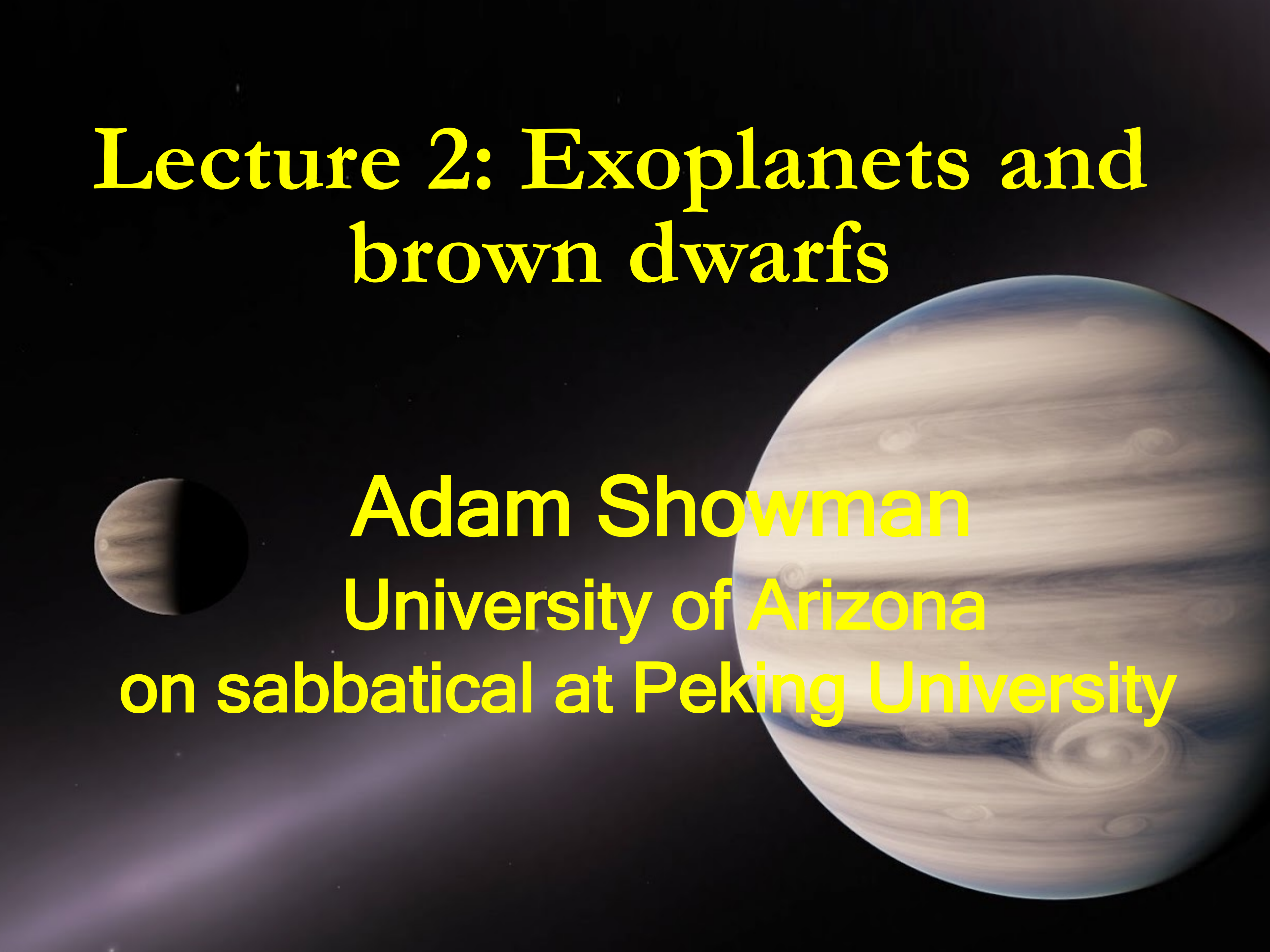
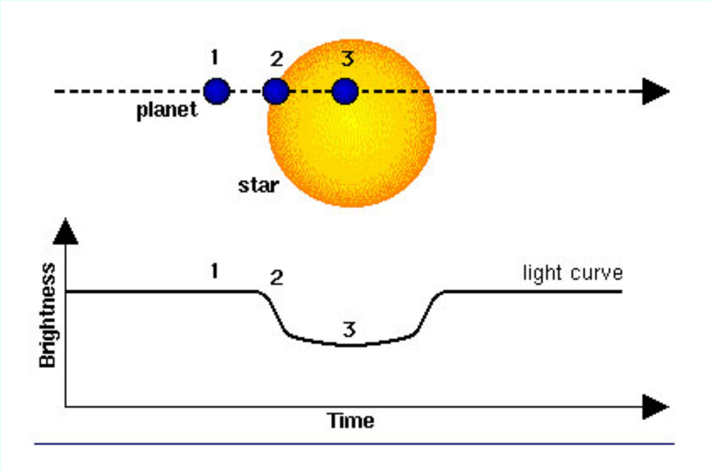
Lecture 2: Exoplanets and brown dwarfs



Adam Showman
University of Arizona
on sabbatical at Peking University

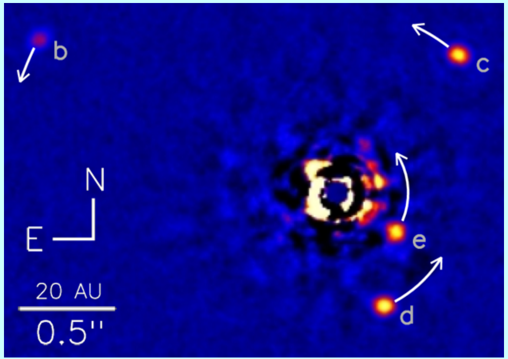
Exoplanets: an exploding new field

- **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):**

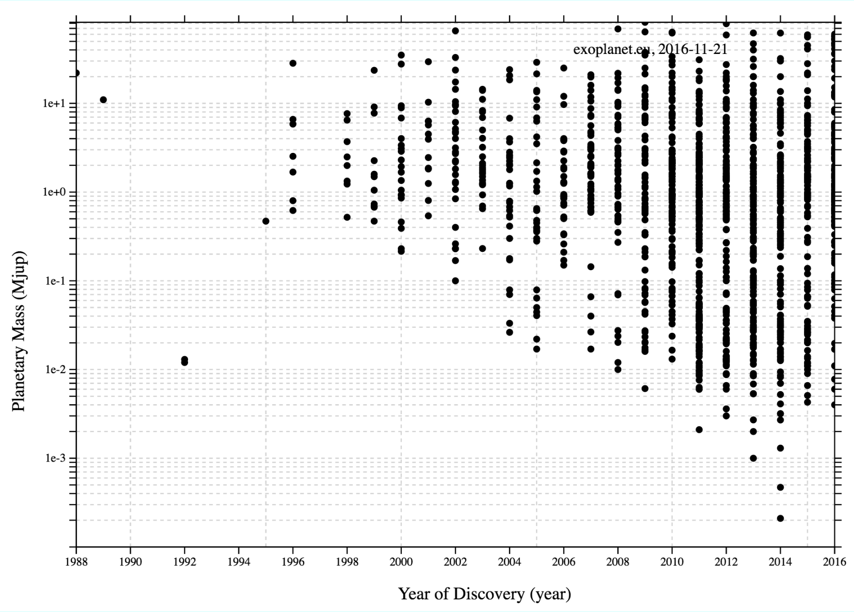


Together, these give the planetary mass, radius, and orbital properties.

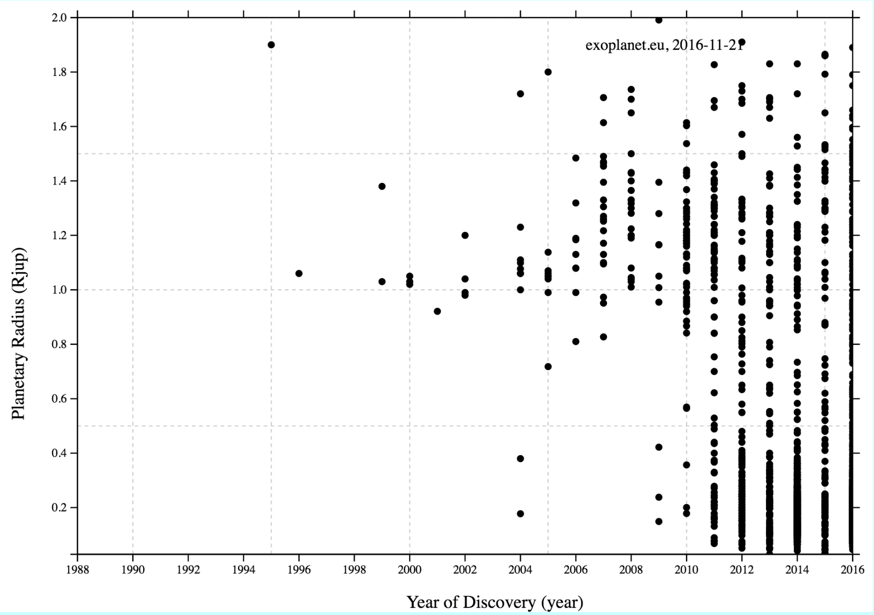
- **~50 planets discovered by direct imaging:**



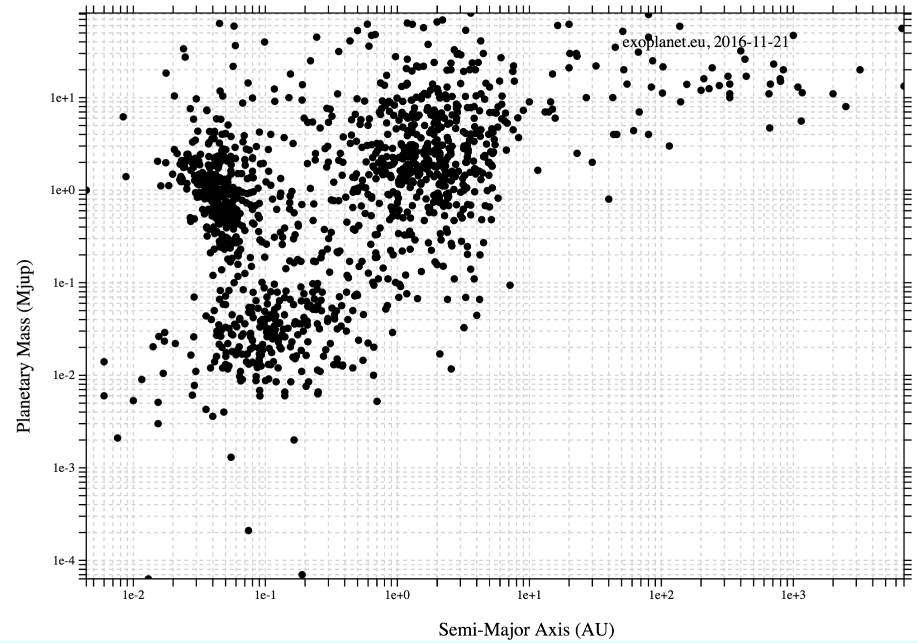
Planet mass vs. year of discovery



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

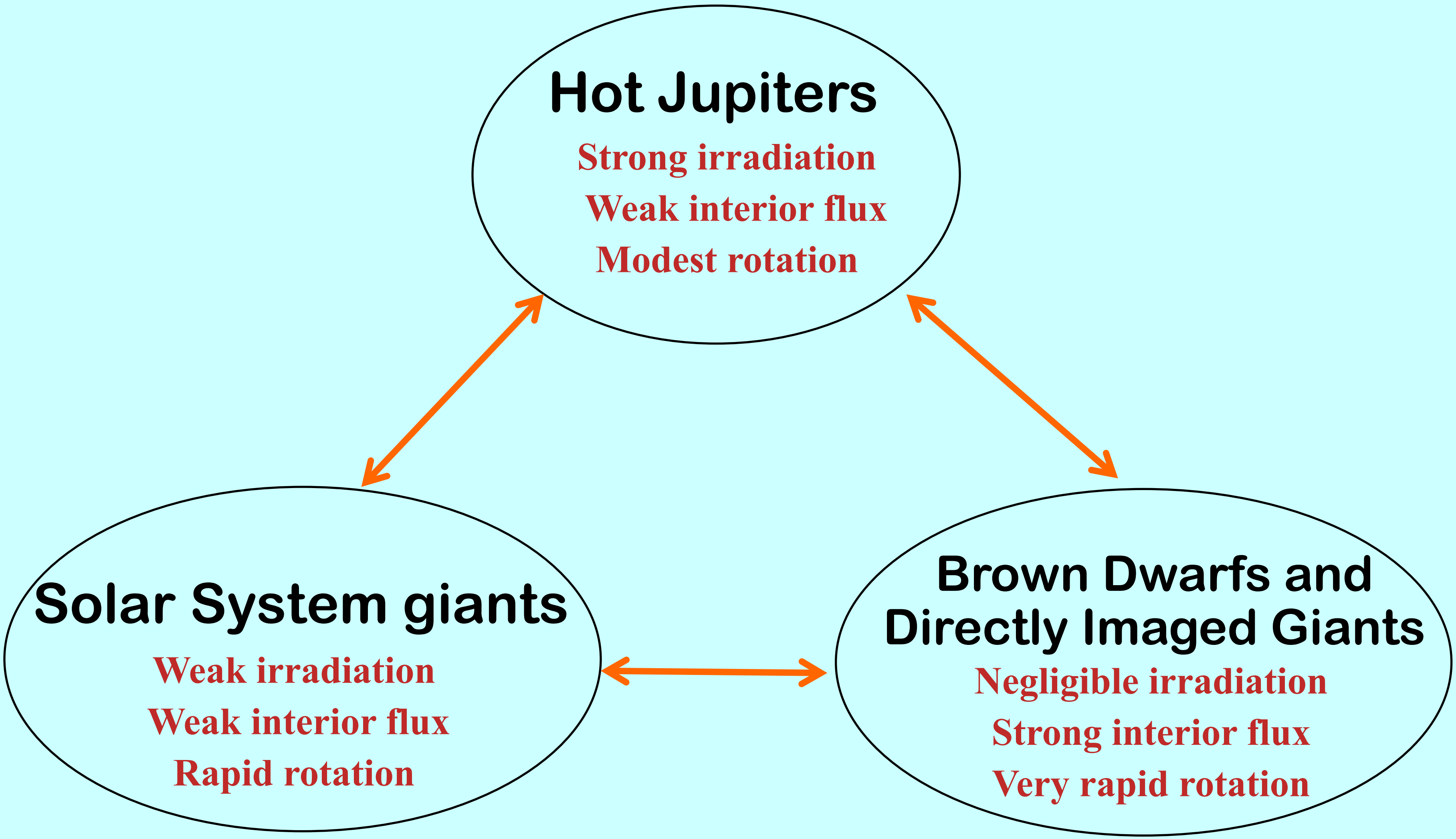
Interaction with interior

History

Factors that affect atmospheric circulation and structure

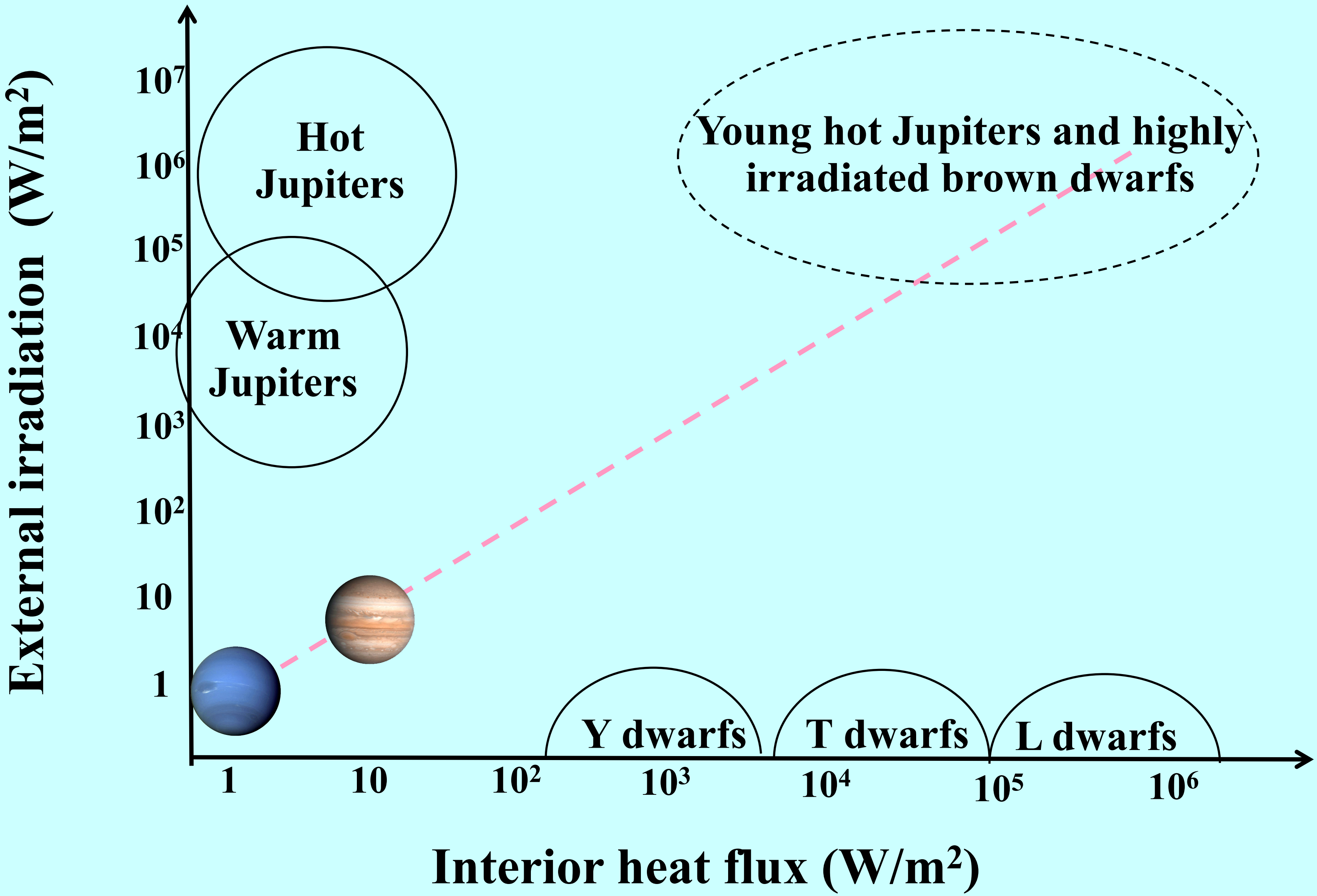
External irradiation	**$\sim 10^7$**
Internal (convective) heat flux	**$\sim 10^6$**
Gravity (mass)	**~ 100**
Rotation rate	**~ 100**
Atmospheric composition	**~ 100**
Clouds/chemistry	
Interaction with interior	
History	

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

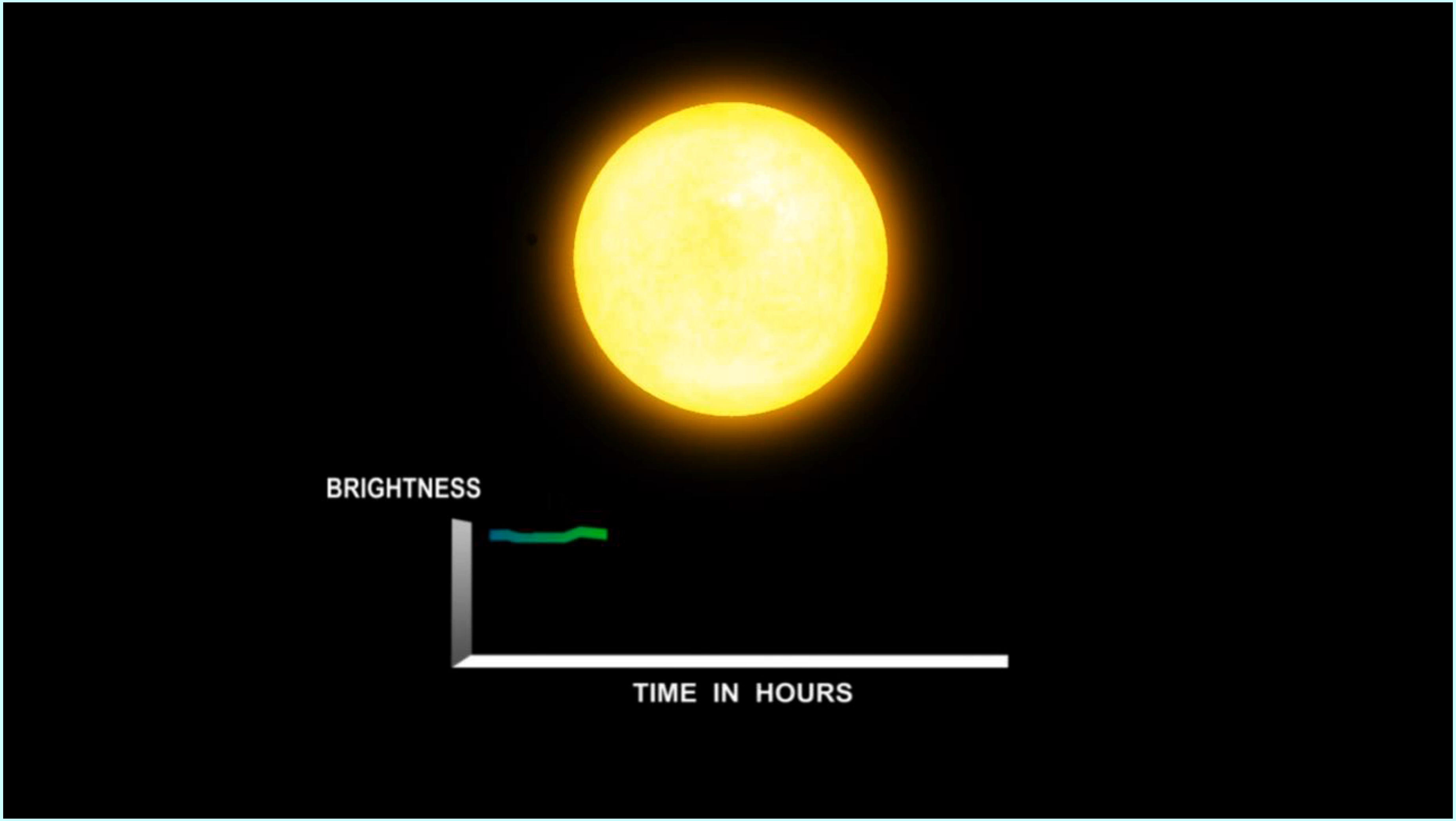


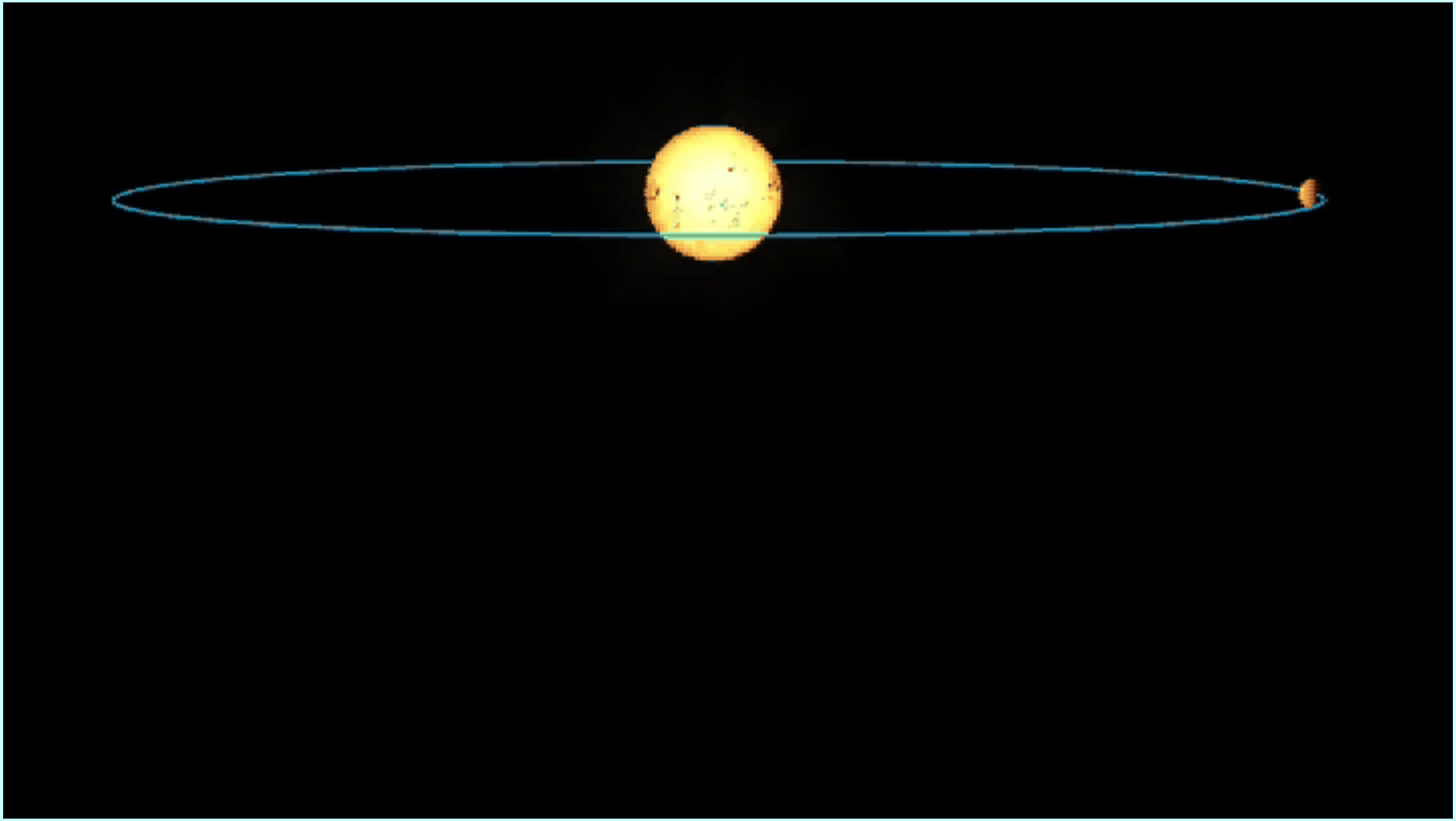
This opens the possibility of synergy between subfields

Observational constraints at the corners of a wide parameter space

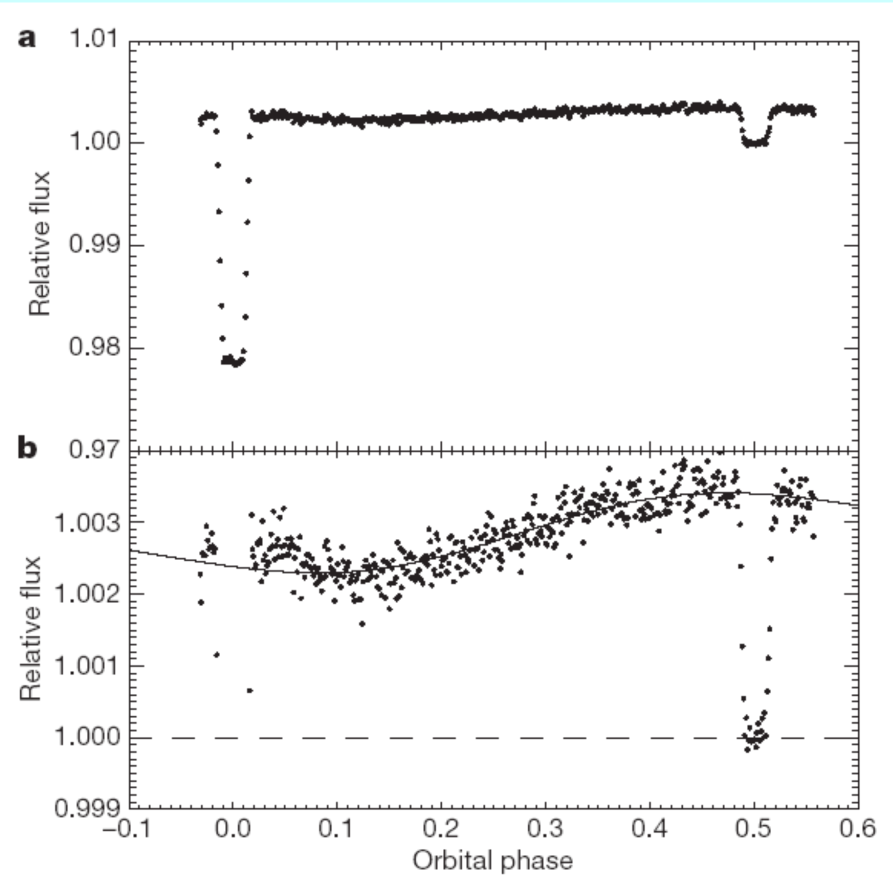


Showman (2016)

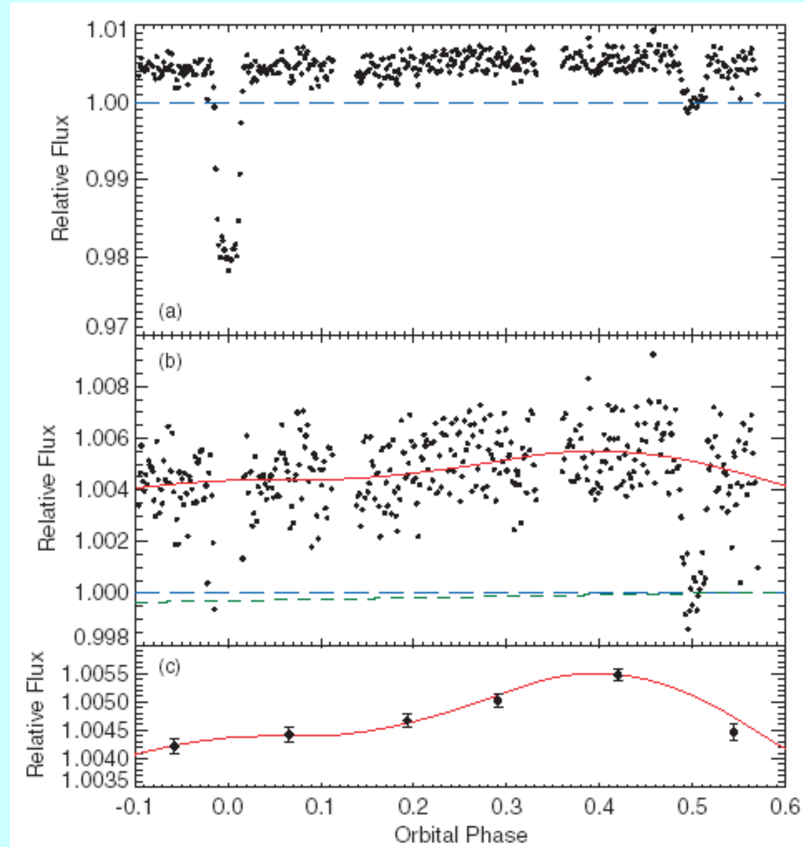

BRIGHTNESS
TIME IN HOURS



Hot Jupiters: Spitzer light curves for HD 189733b

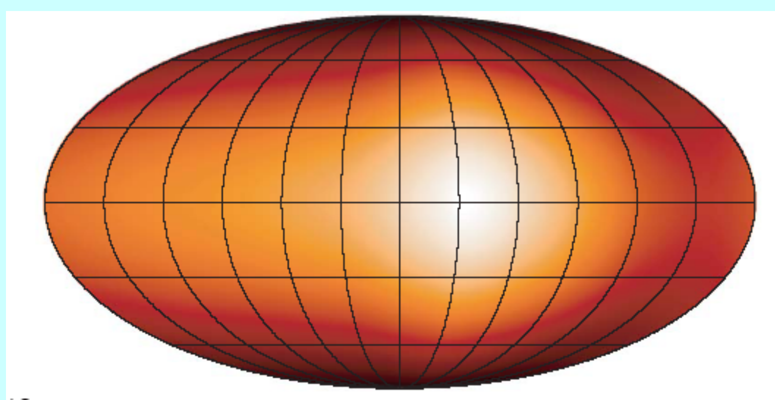


8 μm

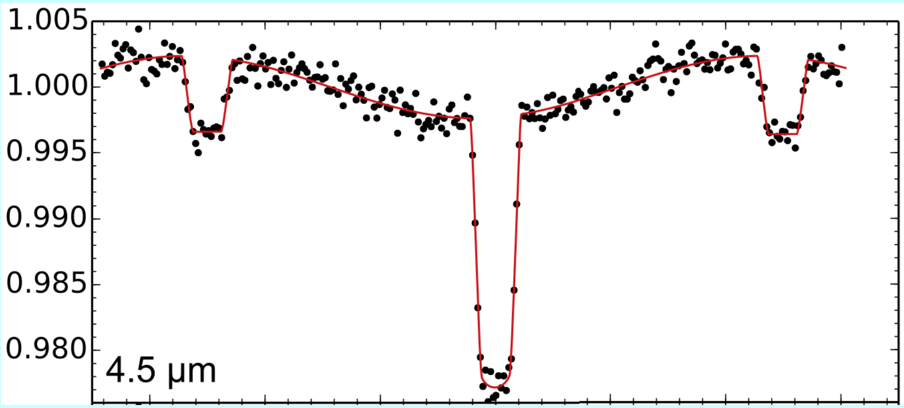


24 μm

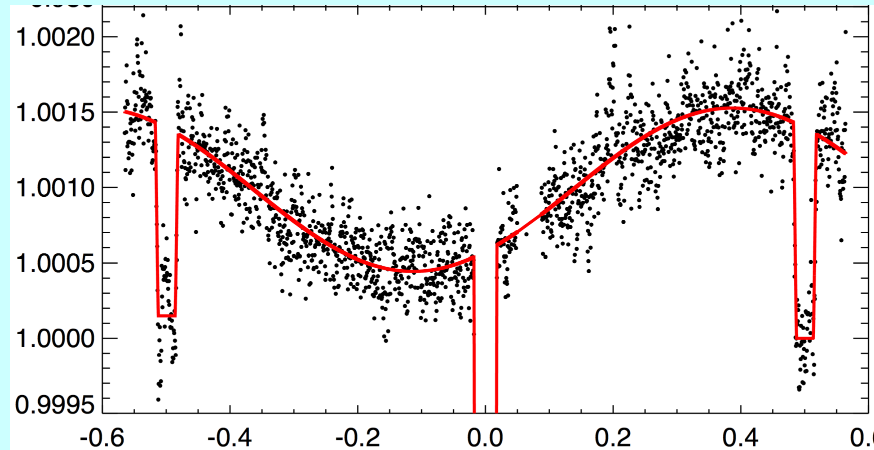
Knutson et al. (2007, 2009)



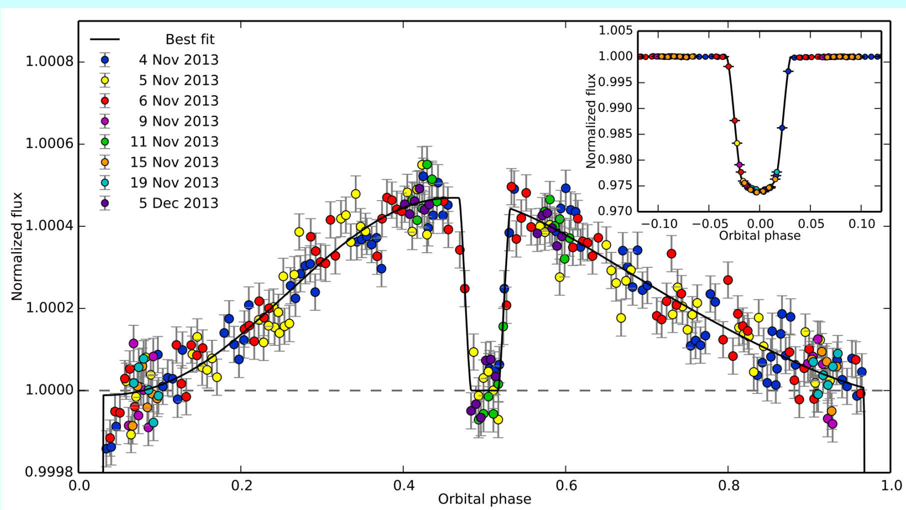
Lightcurves for hot Jupiters



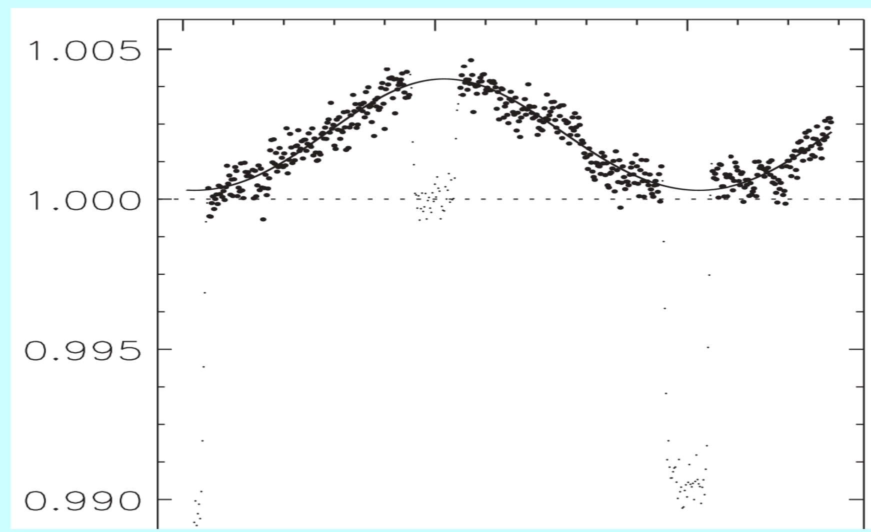
WASP-19b (Wong et al. 2016)



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

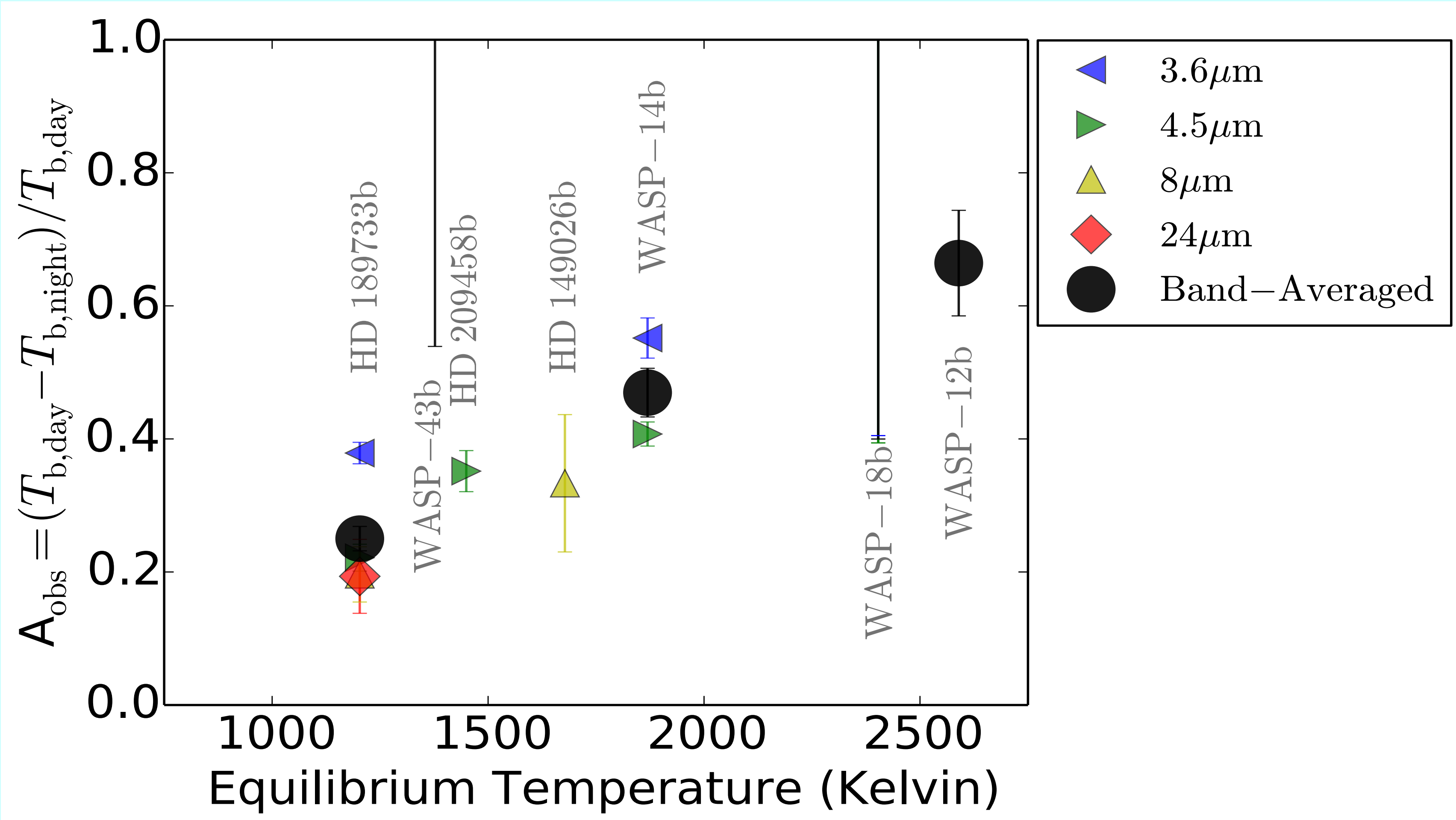
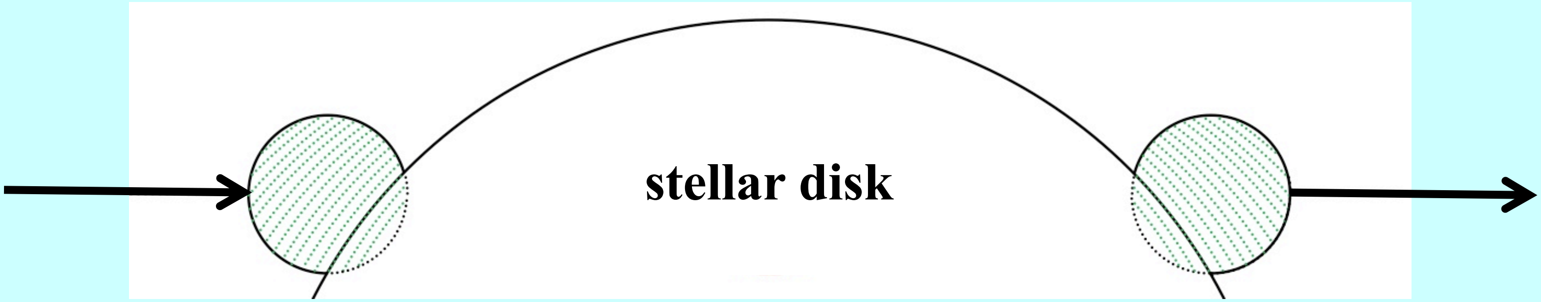
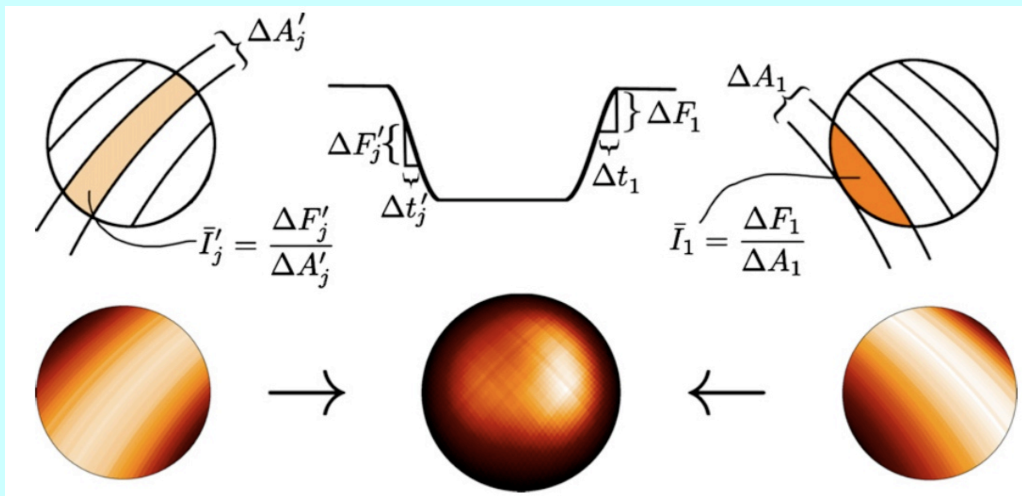
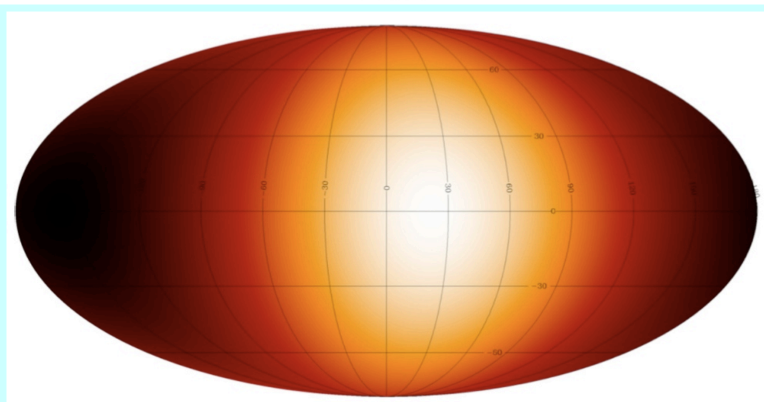


Figure courtesy of Tad Komacek

Eclipse mapping: obtaining 2D maps of the dayside

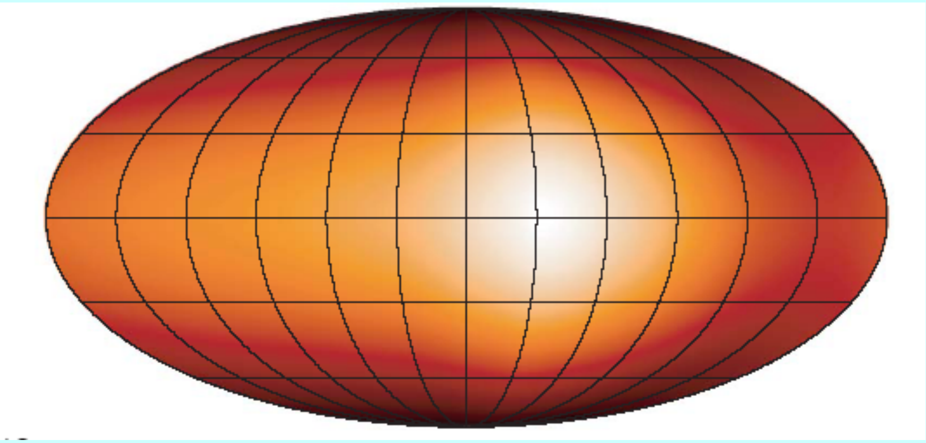


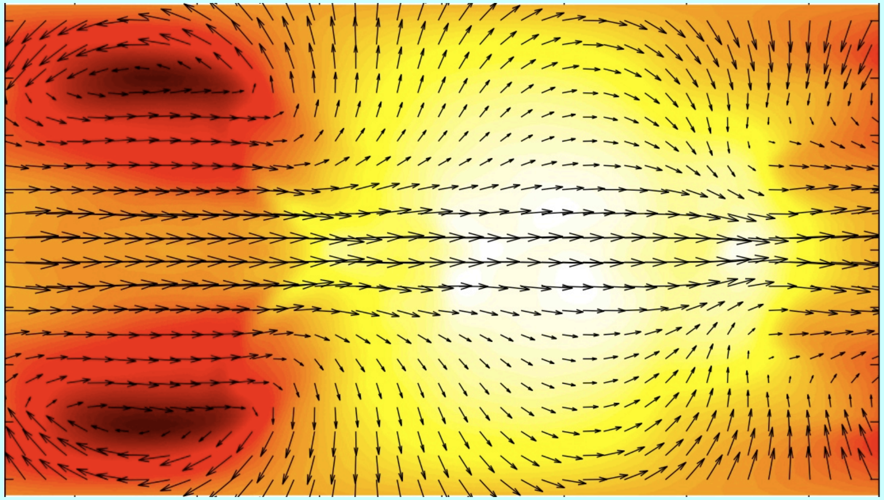




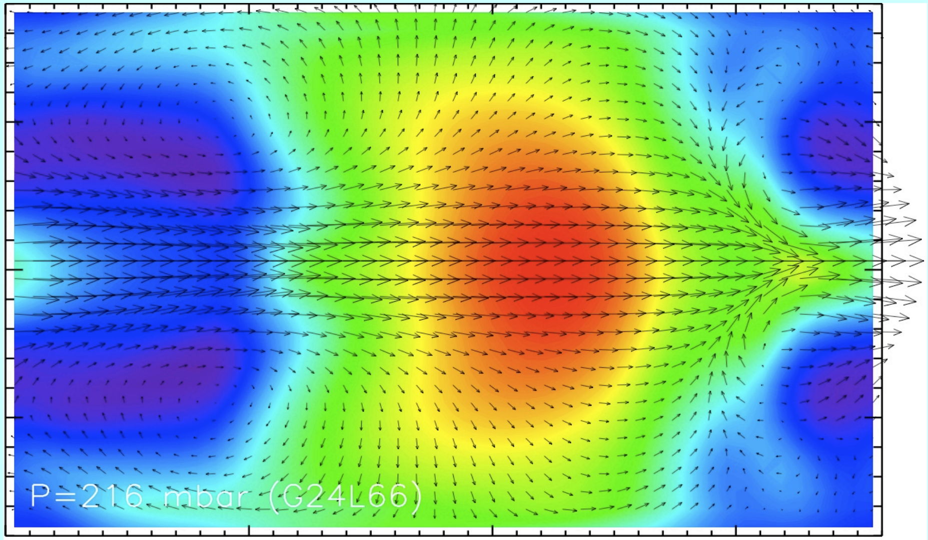
Majeau et al. (2012), de Wit et al. (2012)

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

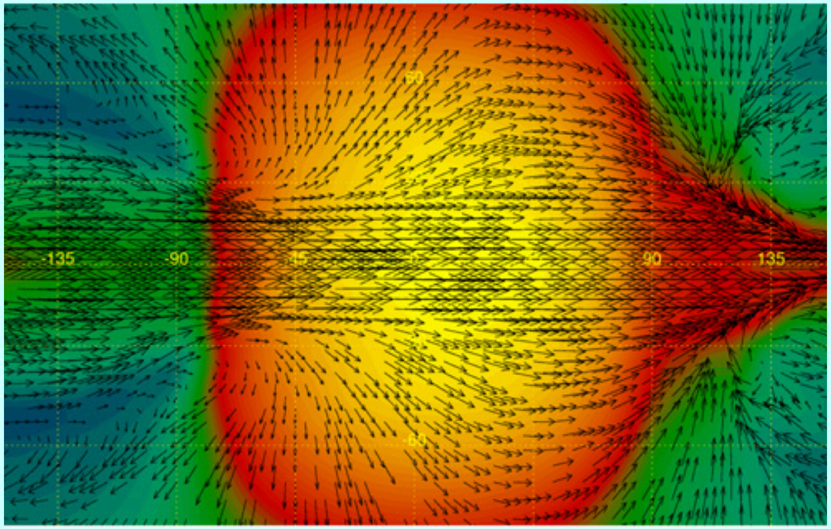




Showman et al. (2009)

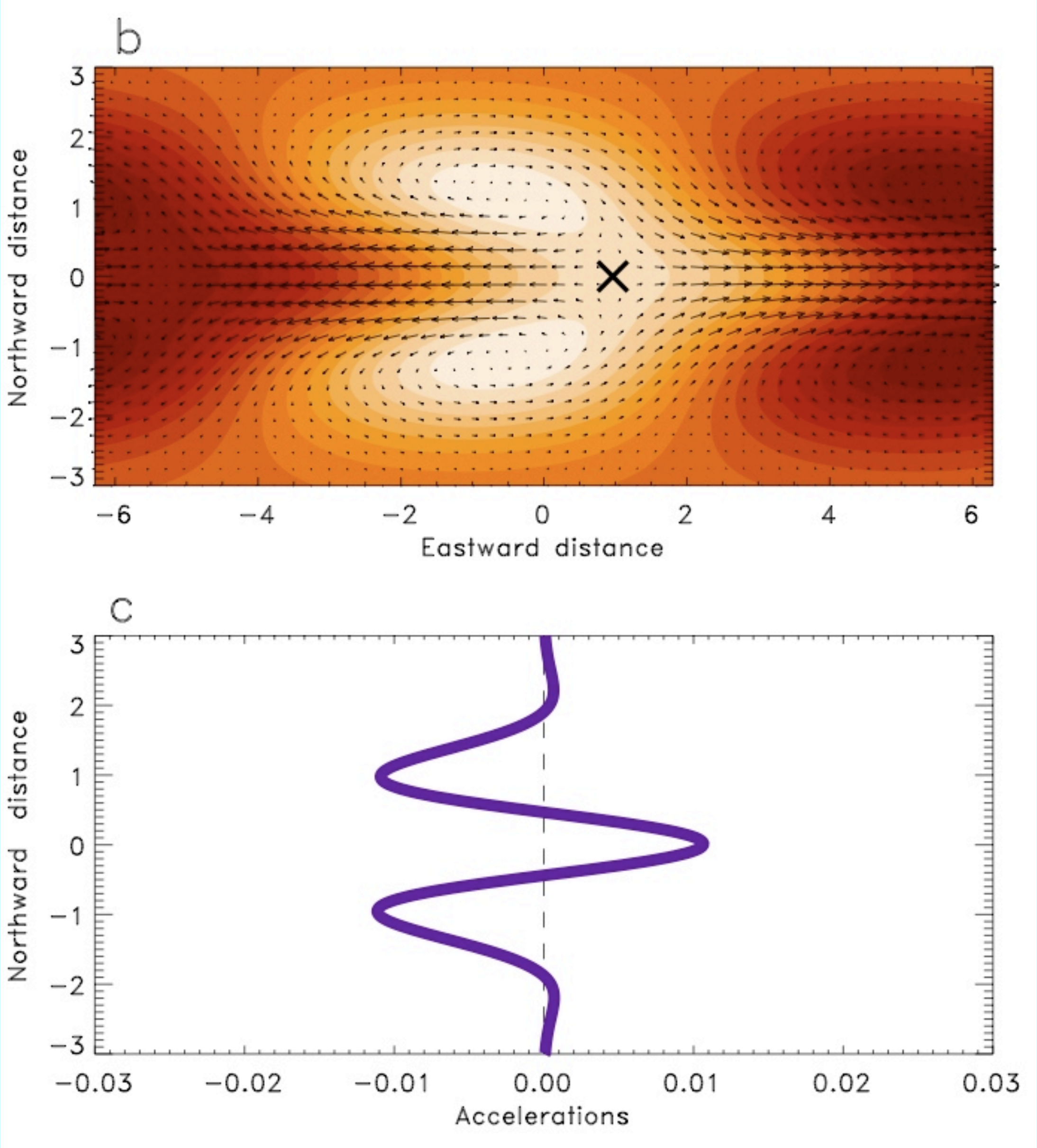


Heng et al. (2010)



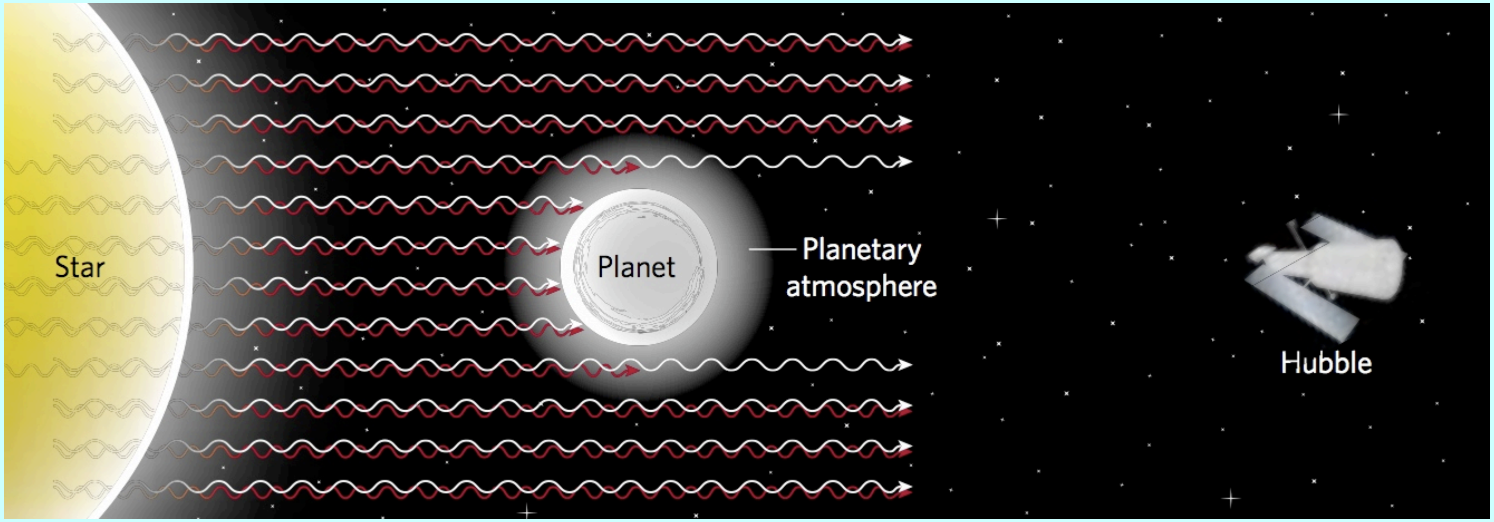
Rauscher & Menou (2012)

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

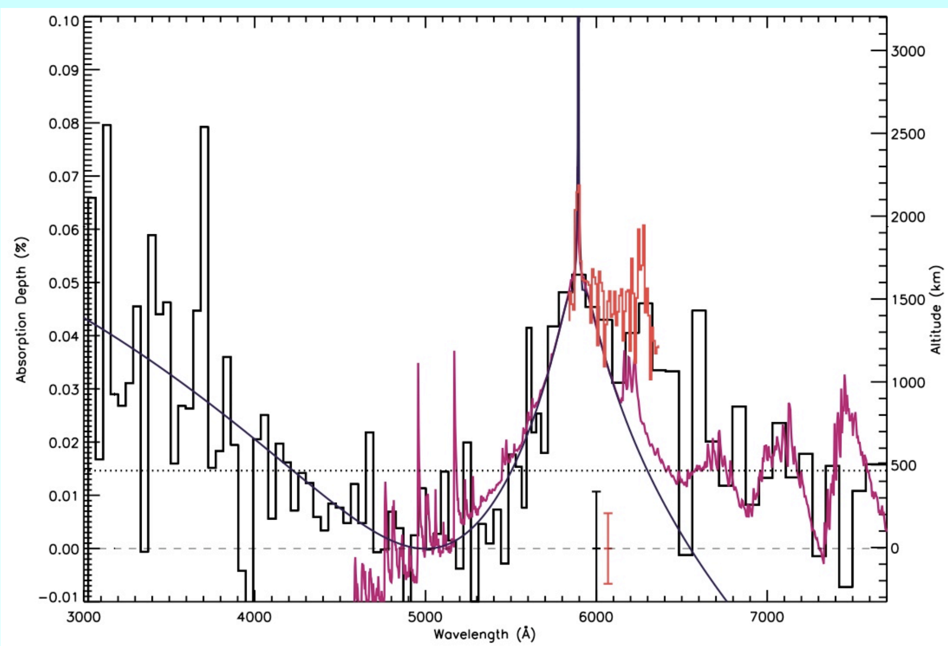


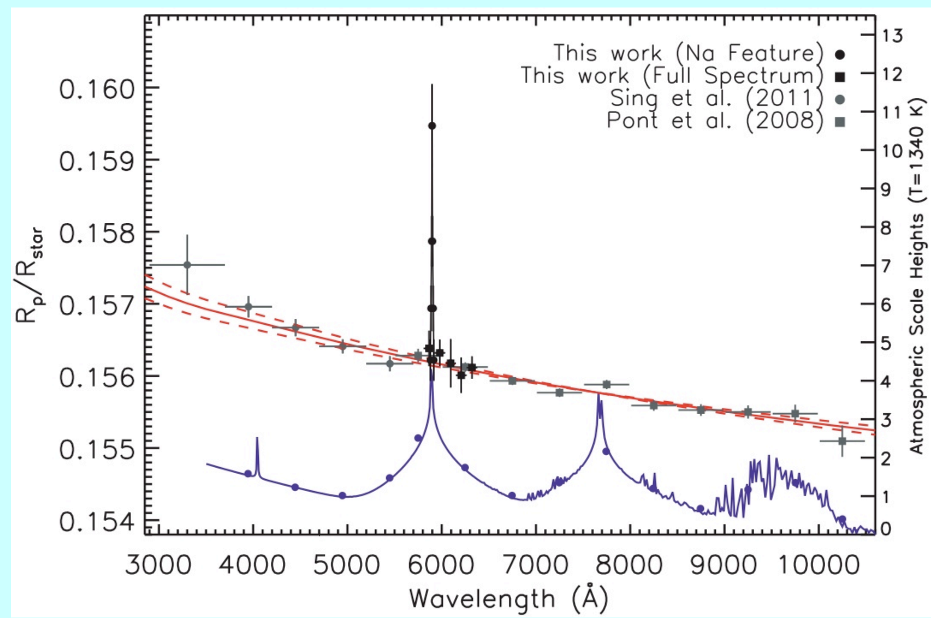
Showman & Polvani (2011), *ApJ* 738, 71

Exoplanet characterization: Transit spectroscopy



Showman (2008)





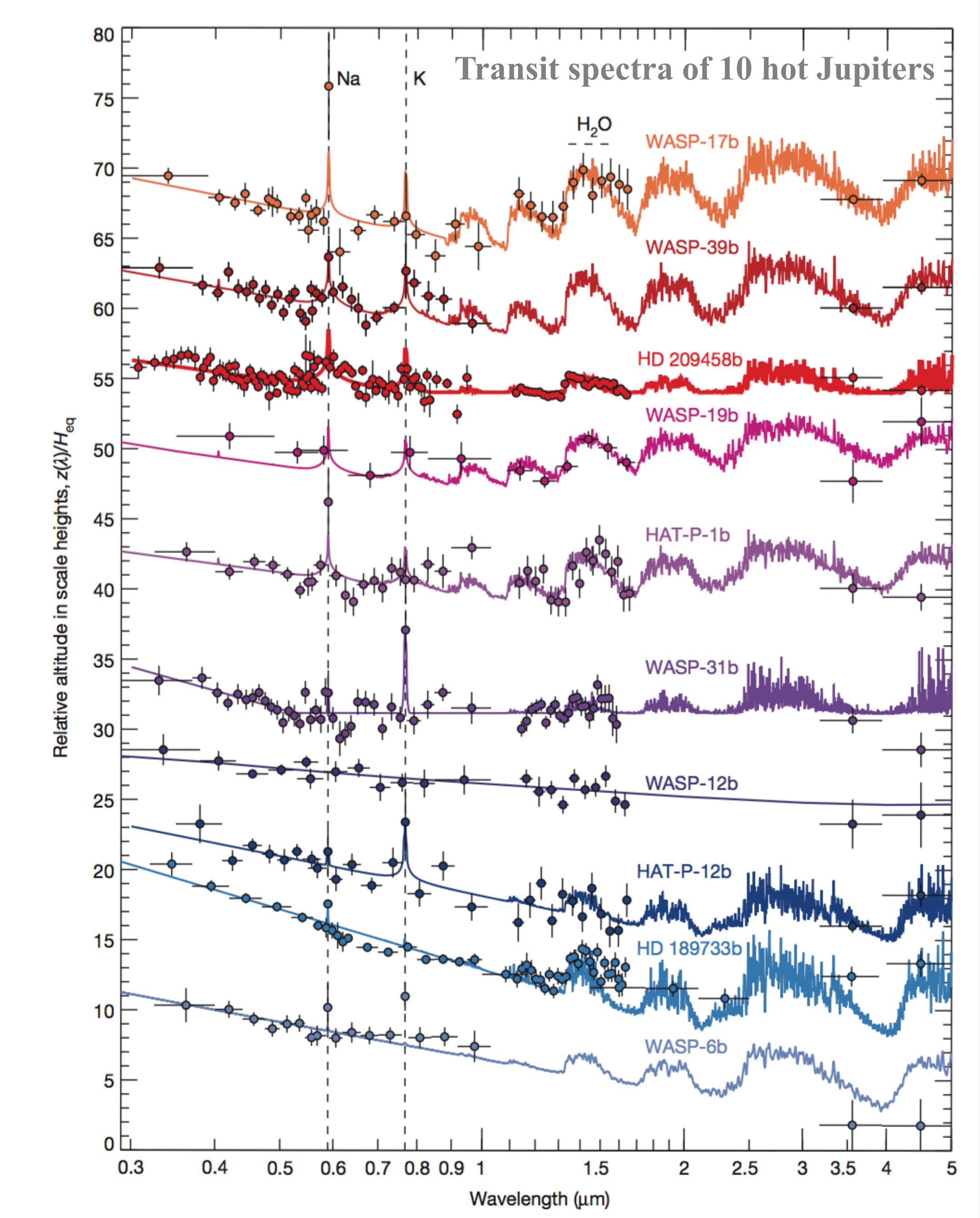
Sing et al. (2008, 2009), Vidal-Madjar et al. (2011), Huitson et al. (2012),Gibson et al. (2012), Barman (2007), Tinetti et al. (2007), Swain et al. (2008),…..

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.**

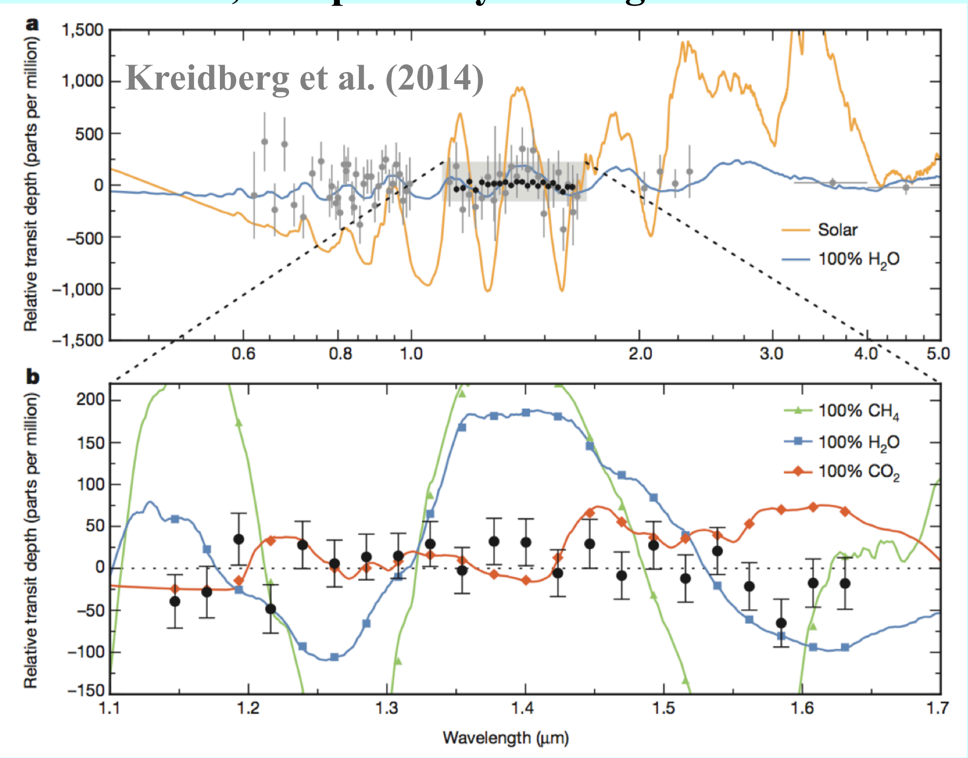
- **In principle, spectra like this can be used to infer the water abundance, but the degeneracy with hazes makes it difficult to obtain absolute abundances.**



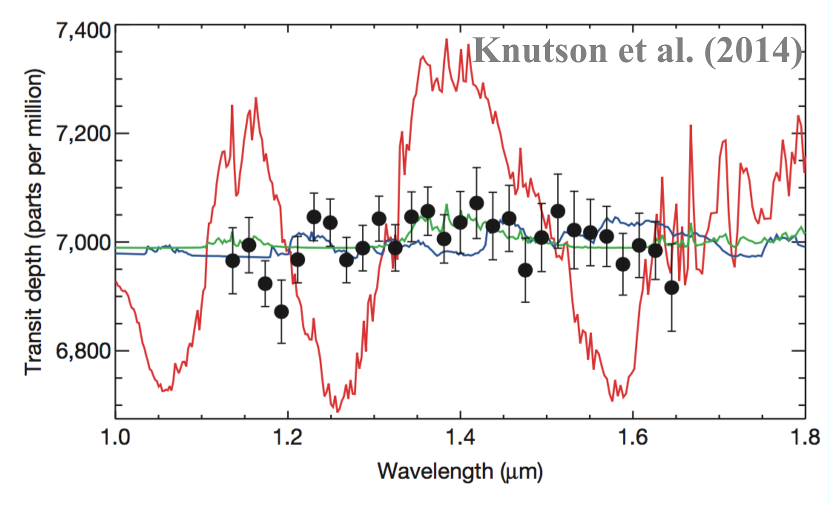
Sing et al. (2016, *Nature*)

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

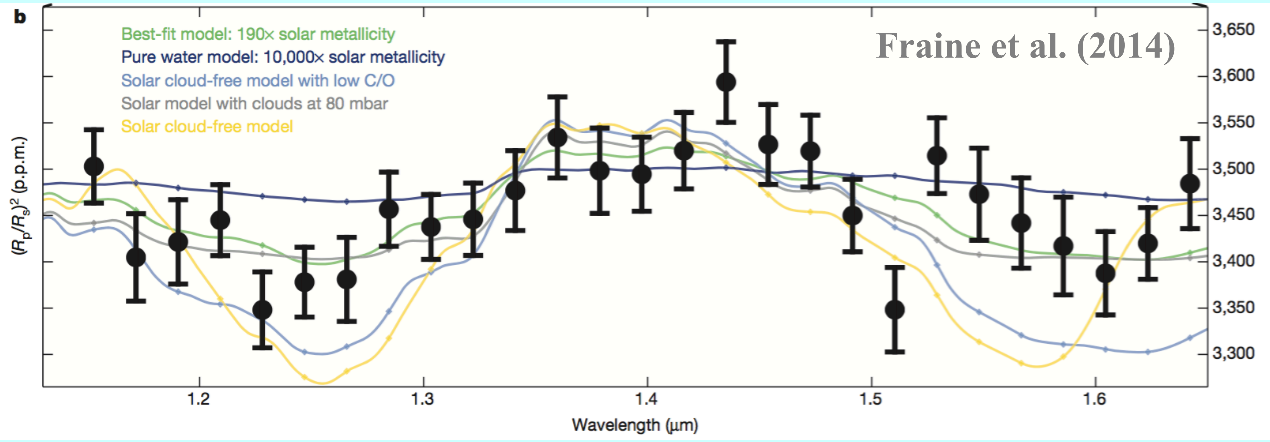
GJ 1214b, very flat spectrum => requires hazes, and probably also high MMW



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



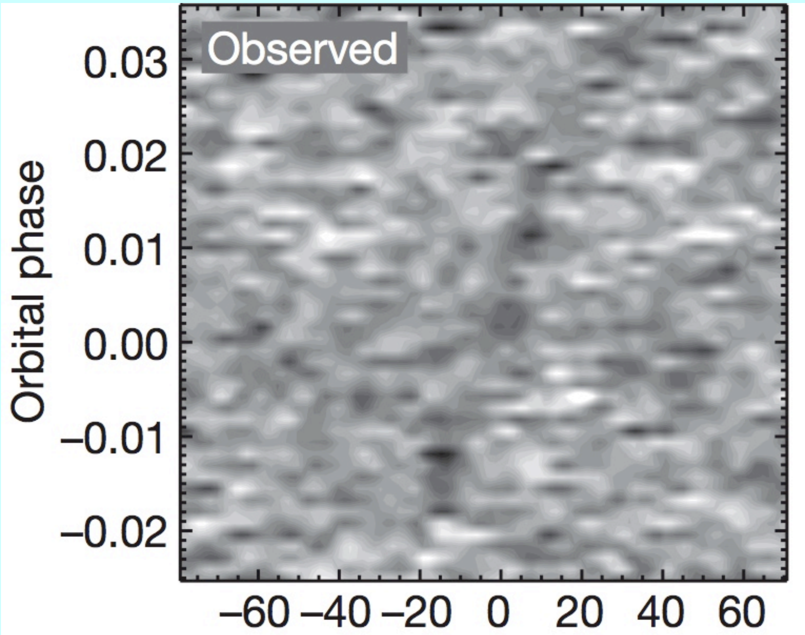
HAT-P-11b, tentative detection of weak water features => suggests puffy H_2 atmosphere

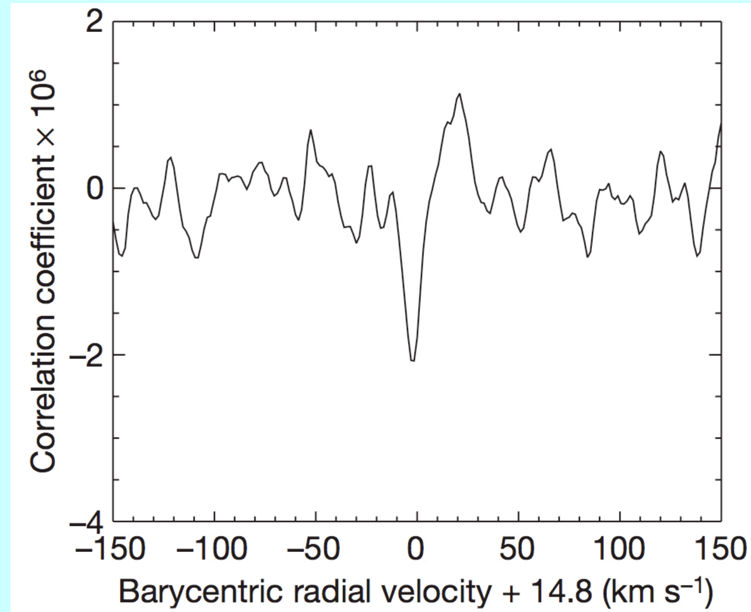


Do super Earths have H_2-dominated atmospheres like Uranus and Neptune? Or high mean molecular weight (MMW) atmospheres of water, N_2, CO_2, etc?

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**



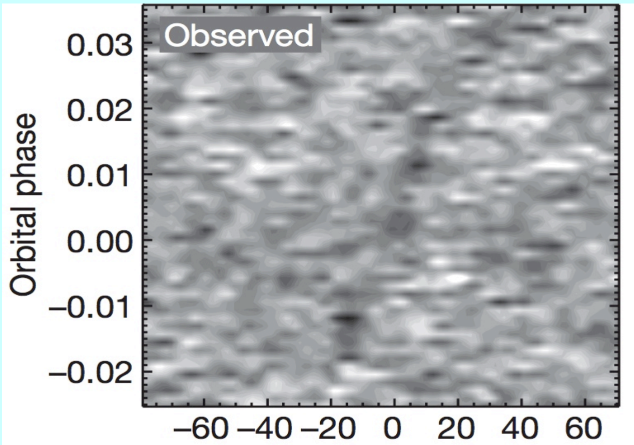


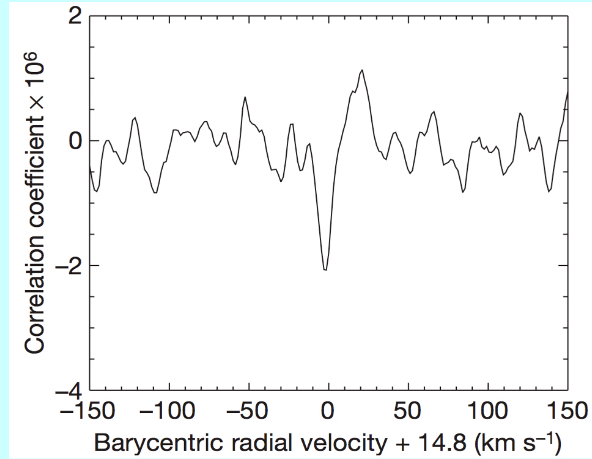
- **Tentative detection of ~2 km/sec blueshift in CO lines during transit of HD 209458b**

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

Doppler detection of winds during transit

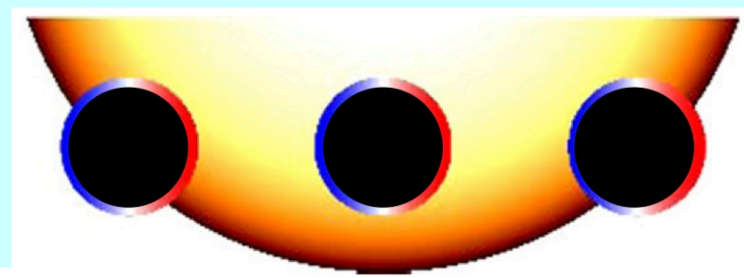
HD 209458b: Residual 2 km/sec blueshift (2 μm, CRIRES)

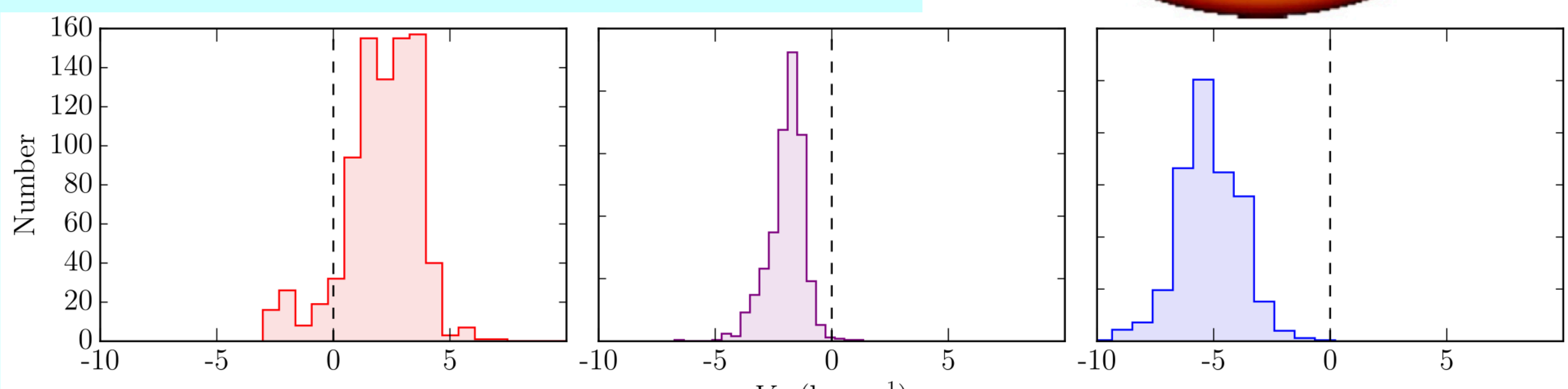




Snellen et al. (2010)

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



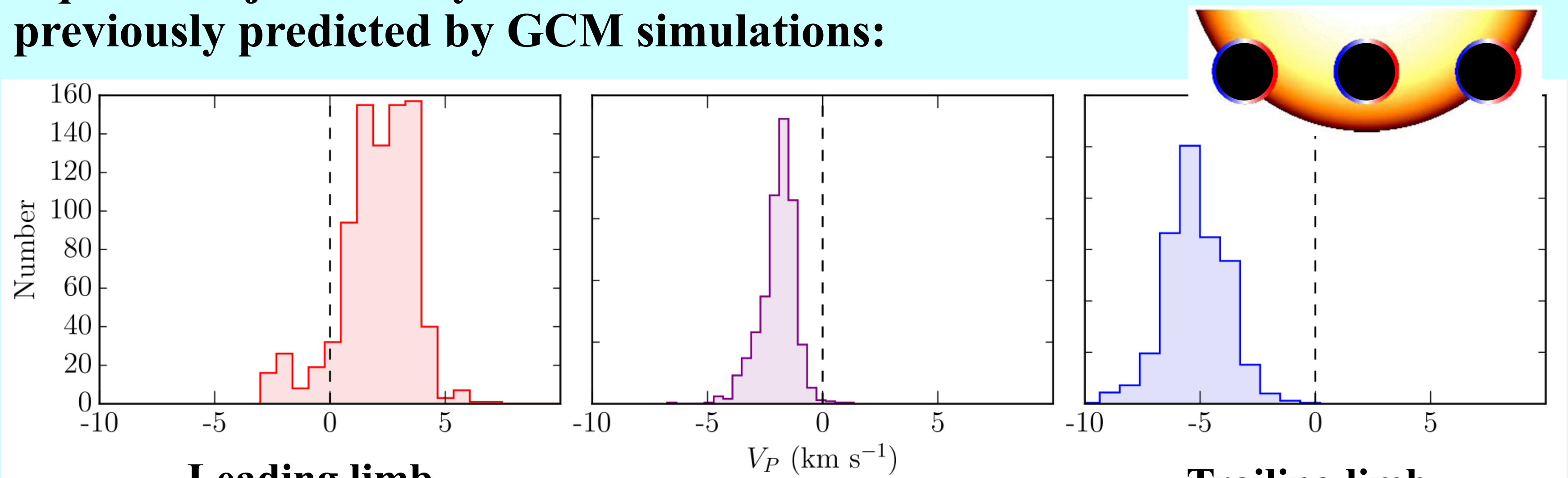


Leading limb **Average during transit** **Trailing limb**

Louden & Wheatley (2015)

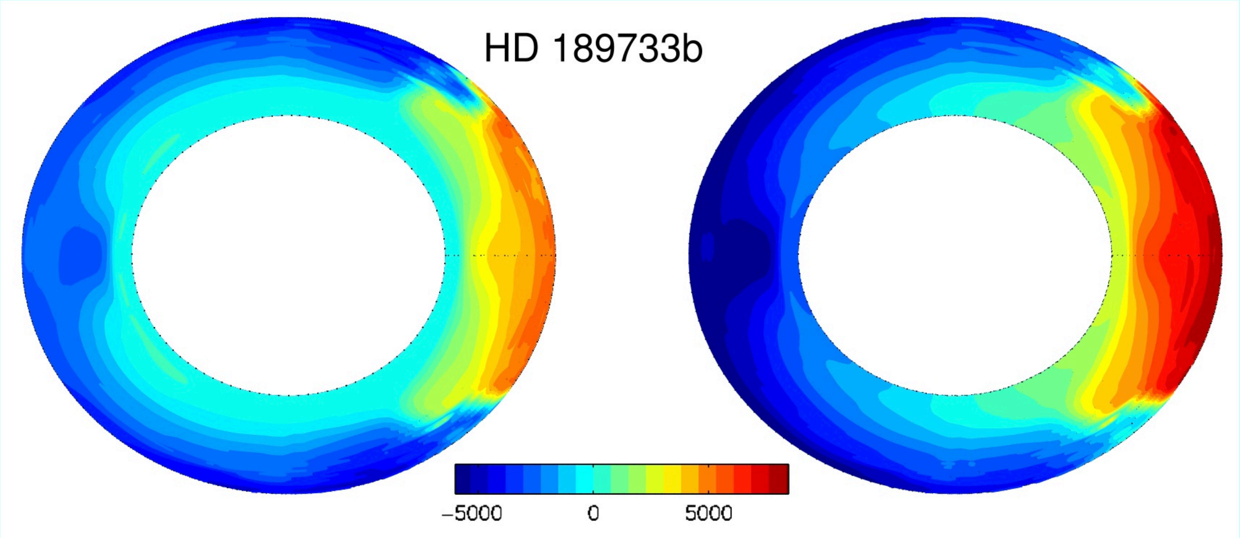
Doppler detection of equatorial jet

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



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

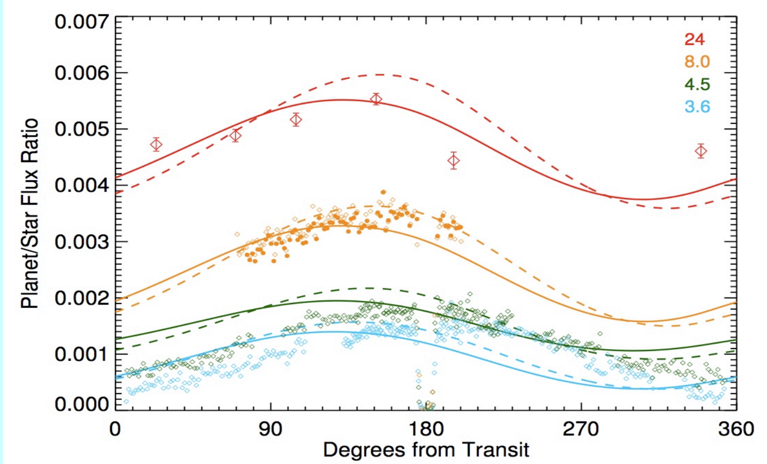
Louden & Wheatley (2015)

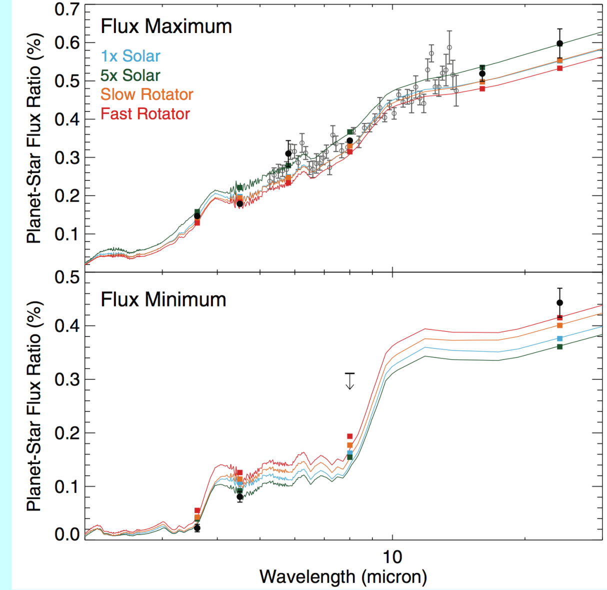


Showman et al. (2013)

Comparisons of data to GCMs

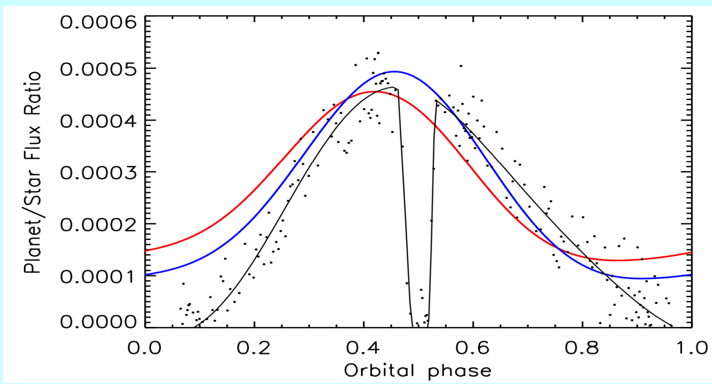
HD 189733b

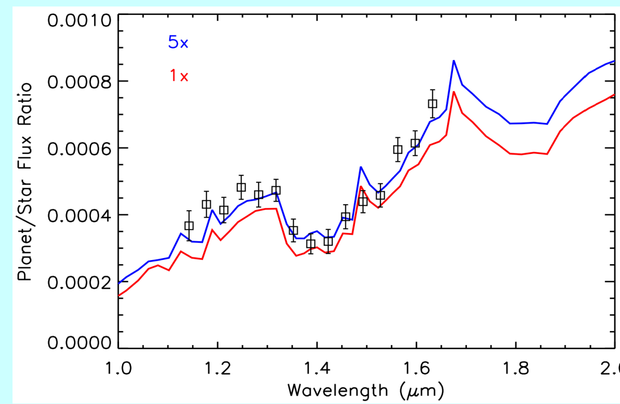




Showman et al. (2009), Knutson et al. (2012)

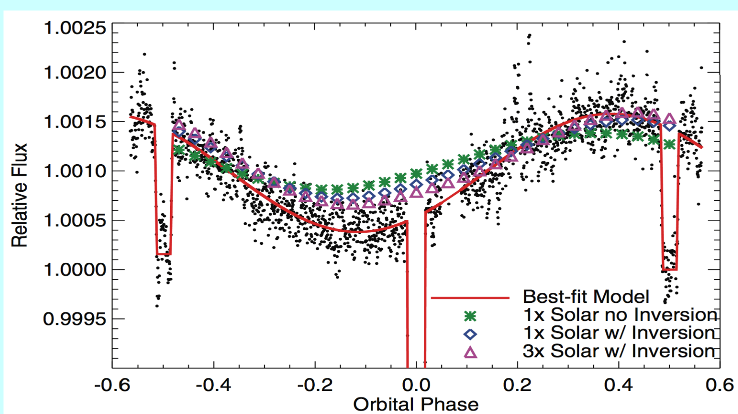
WASP-43b

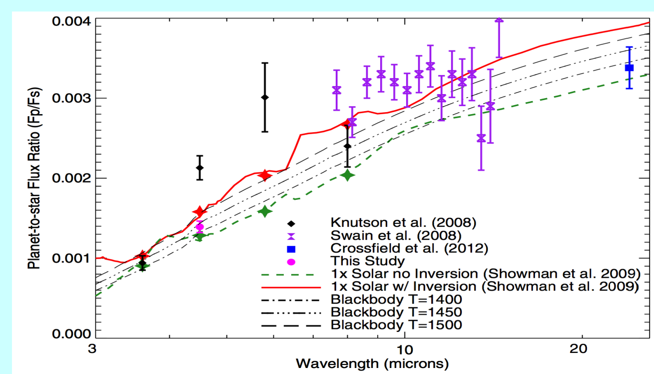




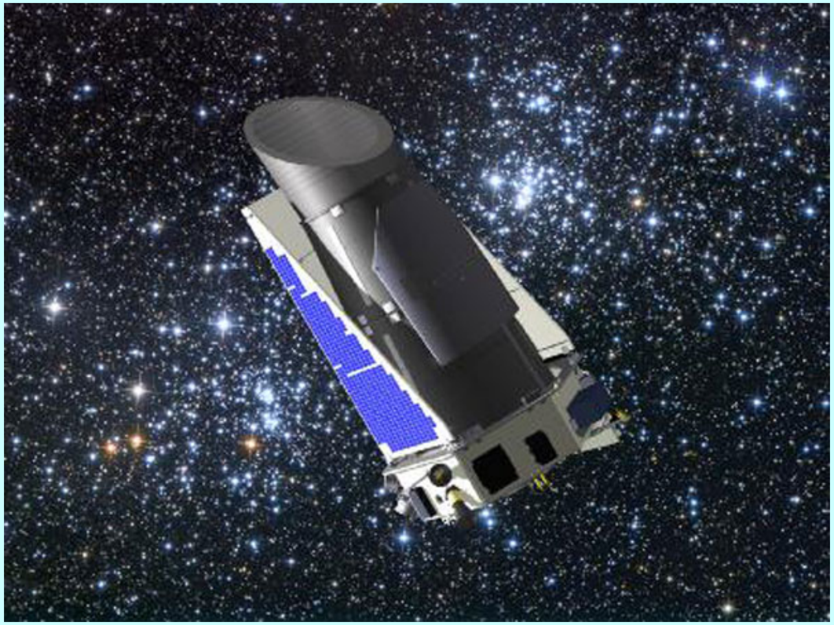
Kataria et al. (2015)

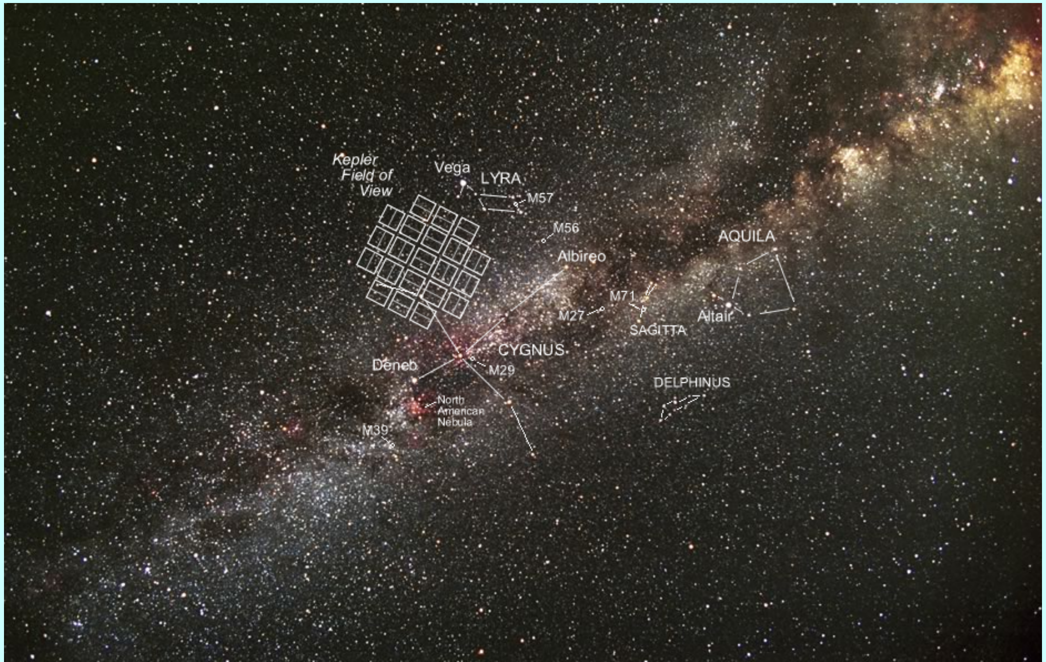
HD 209458b





NASA Kepler mission

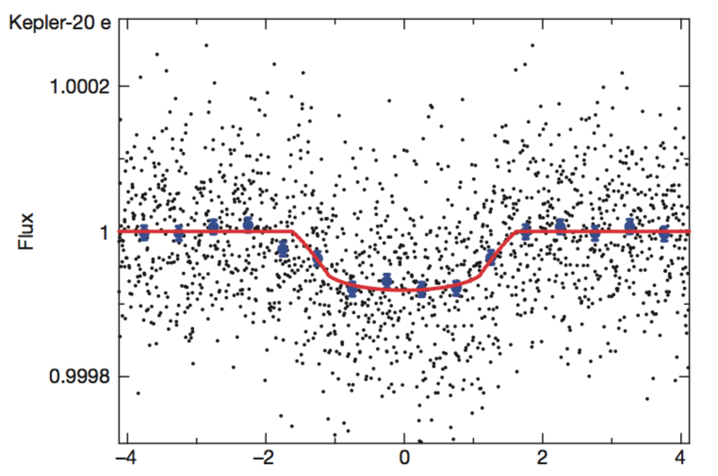




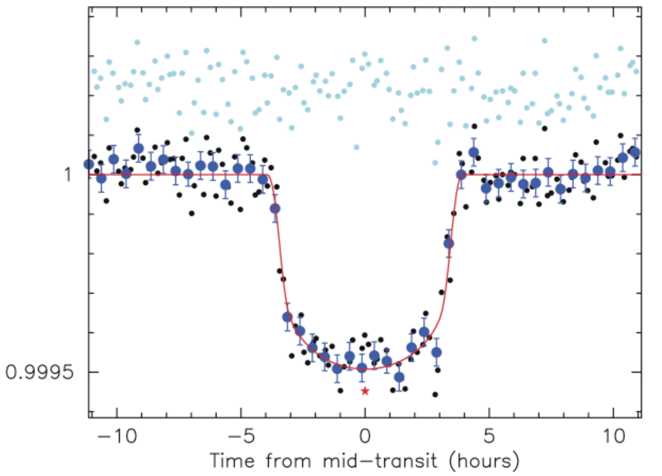
NASA Kepler mission

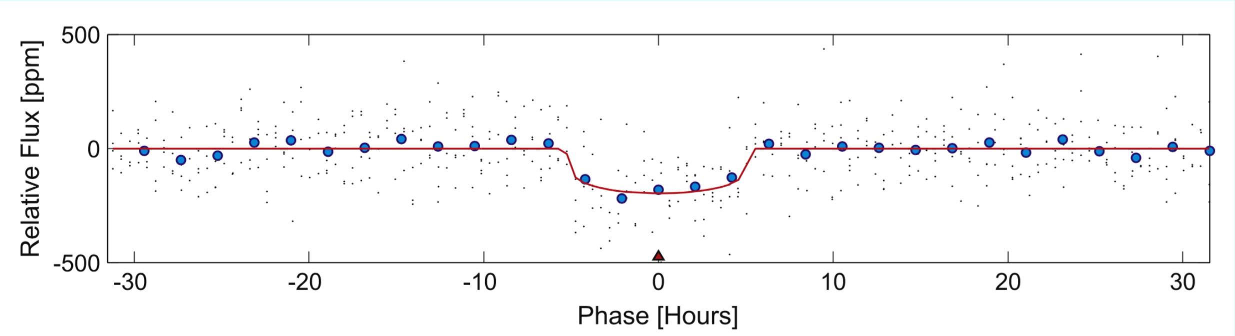
- **Detects planets using the transit technique—about 2300 planets discovered**
- **Roughly half of stars have a "super Earth"… a planet 1-10 Earth masses**
- **Kepler discovered several planets close to the classical habitable zone**

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



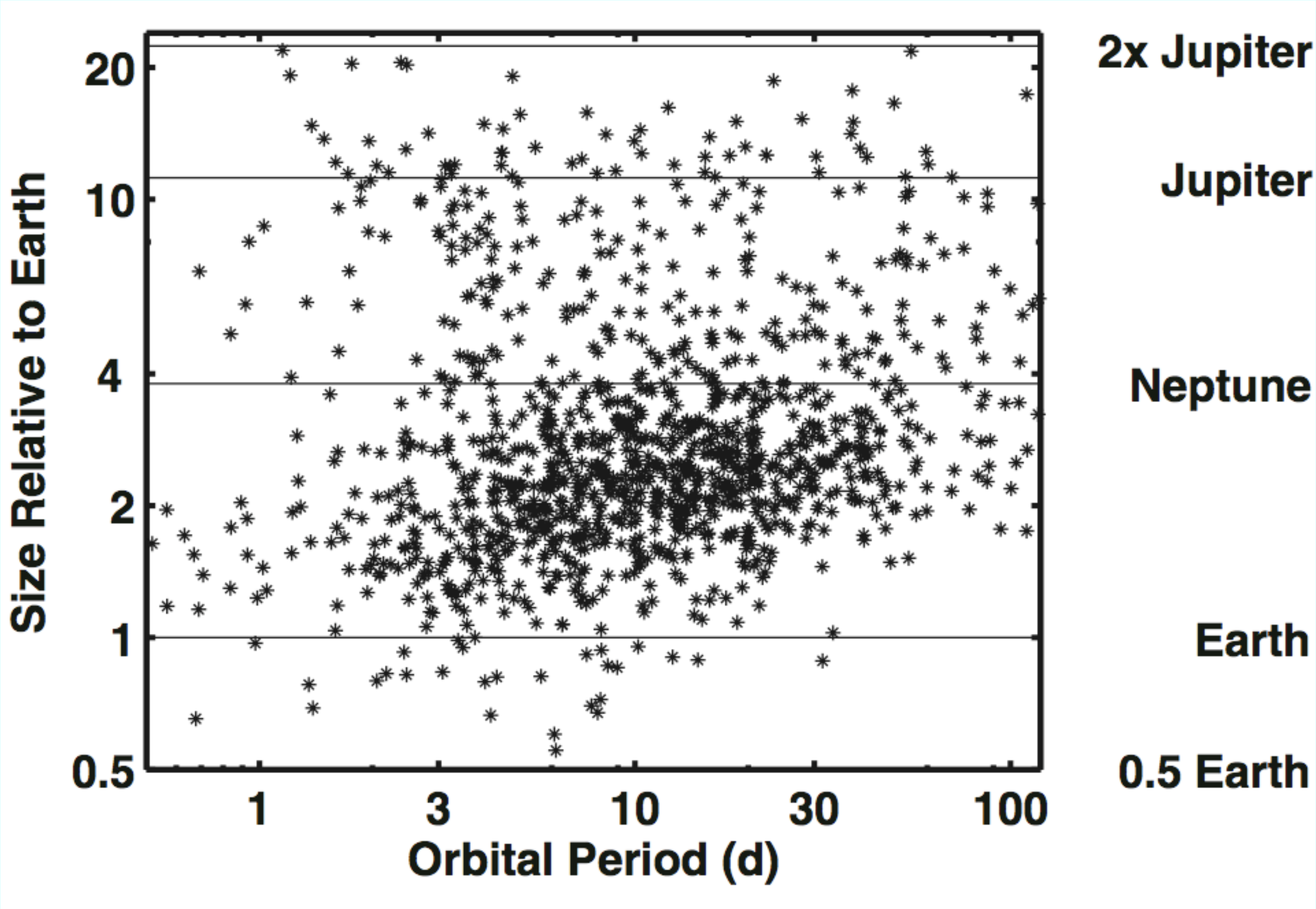
Kepler 22b: a 2.4-Earth radius planet in the habitable zone



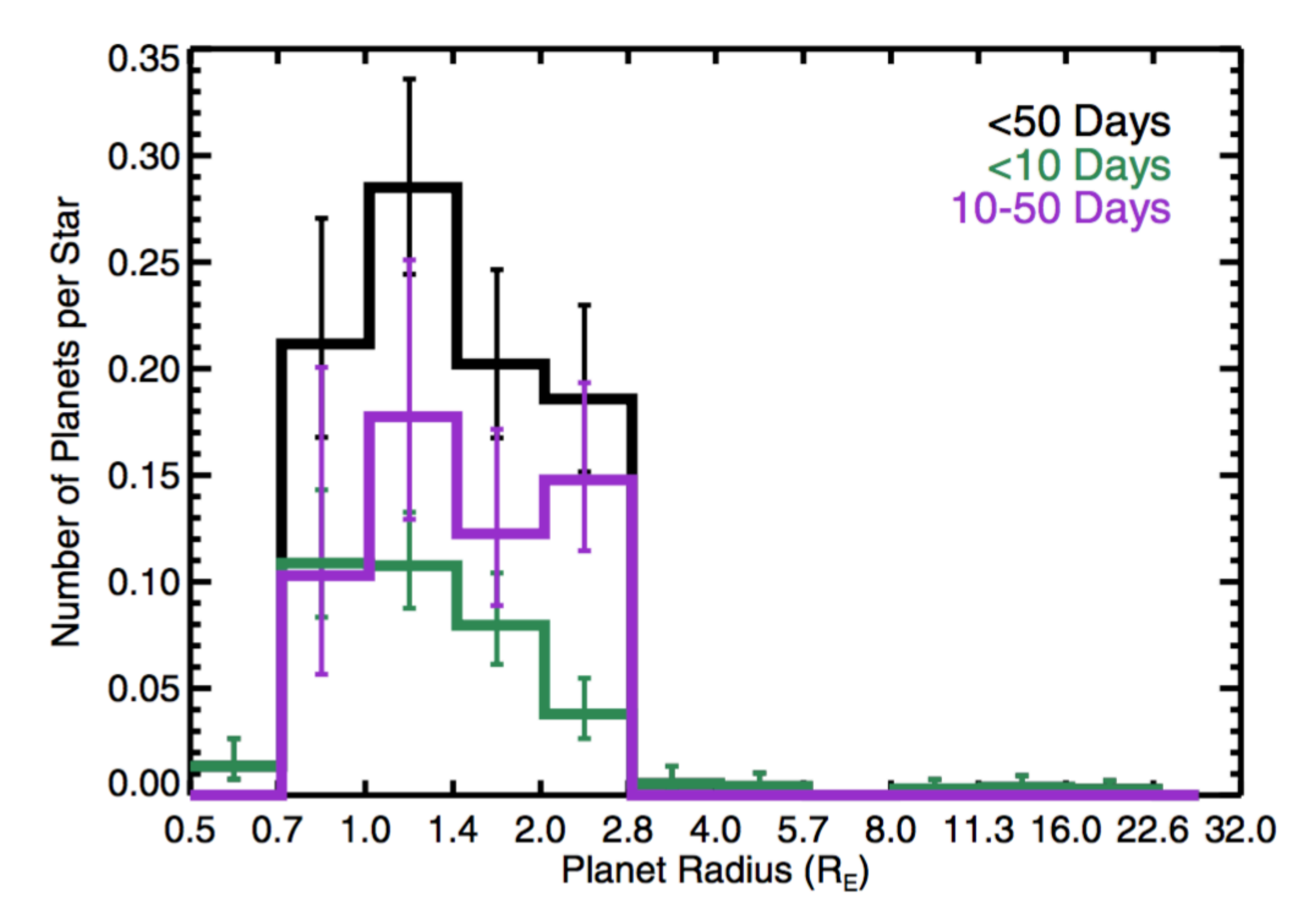


Kepler 452b: a 1.6-Earth radius planet in the habitable zone of a sun-like star

Kepler detected *loads* of "super Earths"



Kepler assessment of planet populations

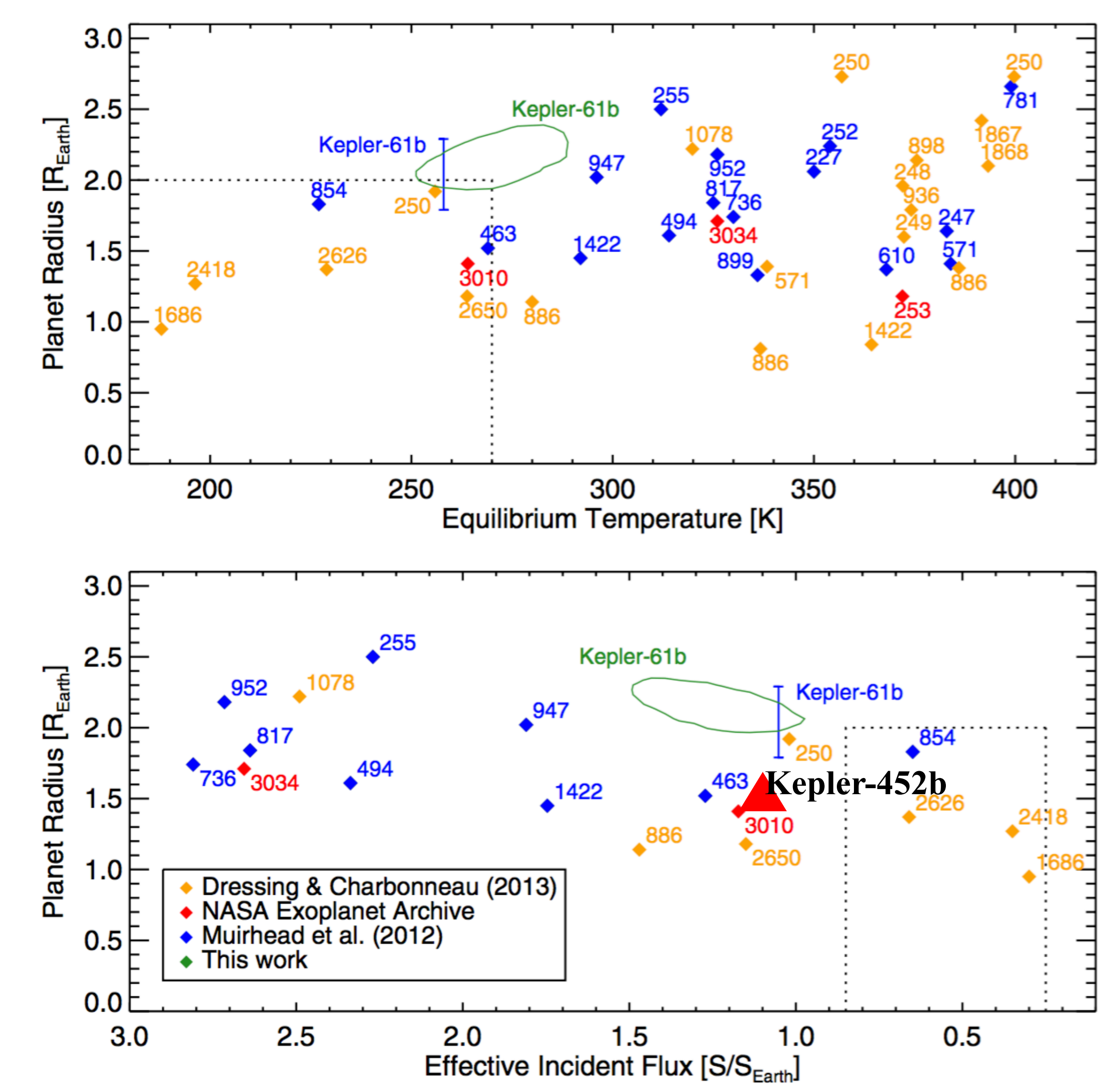


Dressing & Charbonneau (2013)

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).

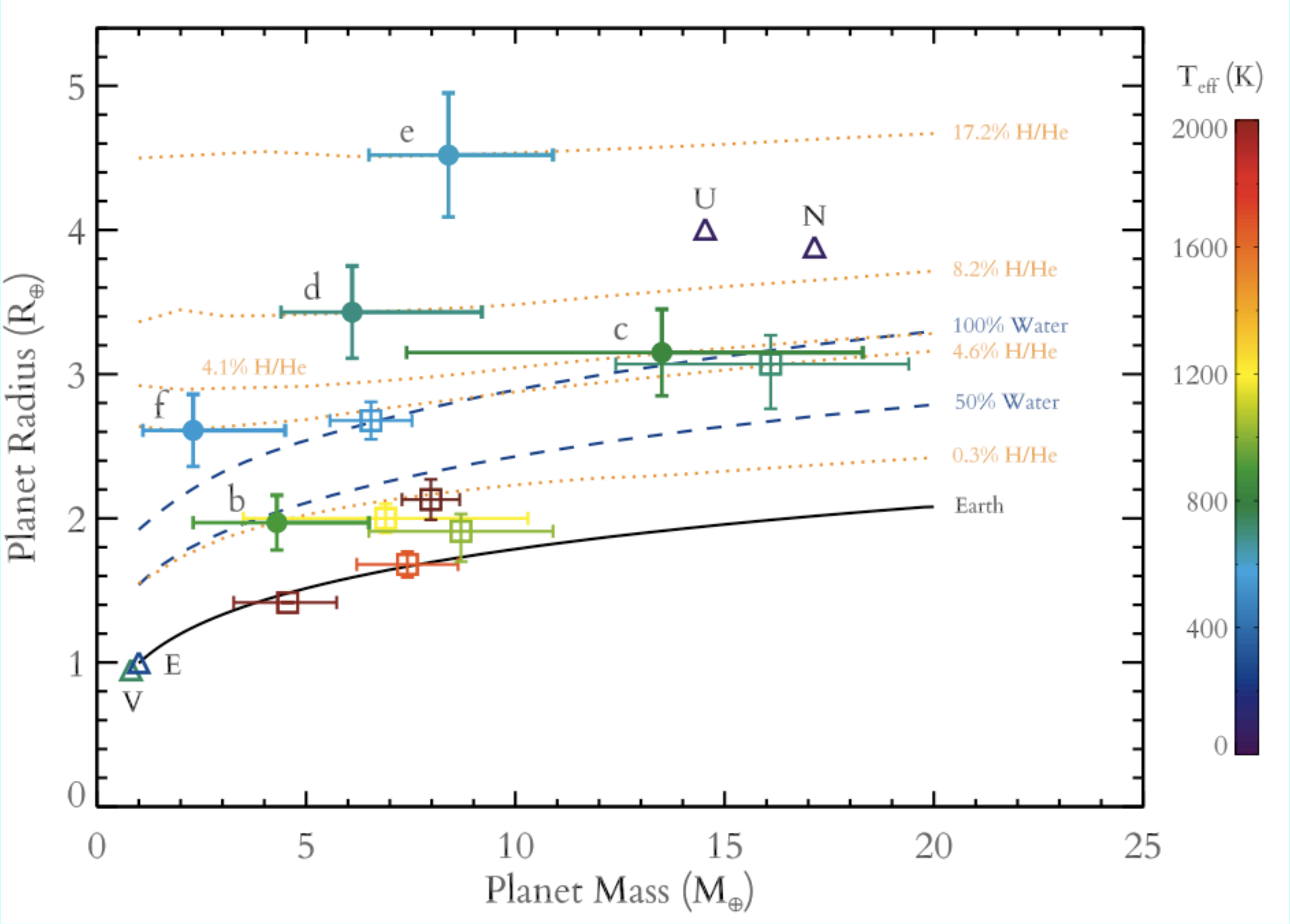
Kepler homing in on habitable planets

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



Ballard et al. (2013)

We can infer densities and therefore learn about composition!

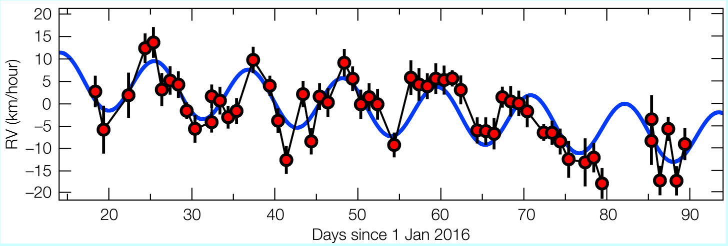


Lopez et al. (2012)

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**

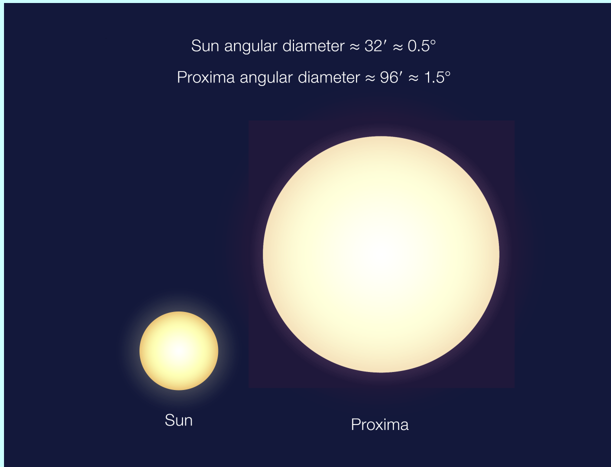
- **Planet was discovered August 2016 by radial velocity—*M*sin*i* of 1.3 Earth masses, orbital period 11.2 days, orbital semi-major axis 0.05 AU, receiving 0.65 the stellar flux of Earth. This would imply an effective temperature of ~230 K if the albedo is similar to Earth's.**

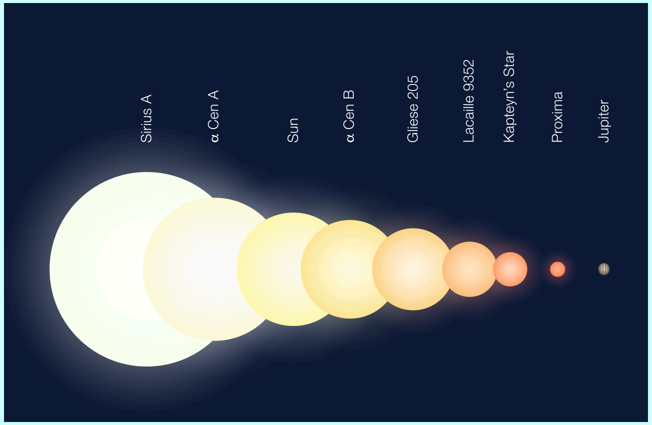


Stellar motion inferred from Doppler shift of stellar lines, indicating a planet.

- **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.