Lecture 2: Exoplanets and brown dwarfs

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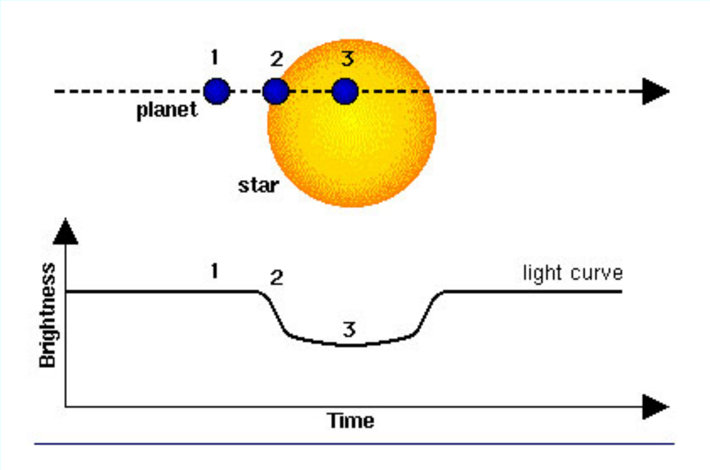
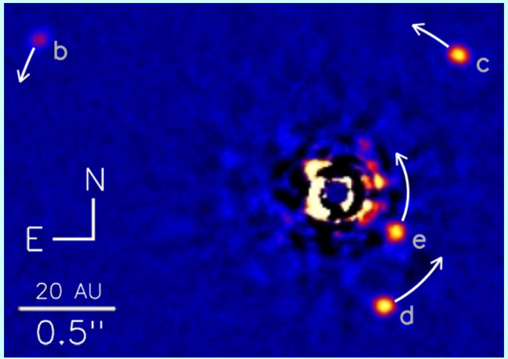
Exoplanets: an exploding new field

- Over 3500 known extrasolar planets
- Nearly 700 planets have been detected with the "Doppler" method
- Nearly 2700 planets have been detected with "transit" method (plus many Kepler candidates):

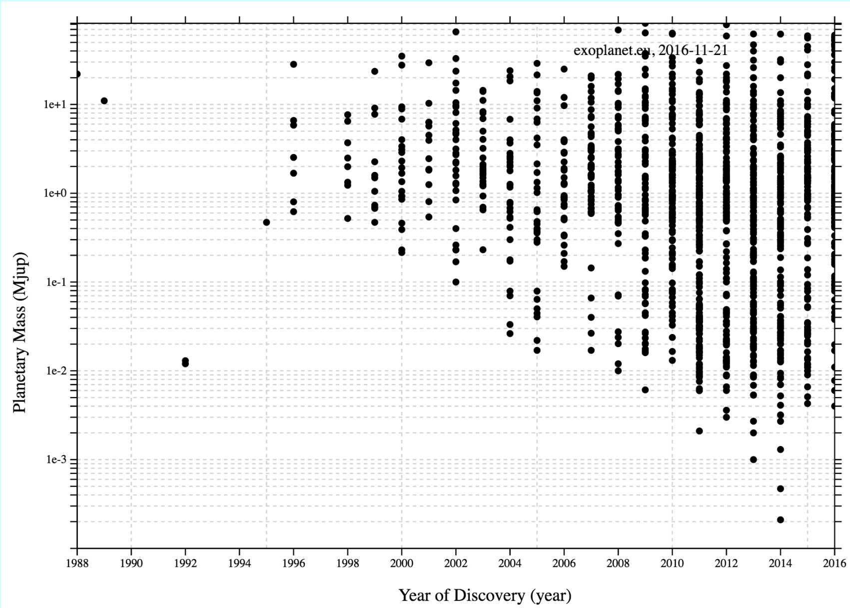


Together, these give the planetary mass, radius, and orbital properties.

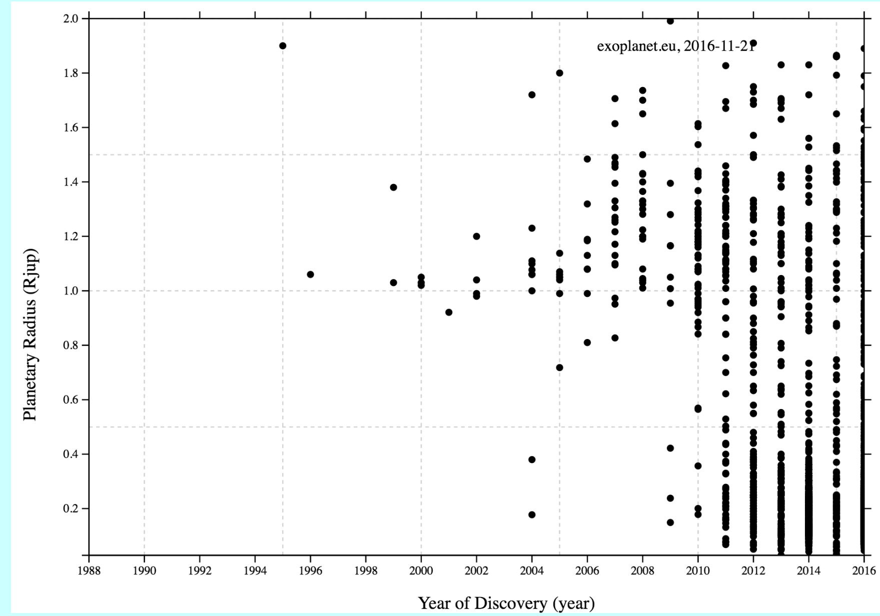
- ~50 planets discovered by direct imaging:



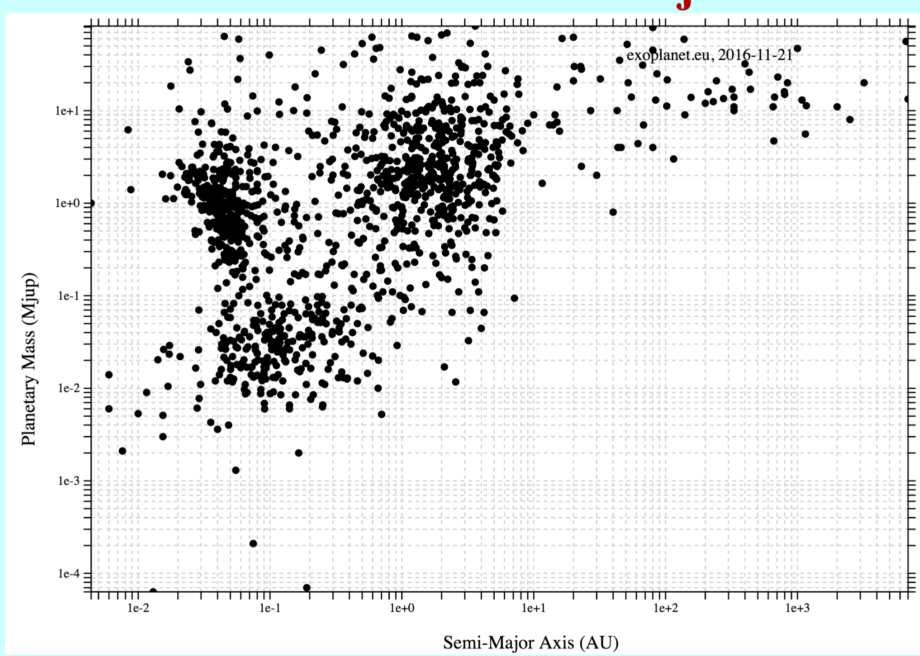
Planet mass vs. year of discovery



Planet radius vs. year of discovery



Planet mass vs. semi-major axis



Why study atmospheres of exoplanets?

- **Atmospheres of other planets exhibit a diverse array of behavior, including composition, mass, history, temperature structure, weather, clouds, climate, and dynamics**
  - **This diversity is inherently fascinating and deserves to be understood**
  - **Earth's atmosphere is just one realization… no more or less interesting than any other**

- **Studying other atmospheres puts Earth in context**

- **Helps us understand *in general* how atmospheres originate/evolve, and what determines their composition, structure, dynamics, clouds and climate**
  - **Such a general understanding *cannot be obtained* from studying just one planet alone**

- **For example, to deeply understand even an Earth-based phenomenon, like what sets the structure, width, and climate of the Hadley cell, you need to understand how the Hadley cell depends on planetary rotation rate, gravity, tropospheric structure, tropospheric humidity, etc. This implies studying other planets.**

- **Atmospheres/oceans are where life is mostly likely to evolve, so studying atmospheres informs our understanding of habitability in the Universe**

Fundamental motivation: to understand the atmosphere/interior circulation and structure on exoplanets and brown dwarfs.

- **What is the nature of the circulation (zonal jets, vortices, storms, turbulence)? What are the wind speeds, temperature variations, key length scales, and time variability? How do they depend on parameters?**
- **How does the circulation work: what are the dynamical mechanisms controlling it?**
- **What is the role of condensation and clouds? Coupling to atmospheric chemistry?**
- **Can we achieve a unified theory of giant planet atmospheric circulation that explains observations of hot Jupiters, brown dwarfs, and solar system planets?**
- **Does this knowledge provide insights about the circulation and climate of (less easily observed) smaller planets?**

Factors that affect atmospheric circulation and structure

External irradiation

Internal (convective) heat flux

Gravity (mass)

Rotation rate

Atmospheric composition

Clouds/chemistry

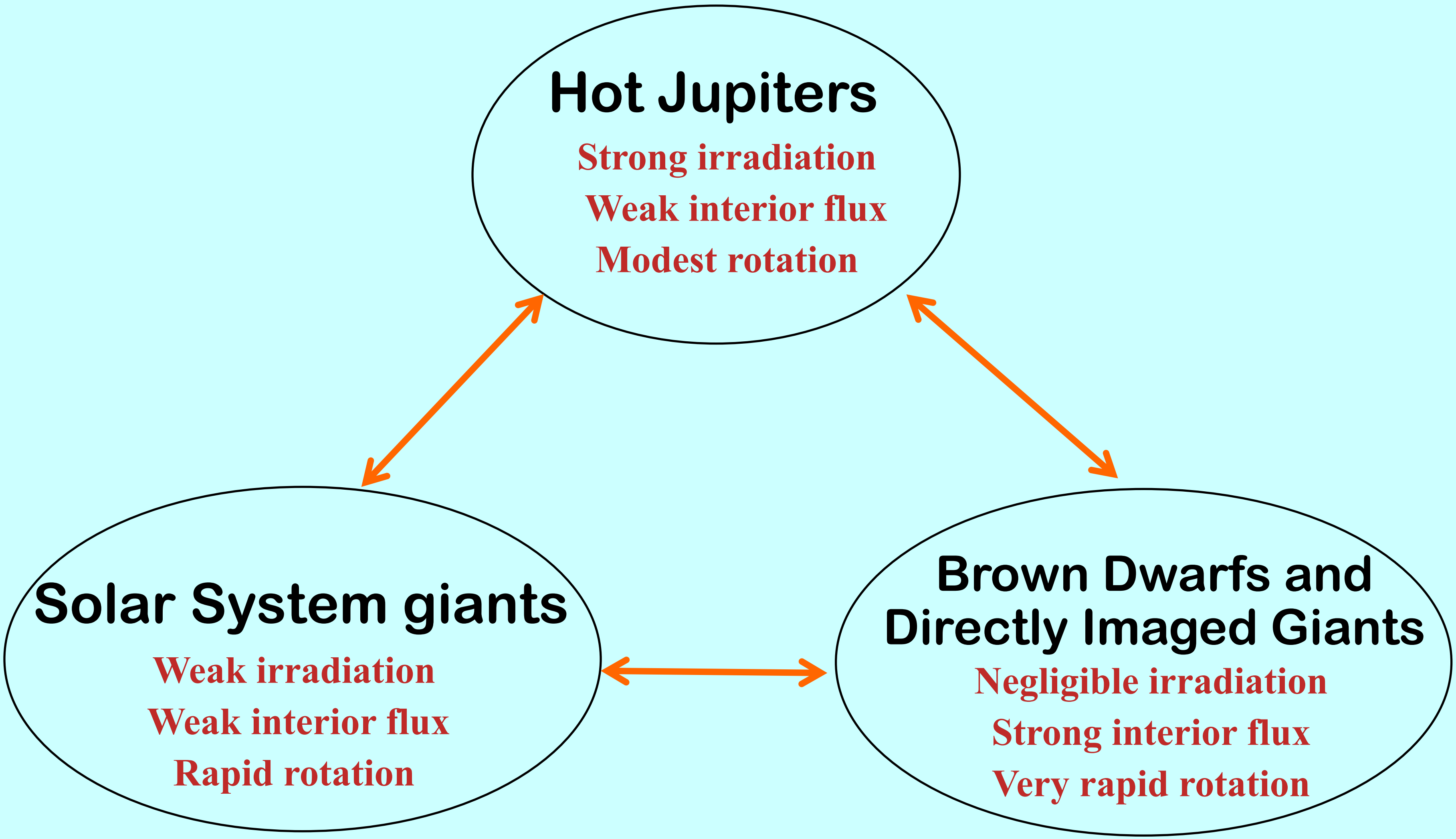
Interaction with interior

History

Factors that affect atmospheric circulation and structure

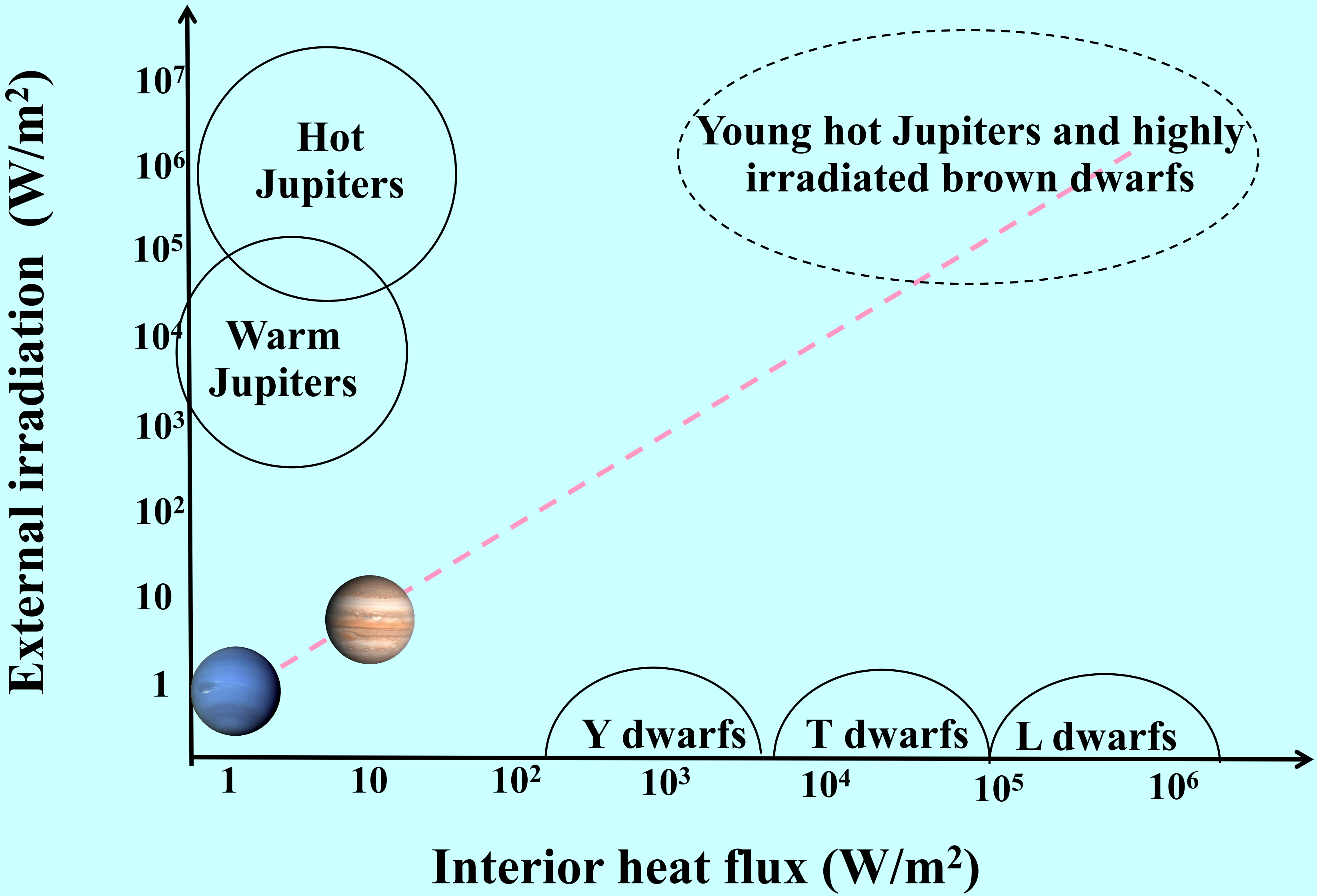
External irradiation	$\sim 10^7$
Internal (convective) heat flux	$\sim 10^6$
Gravity (mass)	~ 100
Rotation rate	~ 100
Atmospheric composition	~ 100
Clouds/chemistry	
Interaction with interior	
History	

Observationally booming subfields yield constraints at the extreme ranges of key parameters

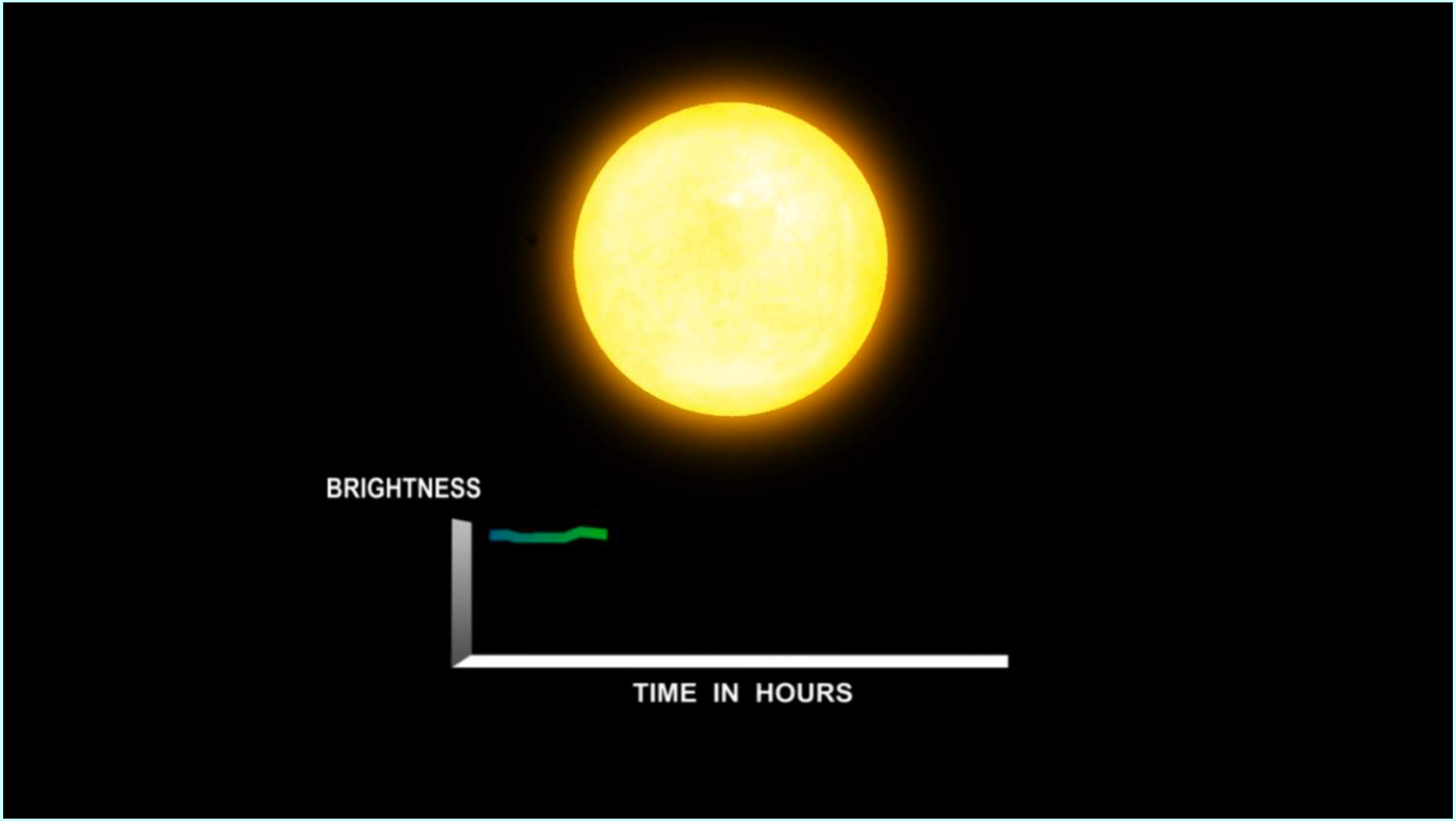


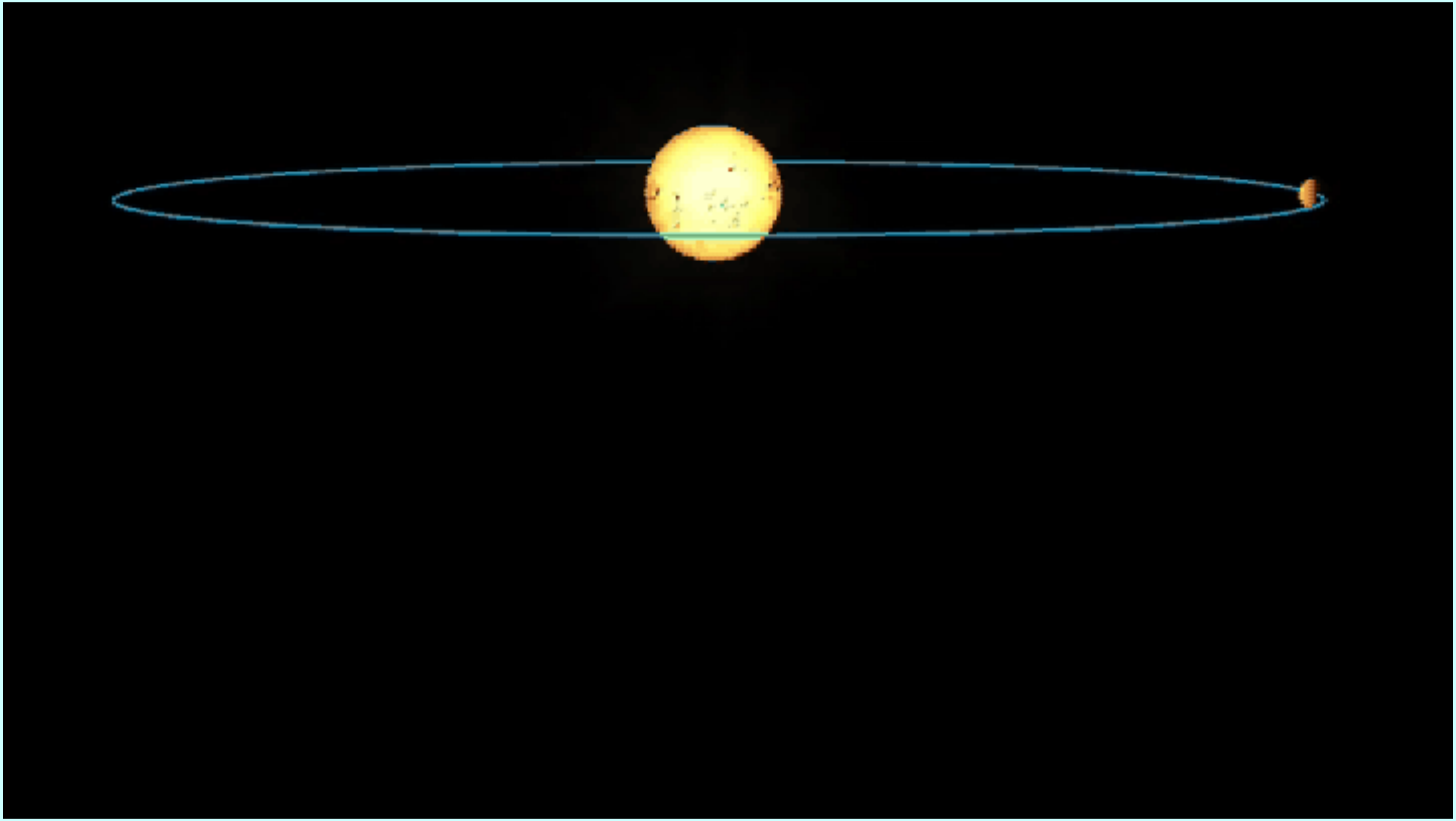
This opens the possibility of synergy between subfields

Observational constraints at the corners of a wide parameter space

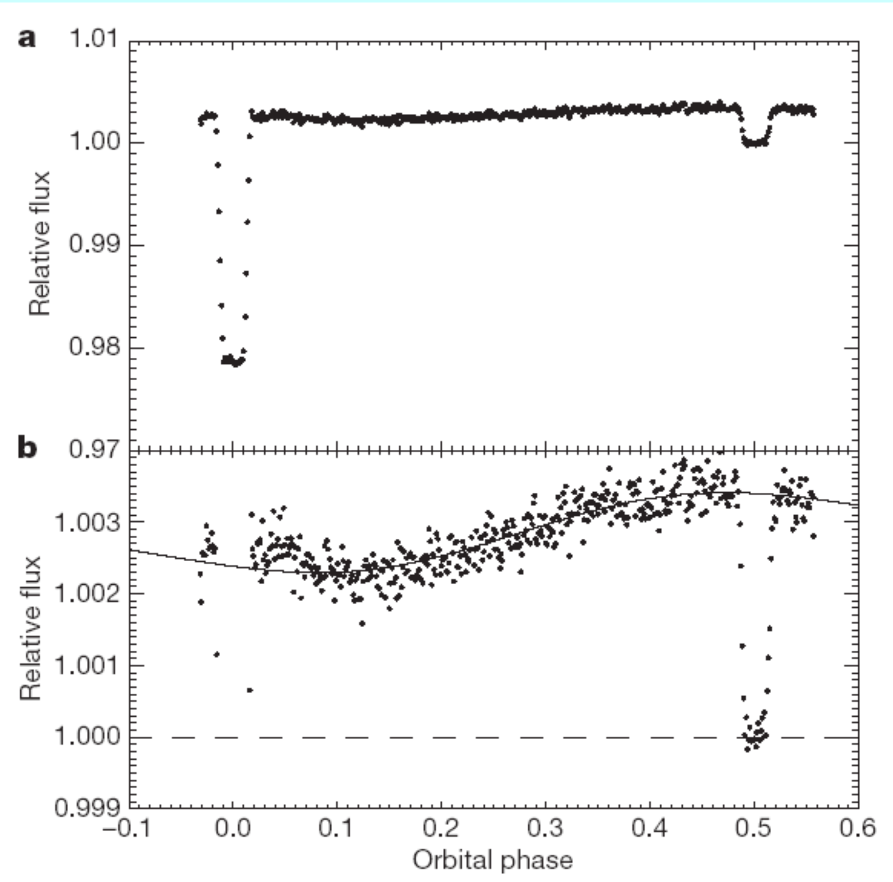


Showman (2016)

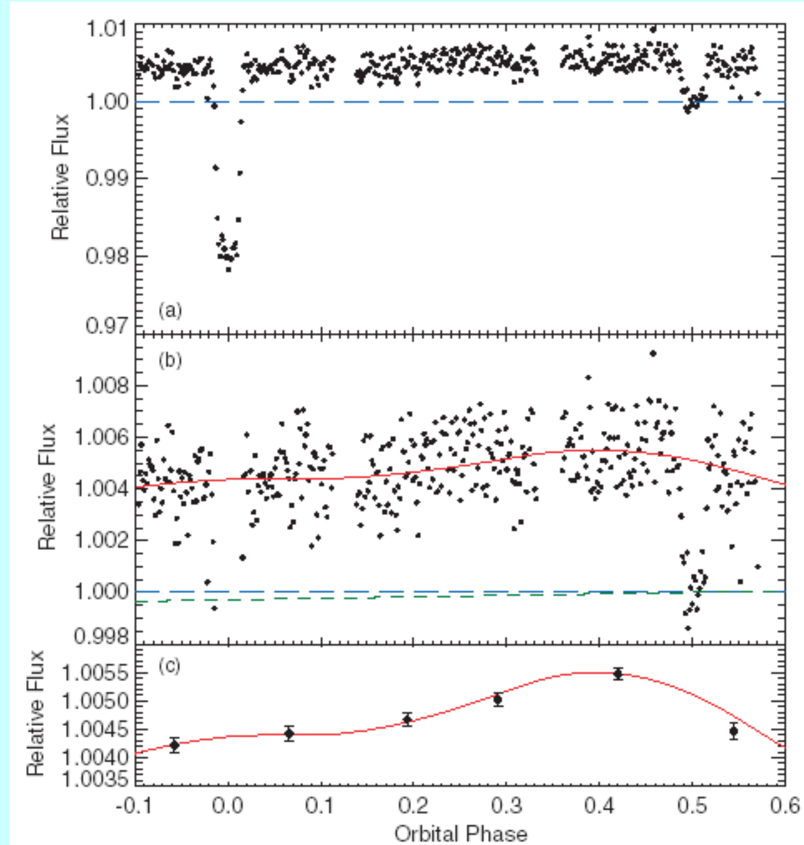

BRIGHTNESS
TIME IN HOURS



Hot Jupiters: Spitzer light curves for HD 189733b

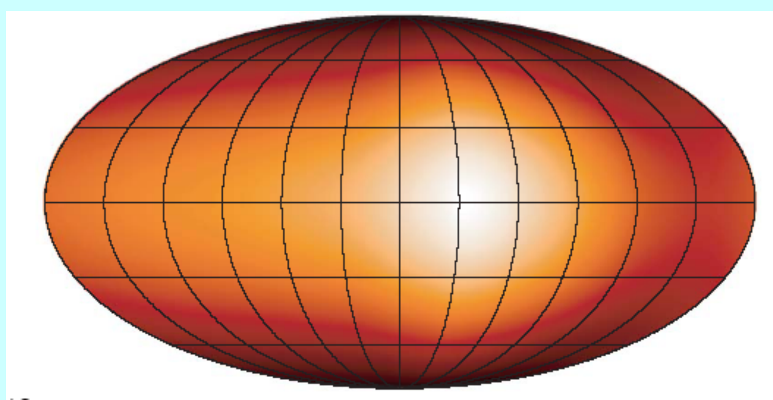


8 μm

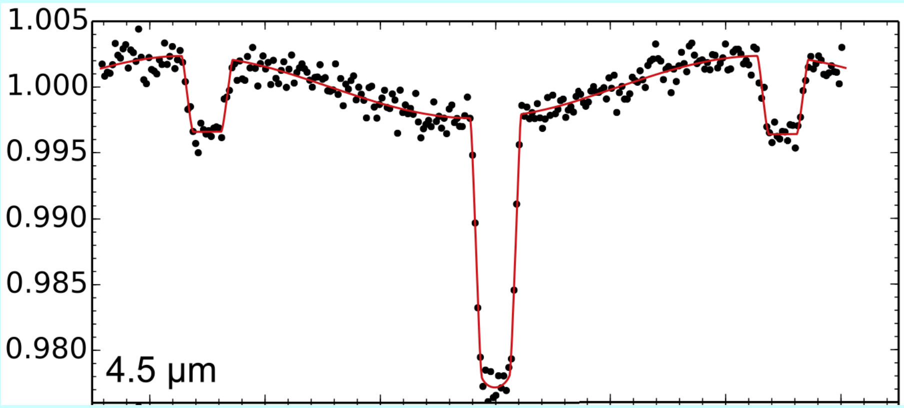


24 μm

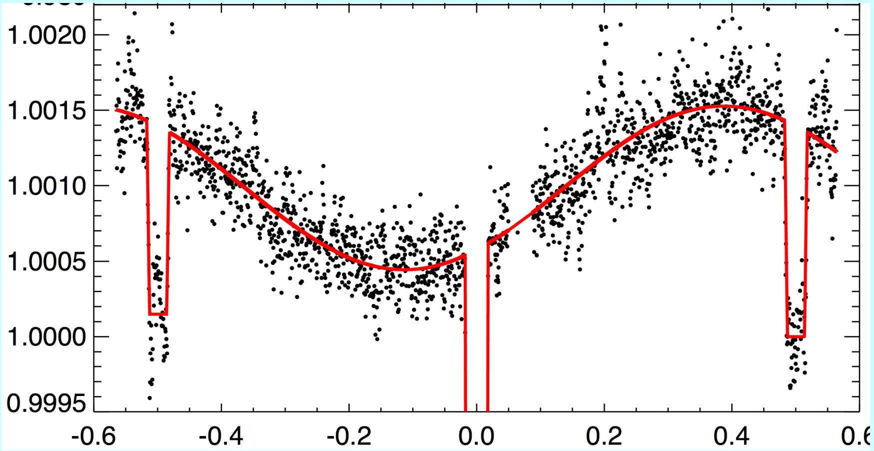
Knutson et al. (2007, 2009)



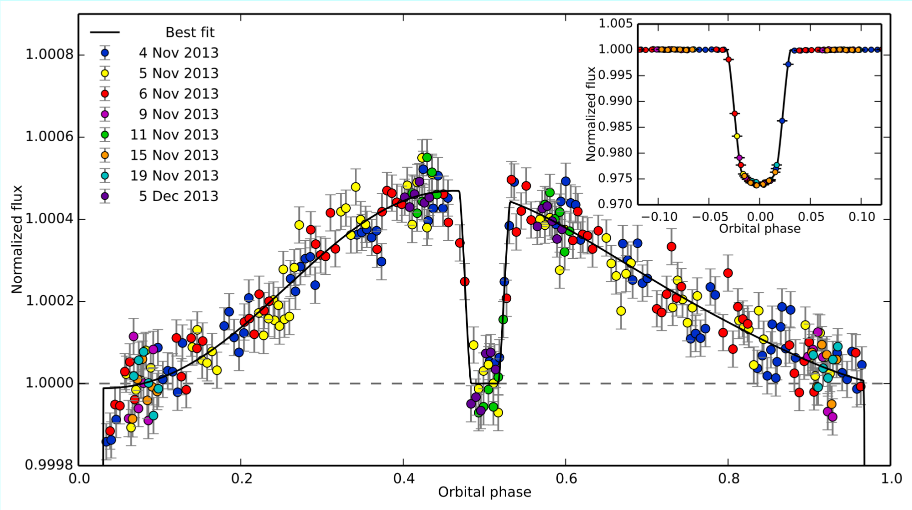
Lightcurves for hot Jupiters



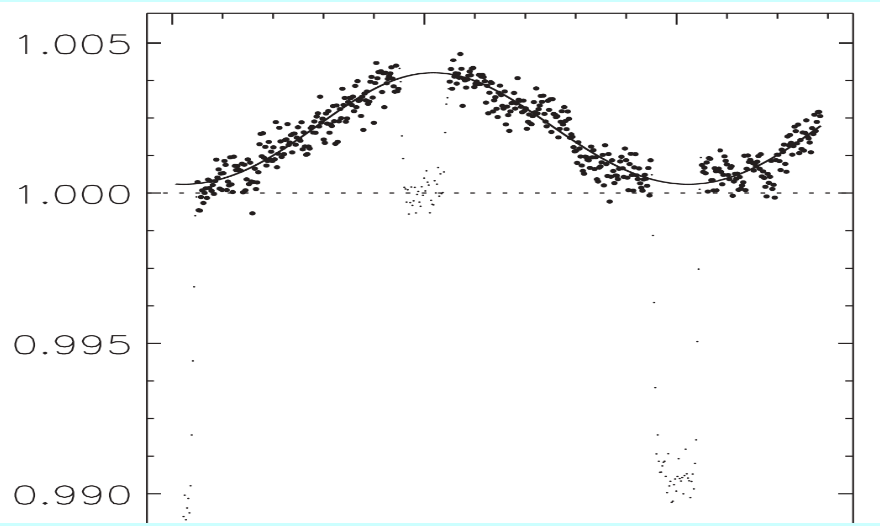
WASP-19b (Wong et al. 2016)



HD209458b (Zellem et al. 2014)



WASP-43b (Stevenson et al. 2014)



WASP-18b (Maxted et al. 2013)

Dependence of day-night flux contrast on effective temperature

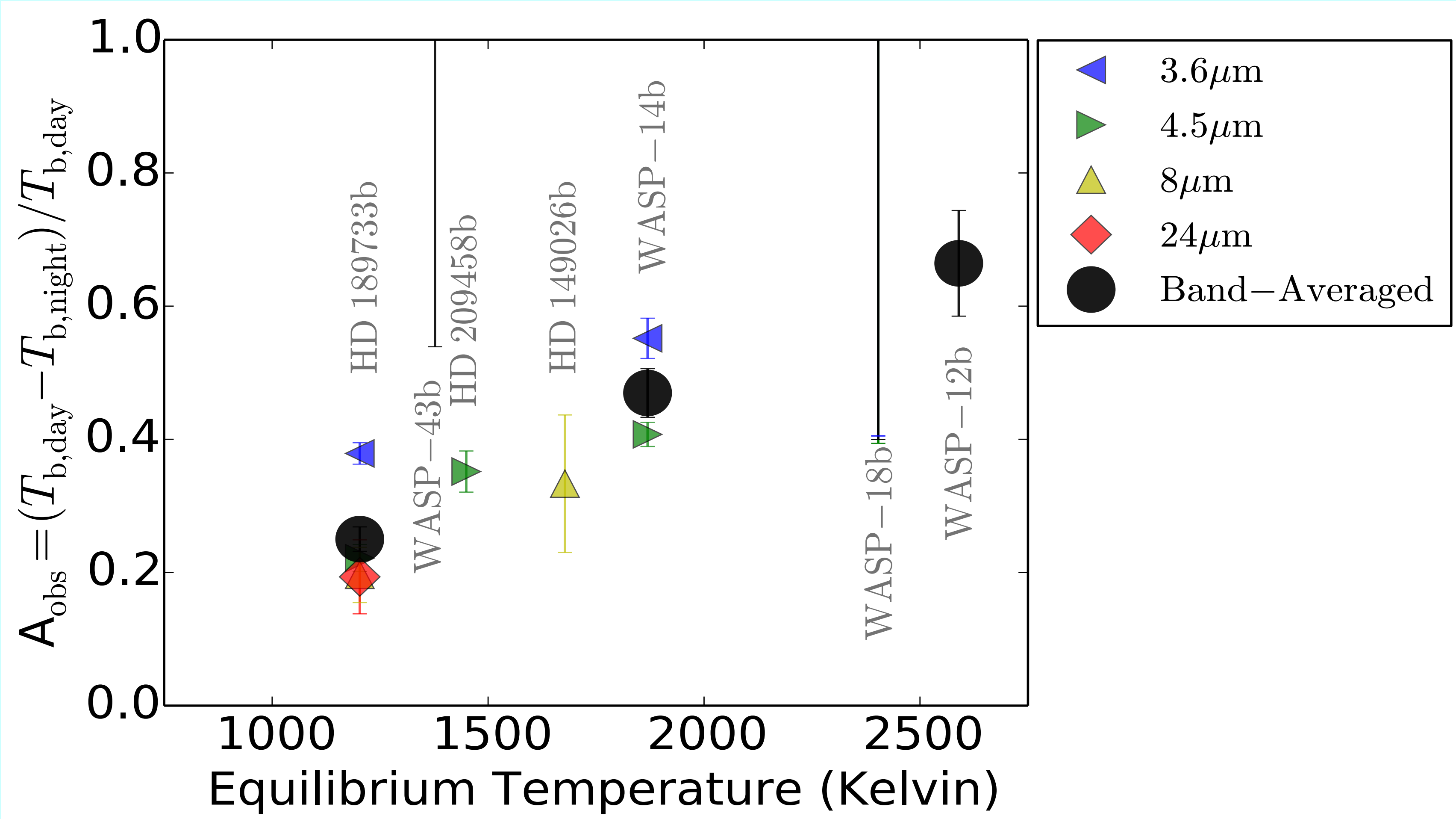
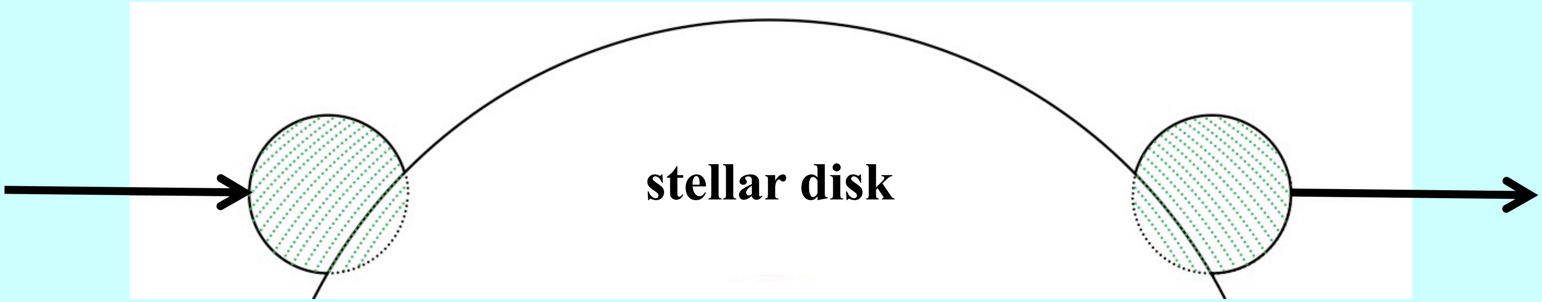
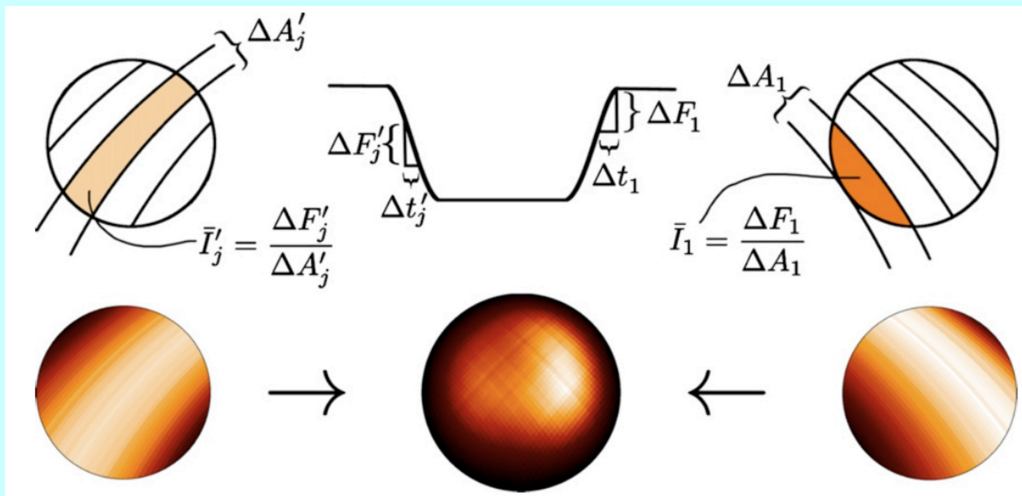
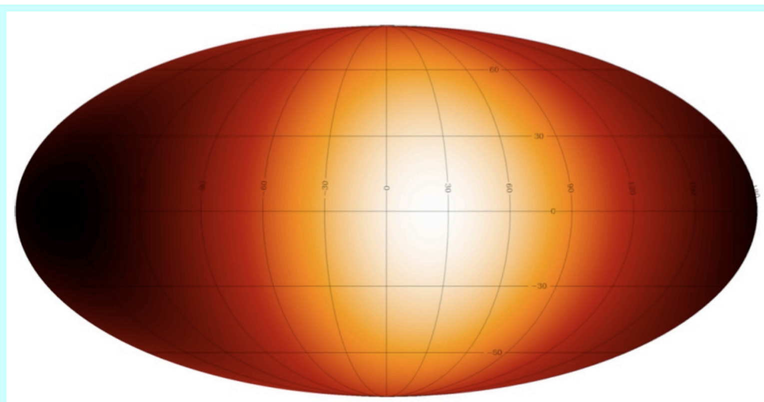


Figure courtesy of Tad Komacek

Eclipse mapping: obtaining 2D maps of the dayside

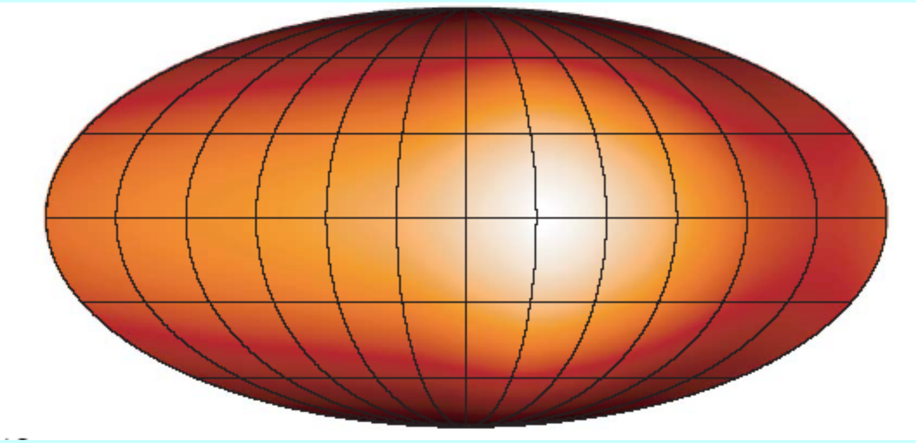


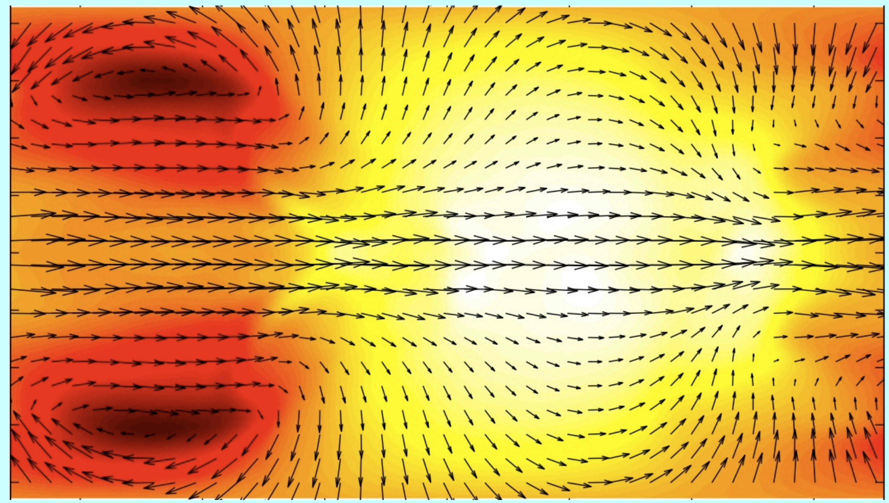




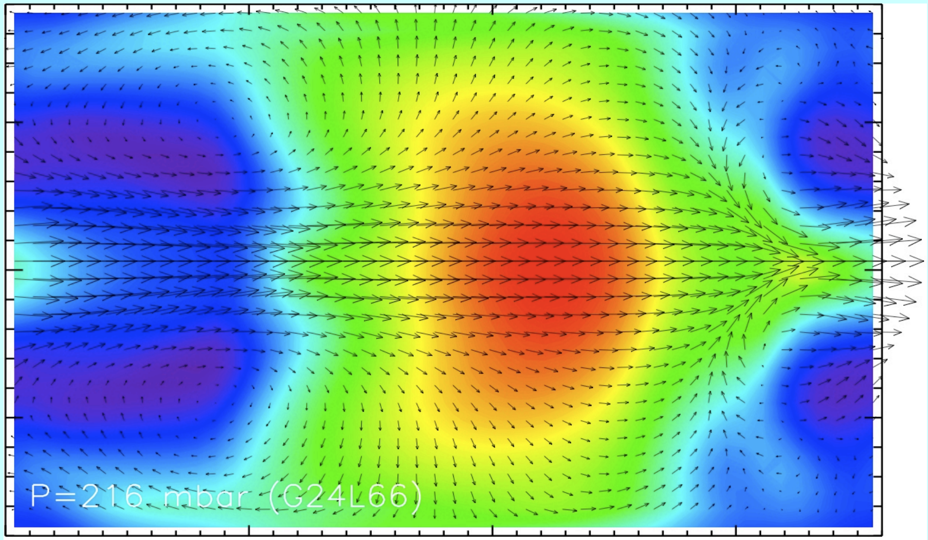
Majeau et al. (2012),
de Wit et al. (2012)

Hot Jupiter circulation models typically predict several broad, fast jets including equatorial superrotation

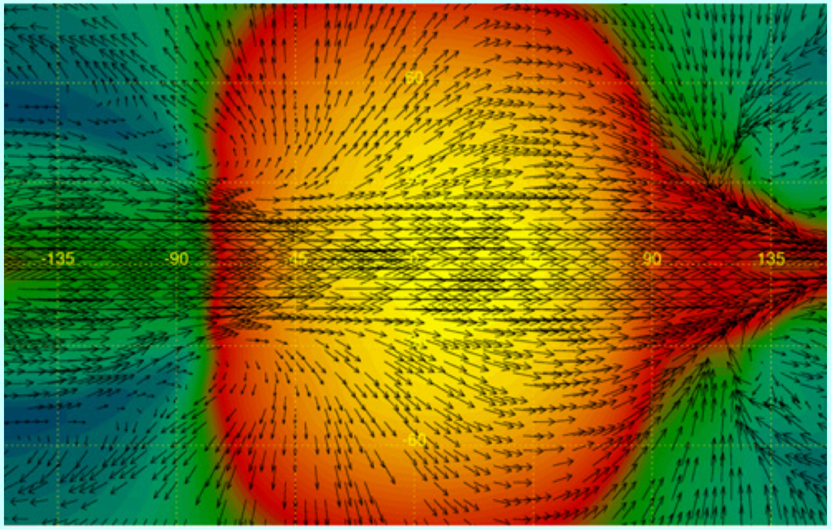




Showman et al. (2009)

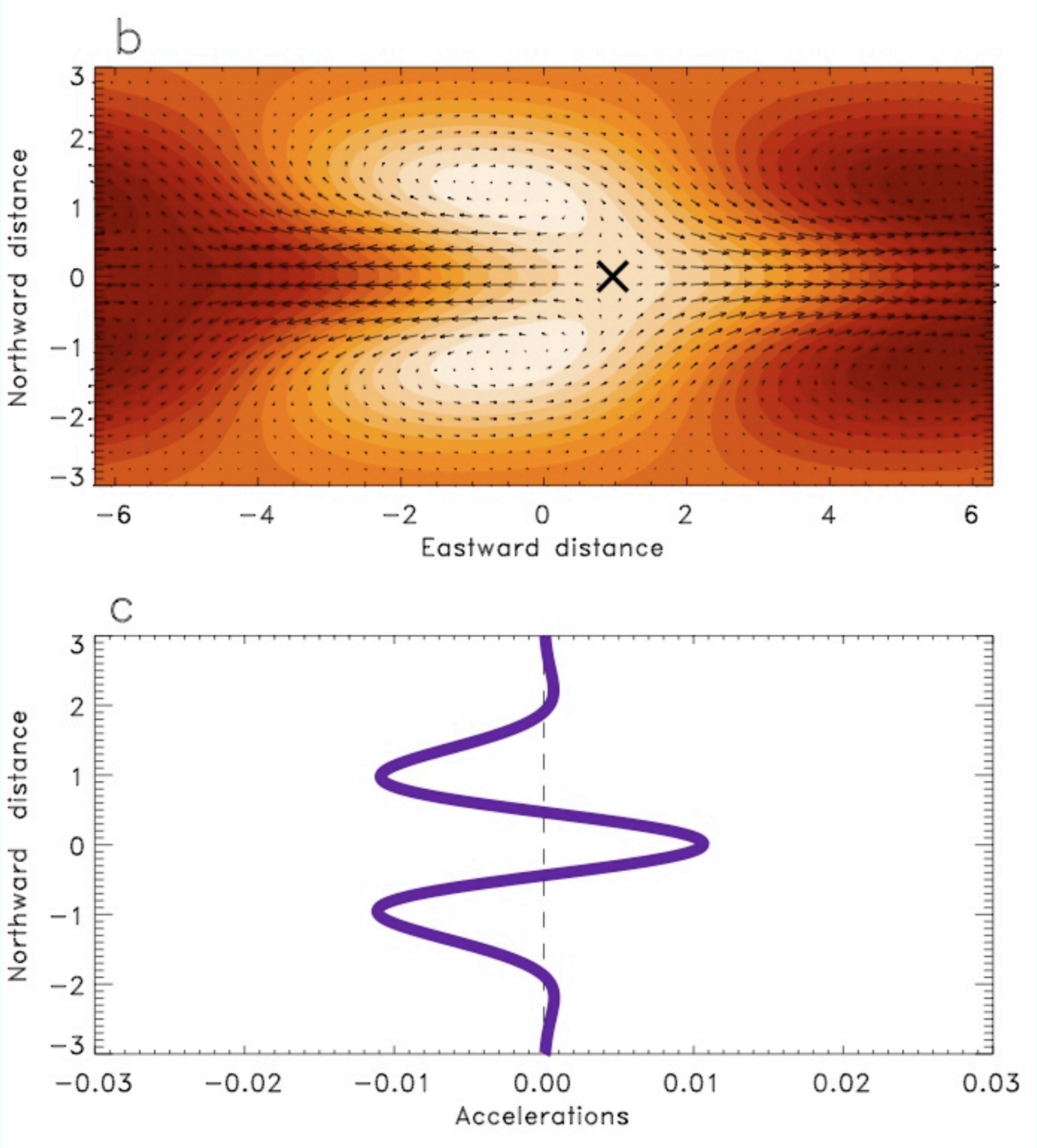


Heng et al. (2010)



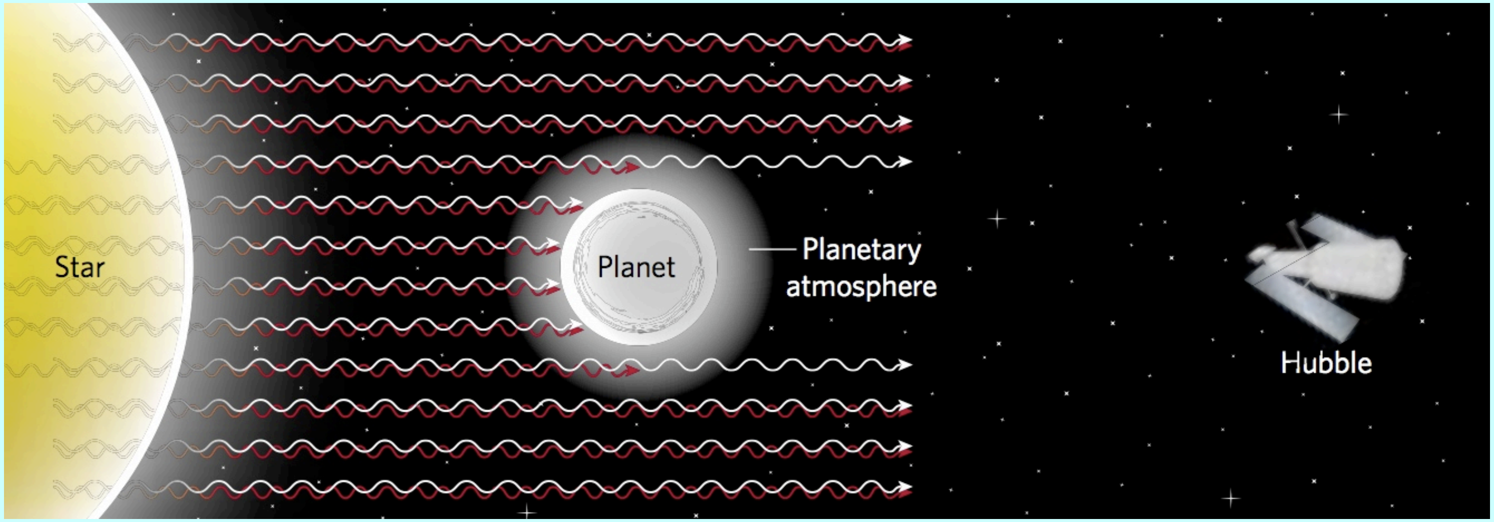
Rauscher & Menou (2012)

What causes the equatorial jet? The day-night thermal forcing induces planetary-scale waves, which pump momentum to the equator

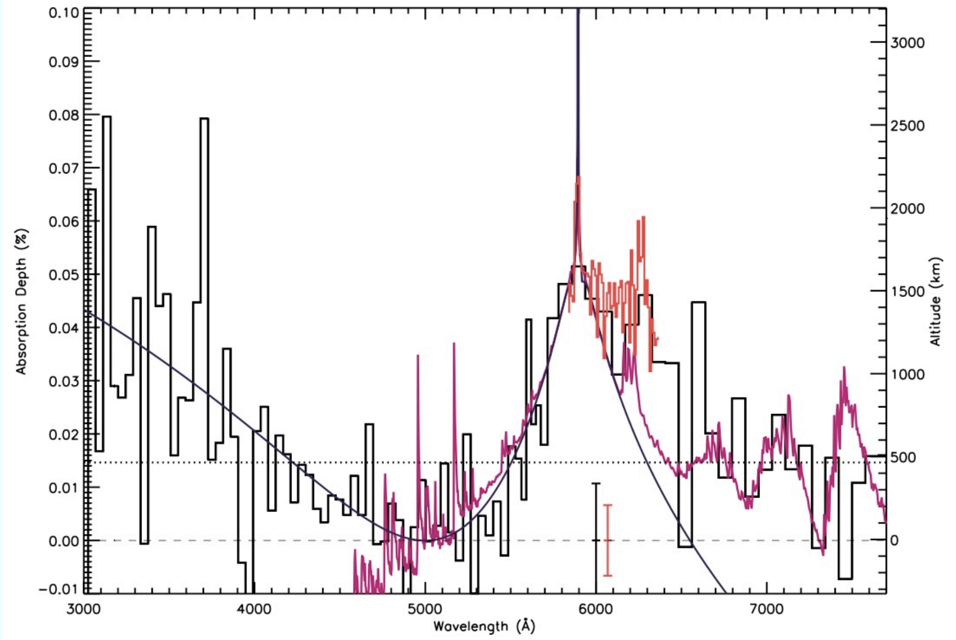


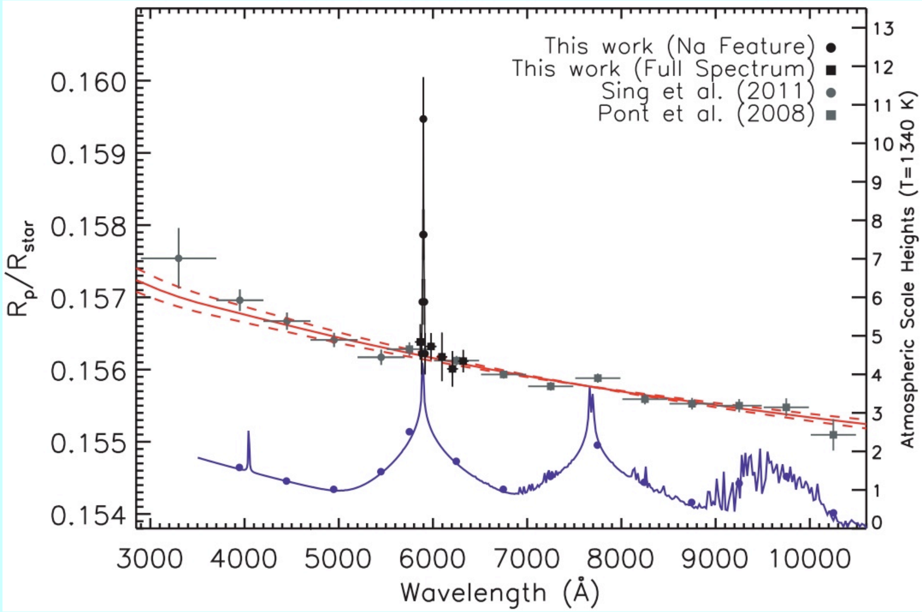
Showman & Polvani (2011), *ApJ* 738, 71

Exoplanet characterization: Transit spectroscopy



Showman (2008)





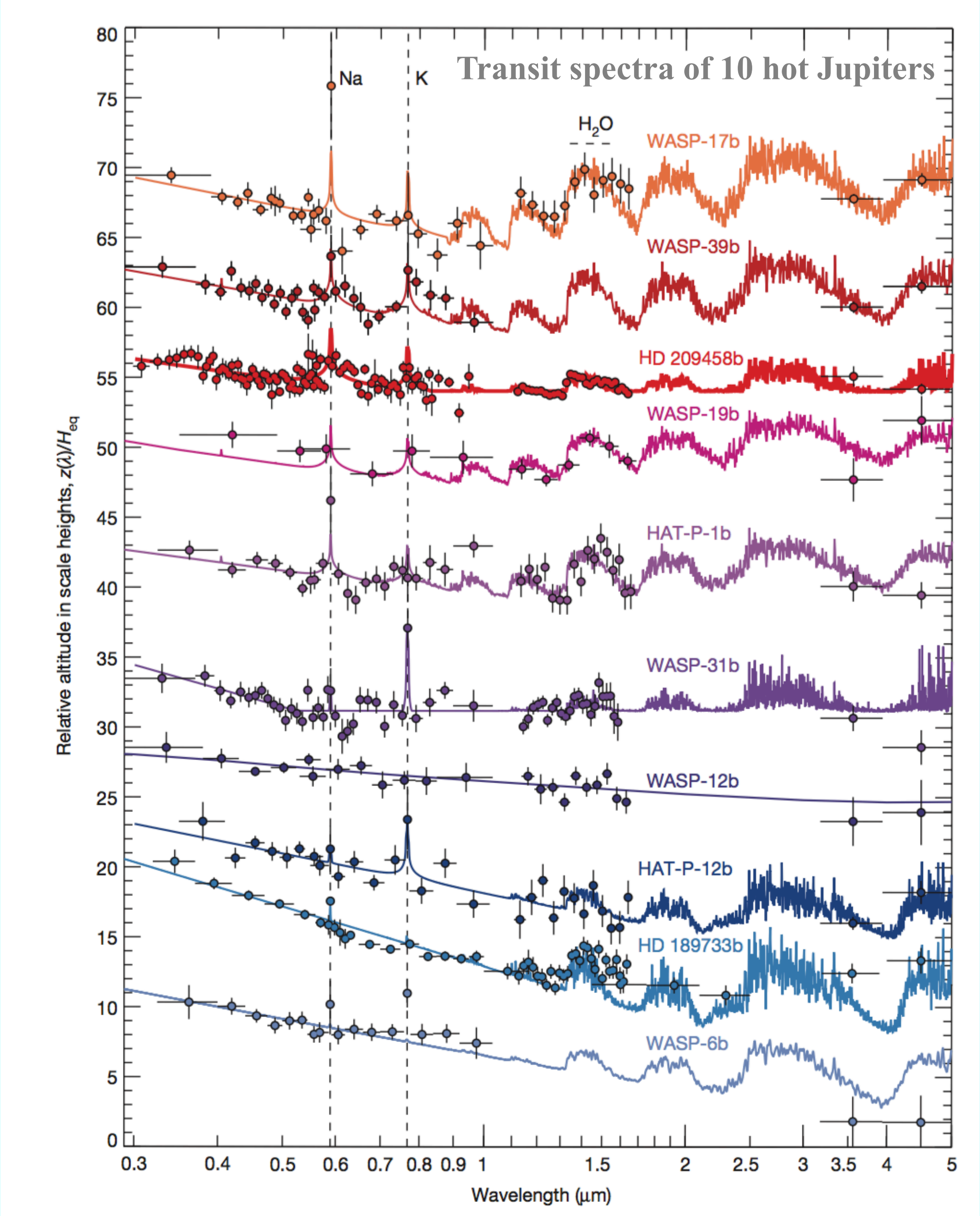
Sing et al. (2008, 2009), Vidal-Madjar et al. (2011), Huitson et al. (2012),Gibson et al. (2012), Barman (2007), Tinetti et al. (2007), Swain et al. (2008),…..

Hazes and composition on hot Jupiters

- Some hot Jupiters have relatively featureless transit spectra, indicating high-altitude, spectrally grey hazes obscuring molecular absorption bands.

- In others, molecular bands (e.g., water) are prominent, indicating less hazes, and constraining the atmospheric composition.

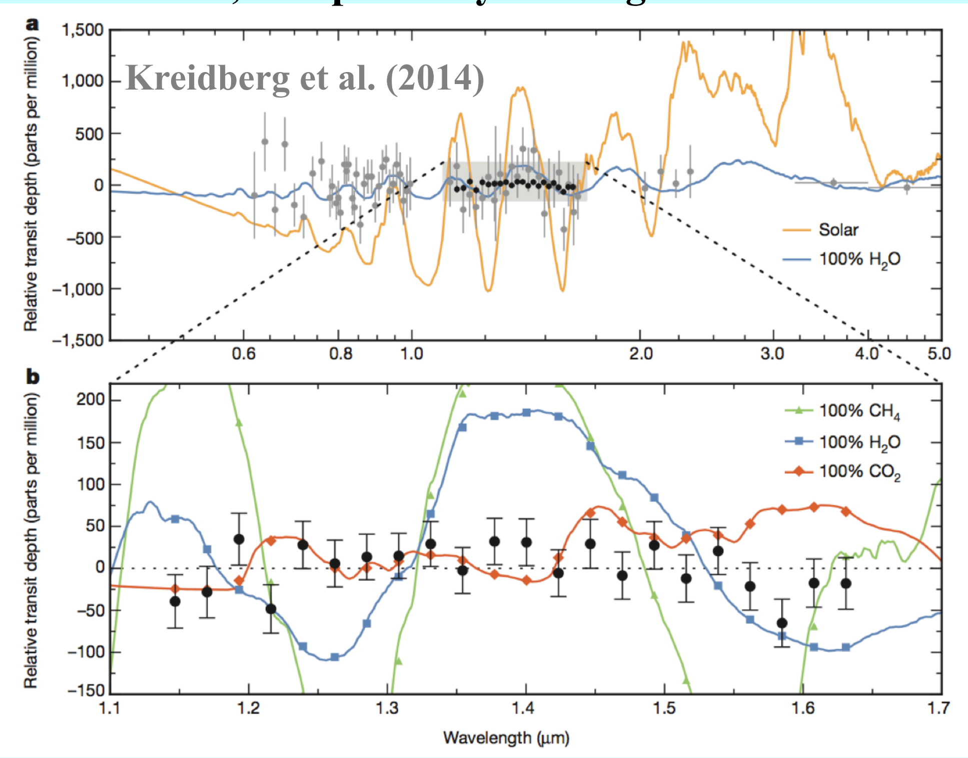
- In principle, spectra like this can be used to infer the water abundance, but the degeneracy with hazes makes it difficult to obtain absolute abundances.



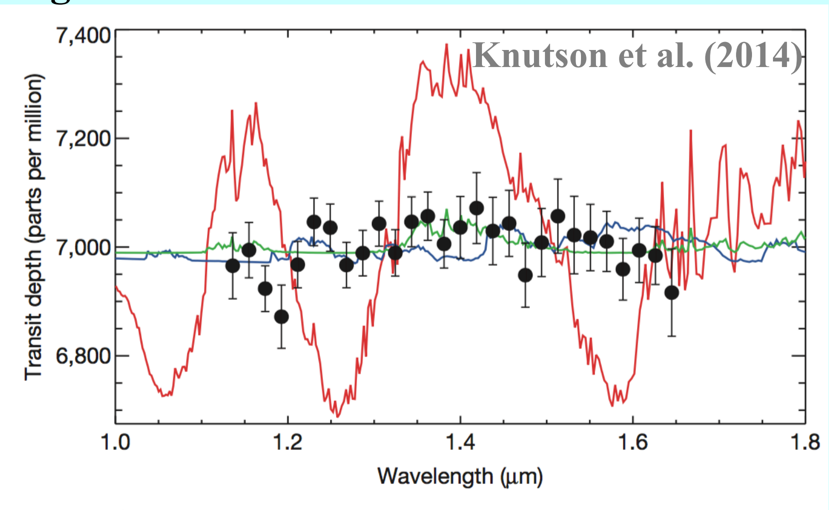
Sing et al. (2016, *Nature*)

Transmission spectra of smaller planets (super Earths / hot Neptunes)

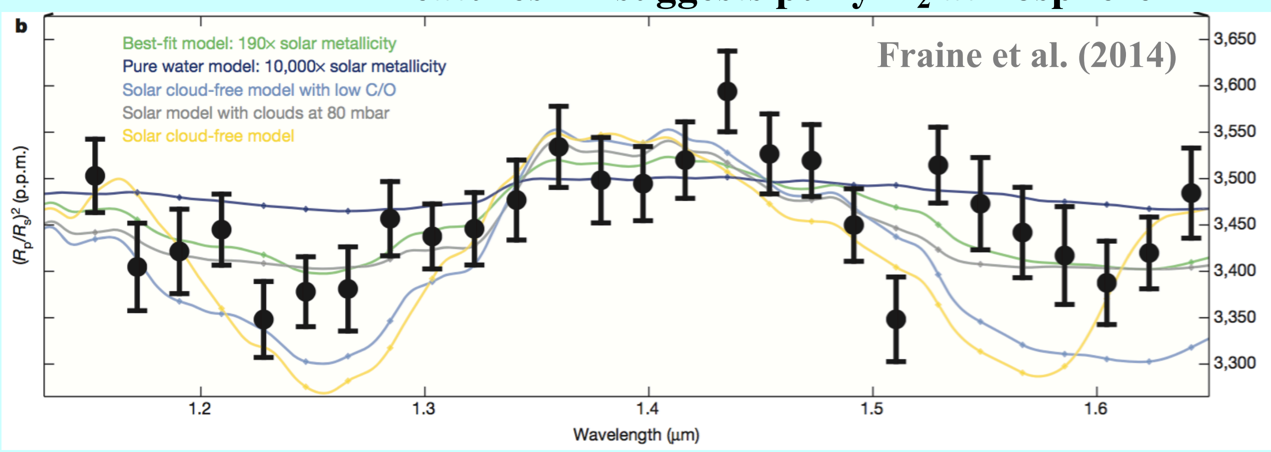
GJ 1214b, very flat spectrum => requires hazes, and probably also high MMW



GJ 436b, flat spectrum => hazes and/or high MMW



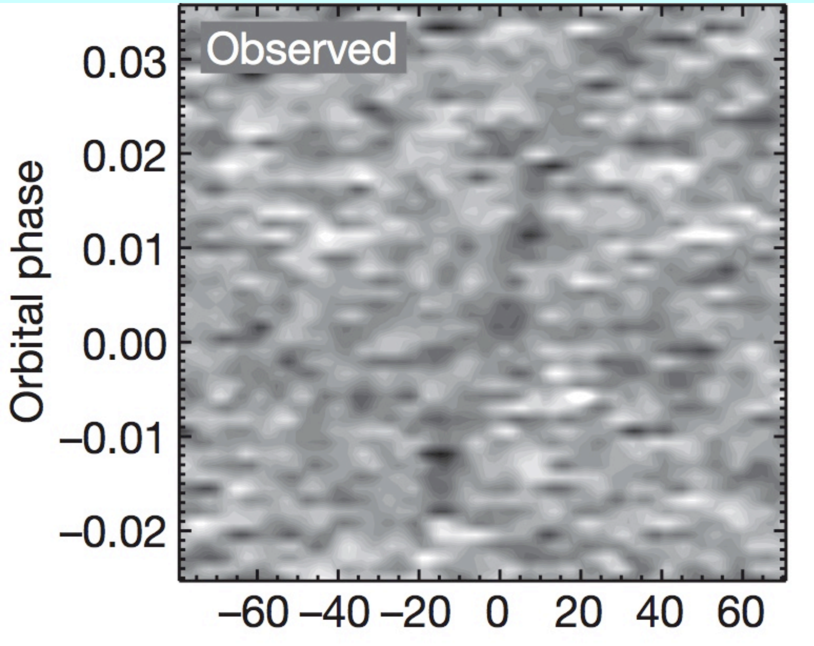
HAT-P-11b, tentative detection of weak water features => suggests puffy H_2 atmosphere

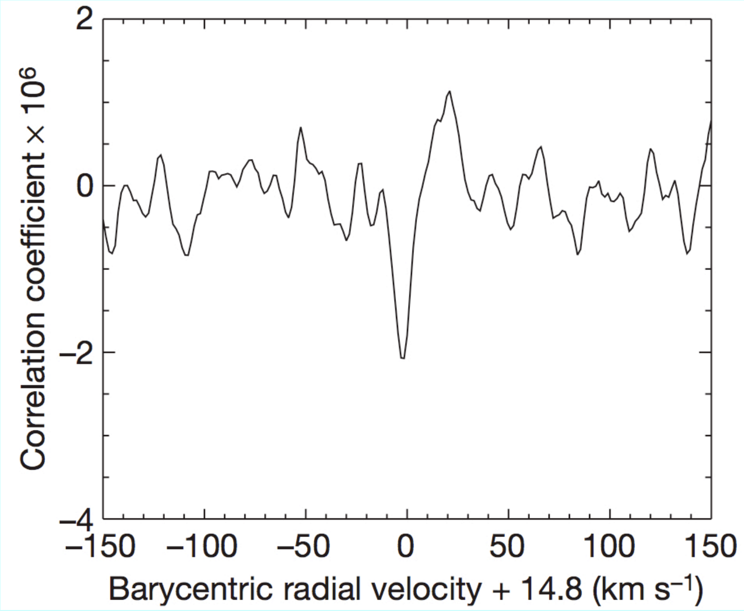


Do super Earths have H_2-dominated atmospheres like Uranus and Neptune? Or high mean molecular weight (MMW) atmospheres of water, N_2, CO_2, etc?

Doppler detection of winds on HD 209458b?

- **Snellen et al. (2010, Nature) obtained high-resolution 2 μm spectra of HD 209458b during transit with the CRIRES spectrograph on the VLT**



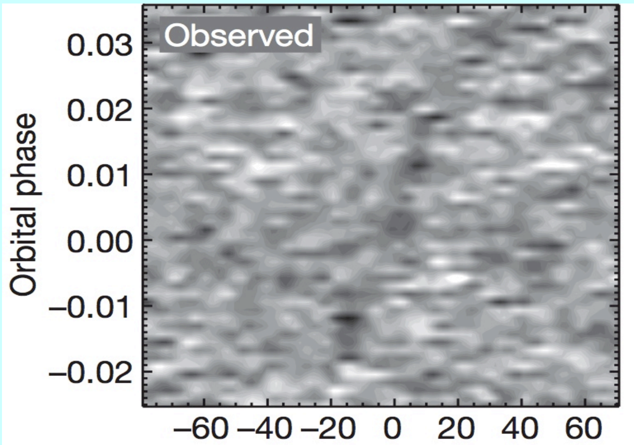


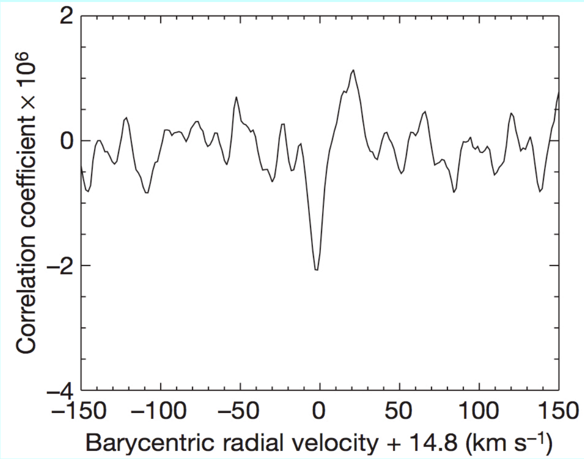
- **Tentative detection of ~2 km/sec blueshift in CO lines during transit of HD 209458b**

- **Interpreted as winds flowing from day to night at high altitude (~0.01-0.1 mbar)**

Doppler detection of winds during transit

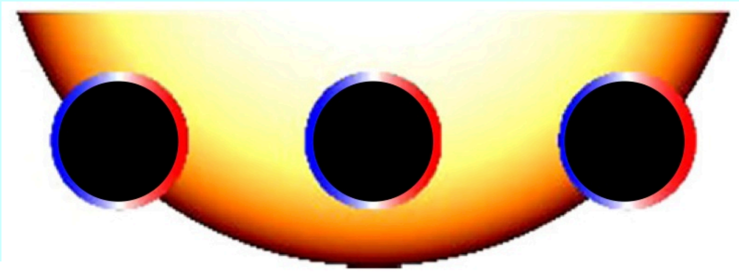
HD 209458b: Residual 2 km/sec blueshift (2 μm, CRIRES)

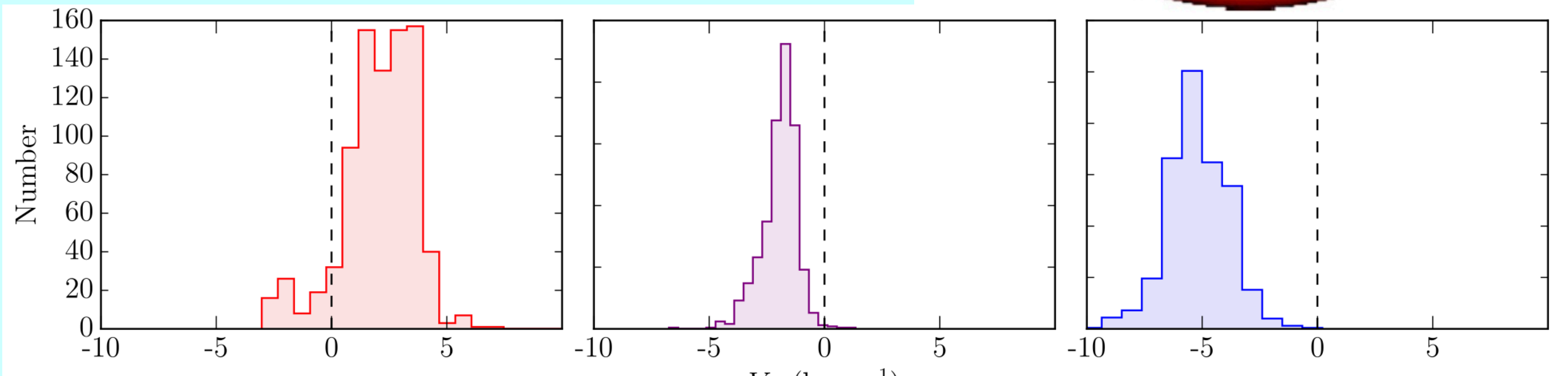




Snellen et al. (2010)

HD 189733b: red (blue) shift on leading (trailing) limb detected using ingress/egress



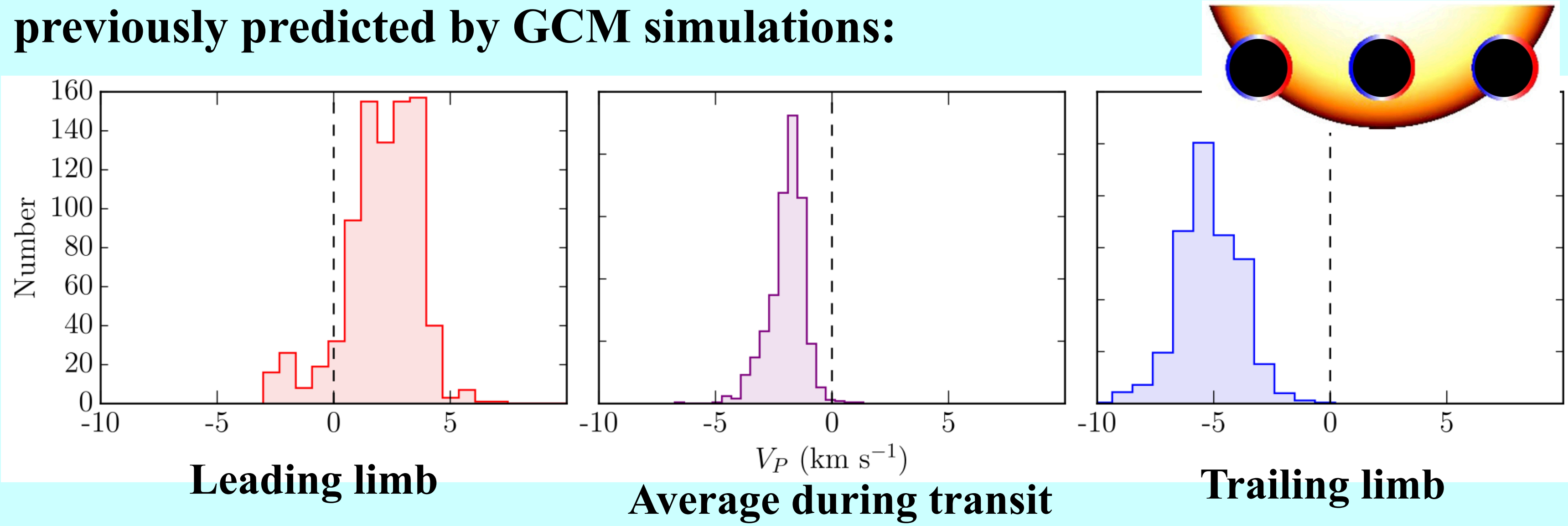


Leading limb **Average during transit** **Trailing limb**

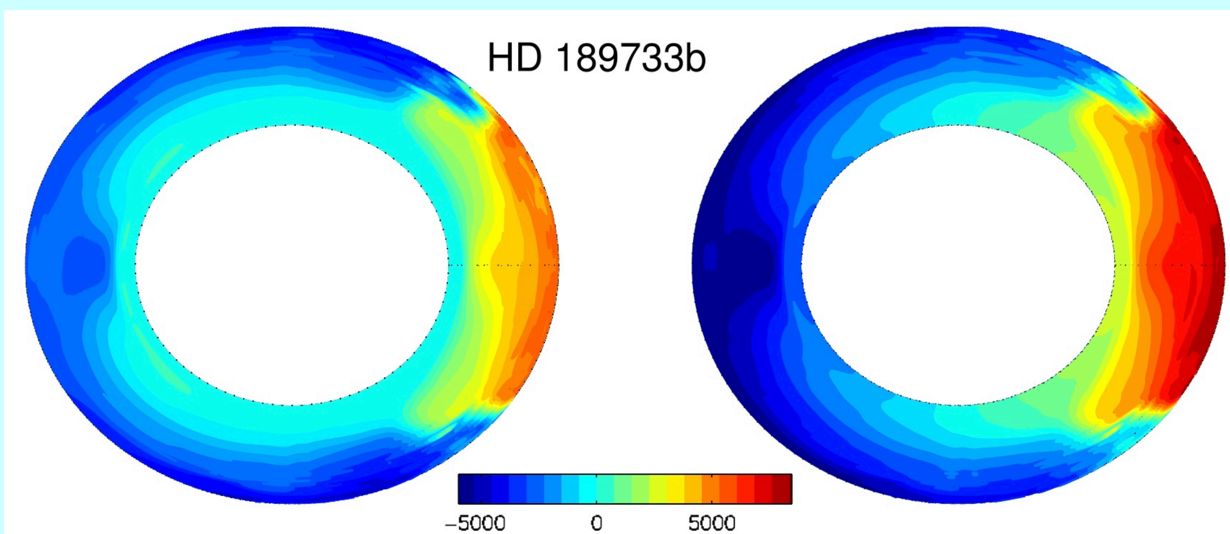
Louden & Wheatley (2015)

Doppler detection of equatorial jet

Equatorial jet recently observed on HD 189733b is similar to that previously predicted by GCM simulations:



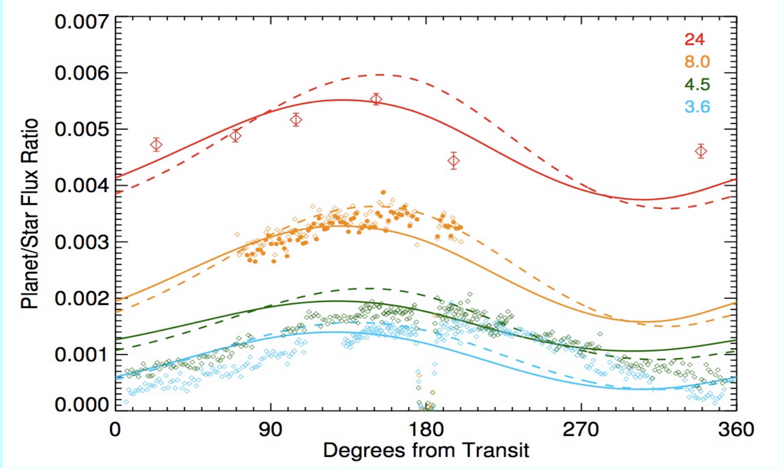
Louden & Wheatley (2015)

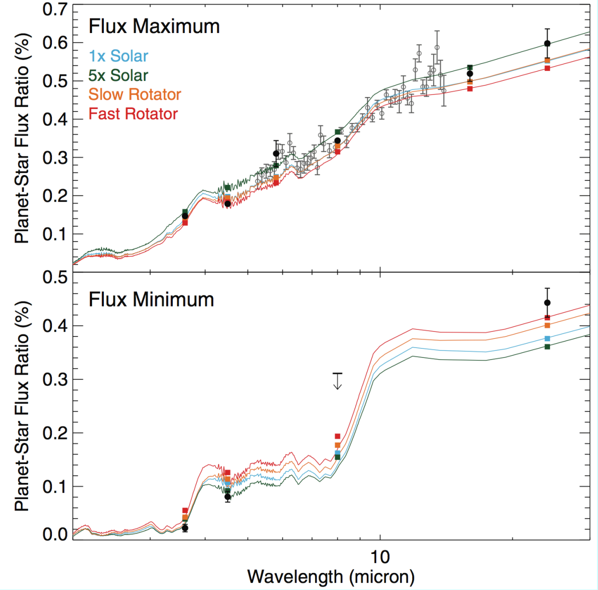


Showman et al. (2013)

Comparisons of data to GCMs

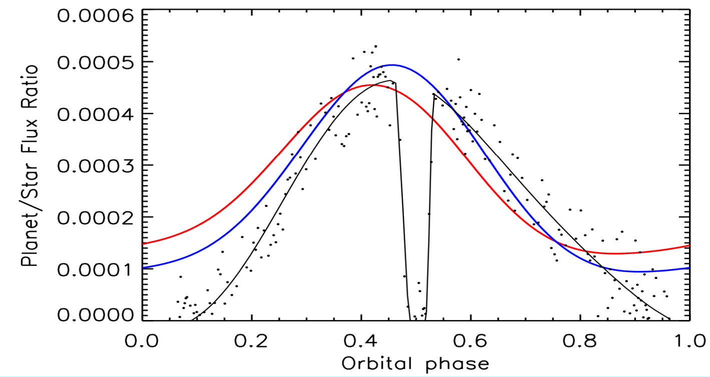
HD 189733b

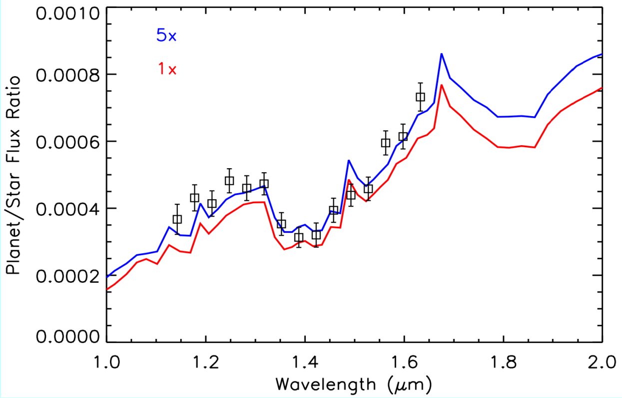




Showman et al. (2009), Knutson et al. (2012)

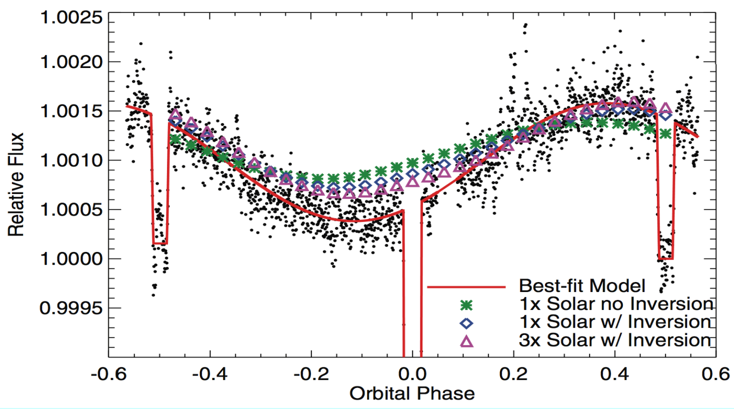
WASP-43b

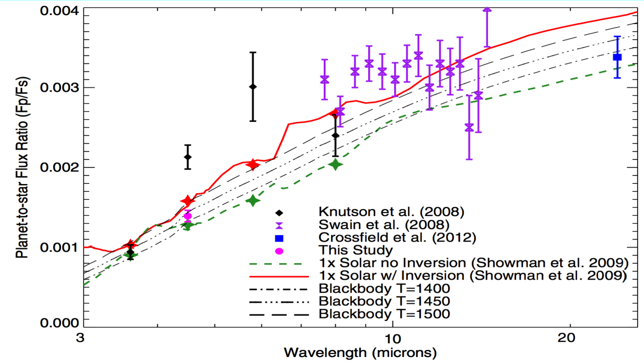




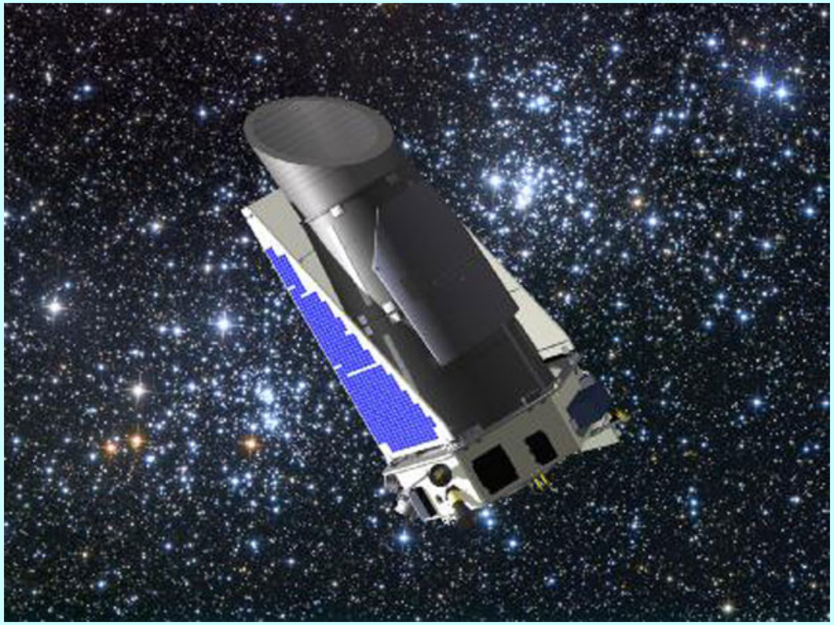
Kataria et al. (2015)

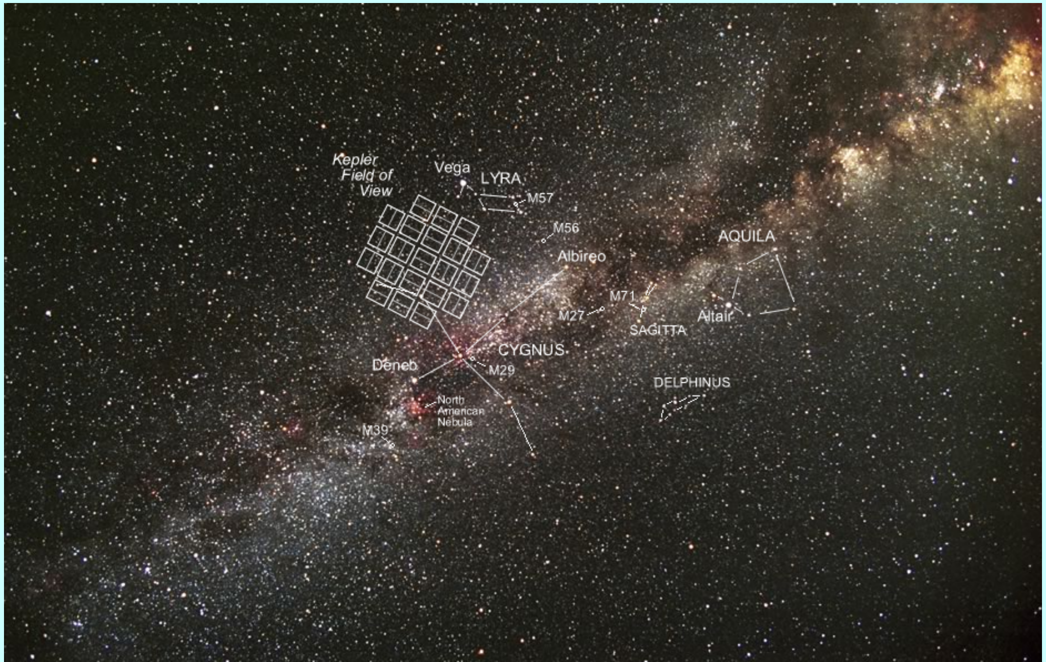
HD 209458b





NASA Kepler mission

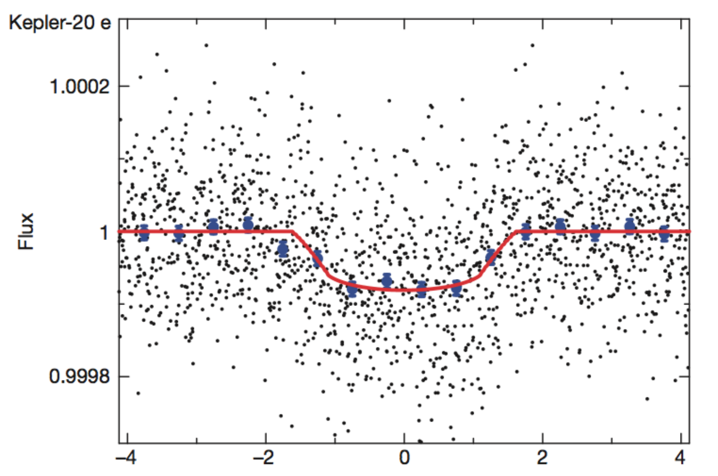




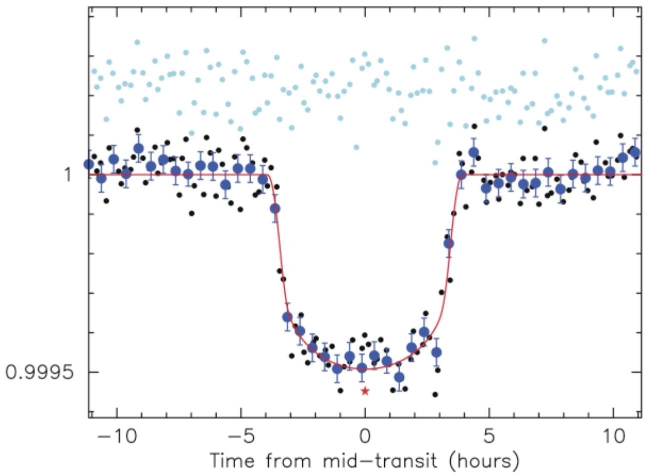
NASA Kepler mission

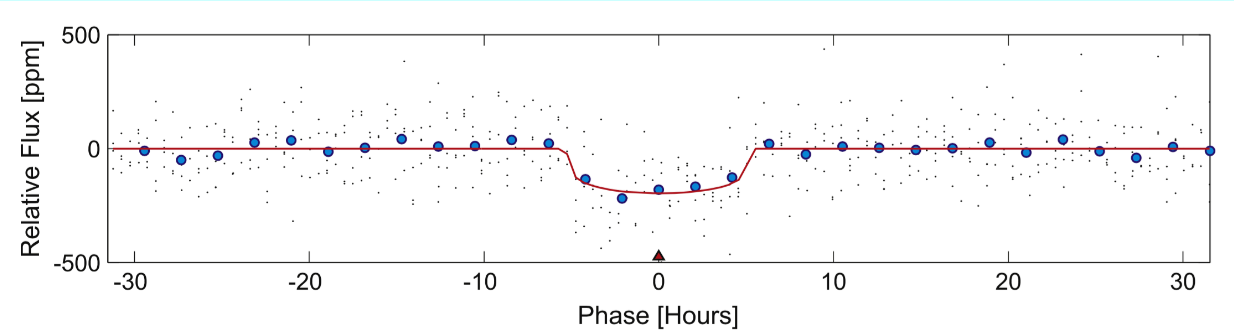
- Detects planets using the transit technique—about 2300 planets discovered
- Roughly half of stars have a "super Earth"… a planet 1-10 Earth masses
- Kepler discovered several planets close to the classical habitable zone

Kepler 20e: a (hot) planet smaller than Earth!



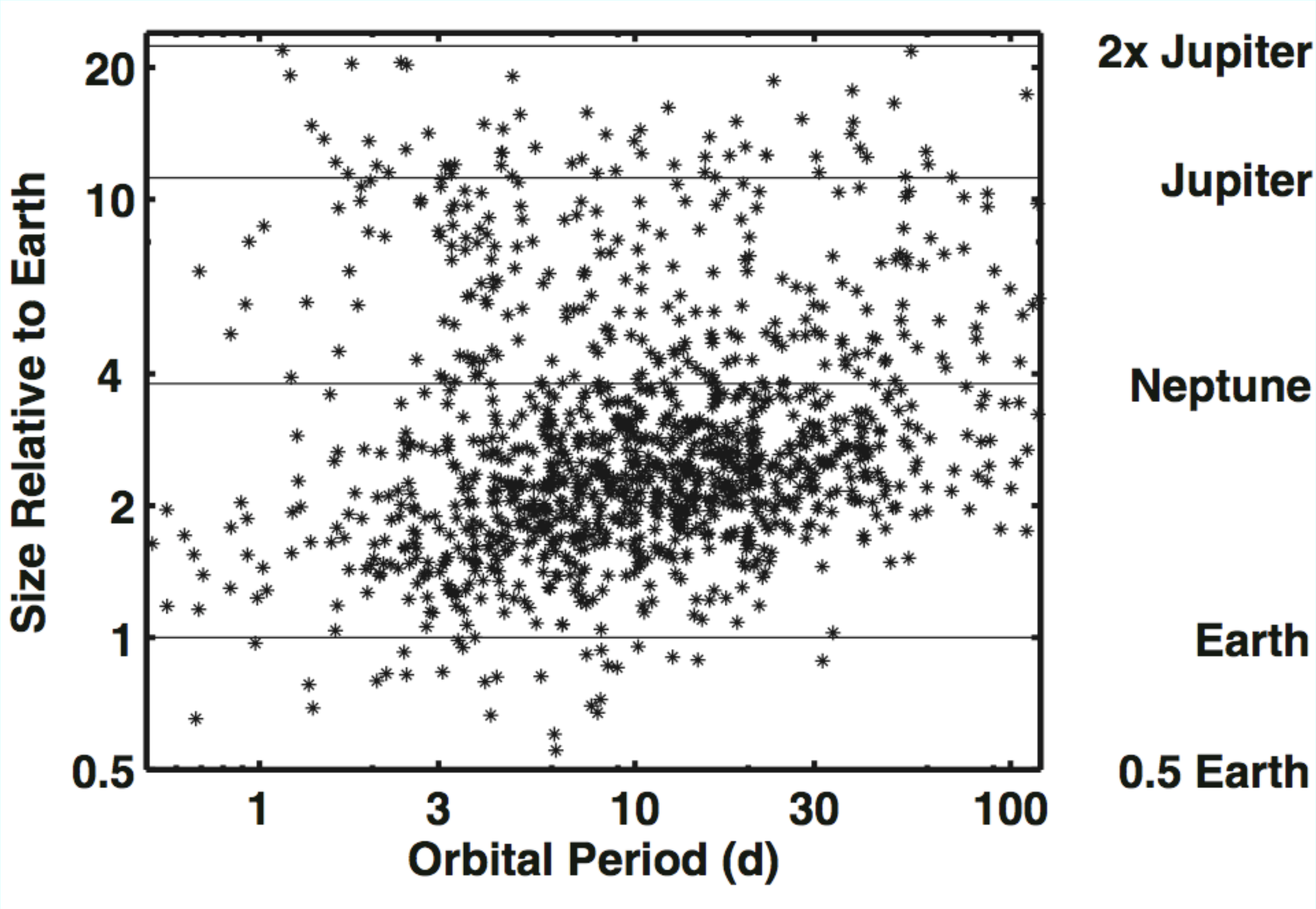
Kepler 22b: a 2.4-Earth radius planet in the habitable zone



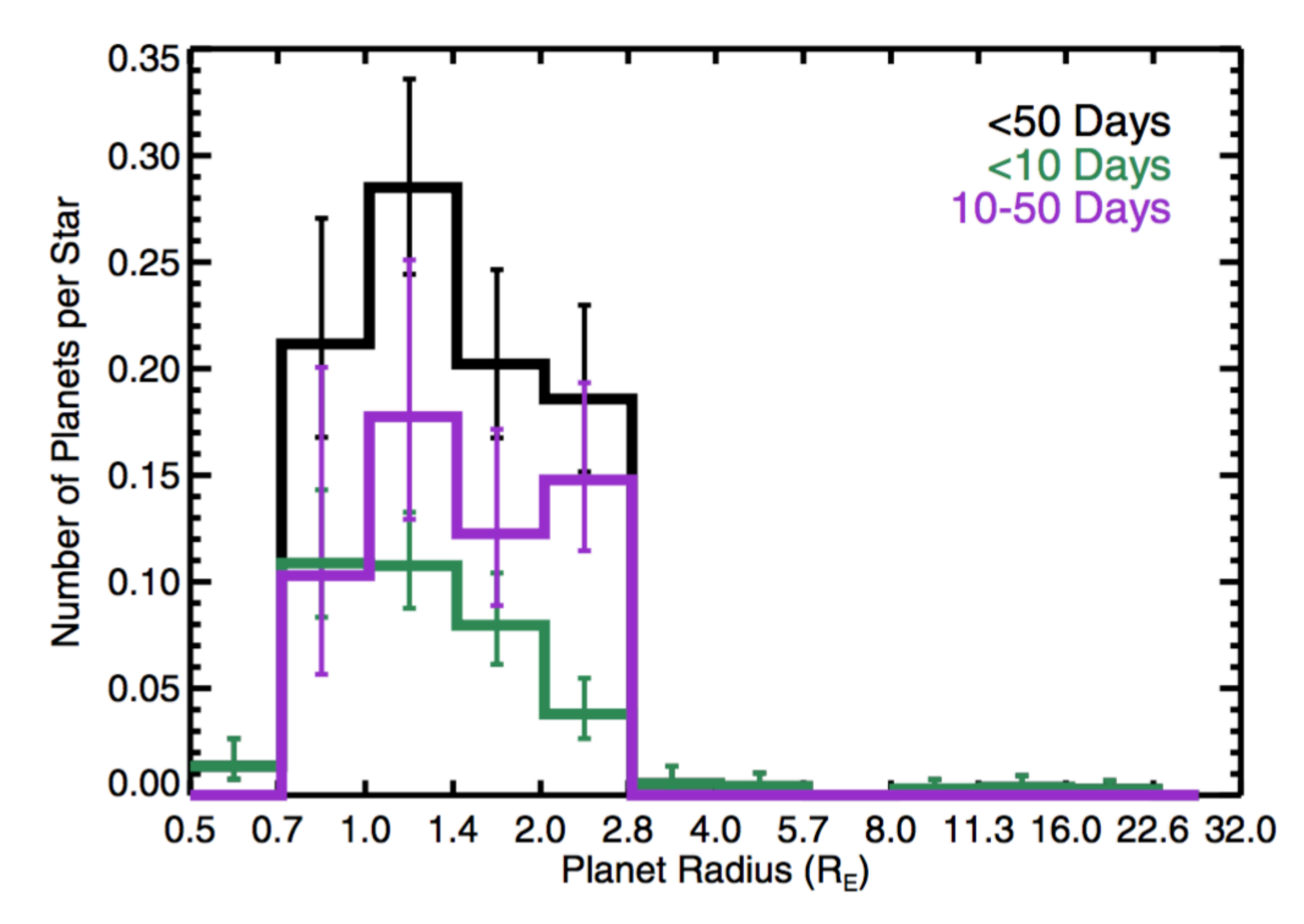


Kepler 452b: a 1.6-Earth radius planet in the habitable zone of a sun-like star

Kepler detected *loads* of "super Earths"



Kepler assessment of planet populations

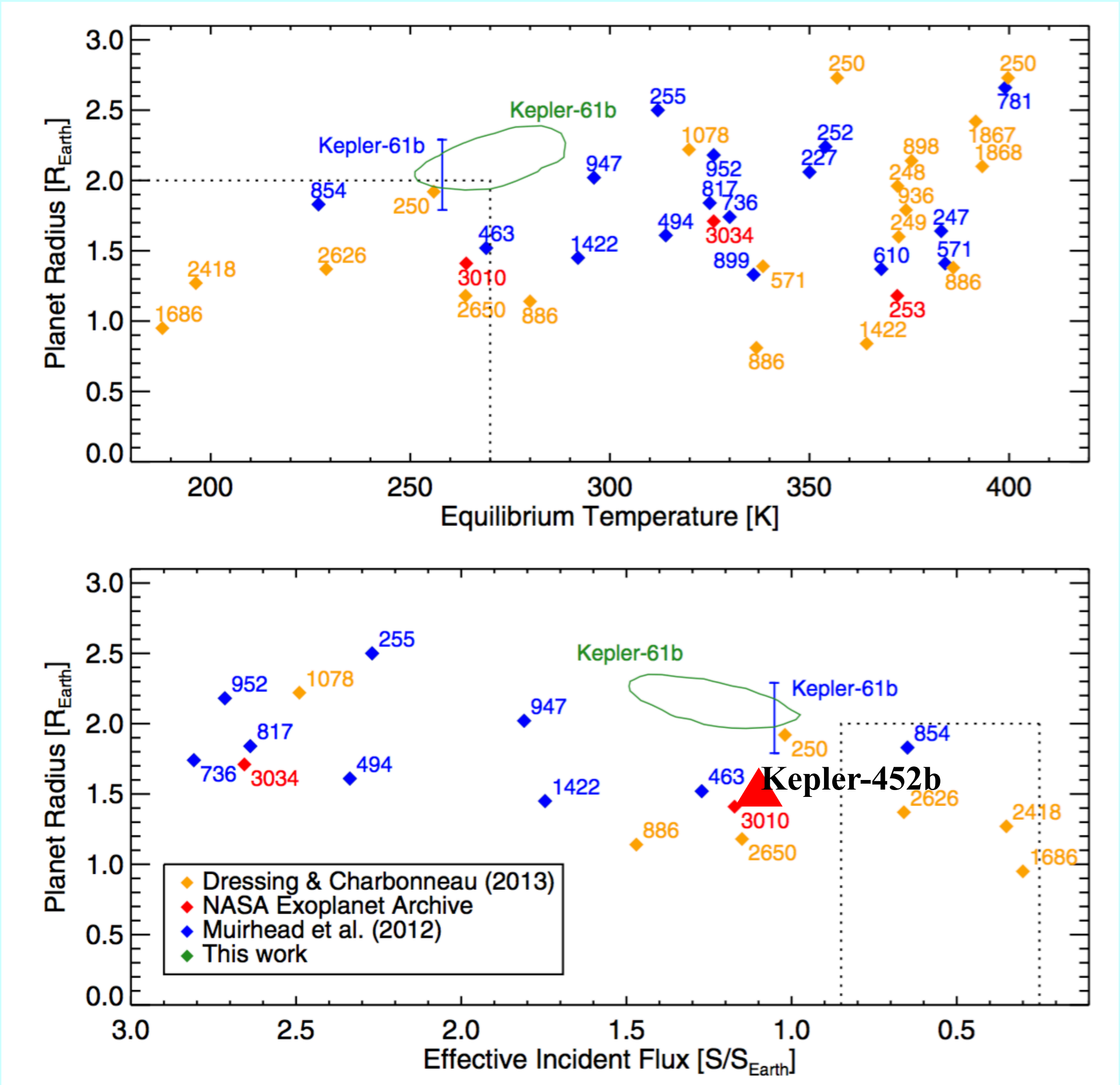


Dressing & Charbonneau (2013)

Kepler showed that close-in super Earths are *far* more common than close-in giant planets (but the issue is still unsettled for more distant planets).

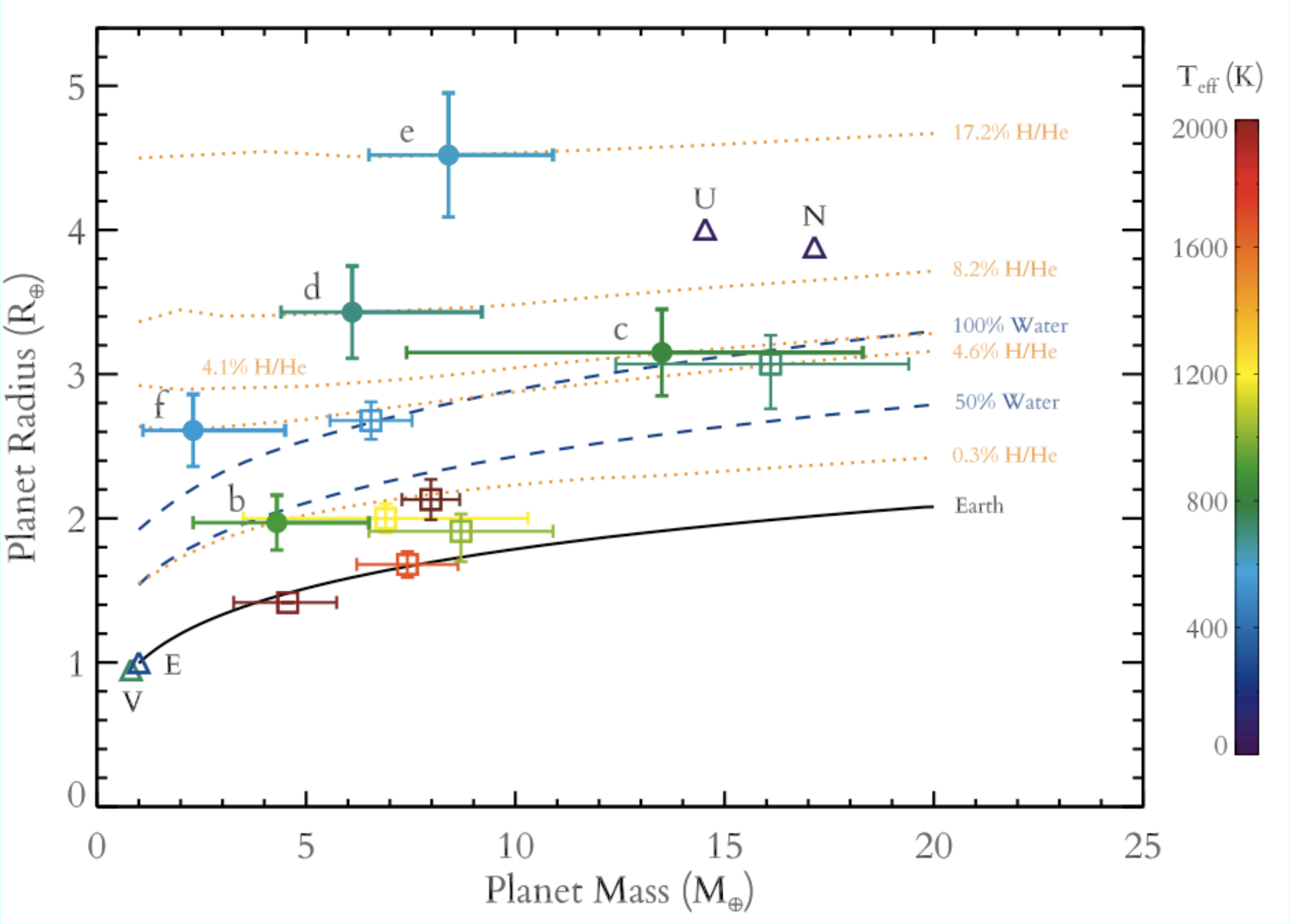
Kepler homing in on habitable planets

Planets <3 Earth radii that receive comparable stellar flux to Earth



Ballard et al. (2013)

We can infer densities and therefore learn about composition!

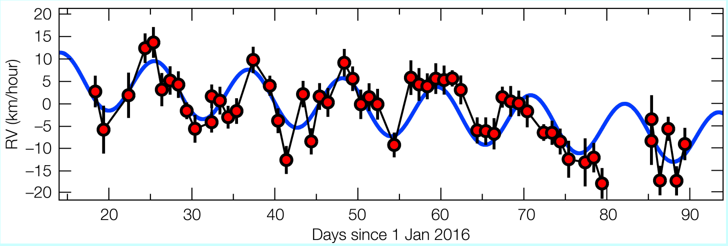


Lopez et al. (2012)

Proxima Centauri b: a habitable-zone planet around the closest star

- **Proxima Centauri is the closest star to the Sun—distance of 4.25 light years—in the constellation Centaurus. It is a dim M dwarf with a luminosity only 0.2% of the Sun's. It may be a third (bound) component of the nearby Alpha Centauri binary star system**

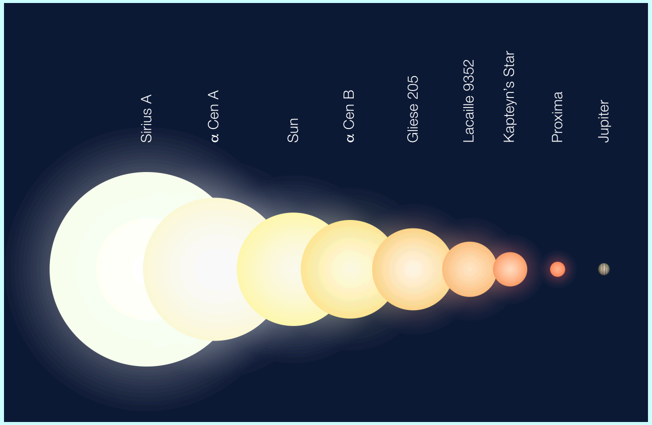
- **Planet was discovered August 2016 by radial velocity—*M*sin*i* of 1.3 Earth masses, orbital period 11.2 days, orbital semi-major axis 0.05 AU, receiving 0.65 the stellar flux of Earth. This would imply an effective temperature of ~230 K if the albedo is similar to Earth's.**



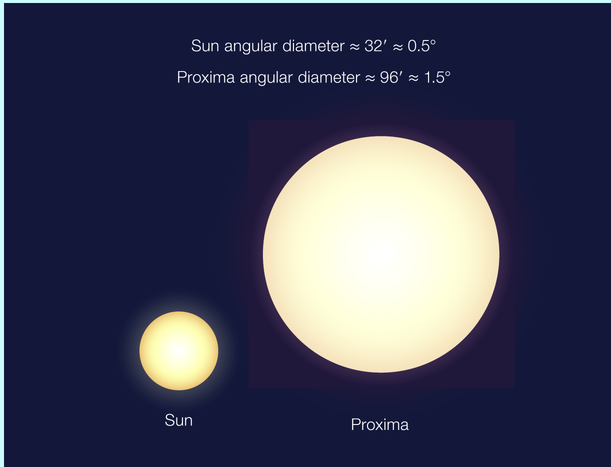
Stellar motion inferred from Doppler shift of stellar lines, indicating a planet.

- **There is great interest in characterizing this planet to see if it has an atmosphere and understand its climate.
It would probably be a synchronously rotating planet with permanent day and nightsides.**

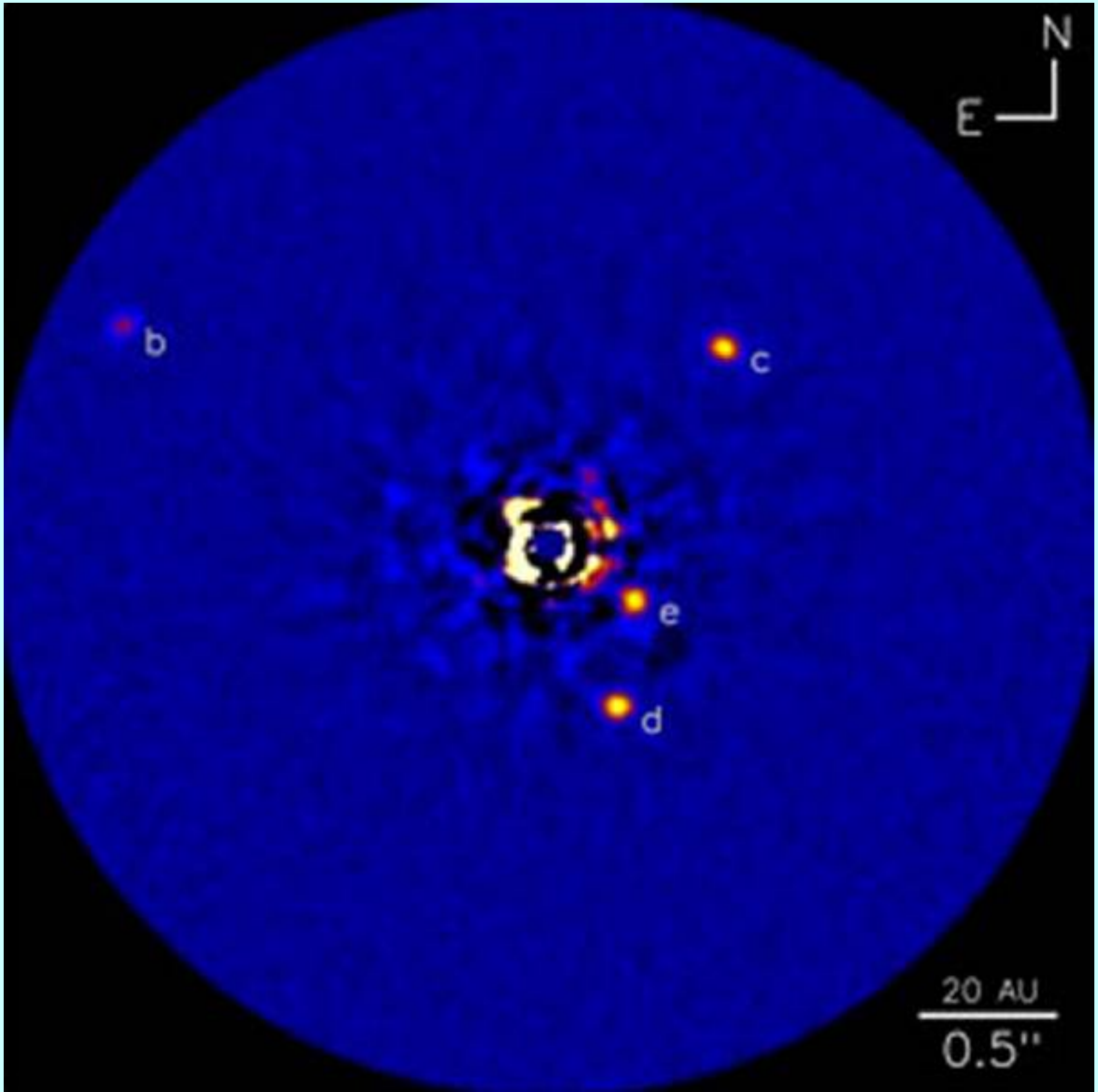
Relative sizes of Sun in our sky to Proxima Cen in this planet's sky



Relative sizes of some stars… Proxima Cen is not much bigger than Jupiter.



A new frontier: directly imaged planets and brown dwarfs



Brown dwarf basics

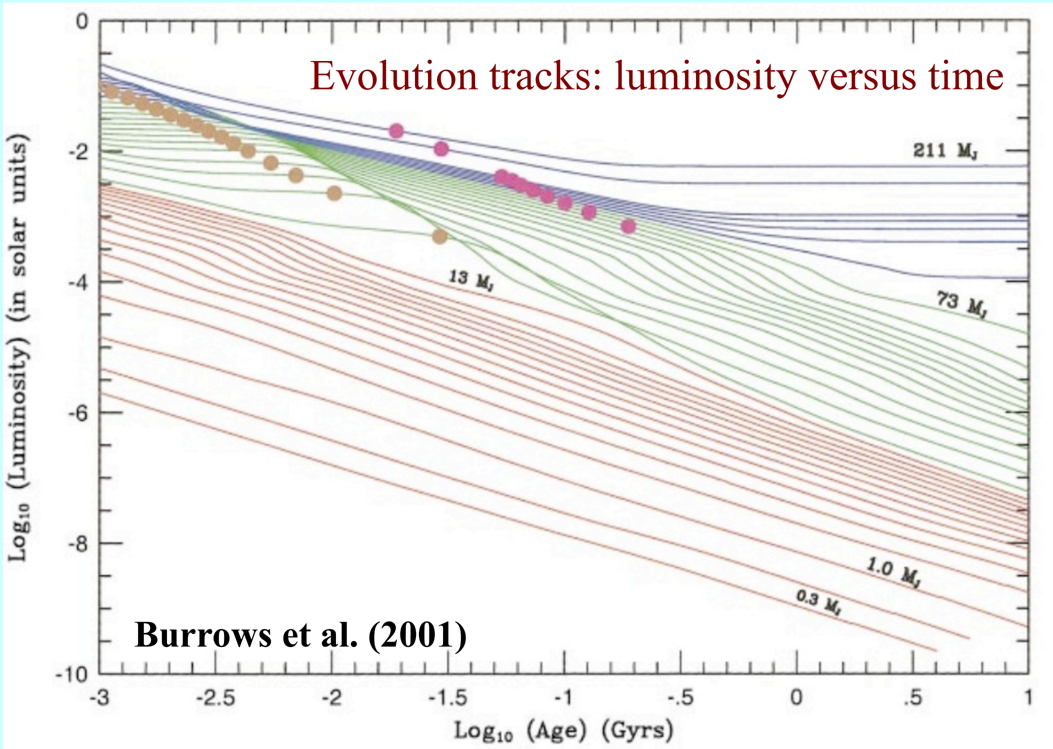
- Brown dwarfs are fluid hydrogen objects intermediate in mass between giant planets and stars. They are often free floating, though many also orbit stars.

- Presumed to form like stars (i.e., directly collapsing from a hydrogen cloud) but have masses too low to fuse hydrogen. Generally defined as objects with masses of 13 to ~80 Jupiter masses.

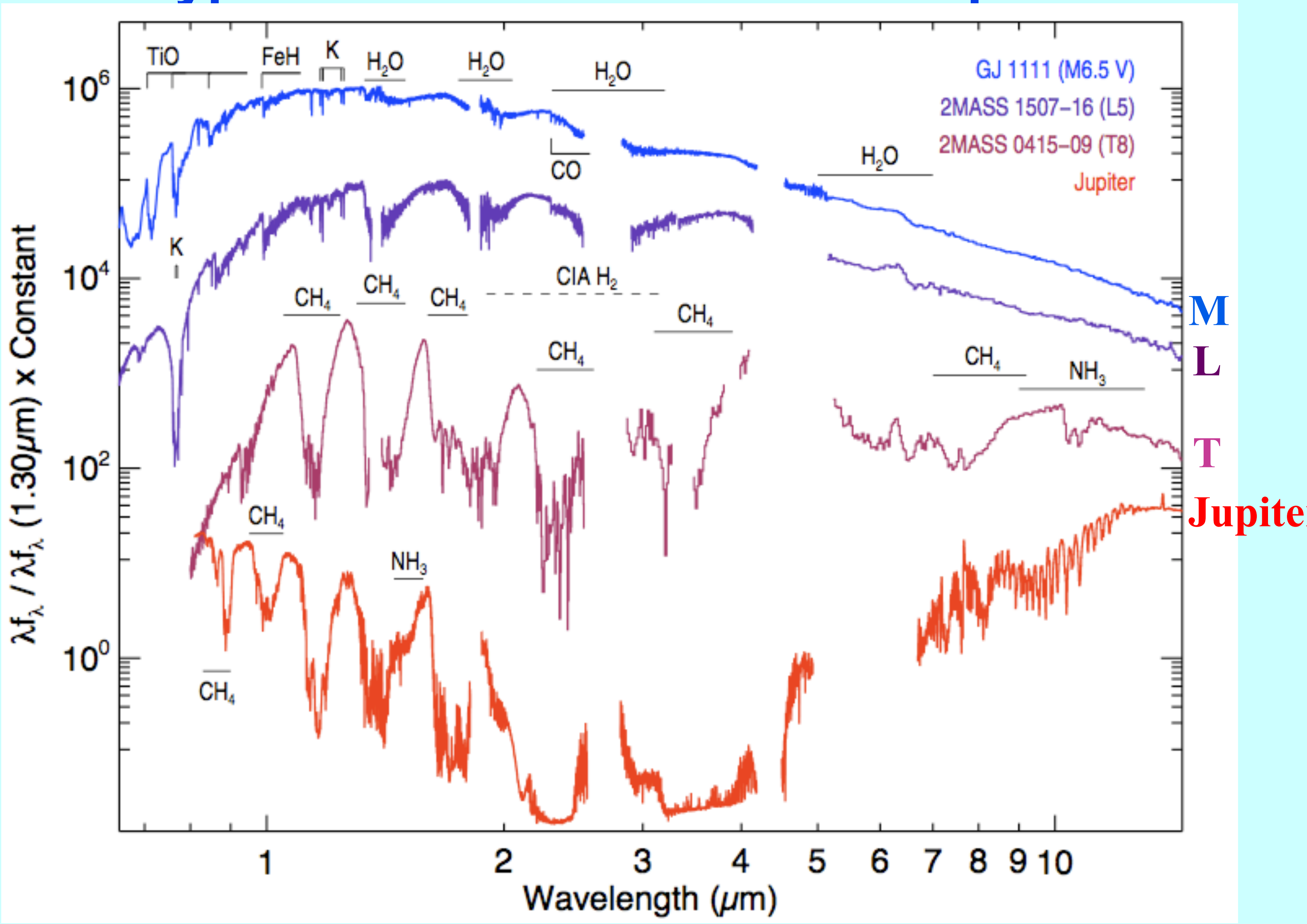
- Since they cannot fuse hydrogen, they cool off over time (like Jupiter). But massive brown dwarfs cool slowly and can still have surface temperatures >1000 K even after many billions of years

- Over a wide mass range (~0.3 to ~80 Jupiter masses), brown dwarfs and giant planets have radii very close to Jupiter's.

- >1000 brown dwarfs have been discovered, mostly with high temperature (>700 K) but now including objects as cool as ~300 K.



Typical brown dwarf infrared spectra

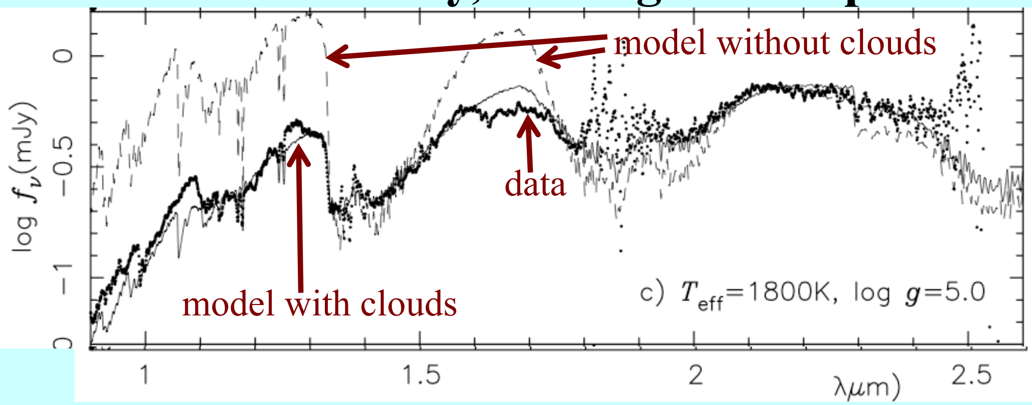


Burgasser (2009, "The brown-dwarf exoplanet connection")

Brown dwarfs are classified according to their IR spectra into M, L, T, and Y (from hot to cold). Unlike most stars, their spectra are dominated by molecular features. Dust (i.e., silicate clouds) affects the spectrum of M and L dwarfs, but not T dwarfs.

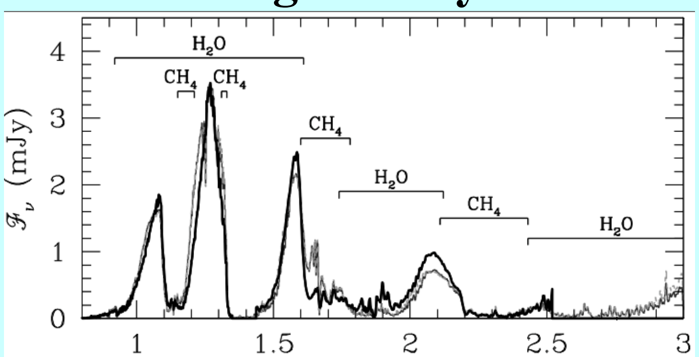
Brown dwarfs show evidence for condensate (dust) clouds

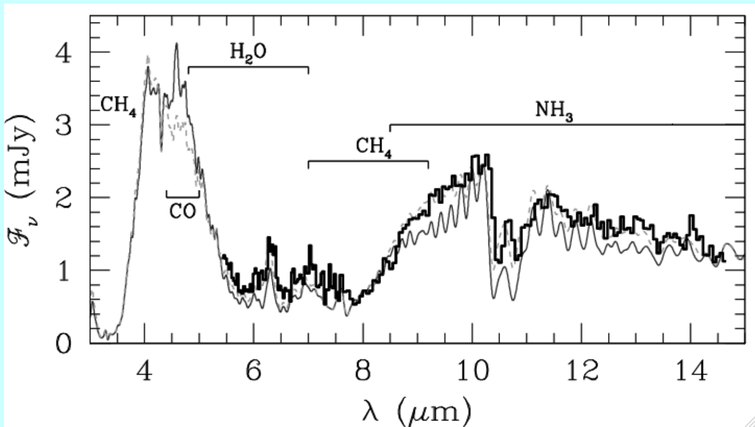
L dwarfs are cloudy, leading to flat spectral features:



Tsuji et al. (2004)

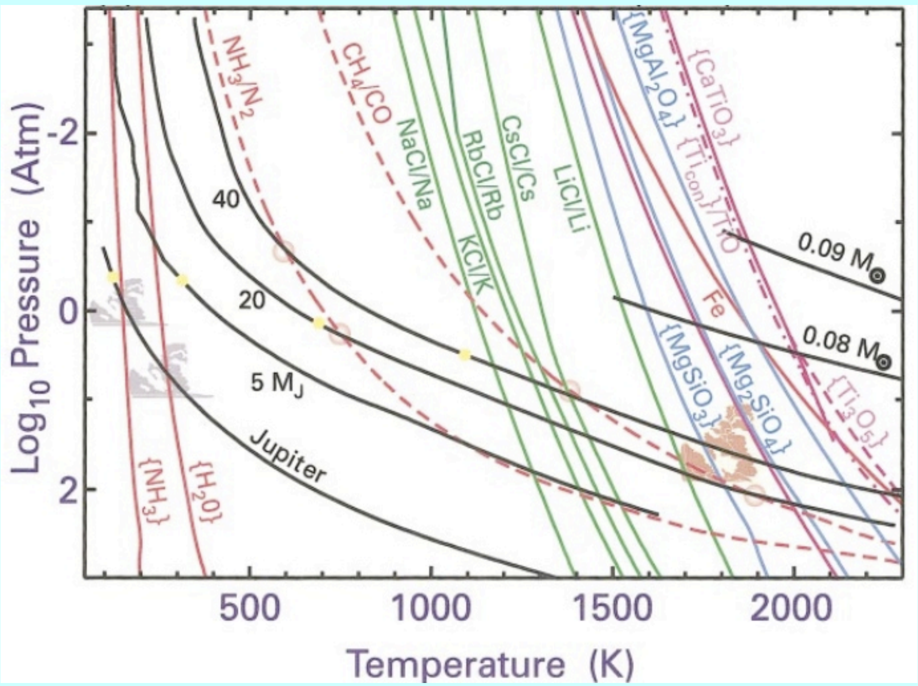
T dwarfs are generally cloud free:





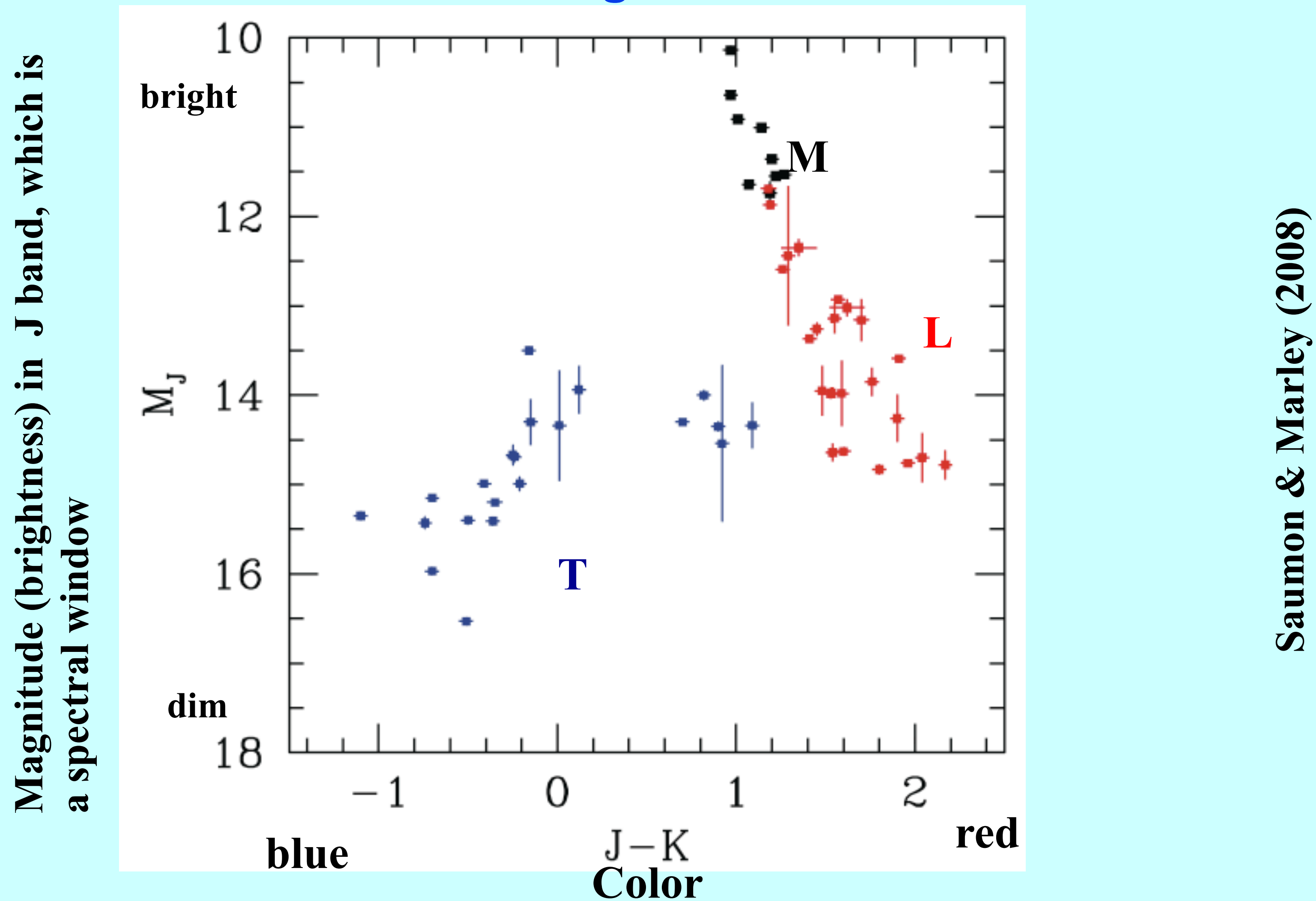
Saumon et al. (2006)

This behavior is explained by the fact that condensate levels lie in the atmosphere for hot objects (M, L dwarfs) but sink into the interior for cool objects (T dwarfs):



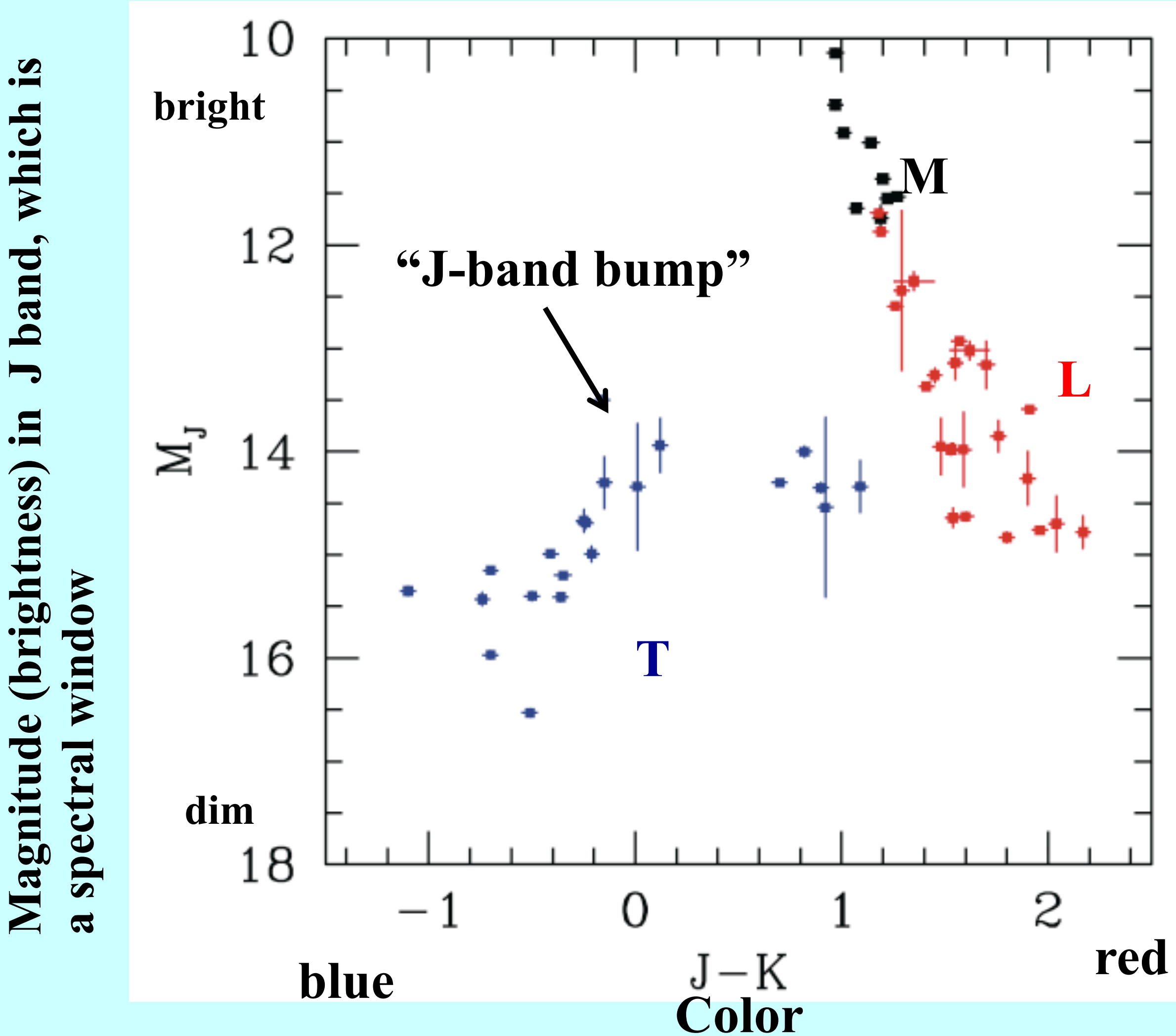
Burrows et al. (2001)

Color-magnitude diagrams are useful for understanding overall trends among brown dwarfs



The change in color across the L/T transition is due to the loss of clouds, which opens the spectral windows. This occurs better in J than K, causing a shift to the blue as the clouds disappear.

Color-magnitude diagrams are useful for understanding overall trends among brown dwarfs



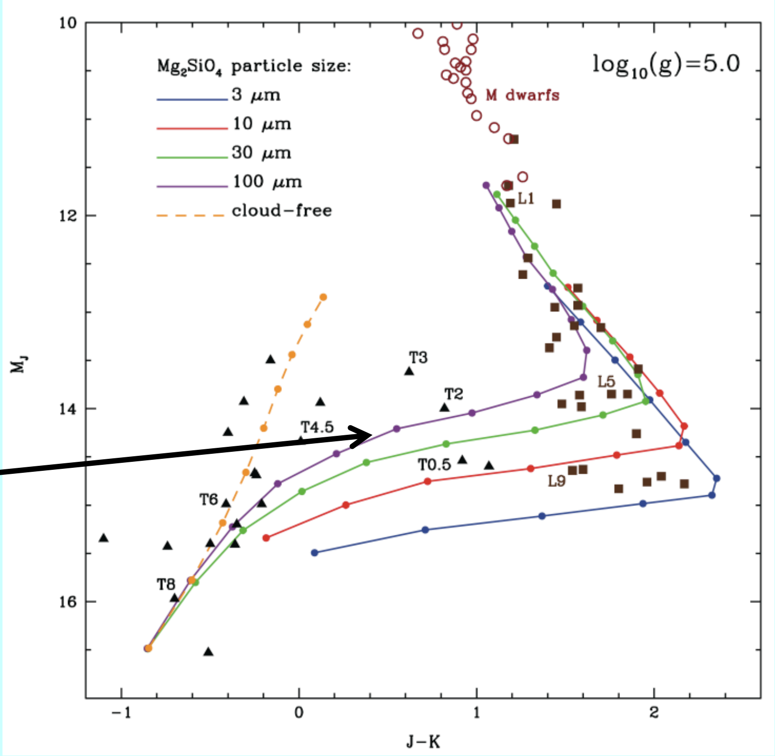
Saumon & Marley (2008)

The change in color across the L/T transition is due to the loss of clouds, which opens the spectral windows. This occurs better in J than K, causing a shift to the blue as the clouds disappear.

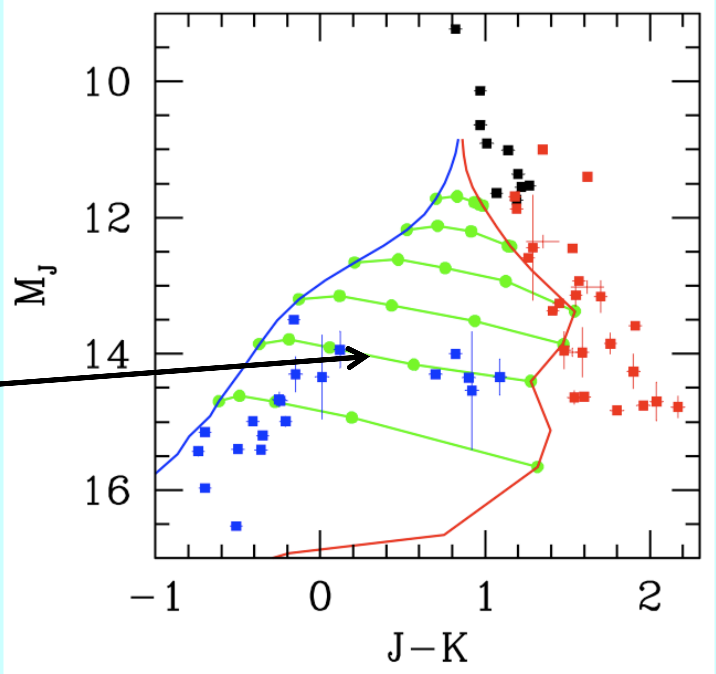
The L/T transition

- **Although the loss of clouds across the L/T transition makes sense, the details are a puzzle: the transition occurs too fast.**
  - **1D models of uniform cloud decks sinking into the interior predict that the J-band flux continually dims across the transition:**
  - **But in reality the J-band flux actually *increases* temporarily across the transition (the "J-band bump"), despite the fact that T dwarfs are cooler than L dwarfs**
  - **This suggests that the cloud decks are not simply disappearing from view, but becoming patchy or getting thin as they do so**
- **1D models that assume the cloud deck gets patchy across the transition do a much better job of reproducing the "J-band bump"**

This suggests a strong role for meteorology in controlling the transition



Burrows et al. (2006)



Marley et al. (2010)

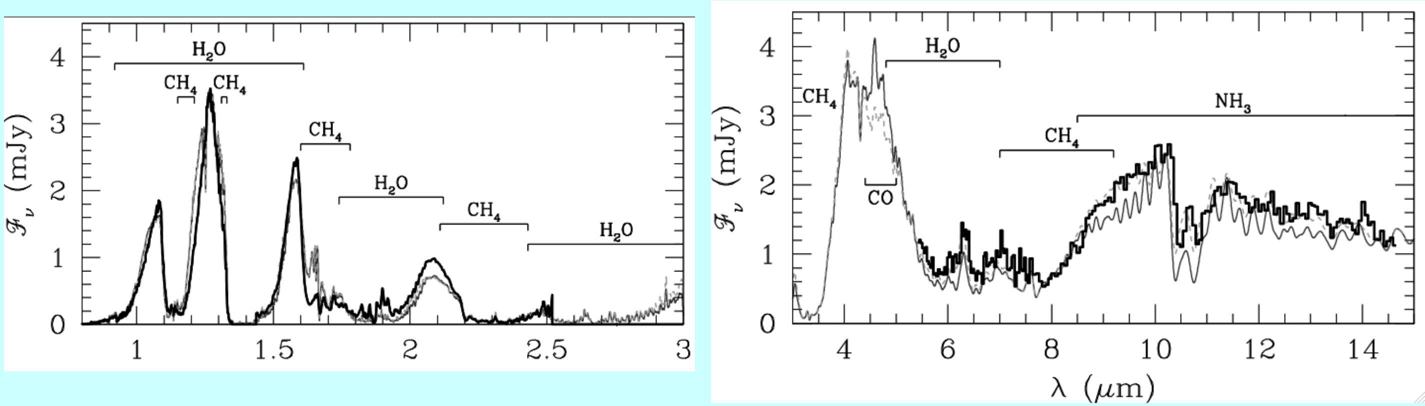
Chemical disequilibrium

- In cool giant planets and brown dwarfs, the equilibrium form of carbon and nitrogen at the top are CH_4 and NH_3. The equilibrium form at depth are CO and N_2.

- In the absence of dynamics, equilibrium would prevail. But vertical mixing can dredge CO-rich, CH_4-poor, and NH_3-poor air from depth and mix it into the atmosphere.

- This will result in an excess of CO, and a deficit of CH4 and NH3, in the atmosphere

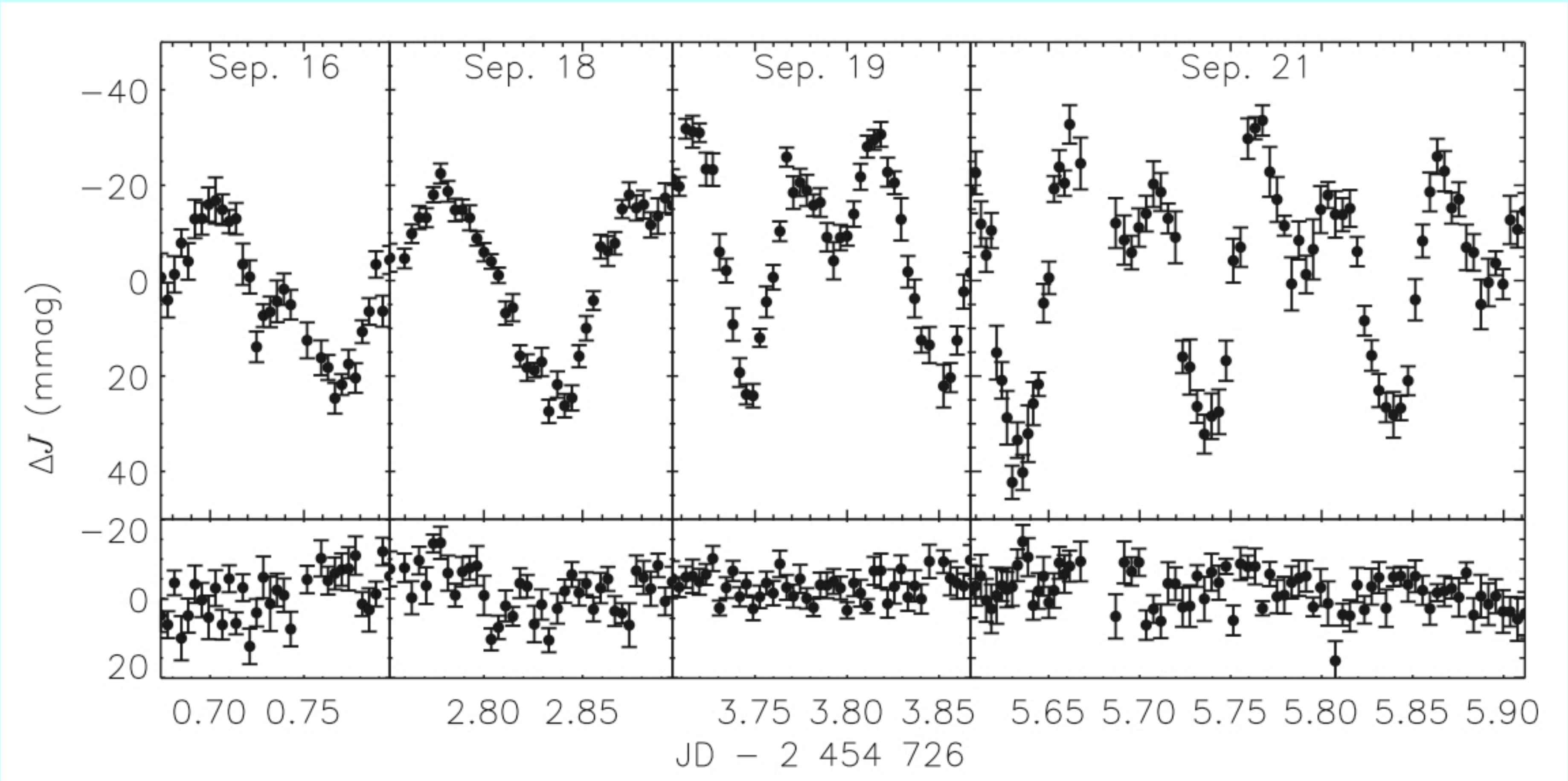
- Just such excesses and deficits are observed, and are interpreted as the result of vertical mixing. The observed abundances can be used to constrain the mixing rates



Saumon et al. (2006)

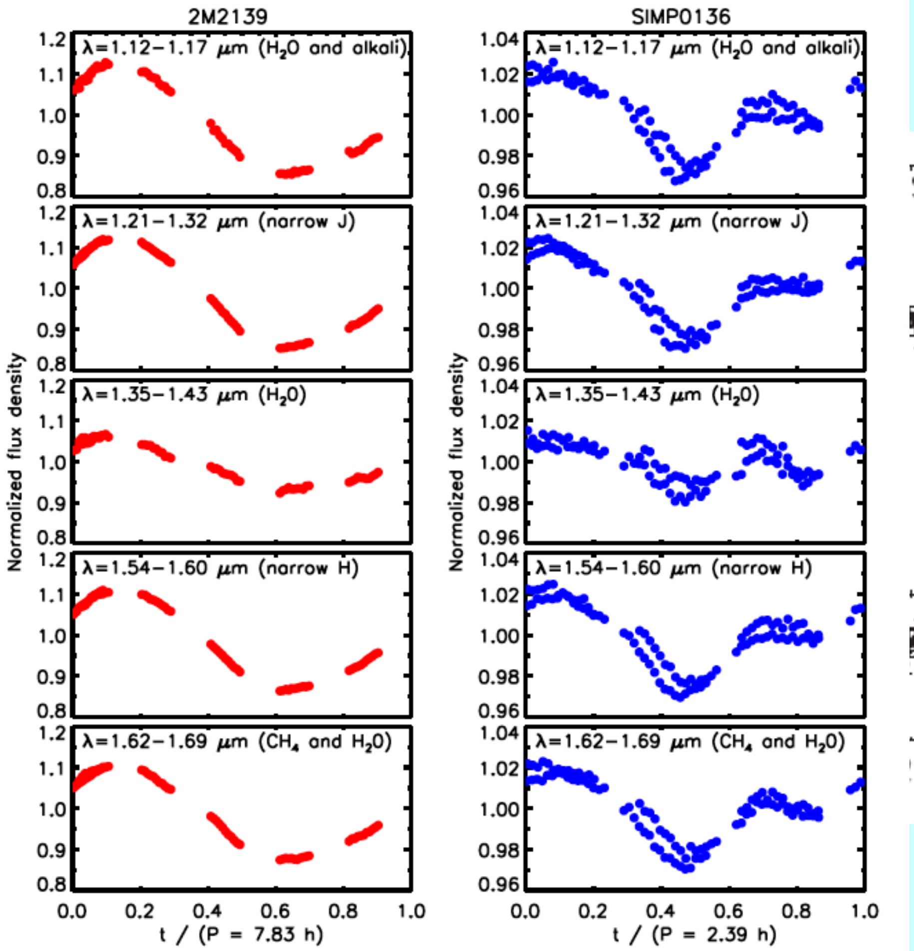
Thus, dynamics is required to explain the chemical disequilibrium

T2.5 brown dwarf SIMP 0136 shows weather variability

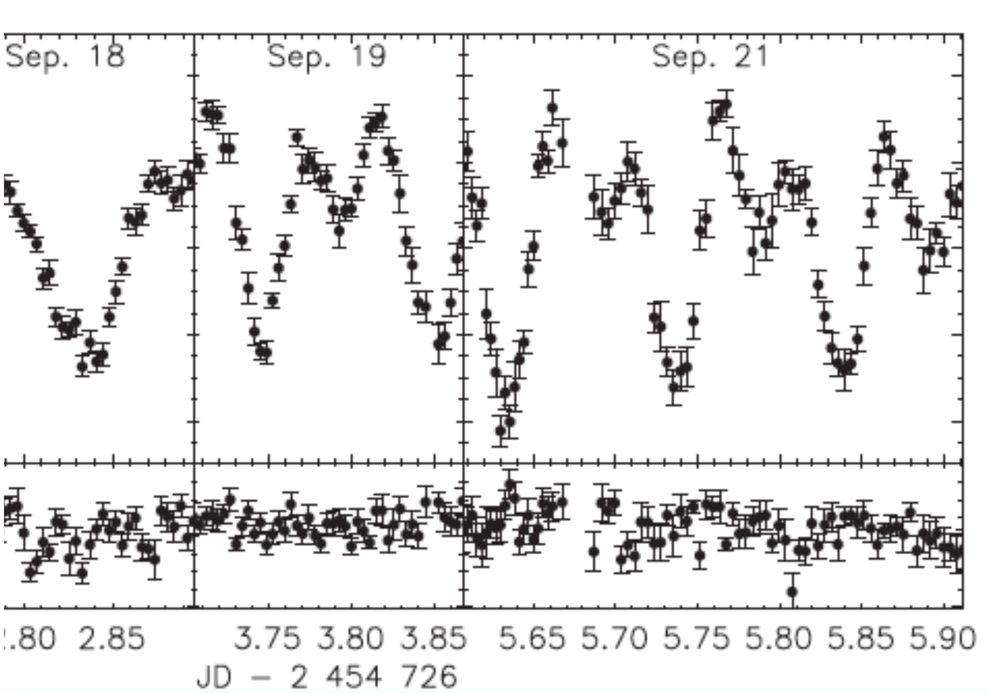


Artigau et al. (2009); see also Radigan et al. (2012), Buenzli et al. (2012), and many upcoming papers by Apai, Metchev, Radigan, Flateau, ….

Light Curves

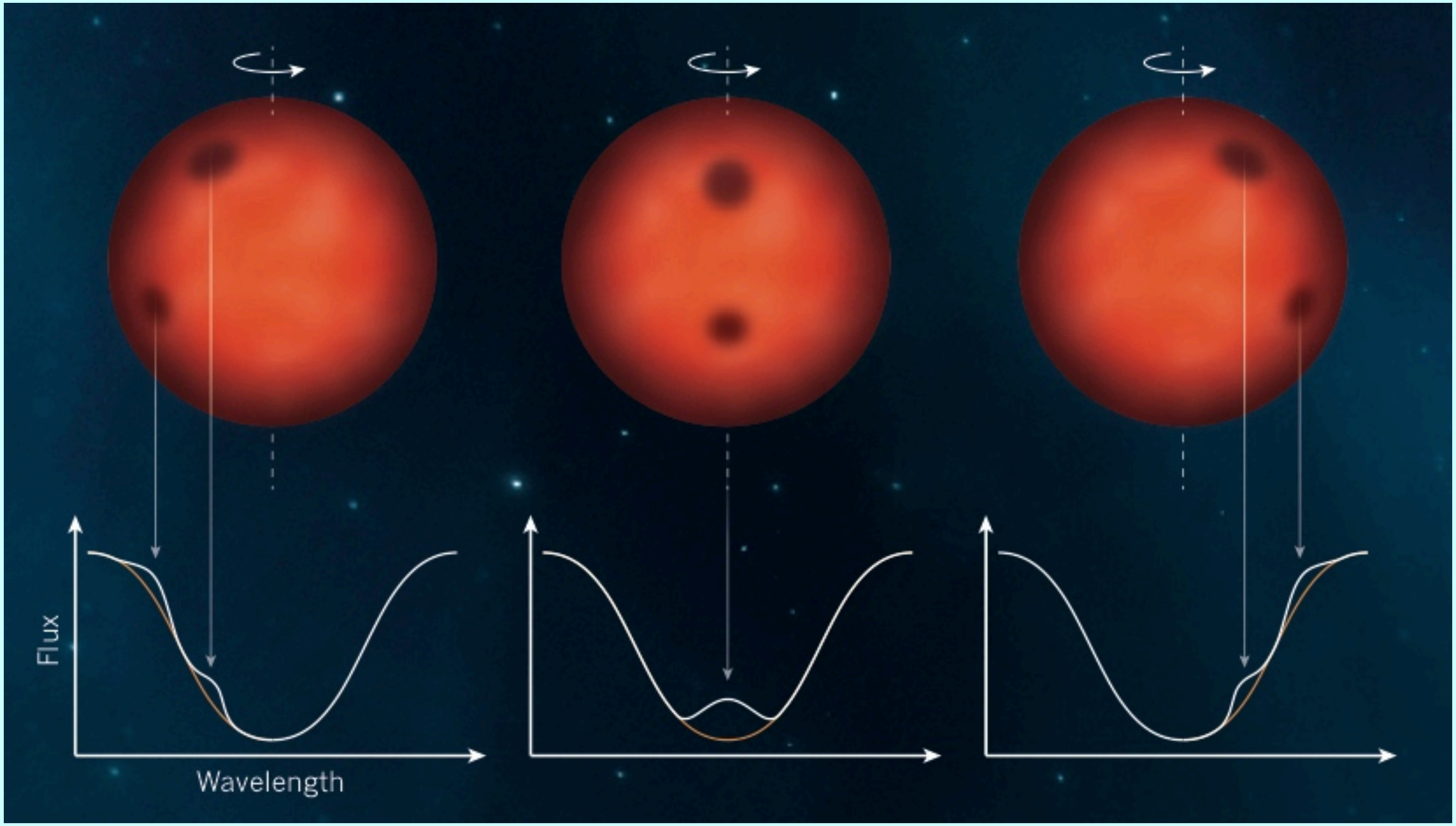


Apai et al. (2013)



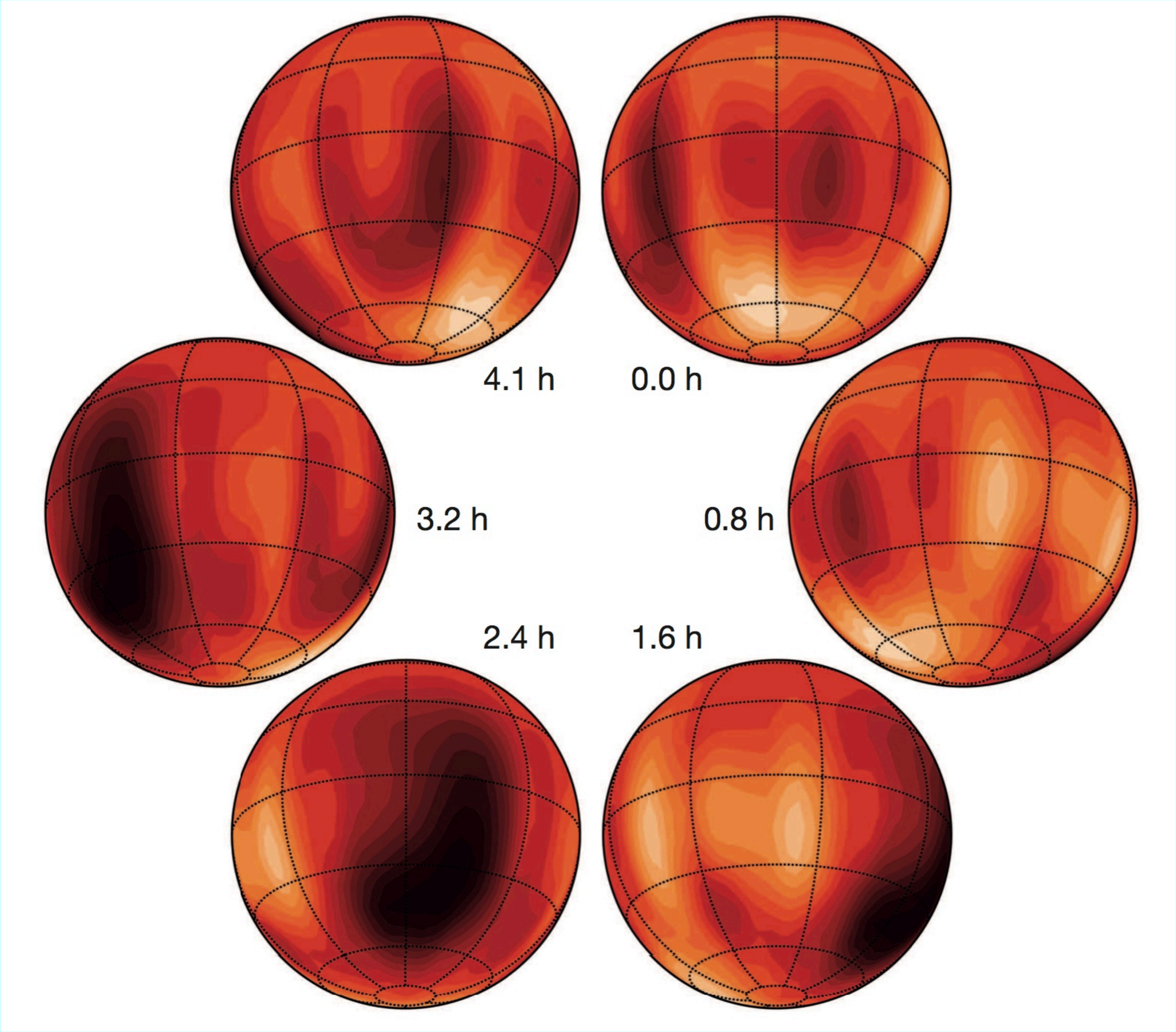
Artigau et al. (2009)

Doppler imaging technique: a method to map the surface patchiness of brown dwarfs



Showman (2014); see also Rice (2002)

Maps of Luhman 16B, the closest known brown dwarf to Earth



Crossfield et al. (2014, *Nature*), see also Showman (2014, *Nature*)

Summary of evidence for dynamics/weather on brown dwarfs

1) **Existence of clouds is required to explain spectra of many brown dwarfs.**

2) **Explaining the L/T transition requires change in cloud dynamics/physics, e.g., opening of holes in the clouds, as objects cool off over time.**

3) **Disequilibrium chemistry (quenching of CO, CH_4, NH_3) implies mixing from below, and allows mixing rate to be inferred if chemical kinetics are understood.**

4) **IR variability implies cloudy and cloud-free patches rotating in and out of view. Shape of lightcurves vary over time, implying that the *spatial pattern* of cloud patchiness evolves rapidly.**

5) **Doppler imaging allows global maps of surface patchiness to be inferred for the brightest brown dwarfs.**

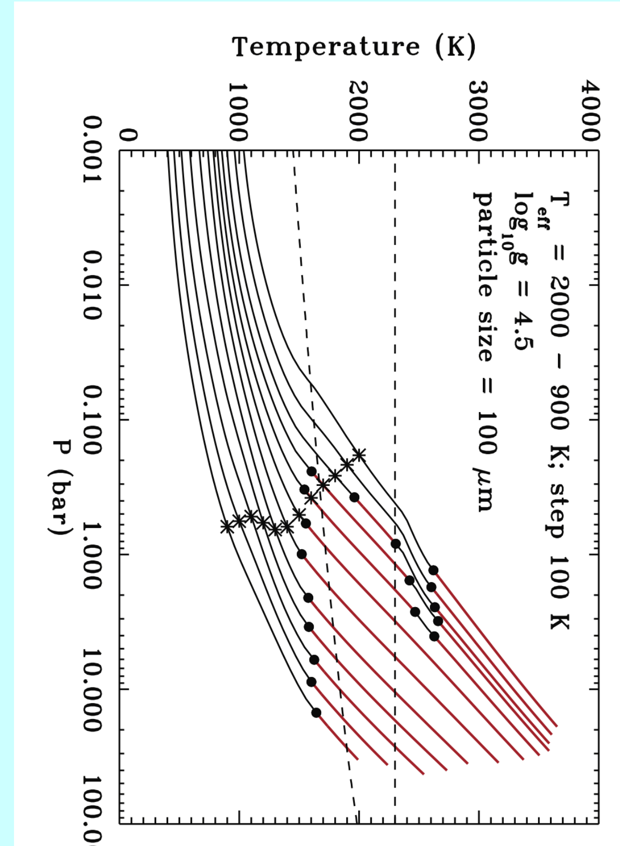
Dynamical Regime of brown dwarfs

- Rapid rotation (Period ~ 1.5-12 hours) implies rotational domination (Rossby numbers << 1)

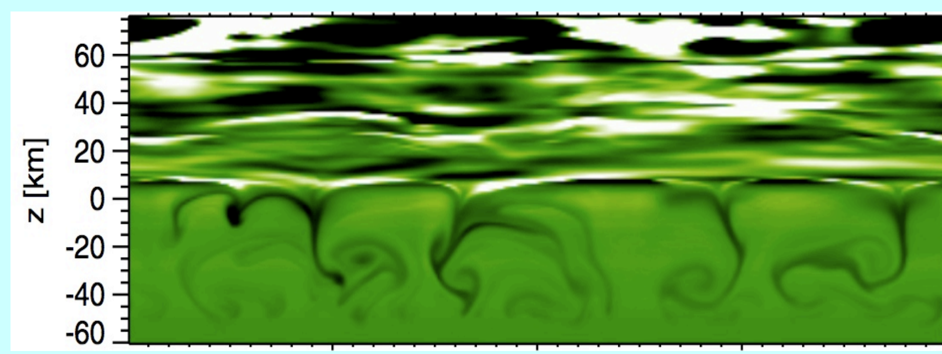
- Stably stratified atmosphere overlies vigorously convecting interior

- No external irradiation $\Longrightarrow$ no imposed horizontal gradients in heating or temperature (unlike solar system planets or transiting exoplanets)

- Wave generation will play a key role. Atmospheres may be mechanically driven, like stratospheres of Earth and Jupiter



Burrows et al. (2006)



Freytag et al. (2010)

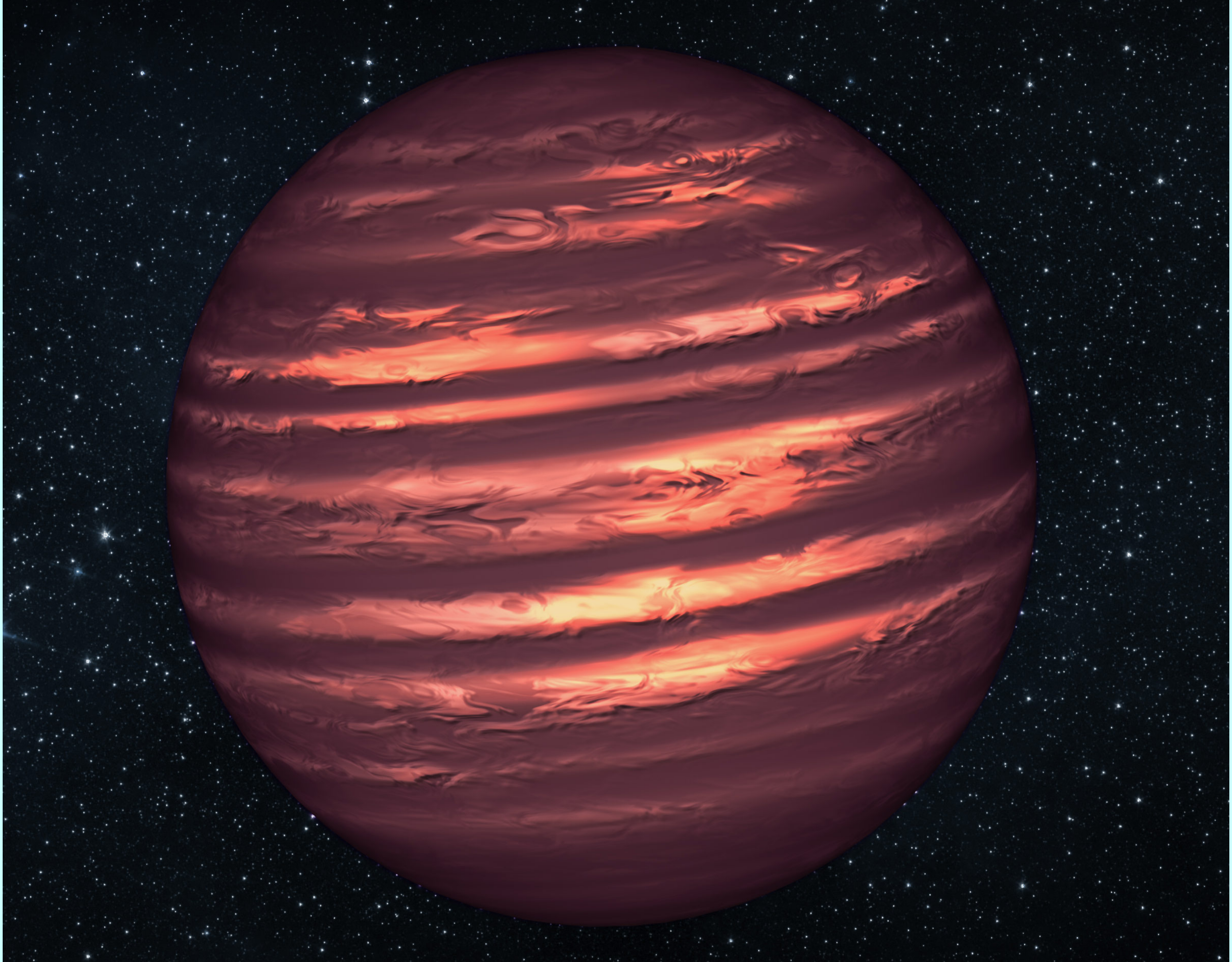
Some questions

- **What is the atmospheric circulation like on brown dwarfs? Are there zonal jets? Large vortices? Fluctuating turbulence? What are the wind speeds, temperature fluctuations, and key length scales?**

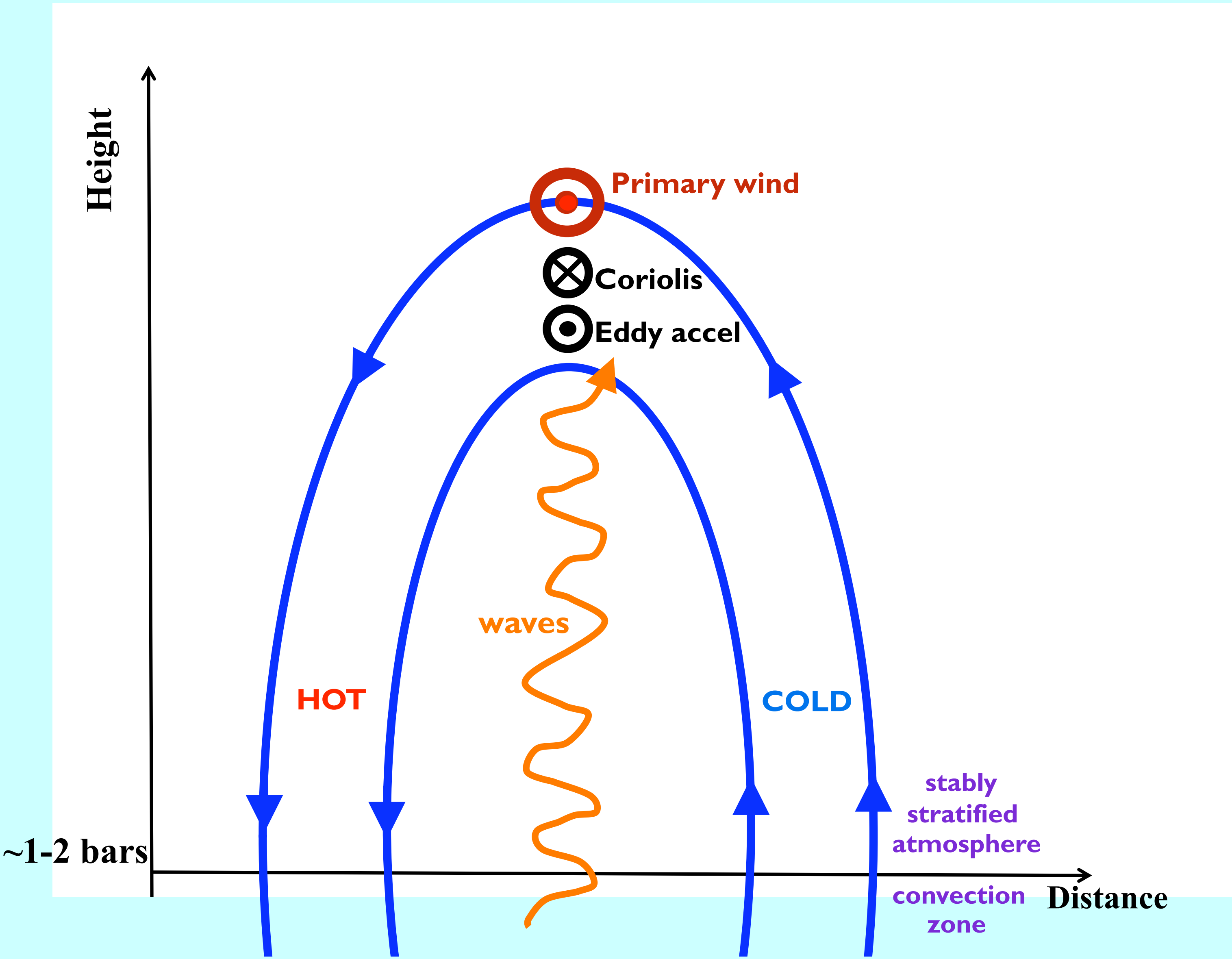
- **How does the circulation work? What types of waves are generated by the convection, and by what mechanisms might they drive a circulation? How coupled is the atmosphere to the interior?**

- **What are the vertical mixing rates? To what extent is the mixing dominated by breaking gravity waves rather than large-scale overturning?**

- **How do clouds couple to the circulation? How patchy are the cloud layers?**



Wave-driven atmospheric circulation on directly imaged EGPs and brown dwarfs



Showman et al. (2013)

Model of wave-driven circulation

- **Assume a given amplitude for the eddy acceleration, *A*, and solve for flow amplitudes using primitive equations in log-pressure coordinates**

- **Zonal momentum balance** $fv \approx A$

- **Continuity** $\frac{\partial v}{\partial y} + e^{z}\left(e^{-z}\varpi\right) = 0$ **which to order-of-magnitude is** $vl \approx \frac{\varpi}{H}$

- **Thermodynamic energy: assume a balance between vertical advection and radiation, parameterized with Newtonian heating/cooling:** $\varpi \frac{H^2 N^2}{R} \approx \frac{\Delta T_{horiz}}{\tau_{rad}}$

- **Meridional momentum balance is thermal wind:** $\Delta U \approx \frac{Rl\Delta T_{horiz} H}{f}$

- **From this set we can derive equations for** $v, \varpi, \Delta T_{horiz}, \Delta U$

$$\Delta T_{horiz} \approx \left(\eta c_p T\right)^{1/2} \frac{NH}{R}$$

$$\Delta U \approx (\eta c_p T)^{1/2} \frac{lH^2 N}{f}$$

$$\varpi \approx \frac{\eta^{1/2} g T^{7/2} \sigma}{c_p^{\ 1/2} pHN} \approx \frac{(\eta c_p T)^{1/2}}{HN\tau_{rad}}$$

where η is a dimensionless efficiency giving fraction of the radiated heat flux that goes into the wave driving

To within factors of order unity,

- ***$\Delta T_{horiz}/T$* is $\eta^{1/2}$ times the ratio of the gravity wave speed to the sound speed**

- ***ΔU* over the sound speed is $\eta^{1/2}$ times the ratio of the Rossby deformation radius to the dominant horizontal length scale of the flow**

- **The time for the flow to advect vertically over a scale height is $\eta^{-1/2}\tau_{rad}$ times the ratio of gravity wave speed to sound speed**