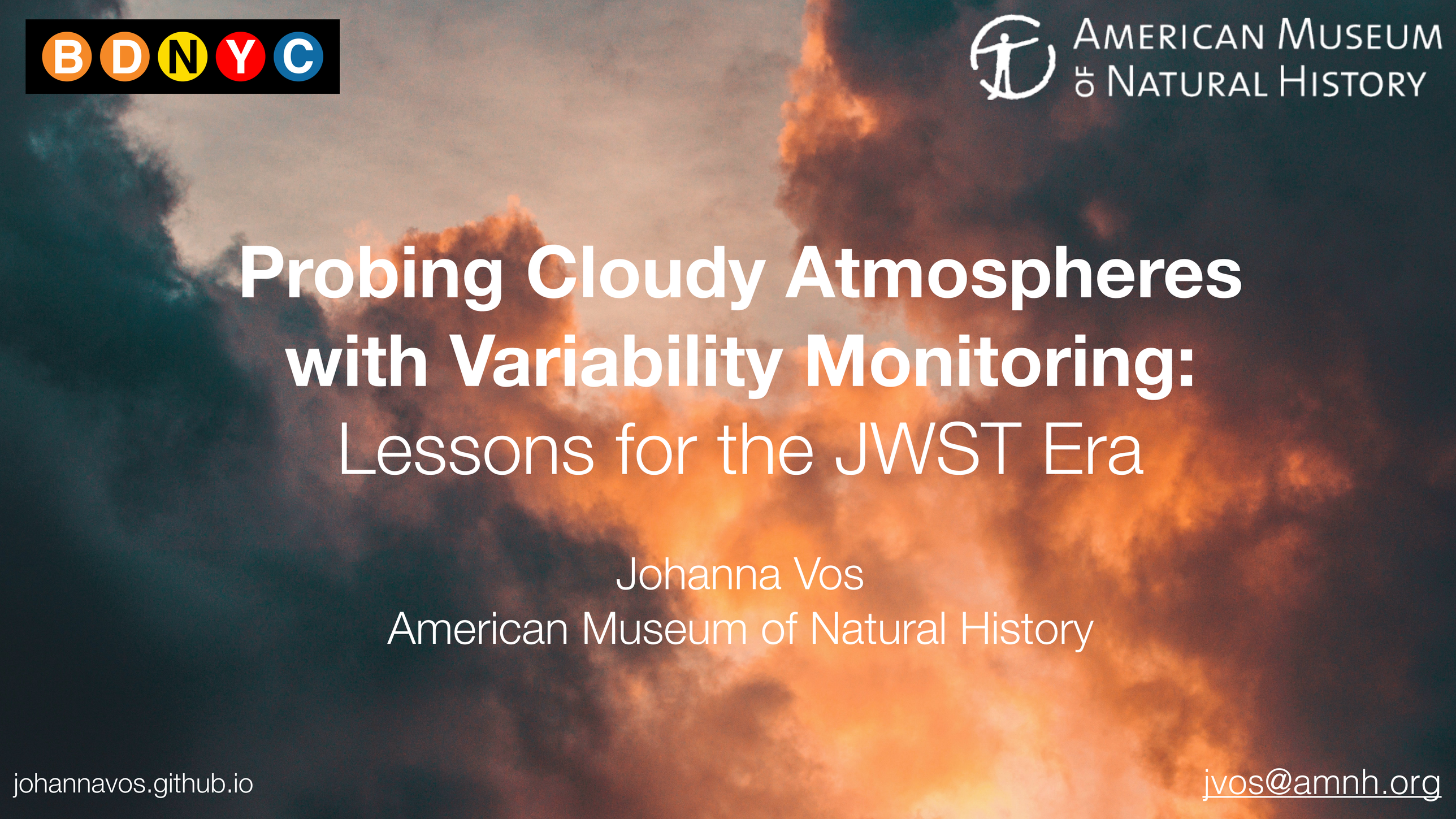

Probing Cloudy Atmospheres with Variability Monitoring: Lessons for the JWST Era

Johanna Vos
American Museum of Natural History

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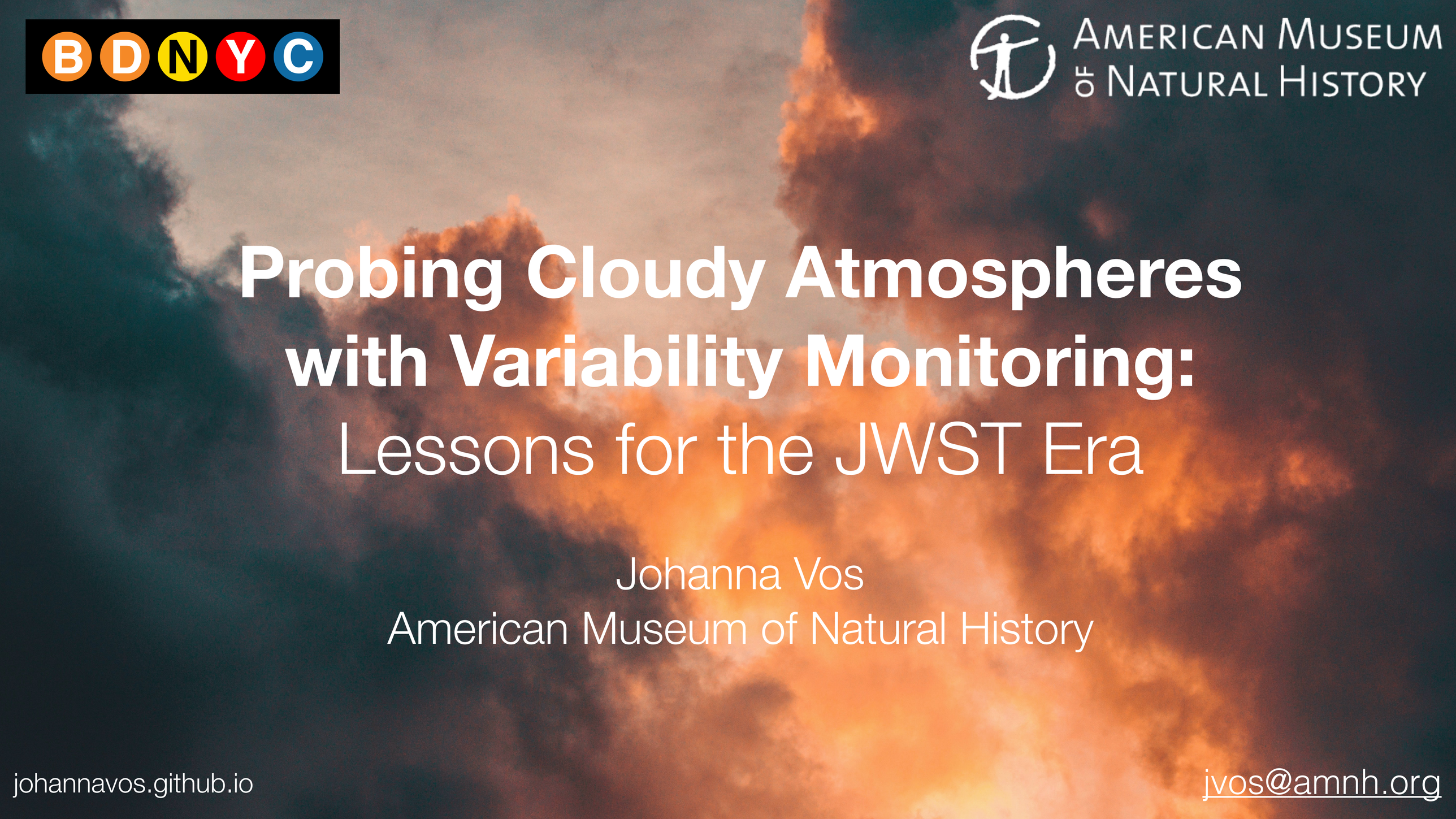

Probing Cloudy Atmospheres with Variability Monitoring: Lessons for the JWST Era

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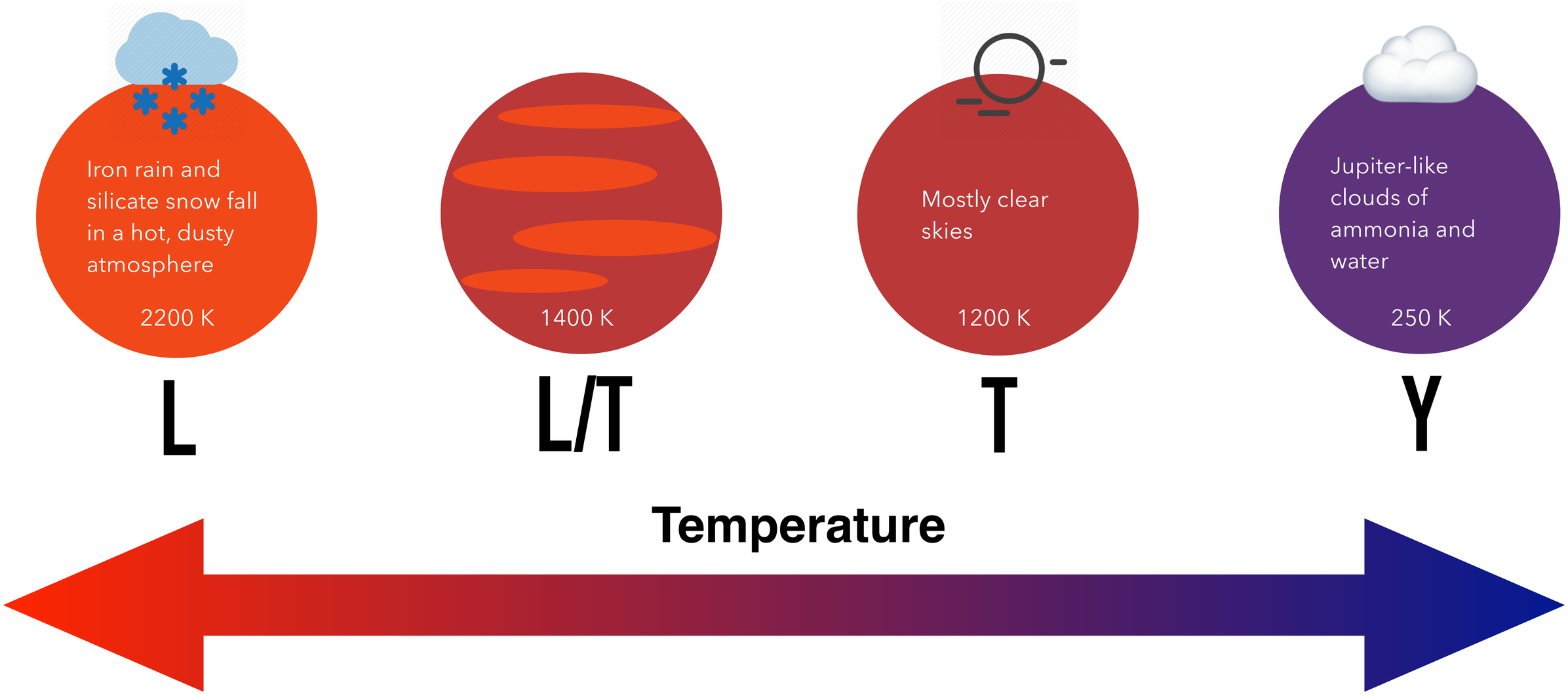
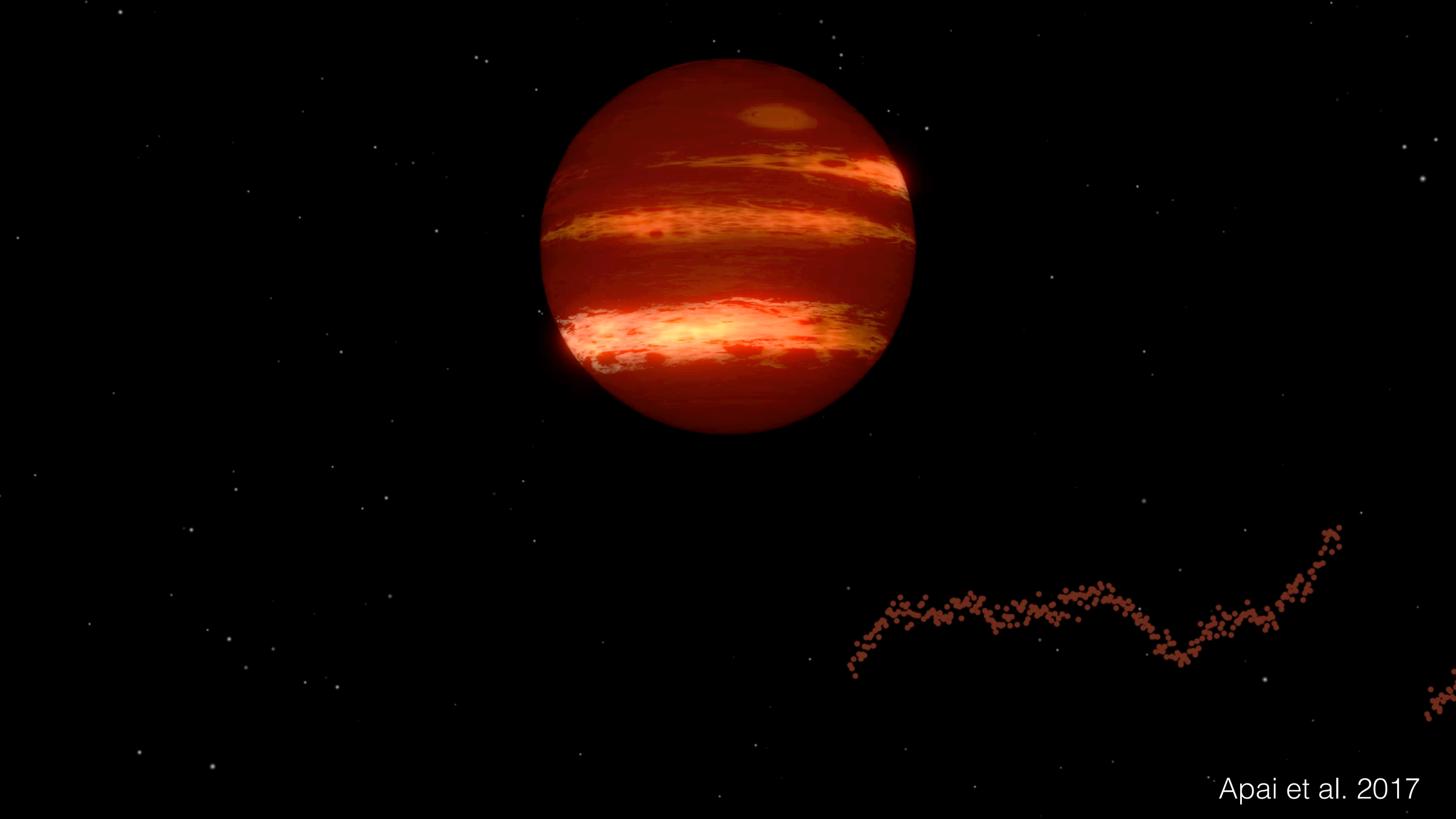
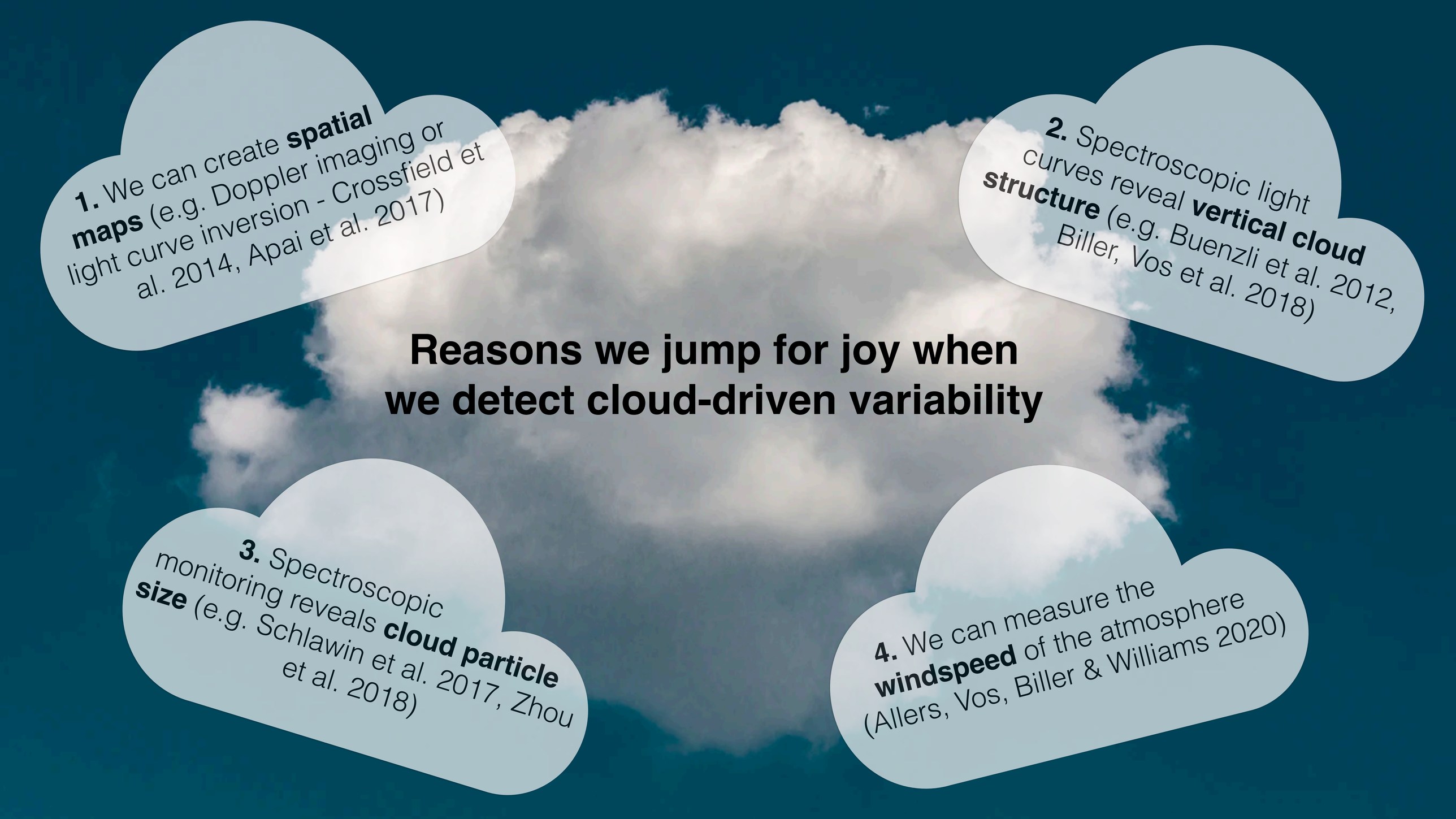
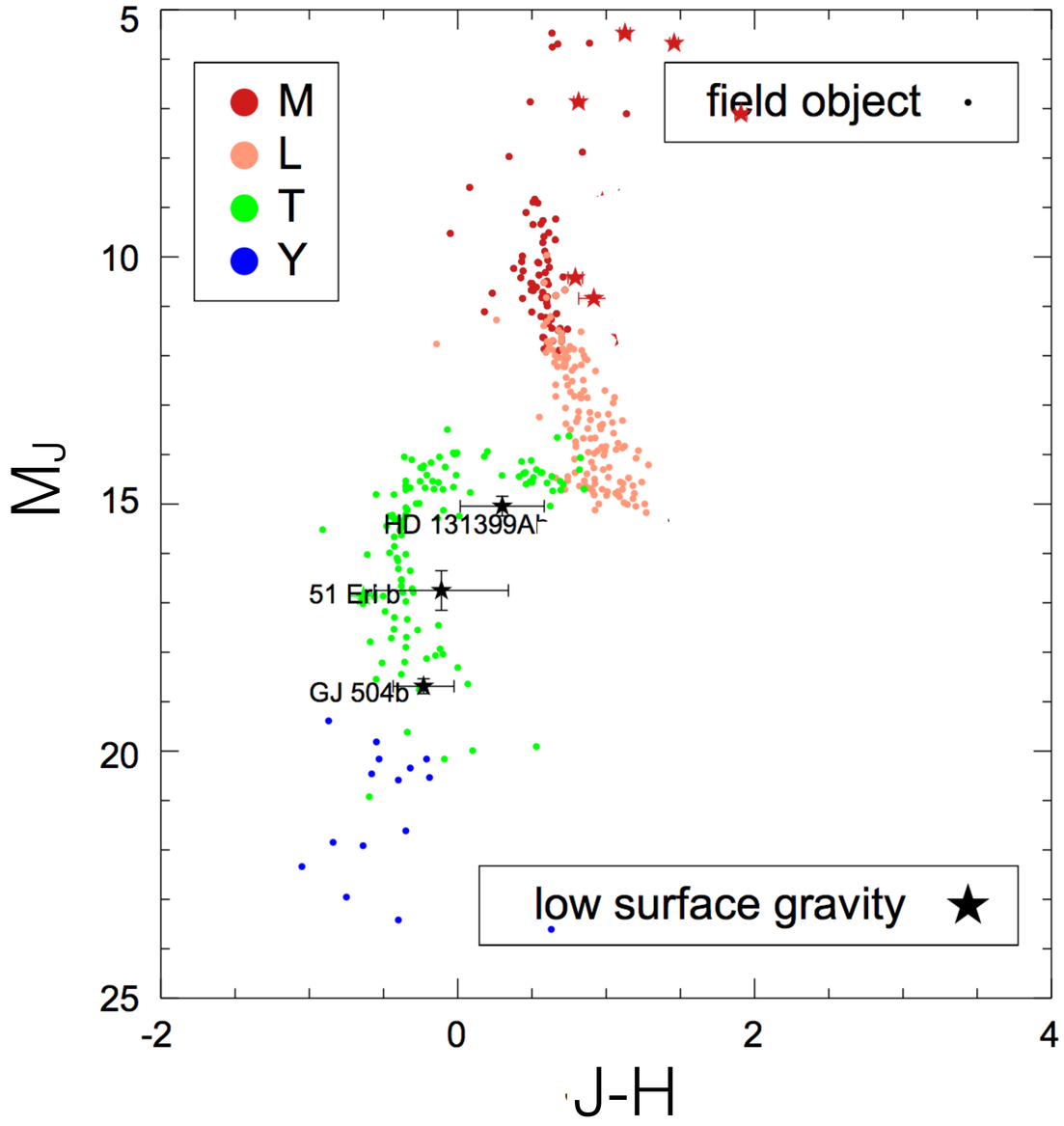
Clouds are important in brown dwarf and giant exoplanet atmospheres




Apai et al. 2017


1. We can create **spatial maps** (e.g. Doppler imaging or light curve inversion - Crossfield et al. 2014, Apai et al. 2017)
2. Spectroscopic light curves reveal **vertical cloud structure** (e.g. Buenzli et al. 2012, Biller, Vos et al. 2018)
Reasons we jump for joy when we detect cloud-driven variability
3. Spectroscopic monitoring reveals **cloud particle size** (e.g. Schlawin et al. 2017, Zhou et al. 2018)
4. We can measure the **windspeed** of the atmosphere (Allers, Vos, Biller & Williams 2020)

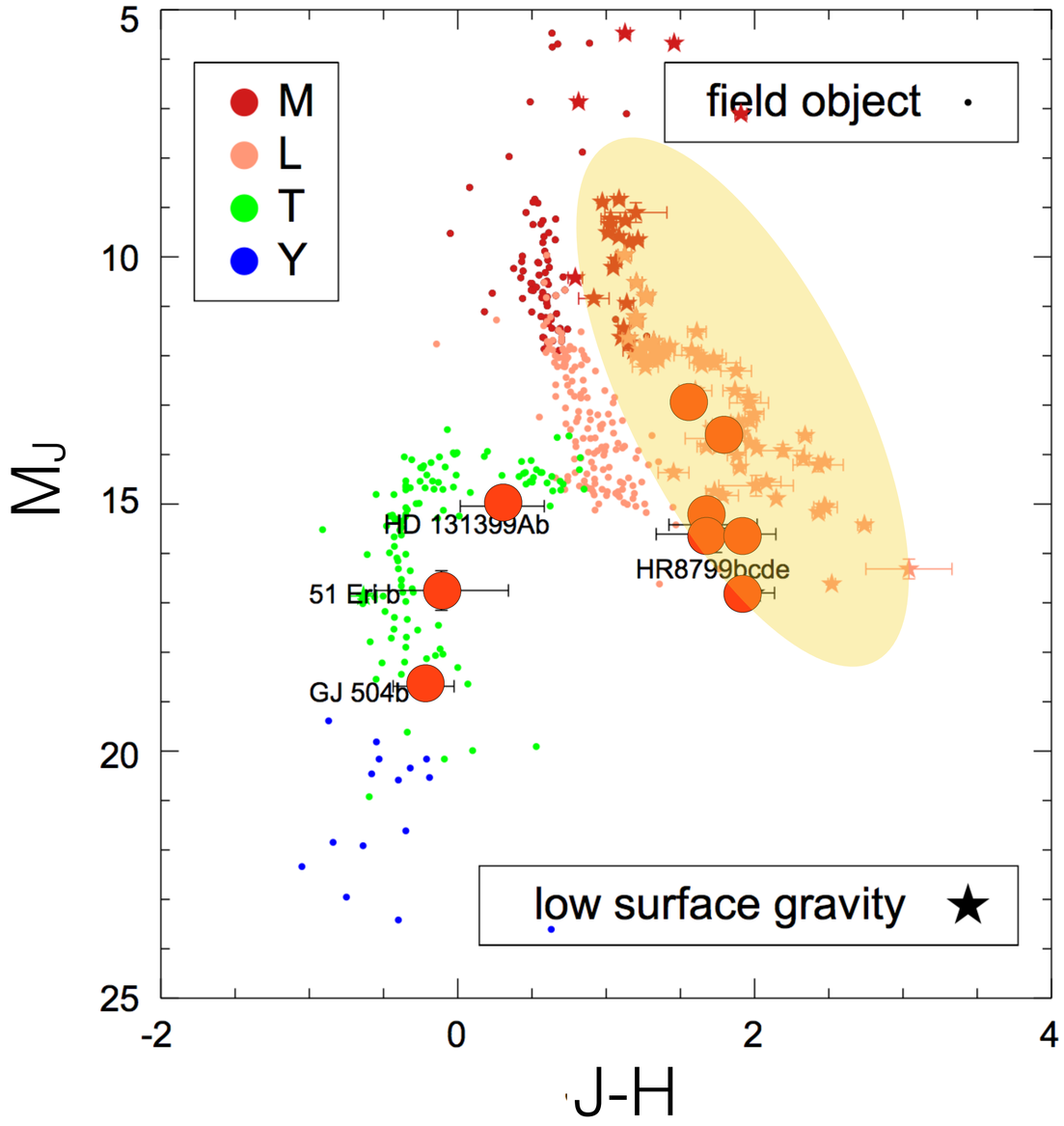
Variability Monitoring of Free-Floating Exoplanet Analogs: Lessons for Directly-Imaged Explanets with JWST



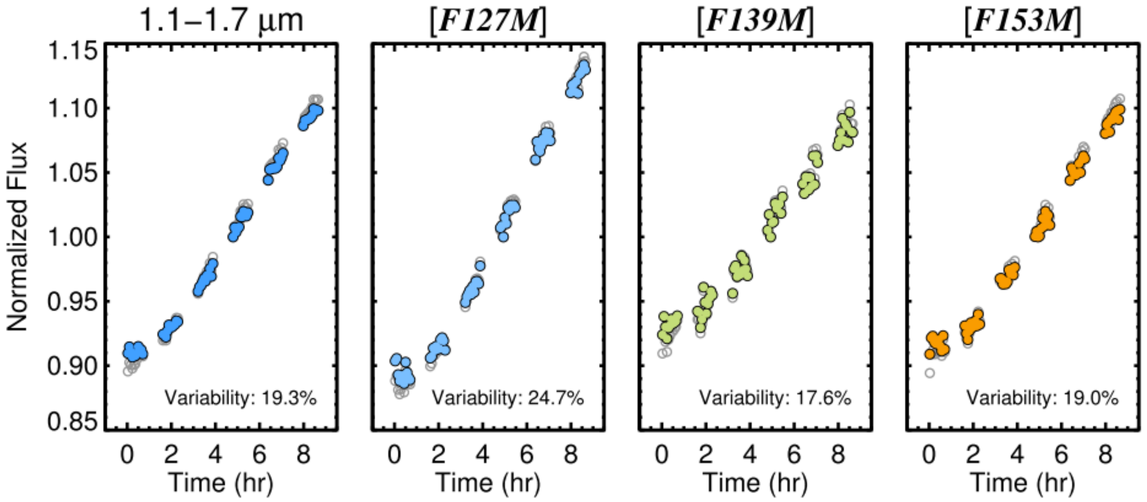
Biller et al. 2017

Low-gravity form a distinct sequence from the high-gravity field dwarfs

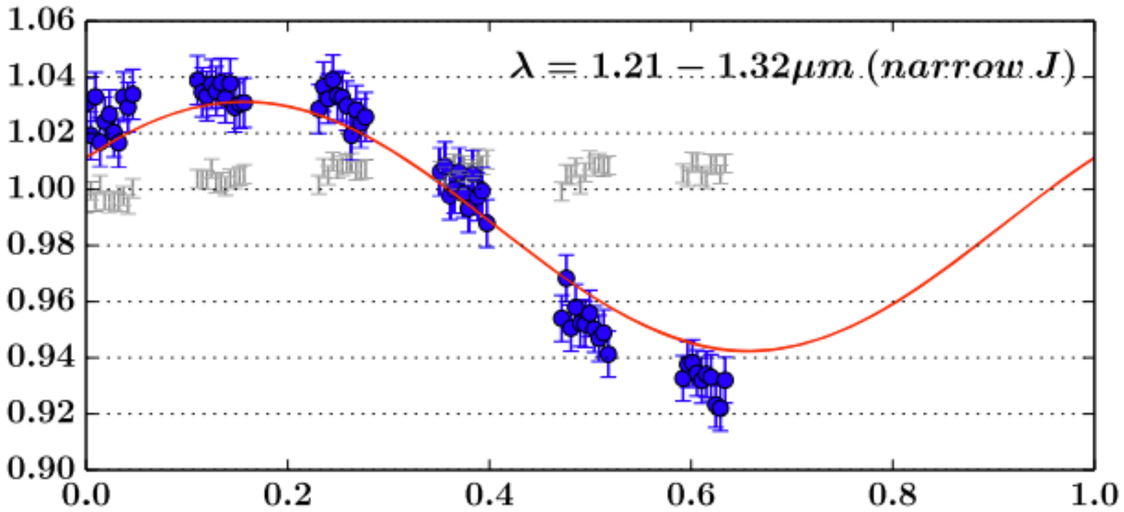
Low-gravity brown dwarfs share a remarkable resemblance with the directly-imaged planets



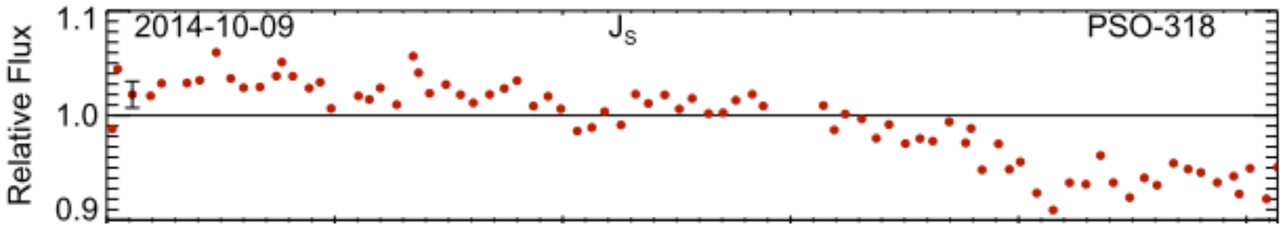
Biller et al. 2017



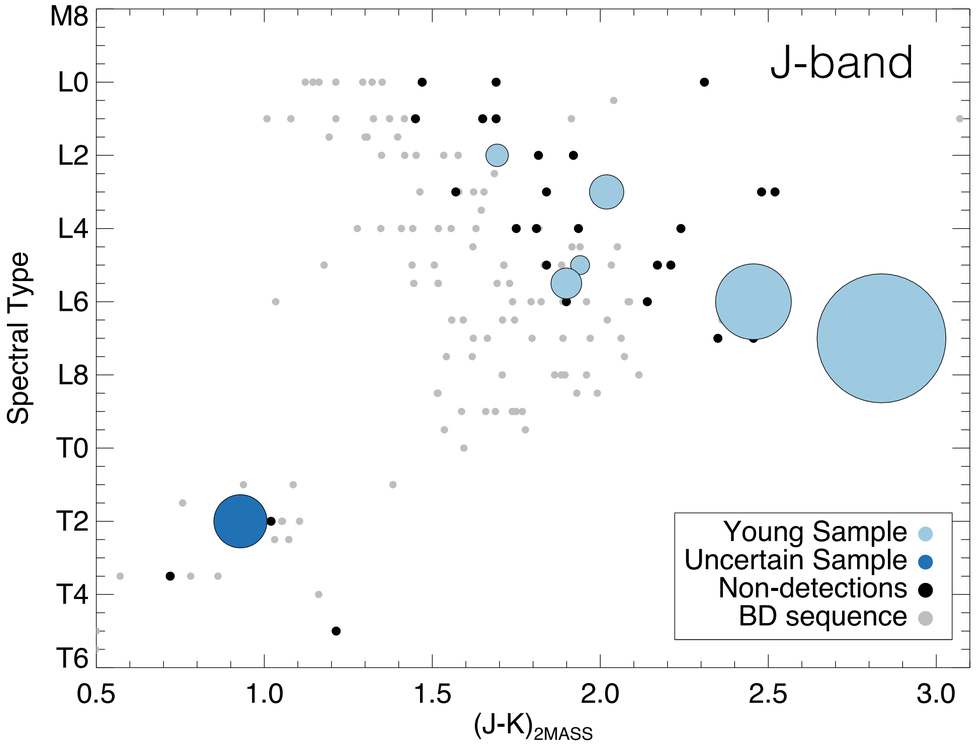
25% VHS 1256b: Bowler, Zhou et al. 2020



8% W0047: Lew et al. 2016, Vos et al. 2018

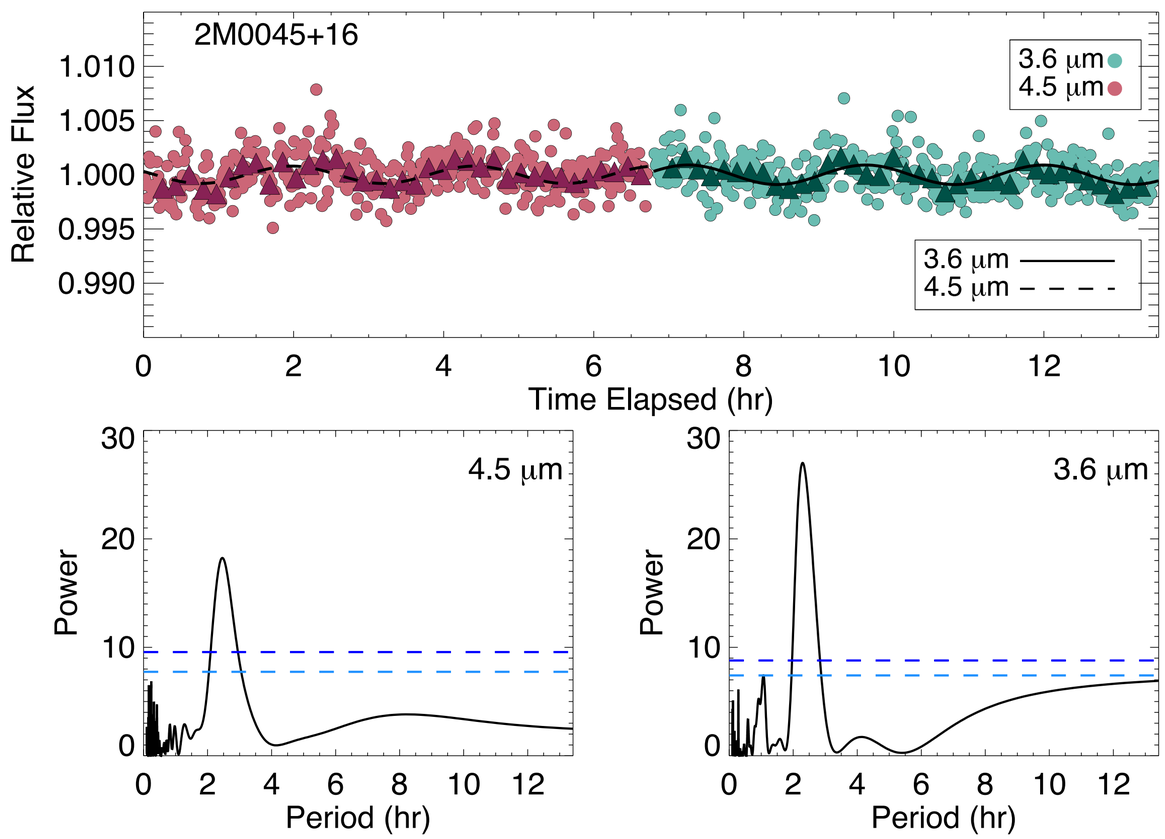


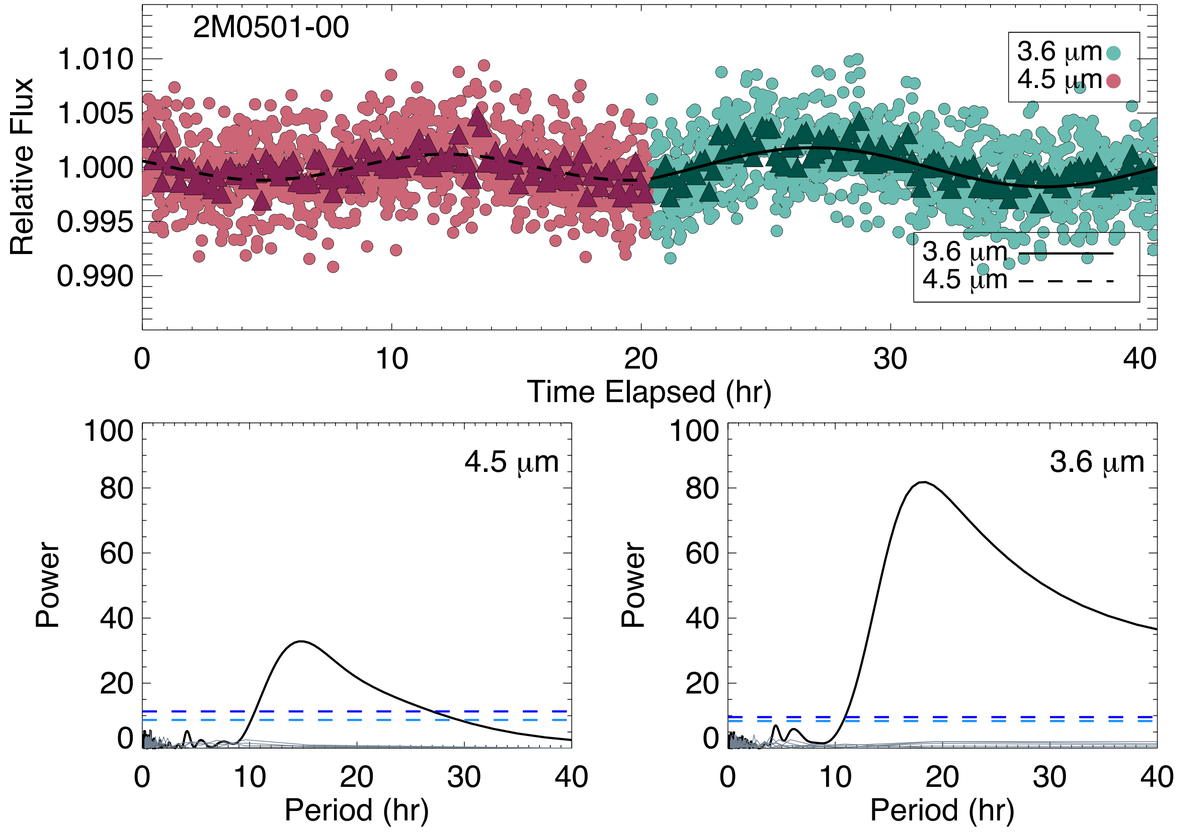
11% PSO J318.5-22: Biller et al. 2015, 2018



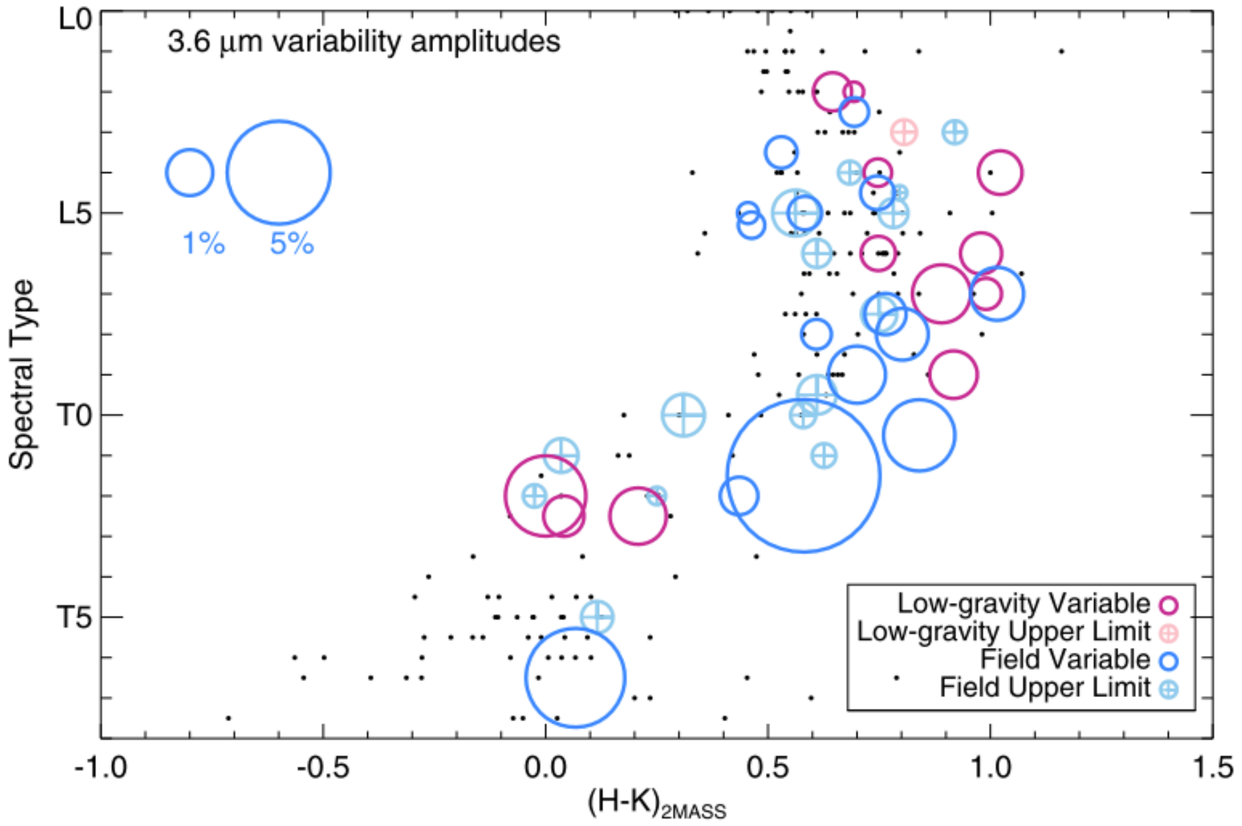
Low-gravity, exoplanet analogues are more likely to be variable than their higher-mass field dwarf counterparts in near-IR - Vos et al. 2019

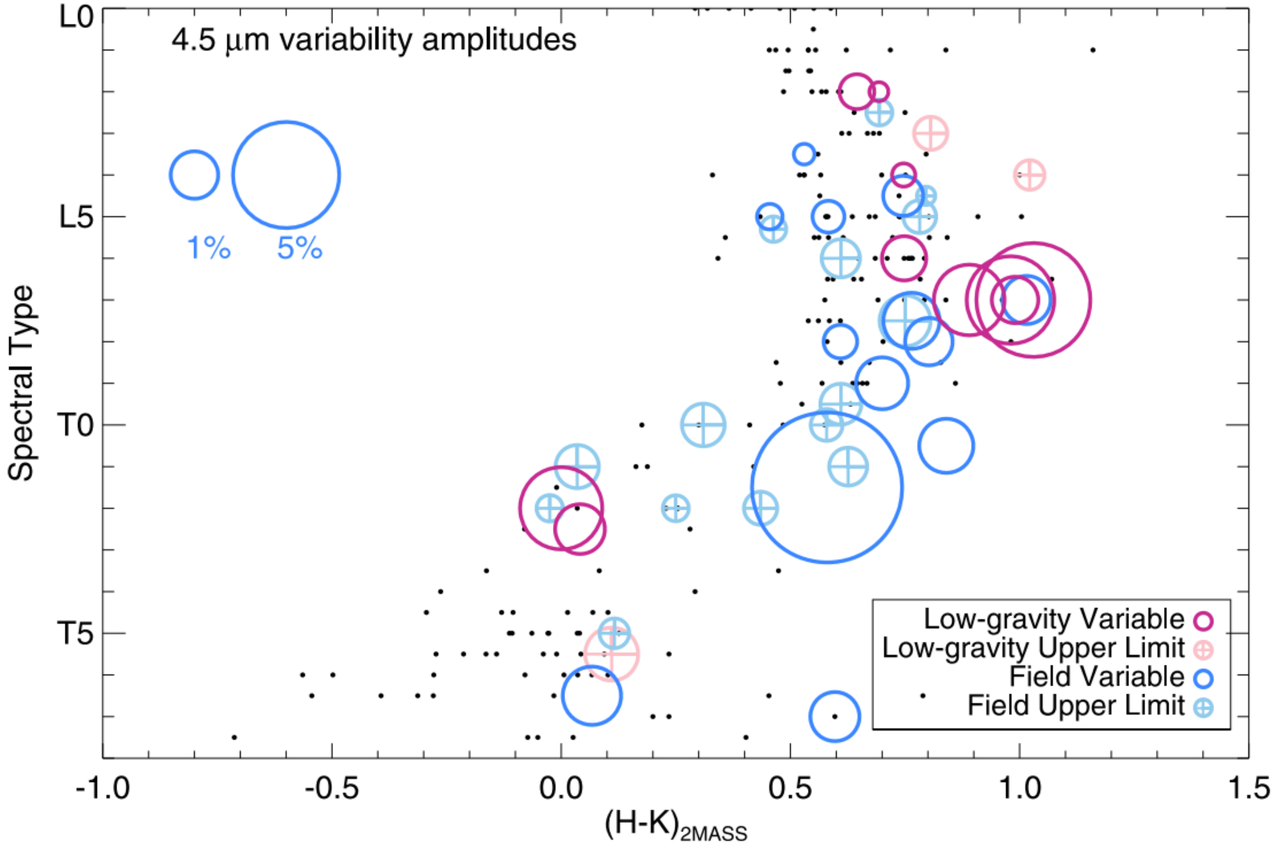
Mid-IR: Spitzer wavelengths reveal high-altitude clouds





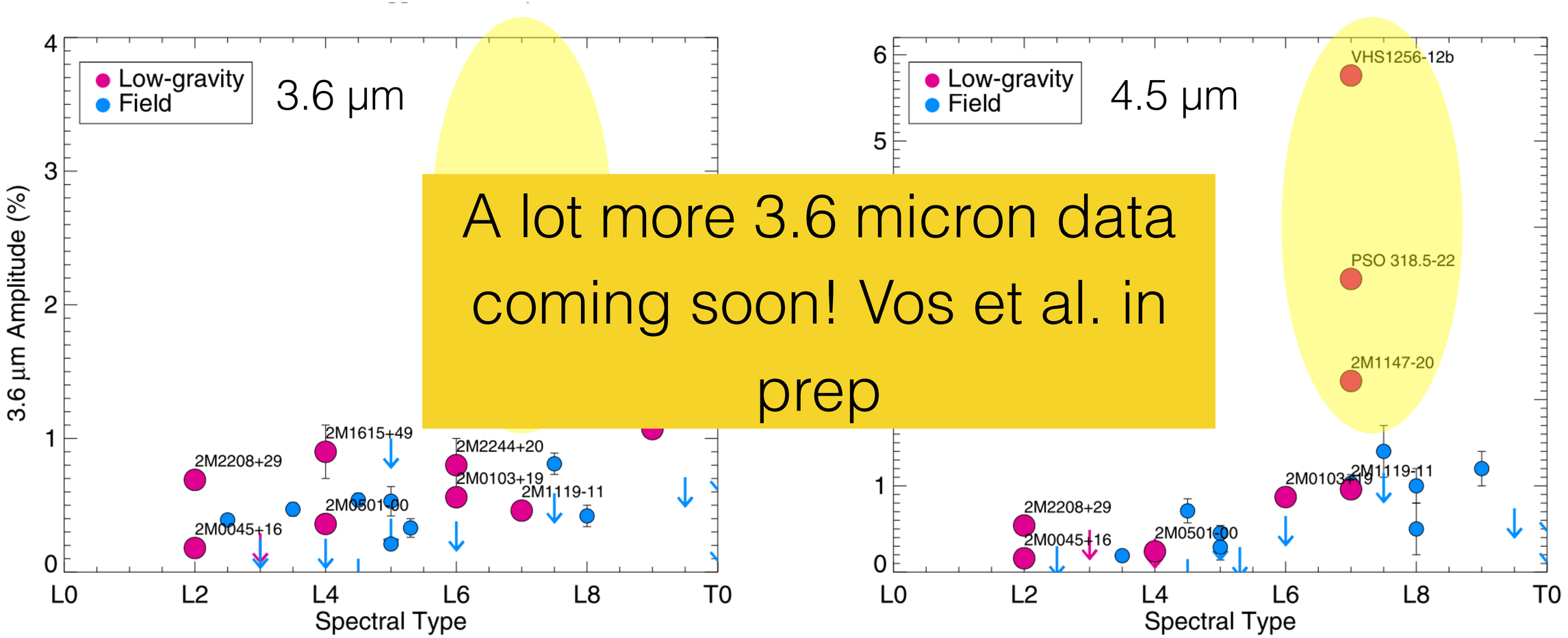
Vos et al. 2020





Vos et al. 2020

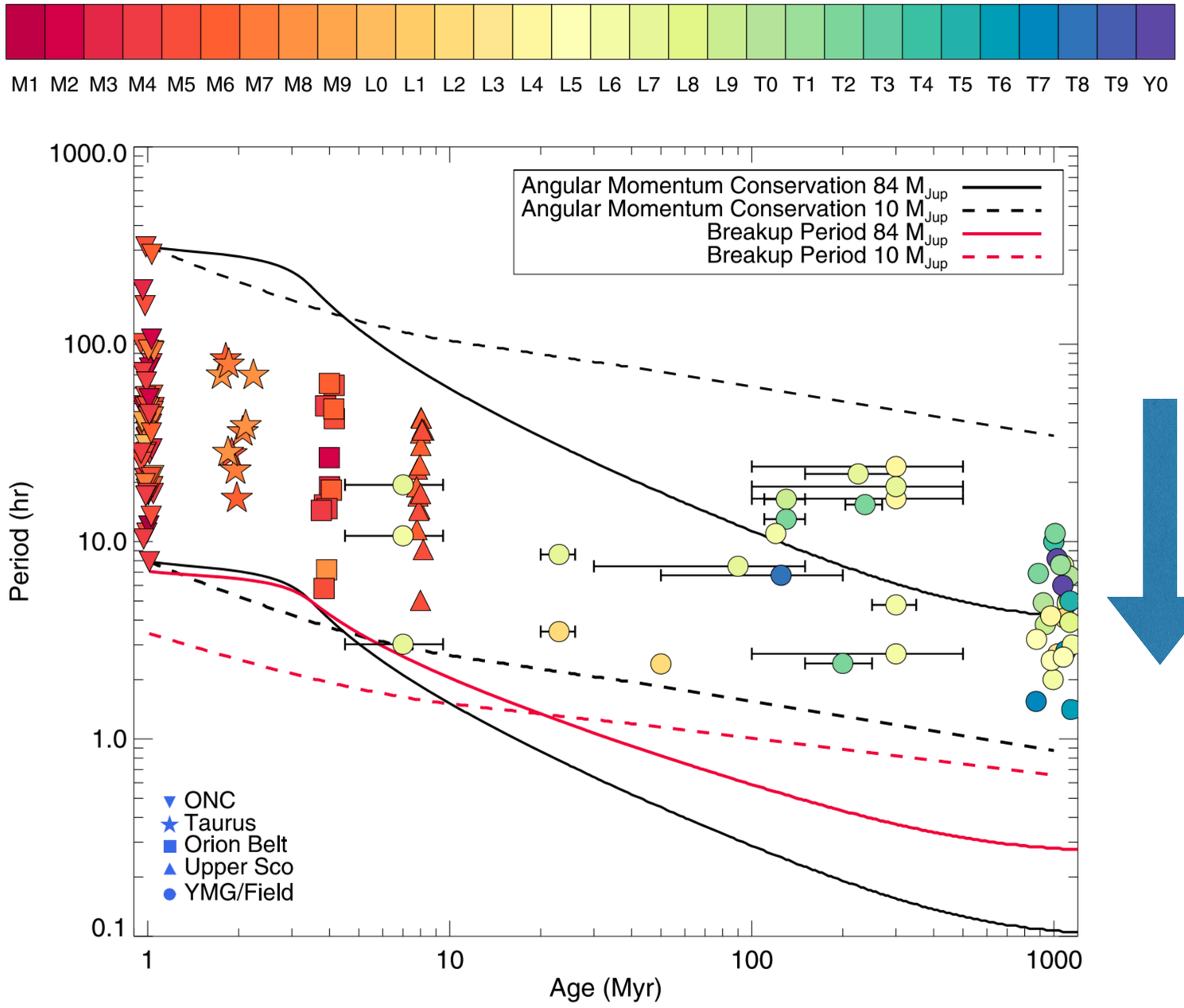
Mid-IR: Dramatic enhancement in variability amplitude for young, late-L objects



A lot more 3.6 micron data coming soon! Vos et al. in prep

Vos et al. 2020

Substellar Angular Momentum Evolution

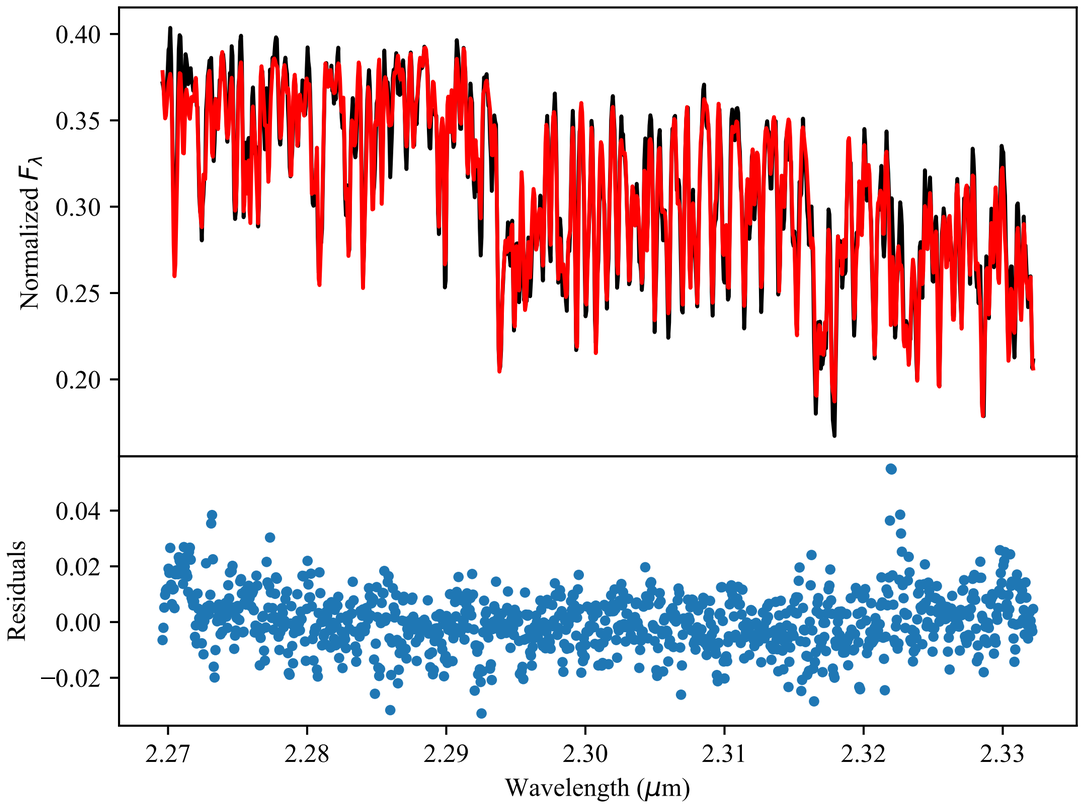


Brown dwarfs and planetary-mass objects spin up over time

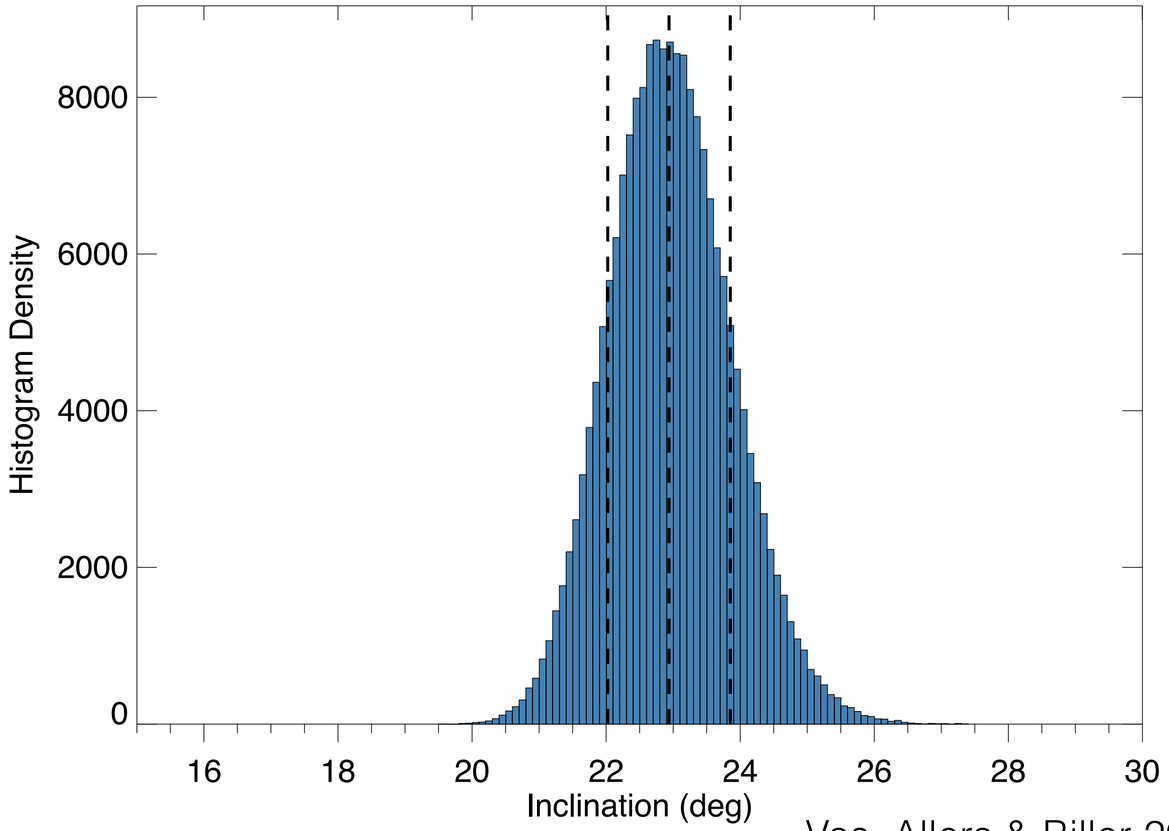
We can combine rotation periods with vsin(i) measurements and radius estimates to measure inclination angles

+ rotational period + radius estimate

Gemini/GNIRS spectrum of 2M0501 → Inclination Angle

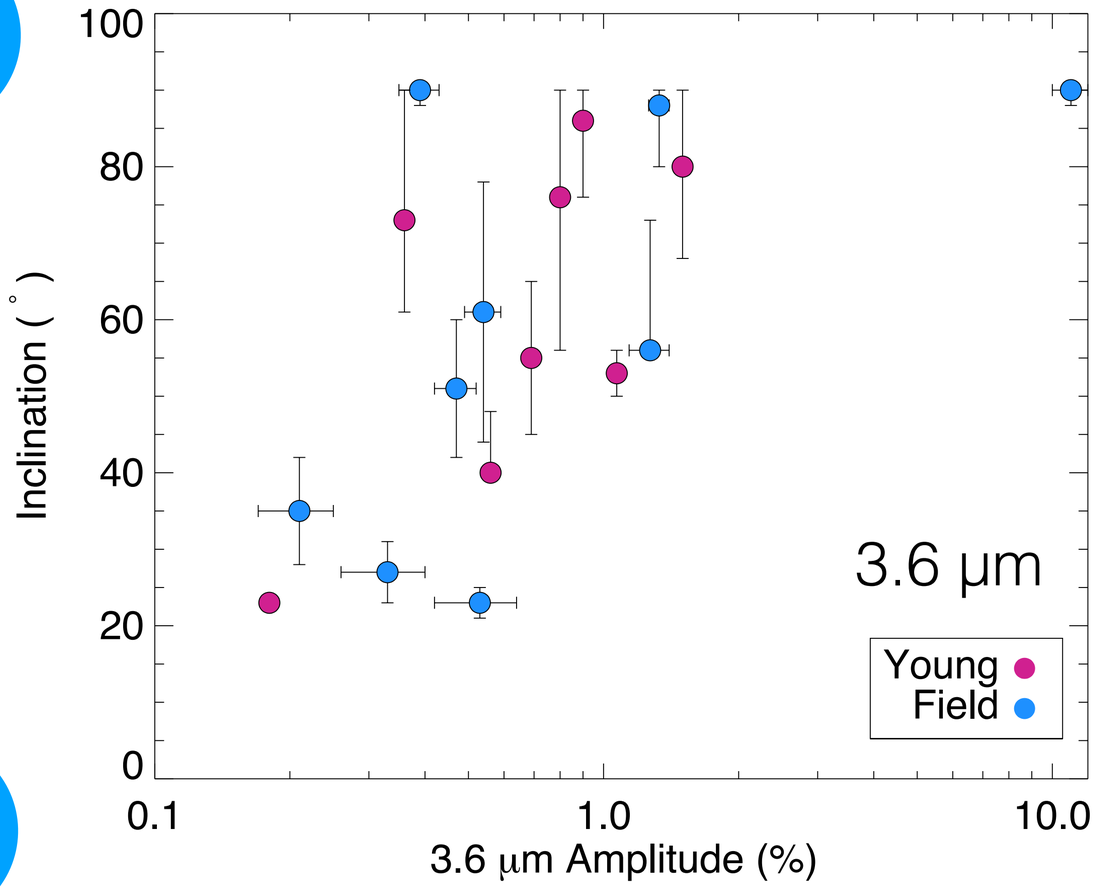


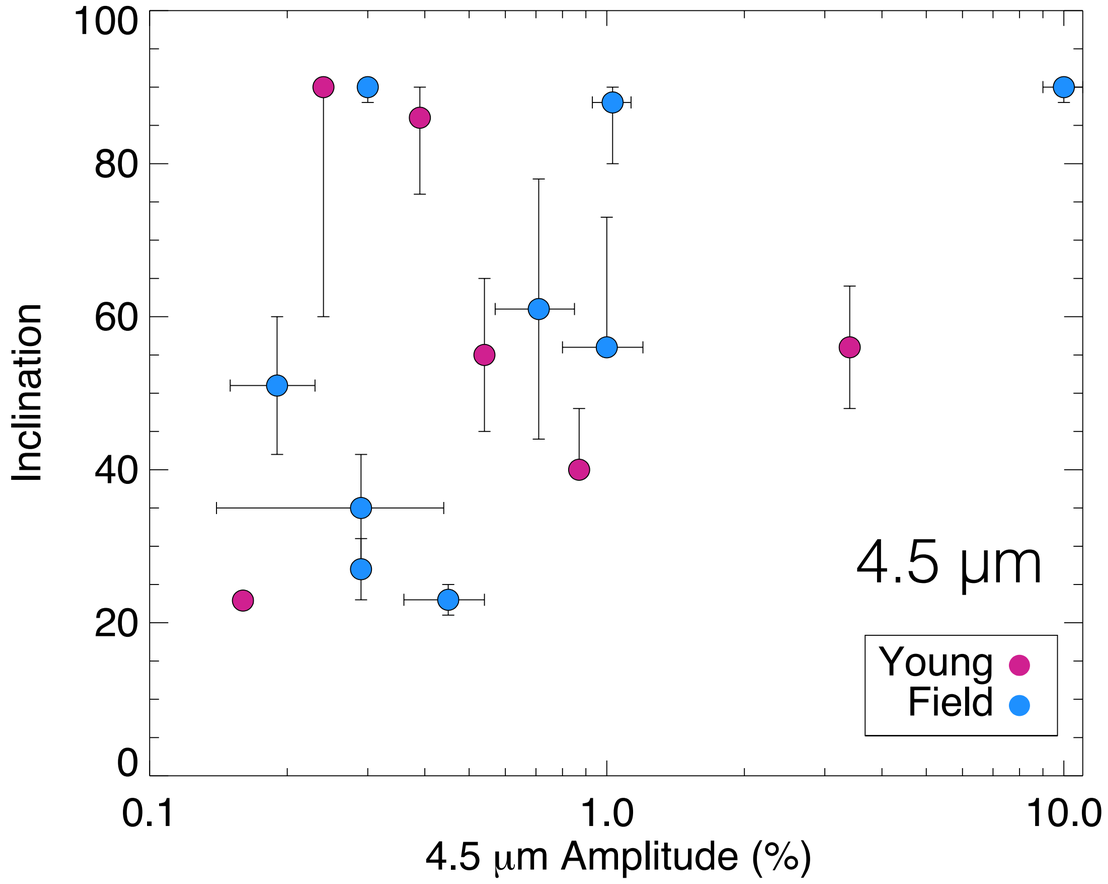
Allers et al. 2016



Vos, Allers & Biller 2017
Vos et al. 2020

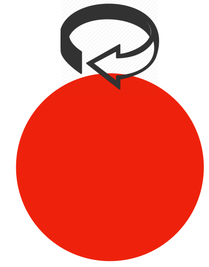
Inclination angle limits the maximum variability amplitude that can be observed





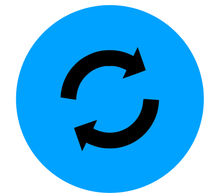
Vos, Allers & Biller 2017
Vos et al. 2020

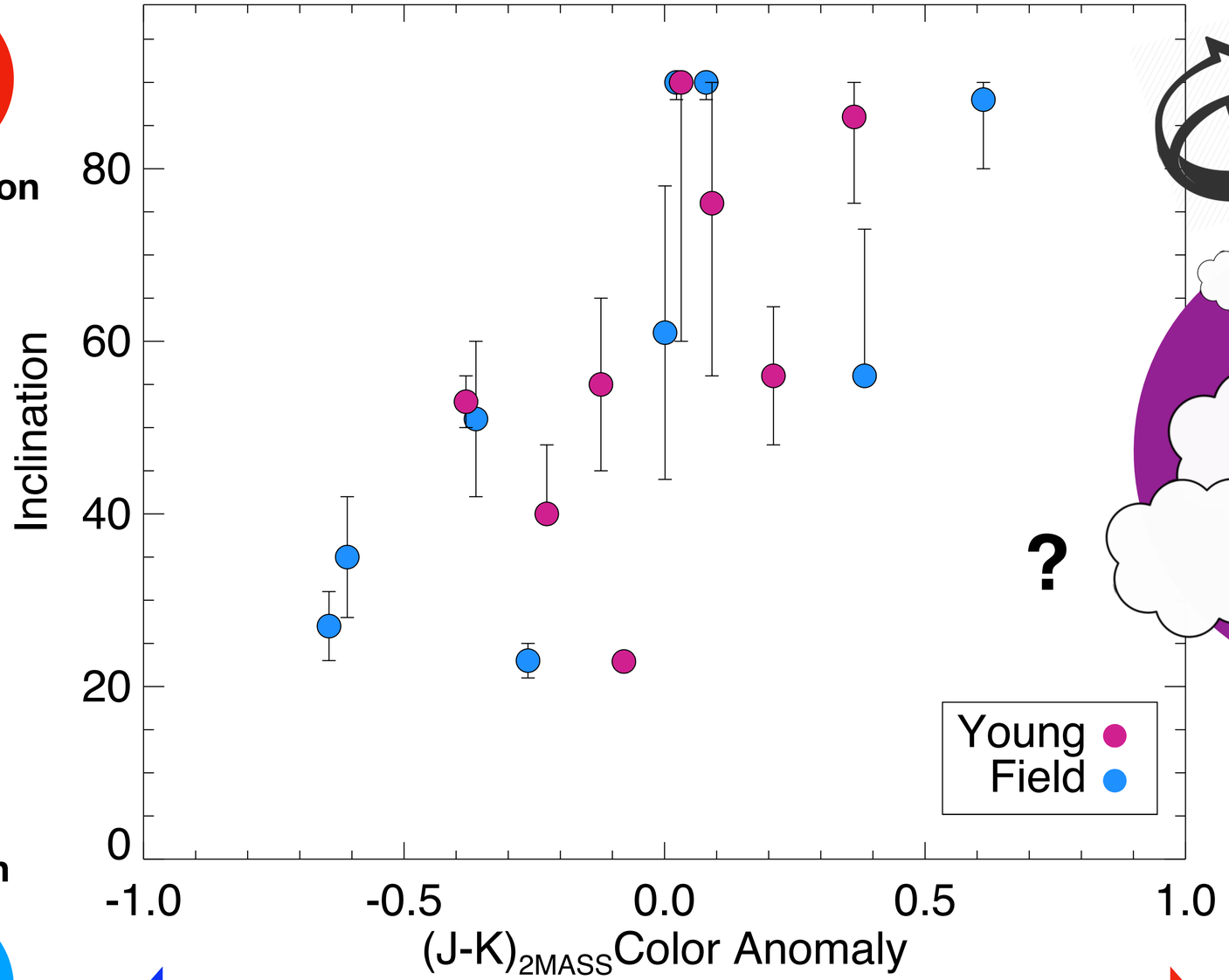
Possible relation between **inclination** angle and J-K color

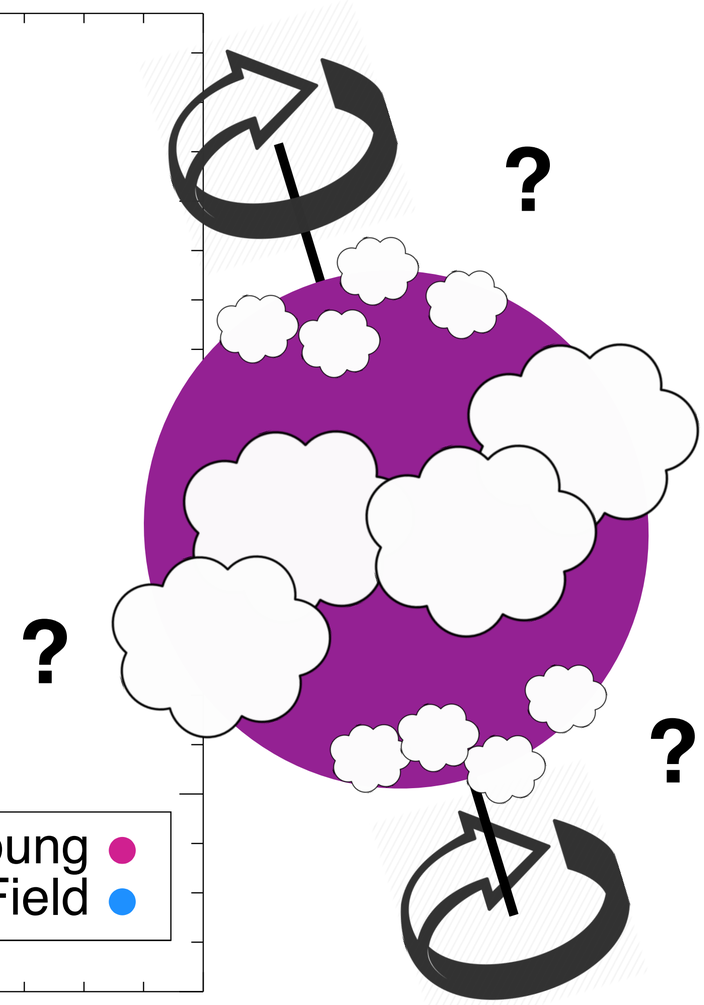


Equator-on

Pole-on

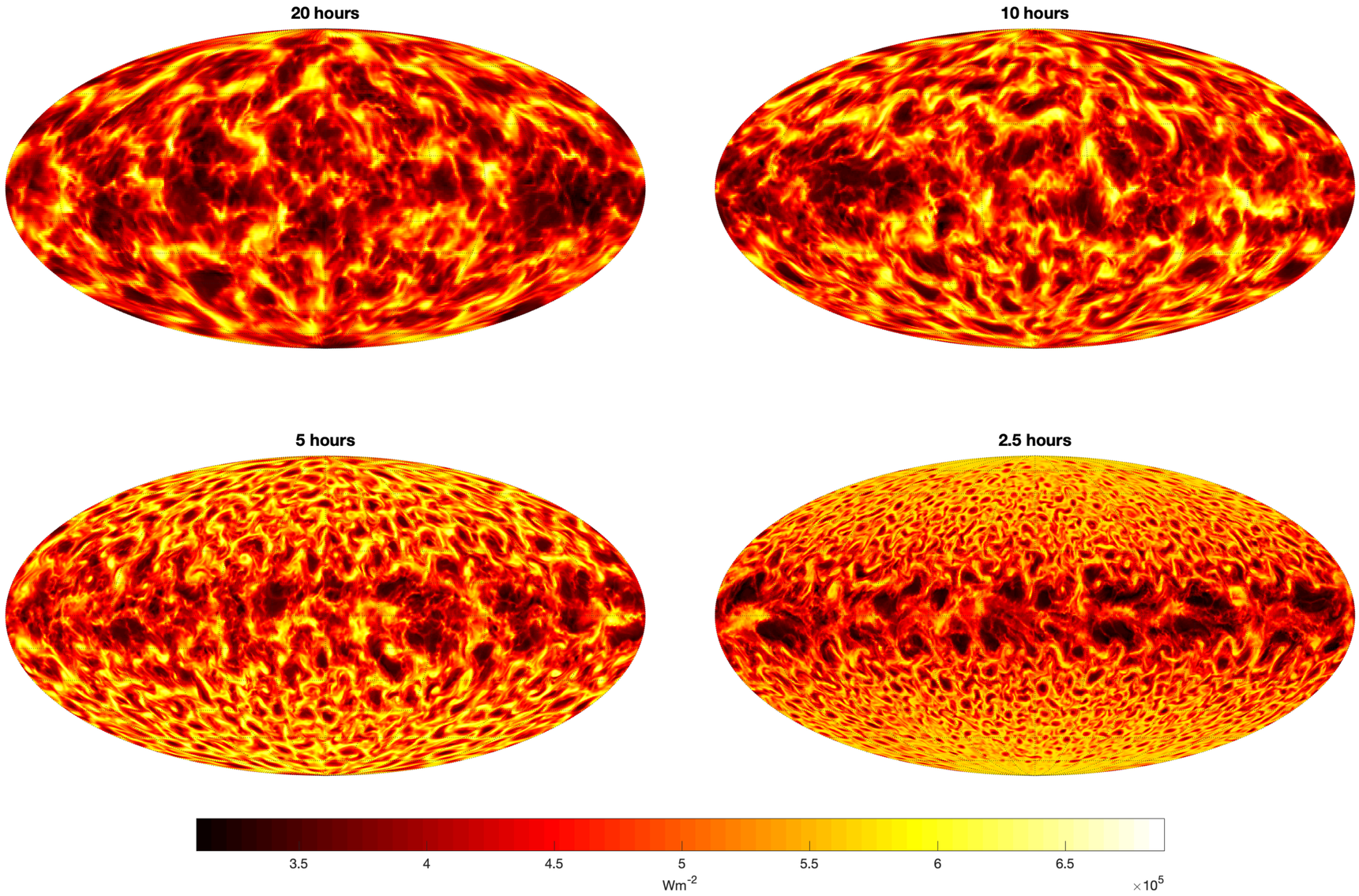






Vos, Allers & Biller 2017
Vos et al. 2020

Thick clouds accumulate at the equator for fast rotators



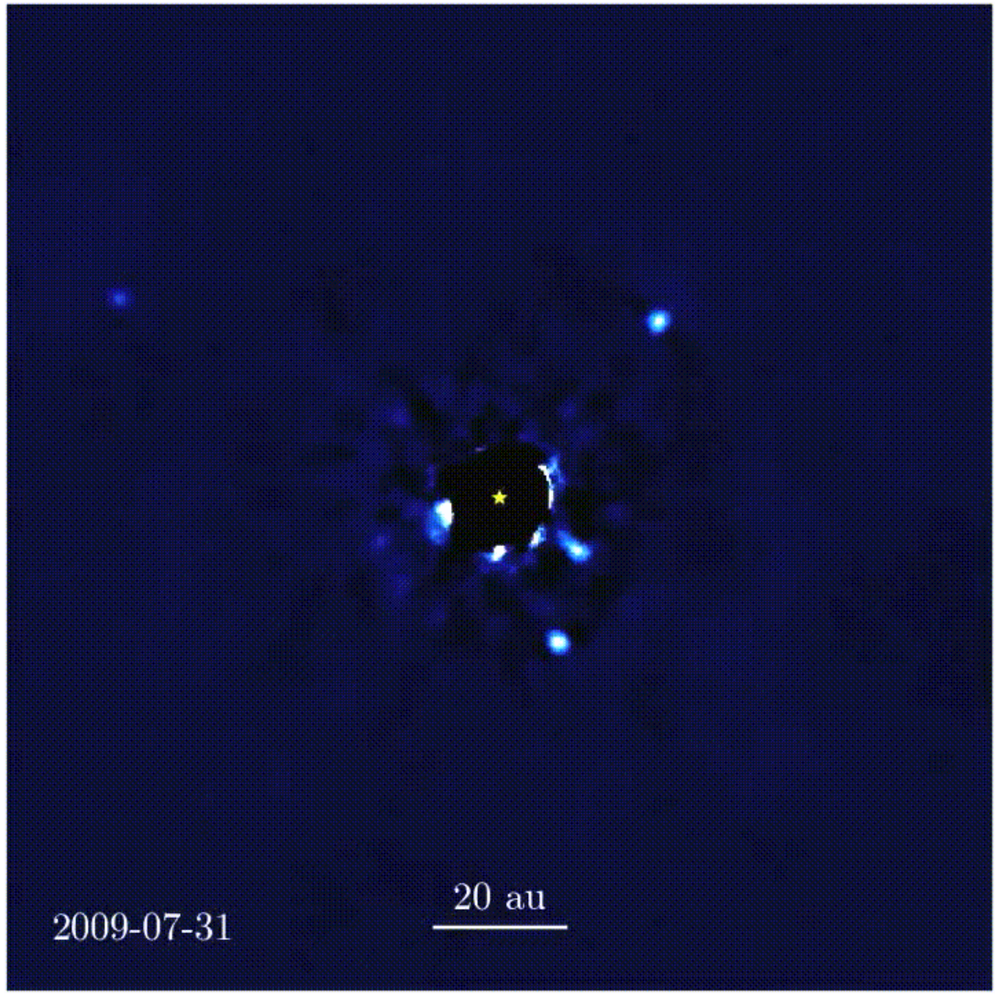
Tan & Showman in prep

NASA/Juno

JWST will enable variability studies of directly-imaged exoplanets

- **Lesson 1:** Directly-imaged exoplanets are likely to be variable

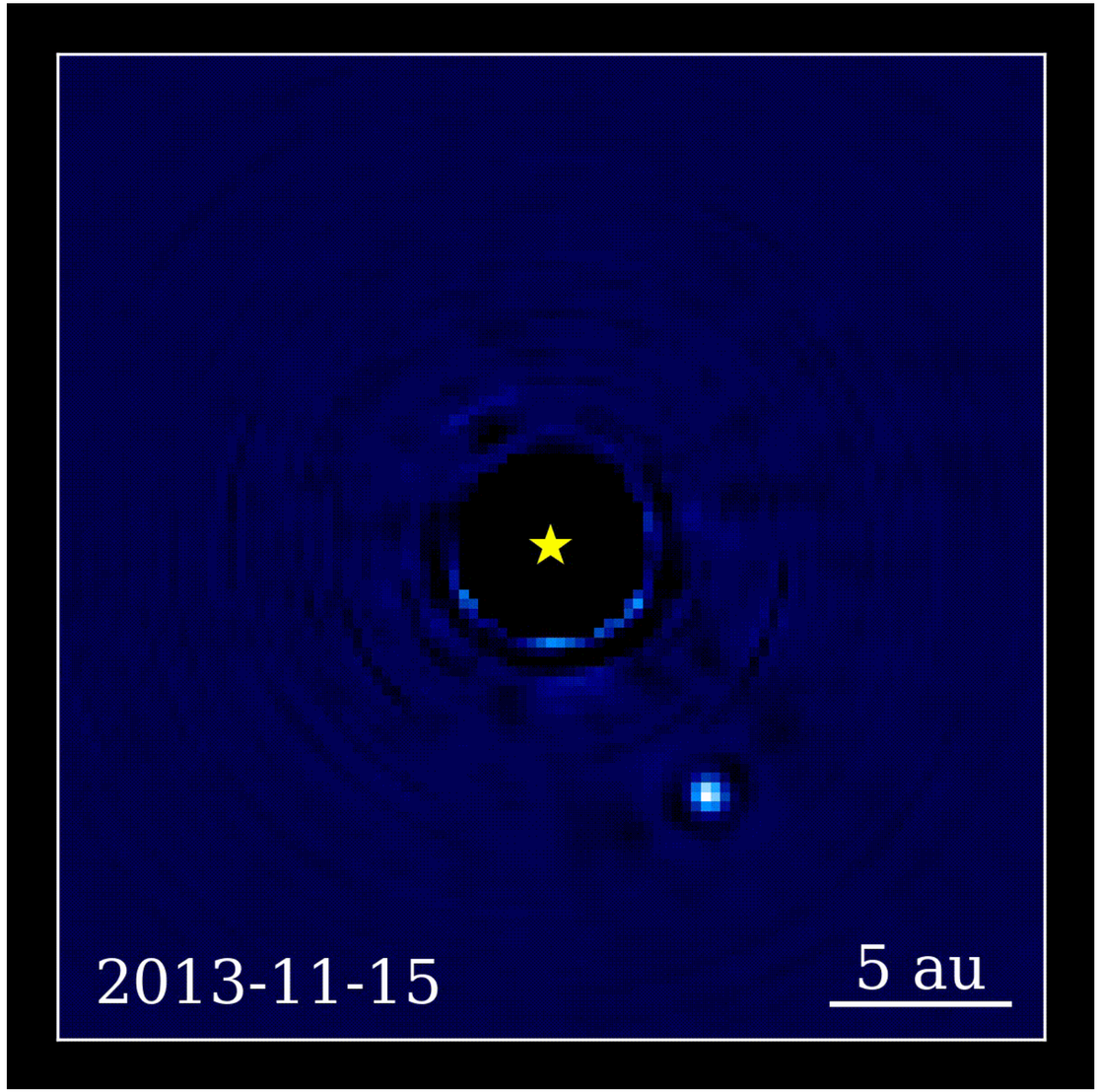
- **Lesson 2:** Viewing angle matters ! !



HR8799bcde

JWST will enable variability studies of directly-imaged exoplanets

- **Lesson 1:** Directly-imaged exoplanets are likely to be variable
- **Lesson 2:** Viewing angle matters
- **Lesson 3:** It will be worth it ! !



β Pic b