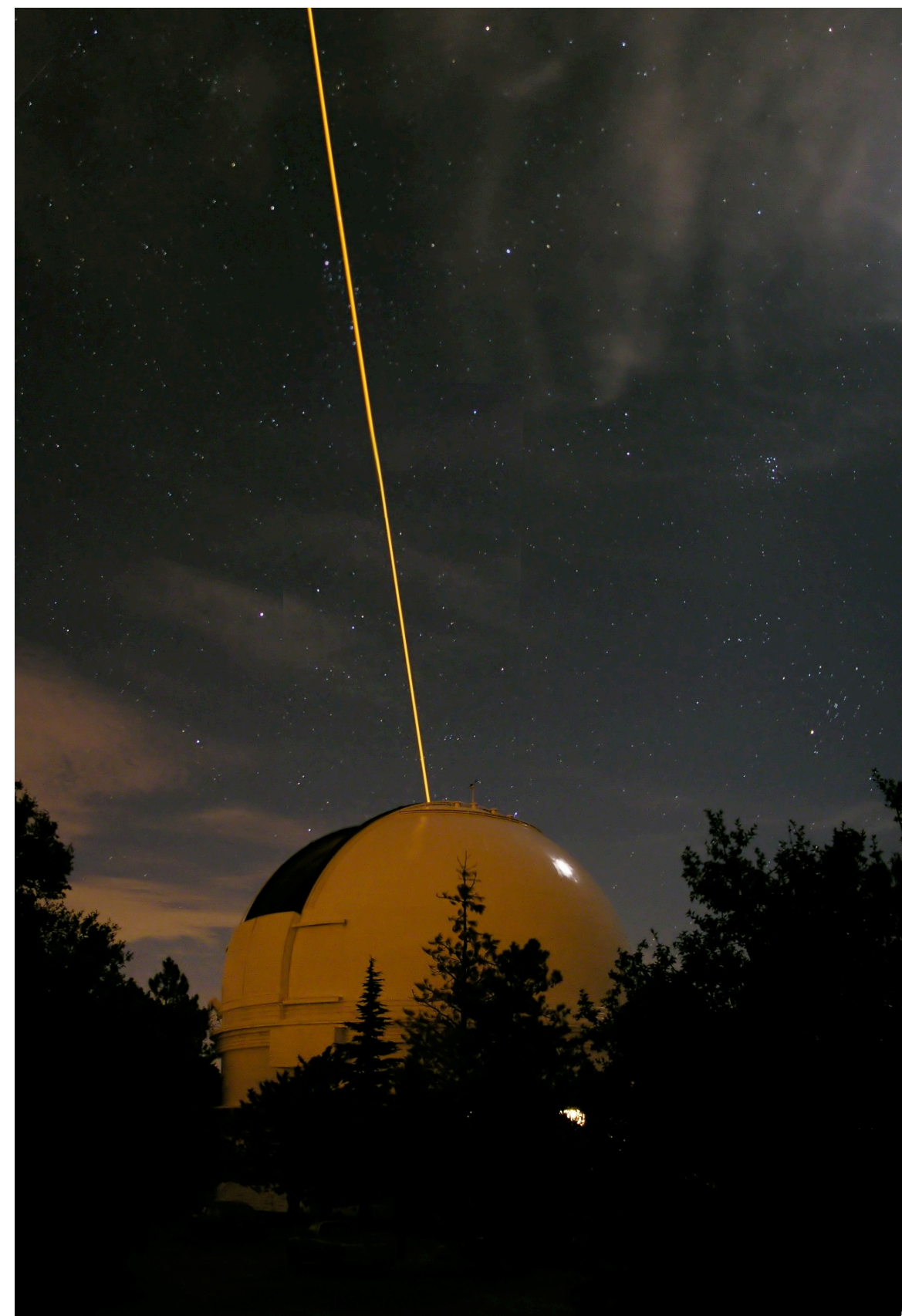




# LGSAO Imaging Polarimetry and Integral Field Spectroscopy of Herbig Ae/Be Stars



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**Above:** The Lick Observatory 3m Shane Telescope with its Laser Guide Star adaptive optics system (Max et al. 1998). The LGS AO system provides diffraction limited imaging at Ks band Strehl ratios of  $\sim 0.3$  on sources as faint as  $R=16$ .

The combination of LGS AO polarimetry at Lick and LGS AO imaging spectroscopy at Keck provides a unique and powerful view of the dusty environments of young stars. Understanding circumstellar material around Herbig Ae/Be stars (HAEBEs) is relevant for studies of star formation, the origin of the outflows associated with young stars, and the conditions in which planet formation may take place. LGS AO is needed to observe the complete population of HAEBEs: even though these massive stars are intrinsically bright, many (particularly the youngest) are very embedded and thus faint.

I have been surveying circumstellar dust around Herbig Ae/Be stars using the Lick AO system in both NGS and LGS modes with a dual-channel imaging polarimeter I developed. Over one hundred stars have been surveyed to date, with extended dust-scattered light detected around twenty-three. The revealed dust structures variously include face-on and edge-on disks, extended circumstellar envelopes, bipolar outflow cavities, and tidal streamers between binary stars.

A subset of targets have been subsequently imaged with a variety of instruments on both Keck and Gemini North. We have recently observed several of these targets using Keck LGS AO and the OSIRIS integral field spectrograph, to search for outflows traced by near-IR [FeII] emission lines. These observations will enable us to test models for jet launching and collimation around HAEBEs. Parsamian 21 and LkHa 233 both display [FeII] emission on subarcsecond scales, in the case of LkHa 233 taking the form of a narrowly collimated jet which can be traced to within 0.1 arcsec of the central source.

## Why AO Polarimetry?

Detecting faint circumstellar material against brighter scattered stellar light requires high dynamic range as well as high resolution. To obtain the needed sensitivity, I developed a dual-channel  $J$ ,  $H$ ,  $K_s$  polarimetry mode for the IRCAL science camera using a YLF Wollaston prism polarizer (Perrin et al. 2004b). Since light scattered from circumstellar dust is linearly polarized, by rejecting unpolarized light with the polarimeter, I can dramatically increase sensitivity to faint nebulosity near bright stars. (e.g. Kuhn et al. 2001, Apai et al. 2004) The IRCAL polarimeter typically rejects  $\sim 98-99\%$  of unpolarized light, providing two orders of magnitude improvement in contrast. Because the dual-beam polarimeter samples both polarization states simultaneously, it is robust against the PSF variations that trouble many AO observing programs. This instrument is unique among AO polarimeters in that it can observe at all three near-IR bands  $J$ ,  $H$ , and  $K_s$ , due to its custom achromatic LiYF<sub>4</sub> Wollaston beam splitter.

## The Lick AO Polarimetry Survey of HAEBEs:

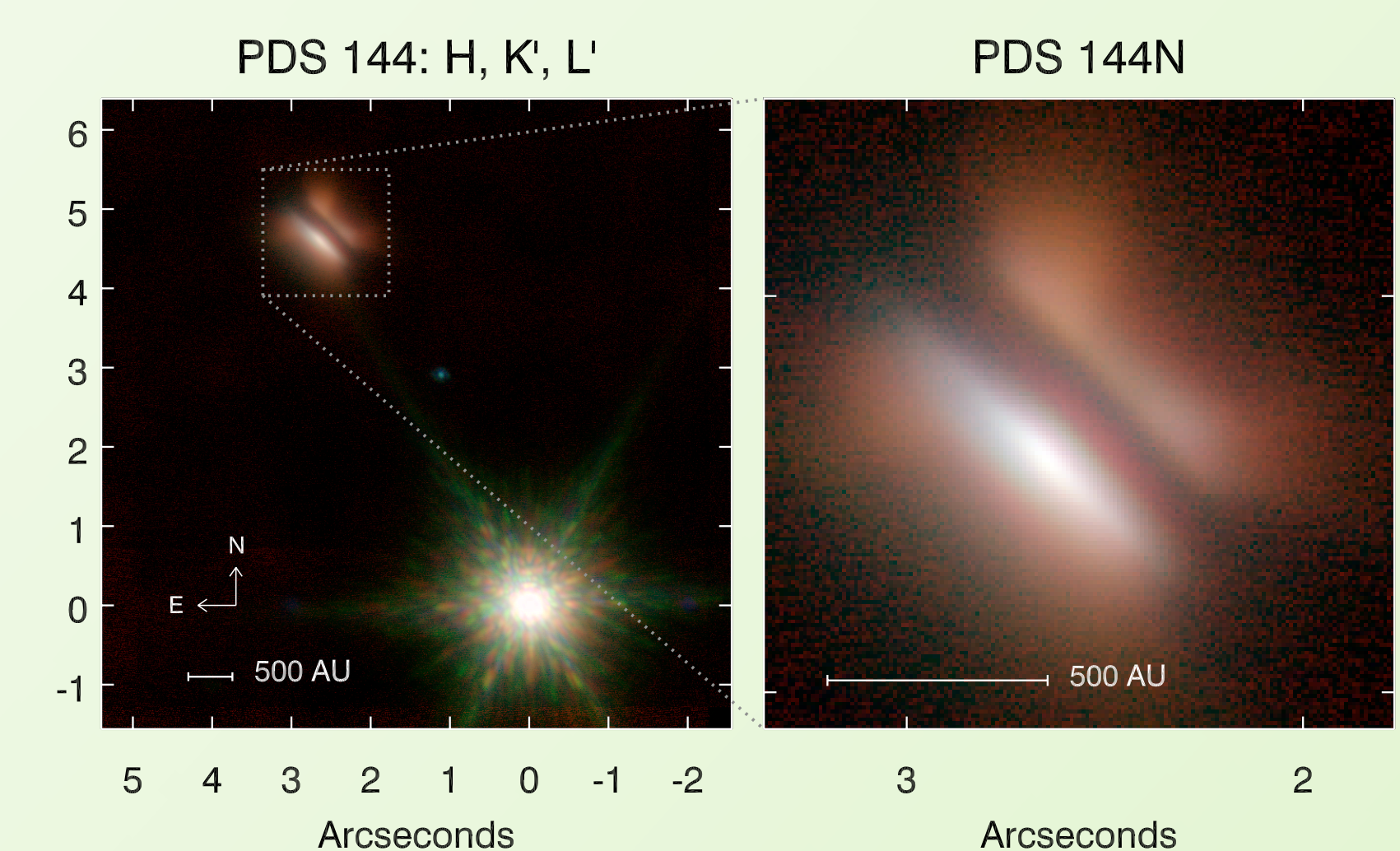
- 107 targets observed so far; 23 have resolved circumstellar dust.
- Faint LGS targets are much more likely to have extended circumstellar dust:
- 11/16 LGS targets are resolved, versus 12/91 NGS targets.

**Left:** Herbig Ae/Be stars imaged with differential polarimetry. For the color images,  $J$ ,  $H$ , and  $K_s$  are blue, green, and red respectively; the grey scale images are  $H$  band. While quantitative color tables vary from image to image, all are logarithmically-stretched polarized intensities. Overplotted vectors show the magnitude and orientation of  $H$  band polarization.

## From Lick, to Keck and Gemini

The Lick AO polarimetry survey has been very successful in identifying targets for followup studies with other telescopes, including Keck and Gemini.

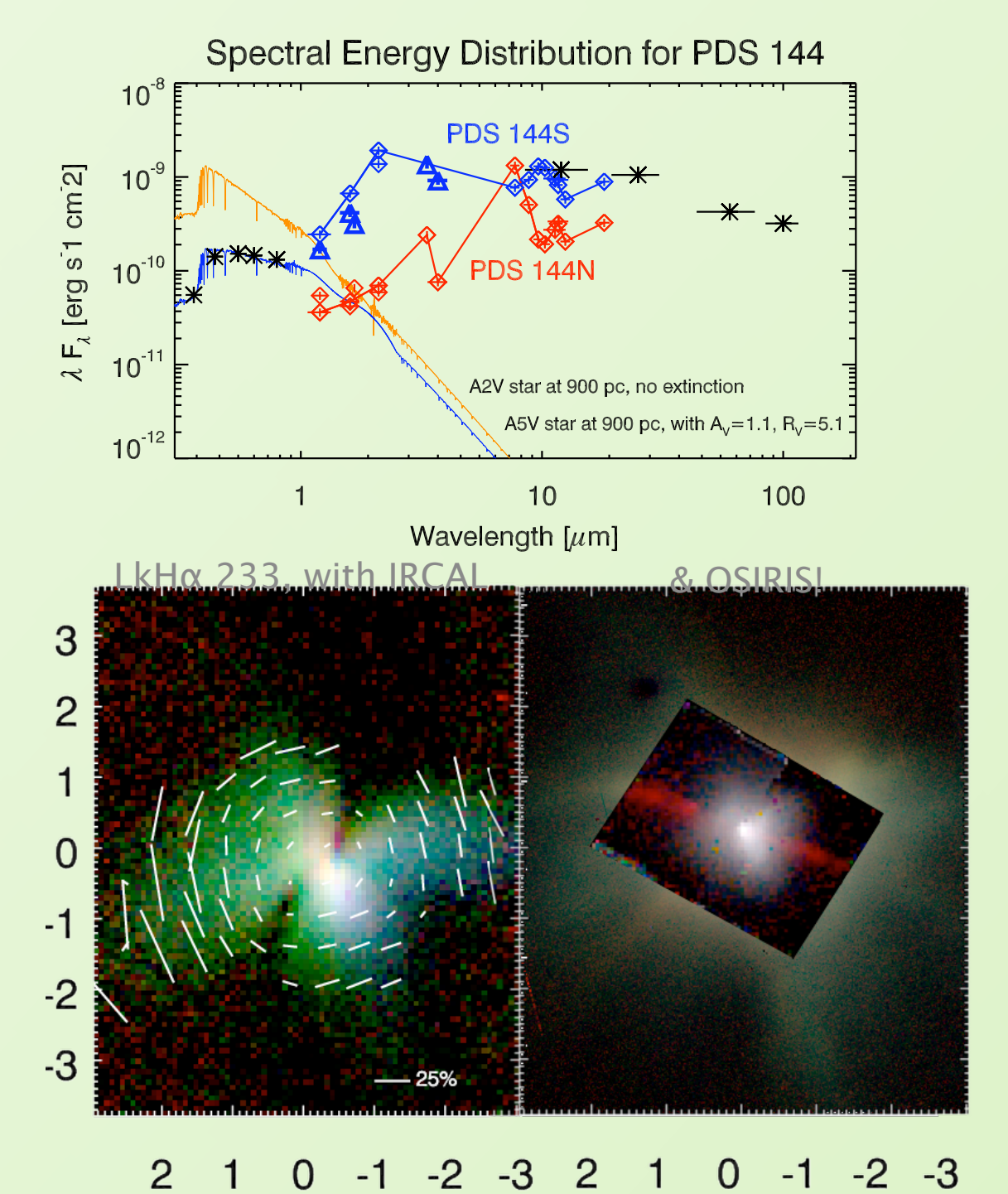
**Right:** At Lick, I discovered the northern member of the binary Herbig Ae system PDS 144 to be hidden by an edge-on circumstellar disk. Keck imaging with NIRC2 and LWS reveals the disk in exquisite detail. Red wings extend vertically from the disk midplane, caused by light scattering from the edges of a cavity in a surrounding rotationally-supported envelope. Gemini Michelle mid-IR observations show strikingly different SEDs for the two sources: PDS 144N shows strong PAH emission at 3, 7, and 11  $\mu\text{m}$ , while PDS 144S has a broad 10  $\mu\text{m}$  silicate feature. In addition, the Gemini observations resolve circumstellar material around PDS 144S at 18  $\mu\text{m}$ . A paper describing these results has been submitted to ApJ



**Right, middle:** SED for PDS 144, incorporating optical points from Veiera et al. (2003), our near and mid IR points from Lick, Keck, and Gemini, and the far-IR IRAS points.

**Left:** Keck LWS imaging of two HAEBEs. Cyan is 11  $\mu\text{m}$  and red is 18  $\mu\text{m}$ . Mid-infrared imaging provides a complementary dataset to near-IR polarimetry, probing thermal emission from dust, and fluorescence from PAHs.

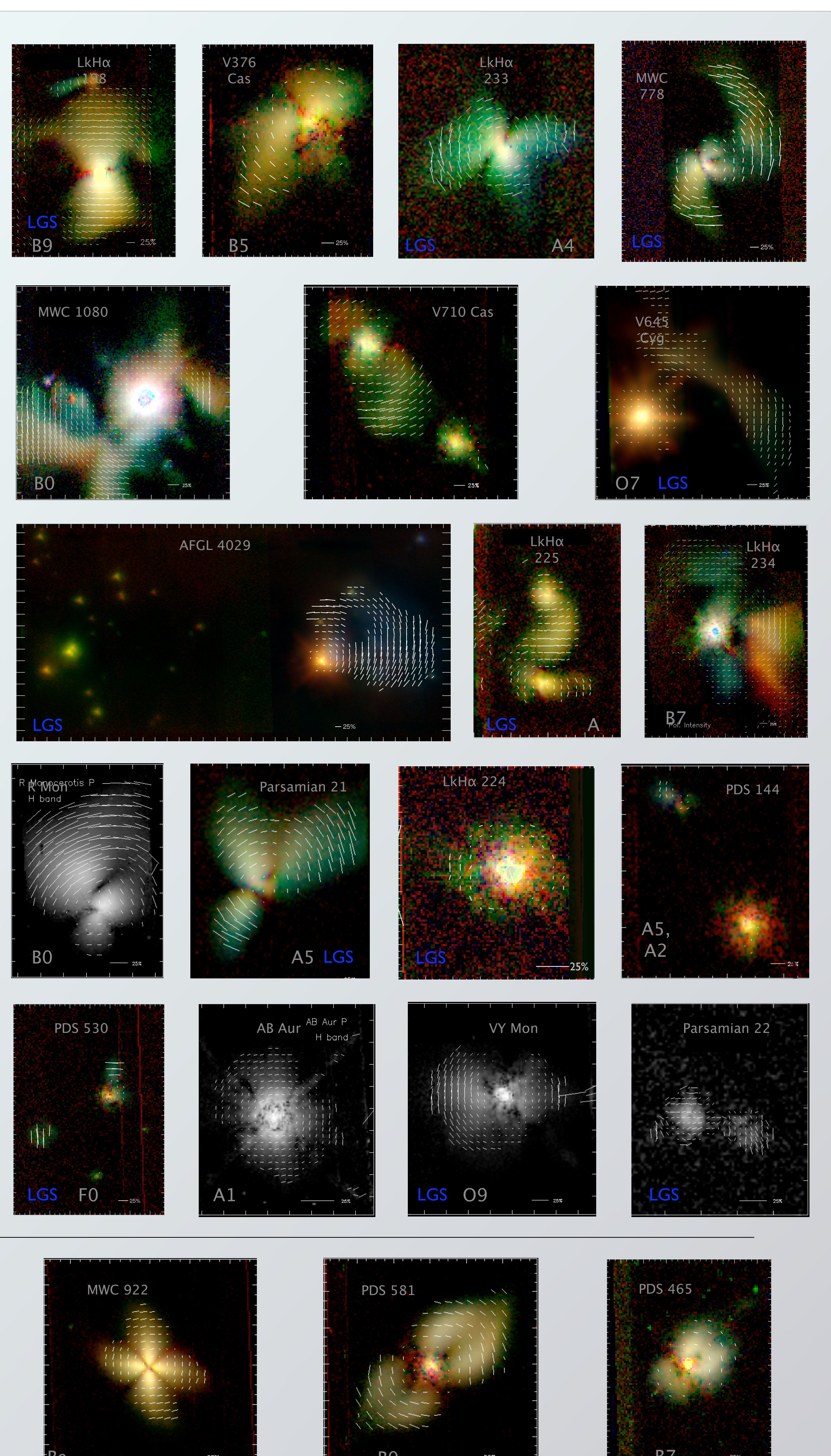
**Right, bottom:** Hot off the presses! Keck LGS AO imaging spectroscopy with OSIRIS. The far-right panel shows a tightly collimated jet seen in the [FeII] 1.644  $\mu\text{m}$  line (inset) from the OSIRIS IFU. The outer part of the field is a JHK composite from the OSIRIS imager. Our Lick AO image is presented in the first panel for comparison. The combination of high spatial and wavelength resolution provides excellent ability to test disk wind and X-wind theories in the inner regions of disks around Ae stars.



This project would not have been possible without the support of many individuals. My advisor, James Graham, provided invaluable guidance, assistance and encouragement. He and Jamie Lloyd developed IRCAL and made my polarimetry upgrade possible. Mike Fitzgerald helped with IRCAL software upgrades. Paul Kalas and Gaspard Duchene helped with target selection and data analysis. Too many people played a part in the development of the Lick LGS system to name here; see my Science paper for full acknowledgements. Even more played a part in Keck LGS AO and OSIRIS. I especially thank James Larkin and Mike McElwain for help with our shared-risk OSIRIS observations. The support from the Lick, Keck, and Gemini observatory staffs has been exemplary throughout. Elinor Gates and Bernie Walp are always wonderful company on those rainy November nights.

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Apai, D., Pascucci, I., Brandner, W., Henning, T., Lenzen, R., Potter, D. E., Lagrange, A.-M., & Rousset, G. 2004, A&A, 415, 671  
Kalas, P., Graham, J. R., & Clampin, M. 2005, Nature, 435, 1067  
Kuhn, J. R., Potter, D., & Parise, B. 2001, Astrophys. J. Lett., 553, L189  
Max, C., Olivier, S., Friedman, H., An, J., Avicola, K., Beaman, B., Bissinger, H., Brase, J., Erbert, G., Gavel, D., Kanz, K., Liu, M., Macintosh, B., Neeb, K., Patience, J., & Walton, K. 1997, Science, 277, 1649  
Perrin, M. D., Graham, J. R., Kalas, P., Lloyd, J. P., Max, C. E., Gavel, D. T., Pennington, D. M., & Gates, E. L. 2004a, Science, 303, 1345  
Perrin, M. D., Graham, J. R., Kalas, P., Lloyd, J. P., Max, C. E., Gavel, D. T., Pennington, D. M., & Gates, E. L. 2004b, in Advances in Adaptive Optics, Edited by Domenico B. Calia, Brent L. Ellerbroek, and Roberto Ragazzoni. Proceedings of the SPIE, Volume 5490, pp. 309-320 (2004), 309-320



These three sources, though classified by some as Herbig Ae/Bes, appear to actually be evolved stars or proto-planetary nebulae instead.