Probing the Heterogeneous Cloud Structure of Variable Brown Dwarfs with HST

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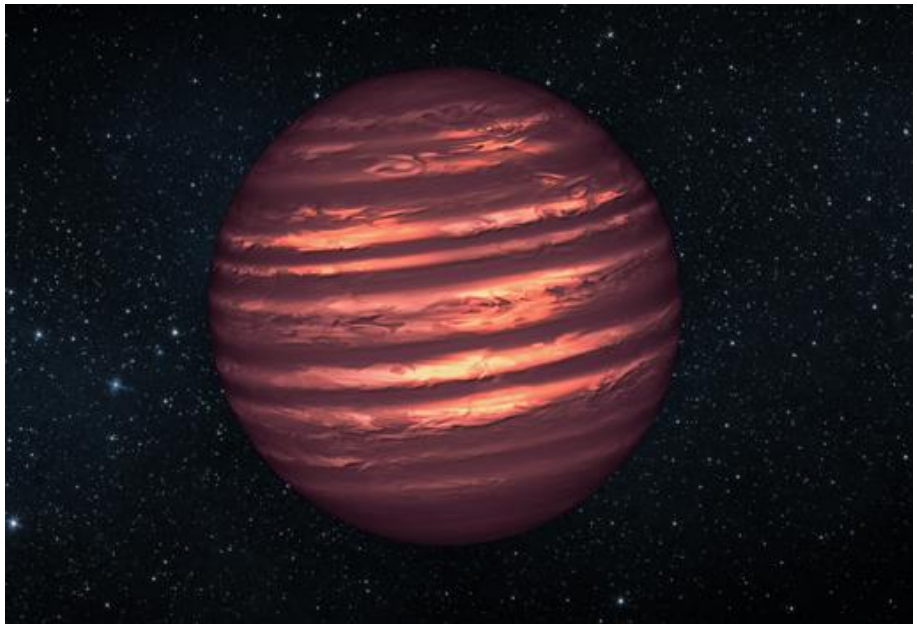


Artist impression of a T dwarf – NASA/JPL

Collaborators: Daniel Apai, Jacqueline Radigan, Caroline Morley, Adam Burrows, Davin Flateau, Adam Showman, Mark Marley, I. Neill Reid, Nikole Lewis, Ray Jayawardhana

Why study Brown Dwarf Atmospheres?

- Temperatures and atmospheric properties are similar to young giant planets, but they are easier to study

  See posters by Faherty, Cruz, Hiranaka, Schmidt, Allers, Sorahana, Rice, Manjavacas, Tottle, …

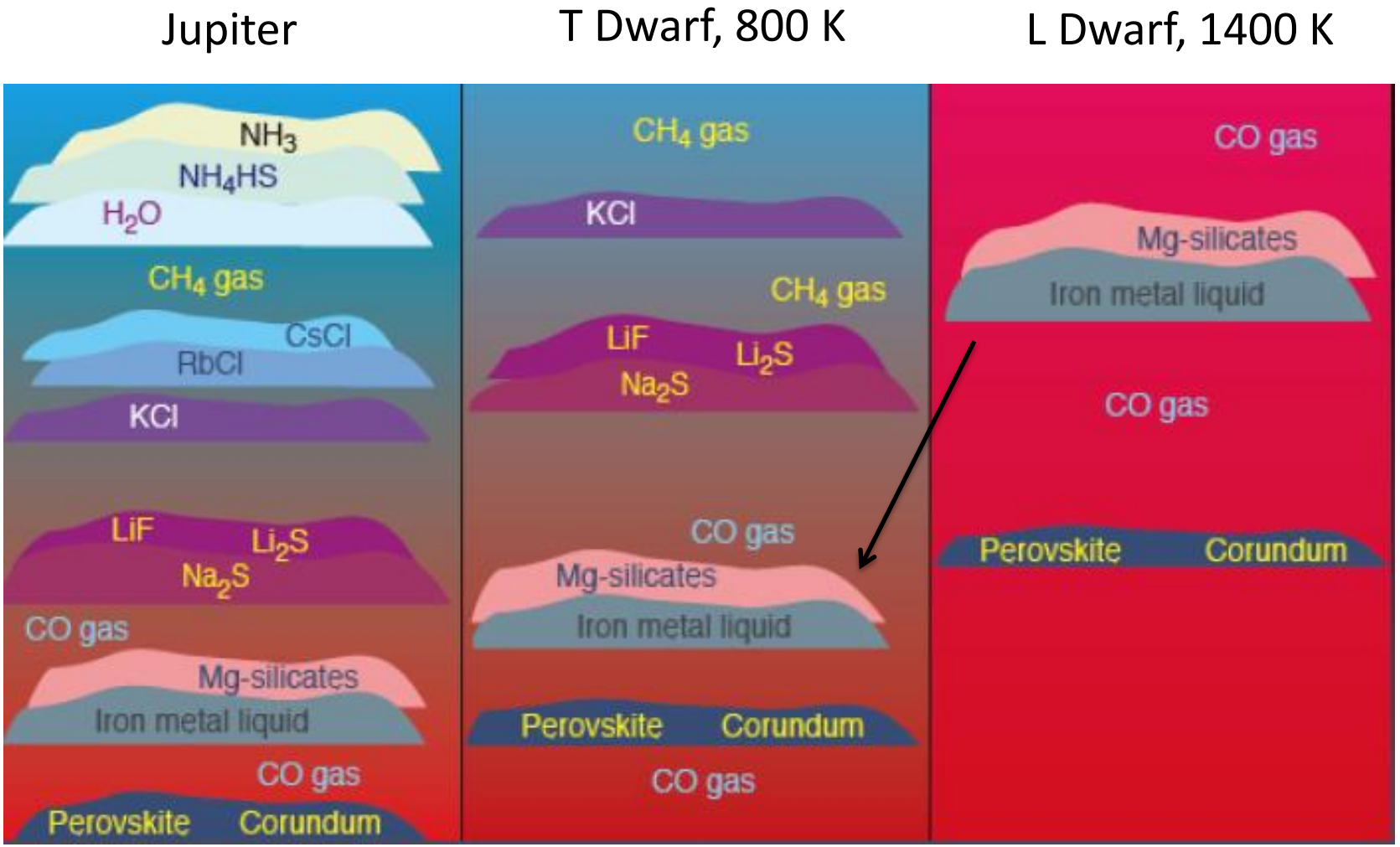
- The transition through the M-L-T-Y sequence is strongly influenced by the evolution of condensate clouds

  e.g models by Allard, Barman, Burrows, Helling, Marley, Morley, Saumon, Tsuji, and collaborators

- Recent discoveries of variable brown dwarfs in the near-IR have indicated the presence of heterogeneous cloud structure and evolving weather patterns

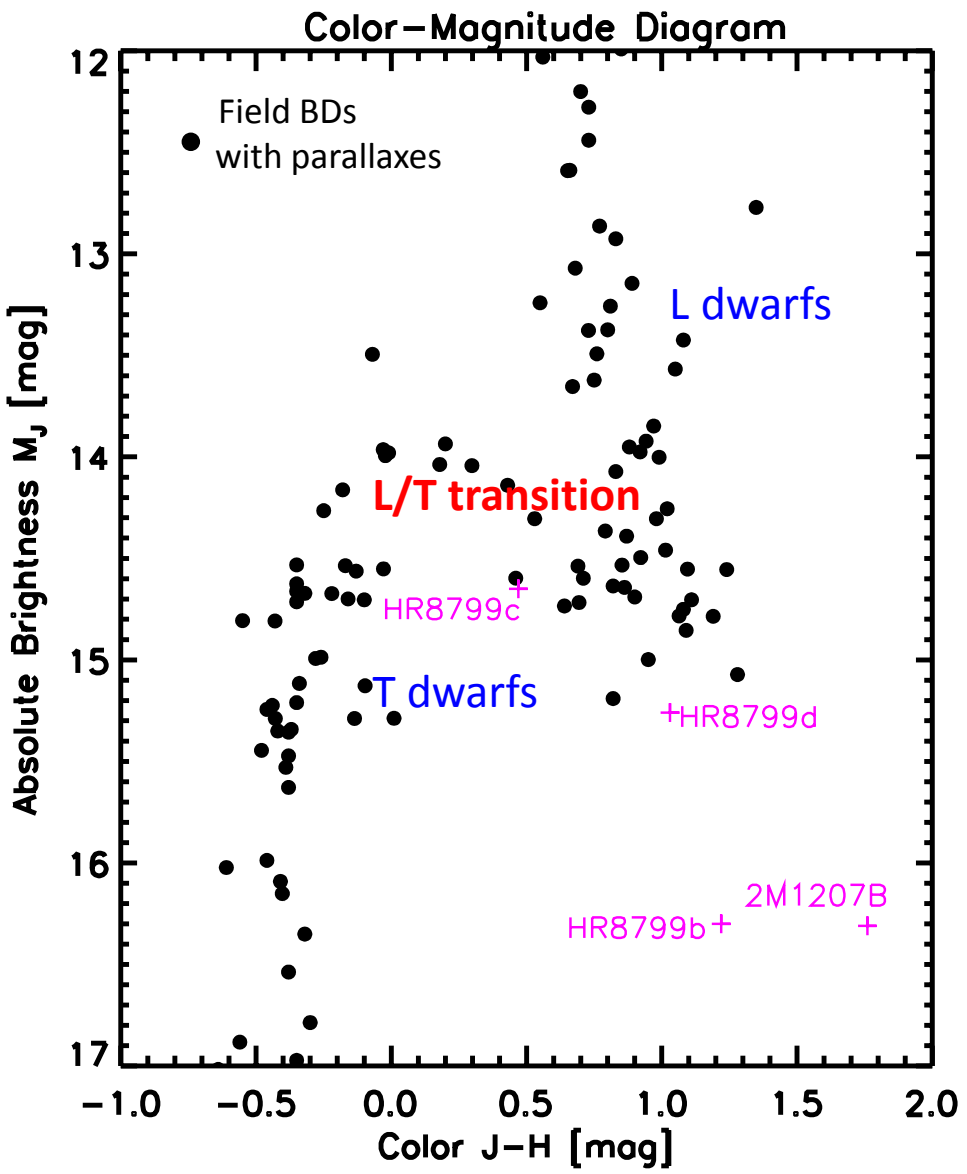
  e.g. Artigau et al. 2009, Radigan et al. 2012, Gillon et al. 2013

Clouds in Brown Dwarfs and Planets



Lodders 2005

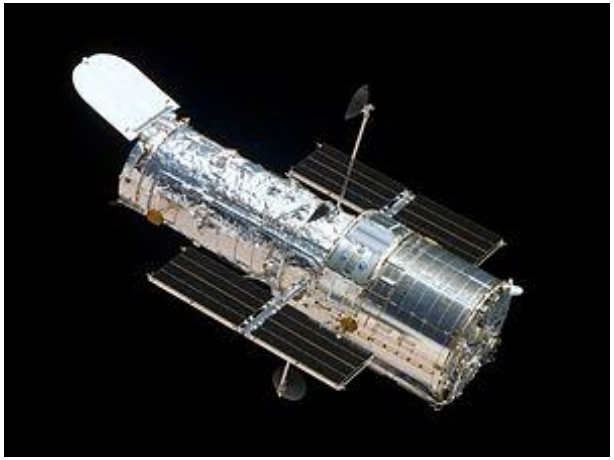
Color-Magnitude Diagram



Data from database of ultracool parallaxes maintained by T. Dupuy

Time-resolved HST/WFC3 spectroscopy

PI: D. Apai (Univ. of Arizona)



NASA

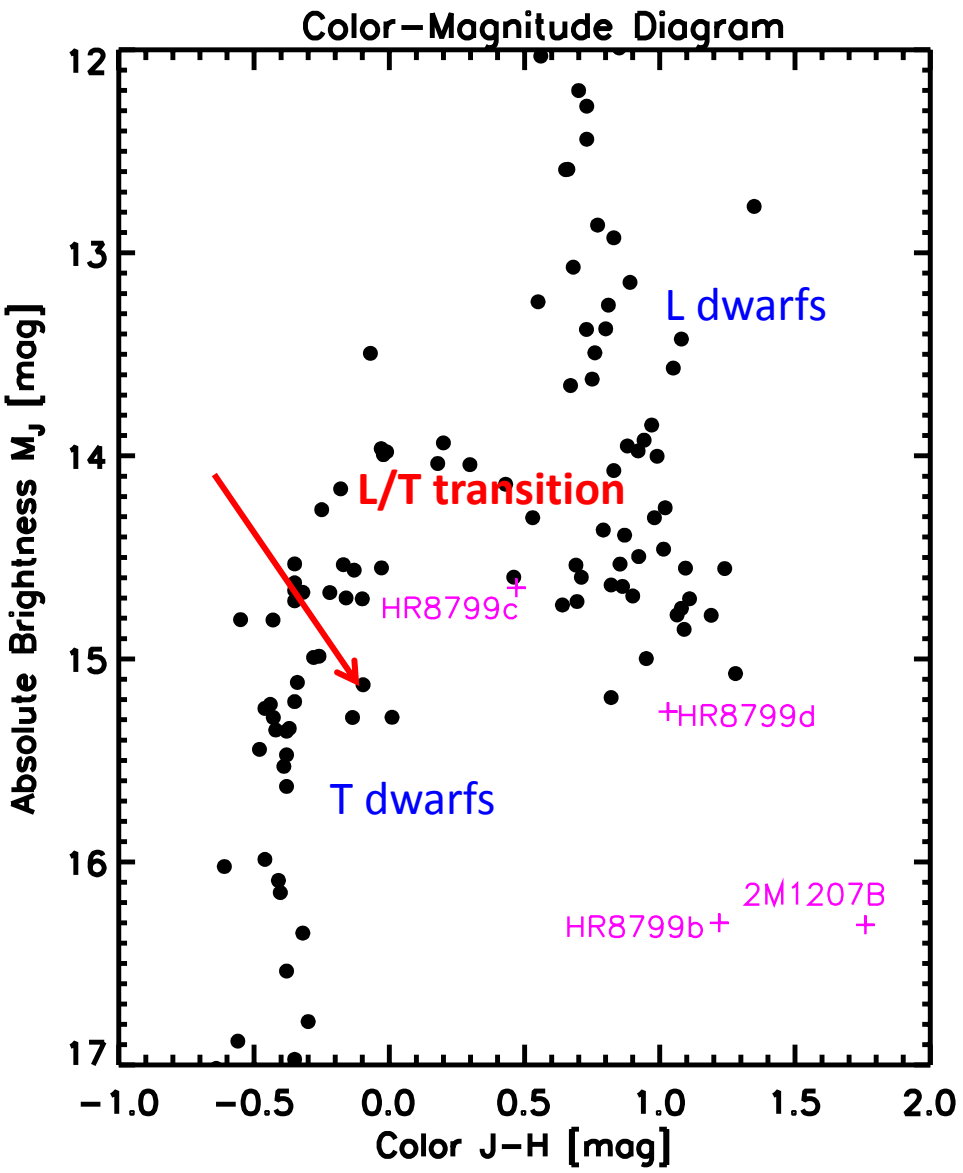
HST/WFC3/IR slitless spectroscopy, 1.05 – 1.7 μm, R~130

2 L/T transition dwarfs: SIMP0136 (T2.5), 2M2139 (T1.5)

1 mid-T dwarf: 2M2228 (T6) + Spitzer/IRAC 4.5 μm photometry

6 consecutive orbits, ~40 min per orbit over ~9 hr, ~1 min time resolution

Color-Magnitude Diagram



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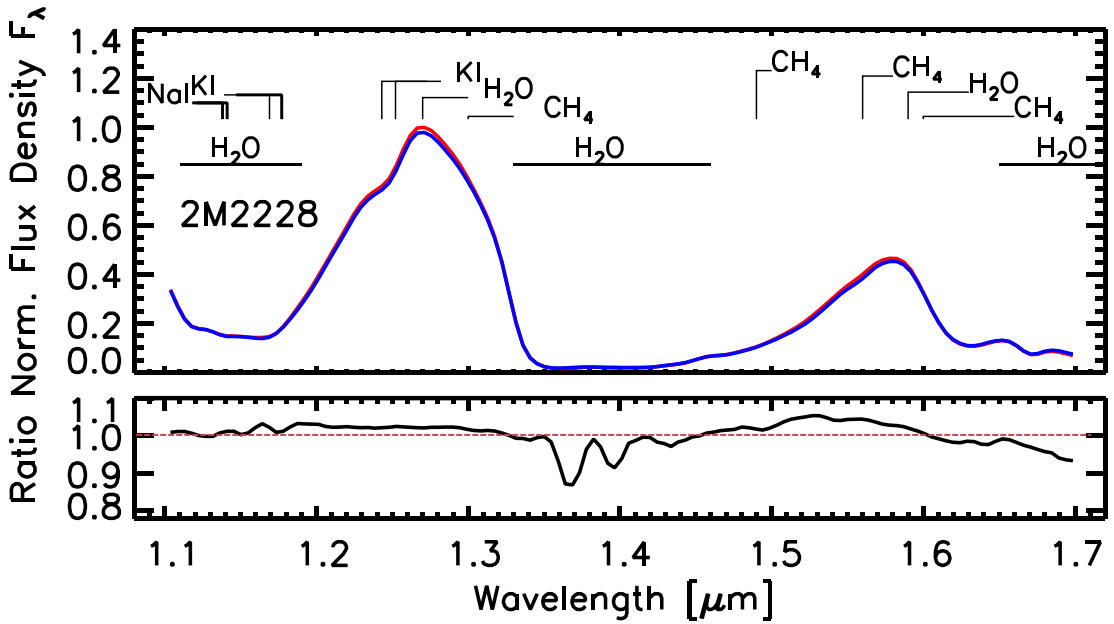
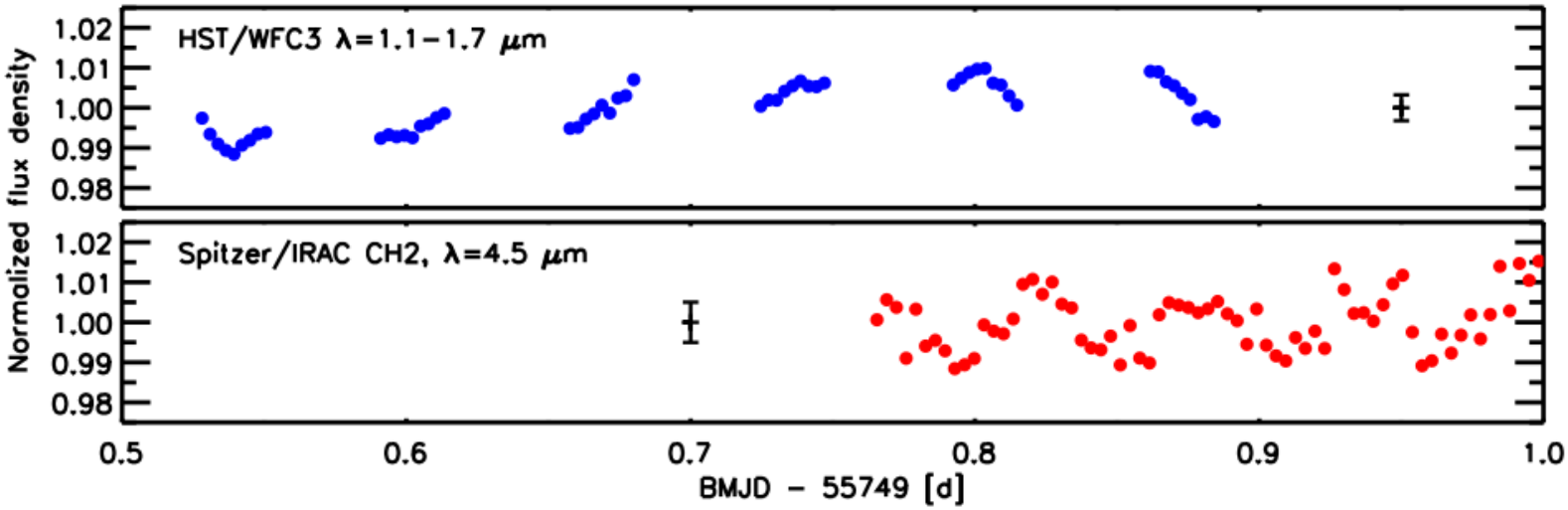
HST and Spitzer time series of 2M2228

Min. and Max.
HST Spectra

Ratio

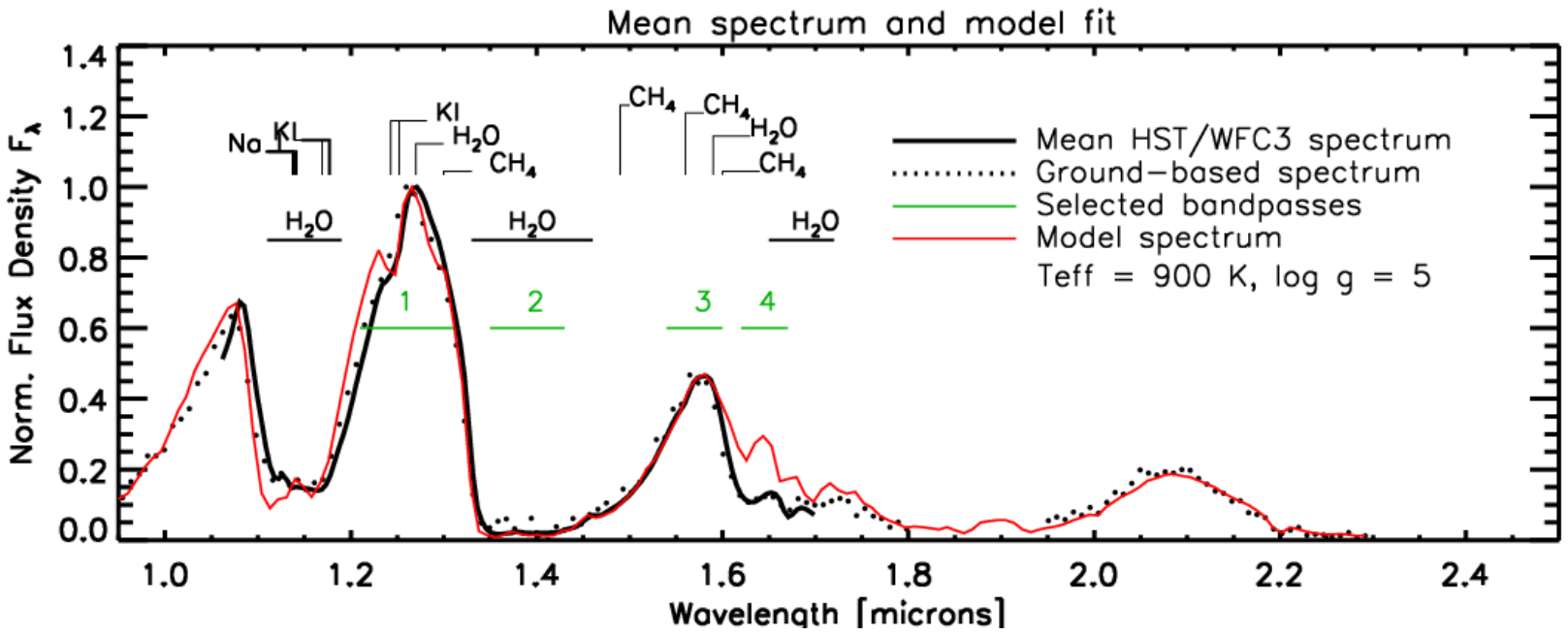


Buenzli et al. 2012



→ First clear spectroscopic detection of variability in a BD!

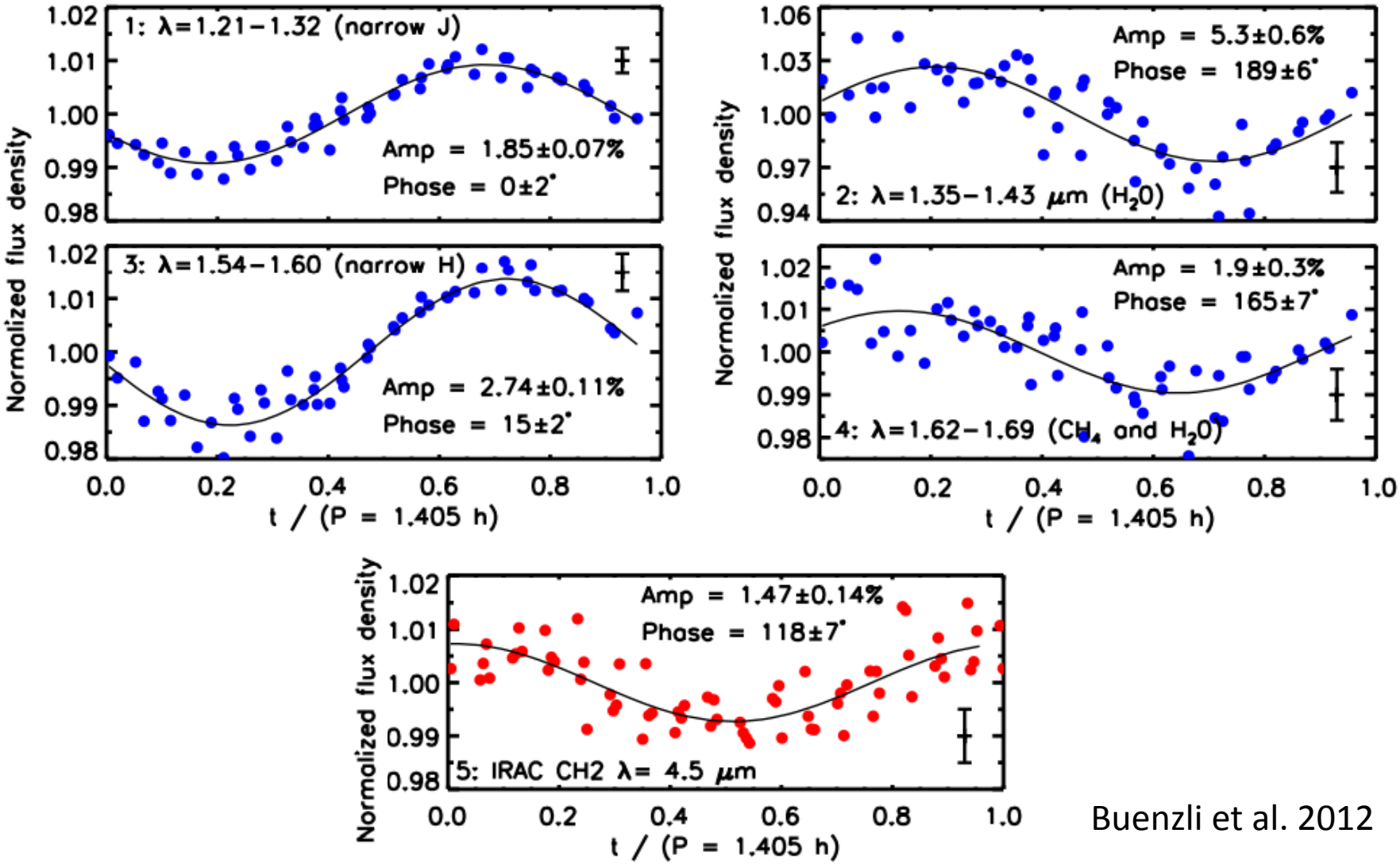
Mean spectrum and model fit



Model from Morley et al. 2012, includes Sulfide clouds
Ground-based spectrum from Burgasser et al. 2004

Buenzli et al. 2012

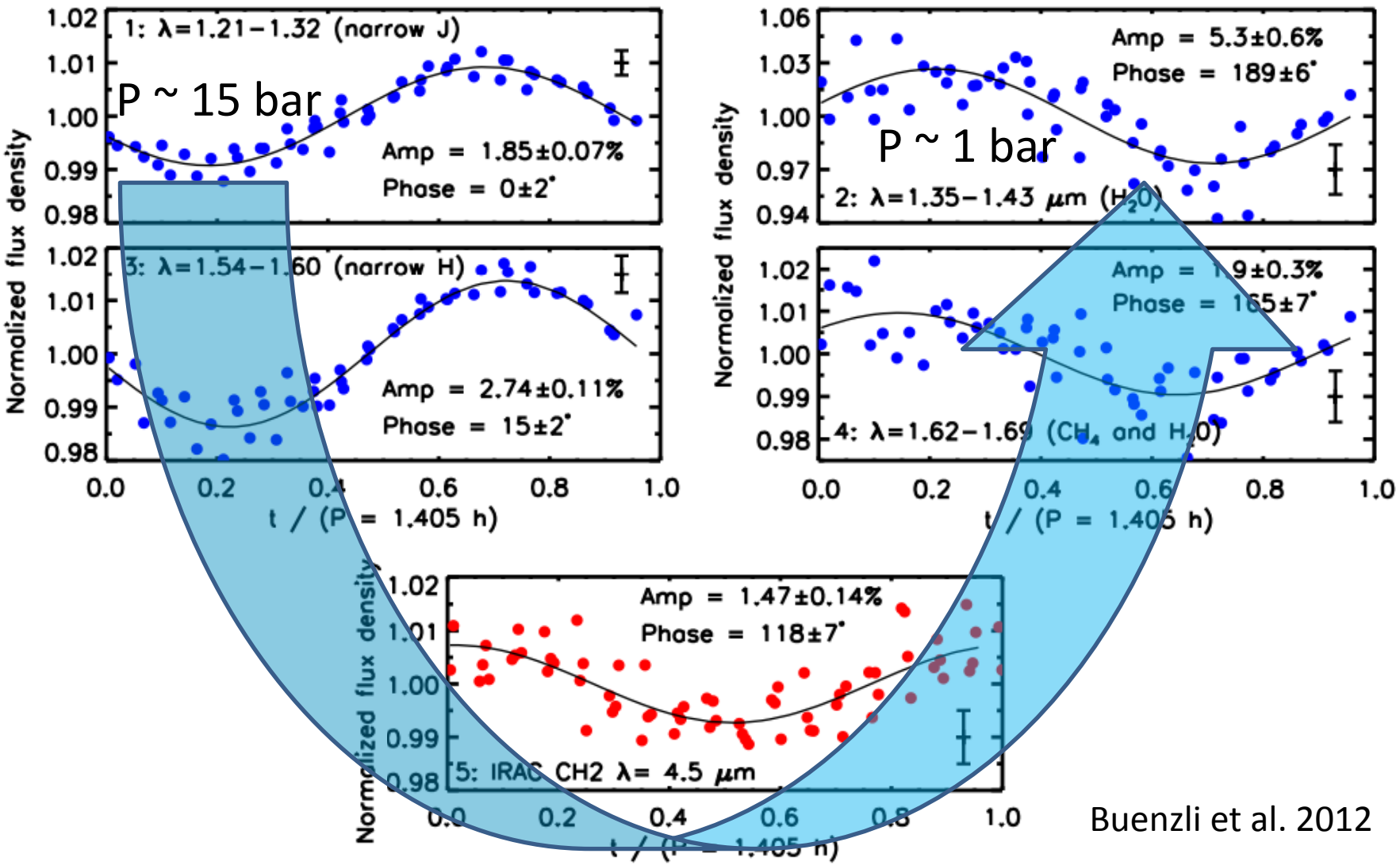
Light curves in selected band passes



Buenzli et al. 2012

→ The phase is shifted significantly for different wavelengths!

Light curves in selected band passes



Buenzli et al. 2012

→ The phase shift correlates with the probed pressure!

What causes the phase shifts?

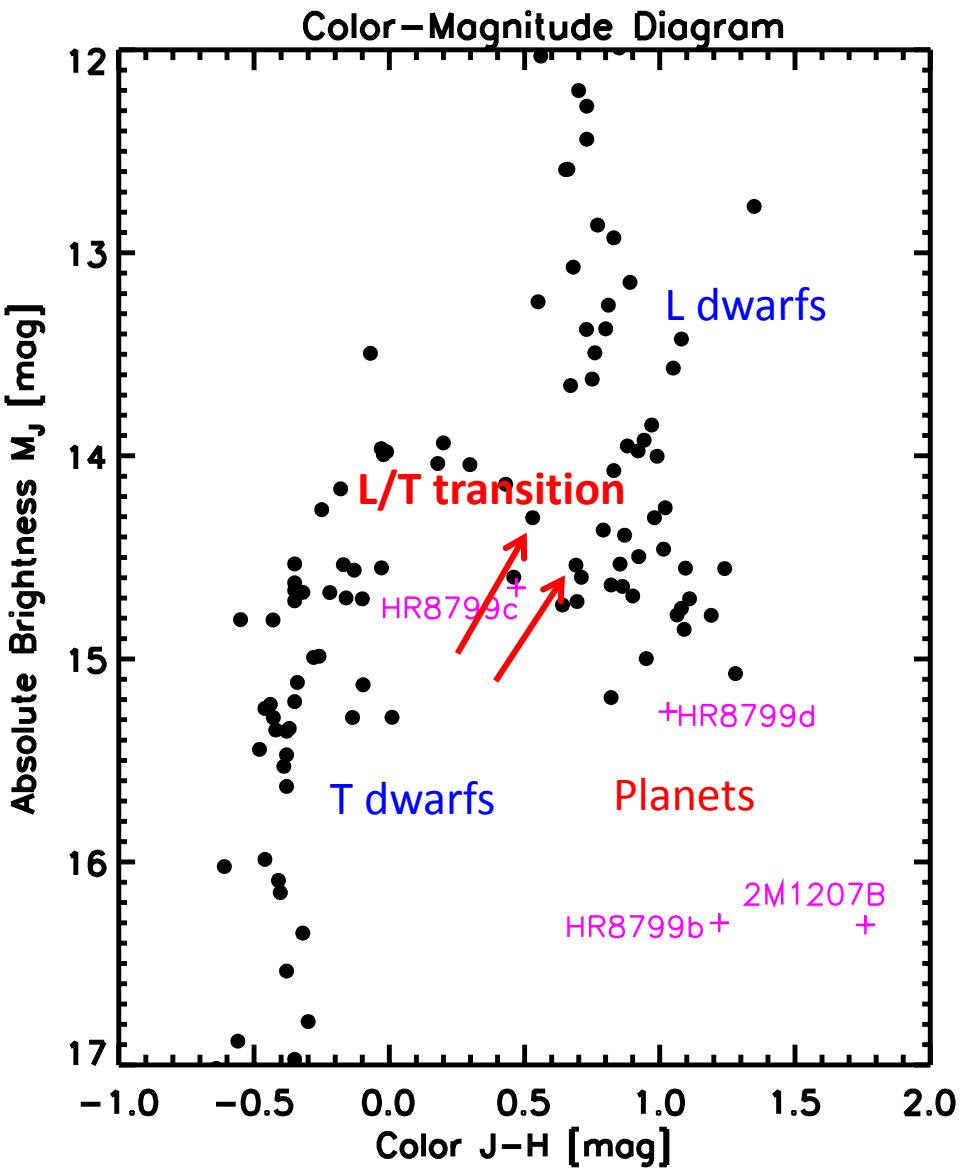
No simple explanation, need comprehensive models! Some speculation:

- Patchy clouds only? unlikely because of large variability at low pressure
- Combination of opacity and temperature changes?

→ Cloud opacity variations at high pressures
temperature perturbations from circulation patterns at low pressures

More HST/Spitzer data to be taken...

Color-Magnitude Diagram



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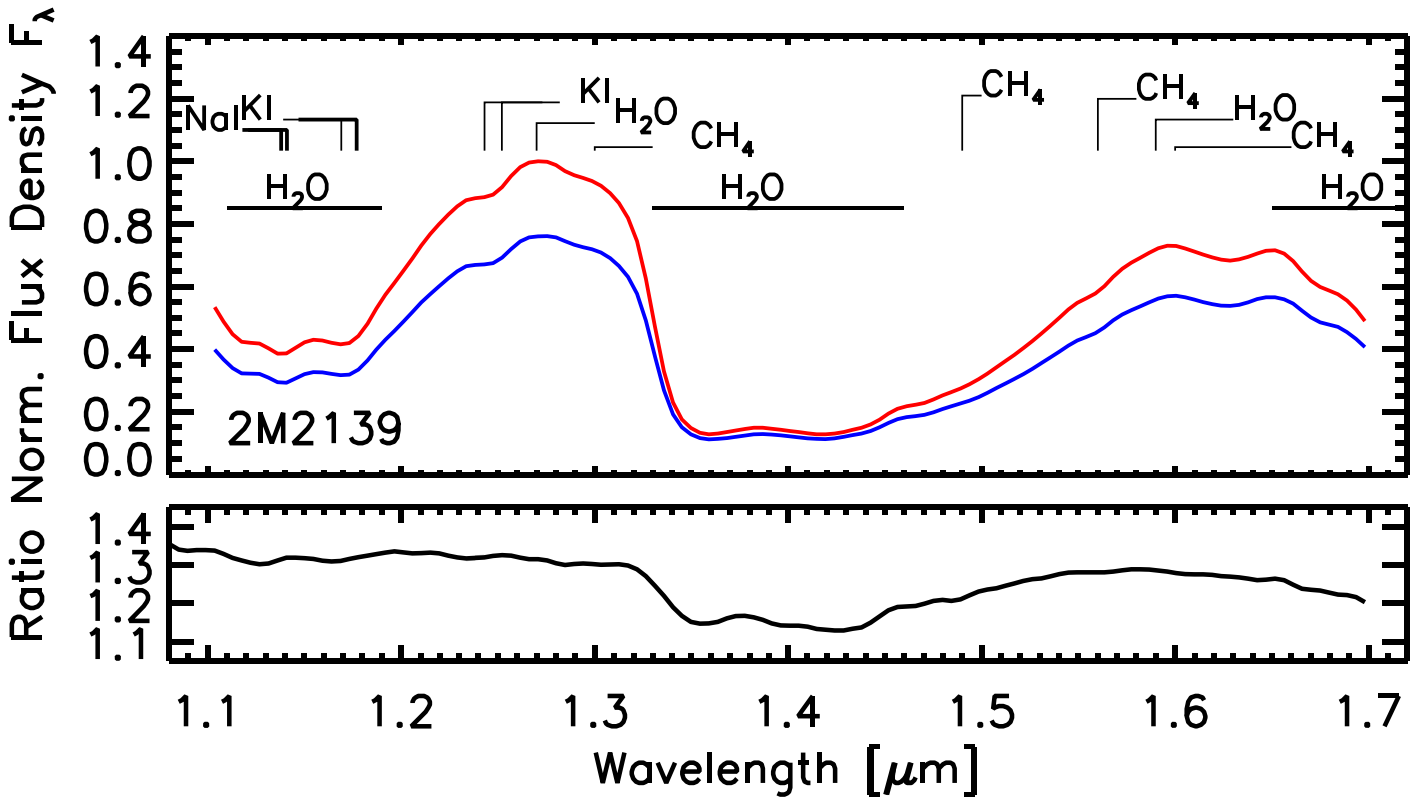
Spectral variability – early T dwarfs

2M2139

Min. and Max. Spectra

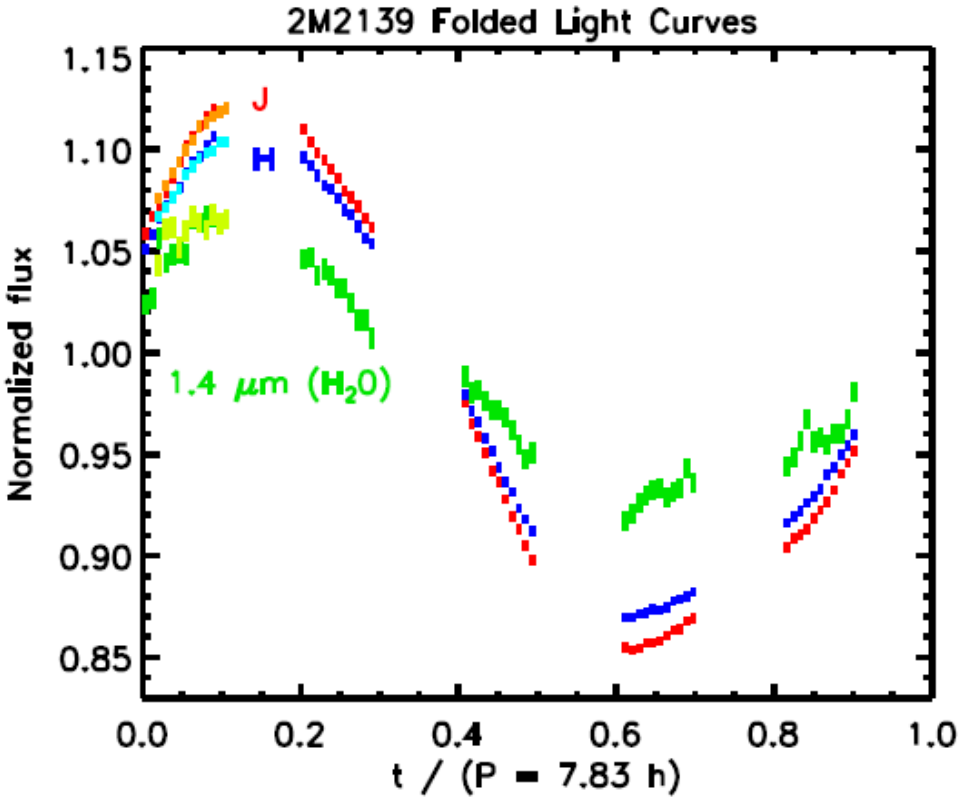
Ratio

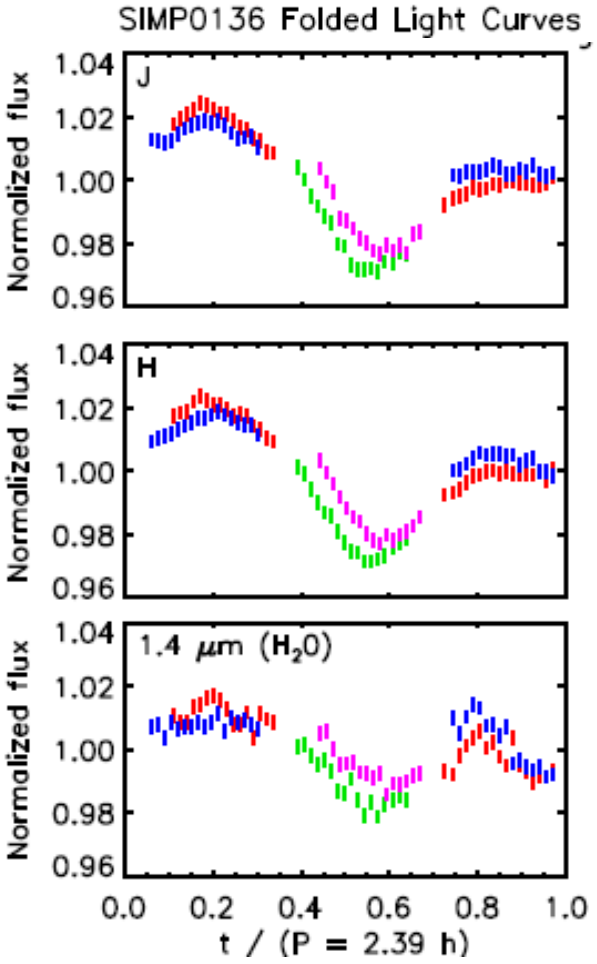


No change of variability in spectral features except water!

Apai, Radigan, Buenzli et al. 2013

Light curves of L/T transition dwarfs

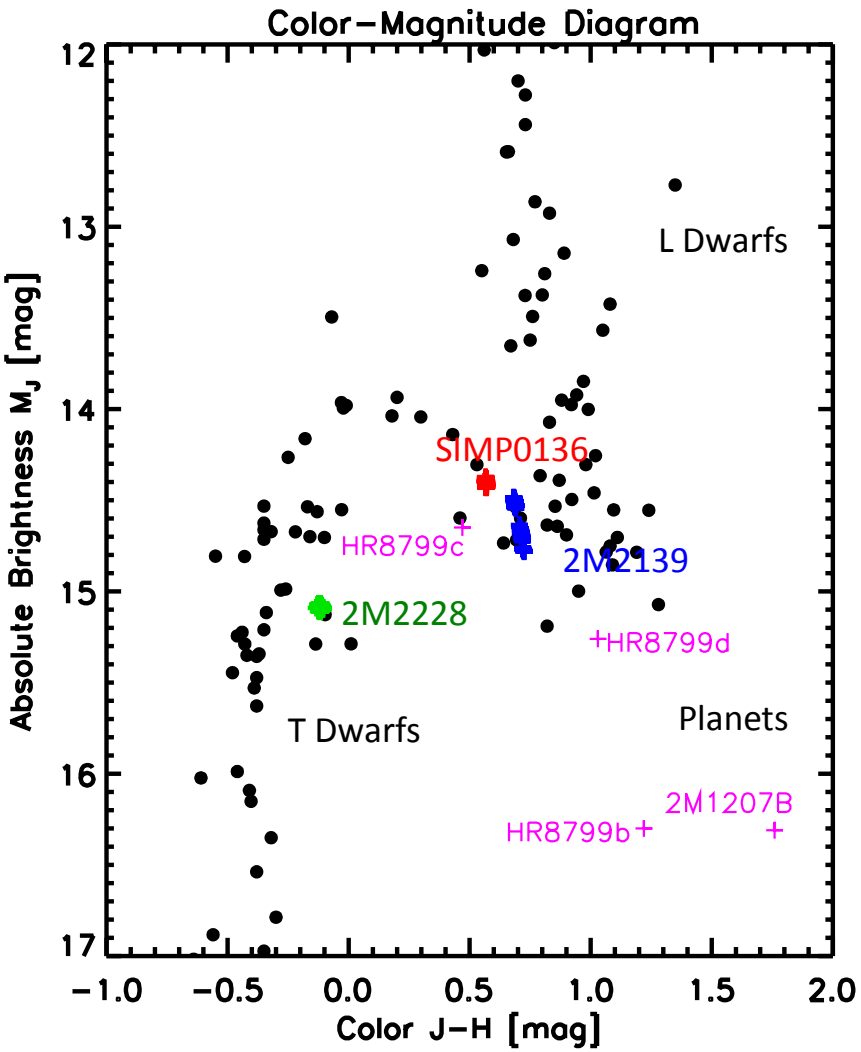


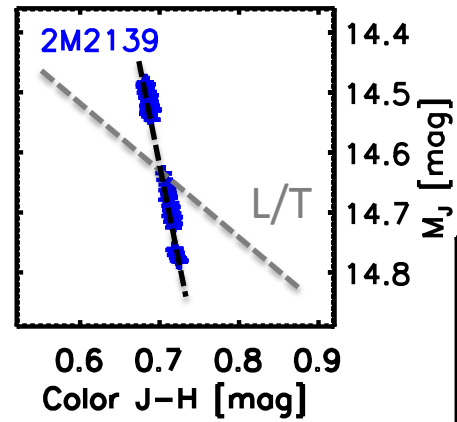


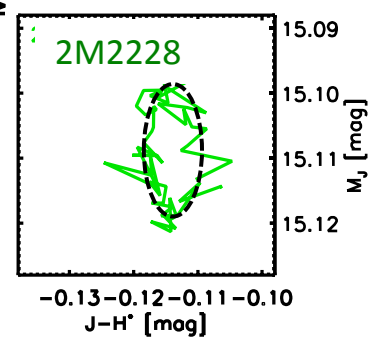
No phase shifts

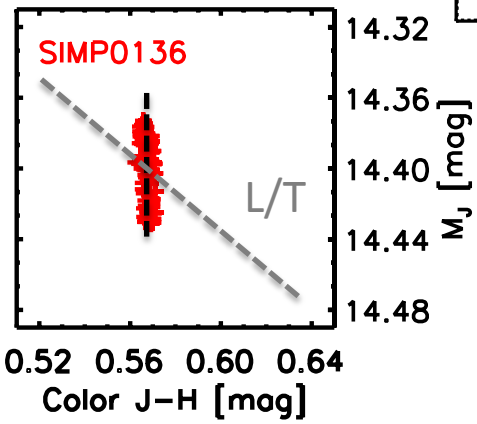
Apai, Radigan, Buenzli et al. 2013

Color-Magnitude Variations









T2 variability does not follow L/T transition! → thin/thick clouds, no clearings

Apai, Radigan, Buenzli et al. 2013

Summary and Conclusions

- We performed the first unambiguous spectroscopic study of variability in brown dwarfs

- Phase shifts correlating with probed pressure indicate complex vertical and horizontal heterogeneities in a T6 dwarf atmosphere
  → Buenzli et al. 2012, ApJ 760, L31

- The variability of the L/T transition dwarfs does not follow the L/T transition, indicates thin/thick clouds rather than clearings
  → Apai, Radigan, Buenzli et al. 2013, ApJ 768, 121

- What's next? Several HST and Spitzer programs to study spectral variability as function of spectral type and monitor time evolution of weather patterns

→ Such observations are greatly needed to constrain higher-dimensional atmospheric models of BDs and EGPs