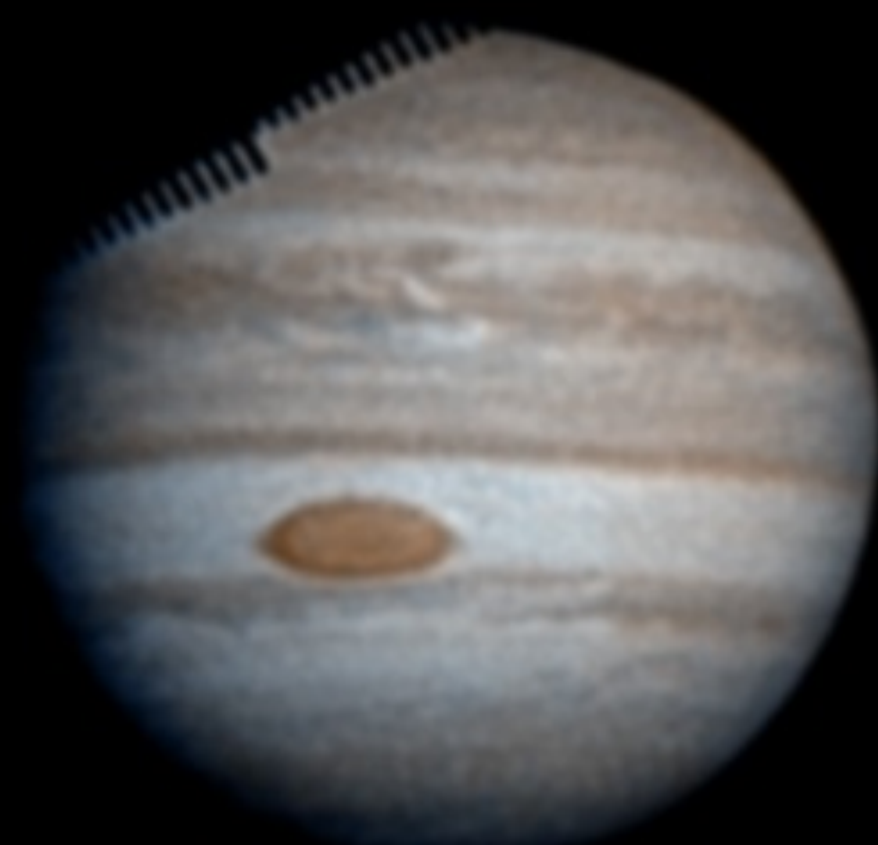
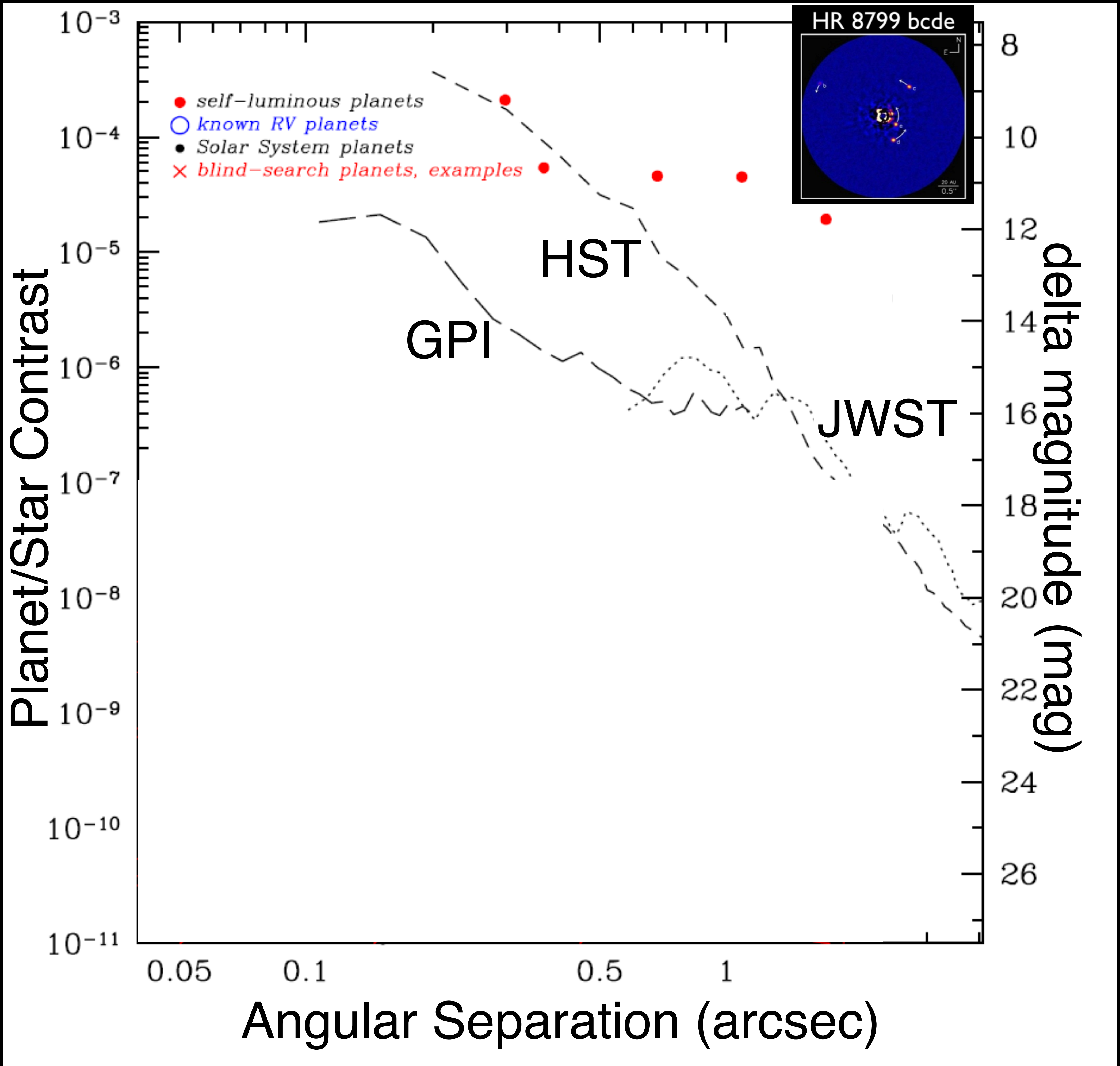
Characterizing Gas and Ice Giant Planets with LUVOIR

Mark Marley
NASA Ames Research Center

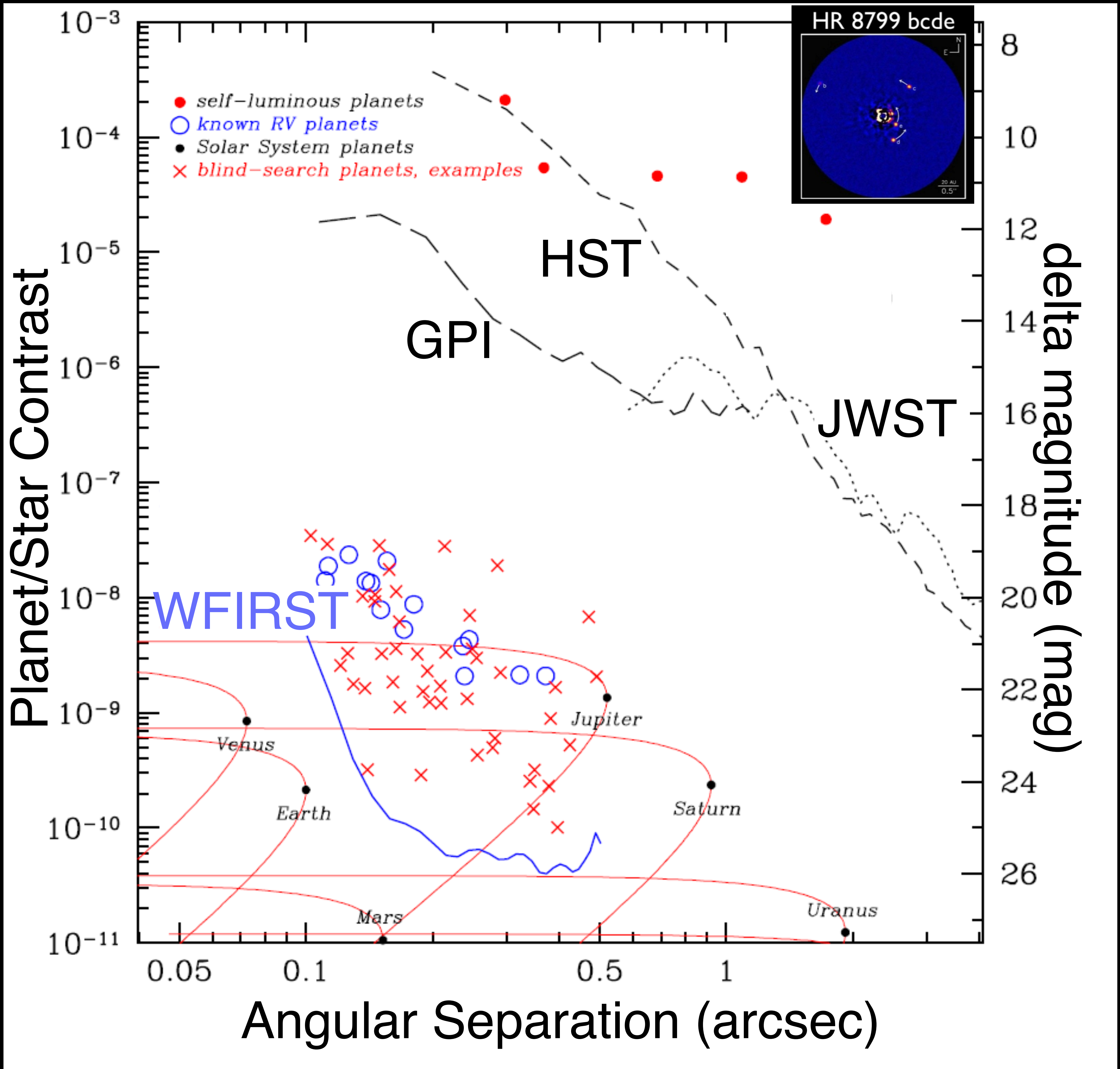


Why Giants?

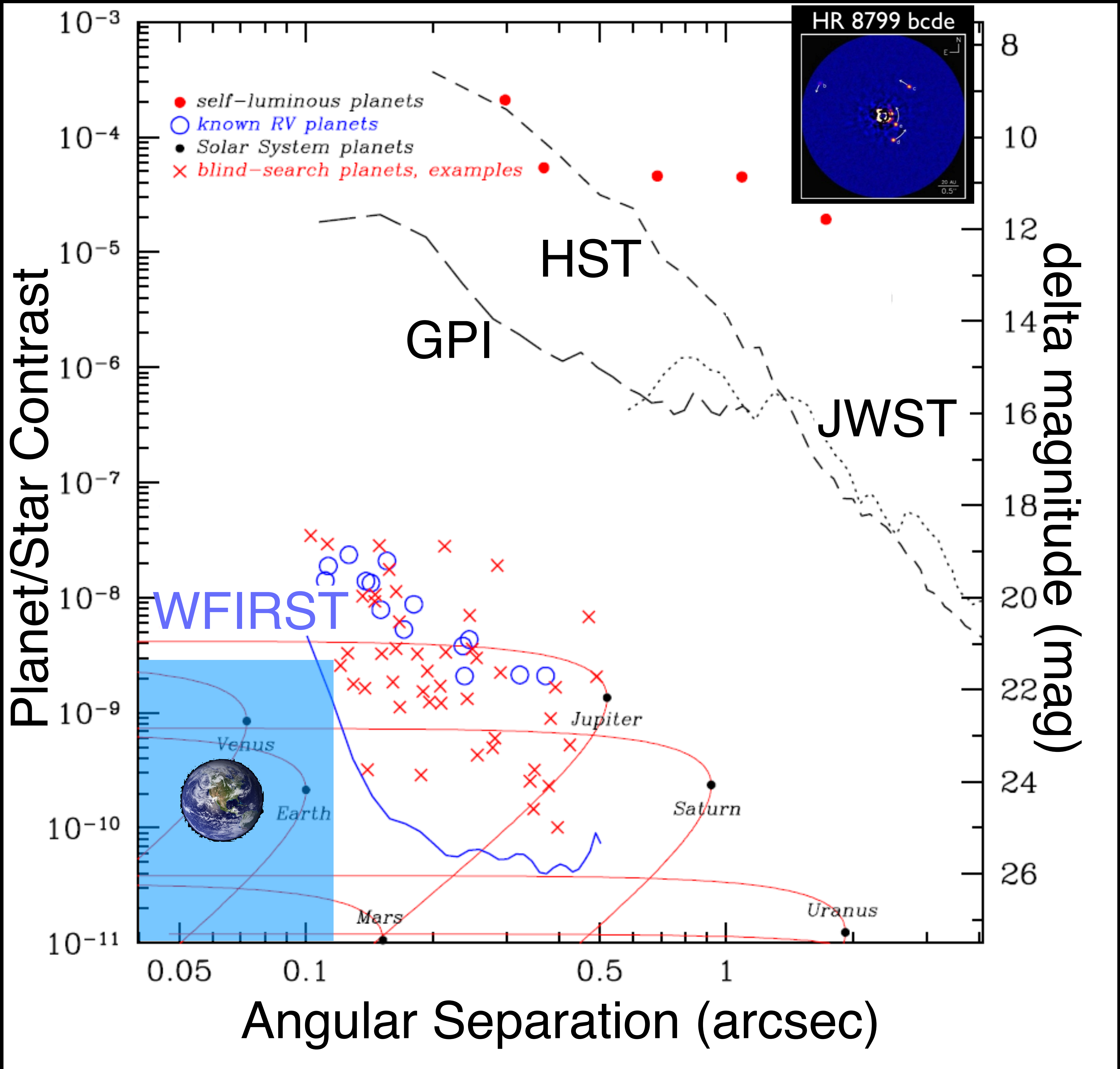
- First directly imaged planets to be characterized in reflected light
- Proving ground for many reflected light challenges (clouds, hazes, abundances, radii, gravity, T, ...)
- Context for directly imaged terrestrial worlds
- WFIRST will not do all that needs to be done



HR 8799 bcde
self−luminous planets
known RV planets
Solar System planets
blind−search planets, examples
HST
GPI
JWST
Planet/Star Contrast
delta magnitude (mag)
Angular Separation (arcsec)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.05
0.1
0.5
1
8
10
12
14
16
18
20
22
24
26



HR 8799 bcde
self-luminous planets
known RV planets
Solar System planets
blind-search planets, examples
HST
GPI
JWST
WFIRST
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Planet/Star Contrast
delta magnitude (mag)
Angular Separation (arcsec)



HR 8799 bcde
self−luminous planets
known RV planets
Solar System planets
blind−search planets, examples
HST
GPI
JWST
WFIRST
Jupiter
Saturn
Uranus
Mars
Venus
Earth
Planet/Star Contrast
delta magnitude (mag)
Angular Separation (arcsec)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
0.05
0.1
0.5
1
8
10
12
14
16
18
20
22
24
26

Today

- Giant planet visible spectra 101
- What do we want to know?
- How do we find out?
  - Cloud heights from narrow band images
  - Methane abundance from spectra
- What will and won't WFIRST do?
- Lessons for space based coronagraphs

Giant Planet Spectra 101

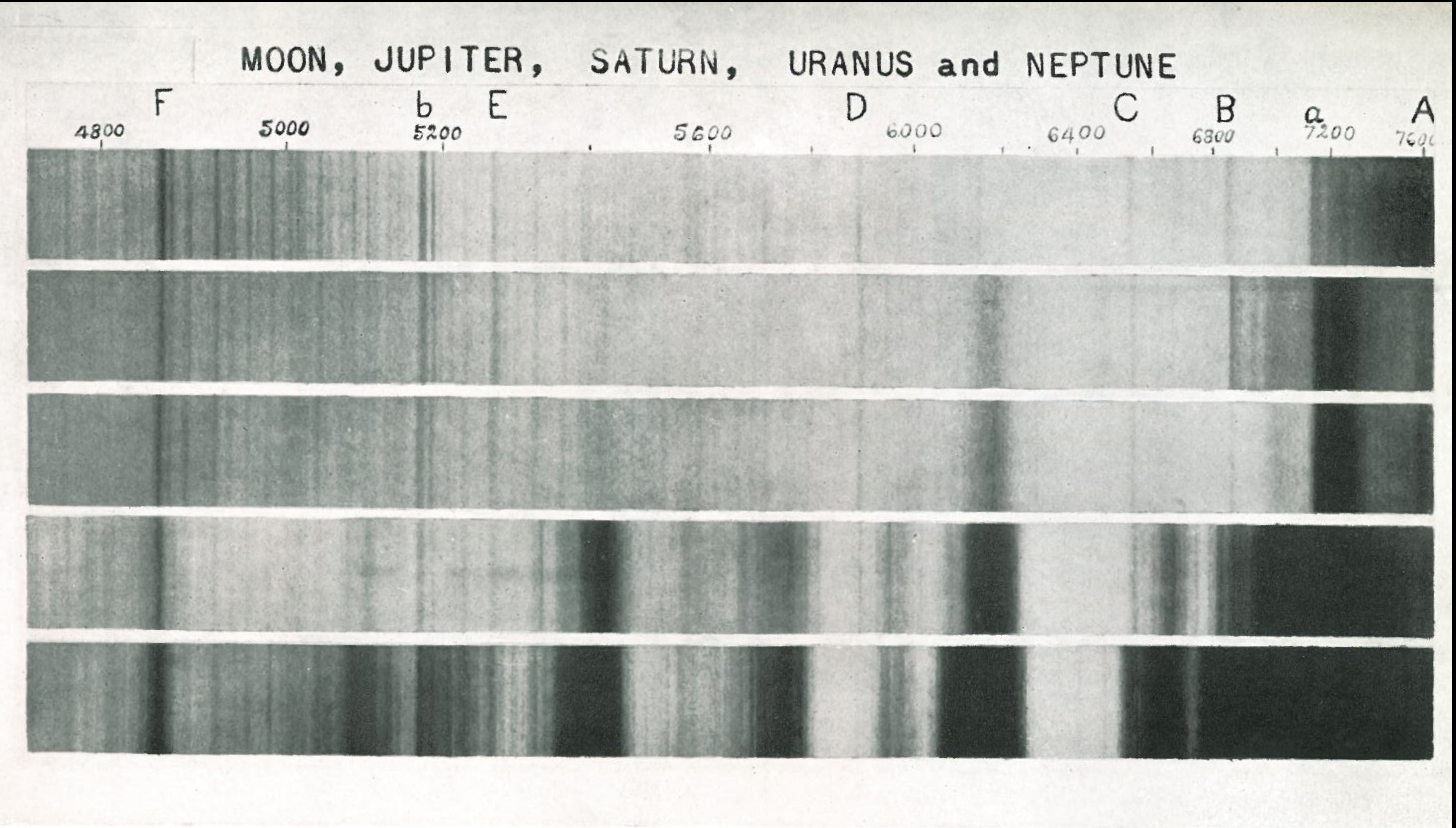
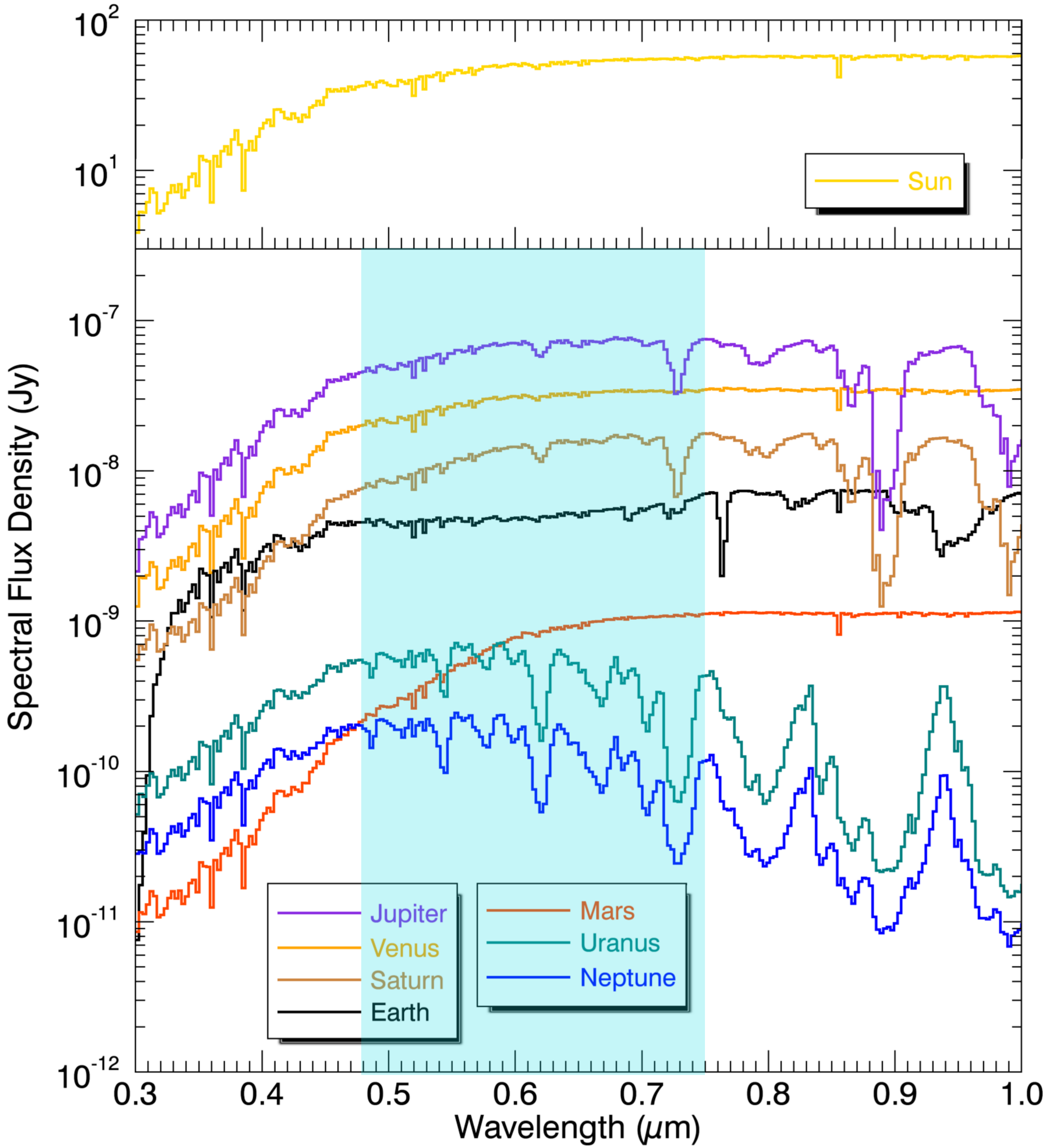
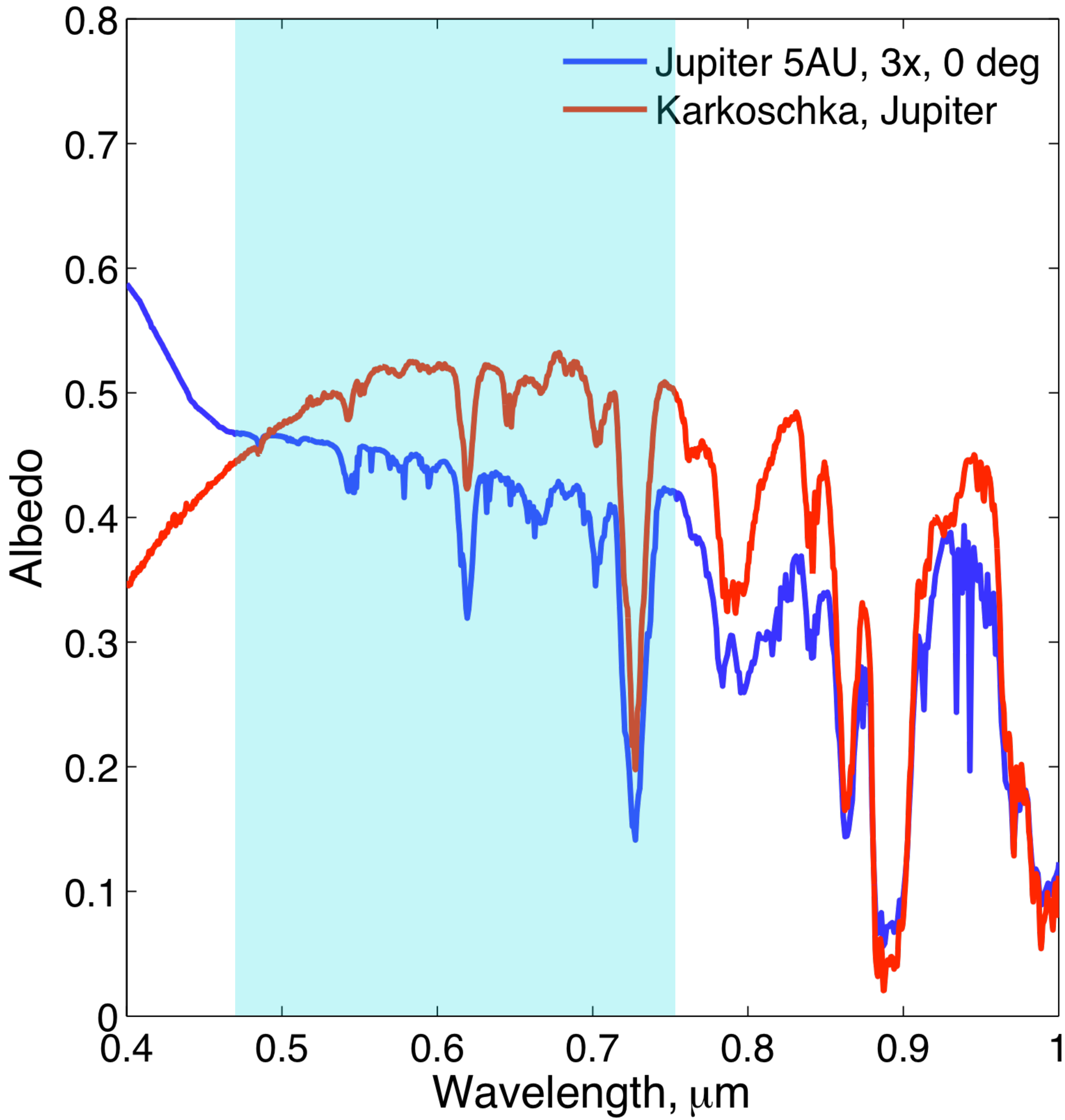


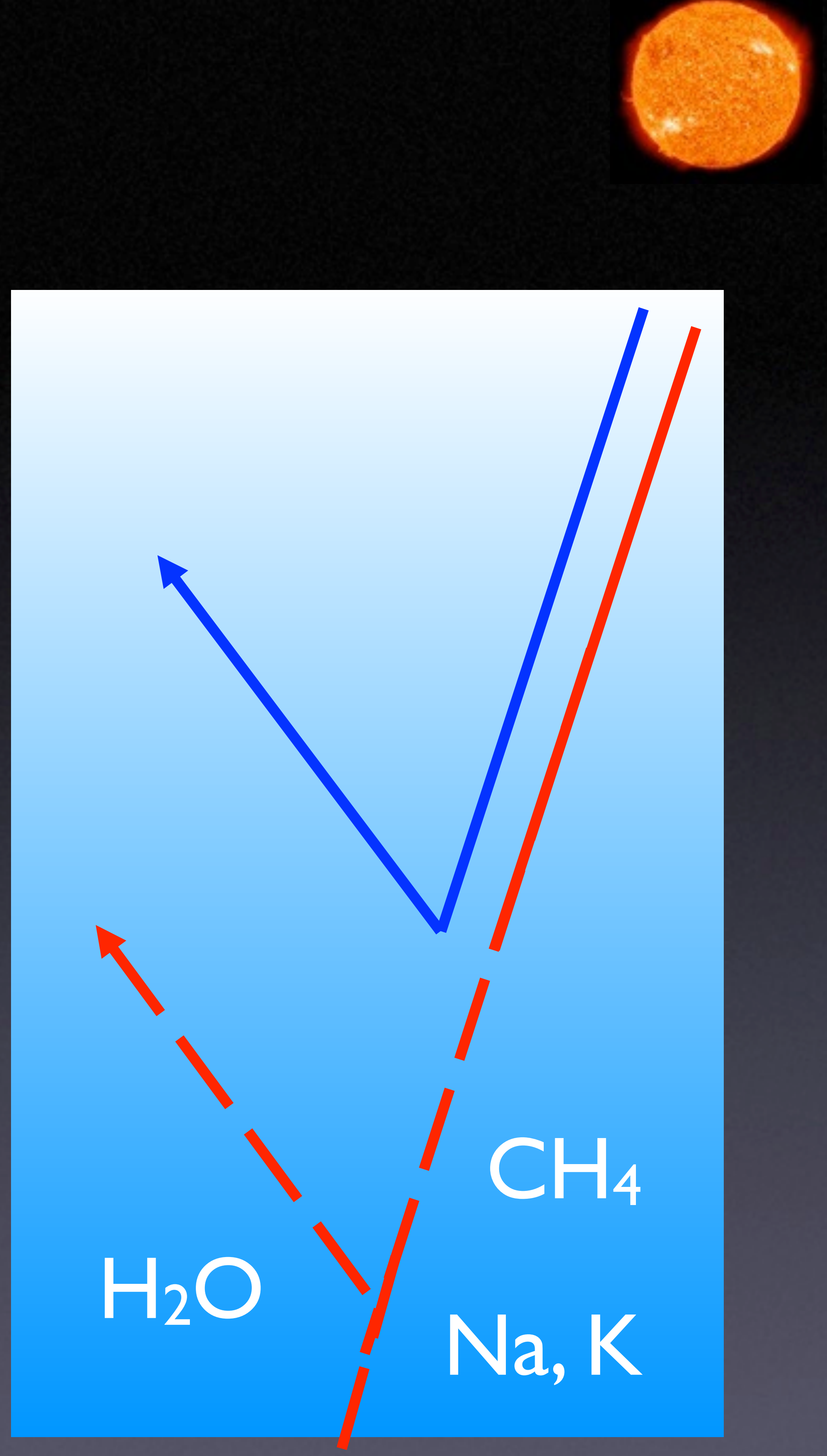
PLATE V.—V. M. Slipher: Photograph of spectra 1909 of (top line) Moon, (2) Jupiter, (3) Saturn, (4) Uranus, (5) Neptune. (From *Lowell Observatory Bulletin* 42; electro supplied by English Universities Press.)

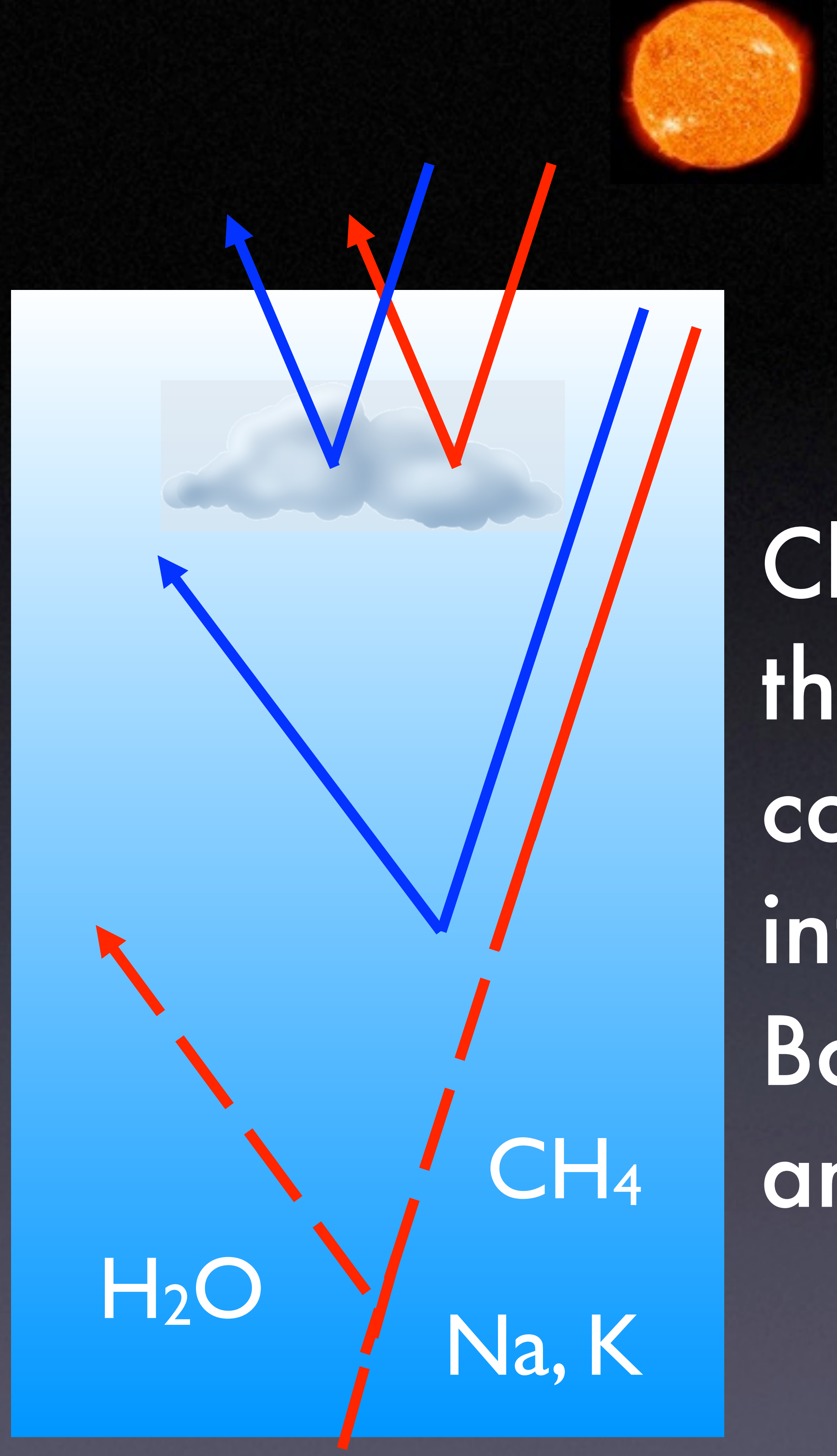


Sun
Jupiter
Venus
Saturn
Earth
Mars
Uranus
Neptune
Spectral Flux Density (Jy)
Wavelength (μm)
10^2
10^1
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

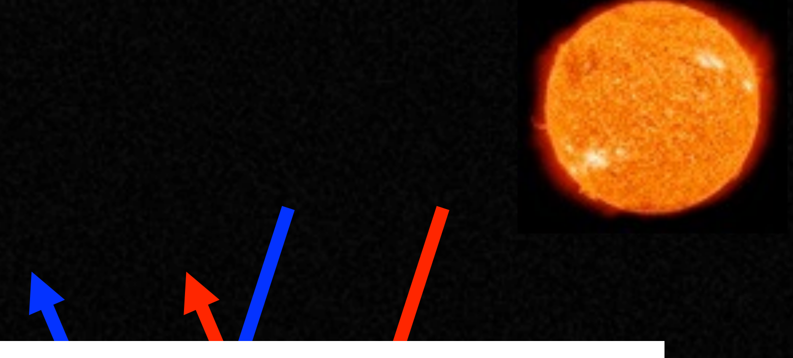


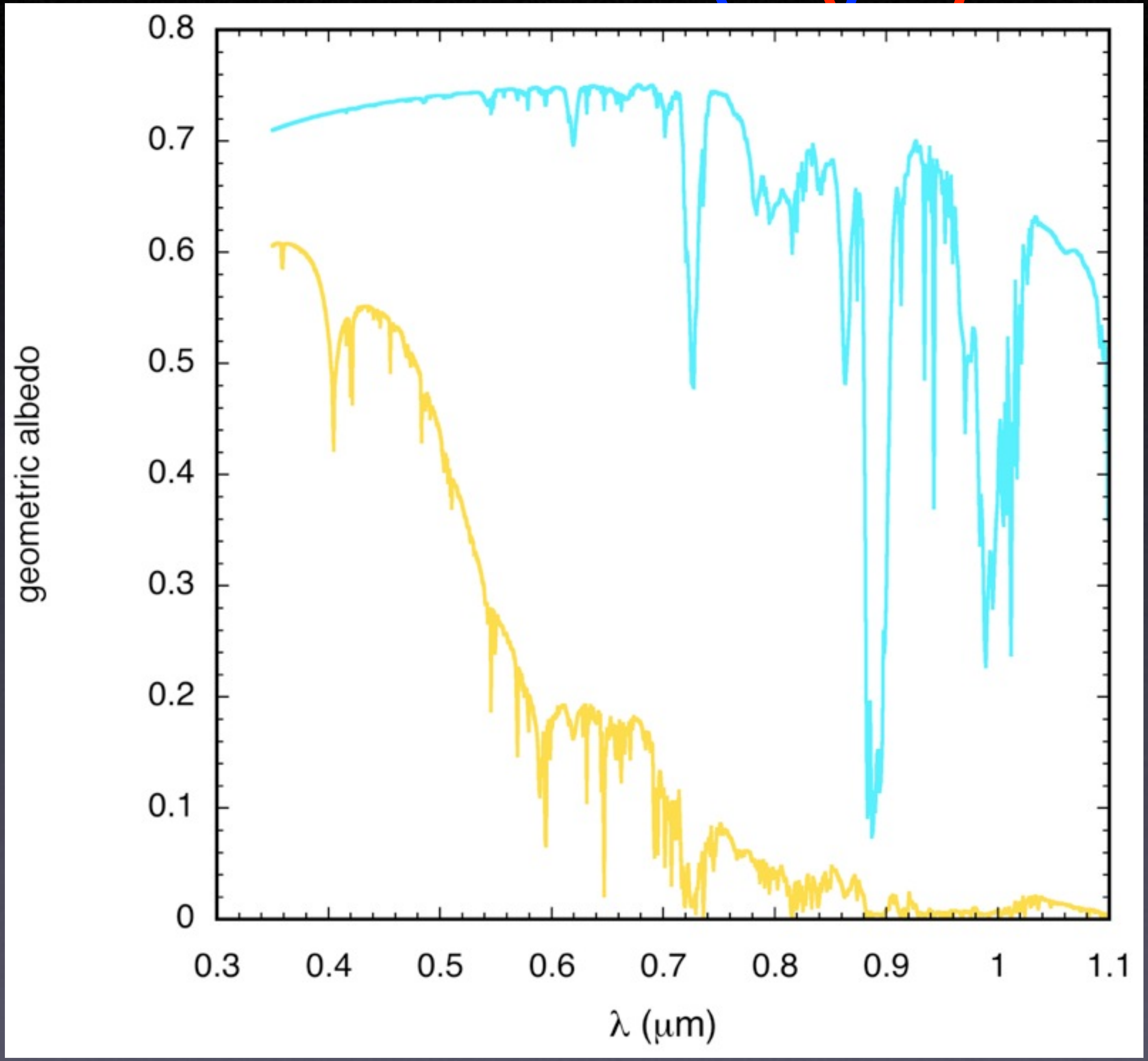
Jupiter 5AU, 3x, 0 deg
Karkoschka, Jupiter
Albedo
Wavelength, μm
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.4
0.5
0.6
0.7
0.8
0.9
1


CH_4
H_2O
Na, K



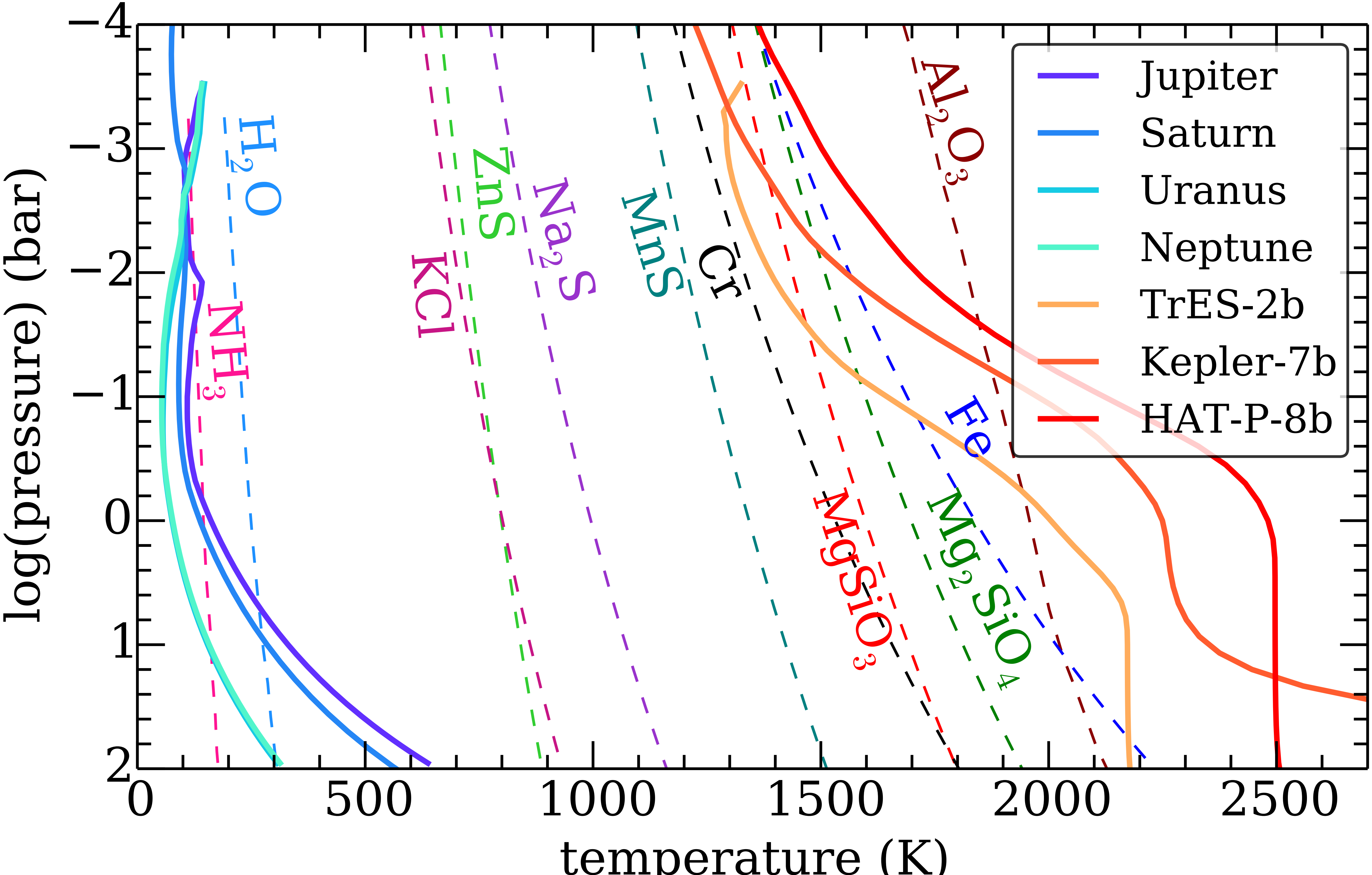
Clouds are the controlling influence on Bond Albedo and T_{eq}



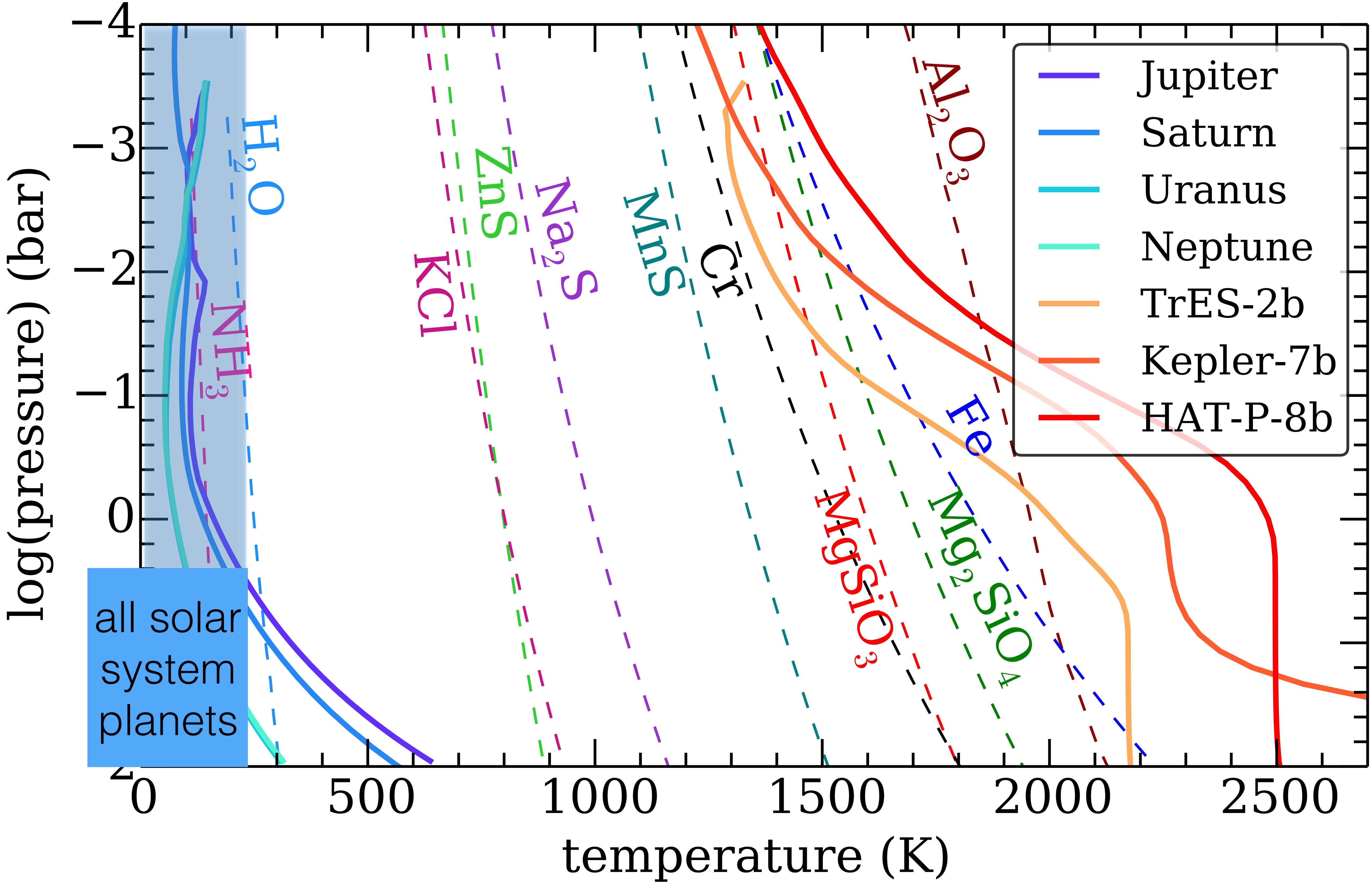


Clouds are the controlling influence on Bond Albedo and T_{eq}

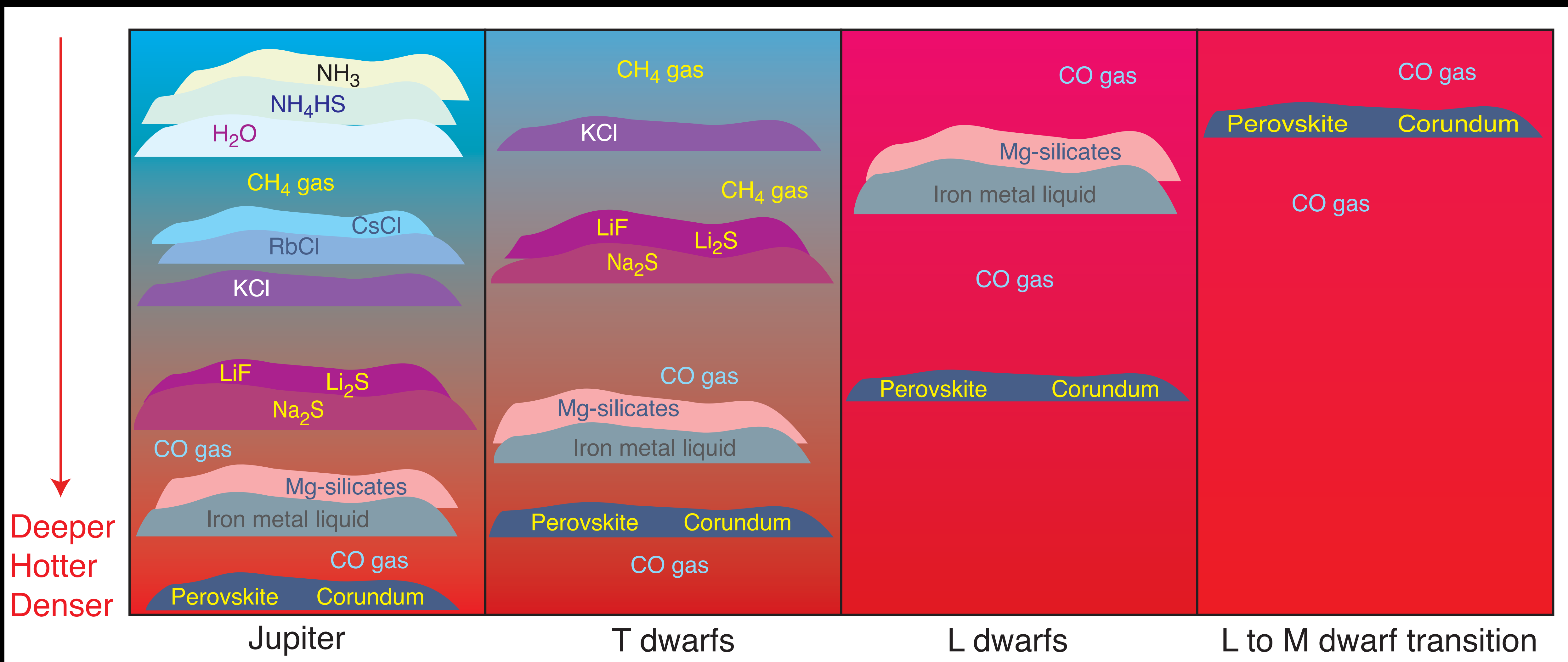
Temperature structure (set by stellar flux) controls chemistry & clouds.



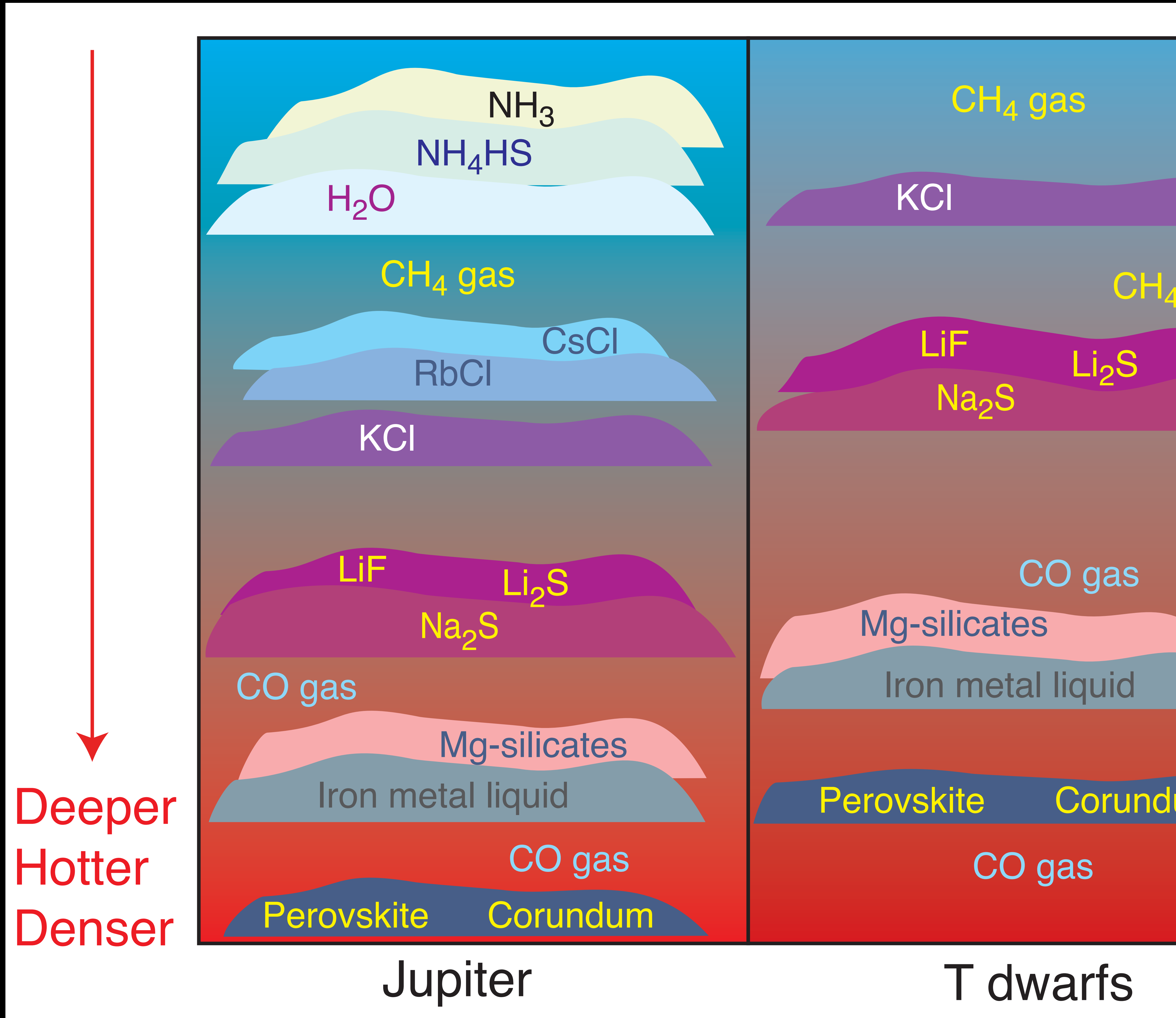
Temperature structure (set by stellar flux) controls chemistry & clouds.



Condensate Cloud Layers



Lodders (2004)



Deeper
Hotter
Denser
NH3
NH4HS
H2O
CH4 gas
CsCl
RbCl
KCl
LiF
Li2S
Na2S
CO gas
Mg-silicates
Iron metal liquid
CO gas
Perovskite
Corundum
Jupiter
CH4 gas
KCl
LiF
Li2S
Na2S
CO gas
Mg-silicates
Iron metal liquid
Perovskite
CO gas
T dwarfs

Thus Not all Jupiters are Jupiter

Color and albedo are functions of type and depth of clouds.

Clouds depend on BOTH internal heat flow (mass, age) and incident flux.

Thus Not all Jupiters are Jupiter

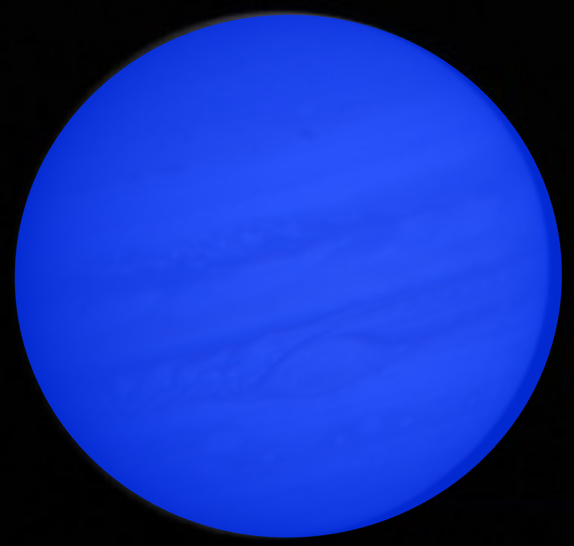
Color and albedo are functions of type and depth of clouds.

Clouds depend on BOTH internal heat flow (mass, age) and incident flux.

Thus Not all Jupiters are Jupiter

Color and albedo are functions of type and depth of clouds.

Clouds depend on BOTH internal heat flow (mass, age) and incident flux.

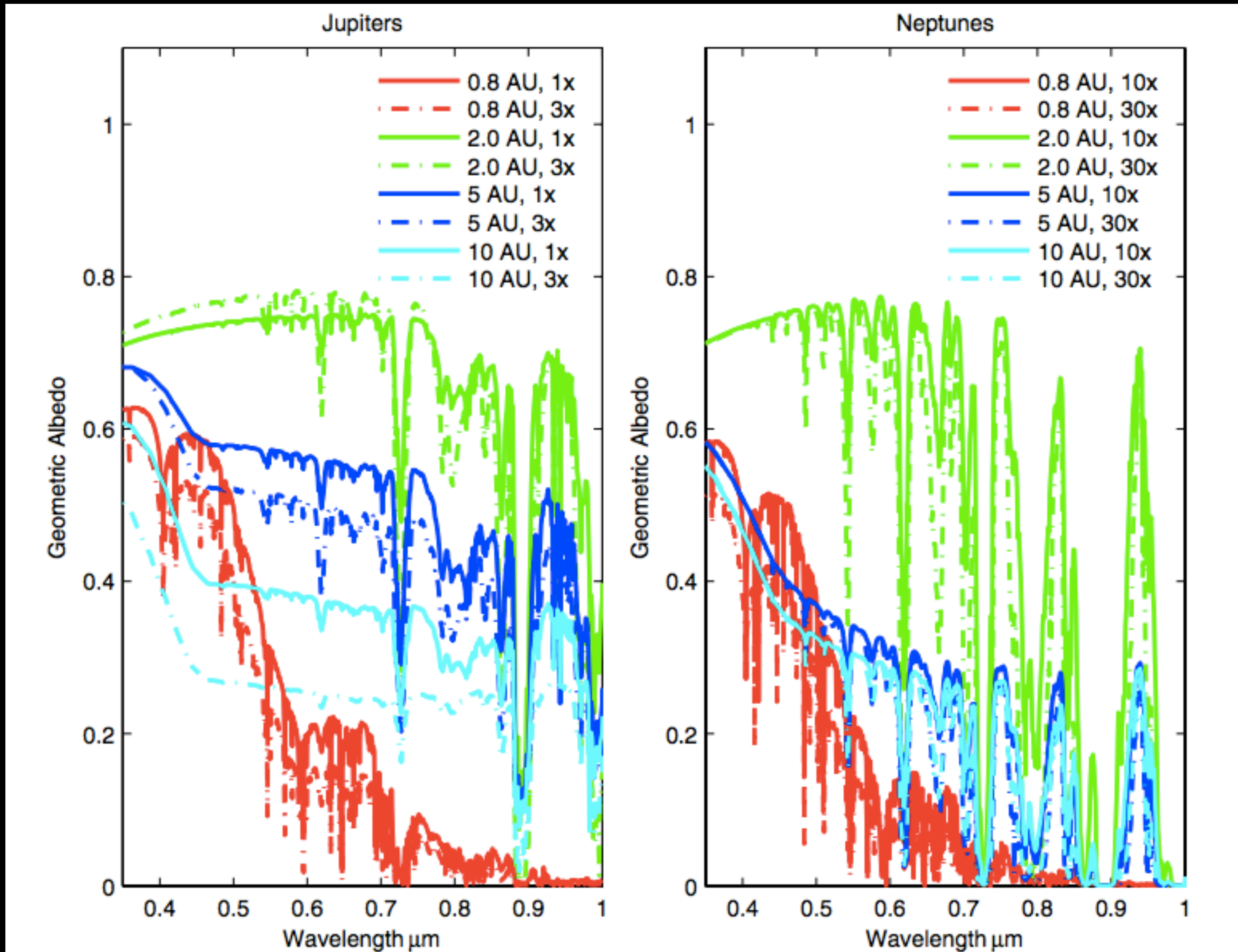


Thus Not all Jupiters are Jupiter

Color and albedo are functions of type and depth of clouds.

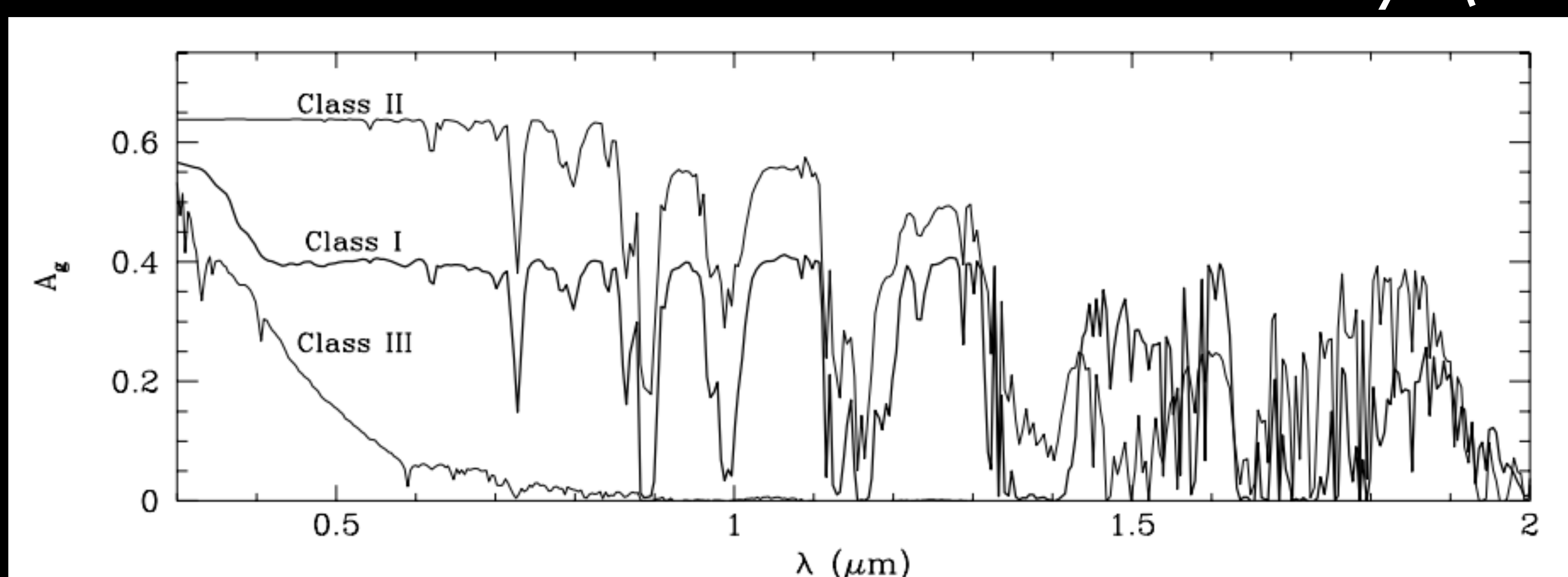
Clouds depend on BOTH internal heat flow (mass, age) and incident flux.

photochemistry

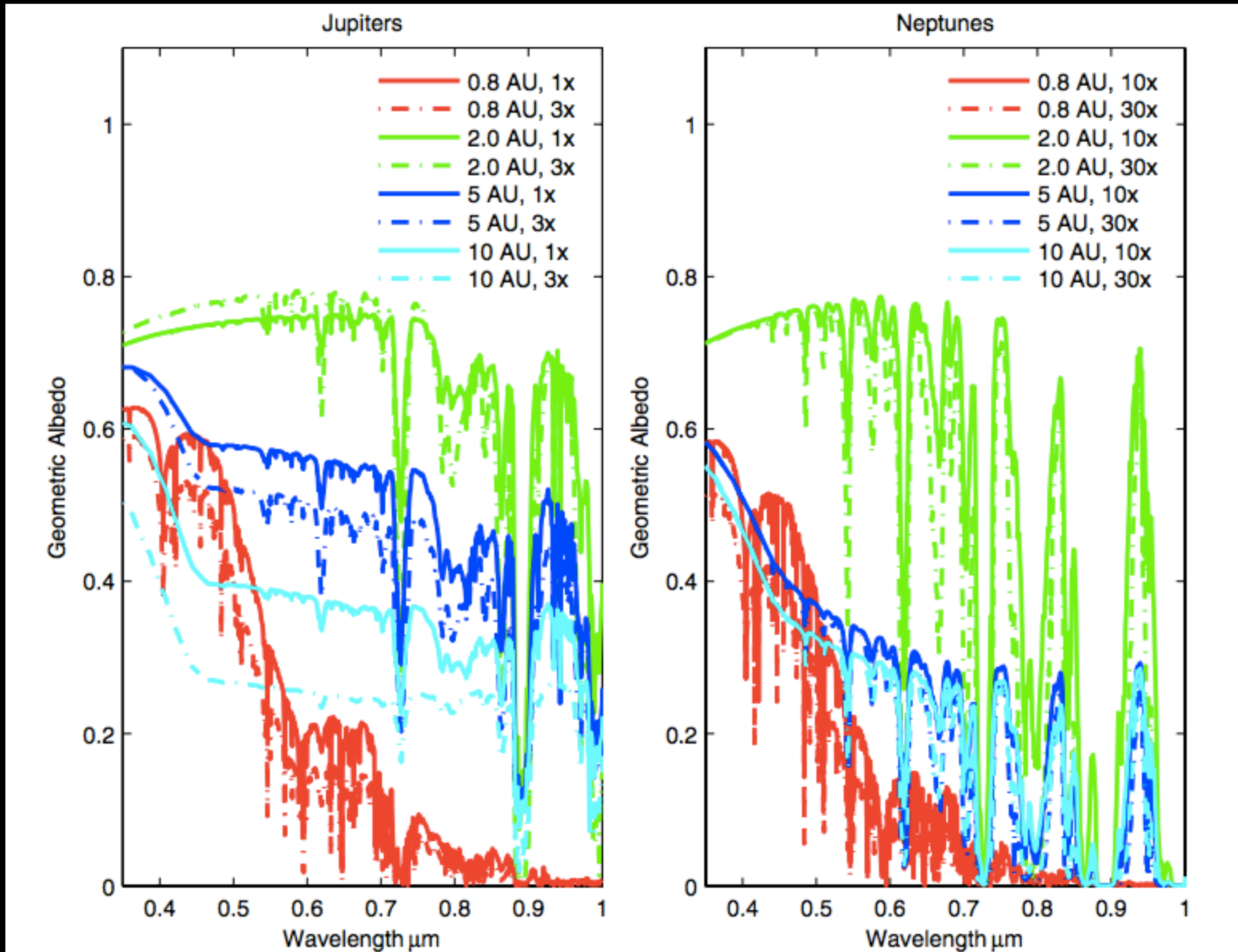


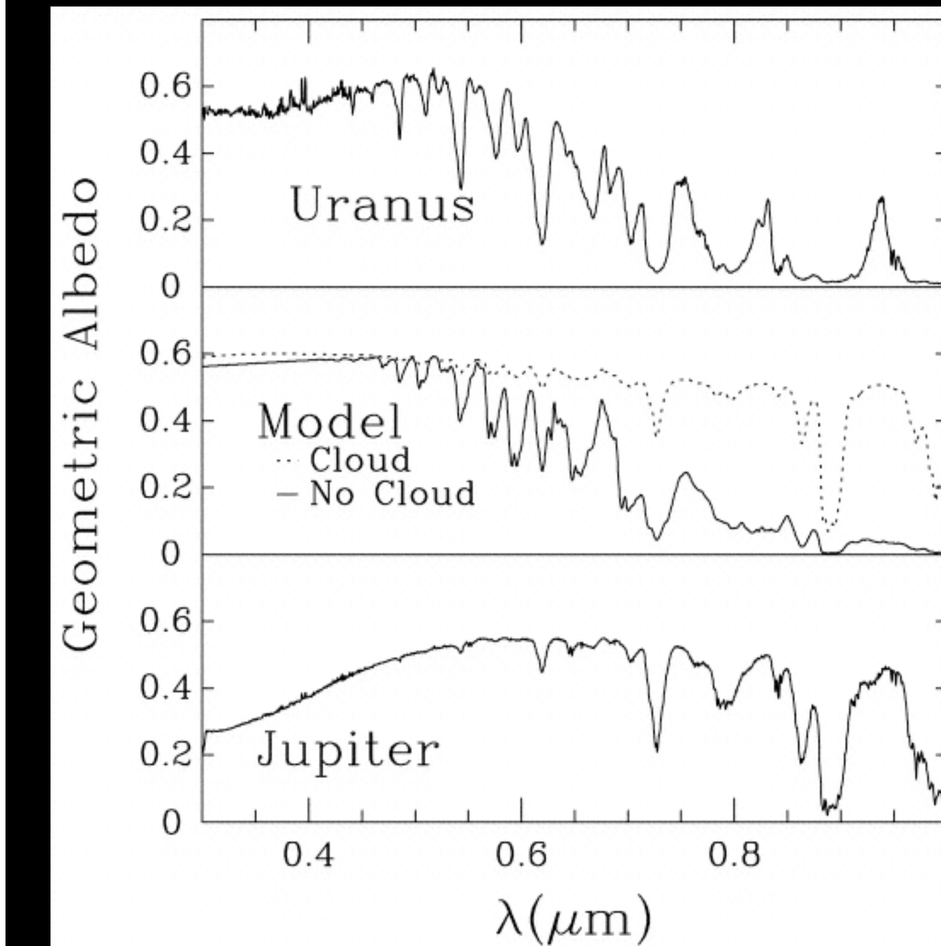
Marley+ (1999)

Cahoy+ (2010)



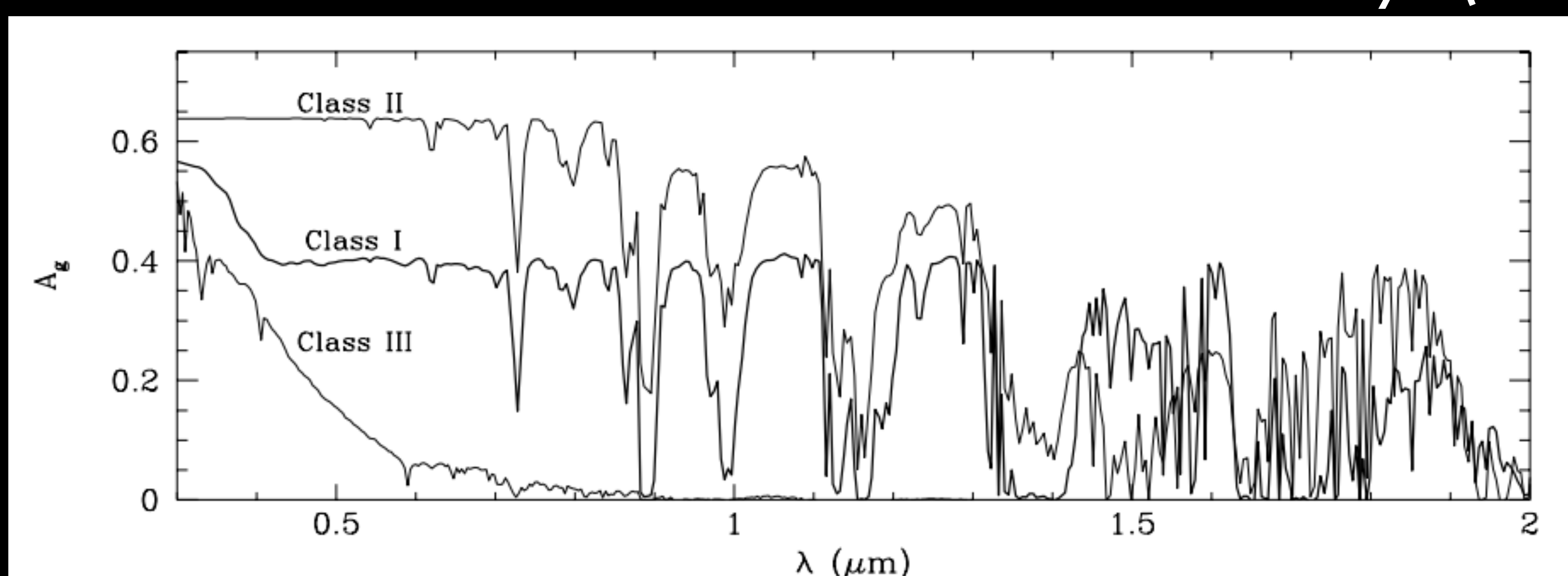
Sudarsky+ (2000)





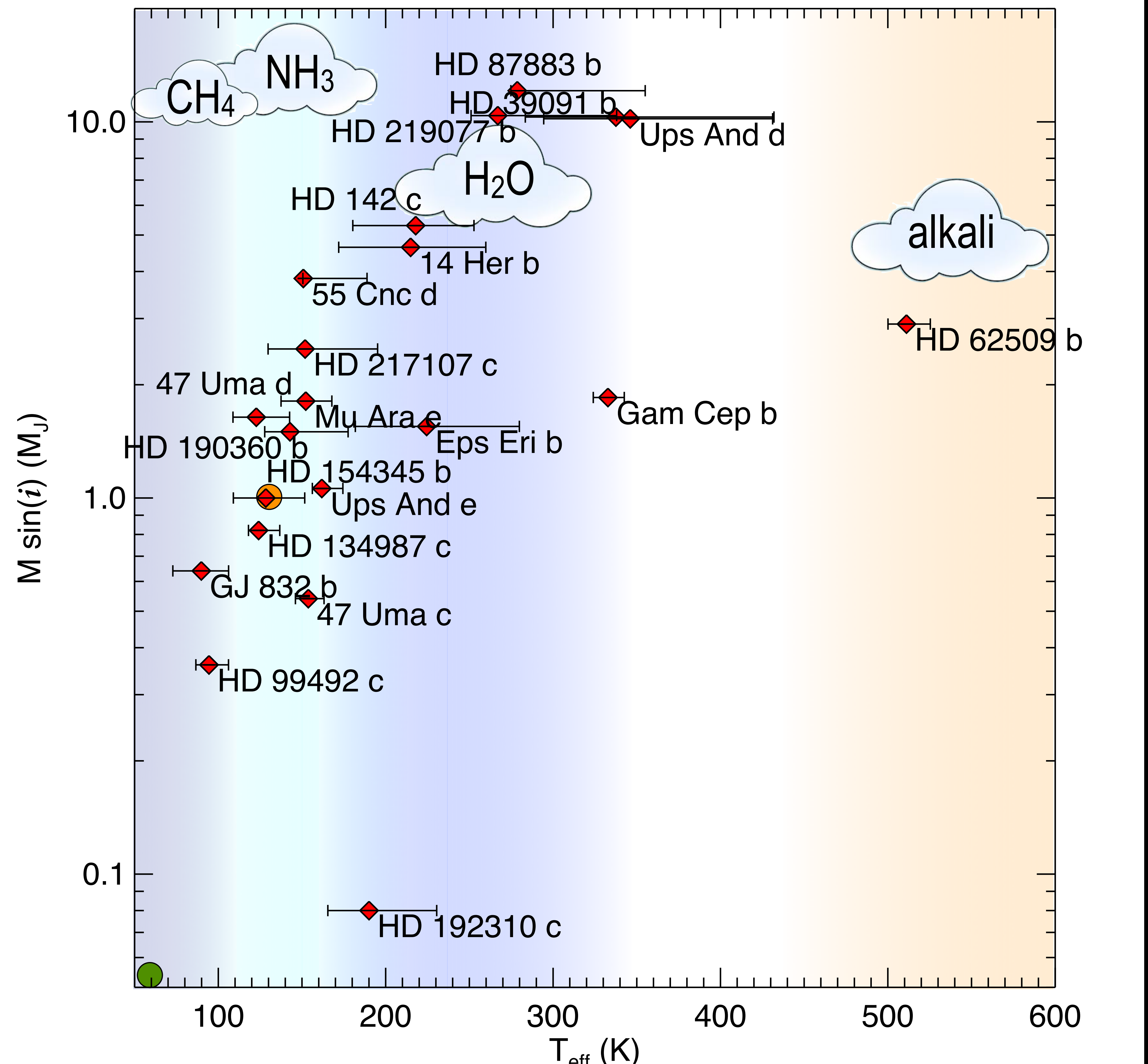
Marley+ (1999)

Cahoy+ (2010)



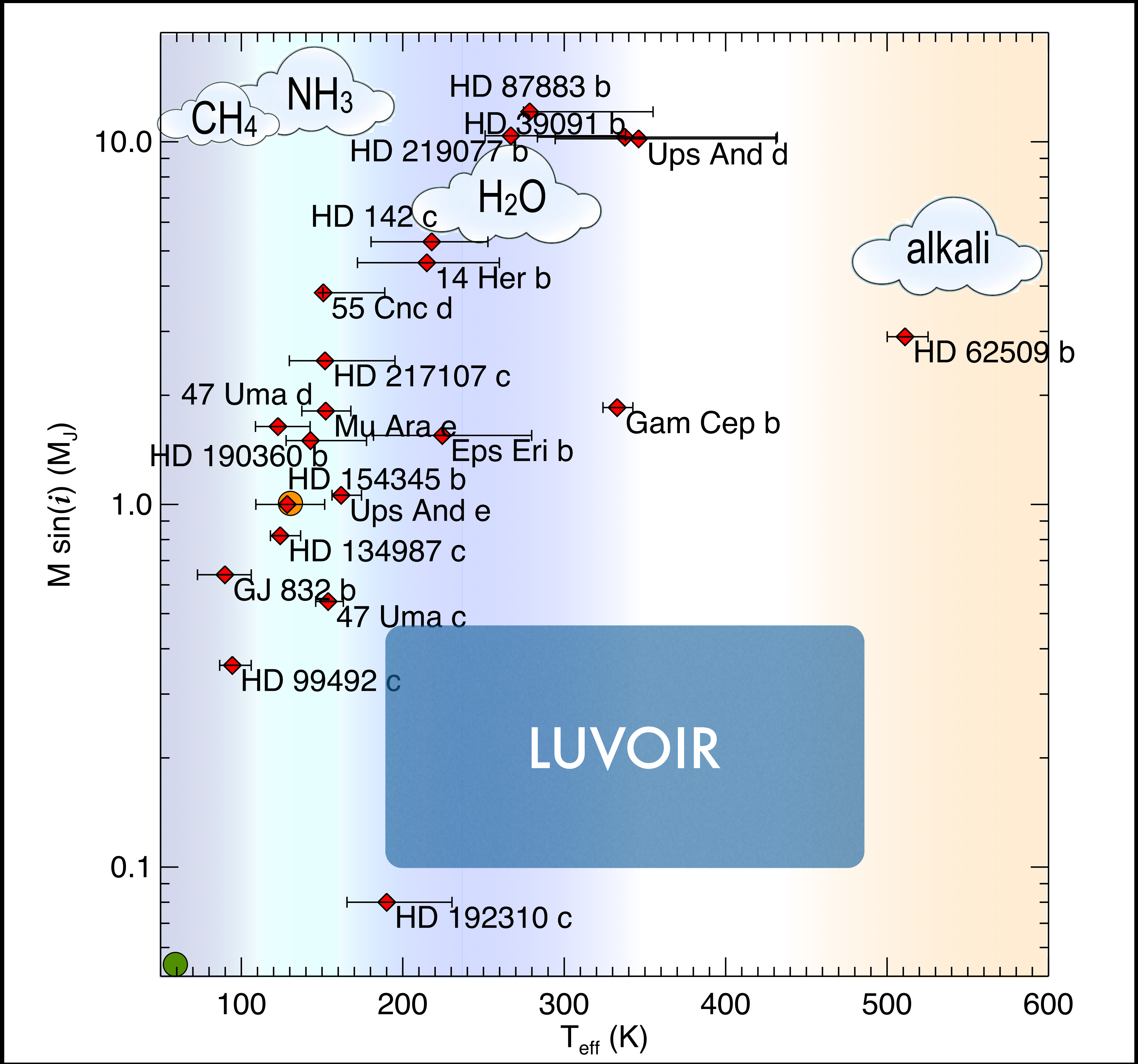
Sudarsky+ (2000)

Favorable RV Planets for Direct Imaging by WFIRST



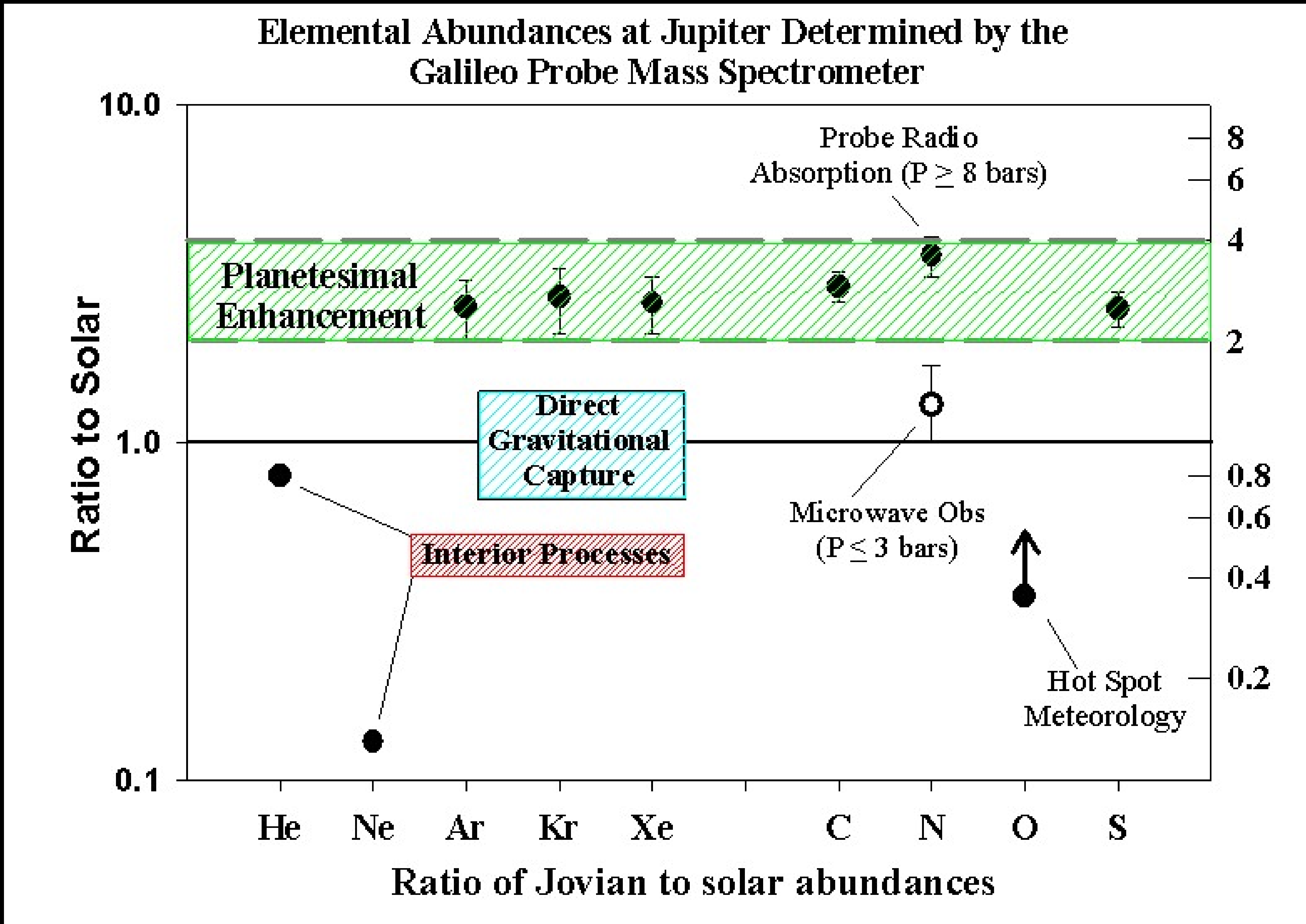
Marley+ 2014

Favorable RV Planets for Direct Imaging by WFIRST

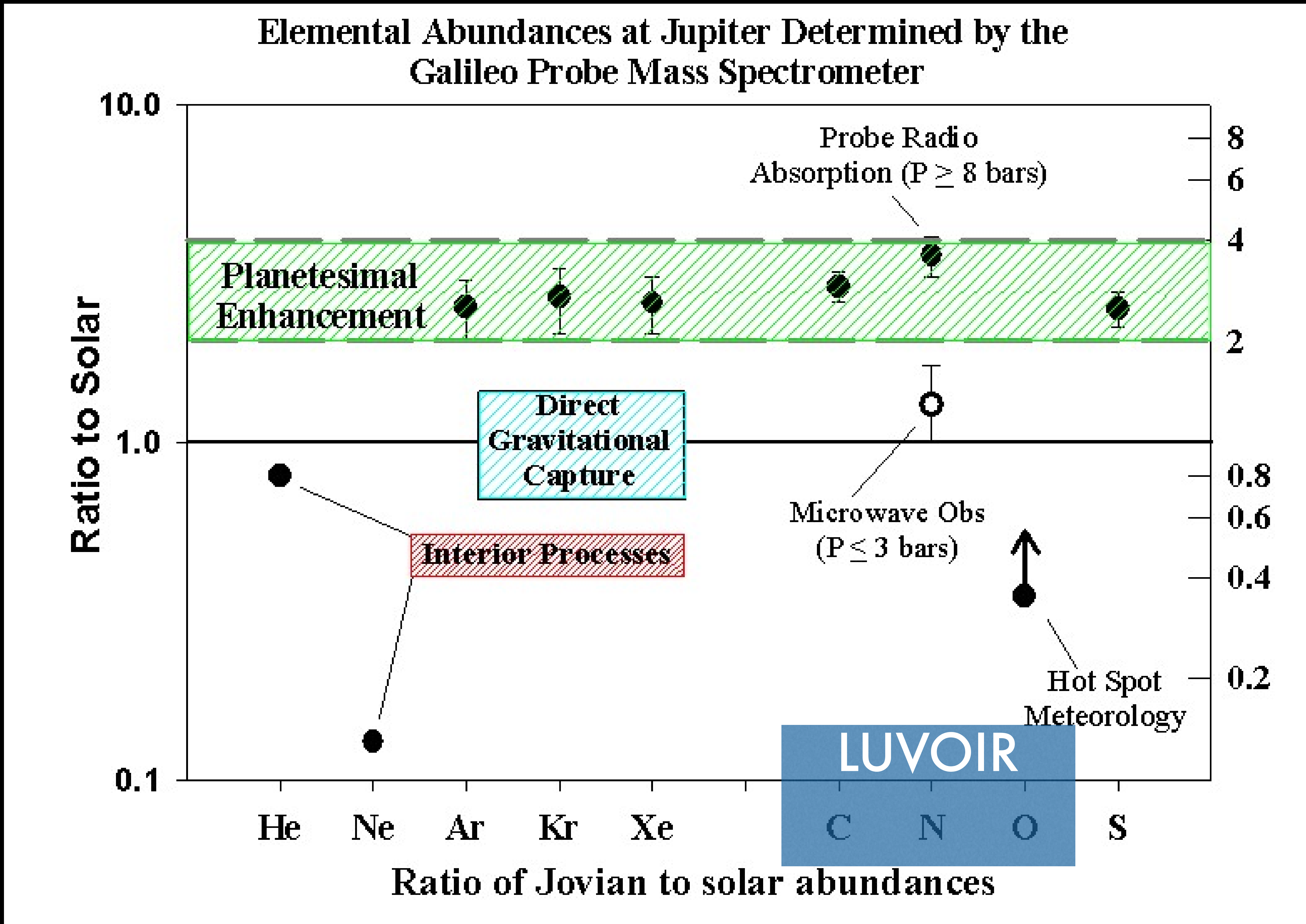


Marley+ 2014

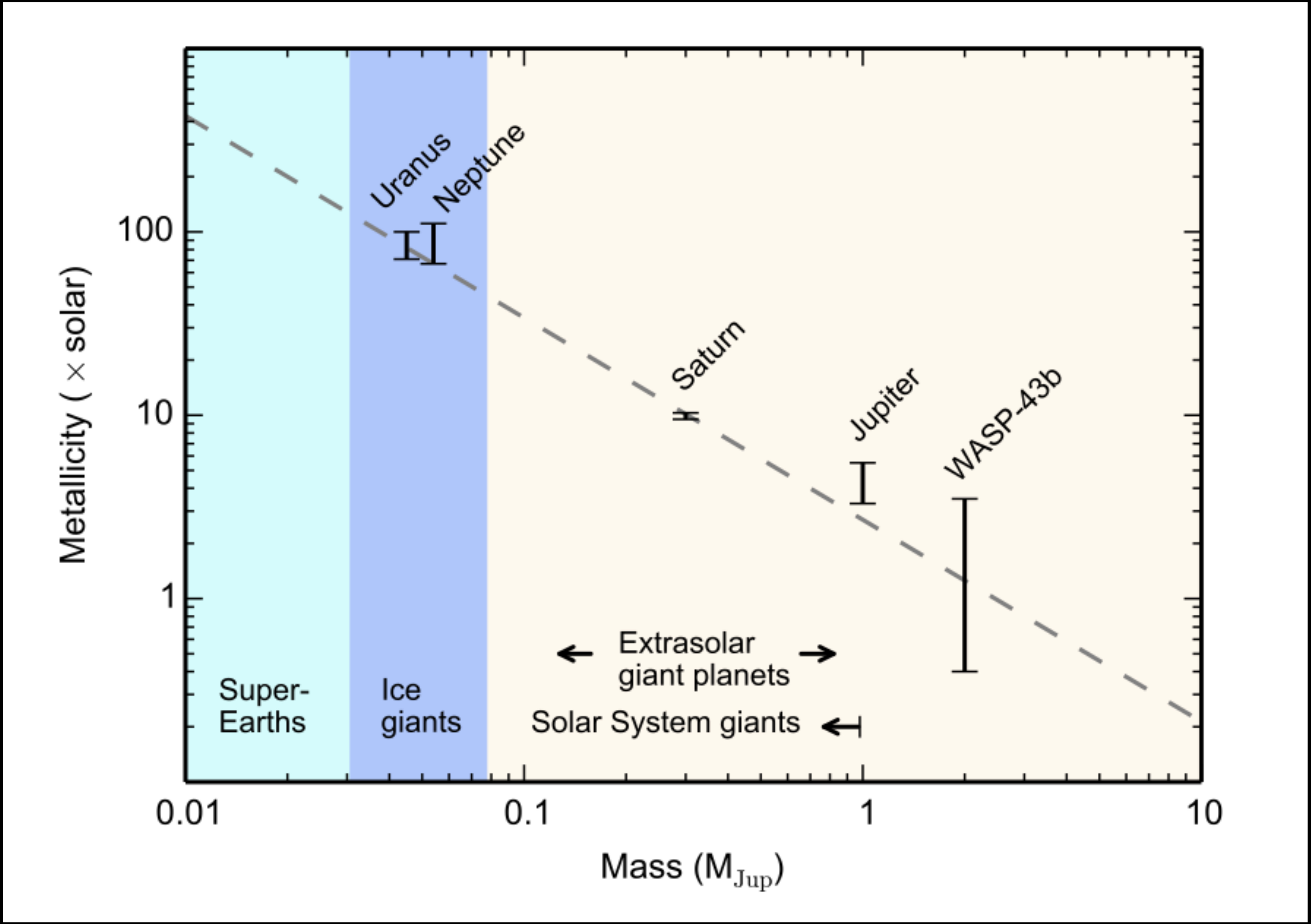
What do we Want to Know?



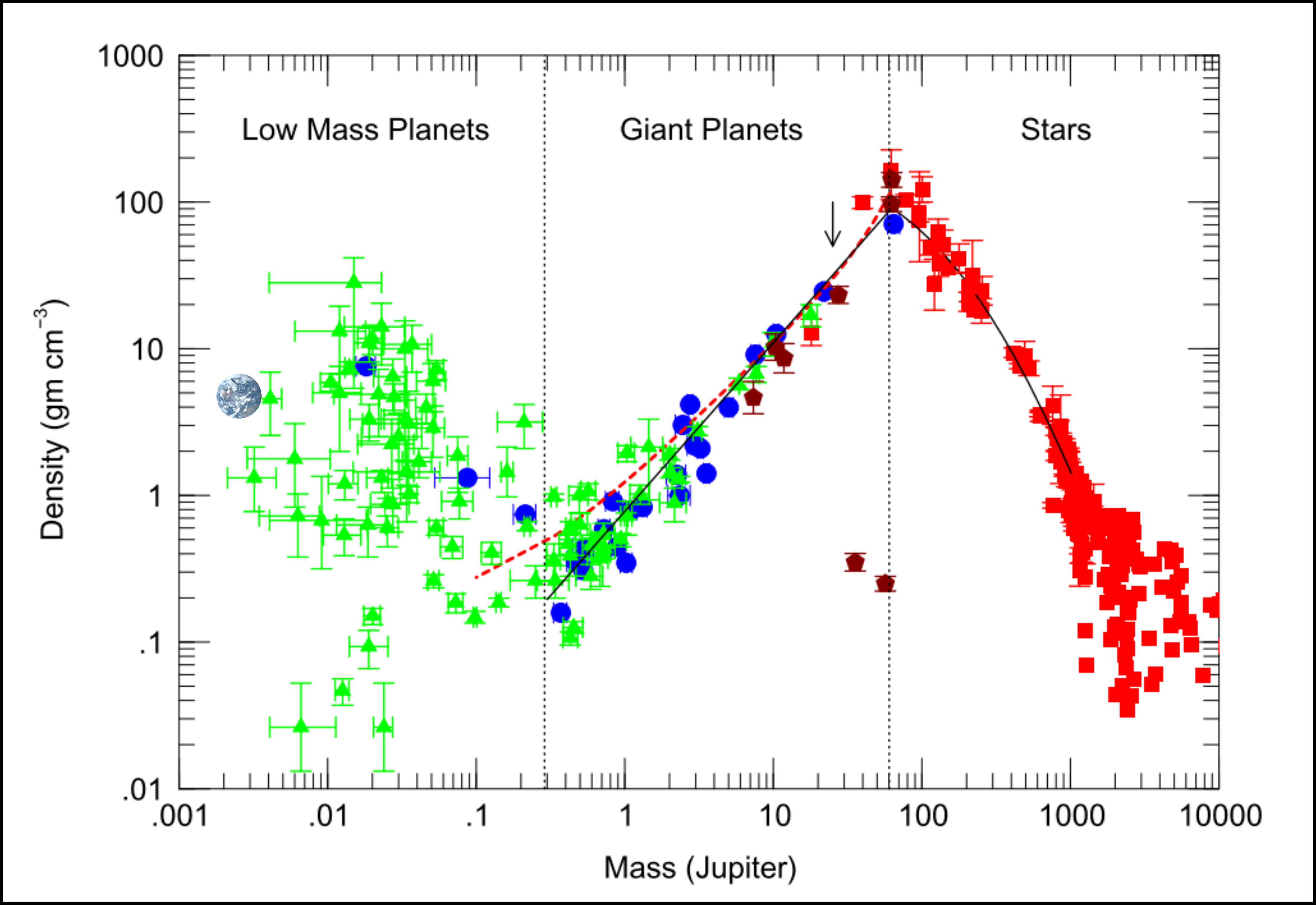
Owen et al. (1999)



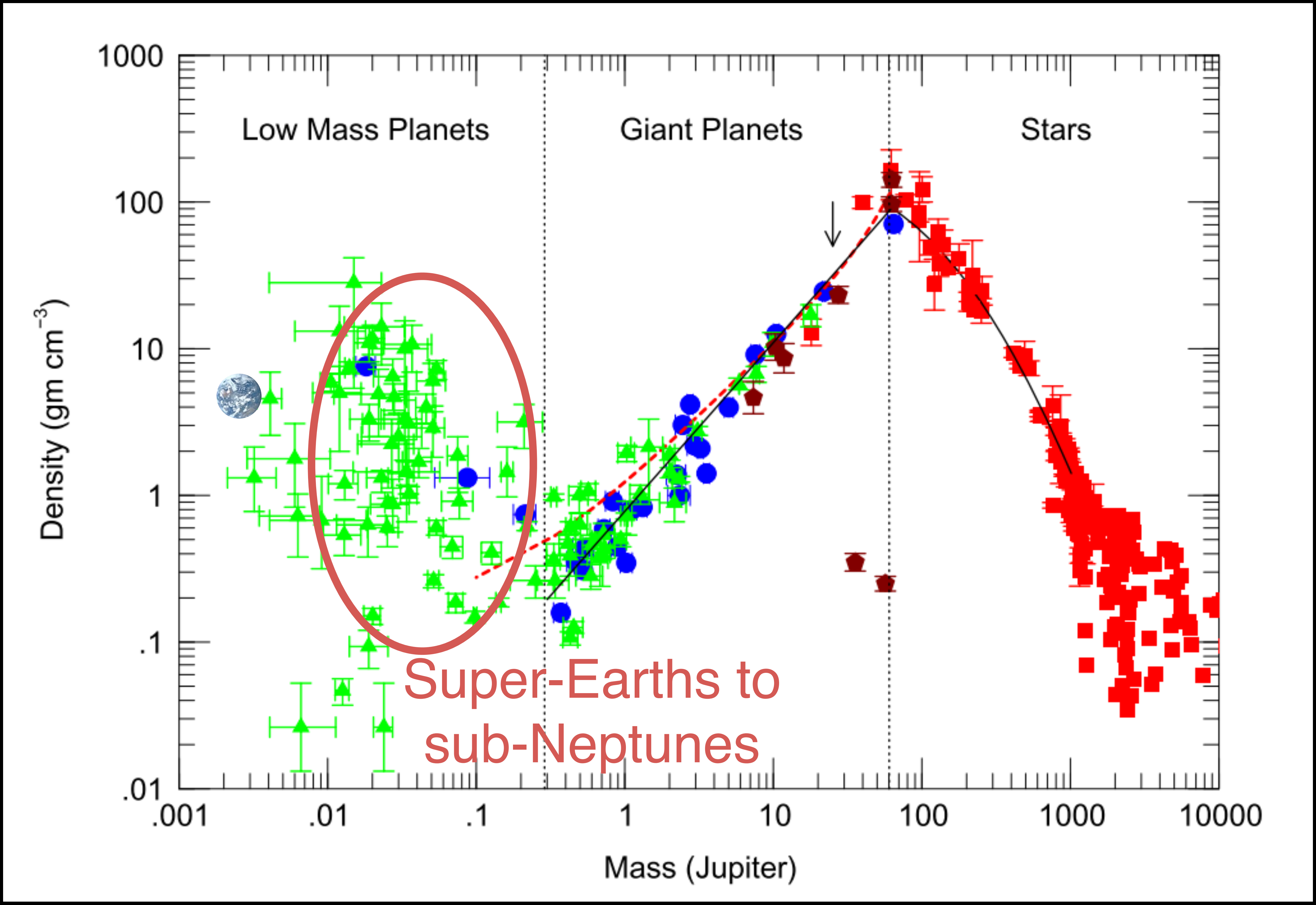
Owen et al. (1999)



Kreidberg+ 2014



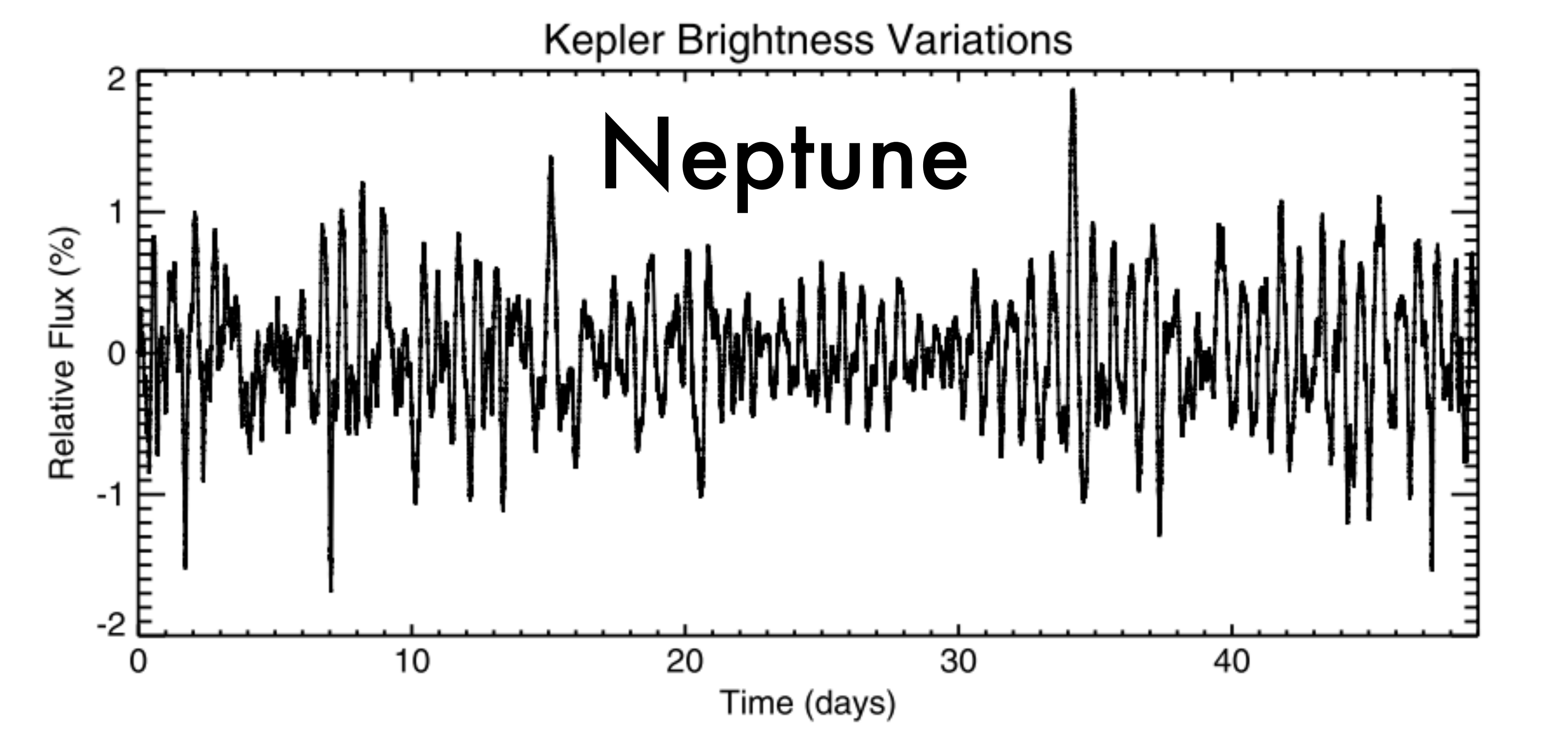
Hatzes & Rauer (2015)



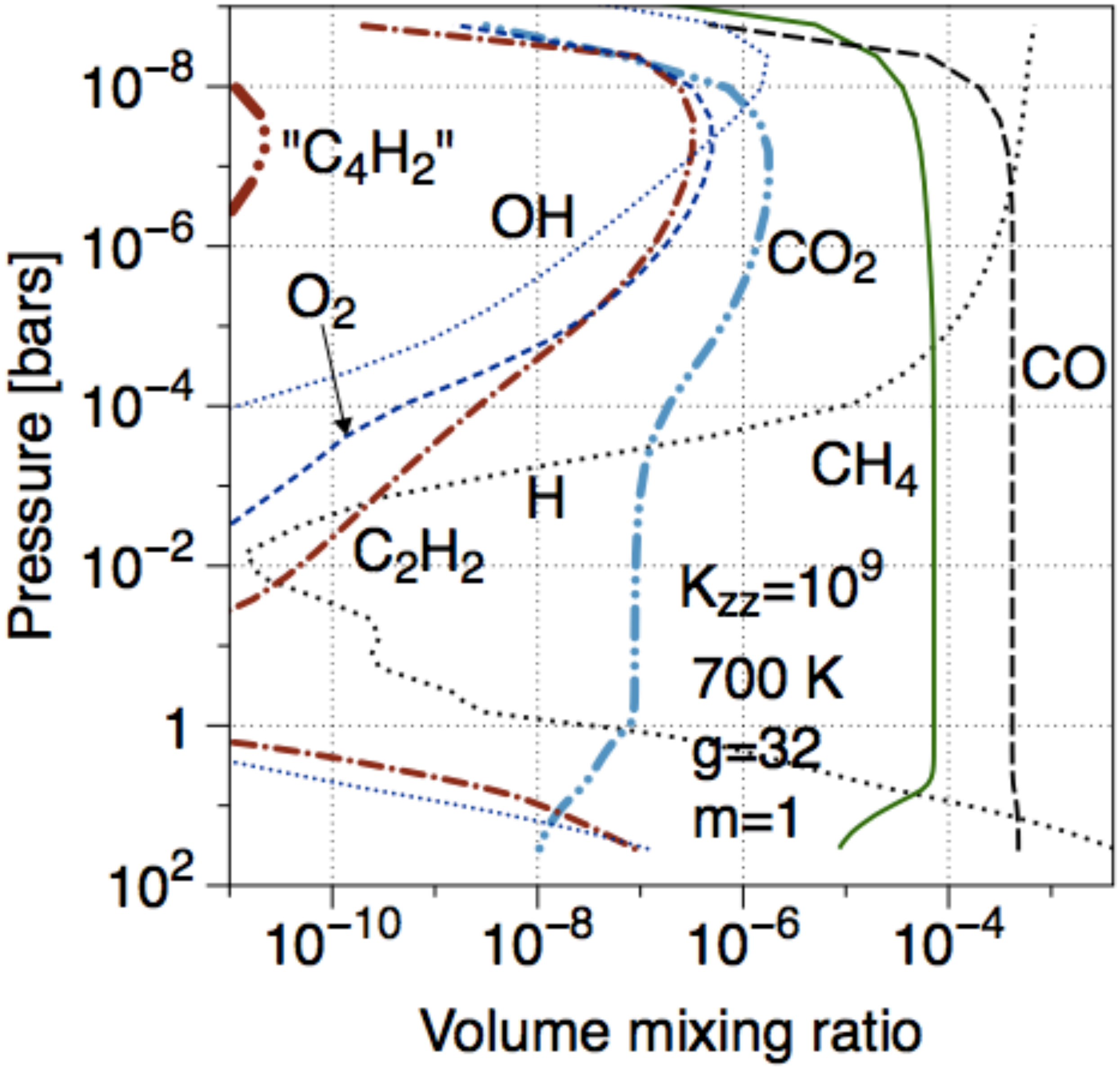
Hatzes & Rauer (2015)

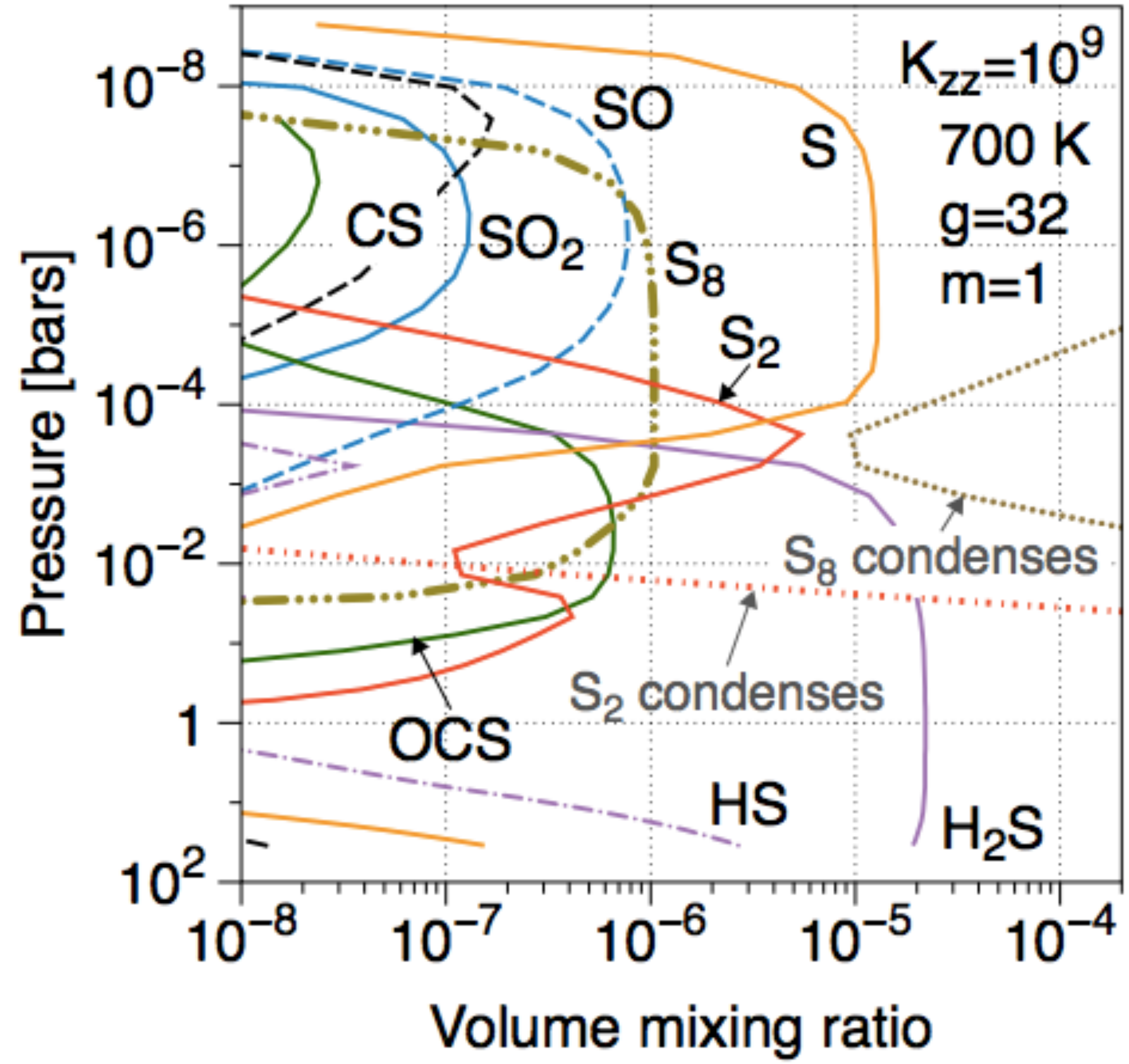
Clouds & Variability

- Clouds reflect atmospheric temperature
- Clouds set continuum flux level for measuring bands
- Training ground for interpreting terrestrial planets
- Variability hints at complex atmospheric dynamics



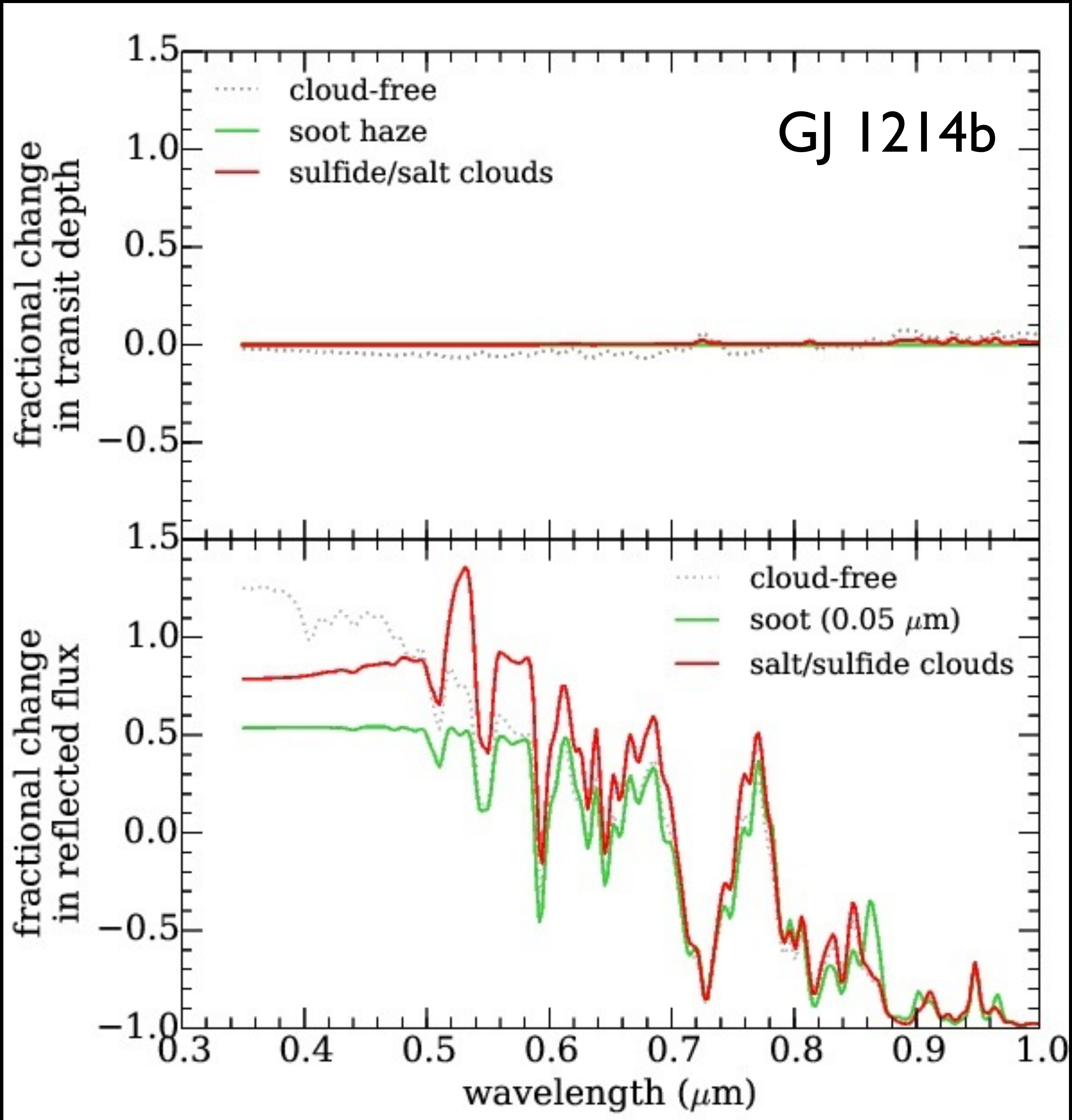
Photochemical Hazes

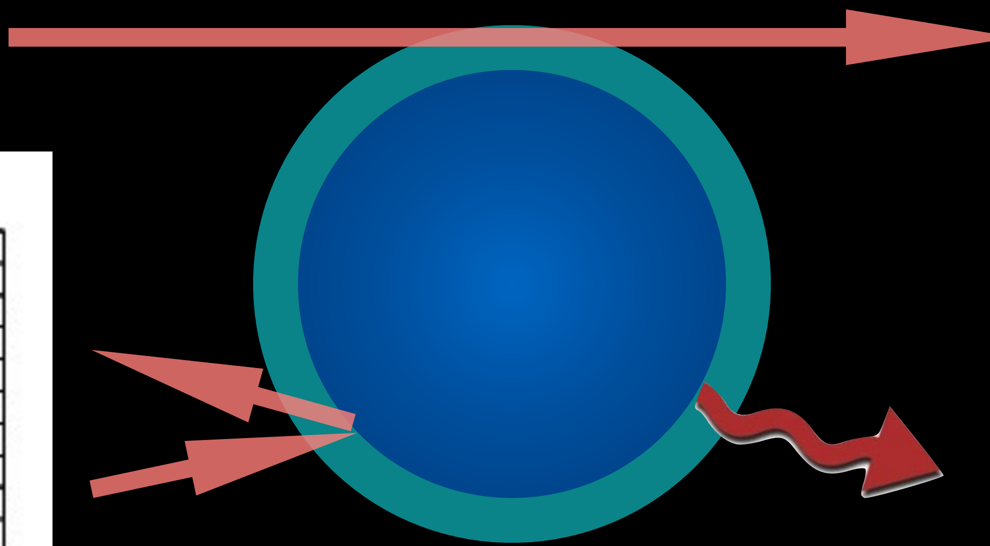




Zahnle+ (2016)

What about Transit Spectroscopy?





Upper vs. deep atmosphere

Atmospheric column is more thoroughly measured by imaging than by transits

Model spectra by Caroline Morley

How do we Find Out?

“Baines Diagram”

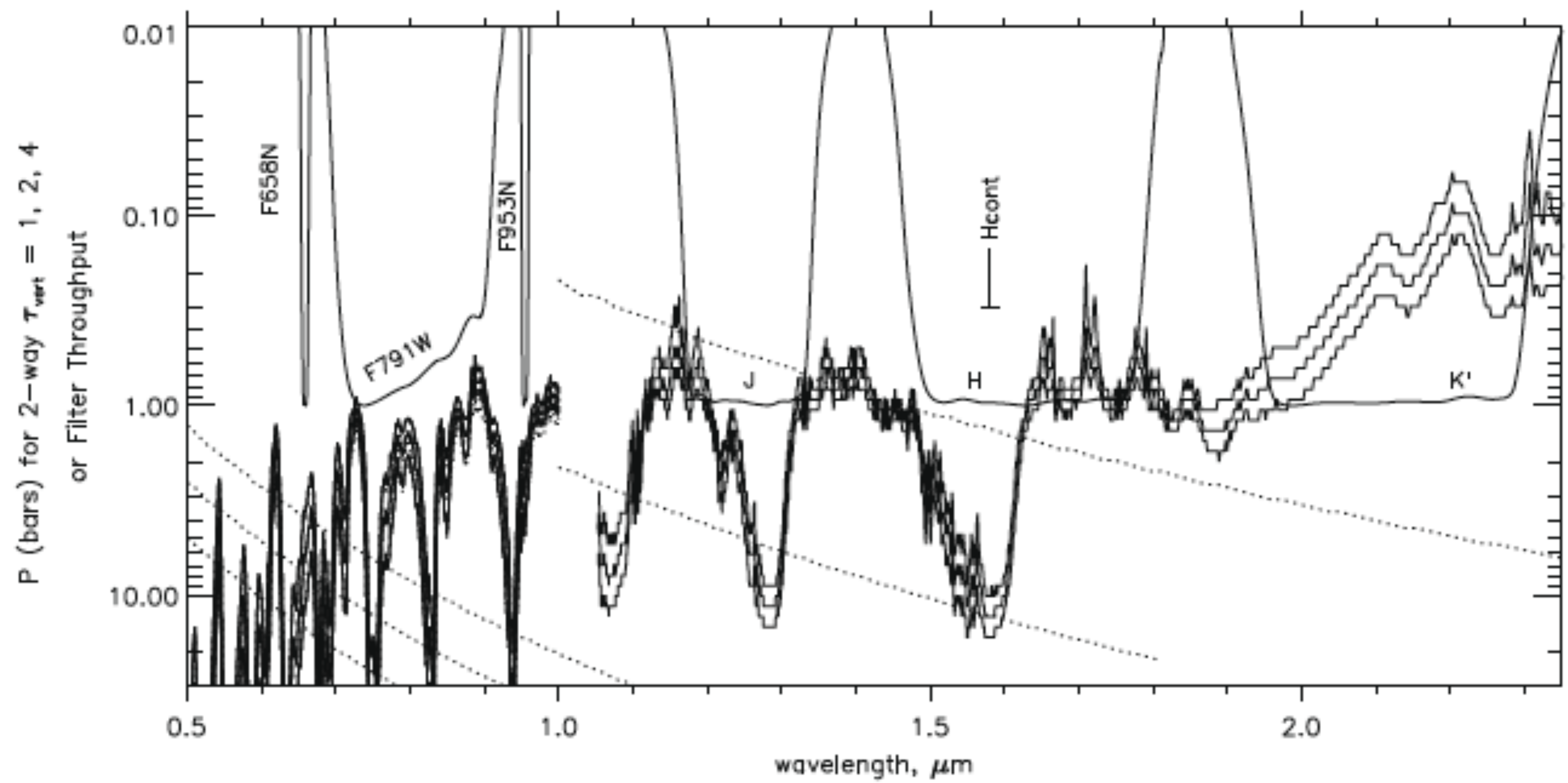
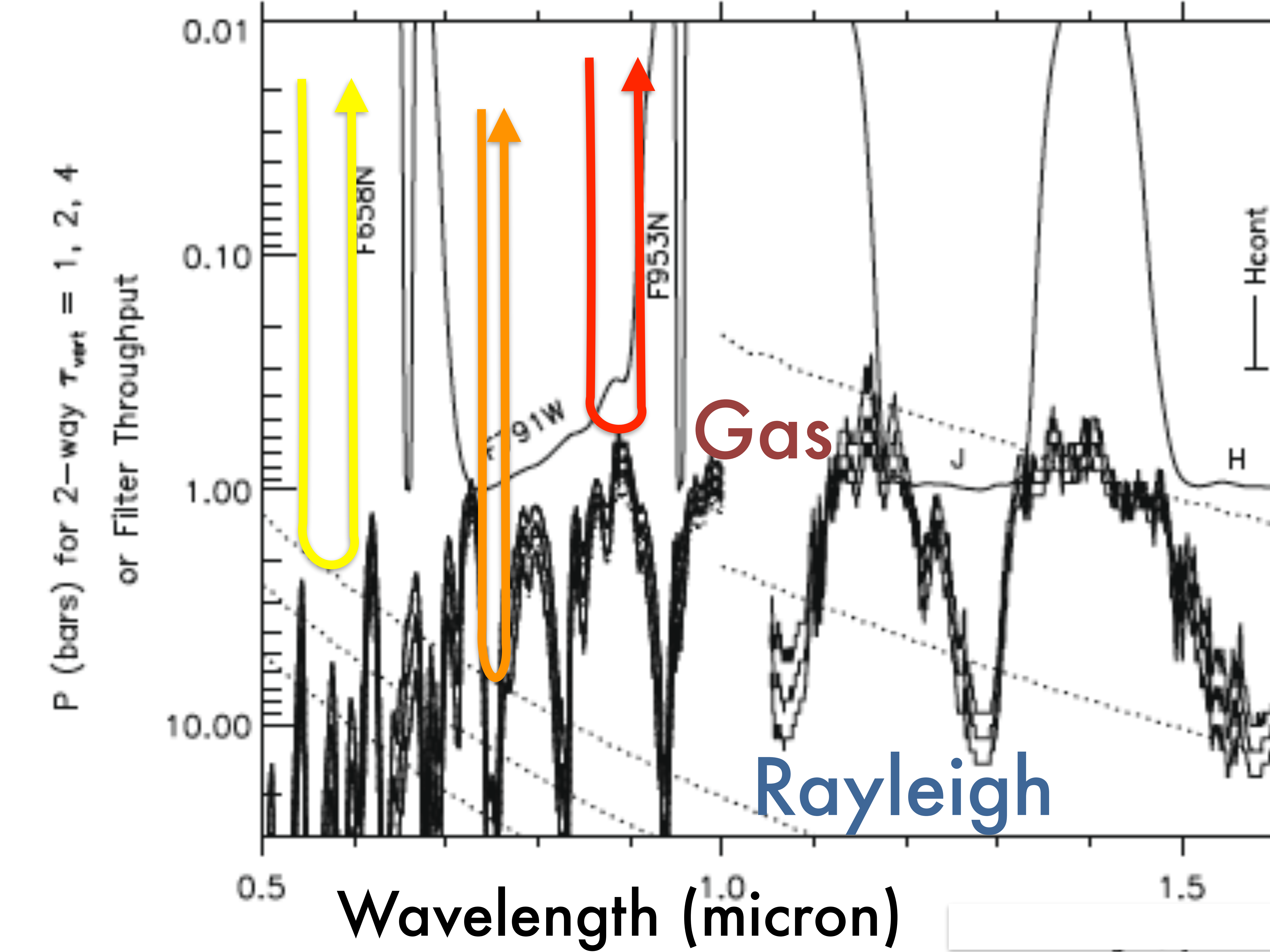
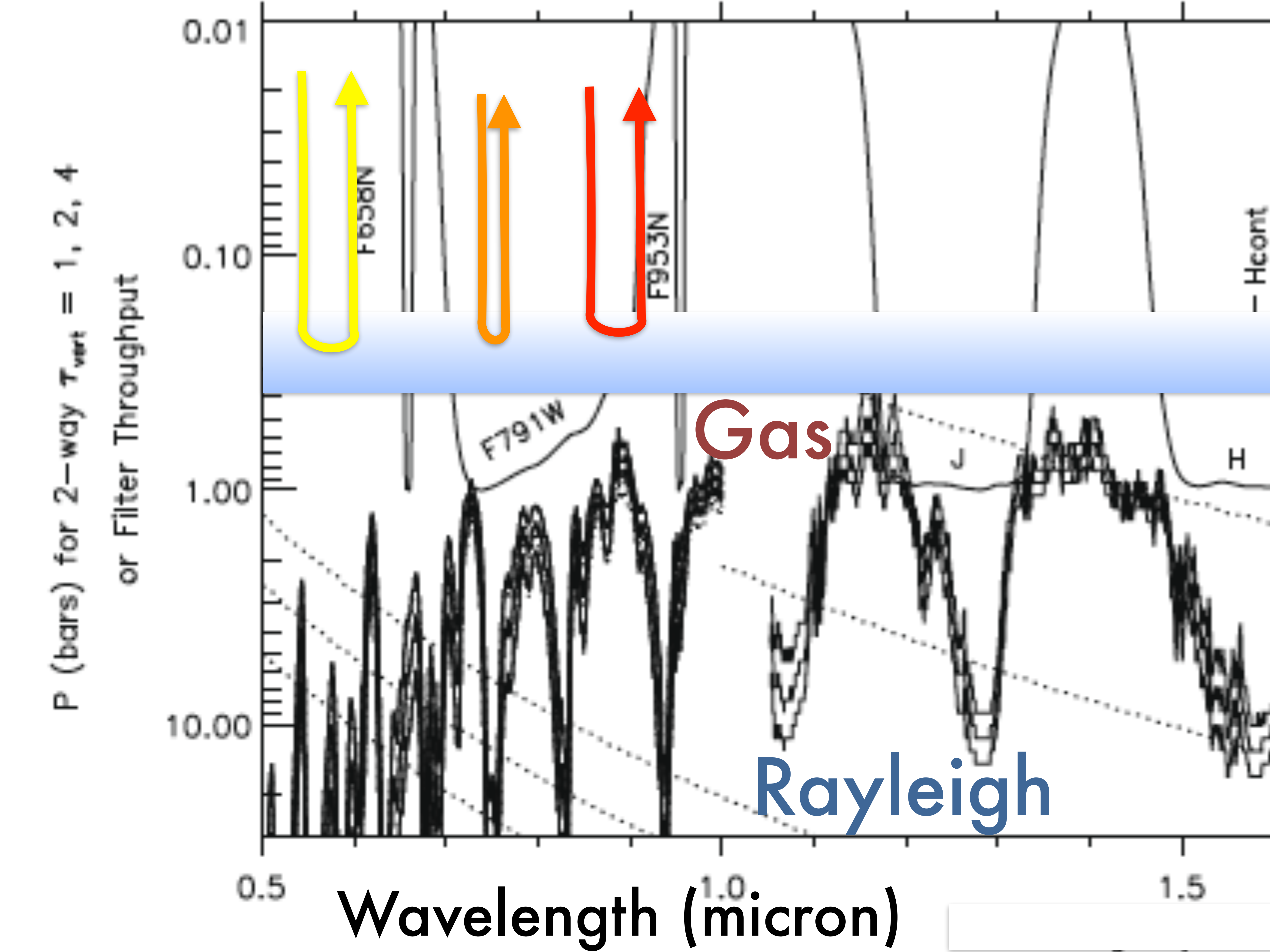
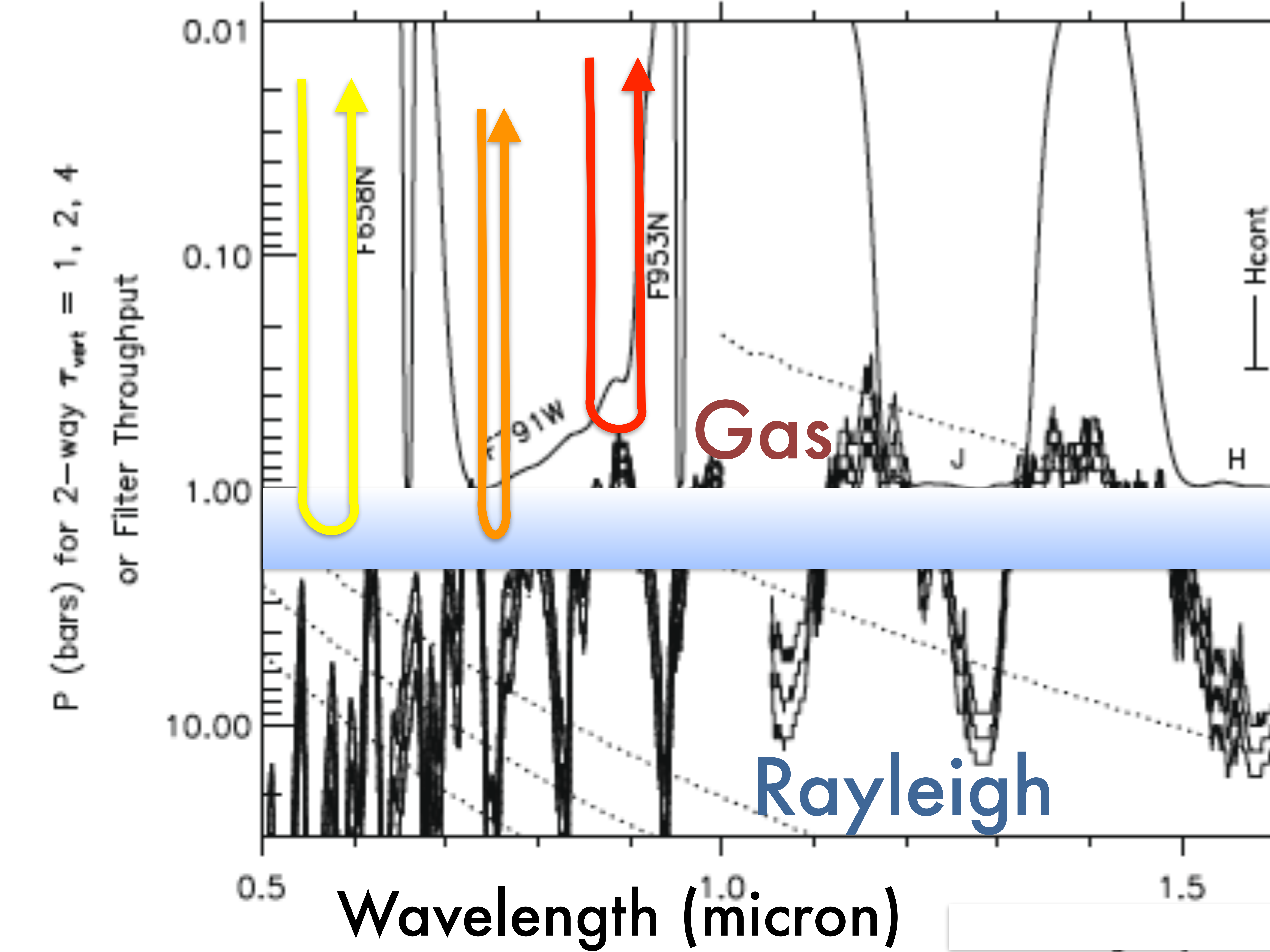


Fig. 1. Penetration of sunlight into the atmosphere of Uranus vs. wavelength. Solid curves are shown for two-way vertical optical depths of 1, 2, and 4 from CH_4 and H_2 absorption, assuming a 2.26% CH_4 mixing ratio. Dotted curves show the same optical depths for Rayleigh scattering, except for $\lambda > 1\mu$m, where curves are shown for Rayleigh optical depths of 0.1 and 0.01. HST/WFPC2, HST/ACS, and Keck/NIRC2 filters are shown as system throughput curves, normalized to unity at their peaks. See Table 3 for additional filter information.

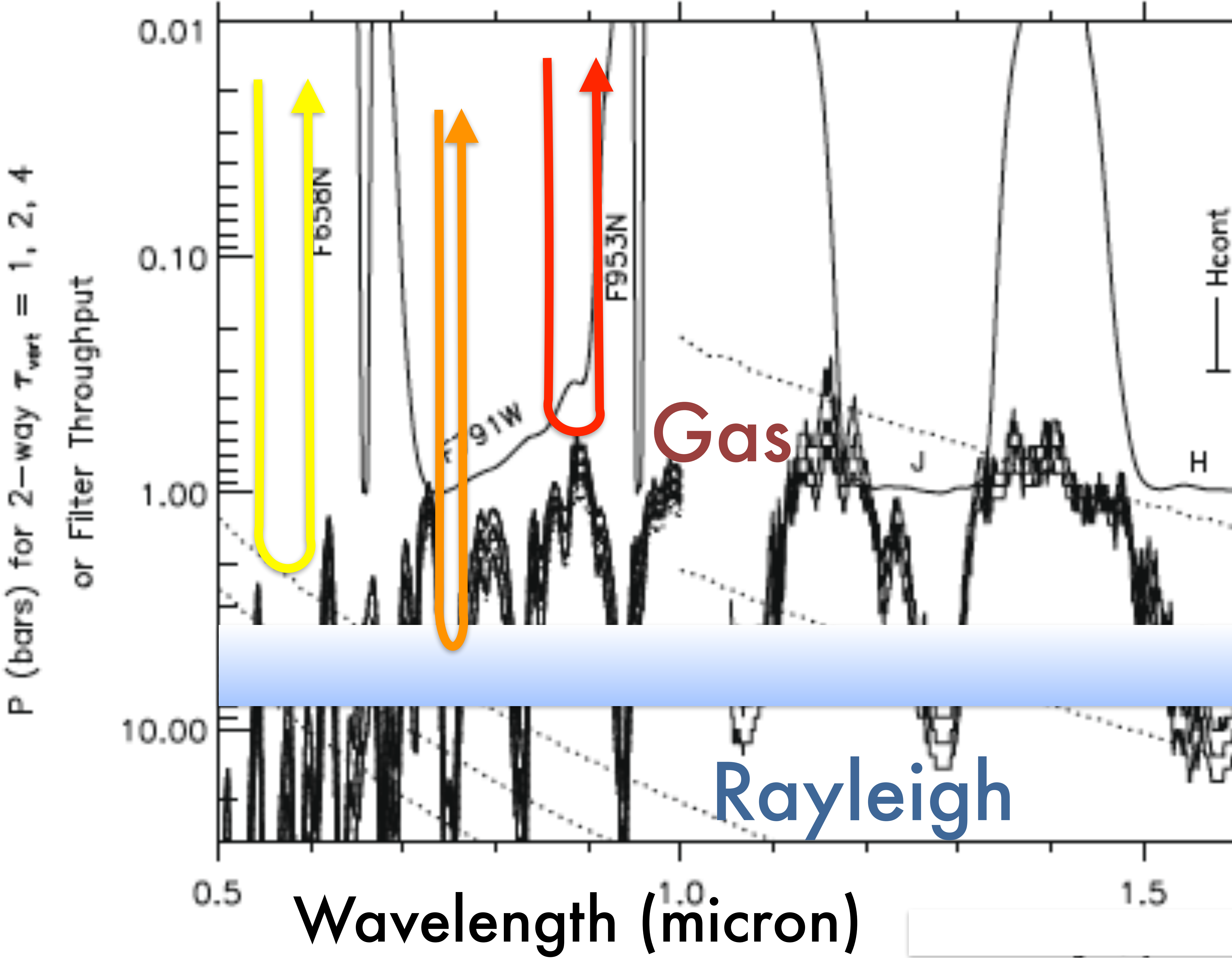

P (bars) for 2-way τ_{vert} = 1, 2, 4
or Filter Throughput
0.01
0.10
1.00
10.00
F658N
F953N
F791W
Hcont
J
H
Gas
Rayleigh
0.5
1.0
1.5
Wavelength (micron)



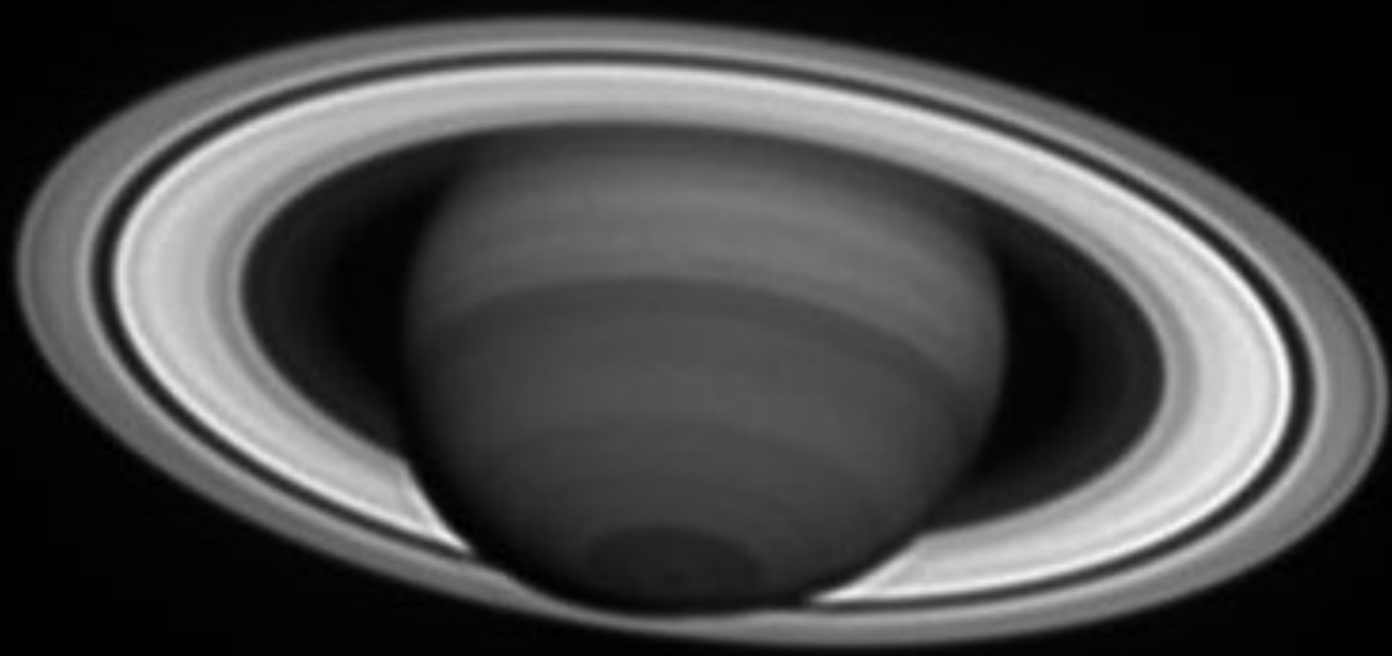
P (bars) for 2−way τ_{vert} = 1, 2, 4
or Filter Throughput
0.01
0.10
1.00
10.00
F658N
F953N
F791W
Hcont
J
H
Gas
Rayleigh
0.5
1.0
1.5
Wavelength (micron)



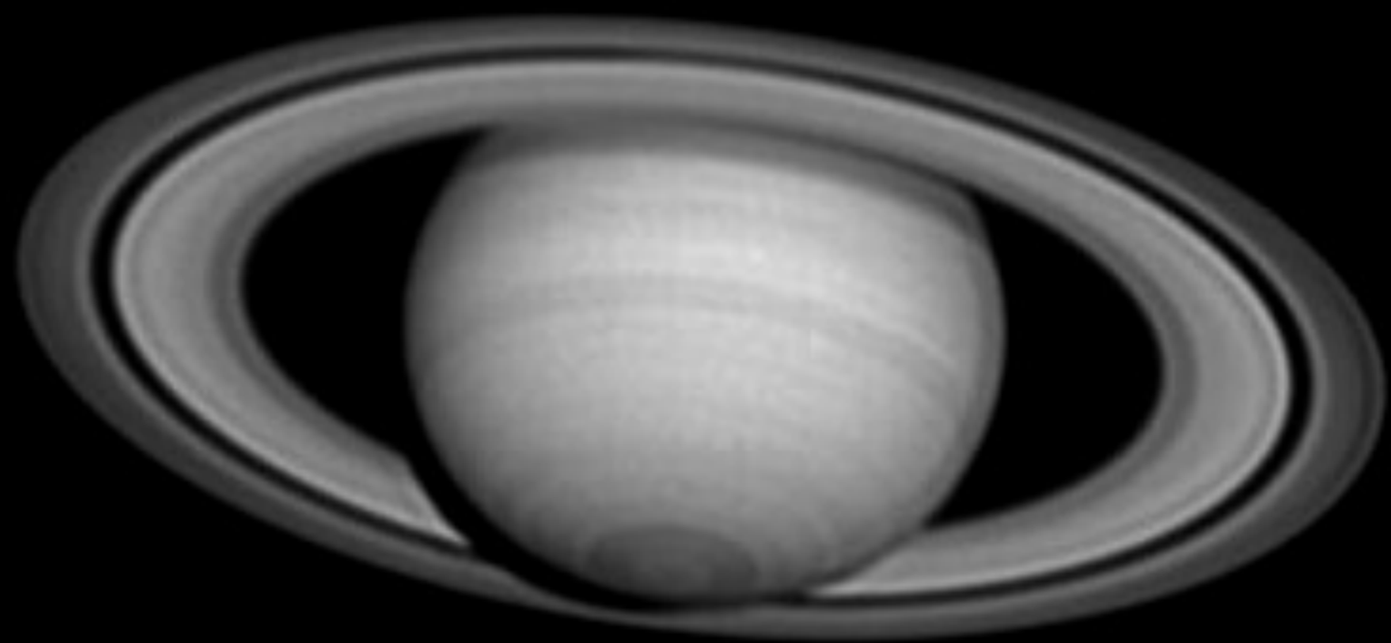
P (bars) for 2-way τ_{vert} = 1, 2, 4
or Filter Throughput
0.01
0.10
1.00
10.00
F658N
F953N
91W
Hcont
J
H
Gas
Rayleigh
0.5
1.0
1.5
Wavelength (micron)



P (bars) for 2−way τ_vert = 1, 2, 4
or Filter Throughput
0.01
0.10
1.00
10.00
F658N
F953N
F791W
Hcont
Gas
J
H
Rayleigh
0.5
1.0
1.5
Wavelength (micron)



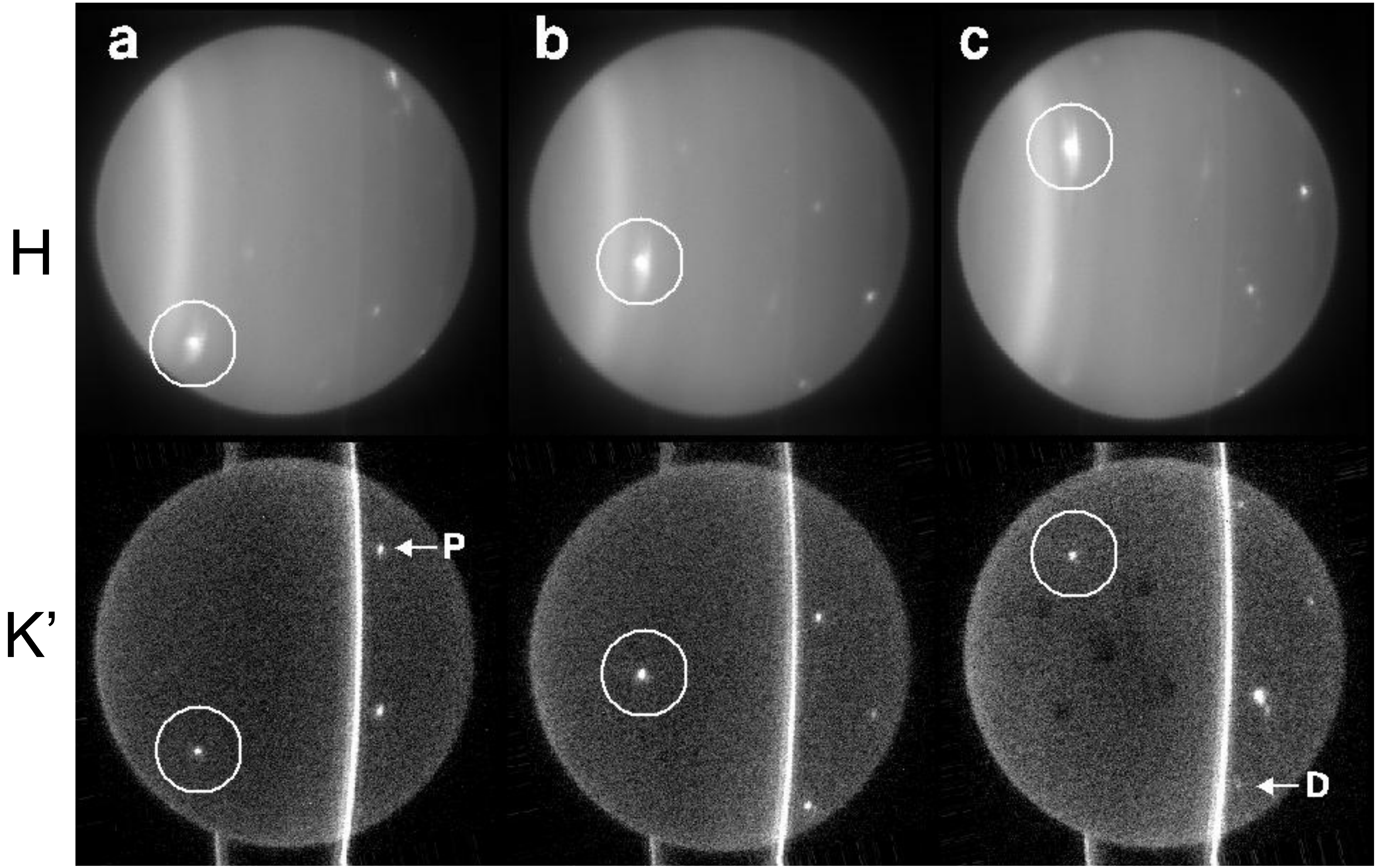
Weak methane (727 nm)



Continuum (751 nm)

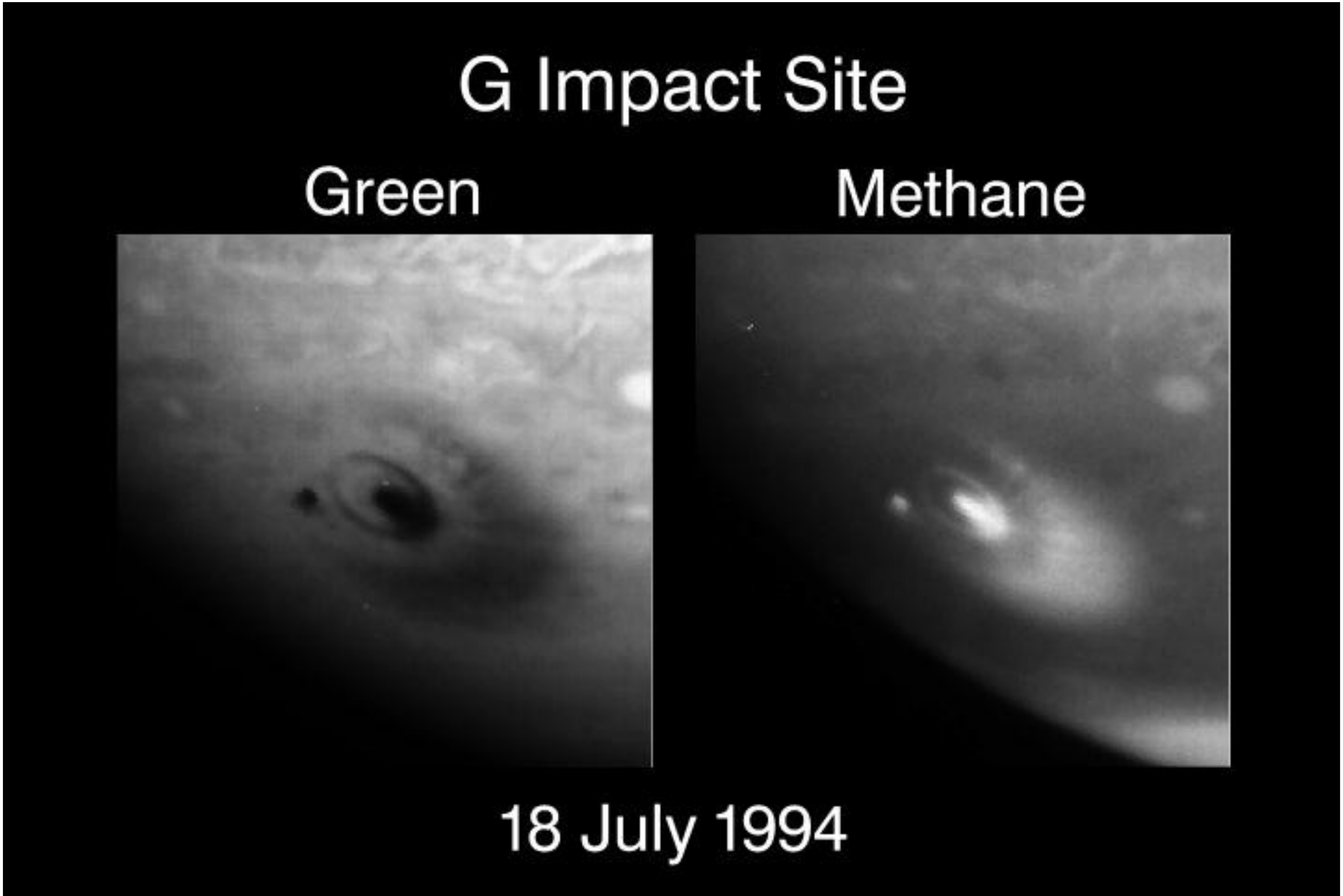
Air Force Advanced Electro-Optical System (AEOS) 3.6-m telescope on Maui

High Clouds on Uranus

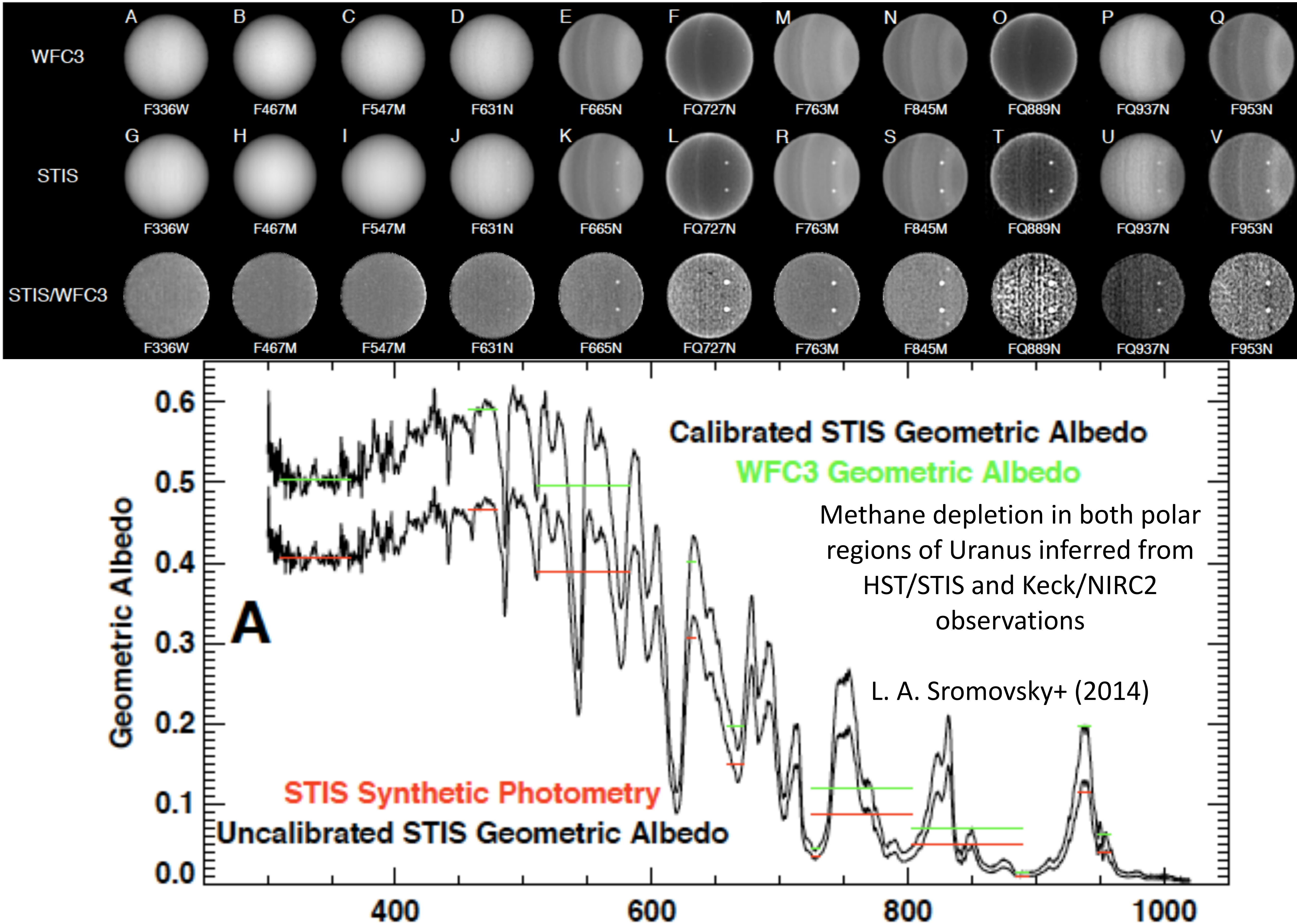


Hammel et al.

Shoemaker-Levy 9 Impact on Jupiter seen with Hubble



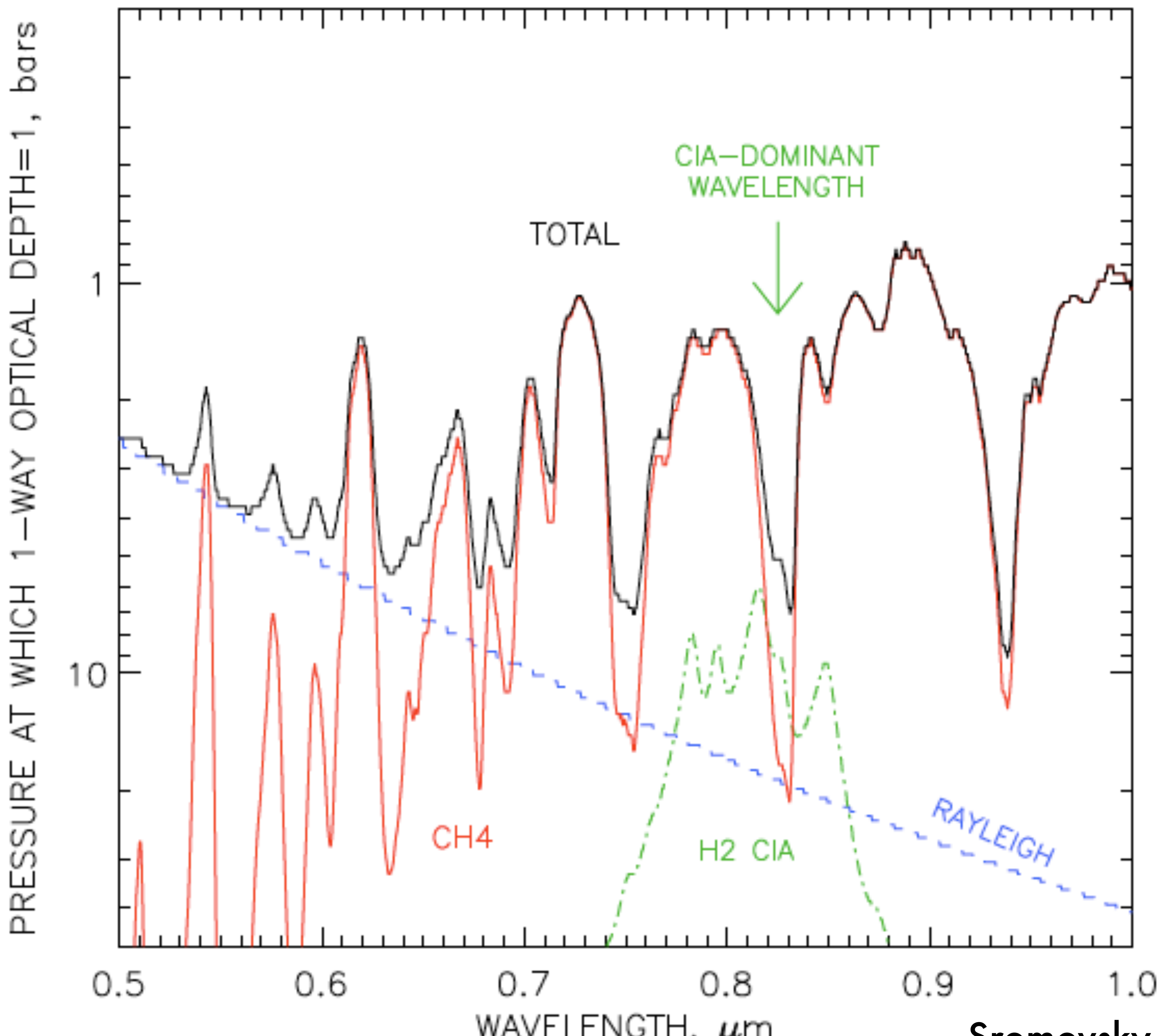
Uranus with Hubble/STIS



Methane depletion in both polar regions of Uranus inferred from HST/STIS and Keck/NIRC2 observations

L. A. Sromovsky+ (2014)

H_2 Opacity Also Important in Ice Giants



Sromovsky et al. (2014)

Jupiter's Atmospheric Composition and Cloud Structure Deduced from Absorption Bands in Reflected Sunlight

MAKIKO SATO AND JAMES E. HANSEN

NASA Goddard Institute for Space Studies, Goddard Space Flight Center, New York, NY 10025

(Manuscript received 2 March 1979)

Classic 1979 paper on deriving giant planet abundances

lent width. Since there are available observations of both weak and strong methane bands, we expect to be able to obtain at least one parameter describing the vertical cloud structure in addition to obtaining the methane abundance.

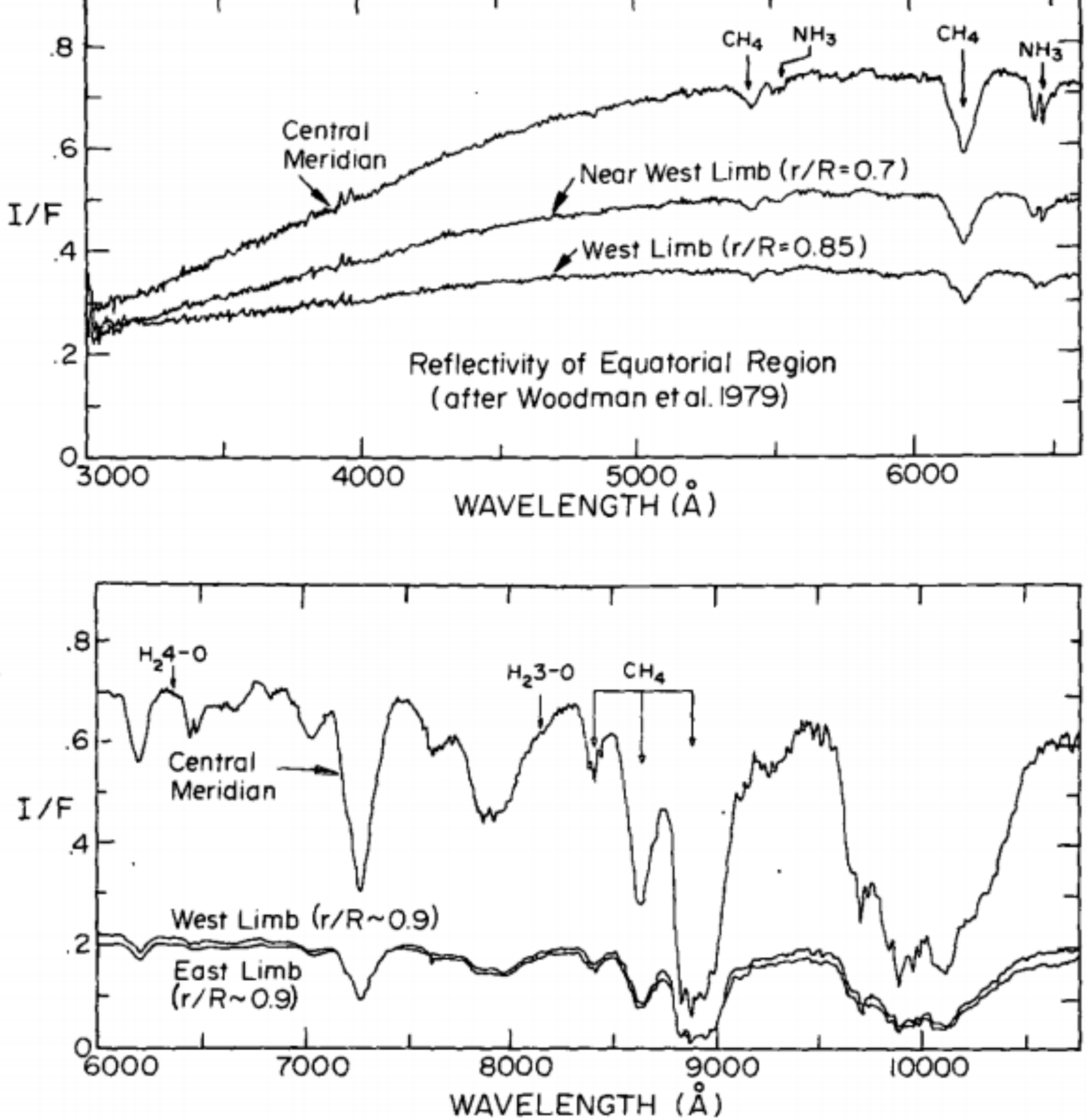


FIG. 4. Reflectivity of the ER observed by Woodman *et al.* (1979).

Step 1: Cloud Model

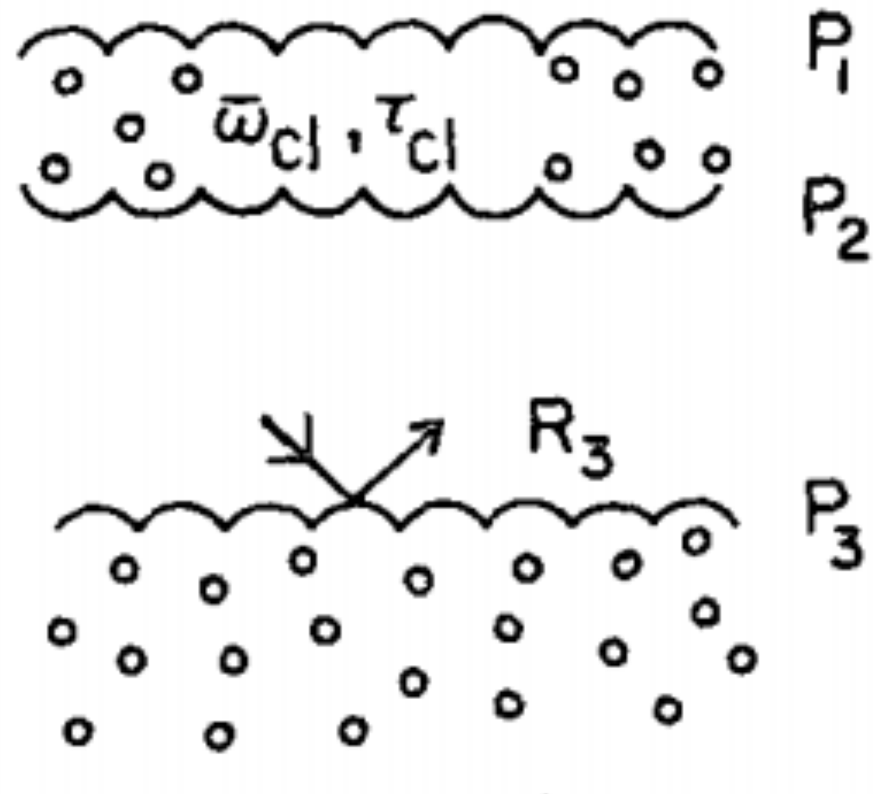
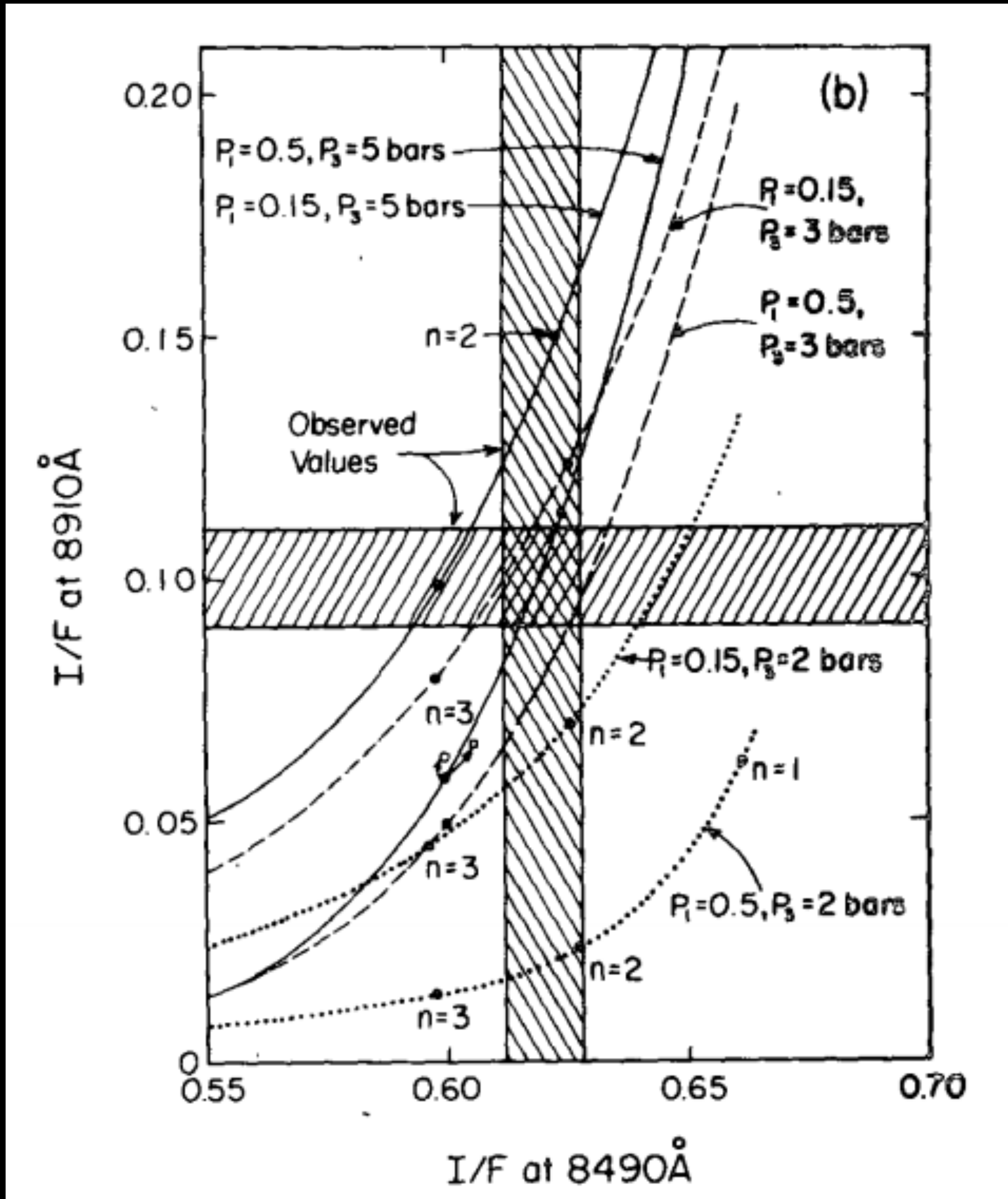


FIG. 6. Schematic illustration of the 6 parameters in our version of the two-cloud model.

First use H_2 quadrupole lines to constrain cloud.

For each model we include the constraint that it yield the observed equivalent width for the 4-0 $S(1)$ hydrogen quadrupole line (Section 4). We

Strong CH_4

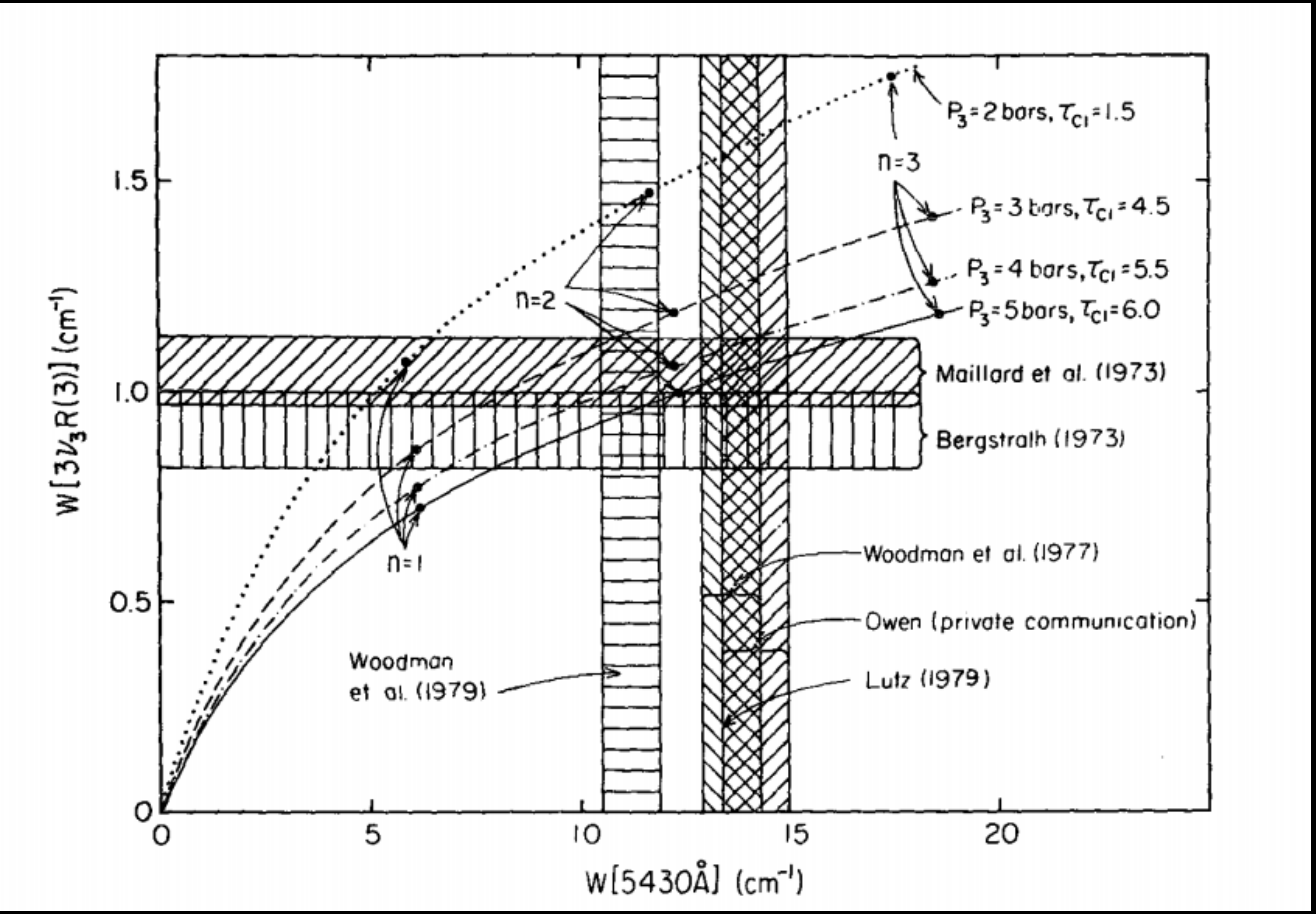


Weak CH_4

Reflectivity in 2 bands constrains clouds

Step 2: CH_4 Abundance

Cloud model plus equivalent widths of other methane bands gives CH_4 abundance



Step 3: Consistency Checks

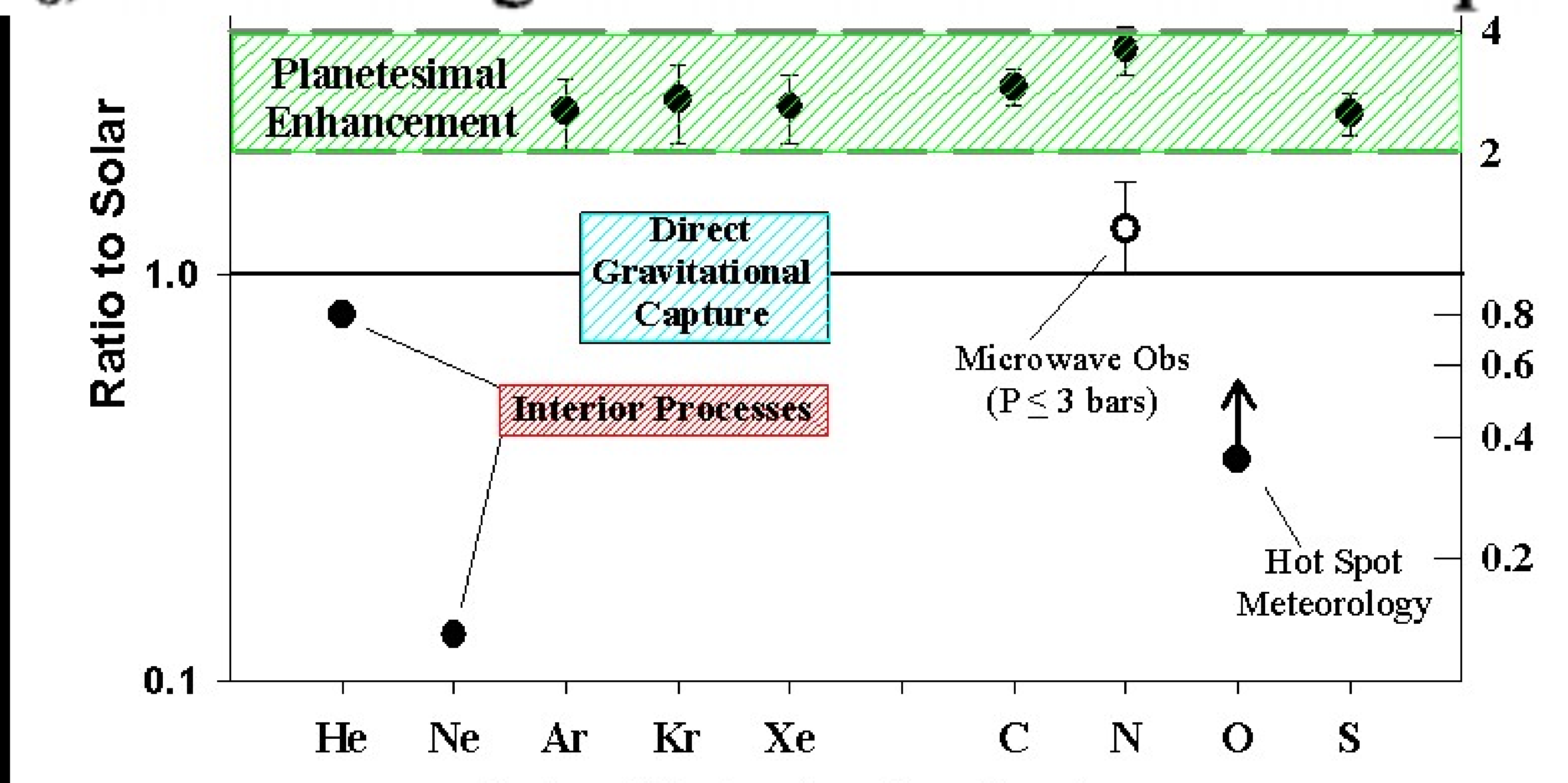
- Utilize entire spectrum to check derived abundance
- Further constrain high altitude hazes and NH_3 abundances
- All by bootstrapping using multiple CH_4 bands plus continuum

Accuracy?

Our results indicate that CH_4 is enriched in the envelope of Jupiter, with an abundance $n(CH_4) \sim 2$ times larger than its solar abundance. Since NH_3 and H_2O are less volatile than CH_4, one would expect their abundances relative to the solar values to be at least as great. Our conclusion that $n(NH_3) \sim 1.5 \pm 0.5$ for $P \sim 1$–4 bars is consistent with $n(NH_3) \sim 2$ through the bulk of the envelope.

Accuracy?

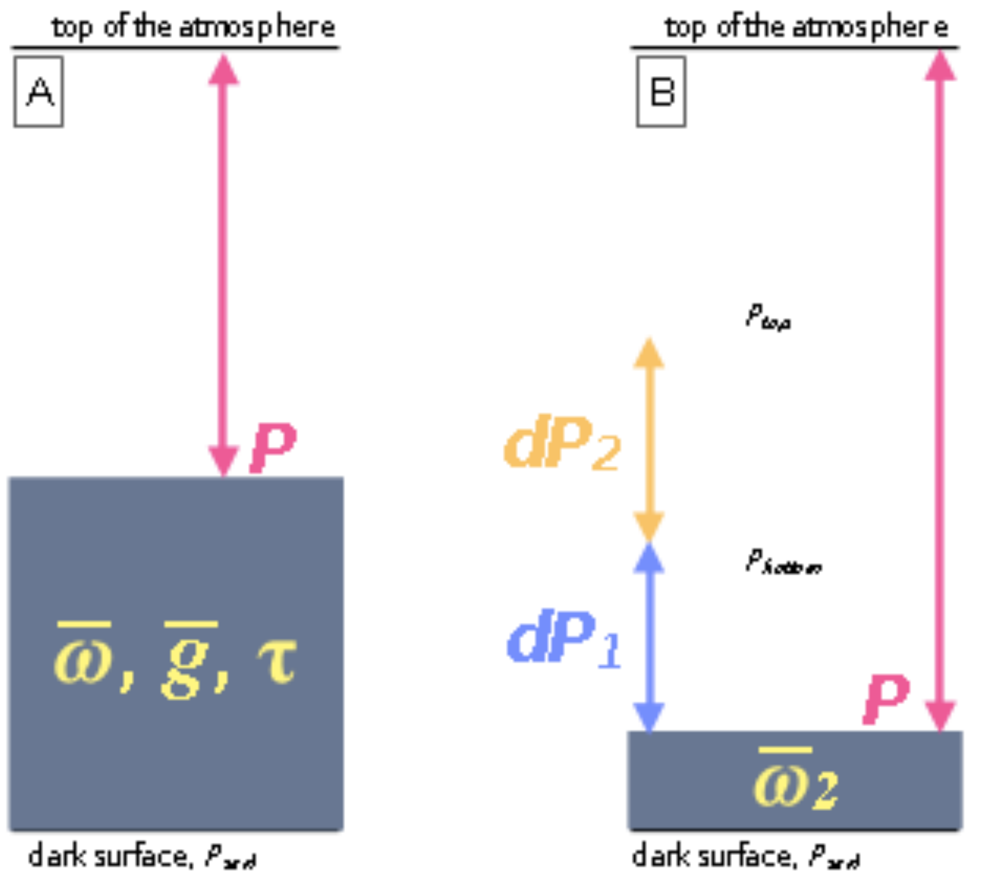
Our results indicate that CH_4 is enriched in the envelope of Jupiter, with an abundance $n(CH_4) \sim 2$ times larger than its solar abundance. Since NH_3 and H_2O are less volatile than CH_4, one would expect their abundances relative to the solar values to be at least as great. Our conclusion that $n(NH_3) \sim 1.5 \pm 0.5$ for $P \sim 1$–4 bars is consistent with $n(NH_3) \sim 2$ through the bulk of the envelope.

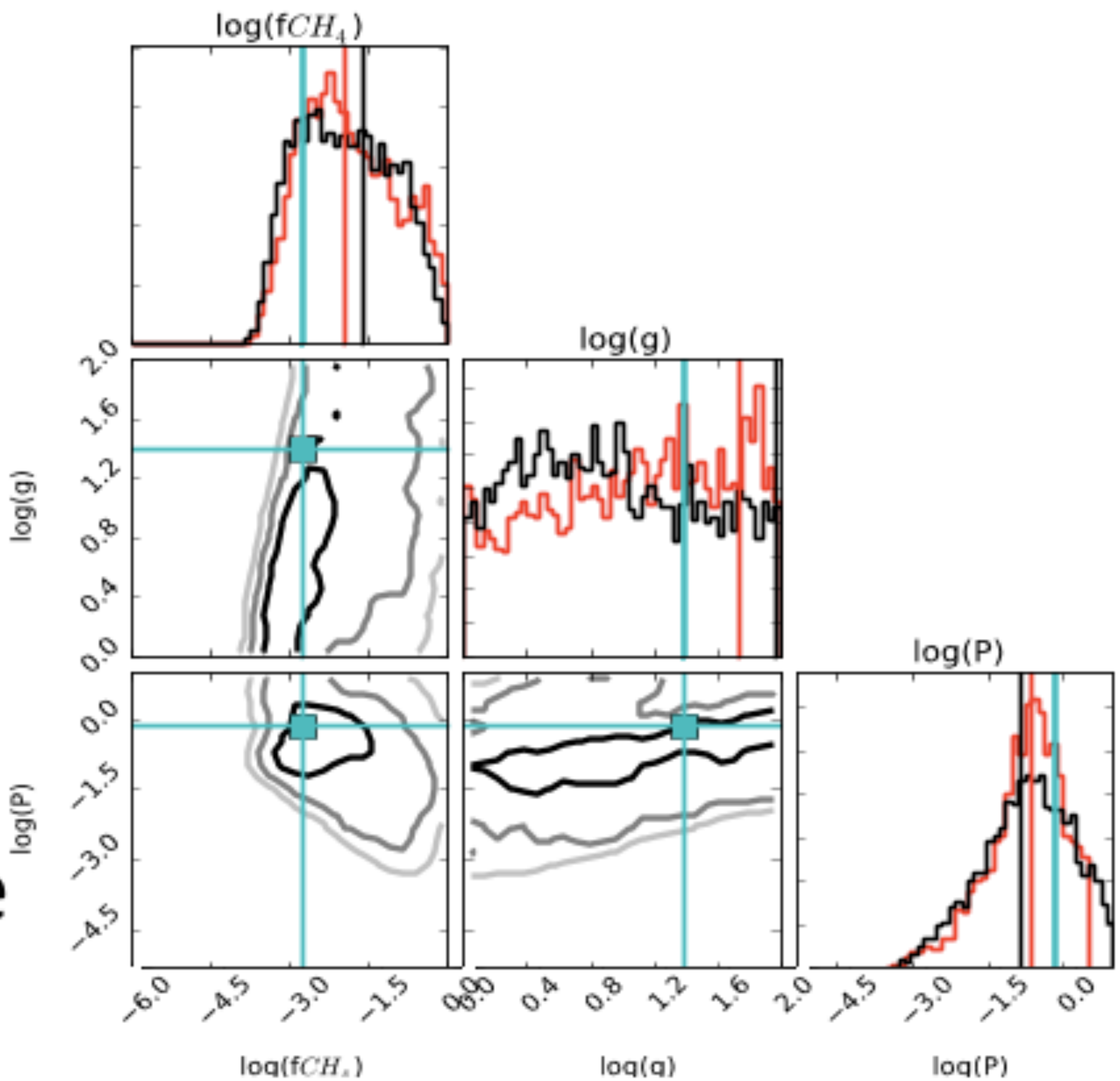


Issues for Giant Exoplanets

- Noisier data
- Little to no a priori knowledge (gravity, radius, gross atmospheric structure, orbital phase, etc.)
- Same issues will be faced by terrestrial planet studies (giants just get there first)

MCMC Retrievals of Cool Giants

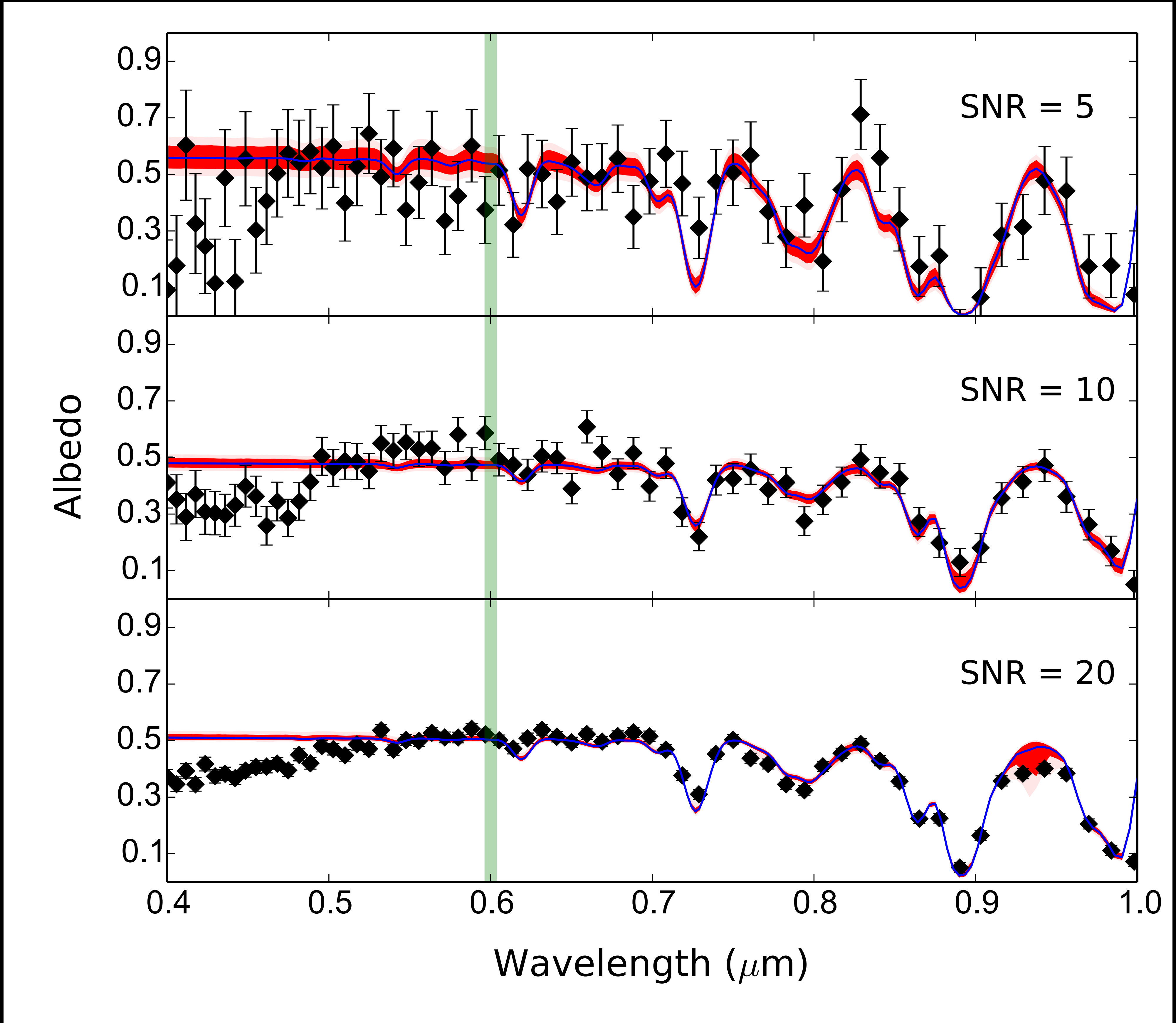




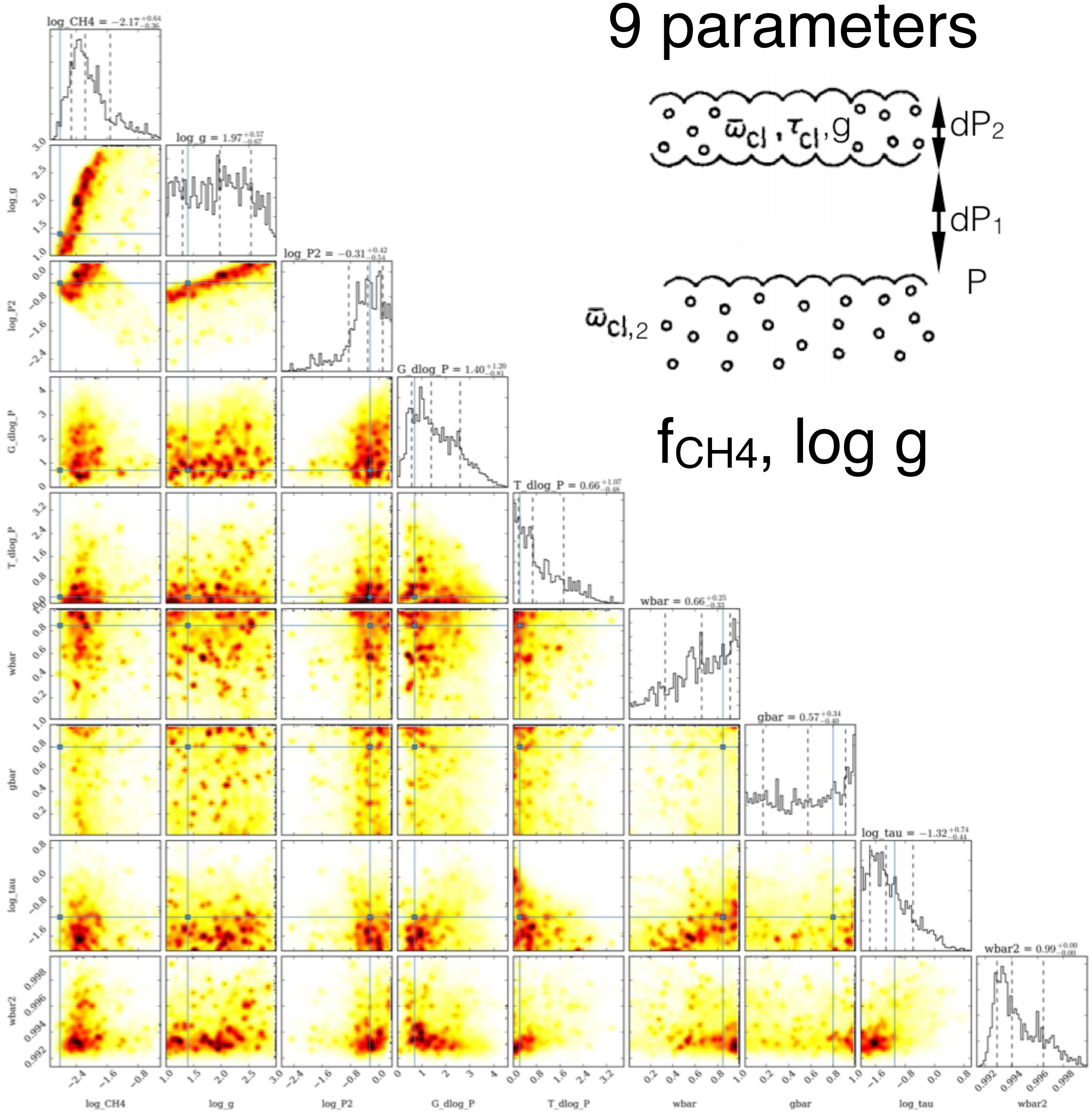
- Methane Abundance
- Surface Gravity
- Cloud Properties

Lupu et al. (2016)

Example: Jupiter

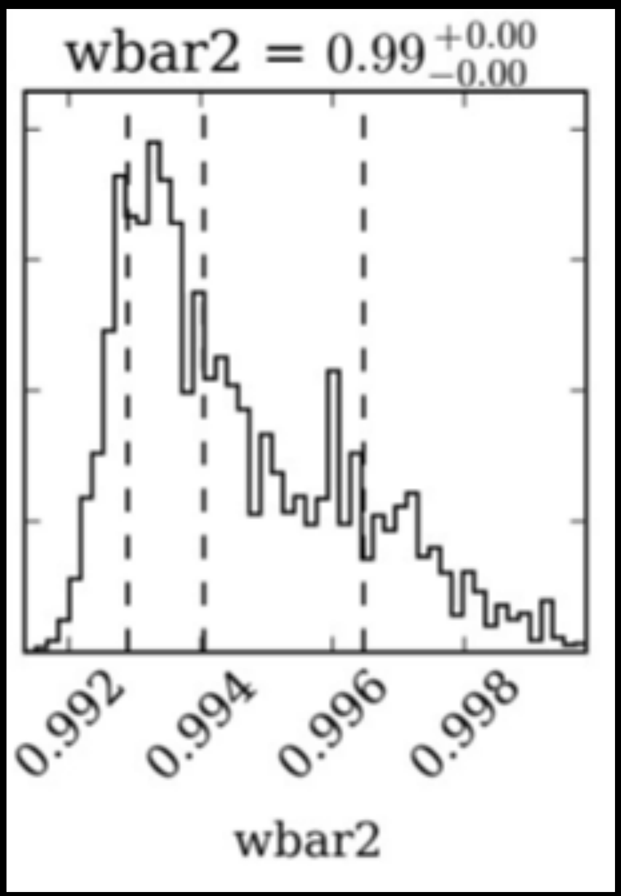


9 parameters



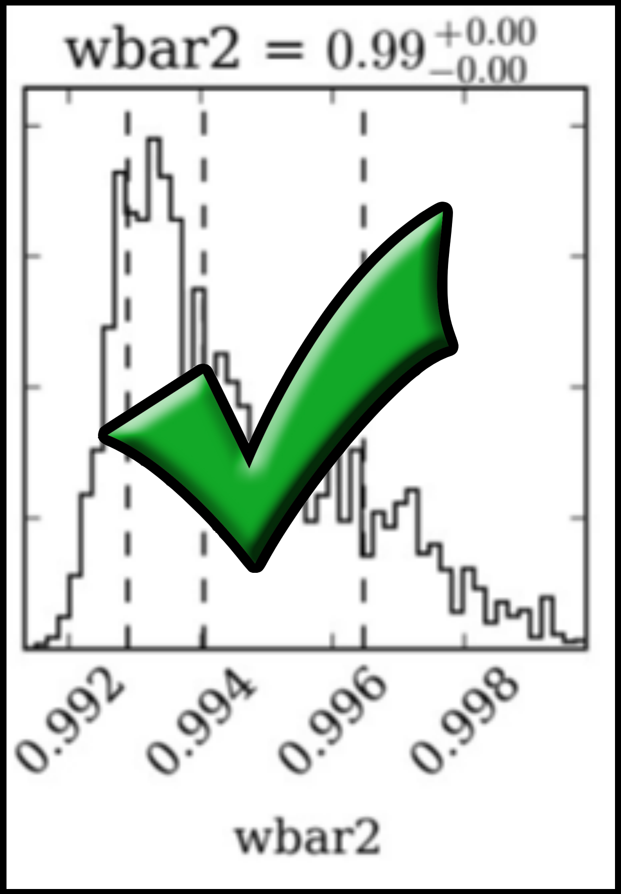
f_{CH4}, log g

Results



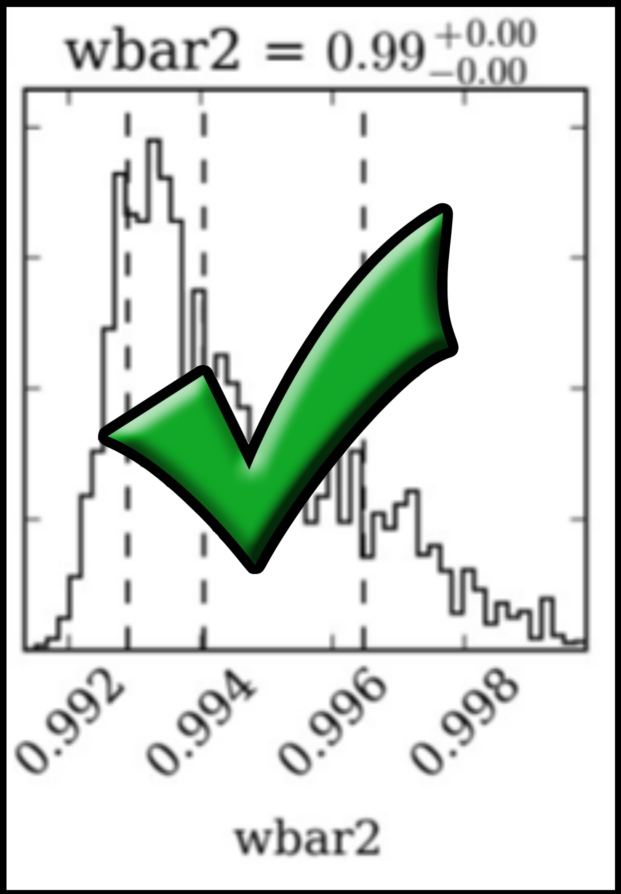
bright NH3
cloud

Results

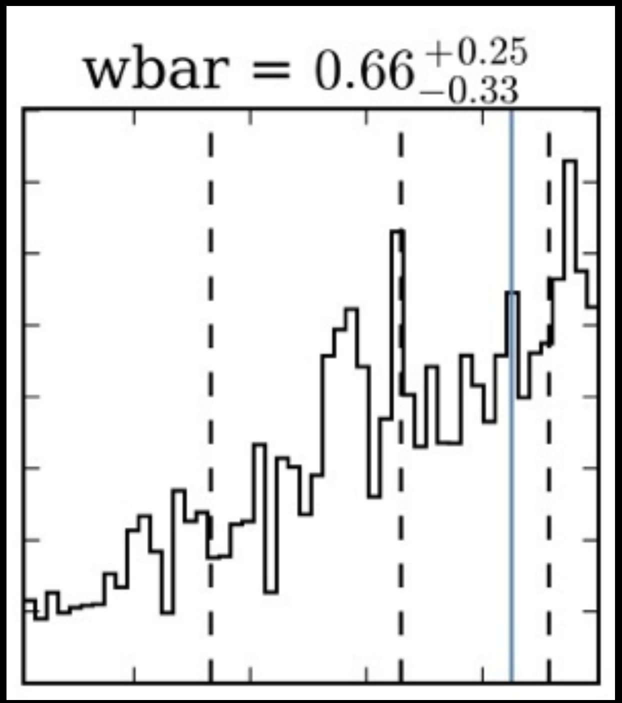


bright NH3
cloud

Results



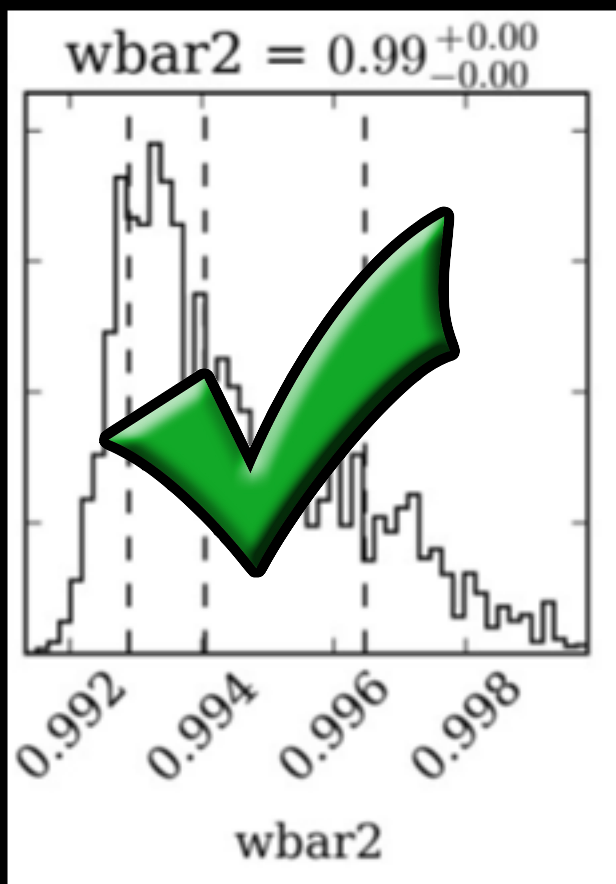
bright NH3
cloud



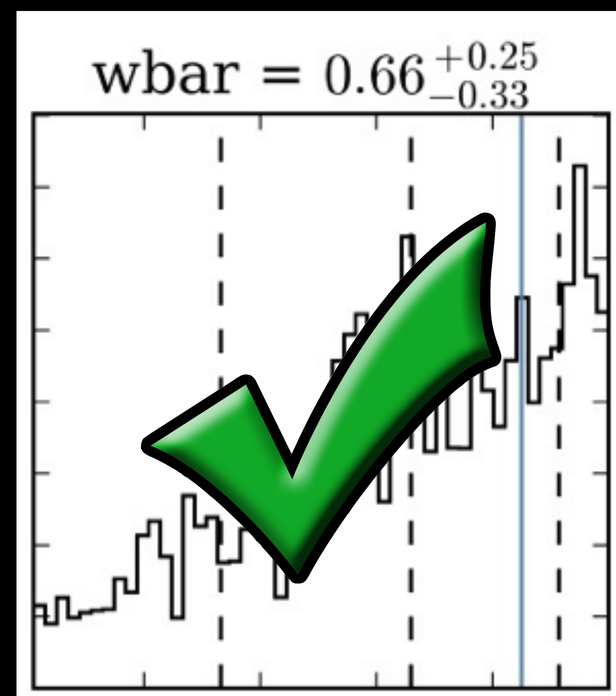
0 wbar 1.0

dark haze

Results



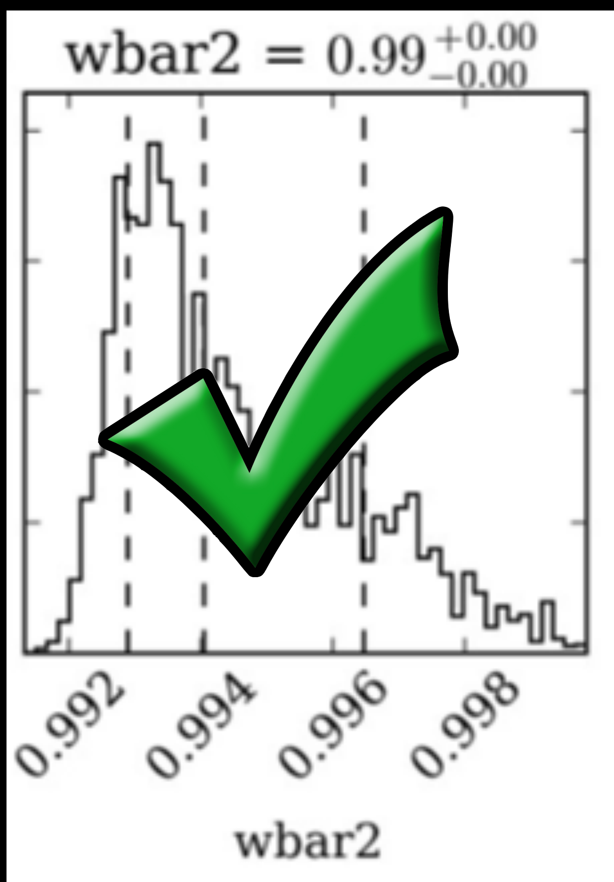
bright NH3
cloud



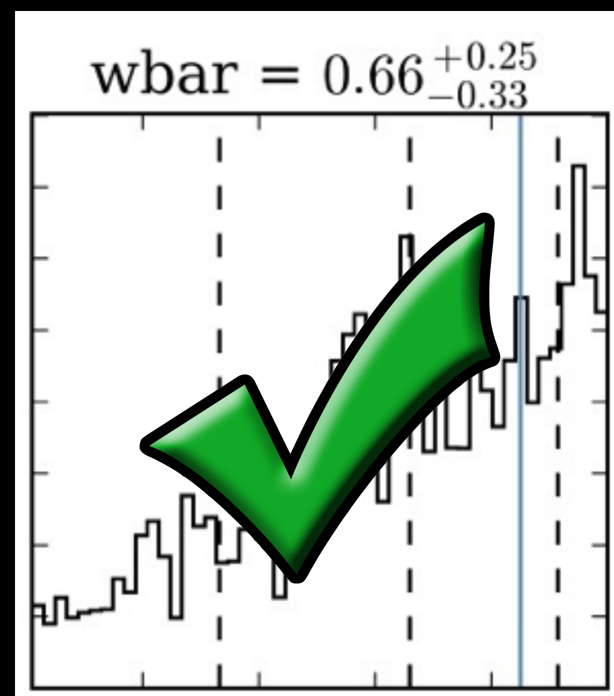
0 wbar 1.0

dark haze

Results

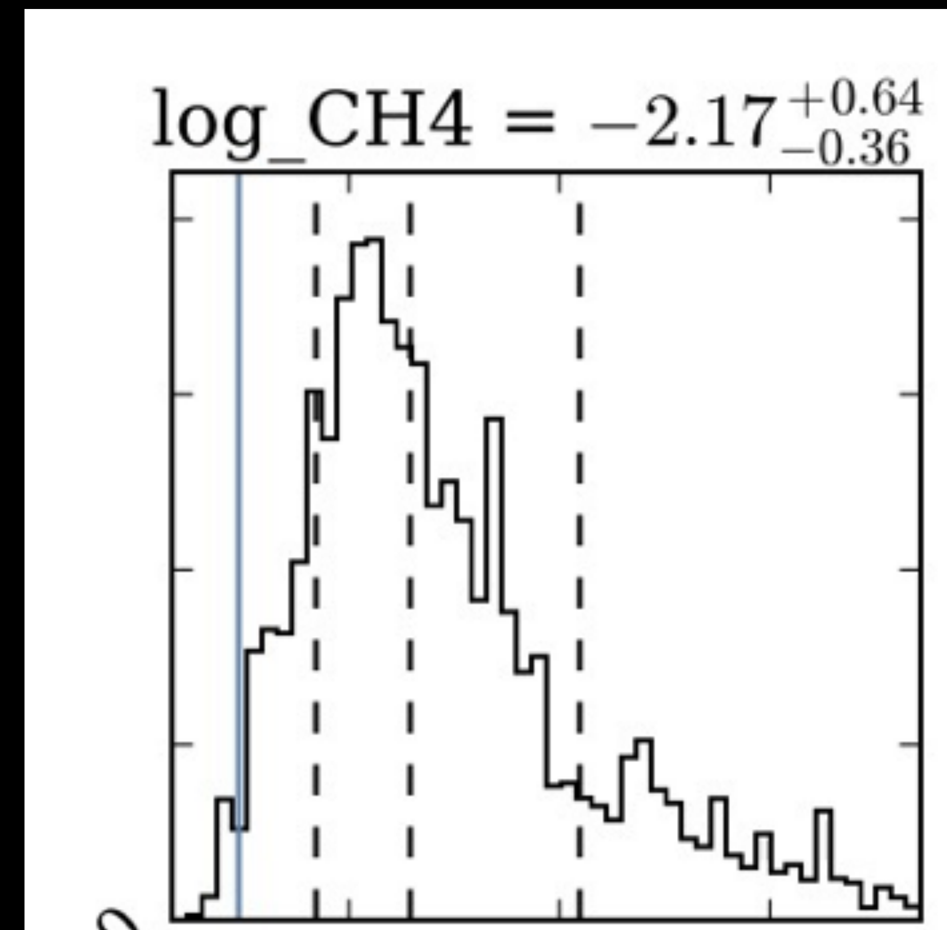


bright NH3 cloud



0 wbar 1.0

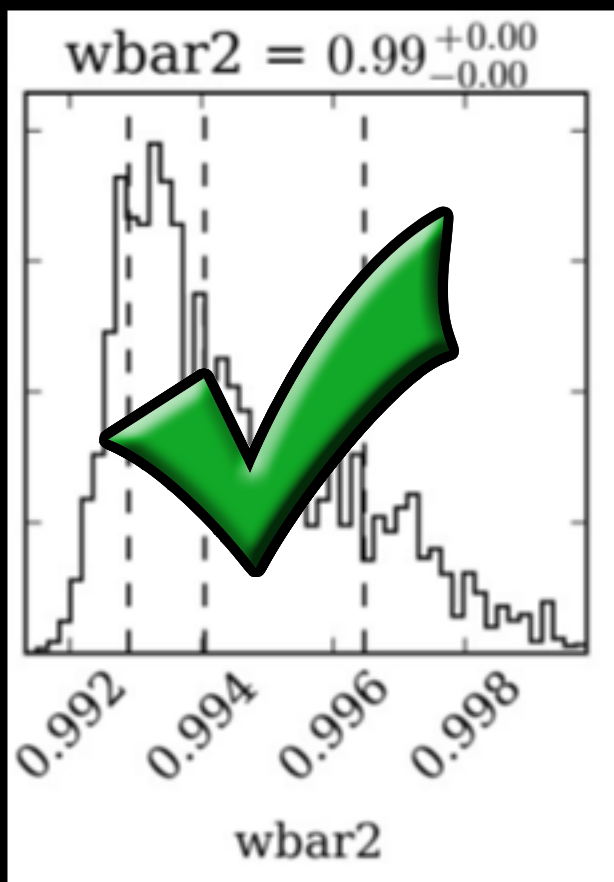
dark haze



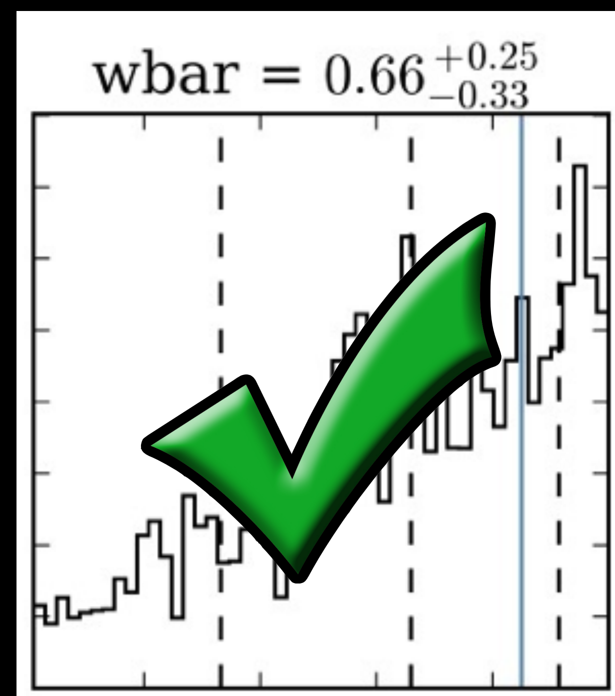
-2.4 -0.8

log f_{CH4}

Results

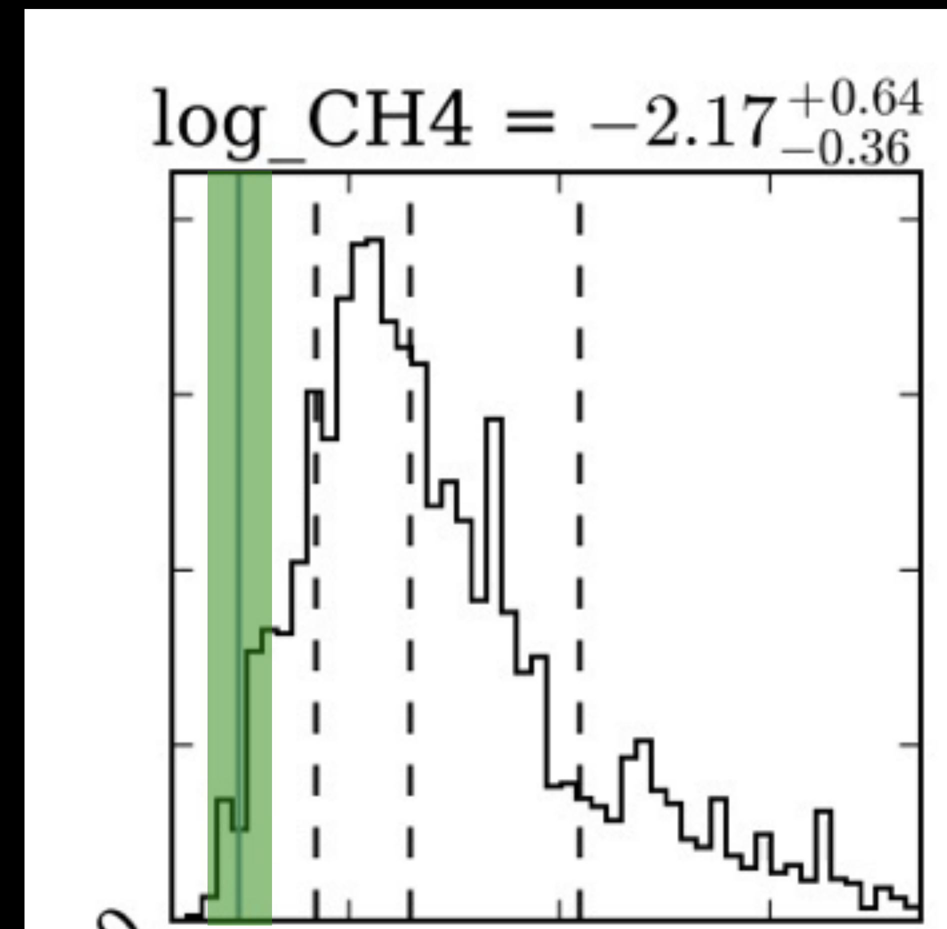


bright NH_3 cloud



0 wbar 1.0

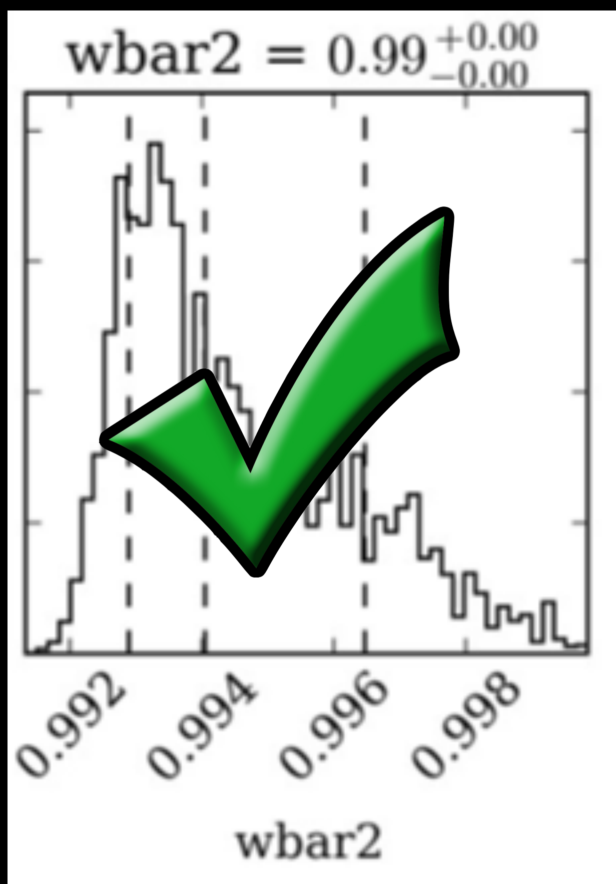
dark haze



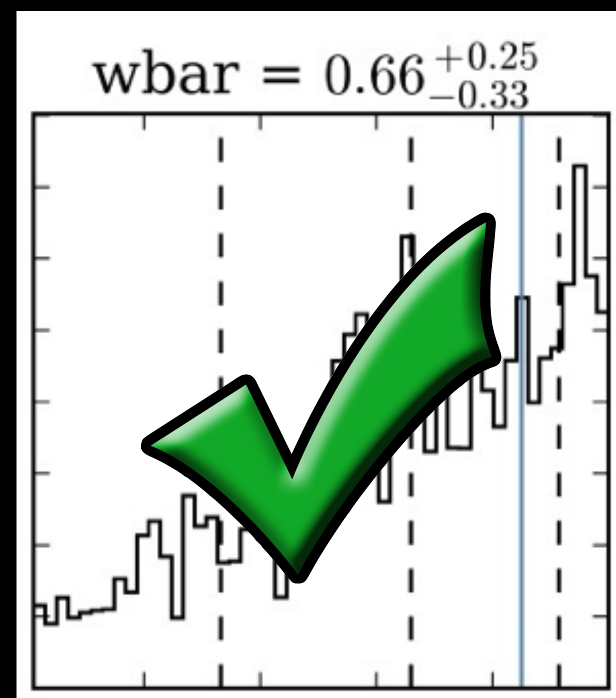
-2.4 -0.8

log f_{CH4}

Results

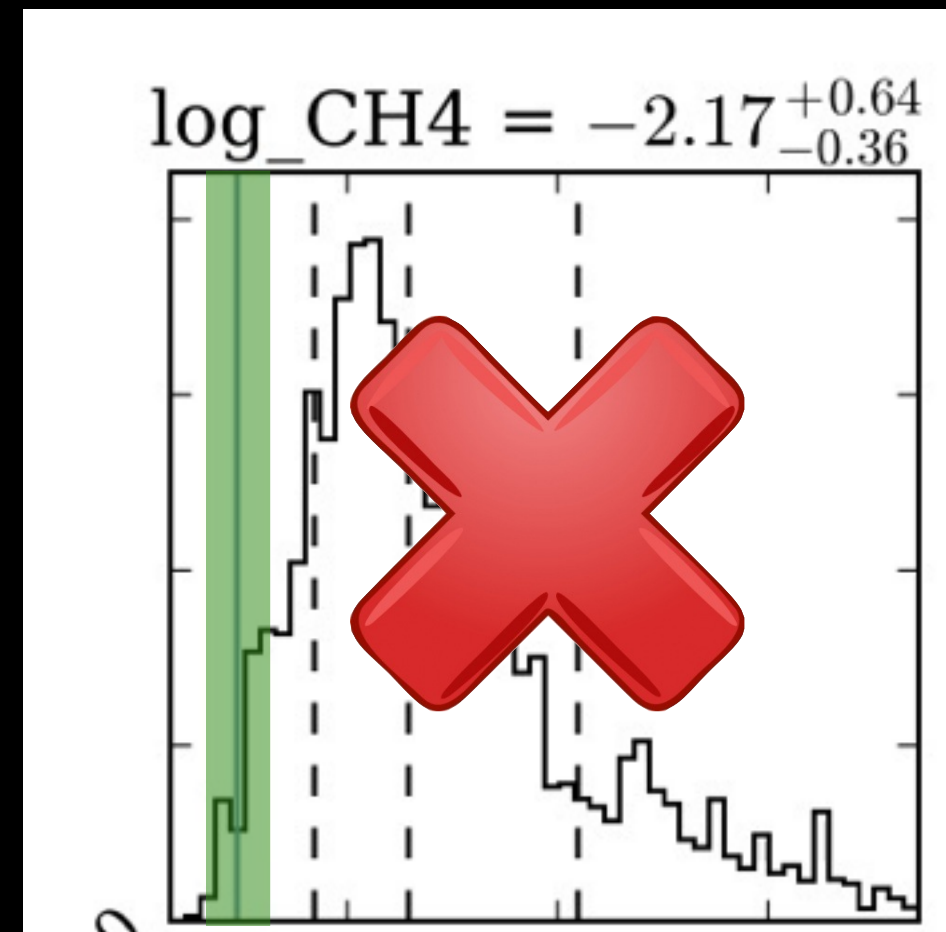


bright NH3 cloud



0 wbar 1.0

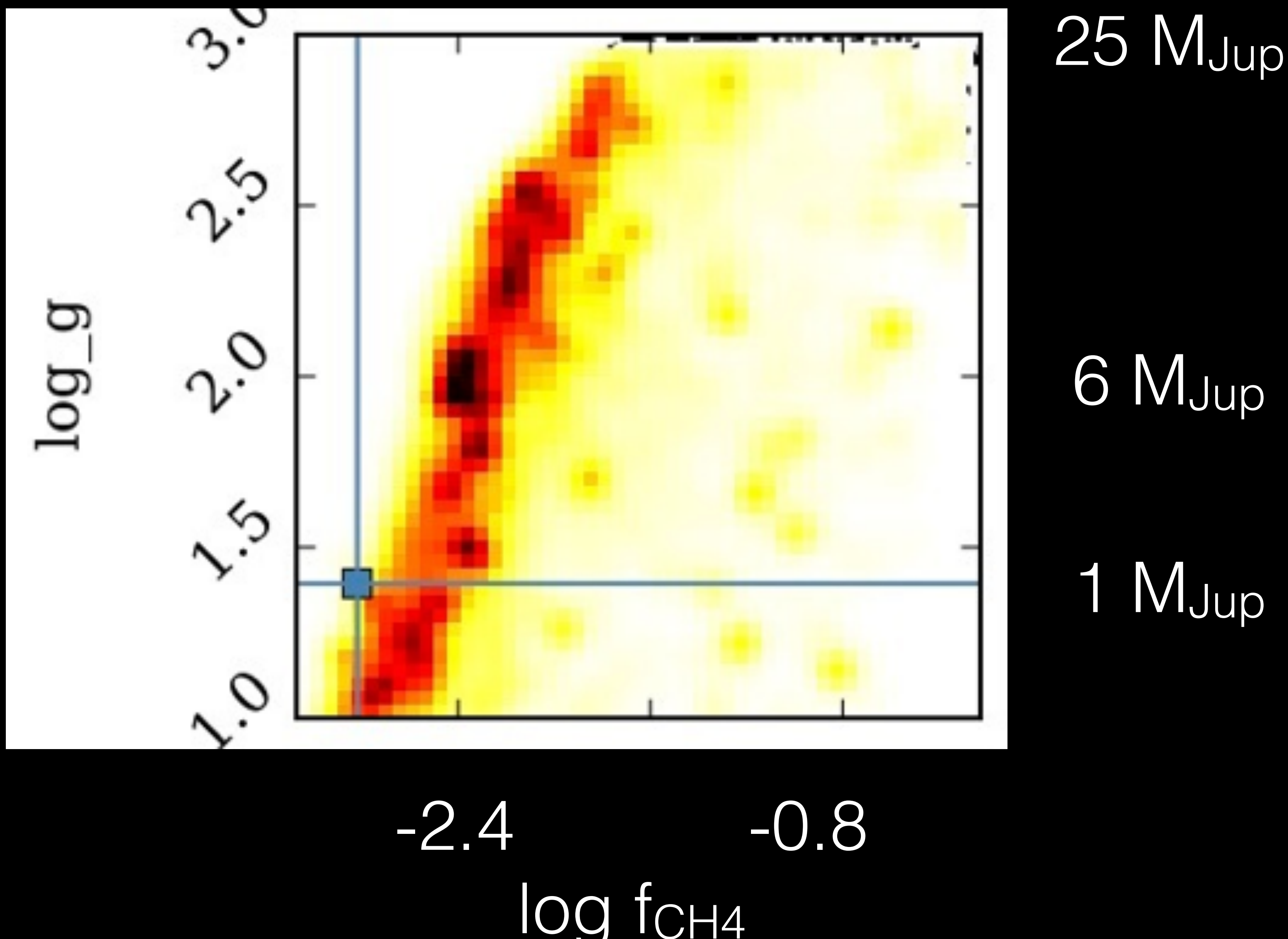
dark haze



-2.4 -0.8

log f_{CH4}

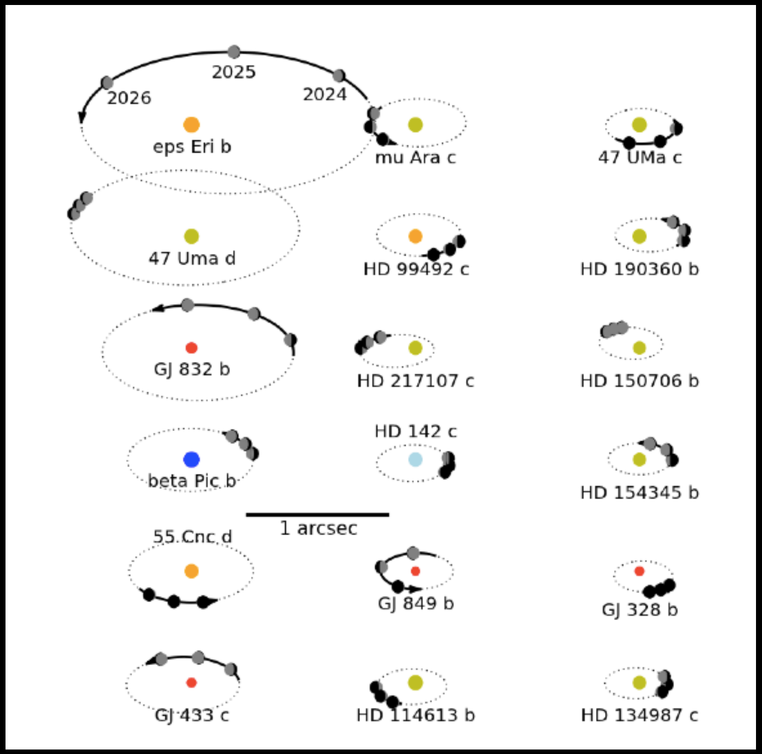
Retrieval Assumed Unconstrained Gravity



Higher gravity implies smaller column abundance above cloud and more CH_4

However…

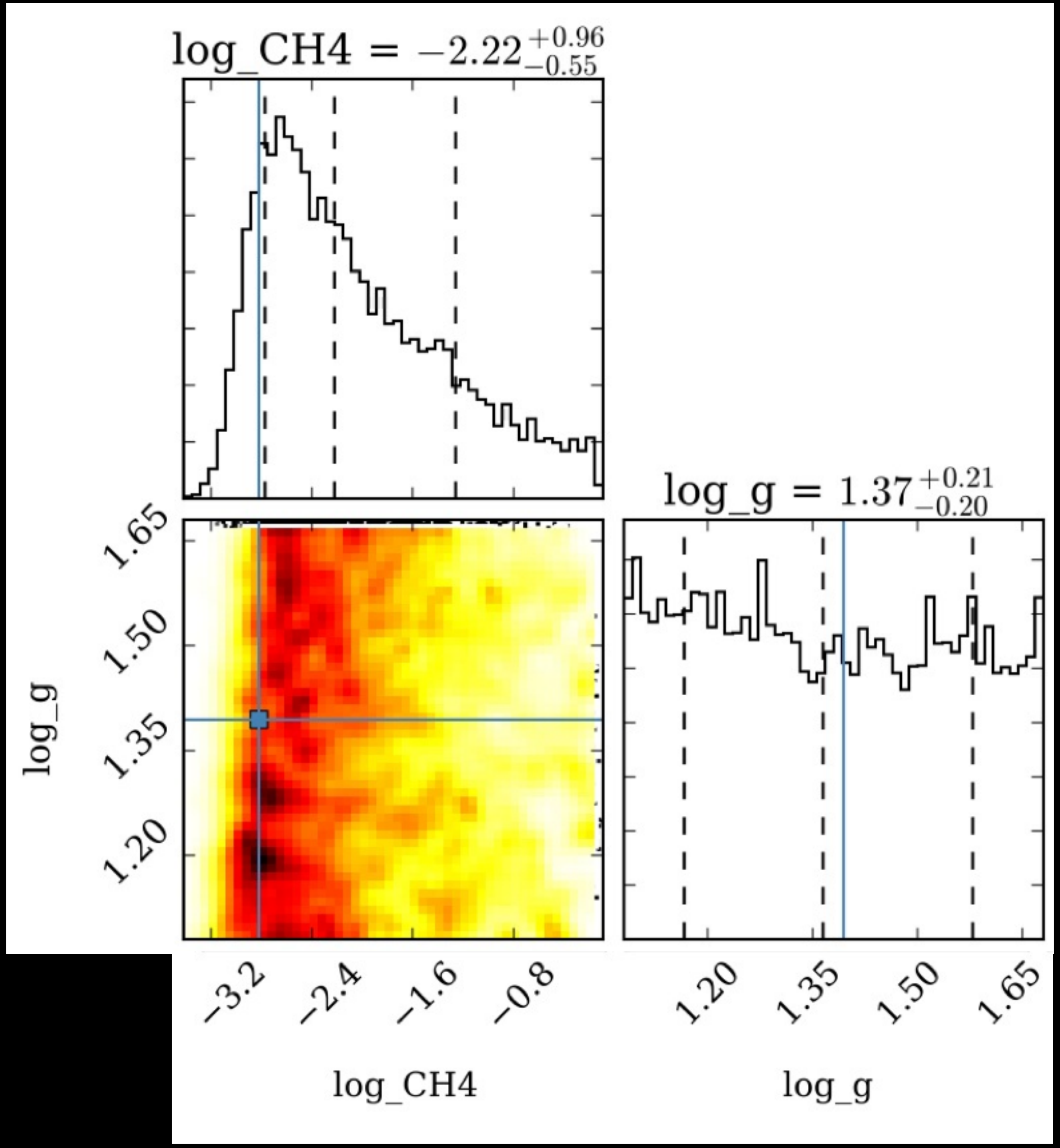
- Astrometry of RV planets will resolve sin *i* uncertainty and constrain masses
- Need about 3 visits for mass good to about 20%
- Along with radius constraints should provide much tighter log g range



Mass constraint combines with multiple radius constraints

Assume gravity known to within 4x

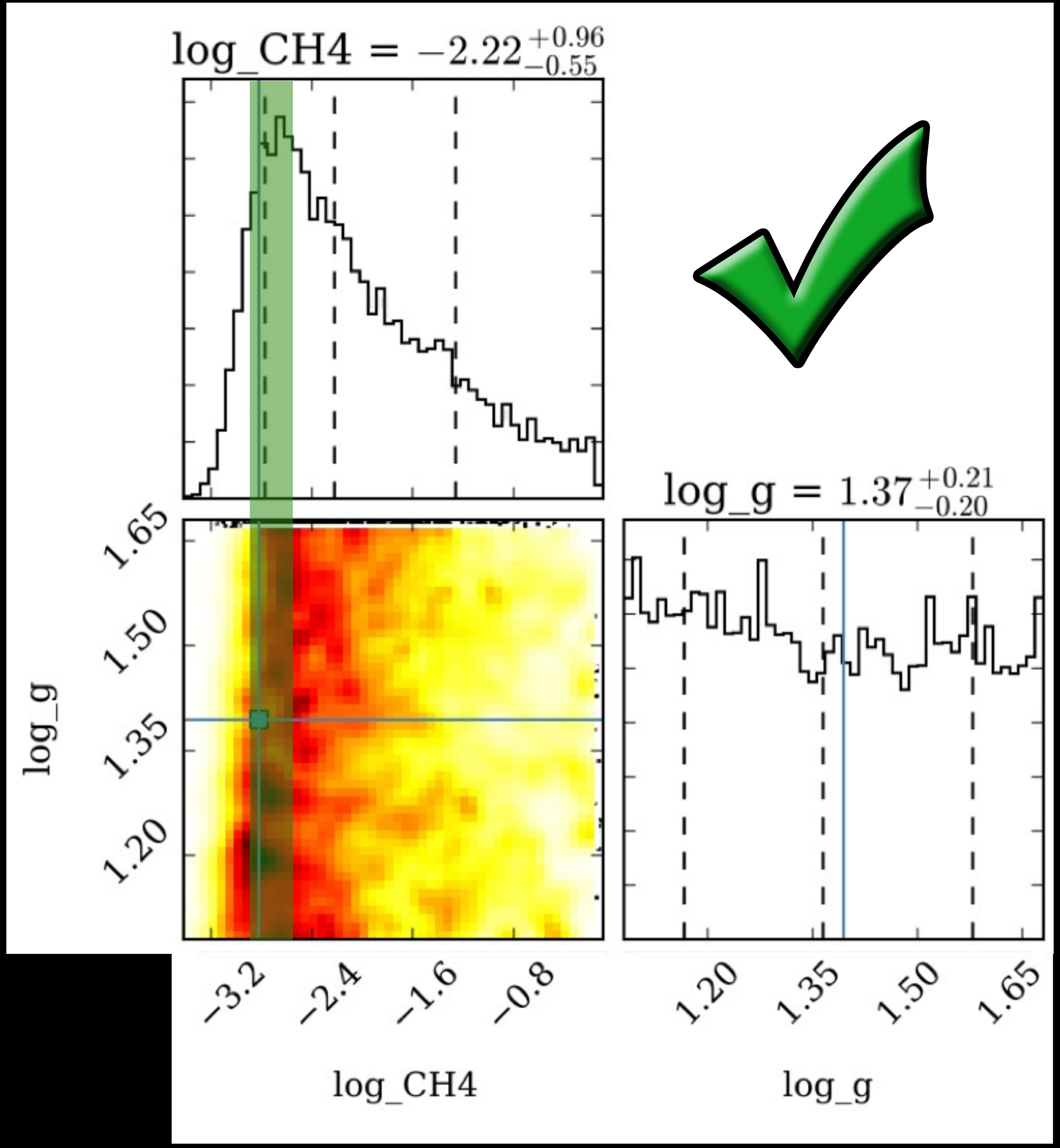
Correct CH_4 retrieval, but no gravity improvement

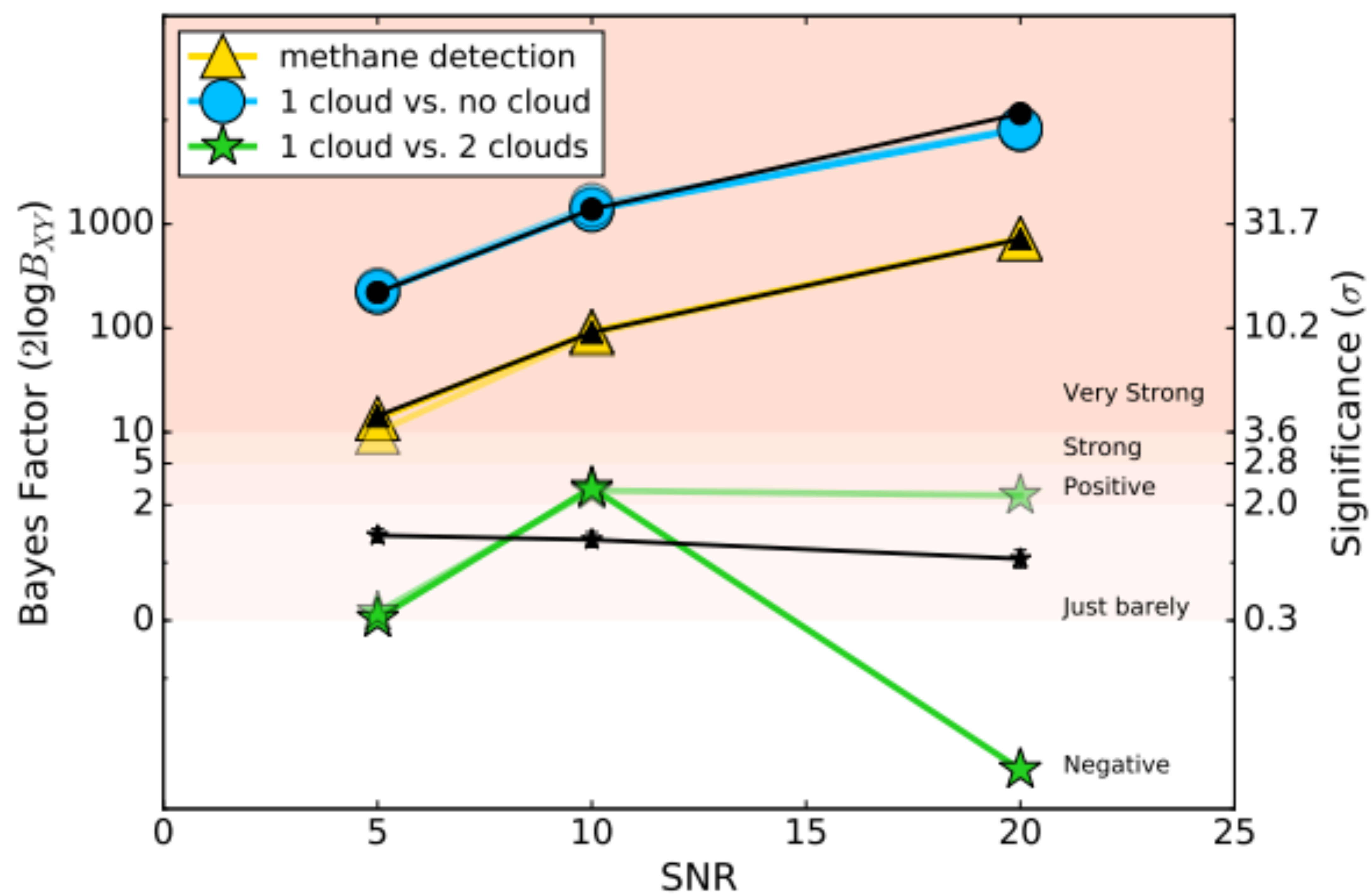


Mass constraint combines with multiple radius constraints

Assume gravity known
to within 4x

Correct CH_4 retrieval,
but no gravity improvement

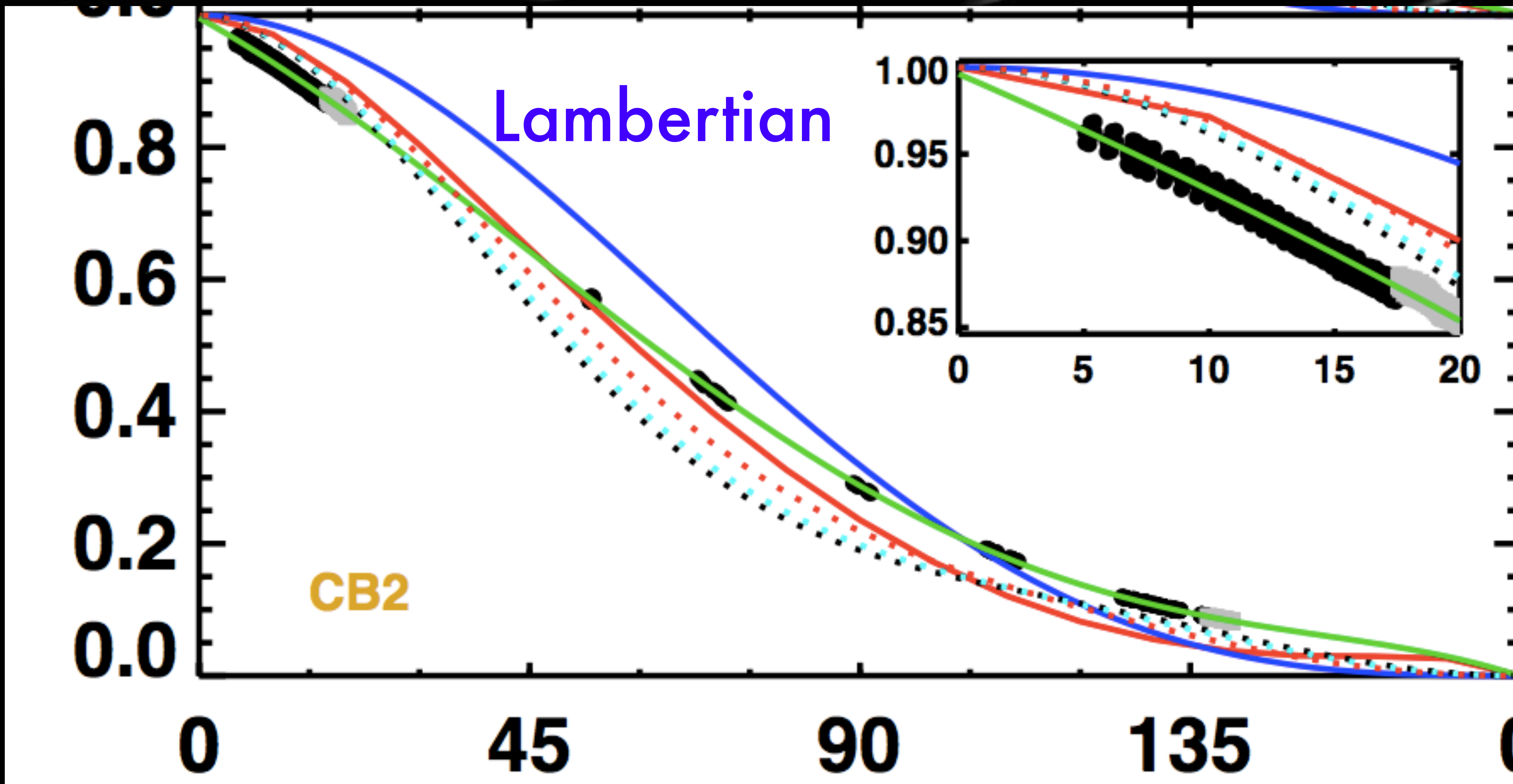




methane detection
1 cloud vs. no cloud
1 cloud vs. 2 clouds
Bayes Factor ($2\log B_{XY}$)
1000
100
10
5
2
0
Significance (σ)
31.7
10.2
3.6
2.8
2.0
0.3
Very Strong
Strong
Positive
Just barely
Negative
0
5
10
15
20
25
SNR

Complications….

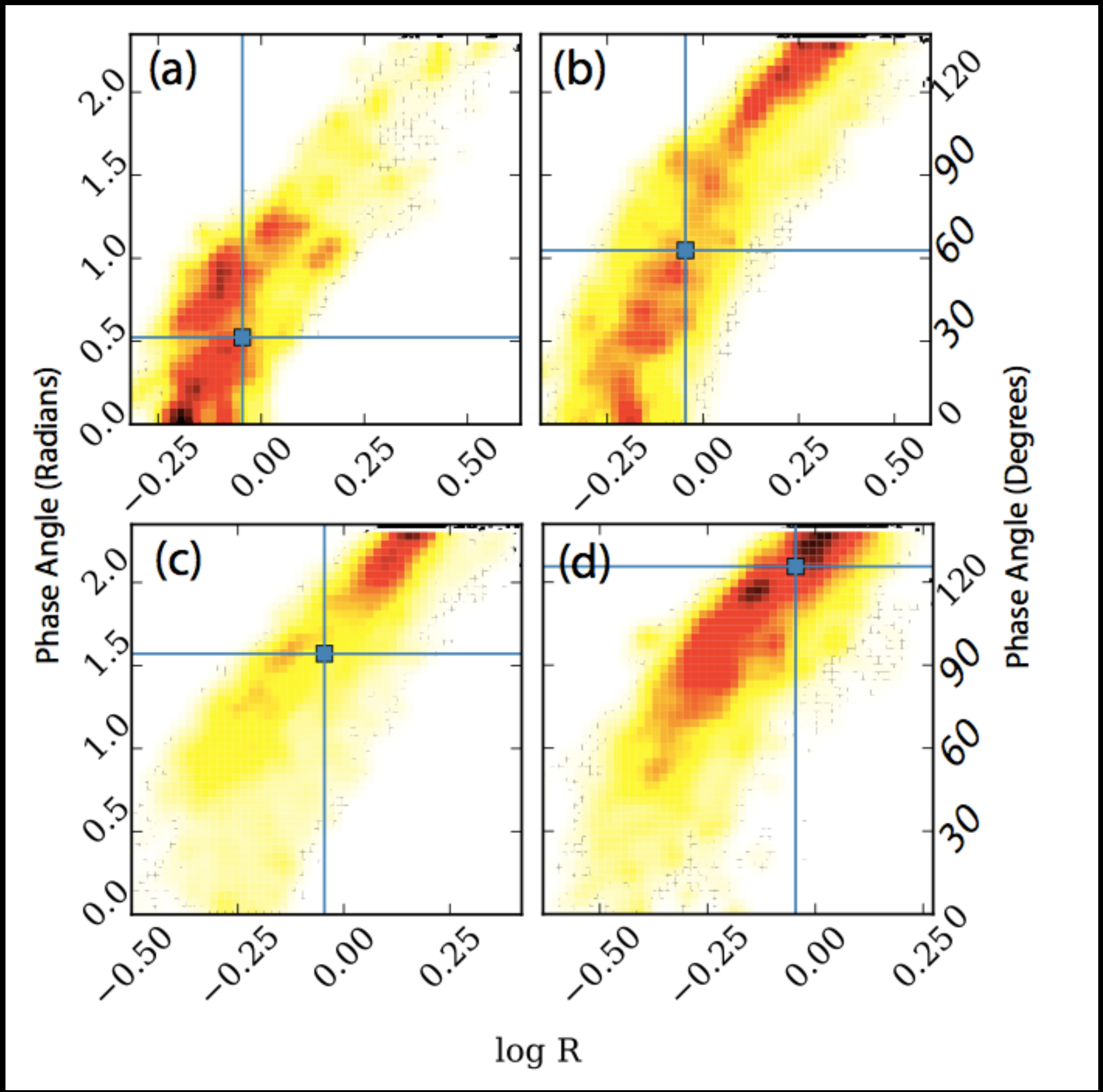
Phase Behavior

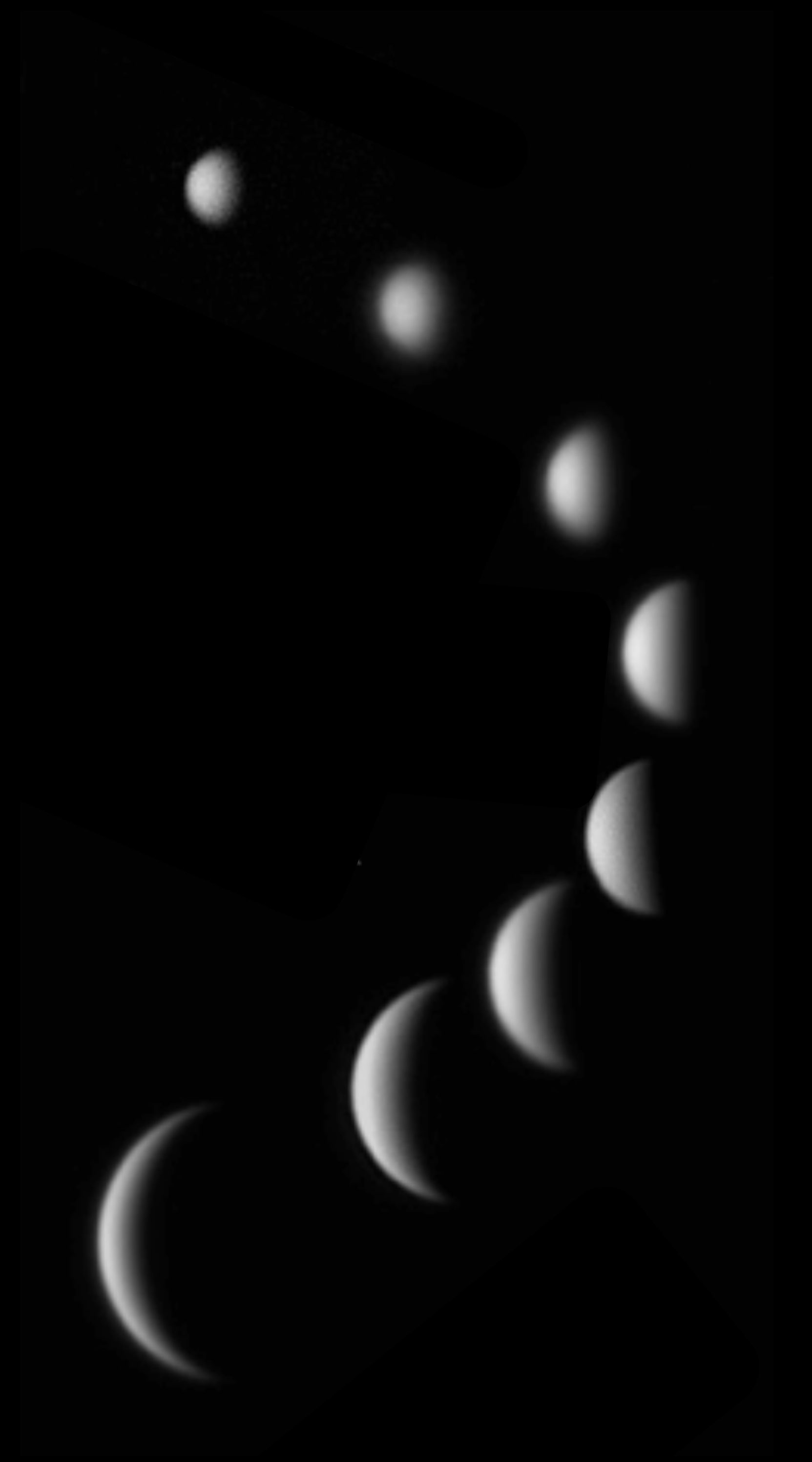


Phase angle (degrees)

Mayorga+ (2016)

Phase Angle – Planet Radius Degeneracy

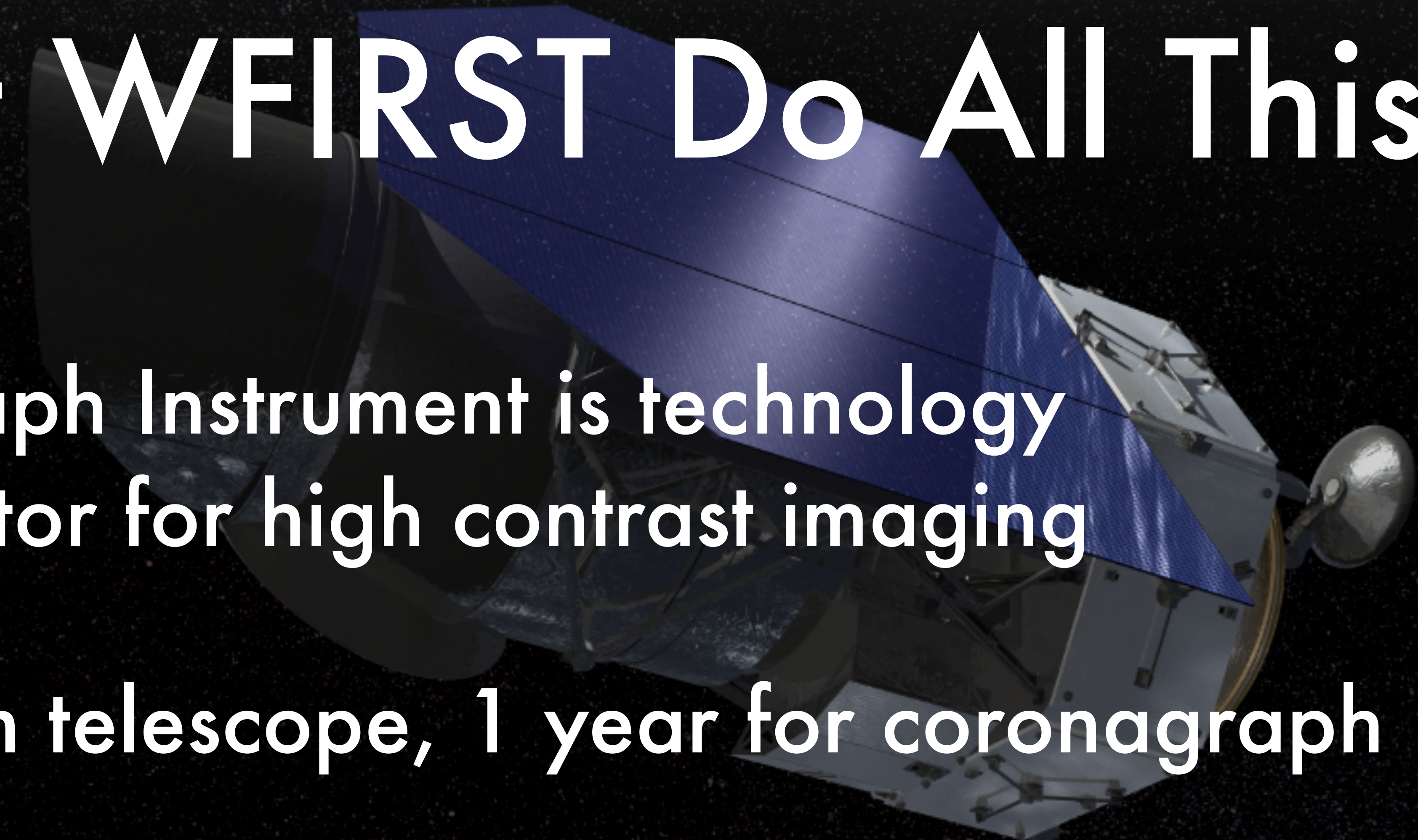




Conclusions

- Decades of experience exist for extracting atmospheric composition for Solar System giants
- Both methane AND continuum samples are important for determining altitudes and compositions
- Observing more than one methane band significantly improves knowledge of atmospheric vertical structure
- Cloud heights, absorber abundances can be accurately derived from visible spectra for $R > 70$

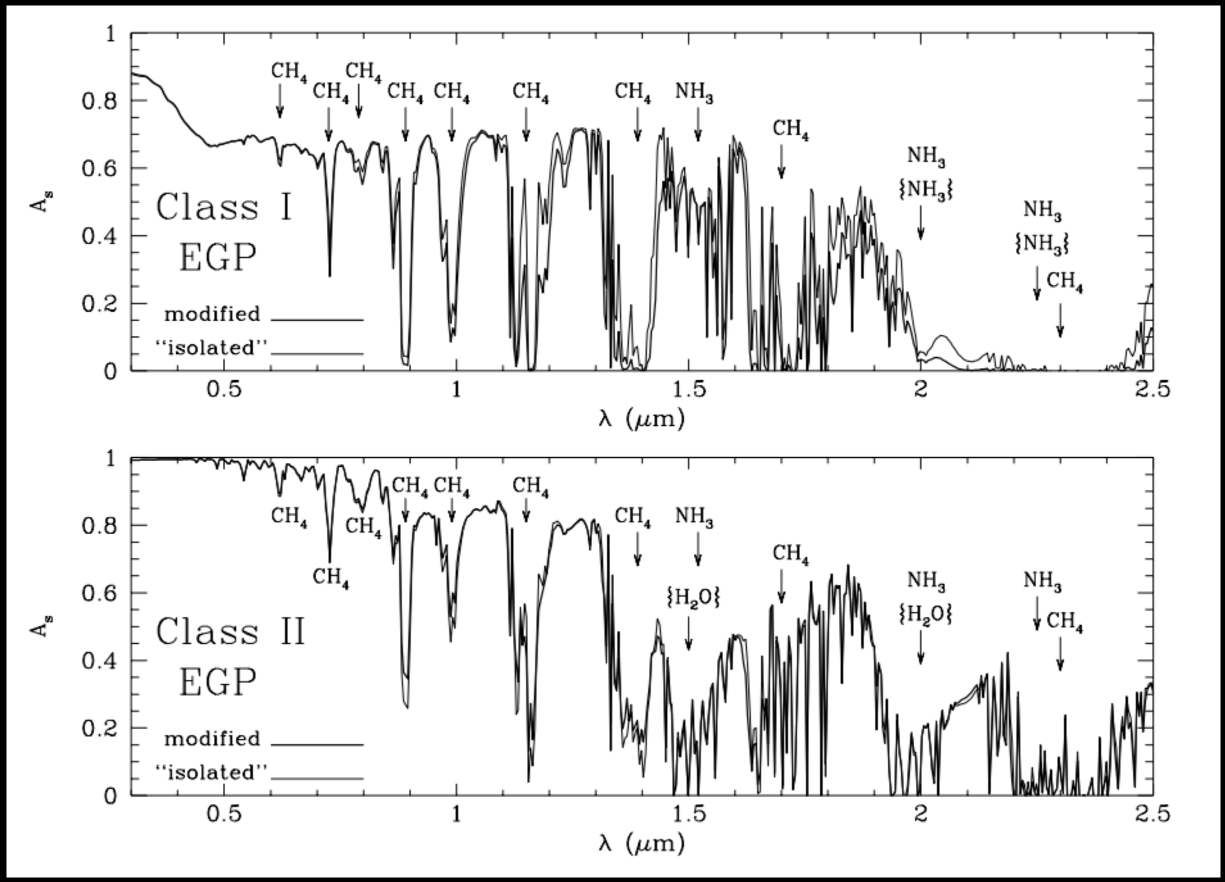
Won’t WFIRST Do All This?



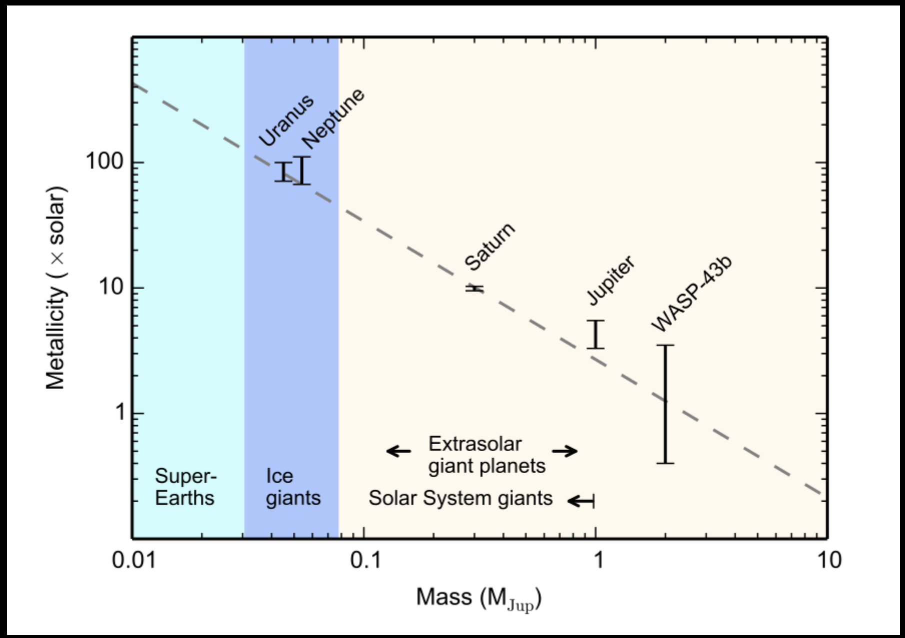
- Coronagraph Instrument is technology demonstrator for high contrast imaging
- Only 2.4-m telescope, 1 year for coronagraph
- Very Limited targets w/spectra only 600 to 900nm
- No NH_3, likely no H_2O, weak constraints on hazes

LUVOIR Advantages

- Spectra from blue through near-IR
  - haze absorption
  - more continuum & CH_4 bands plus H_2O, NH_3, Na, K
- Very high SNR for "free" in terrestrial planet systems
- Time resolved spectra



Sudarsky+ (2000)



Role for LUVOIR

- Characterize all possible planets
  - provides context for habitable planets
  - need to understand systems holistically incl. near misses
- Nature of super Earths/sub-Neptunes
- Giant planets
  - easier, outstanding spectroscopy targets (OWA requirement)
  - laboratories for clouds, composition (CH_4, H_2O, NH_3, Na, K) photochemistry, formation, stellar influence, etc.

Polarization?

Backup

Polarization of Venus
Dollfus & Coffeen (1970)

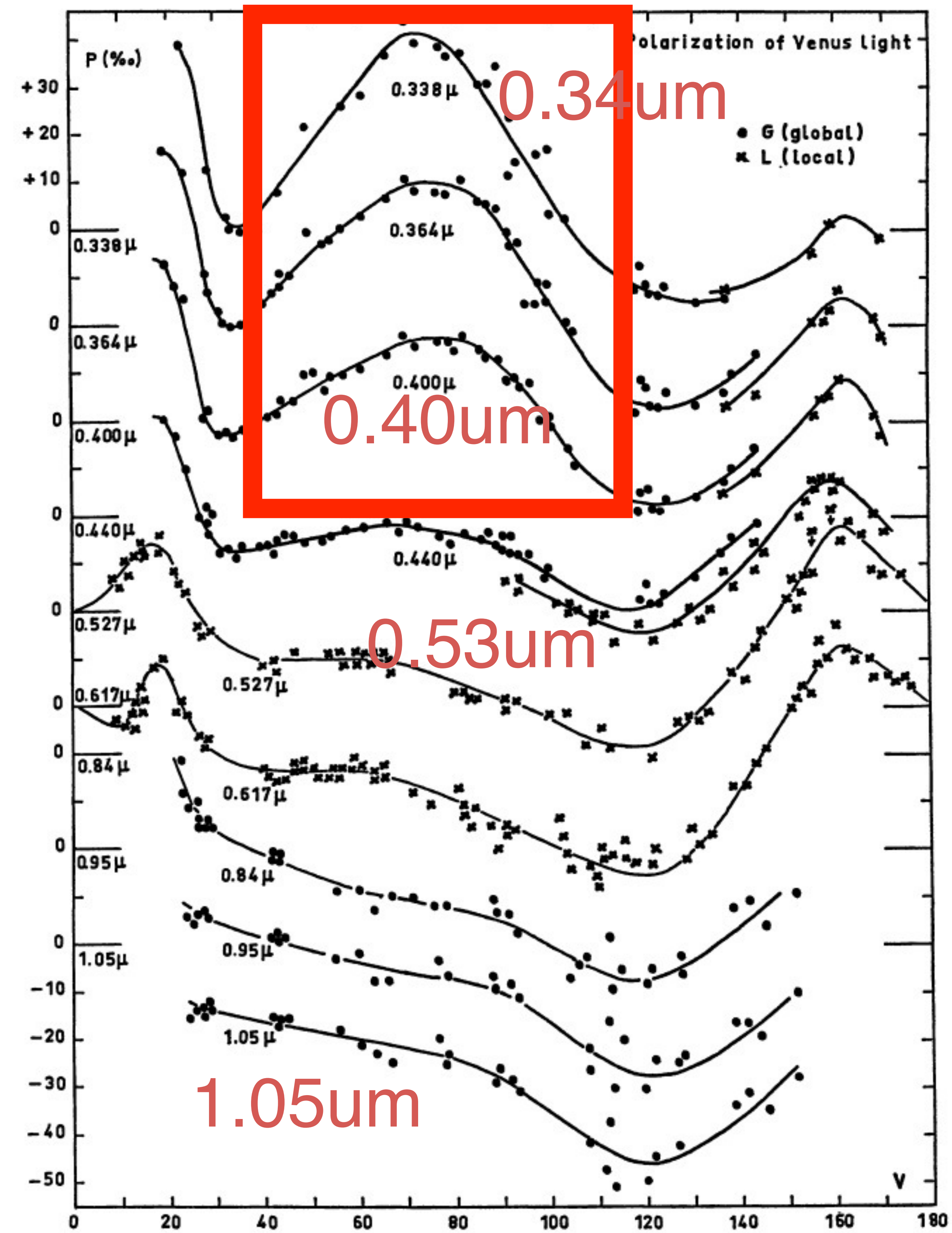


Fig. 1. Polarization of Venus. French Observations. 1950—1970

Polarization of Venus
Dollfus & Coffeen (1970)

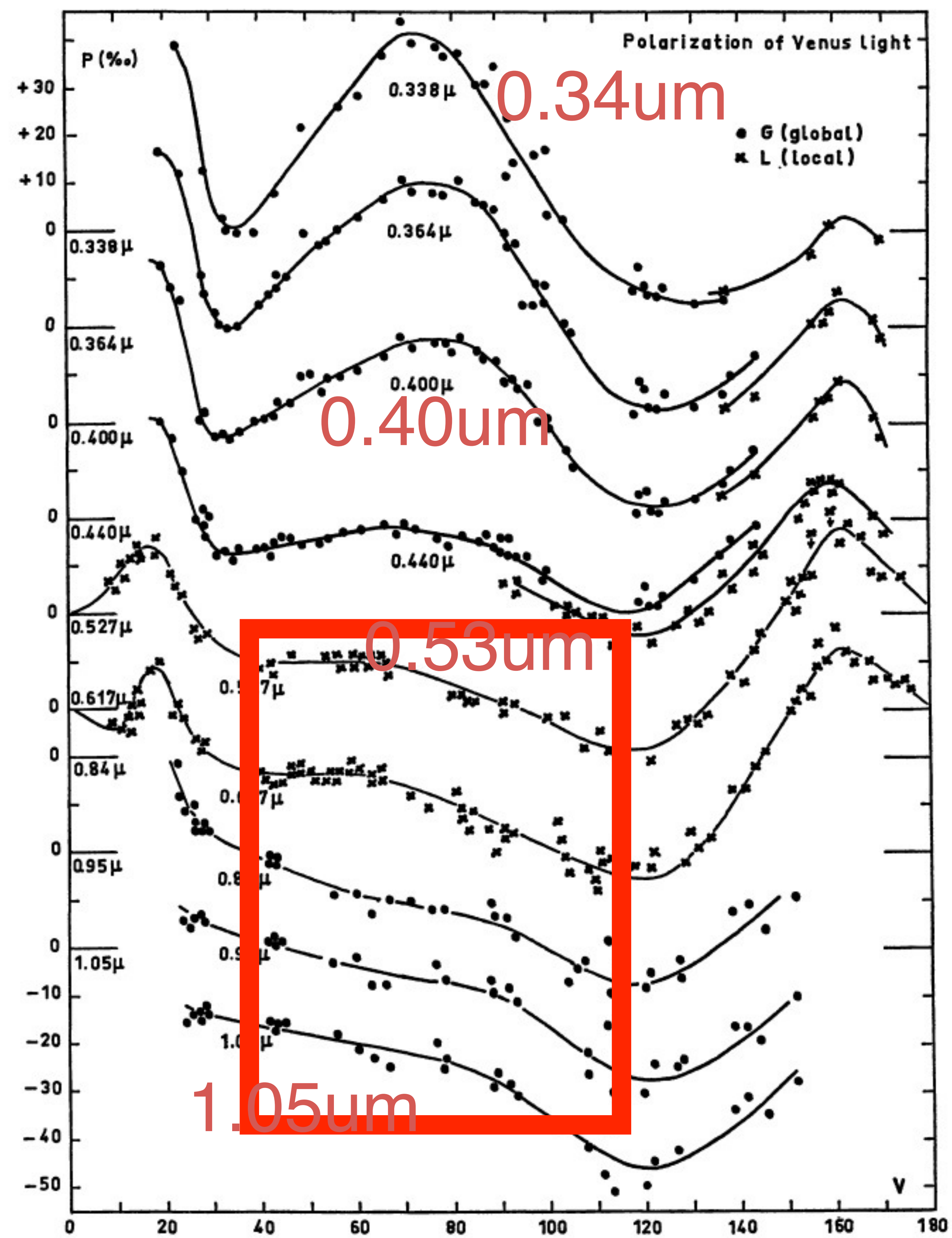
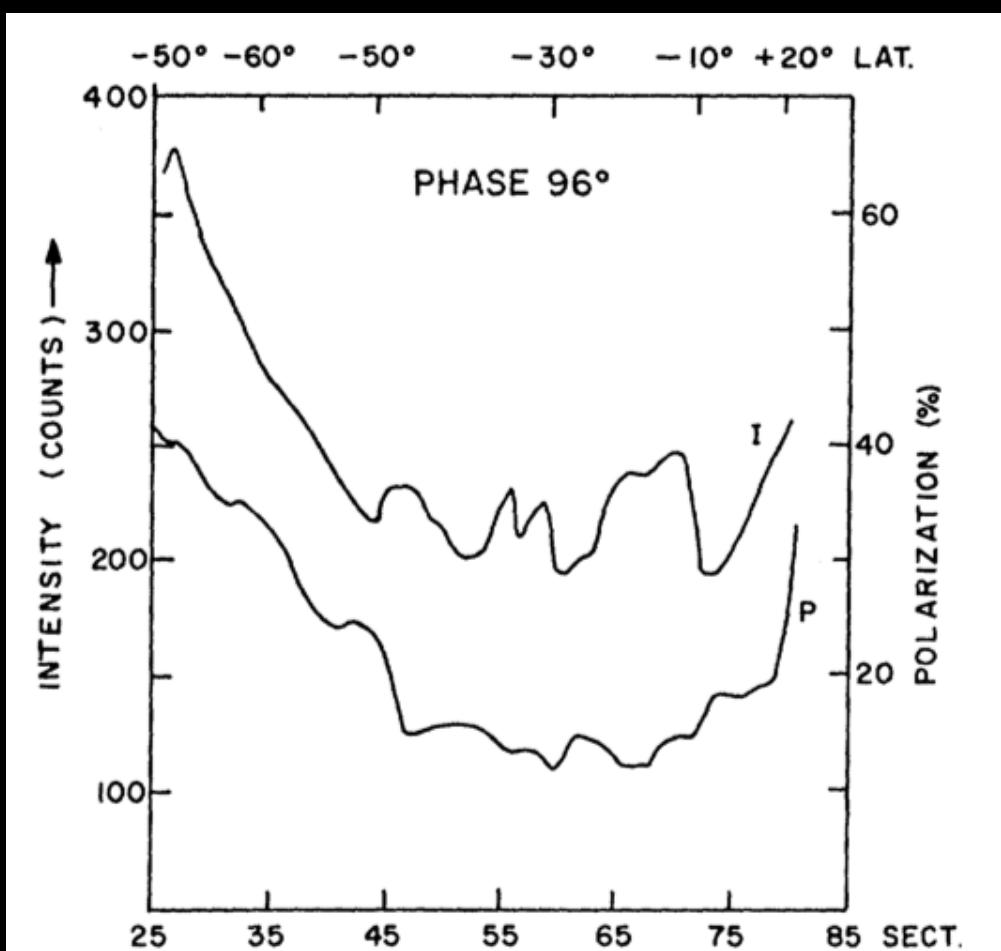


Fig. 1. Polarization of Venus. French Observations.
1950—1970

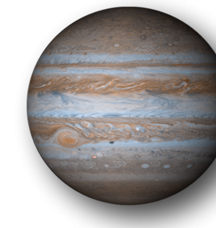
The Imaging Photopolarimeter Experiment on Pioneer 11

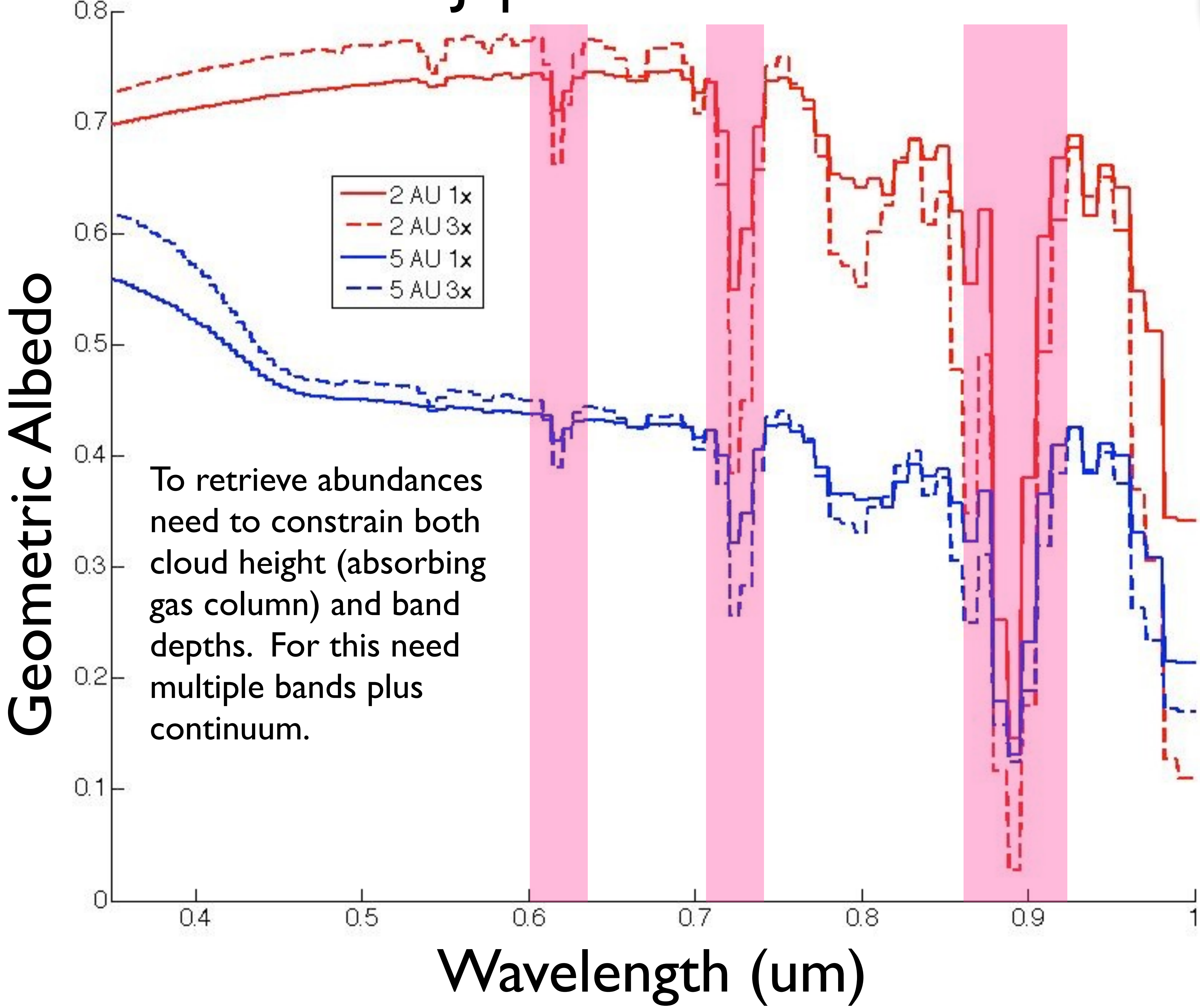
Abstract. *For 2 weeks continuous imaging, photometry, and polarimetry observations were made of Jupiter and the Galilean satellites in red and blue light from Pioneer 11. Measurements of Jupiter's north and south polar regions were possible because the spacecraft trajectory was highly inclined to the planet's equatorial plane. One of the highest resolution images obtained is presented here along with a comparison of a sample of our photometric and polarimetric data with a simple model. The data seem consistent with increased molecular scattering at high latitudes.*



Baker et al. (1975)

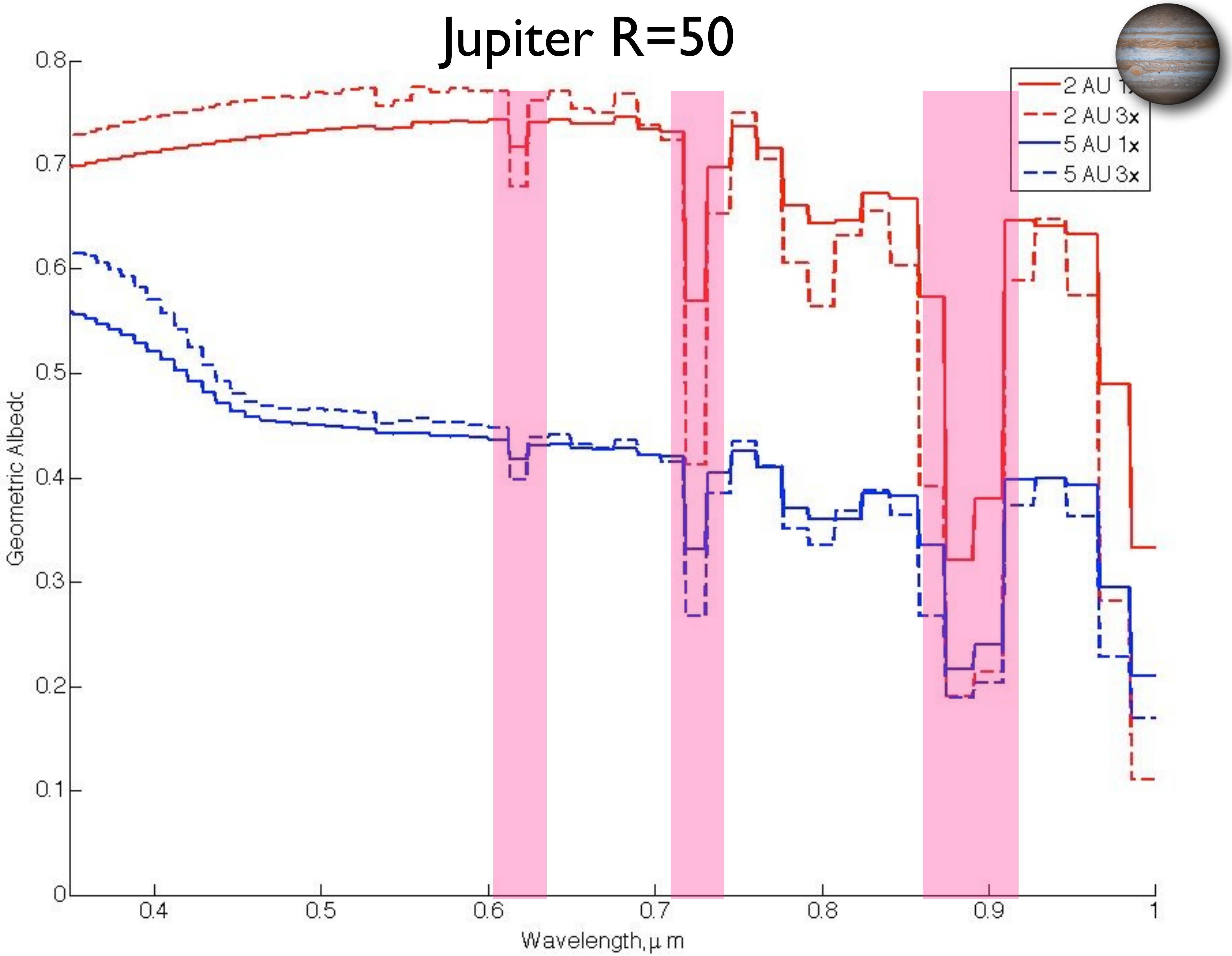
Jupiter R=100





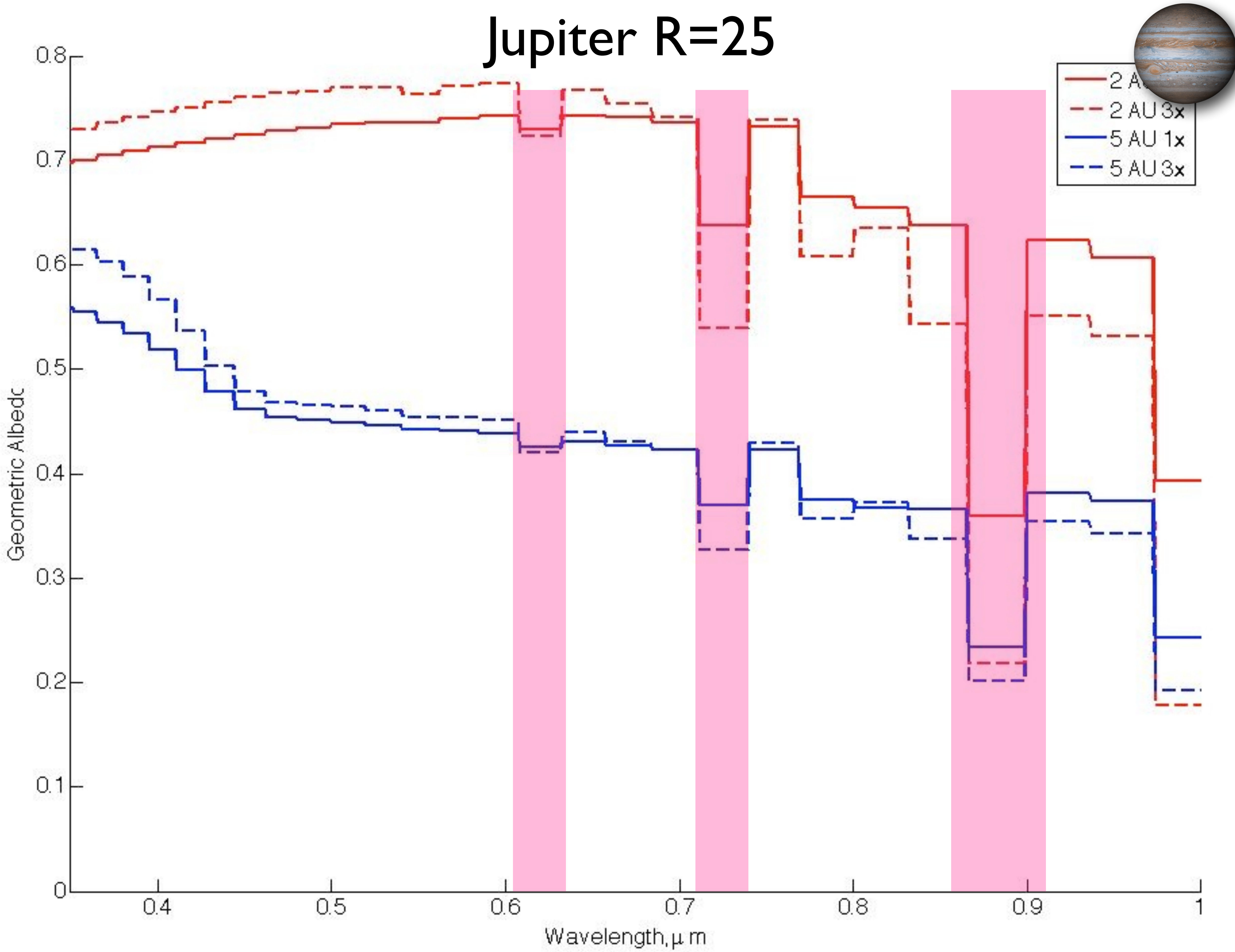
To retrieve abundances need to constrain both cloud height (absorbing gas column) and band depths. For this need multiple bands plus continuum.

Jupiter R=50



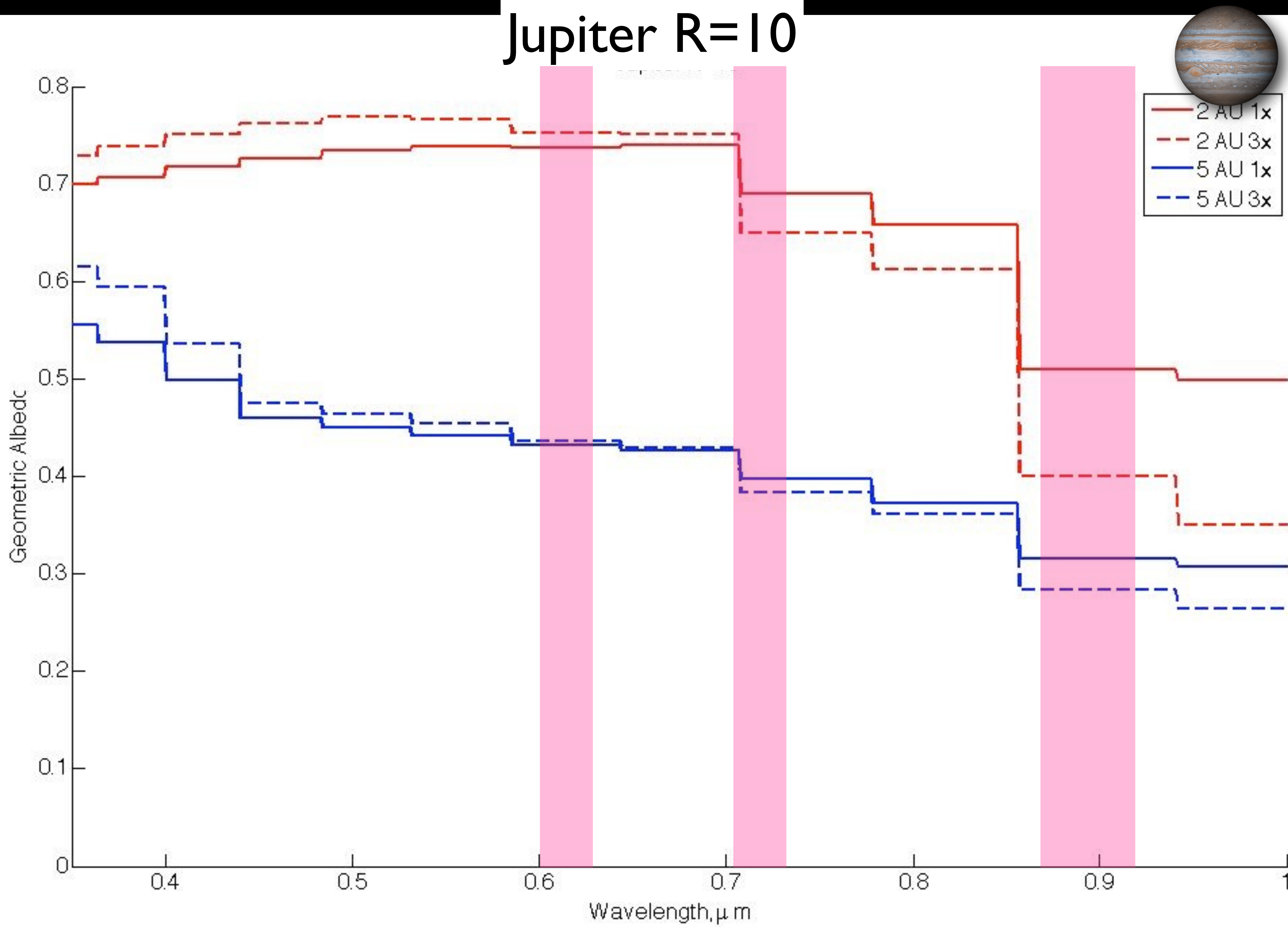
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Geometric Albedo
0.4
0.5
0.6
0.7
0.8
0.9
1
Wavelength, μ m
2 AU 1x
2 AU 3x
5 AU 1x
5 AU 3x

Jupiter R=25



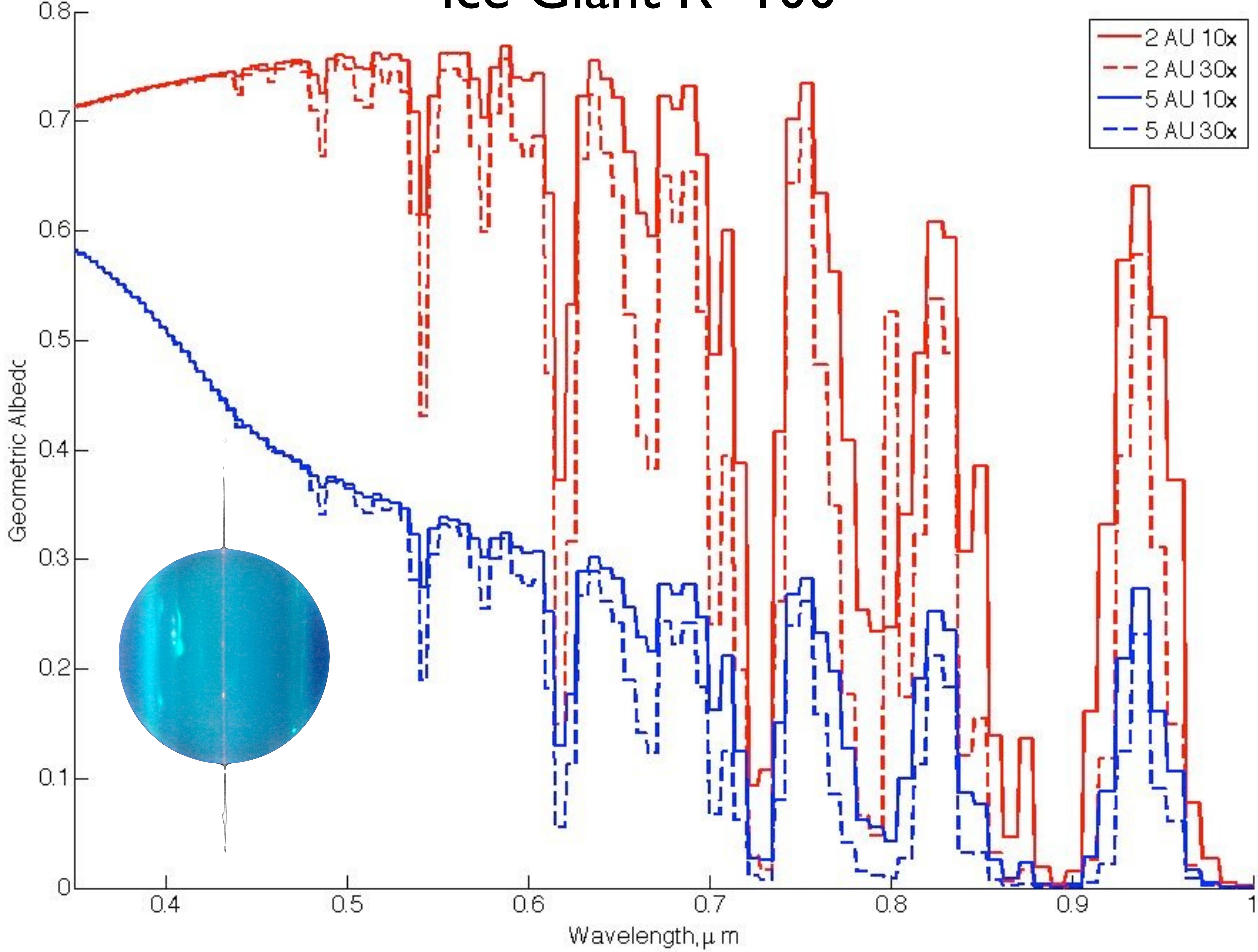
Geometric Albedo
Wavelength, μ m
2 AU 3x
5 AU 1x
5 AU 3x
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.4
0.5
0.6
0.7
0.8
0.9
1

Jupiter R=10

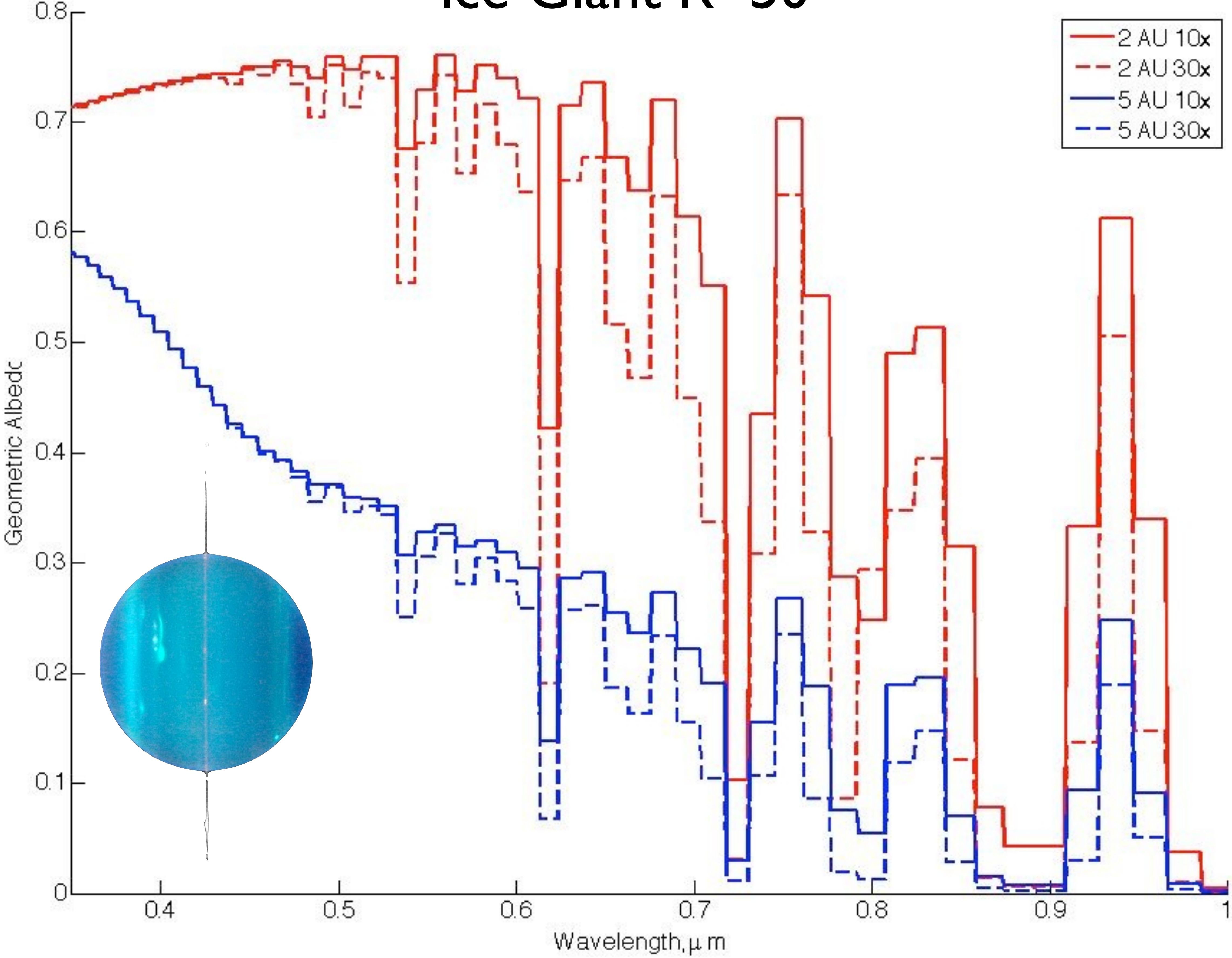


Geometric Albedo
Wavelength, μm
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.4
0.5
0.6
0.7
0.8
0.9
1
2 AU 1x
2 AU 3x
5 AU 1x
5 AU 3x

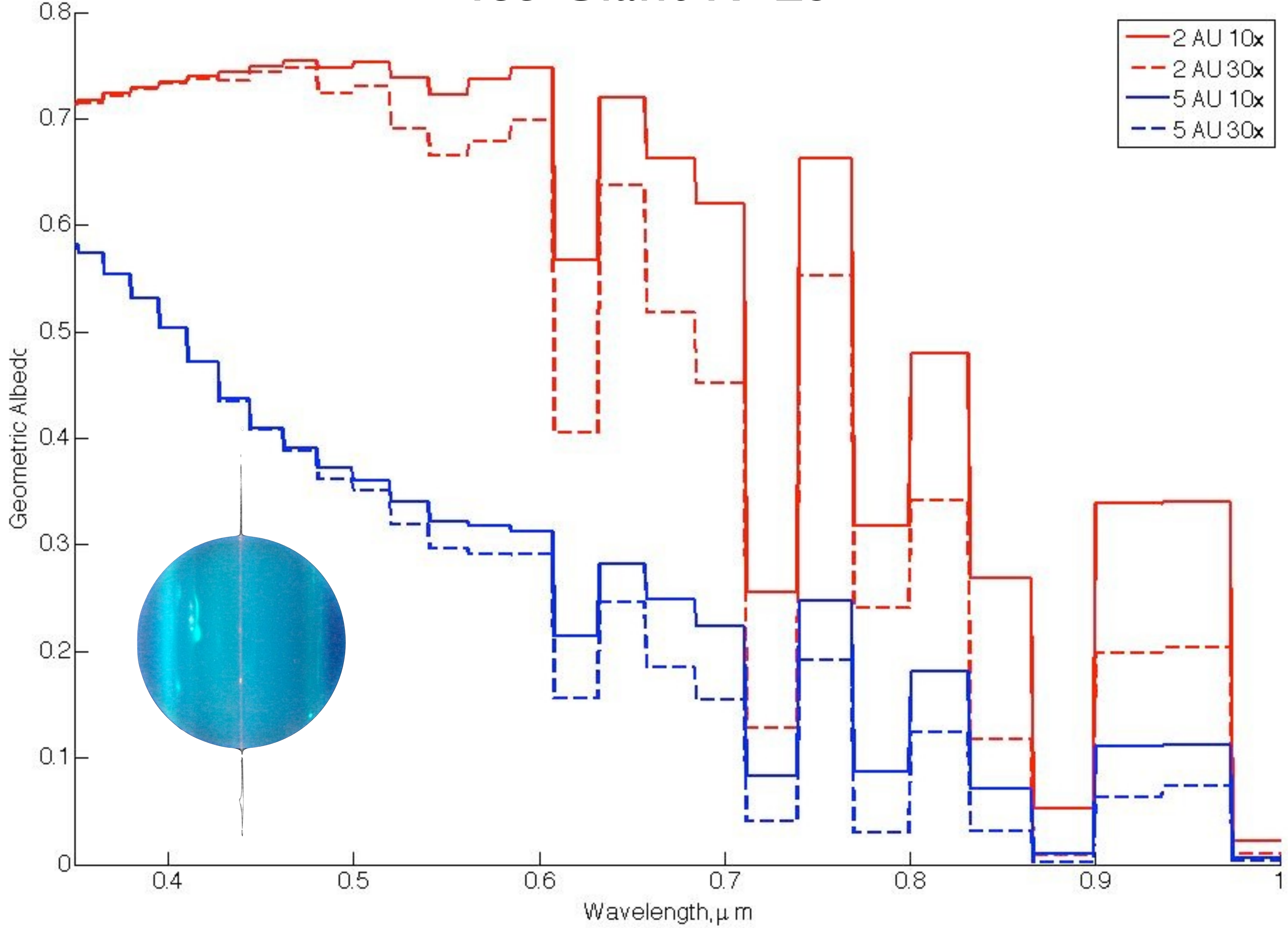
Ice Giant R=100



Ice Giant R=50



Ice Giant R=25



Ice Giant R=10