Spectral Characterization of Directly Imaged Exoplanets with the Subaru Telescope

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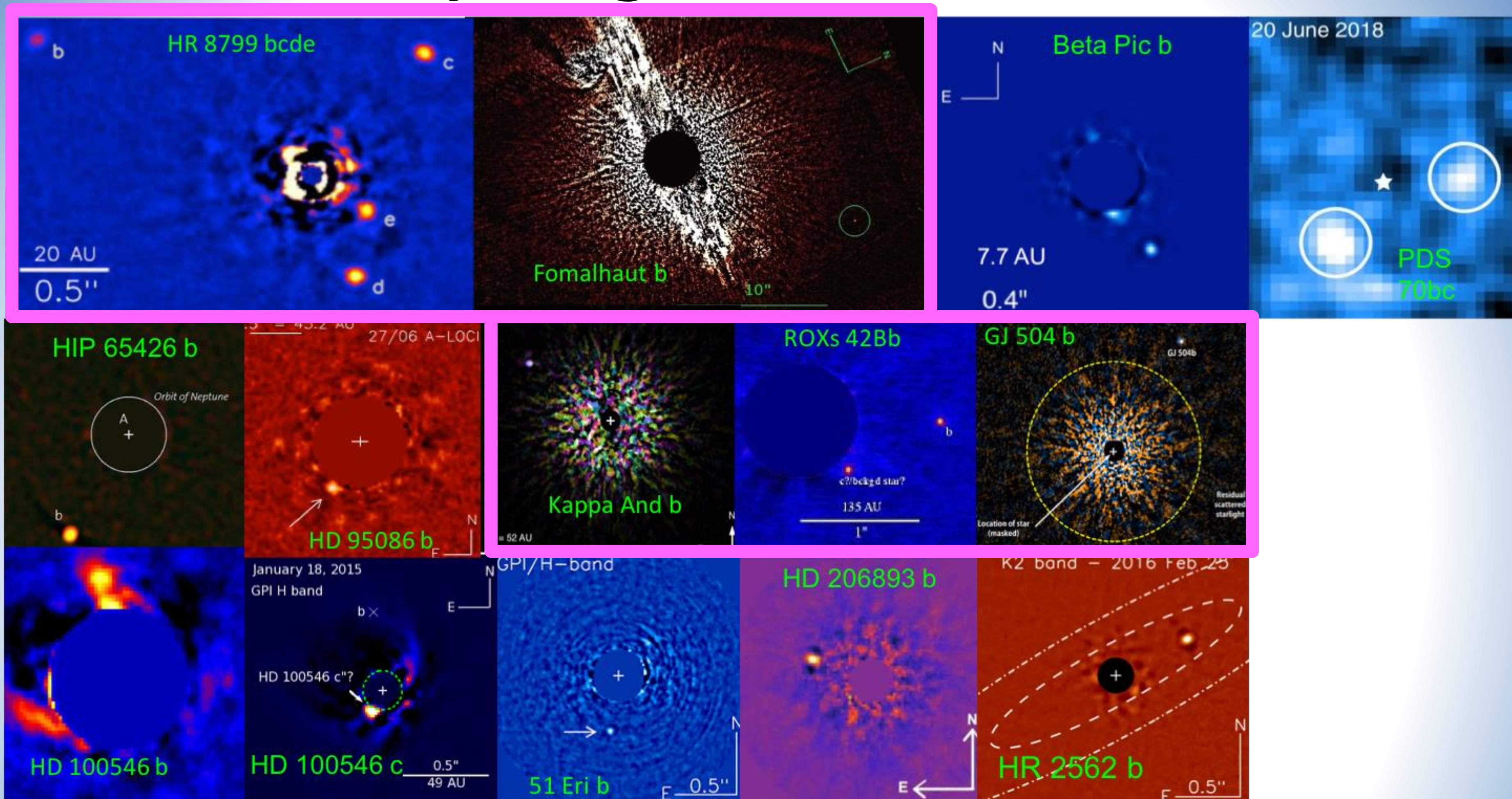
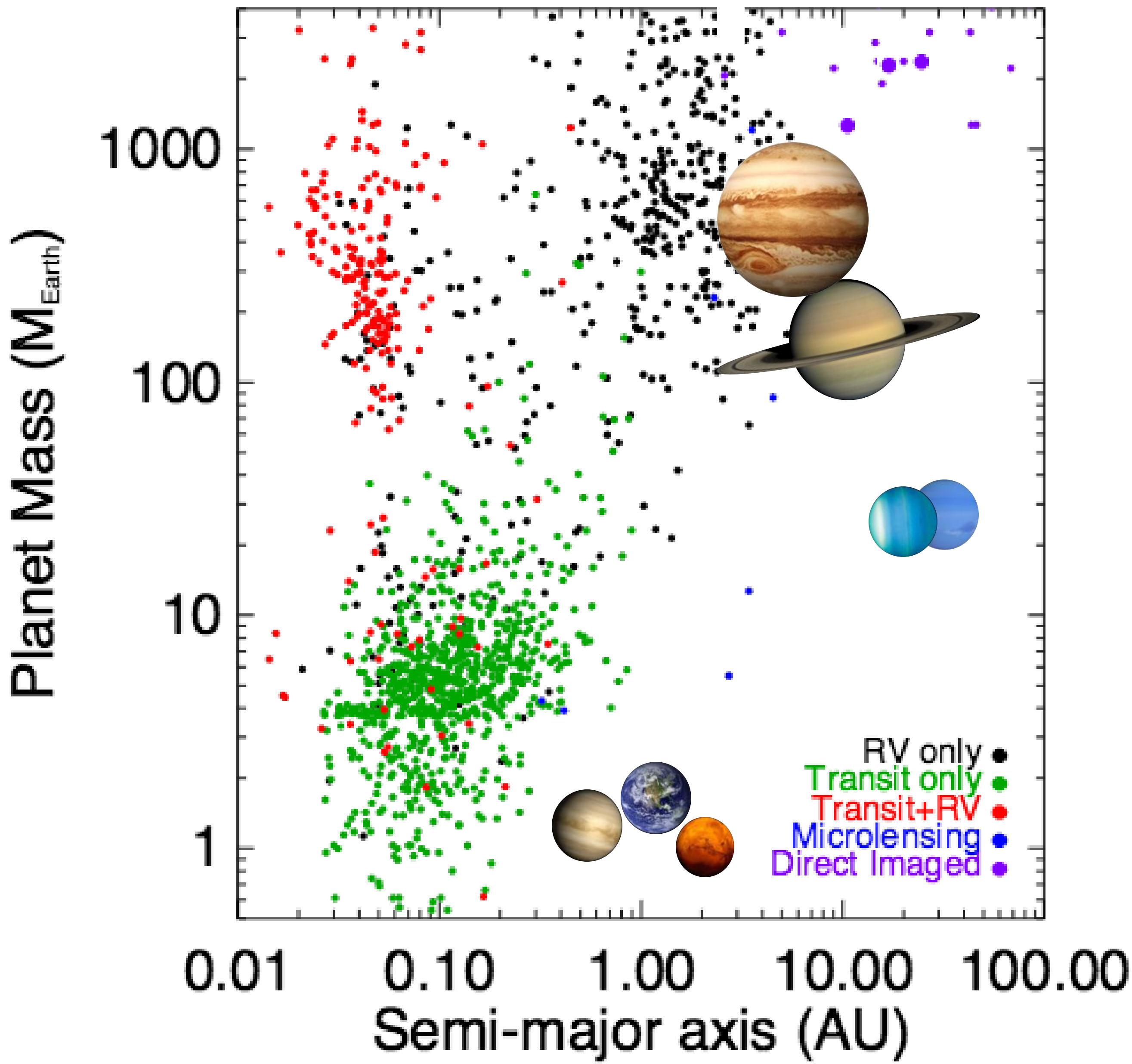
Directly Imaged Extrasolar Planets



- **About 12-20 directly-imaged planets known so far**
- **Most are very massive (M > 5 jovian masses) and at wide separations (15-30 au; typically ~0.5"-1"):**

Planet-to-star contrasts of 10^{-4} to a few x 10^{-6}

(Marois et al. 2008, 2010; Kalas et al. 2008; Lagrange et al. 2010; Rameau et al. 2013; Carson et al. 2013; Currie et al. 2014; Kuzuhara et al. 2013; Quanz et al. 2013; Currie et al. 2015; Macintosh et al. 2015; Milli et al. 2015; Chauvin et al. 2017; Keppler et al. 2018; Haffner et al. 2019)



(image credit: B. Macintosh with modifications)

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The monthly podcast talking all things exoplanet science - hosted by @stellarplanet, @exohugh, @andrewrushby, and a special guest. The Home of #ExoCup

Earth exocast.org Joined April 2016

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Look how great #51Erib looks! Meanwhile, #TRAPPIST1b looks like...oh, that's right, we can't see it... #ExoCup2019

Jason Wang @semaphore_P · Nov 9

A new exoplanet orbit movie just in time for #ExoCup2019. A 4-year time-lapse of 51 Eri b, the coolest directly imaged exoplanet to date! We just published the updated orbit from the Gemini @PlanetImager in a paper led by Rob De Rosa (arxiv.org/abs/1910.10169). twitter.com/exo_cast/statu...

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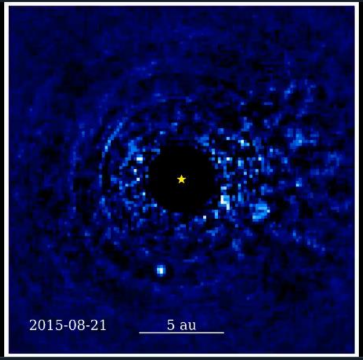

GIF

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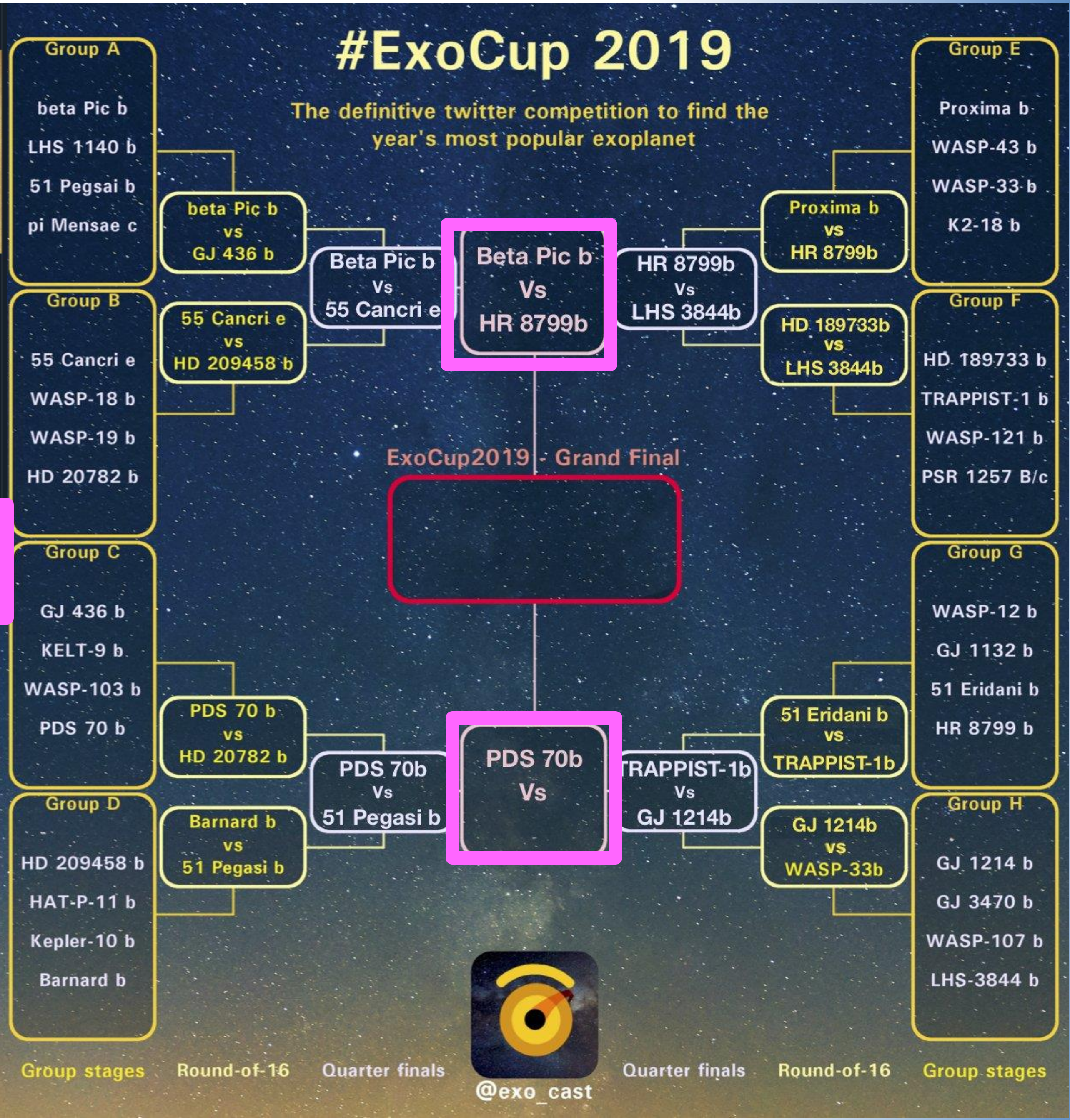
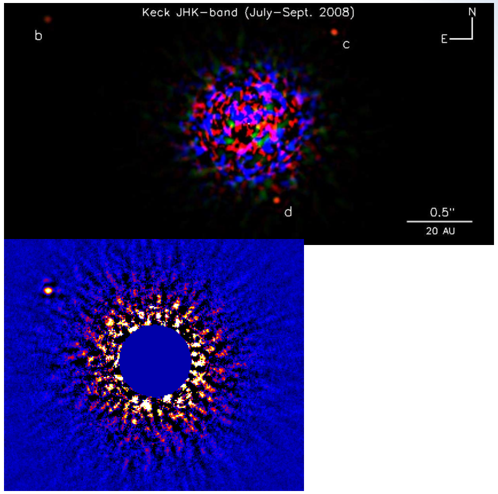


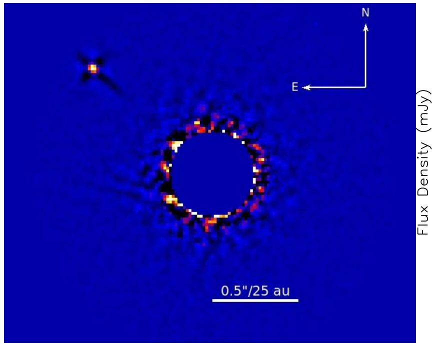
Outline

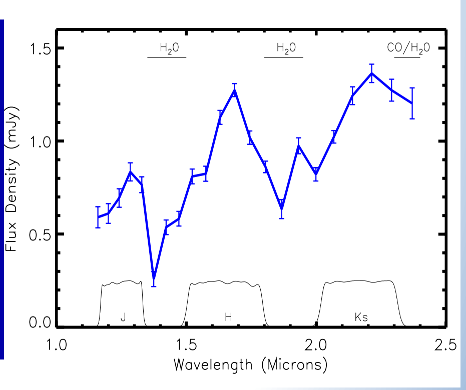
- Characterization of Exoplanets with AO188 (2009-2015)

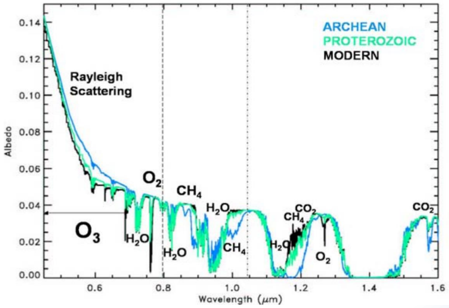
- Spectral Characterization of Exoplanets with SCExAO (2016-)

- The Future with Subaru/SCExAO and TMT

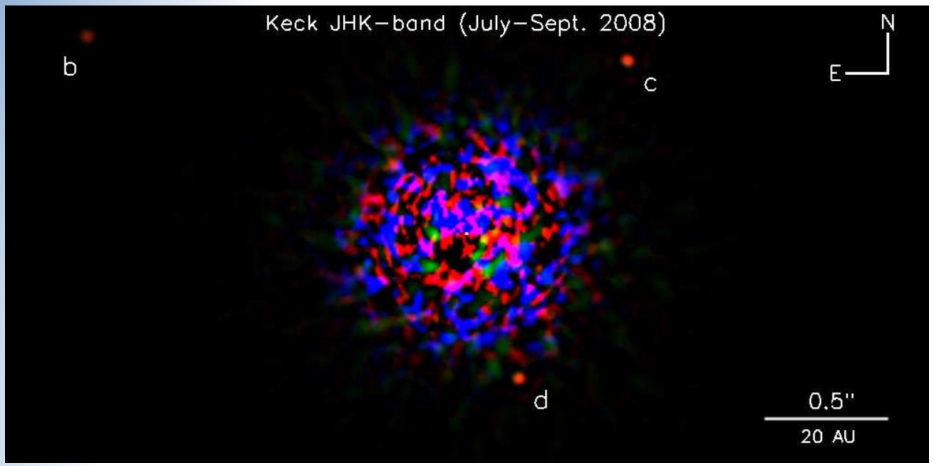




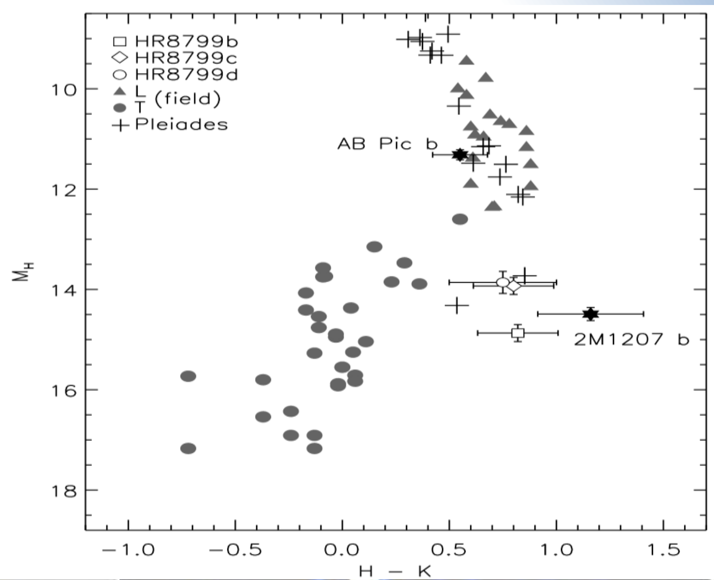




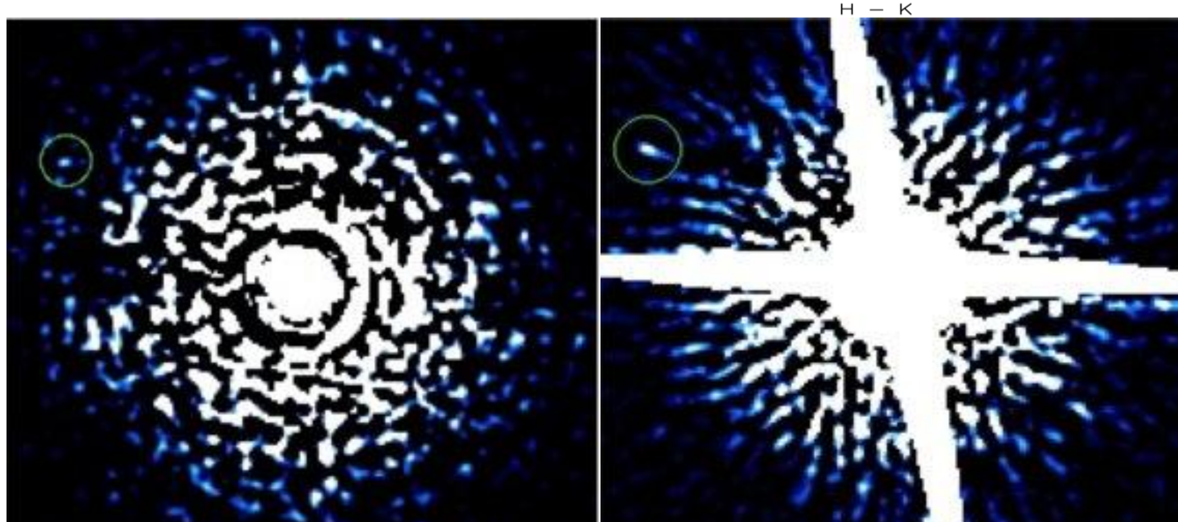
HR 8799 bcd(e)



Marois et al. (2008) (JHK)



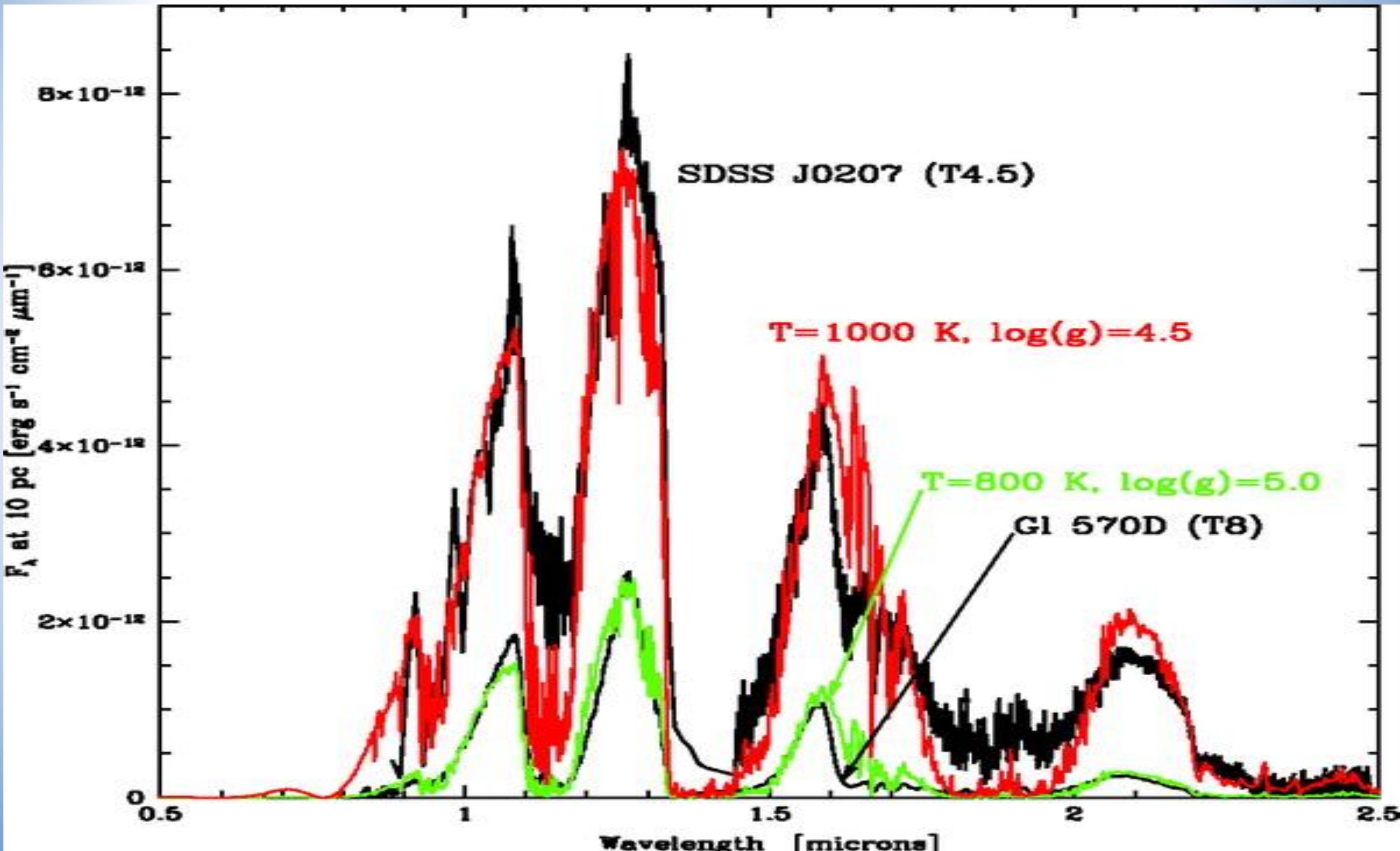
Follow-up Y band data for HR 8799 with Subaru/IRCS (August 2009), weak detection of 'b'



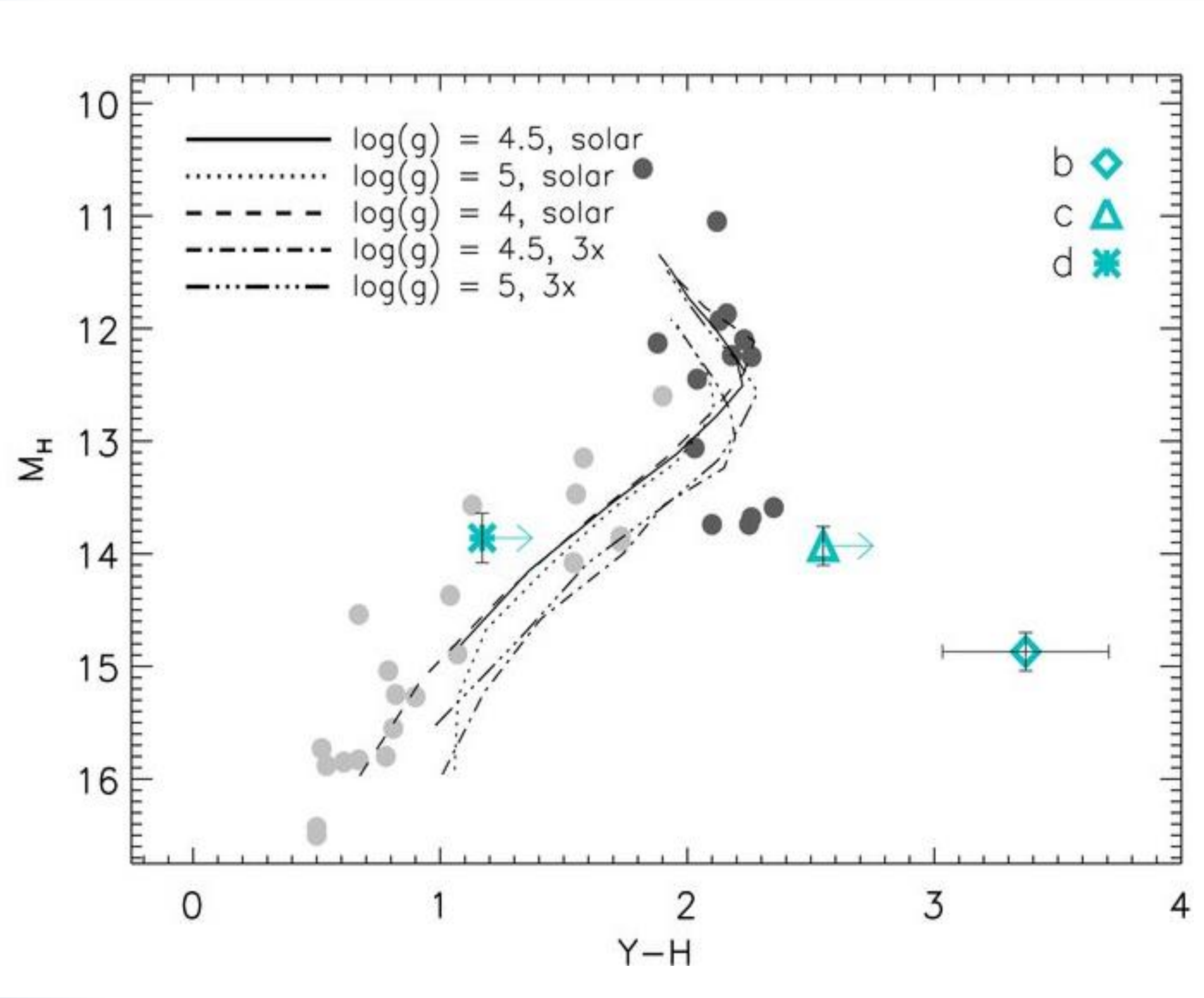
Y band J band

Currie, Burrows, Itoh et al., 2011, ApJ, 729, 128

Atmospheres of Field Brown Dwarfs (Comparison Objects for Planets)



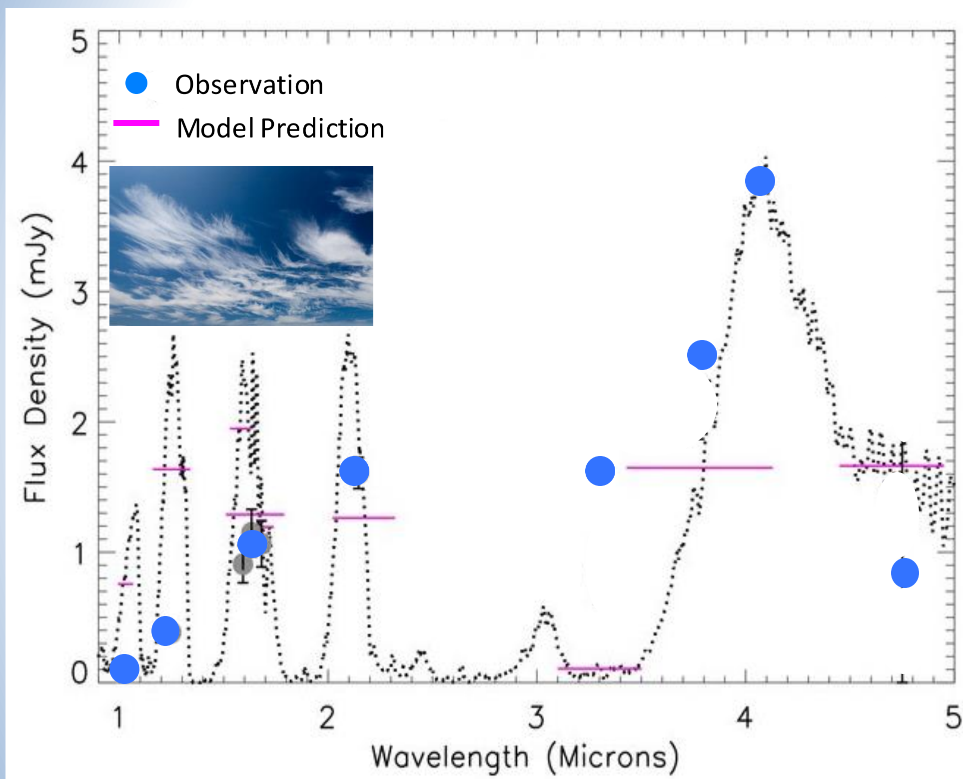
Differences Between Field Brown Dwarfs and HR 8799 bcde



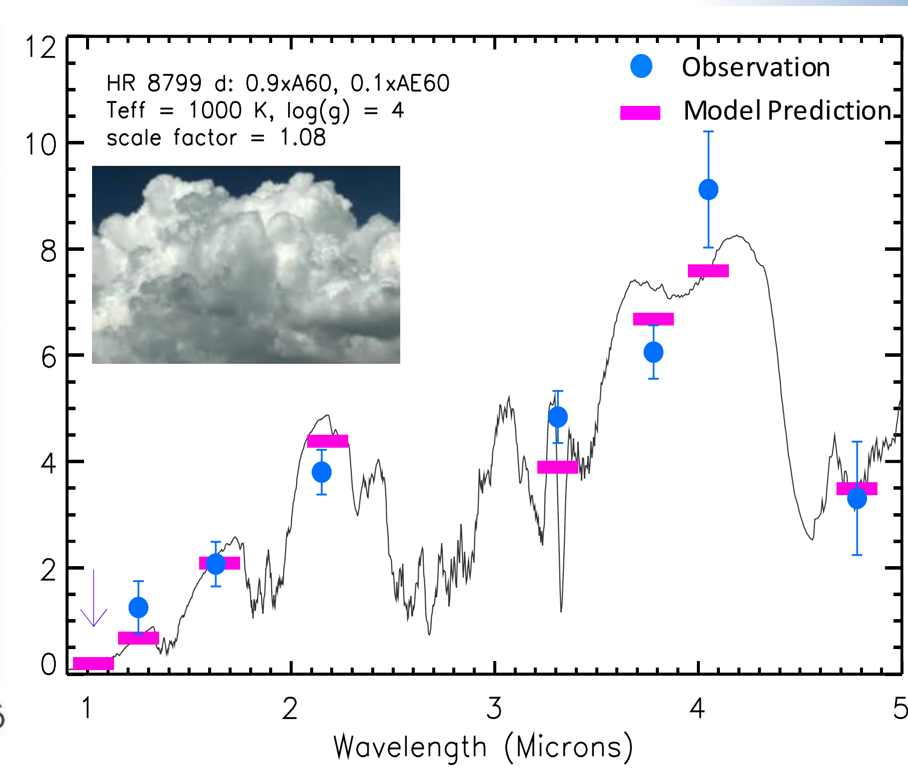
Currie, Burrows, Itoh et al., 2011, ApJ, 729, 128

The Atmospheres of HR 8799 bcde: Thick, (Patchy?) Clouds

(e.g. HR 8799 b and d)



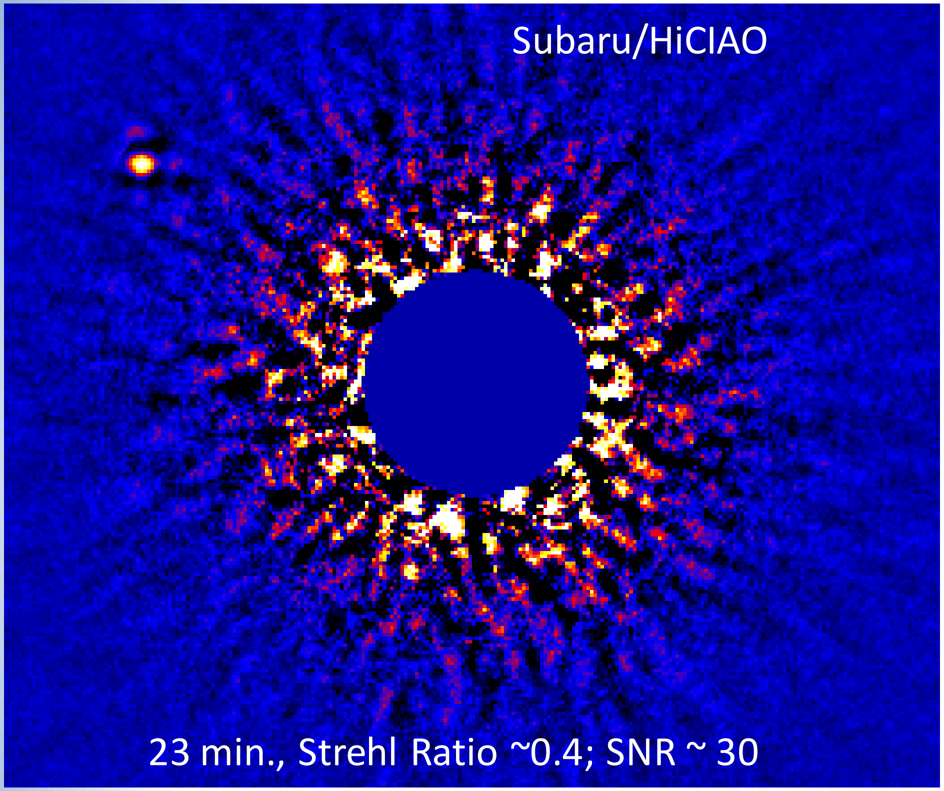
Thin Cloud, Old, Field Brown Dwarf-Like Model Fit

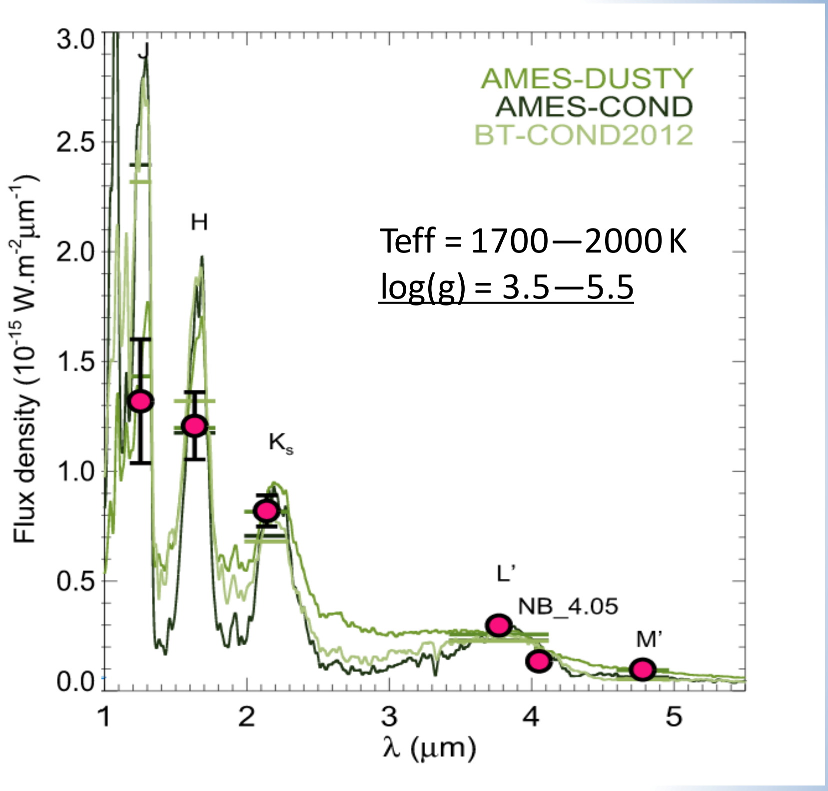


Thick Cloud Model Fit

Currie, Burrows, Itoh et al., 2011, ApJ, 729, 128

Characterization of kappa And b with AO188/HiCIAO

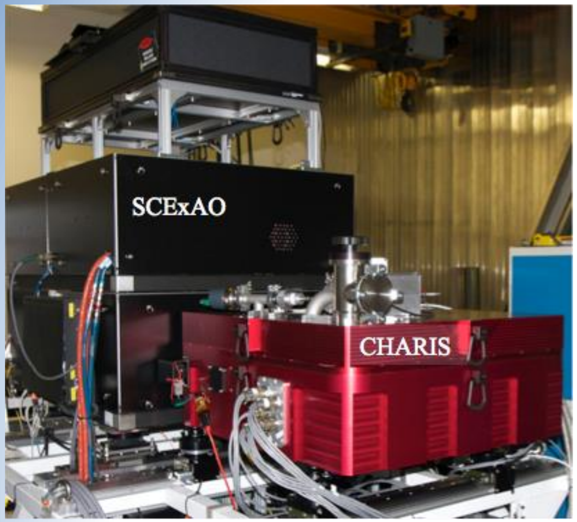


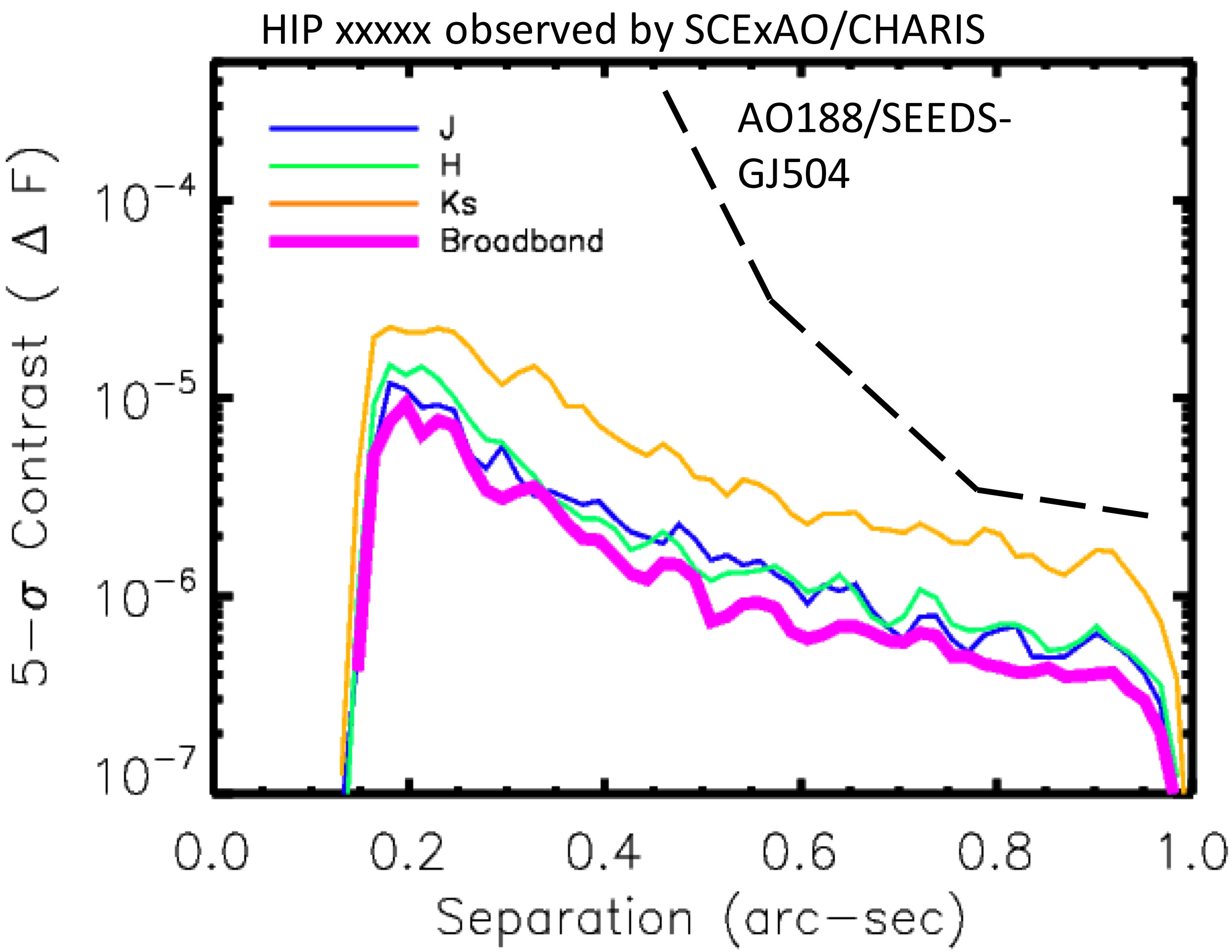


- **Kappa And b: Discovered by Carson et al. (2013)**
- **Mass of the companion is highly uncertain due to uncertainties in age of host star**
- **Photometry shows evidence for some dust/clouds, Teff ~ 1700-2000K**
- **Surface gravity unconstrained**

(Carson et al. 2013; Bonnefoy et al. 2014)

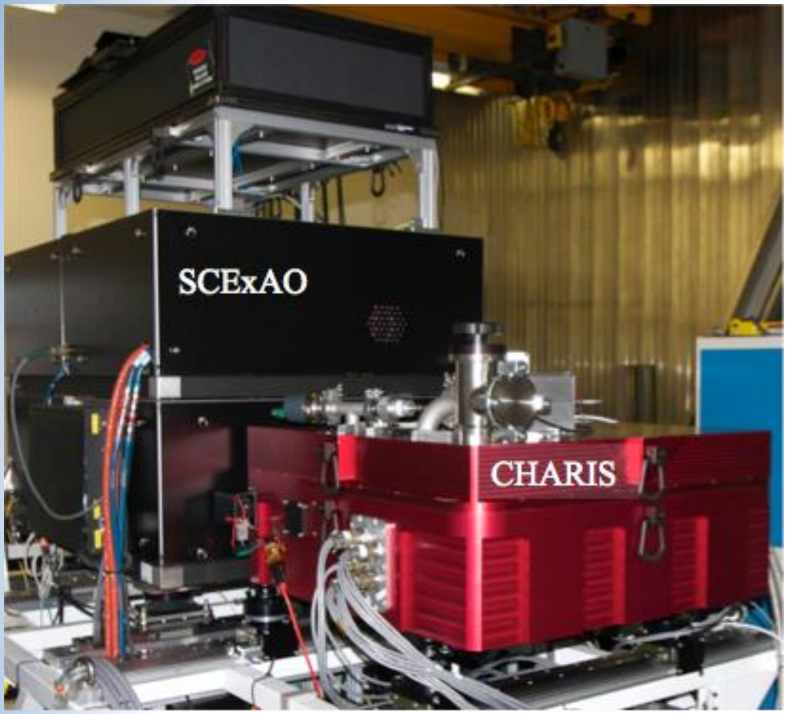
Planet Spectral Characterization with SCExAO

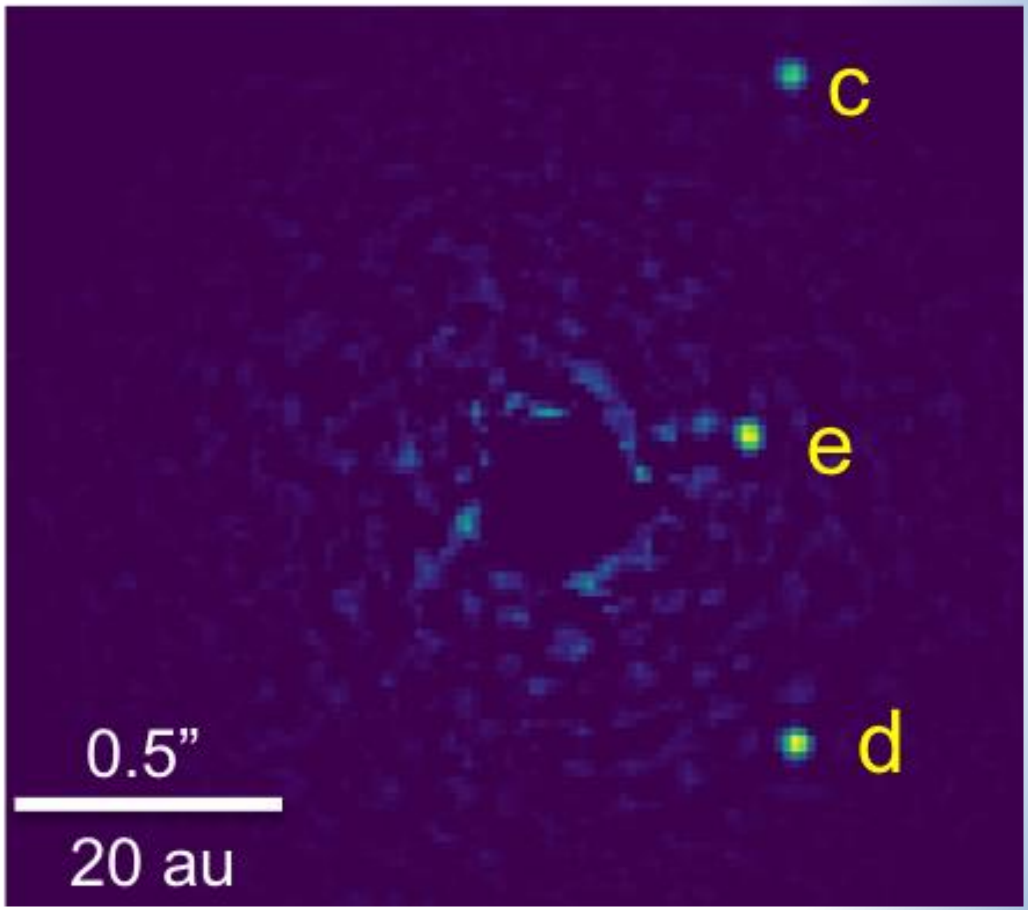




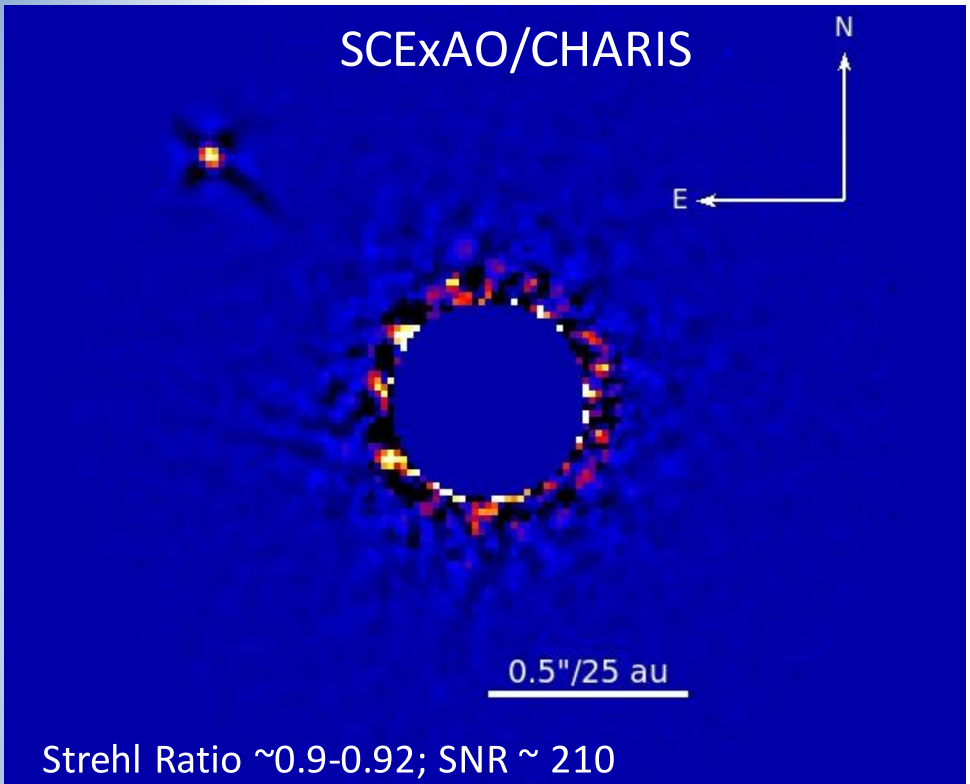
- H-band Strehl of ~0.9 for bright stars (highest reported: S.R. ~ 0.94)
- 5-sigma contrasts (good conditions, aggressive ADI+SDI):
  8e-6 at 0.2"; 1-2e-6 at 0.4-0.5", 7e-7 at 0.75"
- Compared to AO188/SEEDS, 100x deeper at <0.5"

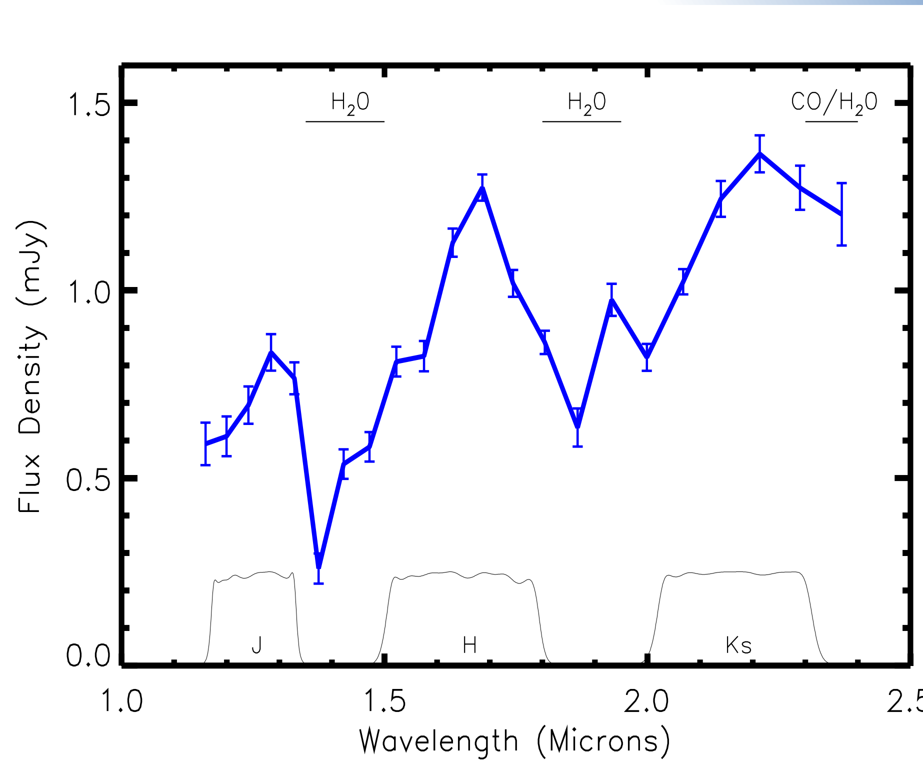
Planet Spectral Characterization with SCExAO





SCExAO/CHARIS Observations of kappa And b

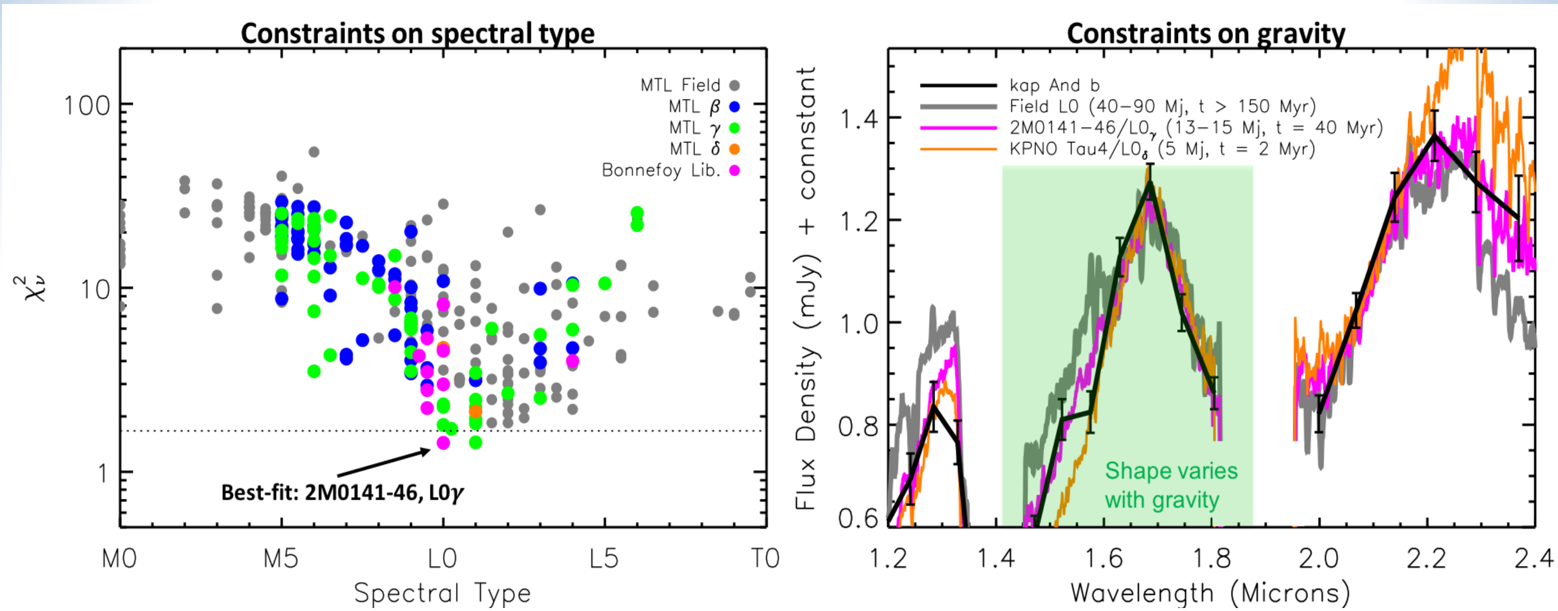




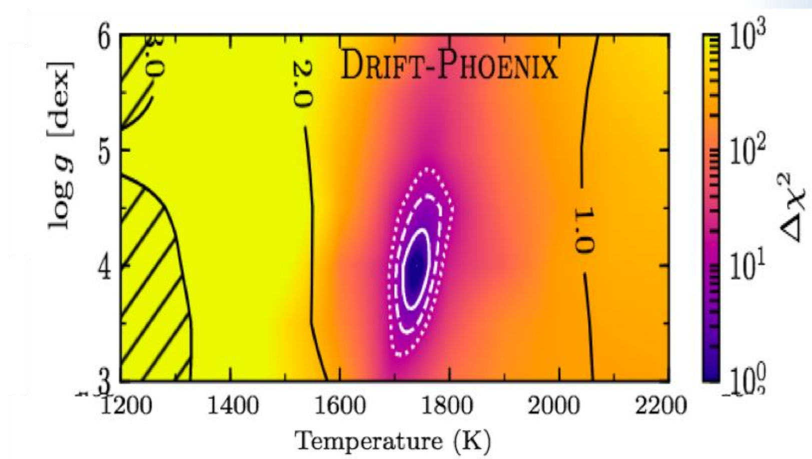
- Decisive detection despite shallow data
- ~5% spectrophotometric precision
- No other companions down to 15 au
- Sharply-peaked H band spectrum suggestive of low gravity

(Currie et al. 2018, AJ, 156, 291)

SCExAO Characterization of kappa And b

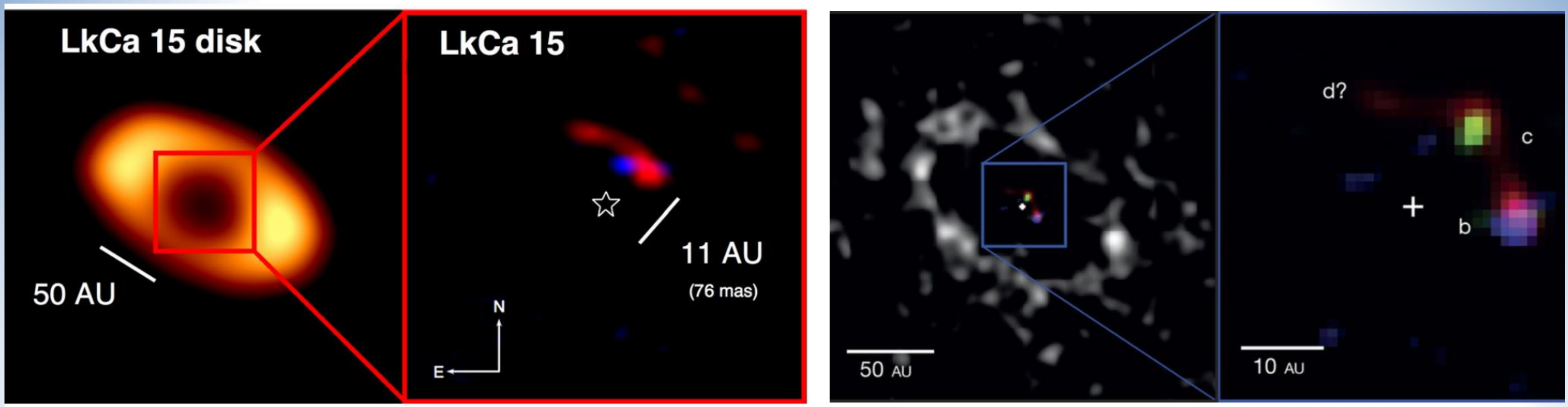


1. Early L spectral type
2. Sharply-peaked H band spectrum suggestive of low gravity
3. Strong preference for cloudy atmosphere, log(g) ~ 4—4.5, Teff ~ 1700-1900 K

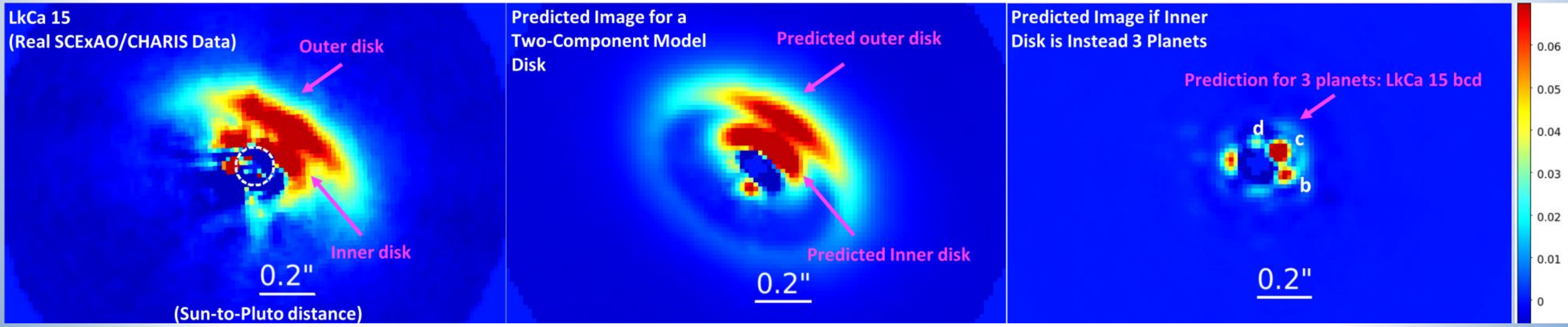


(Currie et al. 2018, AJ, 156, 291; Uyama et al. 2019 under minor revision)

SCExAO/CHARIS Observations of LkCa 15



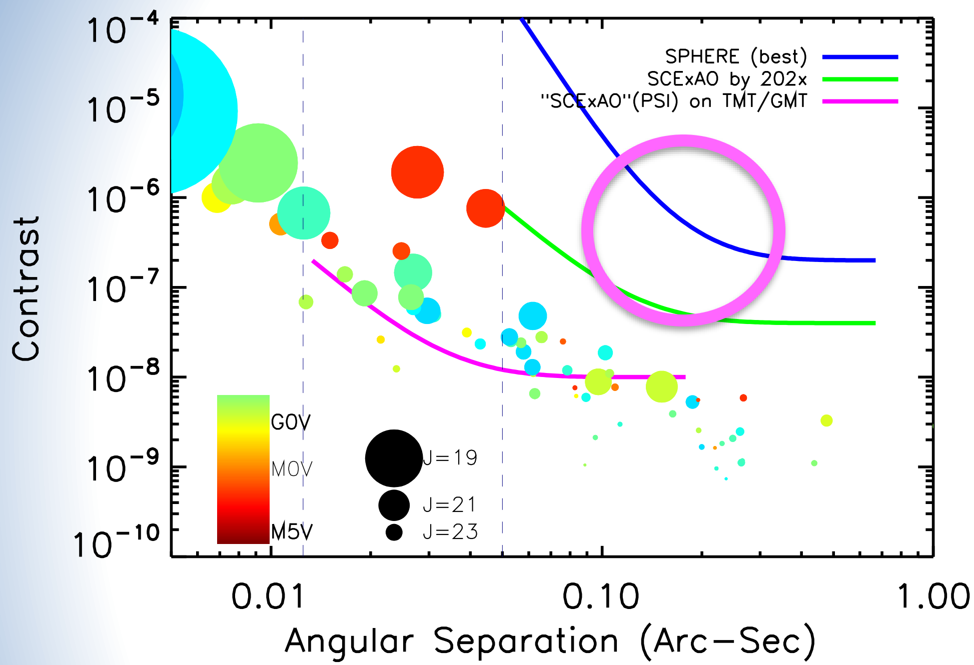
(Kraus & Ireland 2012; Sallum et al. 2015a)



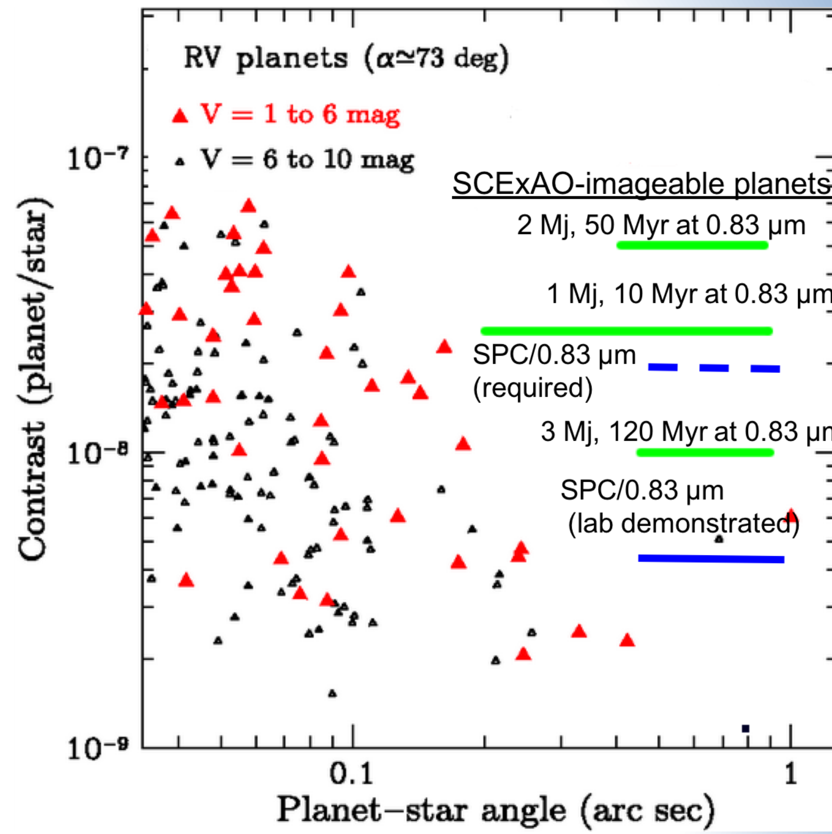
- LkCa 15 bcd: likely inner disk signals, not planets

(Currie, Marois, & Cieza et al. 2019)

SCExAO Discovery Space (2025-2030)



Even if known RV planets out of reach; possibly reflected-light jovians around nearby A stars?

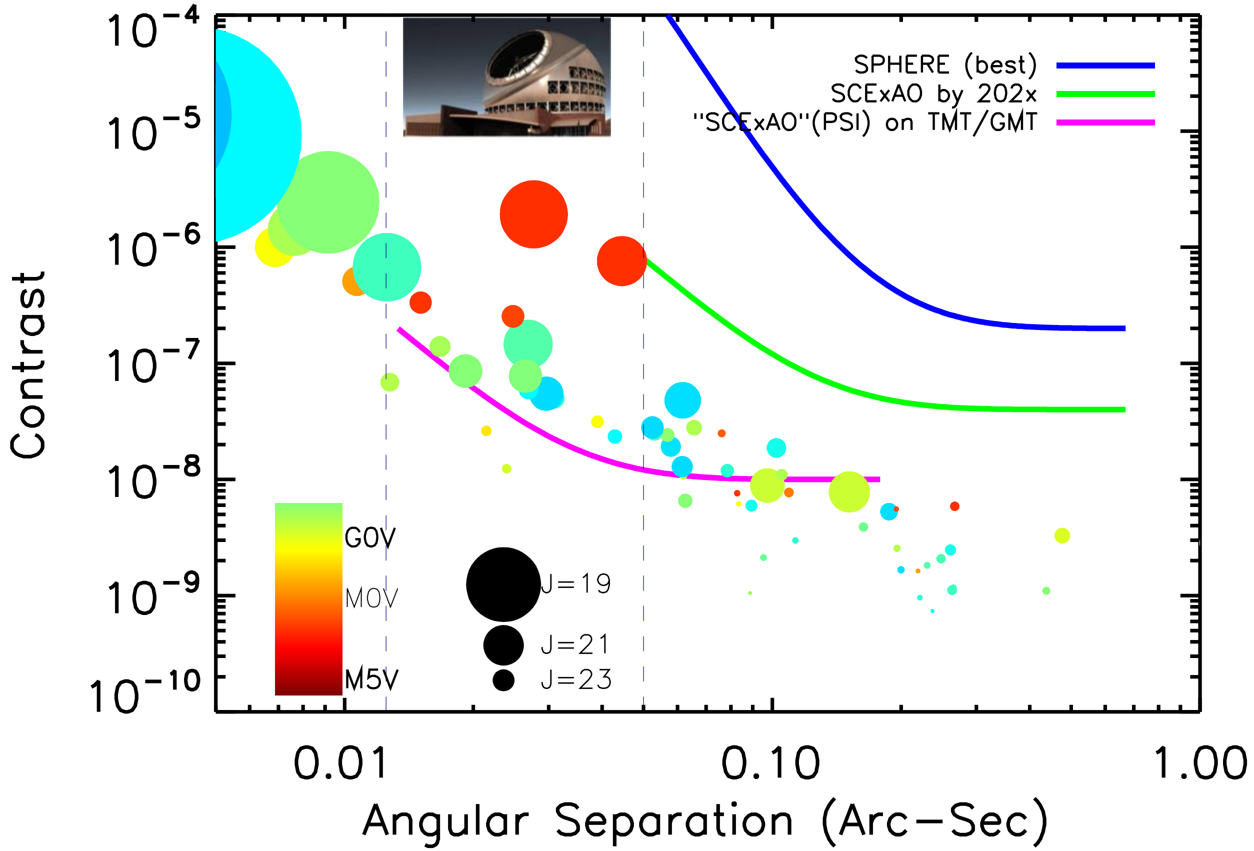


SCExAO-identified planets recoverable with WFIRST-CGI

A Jupiter-mass planet at 0.5 au from Sirius

(Currie et al. 2019, presentation for Decadal Survey)

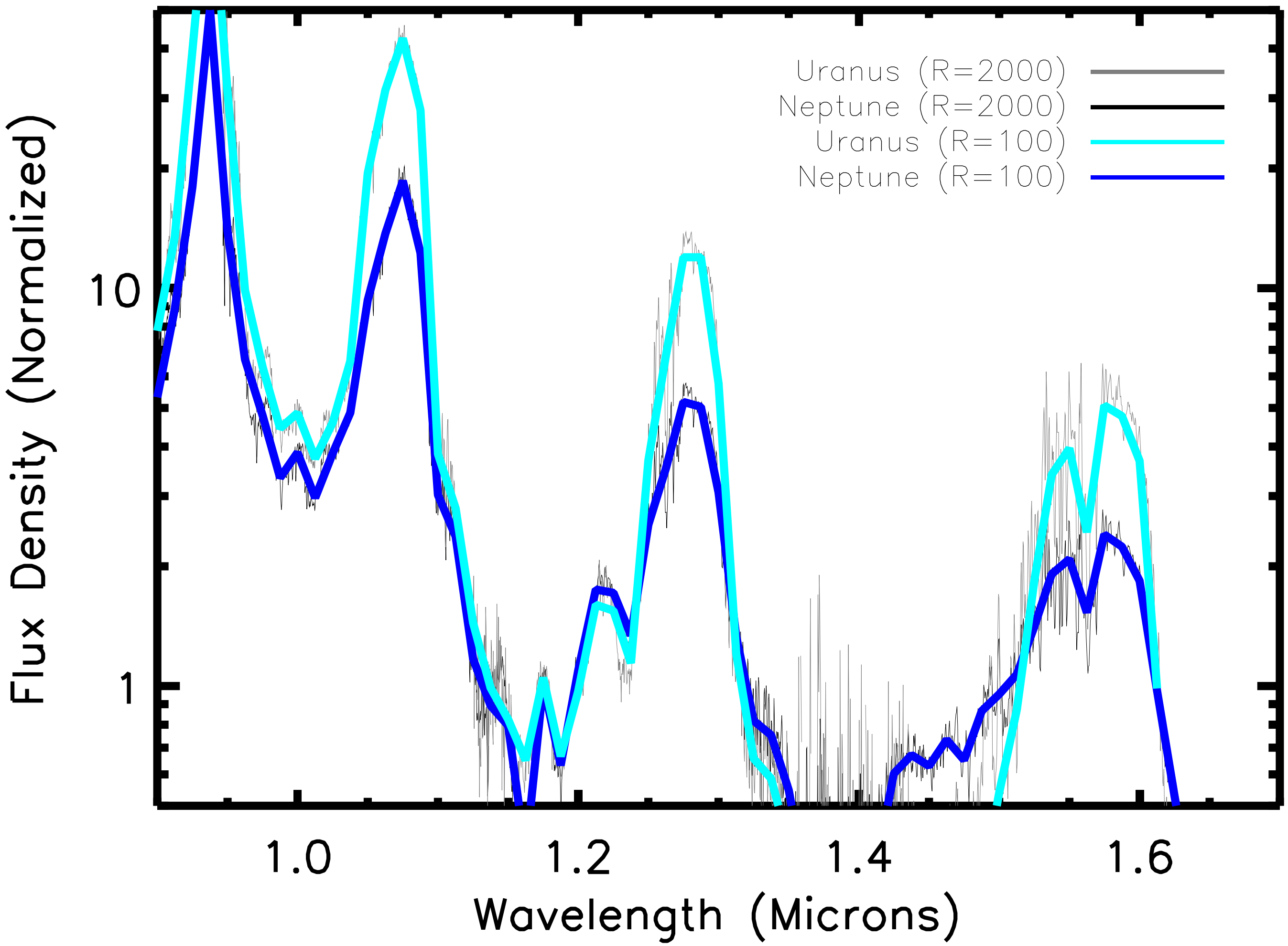
”SCExAO” on TMT (aka PSI-blue)



- Assuming likely gains in AO performance in the next 5 years on 8-10 m class telescopes (lead by SCExAO/KPIC/MagAO-X) put on a 25-30m telescope
- About 25 known radial-velocity detected planets recoverable with either TMT or GMT (many more with TMT + GMT); at most 1-2 with 8-10 m telescopes in optimistic case

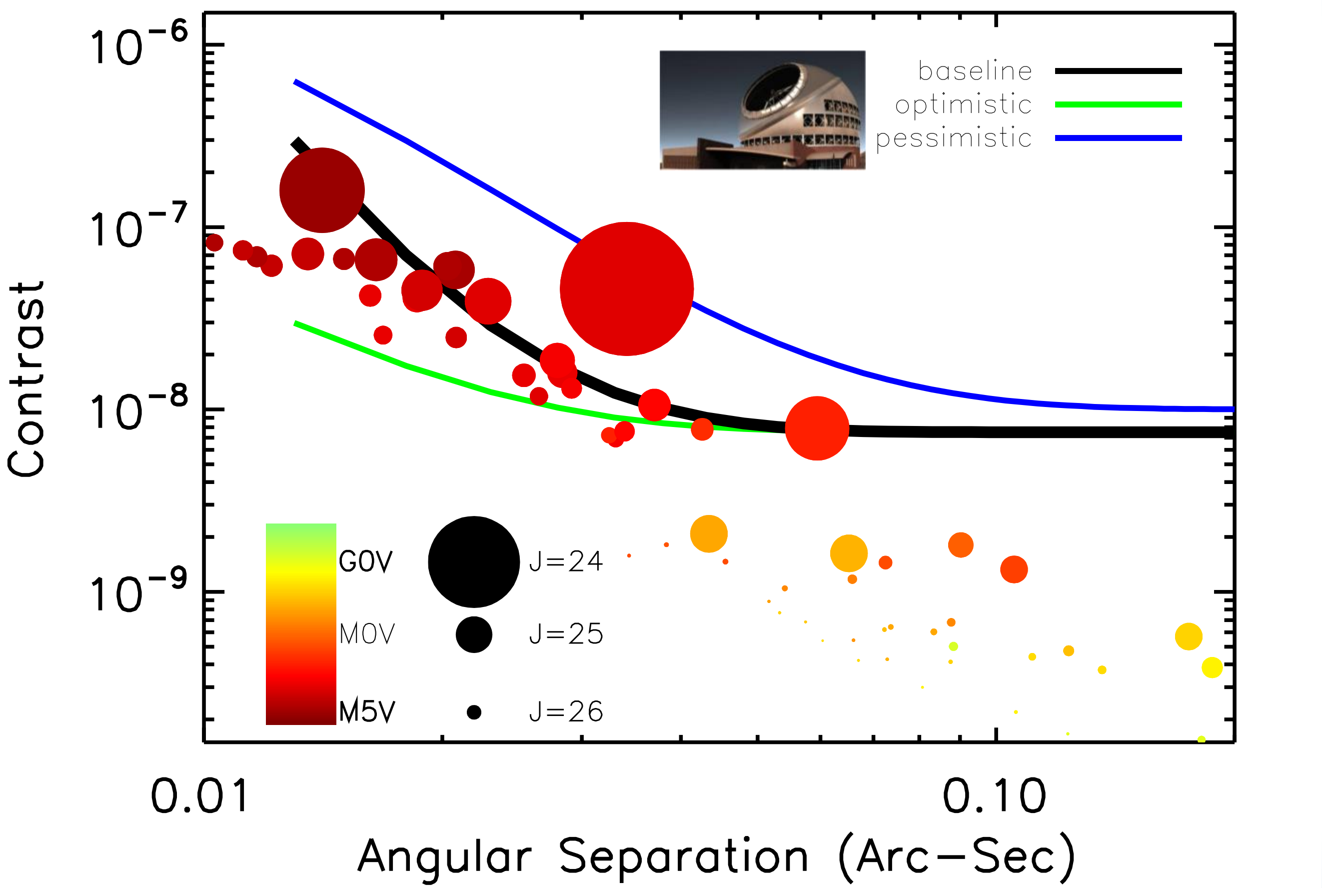
(Currie et al. 2019, presentation for Decadal Survey)

Atmospheres of Reflected-Light Planets



- PSI can study atmospheres of Neptune-mass planets vs. insolation

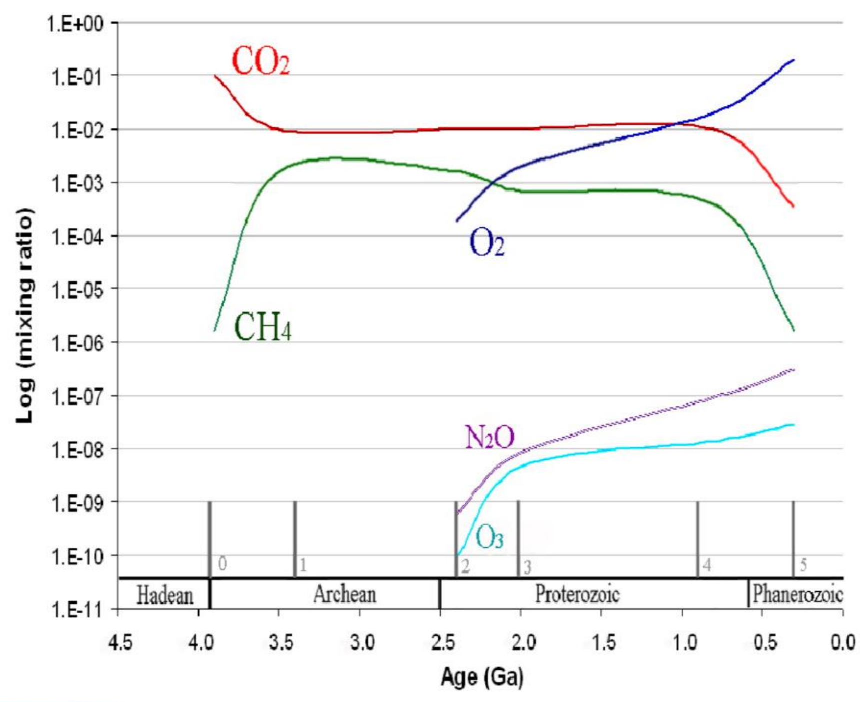
Reflected Light Earths

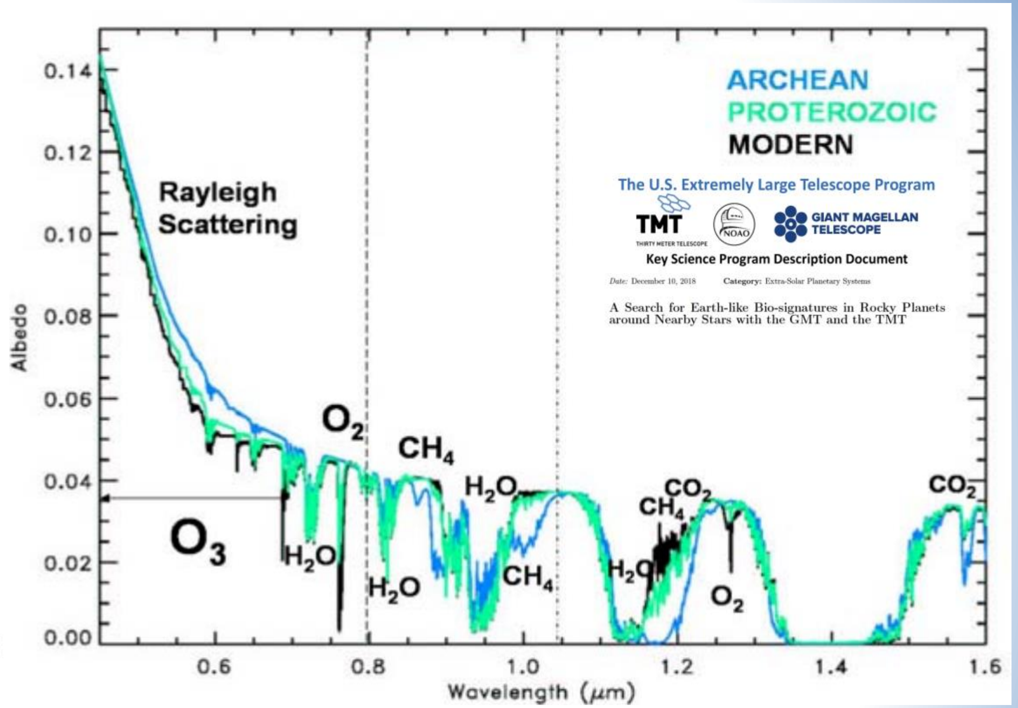


- ‘baseline’: 7-9 stars with detectable Earth-sized planets in the HZ
- ‘pessimistic’: ~1 stars with imageable Earths
- ‘optimistic’: ~21 stars with imageable Earths
- All detections are around M stars

(Currie et al. 2019)

Spectral Evolution of an Earth-like Planet





- PSI can in principle distinguish between a modern Earth and an Earth at earlier stages
- Key diagnostics include oxygen (1.27 microns), carbon dioxide (1.55 microns), water (1.1, 1.4 microns), and methane (1, 1.2 microns)

(Kasting 2004; Meadows 2006)