

These cases benefit from two general categories of instrumental improvements: (A) Upgrades to the quality and accessibility of the narrow-field AO PSF, including higher Strehl ratio, higher sky coverage, and online PSF reconstruction and (B) moderate improvement to the image quality over wider fields (~ 5’) in the optical and near-IR. The AO/Instrument requirements below are broken down by science cases as enumerated above.

- high-throughput optical/near-IR IFU; high Strehl; high sky coverage; PSF reconstruction
- high-throughput near-IR IFU; high Strehl; high sky coverage; high contrast; PSF reconstruction
- low Strehl over large FOV (5’); near-IR, visible
- low Strehl over large FOV (5’); near-IR, visible
- high-throughput near-IR IFU; high Strehl; high sky coverage; PSF reconstruction
- seeing improvement - reduce background
- high-Strehl; high sky coverage; PSF reconstruction
- high-Strehl; high sky coverage; PSF reconstruction; multi-object IFU; near-IR, visible

**Synergies with Other Facilities:**

With all-sky coverage and a sensitive optical detection limit (V ~ 27), LSST will discover many new examples of rare classes of objects at 0.5 < z < 2, including mid stage galaxy mergers, active galaxies, galaxy-galaxy lenses, and high redshift groups and clusters. Rare objects do not have high sky density and do not benefit from moderate field of view (FOV) multi-object spectrograph (MOS) systems. Keck's advantages for following up such objects include rapid slewing capability relative to JWST, high Strehl ratio and higher spatial resolution, and (with KAPA) higher sky coverage than other high Strehl LGS AO systems.

WFIRST could serve as a discovery tool for Keck near-IR follow-up, but WFIRST's High Latitude Survey (HLS) has minimal overlap with Keck's sky at high zenith angle.

JWST's deep surveys will discover many new objects to be followed up, but many of these not already identified by HST will be beyond Keck's detection limits (V ~ 27, K ~ 24). However, JWST's expensive time is not likely to be allocated to programs that could be done from the ground, so the brighter objects could be followed-up by IFU spectroscopy or GLAO-fed near-IR MOS. Here, Keck's advantages are that it is the largest of the 8-10 m class telescopes and possesses arguably the best near-IR MOS.

**Keck Uniqueness:**

- Existing suite of sensitive spectrographs with fine plate scales (DEIMOS, MOSFIRE), suitable for GLAO feed relative to other 8 m competition. Will become even more sensitive with GLAO, and likely the most sensitive medium resolution optical MOS's available until ELT first light.
- Large field of DEIMOS, potentially large AO-corrected field relative to TMT (> 1')
- Potential for highest available spatial resolution at red-optical wavelengths
- Excellent LGS sky coverage with KAPA
- Strong AO user base compared to 8 m competition

## iii. Nearby Galaxies, > 100mpc

There are numerous AO science cases for nearby galaxies ranging from studying the kinematics and dynamics of galaxies, metallicity distributions and chemical composition of galaxies, probing luminous and ultra-luminous infrared galaxies, star formation properties of galaxies and their central starbursts and nuclei.

**AO/instrument Requirements:**

- Wider field of view AO correction for broadband and narrowband (1%) imaging
- Wavelength coverage with spectroscopy to target bluer wavelengths Ca-triplet (840 nm) while maintaining CO-band heads at the end of K-band (2.35-2.45 microns)
- Ability to close the loops (LGS tip-tilt star) on resolved sources like nuclei and increased sky coverage on resolved galaxies
- PSF stable within a few percent across the entire field of view
- IFU AO capabilities with increased Strehl ratio for spectroscopy of stars, ionized gas, and warm molecular gas

## iv. Supermassive Black Holes - Dynamical Mass Measurements

AO plays an important role in directly measuring the masses of supermassive black holes (SMBH) embedded in nearby galaxies. The current AO system resolves the black hole sphere of influence for $10^9$ solar mass black holes out to a distance of 500 Mpc (at Z-band, Figure 3), but does not necessarily have the sensitivity to make the measurement with appreciable S/N in reasonable exposure times. Improvements to the AO system's sensitivity and Strehl ratio (including laser tomography, a cooler AO system, a higher-order DM) as well as the system's sky coverage (near-IR tip-tilt sensor) will increase the number of galaxies for which the SMBH masses can be measured.

Extending correction to visible wavelengths will also improve sensitivity as well as the spatial resolution. Diffraction-limited correction at the Calcium triplet is an important step (Figure 3).

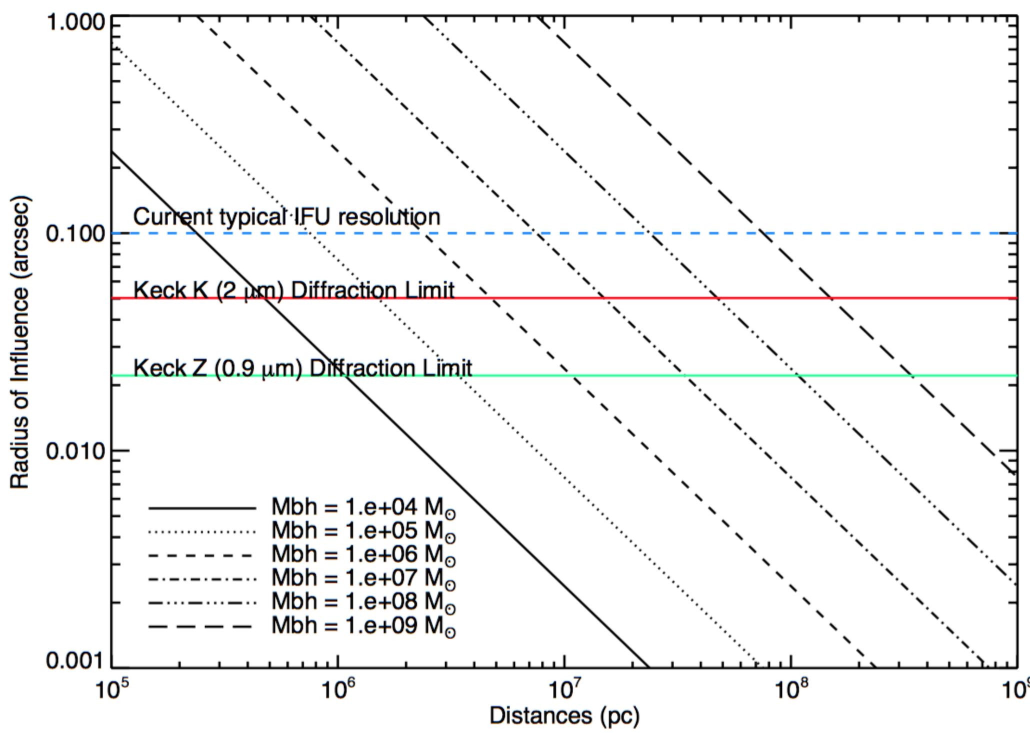


**Figure 3: The relationship between the angular size of the gravitational radius of influence of black holes as a function of distance. Dynamical mass measurements of black holes require resolving this radius of influence. Currently AO performance and sensitivity limits our ability to utilize the full potential of the diffraction limit of Keck for dynamical mass measurements. Achieving visible light AO will enable an increase in the distance out to which we can detect black holes by a factor of 5, or increase our sensitivity to lower mass black holes at the same distance by a factor of 5.**

**AO/instrument Requirements:**

- high-Strehl; high sky coverage; PSF reconstruction
- cooler AO system
- visible light IFU
- multi-object IFU's

## v. The Galactic Center

Keck has been a leading facility in high-angular resolution observations of the Galactic center since the mid-1990s. Starting with speckle imaging and then moving on to natural guide star (NGS) and LGS AO, the ability to obtain the diffraction limit for a 10 m telescope has transformed our understanding of the Milky Way supermassive black hole and its surrounding environment (Ghez et al. 2008, Genzel et al. 2010). In particular the measurement of the mass of Sgr A* and the distance to the Galactic center relies on the determination of stellar orbits close to the black hole (e.g. Meyer et al. 2012). Better measurements of these orbits will enable major unique science goals to be done at Keck: (1) test General Relativity (GR) with stellar orbits (e.g. Weinberg et al. 2005), (2) study the formation and evolution of stars around a supermassive black hole (Do et al. 2013, Lu et al. 2013), (3) measure the extended distribution of mass around Sgr A*, including compact remnants. Since source confusion dominates in this region, improvement in spatial resolution or Strehl ratio has a large impact on both detecting new stars as well as reducing systematic errors in the astrometry.

Obtaining deeper spectroscopy will likely hold the potential for greatest science return at the Galactic center. Radial velocity measurements with spectroscopy are crucial to obtain independent stellar orbits. However, spectroscopy currently is limited to stars 3 magnitudes brighter than stars found with astrometry. The improvements in Strehl ratios and sensitivity provided by laser tomography AO (LTAO; i.e. KAPA), and the OSIRIS upgrade will likely increase the sensitivity by 2 magnitudes. For the three science cases above, this implies that (1) multiple stars can be used to constrain the degeneracy between GR, the reference frame, and the extended mass distribution, (2) reach the pre-main sequence turn-off for the young stellar cluster.

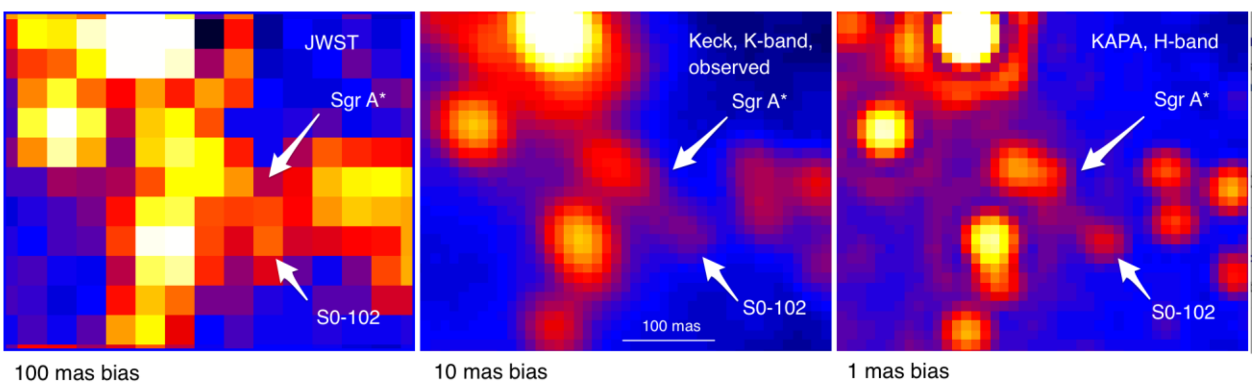


**Figure 4: A comparison of astrometric performance between JWST (left), current Keck AO (center), and future LTAO (KAPA, right) on a faint (K = 17.2) source S0-102, which is the shortest period star known. JWST will have insufficient resolution to trace the orbit of this star, while current AO will likely encounter very strong astrometric bias near closest approach to the black hole. KAPA will reduce the astrometric bias by an order of magnitude by providing high-Strehl and diffraction-limited measurements at H-band, which is not possible today.**

**AO & Instrumentation requirements**

- Near-IR - for stars, Mid-IR - for gas and embedded objects
- High Strehl ratios - to overcome source confusion

- IFU - to obtain spectroscopy of multiple stars efficiently (slit not nearly as useful as IFU)
- Medium resolution spectroscopy (R ~ 4000) - for spectral typing and radial velocities. Many of the science cases require deeper spectroscopy (K = 17.2 mag) than can be currently achieved (K = 15.5 mag)
- High resolution spectroscopy (R ~ 20,000) - to determine abundances, search for binaries.
- Wide field AO (> 20") - reference frame construction relies on being able to measure radio masers that are spread far apart.
- Imager with small plate scale (~10 mas/pix) to optimally sample the PSF
- Shorter wavelengths can provide higher angular resolution - ideally, GC astrometry would be done at H-band at high Strehl ratios
- Need good estimates of the PSF through PSF reconstruction and modeling the effects of anisoplanitism and instrumental aberrations.

**Other facilities**

- VLA - provides accurate maser positions, and absolute position of Sgr A* in quasar reference frame
- TMT - provide very high spatial resolution imaging and spectroscopy for stars closest to the black hole.
- JWST - mid-IR spectroscopy of embedded sources like G2

## vi. Time Domain Astronomy

Optical transient surveys such as the Nearby Supernova Factory, CSS, PTF/ZTF, and ATLAS (and eventually LSST) are producing a flood of data that enable leaps in our understanding of the universe. However, simple detections are insufficient; characterization through high angular resolution images, deeper images, spectra, or observations at different cadences or periods than the main surveys, will be required. The deep sensitivity and increased acuity of LGS AO at Keck can fill a crucial role in the follow on characterization of these important transient astronomical phenomena.

Examples of rapid triggered AO observation include:

- Candidate GRBs subject to the Gunn-Peterson trough are one such class of transient that will require rapid near-IR characterizations, and even moderate-redshift supernovae are only easily detectable by current surveys in their peak emission in the z' band.
- Disentangling transients from their environments. See Figure 5.
- Target of Opportunity (ToO) events, e.g., Keck AO observations of Crab Pulsar Gamma Ray Flares, Rudy et al. (2015).

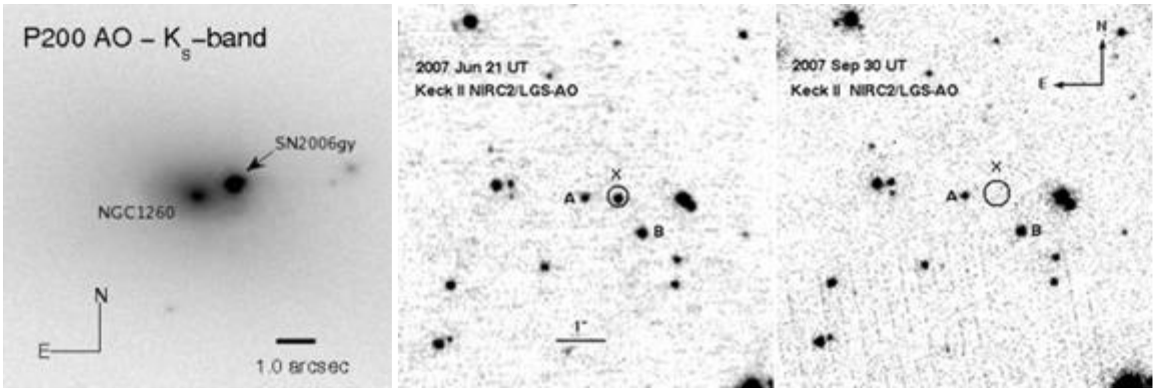


**Figure 5: Left: Supernova 2006GY (Quimby 2006, Ofek et al. 2007), the second-most luminous supernova ever recorded. AO observations were required to separate the supernova from its host galaxy and ascertain if it was simply AGN variability. The AO observations rapidly confirmed the nature of the transient and gave vital information: position in the host galaxy and a light curve resolved from the bright galaxy nucleus. Right: Swift J1955+2614. This galactic transient was discovered in the galactic plane by the Swift Gamma-Ray-Burst detector satellite. Follow-up observations revealed an extremely complex (and still poorly understood) light curve, followed by rapid fading. Since stellar crowding was significant, LGS AO observations were required to separate the transient light from surrounding stars (Kasliwal et al. 2008).**

**It is important to note that high-frequency, high-availability observations are of comparable or greater importance to achieving new astronomical understanding than collecting area alone.**

Requirements for Keck AO to support Time Domain Astronomy (TDA) science:

- Ability to accept regular ToO interrupts. (Logistics, procedural requirements)
    - Standardized format for applying for and charging ToO/follow-up time.
    - Acceptance by the community for interrupts and a standard practice compensation mechanism.
    - Mechanisms for very rapid observations (e.g., minutes for GRB), modest response (e.g., days for SN), or monitoring campaigns (e.g., monitoring for flaring, weather, volcanism).
- Ability to quickly change instruments.
    - Have selected AO instruments prepared at all times.
    - Completion of mechanized tertiary mirror.
- Ability for AO to be started at a moment's notice.
    - Hot start mode for laser guide stars. (Laser always on will save ~20 minutes.)
    - Daily checkout of TBAD.
    - SkyTiles laser clearance active every night.

## vii. Star Formation and Stellar Astrophysics, < 100 Mpc

### 1.vii.1 Galactic Star Formation and Stellar Astrophysics

The Keck AO instrument suite has provided an excellent platform for the study of nearby star formation and stellar astrophysics. The ability to probe young, embedded star forming regions at IR wavelengths and high spatial resolution is essential to achieving a full census of cluster membership and characterization of those members (e.g., Clarkson et al. 2012). This is accomplished through a combination of imaging with NIRC2 and moderate and high resolution spectroscopy with OSIRIS and NIRSPAO. Imaging offers precision astrometry that allows for dynamical studies of the most crowded portions of these star forming regions, as well as probes of extended structure or disk imaging. An example of such imaging is shown in Figure 6. Spectroscopy provides spectral type information and other diagnostics such as accretion indicators (e.g. Duchêne et al. 2002).

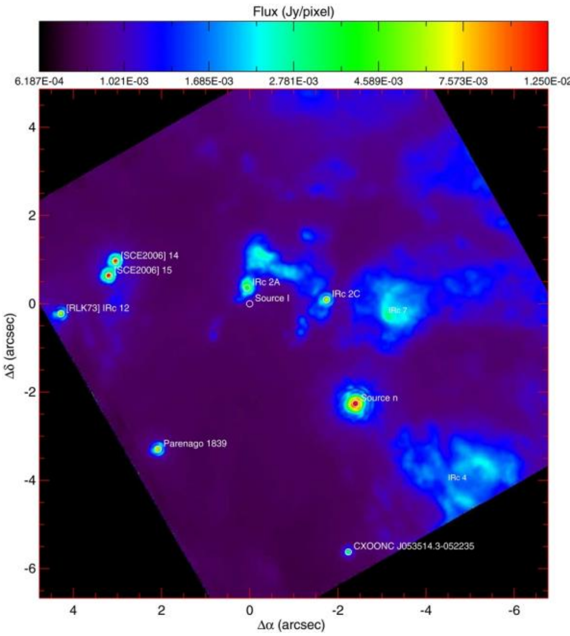


**Figure 6: L' image of the region near the Orion Kleinmann-Lowe nebula. The morphology revealed in these AO images is used to constrain the properties of the disk around the massive protostar labeled "Source I".**

More detailed studies of individual stars with Keck AO have included disk imaging of both protoplanetary and debris disk hosts. Much of this work has been done with NIRC2 (e.g., Esposito et al. 2014), although OSIRIS has provided a unique look at young star disks and outflows (e.g., Perrin & Graham 2007, Figure 6). NIRSPAO has also offered line diagnostics of disks at longer near-IR wavelengths (e.g., Zhang et al. 2015). Keck AO has also yielded numerous measurements of dynamical masses of both young and old binary stars, which helps constrain models of their evolution (e.g., Dupuy et al. 2009, Schaefer et al. 2012).

Thus, the current studies of star formation and evolution have taken advantage of the relatively high Strehl ratio offered by Keck AO compared to other competitive facilities. They have also been able to exploit the near-IR wavebands offered by the AO instrument suite. To more efficiently observe star forming regions, larger fields of view and multiplexing capabilities with spectroscopy would offer substantial improvements. This could be achieved with a wider field of view imager than currently offered by NIRC2 or OSIRIS, or an AO fed multi-object spectrograph. Moderate resolution spectra allow for spectral typing and rough radial velocities, while high spectral resolution can give a more detailed picture of the velocity structure of these regions and allow for the identification of spectroscopic binaries. The multiplexing capabilities like those offered by MOSFIRE would be powerful, but could also be as small as a factor of two, with an example being the RAVEN MOAO demonstrator that provided the ability to integrate on two objects at once rather than one at high spectral resolution (Lardière et al. 2014). To improve detailed studies of protoplanetary and debris disks, polarimetric capabilities would be a fairly straightforward upgrade that would make Keck somewhat unique compared to other facilities. This capability would also be interesting for the study of possible polarization in low mass objects, such as rapidly rotating brown dwarfs (Marley & Sengupta 2011).

### 1.vii.2 Stellar Populations in Local Group Galaxies

- *Stellar astrophysics and stellar populations (<100 Mpc)*
    - Infrared or optical
    - Imaging for binary star work or photometric variability work (not obvious this requires AO); astrometry of dwarf galaxies or globular clusters (old stellar populations)
    - Moderate resolution spectroscopy - spectral types for close binaries (could be multi-object or IFU)
    - High resolution spectroscopy - abundances and RVs for binaries
    - Possible preference for high Strehl ratio here when field is not crowded - ability to resolve tightest systems possible advantage for 10 m telescope, especially if we can push into the optical; moderate Strehl ratio improvement for single systems will improve efficiency of spectroscopic measurements
    - For old stellar populations, moderate to large field of view with moderate correction preferred
    - Dwarf galaxies around Andromeda - is the metallicity different than our dwarfs? Individual stars here - metallicities - red giants brighter in the infrared
    - Star clusters in Andromeda will require high-Strehl ratio observations; large field of view IFUs will be especially helpful to complement the vast optical imaging dataset from HST.
    - Resolving center of Andromeda is largely inaccessible with even HST or AO today. Strehl ratio improvements likely enable IFU observations of some of the brightest stars.
    - Local dwarf globular clusters

## viii. Exoplanets

Keck AO and NIRC2 provided the emblematic images of 4-planet system HR 8799, and numerous others. Keck also pioneered interferometric techniques, including aperture masking (e.g. LkCa 15) and nulling interferometry (exozodi survey), which are opening critical parameters at the smallest angles, revealing the few AU-scale regions. OSIRIS, while not optimized for high contrast imaging, has provided the highest spectral resolution spectrum of two exoplanets to date (HR8799b and HR8799c). New capabilities in LGS and near-IR tip-tilt sensing have enhanced the sky coverage, enabling spectroscopy of companions to M stars.

The recently funded upgrade of NIRSPEC will reinvigorate infrared high-spectral-resolution capabilities at Keck. With a resolution of R ~ 37,500, its nominal seeing and diffraction limited mode NIRSPAO, this instrument will continue to be the workhorse high-resolution spectrograph of Keck, and enables critical access to thermal infrared wavelengths for studies of exoplanets and protoplanetary disks. Several exciting developments are currently on-going. The first one will enable IR precision radial velocity measurement with NIRSPEC by implementing a diffraction-limited fiber feed and a laser comb. The fiber feed will also be used to perform high contrast high resolution spectroscopy of companion brown dwarfs and planets.

KAPA is the long-awaited laser tomography upgrade of the Keck AO. The project has full support of the SSC and a full proposal will be submitted to the NSF MSIP program in Feb., 2016. The capabilities of KAPA will considerably increase the sky coverage of the Keck AO system, enabling high contrast imaging on faint and obscured objects in star forming regions, a capability now out of reach of all other AO facilities.

KPIC, the Keck Planet Imager and Characterizer concept consists of three upgrade modules for the Keck-AO systems: an IR-WFS, a coronagraph bench including a high-density deformable mirror, and a fiber-injection module for NIRSPEC. KPIC has recently been proposed to the SSC who recommended the technological and scientific demonstration of an IR WFS, which is at the core of the project and also on the critical path to future TMT planet finder instrumentation. The fiber injection module for NIRSPEC has also been approved and funded by the Heising-Simons Foundation.

**Landscape:**

- SPHERE and GPI surveys on-going (~1000 young stars)
    - focus on low-res (R ~ 50) spectroscopy and imaging
    - limited to R <~ 9 (GPI), R < ~12 (SPHERE)
    - Y-K only
- High-resolution with CRIRES: 2 results (off for cross dispersion upgrade, back in 2017)
- talks at ESO to link SPHERE to CRIRES
- HST: mostly disks (lack contrast but has sensitivity)
- LBT: LEECH survey at L and M bands (ASM pros and cons), L-band IFS
- SCExAO: no survey yet but ramping up capabilities/performance fast
- SCExAO => IRD (?) new IR spectrograph R=60,000-70,000
- Mag AO (2K, X): leading the pack in visible AO (H alpha)

JWST will do young or slightly older long-period planets, and will do the best on transit spectroscopy. While JWST will bring unparalleled sensitivity, the lack of high-resolution spectroscopy places some limitations on its performance in characterizing exoplanet atmospheres. Current and future instruments at Keck, on the other hand, provide high spectral resolution that complements and enhances the science cases for JWST. Therefore, the joint force between JWST and Keck presents enormous opportunities to study exoplanet atmospheres.

WFIRST-AFTA has goals of reflected light of mature Jupiter and warm Neptunes & micro-lensing. ELT planet finder, realistically around 2030, even if fast tracked (slot in front of IRIS available for high contrast imager).

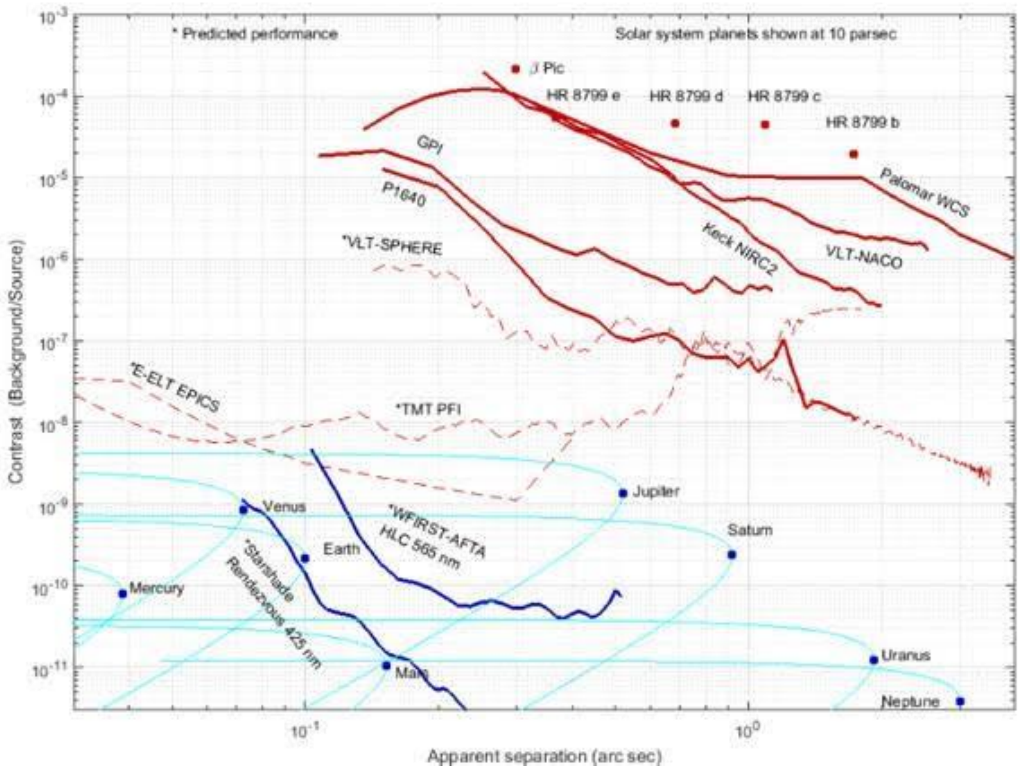


**Figure 7: Contrast versus separation for various facilities.**

**Science cases:**

- Planets around low-mass stars: IR precision radial velocity (PRV) & Doppler Imaging (DI)
- Planet formation in obscured star forming regions: imaging and spectroscopy
- Medium to high resolution spectroscopy of DI planets: composition and DI
- Thermal IR (L/M) characterization: complementarity to SCExAO / GPI / SPHERE
- Accretion of forming planets on 10 mas scales (H alpha)
- Weather variability in BD and exoplanets

**Requirements:**

- IR wavefront sensor (WFS) + fiber injection unit (FIU) for radial velocities
- IR WFS, high order deformable mirror (HODM) + coronagraphy
- All of the above + new diffraction limited spectrograph with sub-e- IR chip
- Cool AO bench
- Two-stage AO: LODM+HODM (ASM?), LGS (? new laser is 10 times brighter as former generation), new optics and layout (non-common path aberration (NCPA)), differential imaging or IFU in the R band (H alpha).
- Stability, time

**Complementarity:**

- More sensitive, sky coverage (IR WFS), L/M band, higher spectral resolution (OSIRIS/NIRSPAO heritage).
- Stability and robustness of Keck AO would benefit time-domain studies.

**Breakthrough:** diffraction limited high resolution spectroscopy enables high precision Doppler measurements. Indeed, single mode fibers can be used, suppressing modal noise issue. Single mode fibers also translate to smaller sizes for the optics and a more compact spectrometer. The benefits here are cost and ease of environmental stabilization.

The feedback from Subaru liaisons (Guyon, Currie, Kirby) included the following:

- Keck long wavelength complementarity in high contrast imaging (e.g. NIRC2 L-band vortex, M band?), push that aspect by improving background limit (DSM?)
- Concerns about overlap between IR PRV projects at Subaru and Keck. Would the Keck IR WFS project solve this issue (yes, likely)?

## ix. Solar System

One key advantage of Keck is the high spatial resolution provided by AO. This enables Keck observations to serve as a cornerstone of many different areas of solar system science. Each subfield places different demands on AO performance, but there are some common AO requirements (see also Figure 8).

**AO/instrument Requirements:**

- **Fields of view:** An AO-corrected FOV with 1 arcmin diameter is sufficient to observe the full disk of Jupiter, or the full diameter of Saturn's major ring system. *MCAO is favored by this requirement. GLAO would not typically enhance solar system science return*.
- Diameters of solar system targets between 1" and 1' also place requirements on the FOV of future AO IFUs and imagers, and on the length of slits for spectrographs.
- **Extended NGS:** Studies of AO publications (Wizinowich 2014) showed that Keck dominated solar system AO science: 10 of 12 solar system AO papers in 2013 were based on Keck data. The main reason for Keck's leadership is the large wavefront sensor field stop size, which provides good performance using extended objects for NGS. Thanks to this capability, Keck can do NGS AO on Uranus and Neptune, which cannot be done well at other facilities. Gemini-N AO cannot perform WFS on Ganymede and Callisto, so Keck's ability to use all four Galilean satellites as NGS enhances the temporal coverage for Jupiter observations. *Future AO systems that cannot use NGS of 1"–4" in diameter will lose Keck's unique capabilities for solar system science.*
- **Differential tracking:** Fixed and moving NGS targets must be usable, as well as differential tracking rates between NGS and science targets.

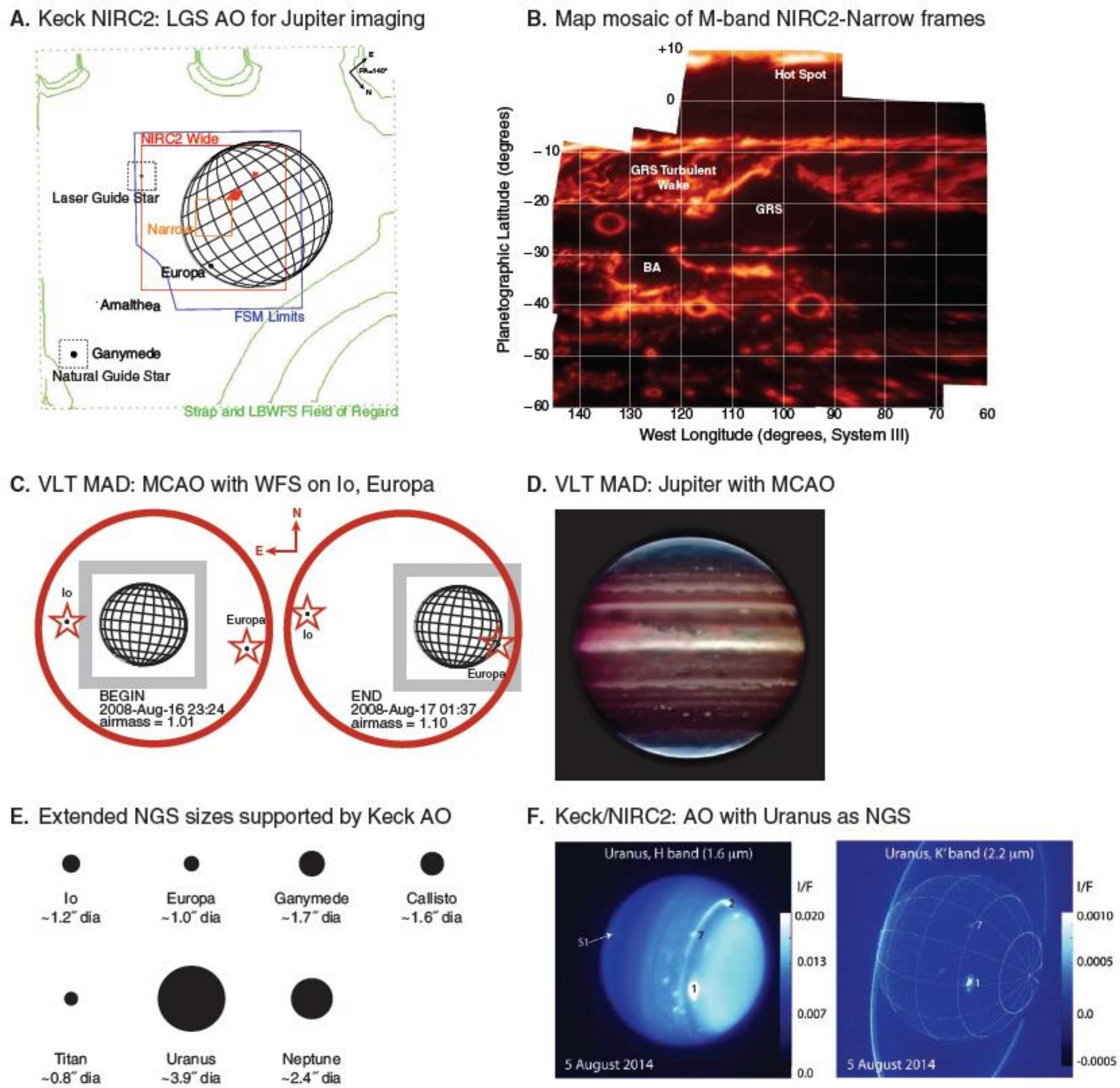


**Figure 8: AO Imaging of Solar System Targets. [A] NGS/LGS setup for Jupiter observations. For NIRC2 narrow camera, the guide star must be within ~30" of the planet's limb, but variable WFS backgrounds preclude the use of guide stars closer than ~15" to the limb, limiting the duration of observations. Using LGS, we can extend the visibility window. [B] The corresponding M-band partial map of Jupiter (de Pater et al. 2010b). [C] Observations with the MCAO demonstrator at VLT used two satellites as guide stars. [D] Corresponding false-color IR image of Jupiter (Wong et al. 2008). [E] Keck AO can use objects as large as Ganymede and Uranus for WFS, while other facilities cannot. [F] NIRC2 Uranus images, with WFS on the planet itself (de Pater et al. 2015).**

**Subject Areas for AO Solar System Science:**

- **Weather and climate of giant planets and Titan.** Studying atmospheres with imaging and resolved spectroscopy provides insight into wind fields, weather, climate cycles, and composition (e.g., Ádámkovics et al. 2016). Keck observations of impacts on Jupiter have also been very fruitful (e.g., de Pater et al. 2010a). For Jupiter and Saturn, imaging at M-band allows cloud structure to be probed at the deepest levels of any wavelength, although only NIRC2's narrow camera can be used

(10" FOV; see Fig. 8 A/B). *AO imaging at M-band over a wider FOV would be a major advance for Jupiter and Saturn. Maintaining Keck's extended-object NGS capability is essential to observations of Titan, Uranus, and Neptune.*

- **Rings.** Ring systems trace the history of giant planet systems, and provide local testbeds for physical processes analogous to those occurring in circumstellar disks. Except for Saturn, rings are faint, so AO is essential for imaging and spectroscopic observations (e.g., Wong et al. 2006, de Kleer et al. 2013).
- **Small bodies.** Binary orbits (and shapes from resolved imaging) can reveal basic properties such as density and macroporosity (e.g., Merline et al. 2013, Marchis et al. 2014). Multiple systems also trace the collisional evolution of the solar system by yielding clues to the conditions of past impacts. Observation of tiny satellites of asteroids and KBOs is one area where very high contrasts may be needed. AO also reduces sky background for better photometry and spectroscopy of faint sources such as smaller Kuiper Belt Objects (e.g., Brown et al. 2006, Takato et al. 2003)
- **Volcanism, cryovolcanism, and exospheres.** Composition of the surfaces and environments of active worlds provide insight to processes of volcanism (Io; e.g., de Pater et al. 2016), cryovolcanism and subsurface liquid water (e.g., Ceres, Europa, and Enceladus; Brown & Hand 2013, Carry et al. 2008), and exospheres (e.g., Mercury; Potter et al. 2006). Keck's existing capability for WFS on extended objects enables both imaging and spectroscopy (IFU), complementing spacecraft data (where available) in terms of temporal coverage or spectral resolution. Wide field AO corrections are not needed for these smaller targets.

**Synergies with Other Facilities:**

A unique aspect of solar system science is the ability to go there with spacecraft from NASA, ESA, and a growing number of Asian space-faring nations. Missions are of limited duration, so long ground-based observational campaigns can provide temporal context for space observations. High spectral resolution is difficult to achieve in space due to instrument mass and volume constraints. Finally, spacecraft observations are often regional in scope, deriving benefit from global context observations from the ground.

**Breakthroughs:**

- **MCAO.** A good correction over a larger FOV could be achieved using MCAO with multiple satellites (each with separate tracking rates relative to the target; see Figure 8 C/D).
- **IR WFS.** For giant planets, the contrast between NGS (a satellite) and target can be increased by performing WFS at wavelengths with strong $CH_4/H_2$ absorption. This reduces background around the NGS, so the loops can stay closed when the NGS is close to (or even transiting?) the planet. Currently, Galilean satellites have short windows of opportunity as NGS for Jupiter observations because they must remain within the field steering mirror range of ~30", but not so close that background variation is too rapid (10-15" from the planet). *In order to take advantage of improved NGS/target contrast in IR CH4 bands, the WFS must be able to use extended NGS of 1–1.7" diameter*.
- **Instrument upgrades in M-band**. Advances would be enabled by a wider FOV for M-band imaging (Figure 8 A/B), in an upgraded NIRC2 or a new imager. AO correction for M-band high resolution (NIRSPEC at R ≥ 20,000) spectroscopy would be a significant advance, perhaps enabled by a cooler AO system.
- **AO at optical wavelengths.** Good AO performance at optical wavelengths would provide even better spatial resolution for studies of giant planet atmospheric flows and storm evolution.

## C. Relationship to other major facilities

Members of the AO Task force met with members of each Keck Task Force to identify areas where science between these major facilities overlapped with current and future AO capabilities. This section summarizes synergies where Keck AO is able to complement science goals in the mid- and long-term between each of these observatories.

### i. Keck and TMT

Keck synergy with TMT could potentially be achieved by: (1) having wide-field AO systems (e.g. GLAO) to feed instruments like MOSFIRE, DEIMOS and LRIS; (2) extending AO-correction into the optical, since this will not be done by TMT at least initially; (3) using Keck AO as a high contract test bed to prepare for a second generation TMT planet-finding instrument; and (4) with AO-corrected spectroscopic observations, at high spectral resolution, in the L and M-bands.

### ii. Keck and Time Domain Astronomy

Currently there are no sustained active AO TDA characterization programs - only ad hoc projects for important ToOs. A large fraction of the Keck community are involved with numerous time-domain projects, e.g., the Nearby Supernova Factory, the Palomar/Zwicky Transient Facility, the Catalina Real-Time Transient Survey, Pan-STARRS and ATLAS, and having the ability to immediately trigger an AO observation of key transients would give the Keck community an edge in this field.

Long term monitoring over very long timescales (e.g. years) with AO is also important; for example the Galactic Center once per week every week or seasonal timescales of the outer planets and their satellites (e.g., the OPAL program with HST, Simon et al. 2015). Robo-AO KP will begin nightly monitoring of the outer planets in 2016 and this could be a source of triggers for higher-resolution/IR imaging at Keck.

### iii. Keck and JWST

A high resolution Keck AO system (e.g. KAPA or NGAO) will have smaller PSFs than JWST (factor 2 at 900 nm and 50% better at 2400 nm). This would benefit a variety of science cases.

The smallest inner working angle of the JWST high contrast instrument is 6 lambda/D, which is a factor of 10 poorer than for a Keck vortex coronagraph.

Keck AO would have a gain in sensitivity for smaller sub-halo masses than JWST. Pushing into the optical wavelengths would complement JWST, especially since HST will eventually be offline.

Keck AO’s higher to moderate spectral resolution will complement JWST since NIRspec with JWST is limited to R~2700.

## iv. Keck and WFIRST & EUCLID

Keck AO-WFIRST synergies largely cluster into two categories: GLAO-enhanced multi-object spectroscopy of regions in the High Latitude Survey (HLS) and narrow-field, high Strehl ratio follow-up of galaxy-galaxy lenses.

The WFIRST HLS in the Southern hemisphere has some visibility to Keck in the summer months at high zenith angle. An important area of concern in cosmology today is the degree to which baryonic matter and dark matter correlate in space. In the HLS, WFIRST will perform weak lensing tomography to map dark matter distributions and a redshift survey with its prism spectrograph (R ~ 460). Keck's niche in this case is performing redshift surveys of faint galaxies that emit the bulk of their luminosity at optical wavelengths. GLAO-assisted DEIMOS spectroscopy would be the most sensitive MOS available at optical wavelengths and could be used to constrain the luminosity function in dark matter-rich, galaxy-poor voids. The intermediate spectral resolution would be necessary to assess cluster membership in strongly lensing galaxy cluster fields. These cases require larger fields (> 5') and no better correction than the typical galaxy size at $1 < z < 3$ (~0.3").

WFIRST, EUCLID and LSST will also require precision calibration of photometric redshifts to accomplish the weak lensing tomography mission. WFIRST's grism spectrograph will suffer from confusion issues for the magnitude and redshift ranges needed for weak lensing. Extensive ground-based MOS spectroscopy of targets spanning a range in redshifts, galaxy types, and luminosity will be critical to calibrating photometric redshifts for LSST and WFIRST. GLAO+DEIMOS/LRIS will be the most sensitive optical MOS spectrographs available for compact sources (< 0.3") at $1 < z < 5$ and will be able to efficiently calibrate optical photometric redshifts in the region of the HLS visible to Keck. GLAO+MOSFIRE, while not as sensitive as JWST's IR MOS, will be helpful for calibrating WFIRST's infrared photometric redshifts for brighter sources.

WFIRST and LSST will identify numerous galaxy-galaxy lenses that can be used to probe the nature of substructure in galaxy-scale halos and the detailed variation in dark matter profiles. In some situations in which the lensed object is time variable, measurement of time delays can constrain critical dark energy parameters such as *w.* Both cases require high-fidelity reconstruction of the source profile of the lensed object, and thus require a high Strehl ratio, stable PSF and would benefit from PSF reconstruction. Optical correction would improve the spatial resolution of substructure in the halo, as well as provide much improved sensitivity to faint sources (lensed background sources are typically observed-frame blue) against the sky background.

WFIRST's coronagraph will also directly image and characterize extrasolar planets identified via ground-based radial velocity surveys. This program will benefit from high-contrast pre-imaging of the targets to identify unseen background stars, perturbing sources, or long-period companions. In addition, RV alone does not pinpoint the position angle of the planet in the imaging field, and the coronagraph of choice only produces a narrow "dark hole" in which the planet can be seen. Measurement of astrometric accelerations of the stellar host from GAIA or Keck AO would constrain companion orbital elements and locate the planet on the plane of the sky, saving an initial "searching" step by WFIRST.

## v. Keck and Planet Finding & Characterization

KPIC consists of an insertable/removable module downstream from the current Keck AO system, equipped with its own efficient IR WFS using the latest low-noise detector technologies (IR-APD), a high-order deformable mirror (HODM), a state-of-the-art coronagraphic bench, and a steerable beamsplitter dividing the science beam into an imaging path and a fiber-injection unit. Both channels are available to feed existing IR science instruments available at Keck: imager (NIRC2), IFU (OSIRIS, or another IFU yet to come) for the imaging channel, and high resolution spectrograph (NIRSPEC) for the fiber-fed spectroscopic channel. An extreme AO (ExAO) high contrast imaging facility optimized for faint red objects by means of IR WFSing can image and spectroscopically characterize exoplanets both around nearby young M stars and in star-formation regions. KPIC will provide the Keck Observatory with capabilities orthogonal to its competitors at a fraction of the cost of GPI and SPHERE. Keck-NIRC2's long wavelength (L and M) capabilities are also the perfect complement to SCExAO.

## vi. Keck and Hubble Space Telescope

HST provides many workhorse instruments for a variety of fields of astronomy. With HST's finite lifetime, there may be roles that Keck can take over. High angular resolution imaging at near-IR or shorter wavelengths may be a role that can be filled with the appropriate AO system and instruments. HST imaging with ACS or WFC3 has a field of view of about 2'. Wide-field AO capabilities may be able to approach this field of view. Deep imaging of single objects with HST is often used to obtain high angular resolution measurement of objects, often at visible wavelengths. Use of AO to complement this with near-IR measurements is already currently a very successful strategy. To replace the HST capabilities will require visible light AO.

## vii. Keck and Subaru

There is some concern over duplication of effort between Subaru and Keck in terms of AO development. One of the biggest pushes for Subaru in terms of future AO systems is the proposed ULTIMATE-Subaru AO system, which is a GLAO system with a notional first light in the early 2020s (http://www.naoj.org/Projects/newdev/ngao/20160113/ULTIMATE-SUBARU_SR20160113.pdf). Subaru is actively seeking contributions of in-kind instruments to put behind the AO system, including a wide-field imager and a multi-object IFU.

A second area of development is a possible near-IR precision RV effort for Subaru called IRD. Much like the Keck plans described previously, the goal would be to use an AO system like SceXAO (Guyon et al. 2014) to feed a fiber to a high resolution spectrograph. In order to avoid redundancy, it is essential to look for the trade-offs and unique capabilities between the two designs. It is possible that time trades rather than upgrades would save money on both fronts. Along these lines, it was suggested that strengthening of the ties between the telescopes, including additional time trades, would be highly advantageous. Additional workshops like those held in Sendai would help foster these bonds.

## viii. Keck AO as a Technical Demonstrator

Keck, being the only US-based adaptively-corrected segmented telescope is the only viable platform to proof test technologies for large segmented telescopes in space and on the ground. The detrimental effect of segmentation, vibration, and generally speaking unfriendly apertures can be studied at Keck in a systematic and controlled operational environment. As a case in point, Keck has been successfully used so far as a co-phasing testbed for TMT. It would be beneficial to the Keck community to allocate a significant fraction of Keck time to technological demonstrators for TMT and for future large segmented telescope in space (e.g. HDST).

# III. New Observational Capabilities Needed to Achieve Goals

**Table 2: New observation capabilities driven by each section II science case**

| Science Drivers | AO/instrument capabilities | AO Type | Primary Synergistic Facilities | Keck Task Force |
|---|---|---|---|---|
| First light galaxies (z > 6) | Improved seeing over large FoV, High sky coverage, High Strehl, Infrared, Integral field spectroscopy, Low-R, Mid-R, Narrowband Imaging | GLAO, LGS | JWST, TMT | Keck → JWST<br>Keck → TMT |
| High-Redshift Galaxies & AGN (1 < z < 5) | Improved seeing over large FoV, High Strehl, PSF Reconstruction, Optical, Infrared, Mid-R, High-R, Multi-object, Integral field spectroscopy, High-spatial resolution, High sky coverage | NFAO/LTAO, GLAO, MCAO (red-optical?) | JWST, TMT, LSST, ALMA | Keck → JWST<br>Keck → TMT |
| Nearby Galaxies and AGNs | Improved wavelength coverage | | | |
| The Galactic Center | NIR high Strehl imaging and spectroscopy, mid-R to high-R spec., IFU (larger fields better), multi-object, mid-IR imaging | SCAO, MCAO | HST, JWST, TMT, VLA | |
| Time Domain Astronomy | Imaging<br>Higher SNR Low-R spectroscopy | NGS, LGS (SCAO) | ZTF, ATLAS, LSST | |
| Star formation and | Infrared (SF regions), Optical (stellar | MCAO, | HST, JWST, | |

| | | | | |
|---|---|---|---|---|
| stellar astrophysics | astrophysics), Moderate Strehl over moderate FOV (SF regions), High(ish) strehl (binaries), Imaging, Polarimetry, mid-R, high-R, Multi-object, IFU | MOAO | TMT, ALMA? | |
| Exoplanets | Infrared/visible narrow-field (1”) high-Strehl imaging, coronagraphy, low-to-high resolution spectroscopy | XAO | SCExAO, GPI, SPHERE, JWST, ALMA | |
| Solar System | High-spatial resolution over FoV up to 1 arcmin, Optical, Infrared, Imaging, Spectroscopy, Integral field spectroscopy | MCAO | HST, JWST, TMT, VLA, ALMA, LSST, Pan-STARRS, planetary spacecraft missions | |

# IV. New or upgraded instrumentation

## A. Description of new science instrument(s) or upgraded instrument

Table 3 lists the new or upgraded science instruments that would benefit each science case discussed in section II. From left to right these are a near-infrared (NIR) imager, NIR integral field unit (IFU), NIR multi-object IFU, visible imager, visible IFU, L-band IFU, a NIR energy sensitive detector (MKIDS) and a polarimeter upgrade for NIRC2. The NIR imager and IFU would likely be a next generation OSIRIS, perhaps like the TMT IRIS or NGAO DAVINCI instrument.

**Table 3: New or upgraded science instrument capabilities benefiting each section II science case.**

| *Science Topic / Instrument Need* | NIR Imager | NIR IFU | NIR Multi-object IFU | Vis Imager | Vis IFU | L-band IFU | IR MKIDS | NIRC2 Polarimeter |
|---|---|---|---|---|---|---|---|---|
| Dark Matter & Energy | X | X | | x | x | | | |
| First Light Galaxies | X | X | | X | x | | | |
| High-z Galaxies & AGN | X | X | X | X | x | | | X |
| Nearby Galaxies | X | X | | X | X | | | |
| Super Massive Black Holes | x | X | | x | x | | | |
| Stellar Populations in MW & Local Group Galaxies | X | X | X | X | X | | | |
| Galactic Center | X | X | X | | | X | | |
| Time Domain Astronomy | x | X | | X | X | | X | |
| Star Formation & Stellar Astrophysics | X | X | X | X | X | X | | X |
| Exoplanets | X | X | | X | X | X | X | X |
| Solar System | X | X | | X | X | X | X | x |

## B. Required technology development including incremental technology demonstrations

A number of technology demonstrations and/or analyses would better position Keck AO to meet the Keck communities science needs. In priority order:

1. An analysis of how to cool the Keck AO systems to reduce emissivity.
2. Evaluate the utility and technical feasibility of GLAO and an ASM on the Keck telescopes.
3. Development of Selex APD IR arrays and H4RG detector testing for science cameras as well as wavefront sensing.
4. Development of wavefront control algorithms for laser tomography and improved AO performance.
5. Coronagraph and WFS test-beds for segmented telescopes to achieve new science on Keck and to demonstrate the required technology for ELTs and segmented space telescopes.
6. Fiber-fed and laser comb, specialize fibers for AO-feed.
7. Evaluate MKIDS for AO and AO-science applications.

## C. Estimation of instrument and activity costs

Table 4 provides a rough cost estimate for the projects and planning recommended in the executive summary. In some cases more than one column has been checked. For the mid-term planning this represents the need to first do a Conceptual Design study to determine which areas are worth pursuing and then if appropriate follow this with a Preliminary Design. In the long-term project this indicates that projects can be implemented at different requirement, and hence cost, levels. For example, we could choose to just implement an ASM with the current AO system or a full GLAO system for one or more science instrument; or we could continue to upgrade the existing Keck AO system instead of building a next generation system.

**Table 4: Instrument cost estimates**

| **Instrument Cost Estimates** | **< 1 M$** | **1-5 M$** | **5-10 M$** | **10-20 M$** | **20-40 M$** |
|---|---|---|---|---|---|
| ***Key Mid-term Projects (< 5 years)*** | | | | | |
| High Strehl, high sky coverage - KAPA proposal | | | X | | |
| High Strehl, high sky coverage - new deformable mirror | | X | | | |
| PSF-Reconstruction Facility | X | | | | |
| High Contrast AO - NIRSPEC fiber injection | X | | | | |
| High Contrast AO - Near-IR pyramid wavefront sensor | | X | | | |
| Support for Time Domain Astronomy | X | | | | |
| OSIRIS Data Reduction Pipeline development & support | X | | | | |
| ***Planning during Mid-Term (< 5 years)*** | | | | | |
| GLAO Conceptual Design Study (<$1M) + Preliminary Design if warranted | X | X | | | |
| Design Studies for new AO science instruments ($1M) + preliminary design for 1 instrument | X | X | | | |
| Planning for next high Strehl, high sky coverage steps | X | | | | |
| Determine future of Keck I | X | | | | |
| ***Key Long-Term Projects (5-15 years)*** | | | | | |
| GLAO (the lower cost is just to implement an ASM) | | | | X | X |
| New AO Science Instrument(s) | | | X | X | |
| Next high Strehl, high sky coverage upgrade (lower cost) &/or NGAO (higher cost) | | | X | | X |

# V. Operations and Policy changes to facilitate Science Goals

## A. New observing modes

In order to support ToO the LGS AO facility should be available at short notice. This can be accommodated with the TOPICA laser by simply leaving the laser powered on at all times and obtaining clearance to use the laser every night. The LGS AO acquisition time should also be reduced which can be accommodated with some efficiency improvements.

## B. Opportunities for collaboration with Subaru (or other Maunakea facilities)

There are already three areas where Subaru, UH and Keck have recently begun collaborations:

- The recently submitted NSF ATI proposal for a near-IR pyramid wavefront sensor for Keck has Chun (UH), Mawet (Caltech) and Wizinowich (WMKO) as co-PIs. Guyon (Subaru) is a technical collaborator and has provided the SCExAO real-time control code for their visible pyramid sensor. Initial experiments are taking place at Subaru with a UH (Hall) near-IR camera.
- We have shared ideas about fiber injection to spectrographs in support of Mawet's fiber injection project and the NIRSPEC PRV proposal.
- The Subaru Ultimate, UH Imaka and Keck AO teams have met to discuss GLAO on our various telescopes and potential risk reduction activities.

One area of non-overlap in AO science capabilities between Keck and Subaru is high Strehl ratios with high sky coverage. Keck also has the better spectrographs to go behind GLAO. These are areas Keck could offer to a collaboration with Subaru.

## C. Data pipelines for existing or new instruments

The data reduction pipeline for OSIRIS should be improved and supported directly at Keck Observatory and resources for instrument pipelines. NIRC2 and NIRSPEC pipelines need to be better supported, developed, documented, and implemented in KOA.

All appropriate AO telemetry should be saved with each science exposure. For each exposure the Keck Observatory Archive should provide a set of PSFs at a grid of positions across the science field and/or the ability to produce a PSF at any point in the science field from the saved AO telemetry.

# VI. Summary

Three summary tables are provided. The first represents the mid-term (3-5 year) science opportunities and the second represents the longer term (> 5 year) goals. The final table is a reference to the AO areas recommended by the other task forces.

**Table 5: Mid-term science opportunities versus instrument capability.**
**Green represents a high priority for a science case and yellow would help a science case.**

| *Science Topic / Instrument Need* | PSF-Recon-struction | NGS NIR Pyramid Wavefront Sensor | LGS IR Tip-tilt Sensor | Laser Tomography | Fiber Injection Unit (+PRV) | Cooler AO Operation | Higher Order AO | Operational Efficiency |
|---|---|---|---|---|---|---|---|---|
| Dark Matter & Energy | X | | X | X | | X | X | X |
| First Light Galaxies | x | | X | X | | x | X | x |
| High-z Galaxies & AGN | X | | X | X | | X | X | x |
| Nearby Galaxies | X | | X | X | | X | X | x |
| Super Massive Black Holes | X | | X | X | | X | X | x |
| Stellar Populations in MW & Local Group Galaxies | X | | X | X | | x | X | x |
| Galactic Center | X | X | X | X | x | X | X | X |
| Time Domain Astronomy | X | x | X | X | x | x | x | X |
| Star Formation & Stellar Astrophysics | X | X | X | X | X | X | X | x |
| Exoplanets | X | X | x | X | X | X | X | X |
| Solar System | X | | x | x | | X | x | X |

Table 5 includes the following instrument capabilities:

- The intent would be for the Keck Observatory Archive to provide a PSF versus position in the science field for every science exposure. Much of the development work has taken place but an operational capability needs to be funded and developed.
- A NSF ATI proposal has been submitted for a near-IR pyramid wavefront sensor science demonstration. If funded this capability would later need to be transitioned to an operational capability.
- A near-IR tip-tilt sensor and laser tomography for Keck II are part of a NSF KAPA MSIP proposal which also includes an upgraded real-time controller and moving OSIRIS and its near-IR tip-tilt sensor to Keck II.
- An AO-fed fiber injection unit to NIRSPEC has been funded by the Heising-Simons Foundation. The NIRSPEC PRV MRI proposal will require some additions to this fiber injection.
- The AO systems currently operate at ~ 10° C warmer than the dome ambient temperature. A modest effort, planned for FY16, should allow Keck AO to operate at much closer to ambient.
- The next logical step after the KAPA upgrade would be to incorporate a higher order deformable mirror (DM) and wavefront sensor. The more general solution would be to replace the existing DM. An option, for high contrast science, would be to add a high order MEMS in the path to one science instrument. For LGS AO this would also require additional laser power.
- Operational Efficiencies. General improvements to software and hardware that enable faster target acquisition time, LGS warm-up and ready time, shorter low-bandwidth wavefront sensor convergence time.

**Table 6: Long-Term Science Goals**

| *Science Topic / Instrument Need* | Keck II AO Upgrade Path | NGAO or ASM High Order LGS AO | NGAO or ASM + High Order NGS AO | MCAO | Next Gen IR IFU | Visible IFU | Multi-Object IR IFU | GLAO + DEIMOS or LRIS | GLAO + MOSFIRE |
|---|---|---|---|---|---|---|---|---|---|
| Dark Matter & Energy | X | X | | | X | x | x | X | X |
| First Light Galaxies | X | X | | | X | | | X | X |
| High-z Galaxies & AGN | X | X | | x | X | X | X | X | X |
| Nearby Galaxies | X | X | | X | X | | | x | |
| Super Massive Black Holes | X | X | | | X | X | | x | |
| Stellar Populations in MW & Local Group Galaxies | X | X | | X | X | x | x | X | X |
| Galactic Center | X | X | | X | X | | X | | X |
| Time Domain Astronomy | x | x | | | x | x | | x | x |
| Star Formation & Stellar Astrophysics | X | X | | X | X | X | X | x | X |
| Exoplanets | X | X | X | | X | X | | | |
| Solar System | X | X | X | X | X | X | | | |

Table 6 includes the following instrument capabilities:

- High Strehl ratio and high sky coverage can continue to be improved via upgrades to the Keck II AO system (these will be limited by the system).
- Higher Strehl ratio and higher sky coverage can be achieved with a new AO system either based on the NGAO concept or an adaptive secondary mirror (ASM). Either approach also significantly reduces the thermal background; the ASM approach would also improve throughput.
- A multi-conjugate AO (MCAO) system could provide a wider (~80" diameter) field, at the expense of lower Strehl ratios and potentially lower sky coverage (due to the need for more tip-tilt stars).
- A next generation OSIRIS could provide some combination of wider field and higher spectral resolution, and likely higher throughput. It could also likely support science at shorter wavelengths.
- Visible and multi-object IFUs are other new instrumentation directions. The former requires much higher Strehls and the latter requires different control algorithms and multiple DMs.
- The GLAO options all assume an ASM, the ability to implement multiple wavefront sensors in front of an existing science instrument and the ability of the science instrument to take advantage of the improved (~2x) image size.

Table 7 is our attempt to summarize the AO capabilities recommended by the other strategic planning task groups. The Keck + Subaru task group's AO instrument priorities were unclear to us, beyond concerns about potential duplication, hence this row has been left blank.

Table 8 summarizes the AO task group's opinion on what AO capabilities would be useful in the era of TMT, JWST, etc. We have also added two additional categories: potential Keck AO roles in the absence of HST and Keck AO in support of planetary missions. We also note that Keck AO offers an excellent testbed for the ELTs and that Keck should continue to collaborate with these projects to advance both the Keck and ELT AO projects.

**Table 7: Mid- and long-term instrument priorities from the other strategic planning task groups.**

| *Task Group / Instrument Need* | Keck II AO Upgrade Path | NGAO or ASM High Order LGS AO | NGAO or ASM + High Order NGS AO | Wide Field AO (e.g. MCAO) | Next Gen IR IFU | Visible Imaging | Visible IFU | Multi-Object IFU | GLAO + DEIMOS or LRIS | GLAO + MOSFIRE |
|---|---|---|---|---|---|---|---|---|---|---|
| Keck + TMT | X | x | | | x | X | X | x | X | X |
| Keck + JWST | X | X | | | X | X | | | X | |
| Keck + TDA | X | X | | | X | X | X | | | |
| Keck + WFIRST/EUCLID | X | X | | | | X | x | | X | X |
| Keck + Subaru | | | | | | | | | | |

**Table 8: Mid- and long term instrument priorities from the AO task group perspective.**

| *Task Group / Instrument Need* | Keck II AO Upgrade Path | NGAO or ASM High Order LGS AO | NGAO or ASM + High Order NGS AO | Wide Field AO (e.g. MCAO) | Next Gen IR IFU | Visible Imaging | Visible IFU | Multi-Object IFU | GLAO + DEIMOS or LRIS | GLAO + MOSFIRE |
|---|---|---|---|---|---|---|---|---|---|---|
| Keck + TMT | X | X | x | | x | X | X | X | X | X |
| Keck + JWST | X | X | x | | X | X | X | X | X | |
| Keck + TDA | X | X | | | X | X | X | | | |
| Keck + WFIRST/EUCLID | X | X | | | | X | x | | X | X |
| Keck + Subaru | x | x | x | x | x | x | x | x | | |
| Keck - HST | X | X | | X | | X | X | | X | |
| Keck + Planetary Missions | X | X | x | X | X | X | X | | | |

From Table 1 our primary ground-based AO competition is predominantly VLT, especially with their investment in a GLAO facility with four LGS and powerful science instruments, as well as the planned high Strehl ratio ERIS AO system and the CRIRES AO-corrected instrument.

For the Keck community to stay competitive scientifically we recommend significant investment in AO facilities and science instruments, as outlined in the Executive Summary. The Keck science community has had a strategic advantage versus other ground-based telescopes with the high performance Keck AO facilities and science instruments. We recommend continuing to maintain that advantage with further investments to improve the Strehl ratio and sky coverage of these systems. We also need to ensure that these facilities are equipped with powerful new science instrumentation. Finally, we recommend determining the strategic benefit of seeing improvements for existing Keck science instruments with GLAO.

## *References*


Ádámkovics, M., Mitchell, J.L., Hayes, A.G., et al. 2016, Icar, doi:10.1016/j.icarus.2015.05.023

Brown, M. E., & Hand, K. P. 2013, AJ, 145, 110

Brown, M. E., van Dam, M. A., Bouchez, A. H., et al. 2006, ApJ, 639, L43

Carry, B., Dumas, C., Fulchignoni, M., et al. 2008, A&A, 478, 235

Clarkson, W. et al. 2012, ApJ, 751, 132

de Kleer, K., de Pater, I., Ádámkovics, M., & Hammel, H. 2013, Icar, 226, 1038

de Pater, I., Laver, C., Davies, A. G., et al. 2016, Icar, 264, 198

de Pater, I., Sromovsky, L. A., Fry, P. M., et al. 2015, Icar, 252, 121

de Pater, I., Fletcher, L. N., Pérez-Hoyos, S., et al. 2010a, Icar, 210, 722

de Pater, I., Wong, M. H., Marcus, P., et al. 2010b, Icar, 210, 742

Do, T., et al. 2013, ApJ, 764, 154

Duchene, G., Ghez, A.M., & McCabe, C. 2002, ApJ, 568, 771

Dupuy, T.J., Liu, M.C., & Ireland, M.J. 2009, ApJ, 692, 729

Esposito, T.M., Fitzgerald, M.P., Graham, J.R., & Kalas, P. 2014, ApJ, 780, 25

Genzel, R., et al. 2010, RvMP, 82, 3121

Ghez, A. M., et al. 2008, ApJ, 689,1044

Guyon, O. et al. 2014, SPIE Proc., 9148, 91481R

Kasliwal, M., Cenko, S., Kulkarni, S. et al. 2008, ApJ, 678, 1127

Lu, J., et al. 2013, ApJ, 764, 155

Marchis, F., Durech, J., Castillo-Rogez, J., et al. 2014, ApJ, 783, L37

Marley, M.S. & Sengupta, S. 2011, MNRAS, 417, 2874

Merline, W. J., Drummond, J. D., Carry, B., et al. 2013, Icar, 225, 794

Meyer, L., et al. 2012, Science, 338, 84

Ofek, E., Cameron, B., Kasliwal, M., et al. 2007, ApJ, 699, L13

Perrin, M.D. & Graham, J.R. 2007, ApJ, 670, 499

Potter, A. E., Plymate, C., Keller, C., Killen, R. M., & Morgan, T. H. 2006, AdSpR, 38, 599

Quimby, R. 2006, Central Bureau Electronic Telegrams, 644, 1

Rudy, A., Horns, D., DeLuca, A. et al. 2015, ApJ, 811, 24

Schaefer, G.H., Prato, L., Simon, M., & Zavala, R.T. 2012, ApJ, 756, 120

Simon, A. A., Wong, M. H., & Orton, G. S. 2015, ApJ, 812, 55

Takato, N., Fuse, T., Gaessler, W., et al. 2003, EM&P, 92, 183

Treu, T. et al. 2013, ApJL 775, L29

Weinberg, N. et al. 2005, ApJ, 622, 878

Wizinowich, P. 2014, Survey of High Spatial Resolution Adaptive Optics Facilities (Oxnard, CA: Keck Strategic Planning Meeting).

Wong, M. H., de Pater, I., Showalter, M. R., et al. 2006, Icar, 185, 403

Wong, M. H., Marchis, F., Marchetti, E., et al. 2008, arXiv, arXiv:0810.3703

Zhang, K., Crockett, N., Salyk, C., Pontoppidan, K., Turner, N.J., Carpenter, J.M., & Blake, G.A 2015, ApJ, 805, 55