

Extrasolar Storms in High Definition: Cloud Physics and Atmospheric Dynamics in Exoplanets

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Extrasolar Storms in High Definition: Cloud Physics and Atmospheric Dynamics in Exoplanets

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Mark Marley (NASA Ames)

Ari Heinze (SUNY)

I. Neill Reid (STScI)

Adam Burrows (Princeton)

Caroline Morley (UCSD)

Patrick Lowrance (SSC)

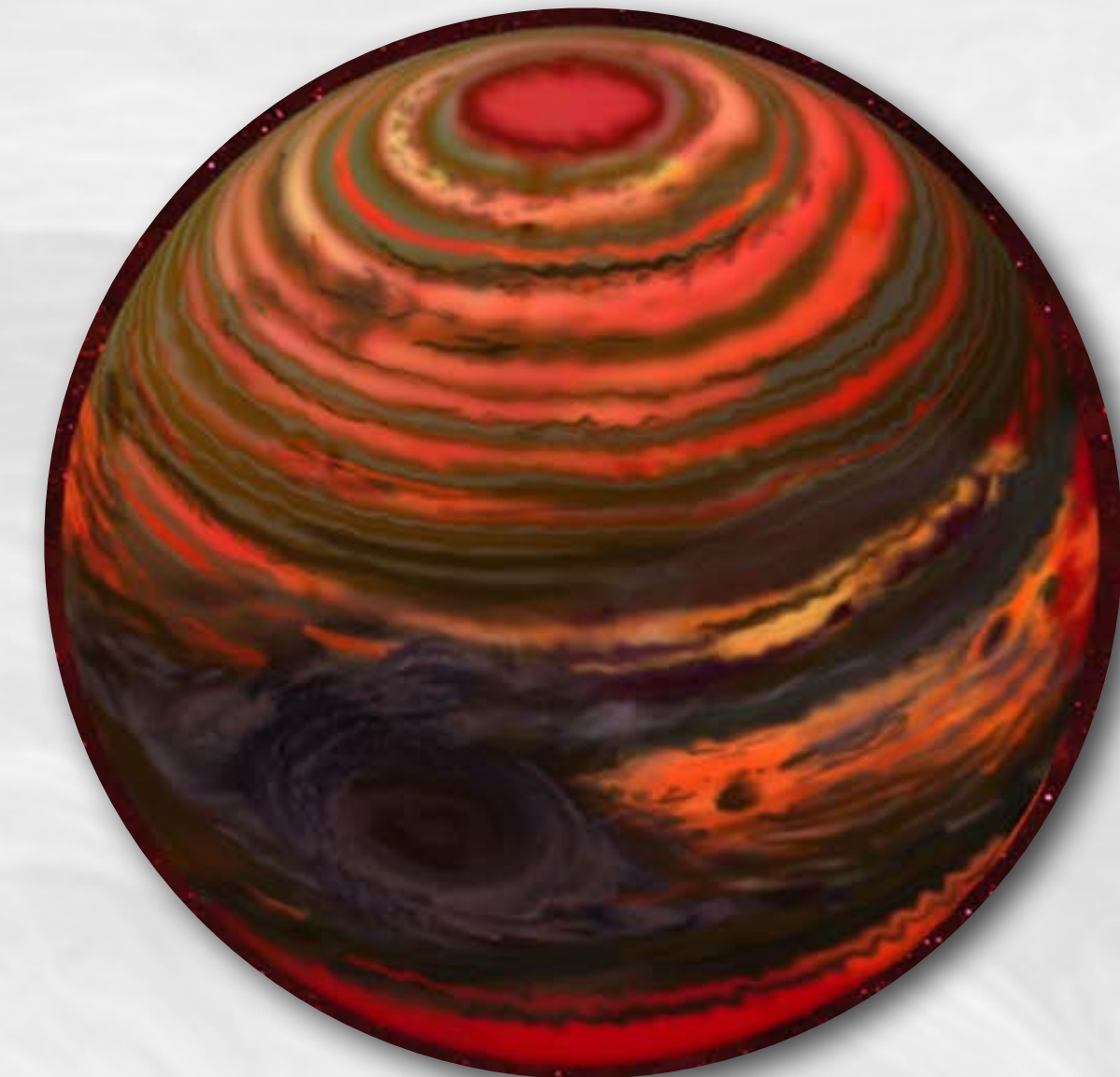
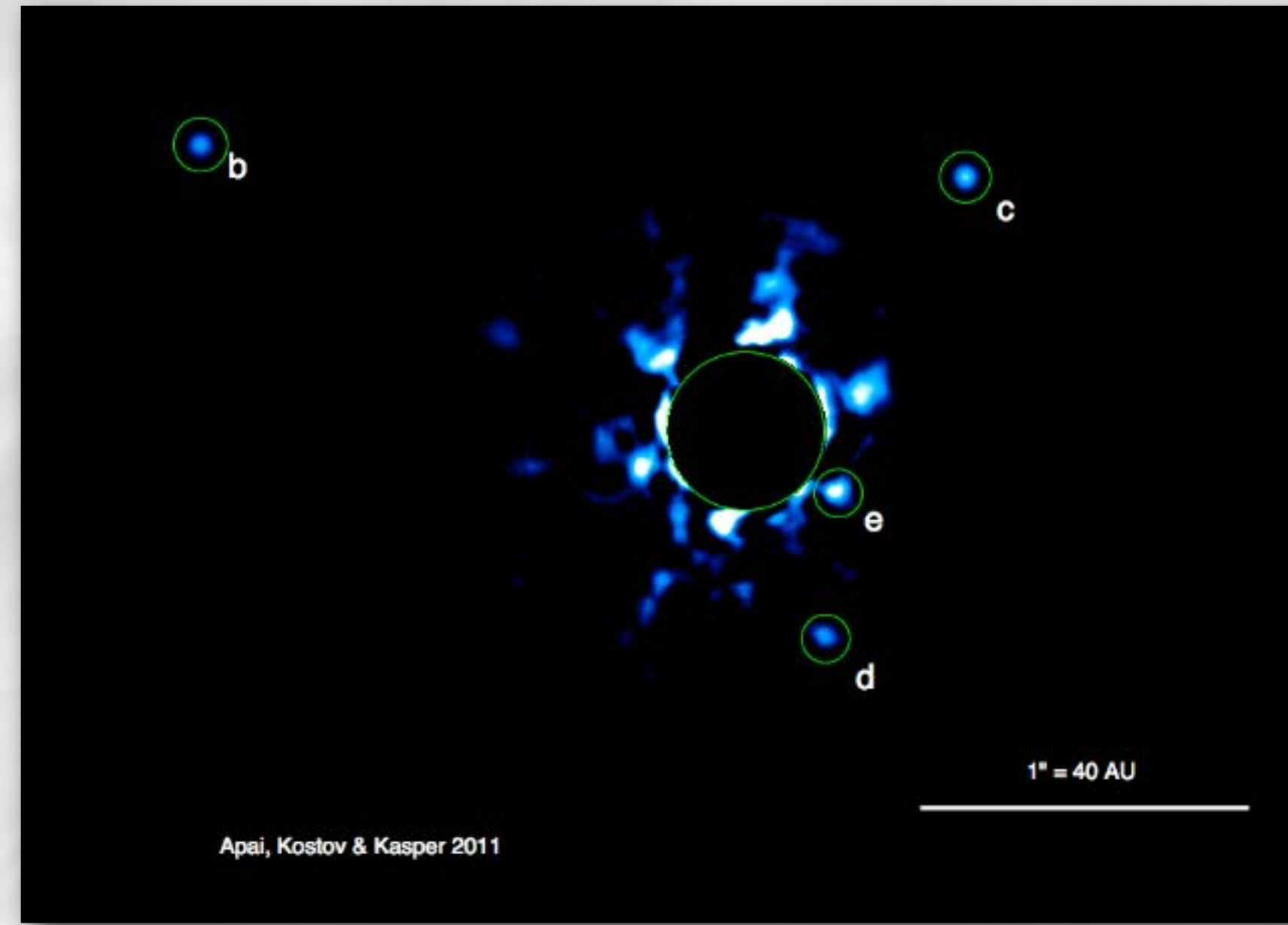
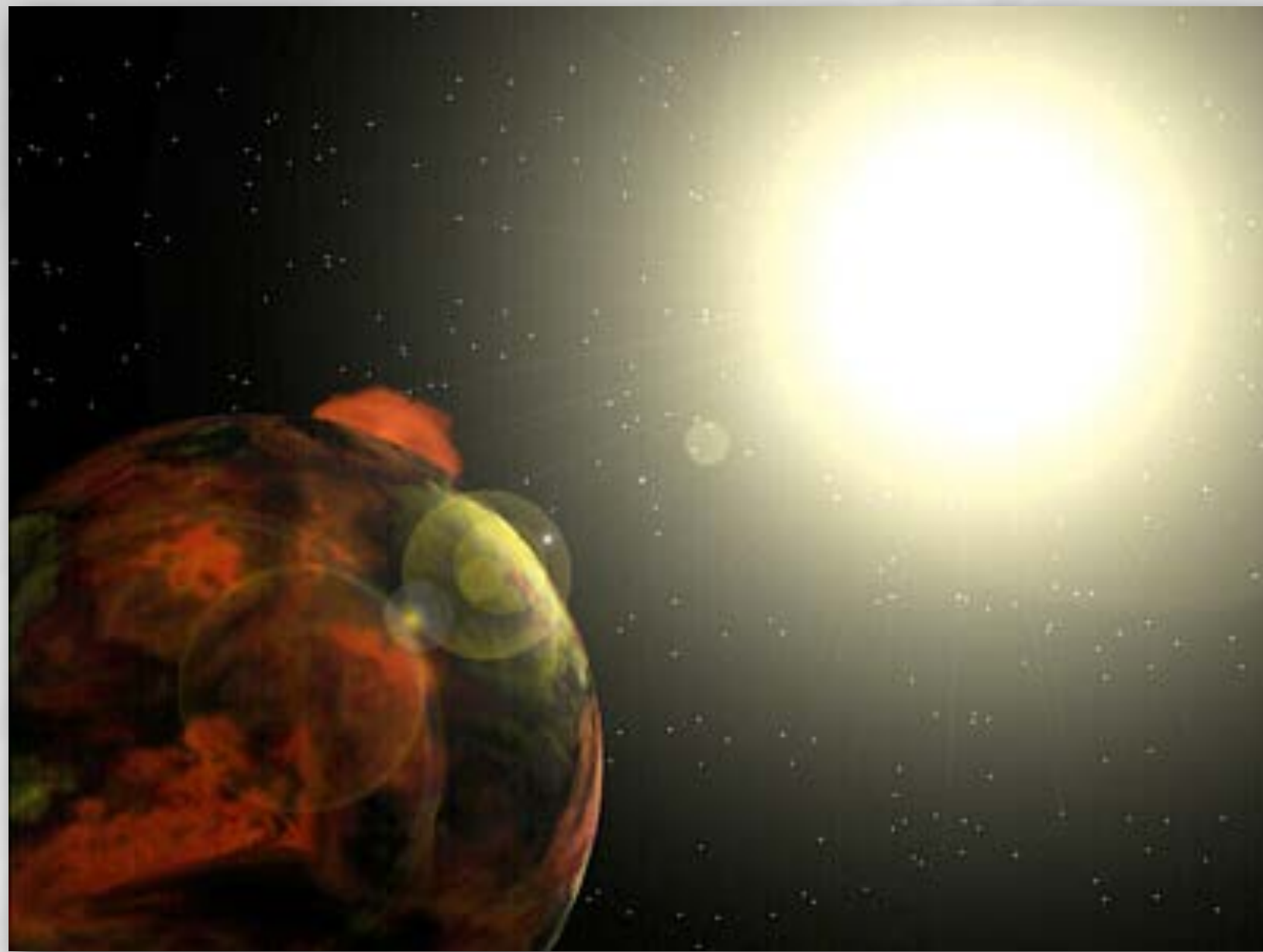
Adam Showman (LPL)

Glenn Schneider (Steward)

Andrew Skemer (Steward)

Peter Plavchan (SSC)

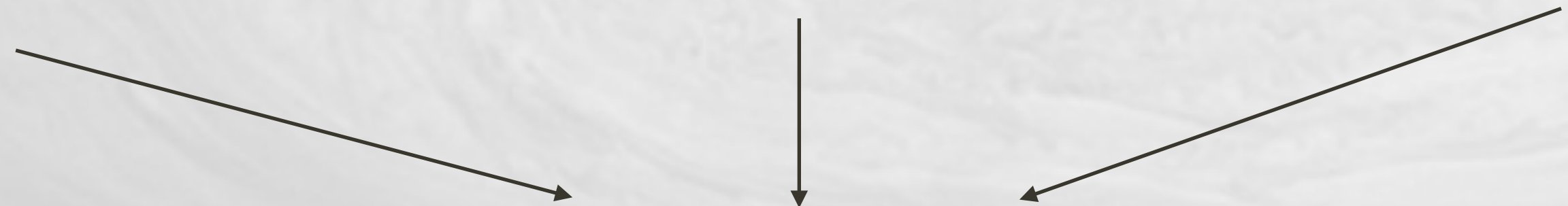
Subhanjoy Mohanty (IC London)



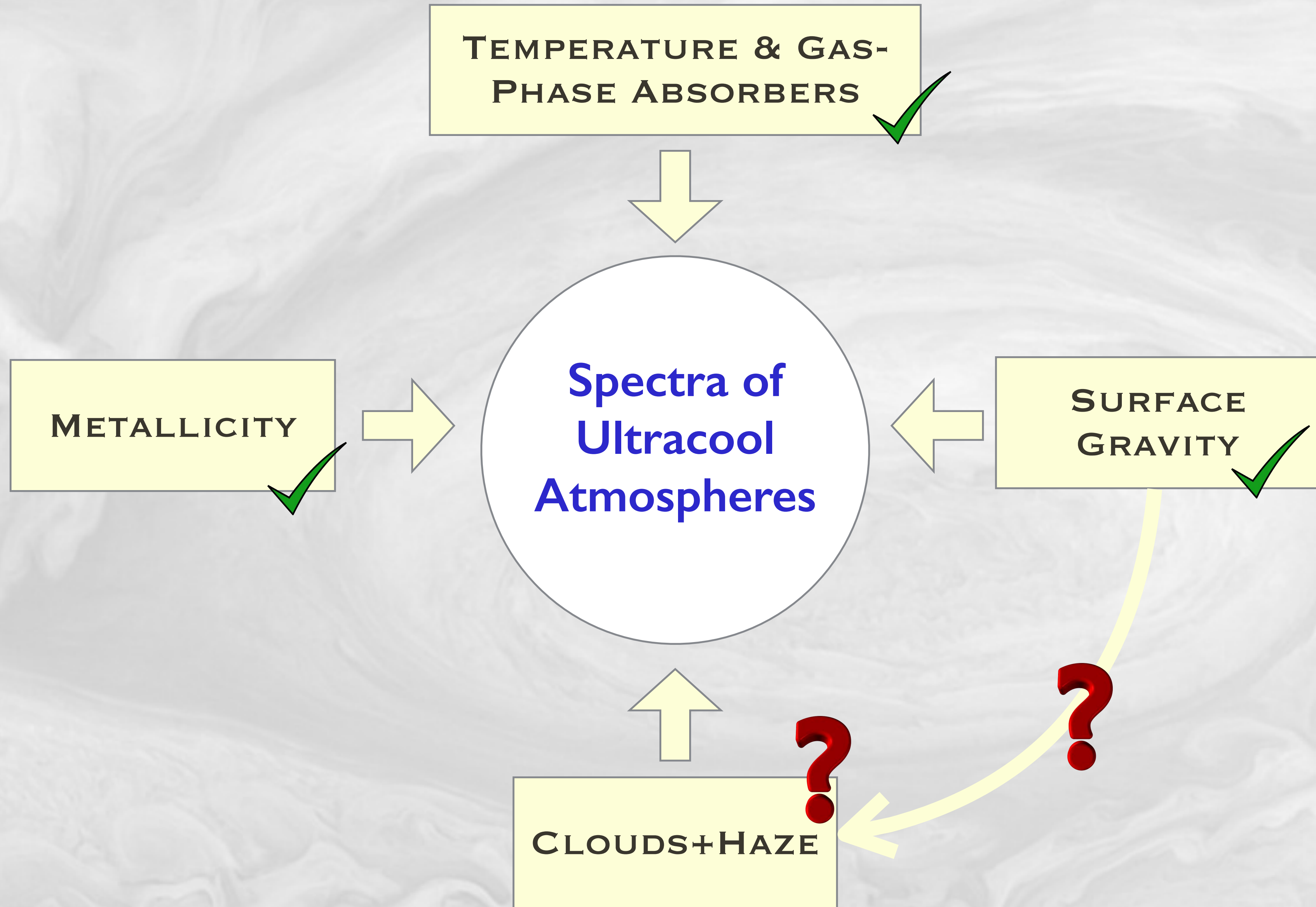
Hot Jupiters
 Tidally locked, hot ($>1,000$ K),
 ~Jupiter-mass, complex
 temperature distribution

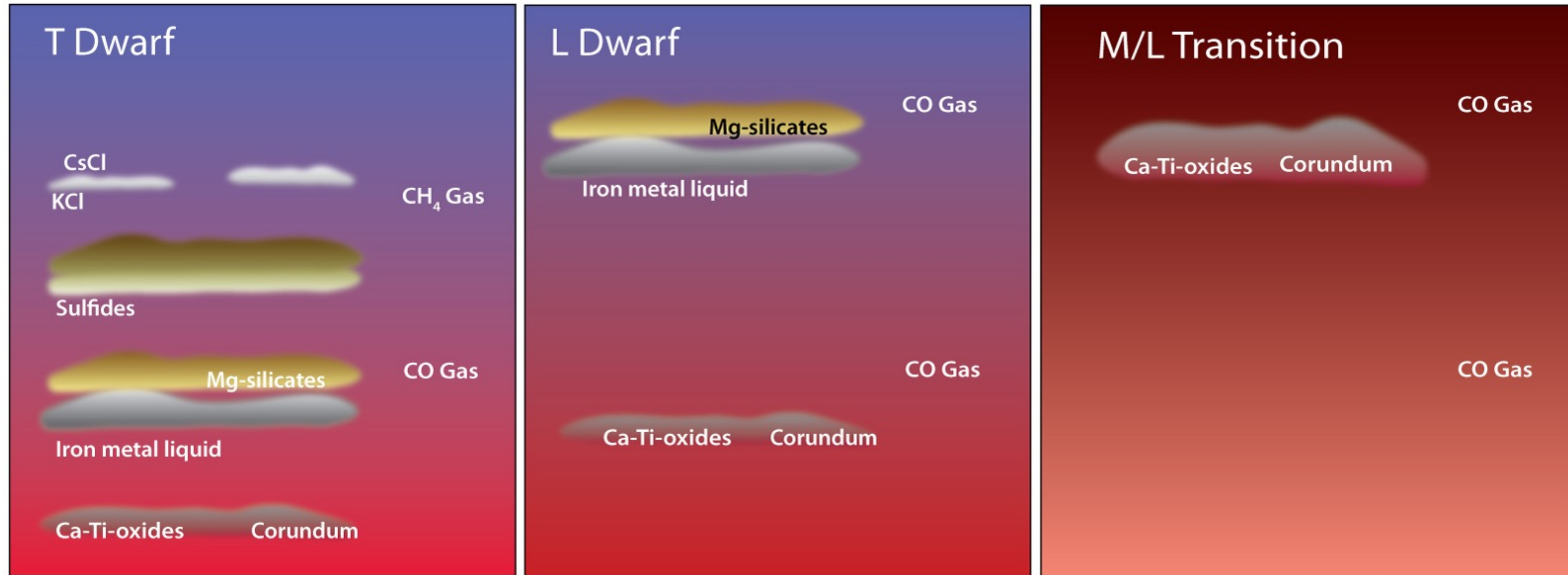
Directly Imaged Exoplanets
 5-15 Jupiter mass, young,
 weakly irradiated
 not tidally locked

Brown Dwarfs
 Masses ~3 to 70 Jupiter masses no
 irradiation, no host star

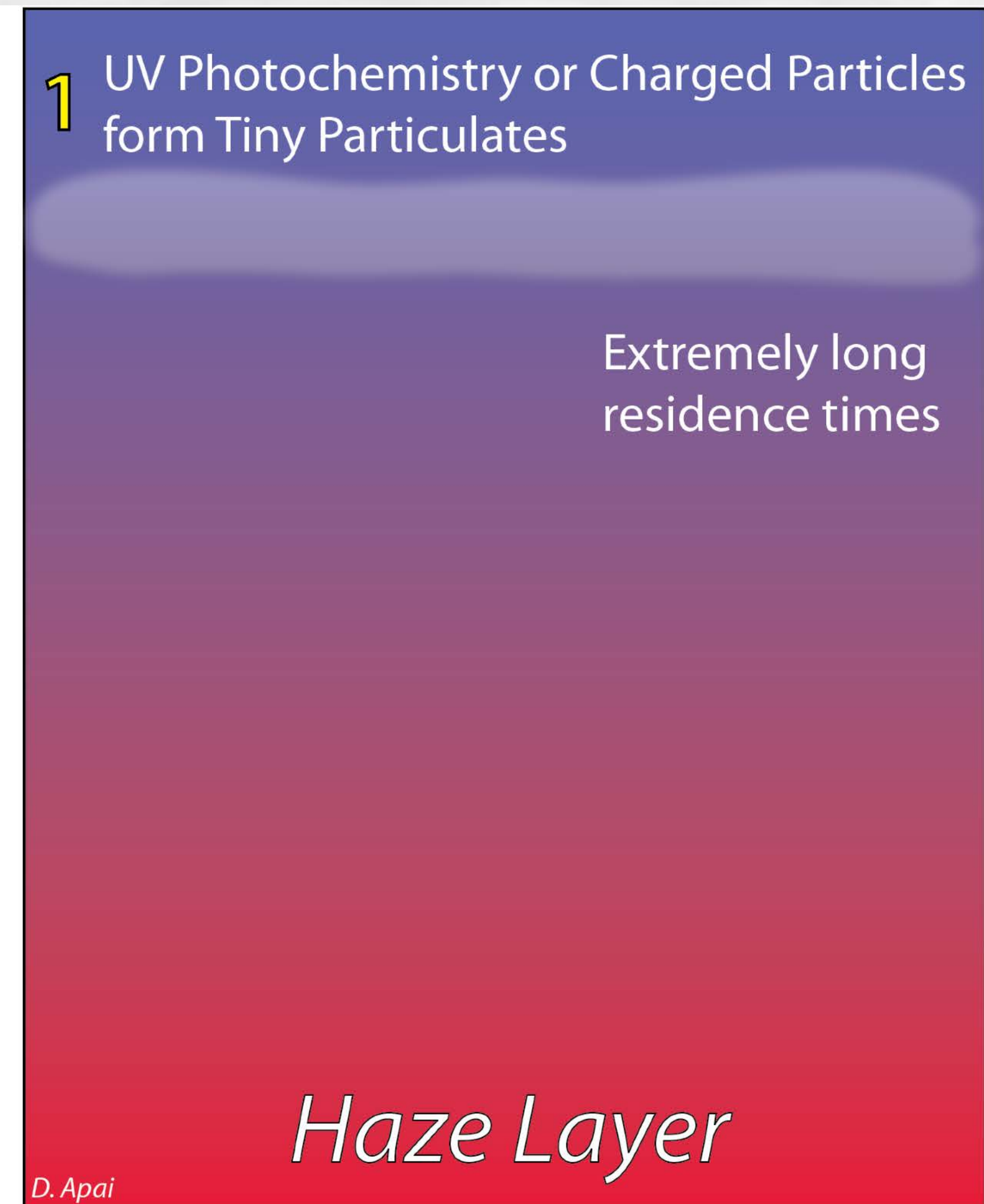
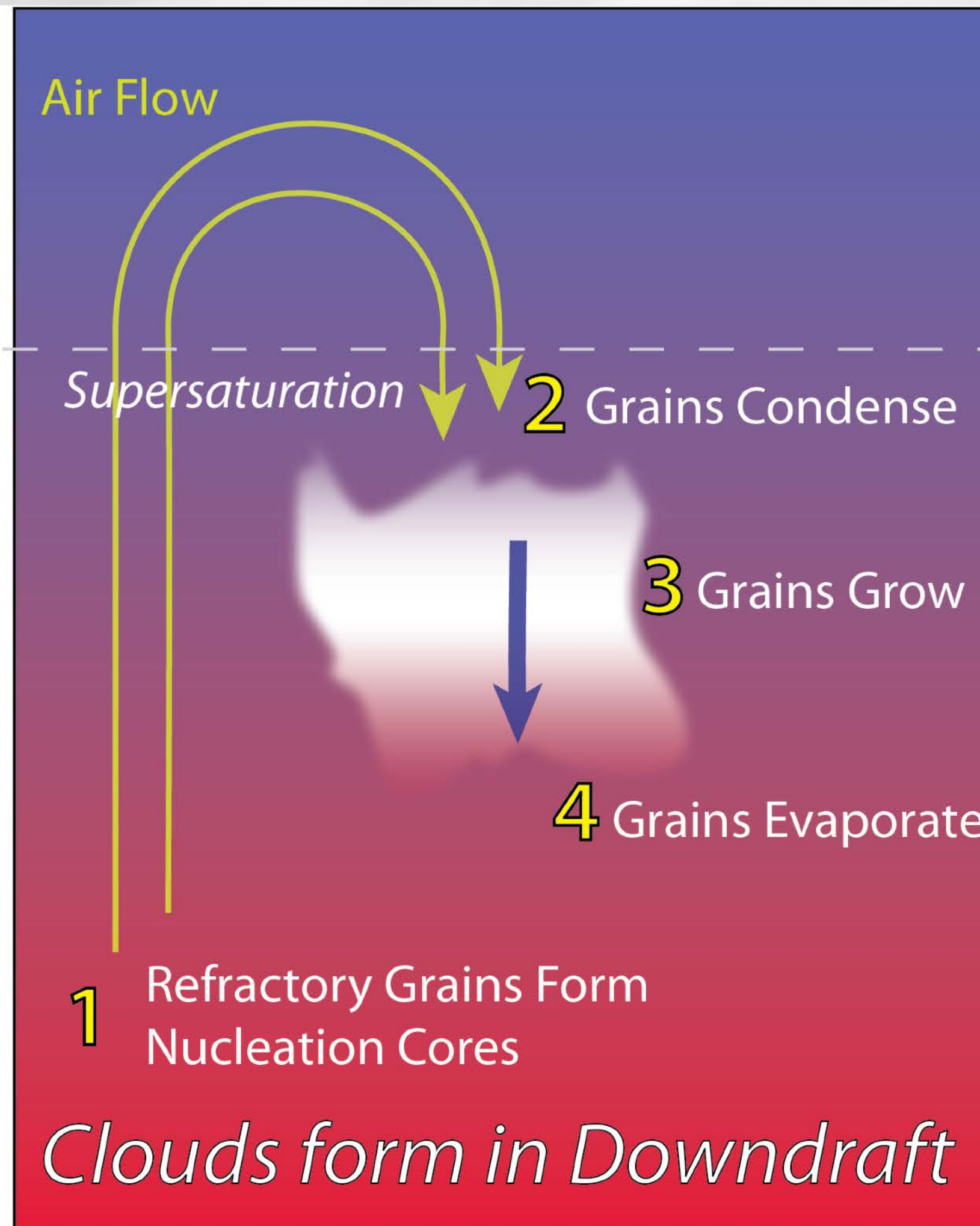
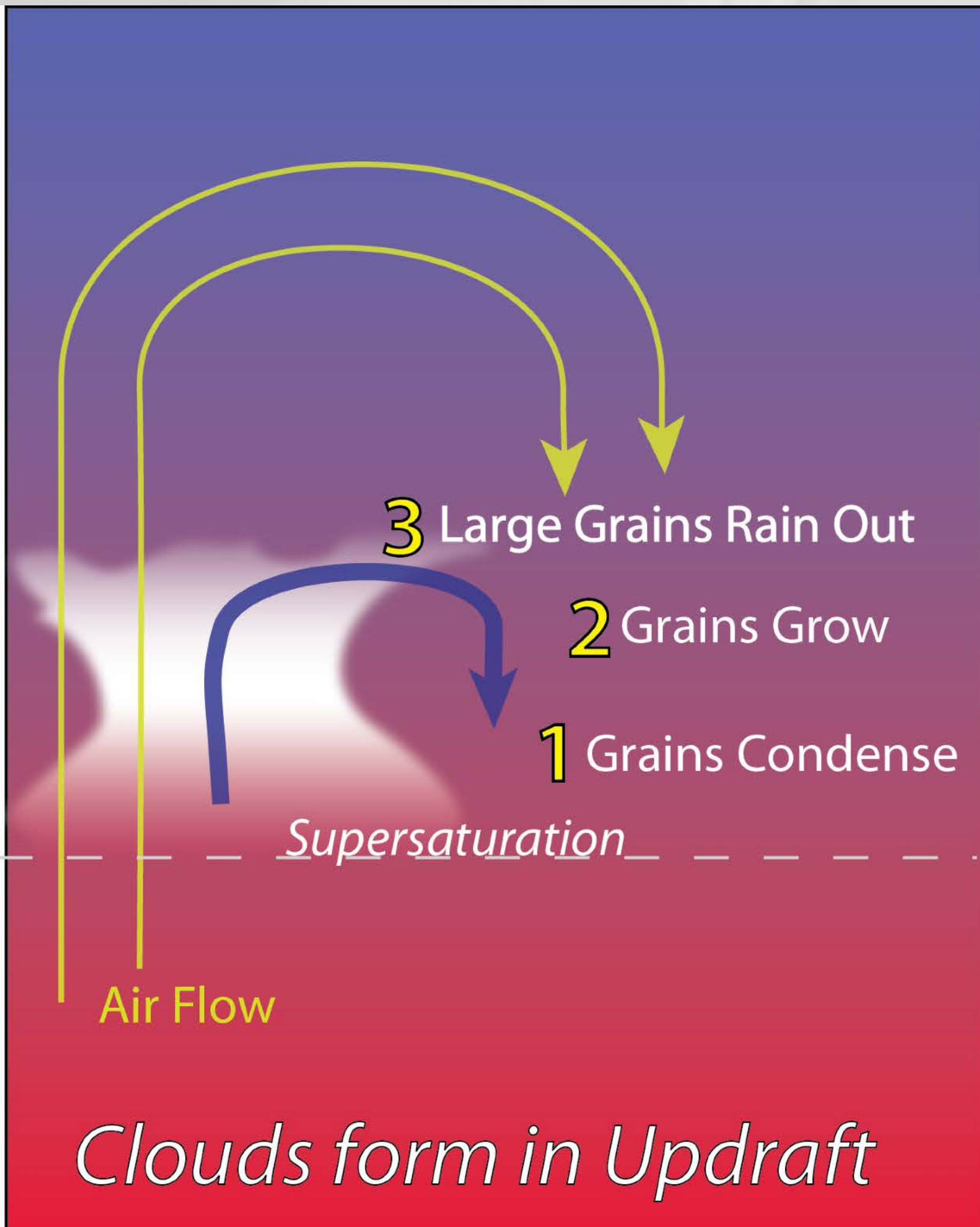


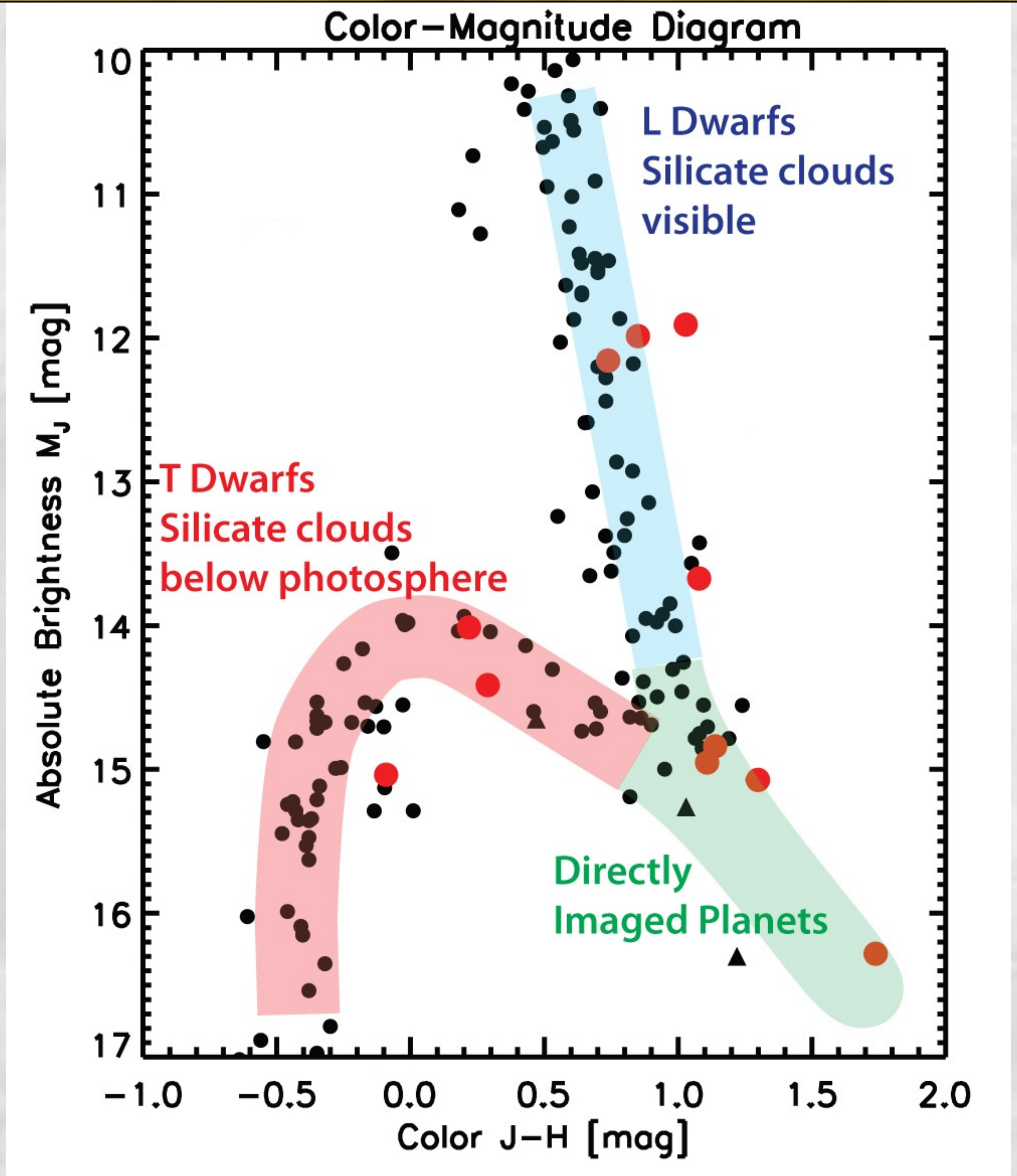
Ultracool Atmospheres



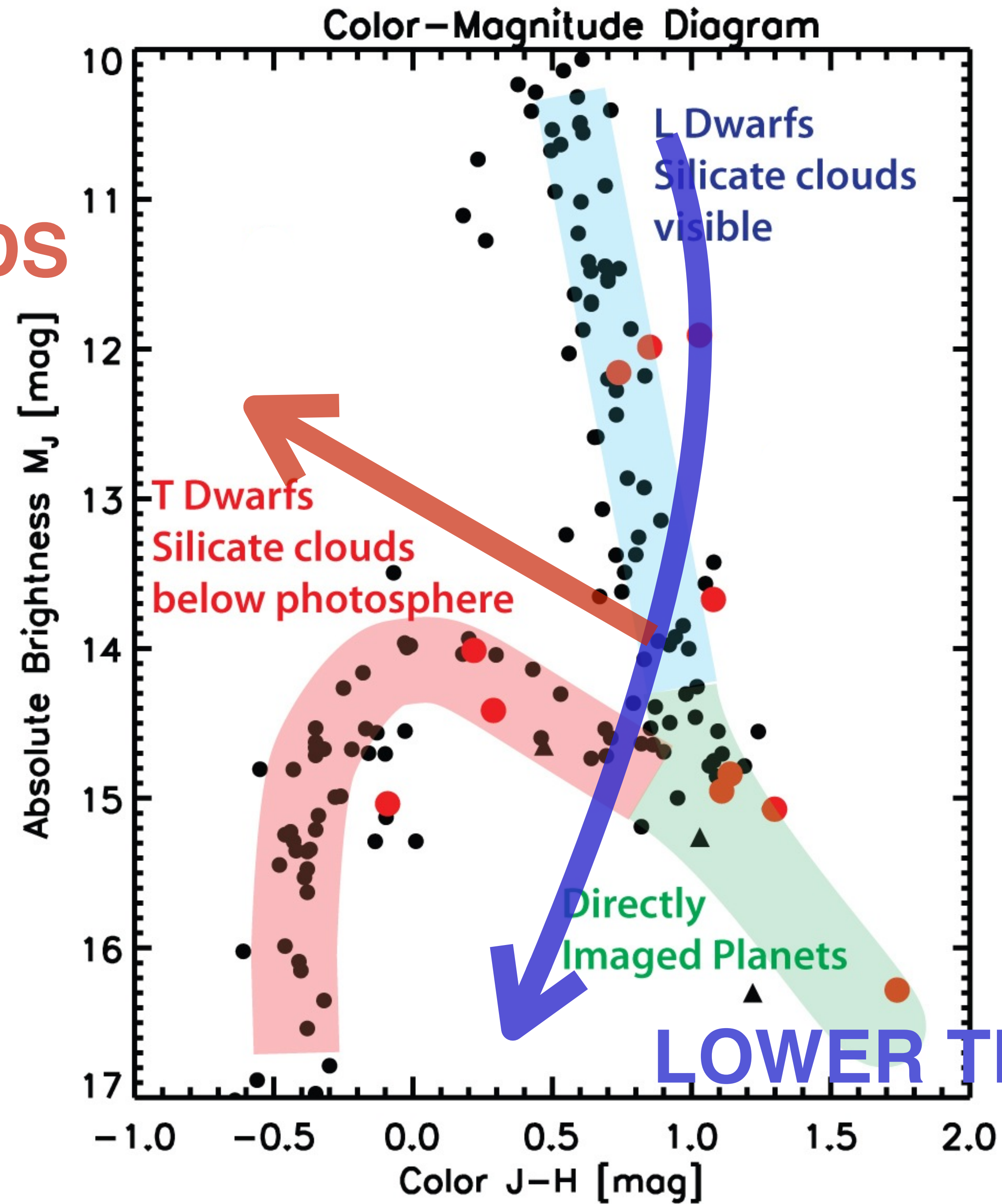


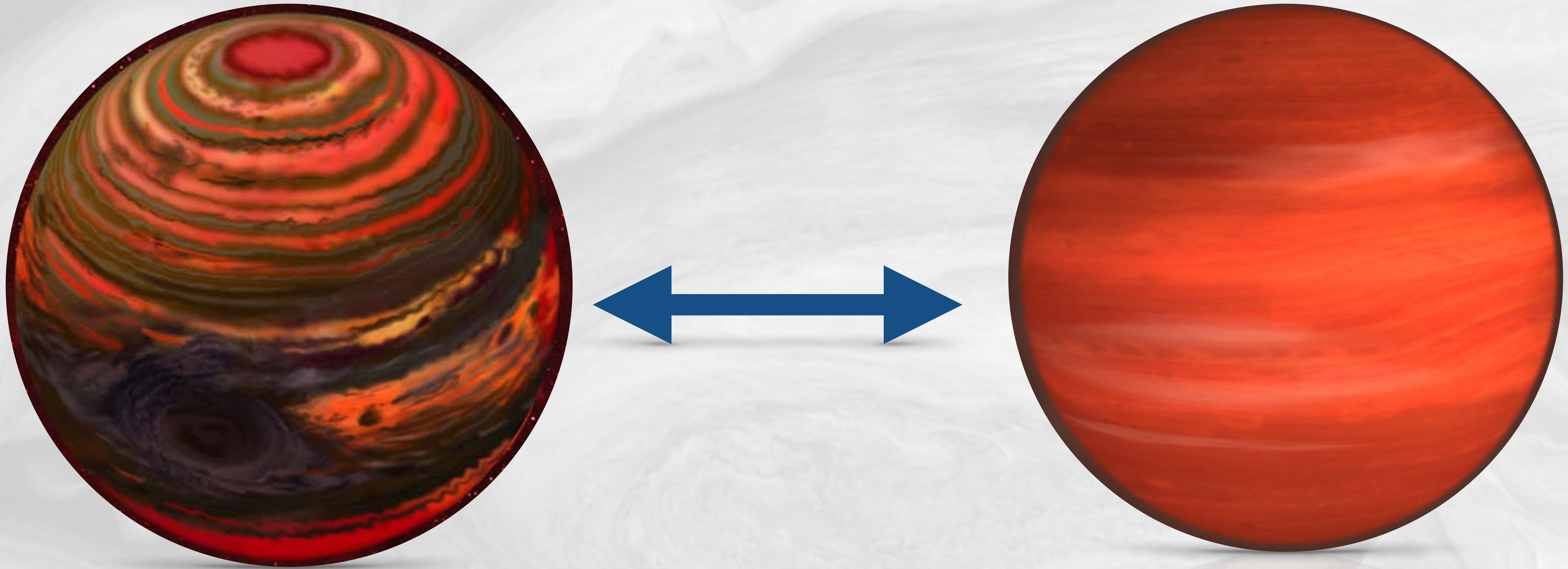
e.g. Marley et al. 2002, 2007 PPV, 2010, 2012; Helling et al. 2008; Burrows et al. 2003, 2007, 2010, 2011; Barman et al. 2012ab; Baraffe et al. 2003; Morley et al. 2012, 2014



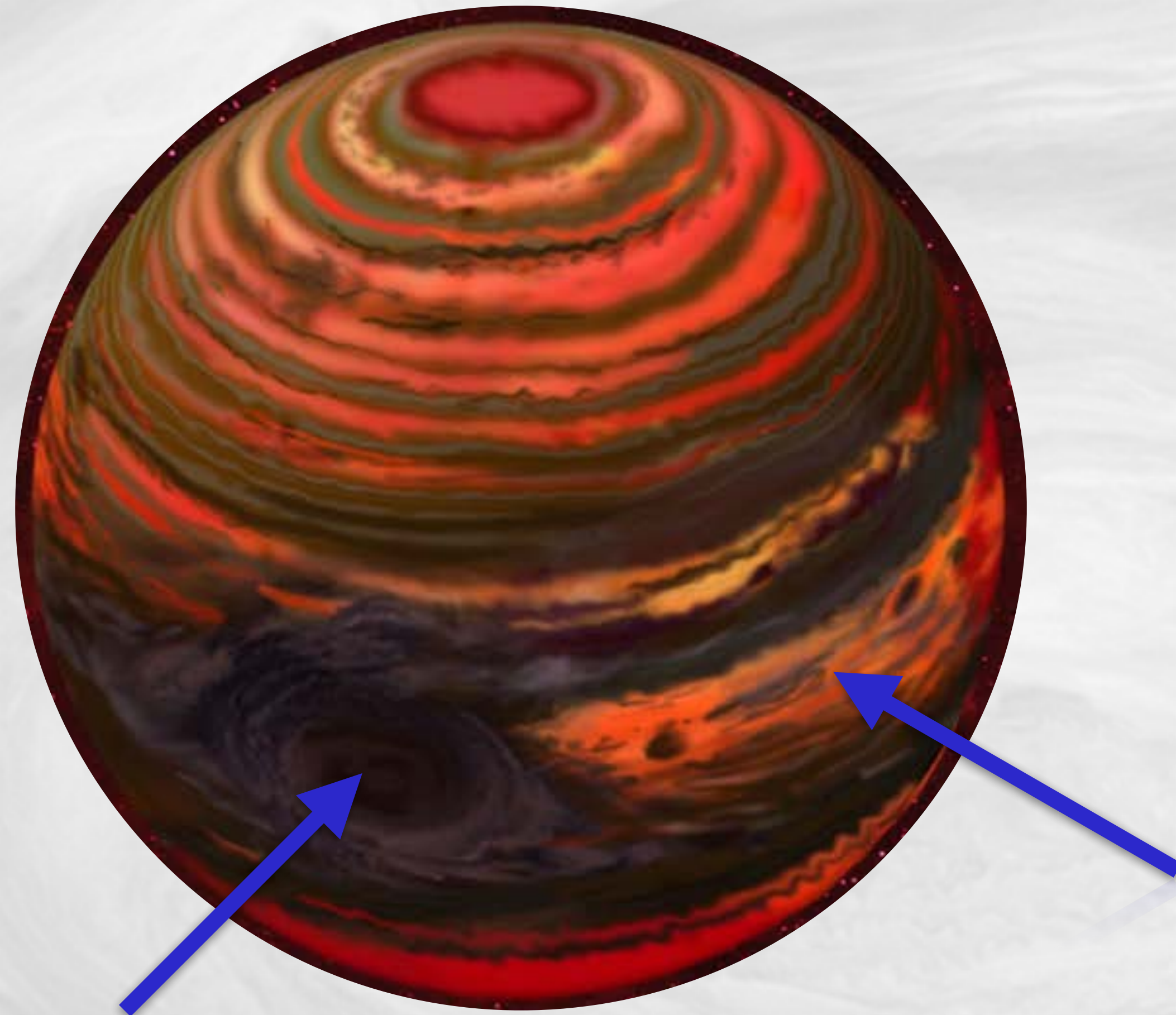


THINNER CLOUDS

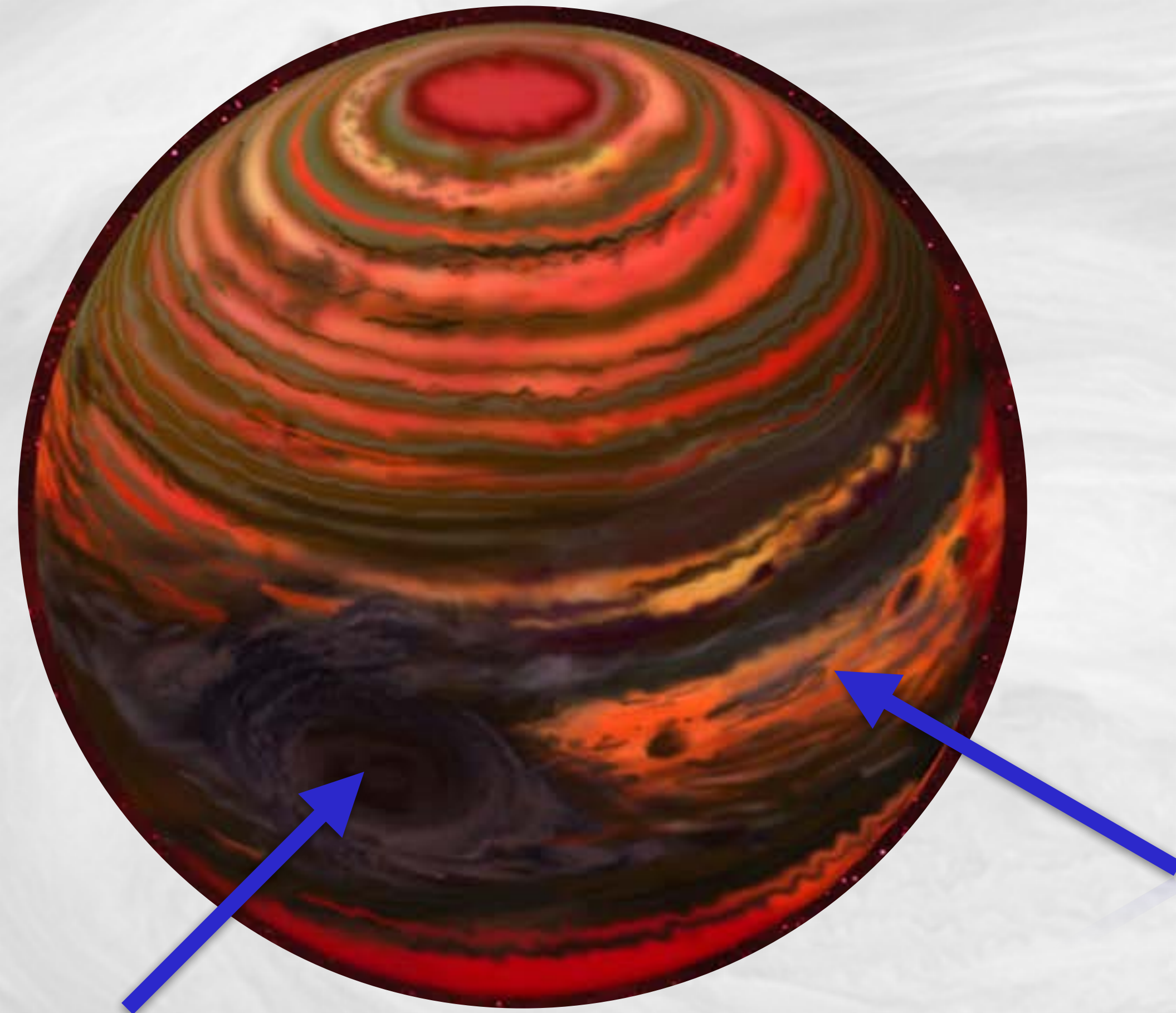




Temperature, Log g , Composition,
Age, Vertical Mixing, Cloud Structure



Temperature, Log g , Composition,
Age, Vertical Mixing, Cloud Structure



~~Temperature, Log g, Composition,~~
~~Age, Vertical Mixing, Cloud Structure~~



6 Hubble Space Telescope programs
PI Daniel Apai, ~220 orbits

Other HST programs ongoing
(Buenzli, Radigan, Cushing, Patience)



Cycle-9 Extrasolar Storms

PI: Daniel Apai 1,144 Spitzer hours + 24 HST orbits

Cycle-8 Weather on Other Worlds

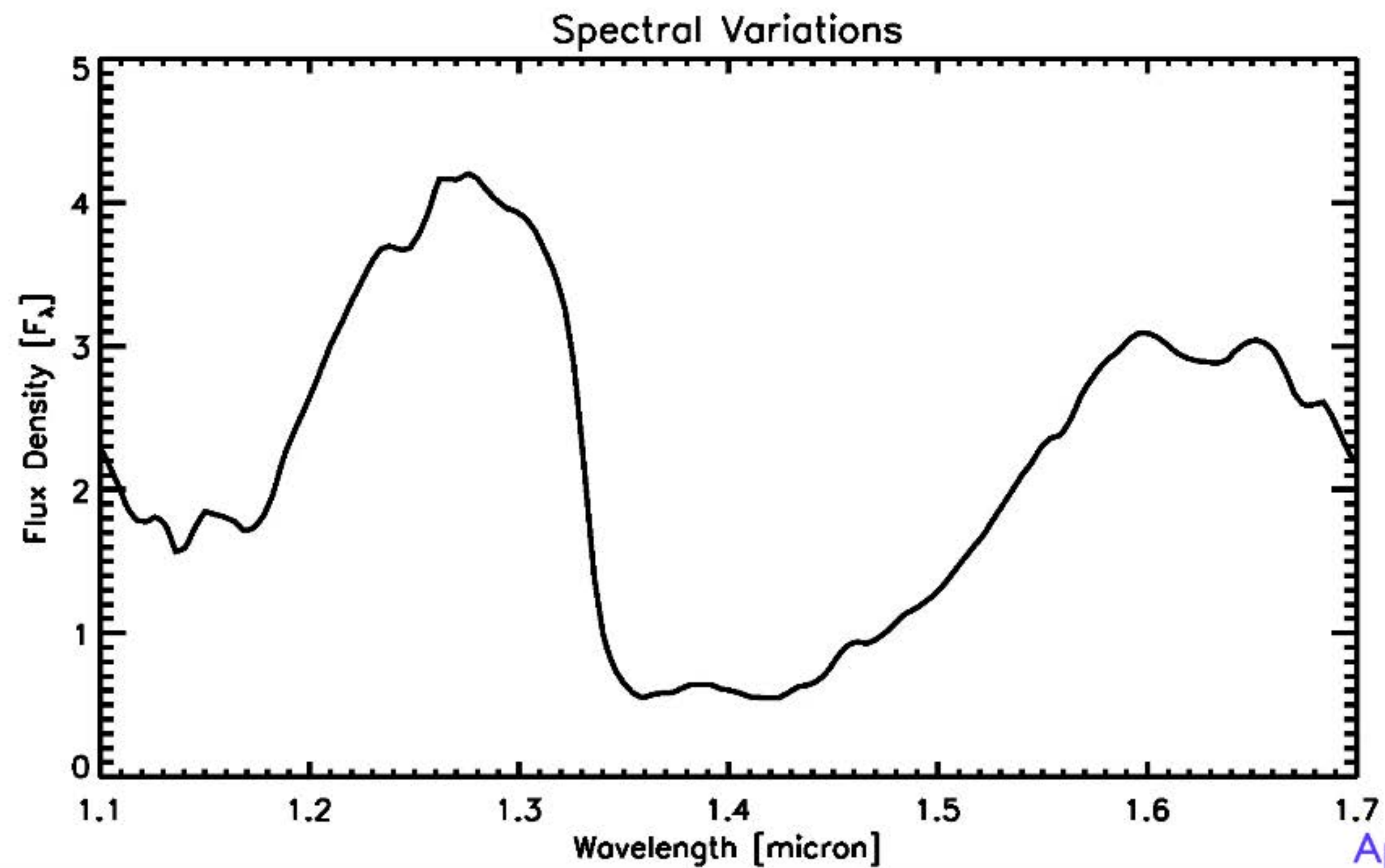
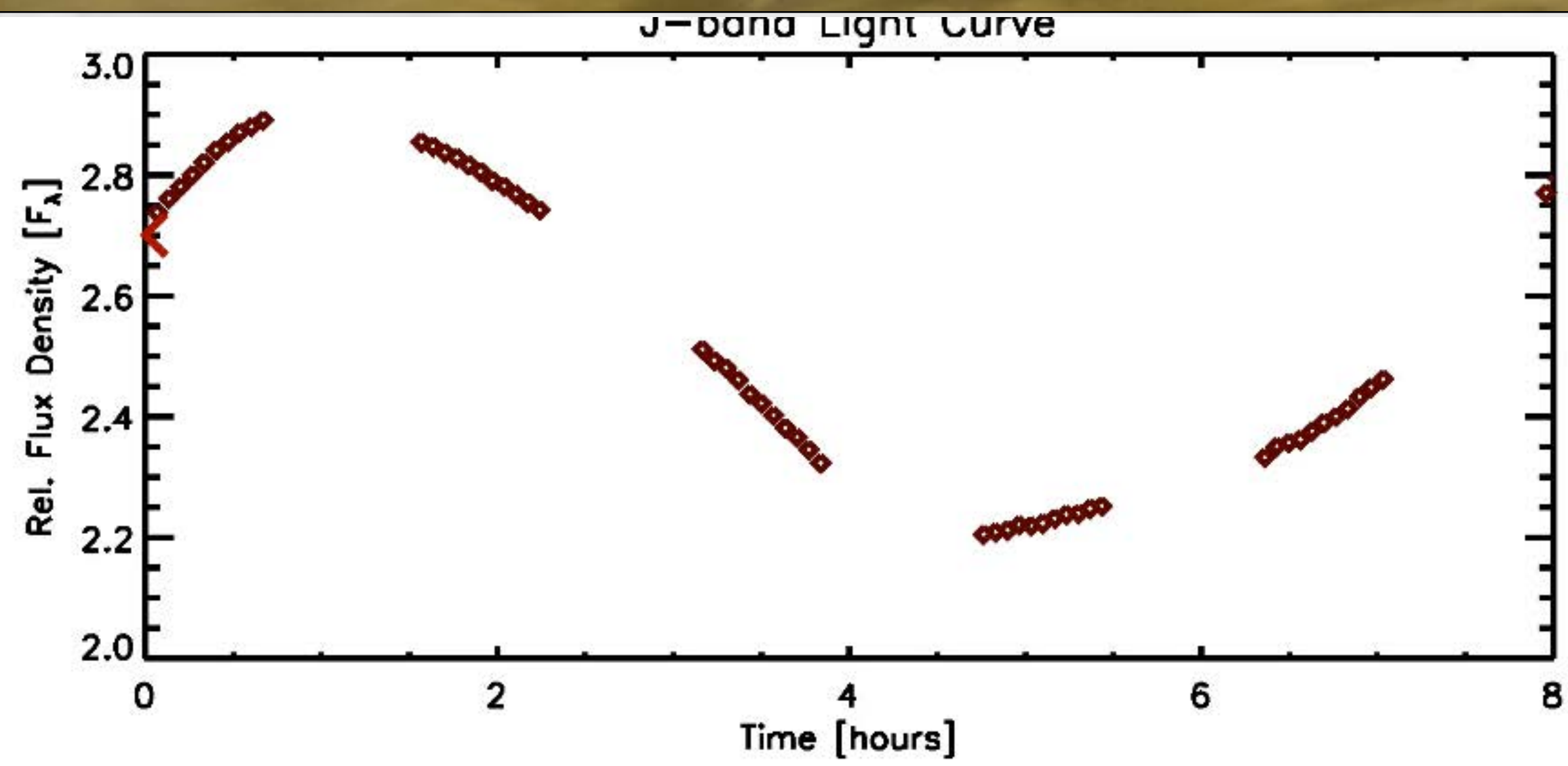
PI Stan Metchev, 880 hours

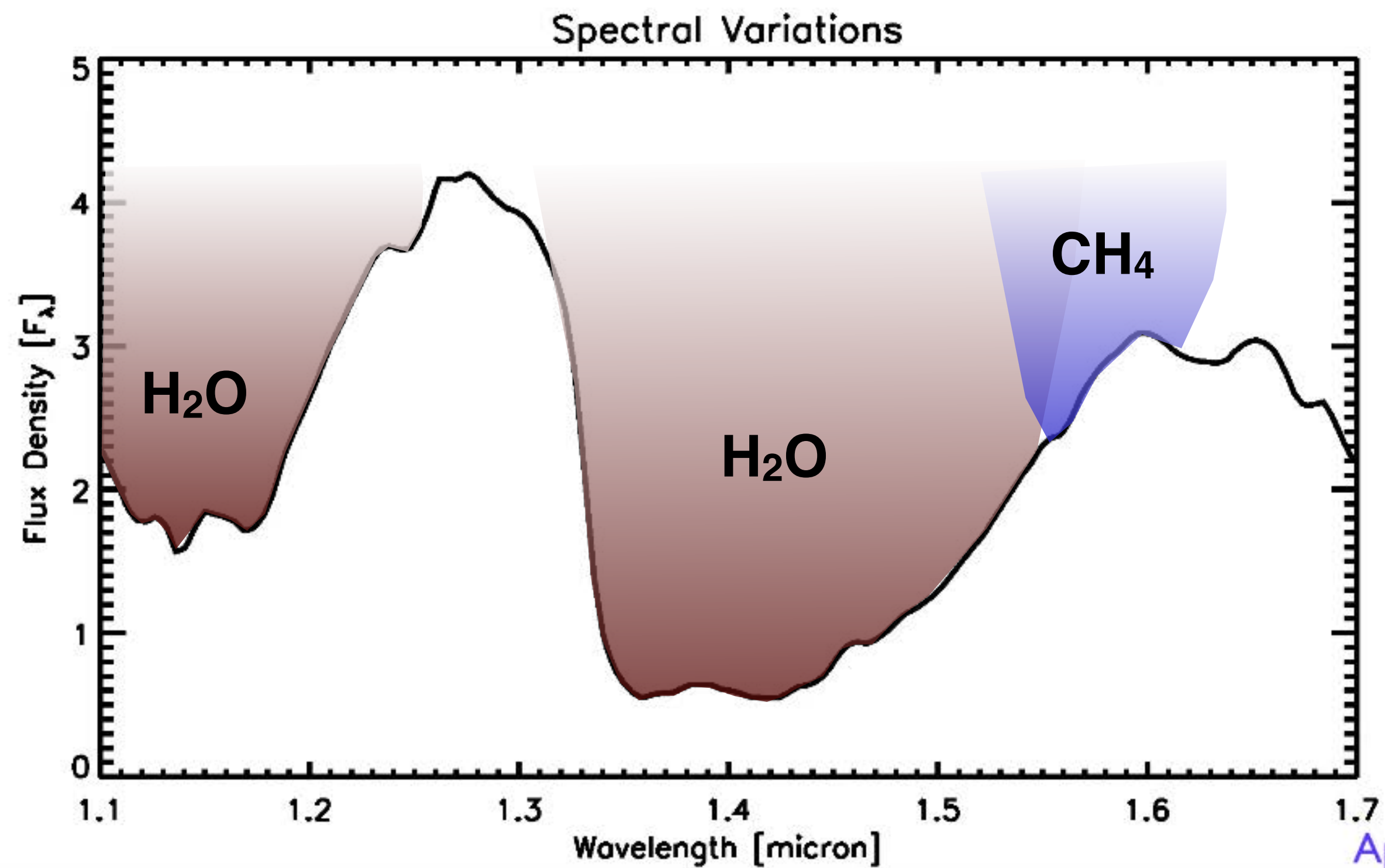
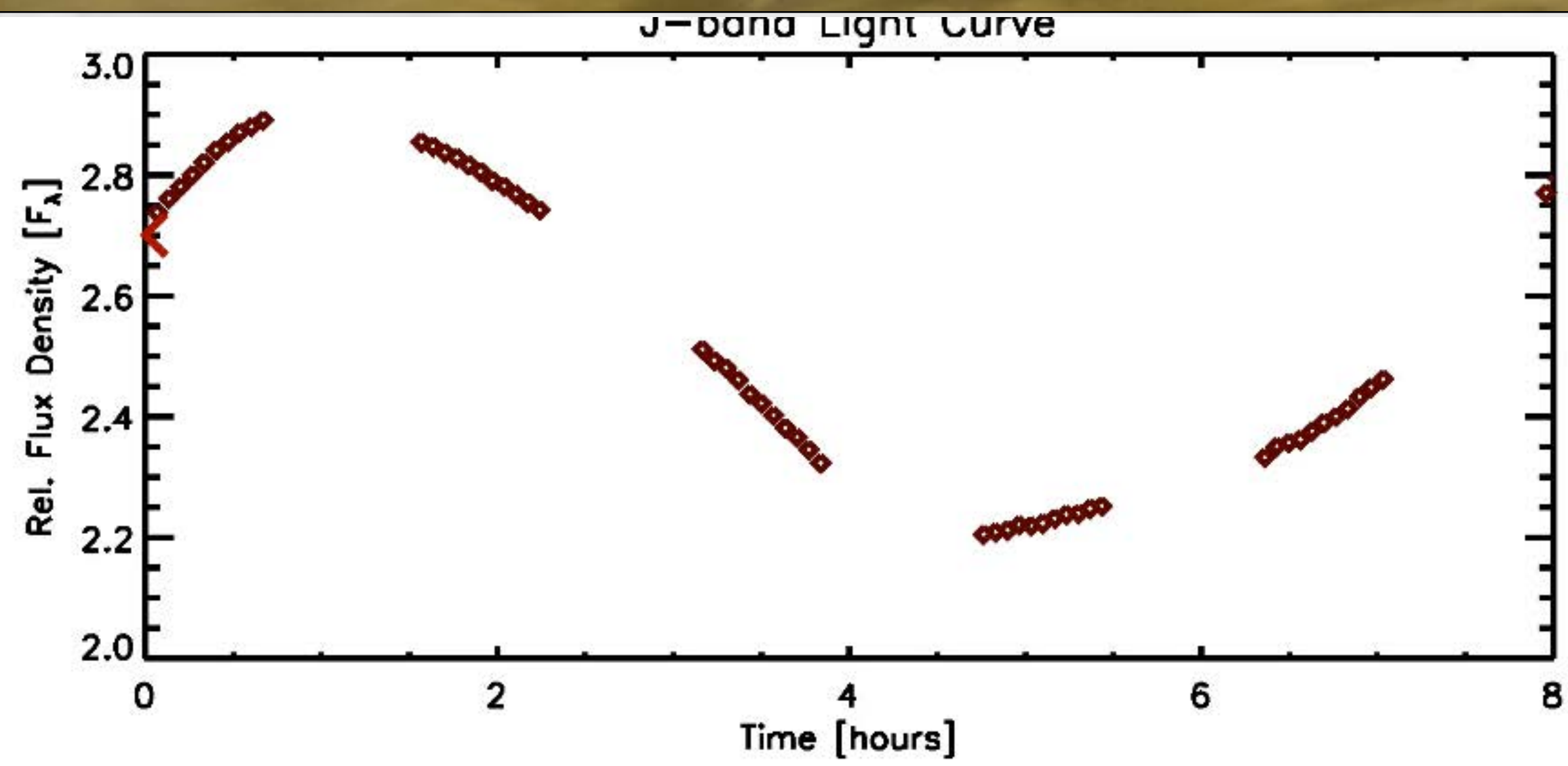
Cycle-11 Weather on Other Worlds 2

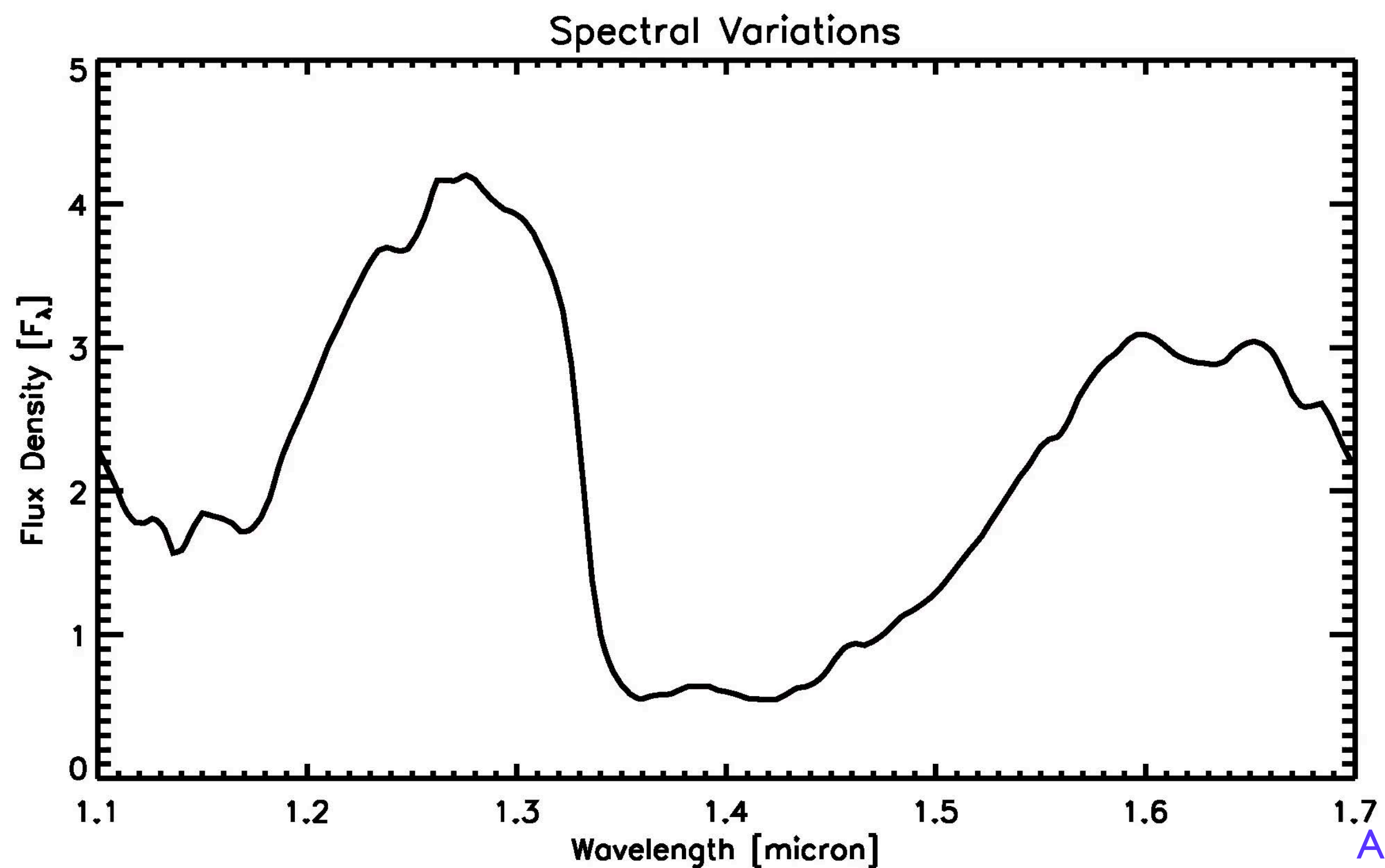
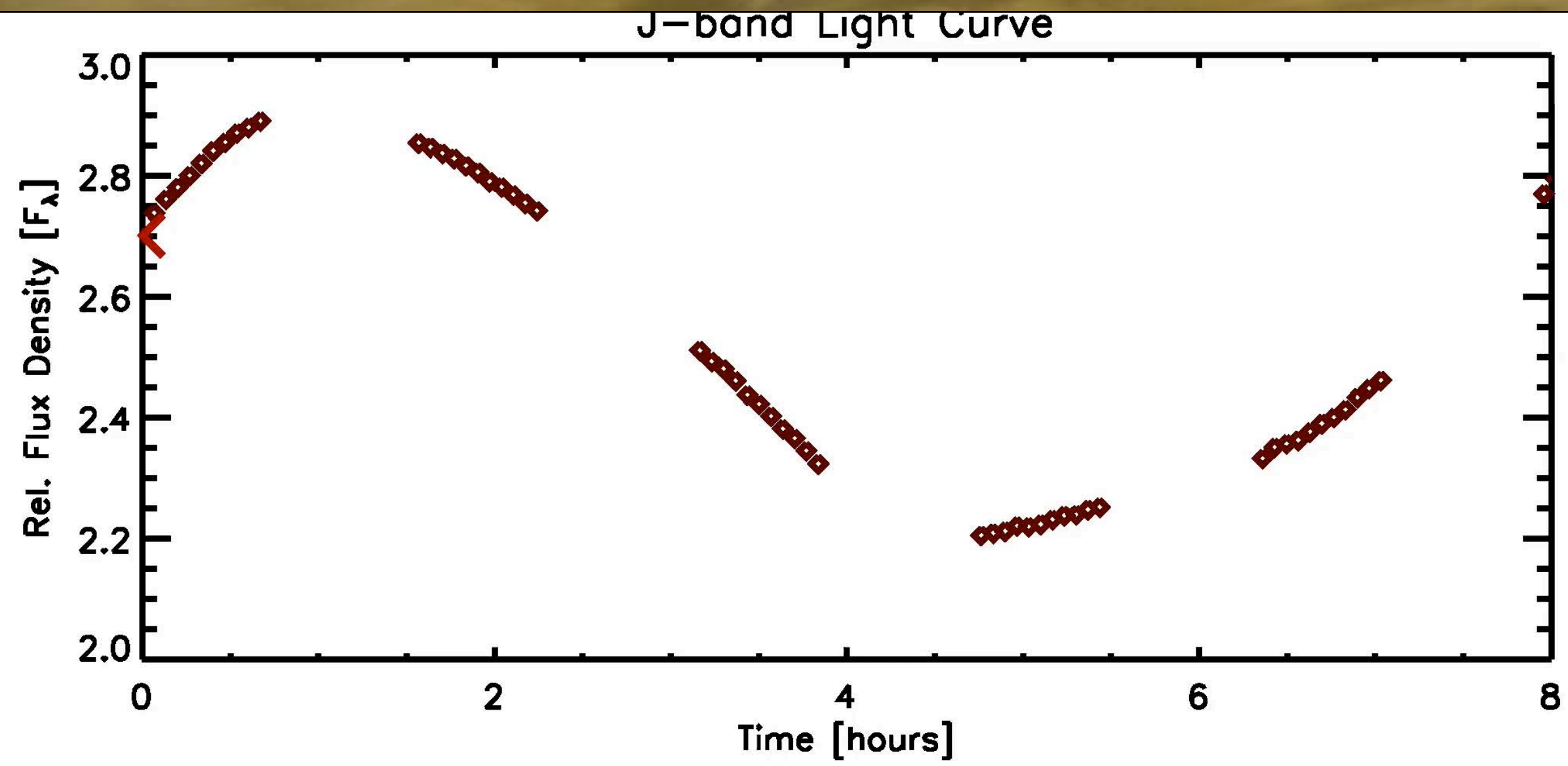
PI: Stan Metchev 540 Spitzer hours

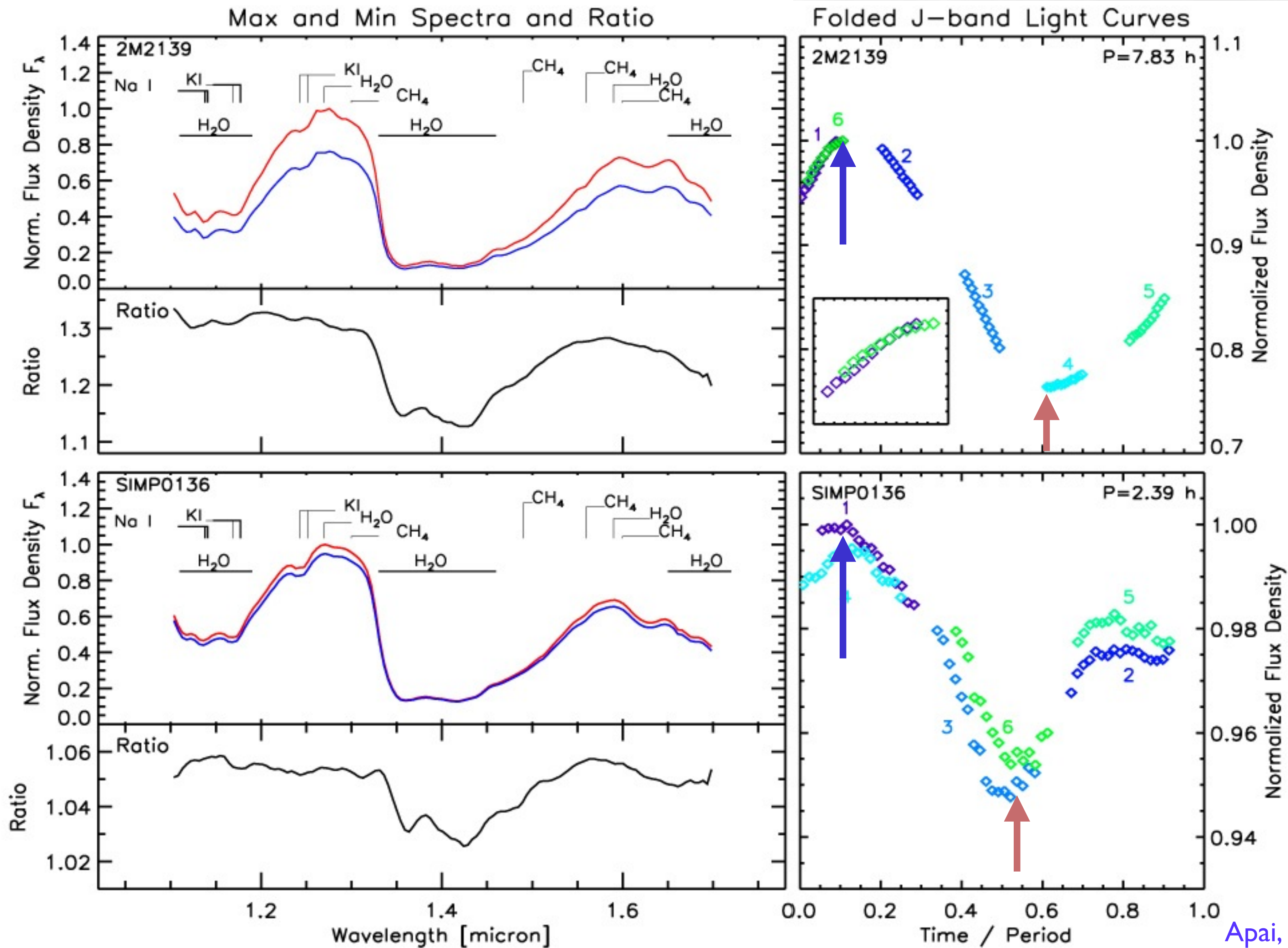
What is the physical cloud structure at the cloudy-cloud free (L/T) transition?

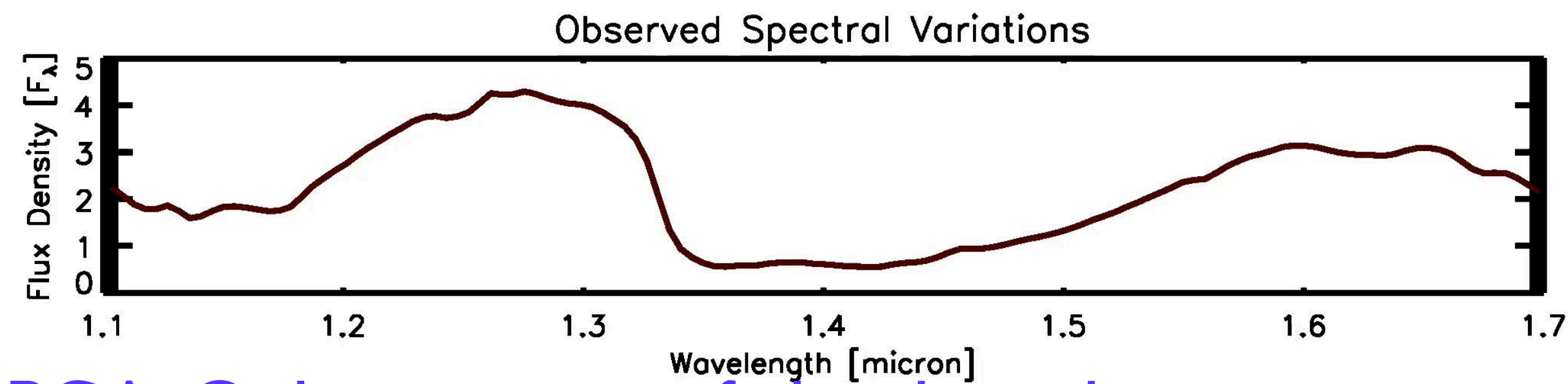
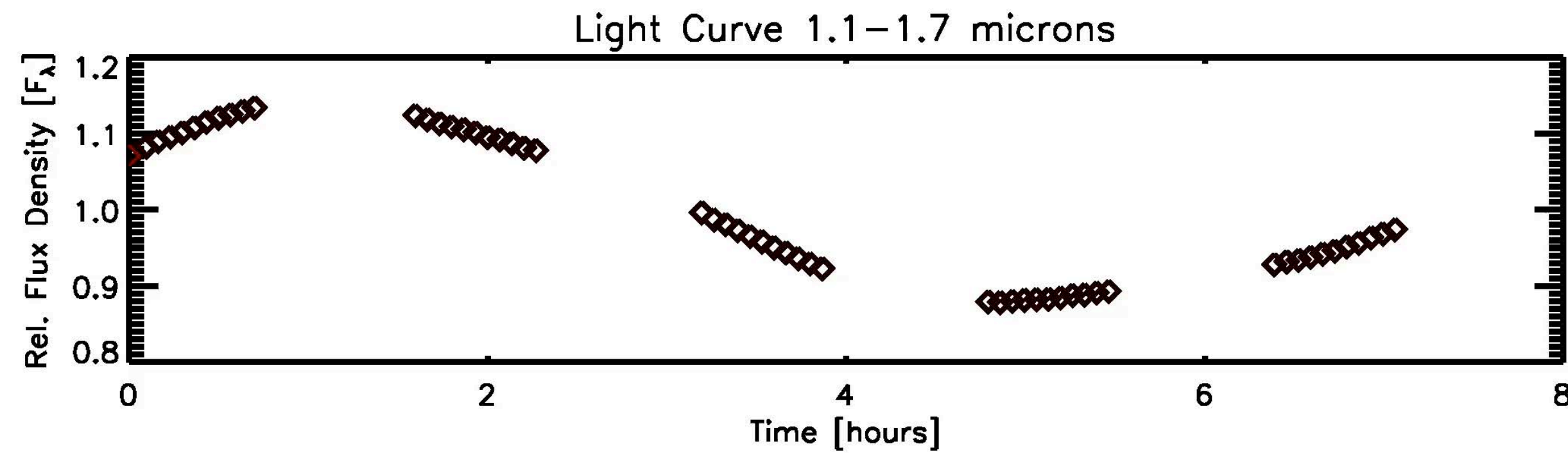
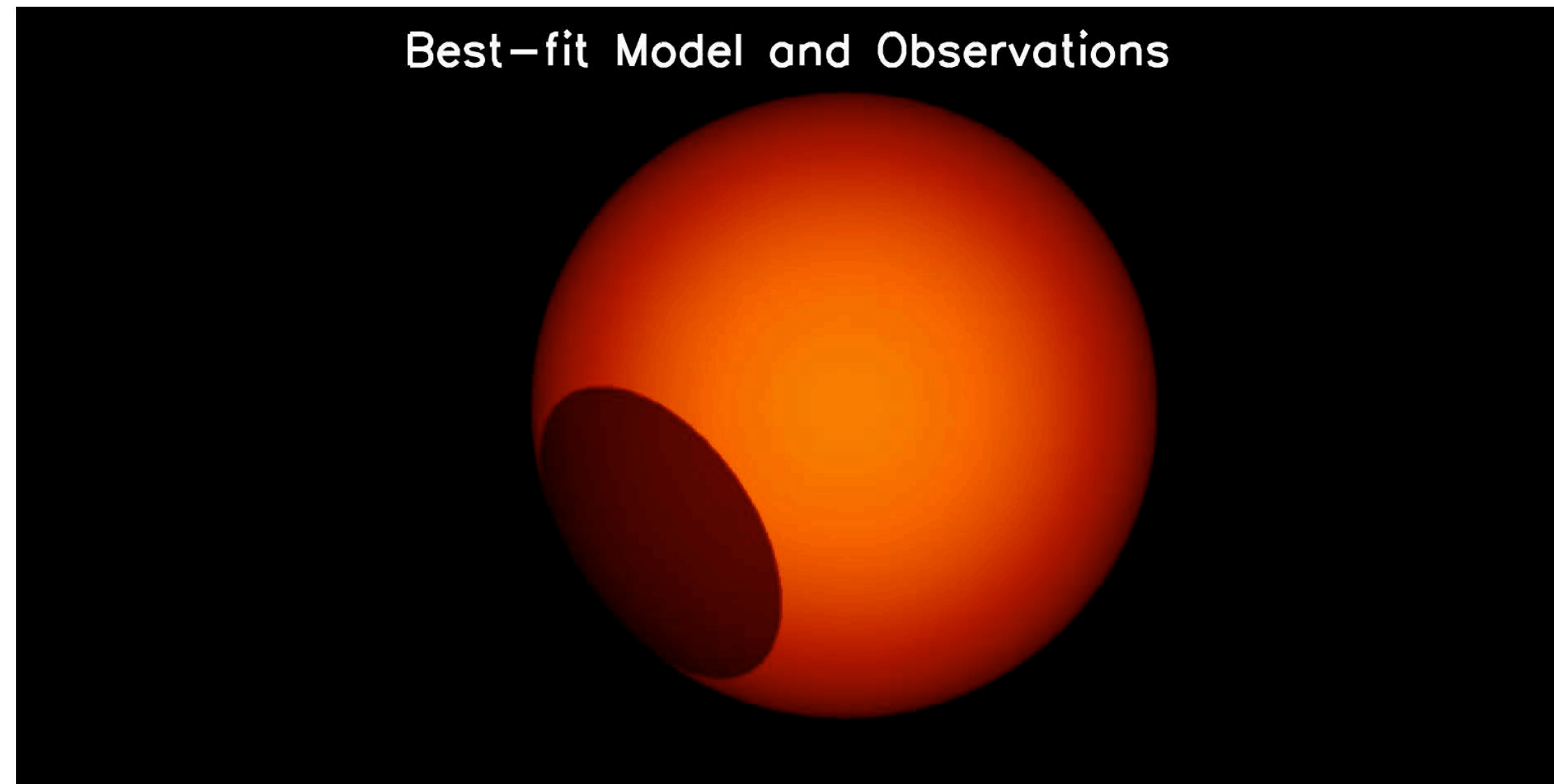




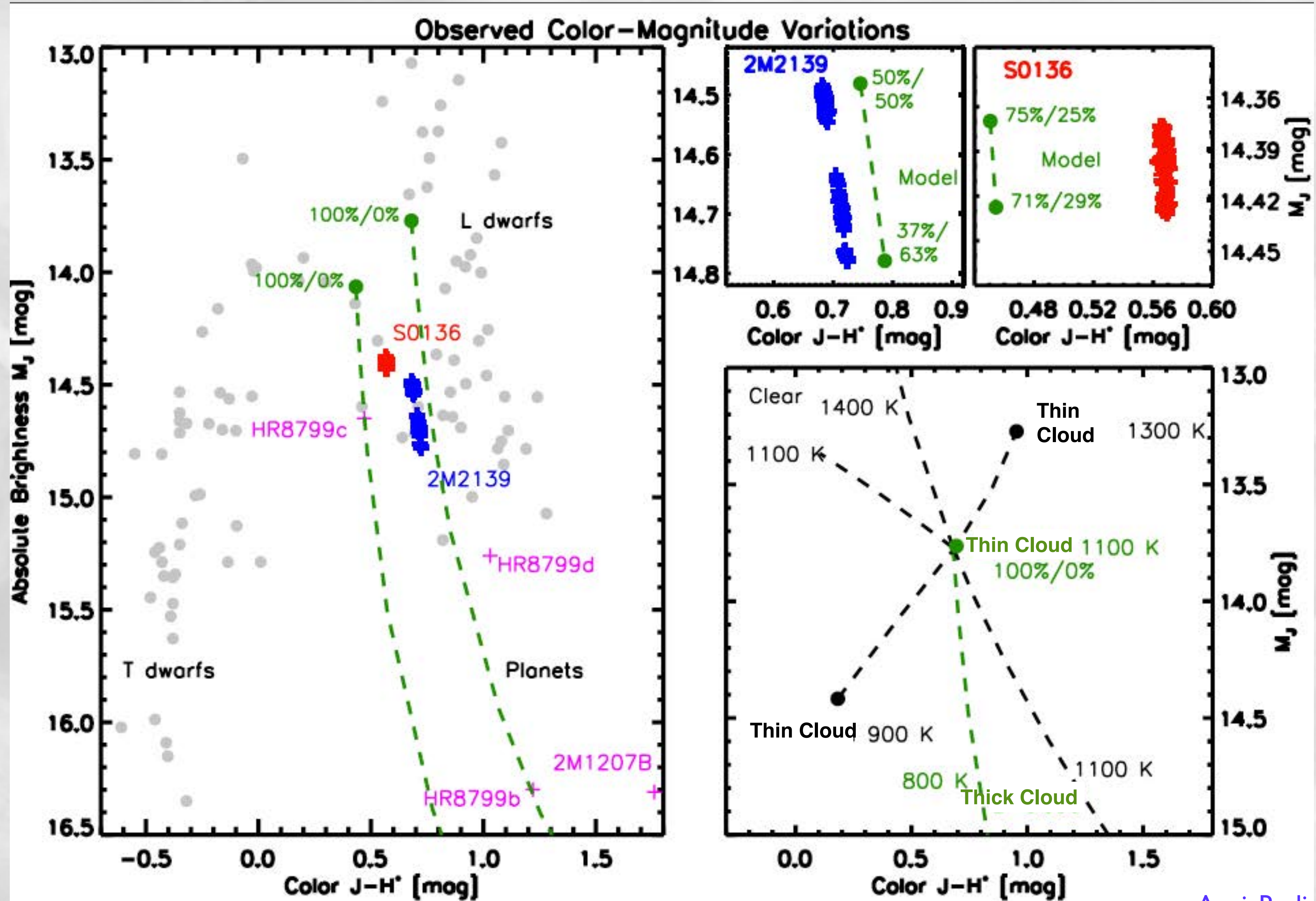






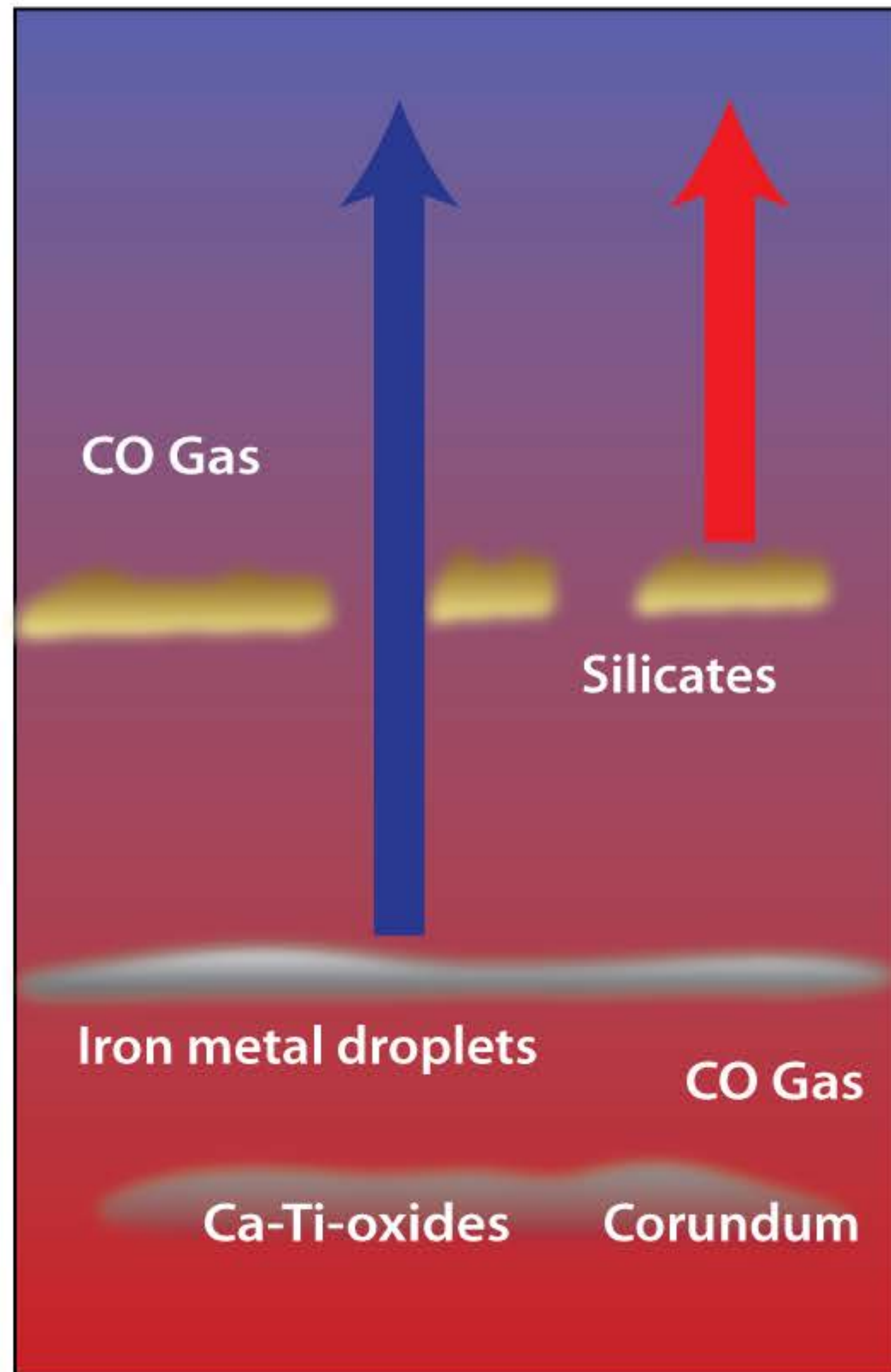


PCA: Only one type of cloud on the mean spectrum



Cloud Holes : Large Color Variations

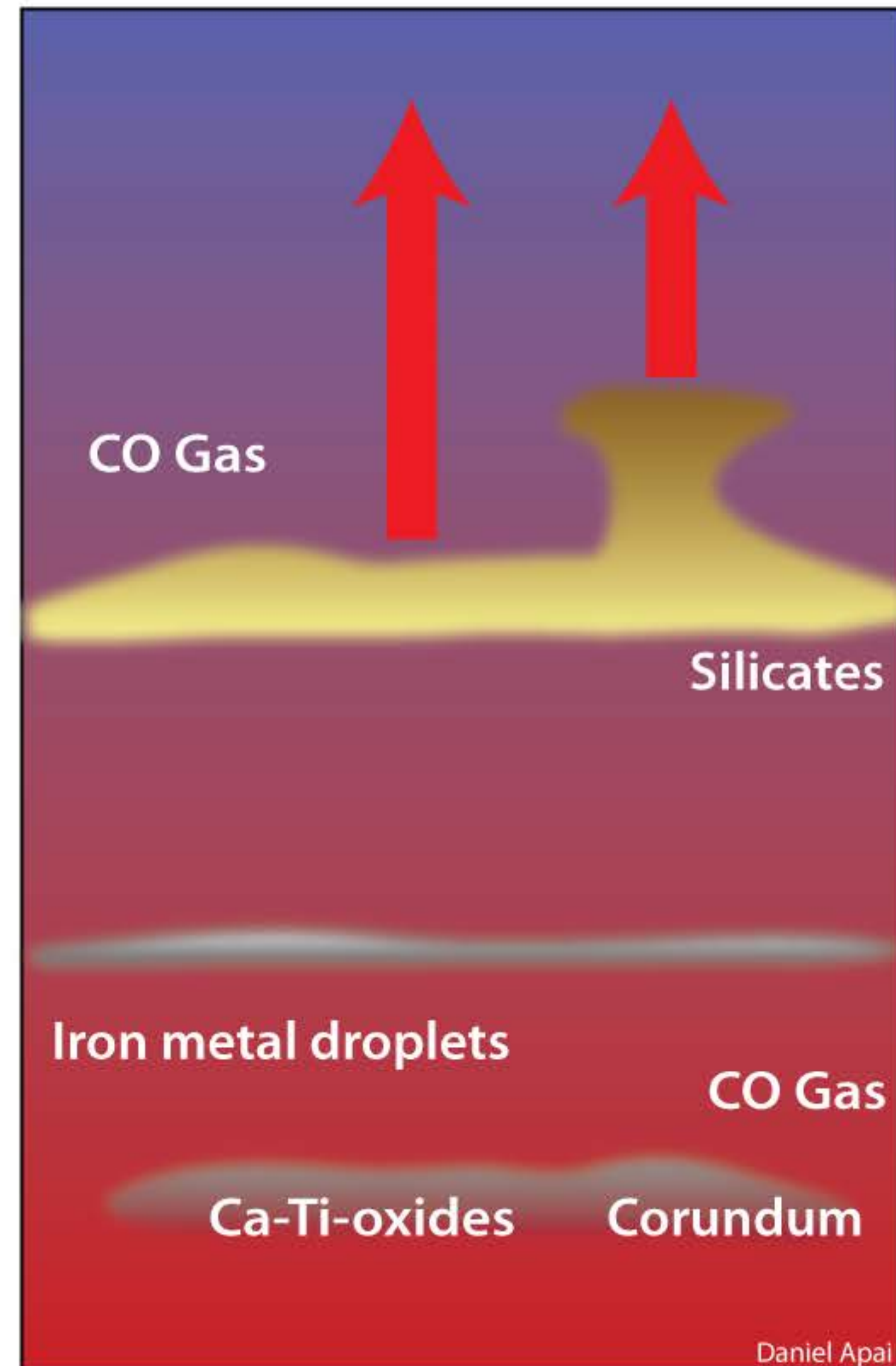
Cloud Thickness: Small Color Variations



Cool Upper Atmosphere

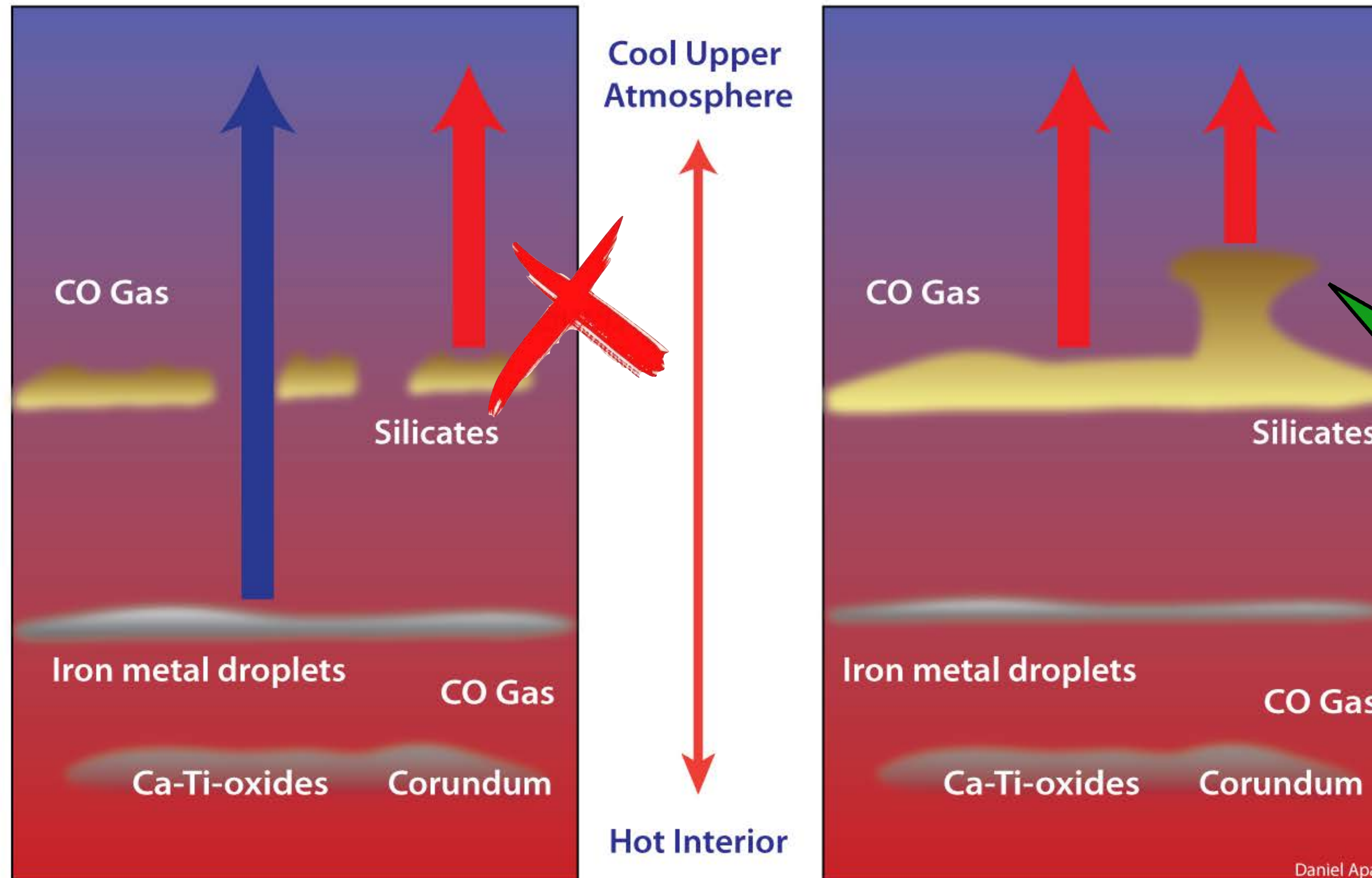


Hot Interior



Cloud Holes : Large Color Variations

Cloud Thickness: Small Color Variations

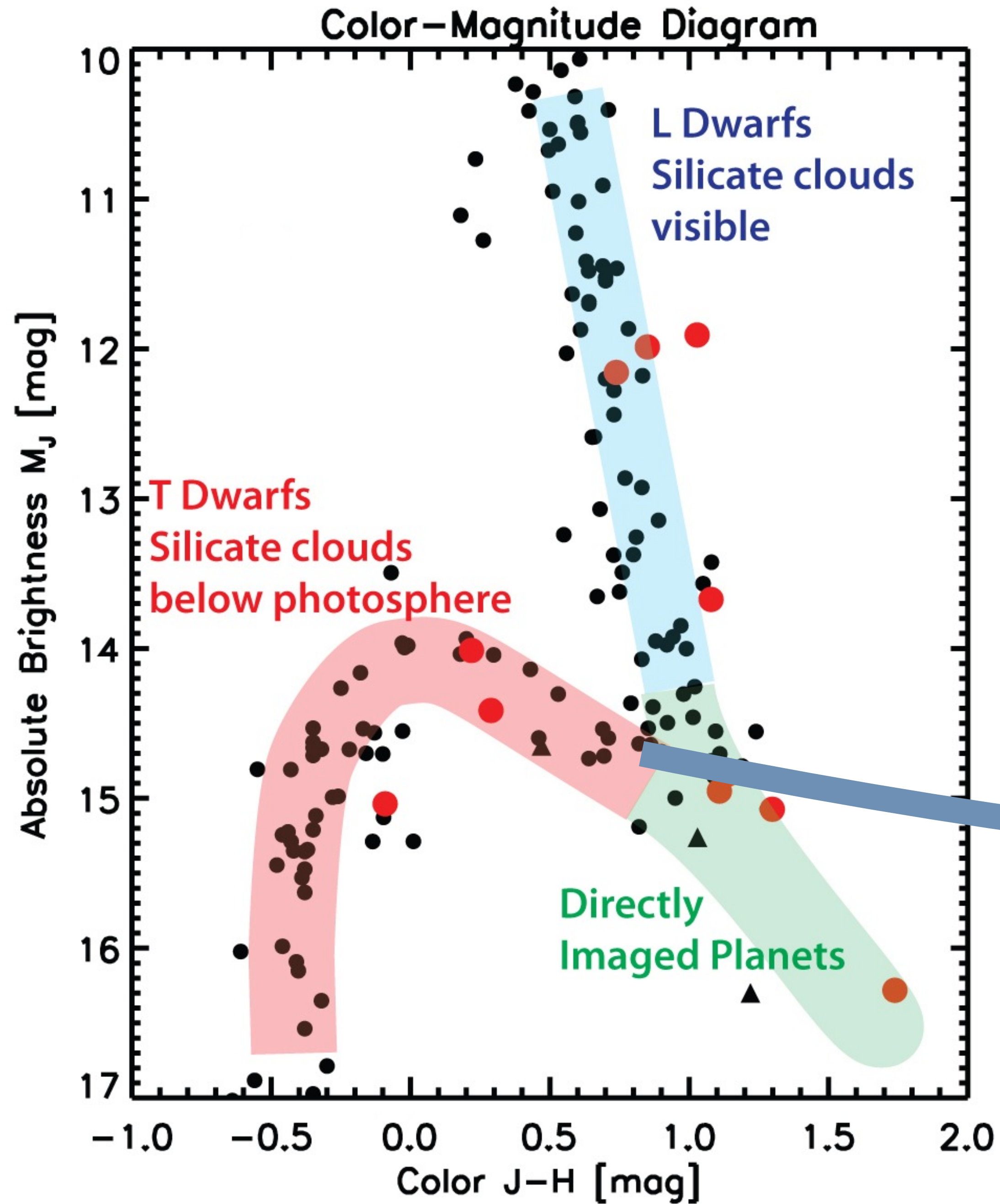


- 1) First spectral maps of an ultracool atmosphere
- 2) Warm Thin - Cooler Thick clouds

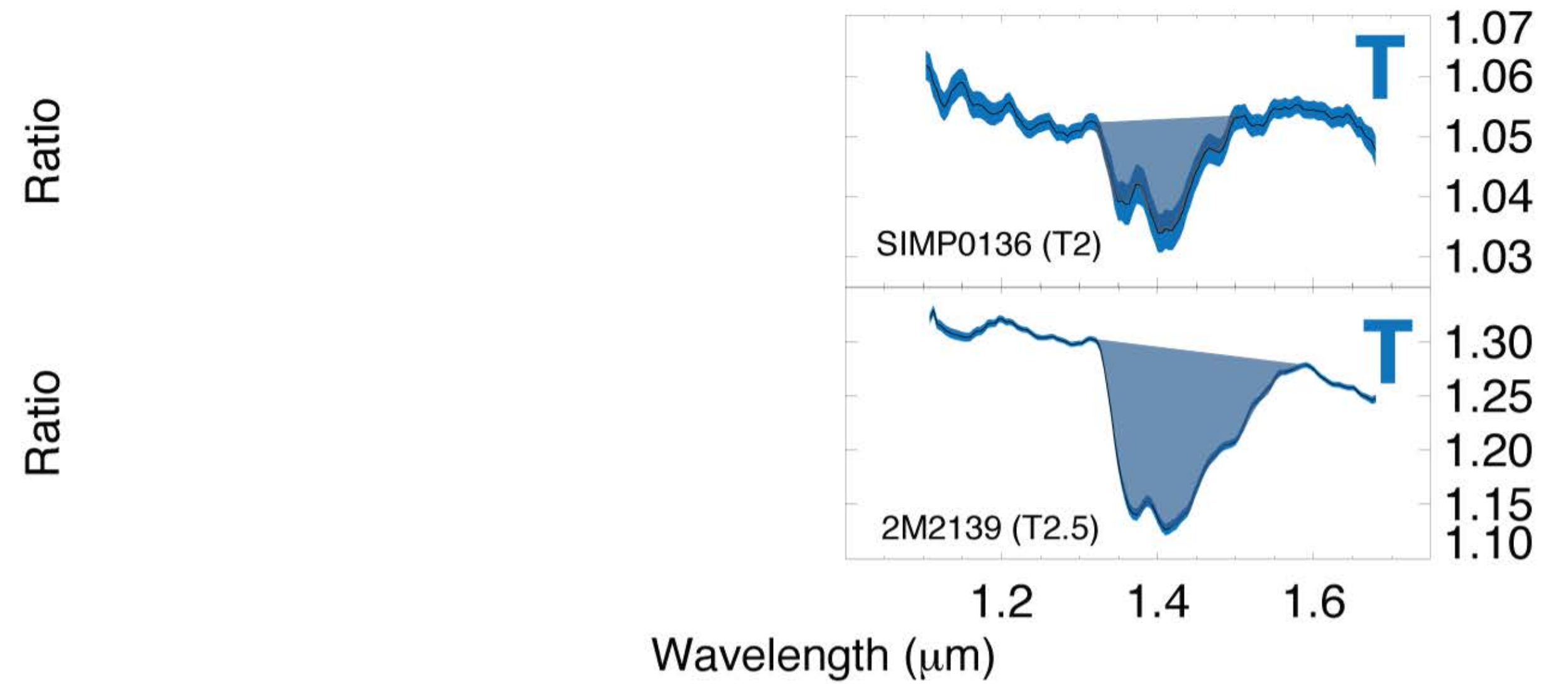
- 3) Only a single type of thick cloud
- 4) Spectral signature of the difference

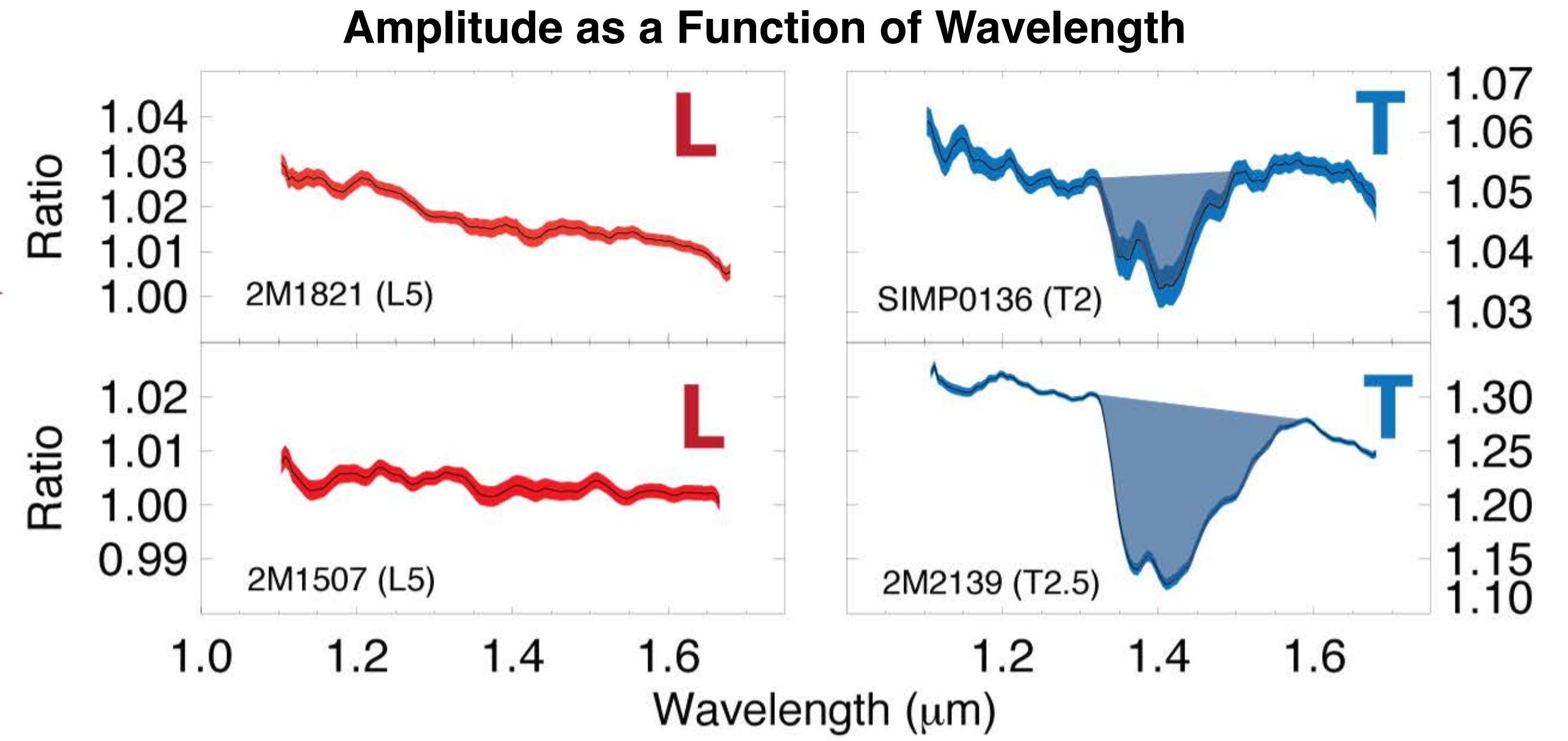
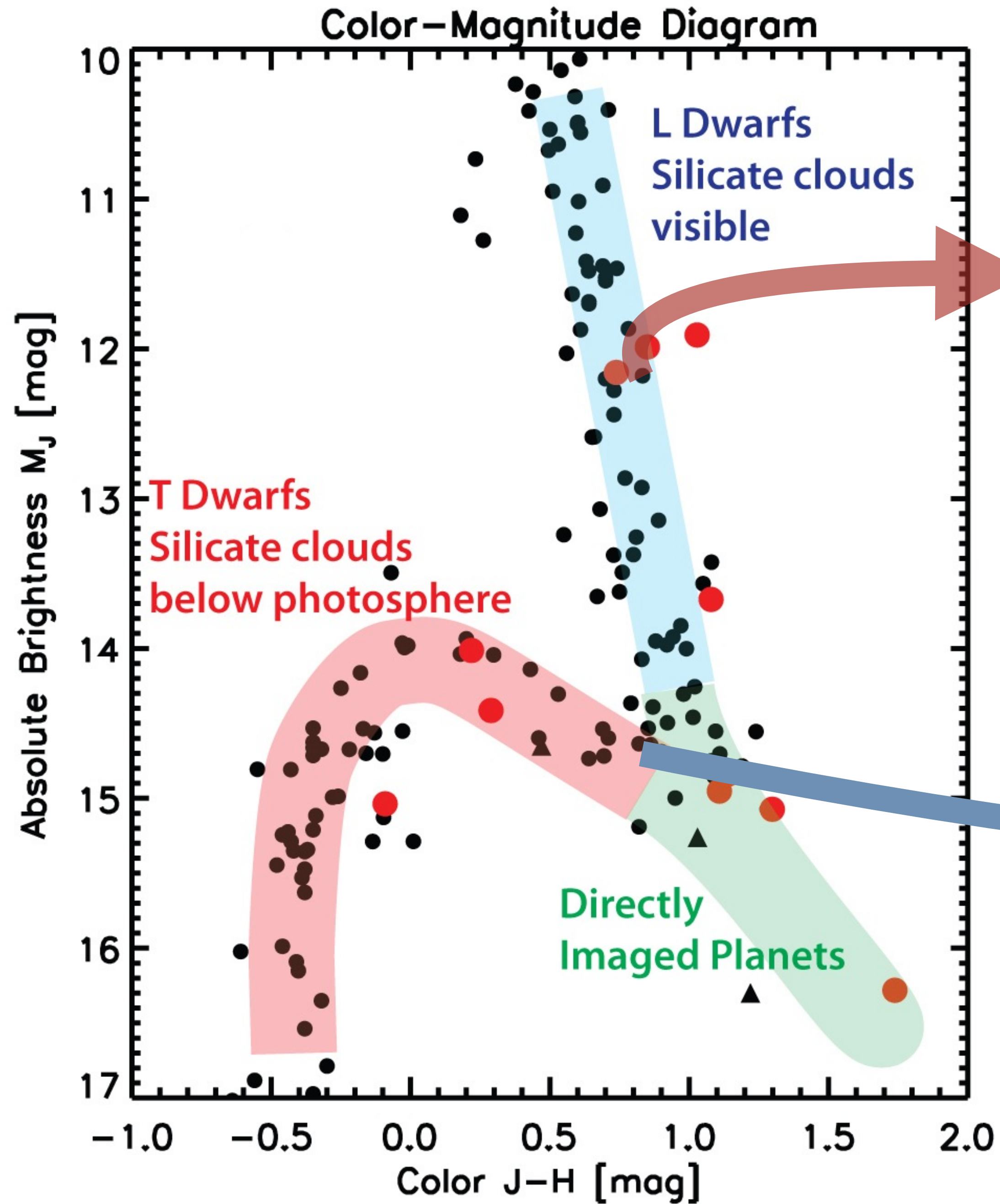
How Do Clouds in L Dwarfs Differ from those in early T dwarfs?

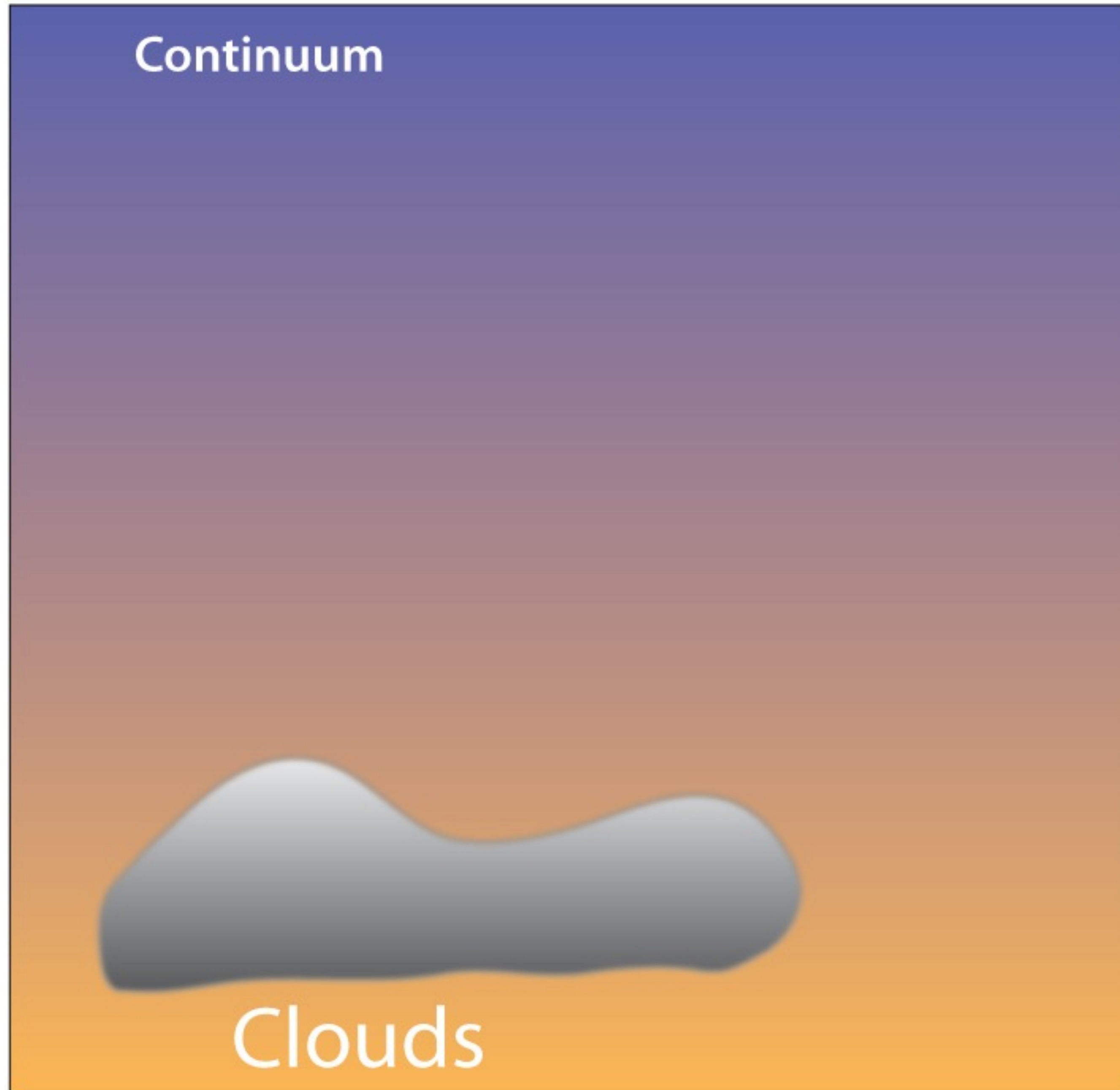


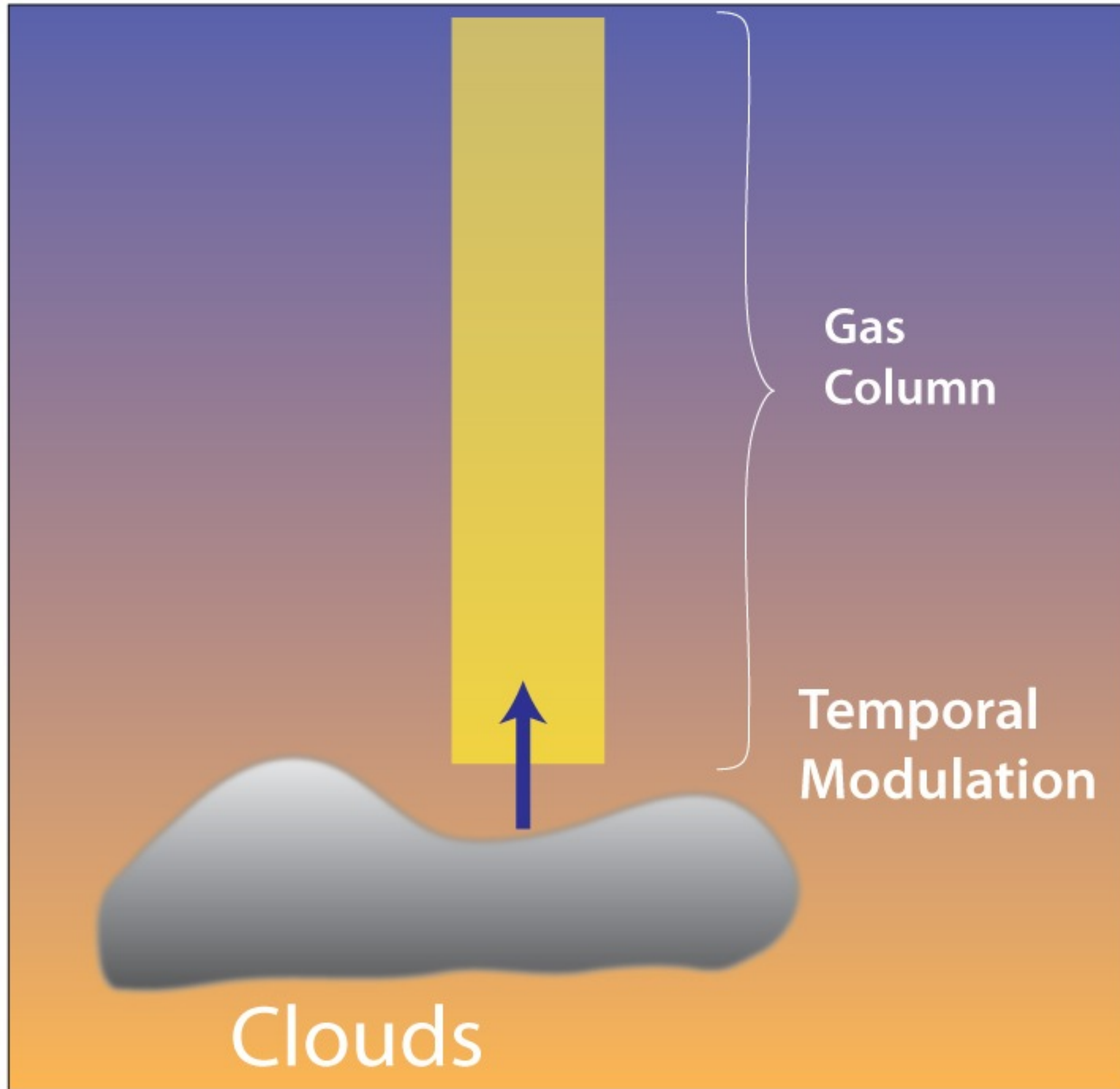


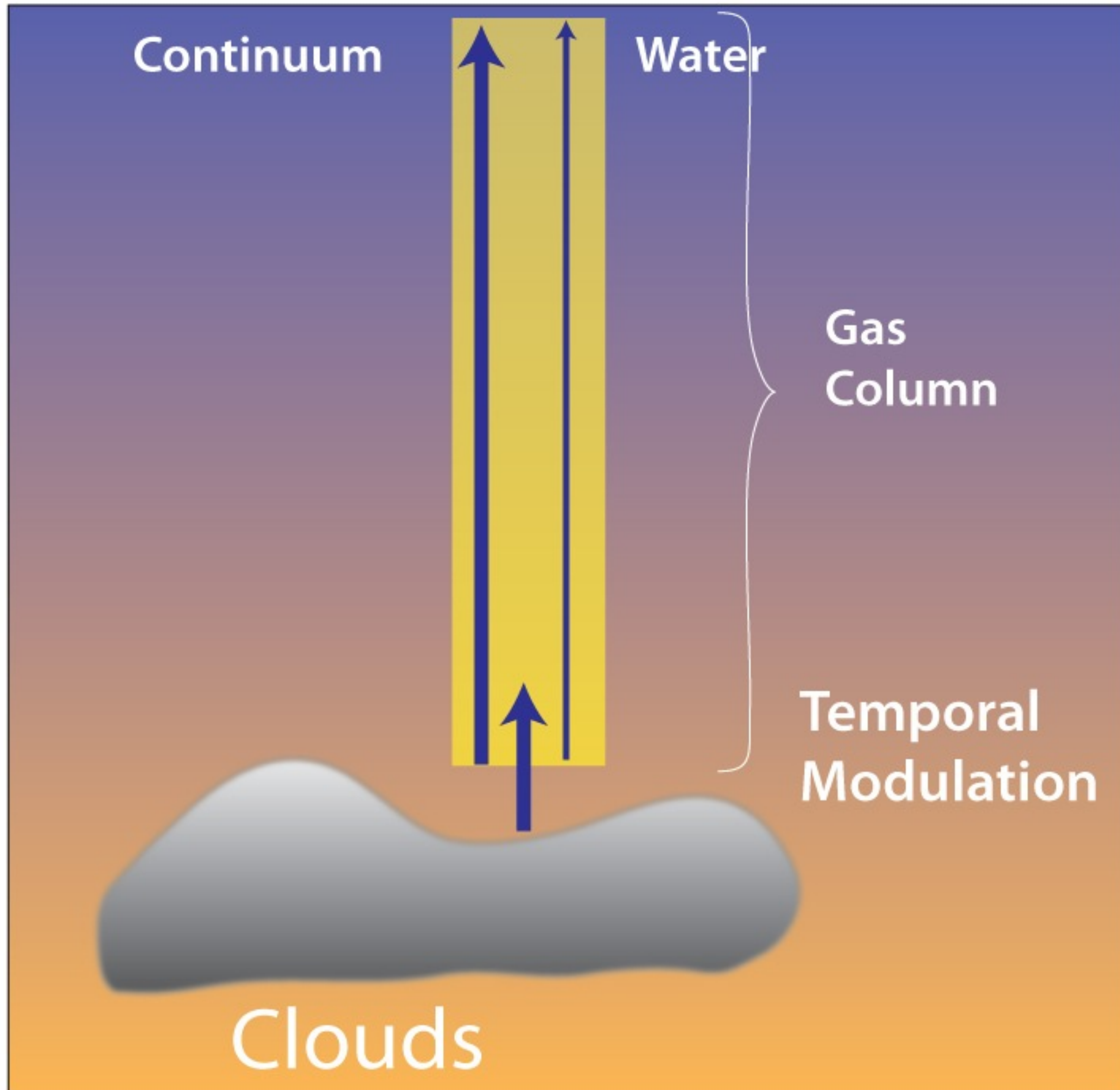
Amplitude as a Function of Wavelength

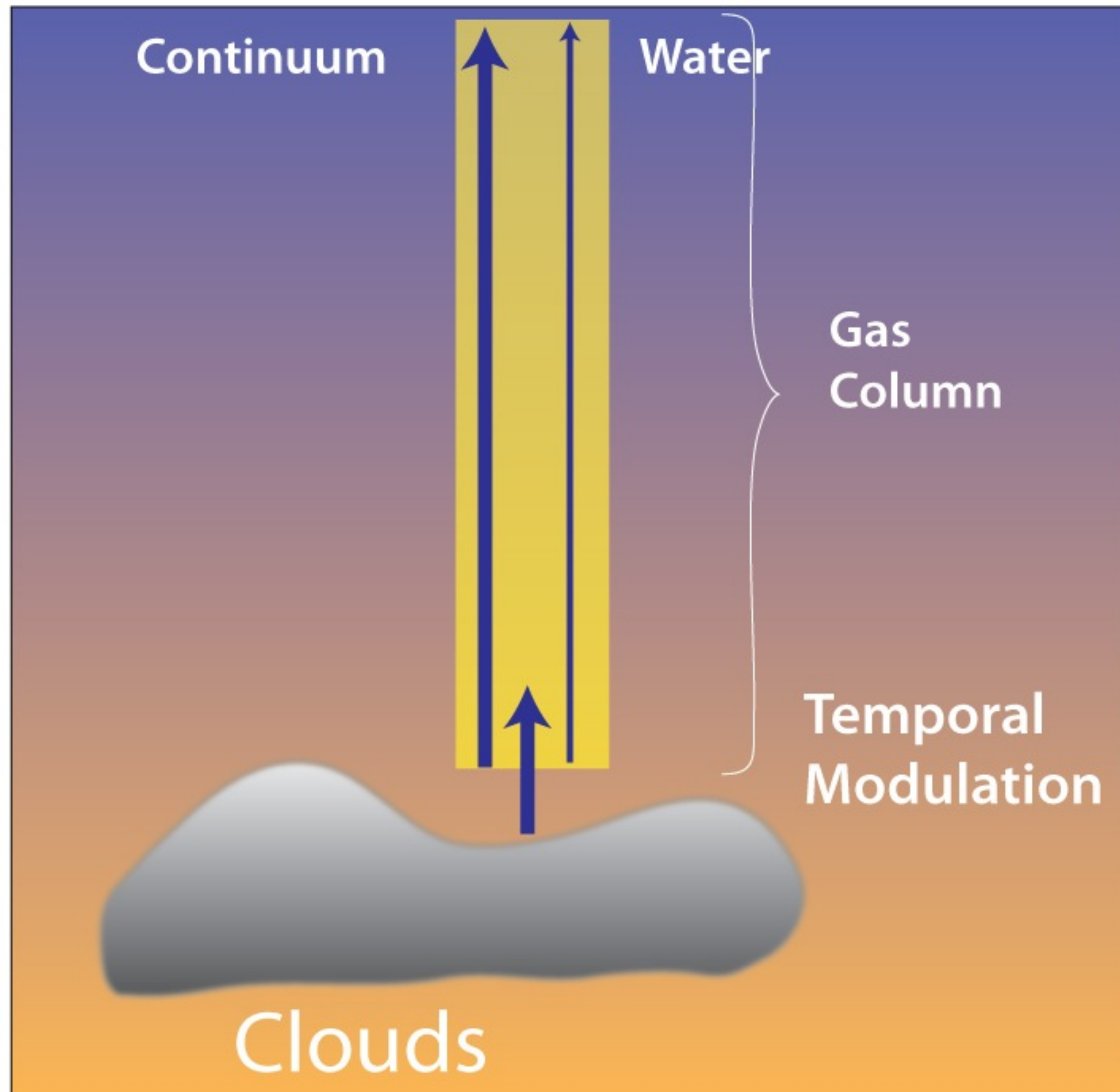








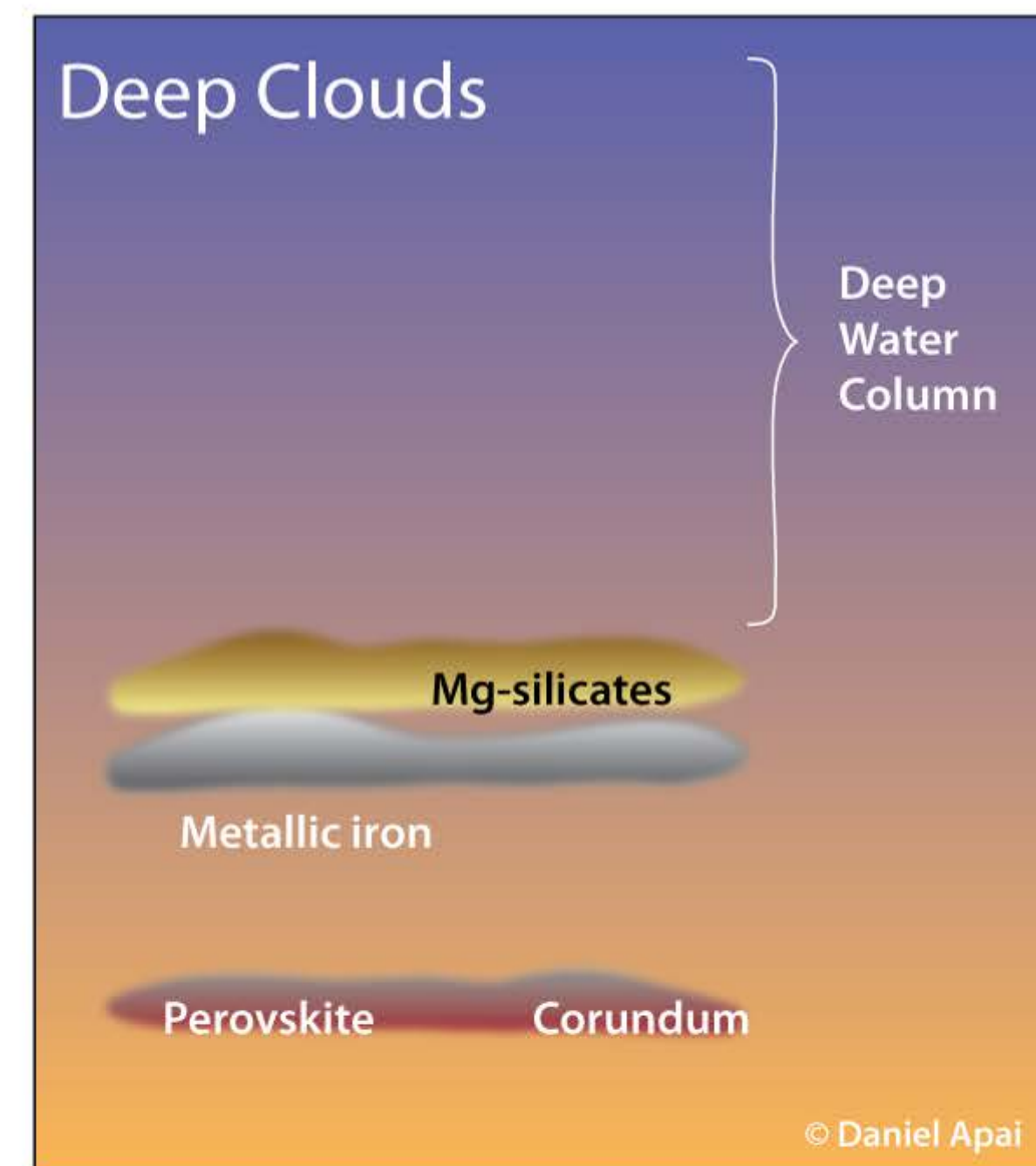
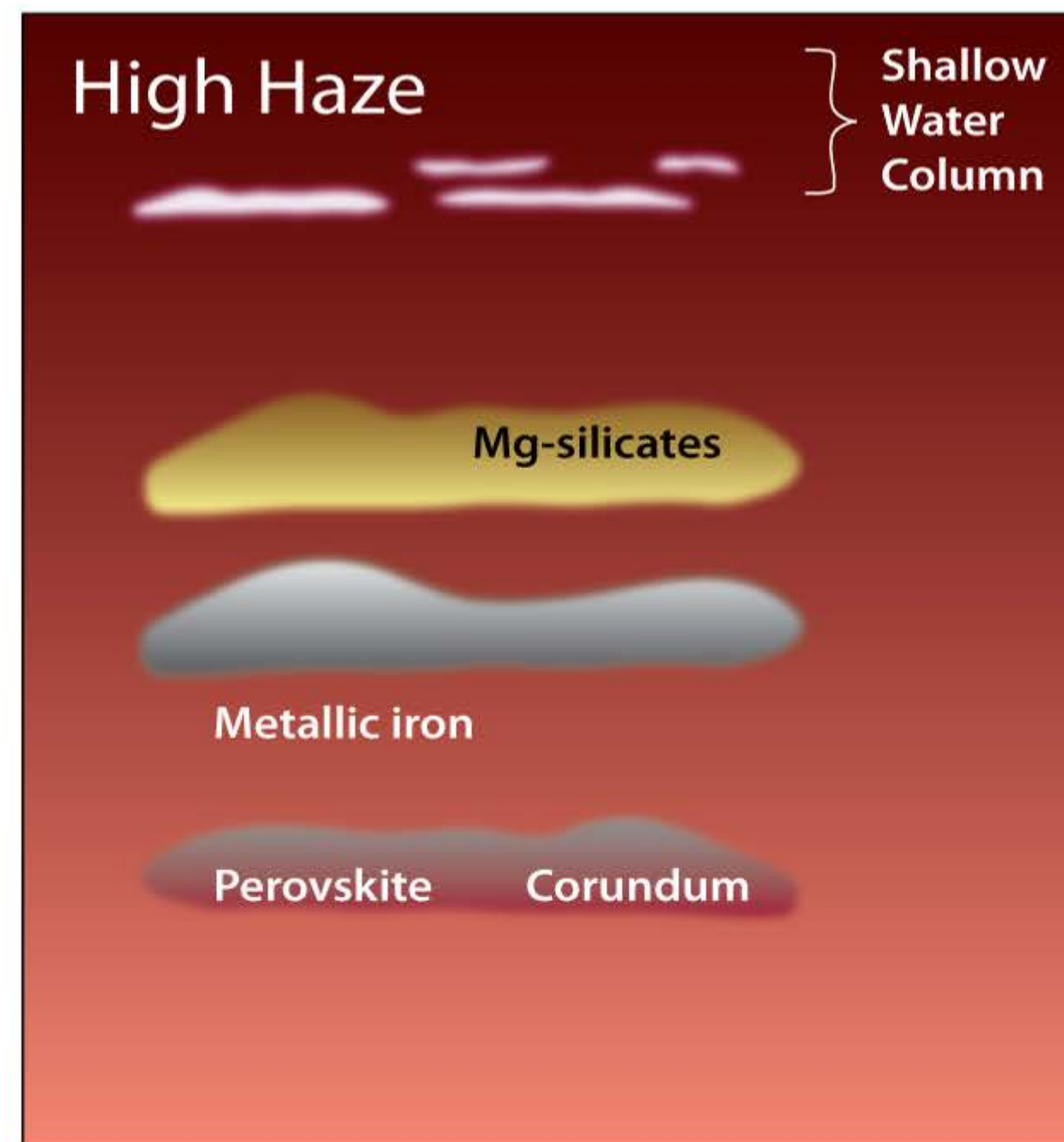
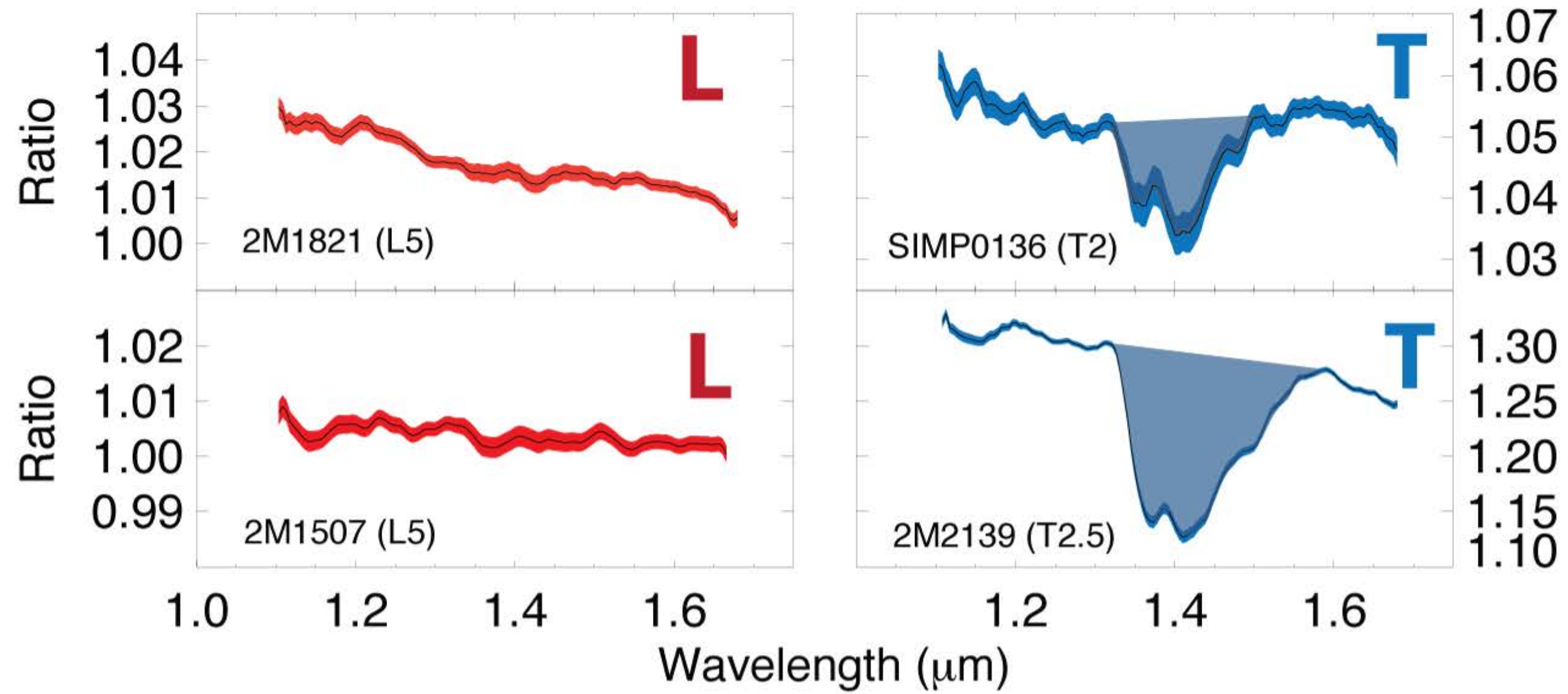


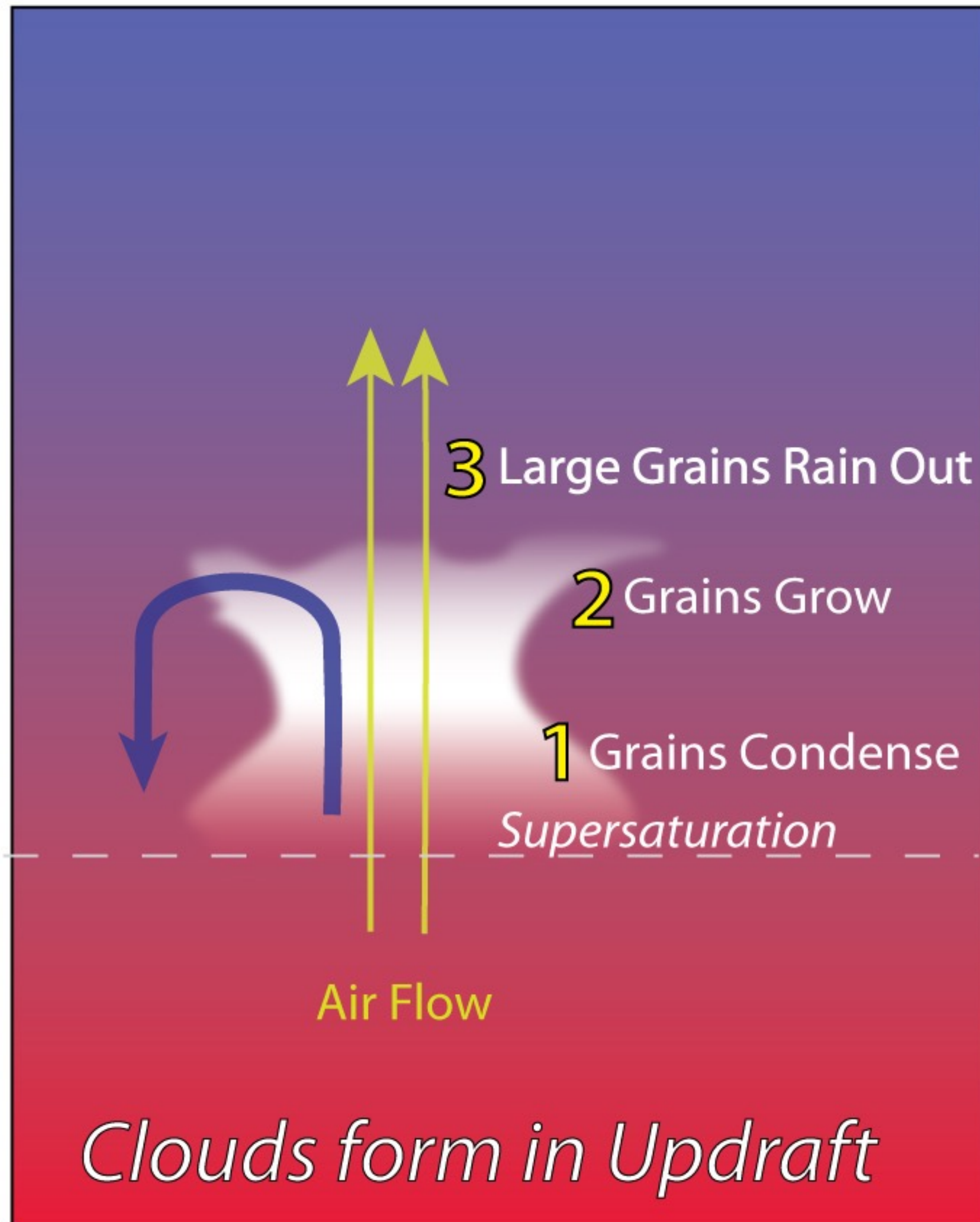


$$\epsilon = \frac{\Delta I_{obs,water}}{\Delta I_{obs,cont}} = \frac{\Delta I_{int} \times e^{-\tau_{water}}}{\Delta I_{int} \times e^{-\tau_{cont}}}$$

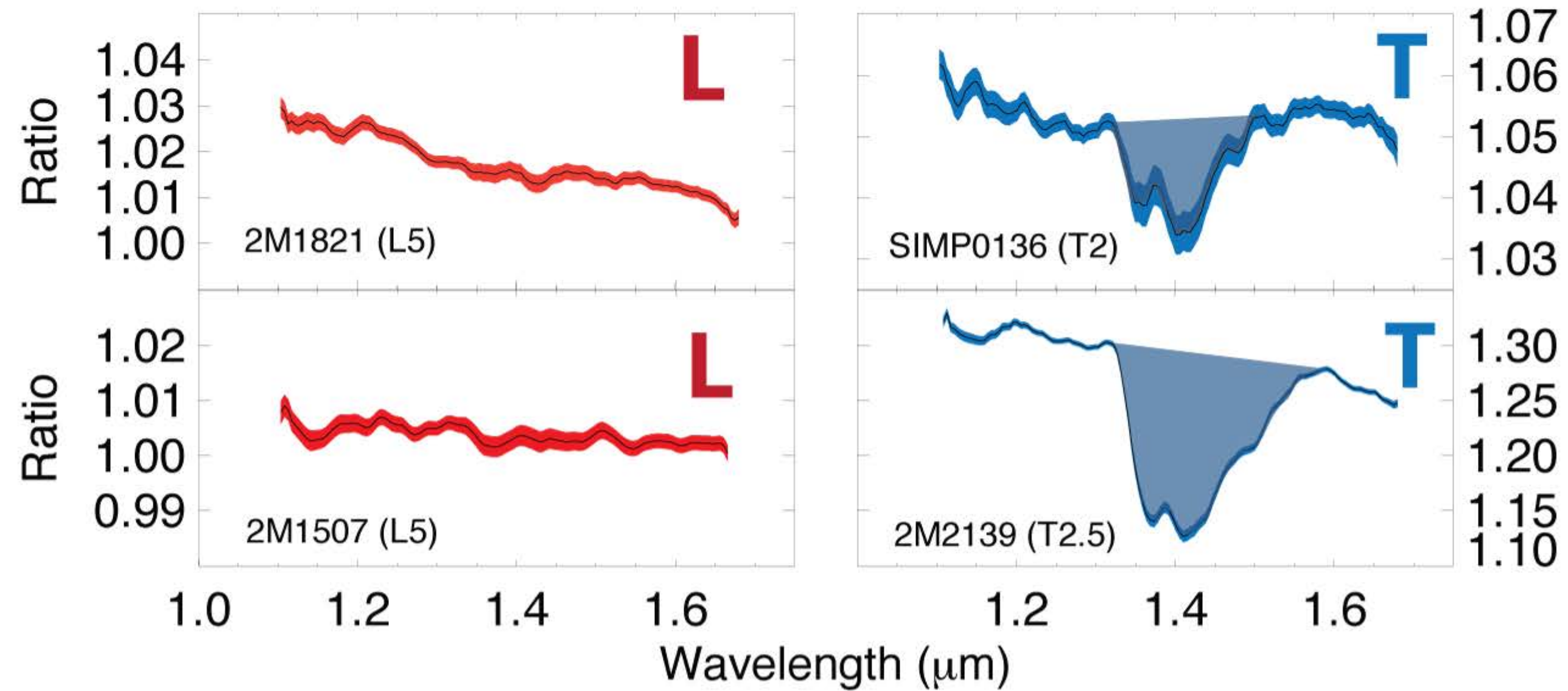
$$\epsilon = \frac{\Delta I_{obs,water}}{\Delta I_{obs,cont}} = e^{-(\tau_{water} - \tau_{cont})}$$

Water-band Amplitude as Cloud Depth Probe





Water-band Amplitude as Cloud Depth Probe



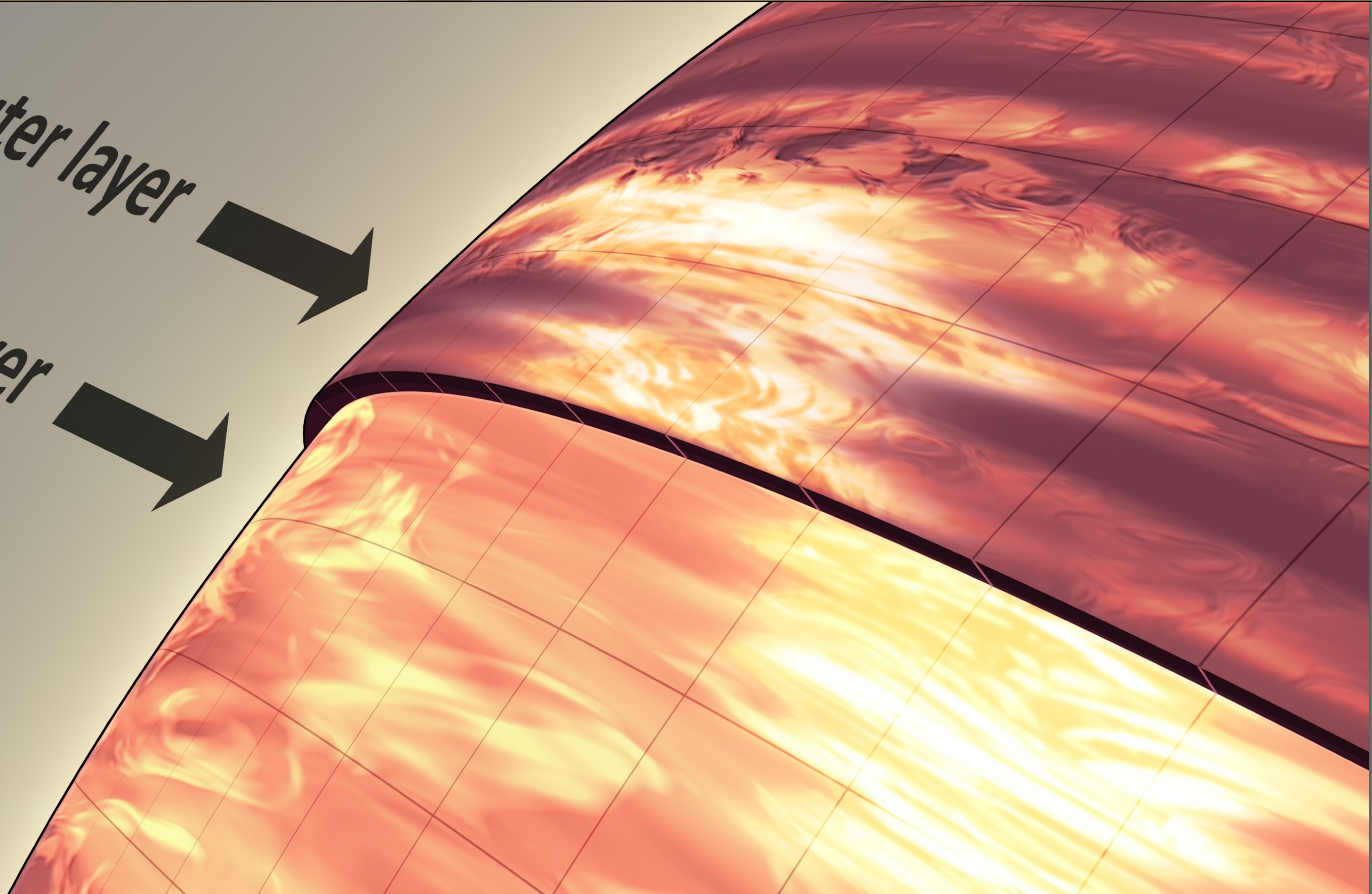
- 1) First spectral maps of L dwarfs
- 2) No reduced amplitude in the water band
- 3) High haze in L dwarfs, deeper clouds in L/T dwarfs



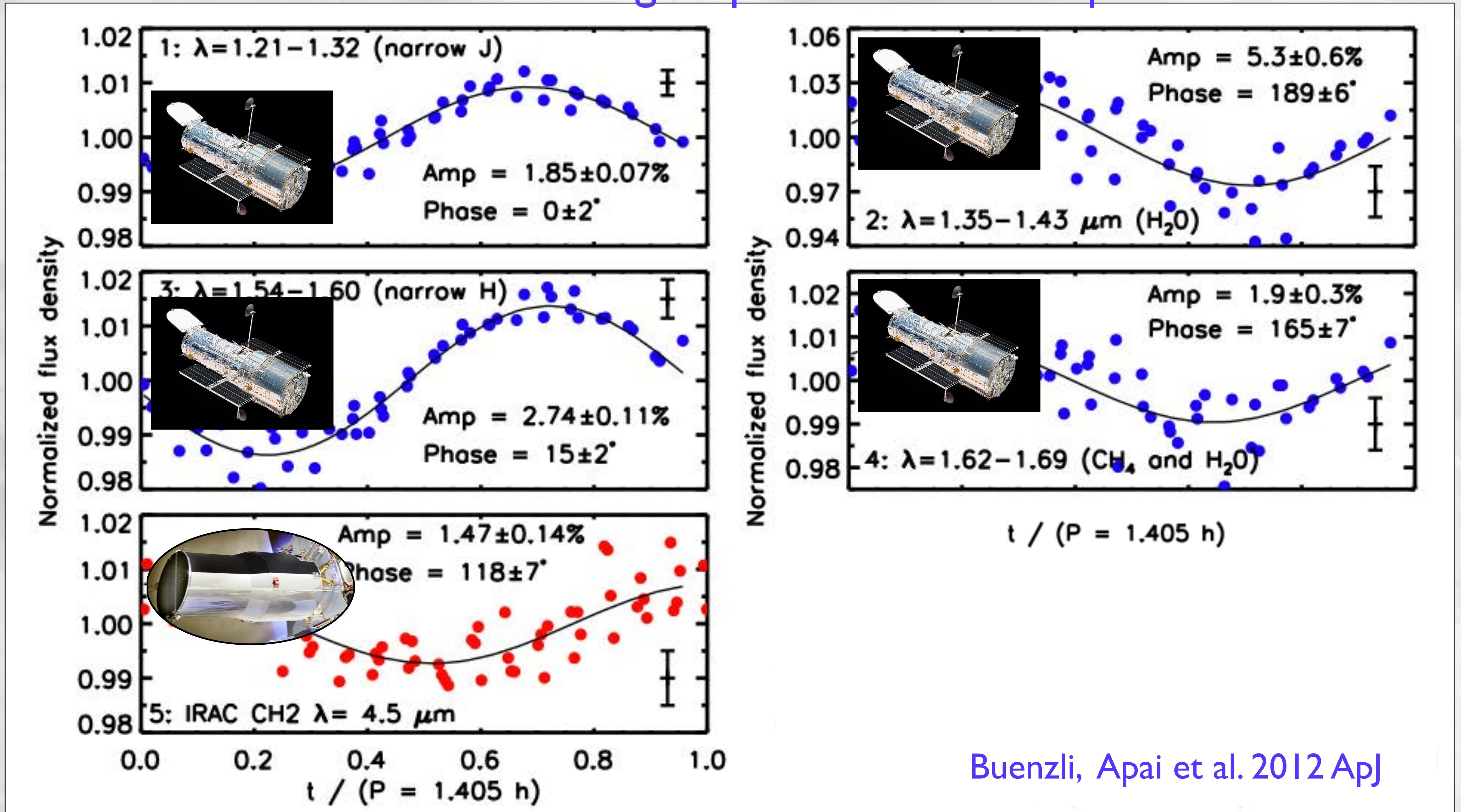
What is the Vertical Structure of
the Cloud Layers?

Outer layer →

Inner layer →

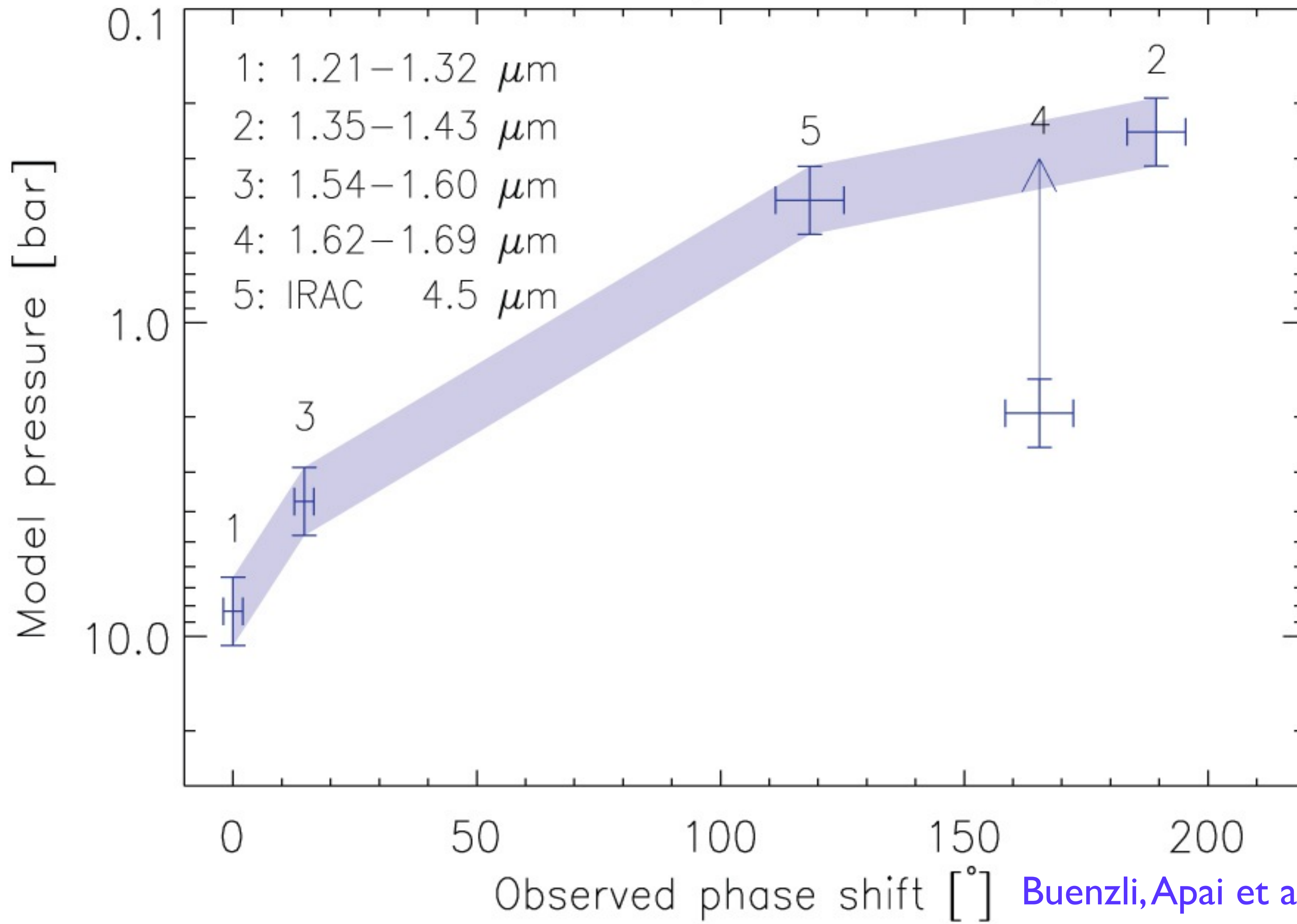


Different wavelengths probe different depths



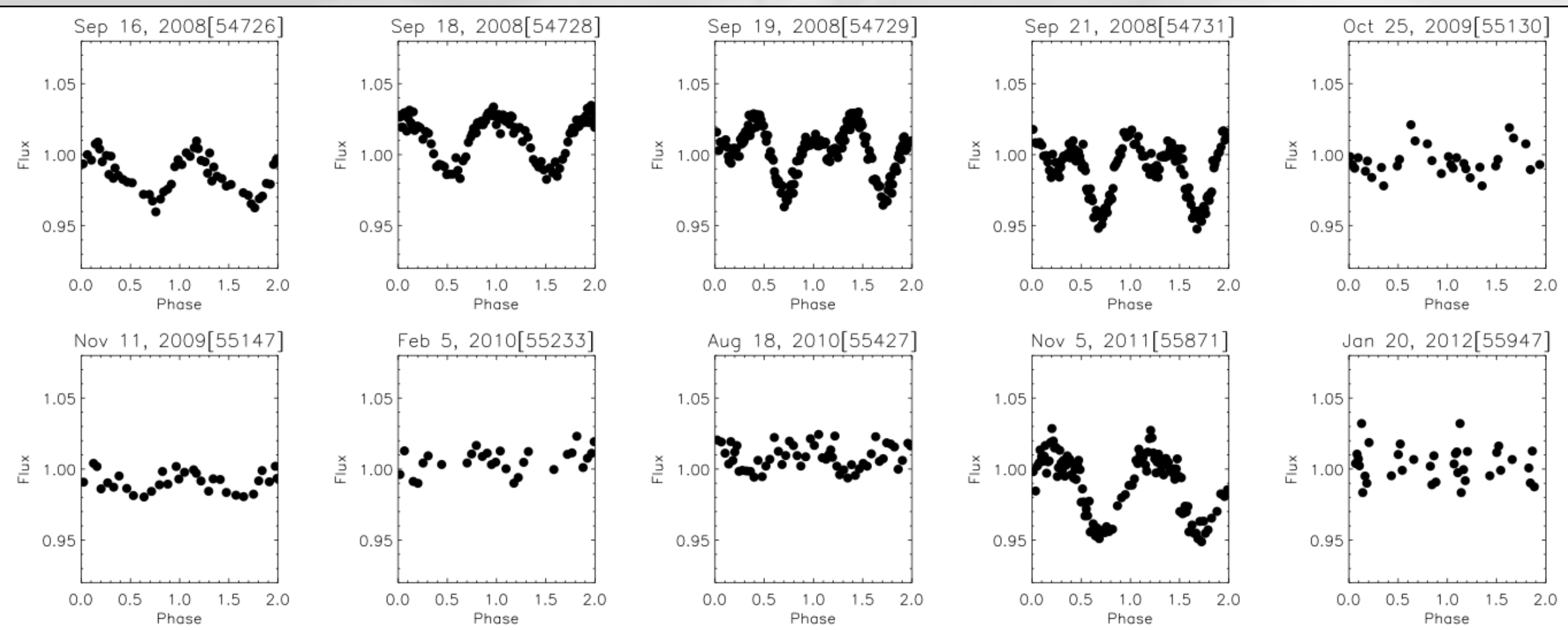
Buenzli, Apai et al. 2012 ApJ

Correlation between phase shift and pressure

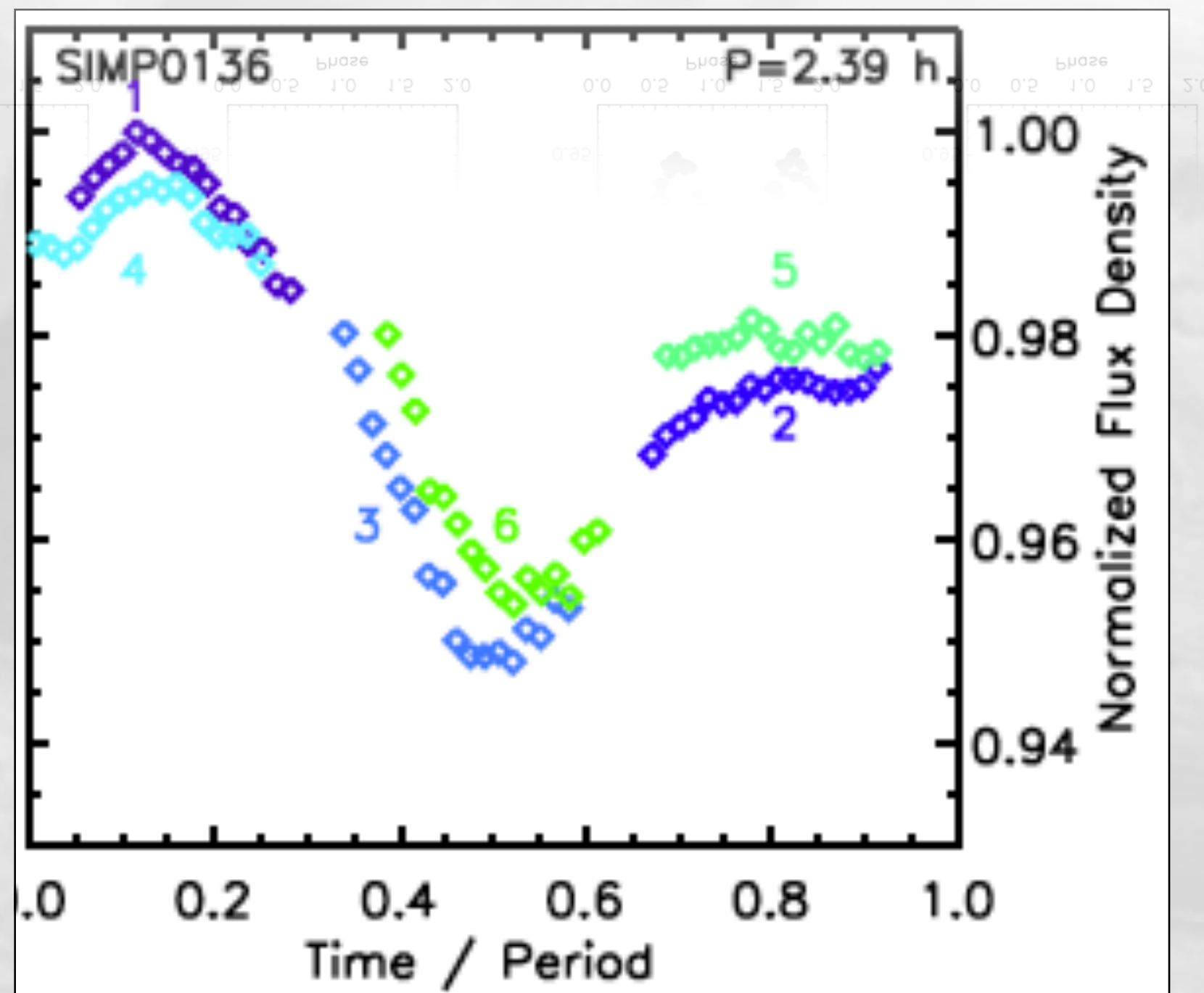


Atmospheric Dynamics in Ultracool Atmospheres

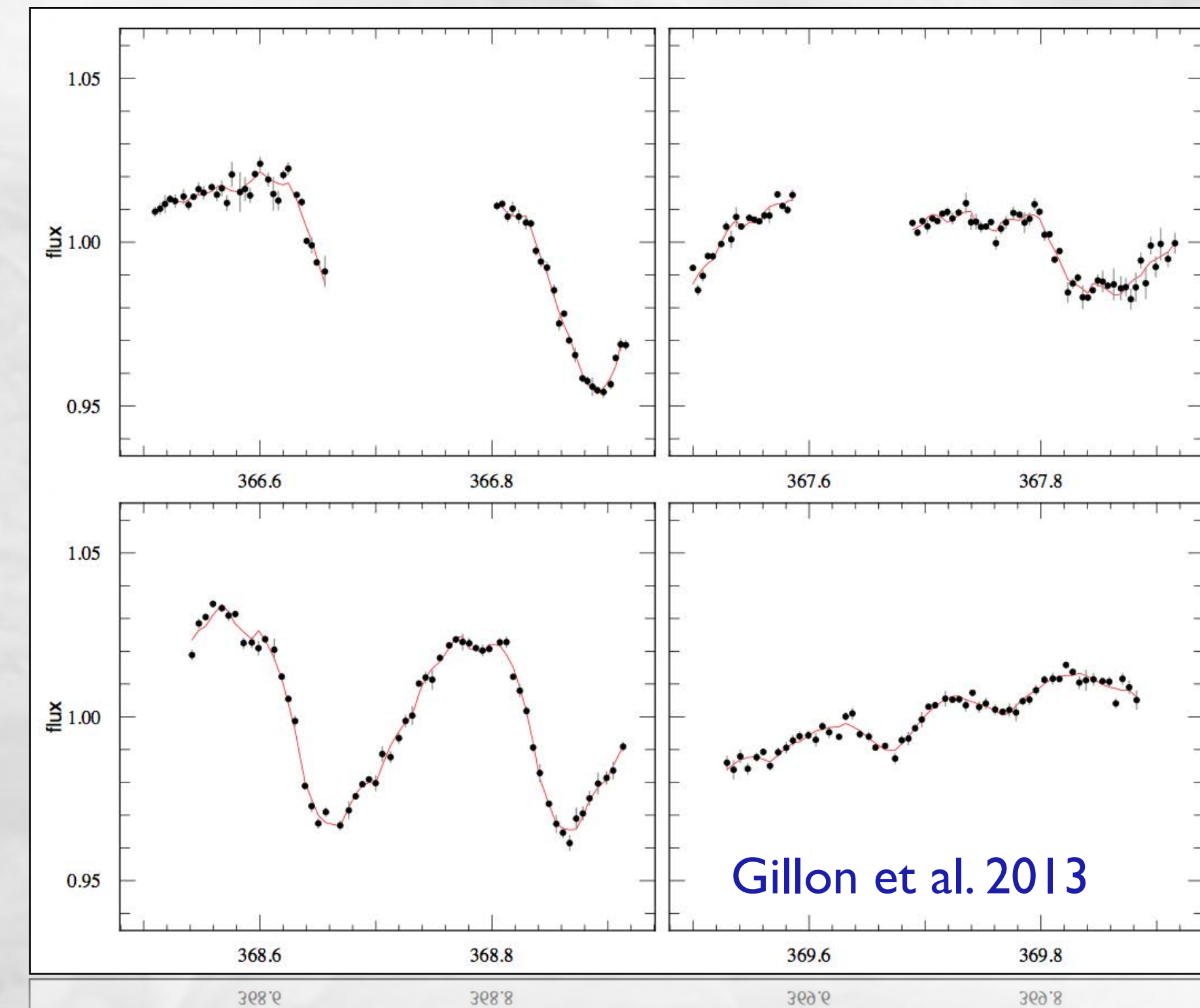




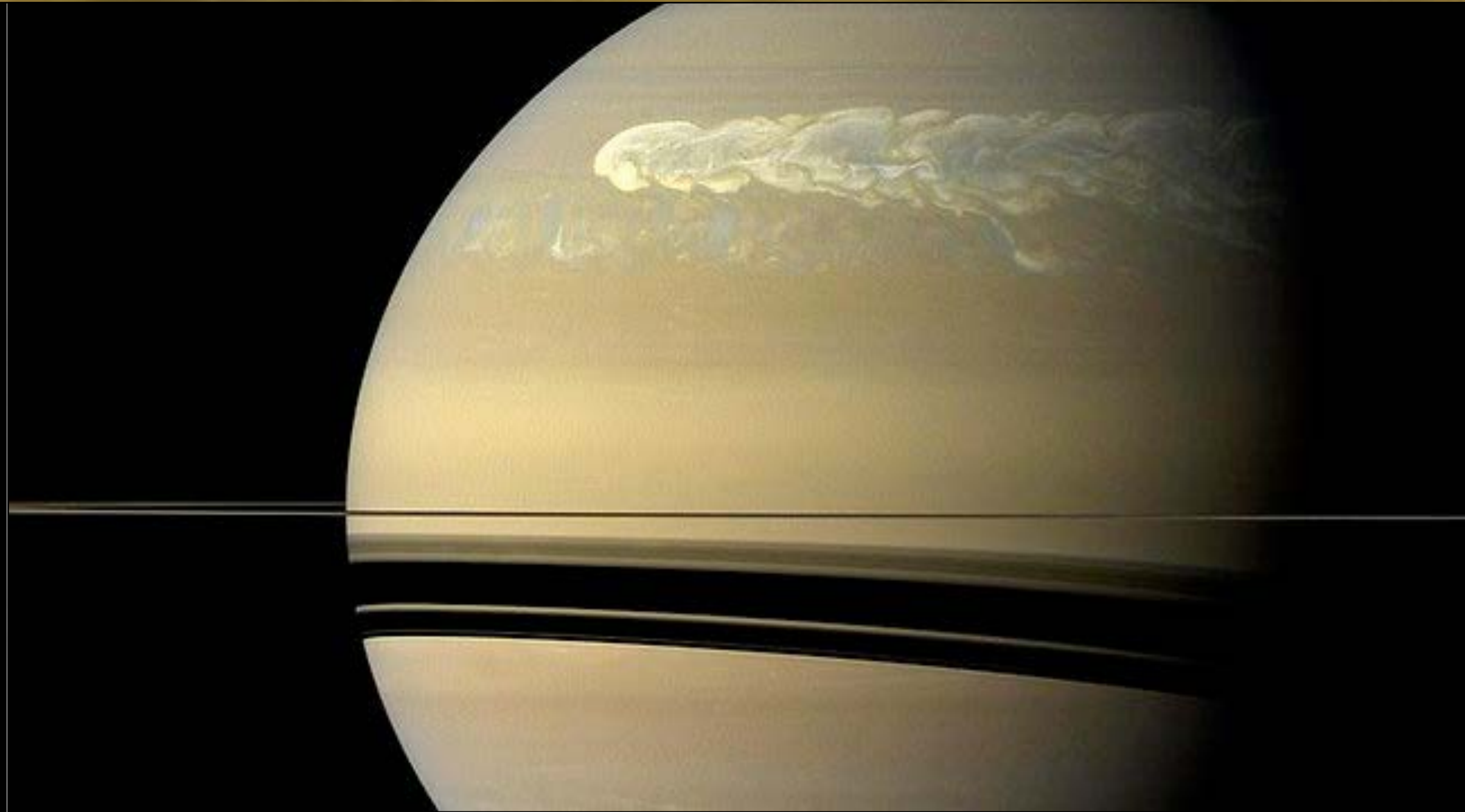
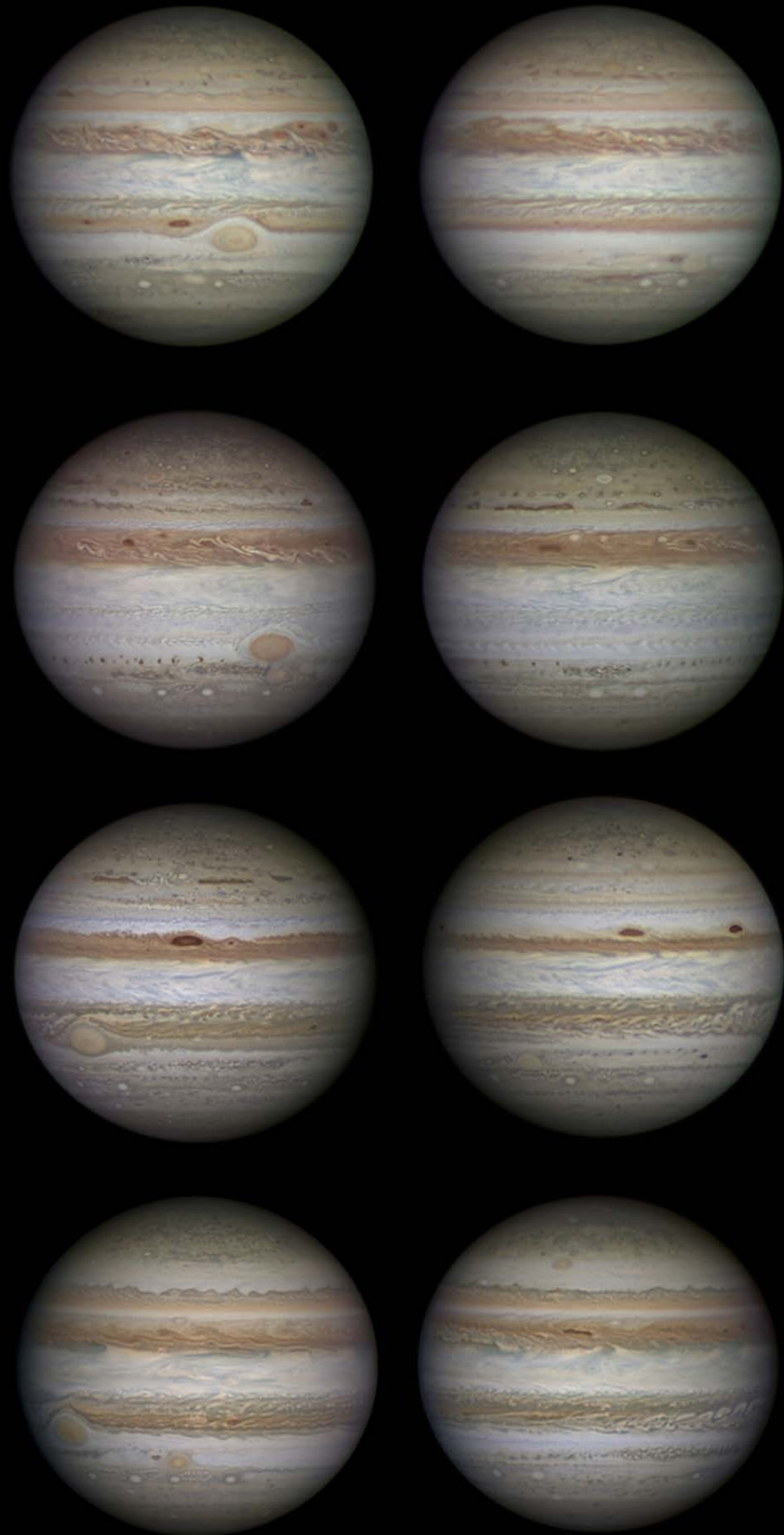
Metchev et al. 2013; data from Artigau

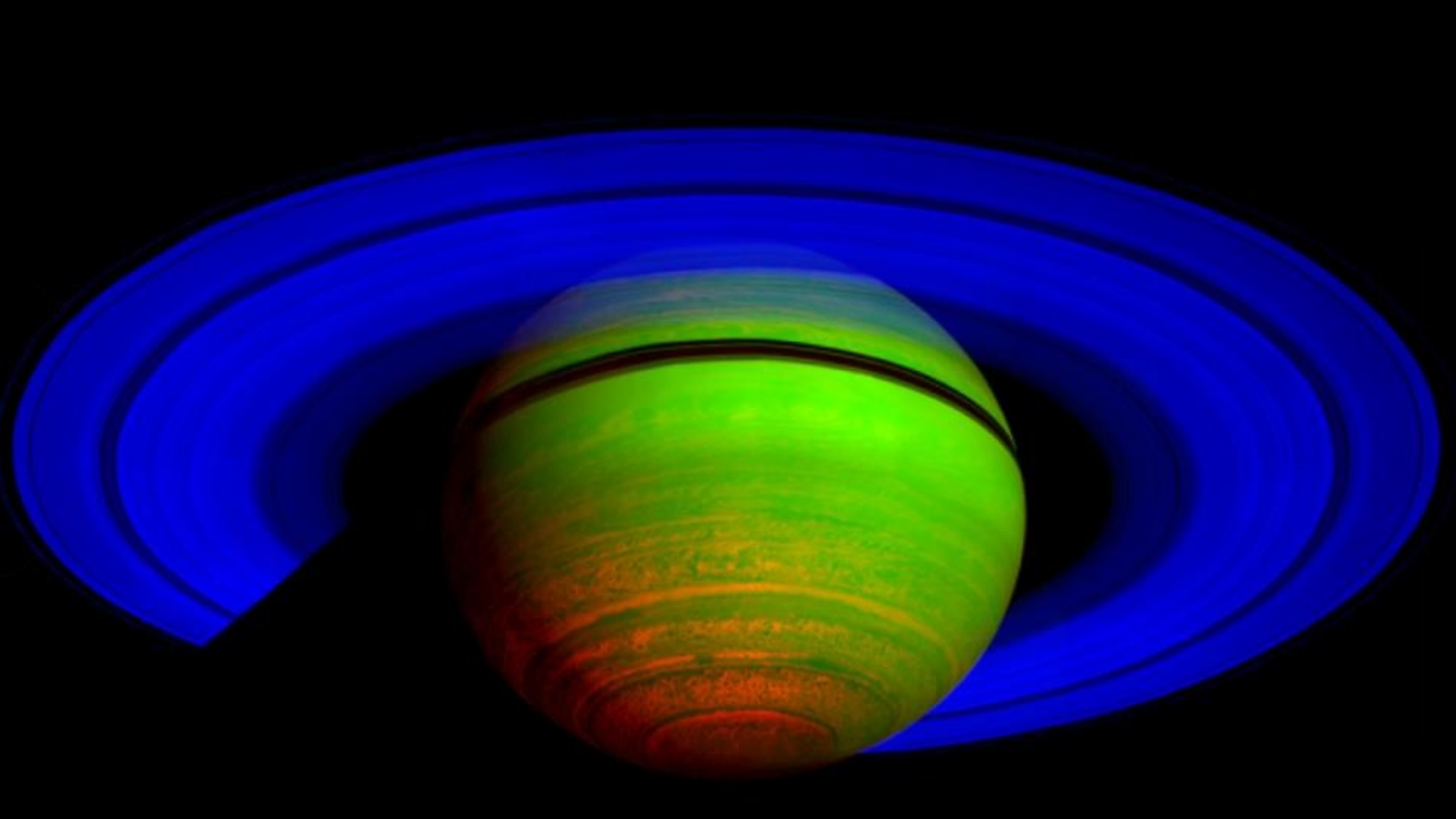


Apai et al. 2013 ApJ



Gillon et al. 2013





What Physical/Chemical Processes Drive the Light Curve Evolution in Brown Dwarfs?

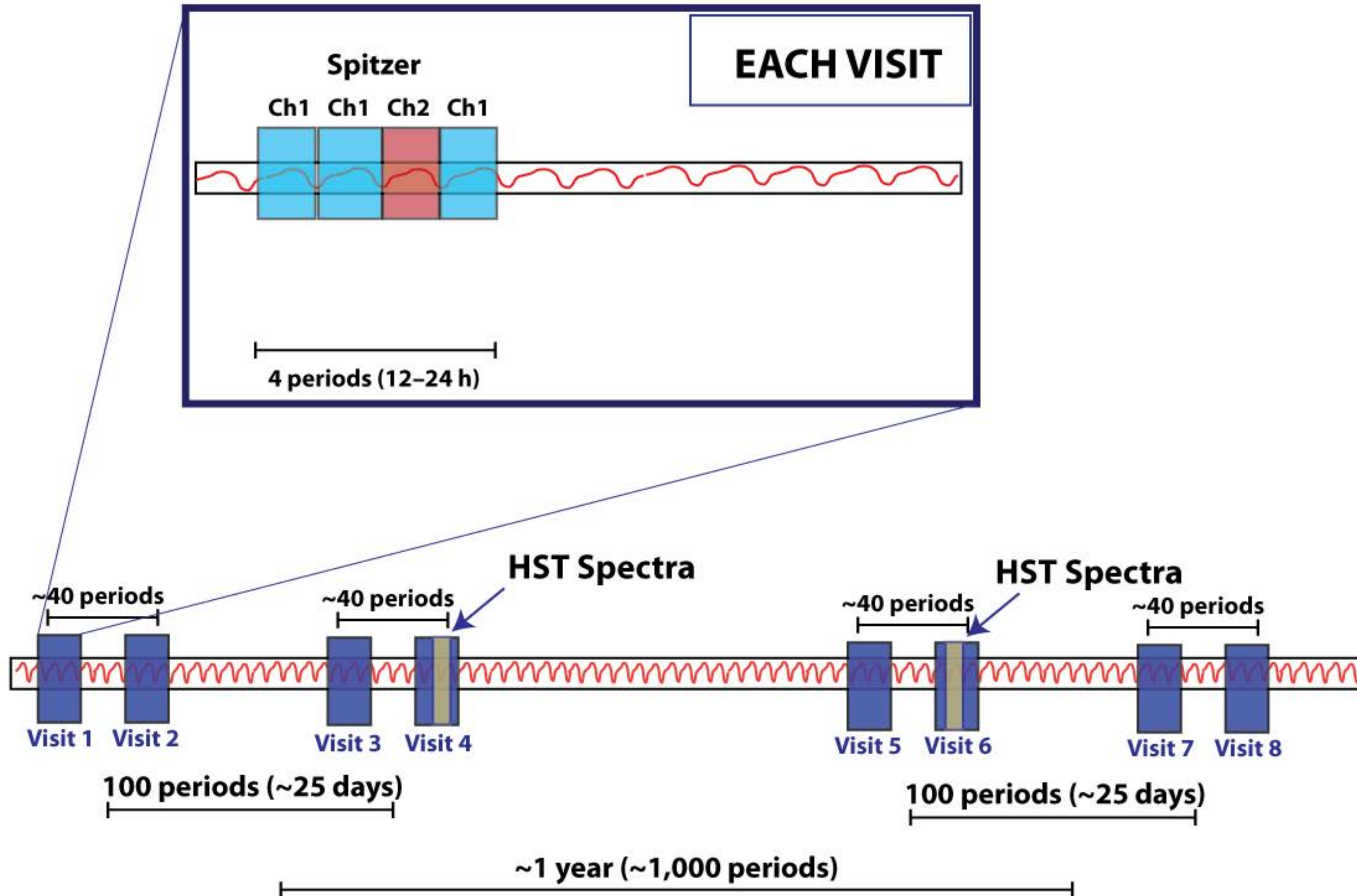
Extrasolar Storms

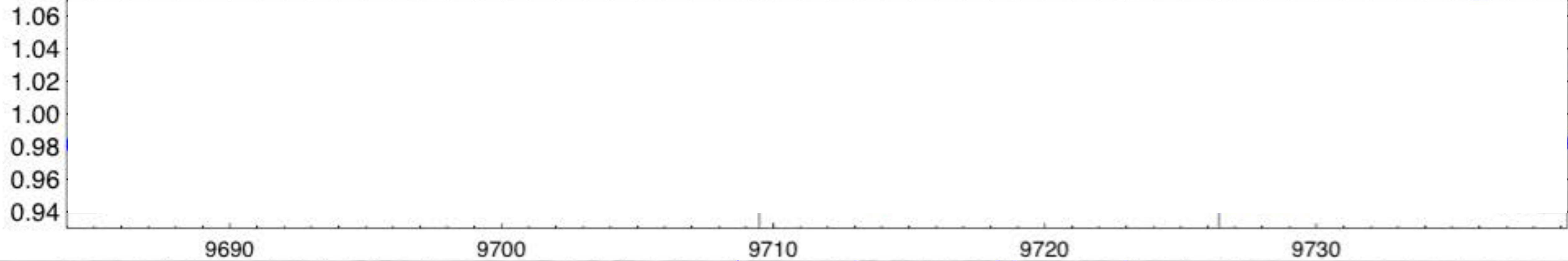
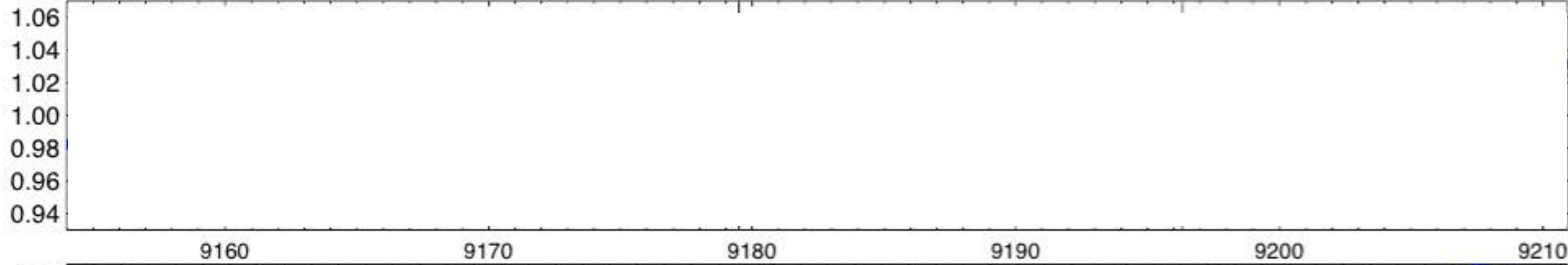
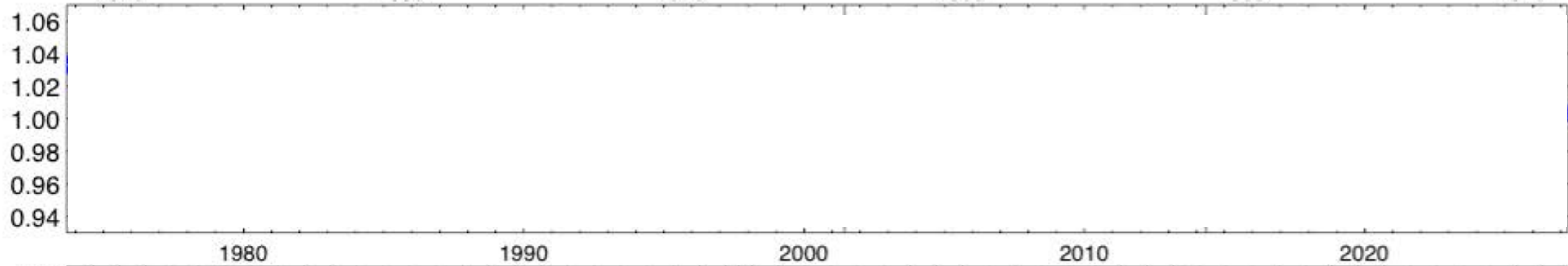
Exploration of Atmospheric Dynamics in Brown Dwarfs

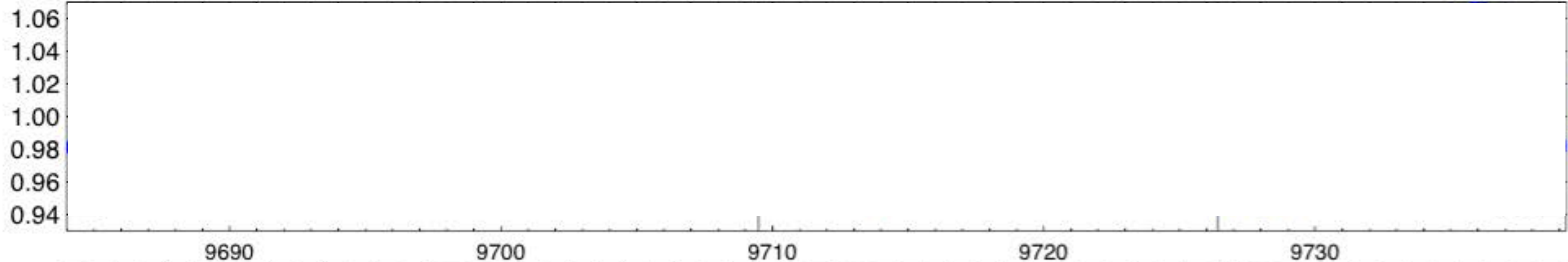
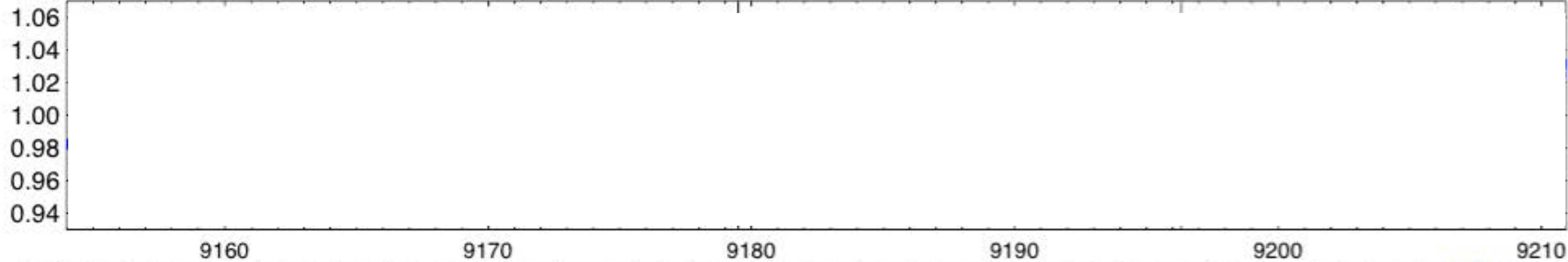
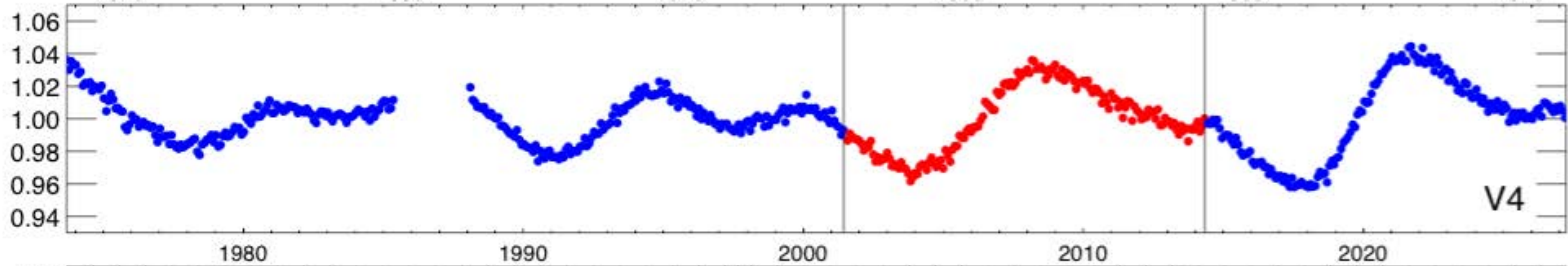
PI: Apai

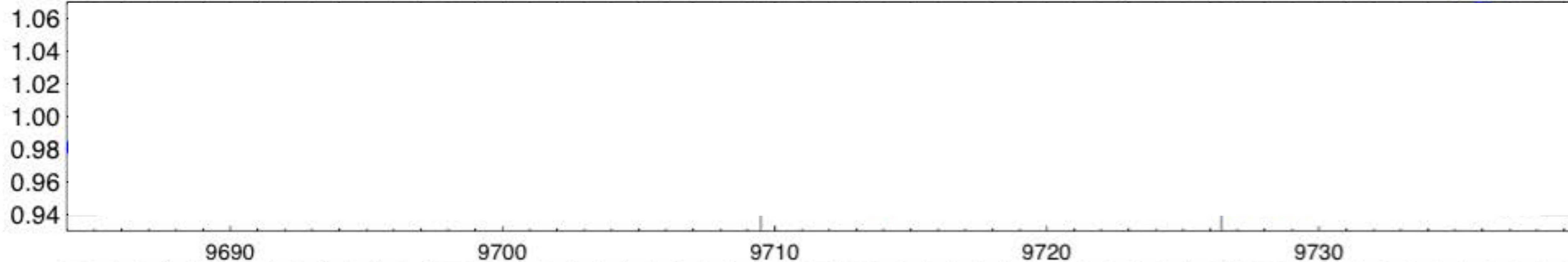
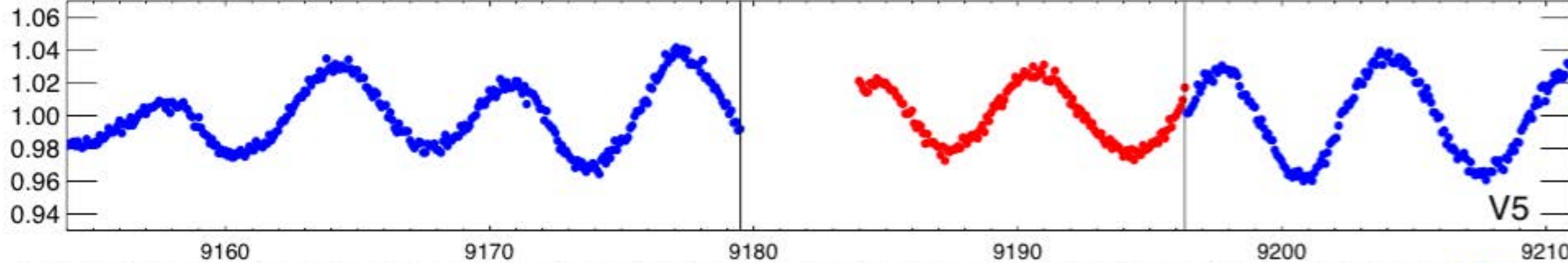
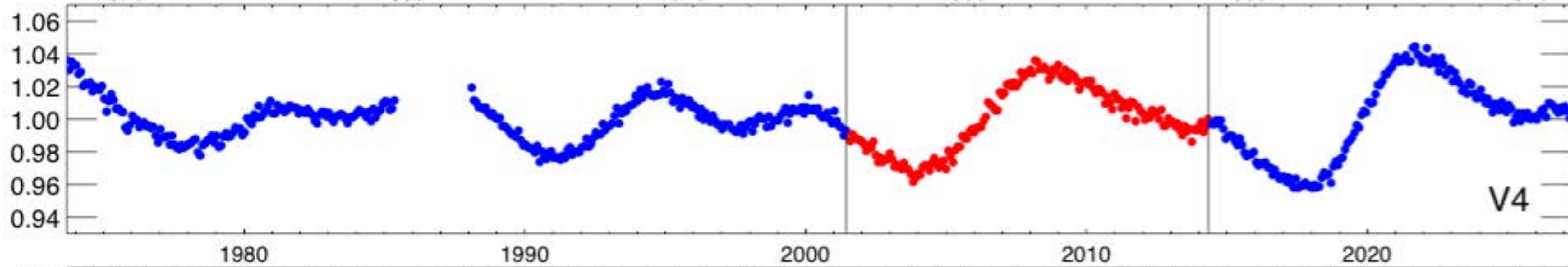
(1,144 hour Spitzer + 24 HST orbits)

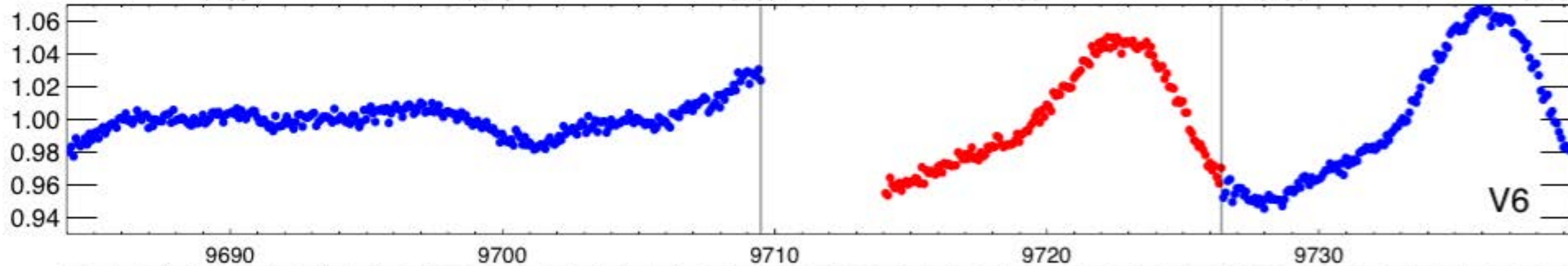
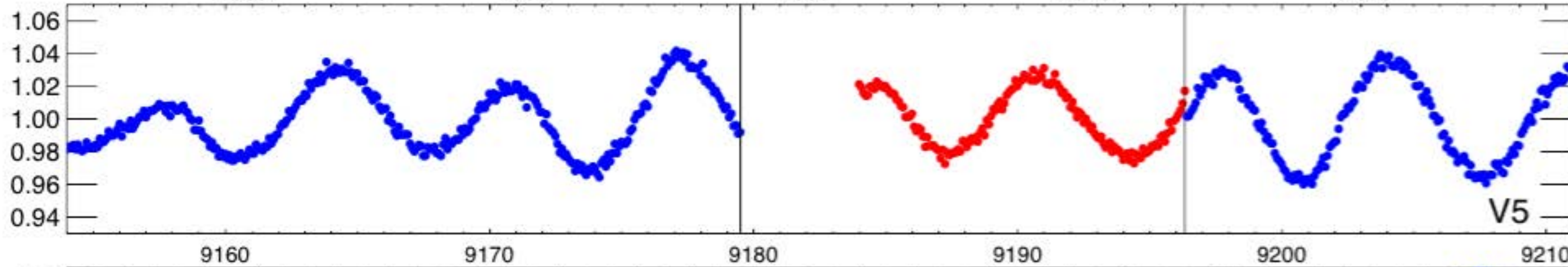
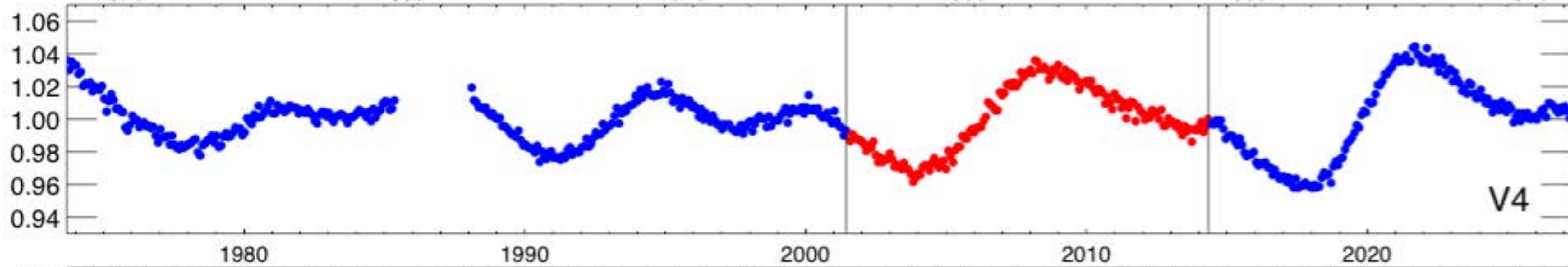
Lightcurves Sampling Multiple Timescales











How Accurately Can We Map Clouds From Lightcurves?



AEOLUS



MCMC MAPPING CODE

ASSUME HETEROGENEITIES ARE ELLIPTICAL SPOTS (E.G. GREAT RED SPOT)

NUMBER OF SPOTS

LOCATION ON DISK

SIZE OF SPOT

CONTRAST RATIO TO BACKGROUND TOA

INCLINATION OF BROWN DWARF/ (EXO)PLANET

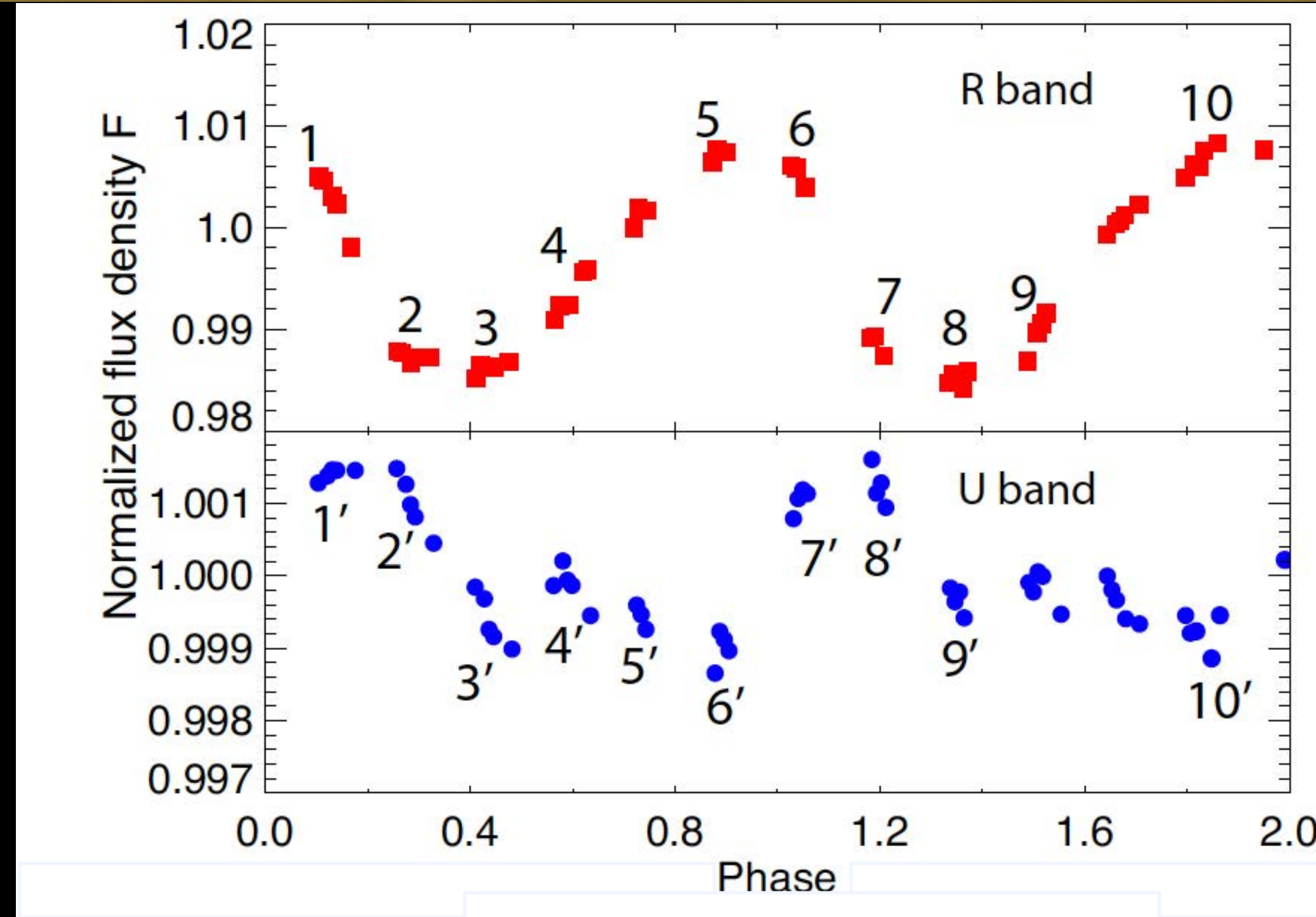
LIMB DARKENING

ABILITY TO MODEL MULTIPLE LAYERS SIMULTANEOUSLY

CAN BE COUPLED TO OUR PIXELIZED RADIATIVE TRANSFER MODEL

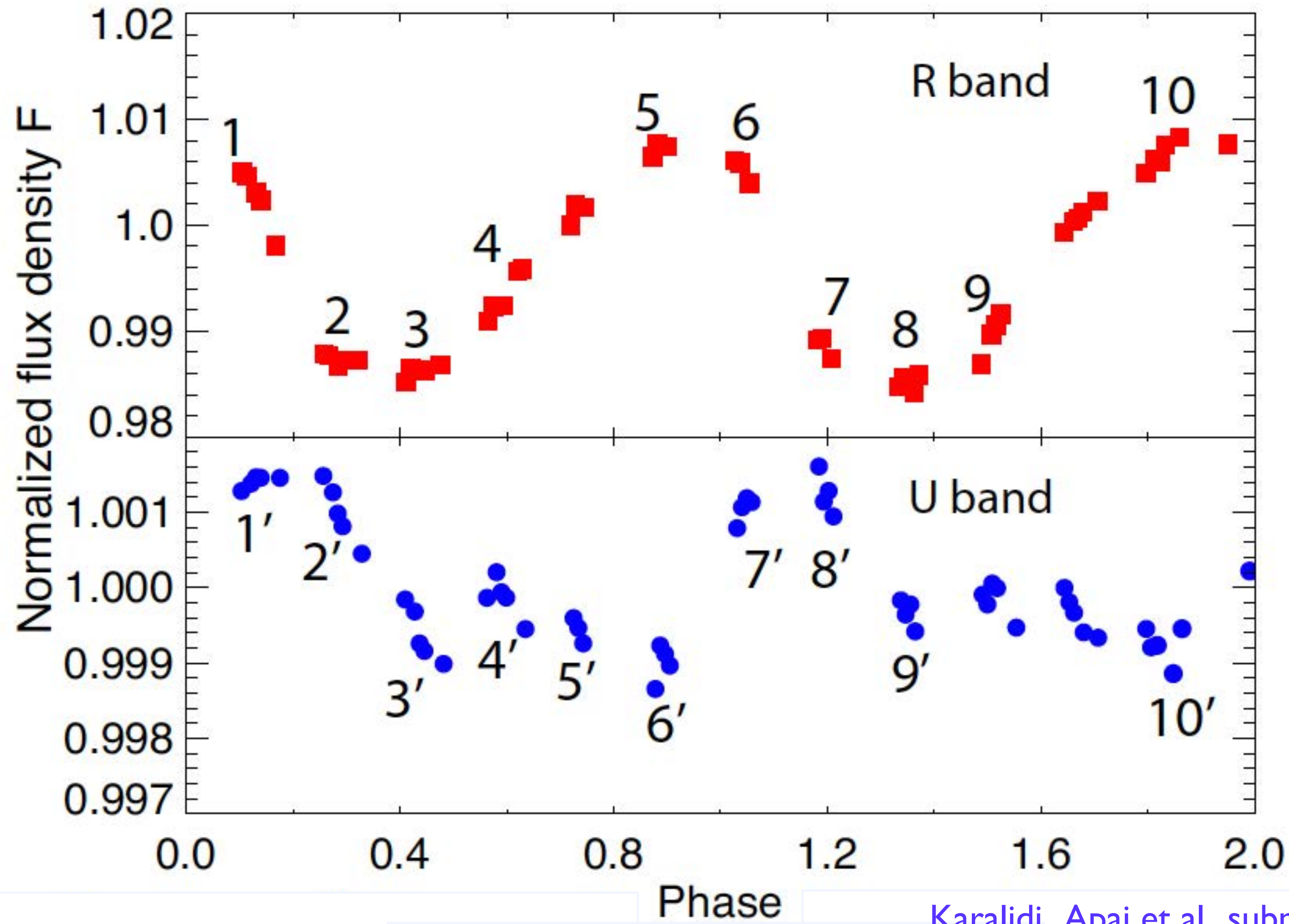
CAN MODEL TIME-EVOLVING FEATURES



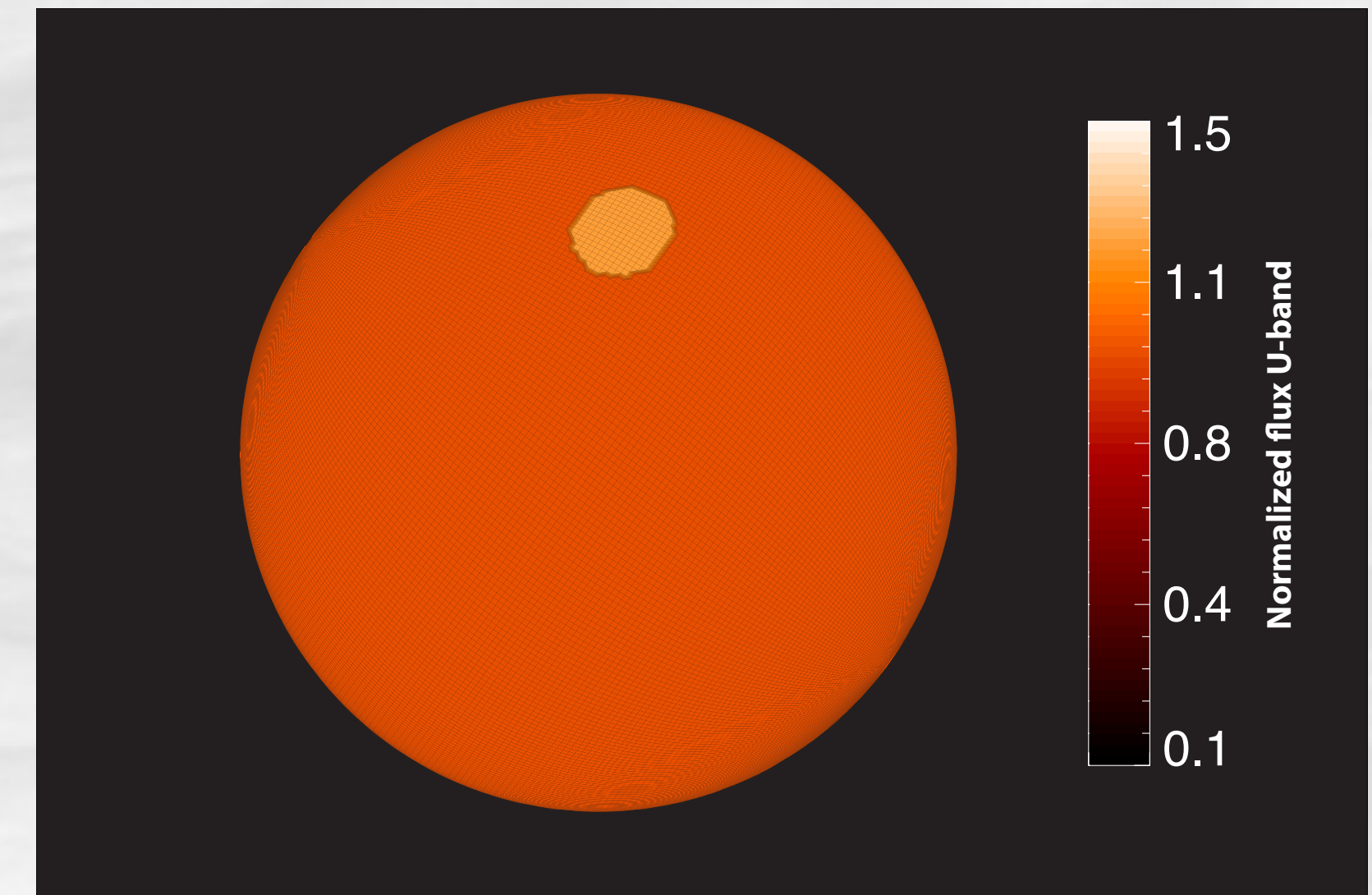


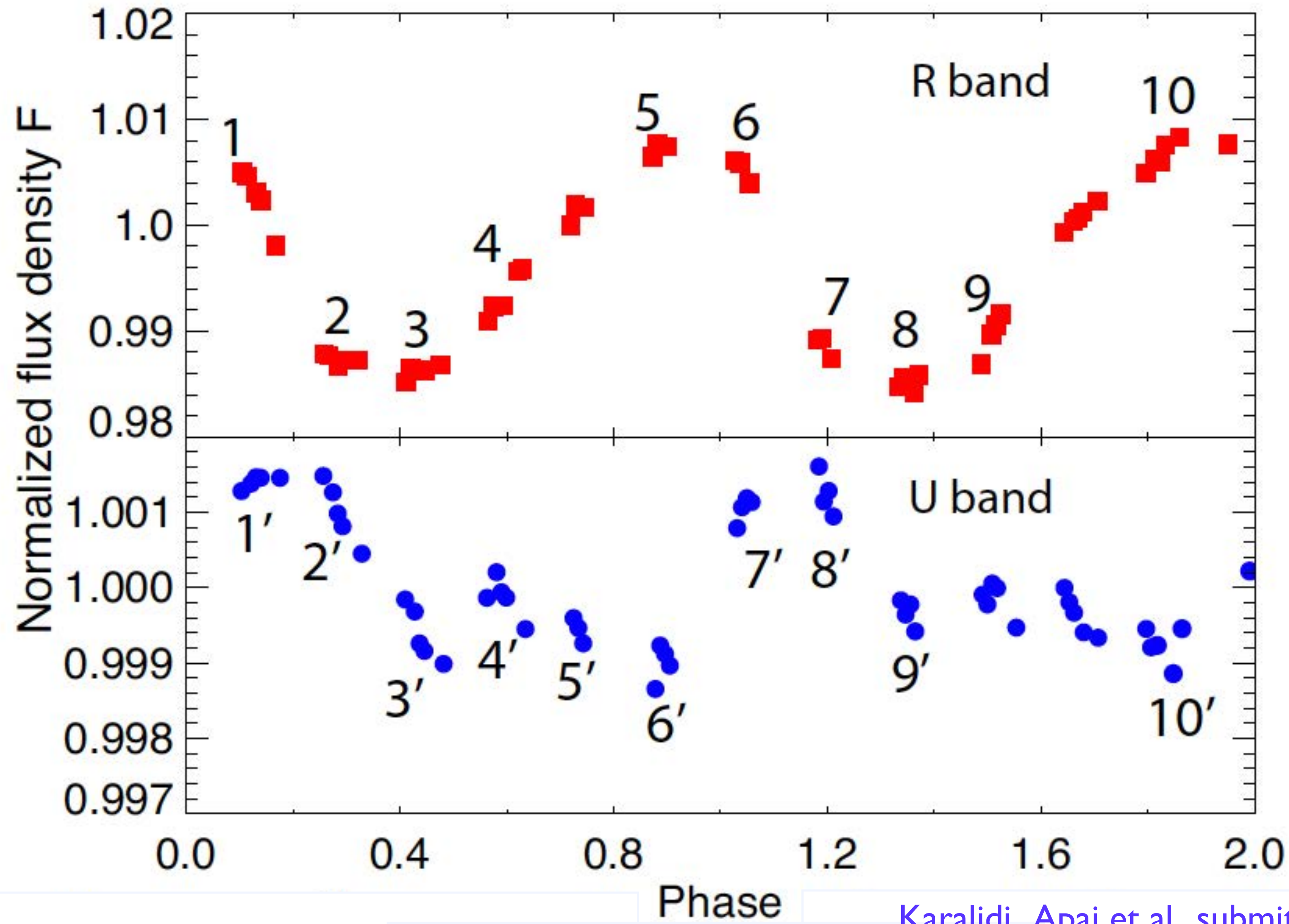
Photometry by Jake Hanson

Karalidi, Apai et al., submitted

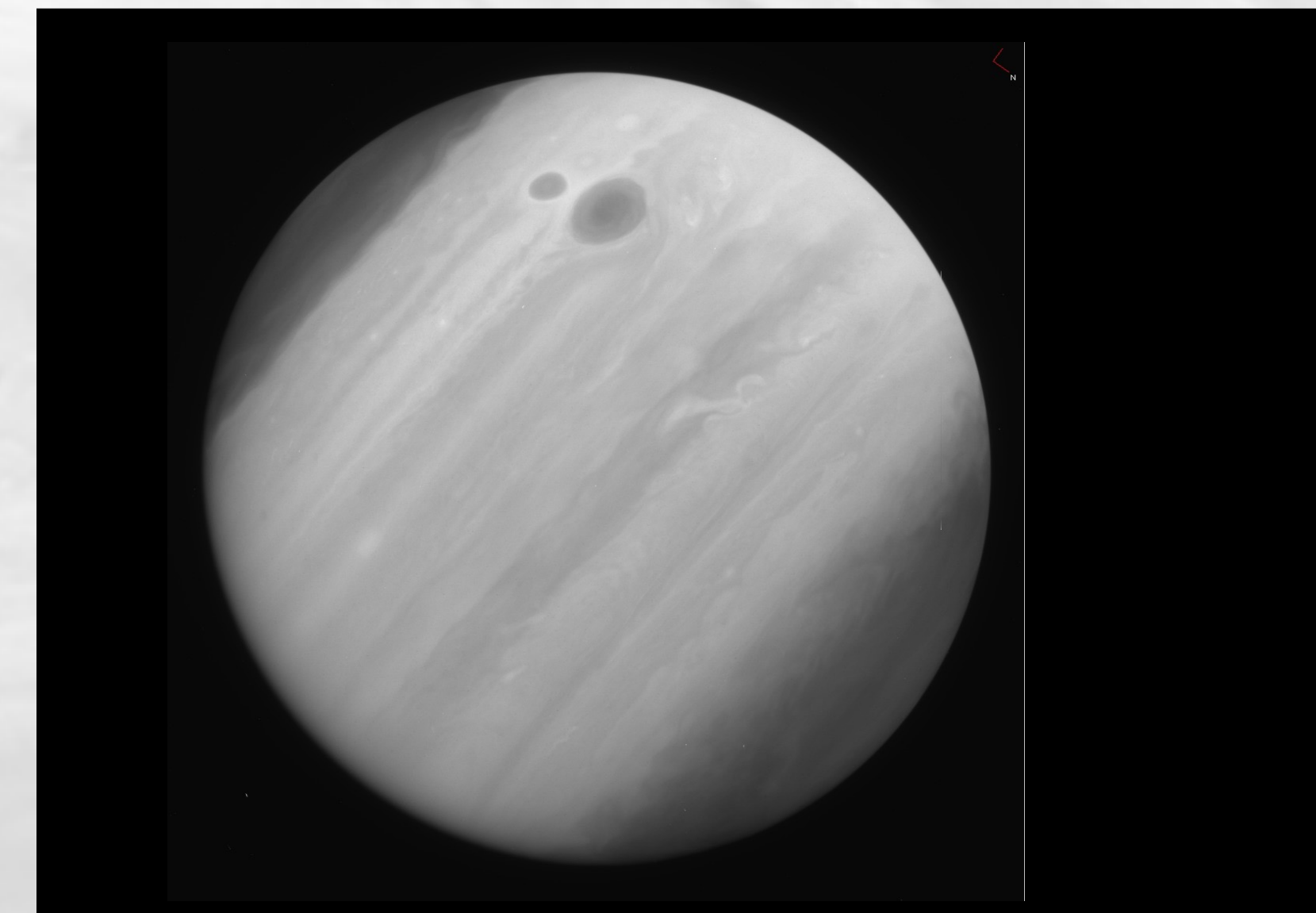
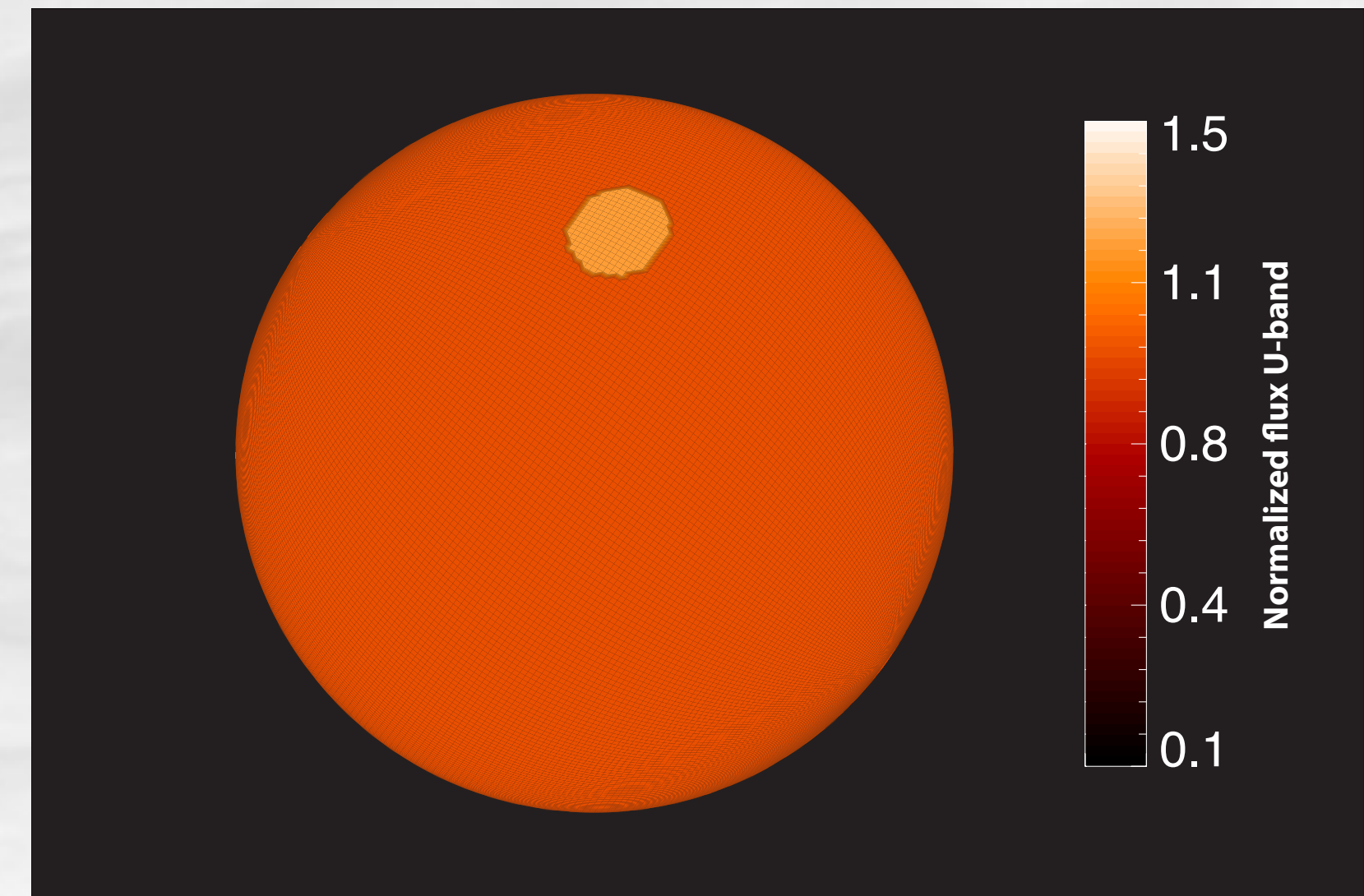


Karalidi, Apai et al., submitted





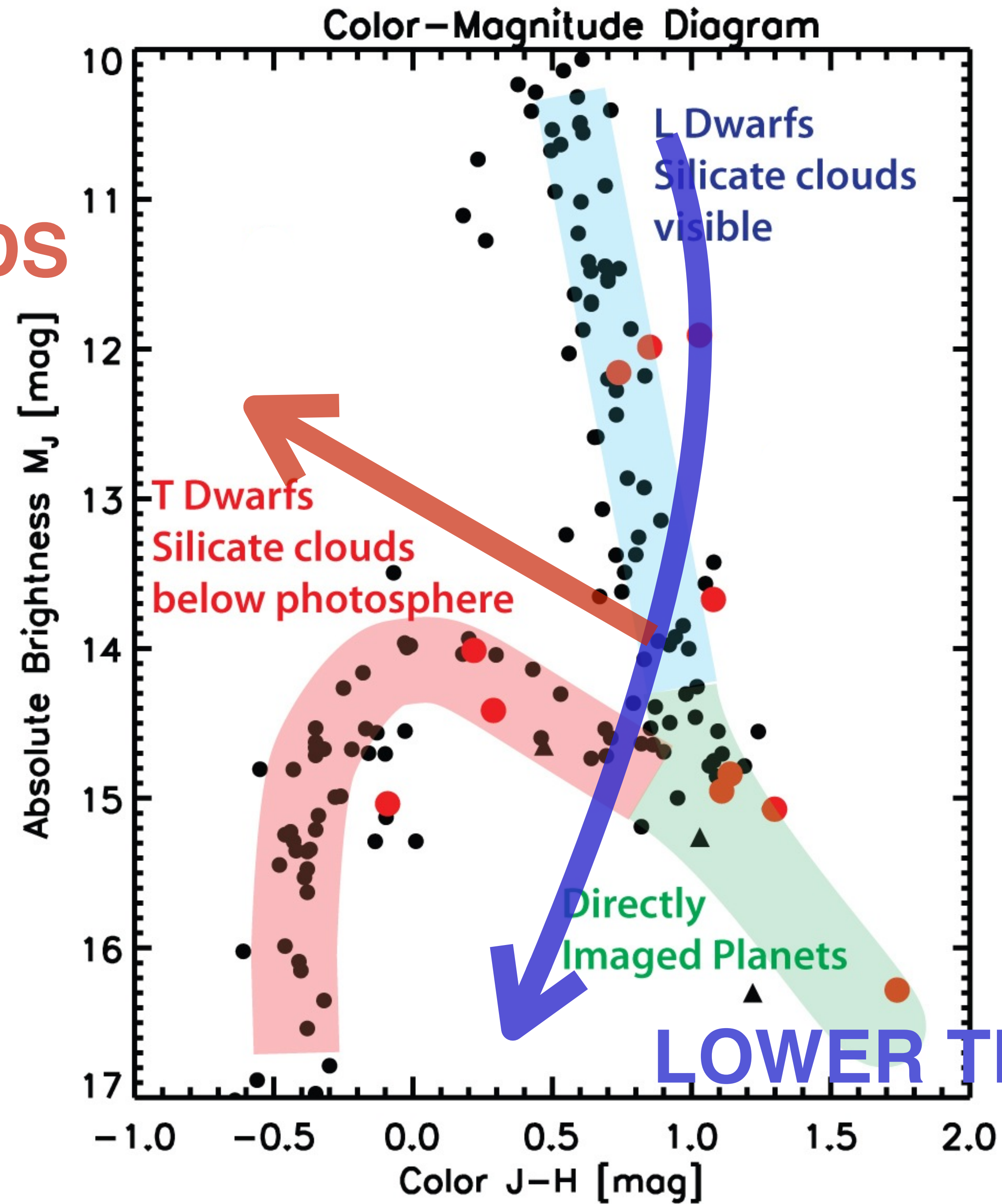
Karalidi, Apai et al., submitted



What Processes Set Cloud Thickness?

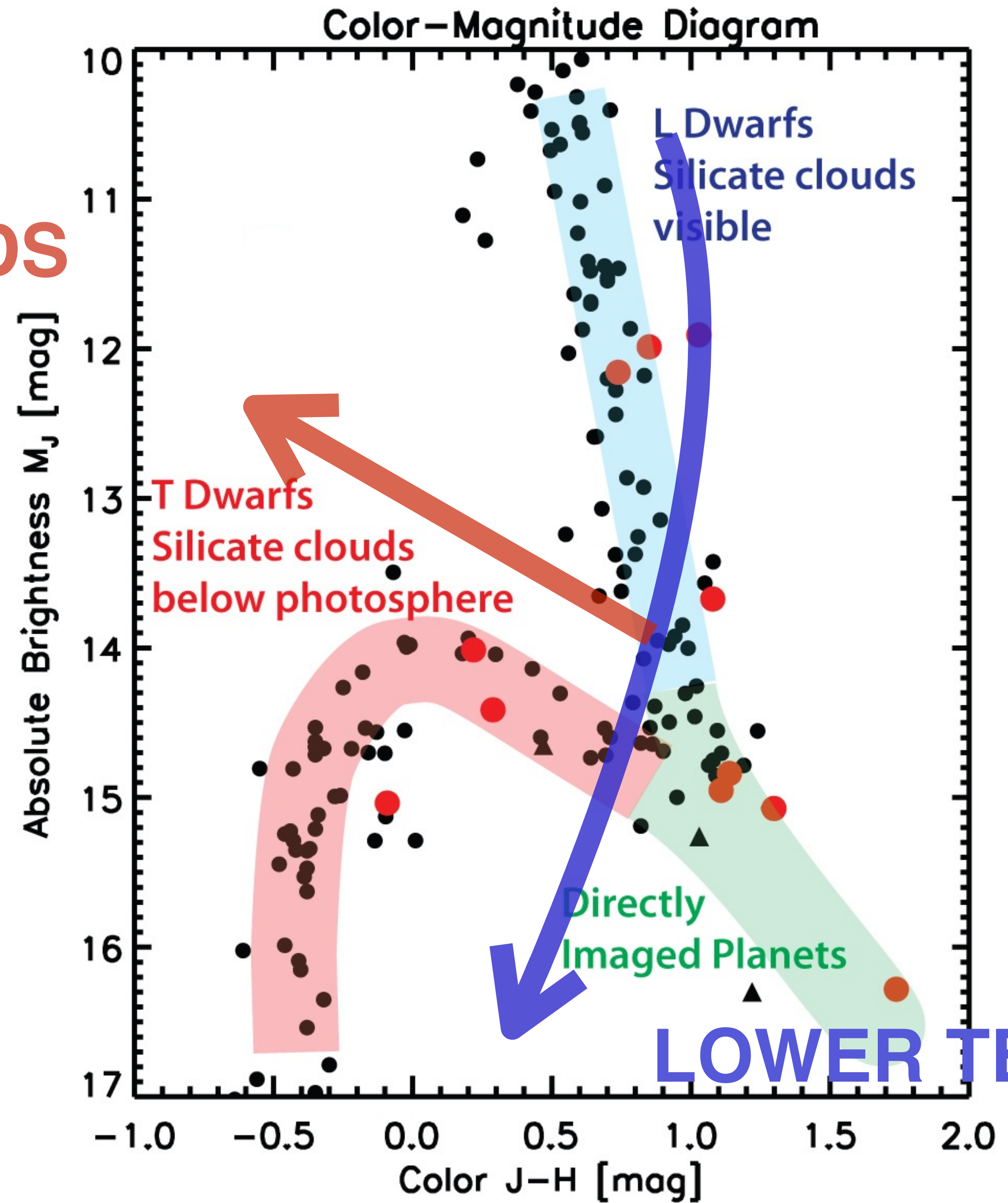


THINNER CLOUDS

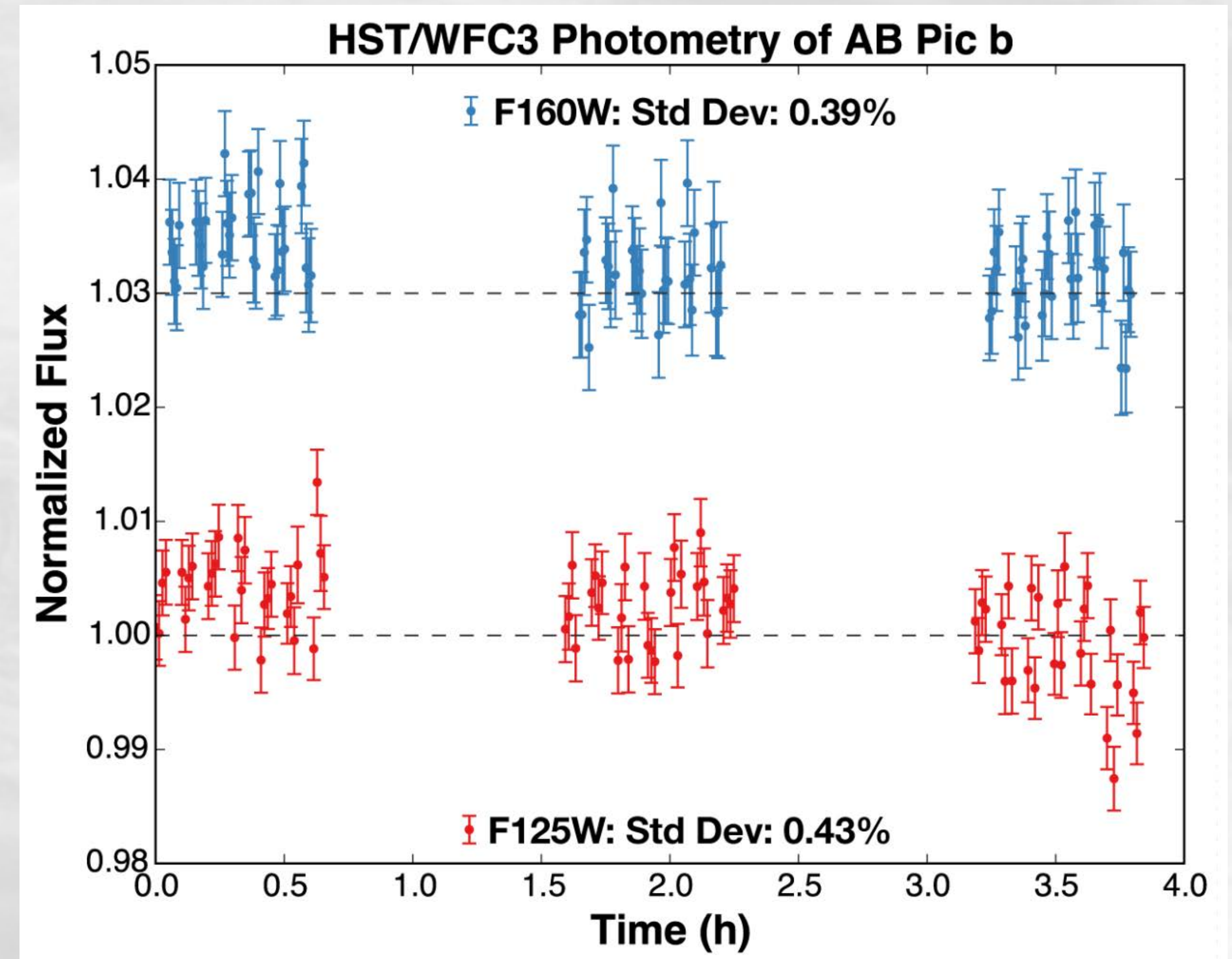
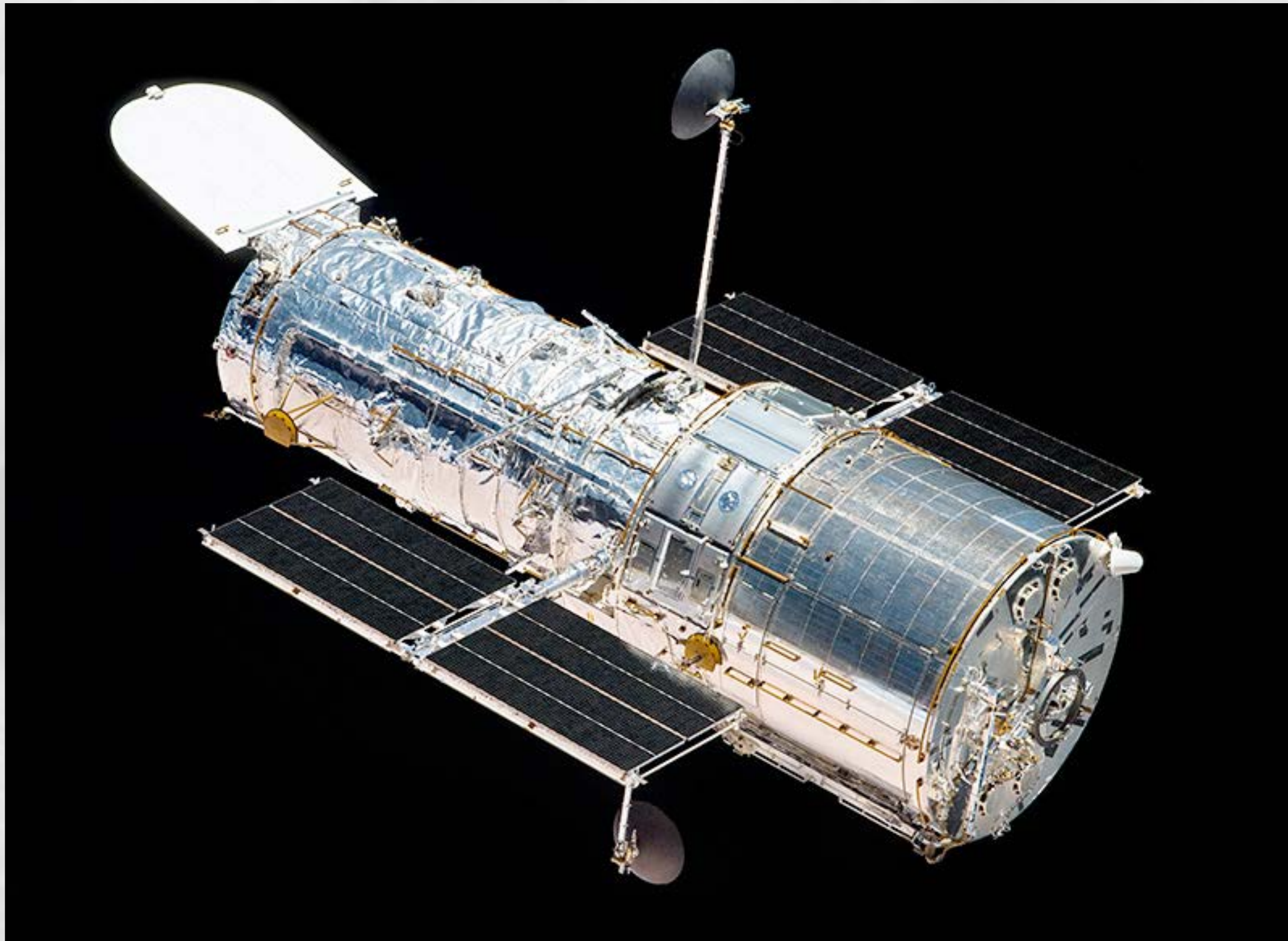


THINNER CLOUDS

**Low-Gravity=
Thick Clouds?**



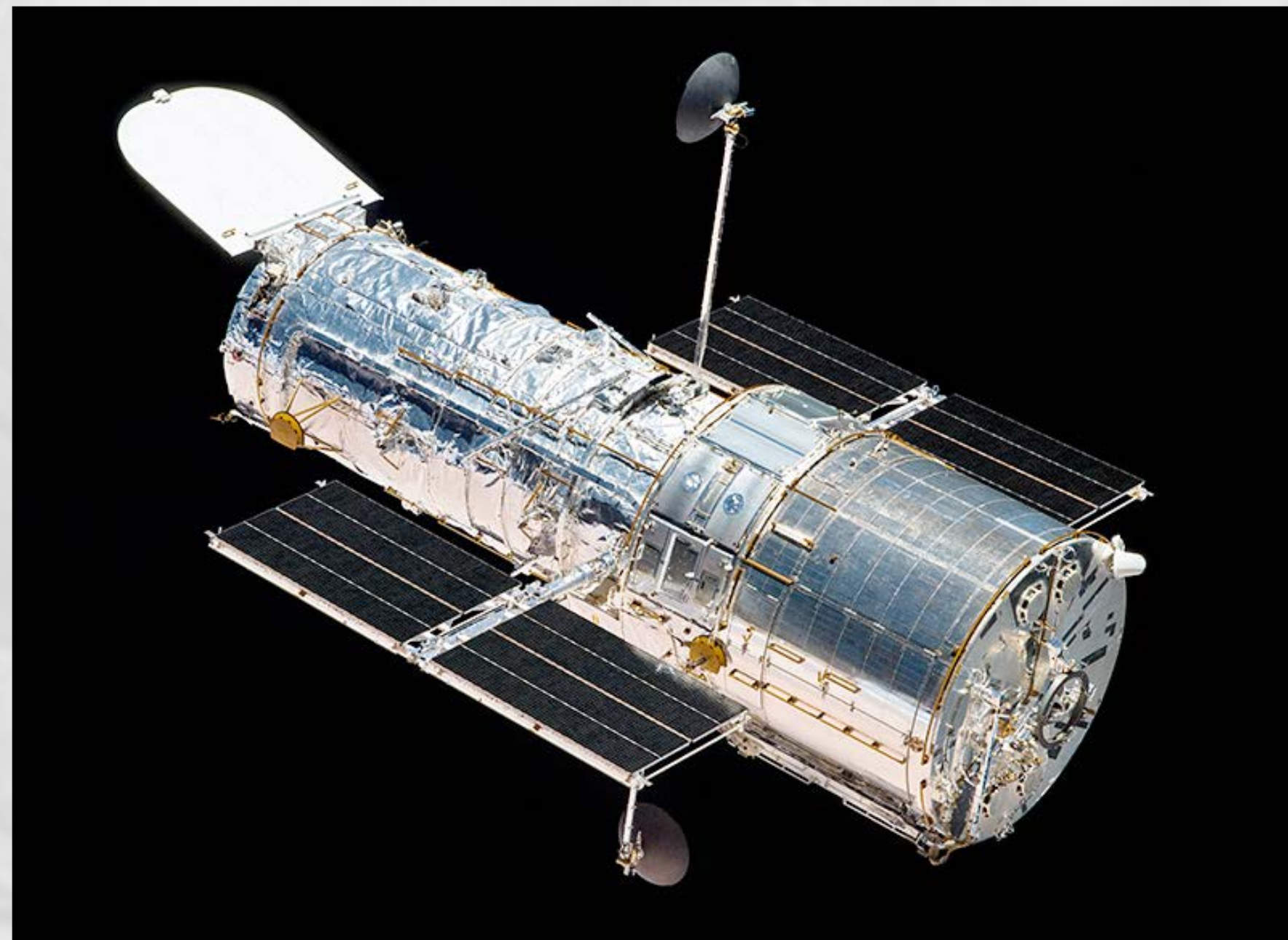
HST Time-resolved High-Contrast Imaging of Exoplanets and Planetary-mass Objects



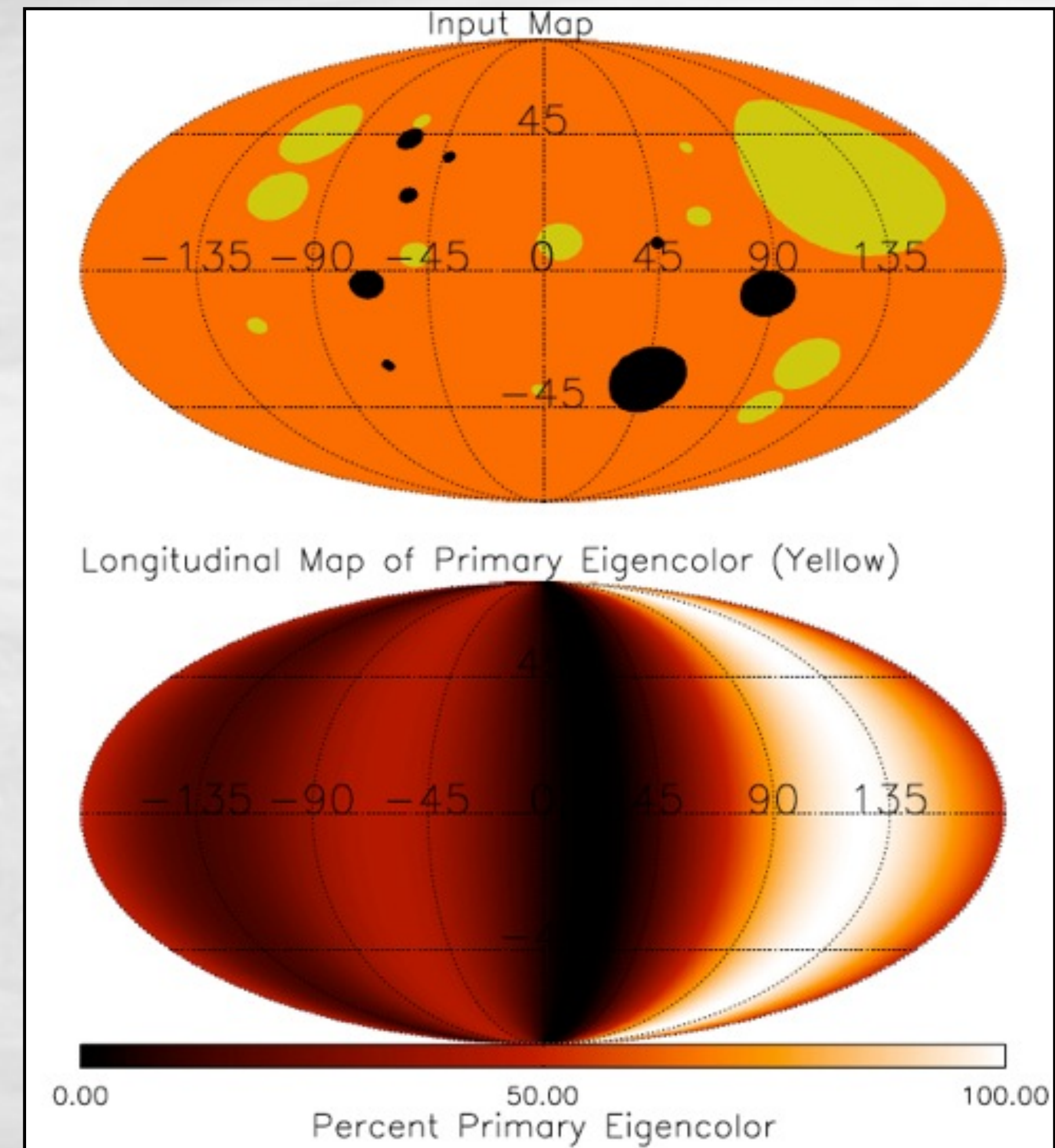
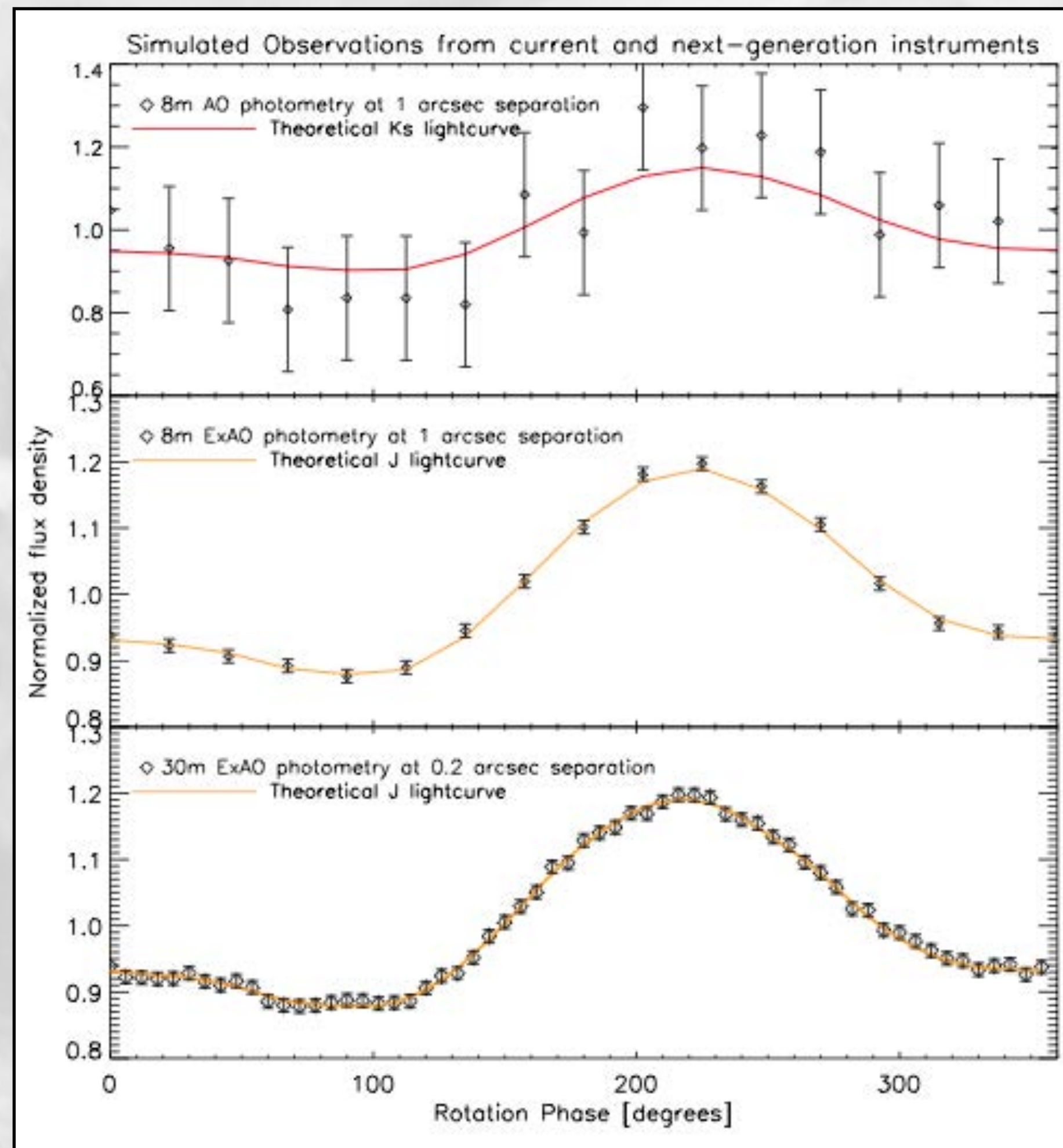
Zhou, Apai et al., in prep.

How Are Cloud Structure and Gravity Connected in Exoplanet and Brown Dwarf Atmospheres?

Cloud Atlas - An HST Large Treasury Program
(112 orbits, PI: Apai)

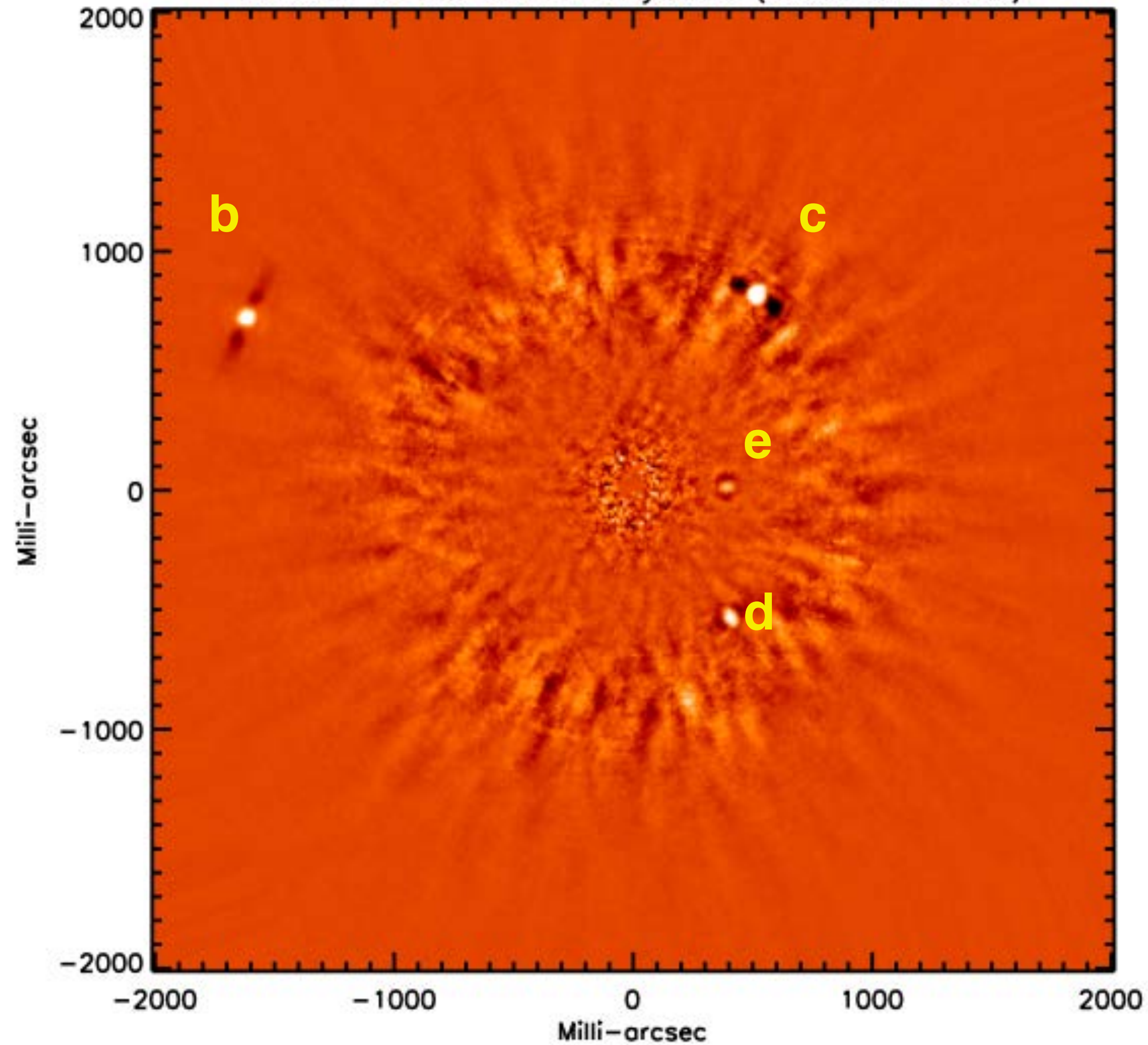


Giant Exoplanet Phase Mapping with XAO Systems

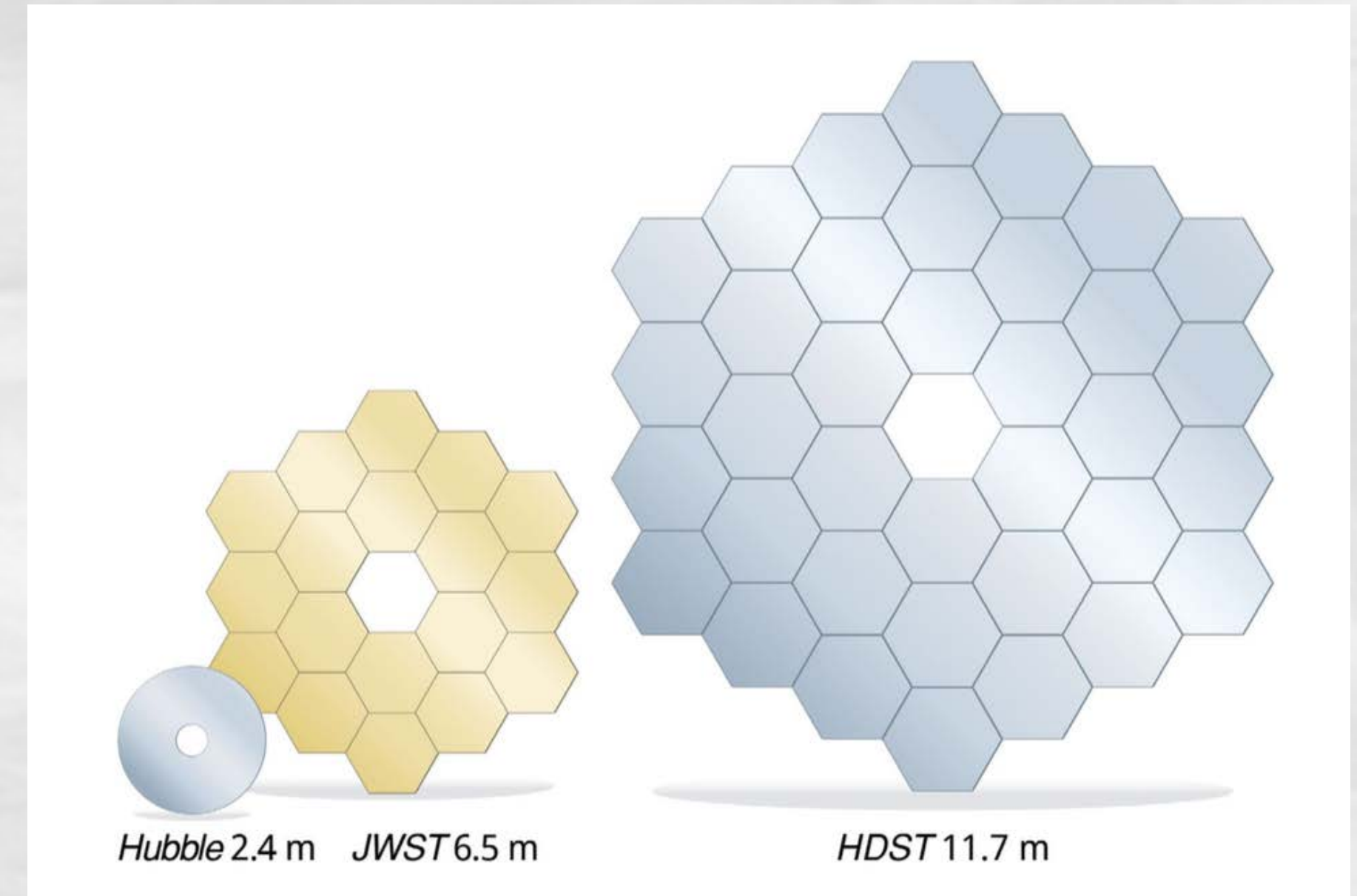
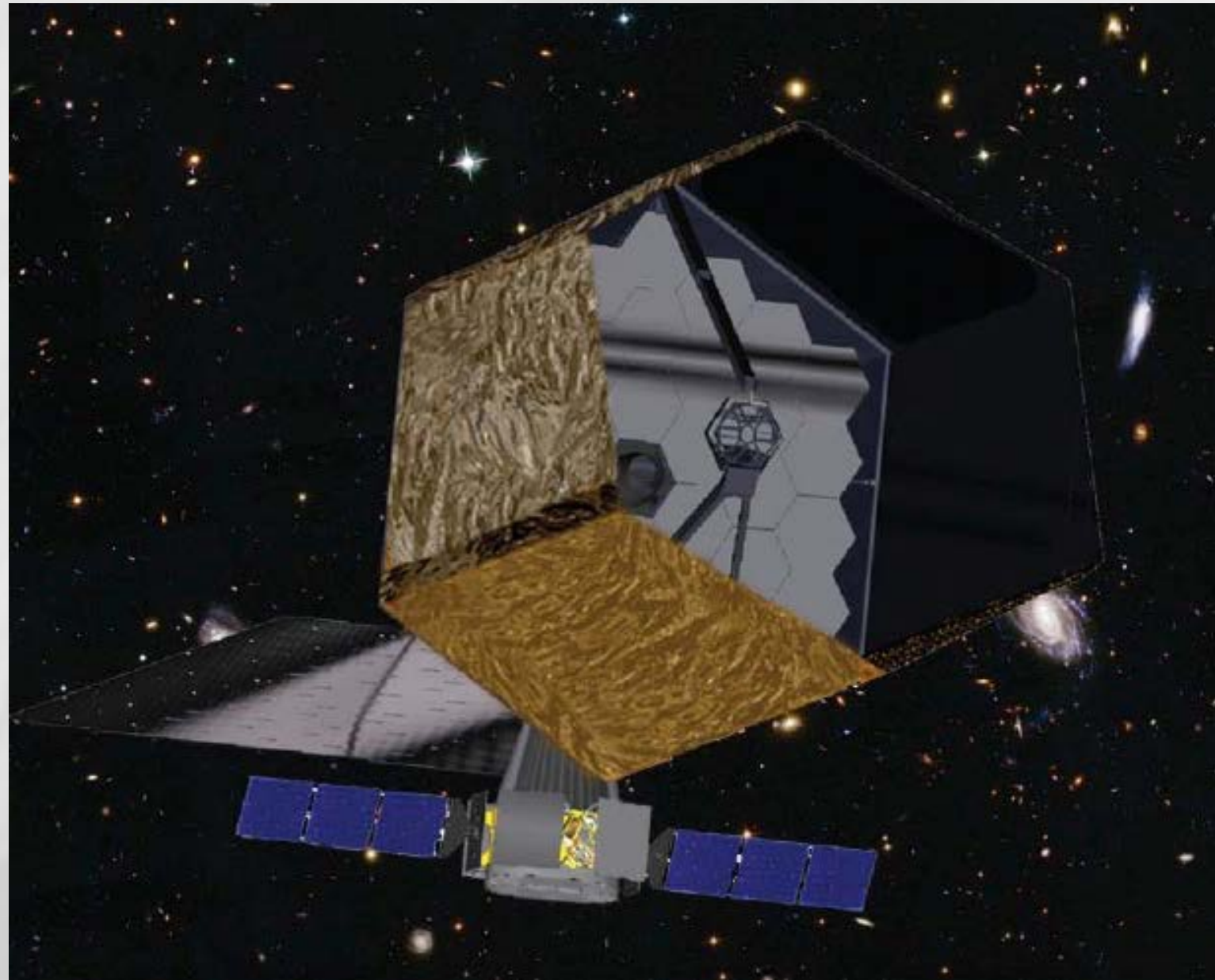


Discussion of the capabilities of future telescopes/instruments, ideal wavelengths/filters for observations, cadence, mapping techniques, limitations, etc.

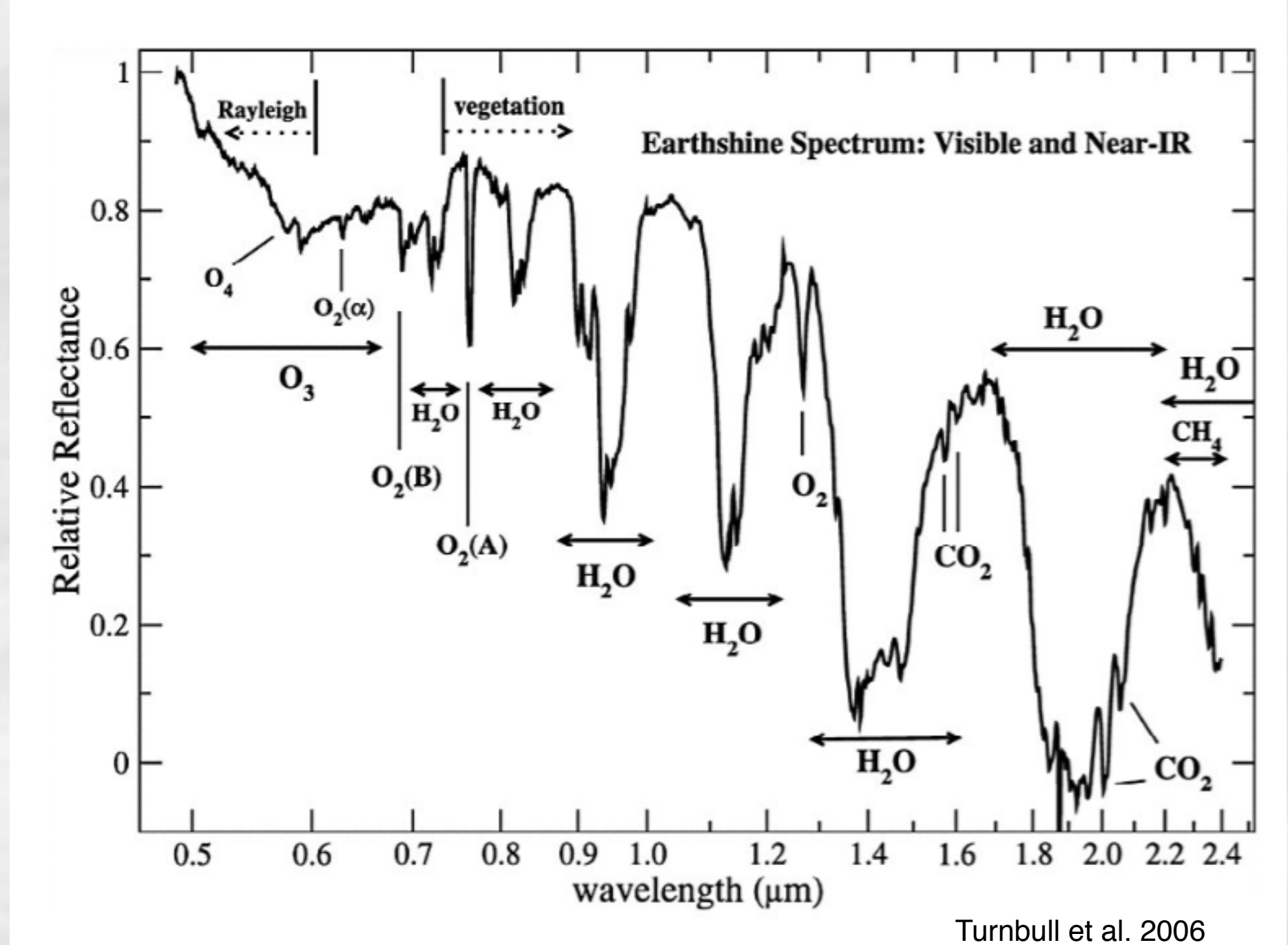
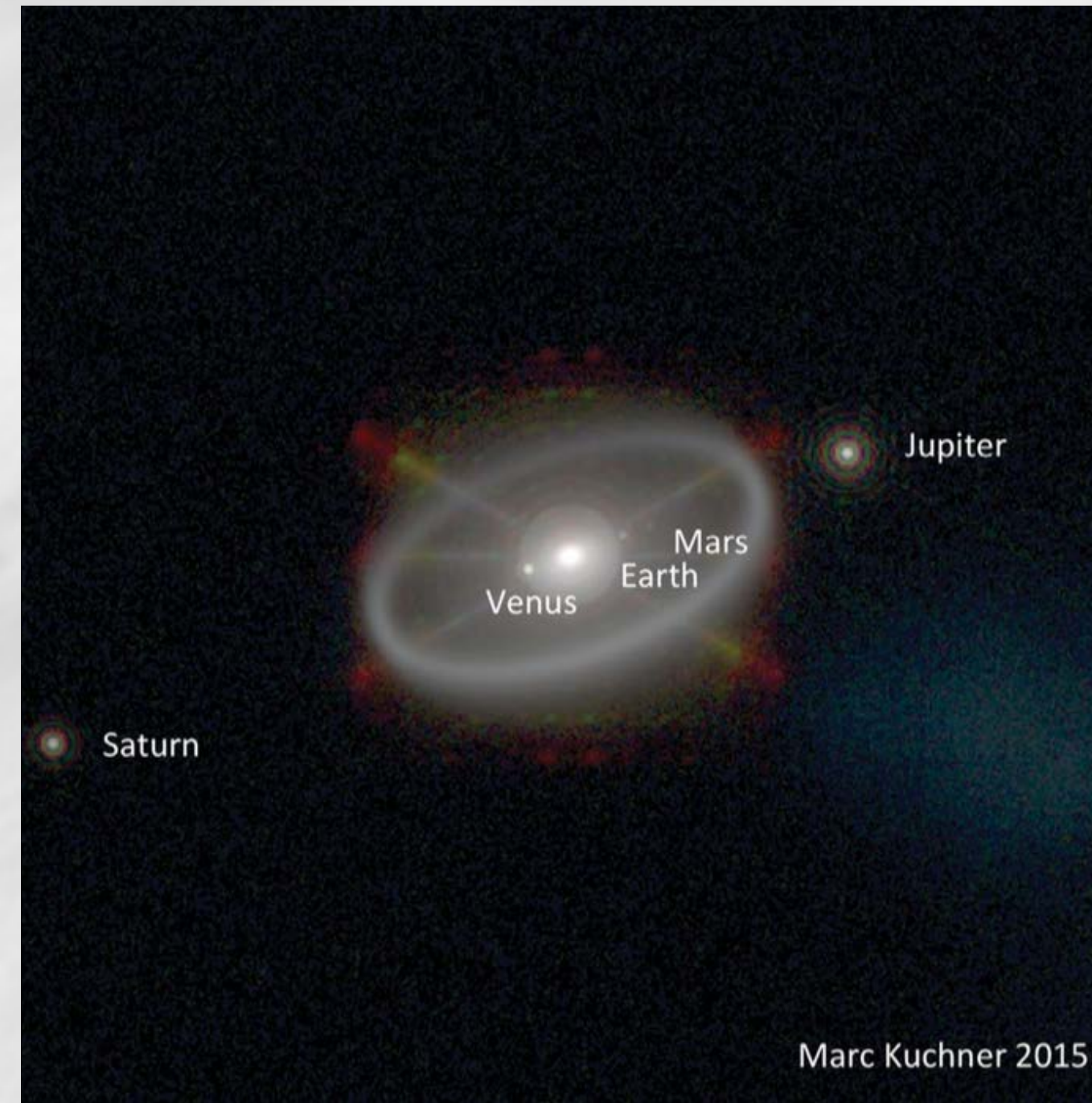
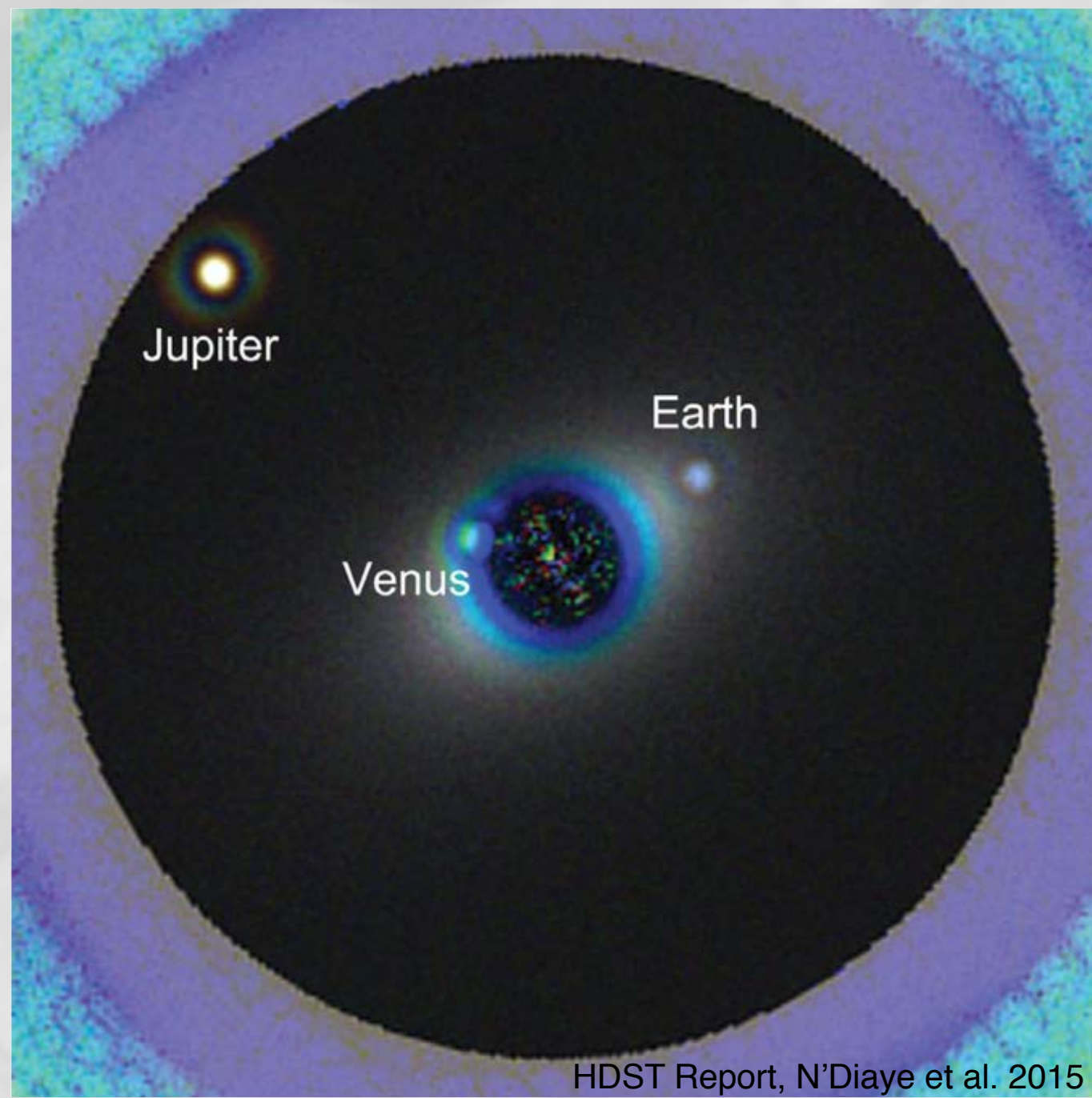
VLT SPHERE Time-Resolved Observations of HR 8799bcde Planets in the HR8799 System (Combined Data)



Clouds in High Definition



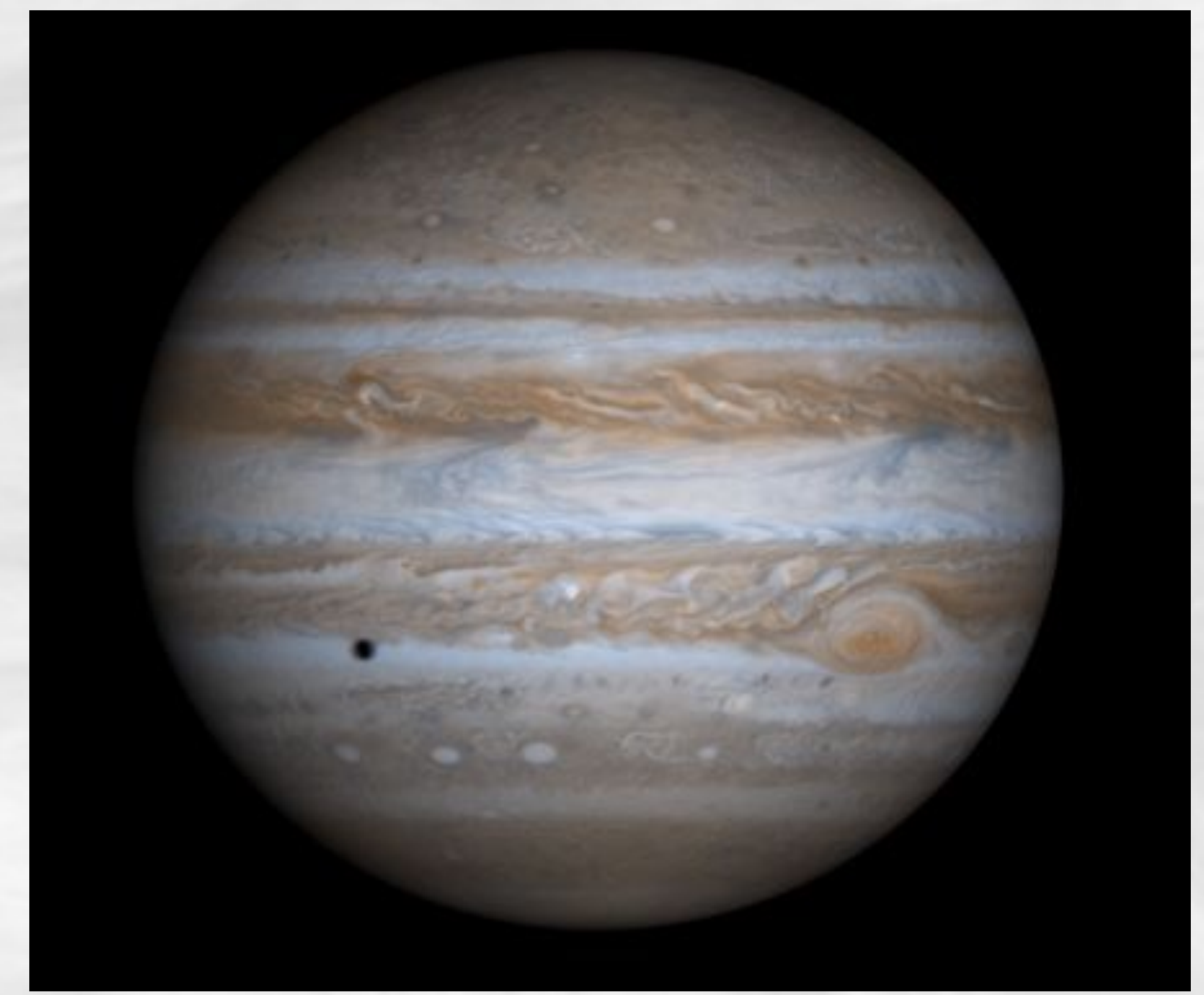
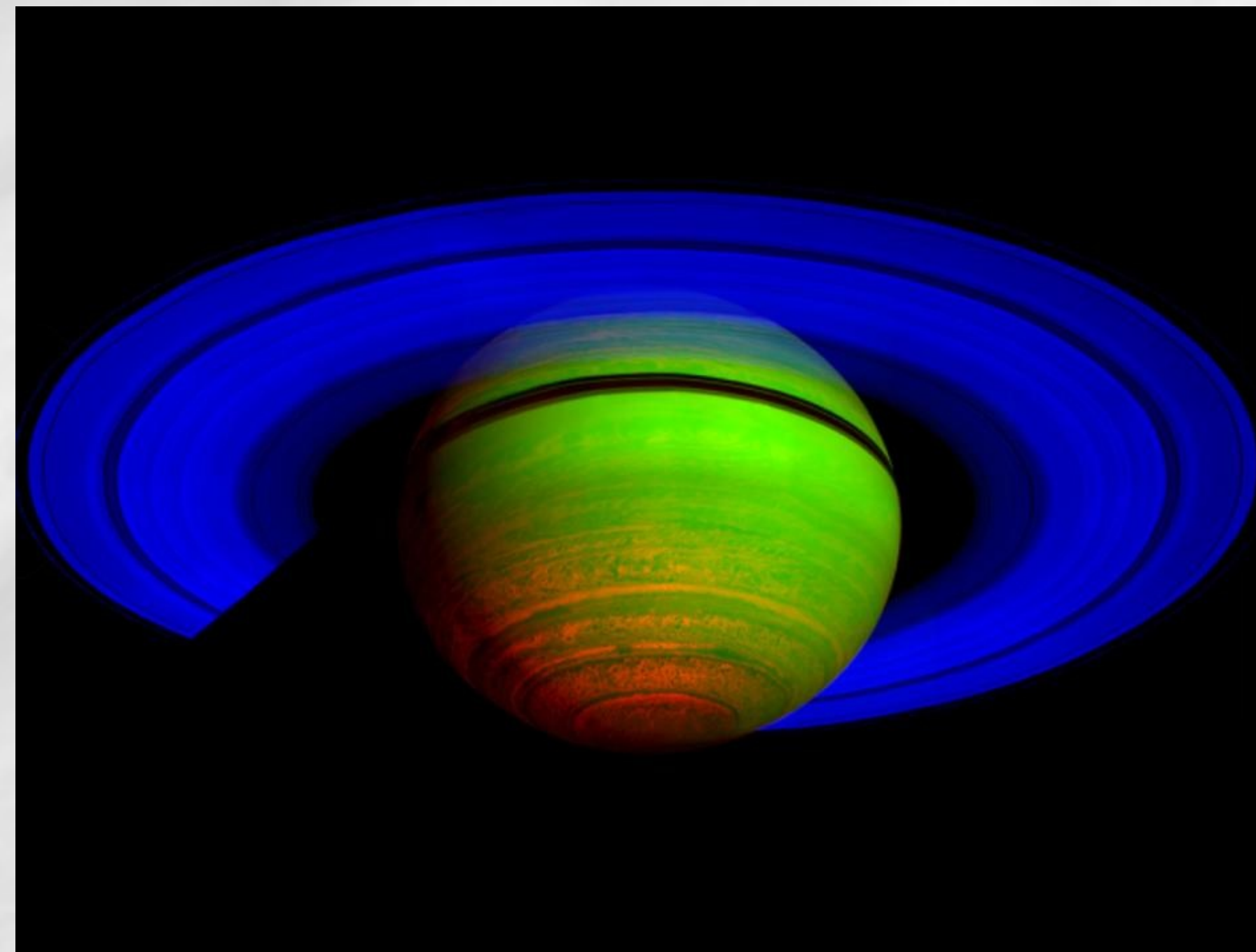
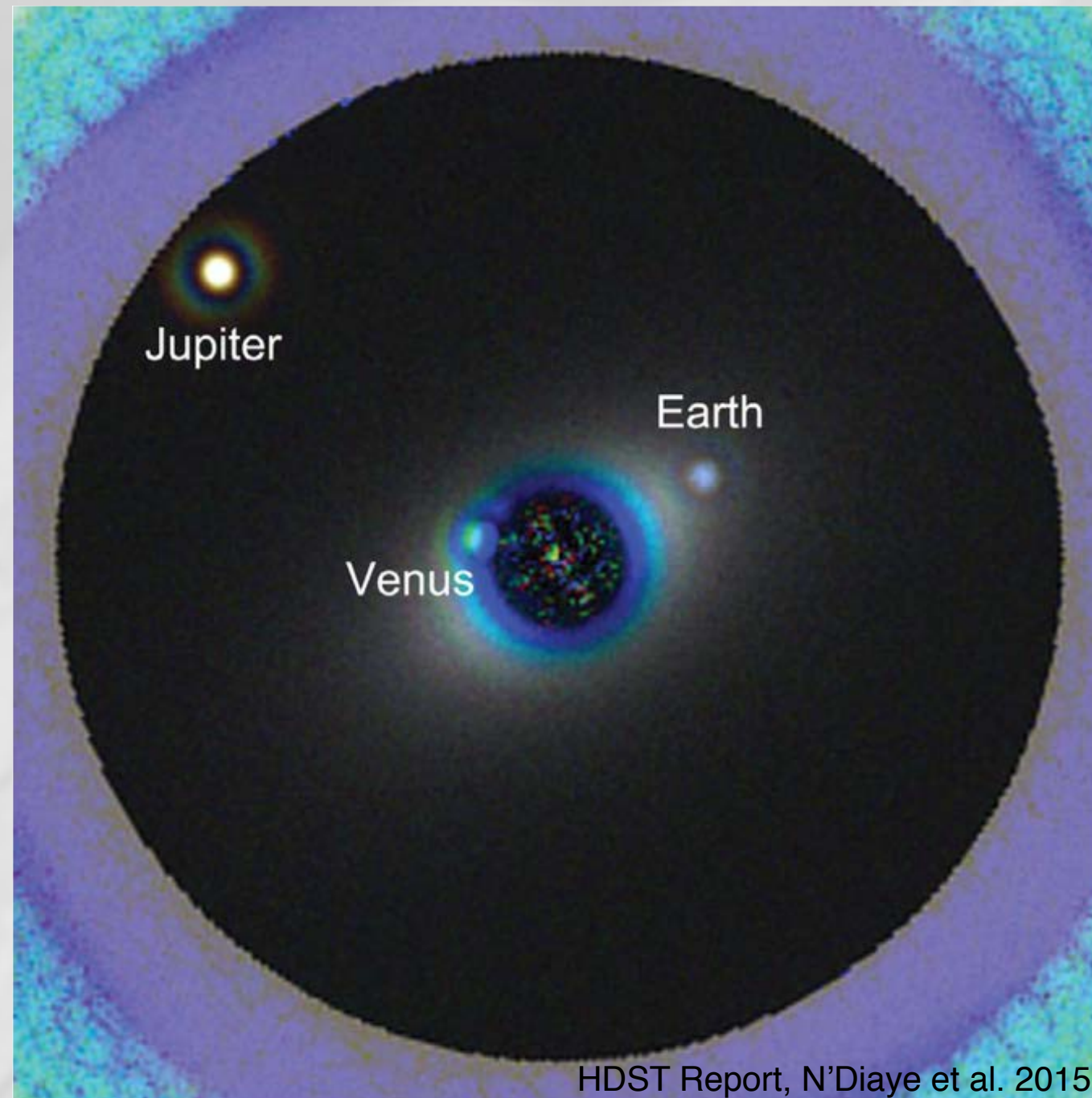
	Science Investigation	Possible Parallel?	Instrumentation					Aperture		Band		Spectral Resolution	Detector Requirement	Photon Min CR
			Exo-Im	Exo-Sp	UV	PI	MOS	Area	PSF	UV	NIR			
Exoplanets	Detect Earth-like planets in HZ		•					•				5		0.05
	Obtain orbital parameters		•					•				5		0.05
	Obtain spectra, detect biosignatures			•				•			•	>70–500	PC	<0.005
	Characterize planetary systems			•				•			•	>70–500	PC	<0.005
	Transit spectroscopy/atmospheres					•		•			•	100–3000	Dyn Rg	10 ⁺⁵



Science Investigation	
Exoplanets	Detect Earth-like planets in HZ
	Obtain orbital parameters
	Obtain spectra, detect biosignatures
	Characterize planetary systems
	Transit spectroscopy/atmospheres

MULTI-HOUR LONG OBSERVATIONS
MULTI-EPOCH

NATURE OF PLANETS FROM REFLECTED LIGHT?
ALBEDO VS SIZE?



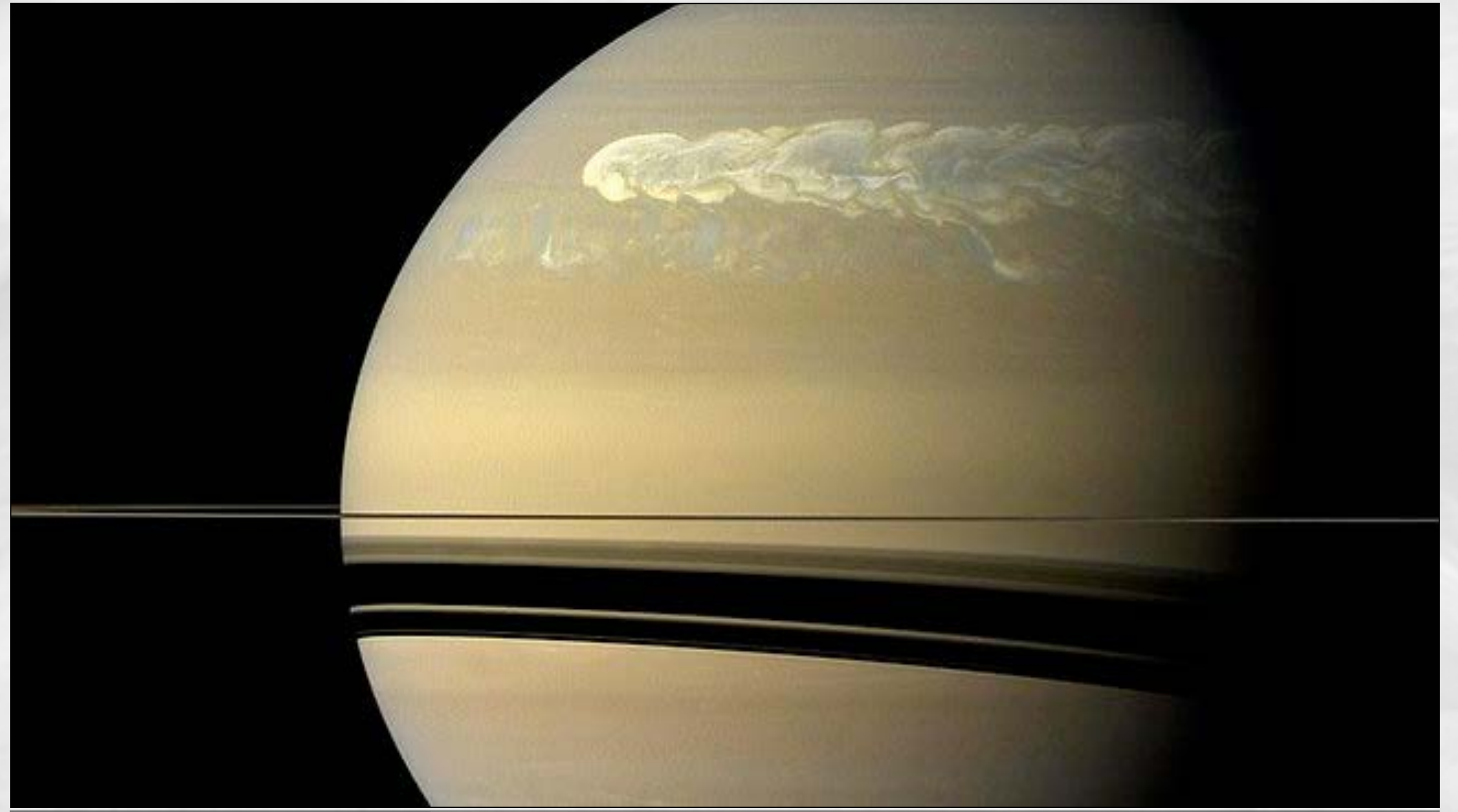
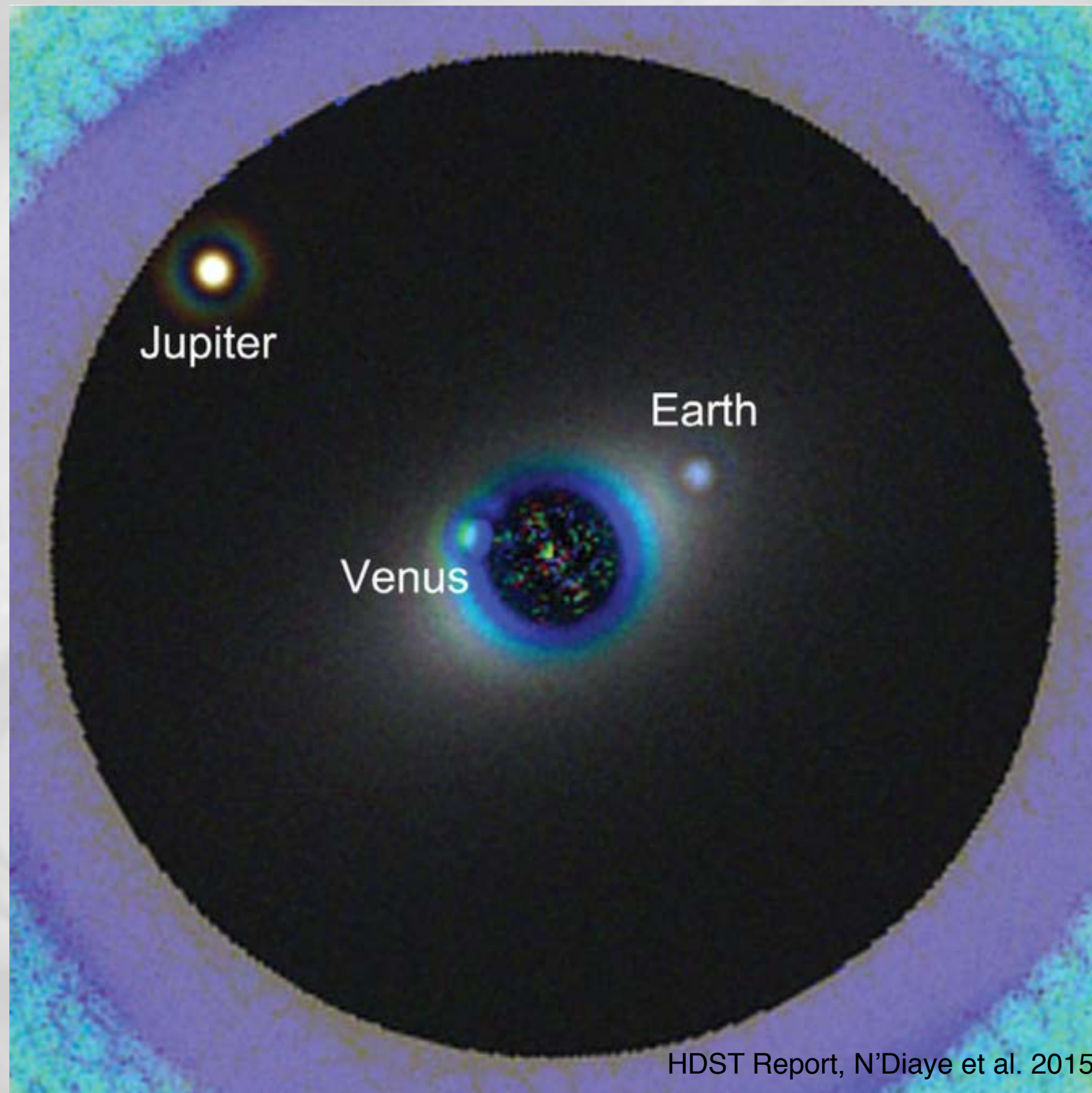
TIME-RESOLVED DATA ON GAS GIANTS, ICE GIANTS, SUPER-EARTHS, EARTHS

ROTATION PERIODS AS A FUNCTION OF AGE AND MASS?

ICE CLOUD COVER STRUCTURE + INFRARED HOTSPOTS?

HAZE DISTRIBUTION AND EVOLUTION?

ATMOSPHERIC EVOLUTION?



ATMOSPHERIC COMPOSITIONAL VARIATIONS

TALK IN THIS SERIES BY N. COWAN ON MAPPING EXOEARHES

Summary

Clouds: Major Challenge in Ultracool atmospheres

Thin-thick cloud structures in L/T transition Brown Dwarfs (Apai et al. 2013 ApJ)

High-level haze in most L dwarfs; clouds deeper in L/T dwarfs (Yang et al. 2015)

Dynamic, rapidly evolving atmospheres (Apai et al., in prep.)

Vertical/Longitudinal Structure in a T6.5 Brown Dwarf (Buenzli et al. 2012)

Rotational Mapping for Directly Imaged Hot Exoplanets: AO+JWST (Kostov & Apai 2013 ApJ)

MCMC-based Light Curve Mapping Tool Validated on Jupiter (Karalidi et al., submitted)

Time-domain observations are important for future LUVOIR telescopes!