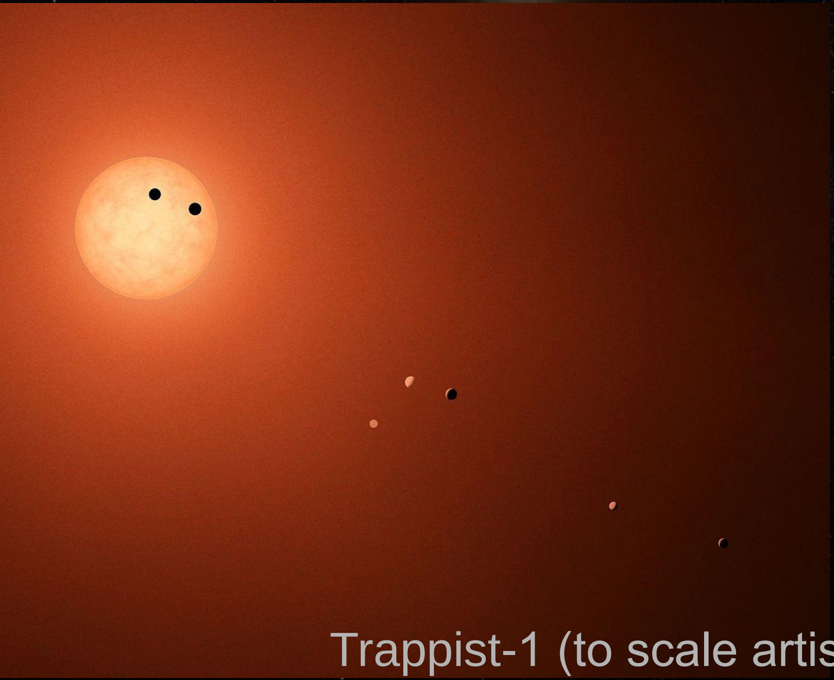
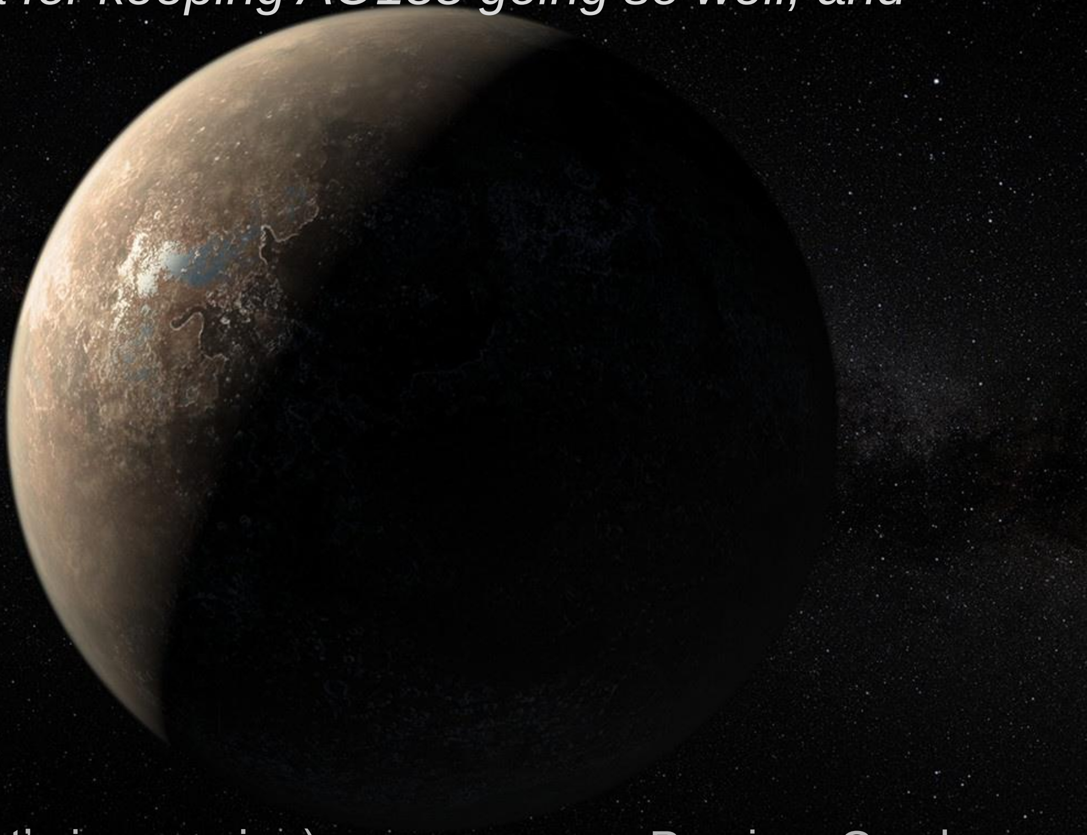
Subaru-Australian collaboration on Technologies for Habitable Planet Spectroscopy

Mike Ireland

Plus many others: thanks to Barnaby Norris and Nemanja Jovanovic for slides. Thanks to Yosuke Minowa for keeping AO188 going so well, and Takayuki Kotani's introduction.



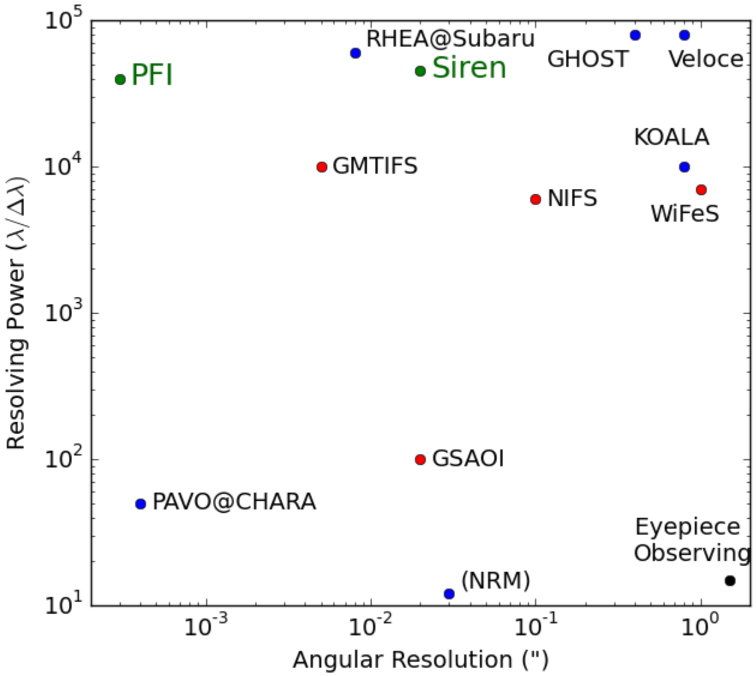
Trappist-1 (to scale artist's impression)

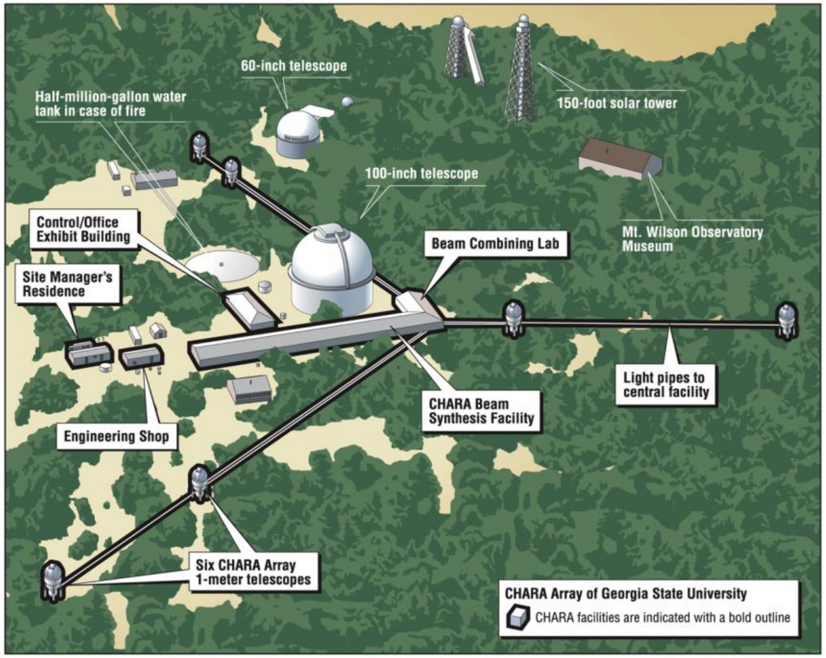


Proxima Cen b

My Background and Interests

- Much of my background is in long-baseline optical interferometry (PAVO@CHARA, and the Planet Formation Imager).
- I spend about half my time on instrumentation, including novel data reduction.
- Currently Co-project scientist for GHOST (Gemini Echelle spectrograph), instrument scientist for Veloce (new AAT echelle spectrograph)
- I have some continued interest in young stars and AGB stars, but my primary future research directions are answering: *How do planets form?* and *Where are the nearby habitable planets?*

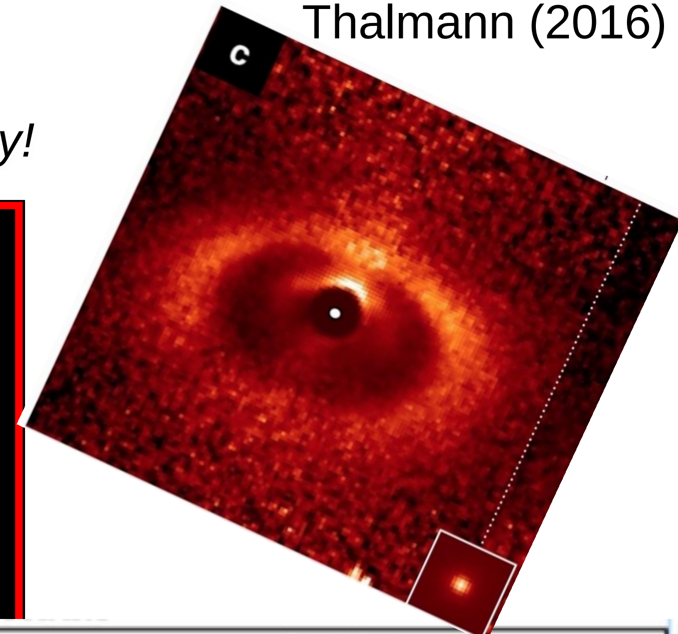


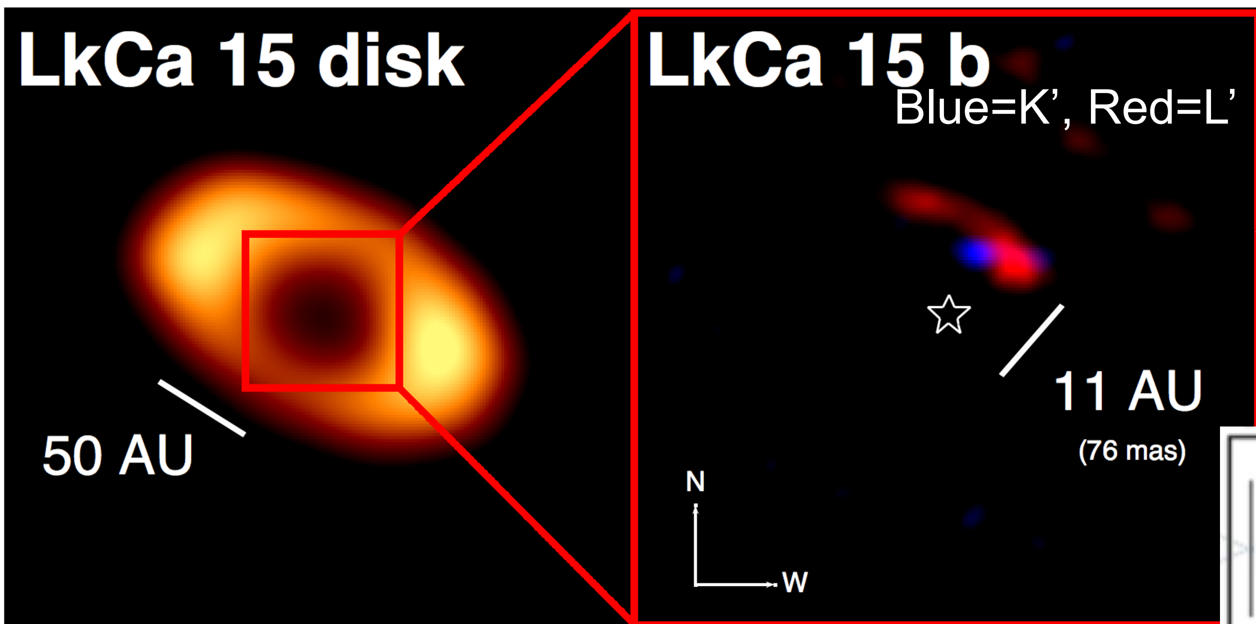


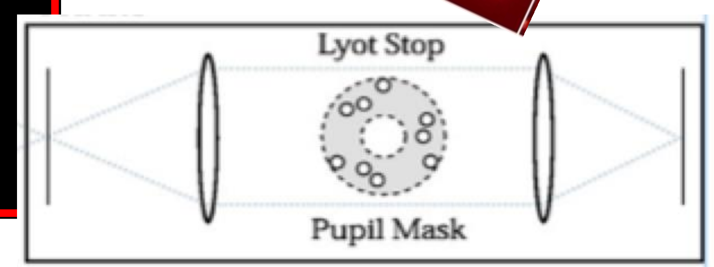
Example Science: LkCa15

- Original publication (Kraus and Ireland 2012): all Non-Redundndt Aperture-Masking..
- Image-reconstruction using MACIM (Ireland et al 2008), plus lots of model fitting.
- The total luminosity (1-3 x 10^{-3} L_{sun}) inconsistent with non-planet explanations, but scattering not completely ruled out with exotic dust/geometry combinations.
- Subaru/SEEDS and new Sphere data complicate the picture (no working models): *planet formation is messy!*

Thalmann (2016)

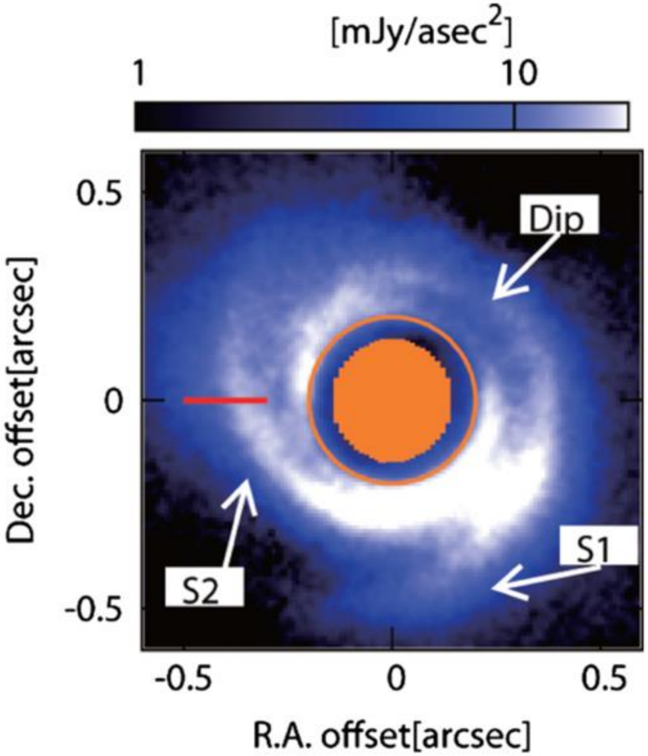




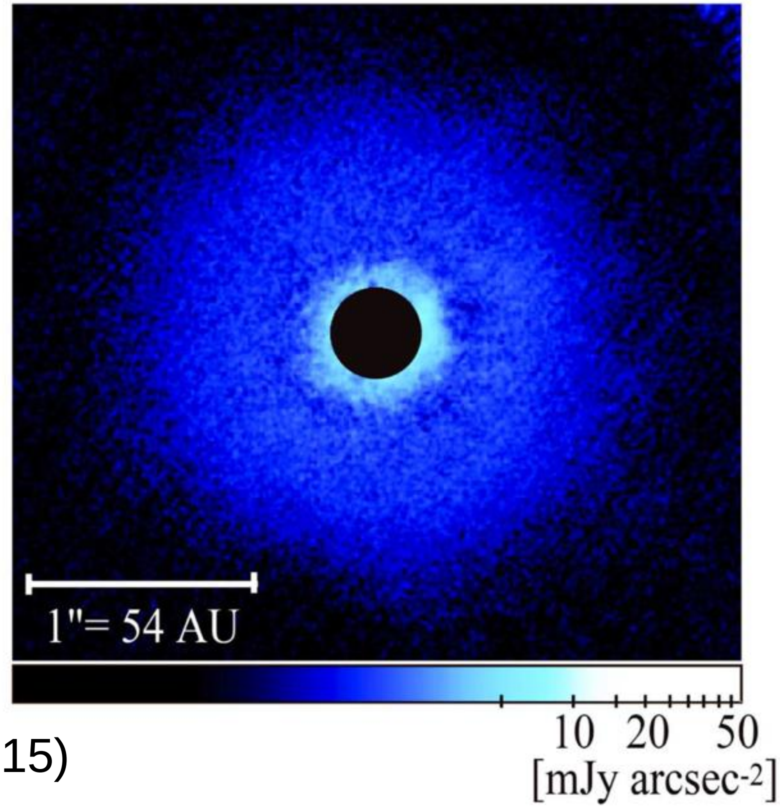


ExAO Background

- Subaru has a history of pioneering Adaptive Optics development.
- Major recent survey has been SEEDS: Strategic explorations of exoplanets and disks with the Subaru Telescope
- SEEDS has >40 refereed papers, many with 100+ citations.
- Australia hasn't been part of SEEDS in its first 5 years, but is part of SCExAO, which is the next generation instrument…



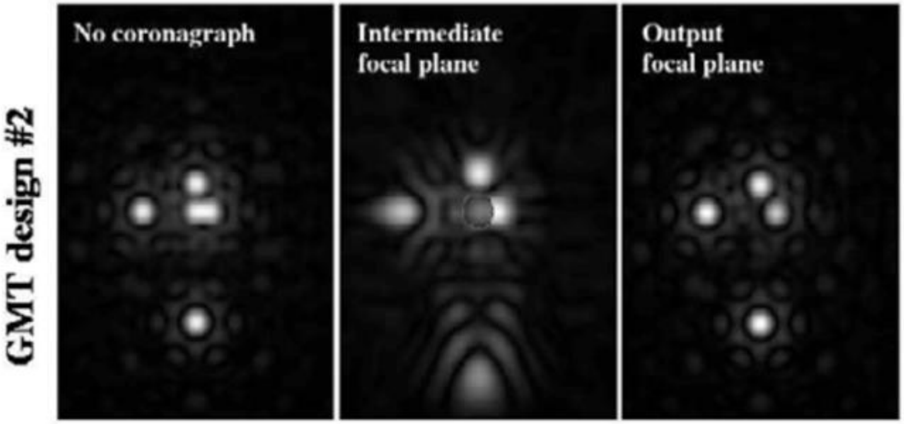
HD 135344B
(Muto+ 2012)

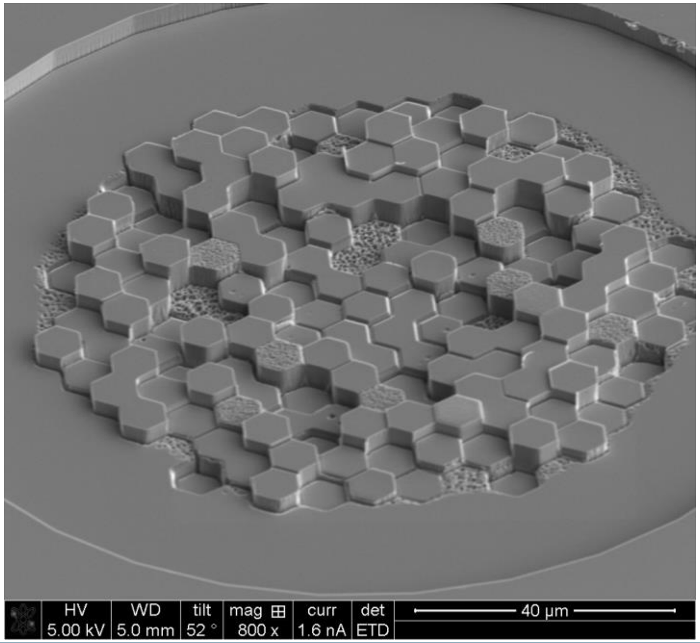


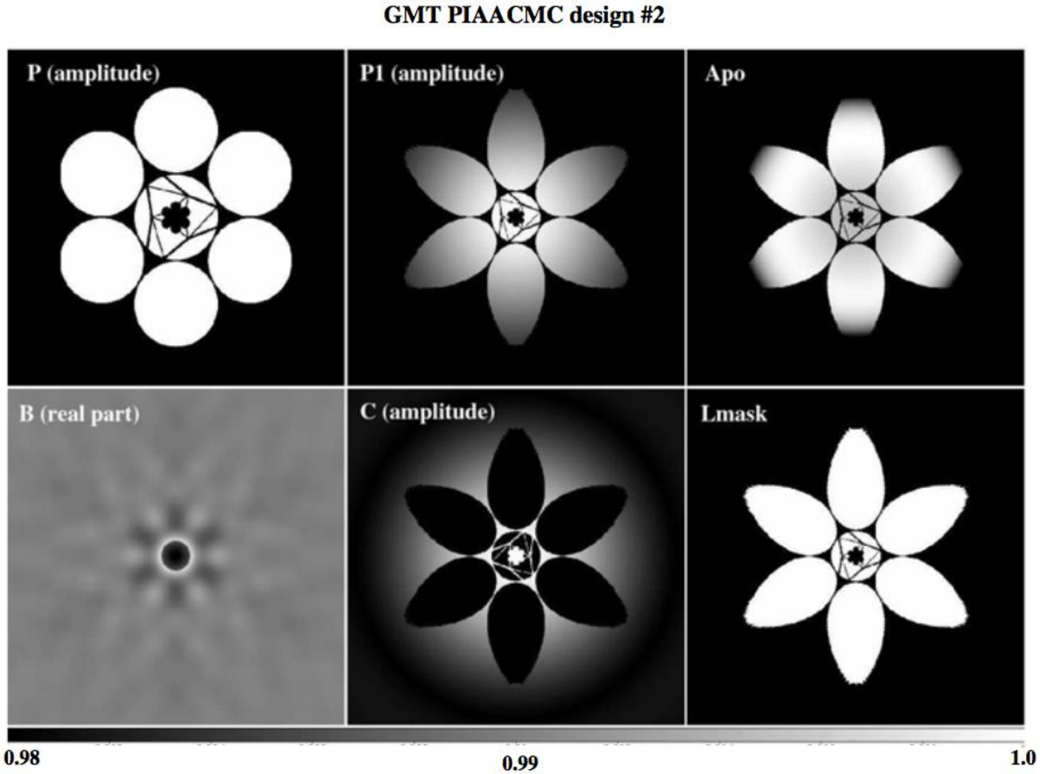
TW Hya
(Akiyama+ 2015)

Coronagraphy

- For perfect input wavefronts: a solved problem in principle at ~10^8 contrast, even for GMT (Guyon 2014).
- Practical achromatic phase-masks (below) being produced.







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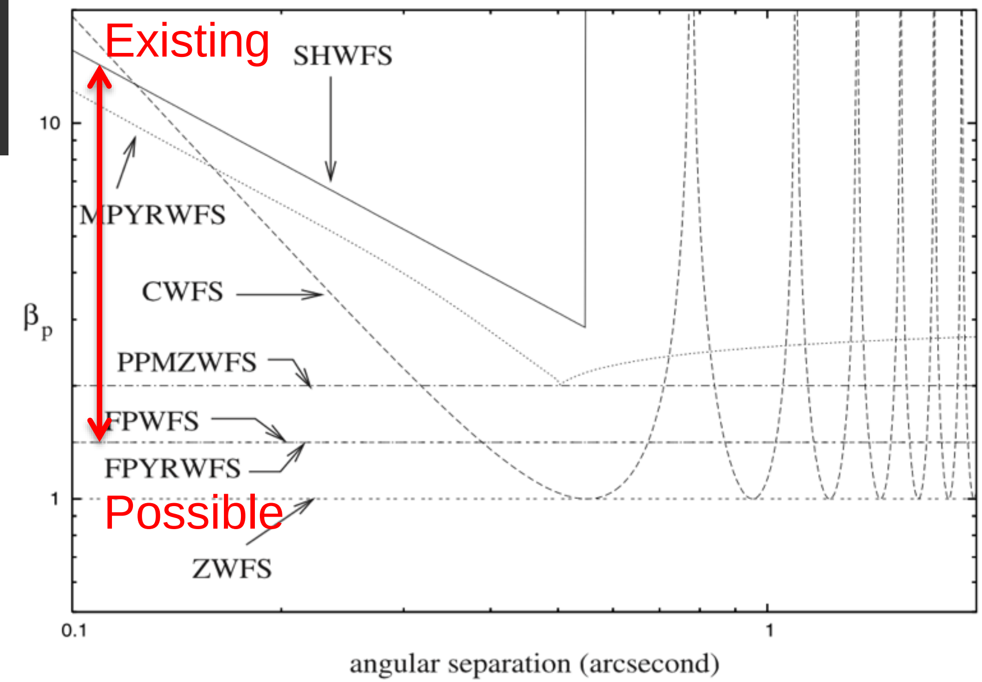
Wavefront Control

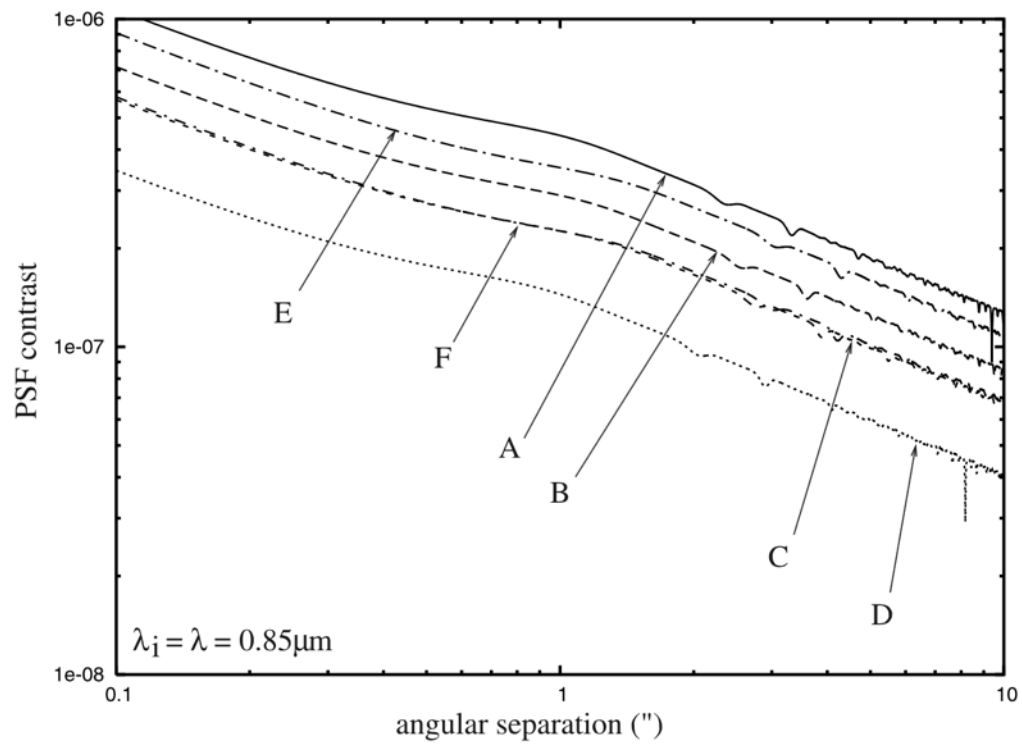
Existing 8m ExAO systems (SPHERE, GPI) are single-conjugate and have wavefront sensors a factor of 10 less sensitive than the theoretical limits (Guyon 2005).

GPUs and eAPD arrays are 2 technologies that solve this.

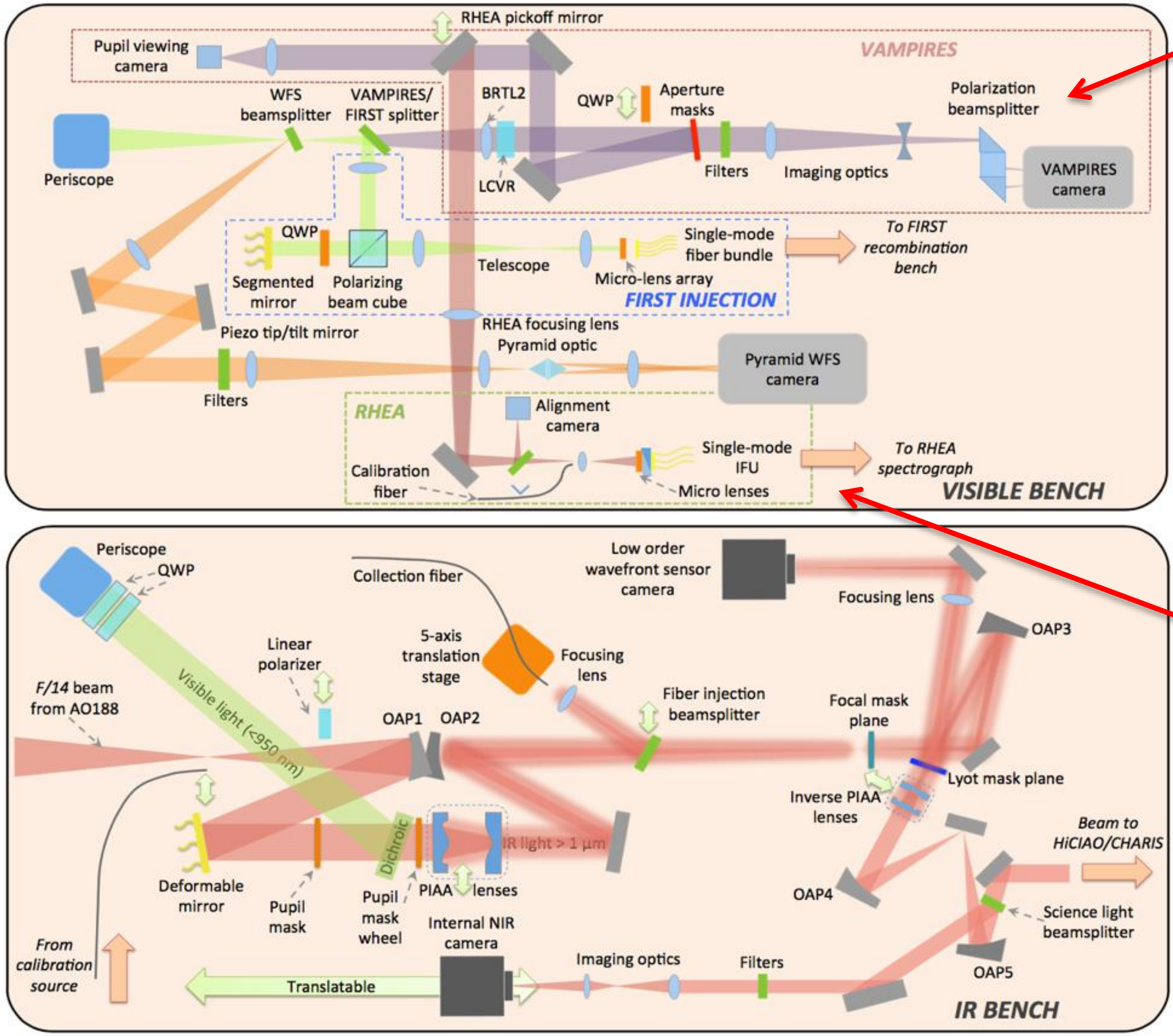
Raw theoretical contrasts at R~5 are better than 10^{-6}.

Can be improved further with multi-wavelength WFS and predictive AO: software research topics.





Subaru – SCExAO



Vampires polarimetry and aperture-masking (Sydney Uni)

Polarimetry

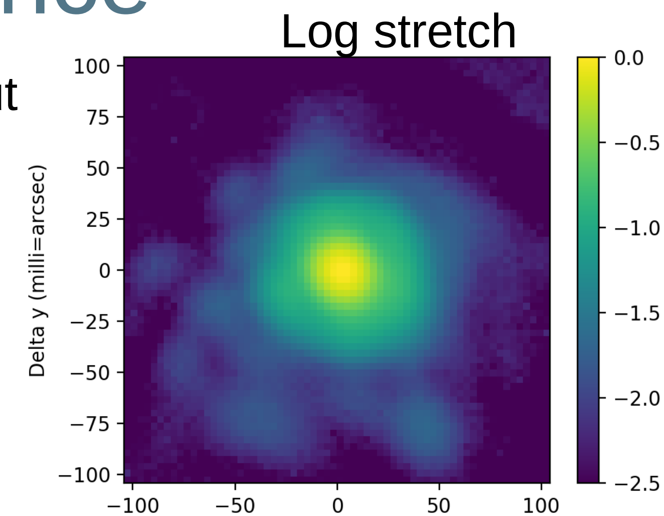
High-contrast

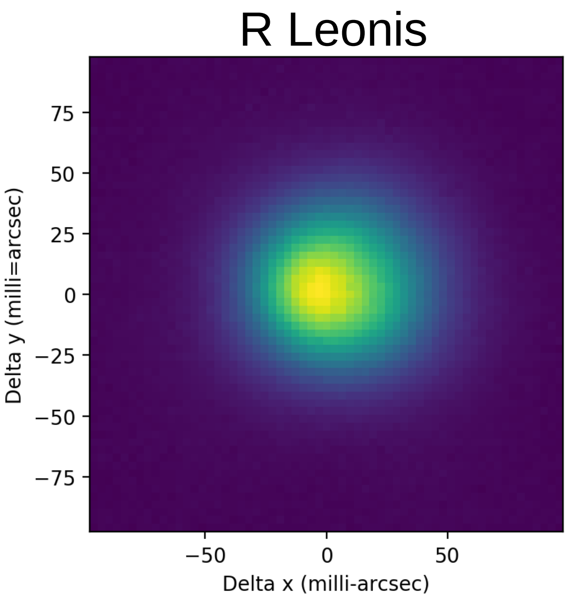
Limited to bright stars (but R~11.5 OK)

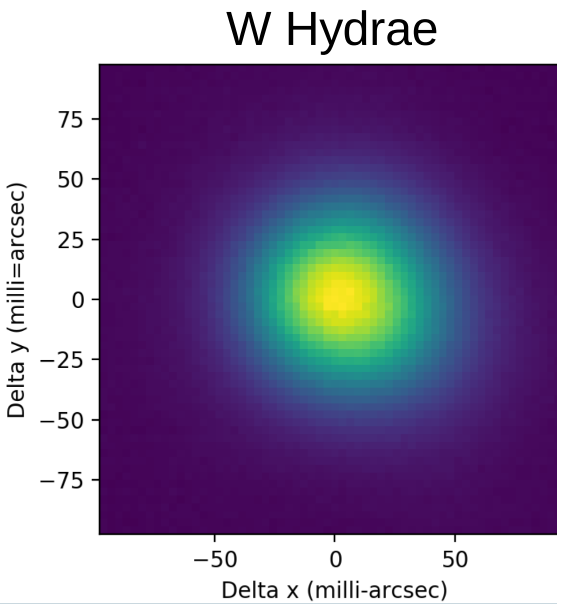
Mini-IFU injection into RHEA (ANU + Macquarie Uni)

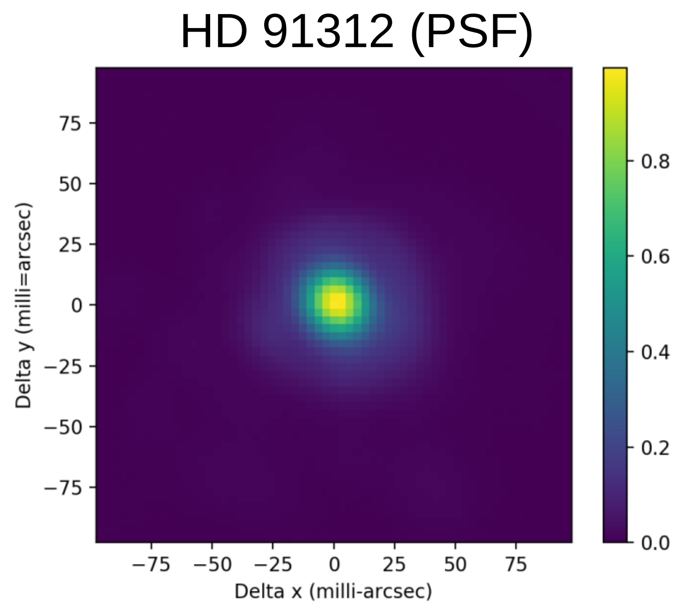
March 2017 AO performance

- The largest stars are now directly resolvable without deconvolution or post-processing image shifts.
- RHEA alignment camera images not only show resolve stars, but an asymmetry in R Leonis.
- Strehl is 33% - limited by tip/tilt and low-order modes. Competitive with ESO’s sphere, but more upgradeable.









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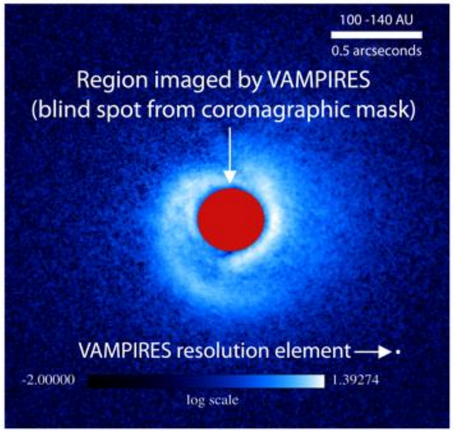
VAMPIRES

Visible Aperture Masking Polarimetric Interferometer for Resolving Exoplanetary Signatures

An insturment to image the inner regions of protoplanetary disks and mass-loss shells

- Directly images the inner 10’s of AU of disks and shells in scattered light.
- Ultra-high resolutions (~10 mas) and contrasts enabled by two key techniques:
  1. **Aperture masking interferometry**
     Converts Subaru’s 8m pupil into array of sub-pupils, producing well-calibrated interference pattern.
  2. **Differential polarimetry**
     Images polarised light scattered by dust in disk. Fast-switching triple-layered calibration.



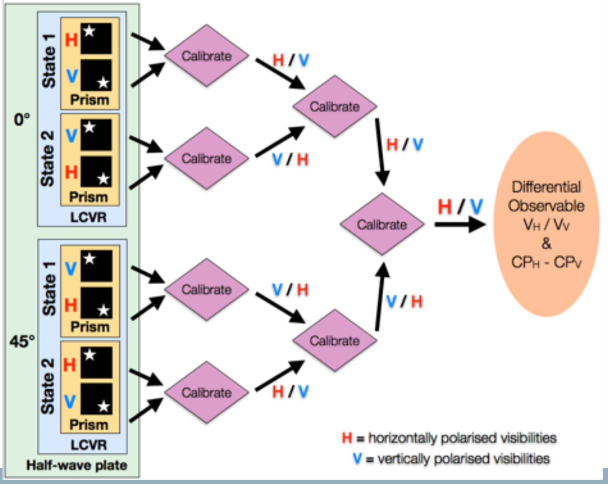
MWC758 - Base image: Grady et al., ApJ, 2013

FOV complements mask of traditional coronagraphs;
IWA 1/2 λ/D

Integrated into SCExAO visible-light channel; VAMPIRES can conduct visible observations *simultaneously* with HICIAO, etc. IR observations

[University of Sydney & SCEXAO/Subaru]

THE UNIVERSITY OF SYDNEY

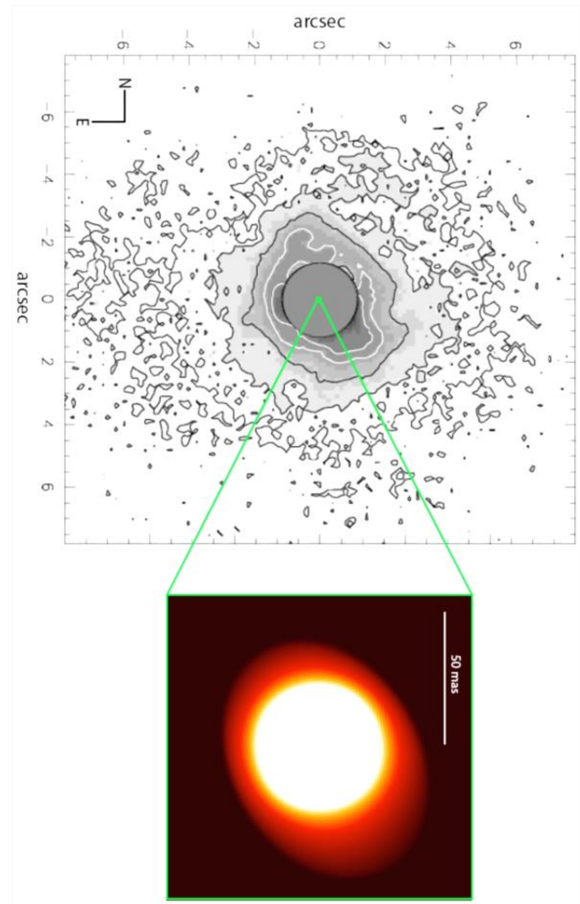


Example VAMPIRES science

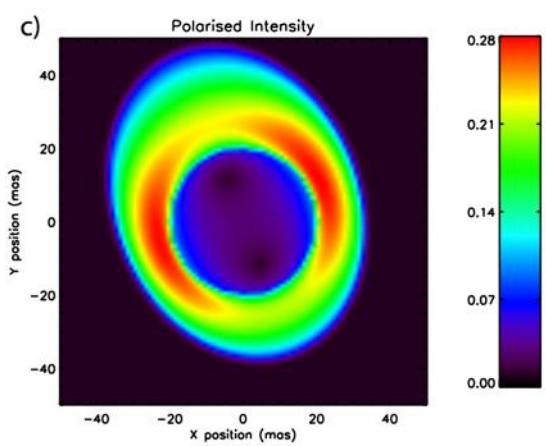
Circumstellar dust around Red Supergiant μ Cephei

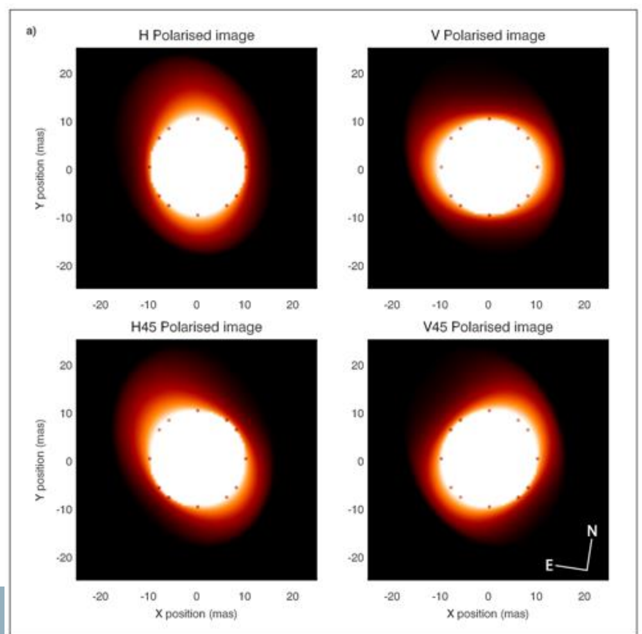
Model-fitting reveals extended, asymmetric dust shell, originating within the outer stellar atmosphere, without a visible cavity. Such low-altitude dust (likely Al_2O_3) important for unexplained extension of RSG atmospheres.

Inner radius: 9.3 ± 0.2 mas (which is roughly R_{star})
Scattered-light fraction: 0.081 ± 0.002
PA of major axis: 28 ± 3.7 ° • Aspect ratio: 1.24 ± 0.03



Left: model image, shown in polarized intensity. **Middle:** model image show in four polarisations. **Right:** Model image (intensity), shown with wide field MIR image (from de Wit et al. 2008 – green box shows relative scales. Axis of extension in MIR image aligns with the close-in VAMPIRES image.

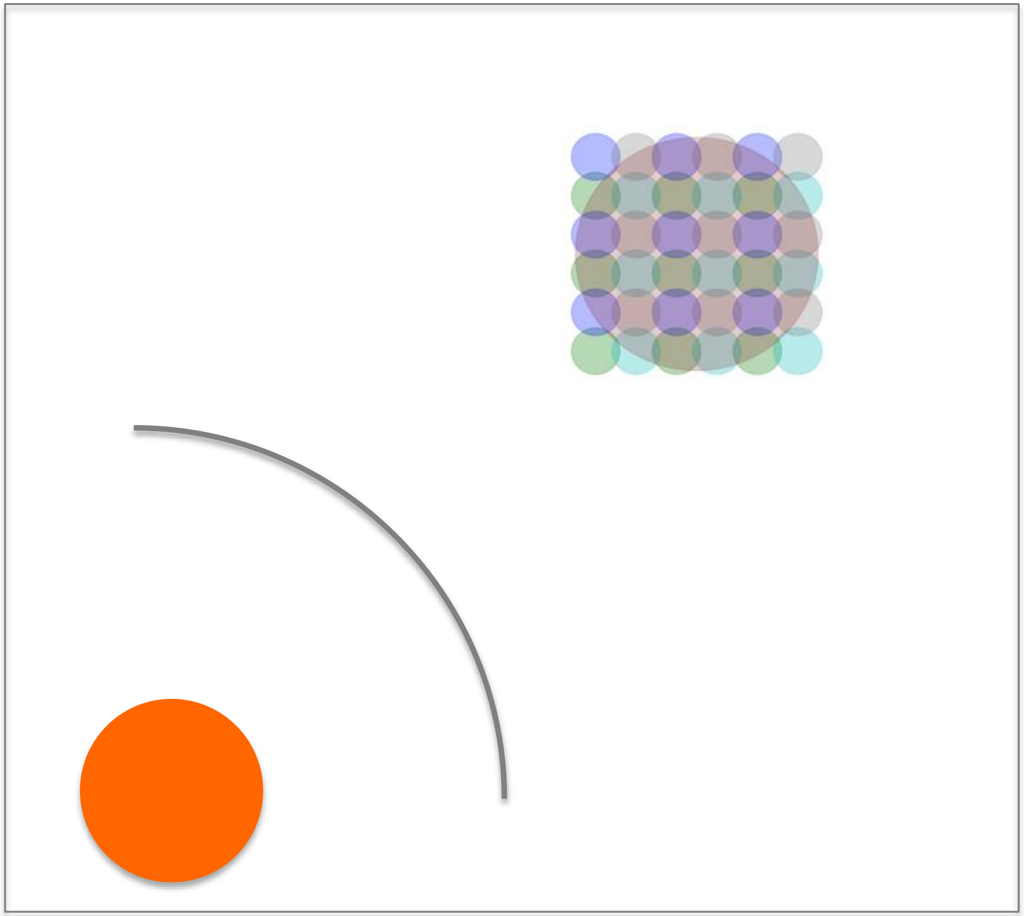




RHEA Injection Unit

Image-Plane View: 3x3 fiber array can be positioned anywhere in the field of view.

Parameter	Value
Fiber Separation	0.016" (new: 0.024")
Fiber acceptance FWHM	~0.01"
Wavelength Range	600-800nm
Positioning accuracy	0.003" (OL) 0.001" (CL)



Reference multi-mode fiber is in the corner of the field of view.

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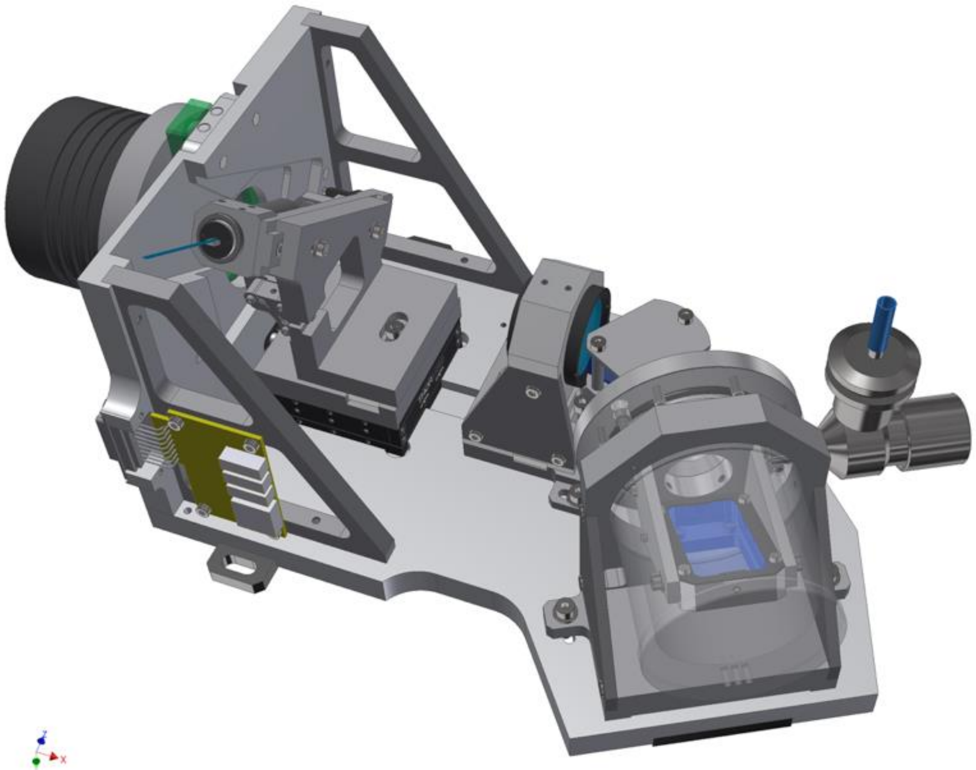
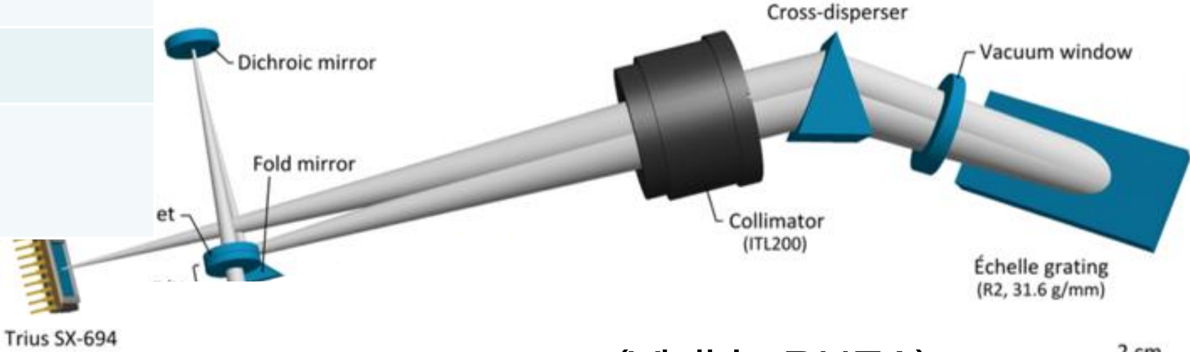
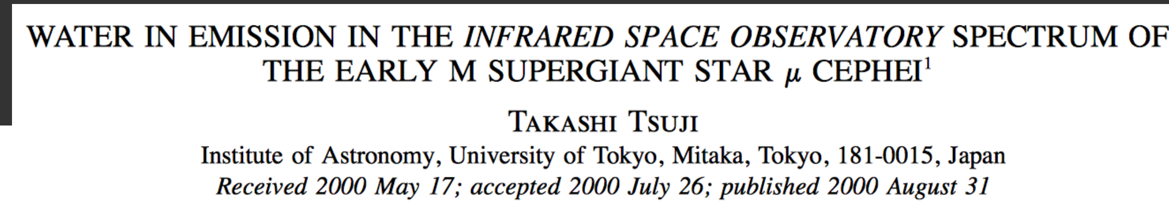
RHEA Spectrograph

Parameter	Value
Spectral Resolution	60,000
Peak Efficiency (expected)	~30%
Slit Length	2.75mm (11 x 0.25mm)
De-magnified slit length	0.25mm
Pupil Diameter	11mm
Baseplate Temp. Stability	0.001K





(Visible RHEA)


WATER IN EMISSION IN THE *INFRARED SPACE OBSERVATORY* SPECTRUM OF THE EARLY M SUPERGIANT STAR μ CEPHEI[1]

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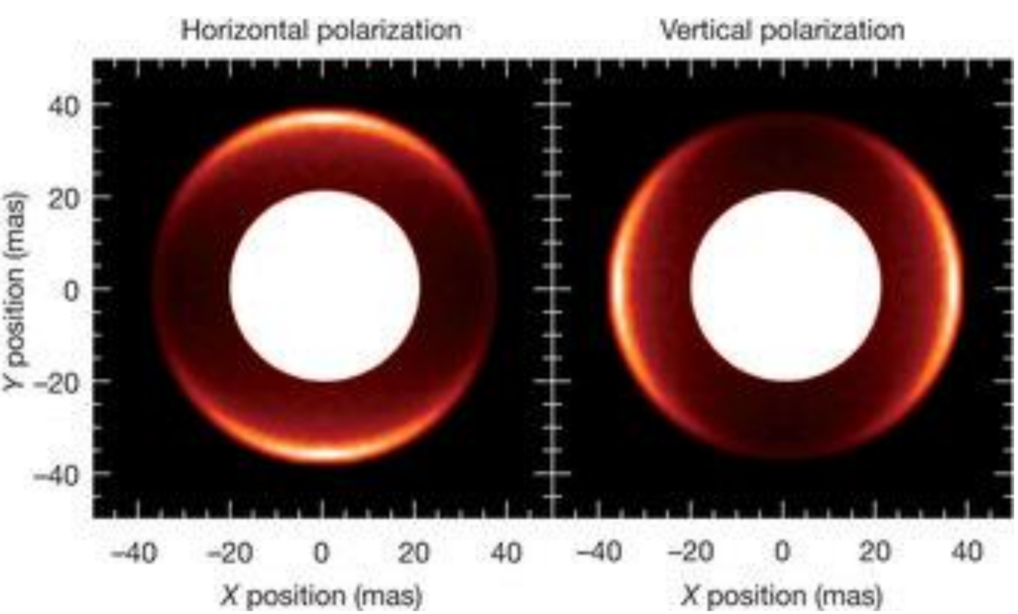
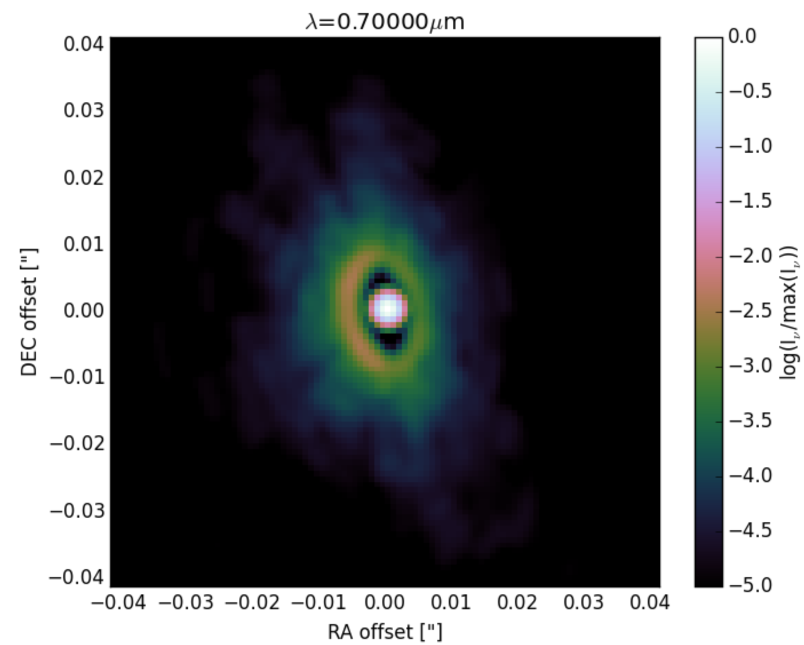
RHEA Science Cases

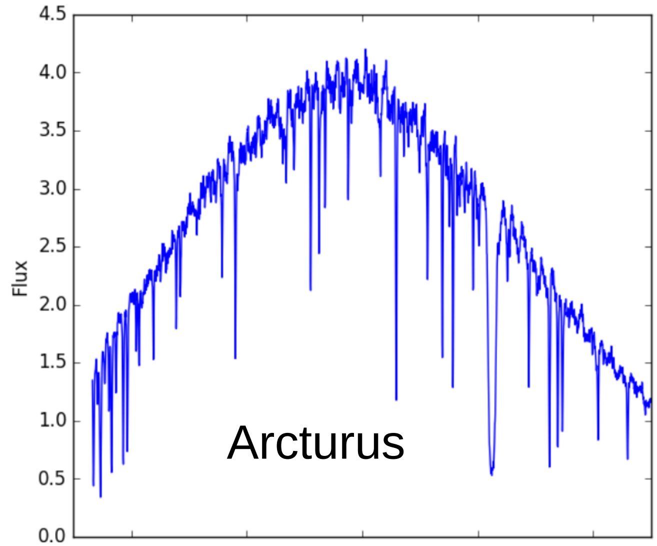
- Velocity-resolved shells of giant stars
- Velocity-resolved convection in giant stars
- Detecting accreting protoplanets and velocity-resolved scattered light protoplanetary disks (*stretch goal)*

Assuming successful commissioning, my team and I are happy to help SCExAO observers in future semesters!

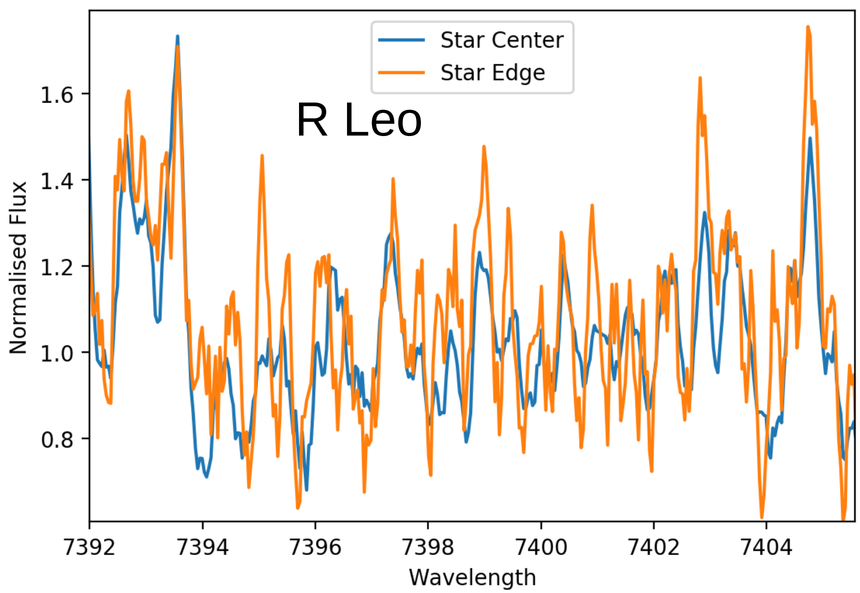


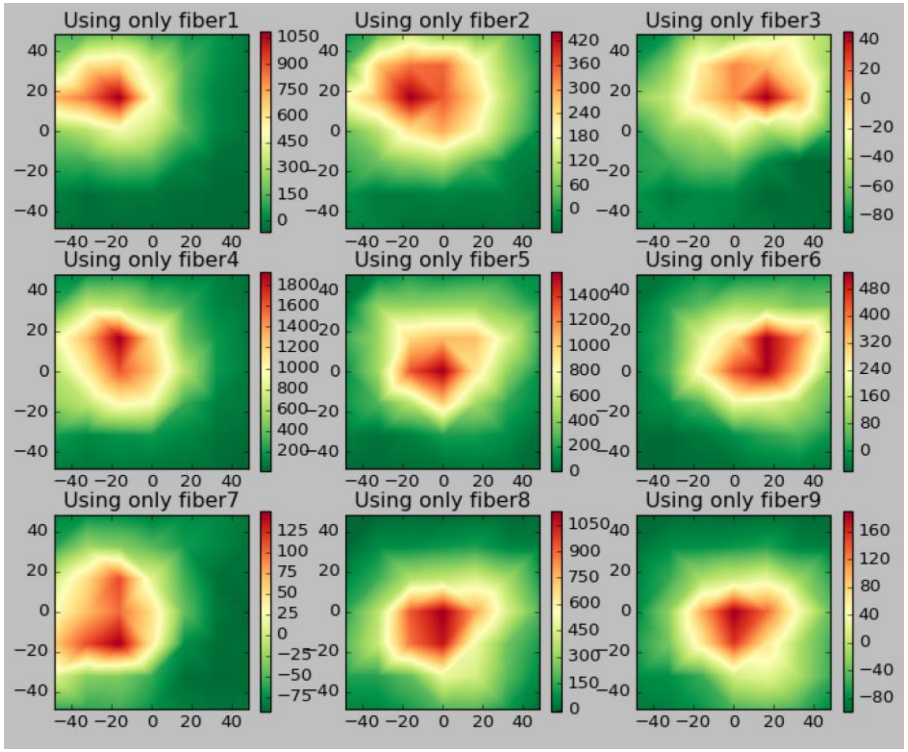


Preliminary Results



- High SNR spectra can be extracted.
- When tip/tilt and low order modes corrected, ~20 milli-arcsec scanning FWHM as expected.
- 2nd-generation fiber cable installed late-last year (fixes modal noise as reported in SPIE)
- R Leo results (9 days ago) subtle, but there is signficantly more spectral variability near the star edge.





Point source scan. x,y units: milli-arcsec

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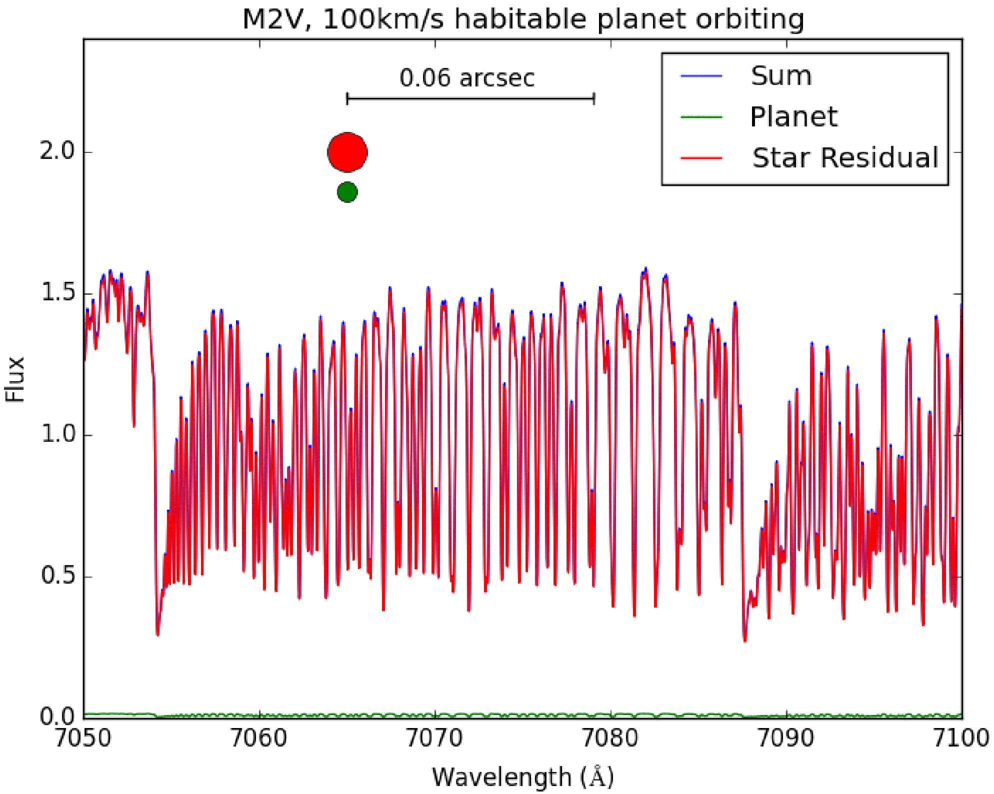
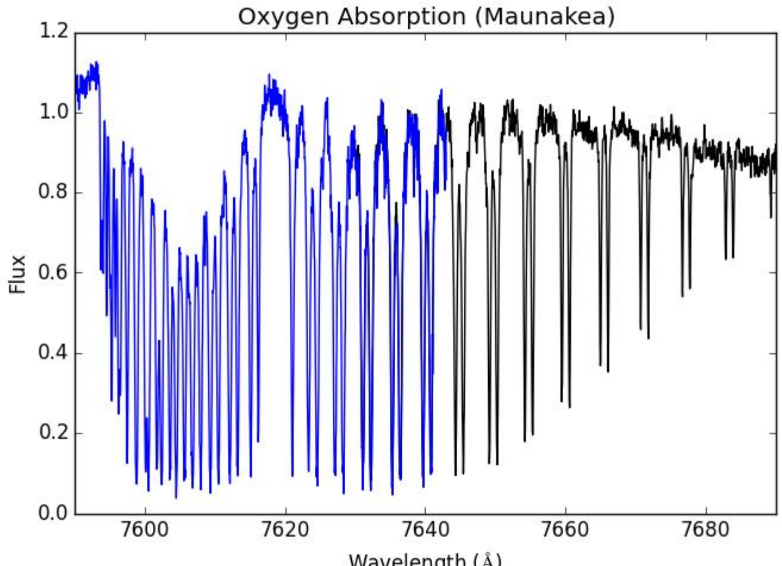
Future Adaptive Optics (*Siren*)

- Habitable planets around nearby, cool (~3500K) stars have an *in-principle* detectable reflected light spectrum : especially with ~30m telescopes
- Key technologies are maturing now (e.g. fast photon counting detectors).
- Doppler-shifted reflected light not only tells us about the planetary albedo (cloud cover) but also has the potential for bio-signatures. *“Are we alone?” is answerable.*





Conclusions

- Bright time on Subaru will be used for Extreme-AO science for some time to come.
- Continued technology development, (including Australian collaboration) will keep Subaru internationally competitive.
- Opportunities for significant new scientific surveys in coming years (e.g. post-SEEDS) to put both our communities at the forefront in the ELT era.
- Much more limited by seeing conditions than other science: some queue scheduling or backup poor seeing science would be useful.