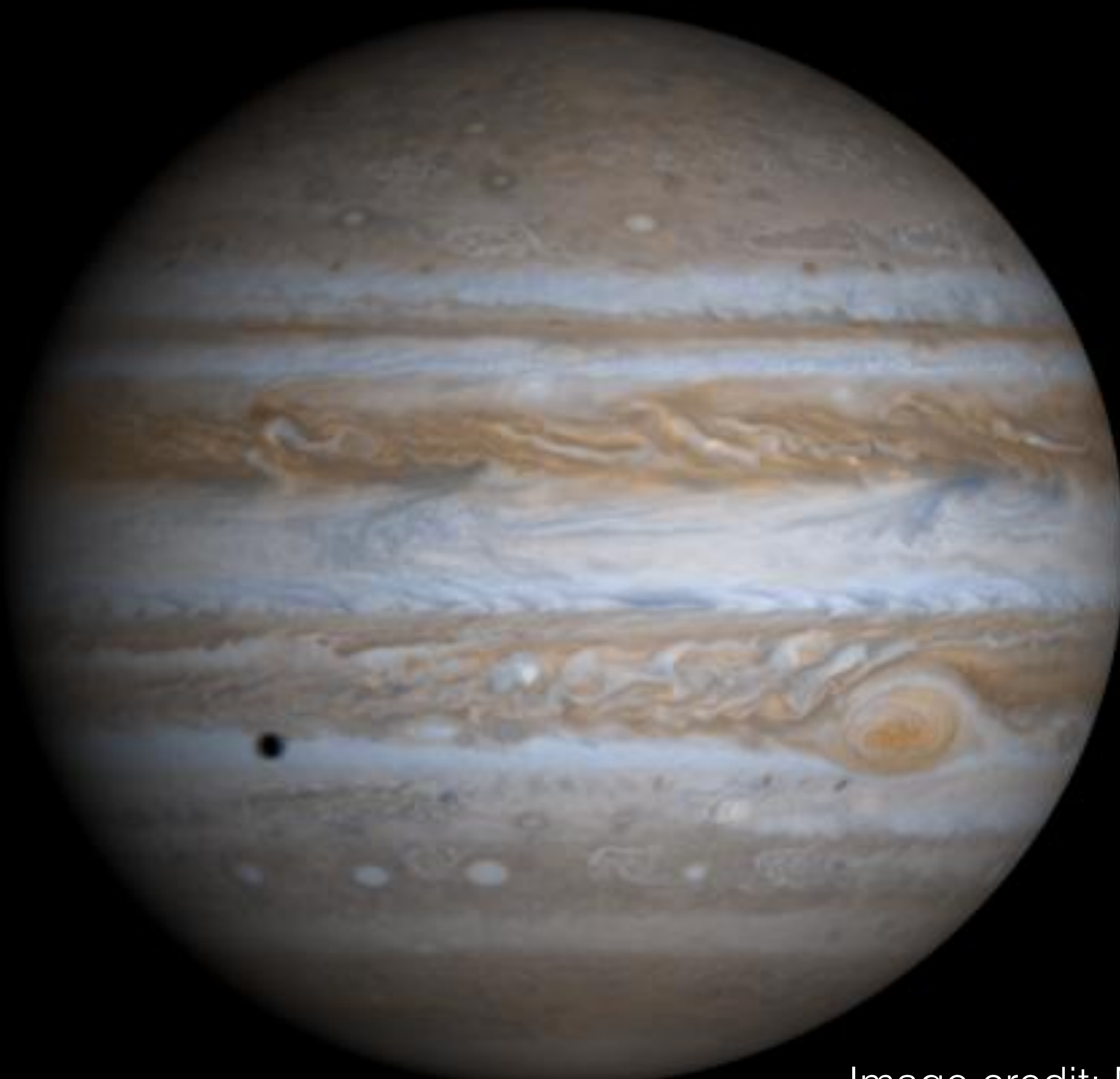
Reflected Light from Giant Exoplanets

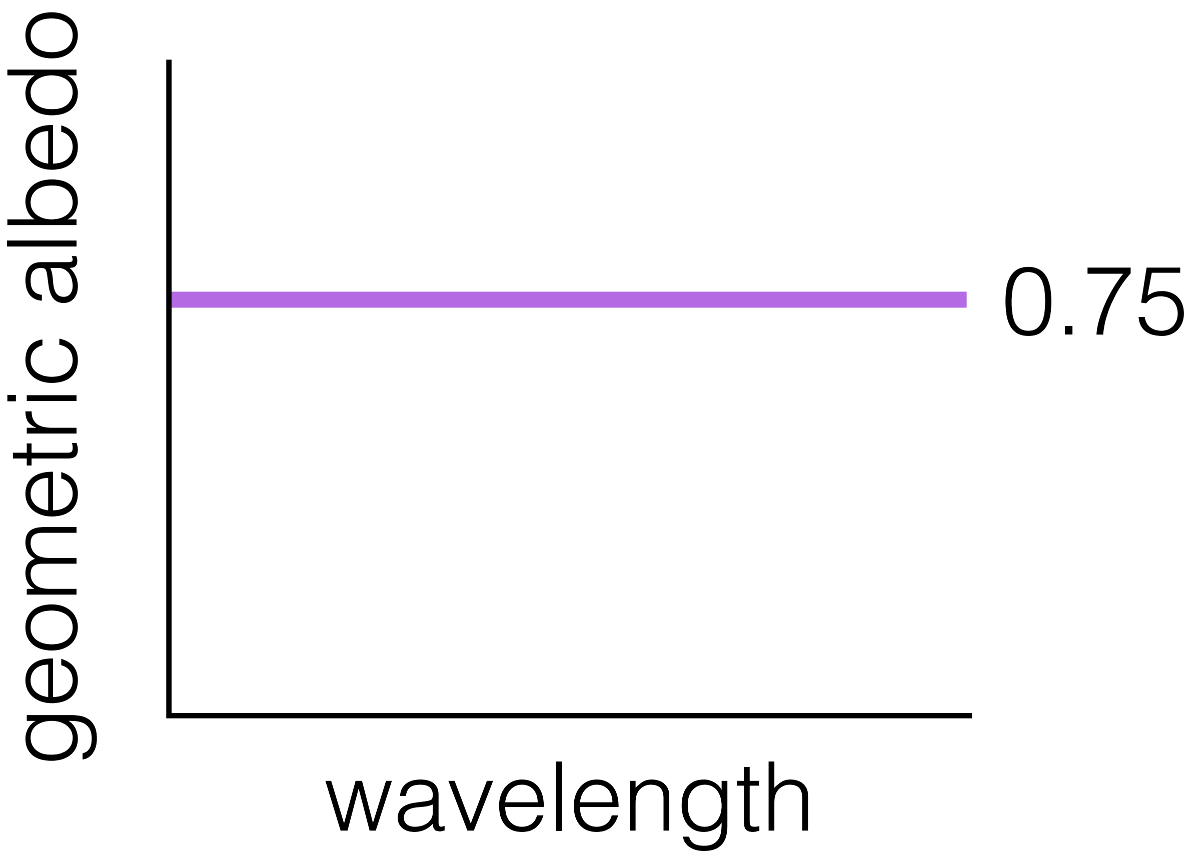


Caroline Morley
UC Santa Cruz

Mark Marley
Nikole Lewis
Roxana Lupu
Jonathan Fortney
Michael Line
Kerri Cahoy

Image credit: NASA/JPL/University of Arizona

Albedo Spectra: Basics



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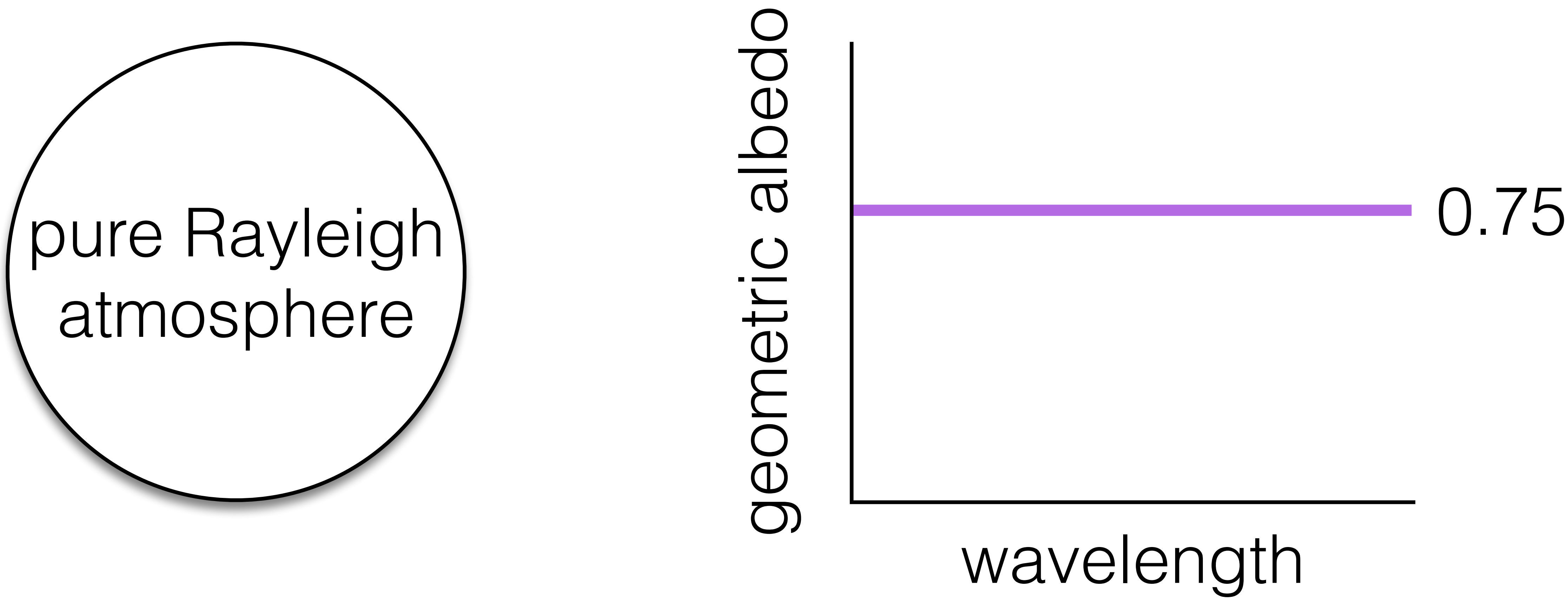

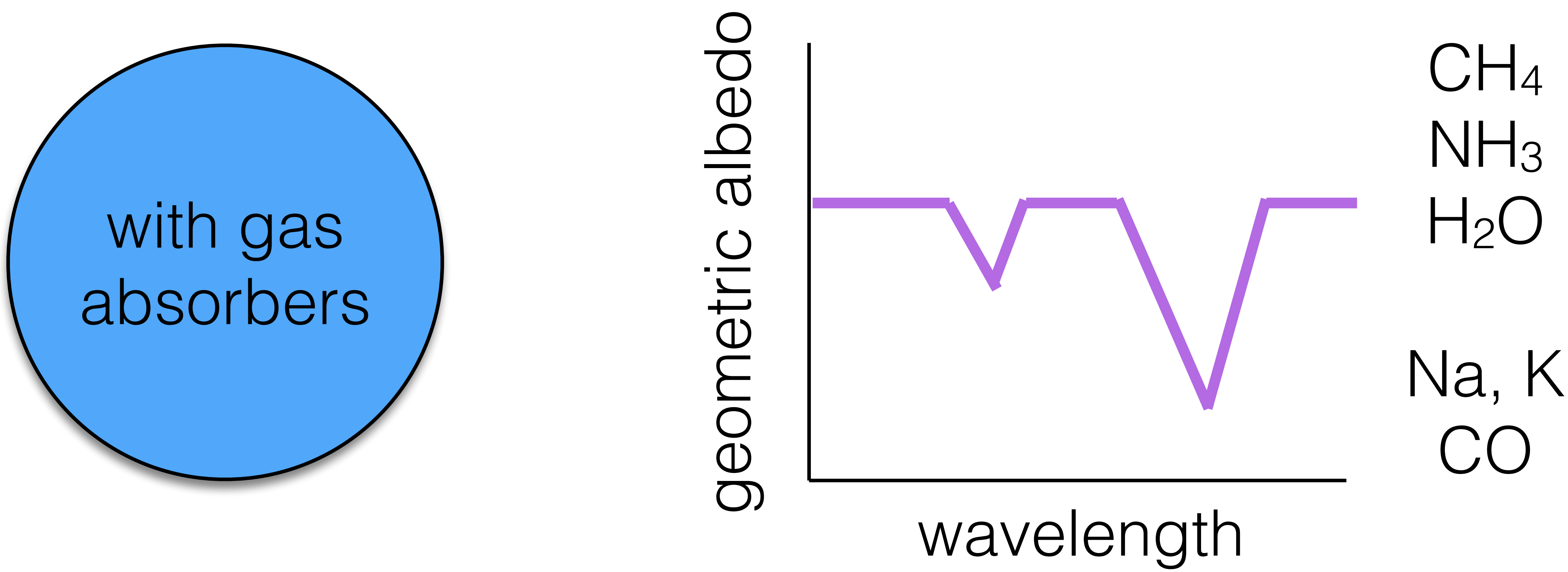

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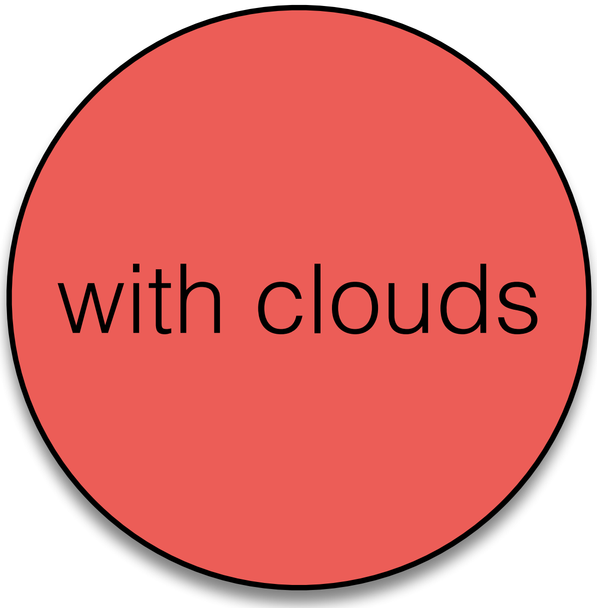

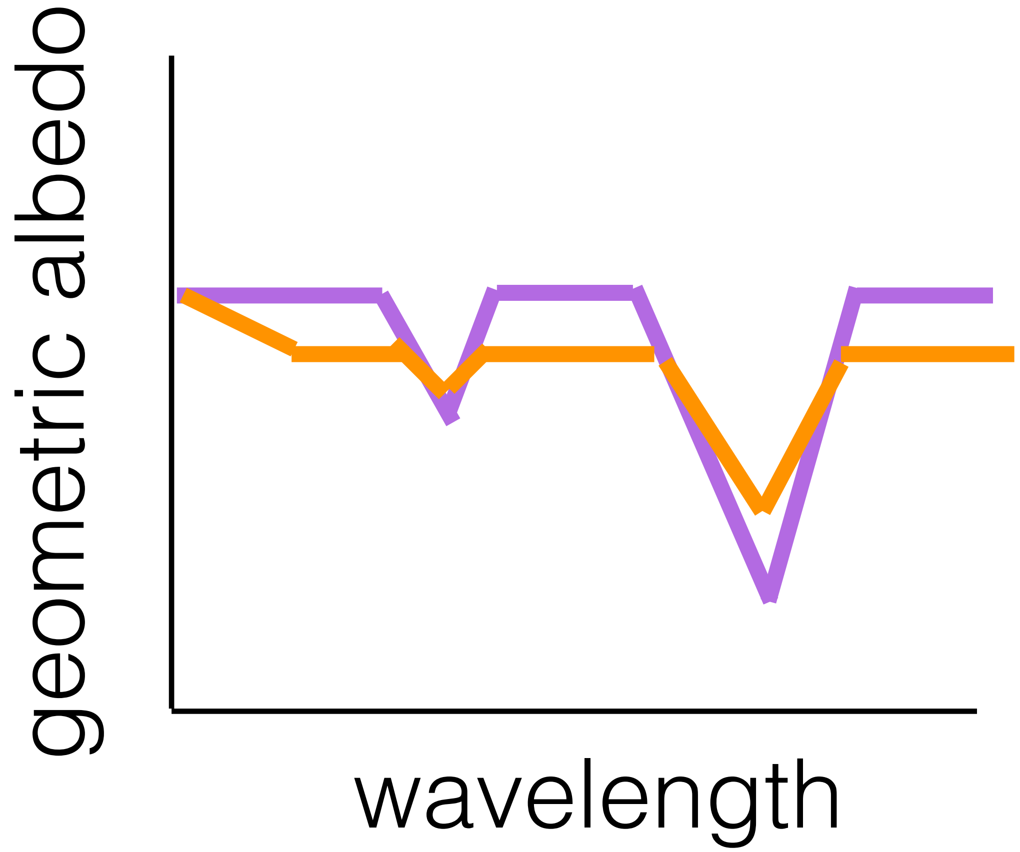

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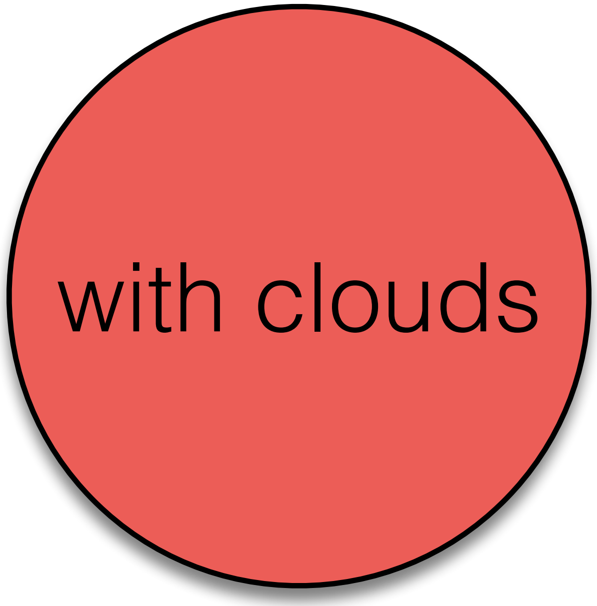

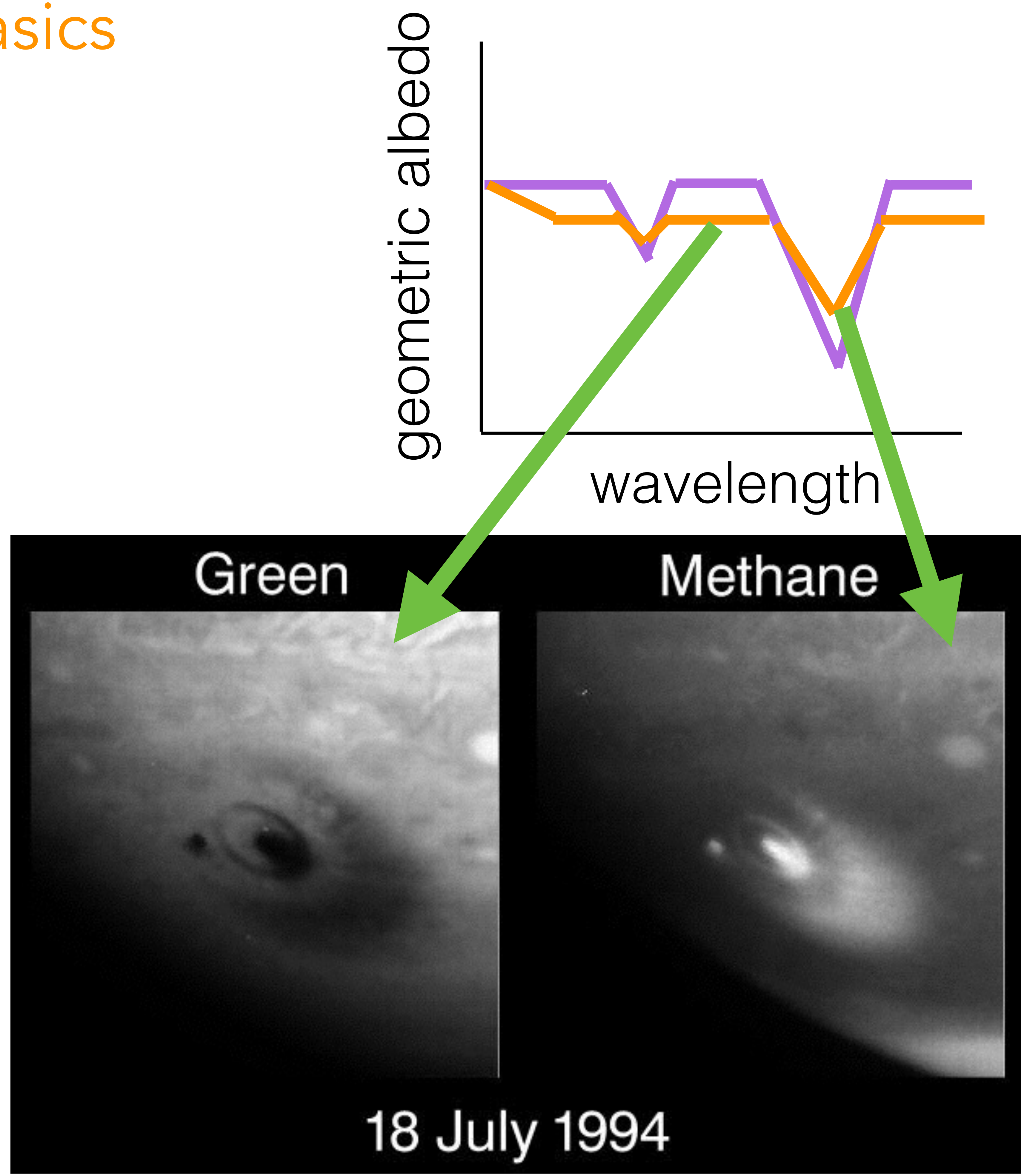

Shoemaker-Levy 9 Impact on Jupiter seen with Hubble

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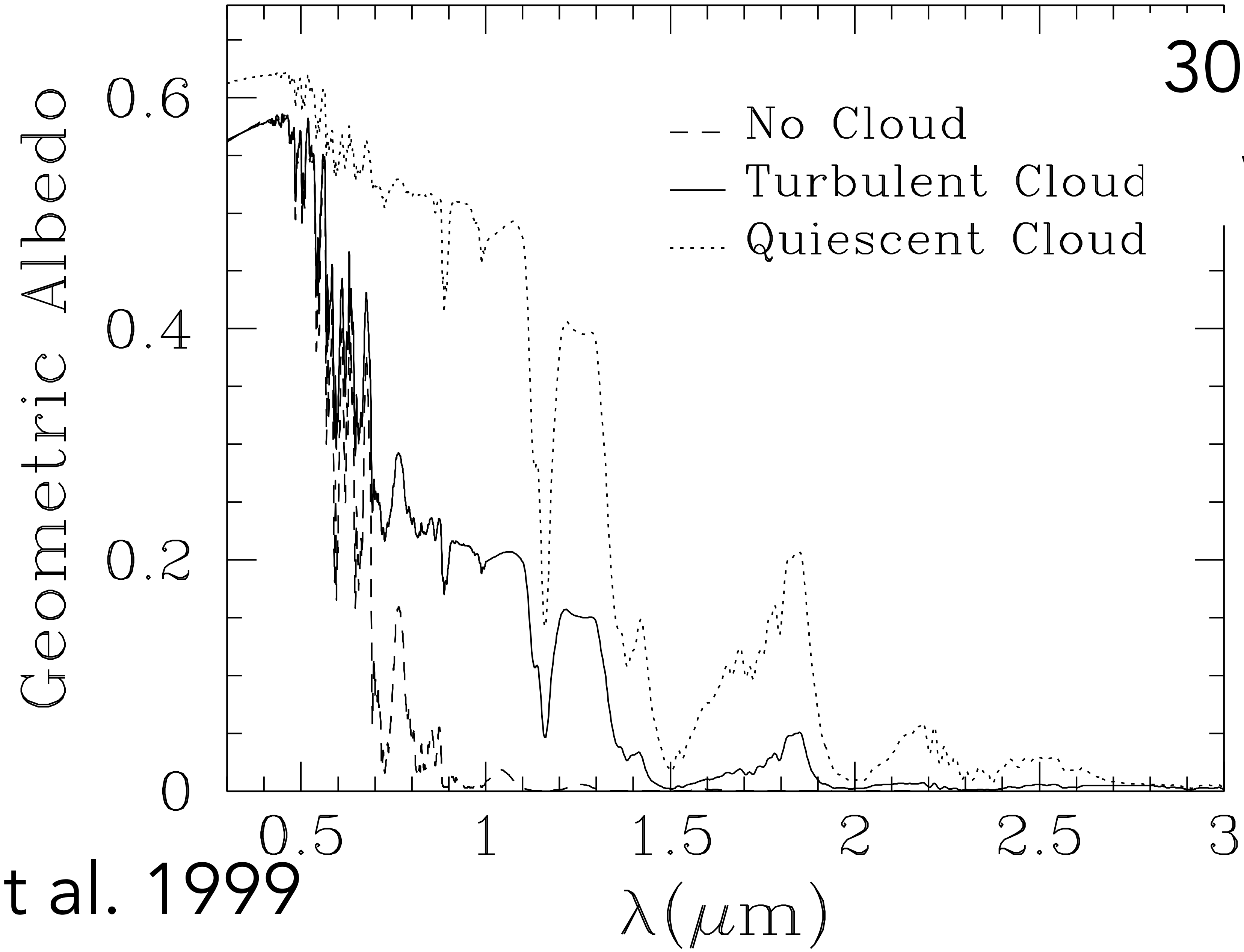

300 K, g=22 m/s^2
water clouds

Marley et al. 1999

degeneracy between methane abundance and continuum opacity: need both weak and strong bands

lots of work done in ~1999-2005 developing models and making predictions for exoplanets

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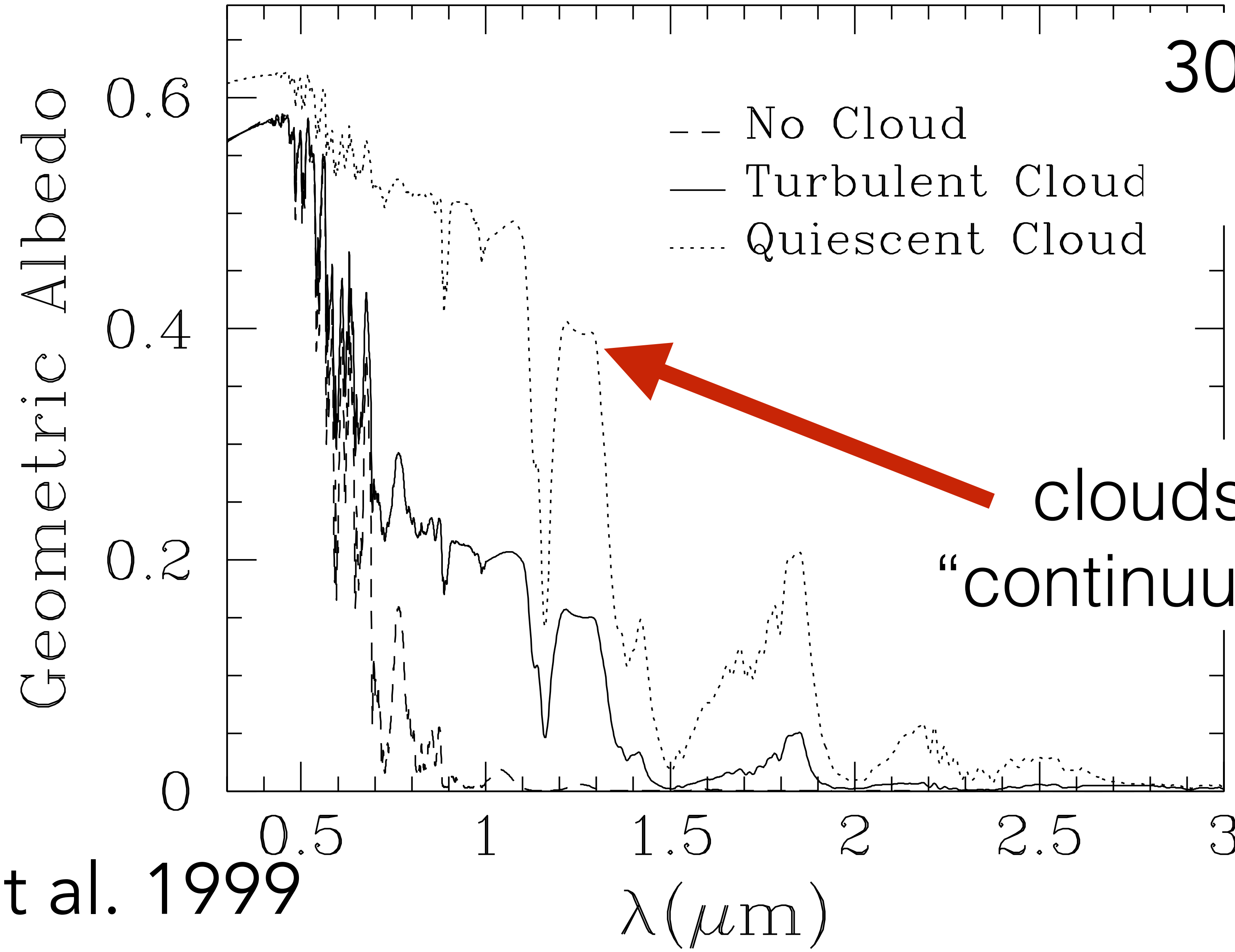

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clouds set the "continuum" opacity

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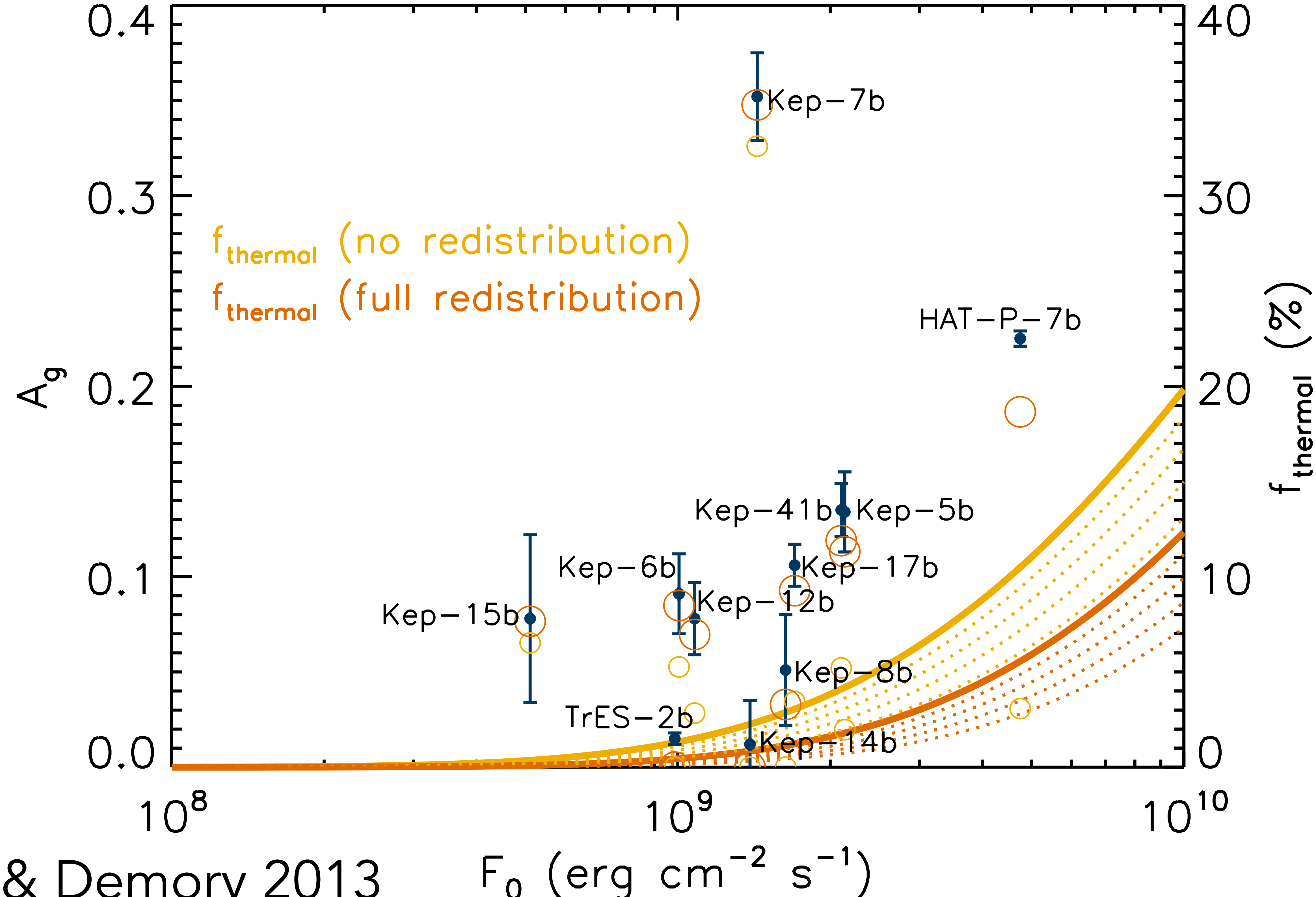
Exoplanet reflection spectra out of fashion for last ~5 years because **hot Jupiters are dark**.



Heng & Demory 2013

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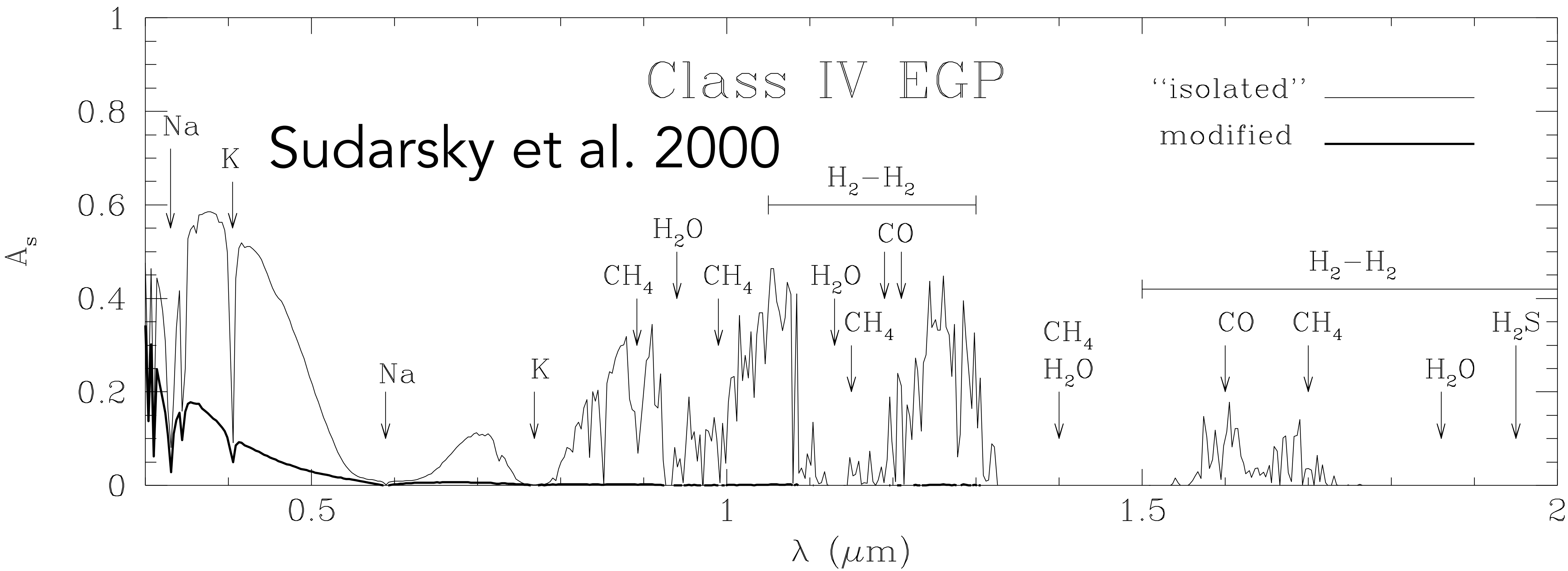
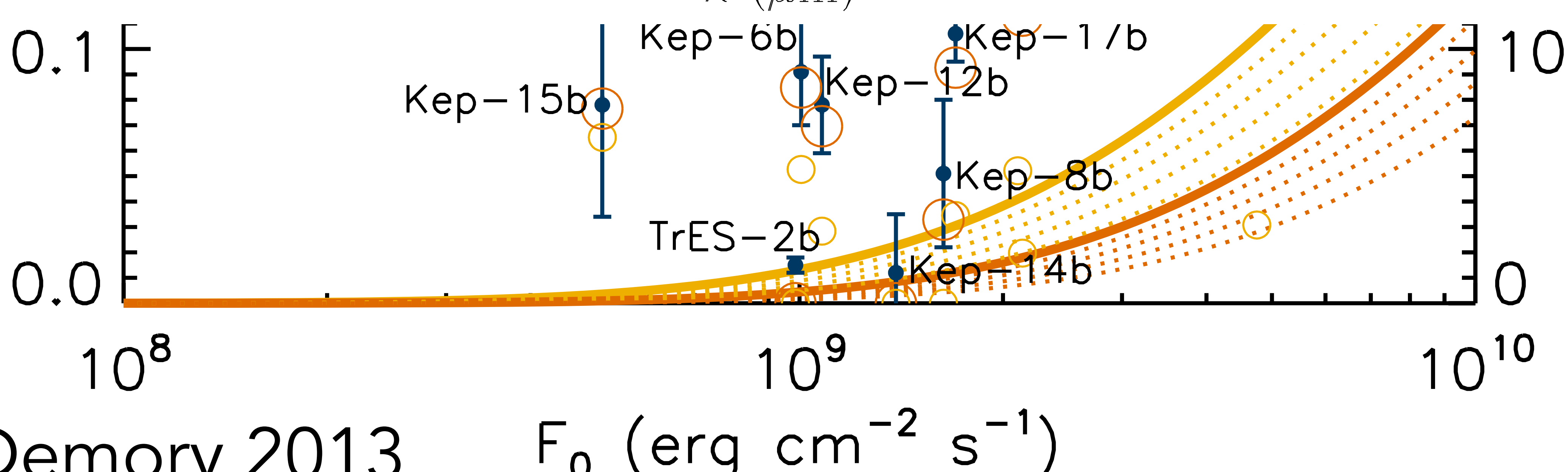


Sudarsky et al. 2000



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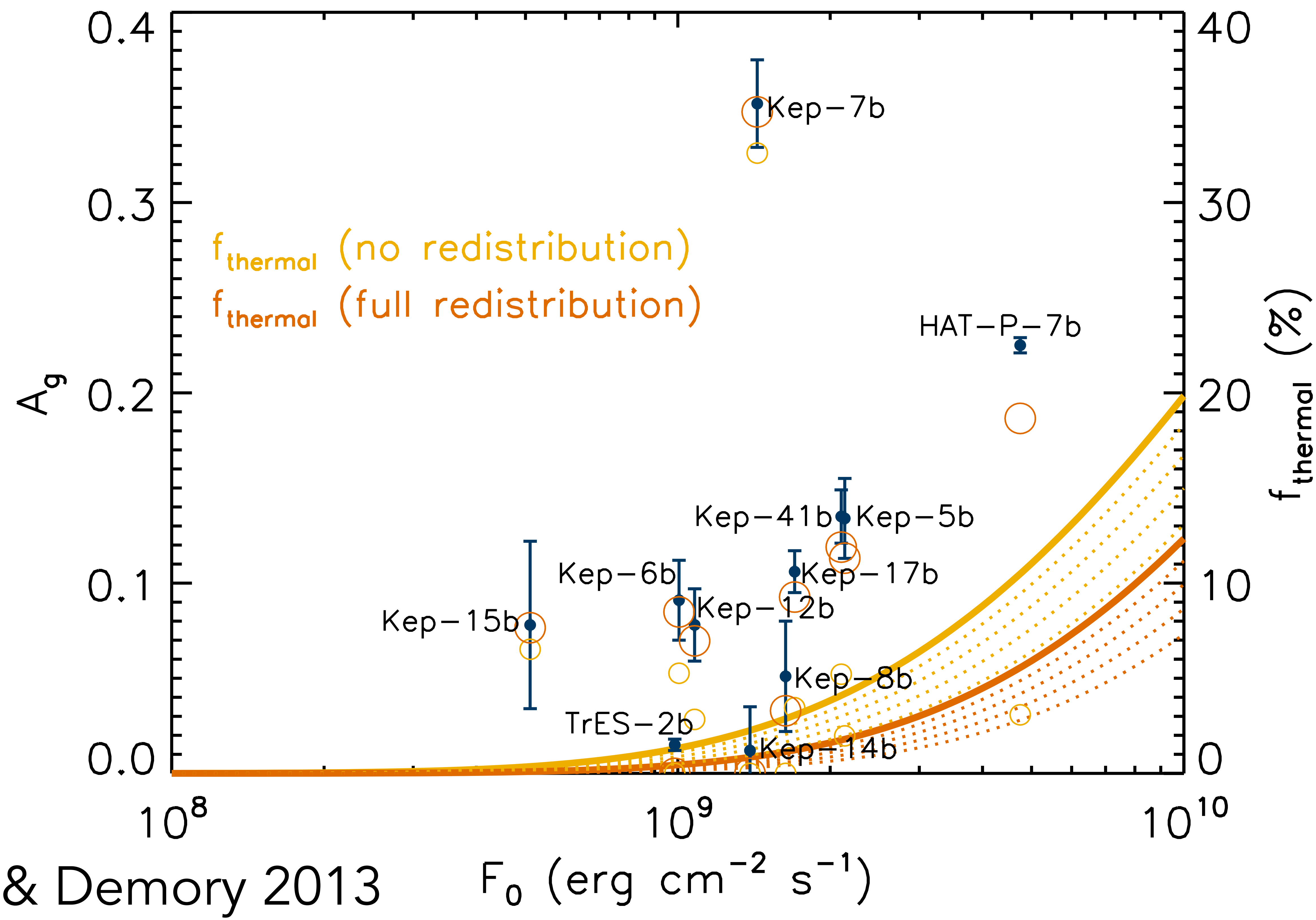
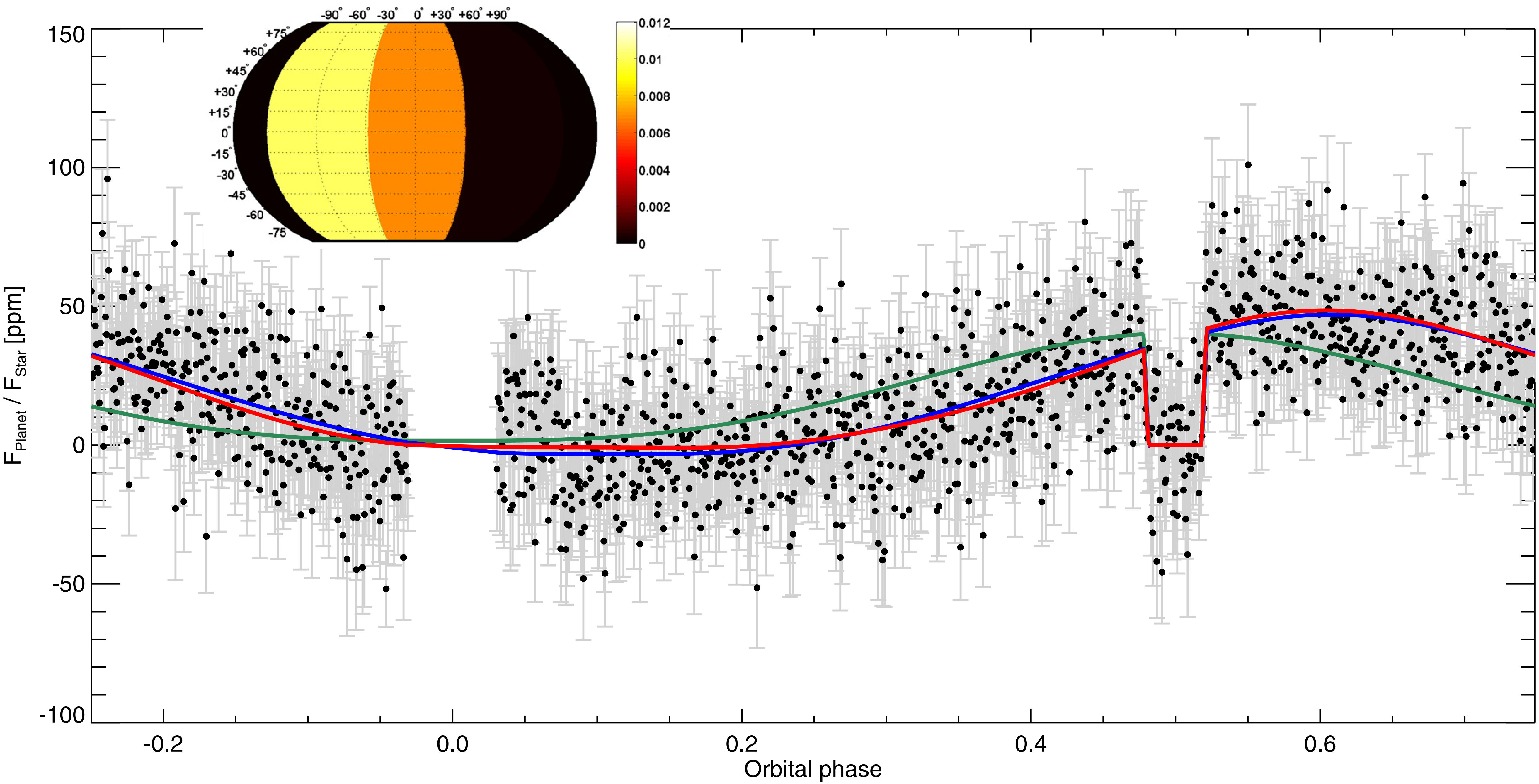


Heng & Demory 2013

Kepler photometry allowed us to infer **inhomogeneous clouds** for the first time.



Demory et al. 2013

Theoretical Albedo Spectra: general approach

1D radiative-convective
equilibrium model:
temperature, composition

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cloud tau, scattering, asymmetry

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1D radiative-convective equilibrium model:
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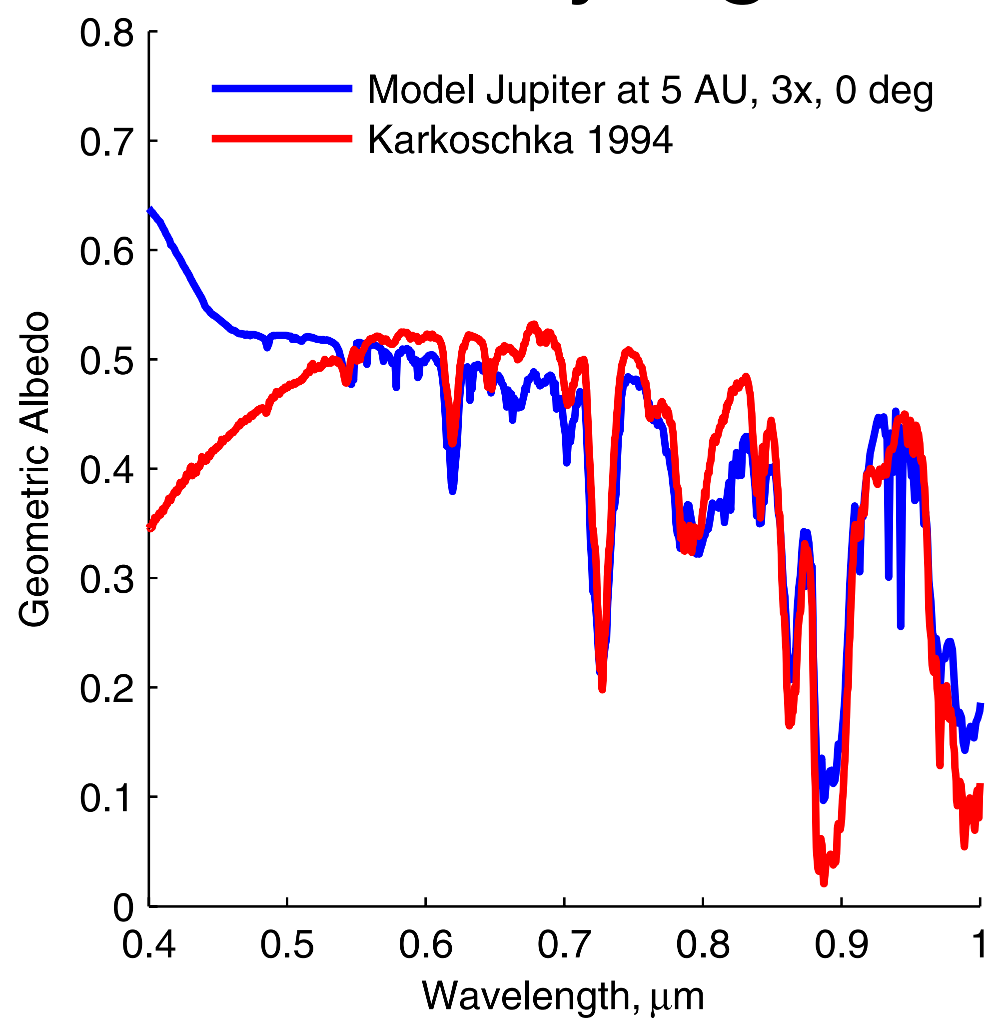
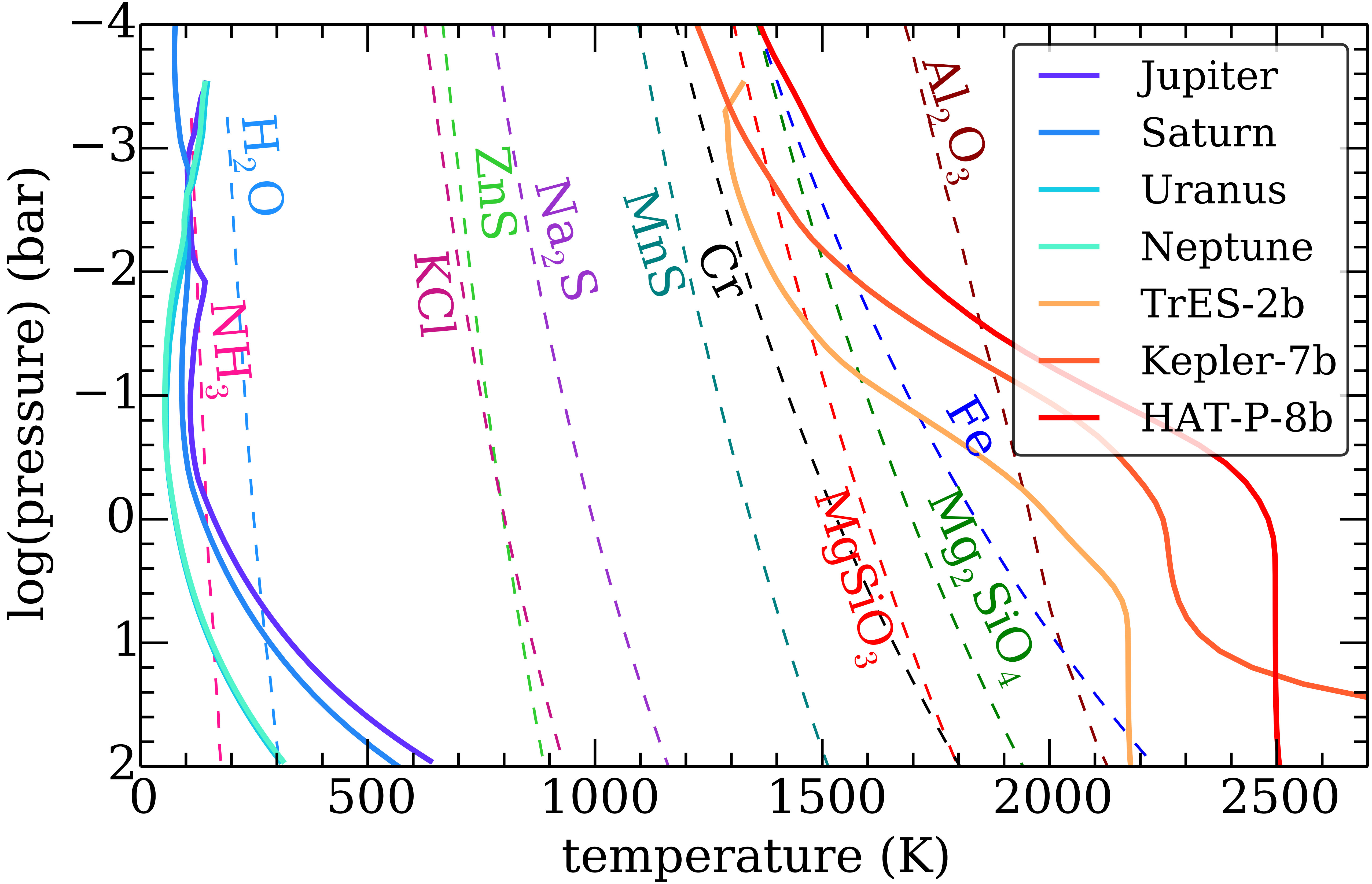
scattered radiation (Rayleigh, Raman, Mie)



Cahoy et al. (2010)

The temperature structure (set by stellar flux) controls the clouds.



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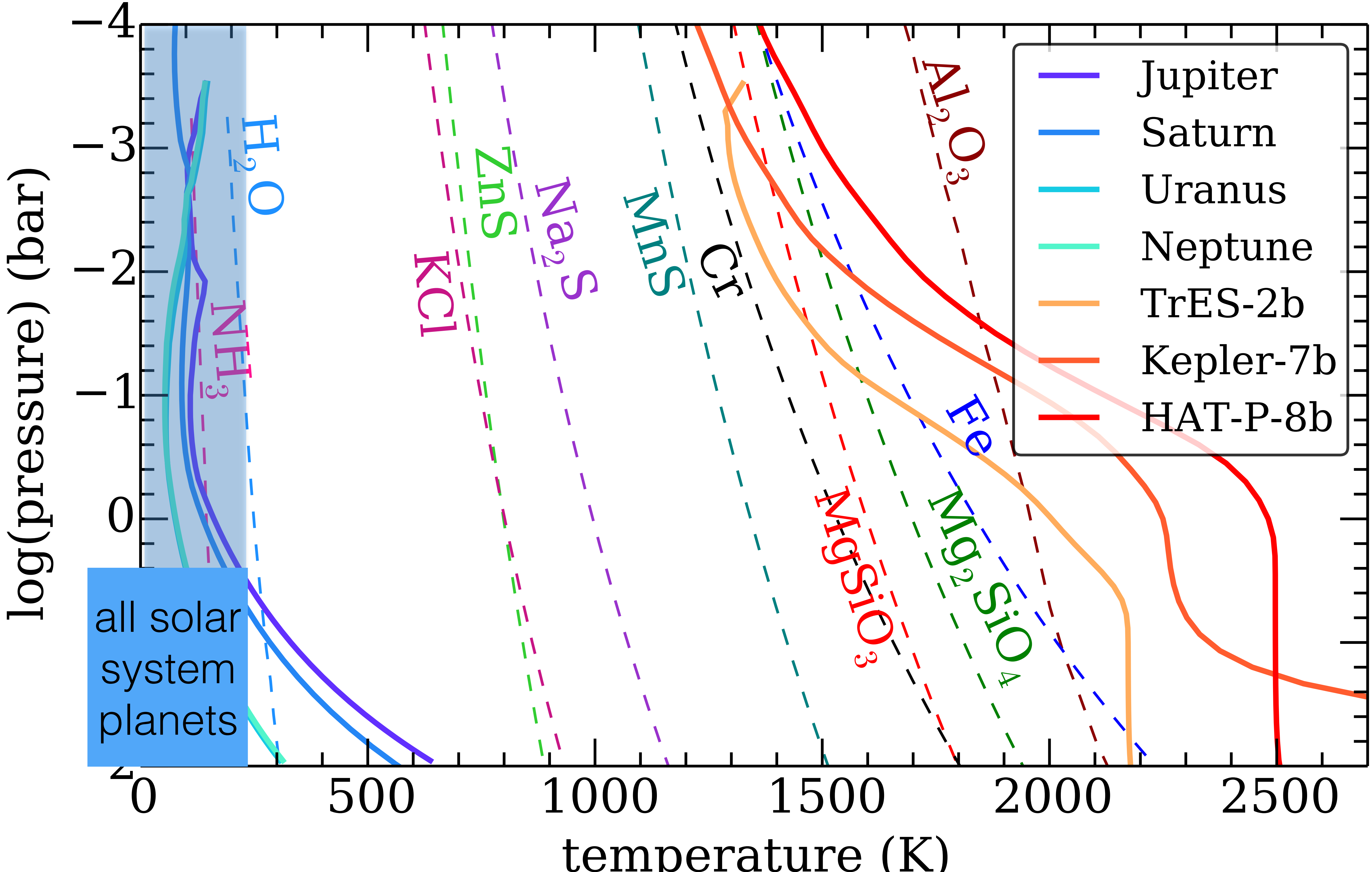

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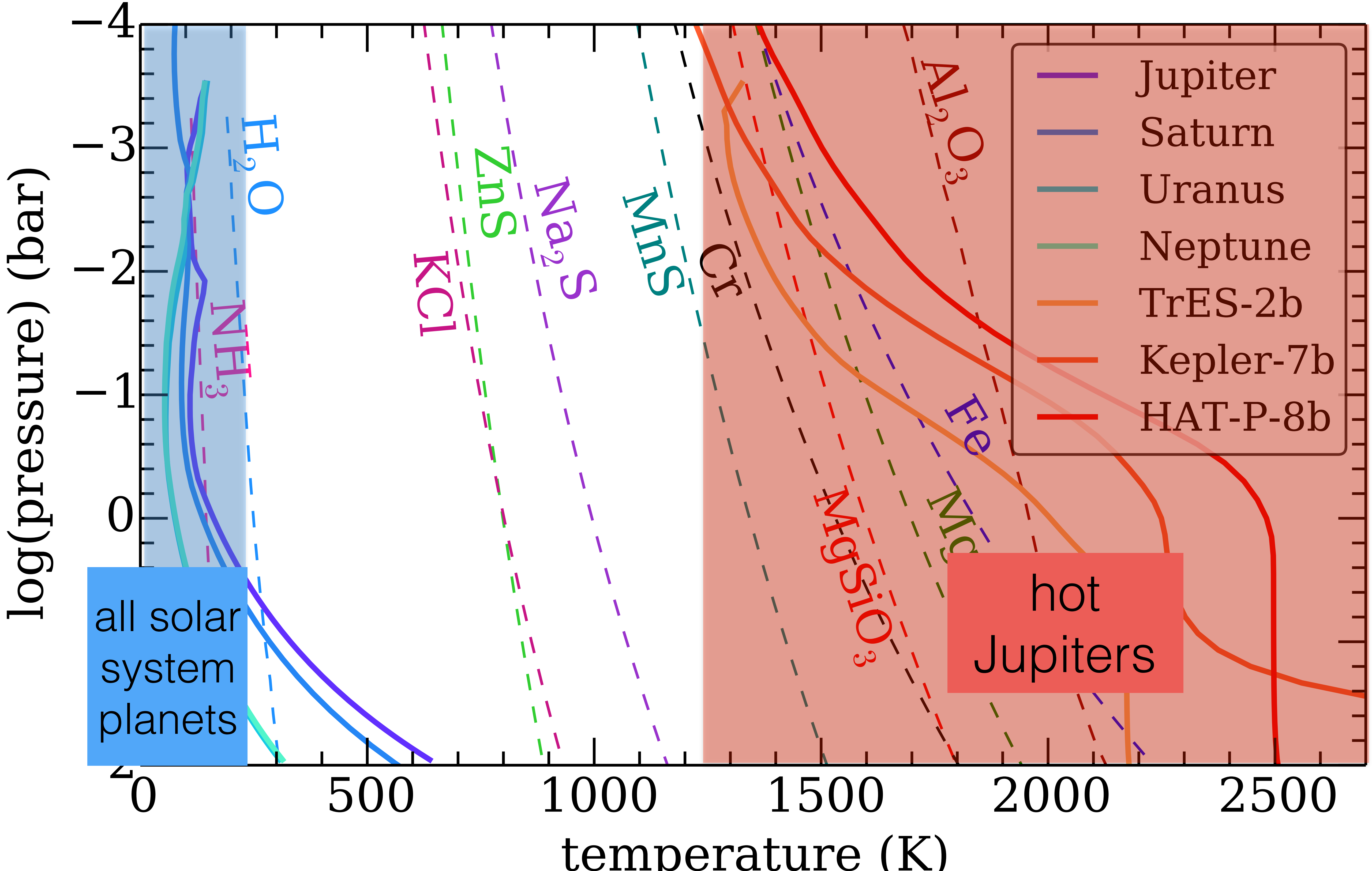
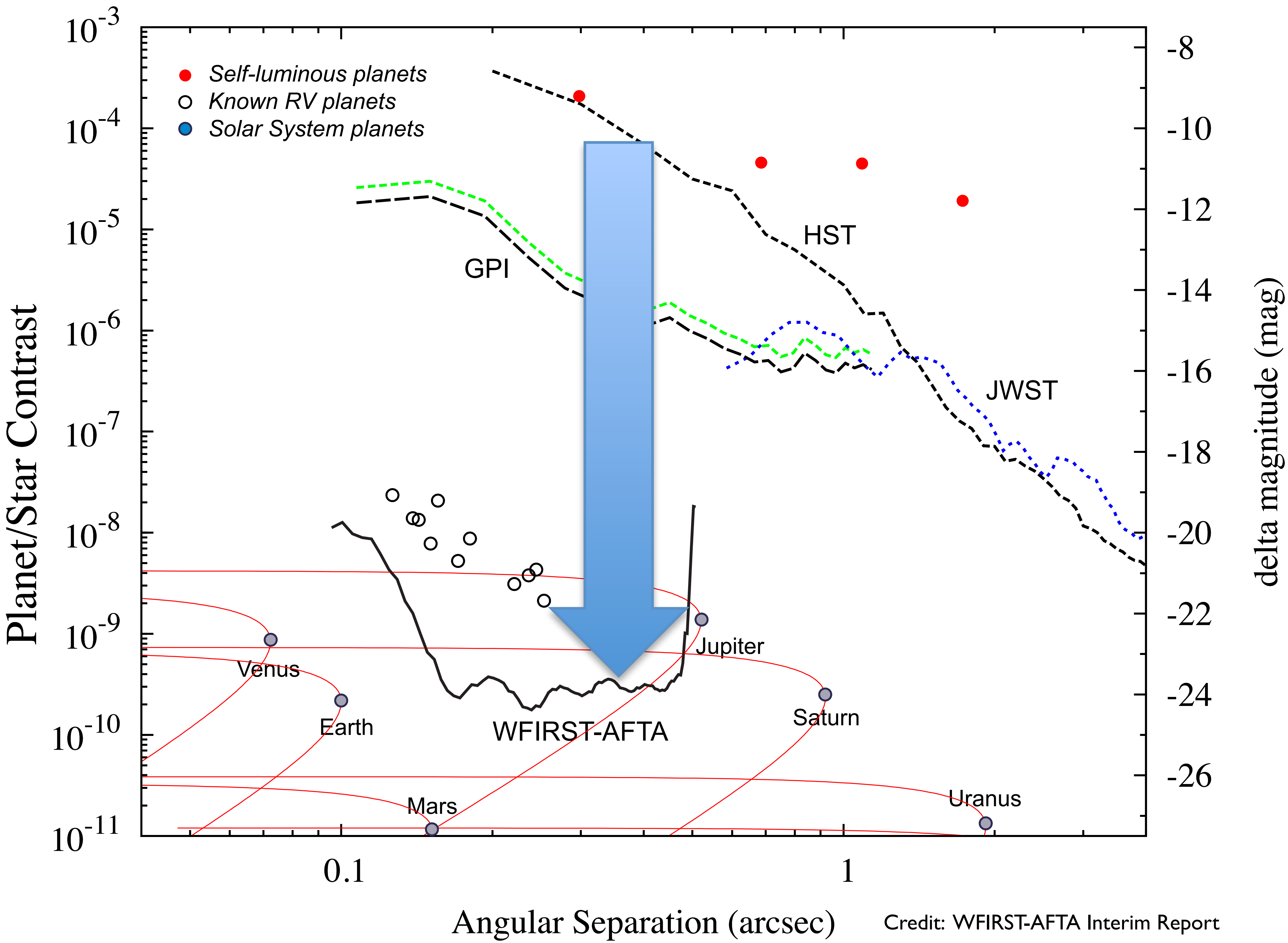
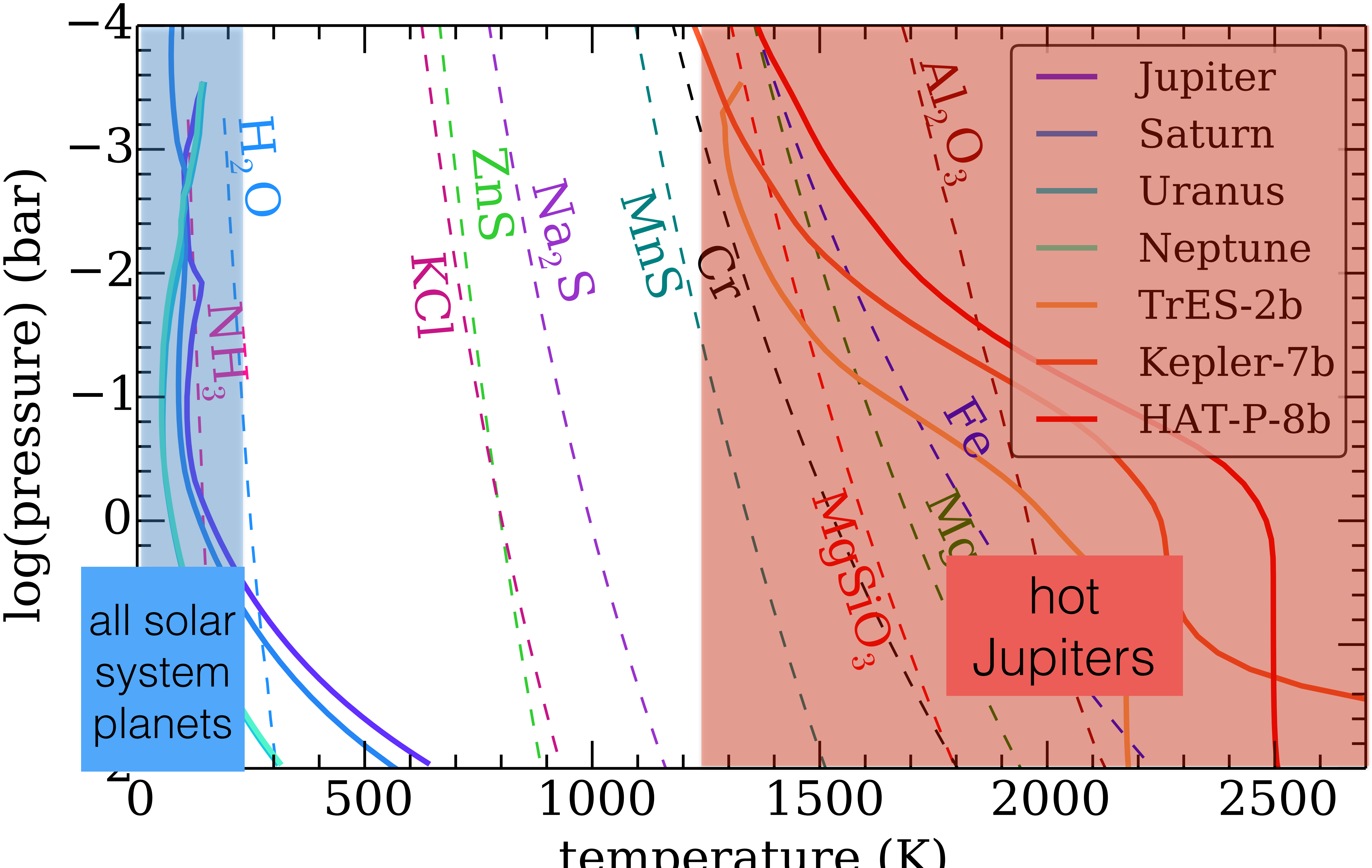


A space coronagraph opens up a totally **different class of planets** for atmospheric characterization.



Credit: WFIRST-AFTA Interim Report

We'll probe solar-system temperature planets AND warmer planets.



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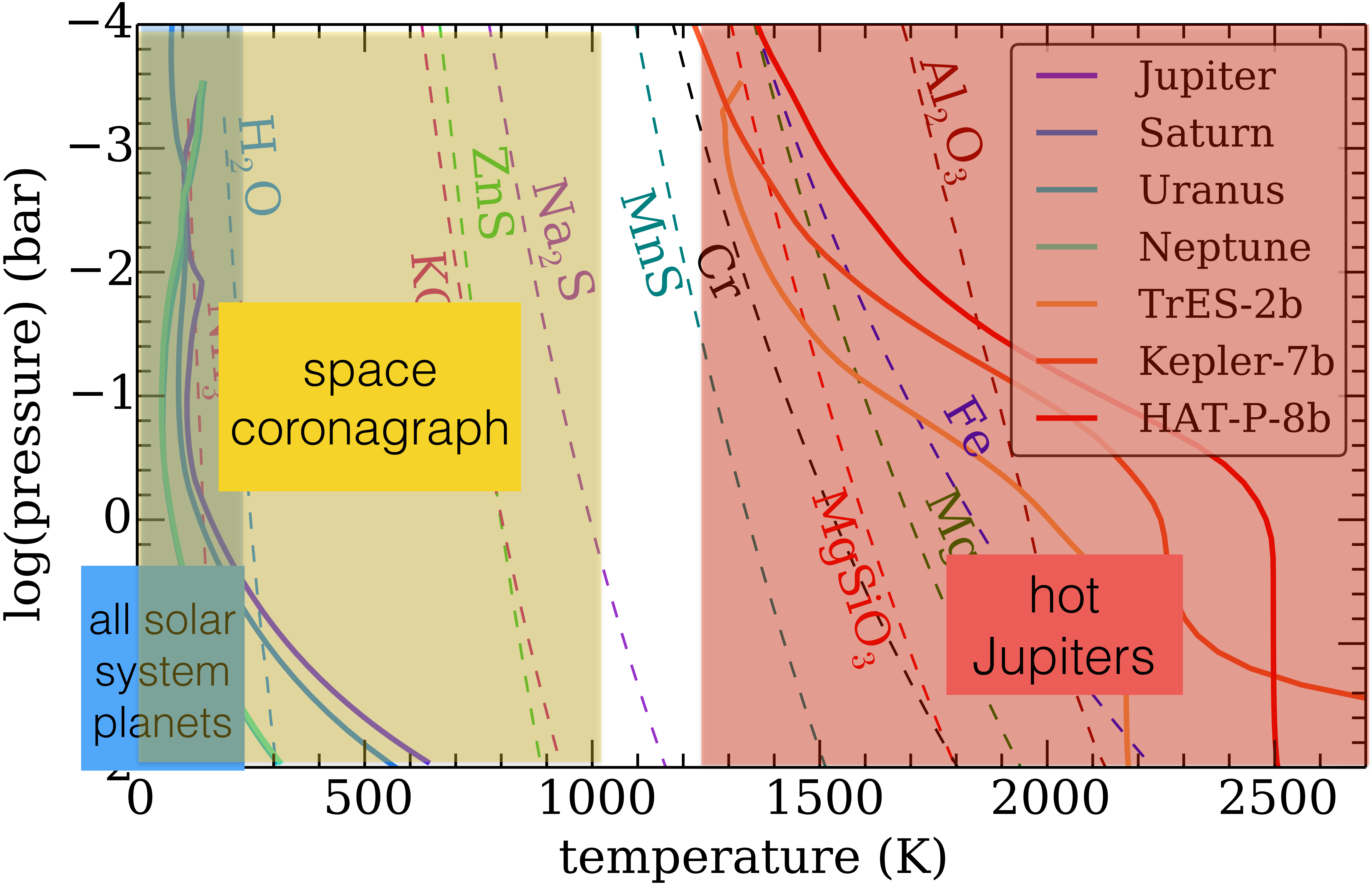

RV targets span temperature range from alkali, to water, to ammonia, to methane clouds.

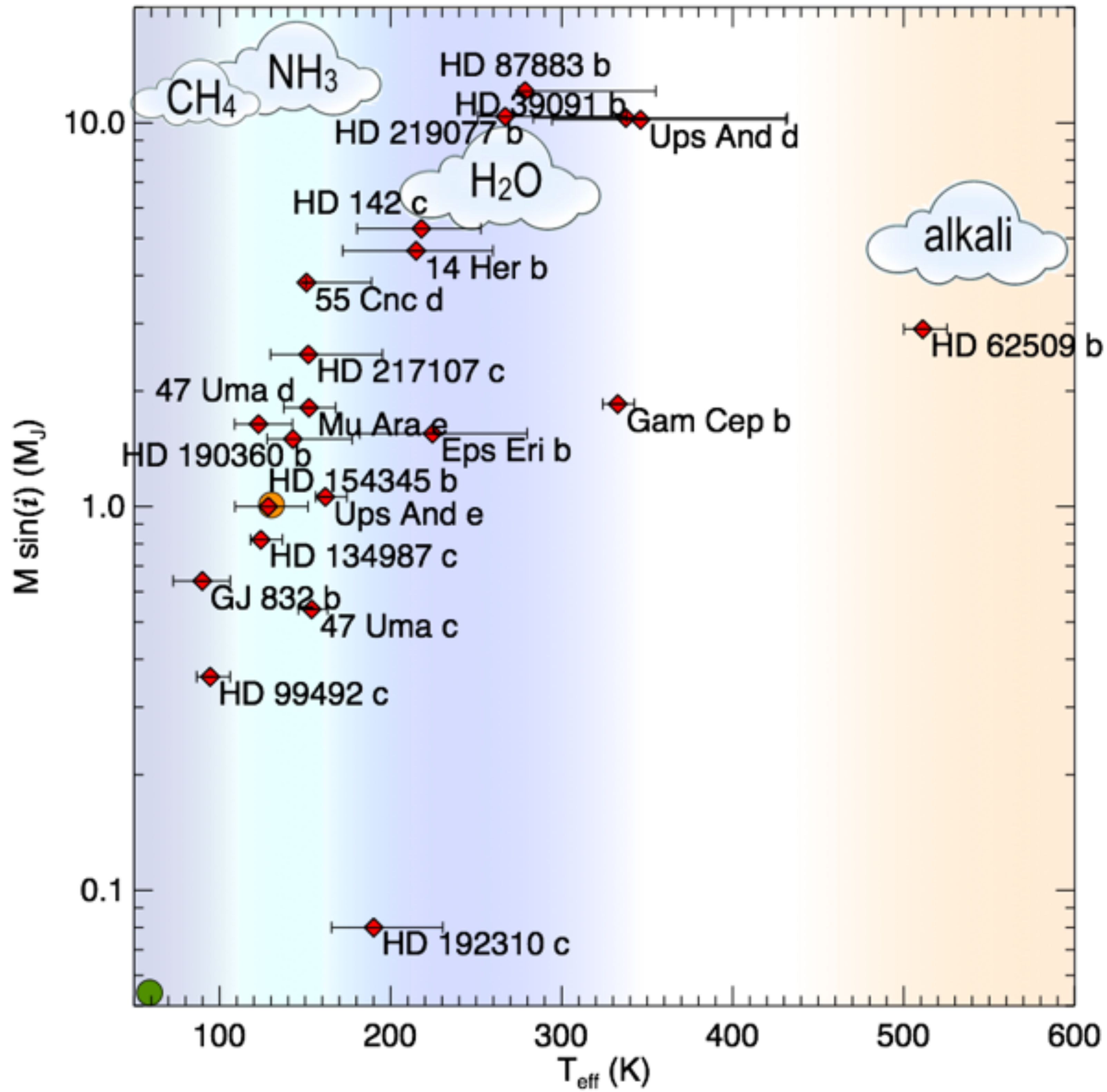

Figure from Nikole Lewis

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HD 62509b (warm, alkali clouds)

HD 99492c (cold, ammonia clouds)

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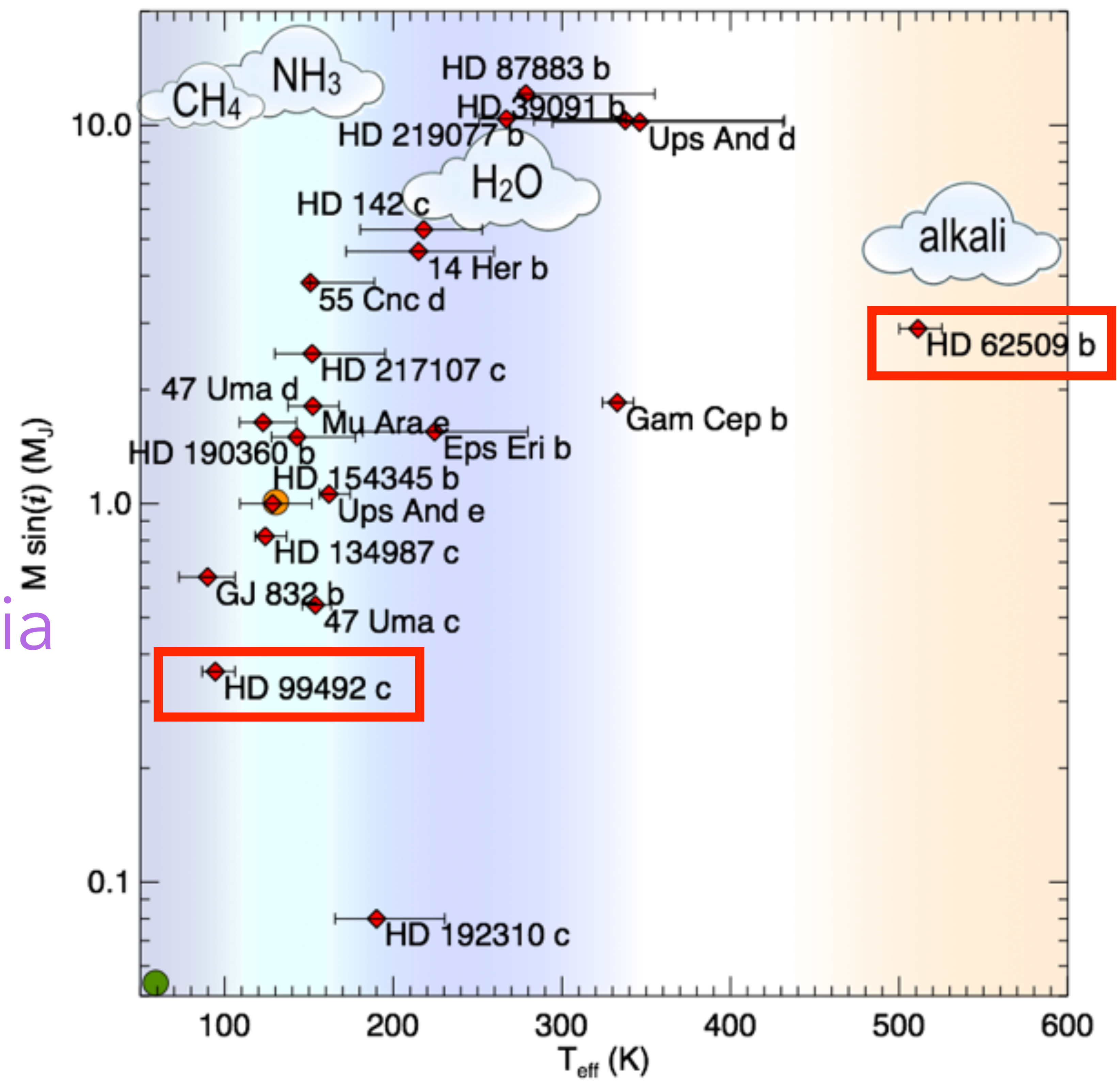

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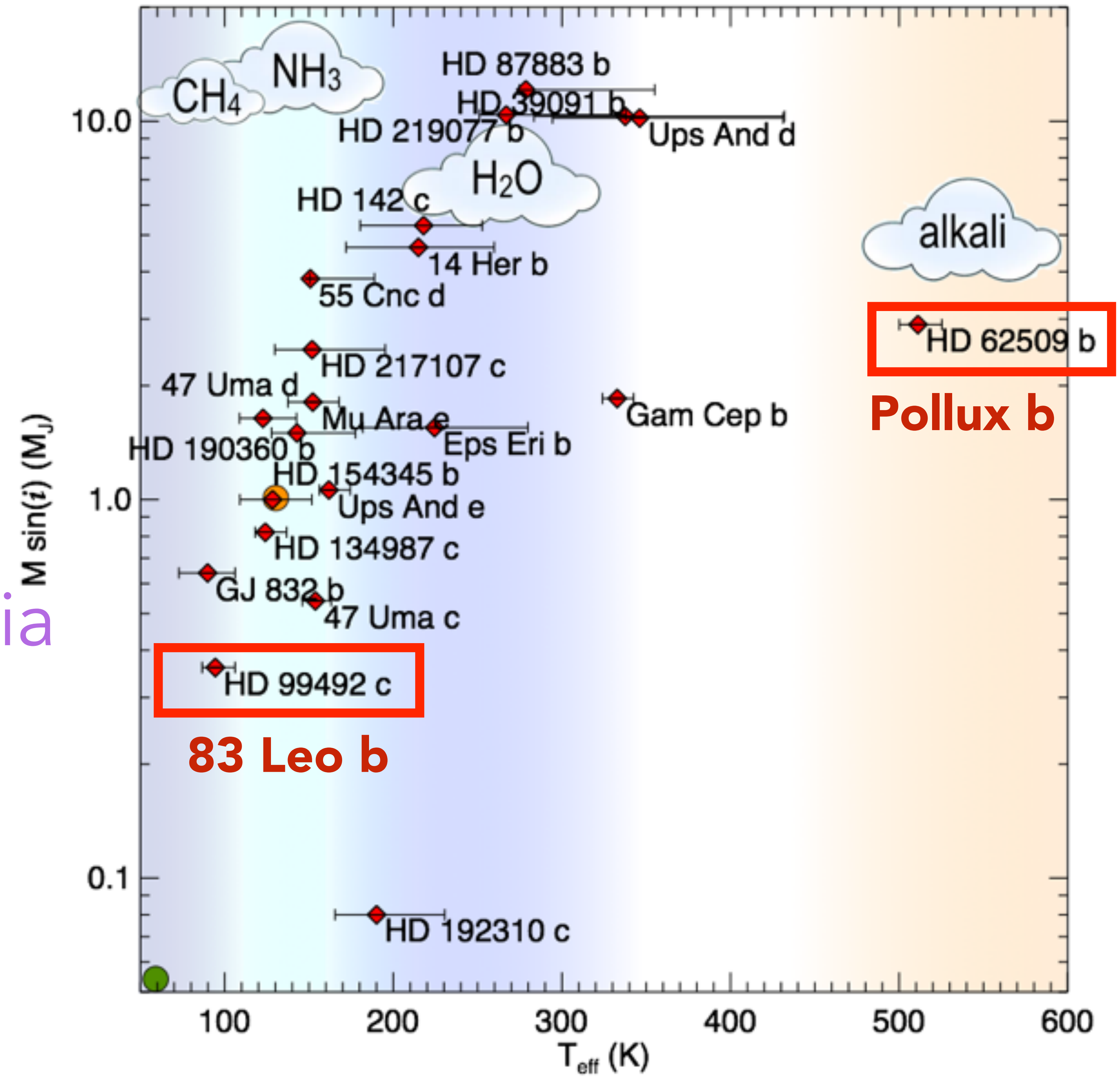
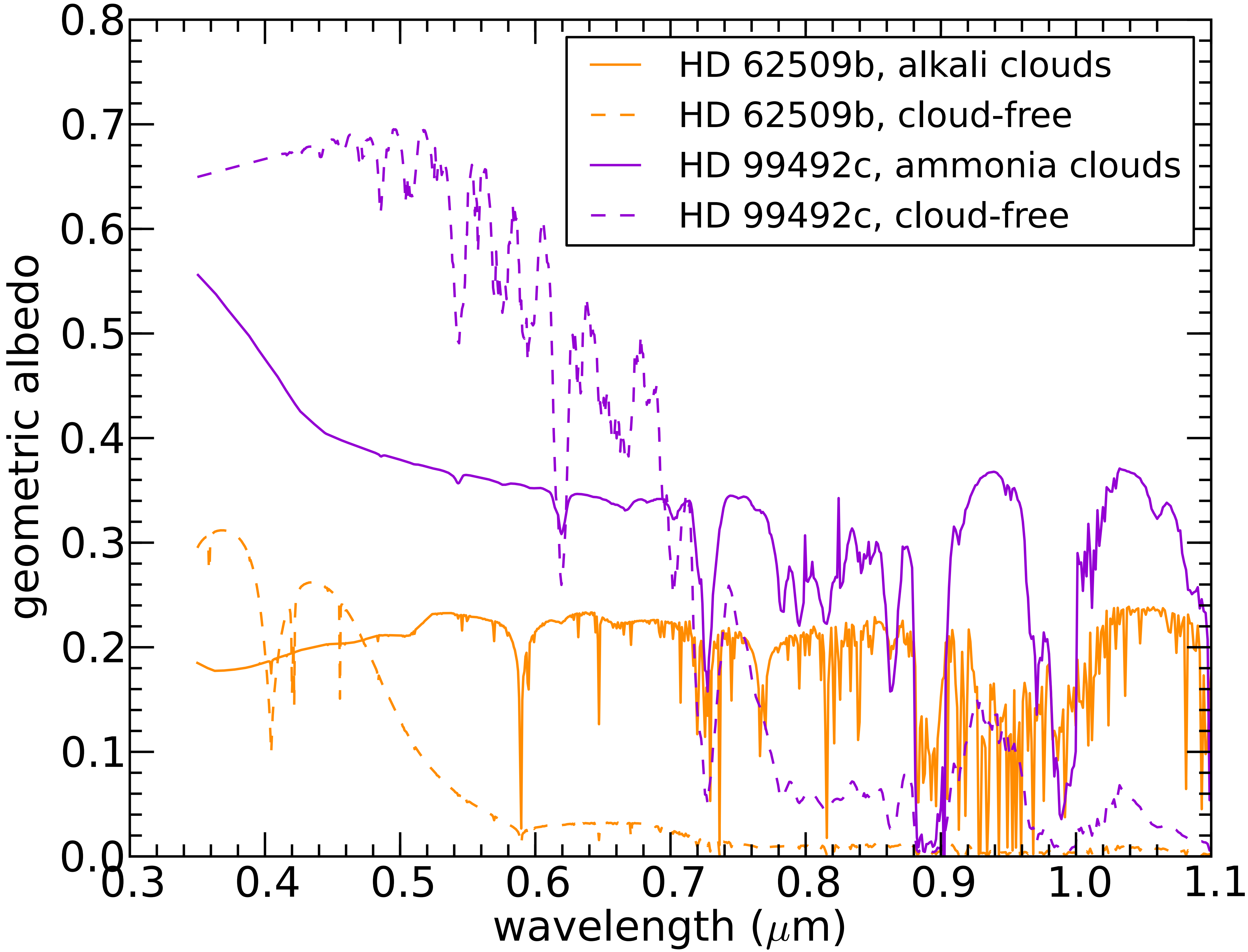
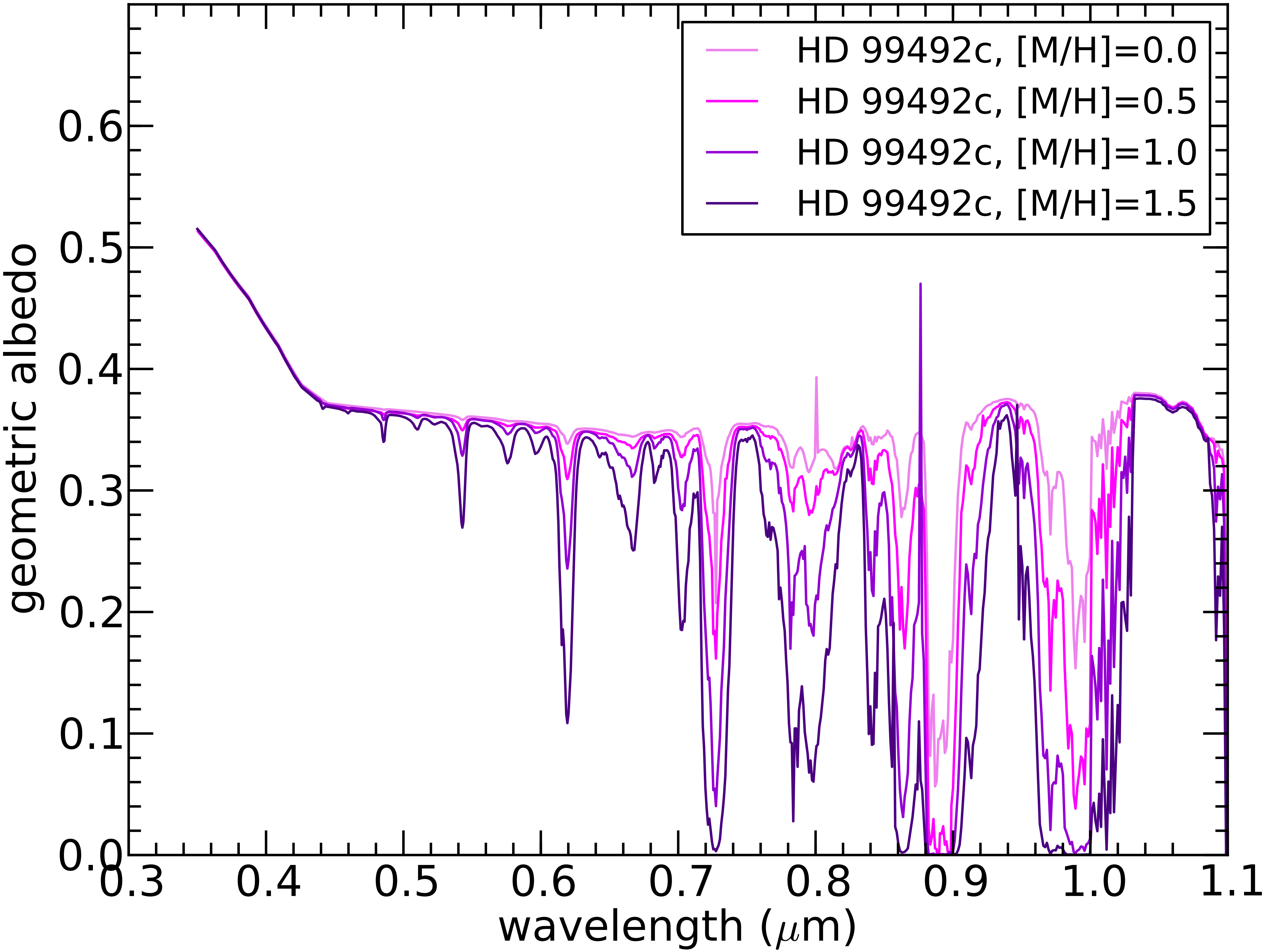


Figure from Nikole Lewis

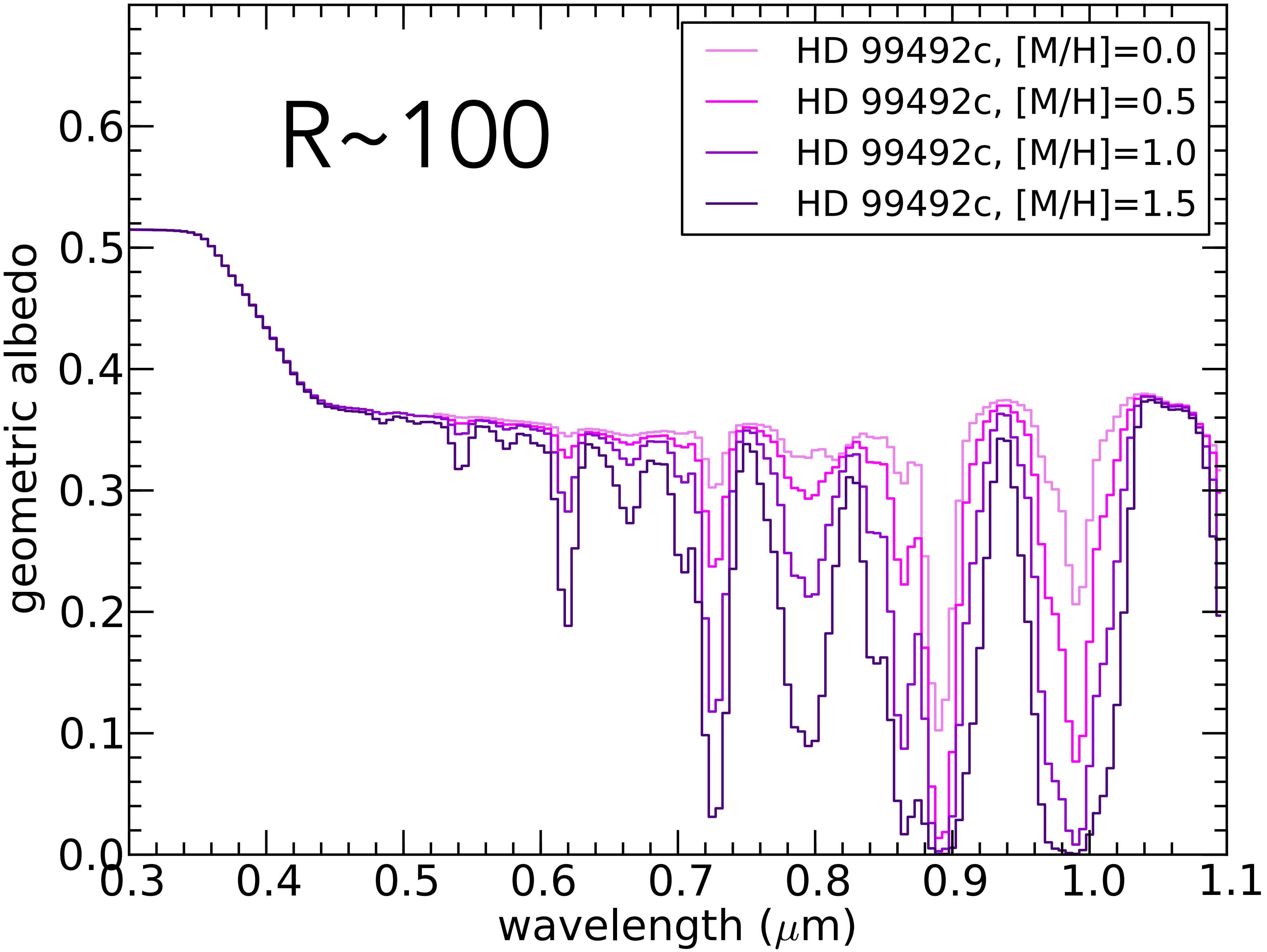
Huge range of spectra possible (not just scaled Jupiters!)



Higher metallicity widens and deepens molecular features: can constrain metallicity!



Need a minimum resolution to resolve both strong and weak features



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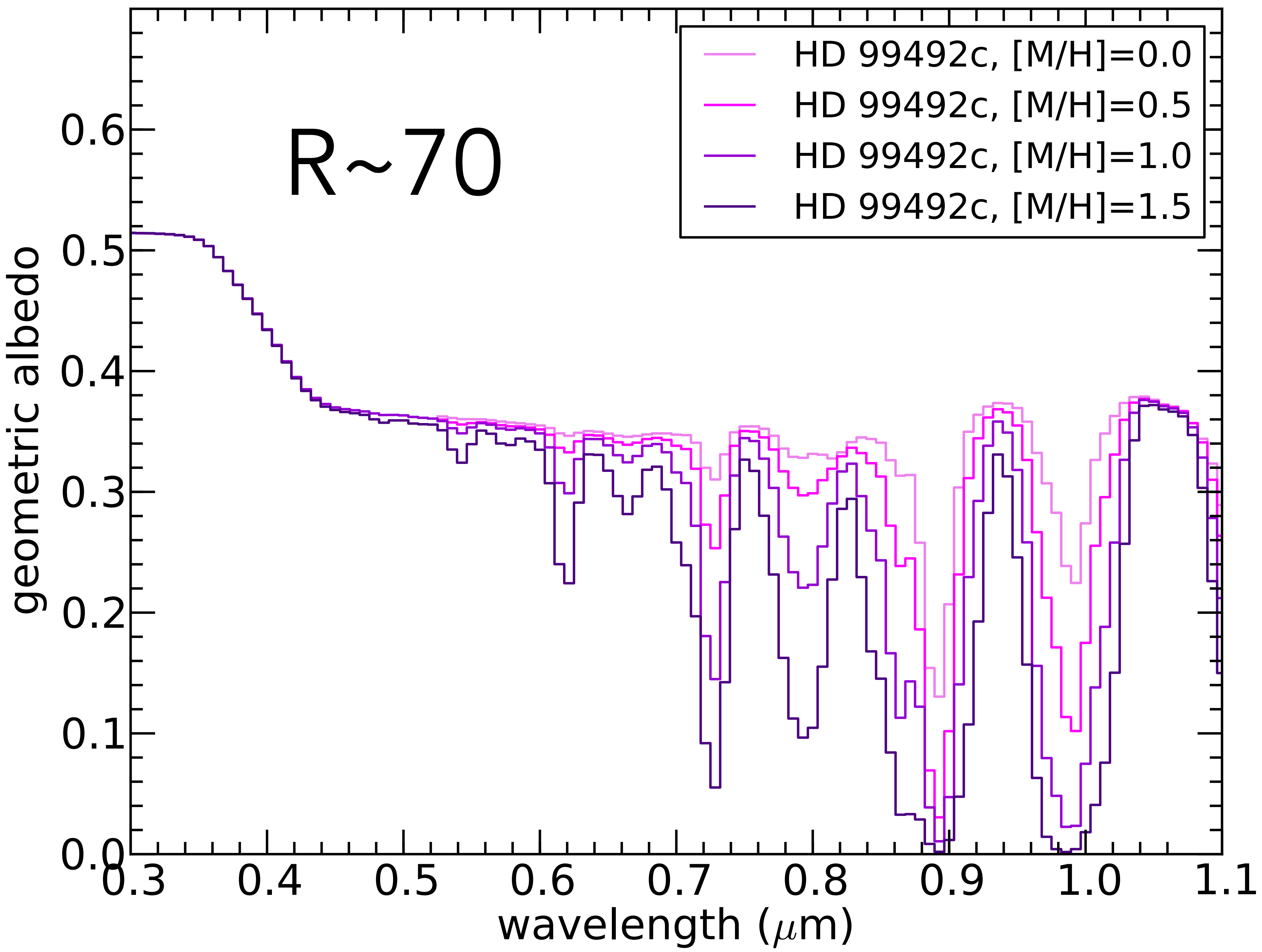

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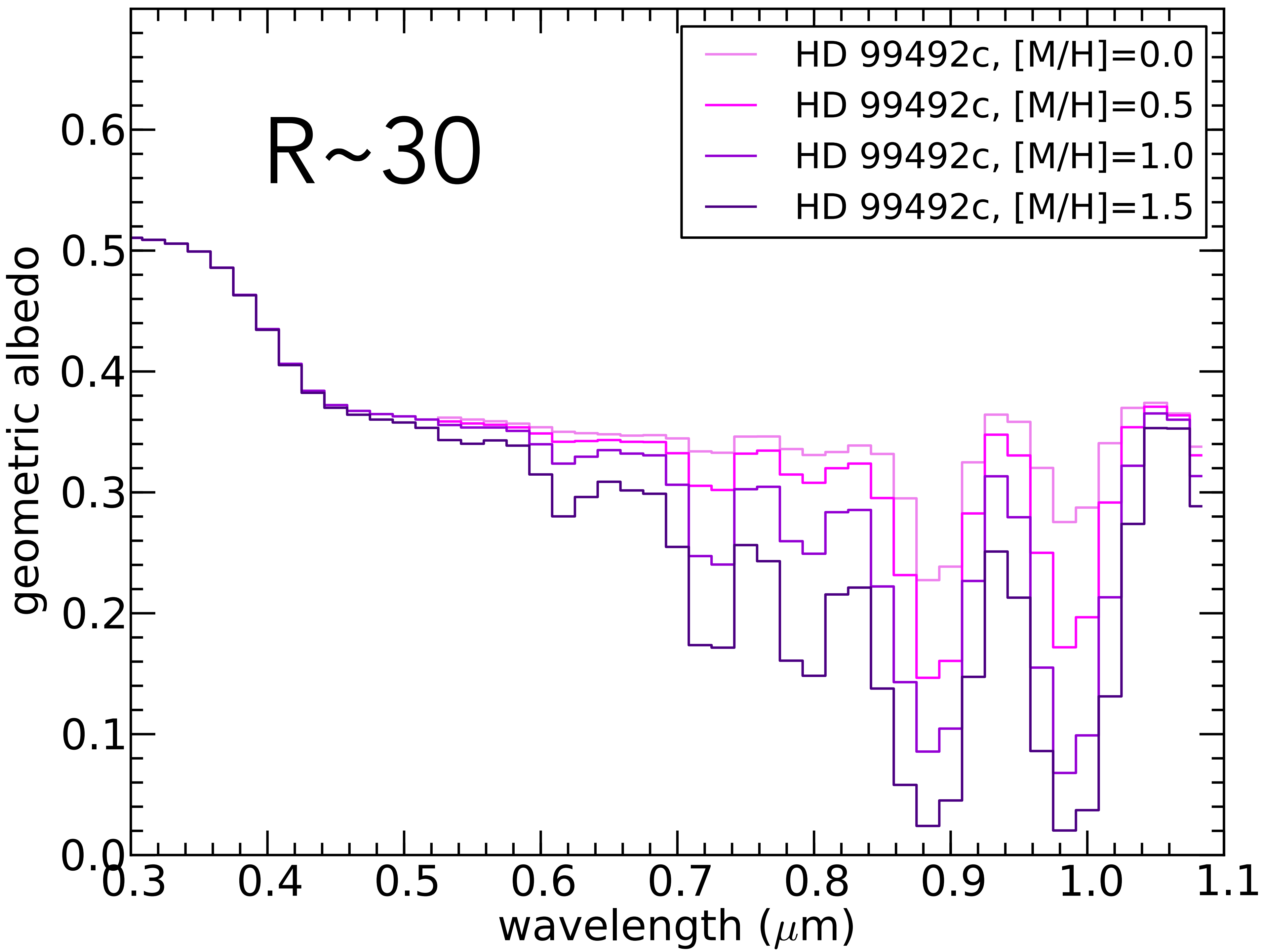

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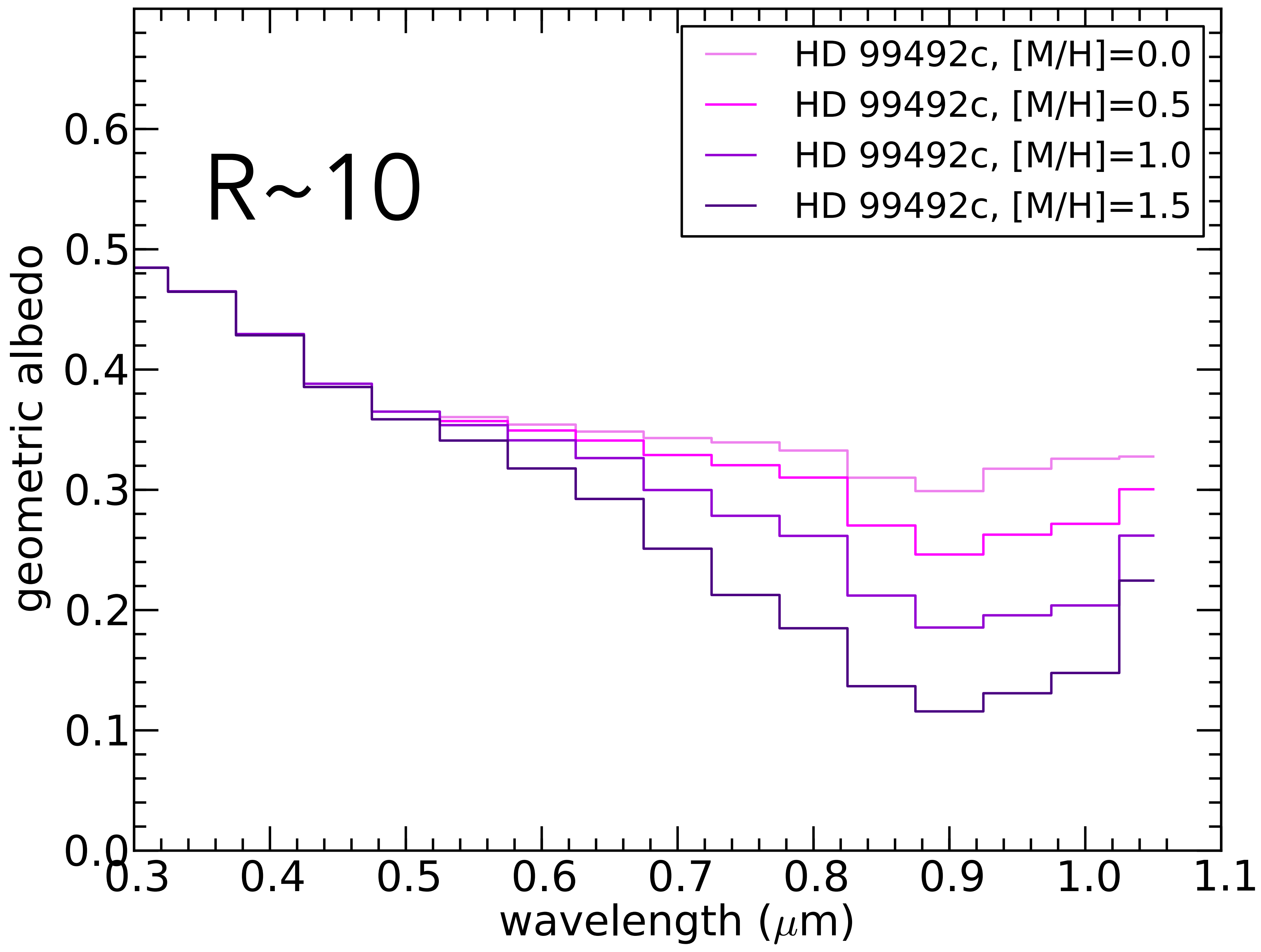

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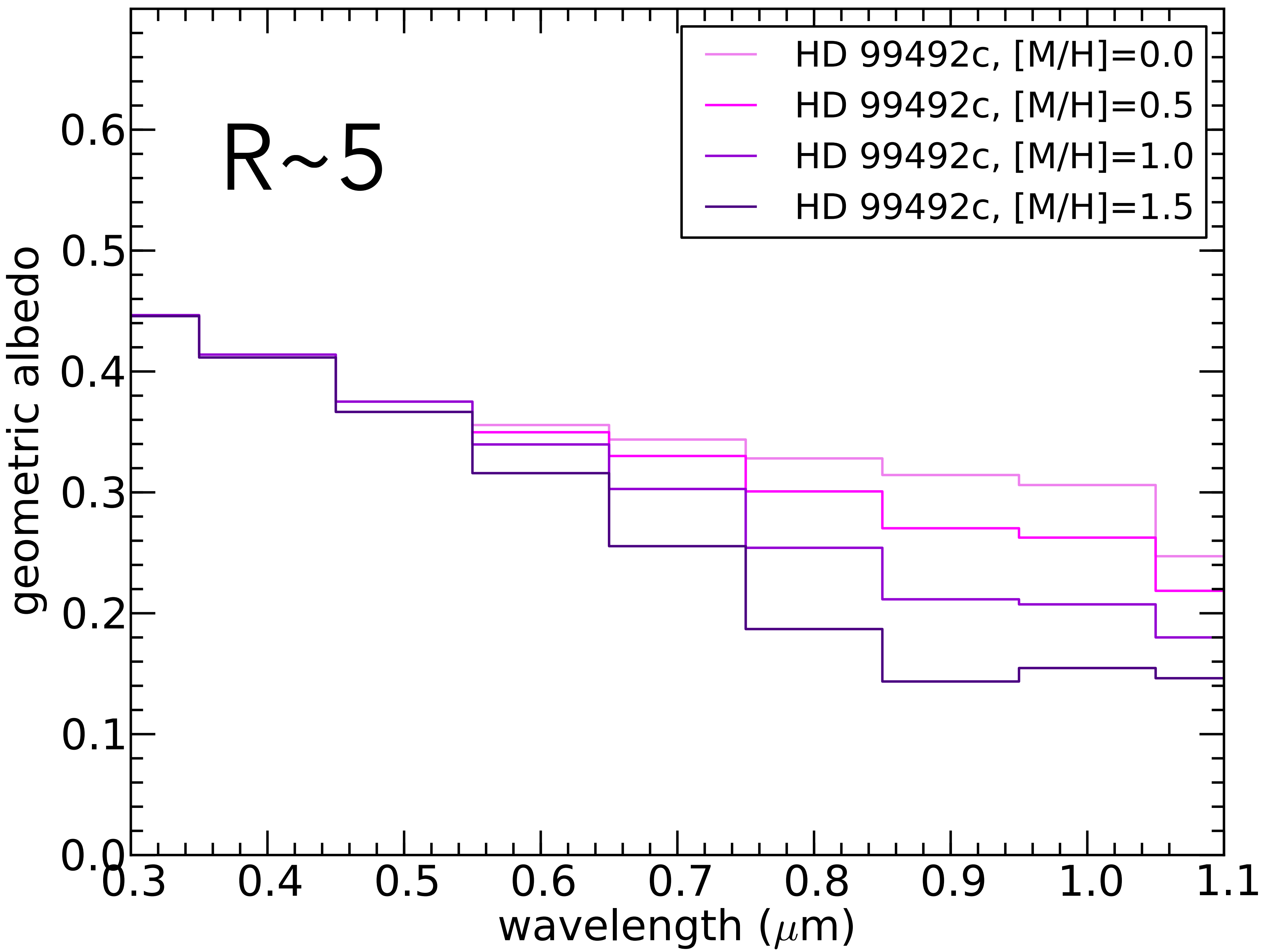
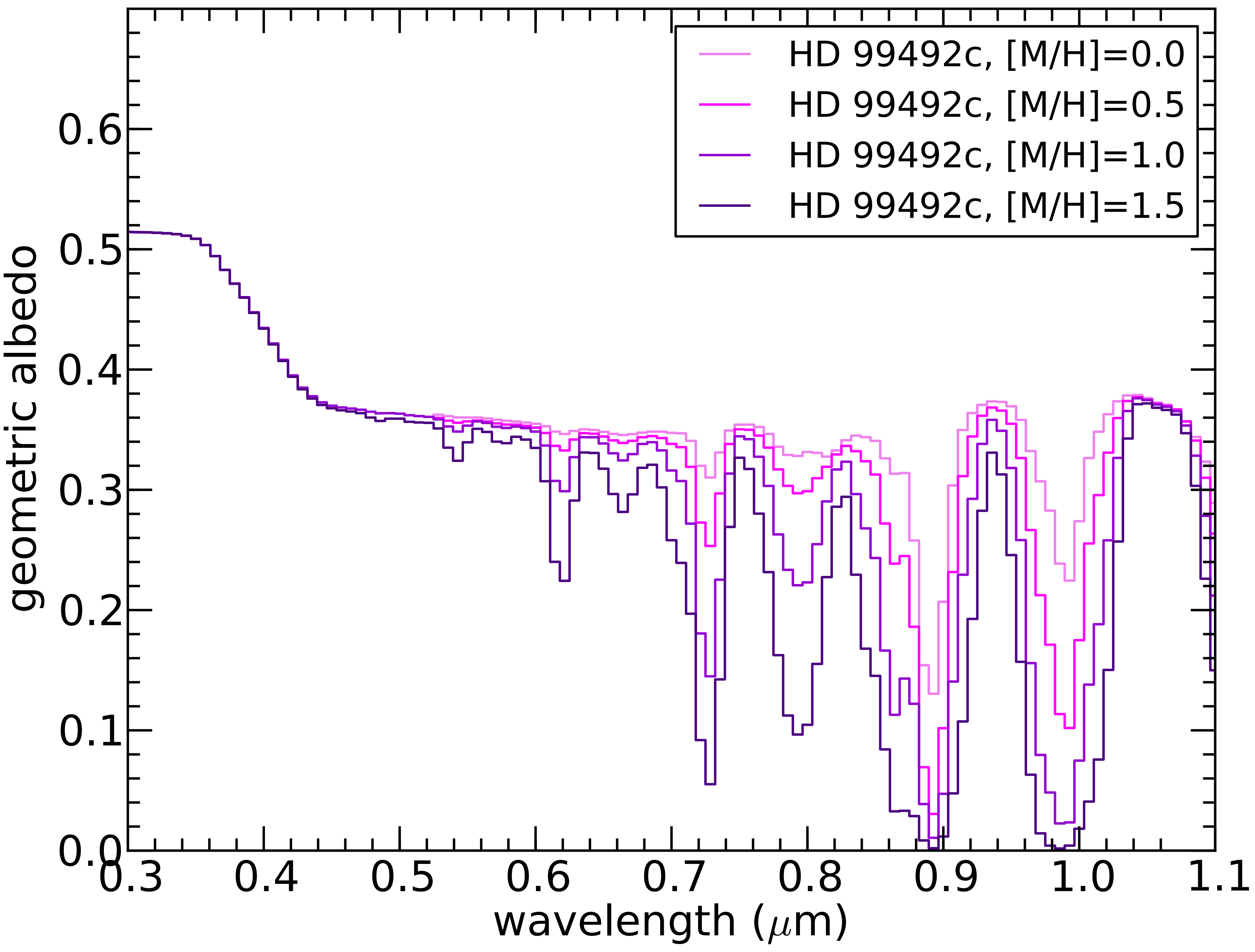


R~70 adequately samples several methane features.



We can apply powerful retrieval techniques to low SNR data to constrain CH_4, clouds, etc.

See Roxana's poster here!!!

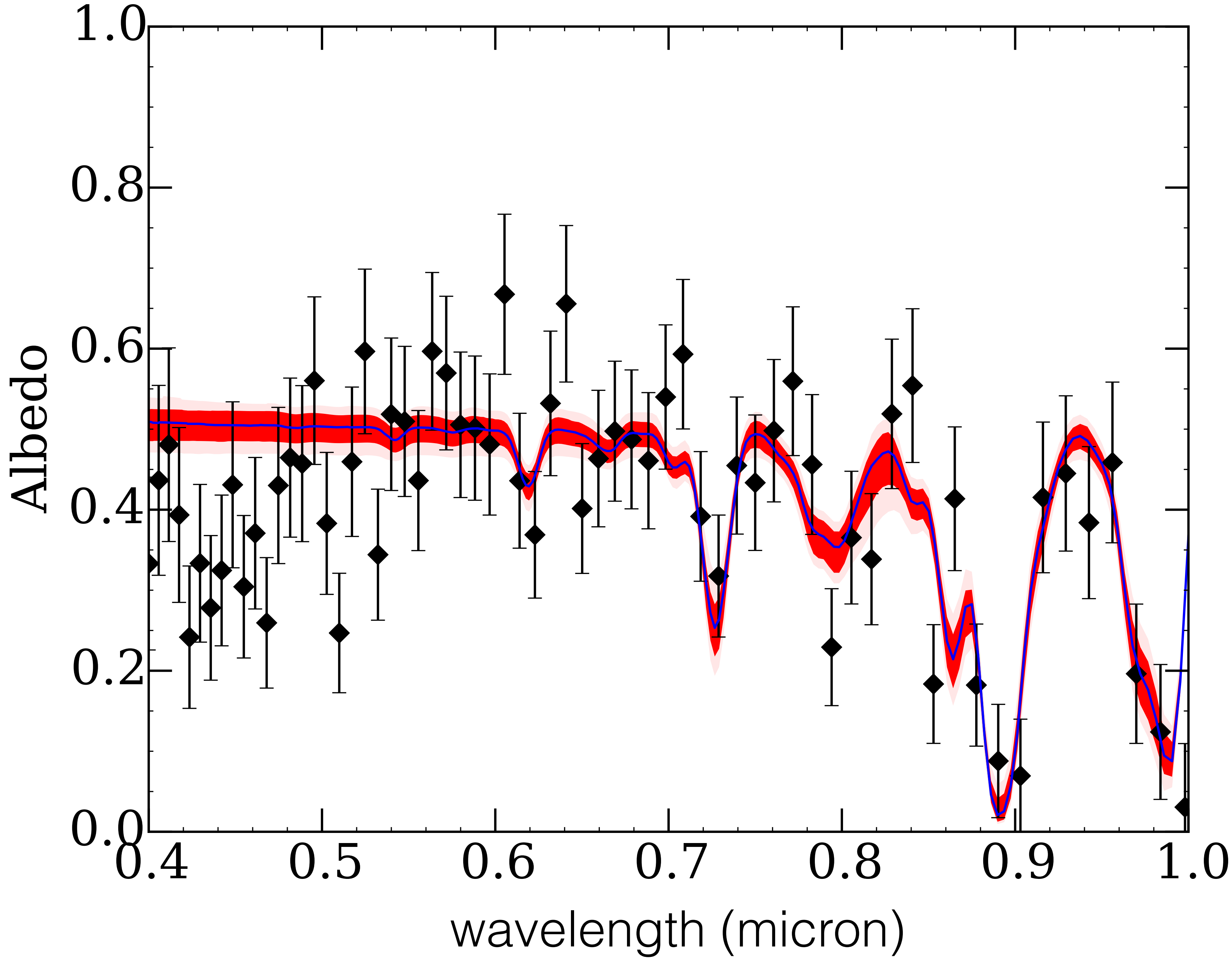
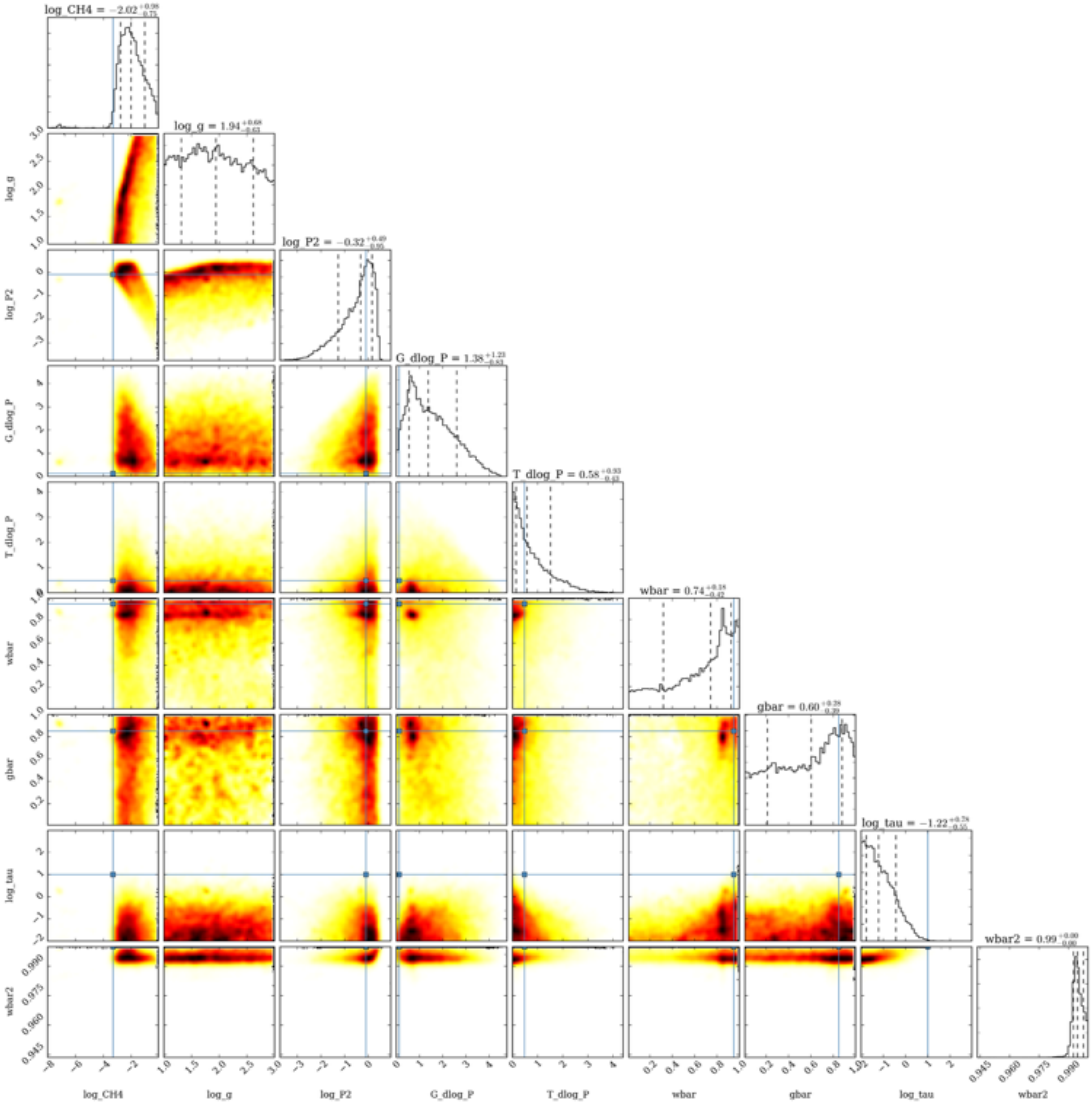


Figure from Roxana Lupu

Observed Jupiter spectrum with added noise to make SNR=5

Karkoschka 1994 spectrum



Figures from Roxana Lupu

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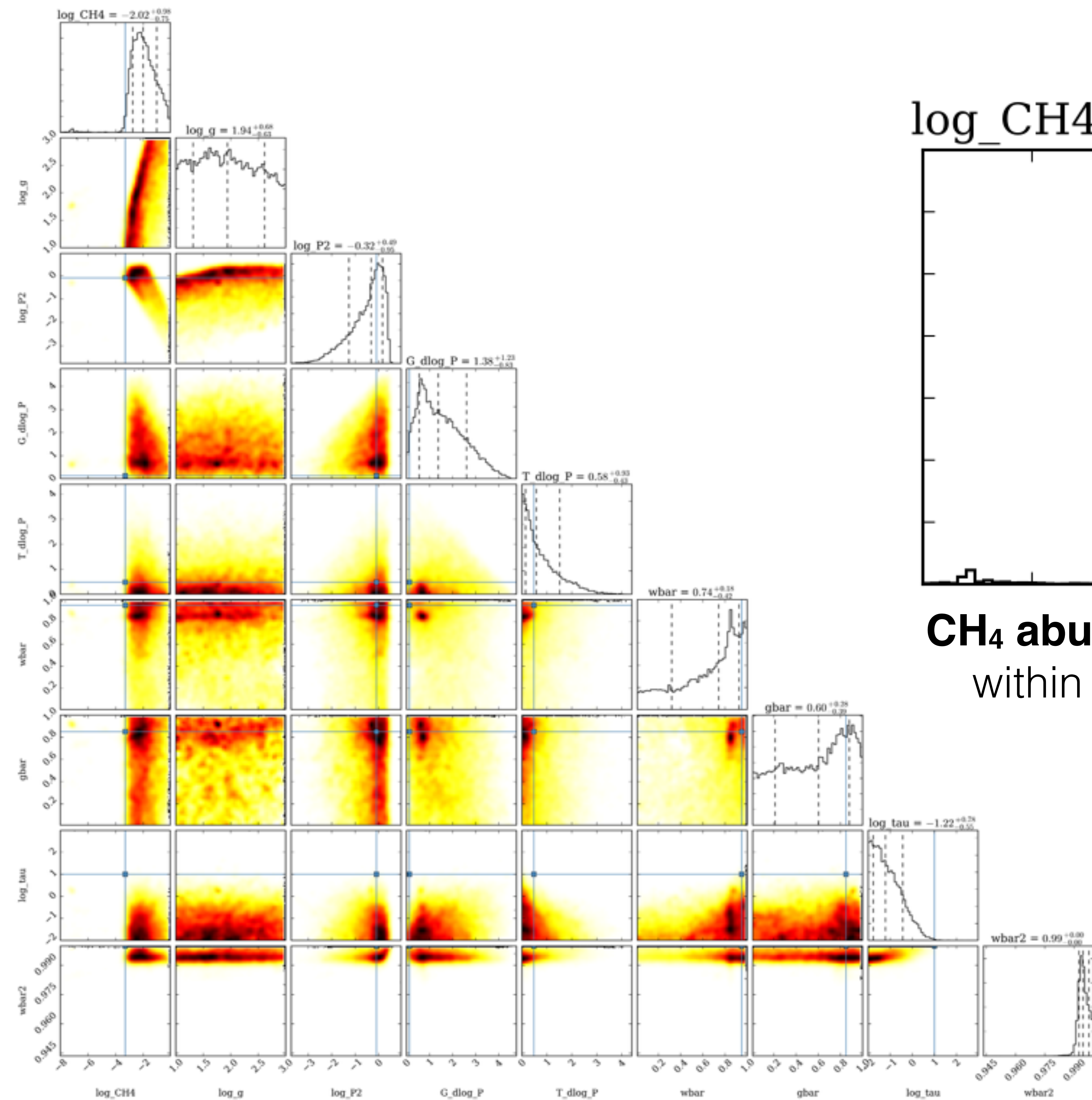

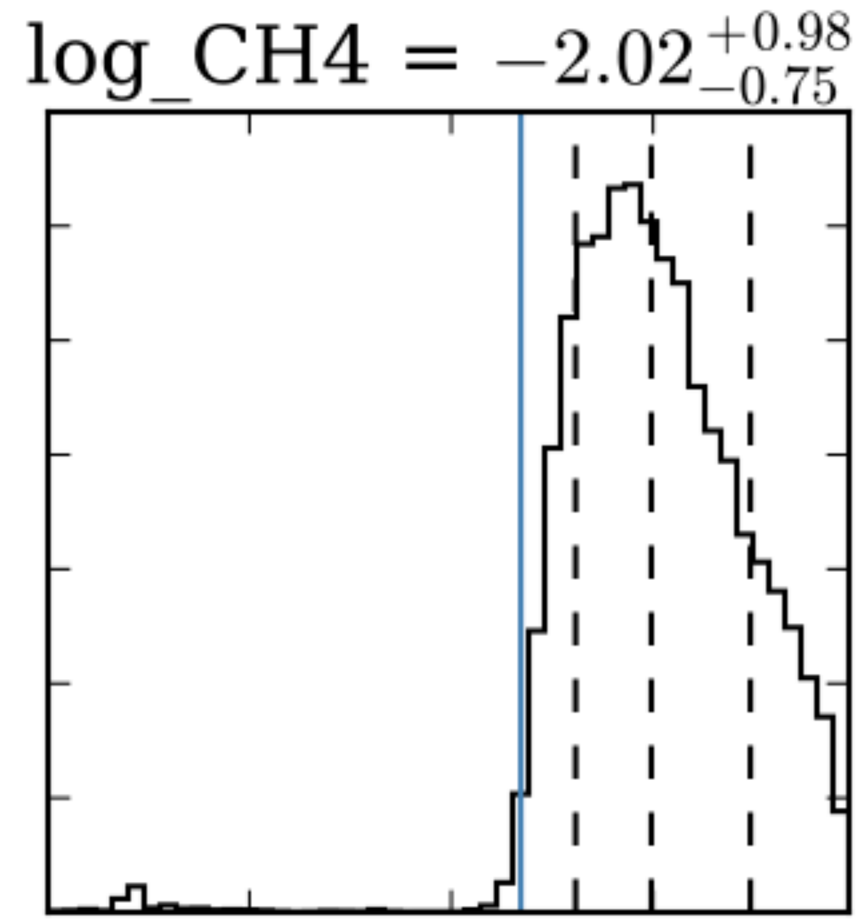

CH_4 abundance (right within one sigma)

Figures from Roxana Lupu

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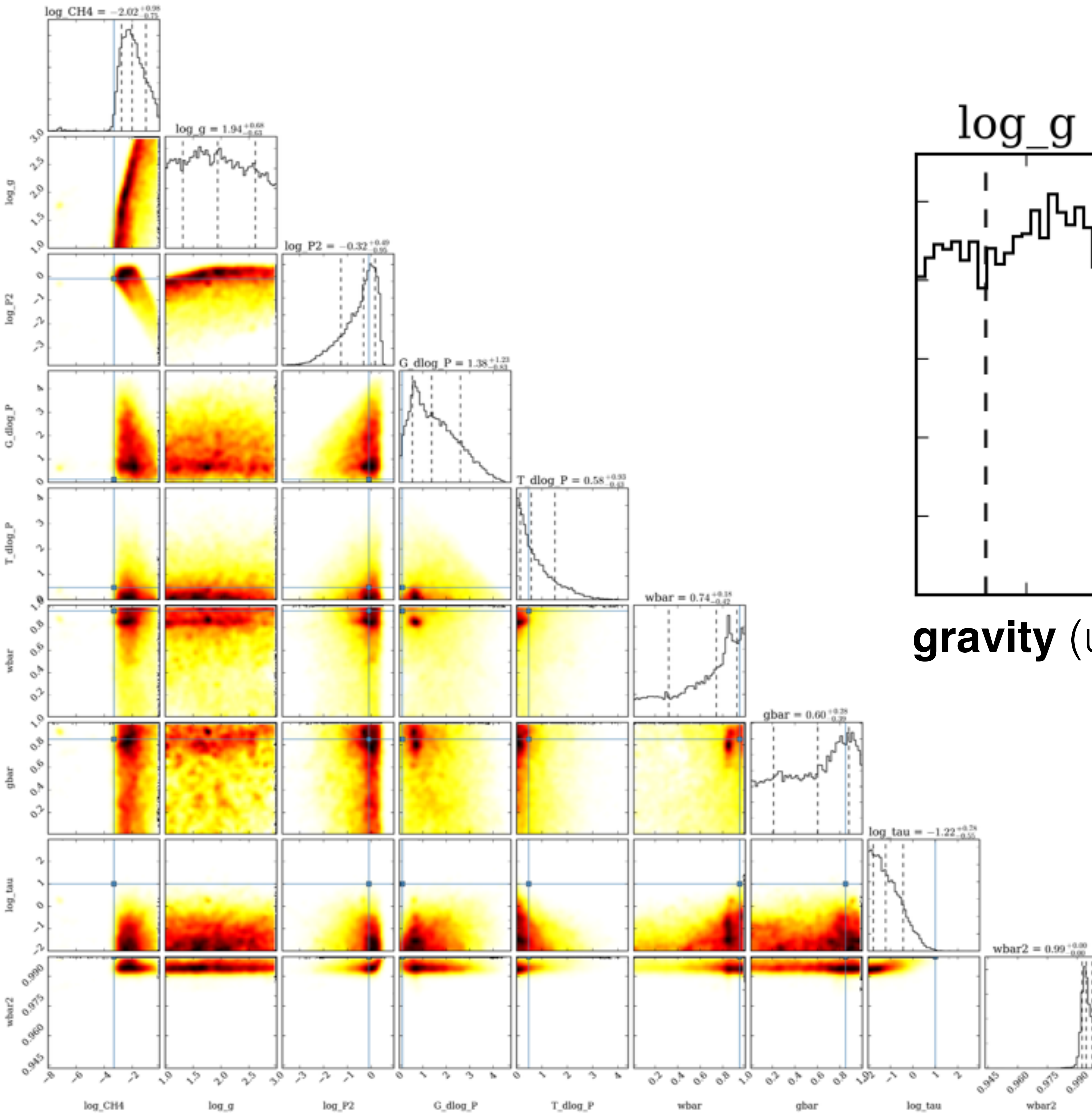
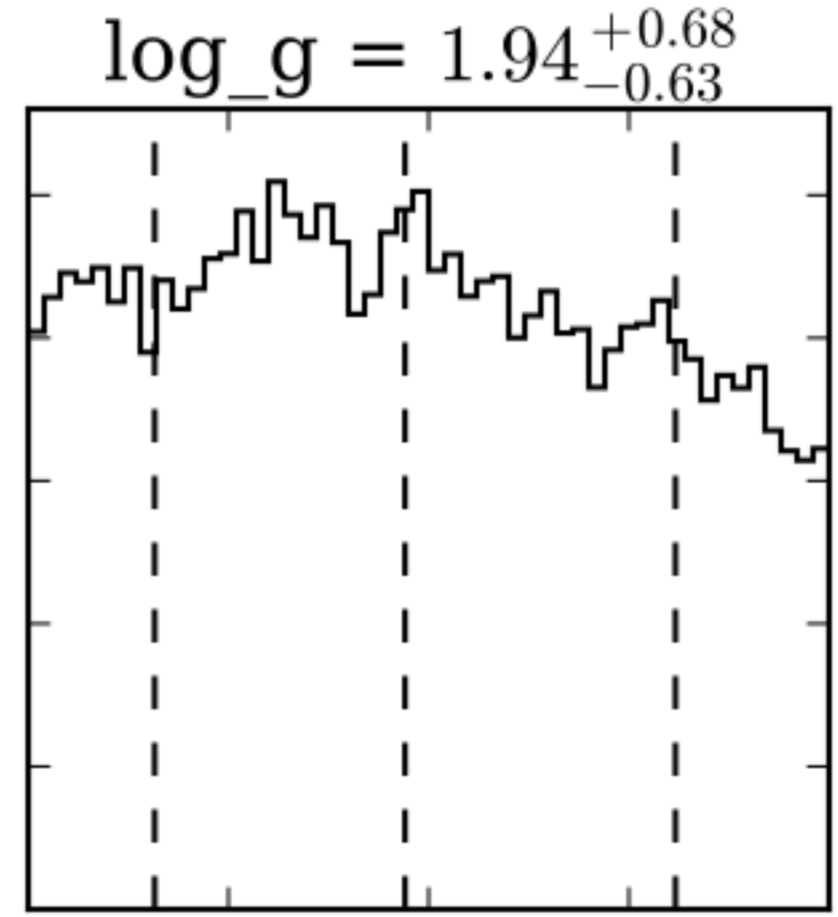
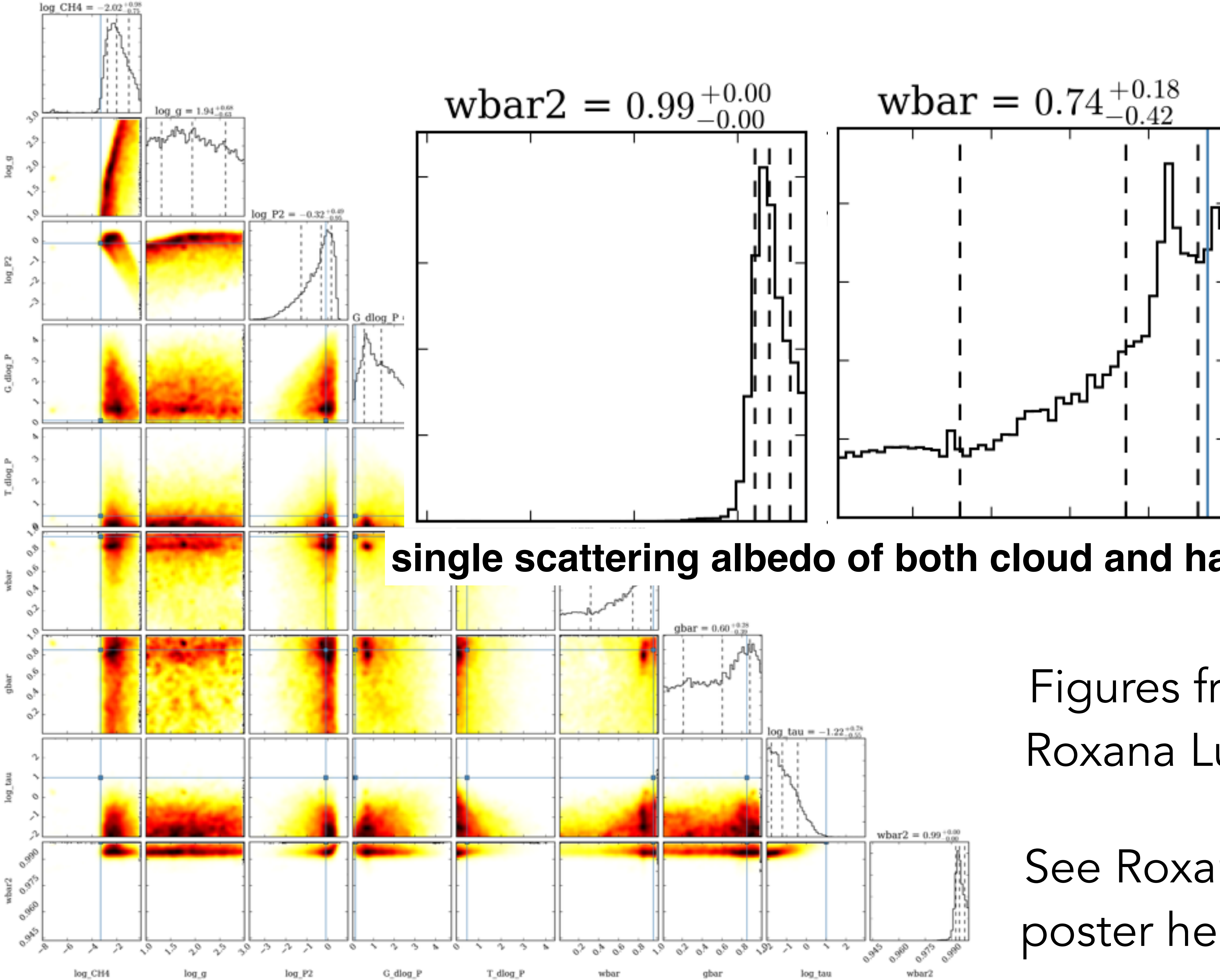




gravity (unconstrained)

Figures from Roxana Lupu

See Roxana's poster here!!!

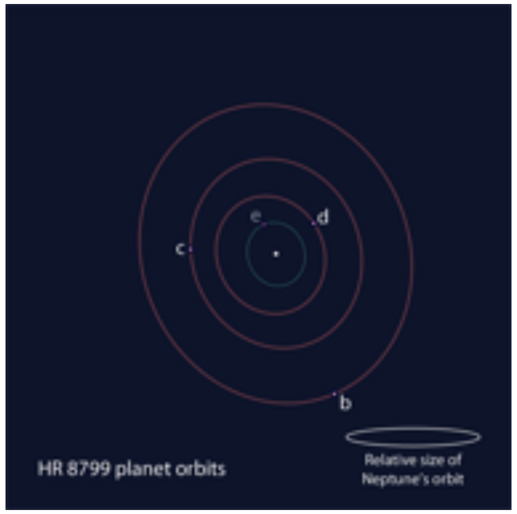


single scattering albedo of both cloud and haze

Figures from Roxana Lupu

See Roxana's poster here!!!

Radial velocities give us critical information for understanding these planets.



NASA, ESA, and R. Soummer (STScI)

orbital information:

temperature

M sin(i) → M

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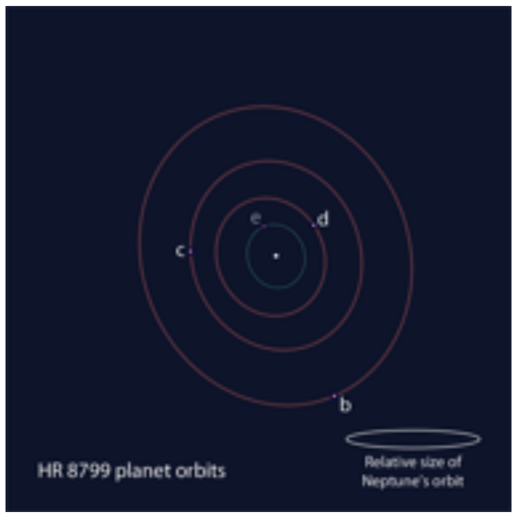

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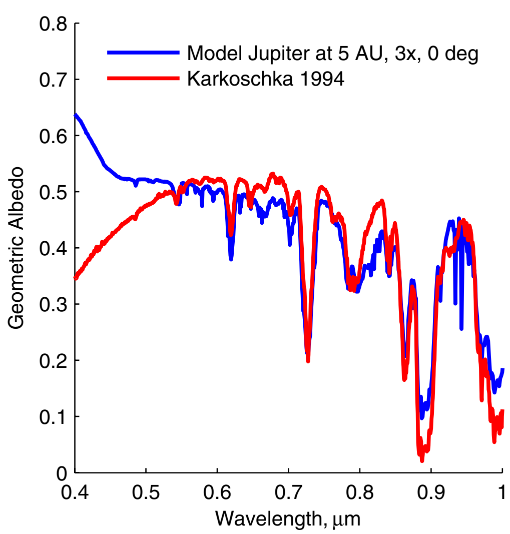

limits on radius

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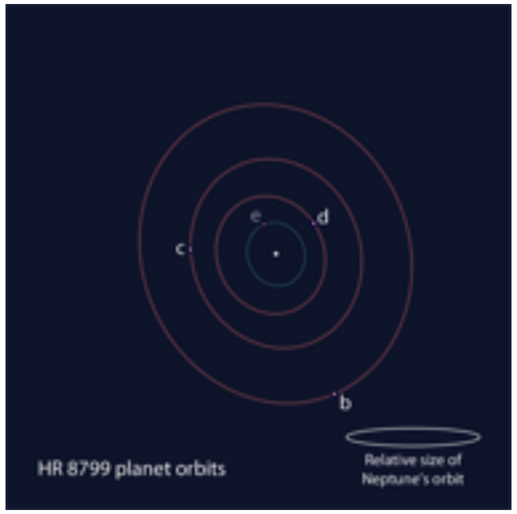

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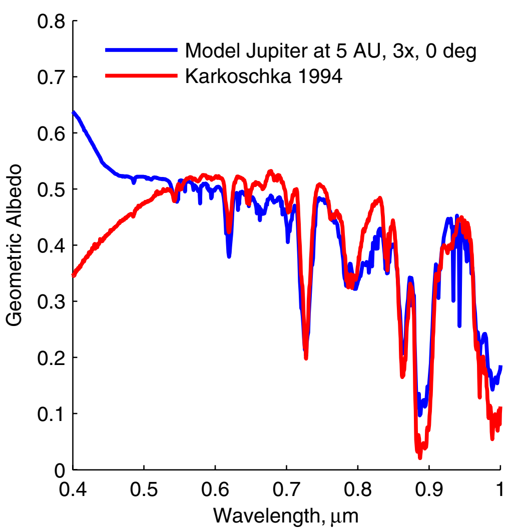

orbital information:

temperature

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limits on radius → limits on gravity

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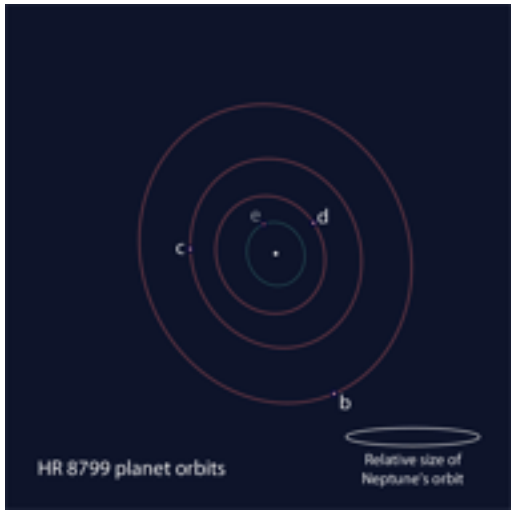

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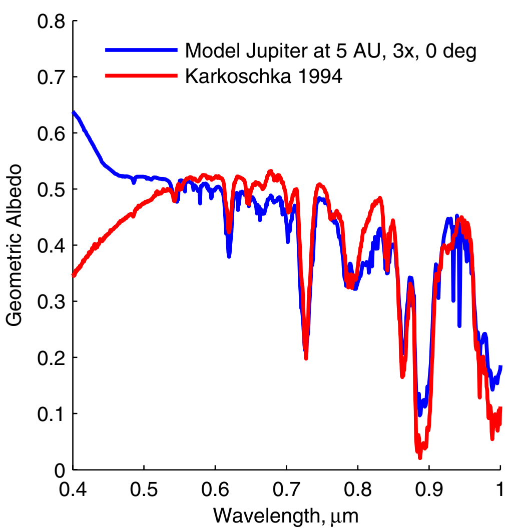

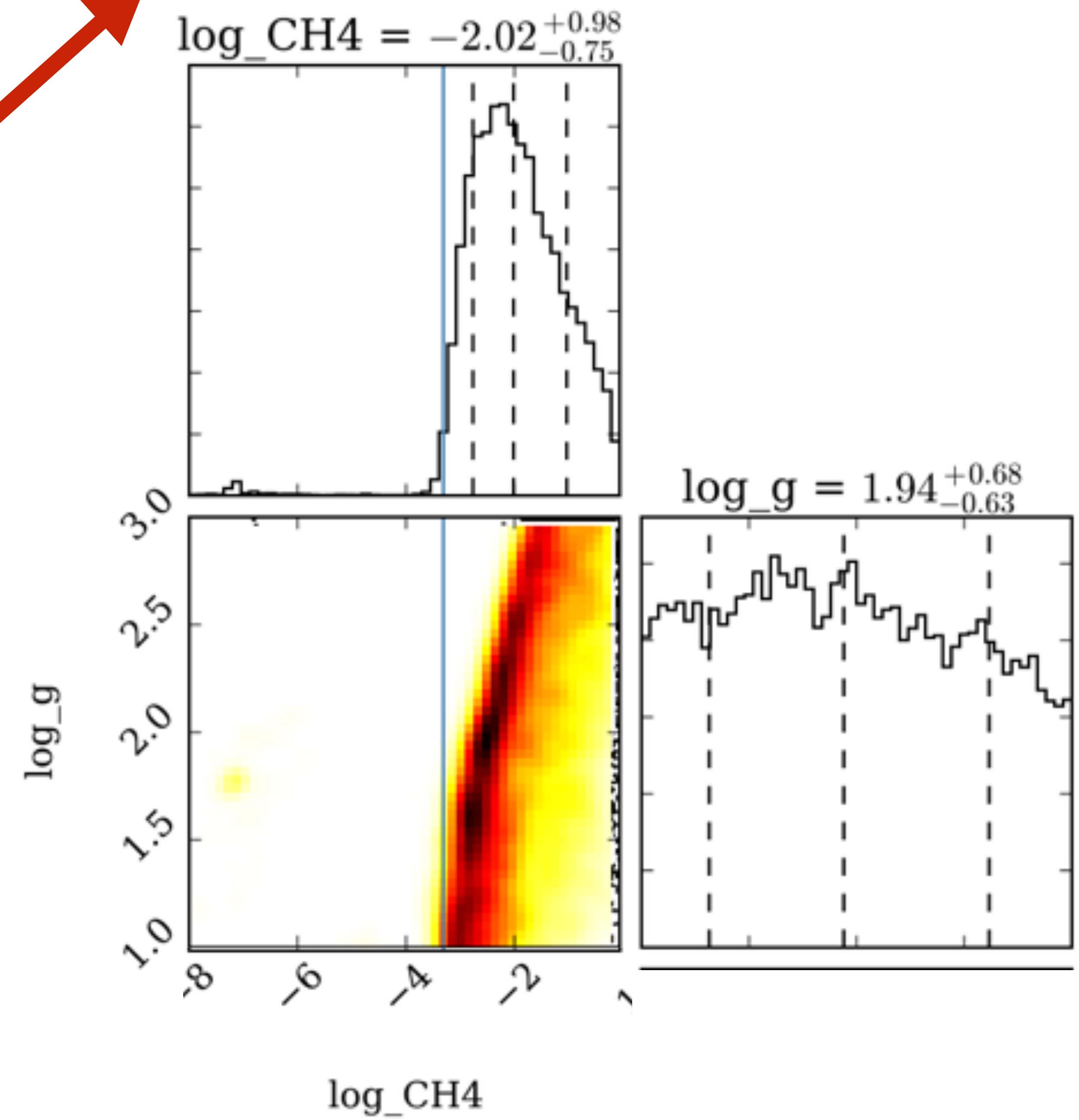

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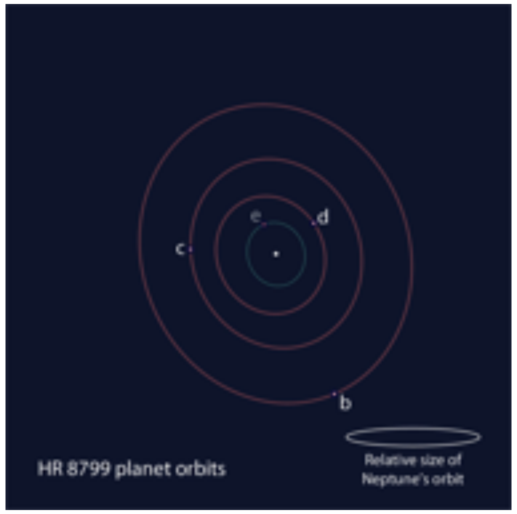

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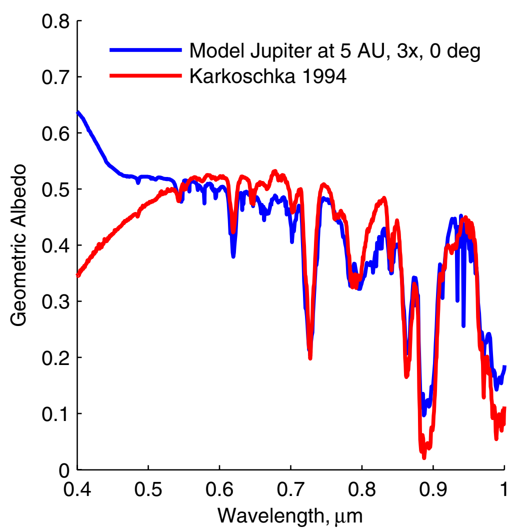

orbital information:

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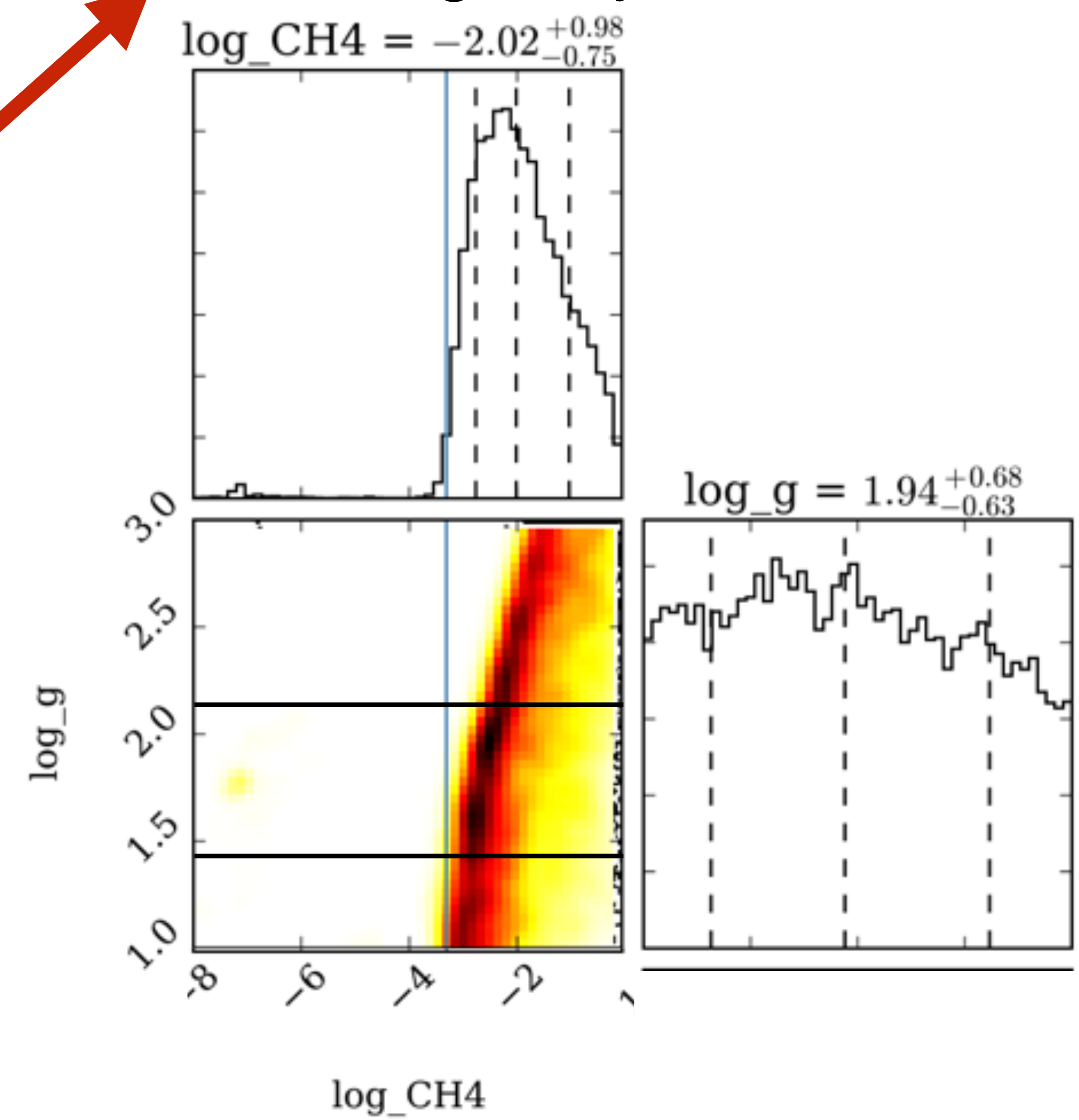
limits on radius → limits on gravity



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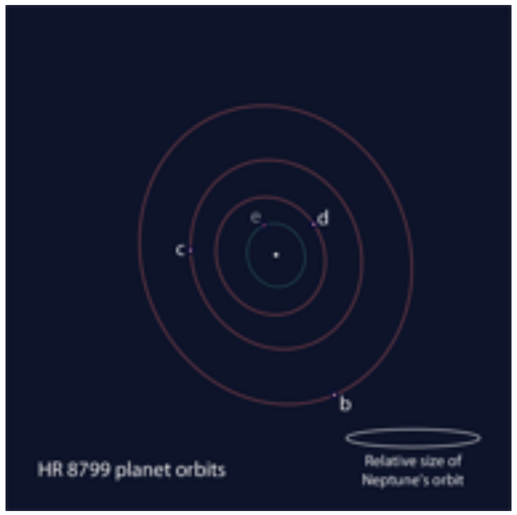
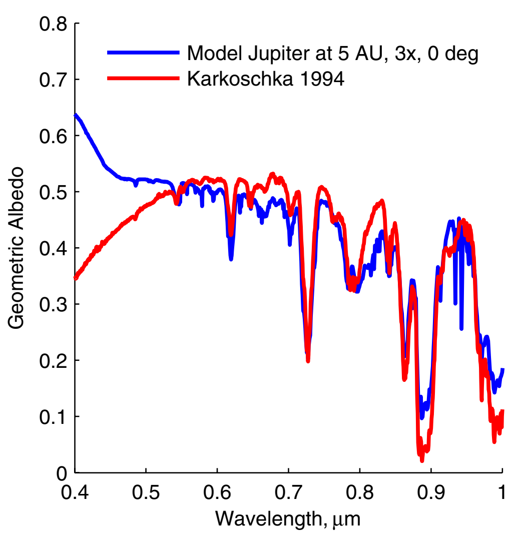


NASA, ESA, and R. Soummer (STScI)



orbital information:

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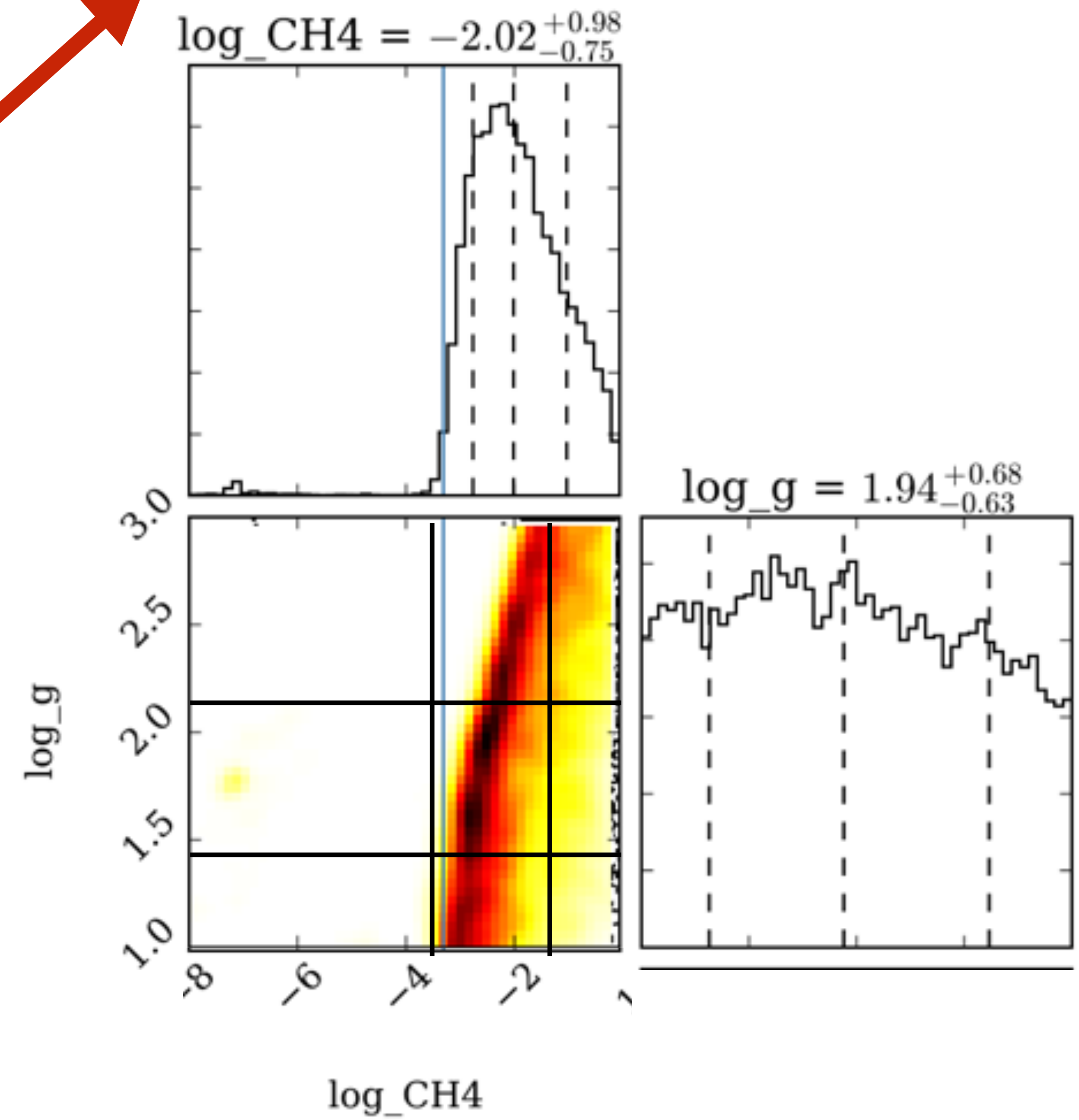
limits on radius



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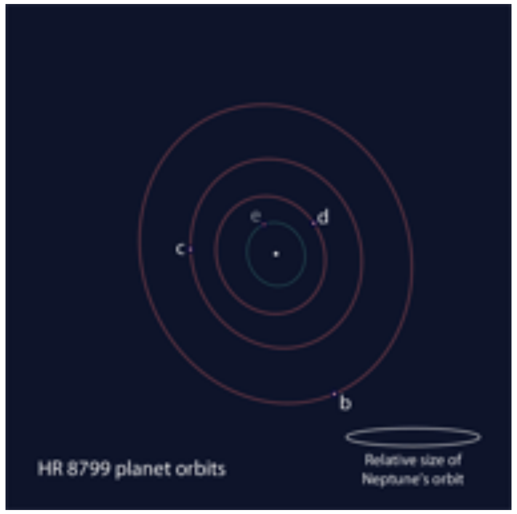

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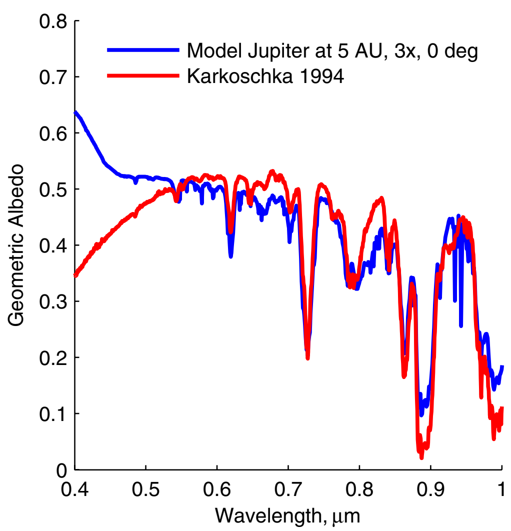

orbital information:

temperature

M sin(i) → M → limits on gravity

limits on radius → limits on gravity

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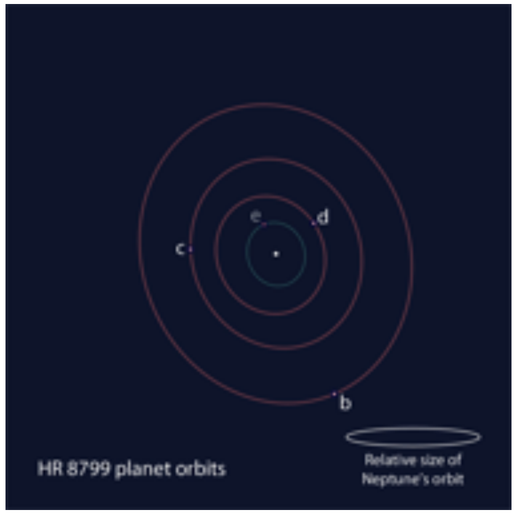

NASA, ESA, and R. Soummer (STScI)

orbital information:

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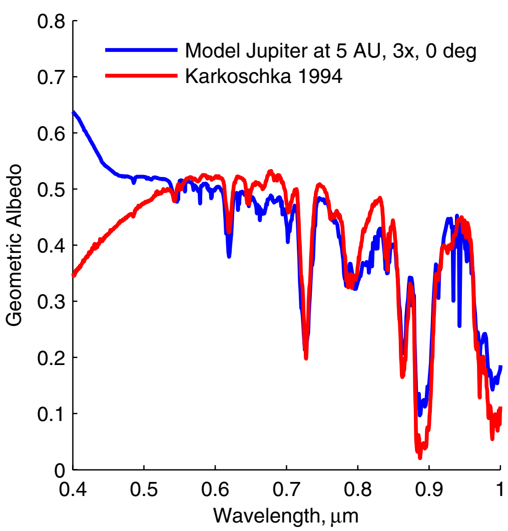

limits on radius → limits on gravity

phase information:
makes interpreting
spectra much easier

European Southern Observatory - ESO

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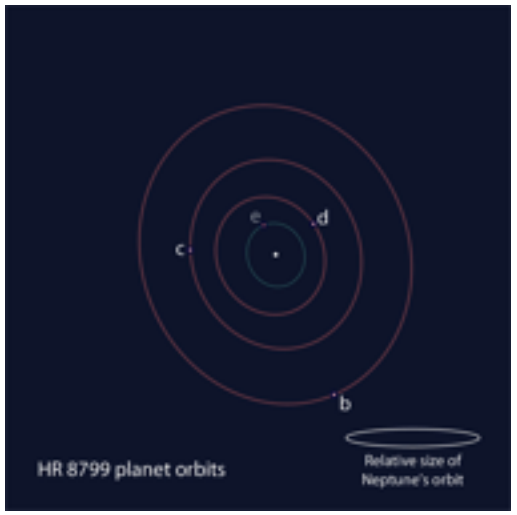

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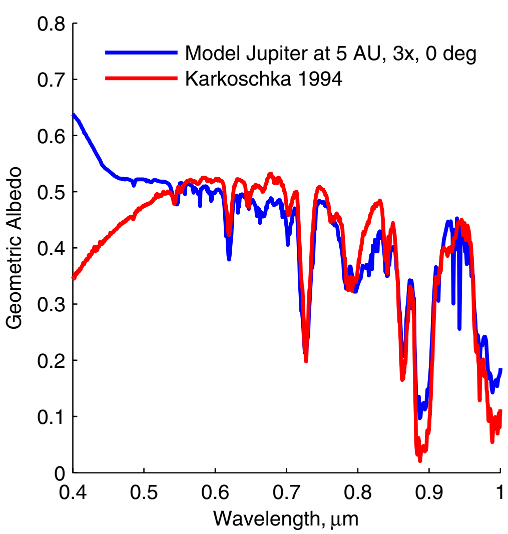

limits on radius → limits on gravity

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Information-rich set of objects

Space coronagraph gives us a catalog of RV planets that spans wide unexplored T_{eff} space.

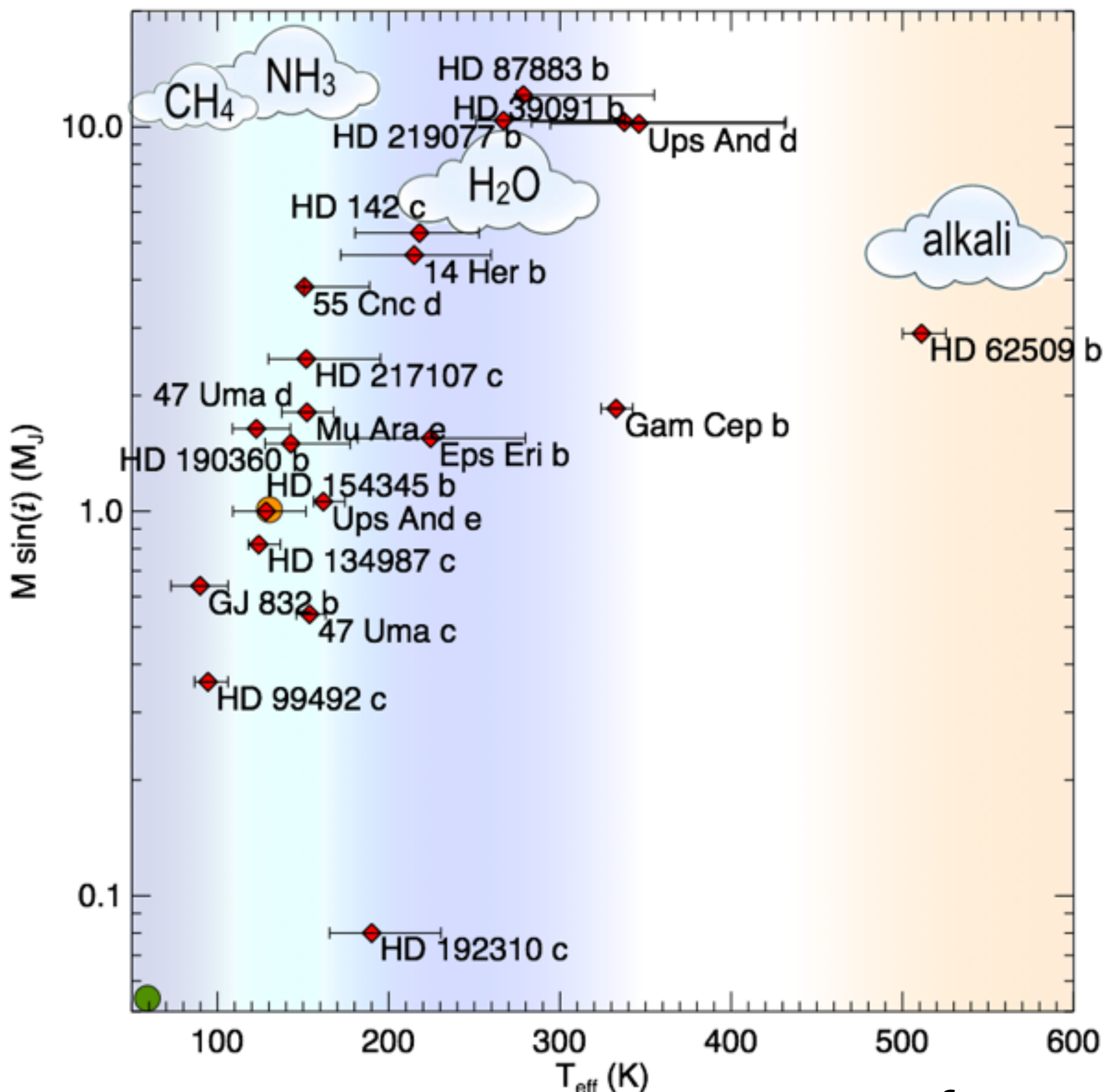

Figure from Nikole Lewis

Conclusions

- Albedo spectra finally poised to provide **powerful constraints on planet properties**
- Can retrieve methane abundance, cloud locations, cloud albedos for Jupiter-like planets
- Critical “catalog” for years to come
- RV sample provides **context for new discoveries**