



Image Credit: Alien Earths/NExSS; Kornmesser NASA/ESA

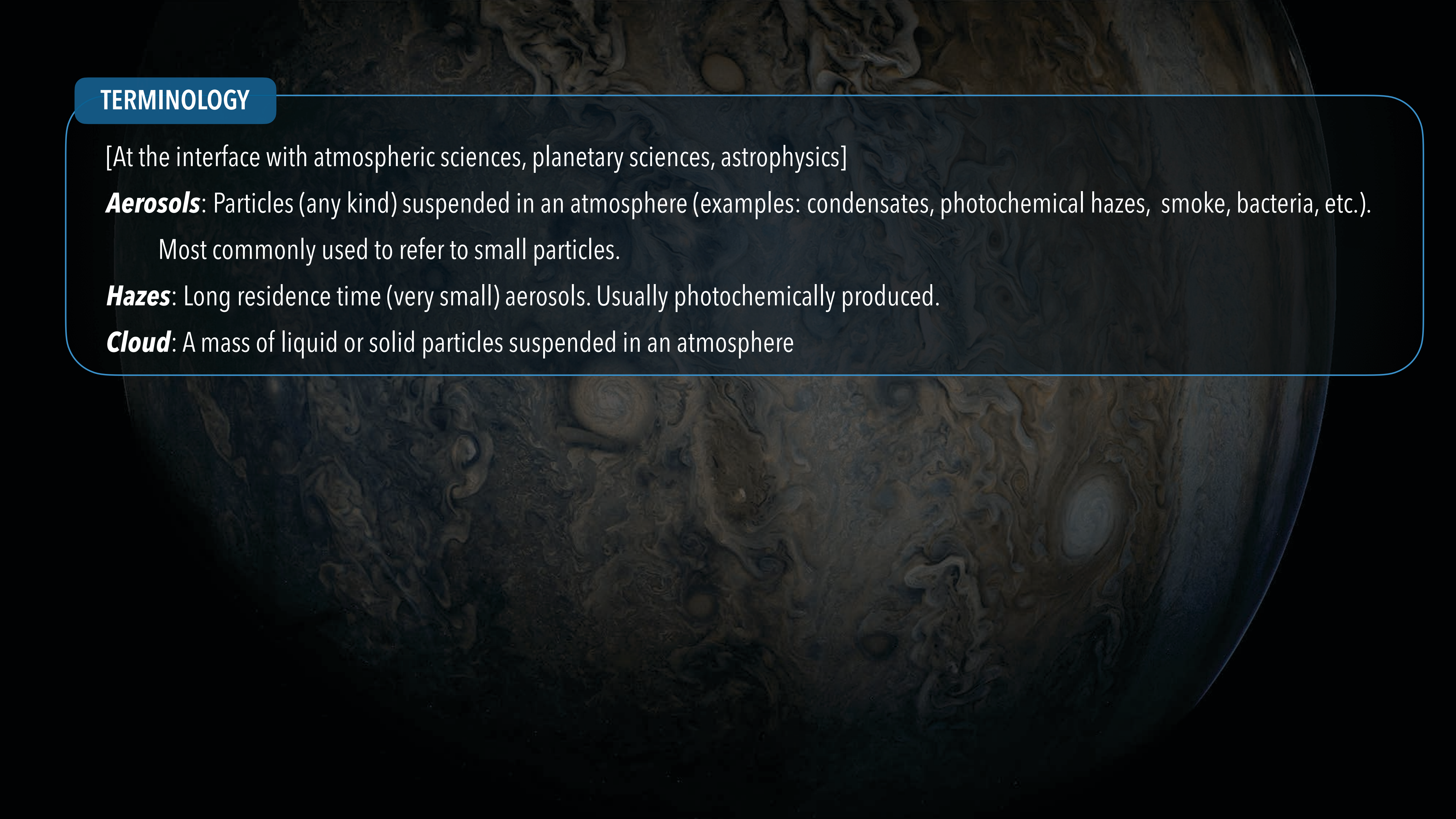
DUST STORMS AND CONDENSATE CLOUDS IN EXTRASOLAR ATMOSPHERES

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1 TERMINOLOGY AND IMPACT





TERMINOLOGY

[At the interface with atmospheric sciences, planetary sciences, astrophysics]

Aerosols: Particles (any kind) suspended in an atmosphere (examples: condensates, photochemical hazes, smoke, bacteria, etc.).

Most commonly used to refer to small particles.

Hazes: Long residence time (very small) aerosols. Usually photochemically produced.

Cloud: A mass of liquid or solid particles suspended in an atmosphere

IMPACTS OF CLOUDS

Radiative energy transport through the atmosphere

Gas-phase abundances and atmospheric opacity

Pressure-temperature profile

Observable pressure levels

Emerging and observable spectra, broad-band colors, albedo

Thermal-chemical evolution of the objects

2 KEY PROCESSES



SIMPLISTIC MODELS FOR CONDENSATE CLOUDS

Saturation vapor pressure as a function of temperature (Clausius-Clapeyron curve):

$$\frac{dP_v}{dT} = \frac{L}{T(V_2 - V_1)}$$

V_1 – specific volume of liquid/solid phase
 V_2 – specific volume of vapor (2) phase
 L – specific latent heat of phase transition

Assuming ideal gas law and specific latent heat approximated as $L = L_0 + \Delta\alpha T + \frac{1}{2}\Delta\beta T^2$

$$\ln(P_v) = \ln(C) + \frac{1}{R_v} \left[-\frac{L_0}{T} + \Delta\alpha \ln T + \frac{\Delta\beta}{2} T \right]$$

Saturation vapor pressure curve: equilibrium between gas and liquid/solid

Cloud base: ~ Intersection of saturation vapor pressure curve and the atmosphere's temperature-pressure profile

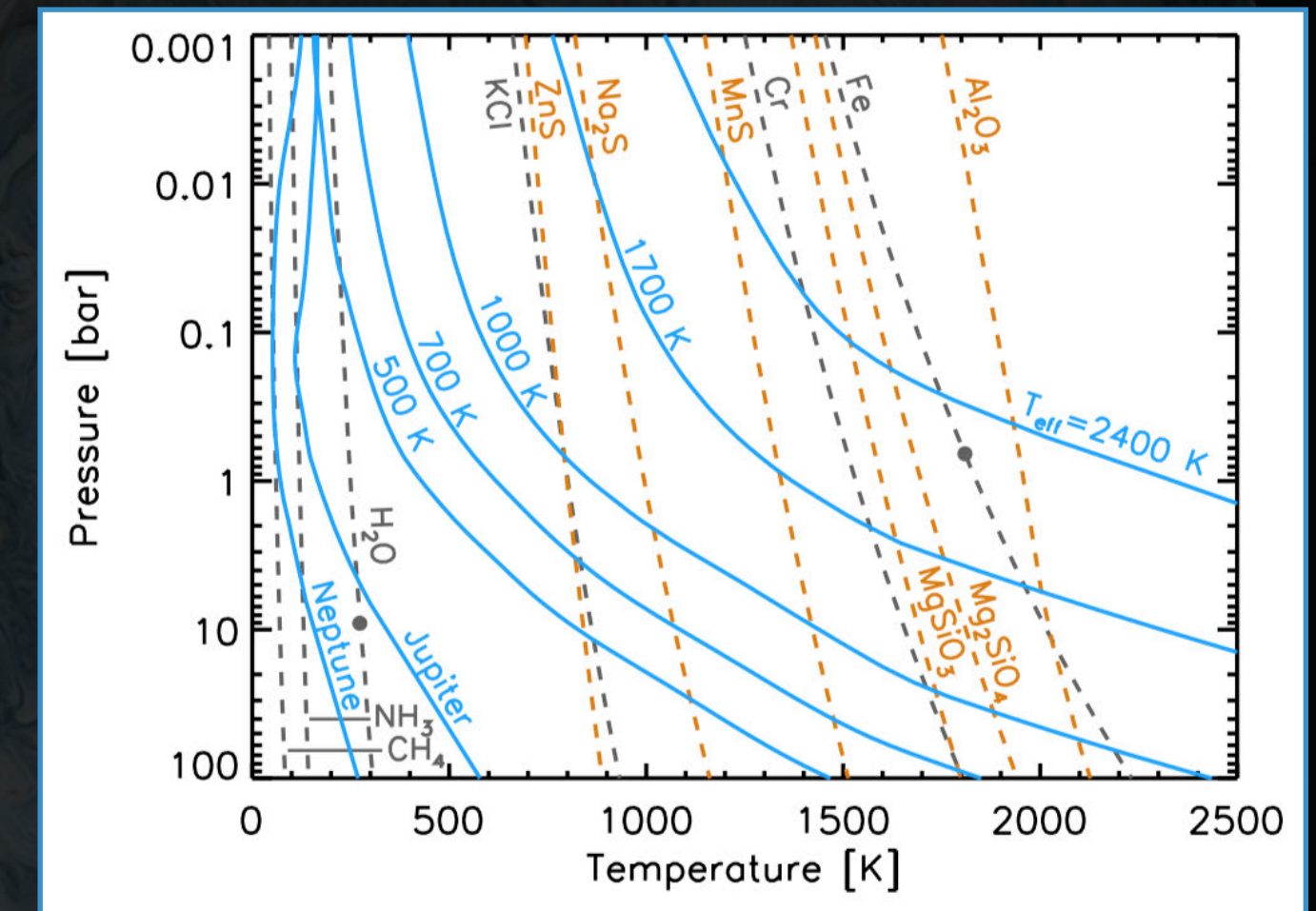
Cloud scale height can be defined as distance over which vapor pressure drops by a factor of e

$$H = \frac{kT}{\mu_m m_H g}$$

pressure scale height

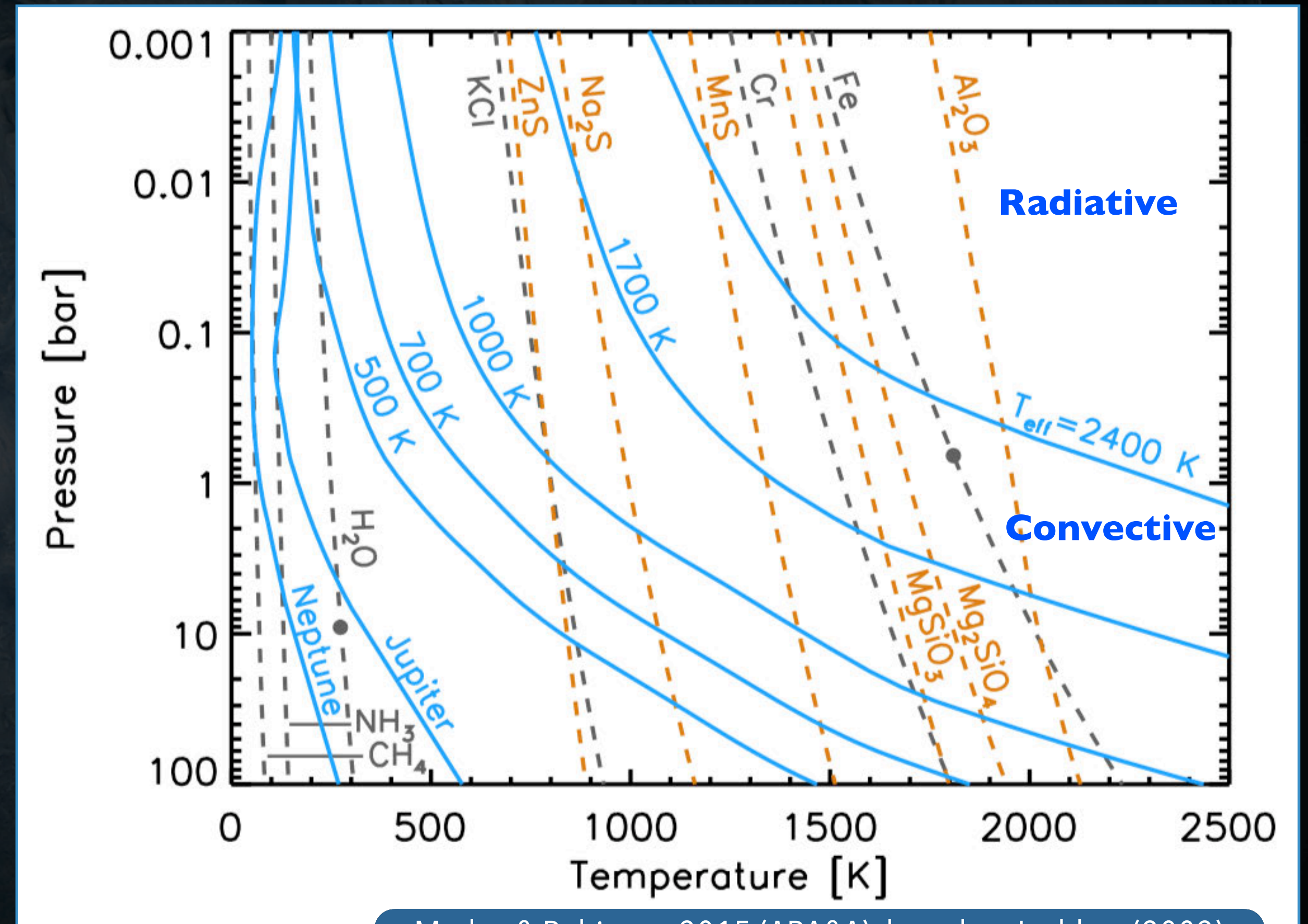
From Clausius-Clapeyron relationship (w hydrostatic equilibrium, ideal gas):

$$\frac{H_c}{H} = \frac{R_v}{R_s} \frac{\mu c_p T_c}{L}$$



P-T PROFILES AND CONDENSATION CURVES

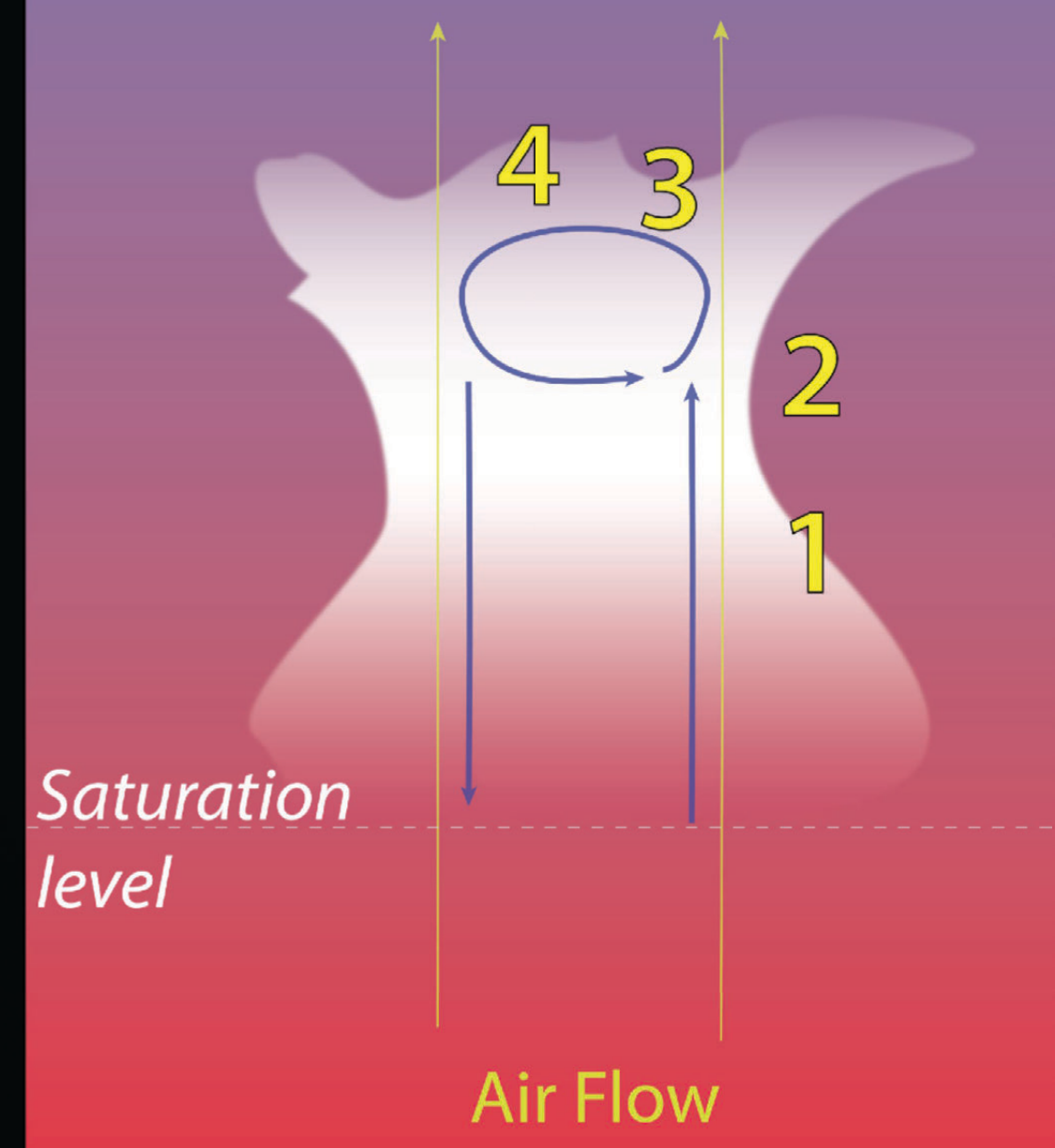
- Condensation curves calculated for different species
- Pressure-temperature profiles intersect condensation curves
- Condensation and cloud formation predicted
- Cloud base pressure ~ intersection points
- Clouds are expected to be thin
- Particle size distributions often approximated with gamma, log-normal, or power-law distributions



Marley & Robinson 2015 (ARA&A), based on Lodders (2003)

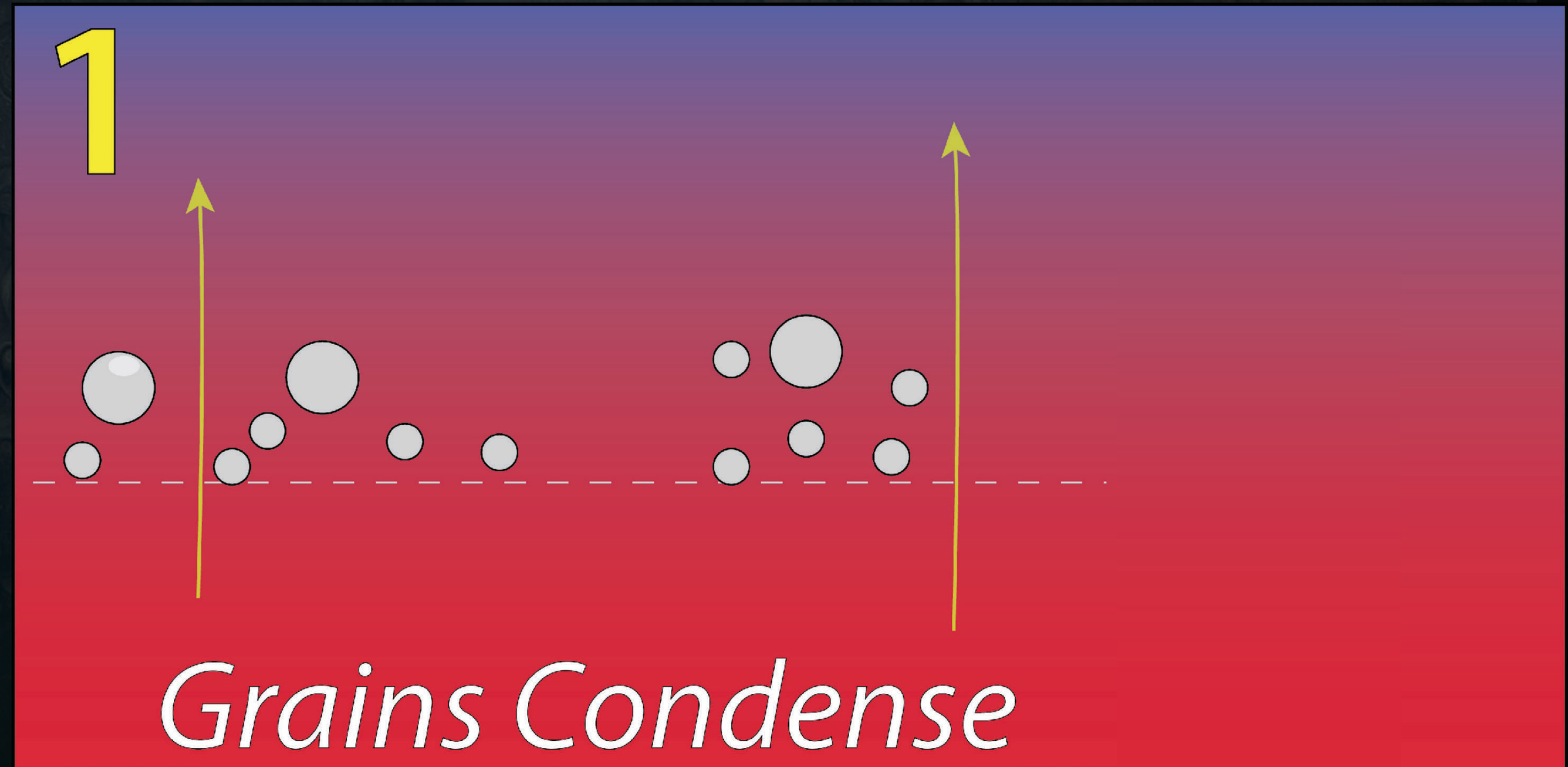
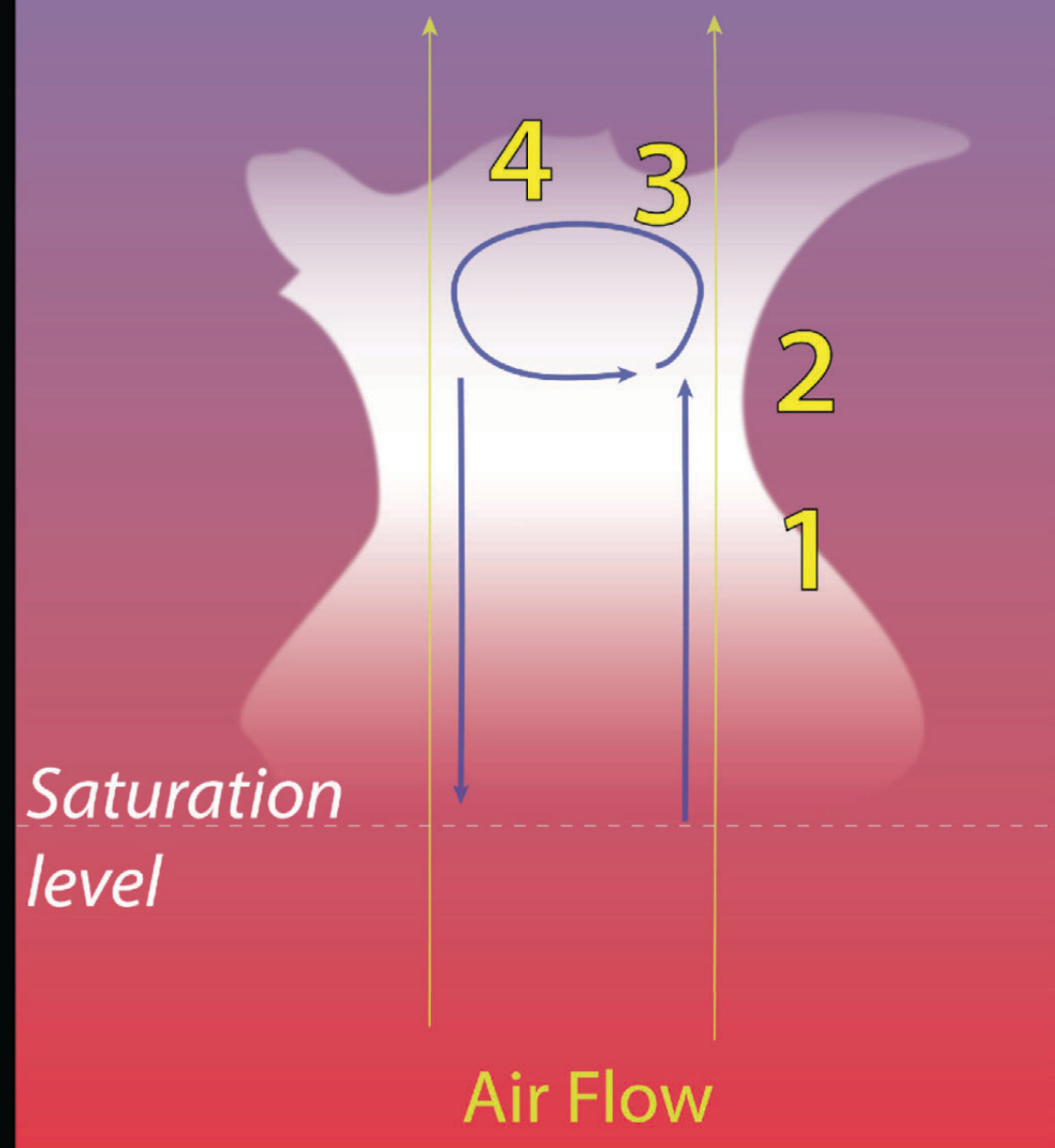
CONDENSATE CLOUD FORMATION : LIKELY MORE COMPLICATED

*Clouds forming
in Updraft*



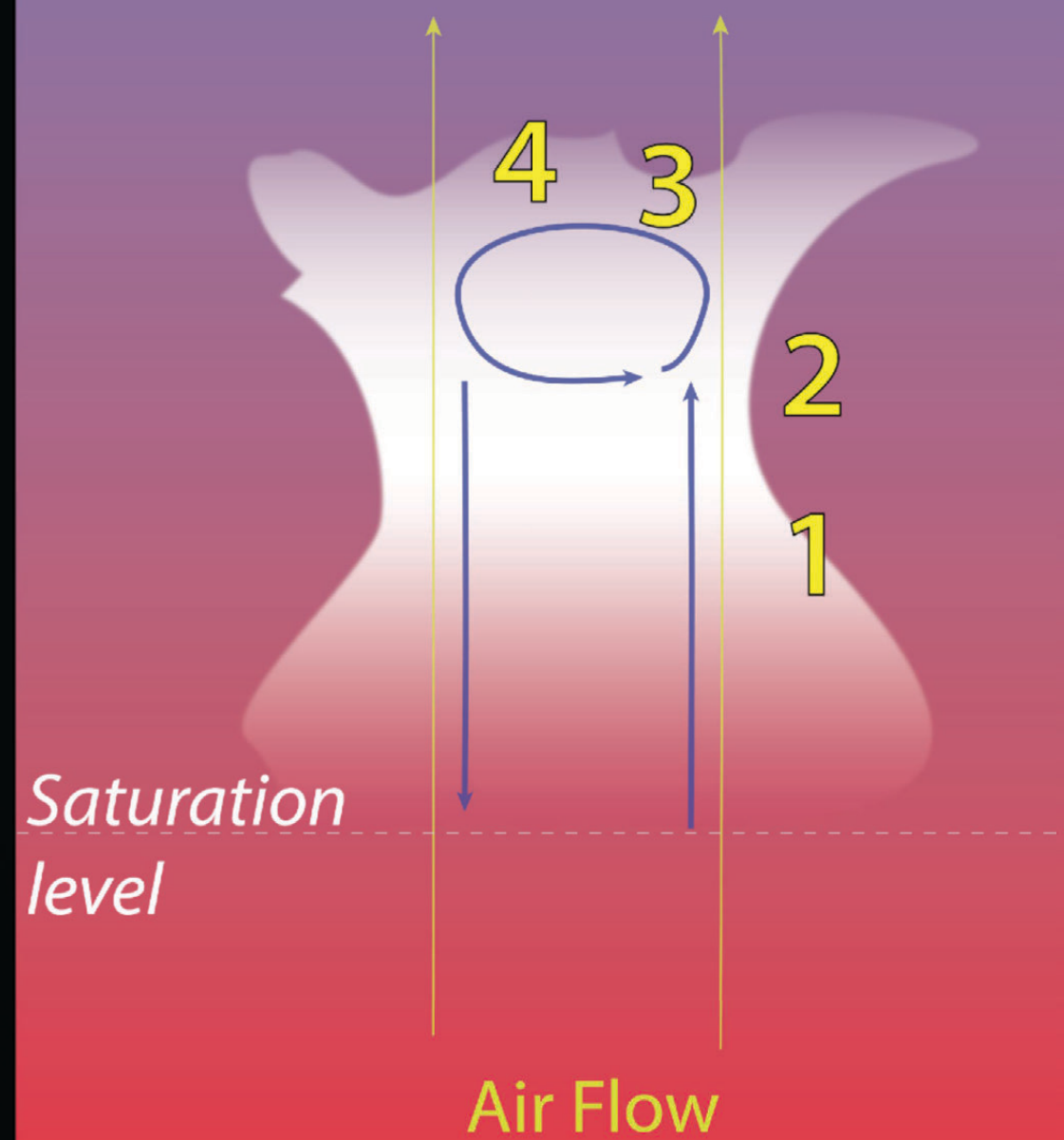
CONDENSATE CLOUD FORMATION

*Clouds forming
in Updraft*

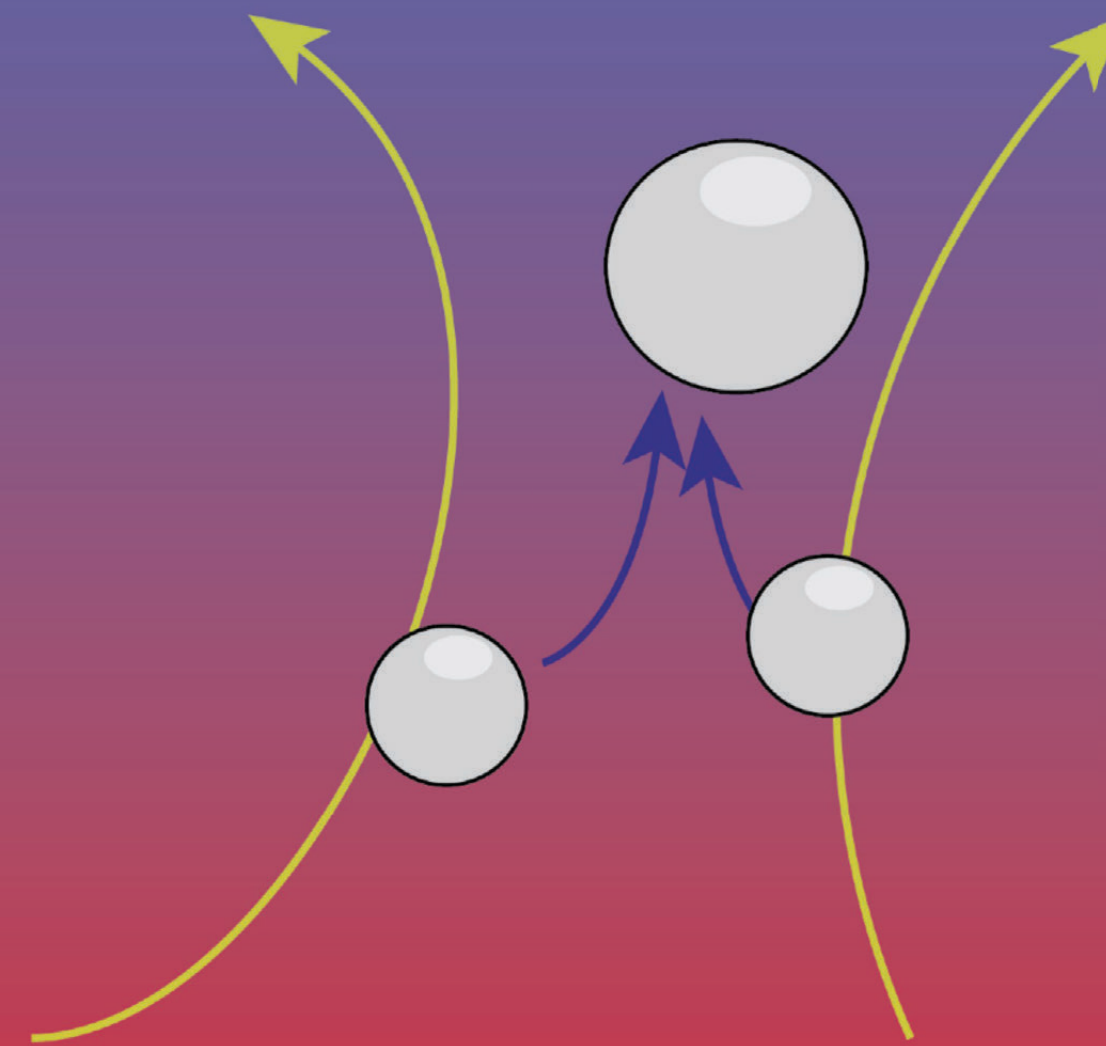


CONDENSATE CLOUD FORMATION

*Clouds forming
in Updraft*



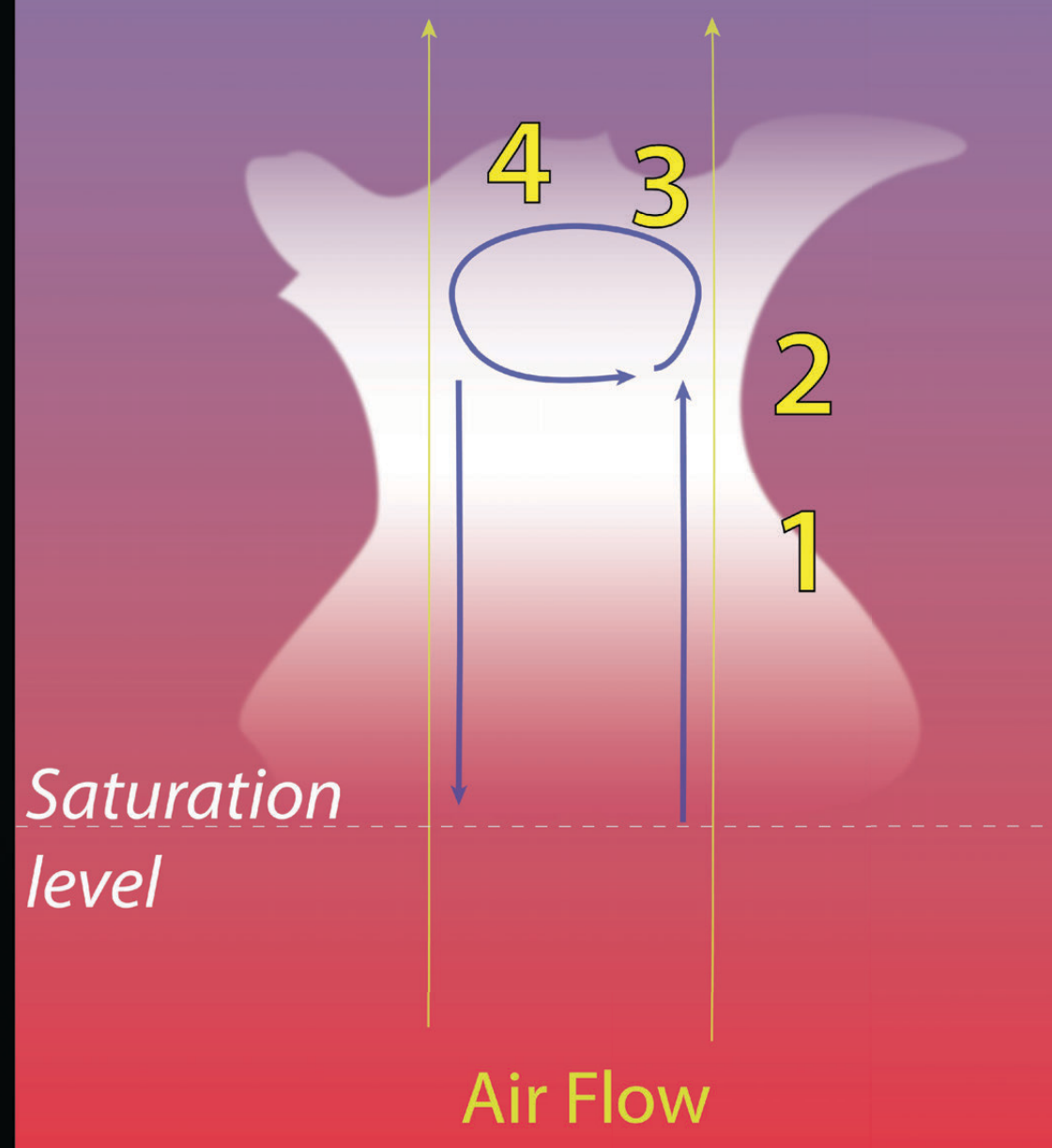
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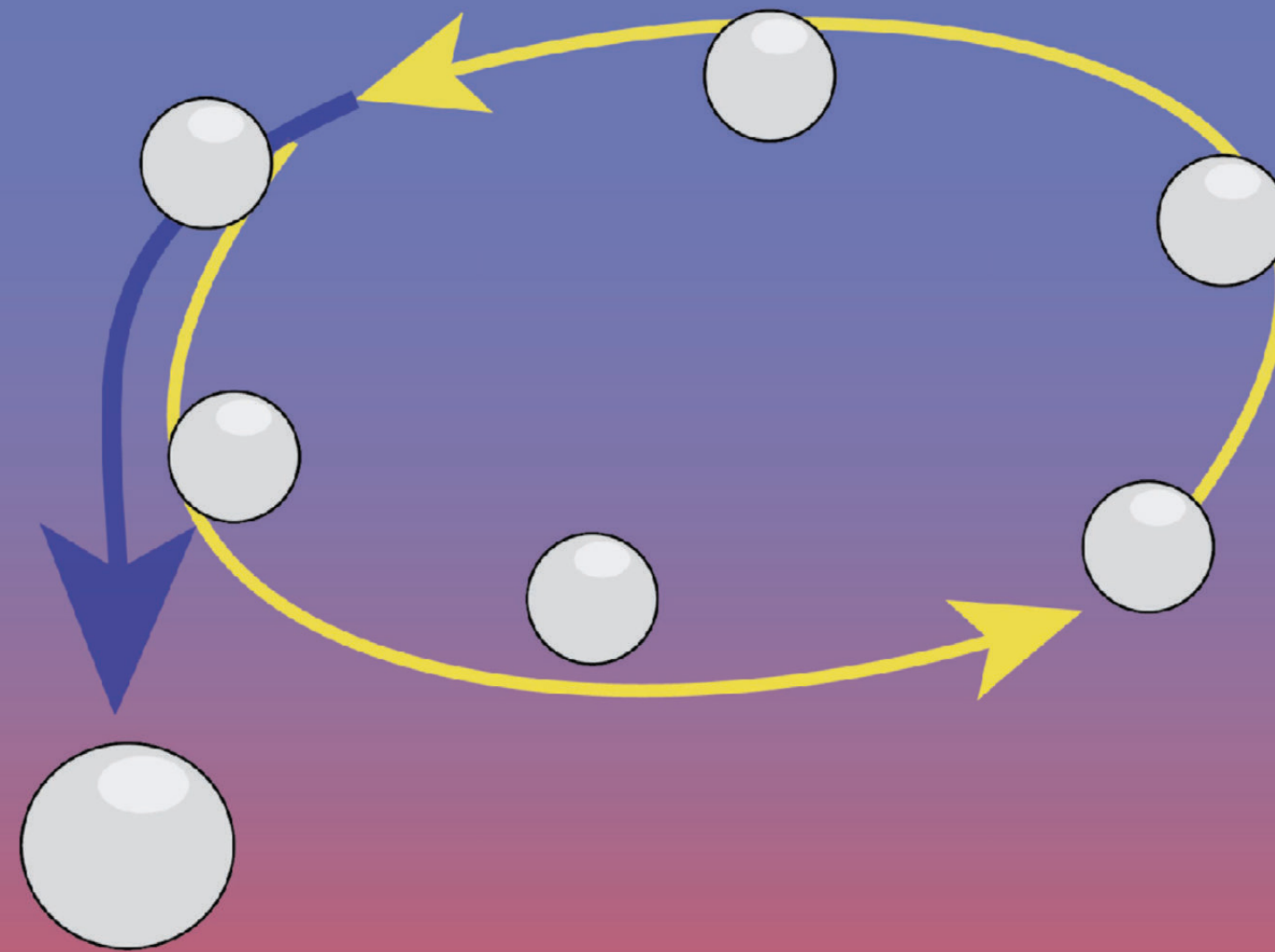
Grains Grow via Collisions

CONDENSATE CLOUD FORMATION

*Clouds forming
in Updraft*



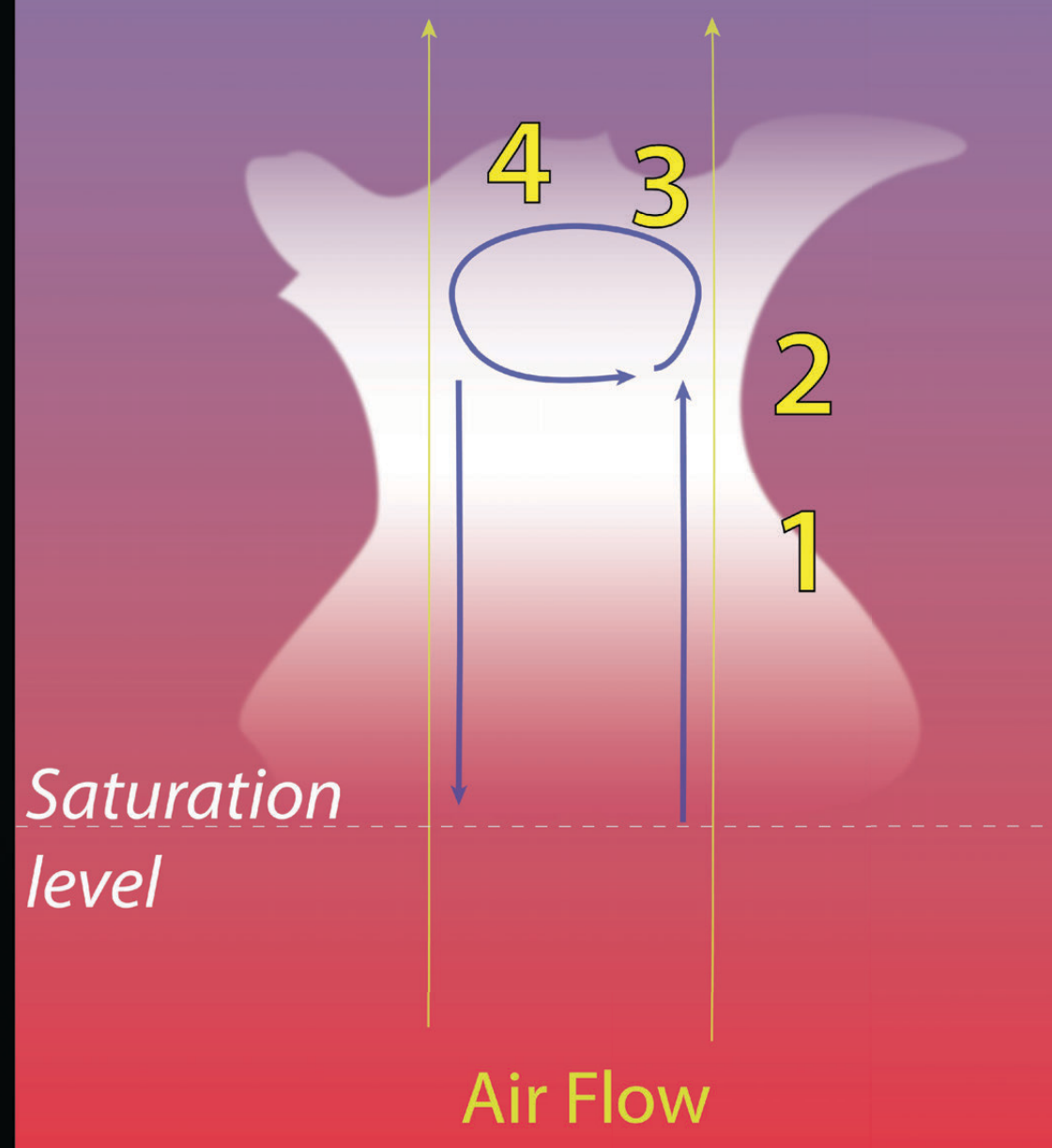
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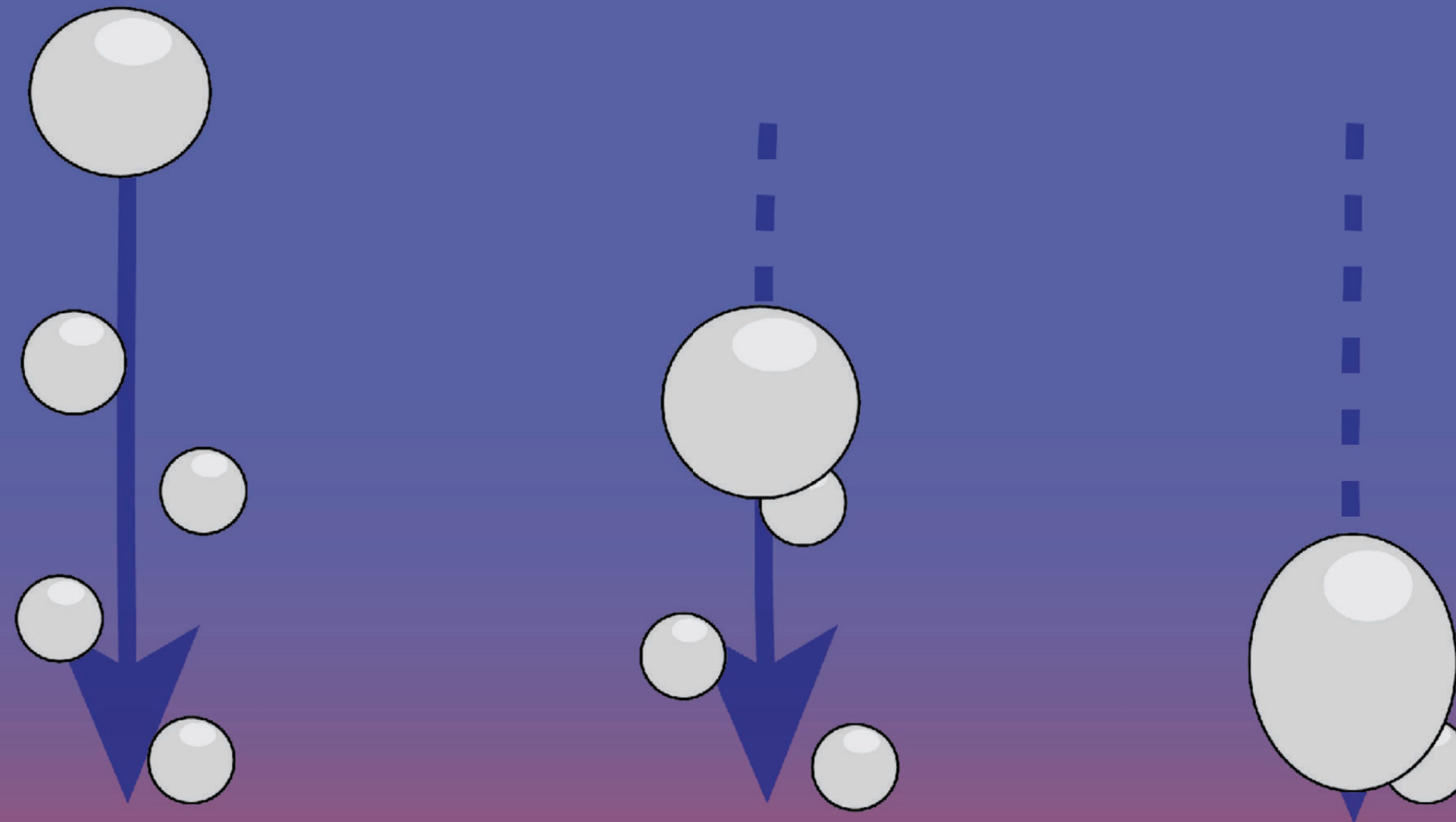
Large Grains Decouple and Rain Out

CONDENSATE CLOUD FORMATION

*Clouds forming
in Updraft*



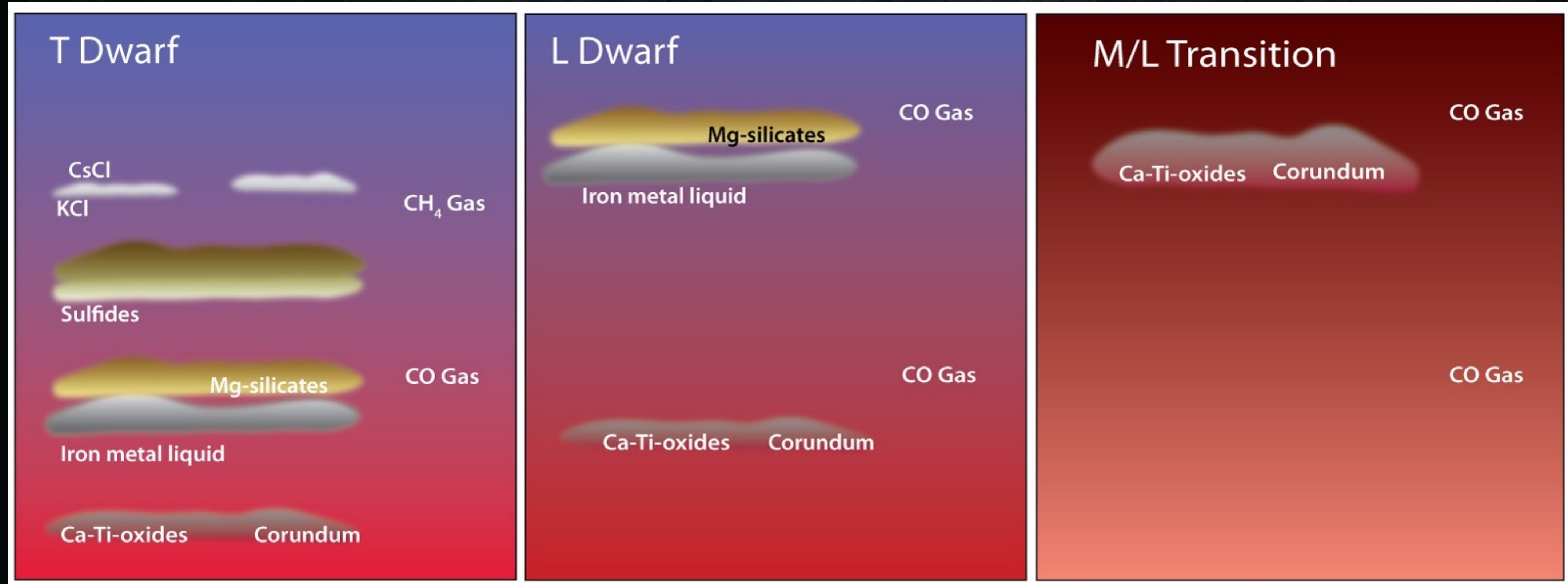
4



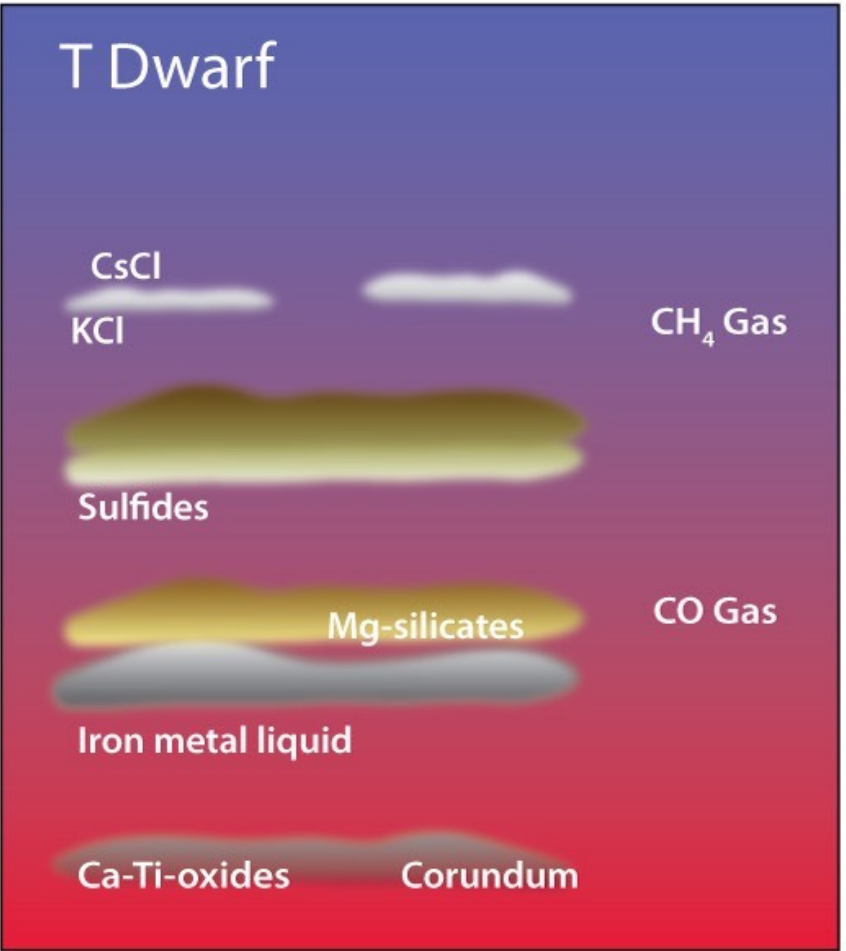
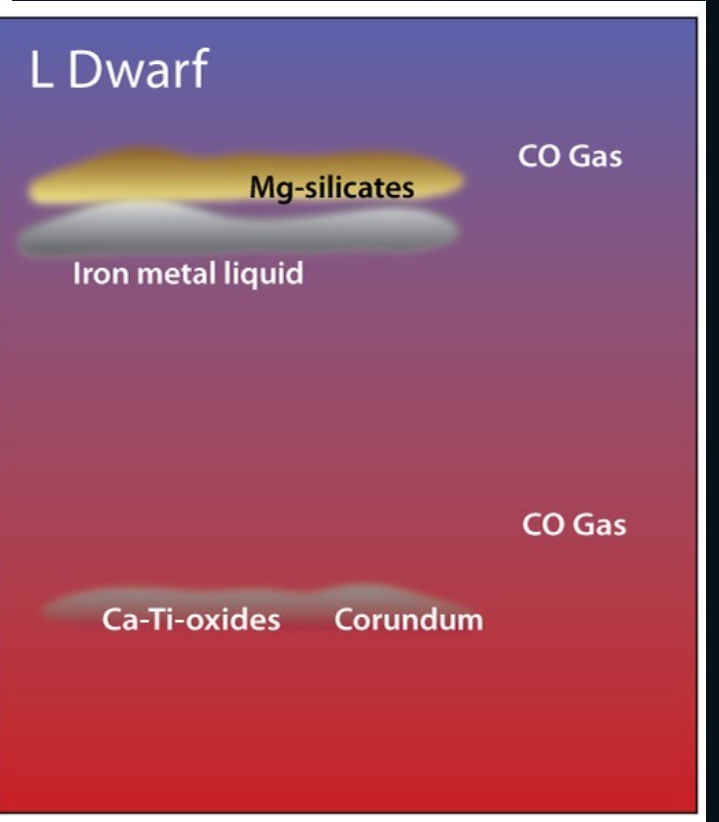
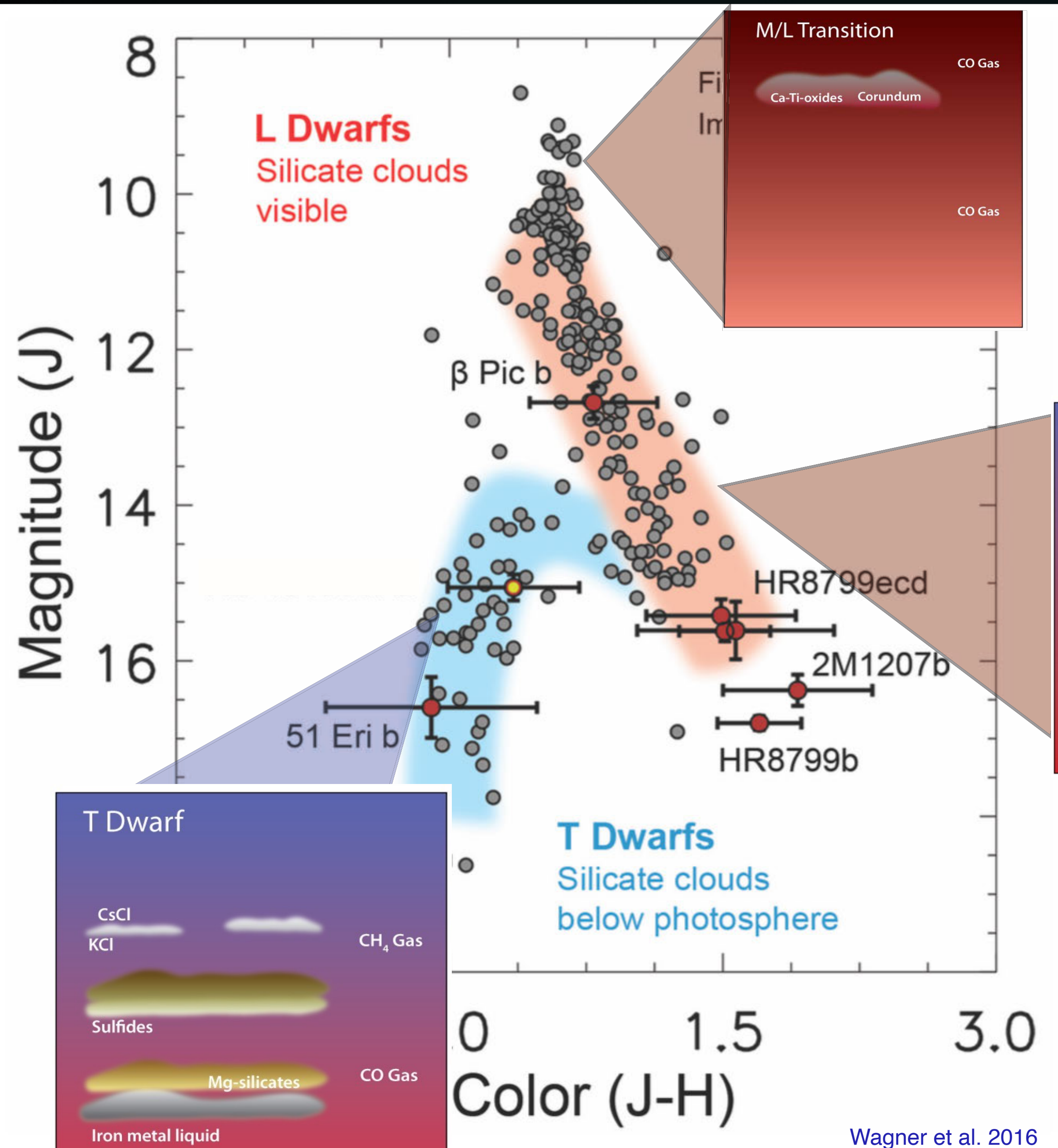
Fall and Sweep Up Small Grains



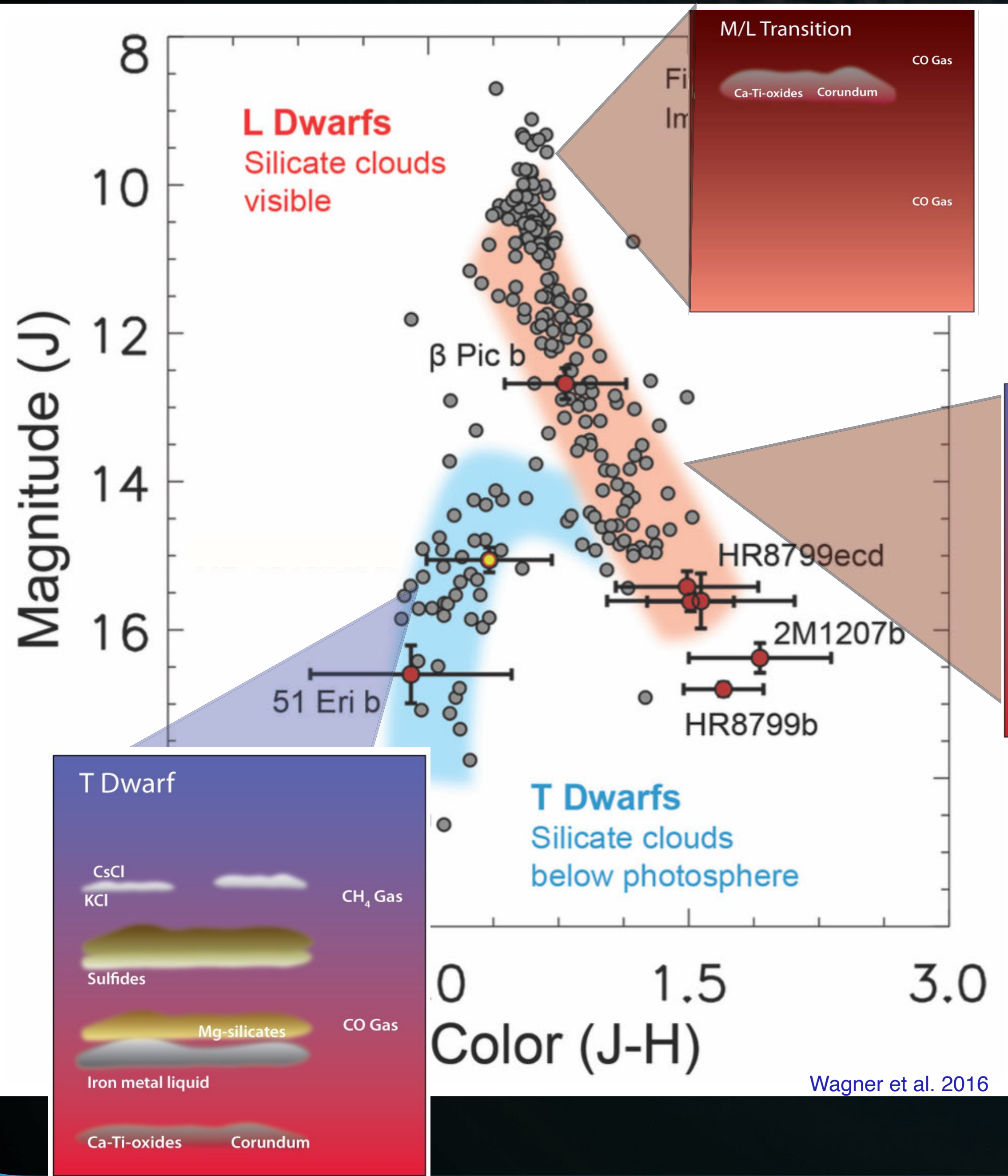
PREDICTED CLOUD LAYERS



Cloud formation/physics: e.g. Marley et al. 2002, 2007 PPV, 2010, 2012; Helling et al. 2008; Burrows et al. 2003, 2007, 2010, 2011; Heng et al. 2012; 2013; Barman et al. 2012ab; Baraffe et al. 2003; Morley et al. 2012, 2014; Gao et al. 2020;



Wagner et al. 2016



CONDENSATES PREDICTED

As consequence of P/T conditions and composition, condensation must occur (e.g., Metal-oxides, Silicates)

CLOUDS CONSISTENT WITH CMD

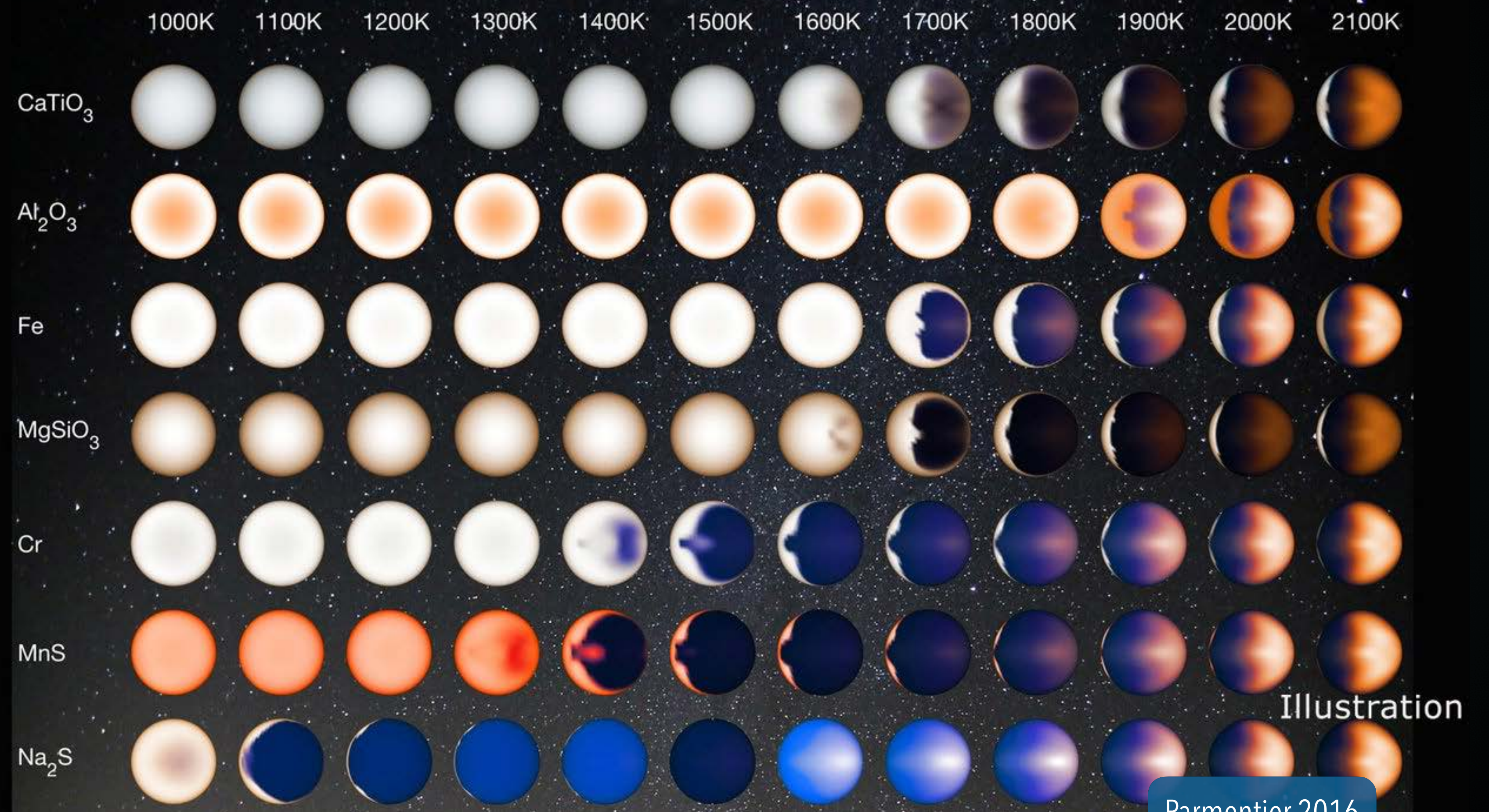
General trends in CMD explained by models that include condensation and cloud formation

Indirect evidence for presence of clouds

NOT UNIQUE EXPLANATION

Non-equilibrium chemistry-introduced P-T variations are an alternative (e.g., Tremblin et al. 2015, 2016, 2017, 2020)

PREDICTIONS FOR HOT JUPITERS



Parmentier 2016

REALITY IS MORE COMPLEX

- Models often assume nuclei-free, homogenous nucleation $\Rightarrow$ distinct cloud layers with unique mineralogy
- Nucleation-mediated heterogeneous condensation is more likely $\Rightarrow$ "Dirty grains"
- Aerosol size distribution often approximation with log-normal distribution derived from Earth
- Atmospheric dynamics $\Rightarrow$ Aerosol particle size distribution
- Strong temporal/spatial variations are possible

NEW MODELS NEEDED

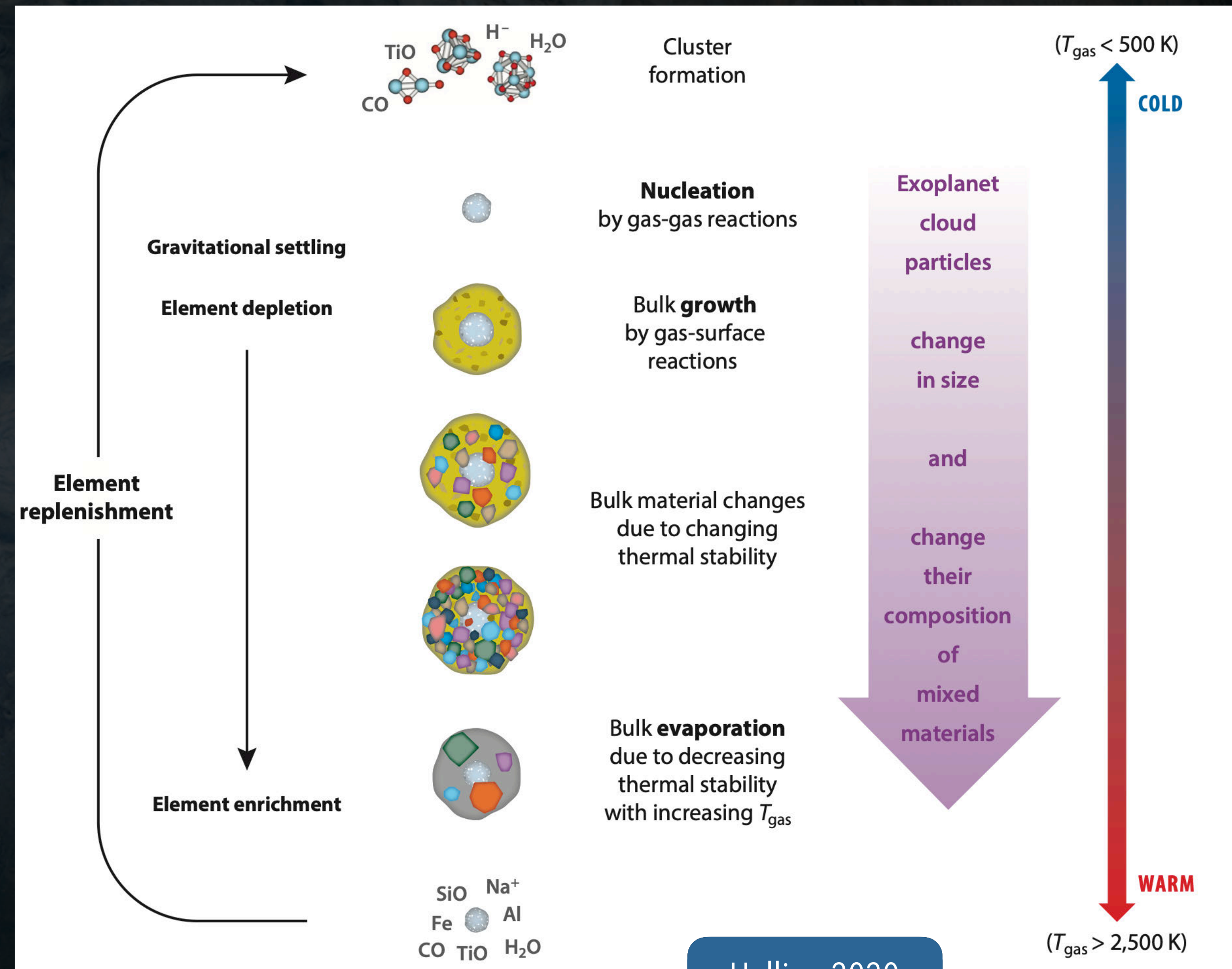
Simple models were suitable for simpler data

With Spitzer, HST, and JWST, increasing conflict between data and models

Microphysics-based models exist and are now growing in importance (e.g., Helling 2020, 2021)

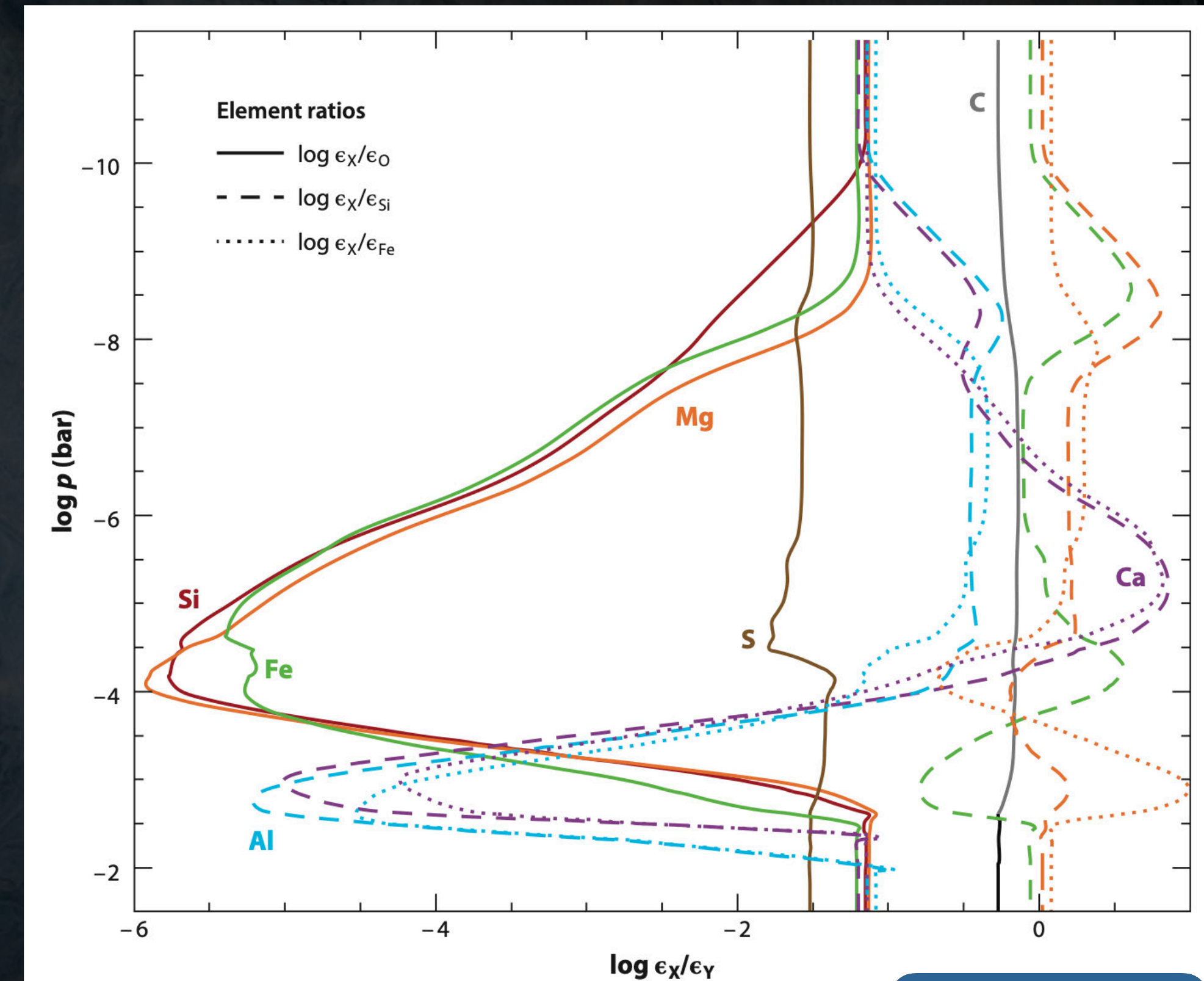
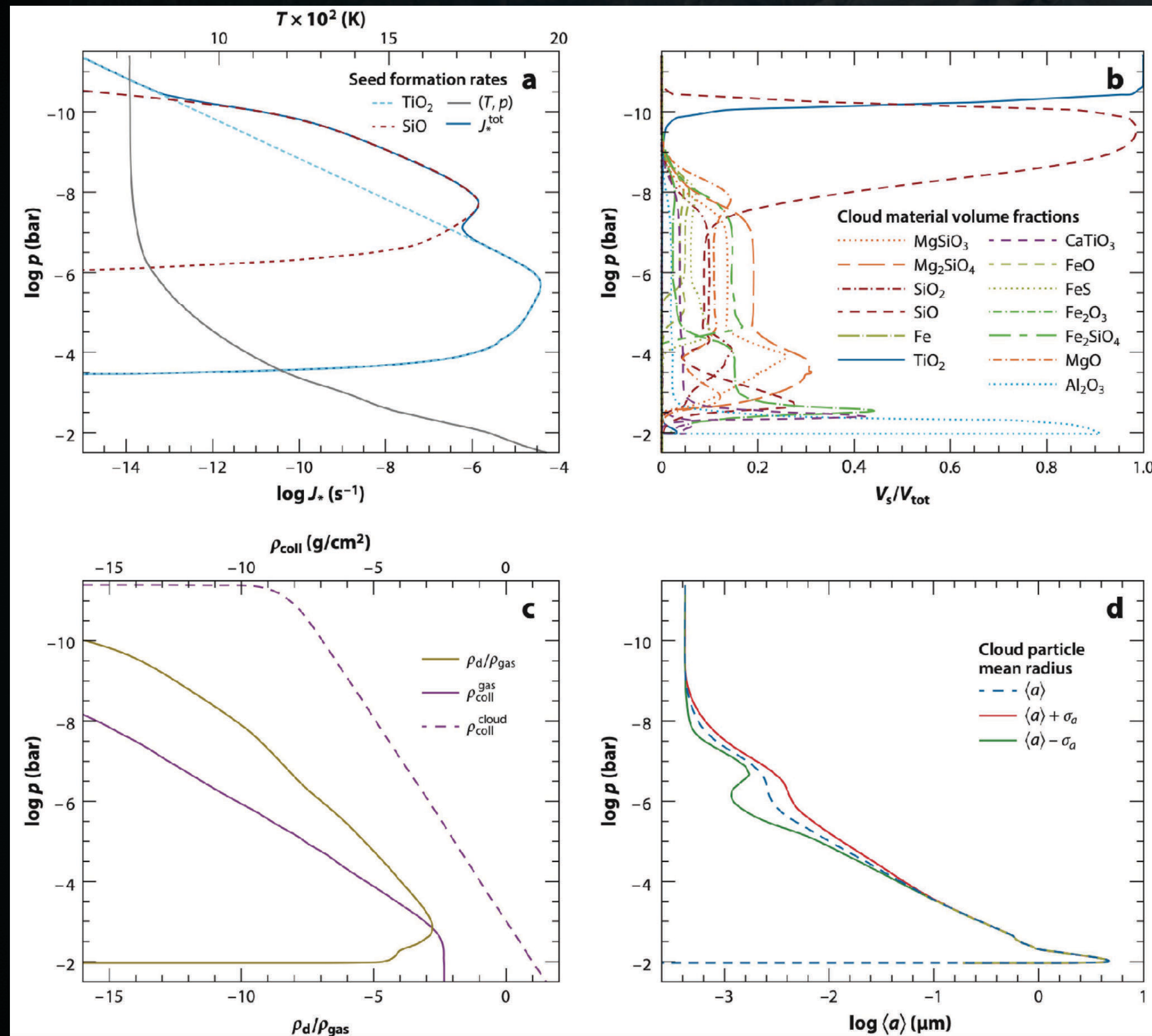
Community Aerosol and Radiation Model for Atmospheres (part of Community Earth System Model, e.g., Gao et al. 2018)

REALITY IS MORE COMPLEX



Helling 2020

EXAMPLE FOR MICROPHYSICS-BASED MODEL

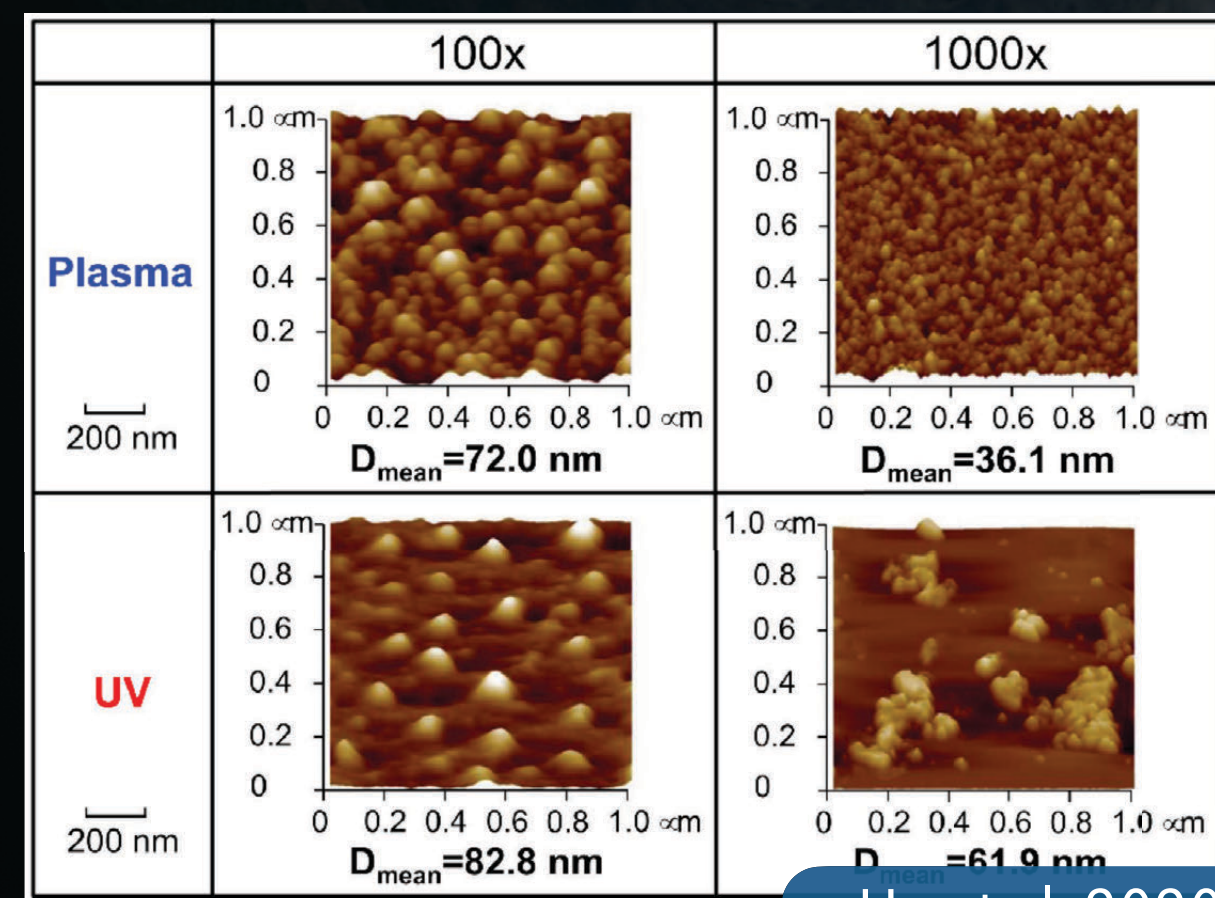


Helling 2020

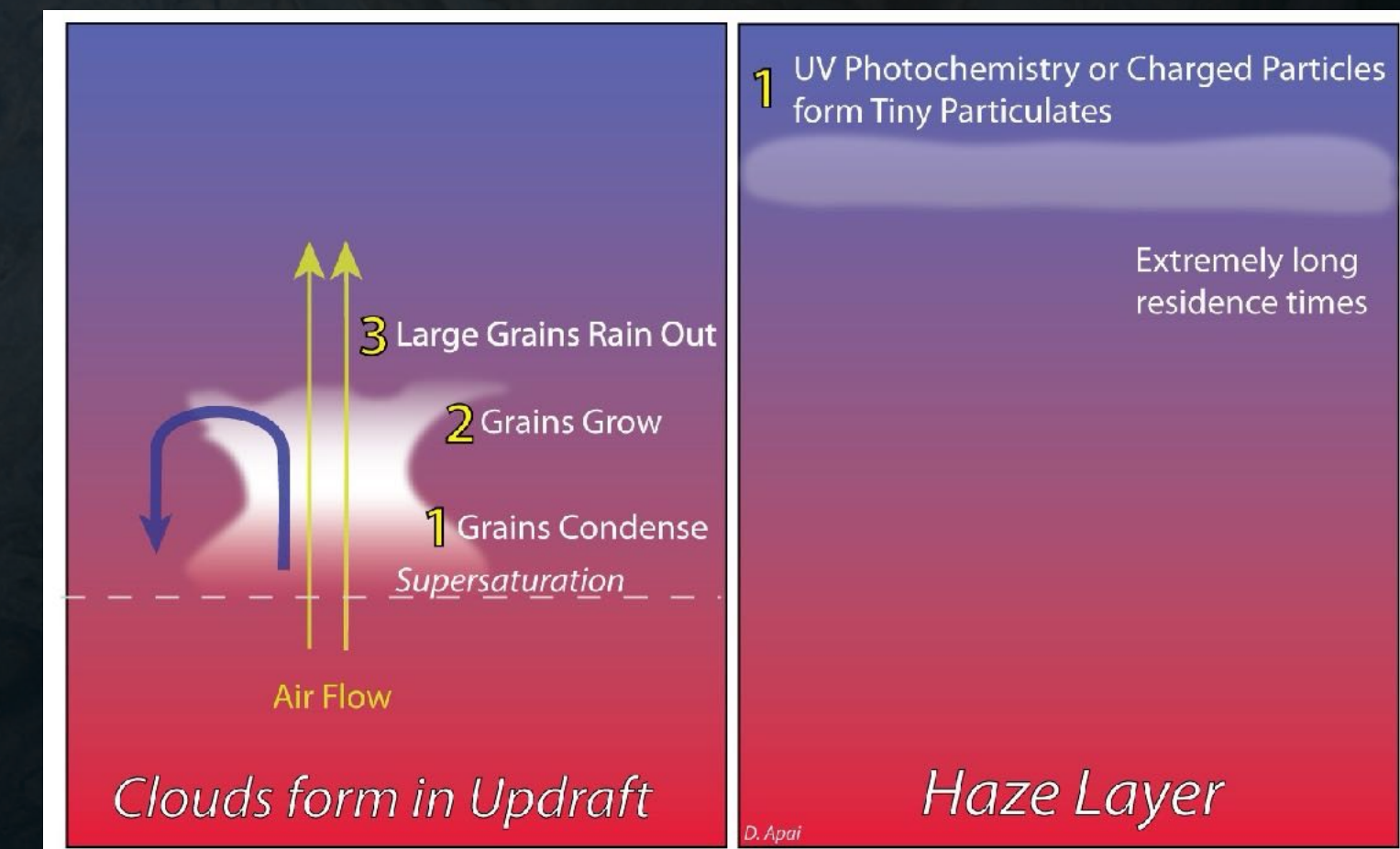
$T_{\text{eff}} = 1,800 \text{ K}$

HAZE FORMATION

- UV and/or plasma + CH_4 leads to hydrocarbon aerosol formation
- CO and CO_2 can also serve as carbon source for haze formation
(e.g., Fleury et al. 2017; He et al. 2020; Hörst et al. 2018)
- H_2S photodissociation leads to S_8 , changing planet's color and albedo (Gao et al. 2020)
- Presence of Sulfur adds to abundance and complexity of hazes in warm exoplanets (e.g., Zahnle et al. 2009; He et al. 2020)
- Models (Gao et al. 2020): Hot giant exoplanets dominated by silicates ($> 950 \text{ K}$), and by hydrocarbon aerosols ($T < 950 \text{ K}$)



He et al. 2020





3 CLOUDS IN IRRADIATED EXOPLANETS

INDIRECT EVIDENCE FOR CLOUDS / AEROSOLS

Featureless transmission spectra

Thick clouds OR no atmosphere

Atmospheric retrievals place constraints on cloud top pressure levels

Inferred cloud tops are sometimes very low pressure (0.1 mbar)

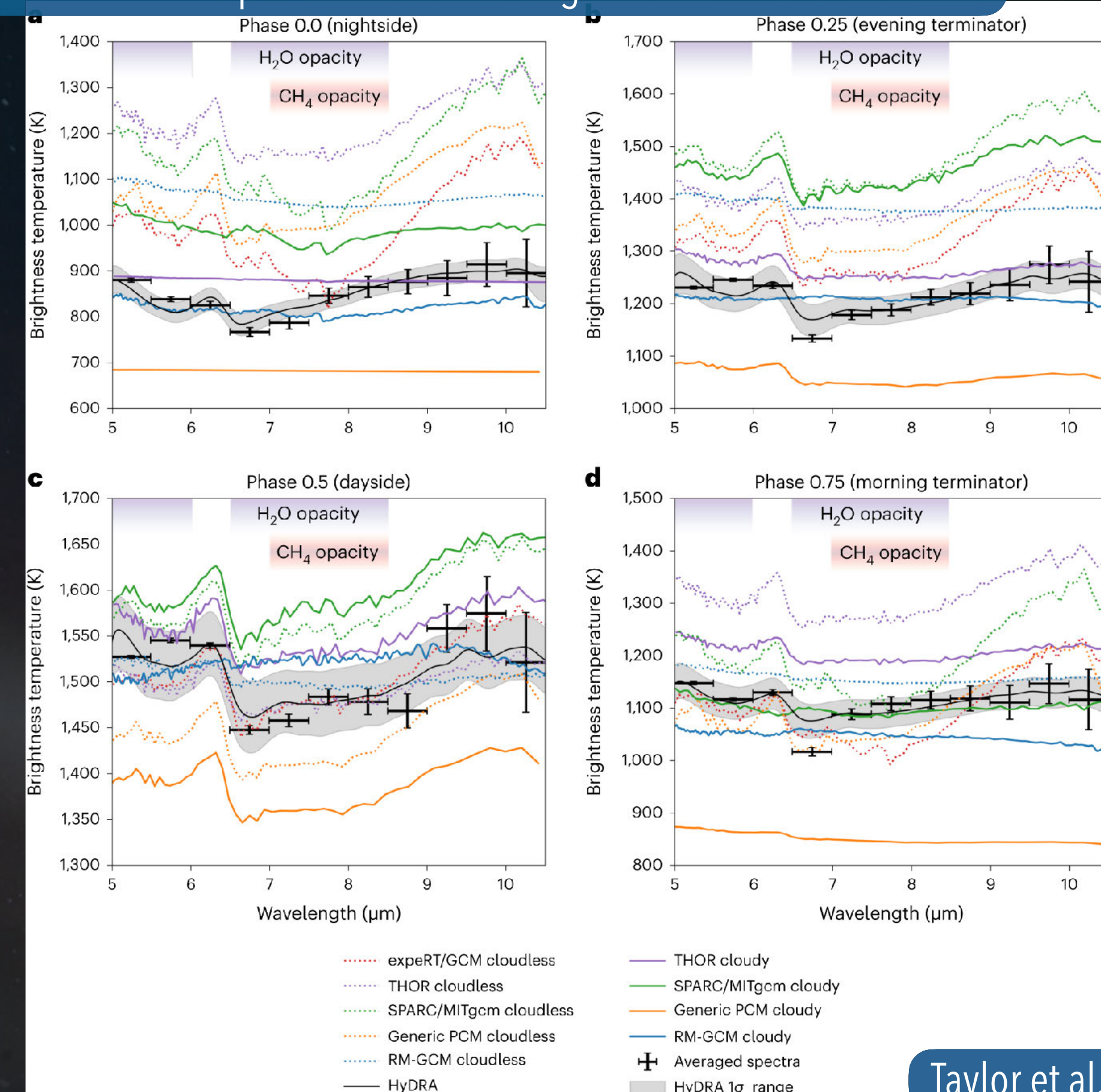
e.g., Kreidberg et al. 2014a; Knutson et al. 2014a; Morley et al. 2015;

Benneke 2015 Benneke et al. 2019a; Bell et al. 2024

Muted spectral features

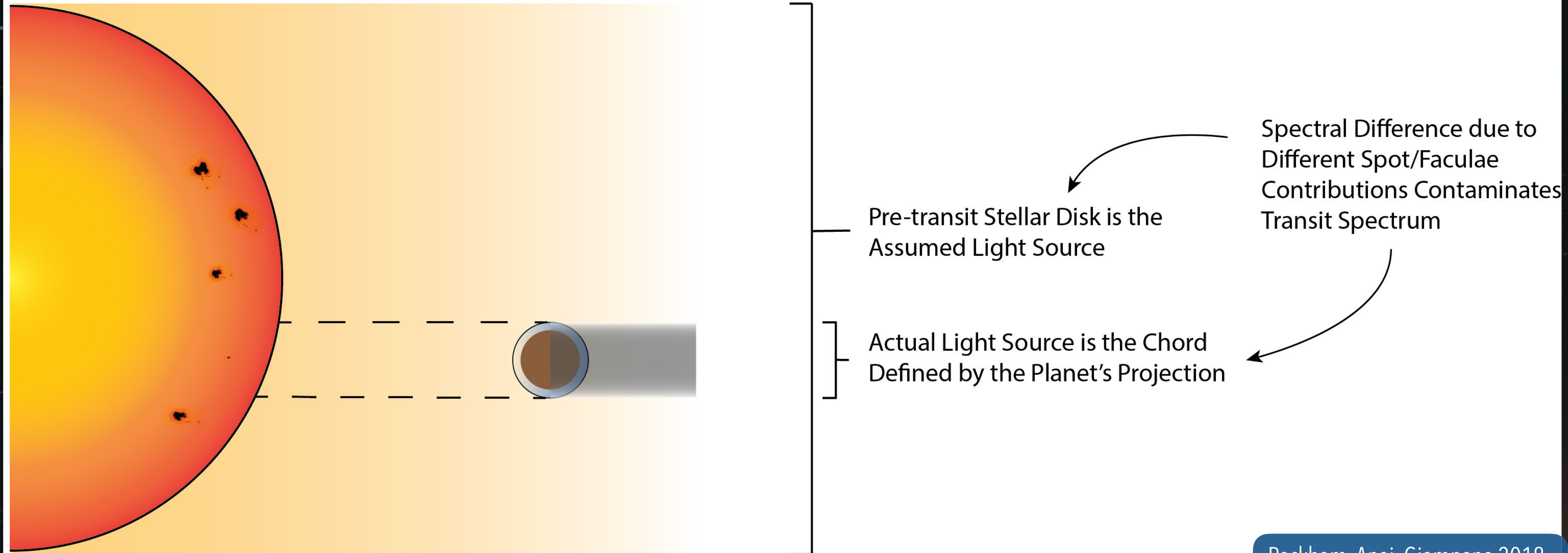
Clouds/haze layer and/or high mean mol. weight atmosphere

WASP-43 Hot Jupiter: Evidence fro night-side cloud at 100 mbar



Taylor et al. 2023

The Transit Light Source Effect

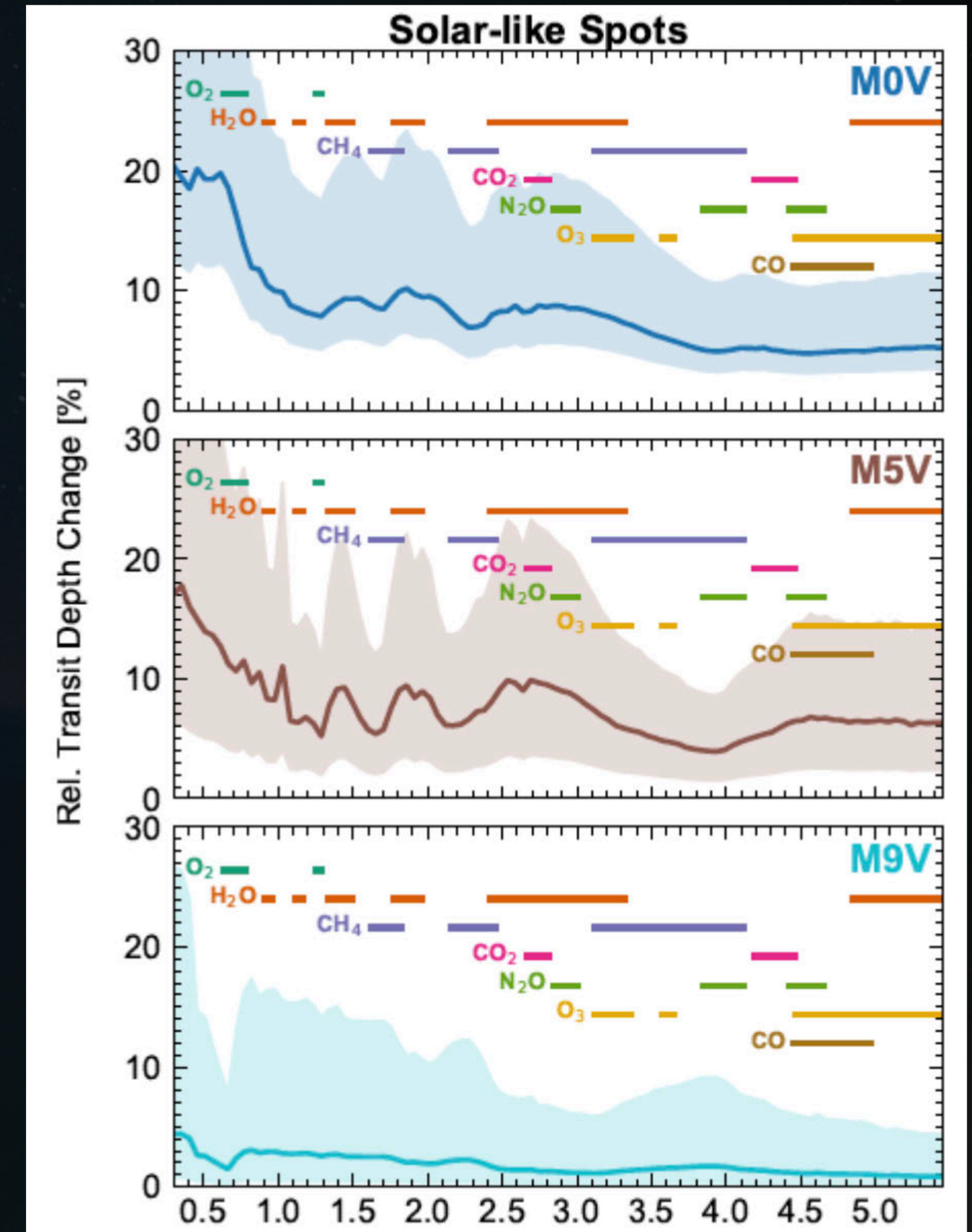


Rackham, Apai, Giampapa 2018

$$\tau_d(\lambda) = \frac{(O \times F_{o,*}(\lambda) + U \times F_{u,*}(\lambda)) - [(O - R_p^2(\lambda)) \times F_{o,*}(\lambda) + U \times F_{u,*}(\lambda)]}{O \times F_{o,*}(\lambda) + U \times F_{u,*}(\lambda)} = 1 - \frac{[(O - R_p^2(\lambda)) \times F_{o,*}(\lambda) + U \times F_{u,*}(\lambda)]}{O \times F_{o,*}(\lambda) + U \times F_{u,*}(\lambda)}$$

STELLAR CONTAMINATION

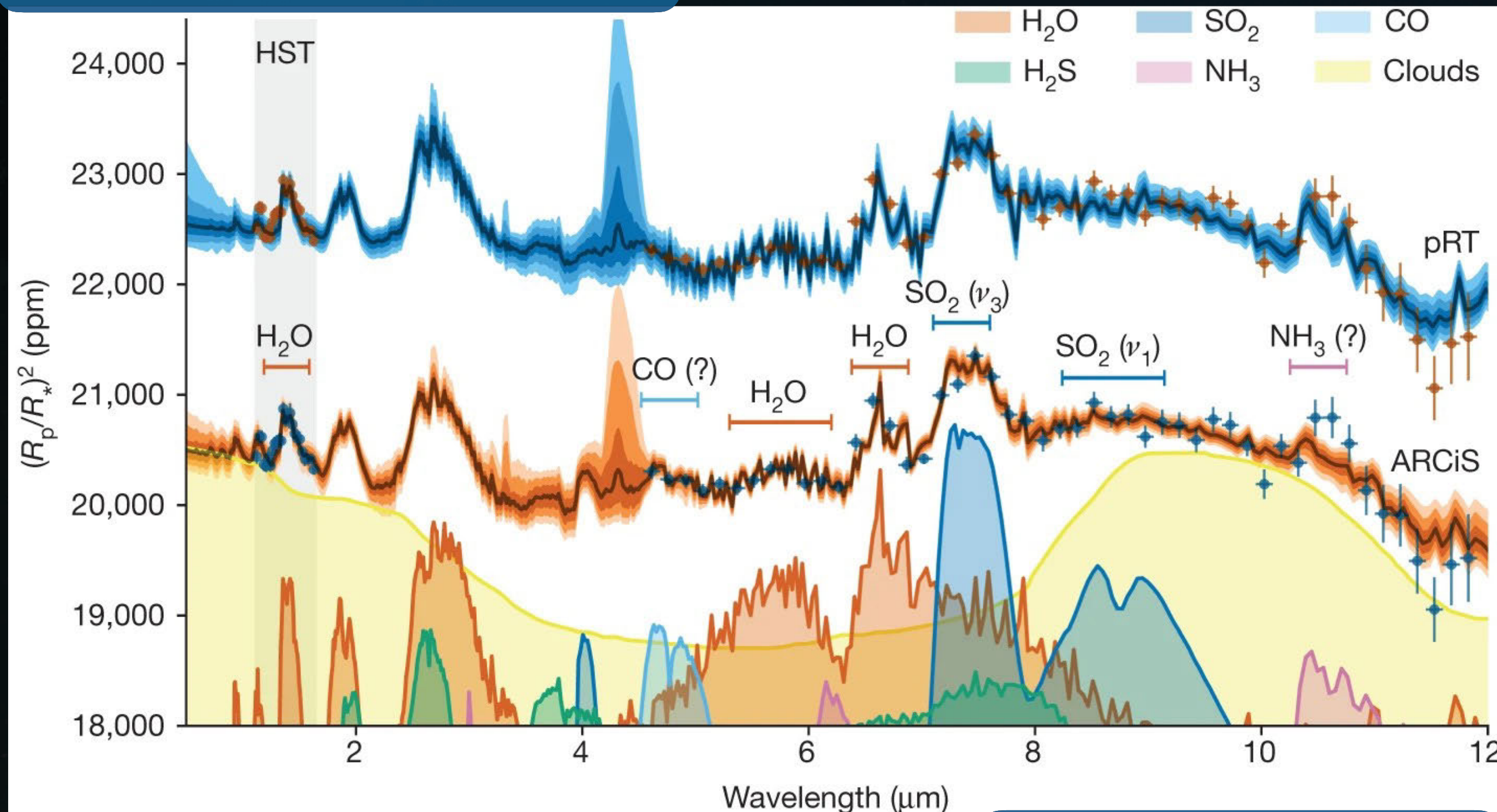
- Photometric variability is a poor measure of stellar heterogeneity
- Stellar heterogeneity contaminates transmission spectra through TLSE
- Contamination can be negligible but can dominate spectra
- For active host stars (many M-dwarfs) TLSE contamination may limit high-precision spectroscopy
- Strong impact on slope in the blue: Often used to probe atm. scatterers



Rackham, Apai, Giampapa 2018

DETECTION OF SILICATE CLOUDS

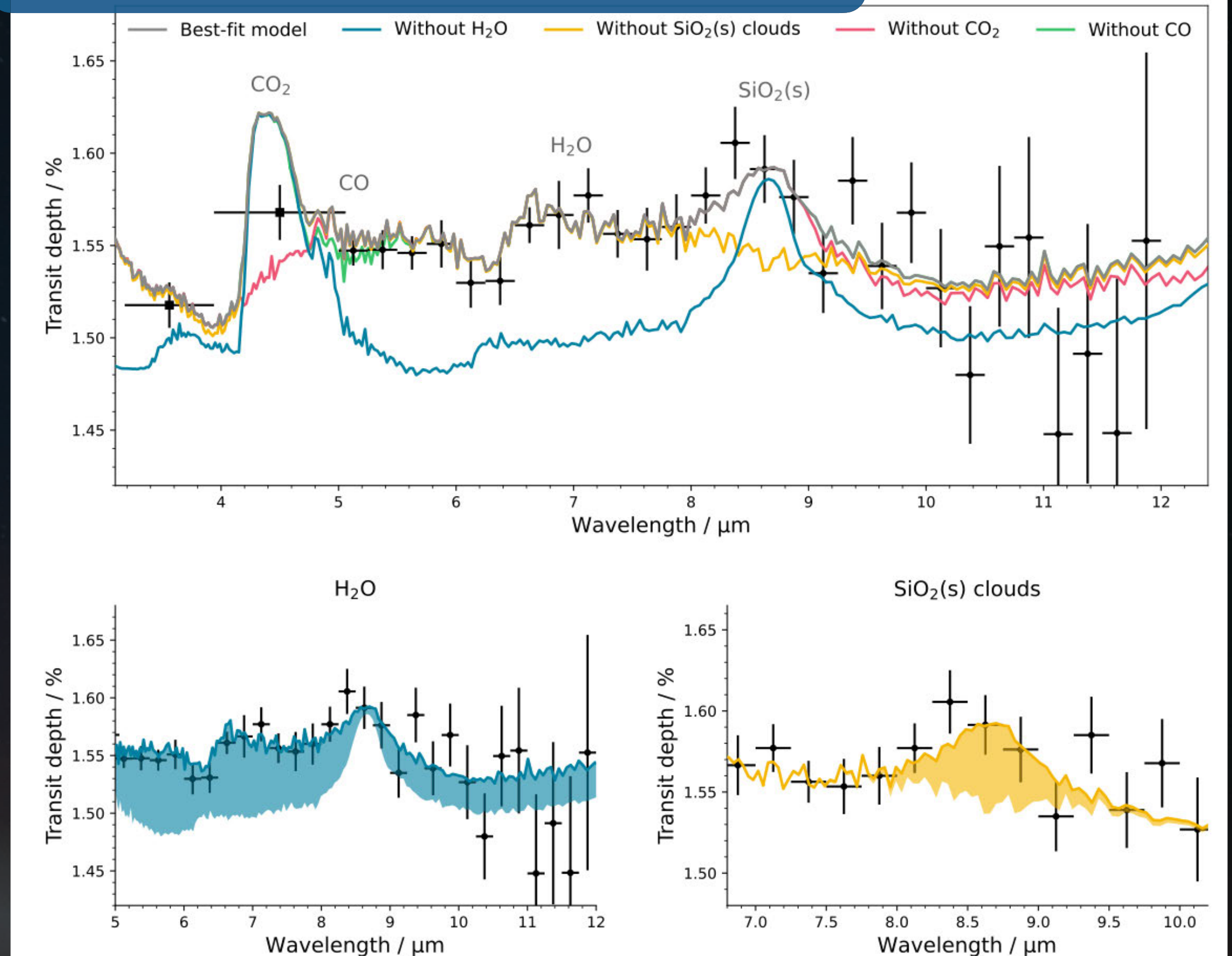
Hot Jupiter: Evidence for silicate particles



WASP-107b – Dyrek et al. (2023)

- Hot Jupiter WASP-107b
- JWST transmission spectrum
- sub-micron amorphous silicate particles

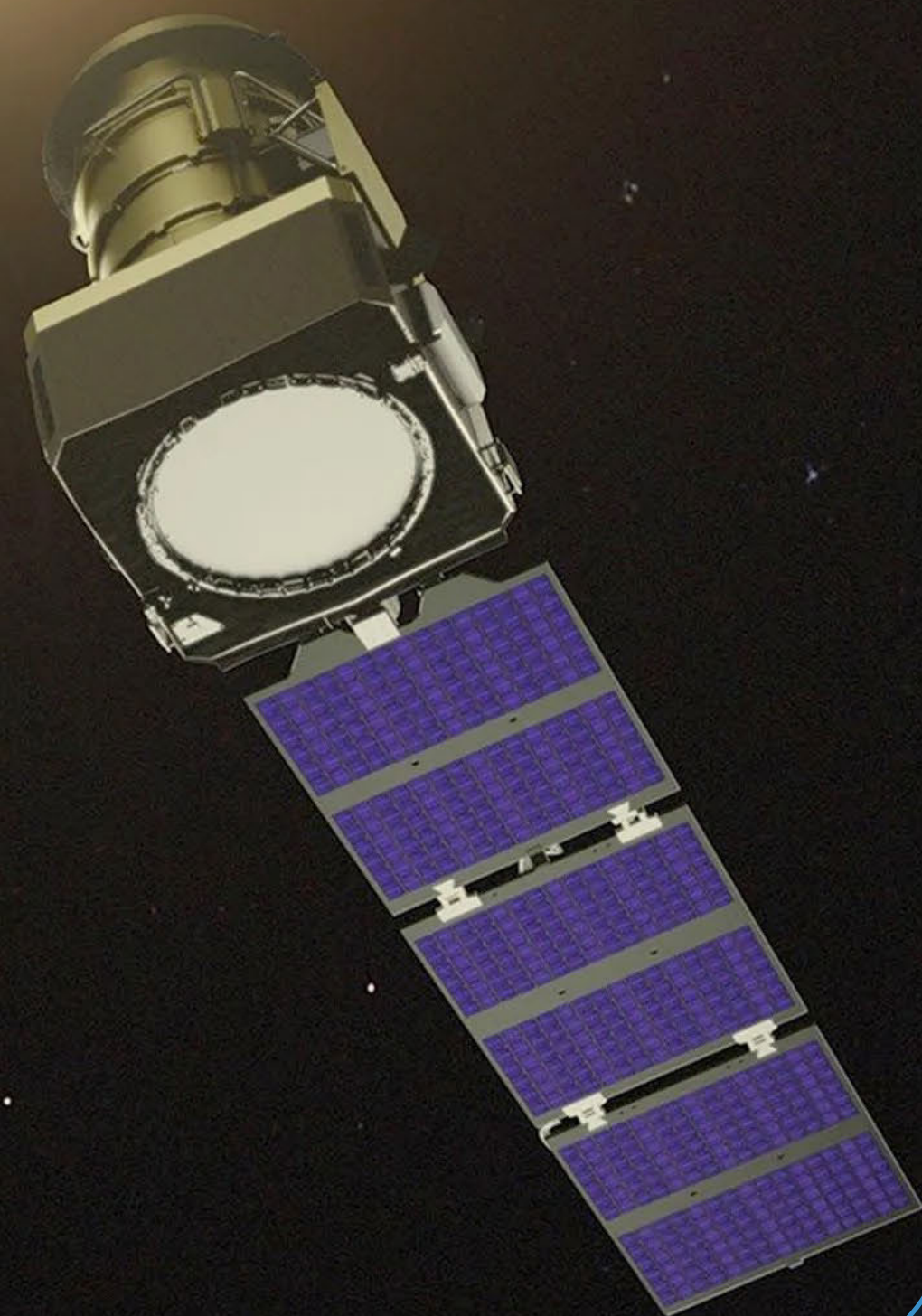
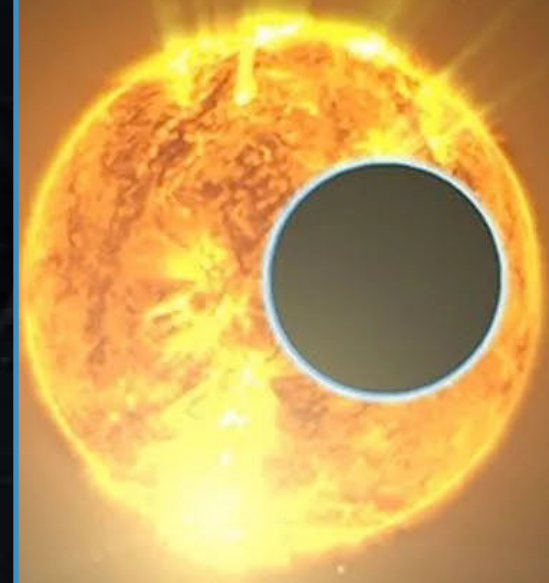
Hot Neptune: Evidence for high-altitude quartz particles



WASP-17b – Grant et al. (2023)

- Hot Neptune WASP-17b
- MIRI transmission spectrum
- Quartz clouds (~ 4 sigma)
- Small particles (~ 10 nm)

PANDORA



**NASA Space Telescope for Exoplanet
Survey Launching in January 2026!**



PANDORA

PI: E. Quintana (GSFC)

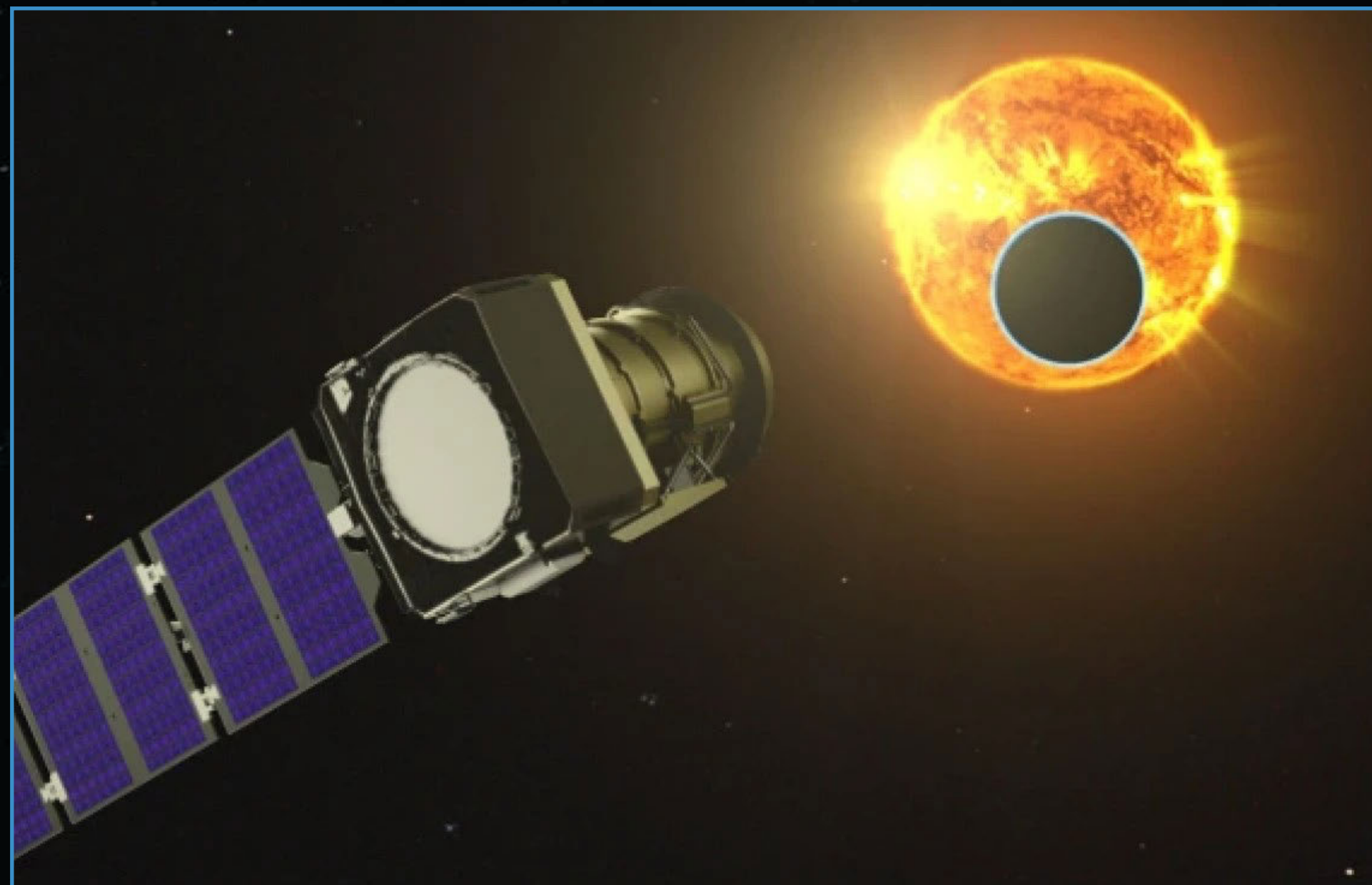
0.45m VIS/NIR spectrophotometry

Goal: Disentangle Stellar and Planetary Signals

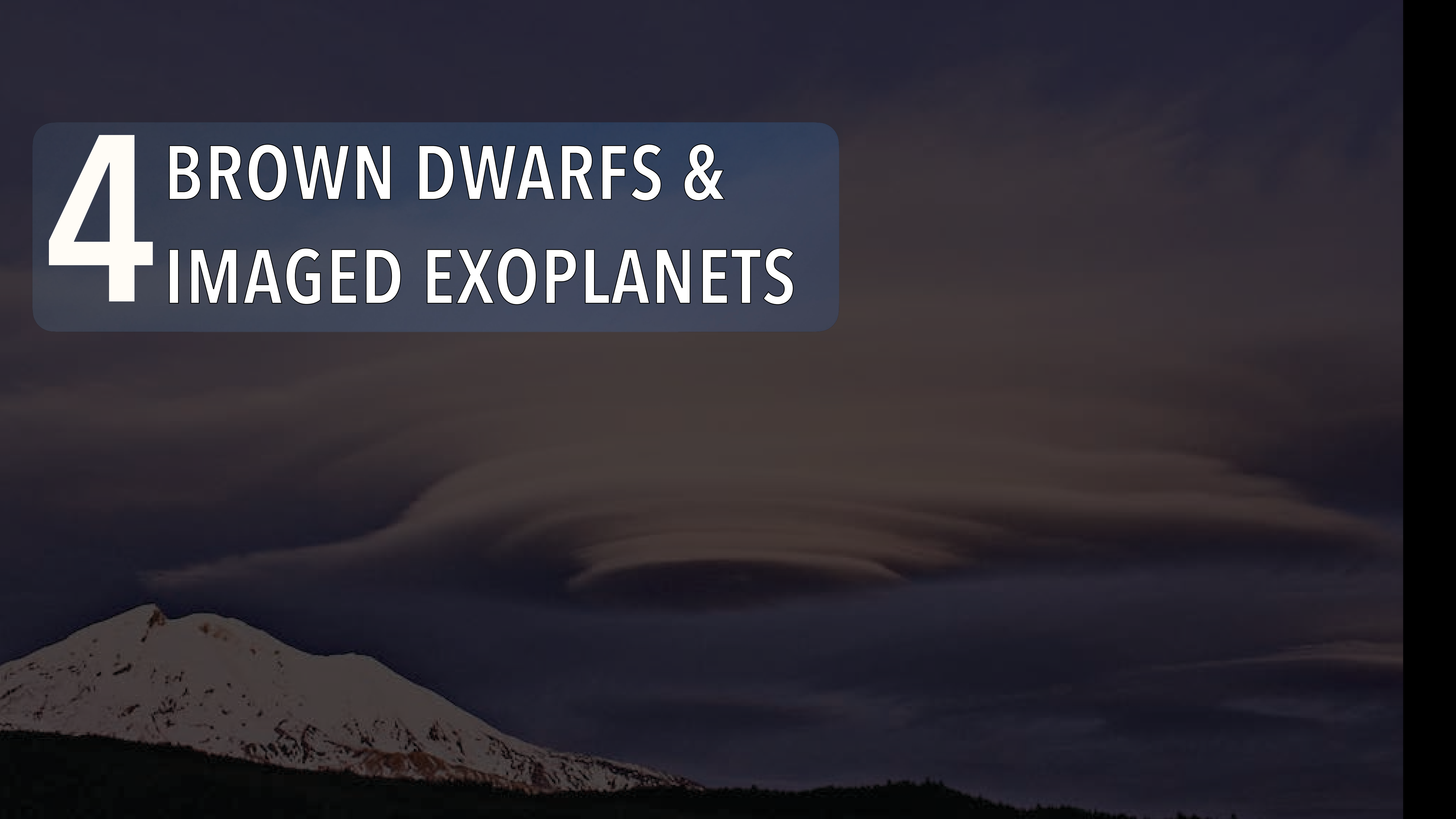
20 exoplanet systems, 10 observations of each

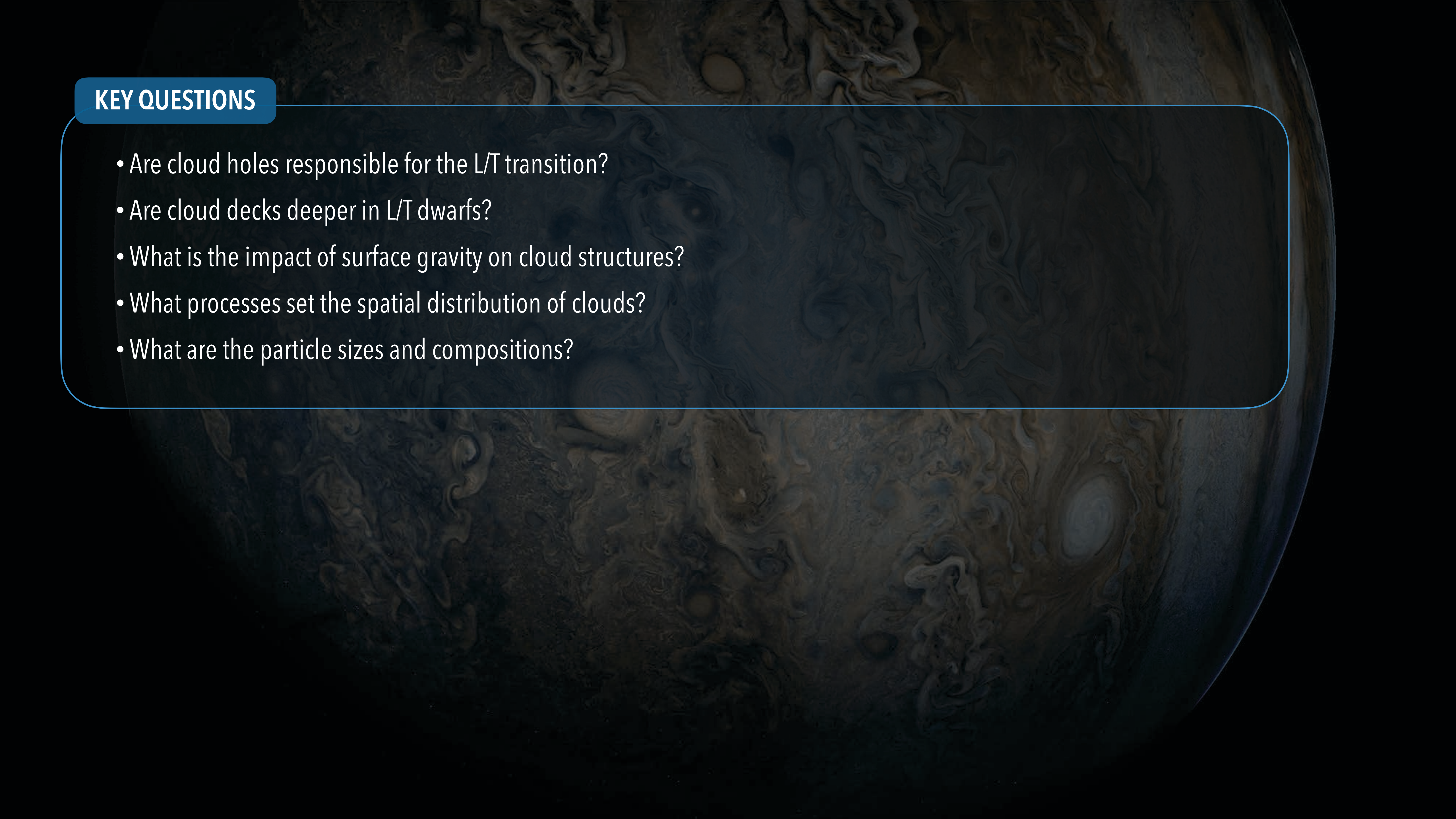
Mission Operations on UA Campus

Launch date: January 5, 2026 w SpaceX Falcon 9



4 BROWN DWARFS & IMAGED EXOPLANETS

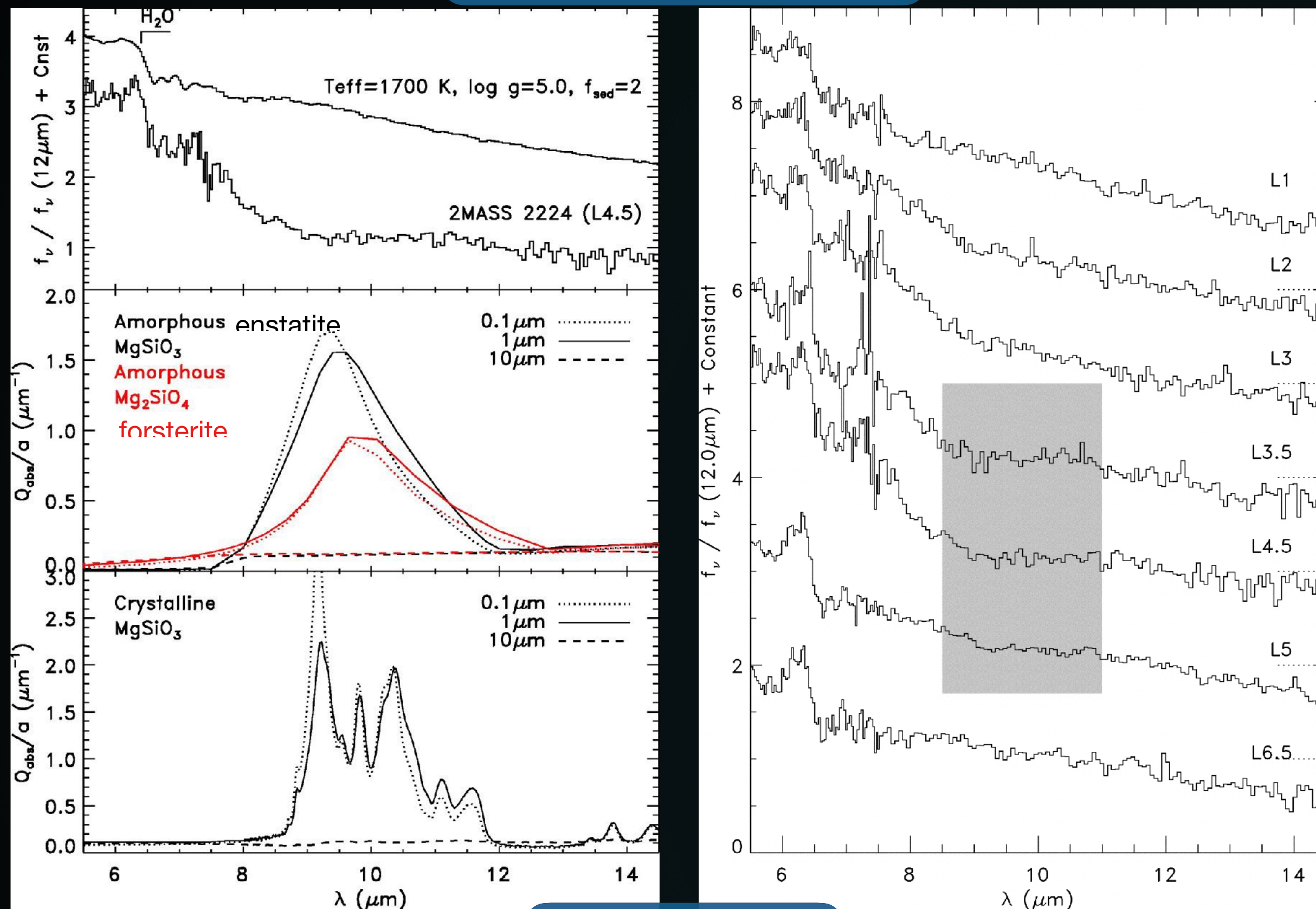




KEY QUESTIONS

- Are cloud holes responsible for the L/T transition?
- Are cloud decks deeper in L/T dwarfs?
- What is the impact of surface gravity on cloud structures?
- What processes set the spatial distribution of clouds?
- What are the particle sizes and compositions?

Direct Feature Detection

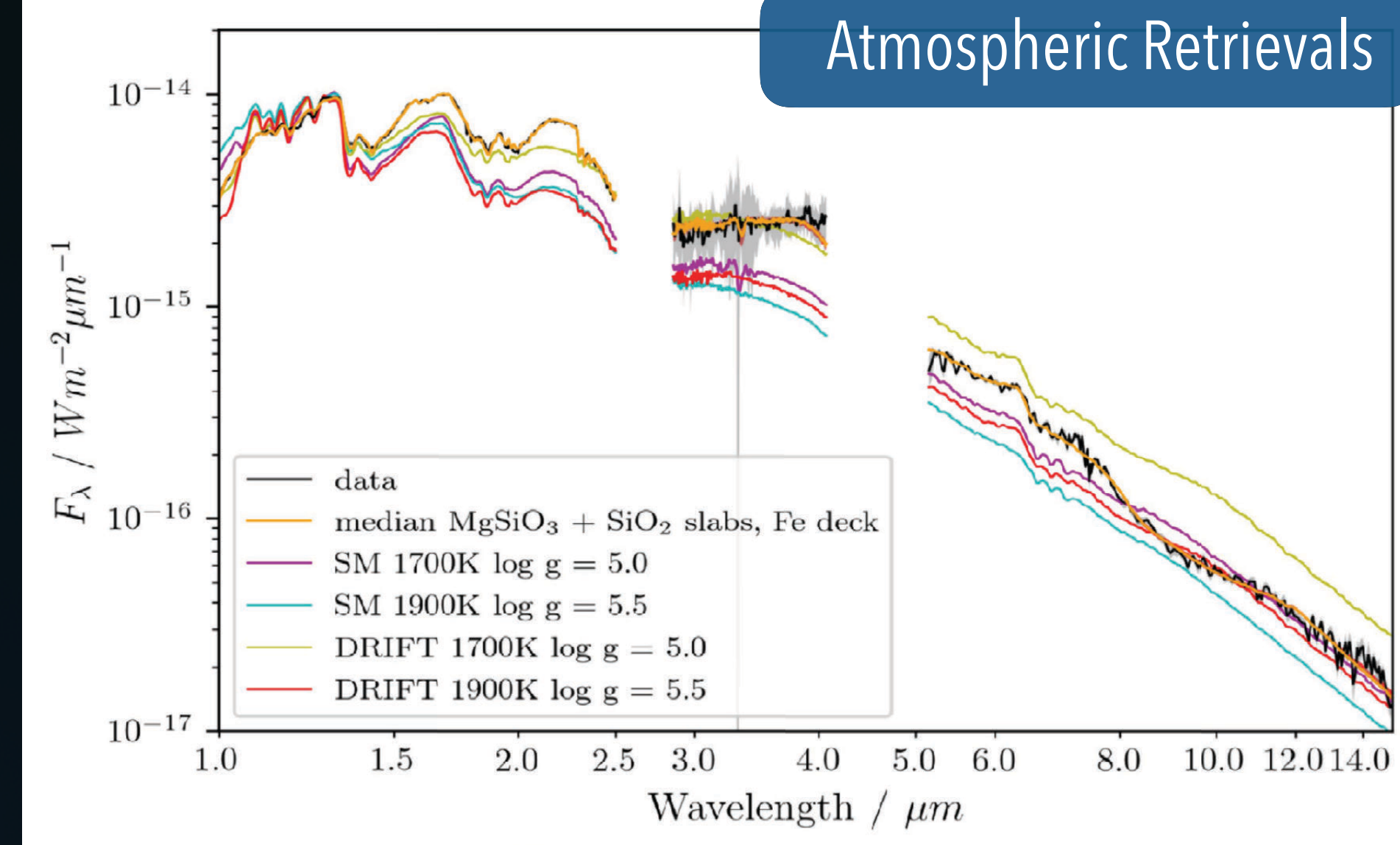


Cushing et al. 2006

see also Suárez & Metchev 2022

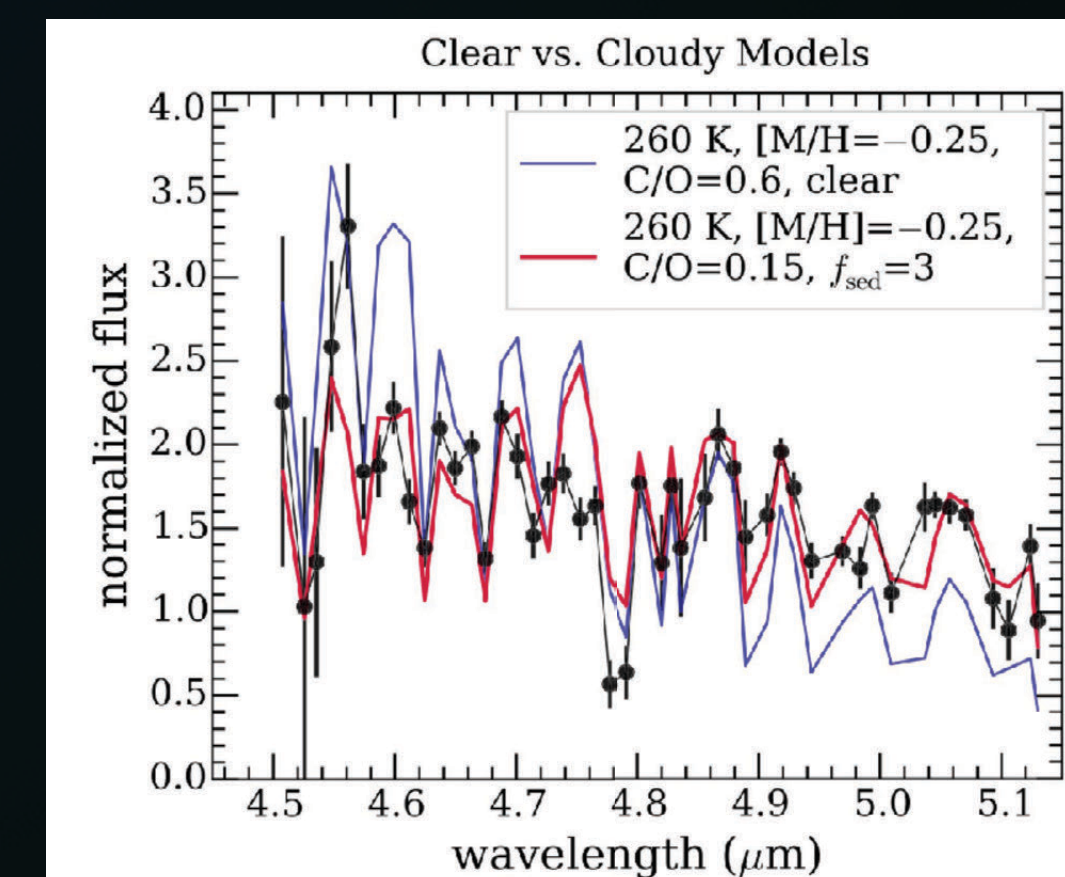
Inference of water ice clouds in WISE0855
(Morley et al. 2018)

Atmospheric Retrievals

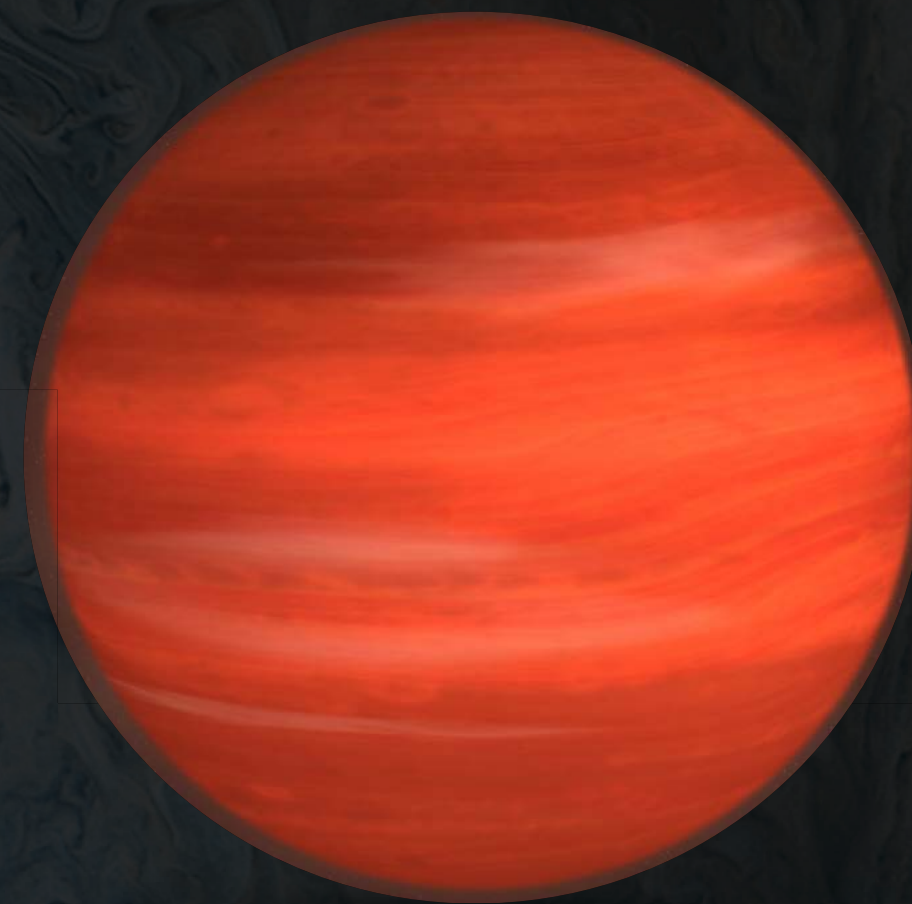
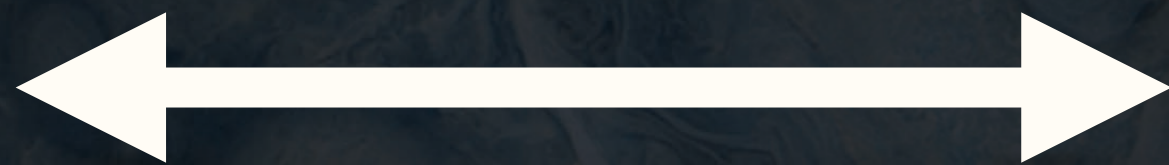
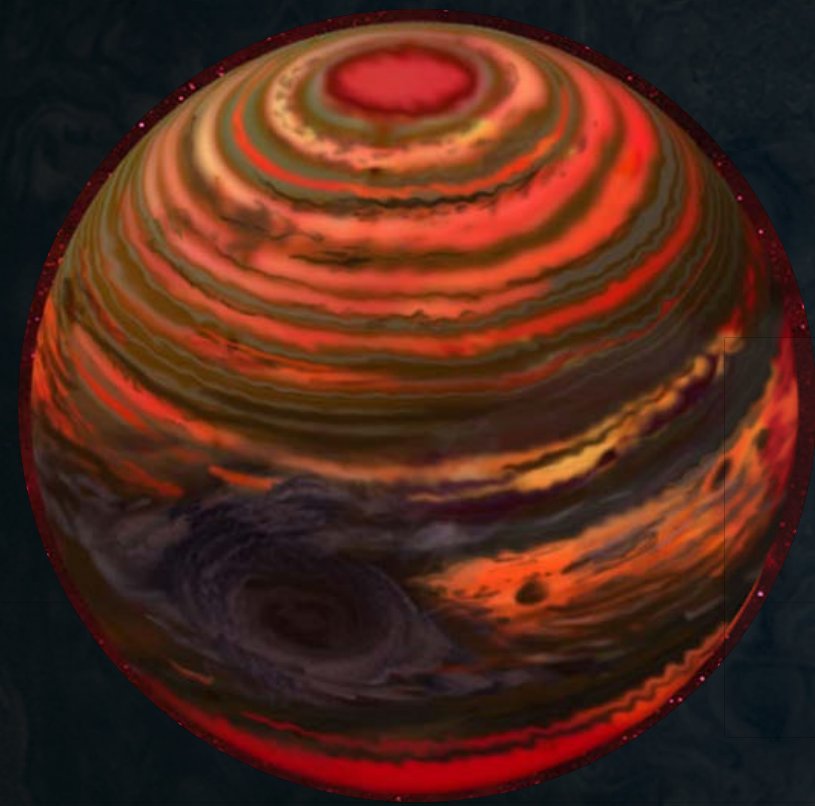


L4.5 dwarf 2M2224-0158 by Burningham et al. (2021)

e.g., Line et al. 2017, Zalesky et al. 2019, Molliere et al. 2020, Vos et al. 2023



IMPORTANCE OF ROTATIONAL PHASE-RESOLVED DATA



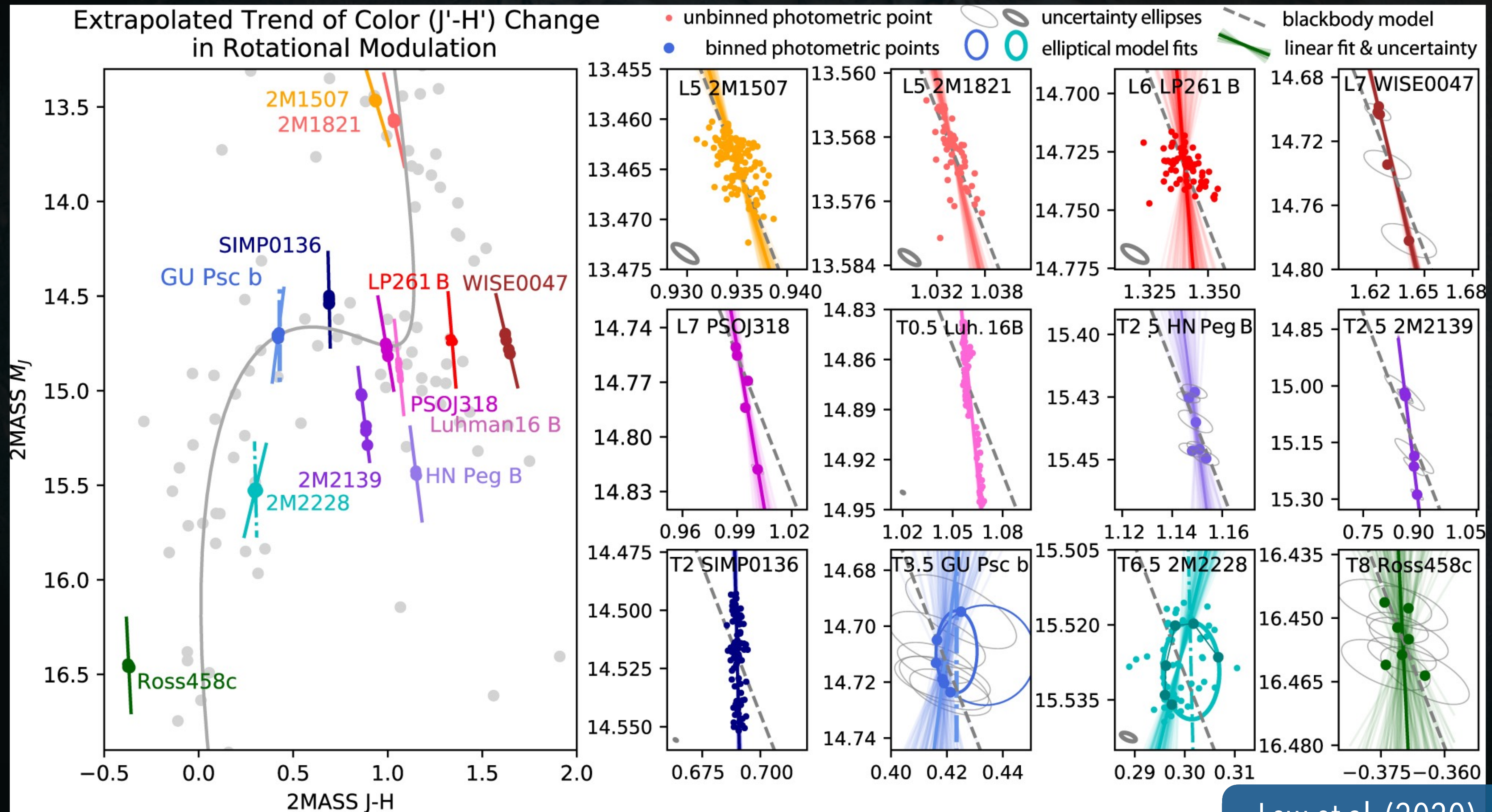
Temperature, Log g , Composition, Age, Vertical Mixing, Cloud Structure

SPATIALLY RESOLVED STUDIES: COMPARATIVE STUDY WITHIN GIVEN ATMOSPHERES



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

WEAK COLOR MODULATIONS: GRAY EXTINCTION

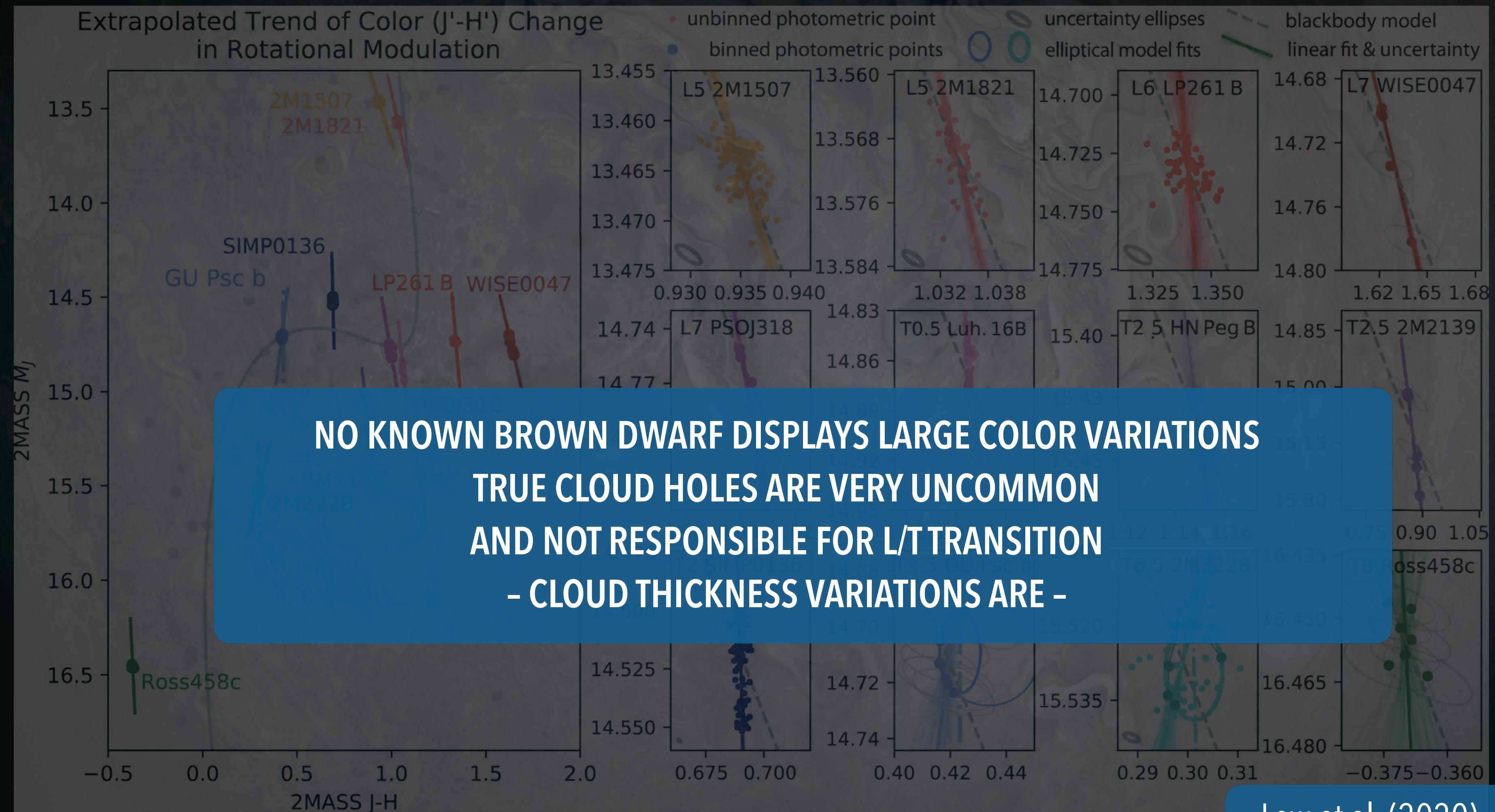


Lew et al. (2020)

Conclusion: ~Micron-sized grains.

See also: Radigan et al. 2012, Apai et al. 2013, Biller et al. 2013, Burgasser et al. 2014, Cloud Atlas (11 papers)

WEAK COLOR MODULATIONS: GRAY EXTINCTION



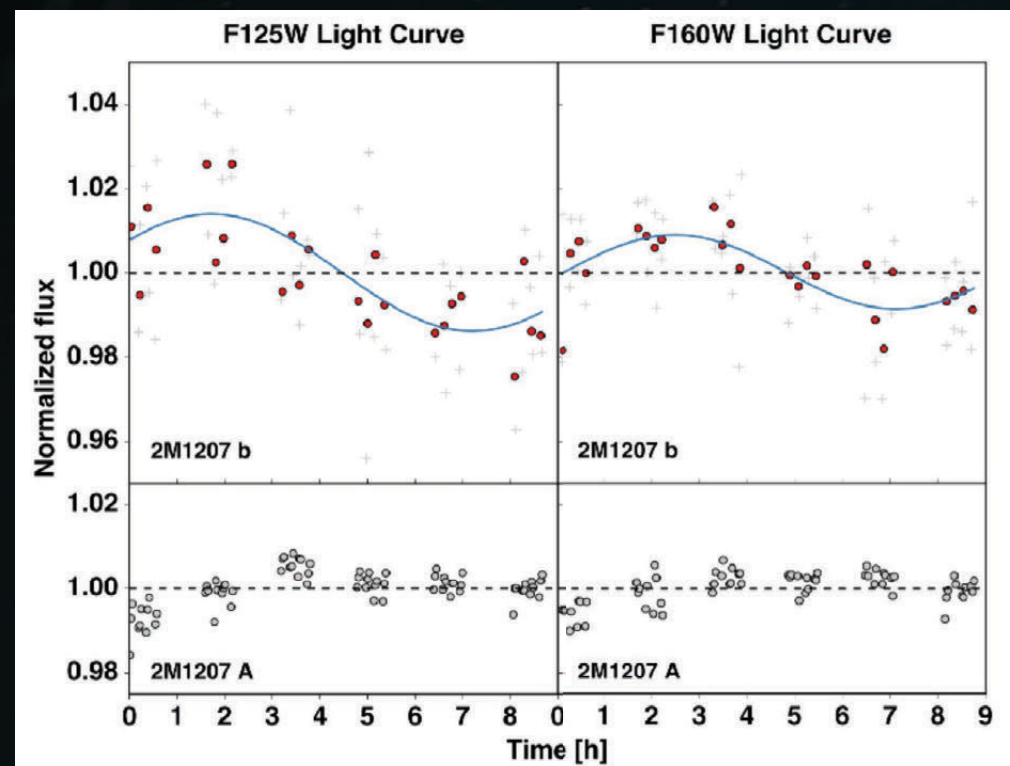
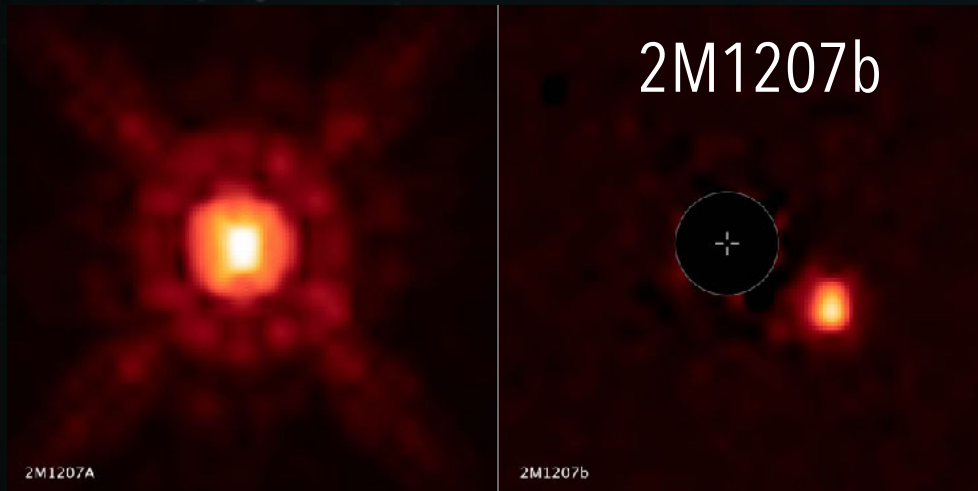
**NO KNOWN BROWN DWARF DISPLAYS LARGE COLOR VARIATIONS
TRUE CLOUD HOLES ARE VERY UNCOMMON
AND NOT RESPONSIBLE FOR L/T TRANSITION
- CLOUD THICKNESS VARIATIONS ARE -**

Lew et al. (2020)

Conclusion: ~Micron-sized grains.

See also: Radigan et al. 2012, Apai et al. 2013, Biller et al. 2013, Burgasser et al. 2014, Cloud Atlas (11 papers)

TIME-RESOLVED SPECTROPHOTOMETRY OF LOW-MASS BROWN DWARFS, PLANETARY-MASS OBJECTS, AND EXOPLANETS



Zhou et al. 2016

Atmospheric Scale Height:

$$H = \frac{kT}{\mu_m m_H g}$$

Very low-mass brown dwarfs/companions:

WISE0047 (Lew et al. 2016, 2020; Vos et al. 2018)

AB Pic B (Zhou et al. 2019)

LP 261-75B (Manjacas et al. 2018)

2M2244 (Vos et al. 2018)

Planetary-mass:

PSO J318.5-22 (Biller et al. 2015)

HD203030b (Miles-Paez et al. 2019)

SIMP0136 (Artigau et al. 2009, Apai et al. 2013, 2017)

2M2139 (Radigan et al. 2012, Apai et al. 2013, 2017)

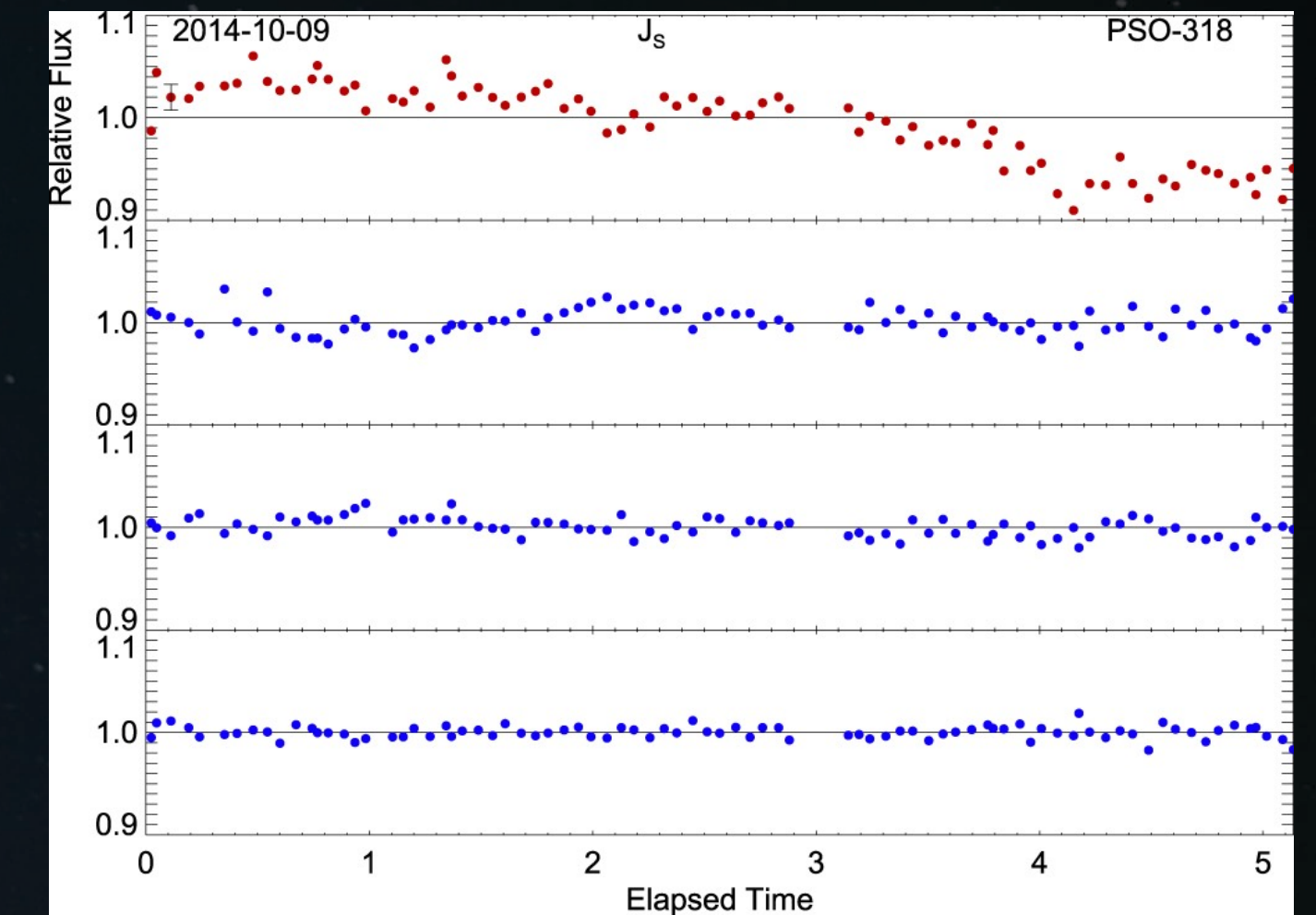
Planetary-mass companions:

2M1207B (Zhou et al. 2016, 2019)

HN Peg B (Zhou et al. 2018)

HD106906b (Zhou et al. 2020)

Ross 458C (Manjavacas et al. 2019)



PSO J318.5-22 – Biller et al. (2015)

Higher amplitudes in low-g?

Metchev et al. 2015

Biller et al. 2015, Vos et al. 2020

Cooler Objects

Some (cloud) heterogeneity even in T dwarfs and Y dwarfs

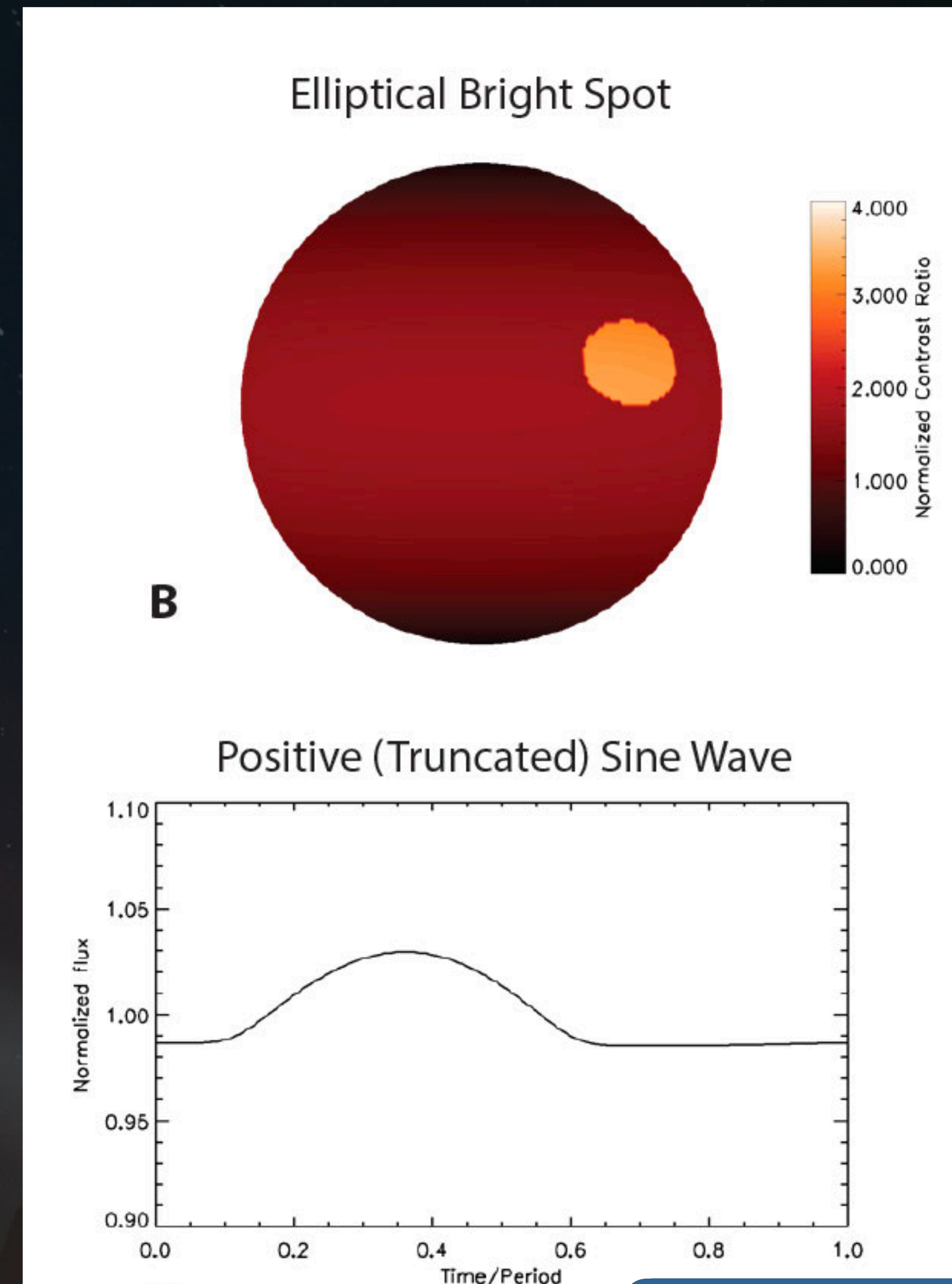
(e.g., Esplin et al. 2016, Leggett et al. 2016, Cushing et al. 2016, Manjavacas et al. 2019)

5 ATMOSPHERIC DYNAMICS

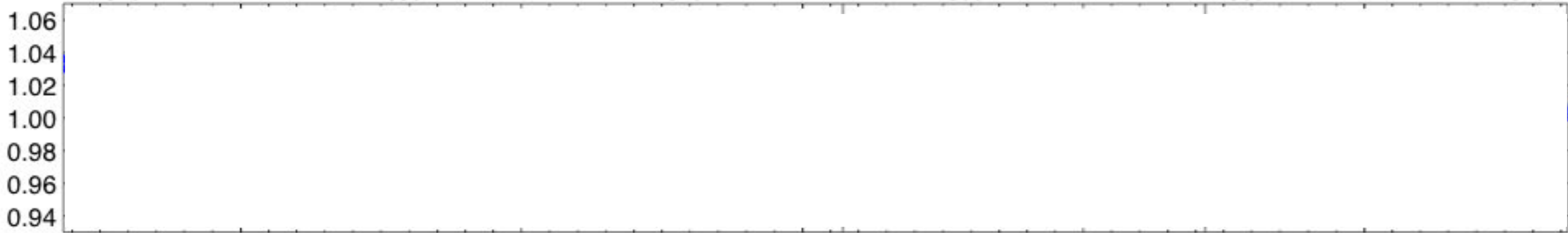




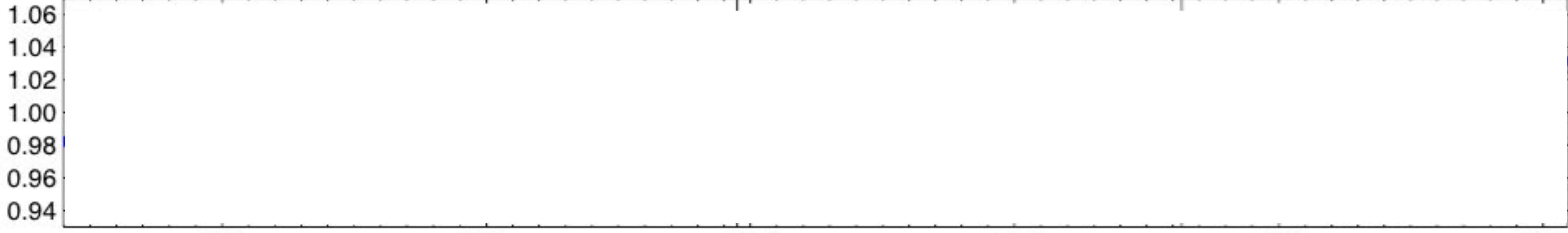
Extrasolar Storms



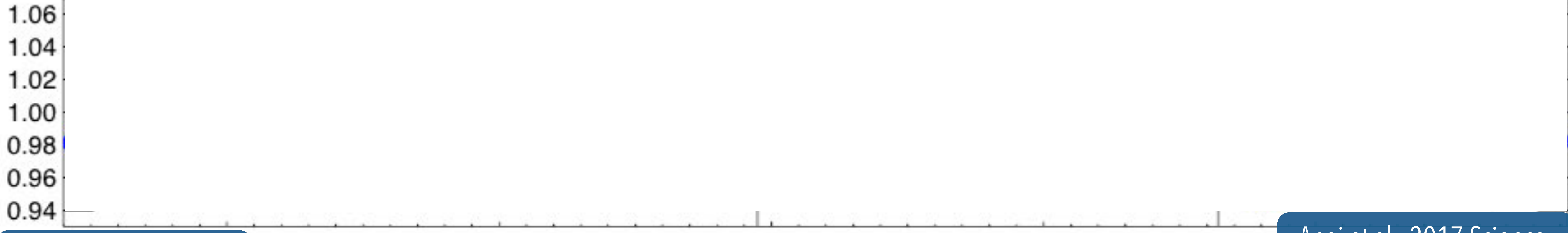
Apai et al., 2017 Science



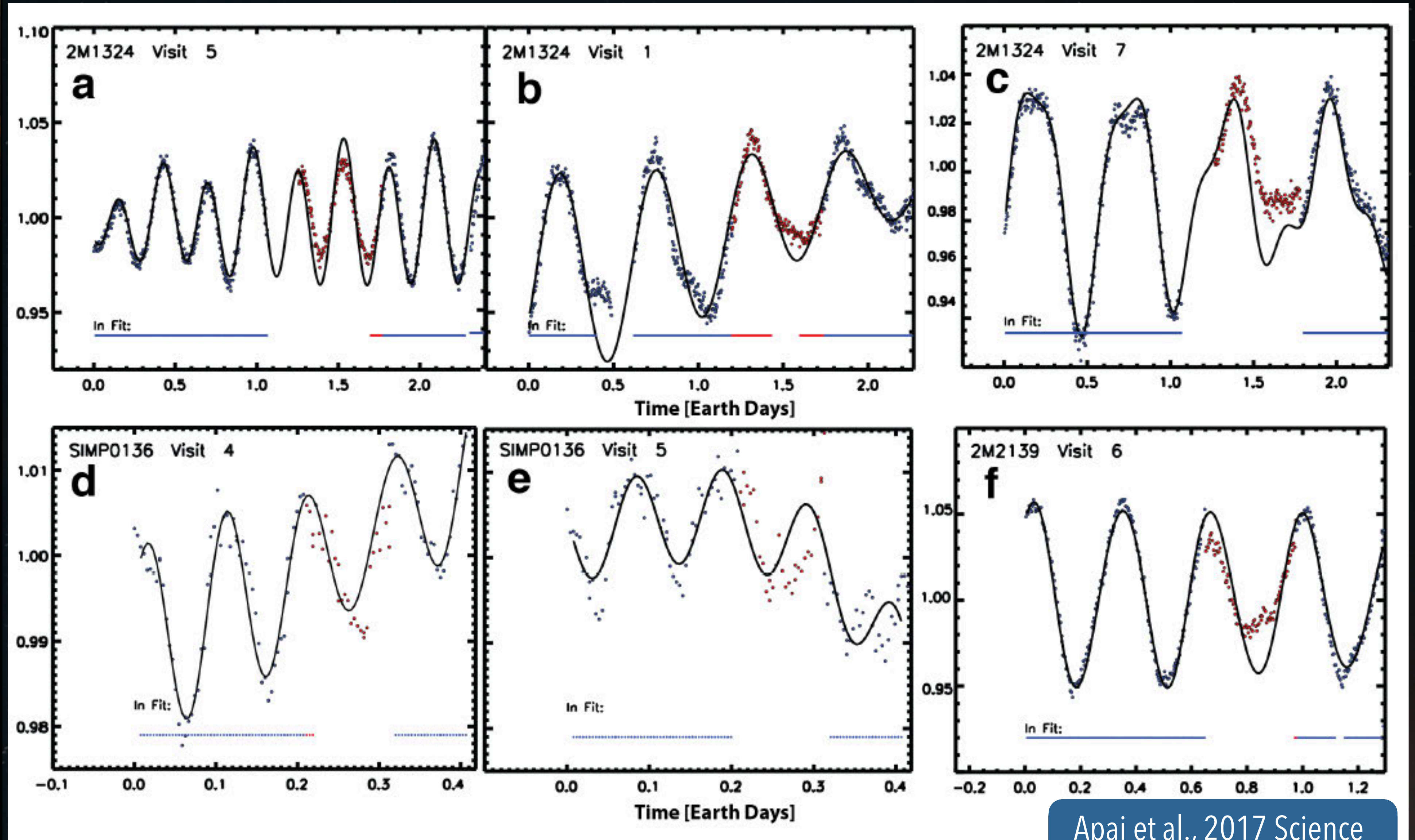
1980 1990 2000 2010 2020



9160 9170 9180 9190 9200 9210



9700 9710 9720

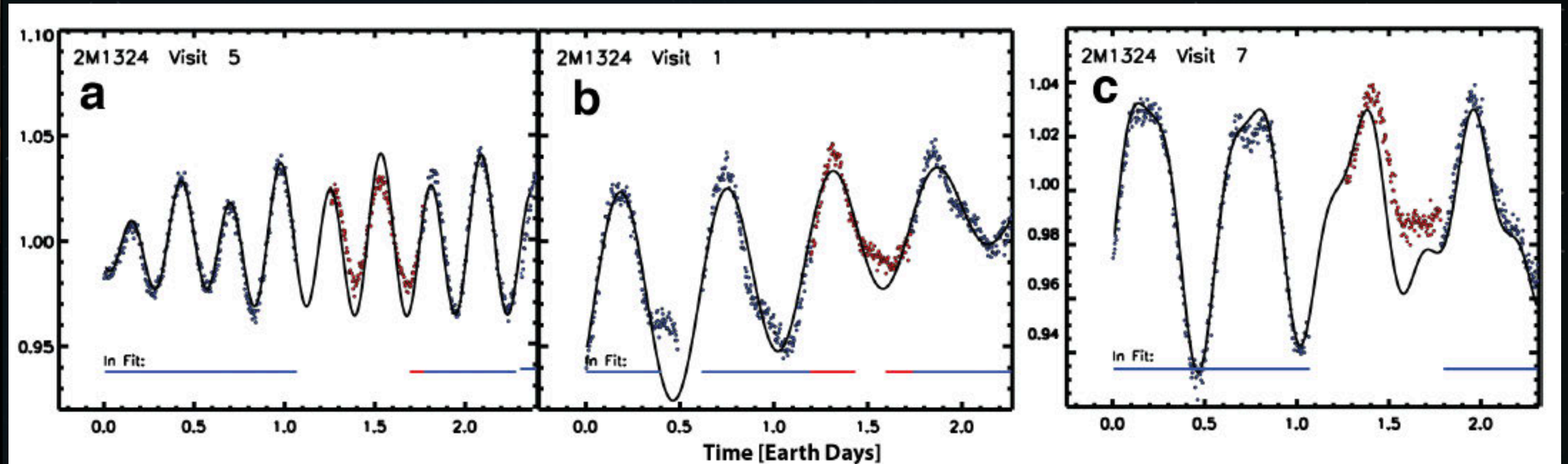


Extrasolar Storms

Apai et al., 2017 Science



Extrasolar Storms

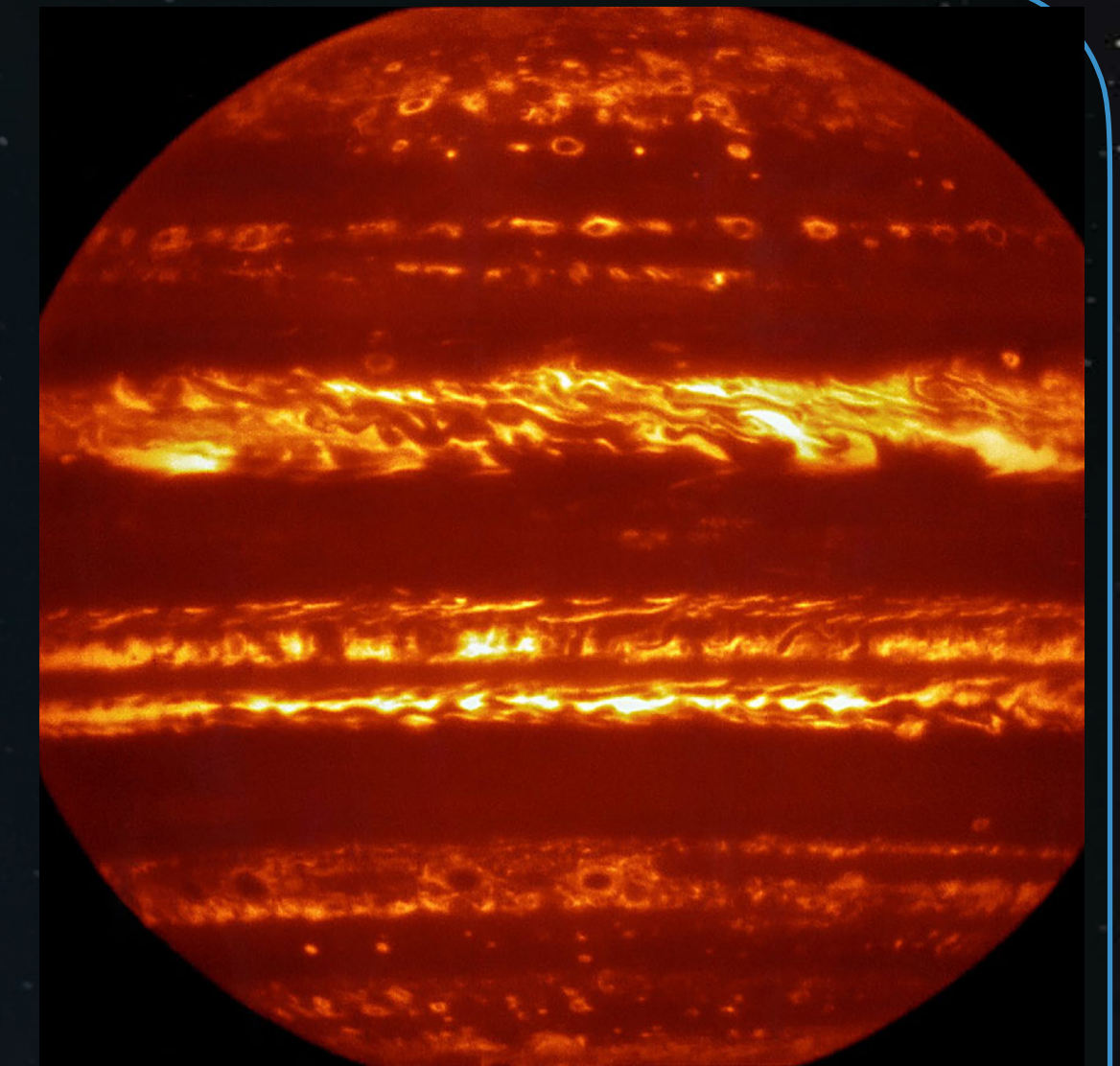
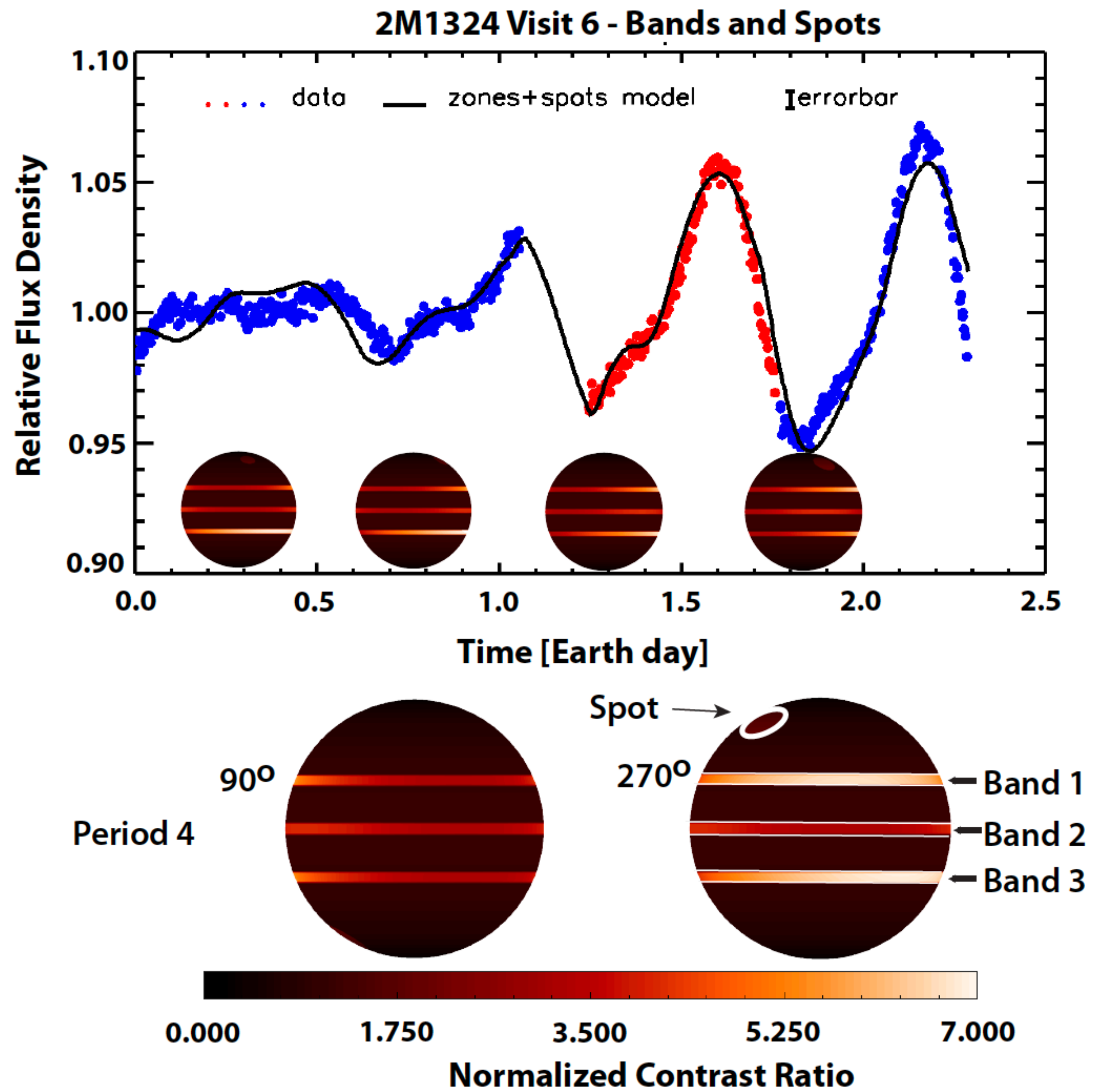


Planetary-scale waves reproduced multi-epoch (8 x 4-rotations) for three L/T transition BDs

Apai et al., 2017 Science



Extrasolar Storms



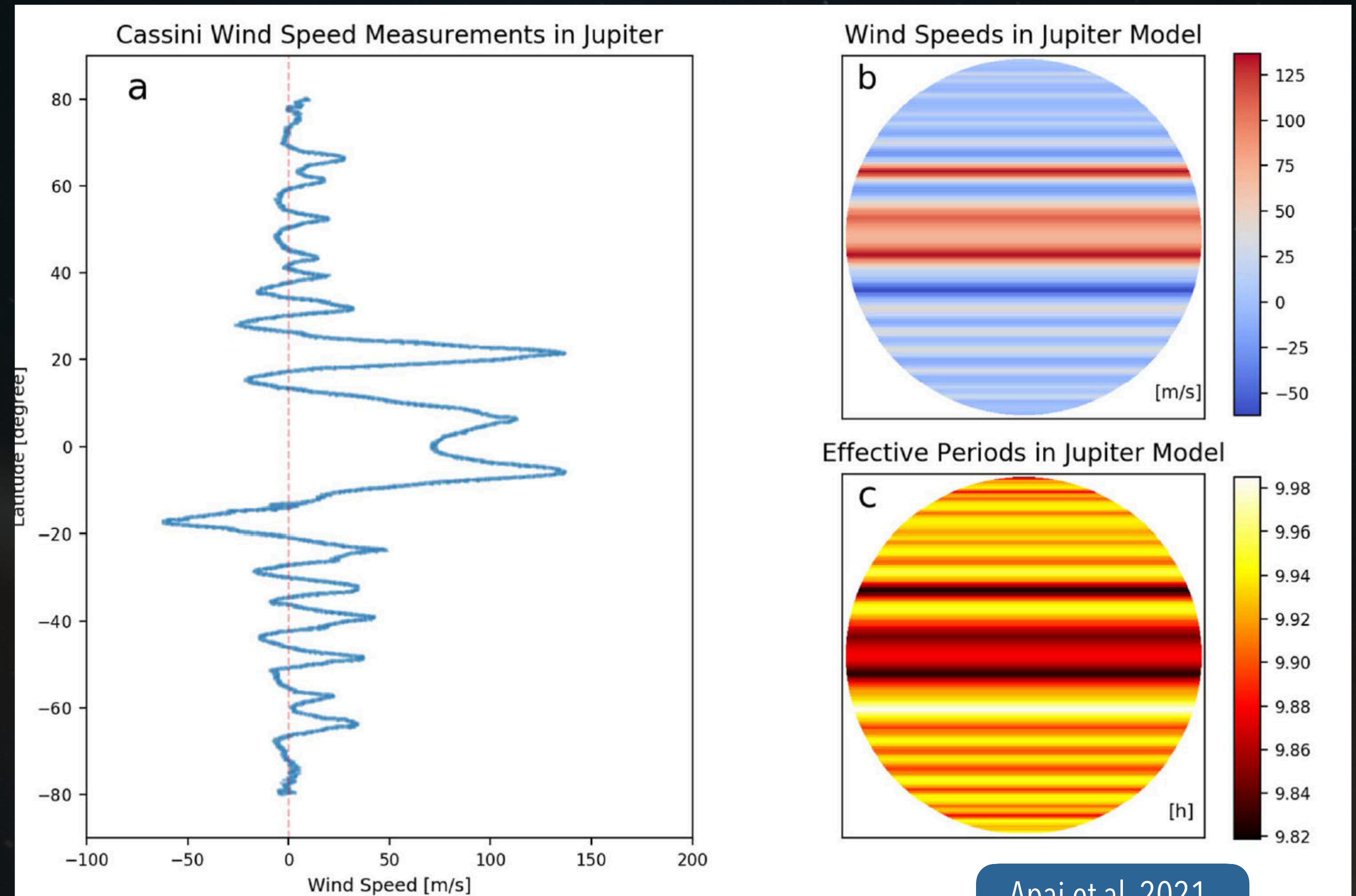
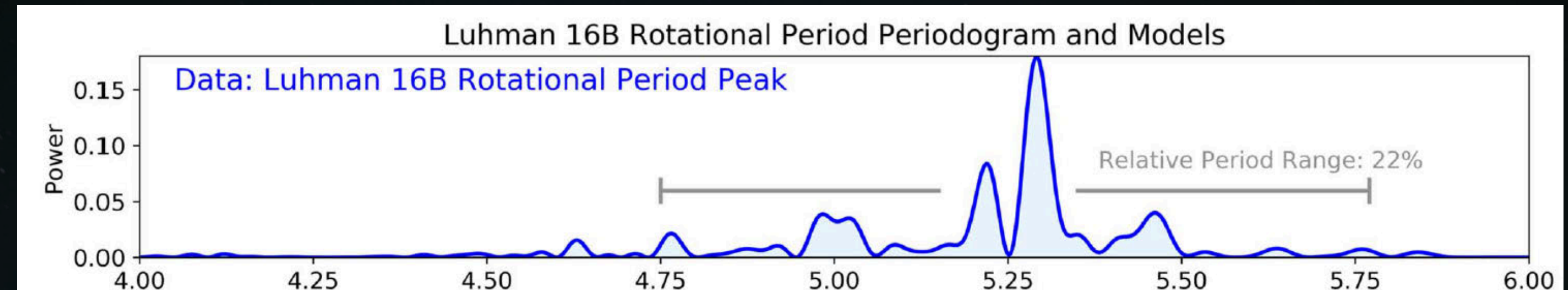
Jupiter in thermal IR (ESO)

Apai et al., 2017 Science

COMPARISON TO JUPITER

Wind speeds - Cassini (Porco et al. 2003)

Toy model to predict periodogram

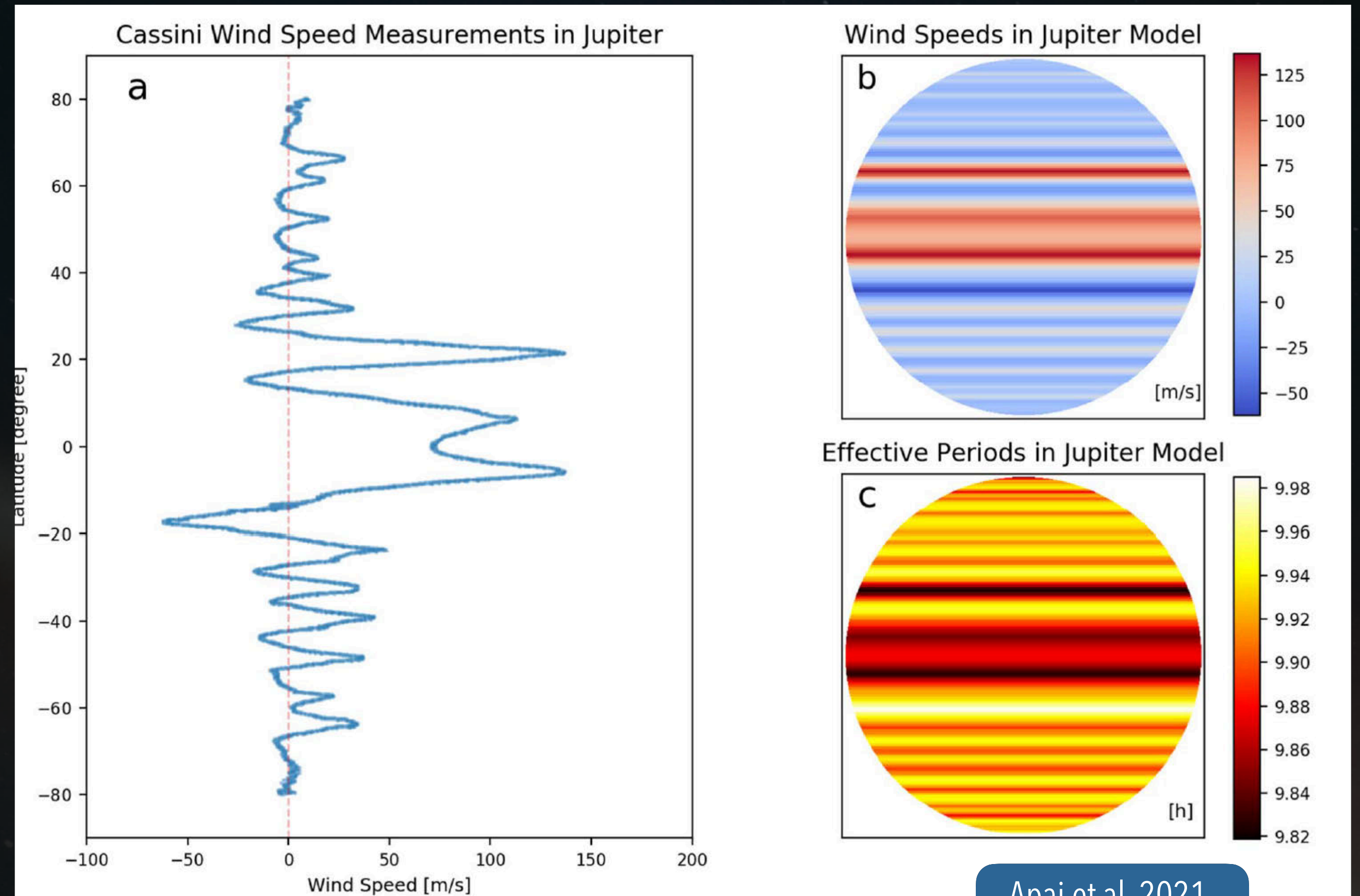
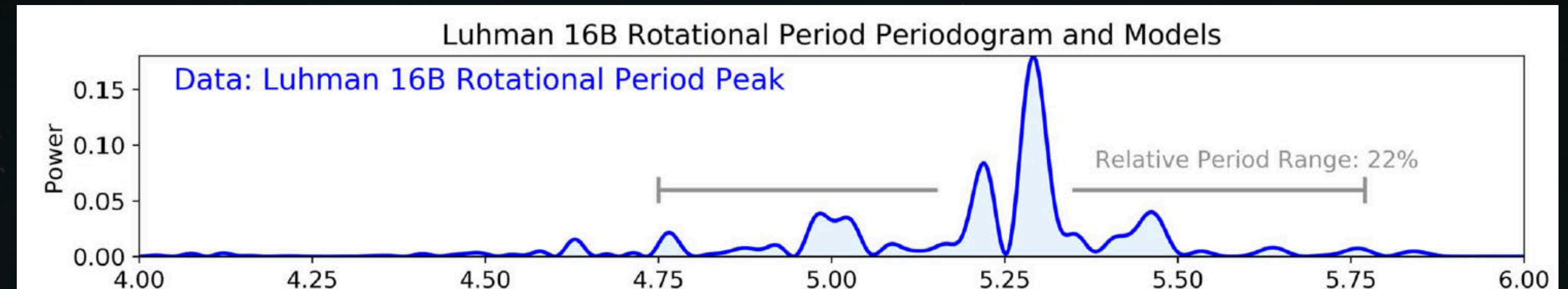
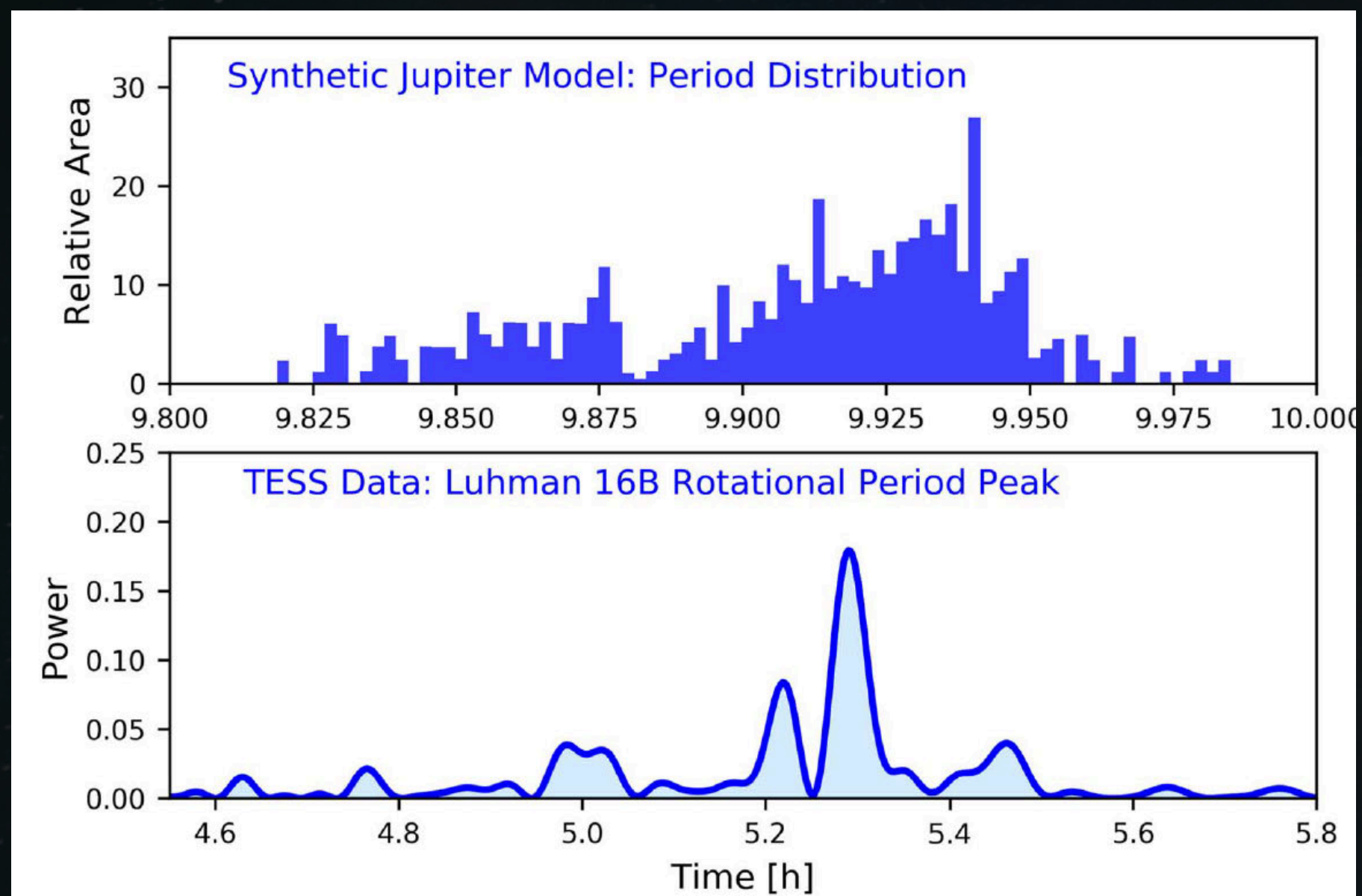


Apai et al. 2021

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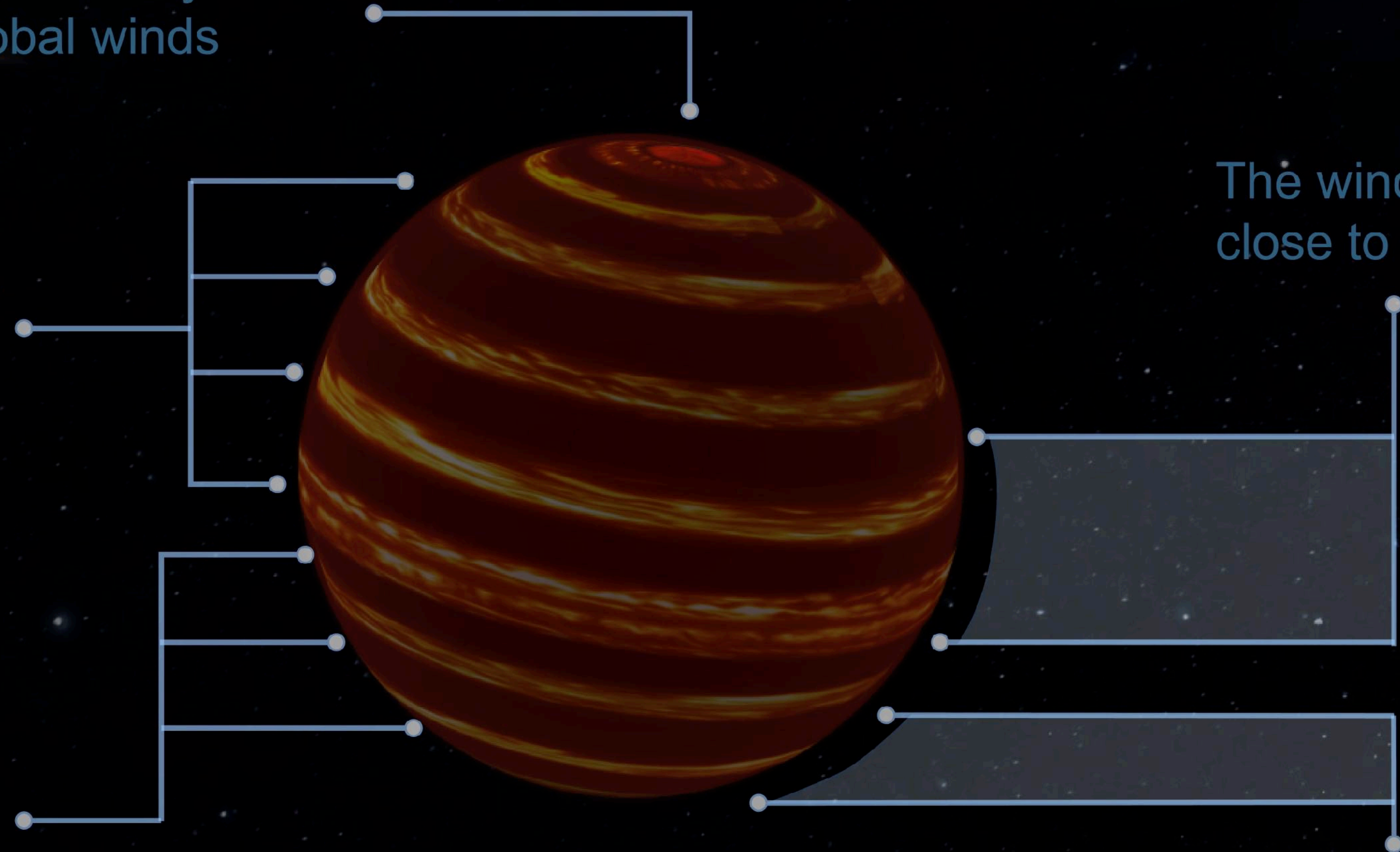
Apai et al. 2021

Global Winds and Polar Storms in the Nearby Brown Dwarf Luhman 16B

The polar regions are dominated by local storms and not by global winds

The light zones have thin cloud decks illuminated by light from the hot interior

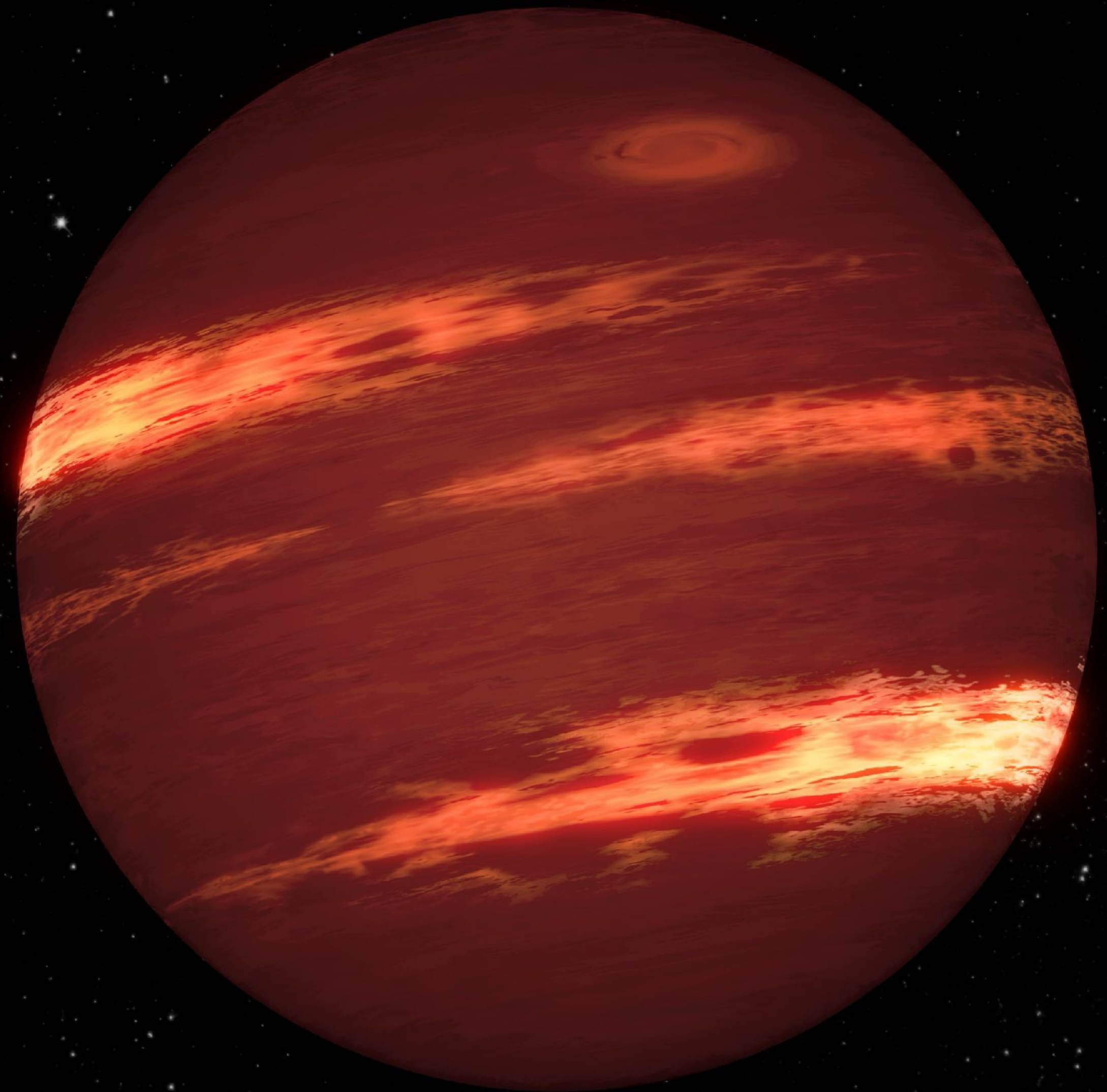
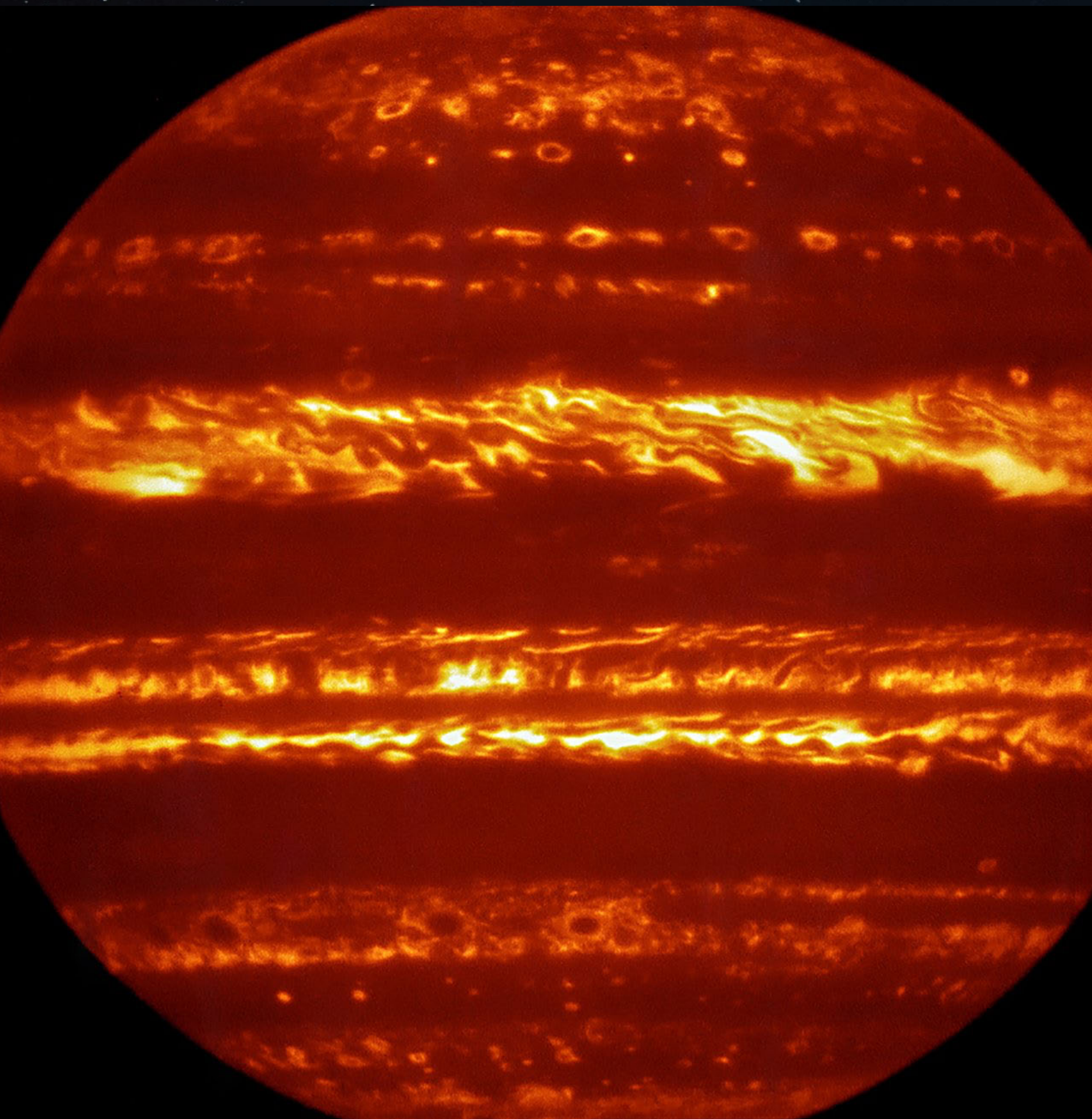
In dark belts thick cloud decks block light from the hot interior



The winds are fastest close to the equator

The winds are slower close to the poles

Apai et al. 2021; Fuda, Apai et al. 2024; Fuda & Apai 2024



SUMMARY

- Condensate clouds and haze layers are inferred from observations and likely very common
- Data on particle sizes, composition is limited but improving
- Complex, multi-component, multi-layer, time-evolving clouds are expected
- Time-differential measurements are important in disentangling degenerate signals
- Atmospheric circulation is very important: Cloud formation/distribution is shaped by it
- Strong evidence for silicate condensate clouds with cloud thickness variations
- Forced circulation (in heavily irradiated planets) and zonal circulation/jets and atmospheric waves (in non-irradiated planets)

