IR spectroscopy and high-contrast imaging of brown dwarfs and exoplanets

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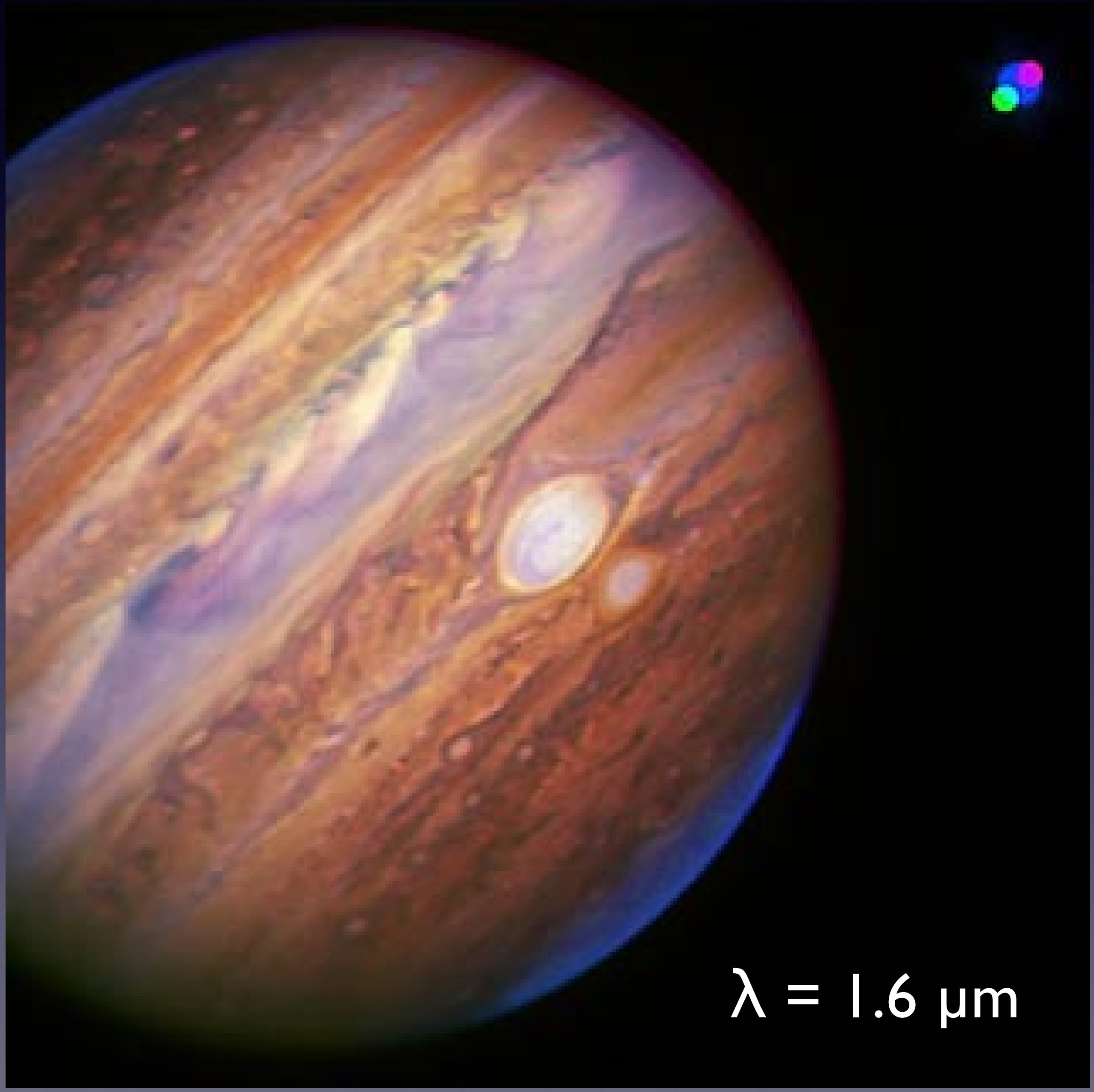
- **clouds and weather on brown dwarfs**
- **imaging of exoplanets and circumstellar disks**

Illustration by Tim Pyle (NASA/IPAC)

Rotational monitoring can reveal clouds and spots



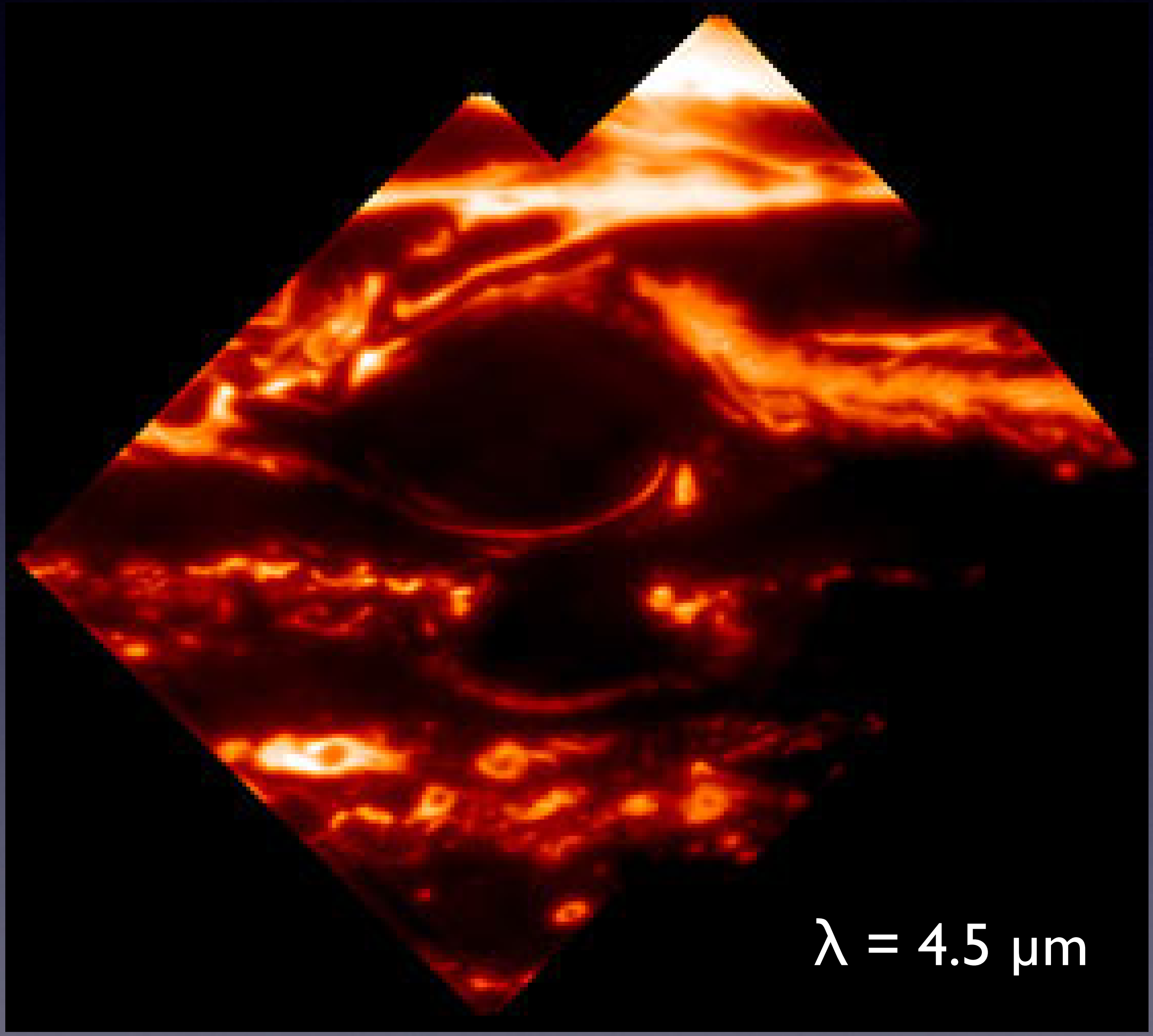


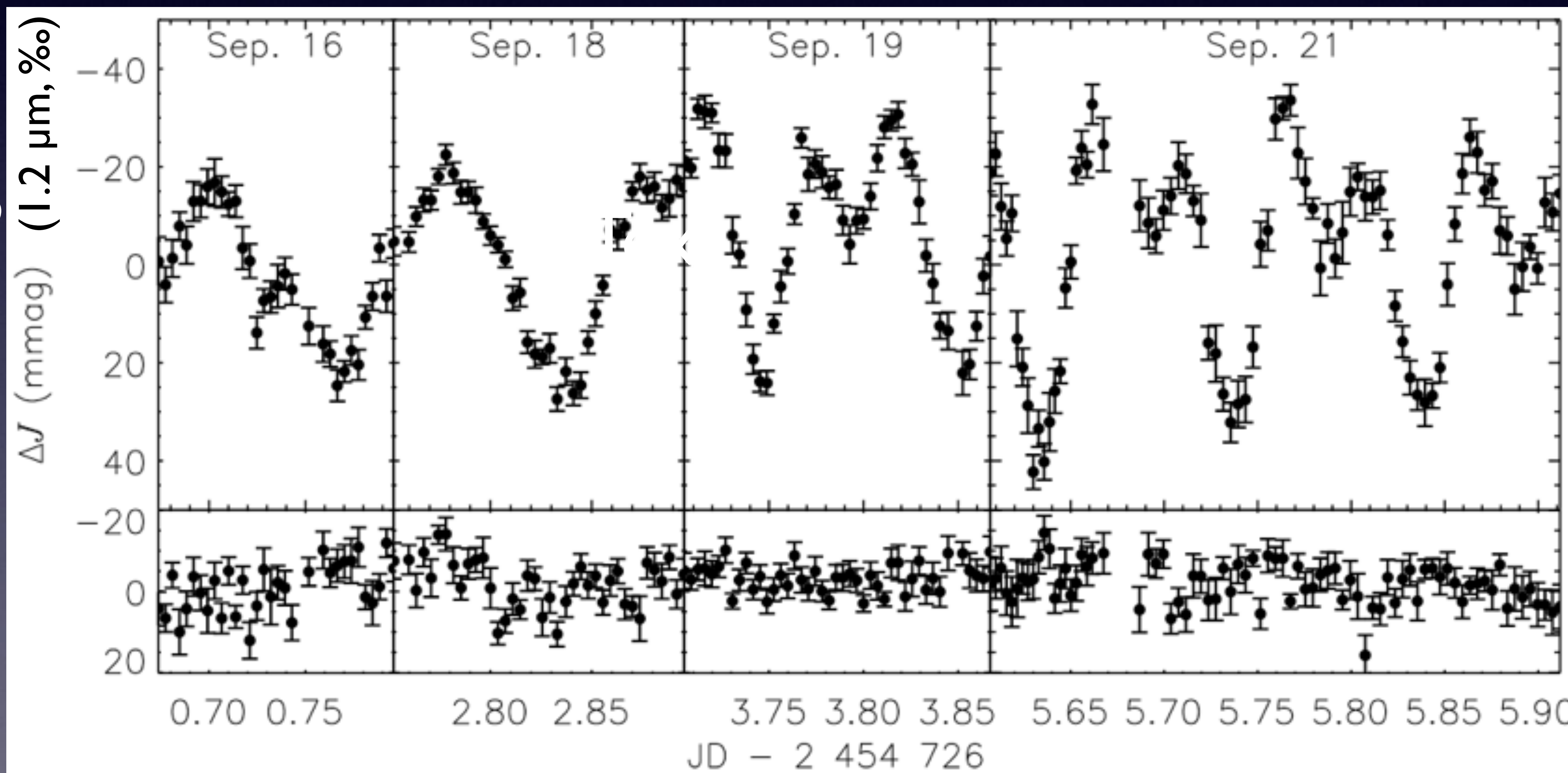
Image credit: Imke de Pater, UC Berkeley

Early detection of variability from patchy clouds on brown dwarfs

P = 2.4 hr amplitude = 0.5%

SIMP 0136+09 (T2.5)

reference star



Artigau et al. (2009)

Spitzer Exploration Science Programs (all post-cryo!):

Weather on Other Worlds (WOW; Cy 8)
Extrasolar Storms (Cy 9)
Brown Dwarf and Exoplanet Weather Forecasts (Cy 9)
Weather on Other Worlds 2 (Cy 11)

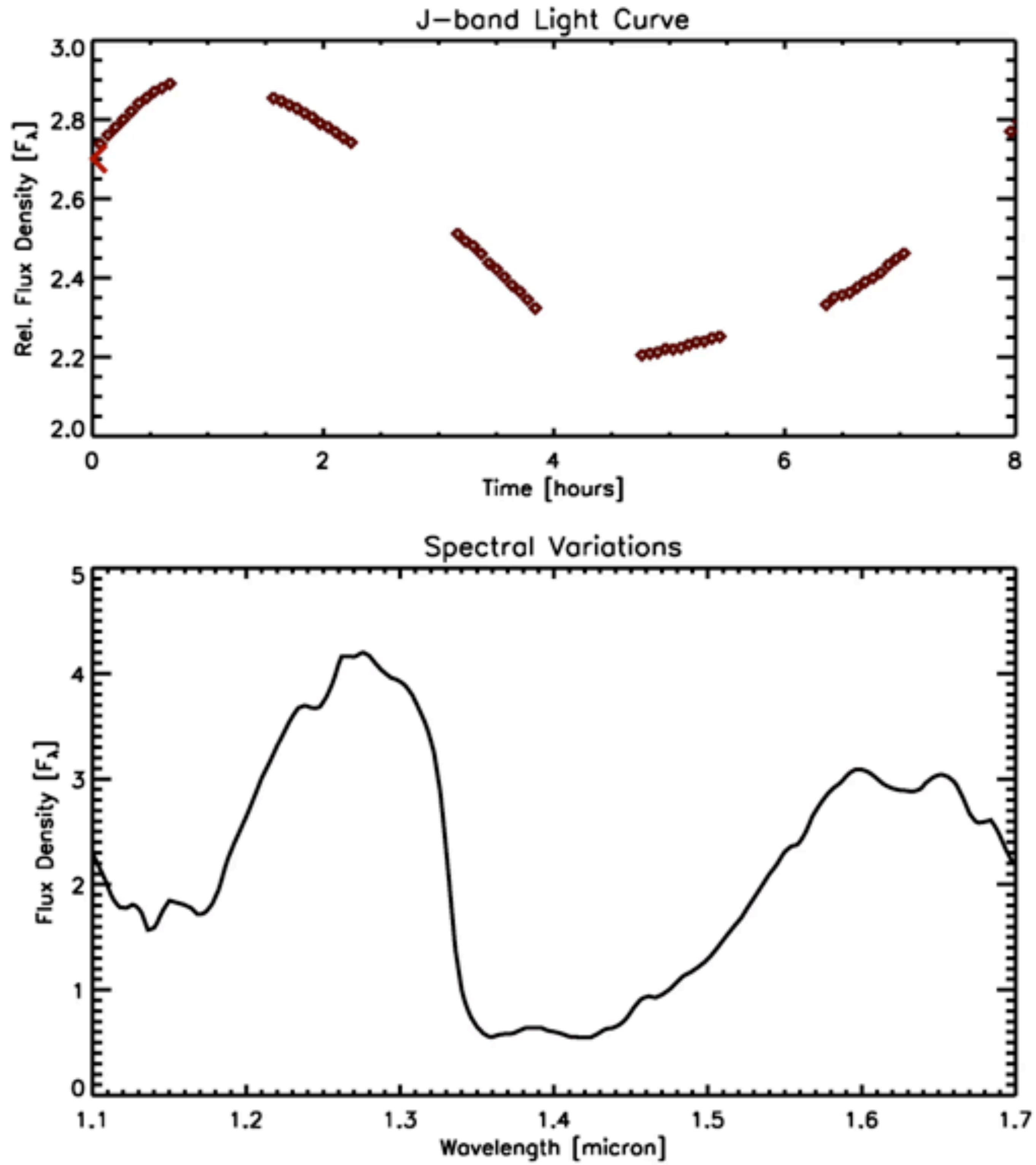
- **Advantage:** x10 higher photometric precision compared to ground
- **Goal:** detect Great Red Spot analogs on brown dwarfs
- **Result**: all L dwarfs and majority of T dwarfs are spotted.

Metchev et al. (2015)

Spectroscopic variability of L and T dwarfs

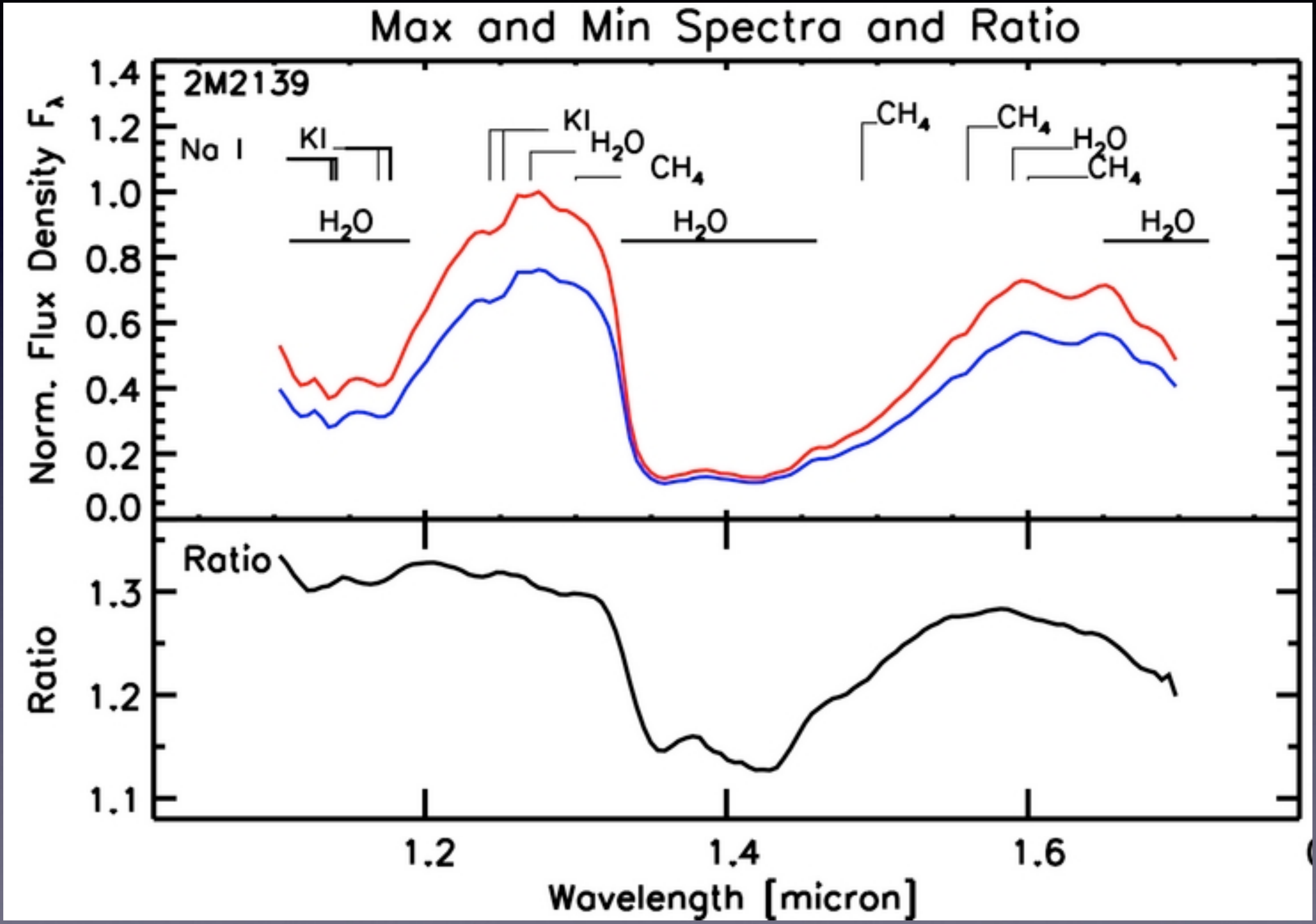
2MASS 2139–0220 (T1.5):

HST/WFC3 grism spectroscopy



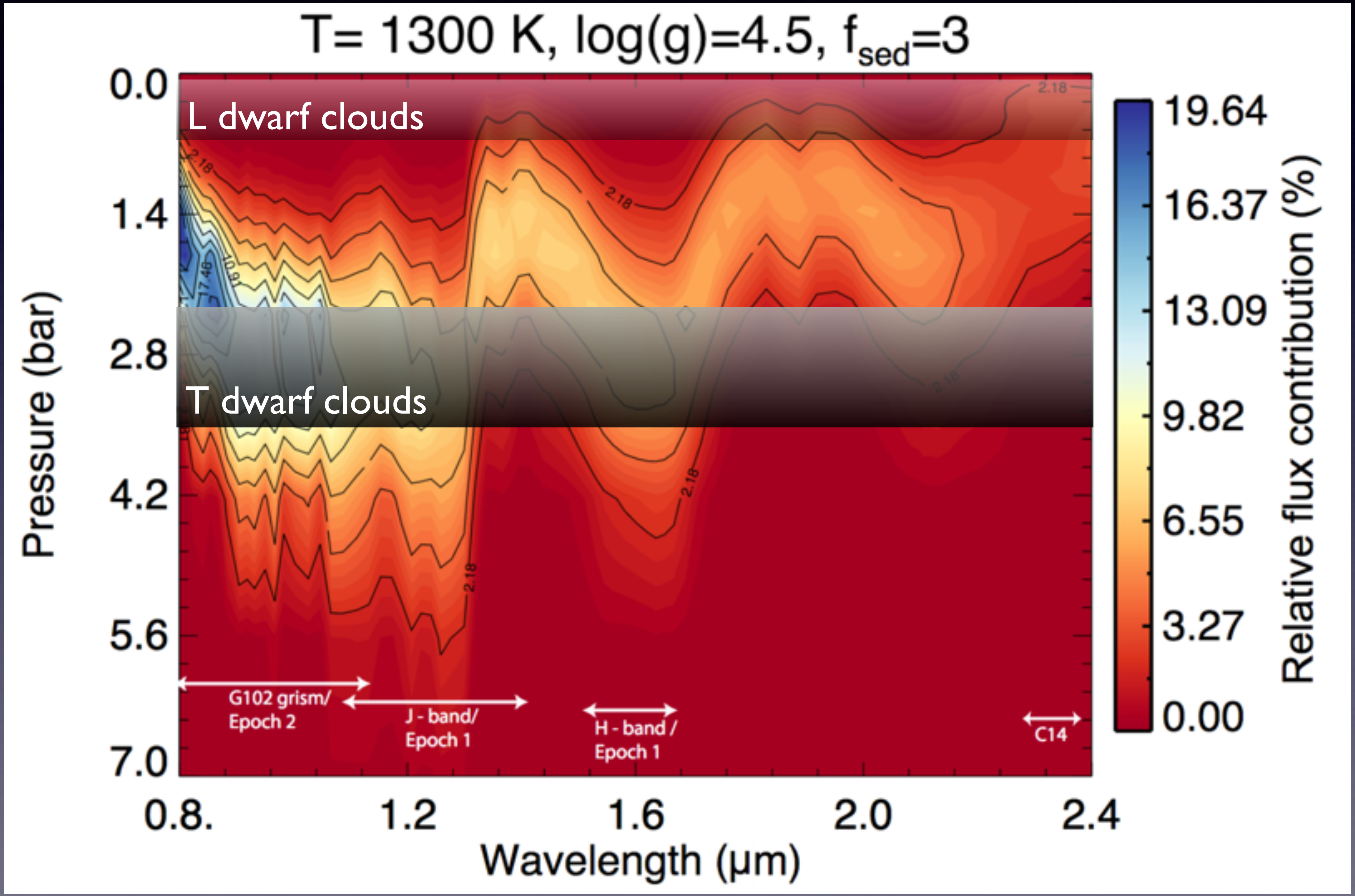
Apai et al. (2013)

Spectroscopic variability of L and T dwarfs



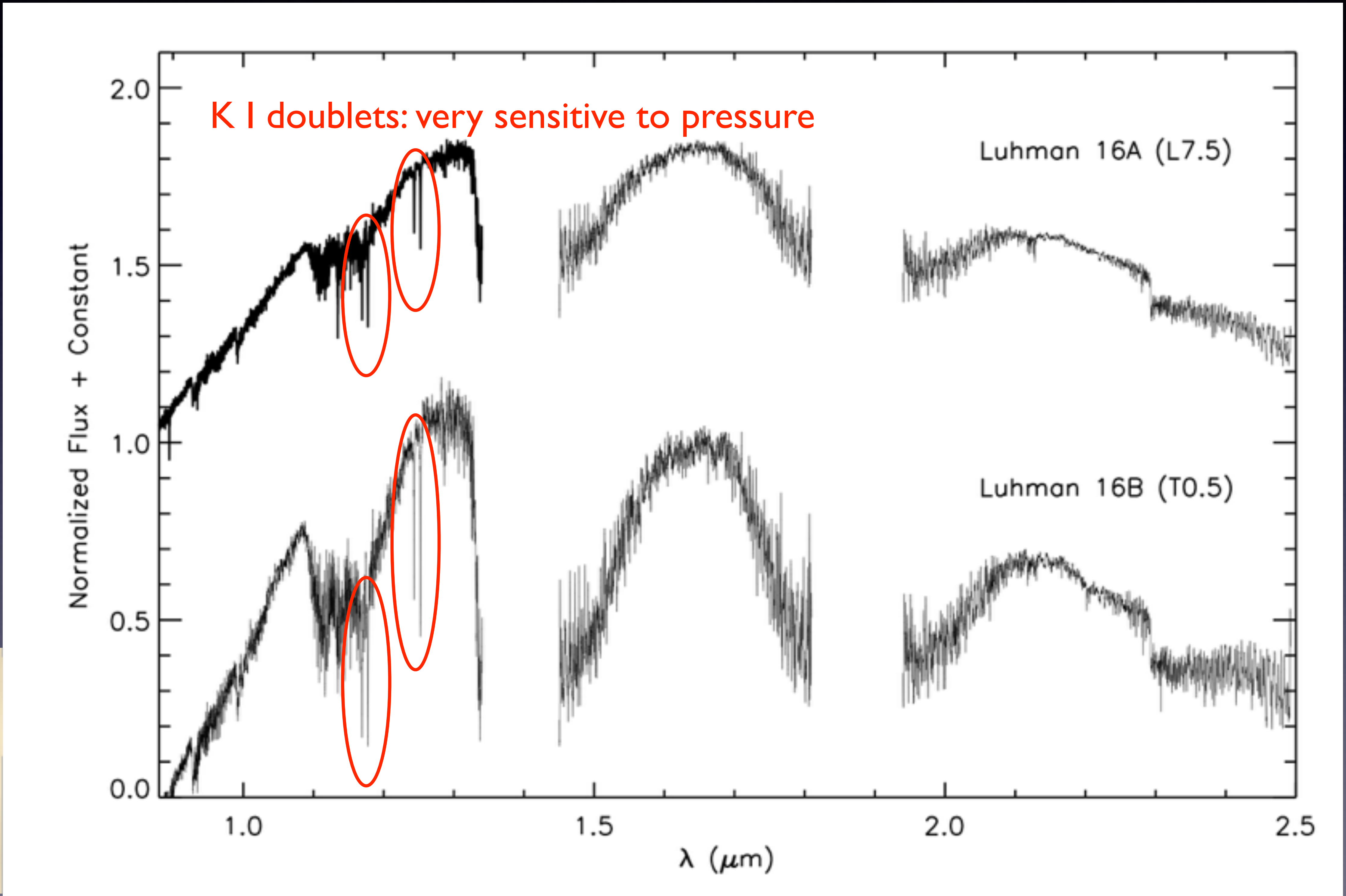
Apai et al. (2013), Yang et al. (2015)

Clouds reside mostly below τ~1 level in the 1.4 µm water band of T dwarfs



Luhman 16B relative flux contributions (Buenzli et al. 2015; Karalidi et al. 2016)

Continuous *R* = 4000 spectroscopy of brightest T dwarf: determining accurate cloud heights

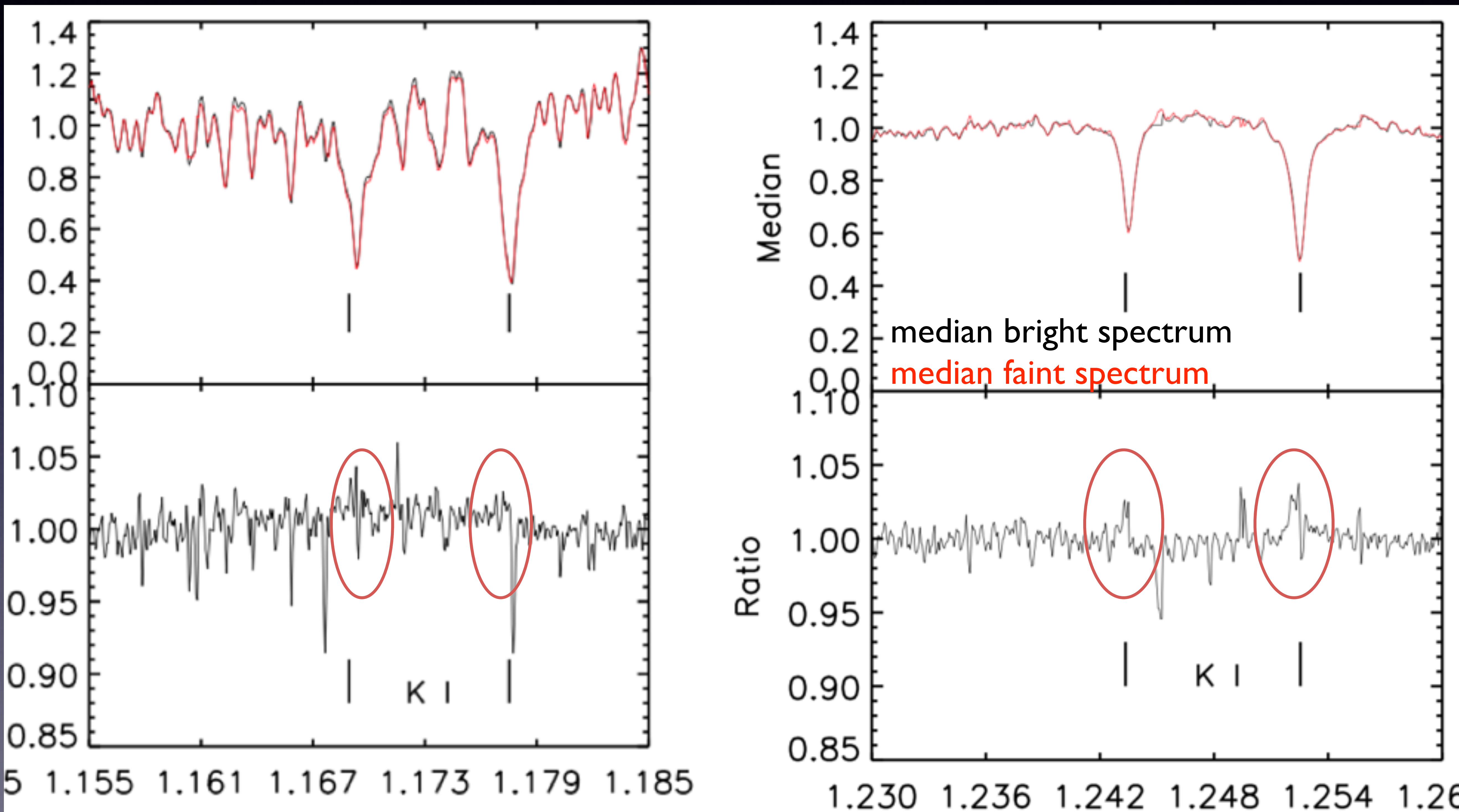


FIRE

Magellan 6.5 m telescope

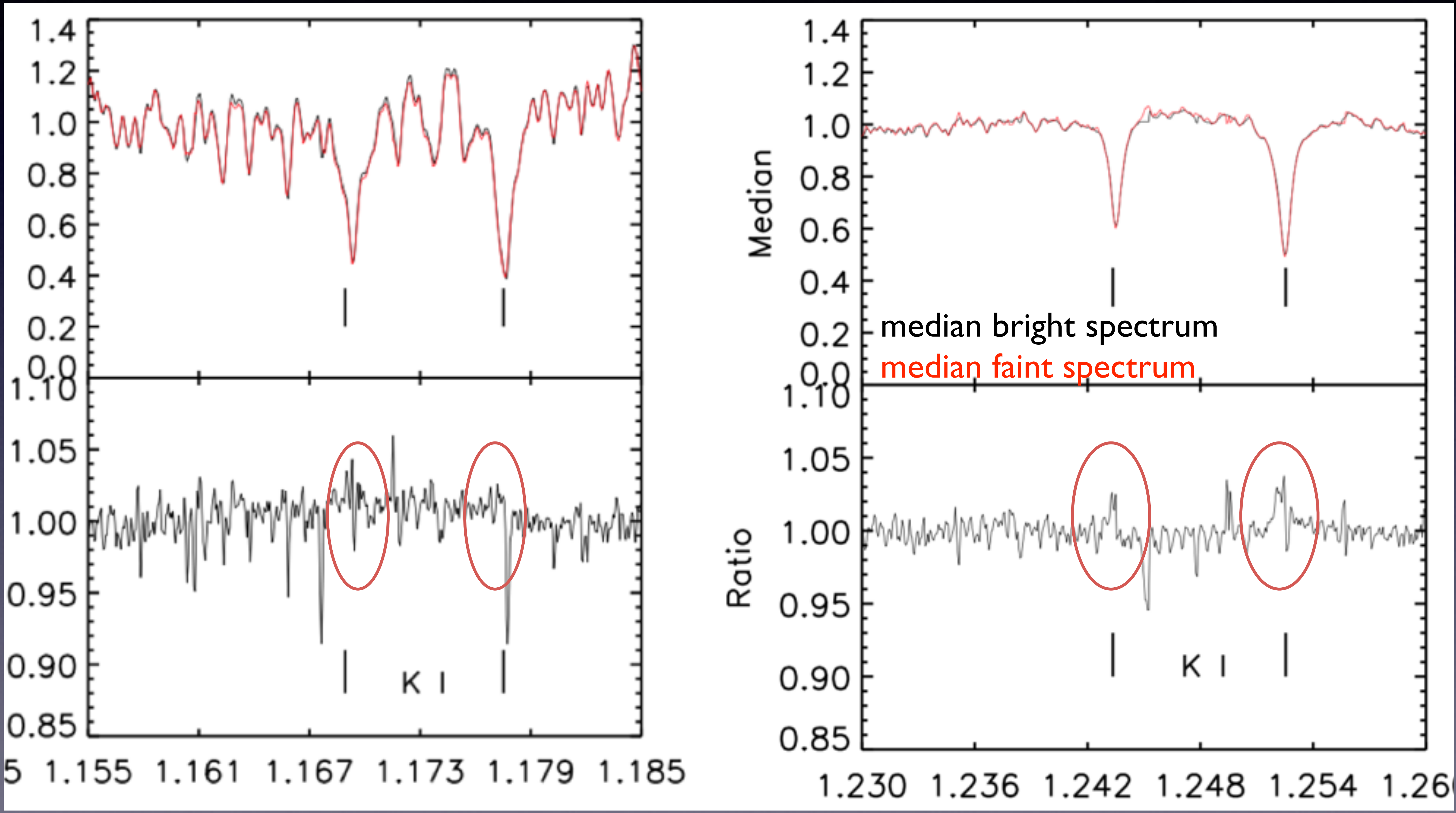
Kellogg et al. (in prep.)

Bluer potassium doublet is not affected by variations, while redder one is: clouds are near P ~ 3 bar



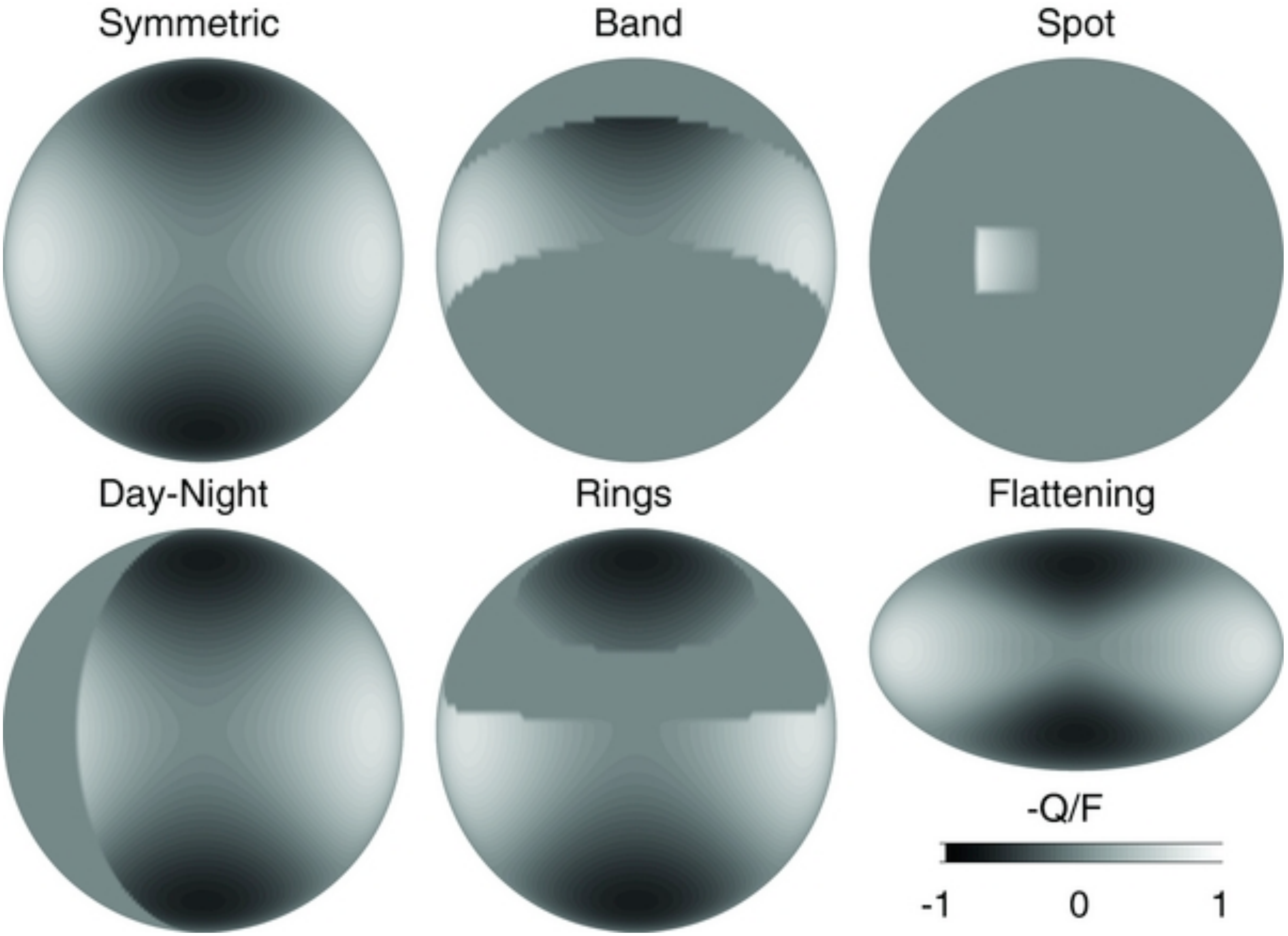
Kellogg et al. (in prep.)

Potassium absorption in the red doublet is *stronger* in the faint state: a potassium haze?



Kellogg et al. (in prep.)

Surface Asymmetries produce net **polarization**



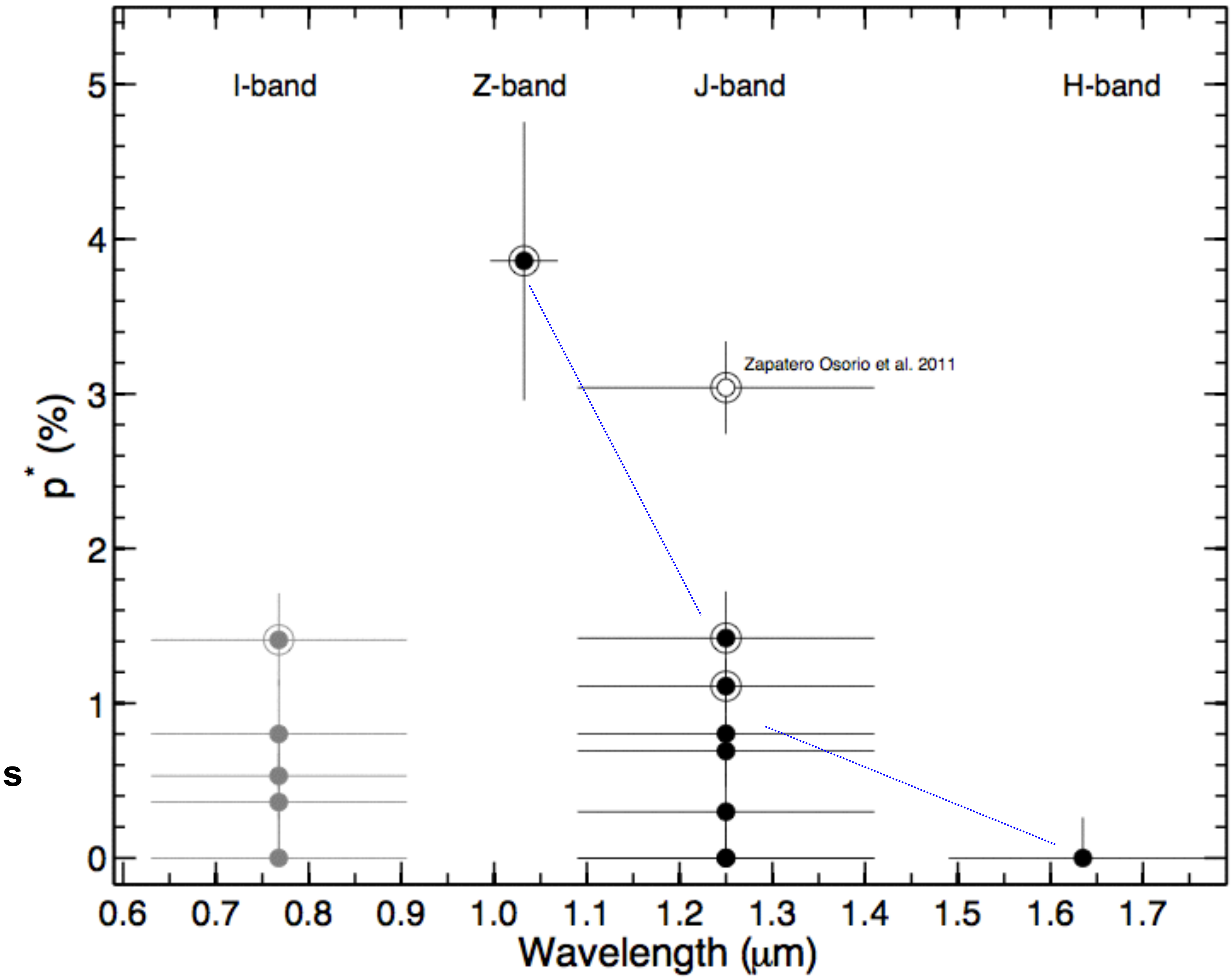
de Kok et al. (2011)

Linear polarization fraction can indicate grain sizes

Polarization observations of TVLM 513-46546
(M9, ~2300 K)

When grain size is comparable to wavelength, polarization increases significantly
(Sengupta 2003, 2005)

Simultaneous observations at different filters and rotational phases are needed.

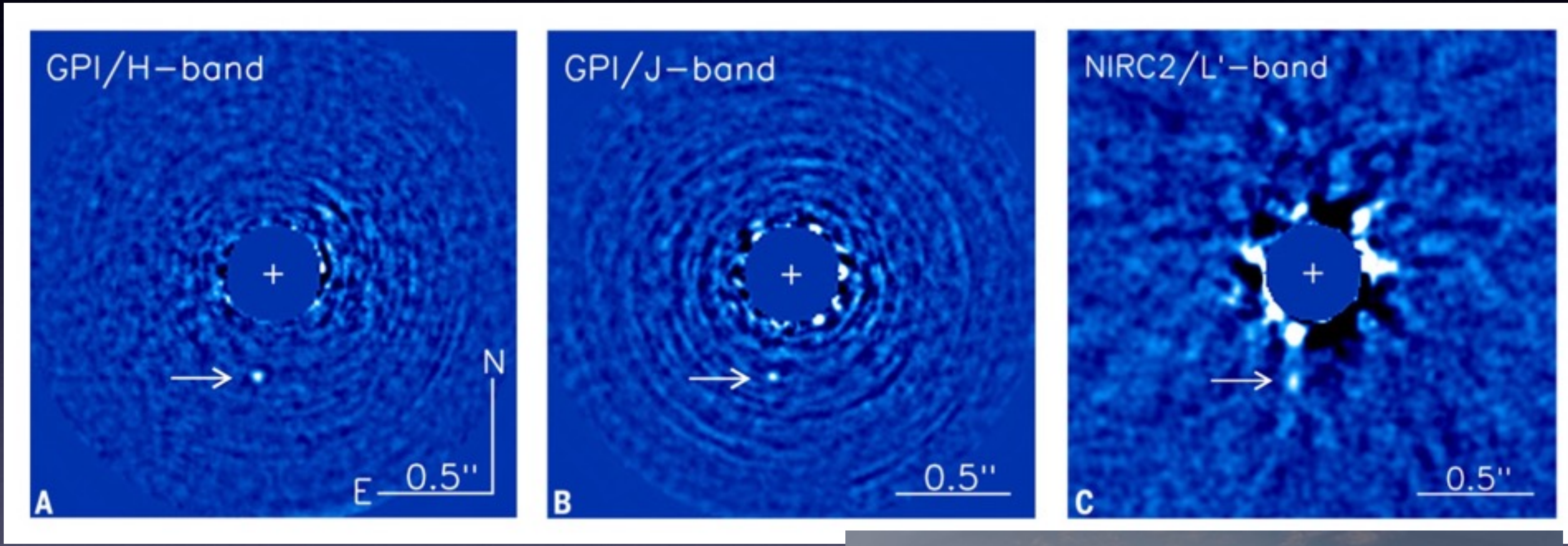


(*Miles-Páez et al. 2016*)

Weather on brown dwarfs:
Some new findings

- Where do clouds reside in brown dwarfs?
  - Near the P = 3 bar in T dwarfs, at P < 1 bar in L dwarfs.
- What is their composition?
  - Potassium haze above cloud?
  - ~1 micron grains

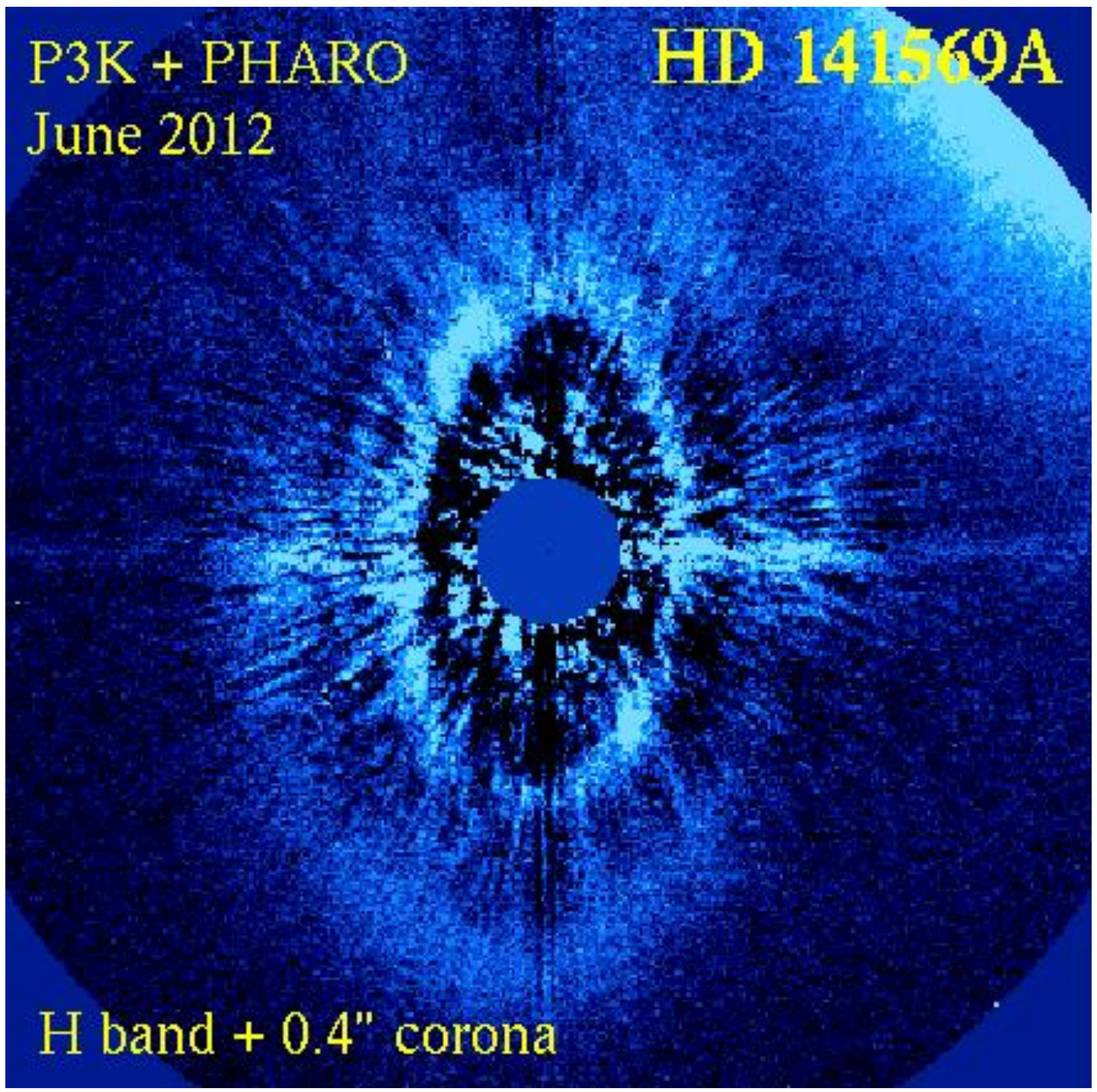
51 Eridani: a 20 Myr-old debris disk host with a Jupiter-like planet



51 Eridani planetary system architecture:

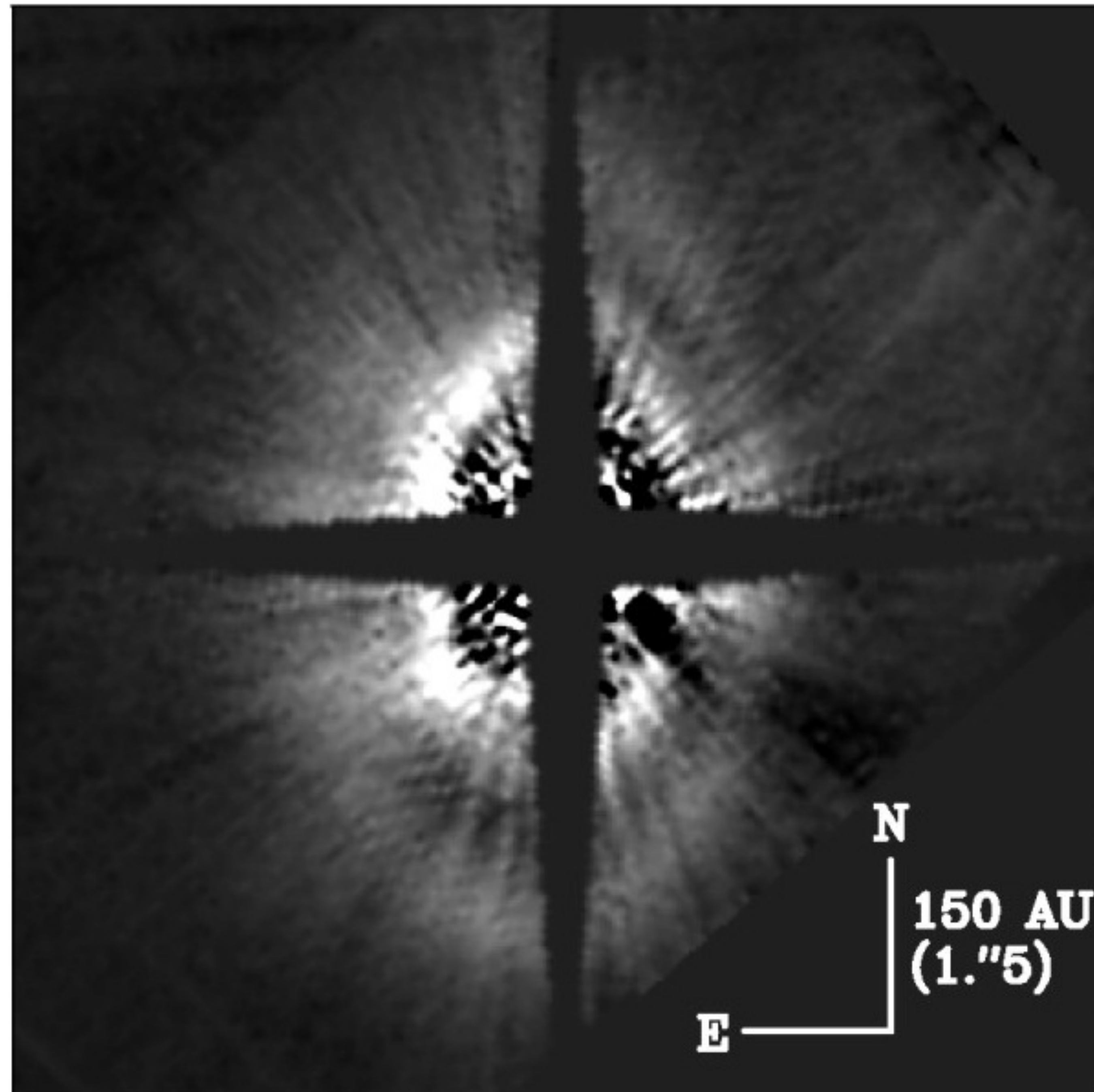
- 5.5 AU asteroid belt analog (Patel et al. 2014)
    - verified with Subaru/COMICS
- 13 AU, ~2 $M_{Jupiter}$ planet (Macintosh, GPIES team 2015)
- 80 AU Kuiper belt analog (Riviere-Marichalar et al. 2014)

Extreme Adaptive Optics Imaging of a 5 million year-old planet-forming disk

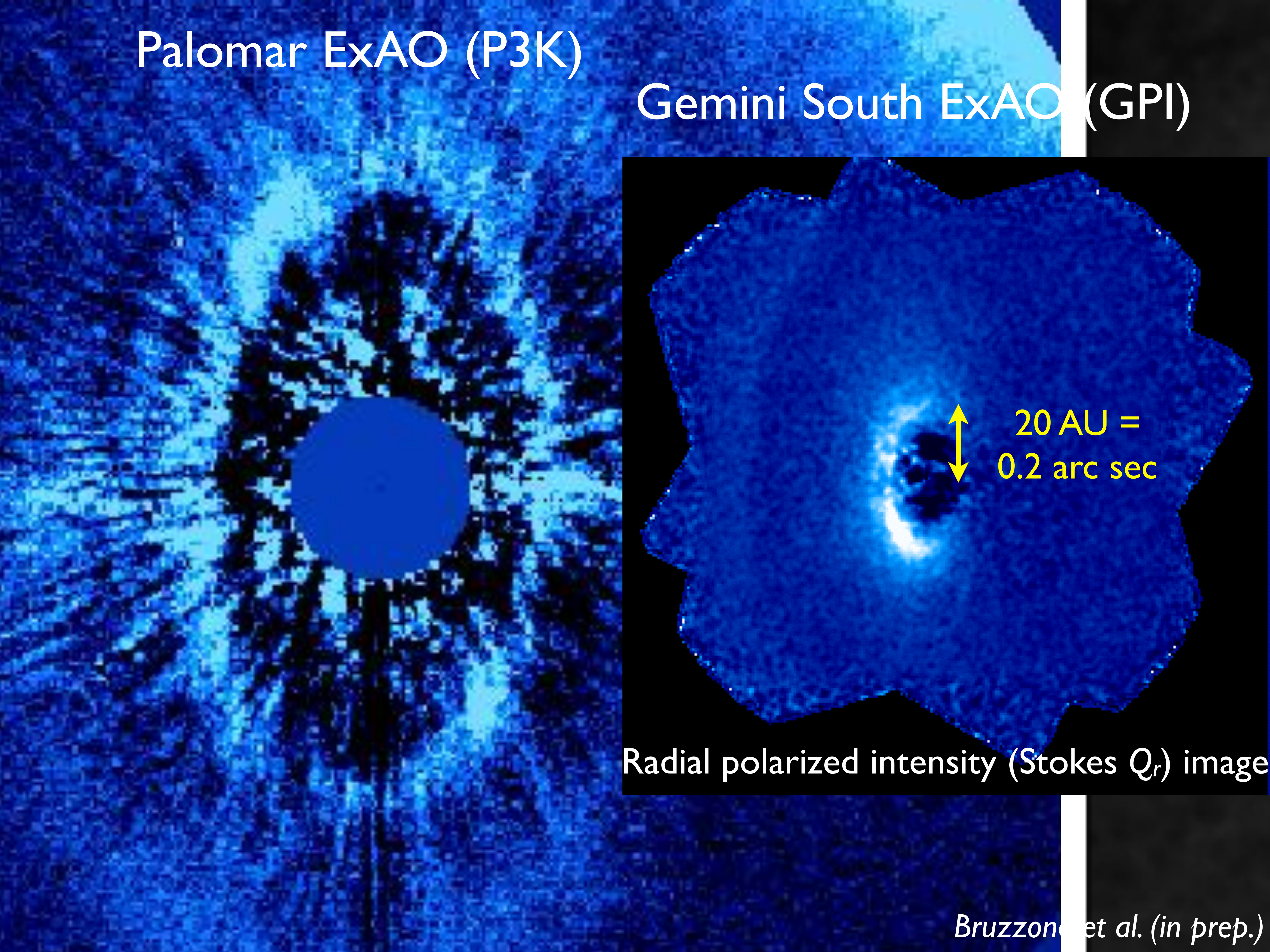


H-band Strehl ~ 52%; t_{exp} = 1.1 h
V = 7.1 mag

Wahl, Metchev et al. (2013)



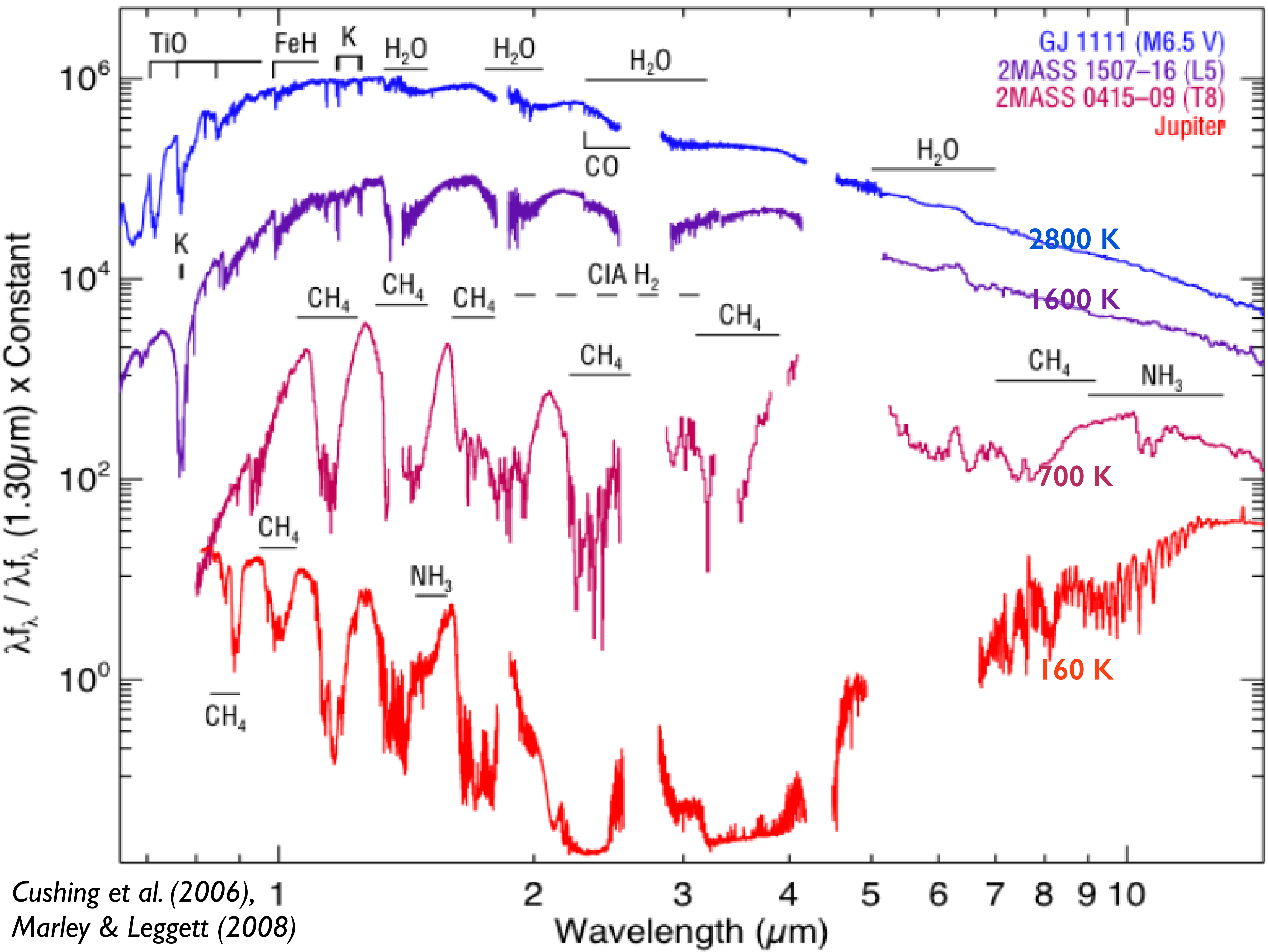
HST / NICMOS F110W; t_{exp} = 0.3 h
(Weinberger et al. 1999)



Bruzzone et al. (in prep.)

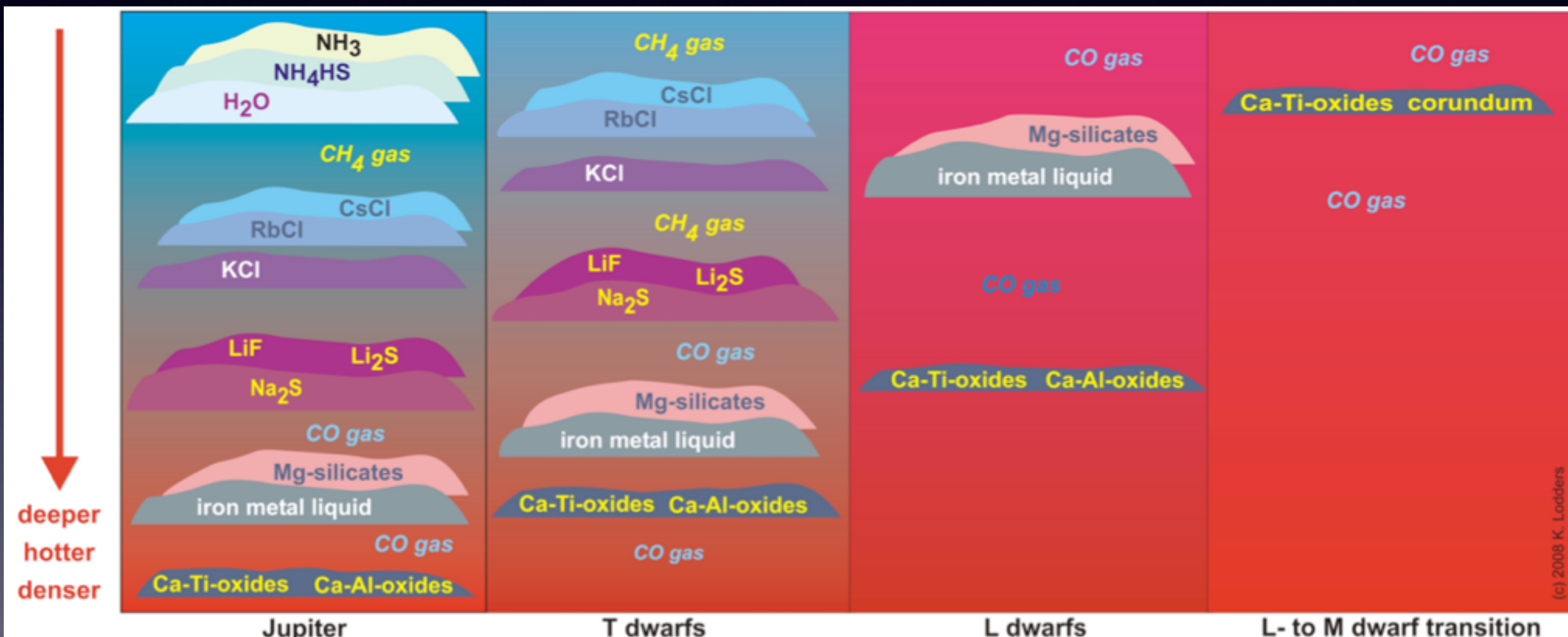
IR facilities of interest on Subaru

- **MOIRCS** or **SWIMS**: multi-object 0.9–2.5 micron spectroscopy enables simultaneous calibration of telluric variations in brown dwarf spectra.
  - + **Ultimate Subaru** to reach fainter
- **IRCS**: 0.9–2.5 micron polarimetry probes the peak of the condensate size distribution in brown dwarf atmospheres.
- **IRD**: strong complementarity to CFHT/SPIRou
- **SCExAO/CHARIS**: extreme-contrast imaging and spectroscopy of exoplanet systems.
- **COMICS**: circumstellar debris disk imaging and spectroscopy.



Cushing et al. (2006), Marley & Leggett (2008)

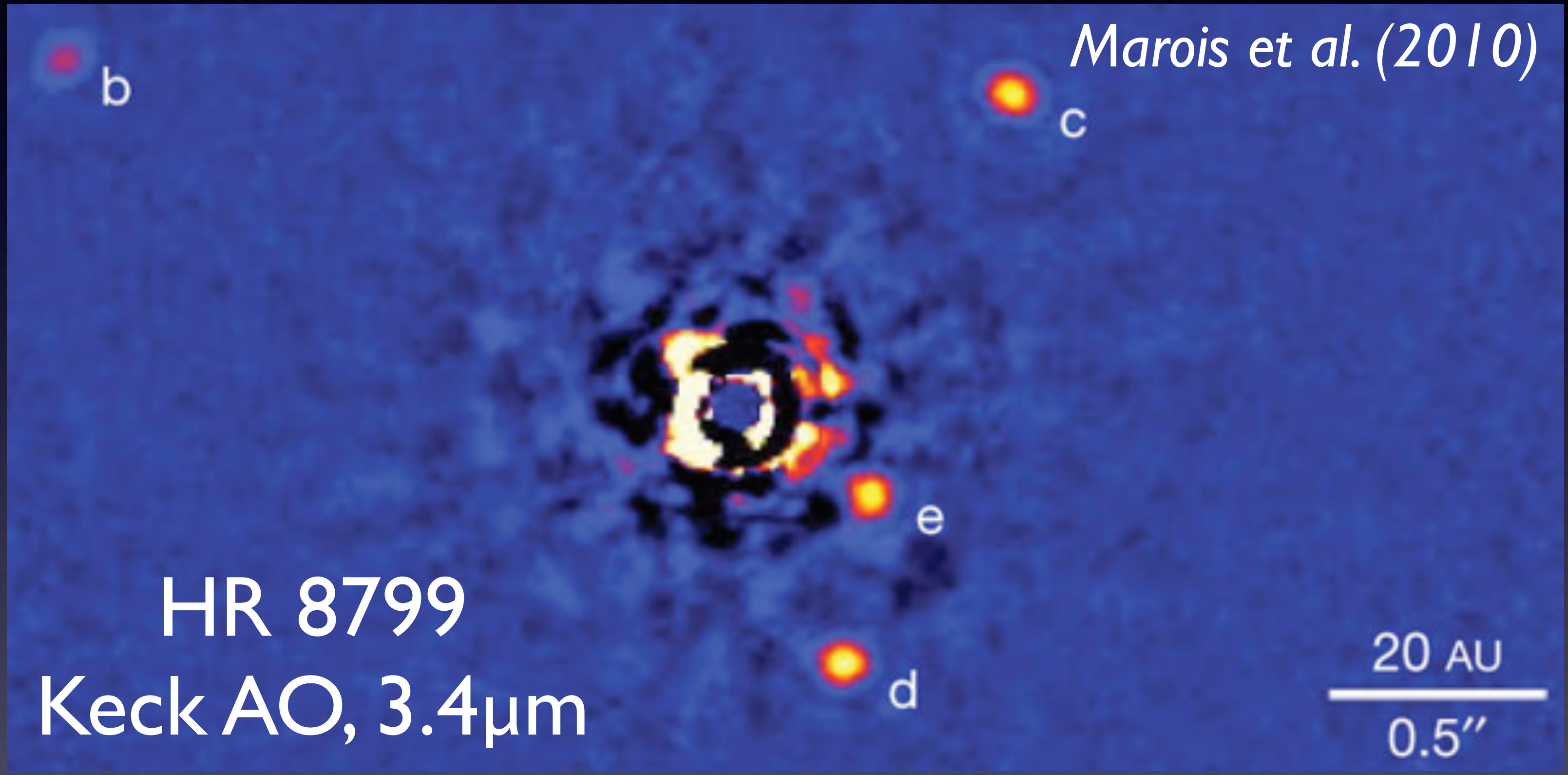
Cloud structures are increasingly complex at cooler temperatures



Lodders & Fegley (2006)

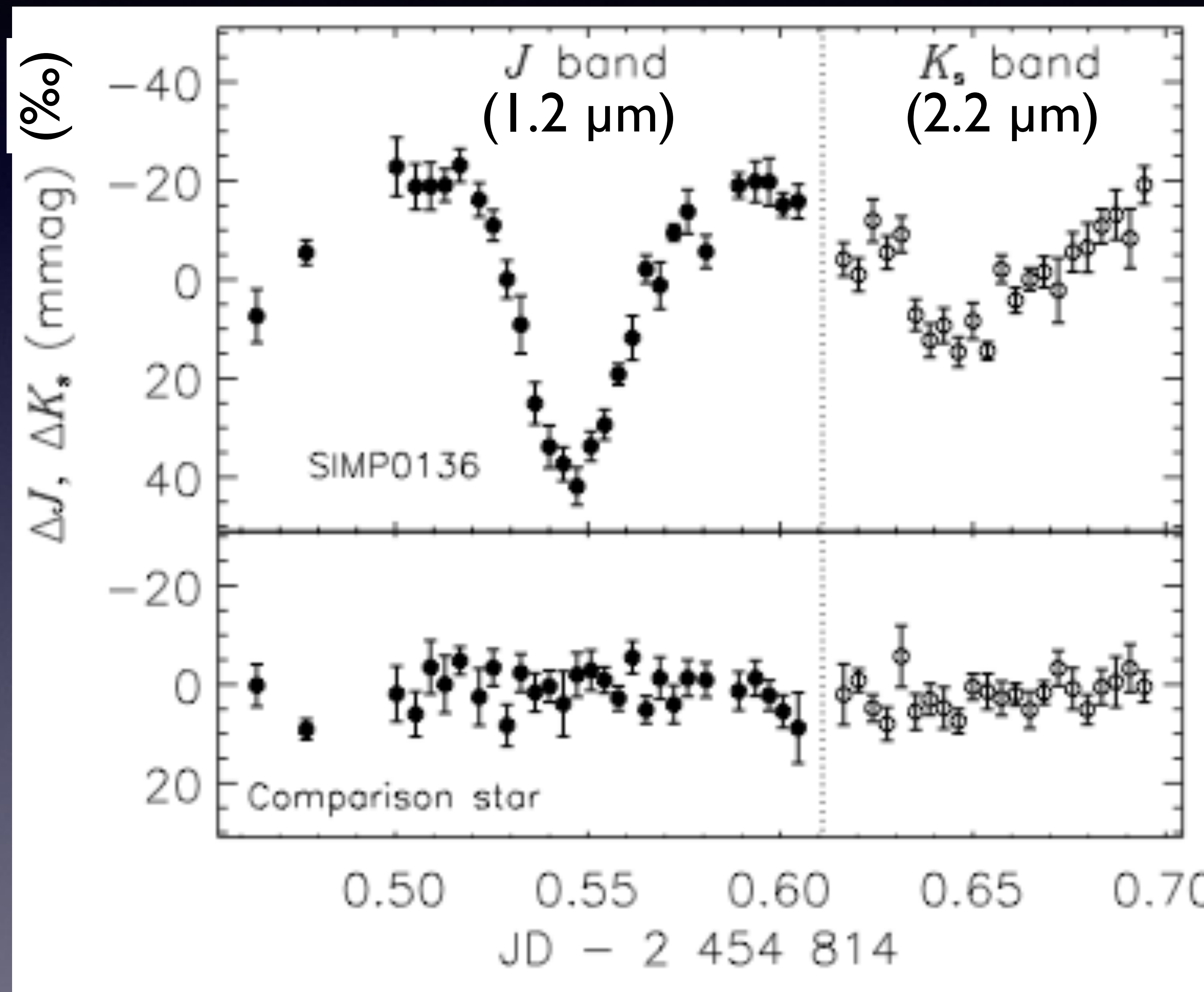
We would really like to do this on directly imaged exoplanets …

- contrast, precision, and stability challenges
- potential with ExAO systems
  - GPI, SPHERE, MagAO



… revealed a two-temperature surface

- *J*/K_s-band amplitude ratio is not unity
- Δf ~10% change in cloud fill factor
- combination of grain-free and ~100 K cooler cloudy regions



Artigau et al. (2009)