

# Keck Planet Imager and Characterizer

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## Abstract

The advent of fast low-noise infrared cameras (IR-APD), the rapid maturing of efficient wavefront sensing techniques (Pyramid/Zernike), small inner working angle coronagraphs (vortex, HLC, PIAA) and associated low-order wavefront sensors, as well as recent breakthroughs in Doppler imaging techniques applied to brown dwarfs and exoplanets, open new avenues complementary to first and second-generation extreme adaptive optics (ExAO) systems. For instance, the search and characterization of planetary systems around M-dwarfs, the prime science case for future extremely large telescope planet finder instruments, such as PFI and PCS on TMT and the EELT, respectively, can be initiated now on a 10-meter class telescope. The Keck Planet Imager and Characterizer (KPIC) is a cost-effective module for Keck-AO, building on the lessons learned from Subaru Coronagraphic Extreme Adaptive Optics (SCEAO), VLT SPHERE, Gemini Planet Imager (GPI), Palomar P3K/P1640 and Stellar Double Coronagraph (SDC) to explore new scientifically exciting niches paving the way to the TMT-Planet Finder Instrument (PFI) core science, while maturing system-level and critical components for future ground- and space-based instrumentation (TMT, WFIRST-AFTA, EXO-C/S).

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## 1. What is KPIC?

KPIC consists of an insertable/removable module downstream from the current Keck AO system, equipped with its own efficient infrared wavefront sensor (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 infrared 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 adaptive optics (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, and more ambitious projects such as NGAO.

## 2. Science cases

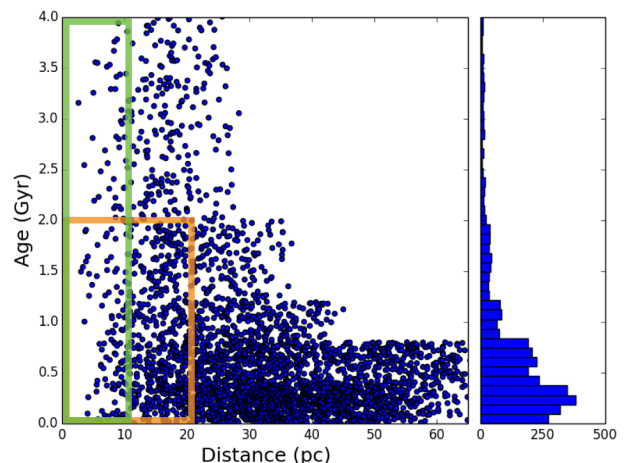
**Exoplanets around M-dwarfs.** M dwarfs constitute the most promising reservoir to advance our understanding of planetary formation and evolution. Indeed, M dwarfs vastly outnumber all earlier-type stars together [10]. Their abundance and low close binary fraction imply that they are common sites of planet formation. Close separations ( $< 1$  AU) have been extensively probed by Doppler and transit surveys with the following results: the frequency of close-in giant planets ( $1 - 10M_{Jup}$ ) is only  $2.5 \pm 0.9\%$ , consistent with core accretion plus migration models [9]. On the other hand, Kepler indicates that Earth- to Neptune-sized planets might be as common as one per star [23, 7, 15].

The outskirts of young M-dwarf systems ( $10 - 100$  AU) are being probed by first-generation direct imaging instruments, and preliminary results show that massive planets are rare: less than 10.6% of M-dwarf systems surveyed harbor  $1 - 13M_{Jup}$  giant planets in their outer regions [3]. Disk instability does not seem to be a common mechanism of giant planet formation. The  $1 - 10$

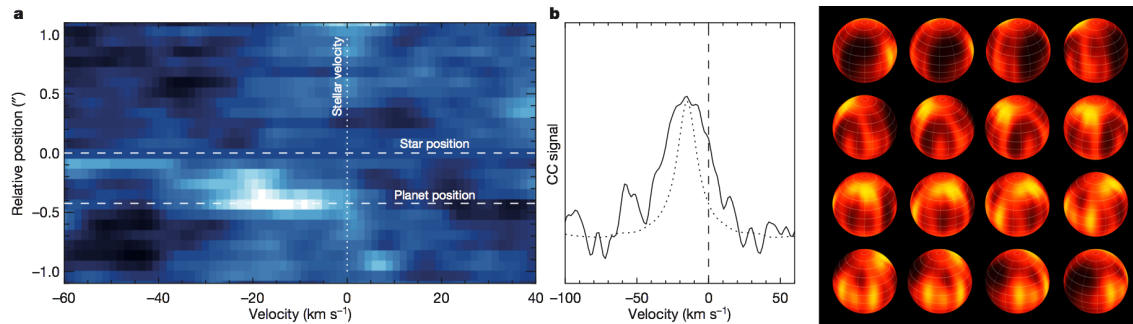
AU parameter space is thus believed to be the El Dorado of planet formation. Across the entire range of sensitivity ( $10M_{\oplus} - 10M_{Jup}$ ), the occurrence rates measured by microlensing survey imply an average  $1.6_{-0.9}^{+0.7}$  planets per star [4]! Microlensing probes the full range of planetary masses in this region, but the masses and metallicities of the host stars are usually poorly constrained and so are of limited value for statistical studies. High contrast imaging is therefore the perfect complement.

KPIC will target this reservoir (Fig. 1) with the most advanced high contrast imaging techniques, imaging these planets down to unprecedented sensitivities, but also directly analyzing their emitted light with medium-resolution (e.g. NIRC2 grisms or OSIRIS) and/or high-resolution spectroscopy (NIRSPEC), enabling molecular composition atmospheric retrieval [1] and dynamic Doppler imaging of surface and/or cloud features [6, 21, 20] (see Fig. 2).

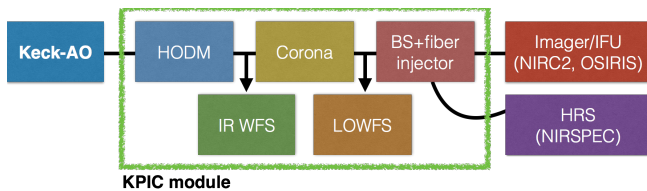
**Planetary systems in star forming regions (SFR).** Sky coverage with an IR WFS is typically 50% higher than in the visible



**Figure 1.** Age vs distance scatter plot of nearby active M stars visible from Keck, the basis for the proposed large-scale M-dwarf surveys of KPIC (color rectangles).



**Figure 2.** Doppler imaging applied to exoplanets and brown dwarfs. Left: a. position velocity plot showing the blue shifted peak of planet  $\beta$  Pictoris b as measured by VLT’s AO-fed high-resolution infrared spectrograph CRILES. b. Rotational broadening of the line profile of  $\beta$  Pictoris b over molecular lines in the K band, effectively measuring the spin of an exoplanet for the first time [21]. Right: Doppler imaging of the cloud structure of brown dwarf Luhman 16b over a full rotation period [6].



**Figure 3.** Sketch of the proposed KPIC module concept reuses the Keck interferometer Dual Star Module (DSM) port, and incorporates its own ExAO system in cascade with Keck-AO, using a scheme inherited from SCEXAO and recognized as the optimal configuration for TMT-PFI. The concept makes simultaneous use of the classical imager or IFU and fiber-fed high-resolution spectrograph.

[5], but in obscured areas such as SFR, the gain is much more dramatic. The population of young stars in Taurus, 140 pc away, is dominated by M stars and very late K stars [8], making IR WFS essential for these very red stars. Indeed, an R-band WFS sensitivity rolloff at  $R \simeq 10$  currently provides access to only a handful of T Tauri stars, while a rolloff at  $J/H \simeq 10$  mags would enable high contrast on a hundred young stars in Taurus alone. Thus, IR WFSing enables high contrast imaging studies of extrasolar planetary systems (both disk + protoplanets) in their infancy.

**Galactic center (GC).** IR WFS has proven to be very robust to study the GC with VLT-NACO: IRS 7 ( $H = 9.3$ ,  $K = 6.5$ ) is only  $6''$  North of  $SgrA^*$ . An IR WFS ExAO would boost the Strehl ratio (SR) by a factor of a few compared to current LGS assisted observations (10 – 30% SR at K), therefore enhancing SNR, enabling shorter wavelengths, and thus improving resolution and astrometric precision (reduced confusion).

### 3. Technical case

Powerhouse second-generation AO systems such as SPHERE and GPI were designed 10+ years ago. The technological landscape has evolved considerably since then, in particular in wavefront sensing, coronagraphic, and detector technologies. Specifically, we propose to supplement the current Keck-AO system with a cascaded IR-WFS based ExAO system using a state-of-the-art fast, low read-noise detector, and high-order deformable mirror.

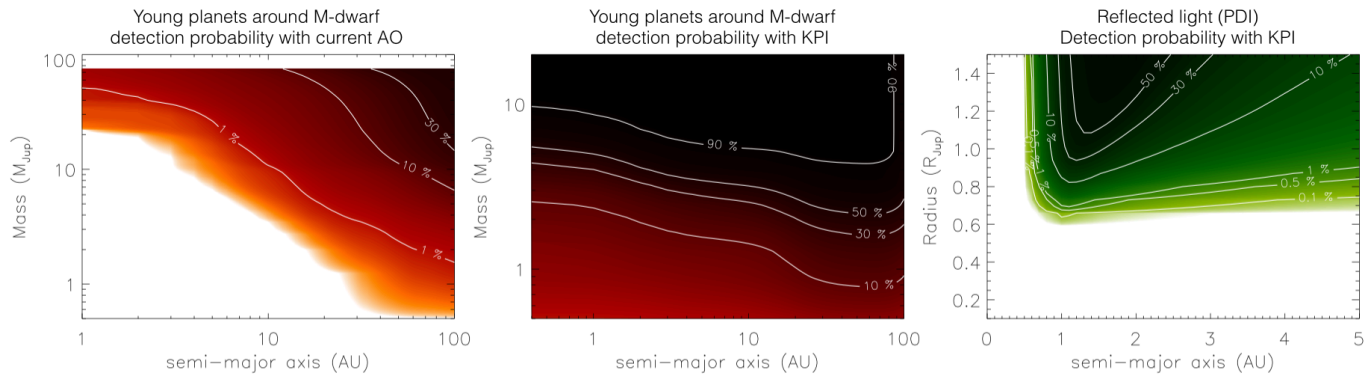
**Phased low-cost implementation.** The new proposed module maximises the use of current Keck infrastructure and assets (Fig. 3).

New developments are kept to a minimum, and focussed on key areas, such as efficient wavefront sensing techniques (Pyramid/Zernike), and low-noise infrared cameras (IR-APD, MKIDS), which are highly strategic to future TMT instrumentation.

**Complementarity/synergy with other (space-based) facilities.** KPIC, with its IWA of  $\simeq 25 - 50$  mas at J-band, will complement JWST at very small angles (the IWA of NIRCAM and MIRI will be 5-10 times larger). KPIC benefits from recent advances in coronagraphy, wavefront control [16] and low-order wavefront sensing techniques developed for space-based coronagraph projects such as WFIRST-AFTA, EXO-C, and ATLANTIS, while providing a platform for demonstrating and optimizing these techniques in an operational environment. Specifically, the vector vortex coronagraph (VVC) has demonstrated  $\simeq 10^{-9}$  raw contrast at  $2\lambda/D$  on the high contrast imaging testbed [18]. Moreover, a pupil plane low-order wavefront sensor (LOWFS) on a VVC on SCEXAO at Subaru has recently demonstrated closed loop  $\simeq 10^{-3} \lambda/D$  tip-tilt and focus retrieval accuracy on-sky [19]. KPIC’s high resolution spectroscopic mode will demonstrate crucial capabilities that will be essential to follow-up discoveries from JWST, TESS and later on WFIRST-AFTA.

**Other high contrast observational modes.** One example is cross-aperture nulling, which can be implemented efficaciously within KPIC by means of drop-in phase shifters in pupil and/or focal planes, placement of a fiber coupler at the KPIC output focus, and the use of an existing fast Keck FATCAT fringe-tracker camera. Such a mode would enable searches for young hot companions in nearby star formation regions at uniquely small angles and contrasts (in to  $\simeq 15$  mas and to contrasts of order  $10^{-4}$ , i.e., to better contrasts than non-redundant masking). Identification of populations of hot young companions (brown dwarfs and exoplanets) to recently formed stars would be a critical discriminator of star formation theories. An optimized nulling mode can potentially also directly observe a small number of Hot Jupiters, as well as search for hot exozodi emission in several promising candidates.

**Pathfinder to TMT’s planet finder.** An ExAO high contrast imager at Keck will bridge the gap between Keck first-generation AO and TMT-PFI [12]. While theoretical designs exist for segmented telescopes, there is still much to learn about coronagraphy on segmented telescopes. Keck provides the most credible pathfinder for ExAO on the highly-segmented TMT. KPIC will allow demonstrating critical component-level and system-level



**Figure 4.** Results of simulated M-dwarf survey in terms of average detection probability per target, using QMESS [2], and assuming flat priors for the mass and semi-major axis (Gaussian for the eccentricity), hot start evolutionary models for the thermal emission.

aspects, gain operational experience on segmented telescopes, and enable unique science, vetting the most promising targets for future follow-ups.

#### 4. Yield estimates

To demonstrate the superiority of KPIC over current high contrast imaging capabilities in the regime of faint NGS in the visible, we ran simulations to estimate the yield of a putative 3-year survey, assuming roughly 50 nights per year.

**Sample.** We started from the Bright M Dwarf All-Sky Catalog MDWARFASC [11], did a cut of objects only visible from Keck, retained active M-stars only (either X-ray, FUV, or NUV detections). Ages for active M stars were derived using 2 complementary methods, based on their activity lifetime and decay [24, 22]. This produced the sample shown in Fig. 1. We then arbitrarily did a cut at 20 pc (=1 AU with KPIC’s 50 mas IWA), and 2 Gyr yielding a sample of 569 relatively young M-stars with spectral types ranging from M0 to M7.

**Instrument performance.** To represent current AO performance on M-stars, we used the median contrast curves published in Ref. [3] ( $\Delta mag \simeq 2.5, 4.4, 9.8$  at  $0''.1, 0''.2, 0''.5$ , respectively). We emphasize that for typical M-star R magnitudes, 2nd-generation AO with visible SH WFS do not significantly deliver better performance than first generation AO instruments (e.g. SPHERE, with its EMCCD starts to be photon-starved at  $R > 11$ ; GPI at  $R > 9$ ).

A preliminary error budget shows that KPIC’s efficient low-noise IR WFS provides optimal ExAO-like performance for  $J < 10$ , which is the cutoff J magnitude of our MDWARFASC sample. To anchor our post-processed contrast estimates to reality as best as we can, we used an ExAO performance estimator validated with an existing instrument in operations (SPHERE), scaled and transposed the results to KPIC yielding on average  $\Delta mag \simeq 12.7, 13.8, 14.5, 15$  at  $0''.05, 0''.1, 0''.2, 0''.5$ , respectively. We also assumed improved performance at the IWA of 50 mas, corresponding to  $2\lambda/D$  at J. Indeed, an aggressive, but realistic IWA requires using a proven small-IWA coronagraph such as the vector vortex [13, 17]. To ensure the best contrast at the IWA, the vortex needs to be matched with a low-order wavefront sensor (LOWFS), as has been demonstrated on SCEXAO [19].

#### 5. Expected results and conclusions

Projected results for our virtual survey with KPIC are very compelling. KPIC will be able to probe a brand new parameter space left open by all other extant exoplanet detection techniques (Fig. 4). **Two striking outcomes of KPIC is that it could potentially detect the reflected light signature of exo-Jupiters or even a handful of Earth-to-Super-Earth like planets [14] for the first time (Fig. 4, right), and by way of post-coronagraphic high resolution spectroscopy, apply Doppler imaging techniques to exoplanets to measure their spin, map their atmosphere and potentially resolve cloud dynamics.**

We have entered the golden age of high contrast imaging. Keck is the biggest, most sensitive telescope, in one of the best sites in the world. KPIC is a cost-effective concept based on the modular/incremental approaches demonstrated by SCEXAO and P3K-SDC, and so falls into the medium-scale project category as defined in the 2009 W. M. Keck Observatory Scientific Strategic Plan (WMKOSSP2009). KPIC will provide unique capabilities that will allow the Keck community to mature scientific niches into key TMT-PFI science. For instance, the exploration of M-dwarf planetary systems, currently in its infancy, will be pushed into the territory of the reconnaissance and characterisation of exoplanets from the ice lines into the habitable zone, fully exploiting the promises of high contrast high resolution spectroscopy. KPIC will thus cover two key science goals outlined in the WMKOSSP2009: understanding the formation of planetary systems around nearby stars, and exploring the origins of our Solar system. Infrared wavefront sensing at the ExAO level will also allow to greatly enhance the Keck community ability to test the theory of General Relativity in the Galactic Center, which constitutes a third key science goal of the WMKOSSP2009.

KPIC can be quickly deployed, to be on time to follow-up TESS candidates, and be in sync with JWST. Last but not least, KPIC will demonstrate key technologies for TMT-PFI, leverage and proof-test decades of technical developments in high contrast imaging at NASA, all within an operational and scientifically productive framework. The validation of high contrast high resolution spectroscopy with KPIC will plant the seeds for a strategic and powerful follow-up mode using TMT-PFI in the WFIRST-AFTA coronagraph era.

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