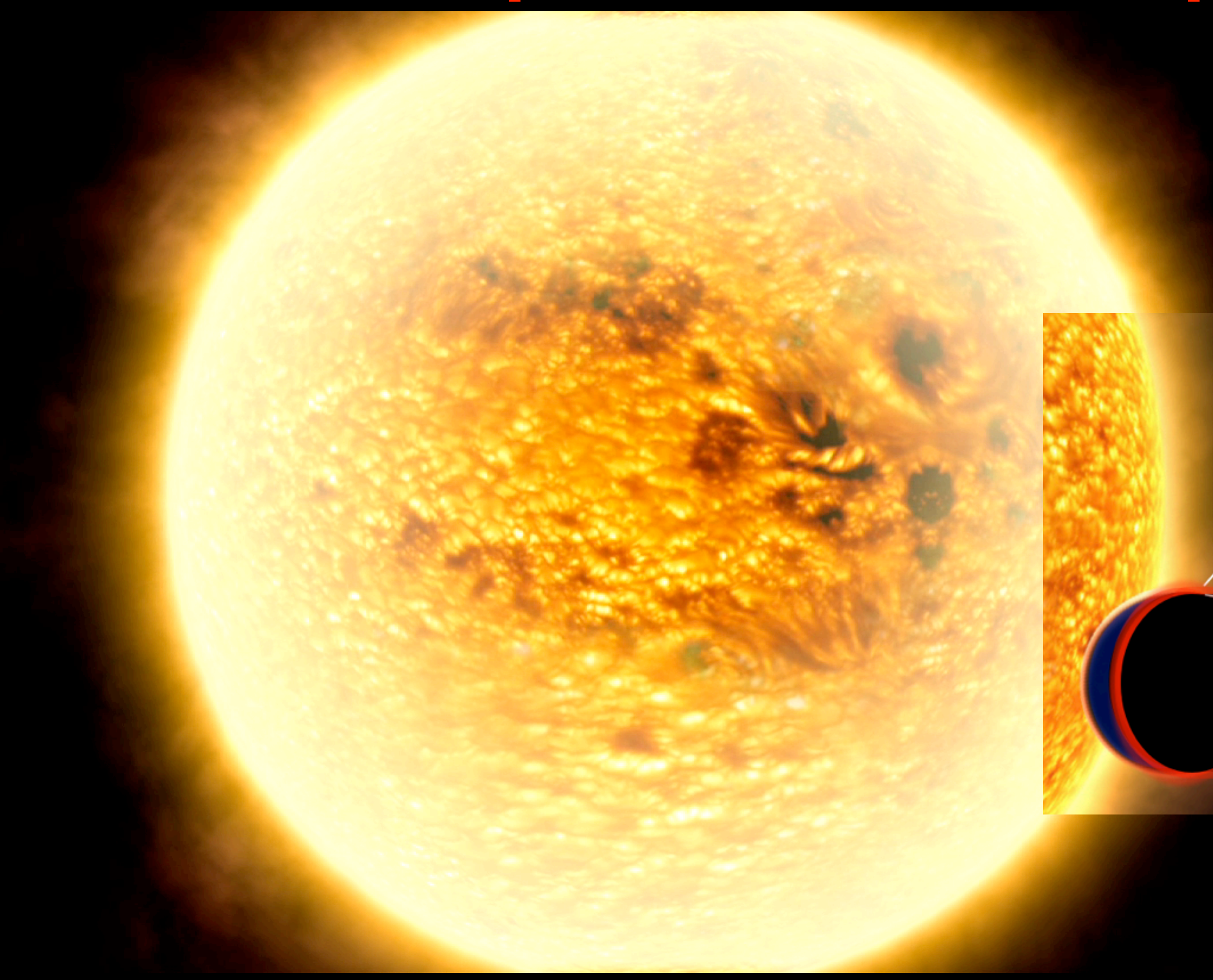
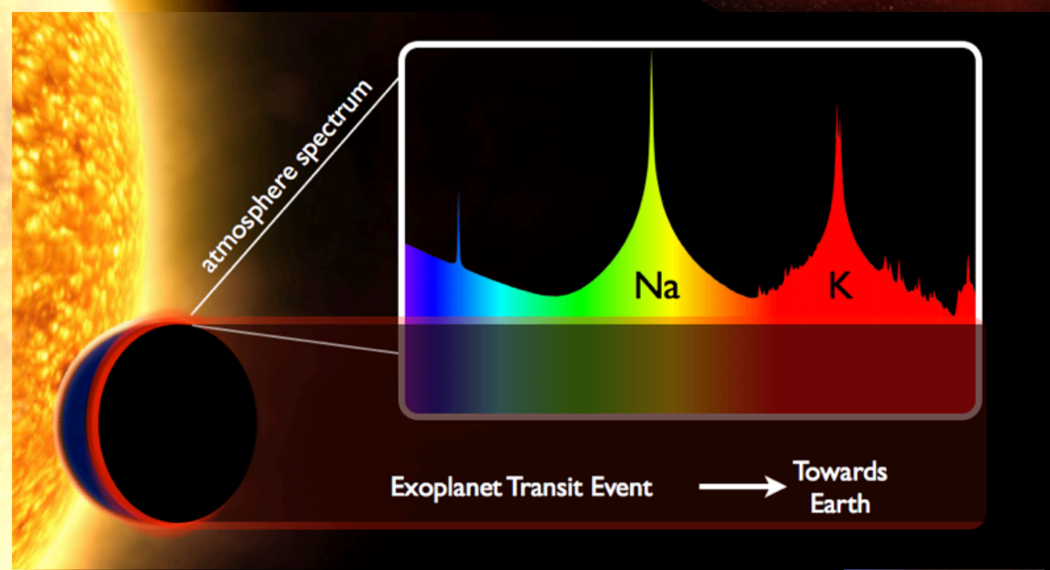
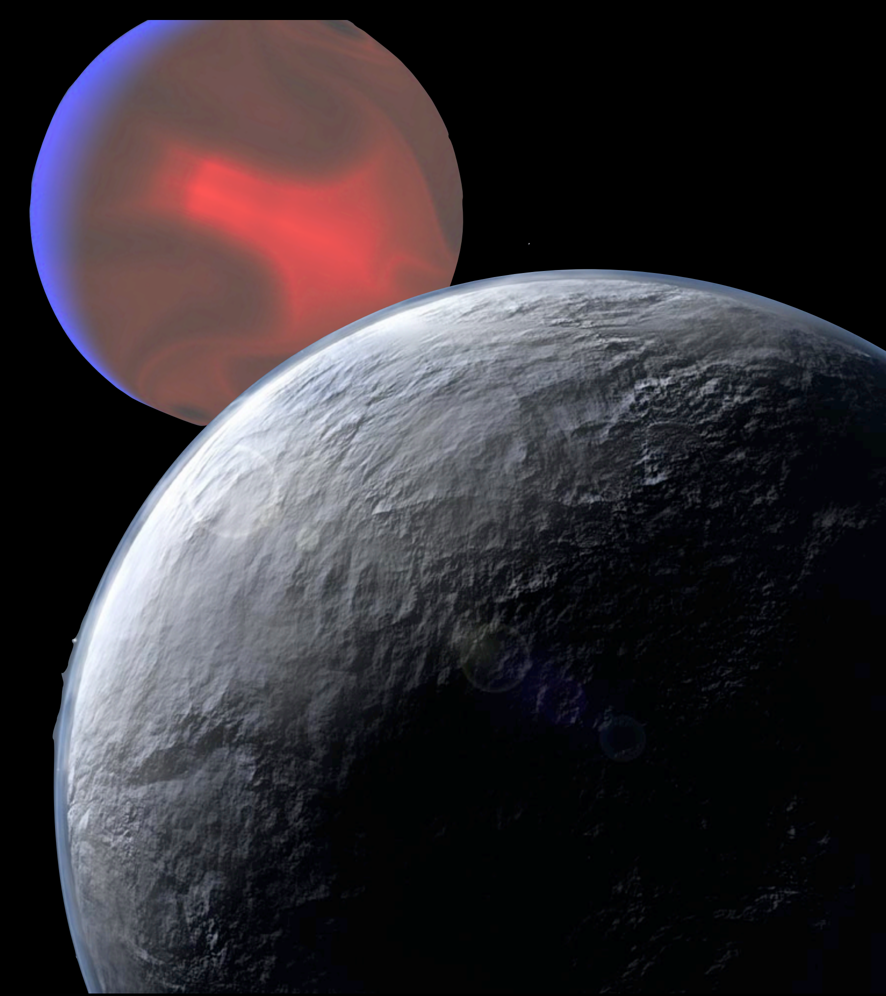
Exoplanet Atmospheres by Transmission Emission & Phase Curves







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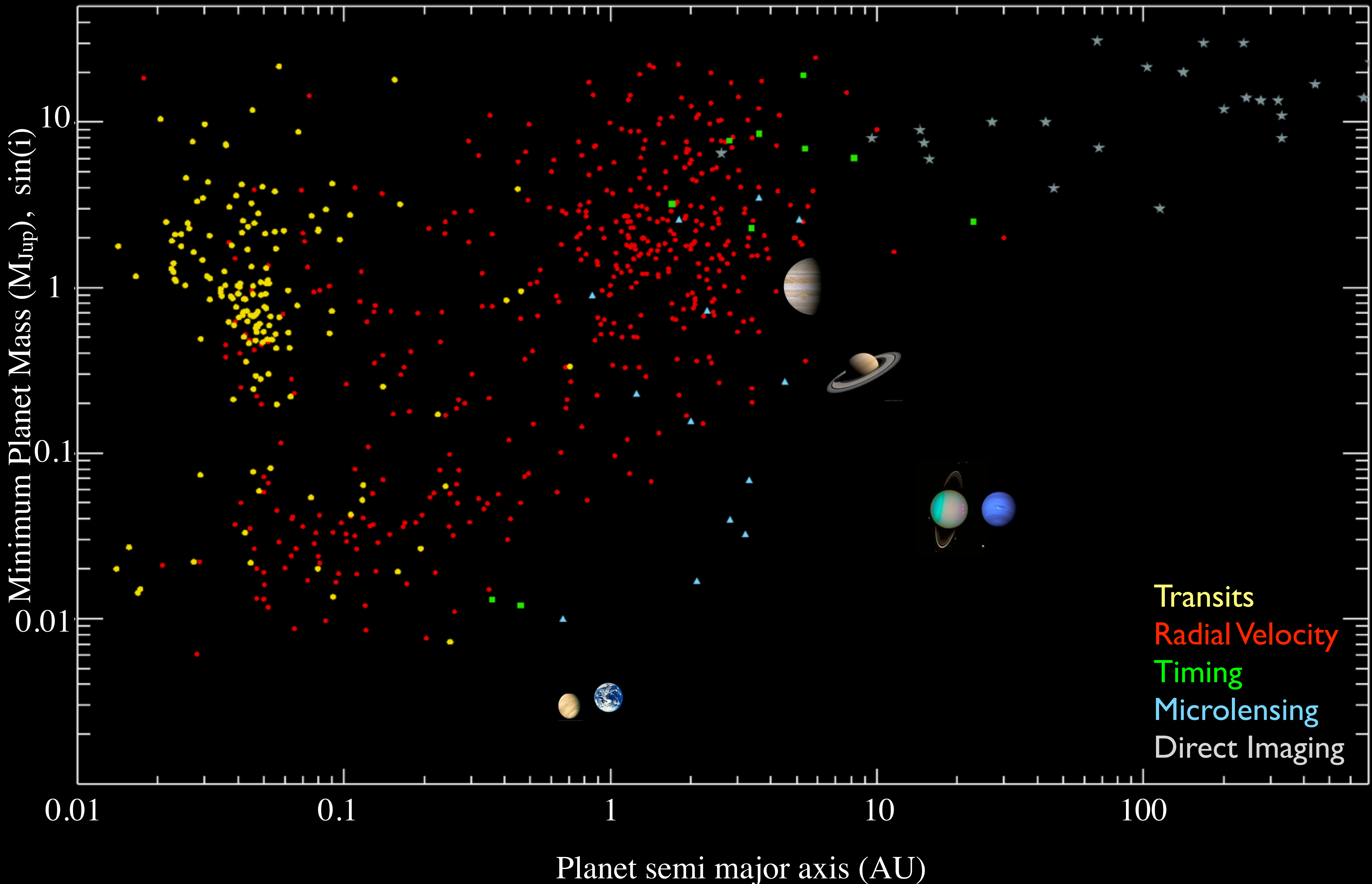
Exoclimes - Aspen 18 Jan 2012

Outline

- Introduction
    - Exoplanets & spectra
- Atmospheres of Transiting Planets
    - Transmission
    - Emission
    - Phase curve
- What's been discovered
- What physical information and quality are possible



1/12/2011 exoplanet.eu

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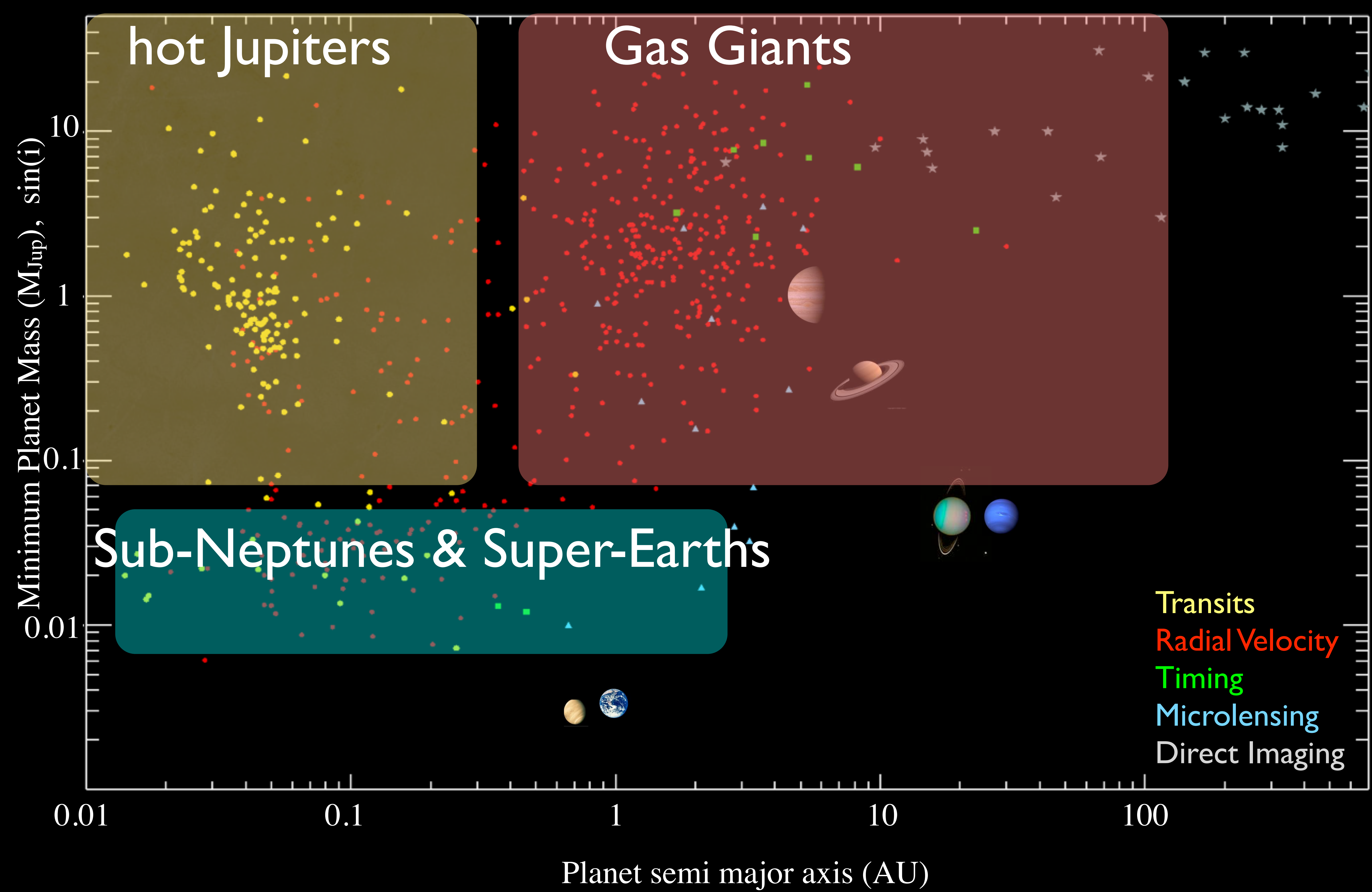

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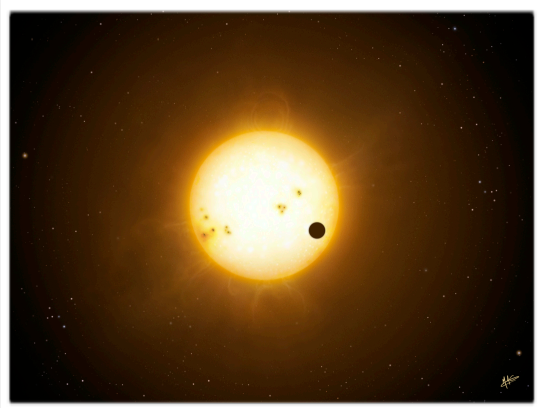
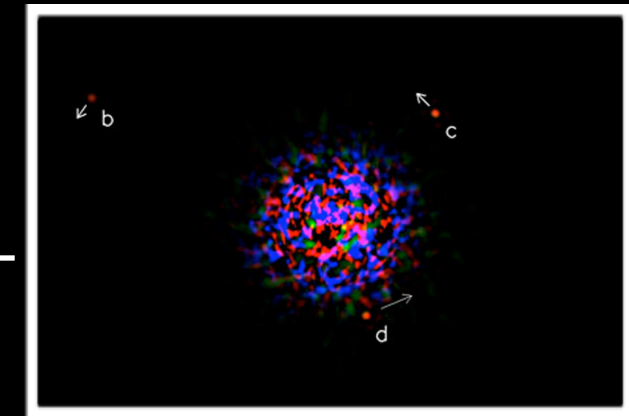
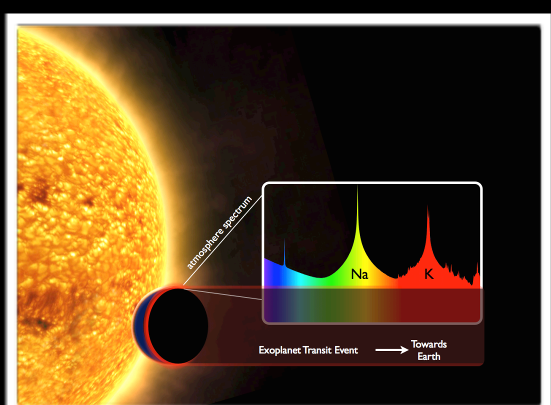
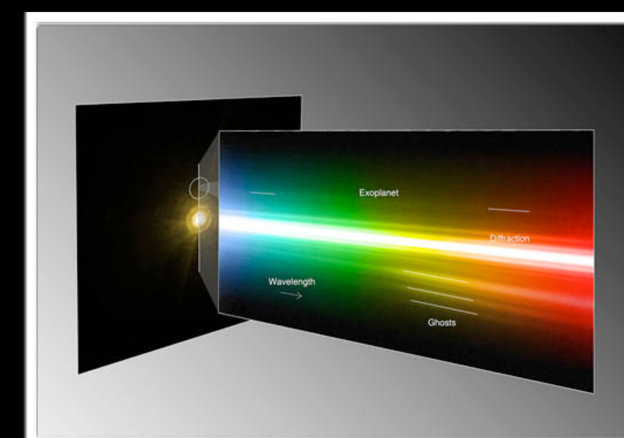
Exoplanet Atmosphere Characterisation by Spectra

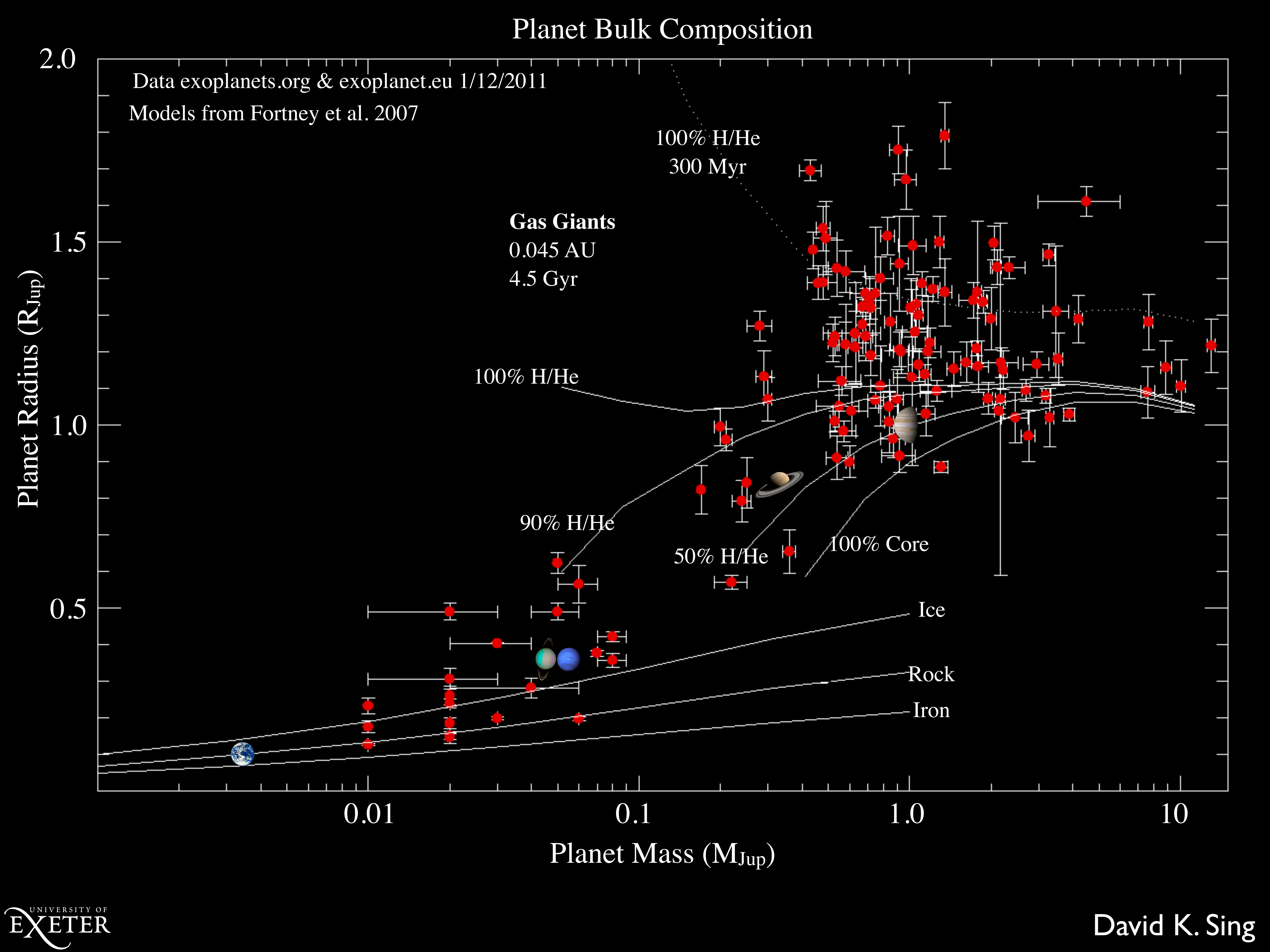




Transits	Direct Imaging
Close-In Planets	Wide-Separations
M_{pl}, $R_{pl}(\lambda)$, i, P, a, $Flux_{pl}(\lambda,\Phi)$	$a\sin(i)$, $Flux_{pl}(\lambda)$
Atmo. Composition	Atmo. Composition
Clouds/Hazes	Clouds/Hazes
Thermal profile	Temperatures
Stratospheres	
Thermospheres	
Exospheres	
Escape	
Dynamics, Winds	Dynamics
Photochemistry	Chemistry







Planet Bulk Composition
Data exoplanets.org & exoplanet.eu 1/12/2011
Models from Fortney et al. 2007
100% H/He
300 Myr
Gas Giants
0.045 AU
4.5 Gyr
100% H/He
90% H/He
50% H/He
100% Core
Ice
Rock
Iron
2.0
1.5
1.0
0.5
0.01
0.1
1.0
10
Planet Radius (R_{Jup})
Planet Mass (M_{Jup})
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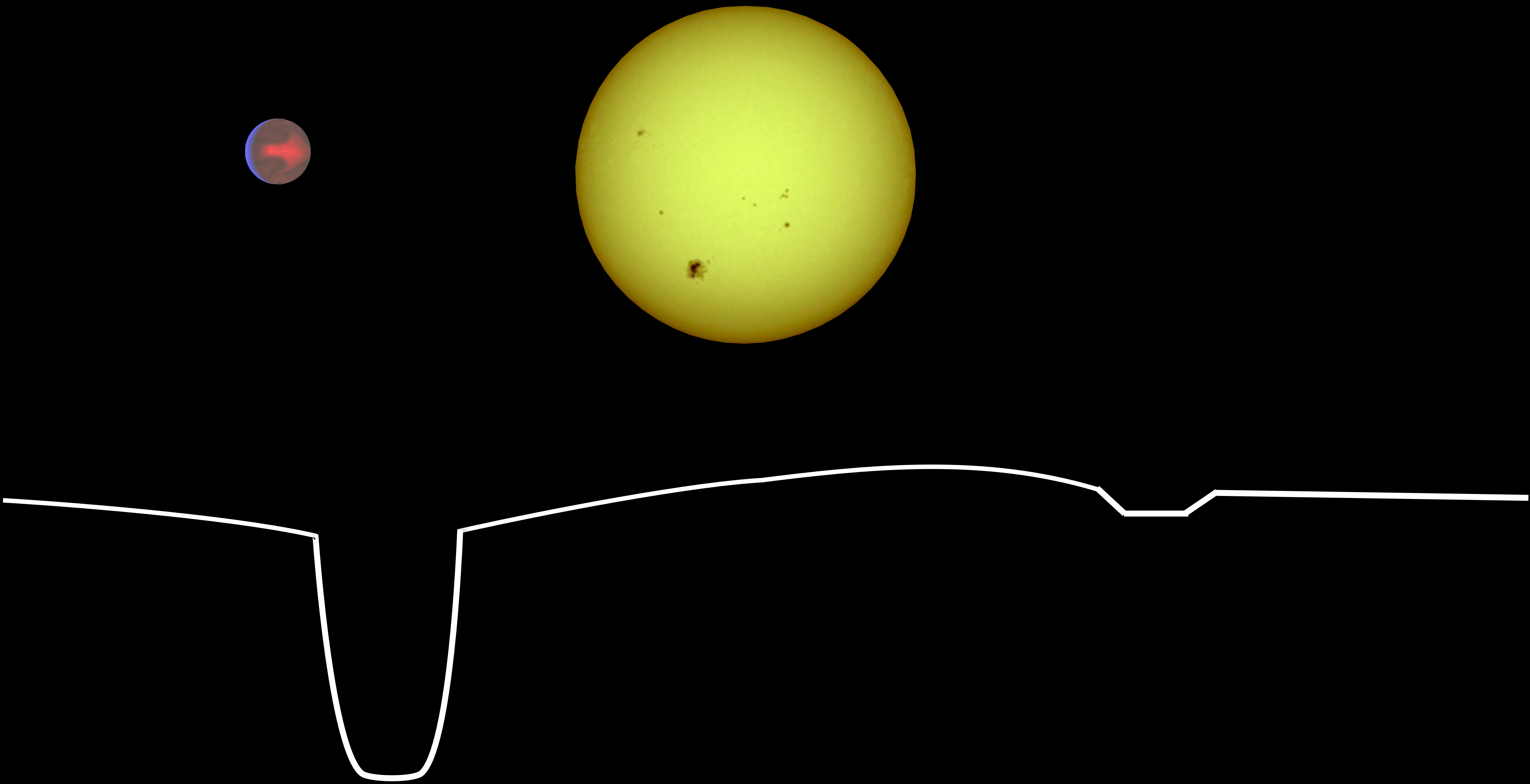
Transiting Planets

Transiting Planets



EXETER logo omitted; UNIVERSITY OF EXETER

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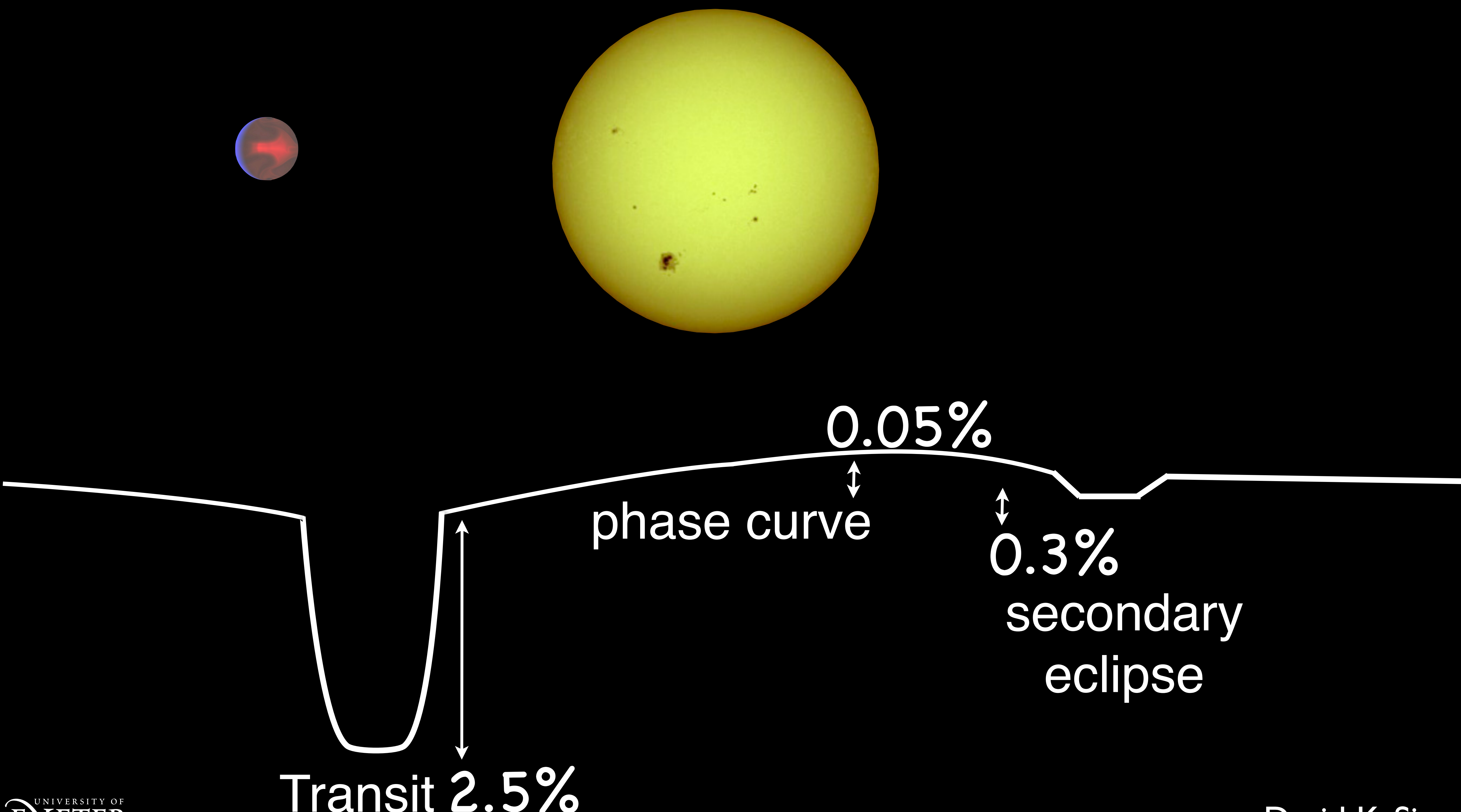
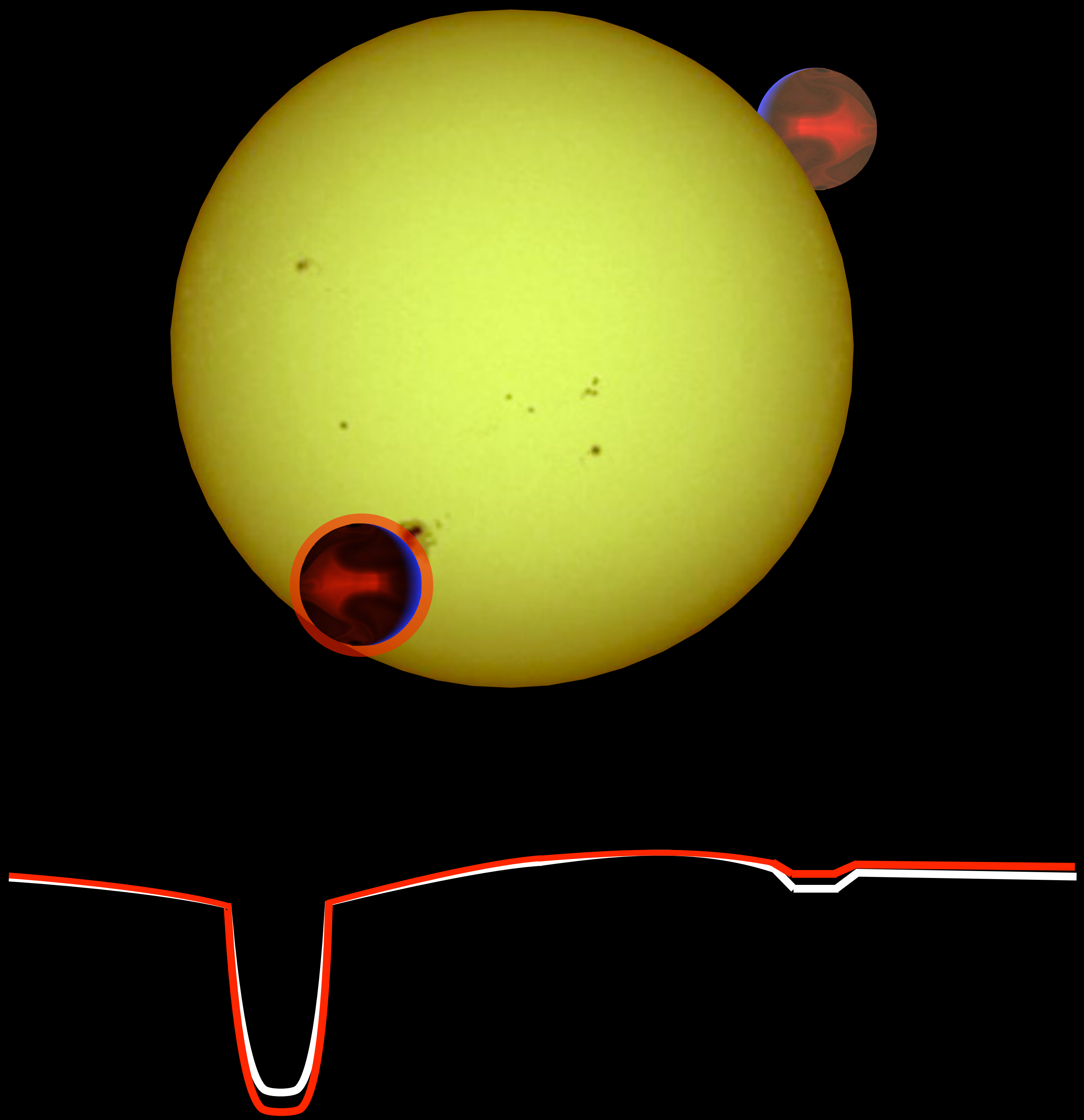
Transiting Planets



Exoplanet Spectra



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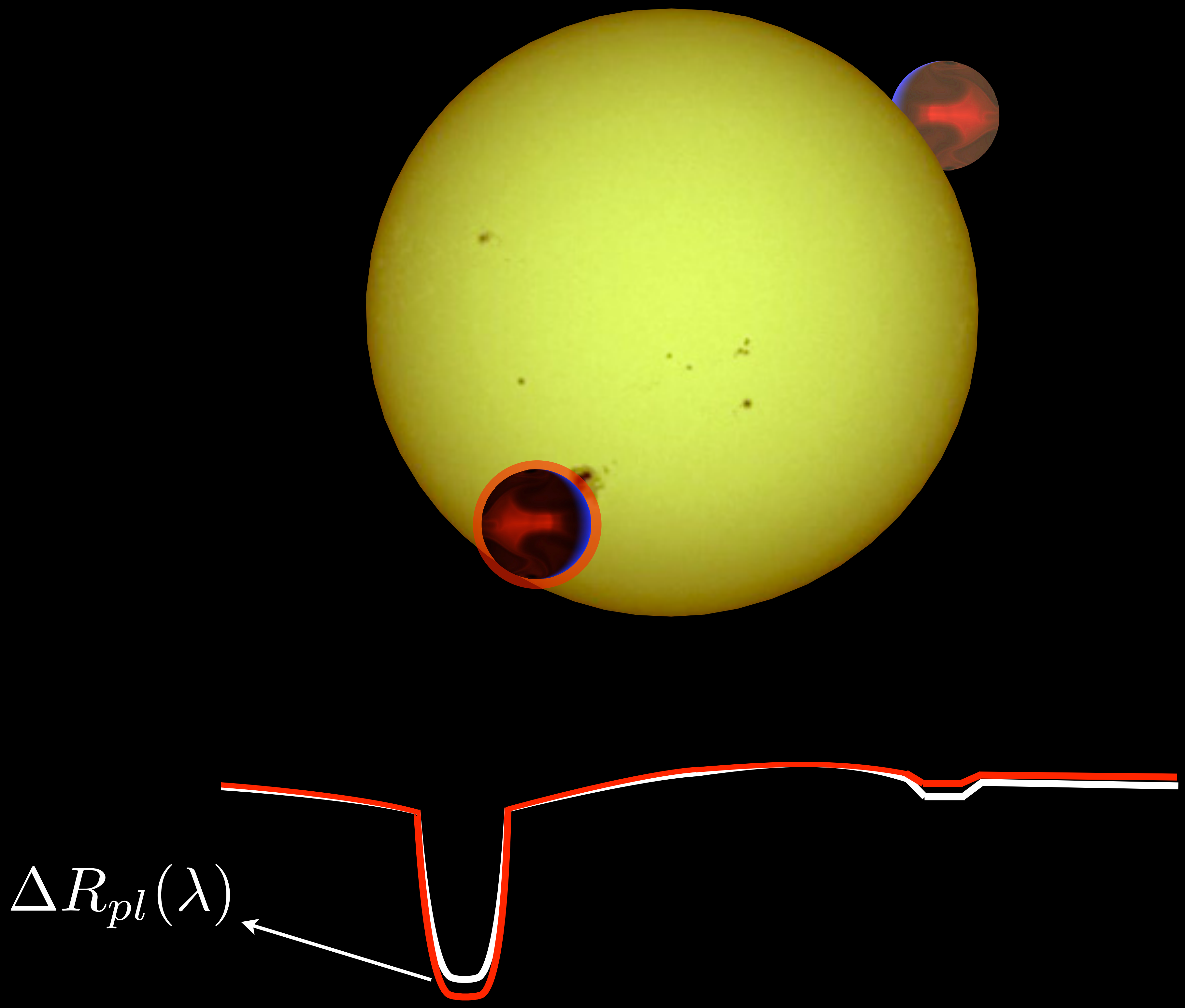
Exoplanet Spectra



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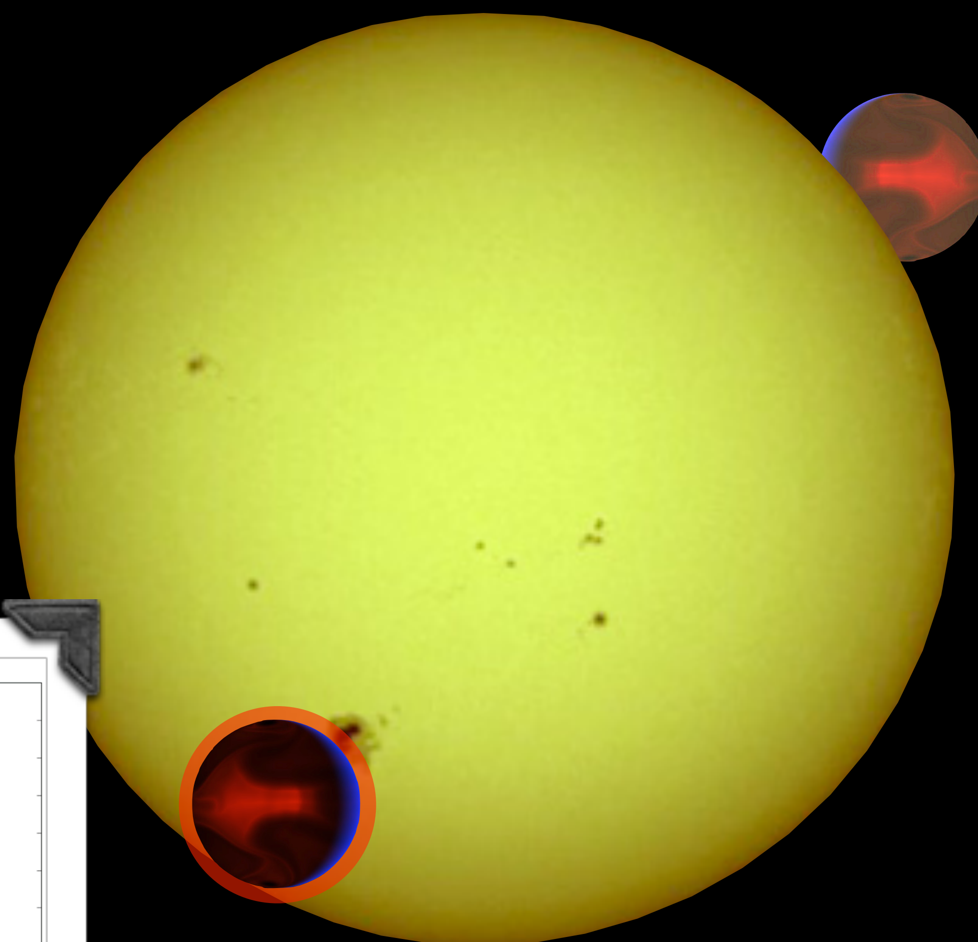
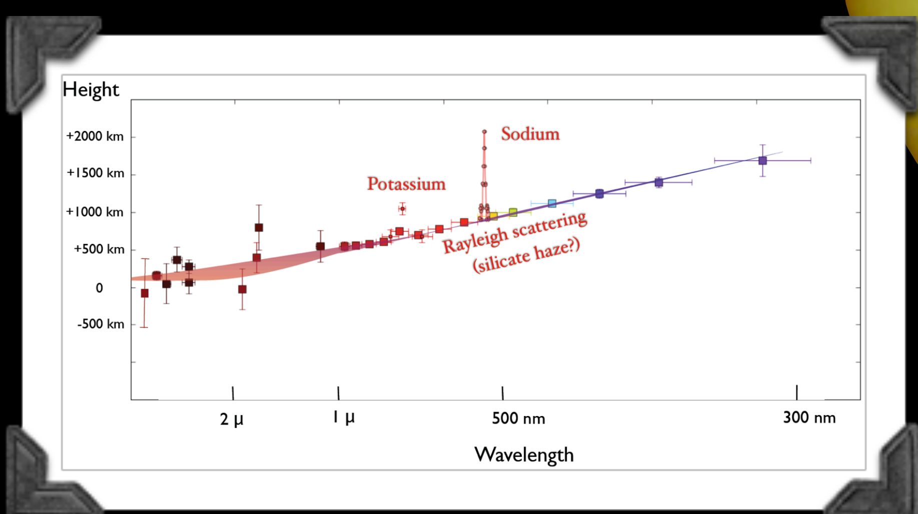
Exoplanet Spectra



Transmission spectra



$$\Delta R_{pl}(\lambda)$$

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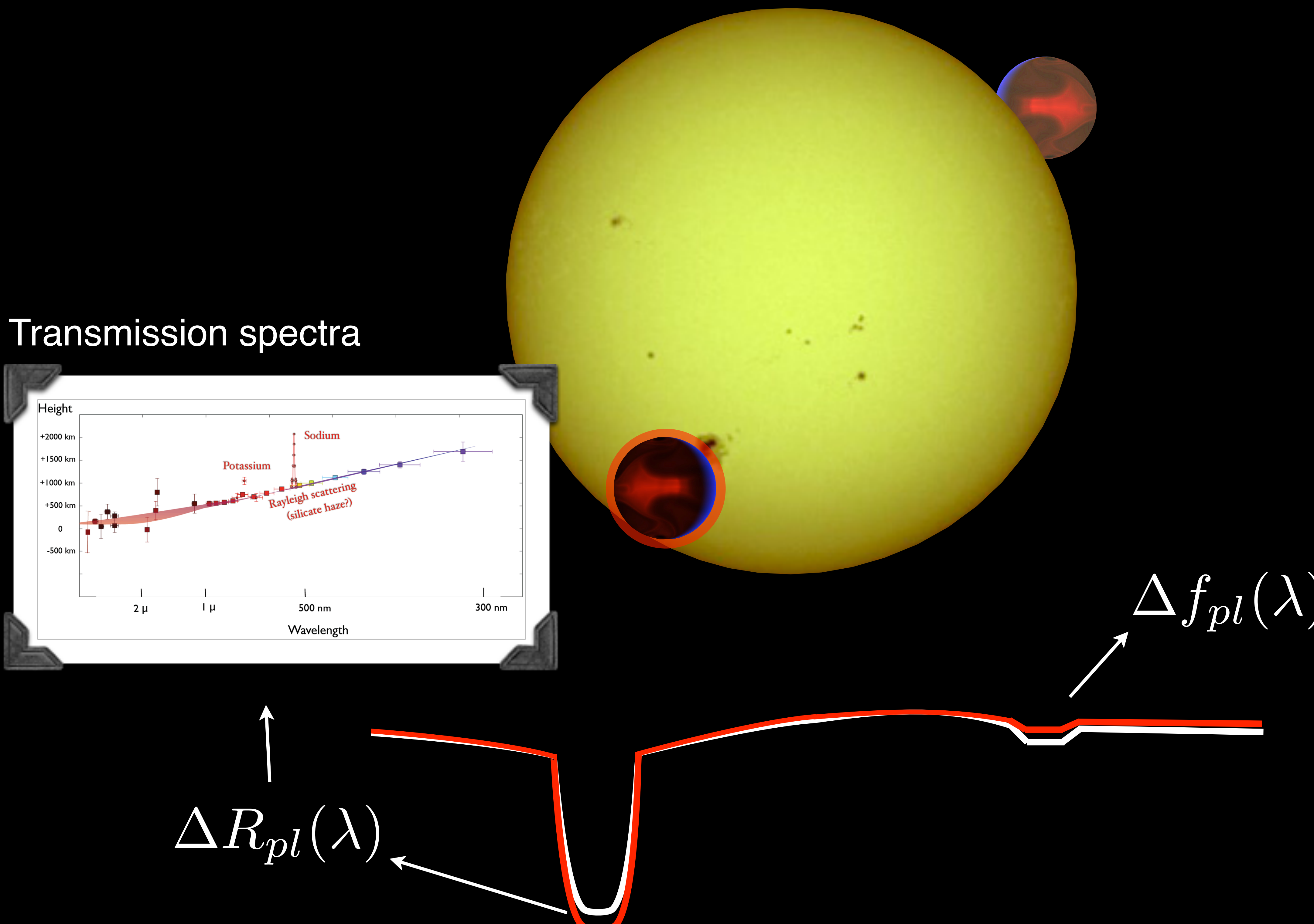
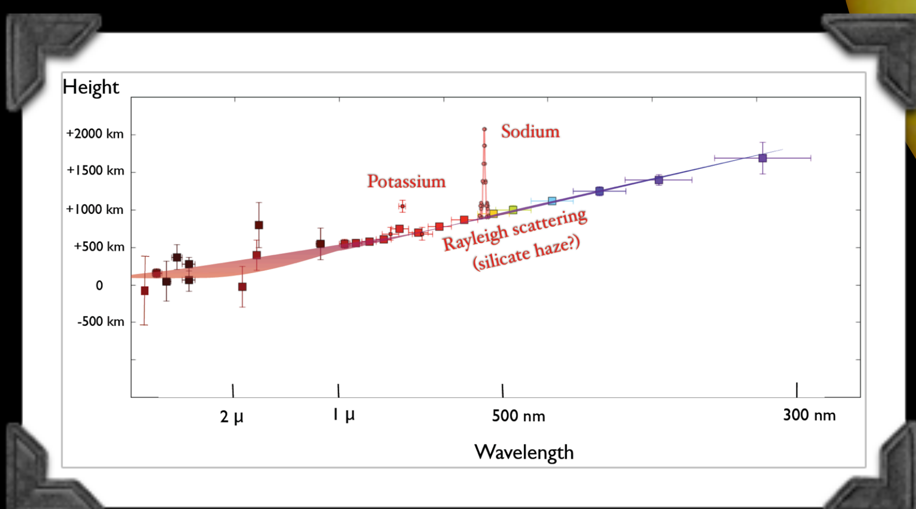
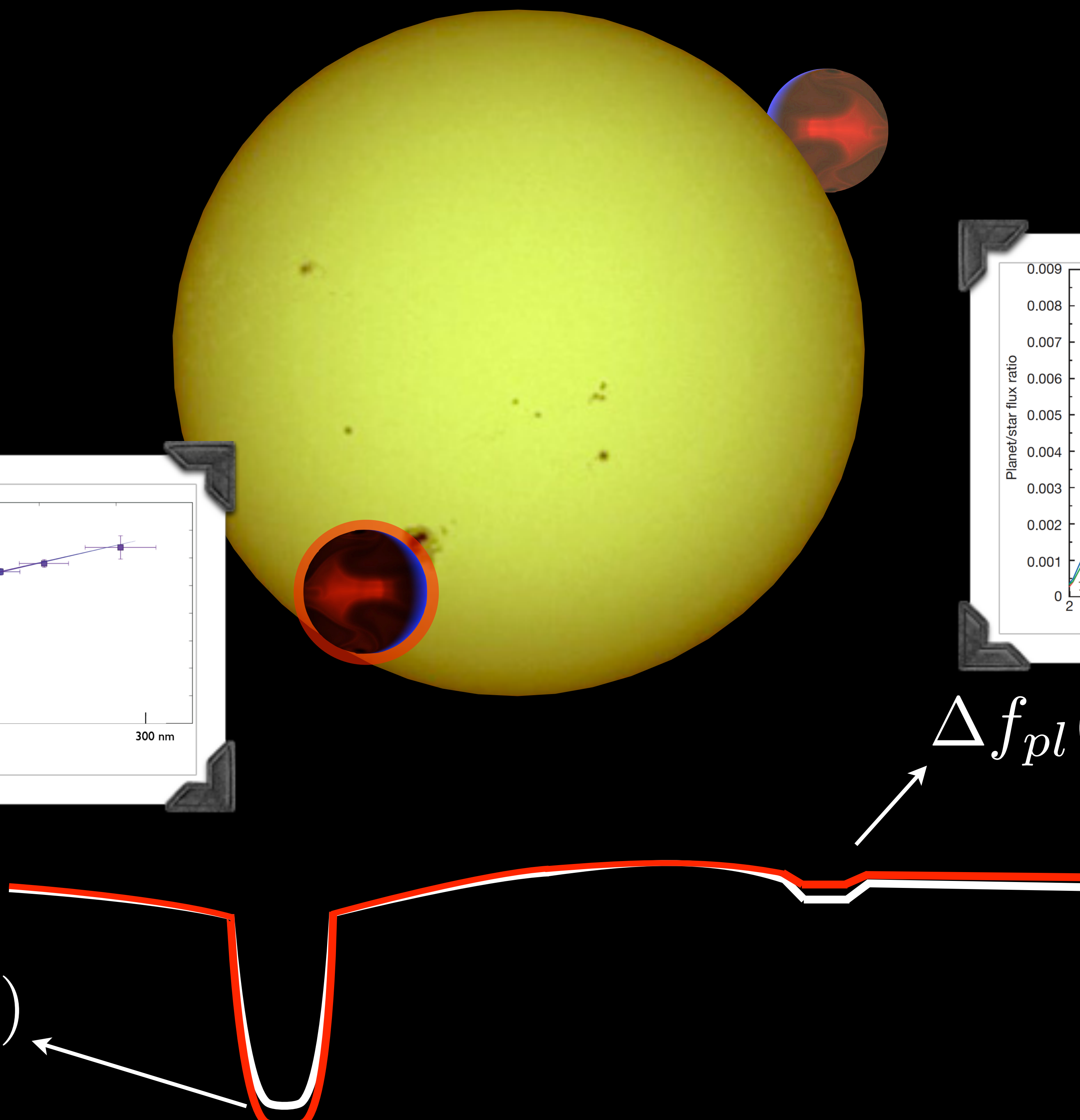
Exoplanet Spectra



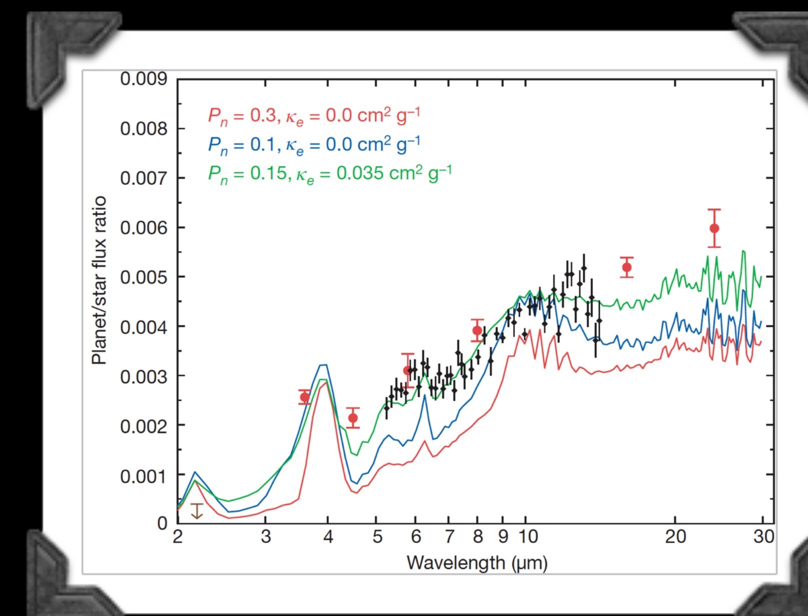
Exoplanet Spectra

Transmission spectra





Emission spectra



$\Delta f_{pl}(\lambda)$

$\Delta R_{pl}(\lambda)$

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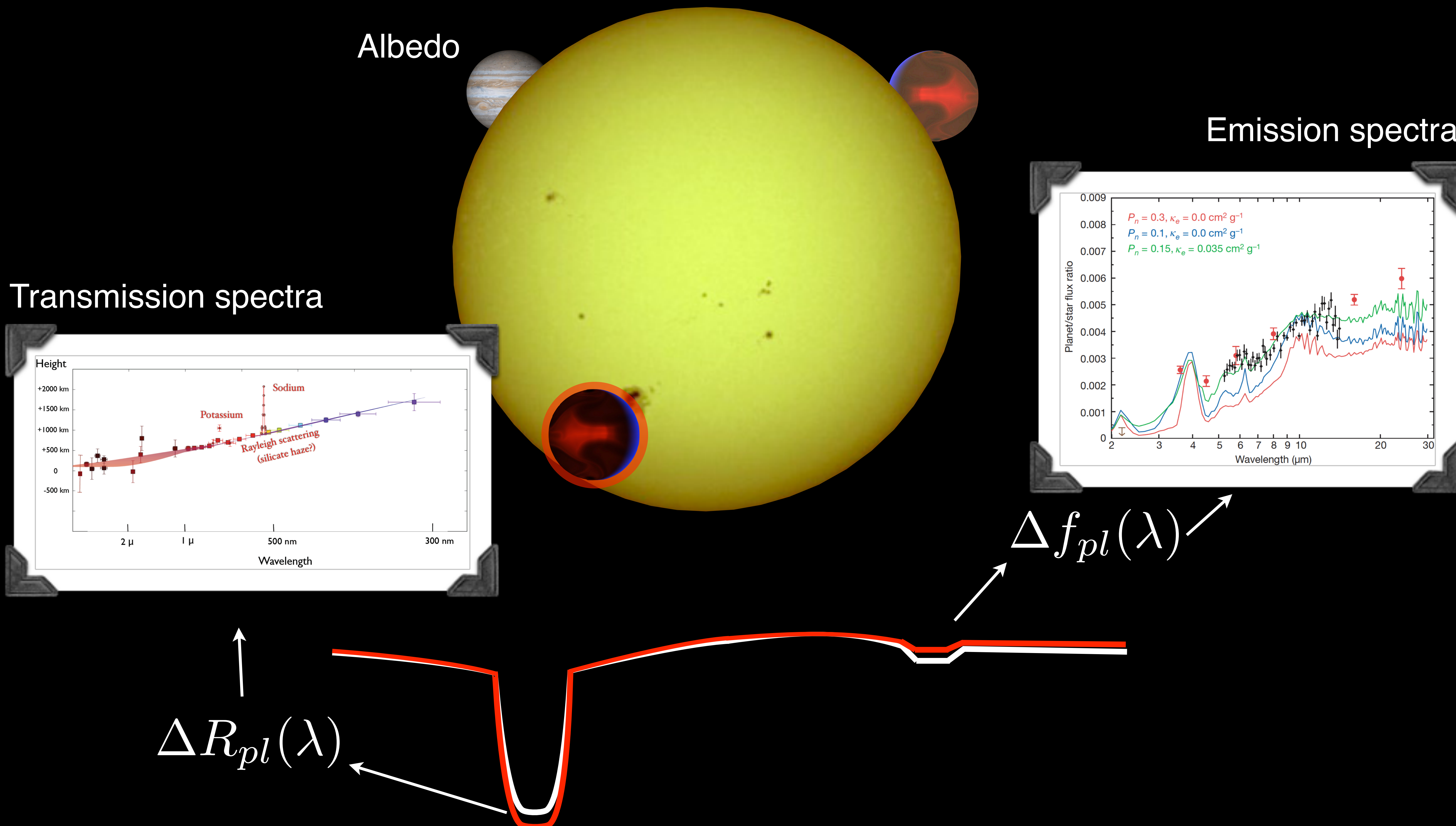
Exoplanet Spectra



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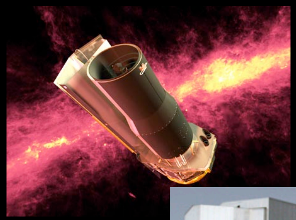
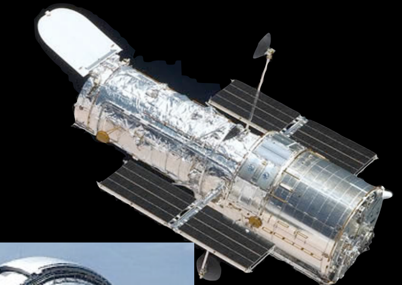


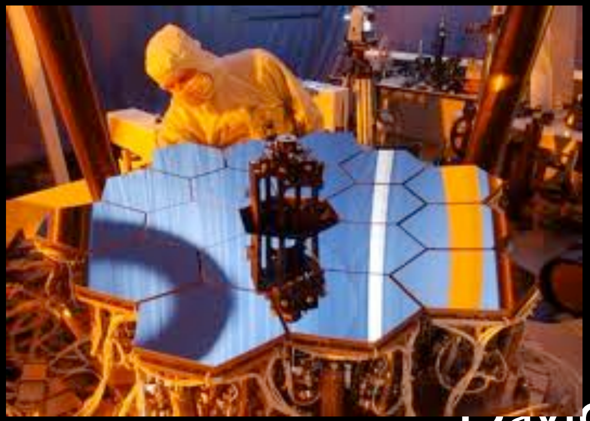
Exoplanet Spectroscopy

What Observatories have been used?



		UV	Optical	nIR	IR
Transit	S	HST	HST	HST	Spitzer
	G	-	6 - 10m	8 - 10m	-
2nd Eclipse	S	-	Kepler, CoRoT	HST	Spitzer
	G	-	6 - 10m	4 - 10m	-
Phase Curves	S	-	Kepler, CoRoT	-	Spitzer
	G	-	-	-	-

- Field Traditionally Space-based
- Increasing activity from the ground



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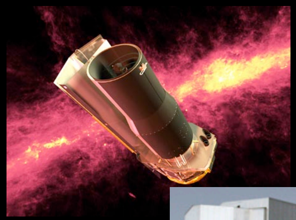
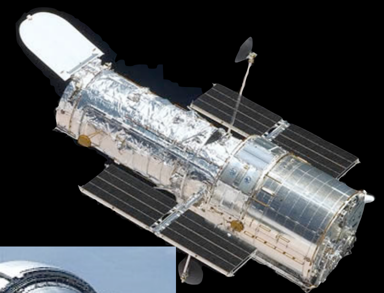



Transiting Planets
What can the observations tell us?




Different methods are Very Highly Complementary

- Transit Transmission Spectra (mbar and lower)
  - *Composition*
  - *Escape*
  - *Temperatures*
  - *Pressures & Abundances*
  - *Winds*

  easier ↓ harder

- Secondary Eclipse Emission Spectra (bar to mbar)
  - *Temperatures (or albedo)*
  - *Thermal Structure*
  - *Composition & Pressures & Abundances*

  easier ↓ harder

- Phase Curves (bar to mbar) Non-transiting too
  - *Global Temperature Map*
  - *Winds*

Want All methods at All wavelengths for the Strongest Constraints

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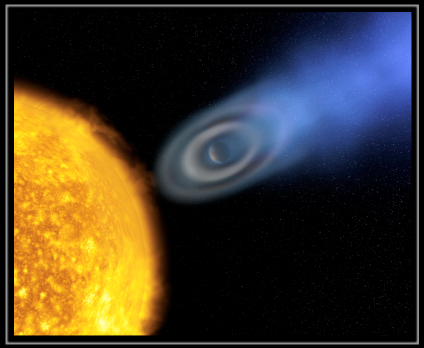
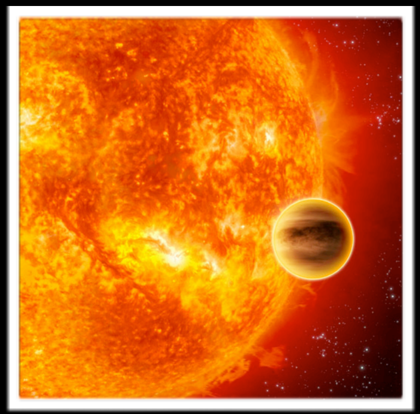


Transmission Spectra

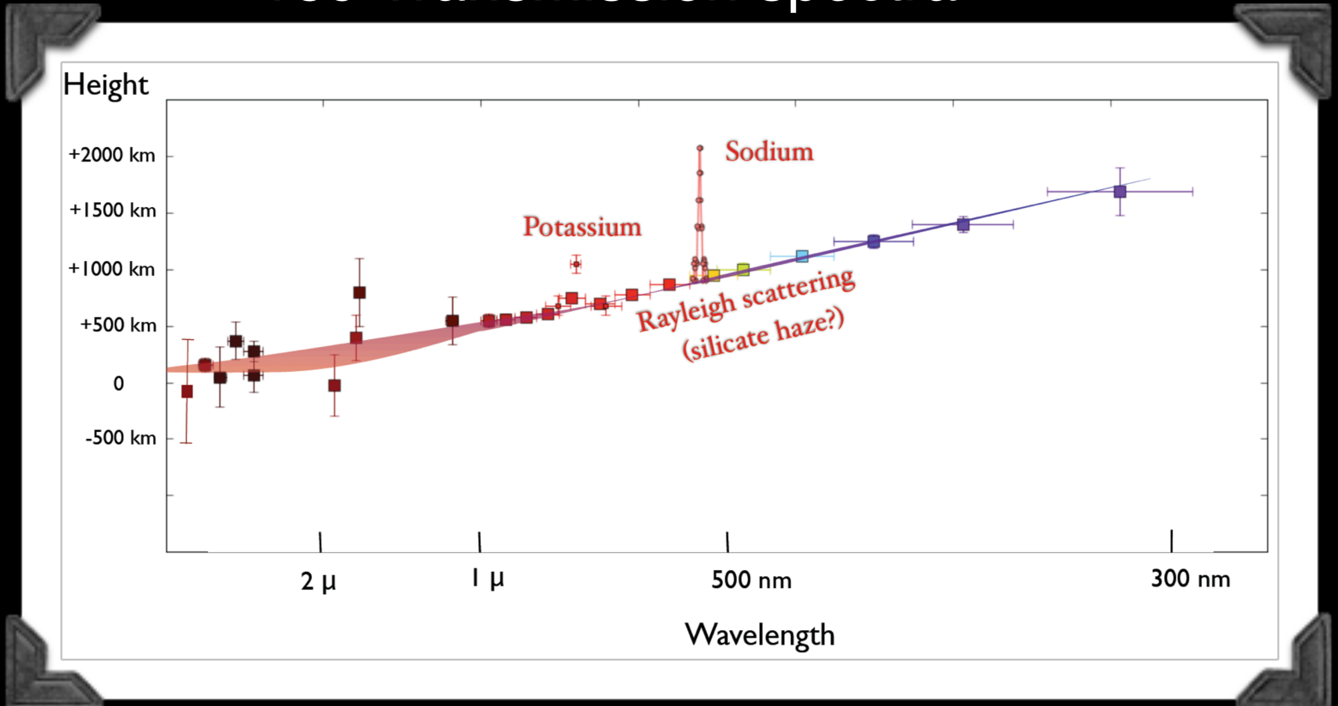
Composition



Examples

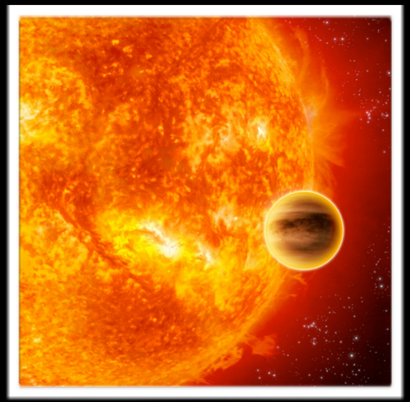
- First Exoplanet Atmospheric Detection
  '209 Na (Charbonneau et al. 2002; Snellen et al. 2008; Sing et al. 2008)
- '189 Na (Redfield et al. 2008; Huitson et al. submitted)
- '189 Rayleigh scattering (Pont et al. 2008; Lecavelier et al 2008; Sing et al. 2011) silicate haze?

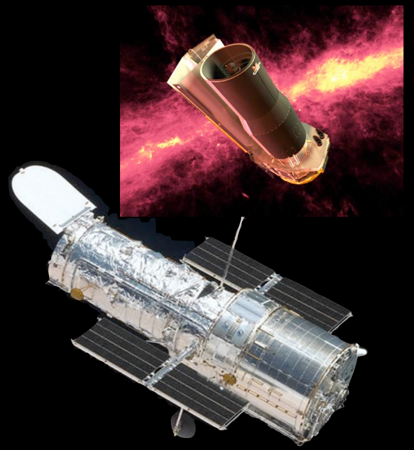
'189 Transmission spectra

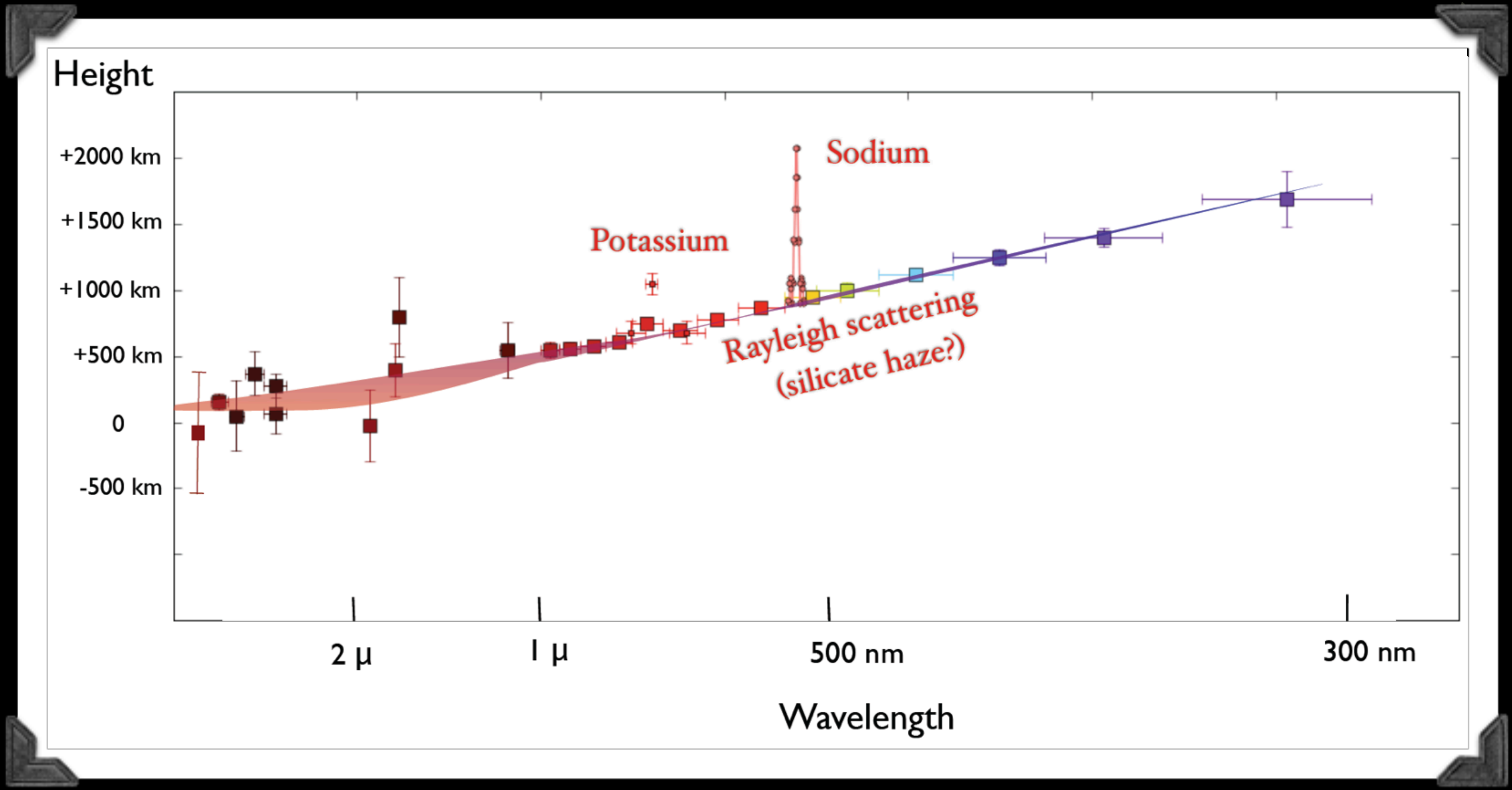


Transmission spectrum

Composition



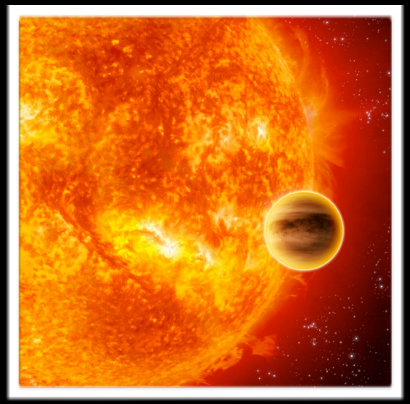


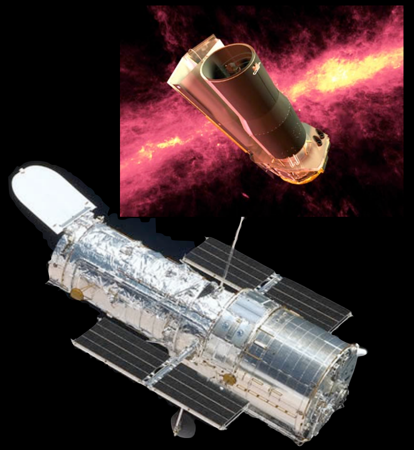


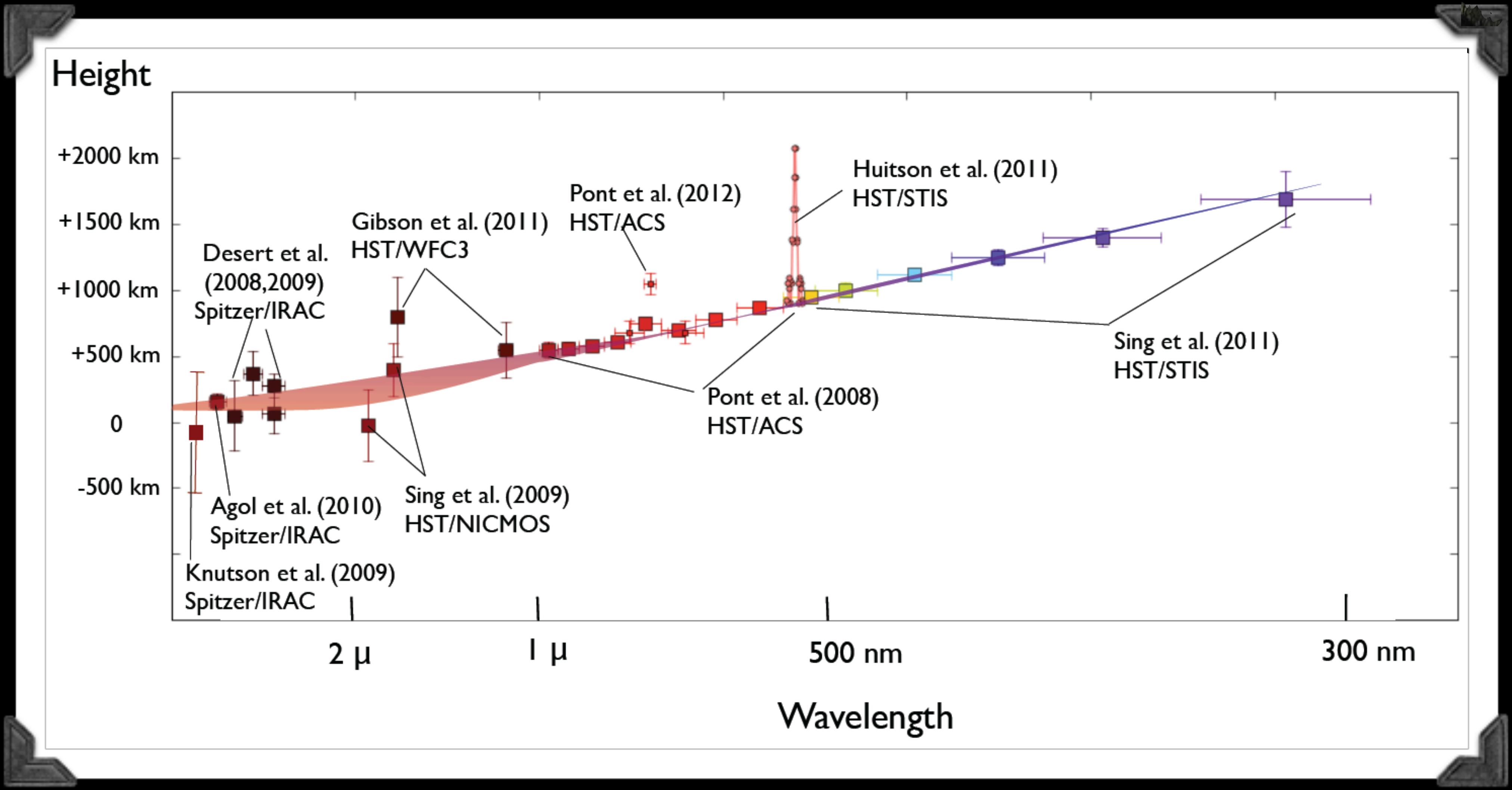
Can identify Rayleigh scattering (haze)
Alkali Metal Na

Transmission spectrum

Composition







Can identify Rayleigh scattering (haze)
Alkali Metal Na

see poster Husnoo

60+ orbits HST
100+ hrs Spitzer

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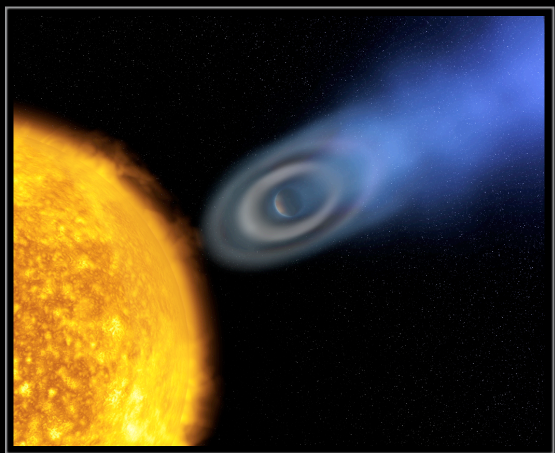
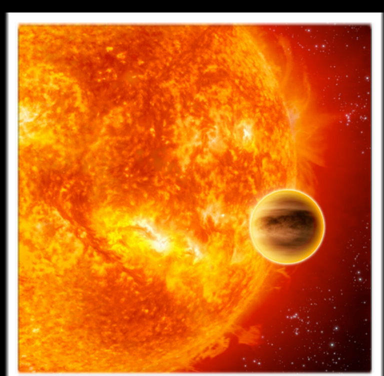
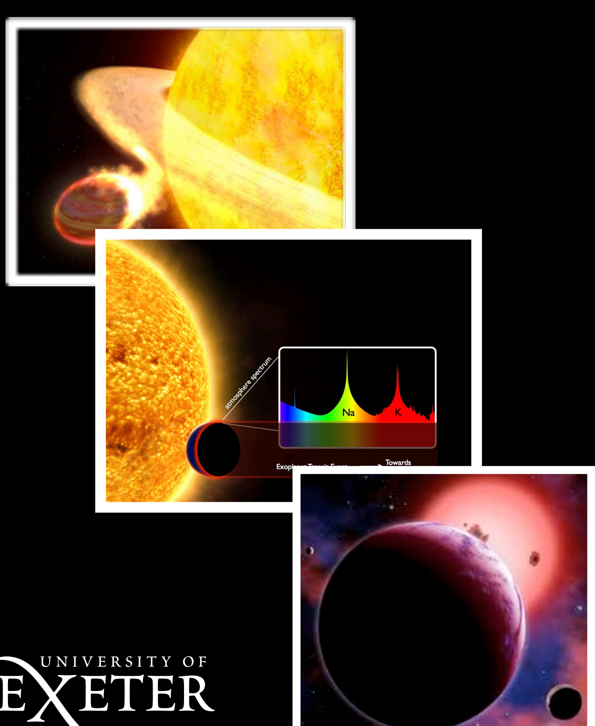
Overview Identified Atmospheric Constituents







<u>HD209458b</u>		
Na	confirmed:	HST & Subaru
C II	confirmed:	HST
H_2O, H I, H_2, TiO/VO	initial:	HST
CO	initial:	VLT
H I, O I, Si III	initial:	HST
H_2O	initial:	Spitzer
<u>HD189733b</u>		
Na	confirmed:	HET & HST
Rayleigh-haze	confirmed:	HST
H_2O	confirmed:	Spitzer
CO_2, H I	initial:	Spitzer; HST
<u>Wasp-12b</u>		
Mg II, Metals	initial:	HST
Molecules	initial:	VLT, CFHT, Spitzer
<u>Wasp-17b</u>: Na	initial:	VLT
<u>XO-2b</u>: K	initial:	GTC
<u>GJ1214</u>:		
metal-rich/haze	likely:	VLT, HST, CFHT, Spitzer
<u>GJ436</u>: Molecules	initial:	Spitzer

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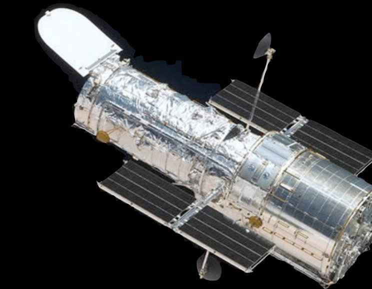
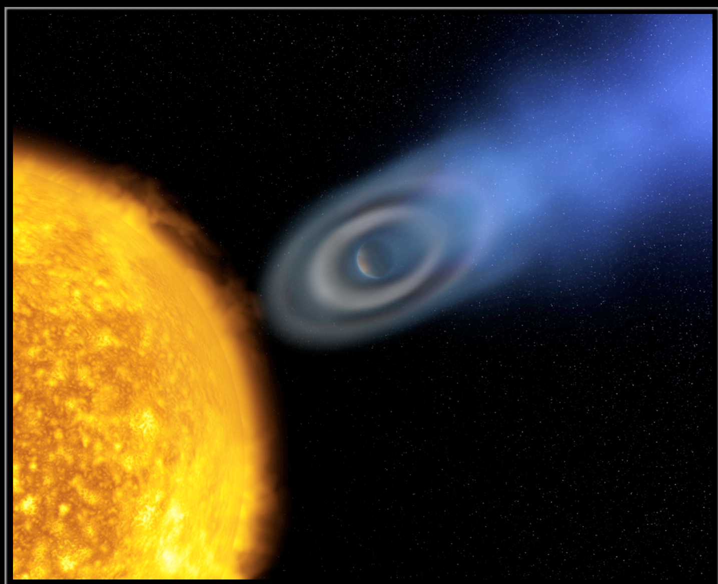
Transmission Spectra

Atmospheric Escape





- UV is sensitive to atomic transitions (H, C, Si, O)
- Hot-Jupiters loose mass due to intense stellar irradiation
- Very large Transit depts

HD209458b

Vidal-Madjar et al. (2003, 2004)

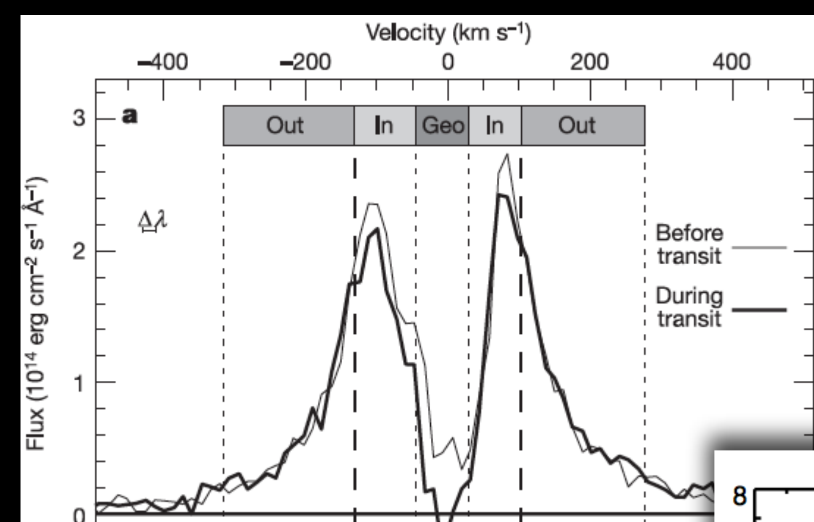
Linskey et al. (2010)

HD189733b

Lecavelier et al. (2010)

Wasp-12

Fossati et al. (2010)

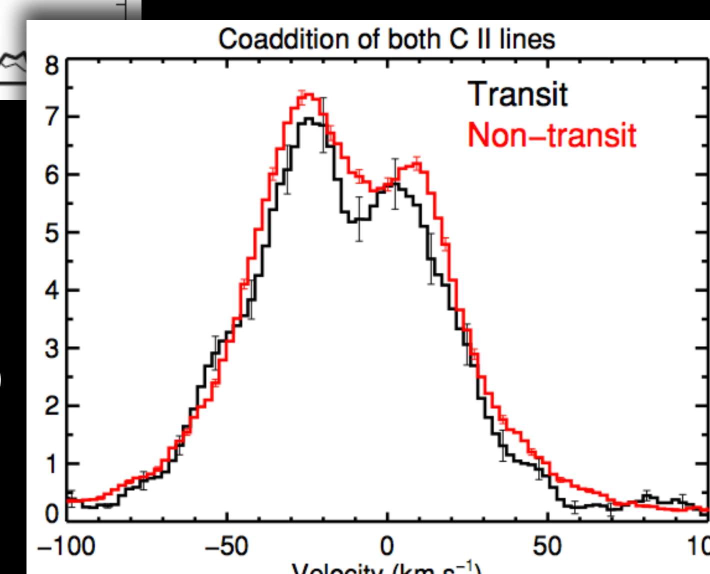


H I Lyman-α

$15\pm4\%$

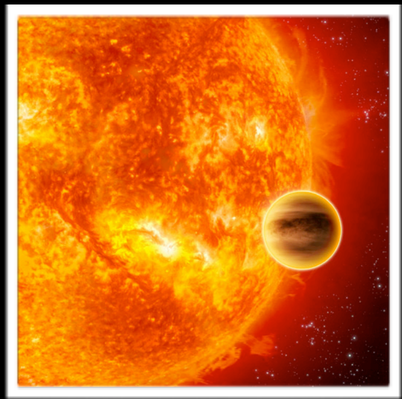
C II

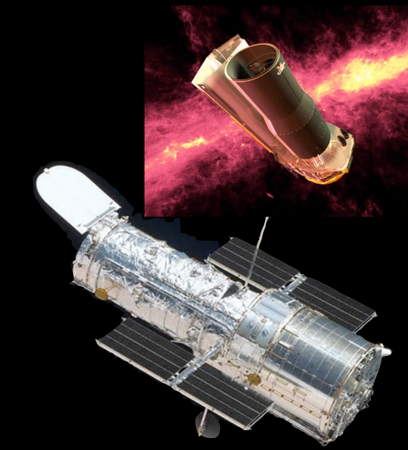
$7.8\pm1.3\%$

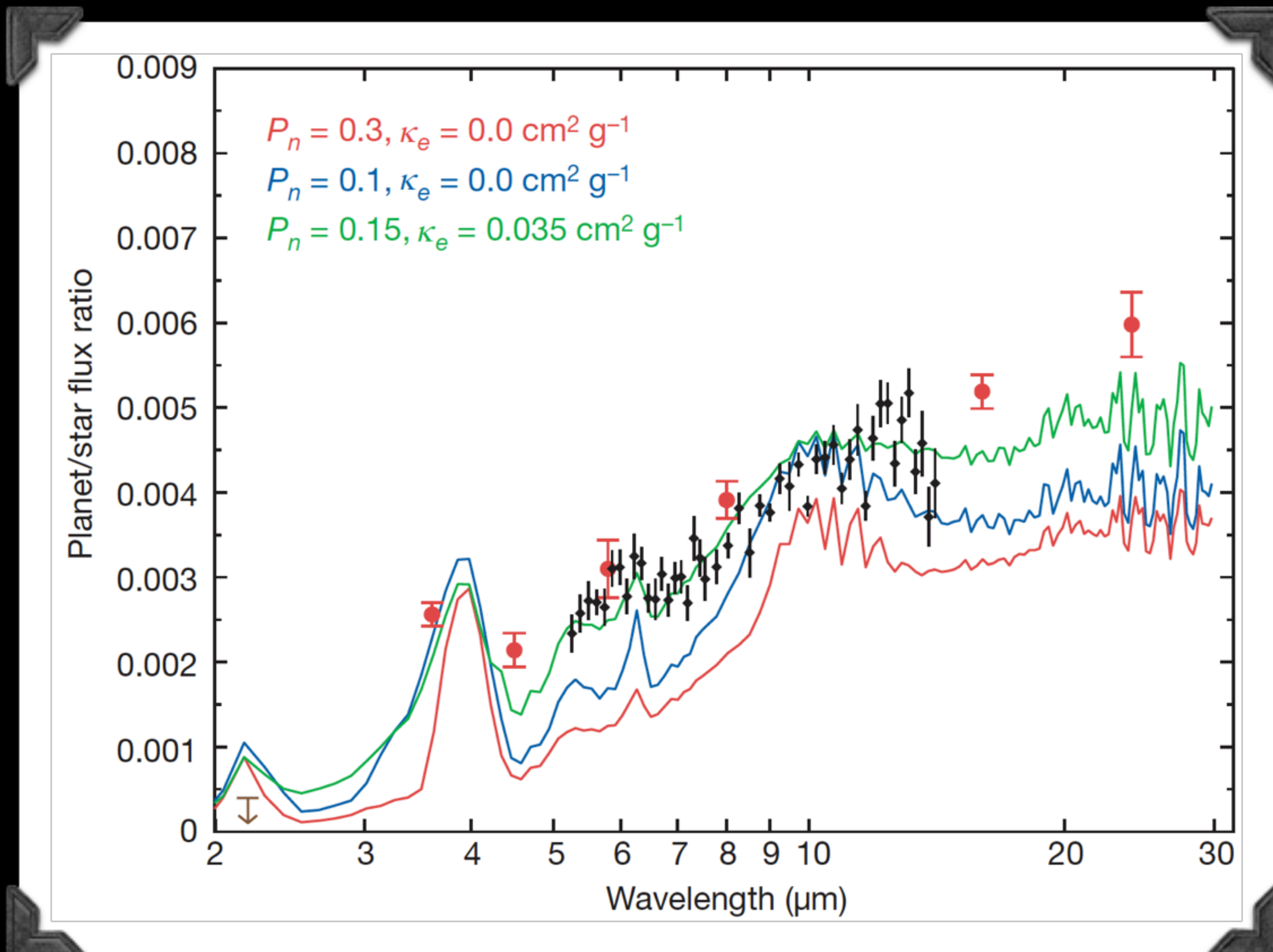


Emission spectrum

Composition
Temperatures







Can identify H_2O, CO_2

Grillmair et al. (2008)
~100 hrs Spitzer

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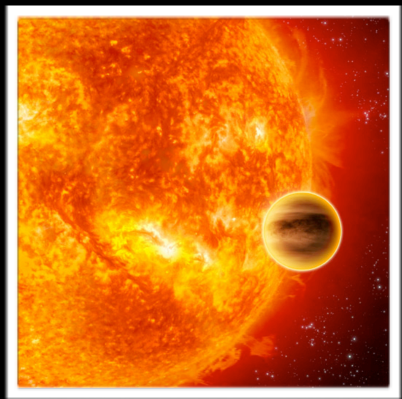
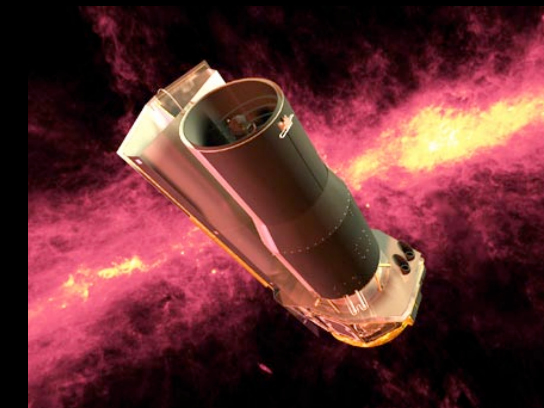


Emission spectrum

Temperatures & Albedo



- Thermal Emission flux from planet probes temperature
- Hot-Js ~1000 to 3000 K
- Albedo (optical) & Re-circulation
- Hot-Js often have low albedos (*but not always*)

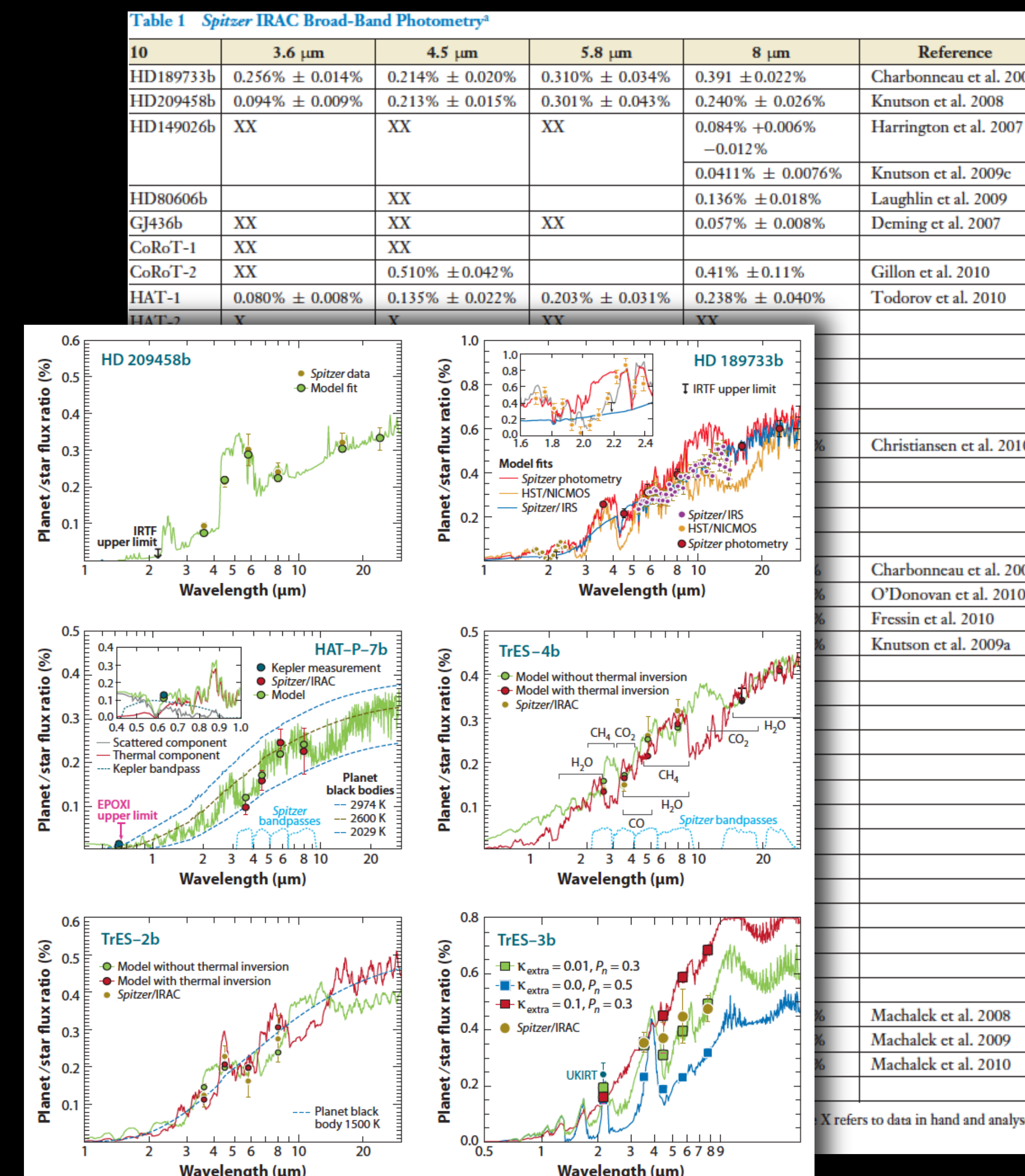
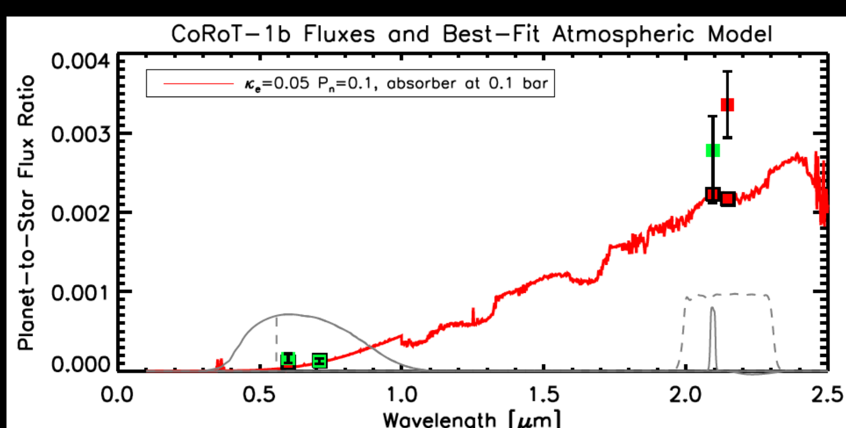


Table 1 *Spitzer* IRAC Broad-Band Photometry[a]

10	3.6 µm	4.5 µm	5.8 µm	8 µm	Reference
HD189733b	0.256% ± 0.014%	0.214% ± 0.020%	0.310% ± 0.034%	0.391 ±0.022%	Charbonneau et al. 2008
HD209458b	0.094% ± 0.009%	0.213% ± 0.015%	0.301% ± 0.043%	0.240% ± 0.026%	Knutson et al. 2008
HD149026b	XX	XX	XX	0.084% +0.006% −0.012%	Harrington et al. 2007
				0.0411% ± 0.0076%	Knutson et al. 2009c
HD80606b		XX		0.136% ±0.018%	Laughlin et al. 2009
GJ436b	XX	XX	XX	0.057% ± 0.008%	Deming et al. 2007
CoRoT-1	XX	XX			
CoRoT-2	XX	0.510% ±0.042%		0.41% ±0.11%	Gillon et al. 2010
HAT-1	0.080% ± 0.008%	0.135% ± 0.022%	0.203% ± 0.031%	0.238% ± 0.040%	Todorov et al. 2010

Seager & Deming (2010)
Cowan & Agol (2011)

CoRot + nIR

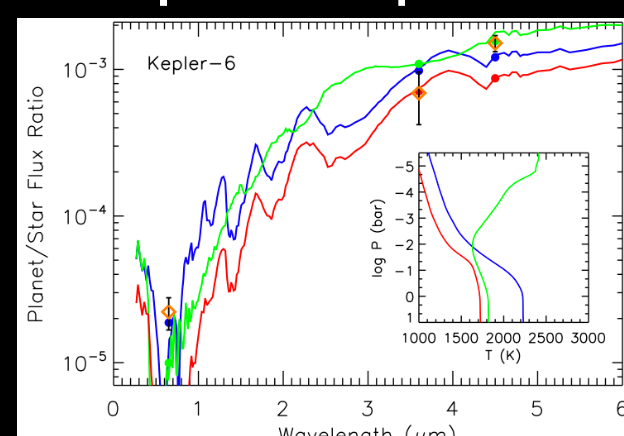


Rogers et al. (2009)

$A_B = 5\%$

$T = 2300$ K

Kepler + Spitzer



Desert et al. (2011)

$A_B = 11\%$

$T = 1660$ K

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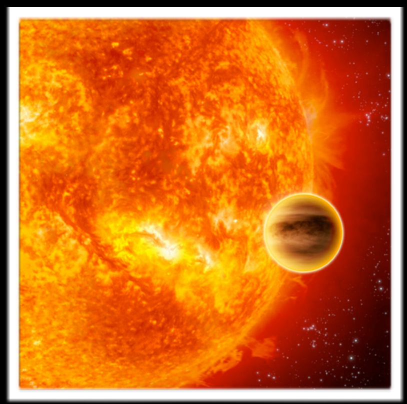
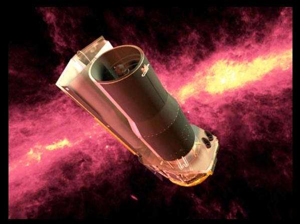
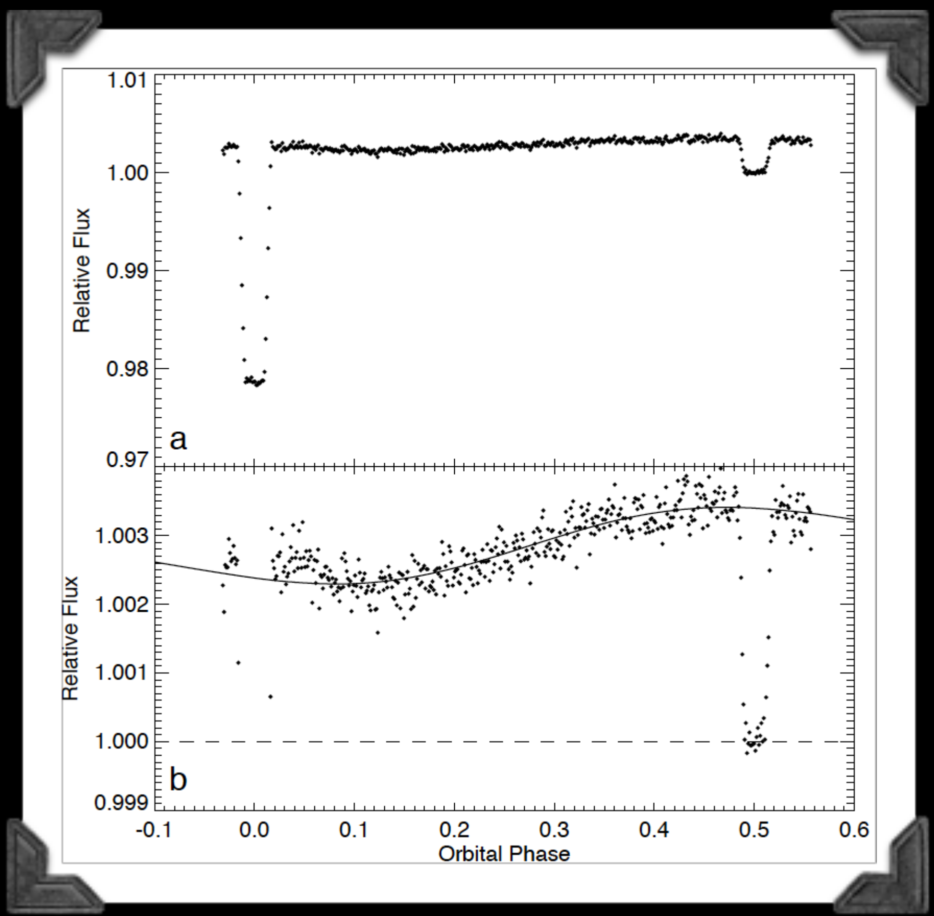


Phase curves

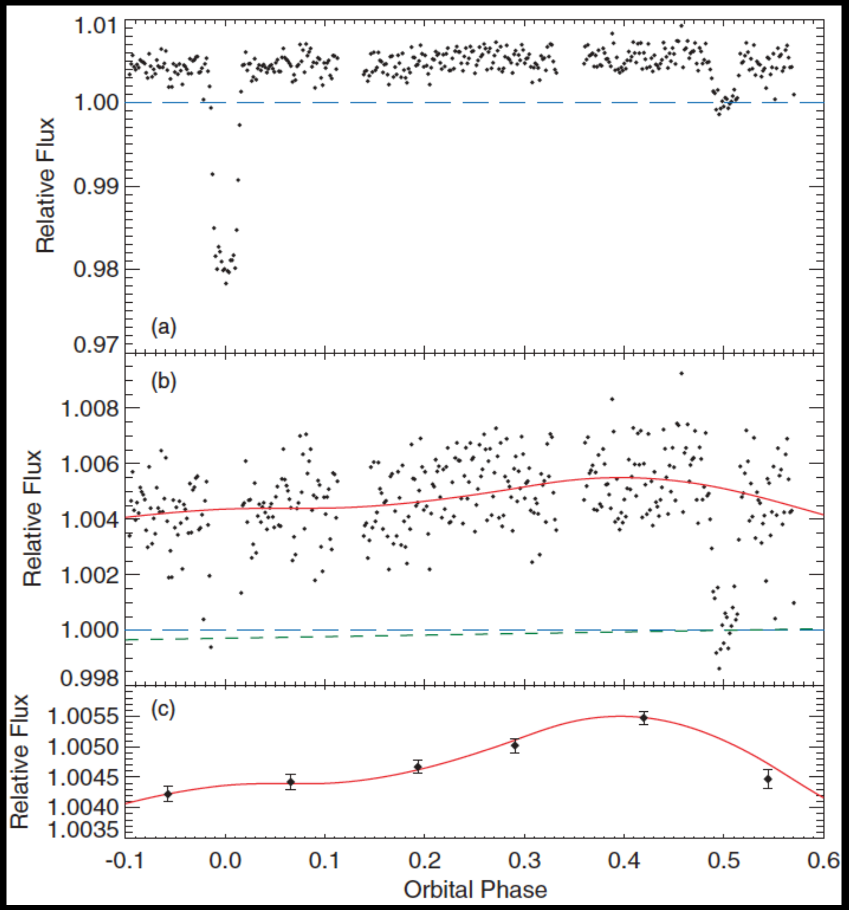
Temperature map
Winds



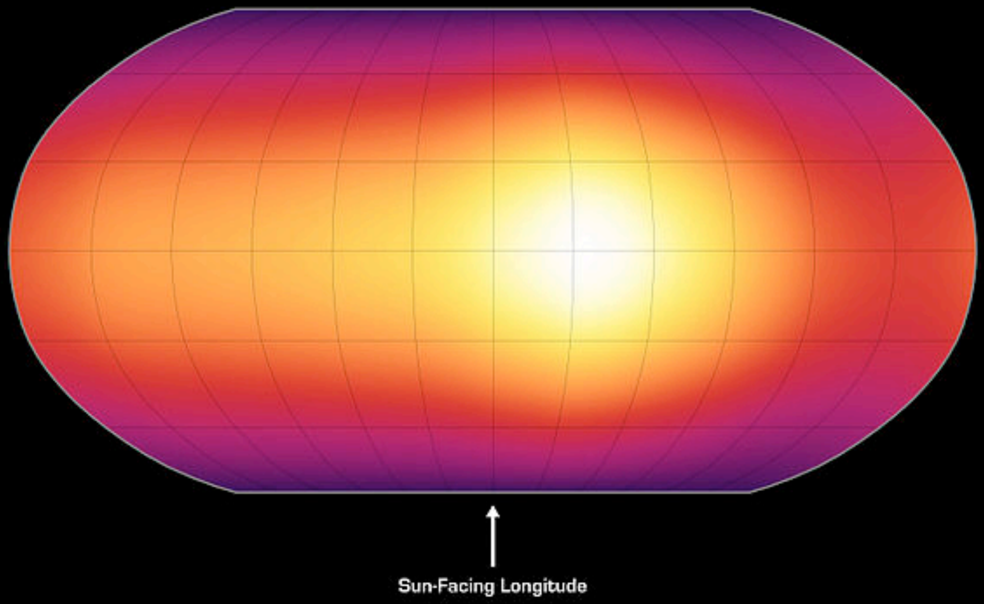
8 μm



24 μm



- Hot-spot eastward of sub-stellar point
- Eastward jets



Knutson et al. (2007; 2009)
3 & 4.5 μm curves too

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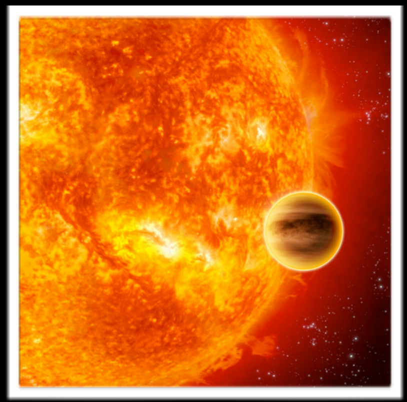
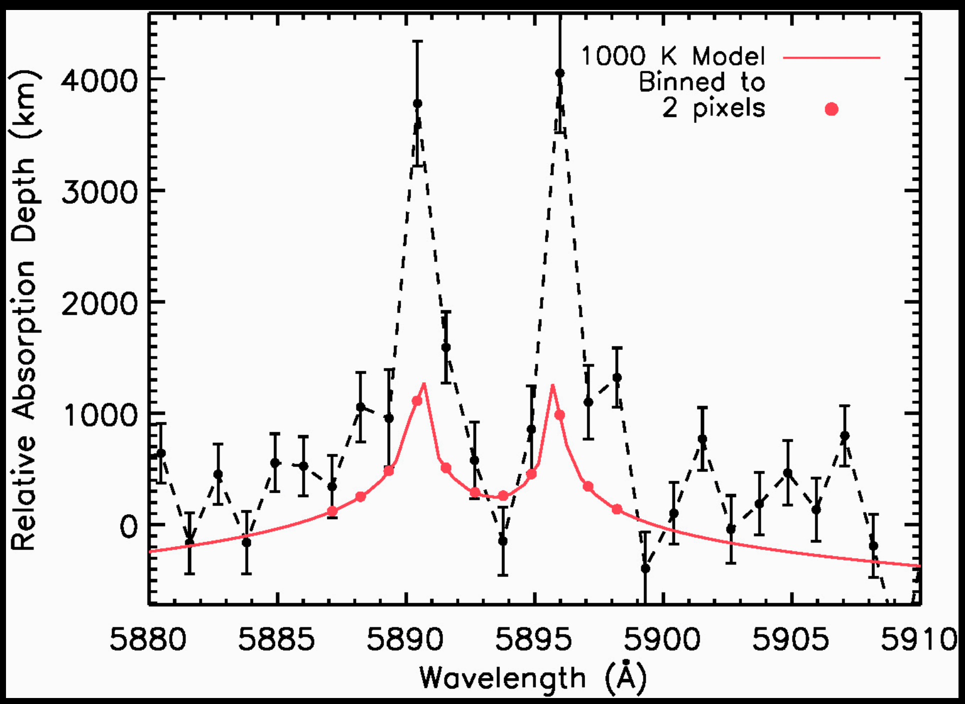


Emission & Transmission

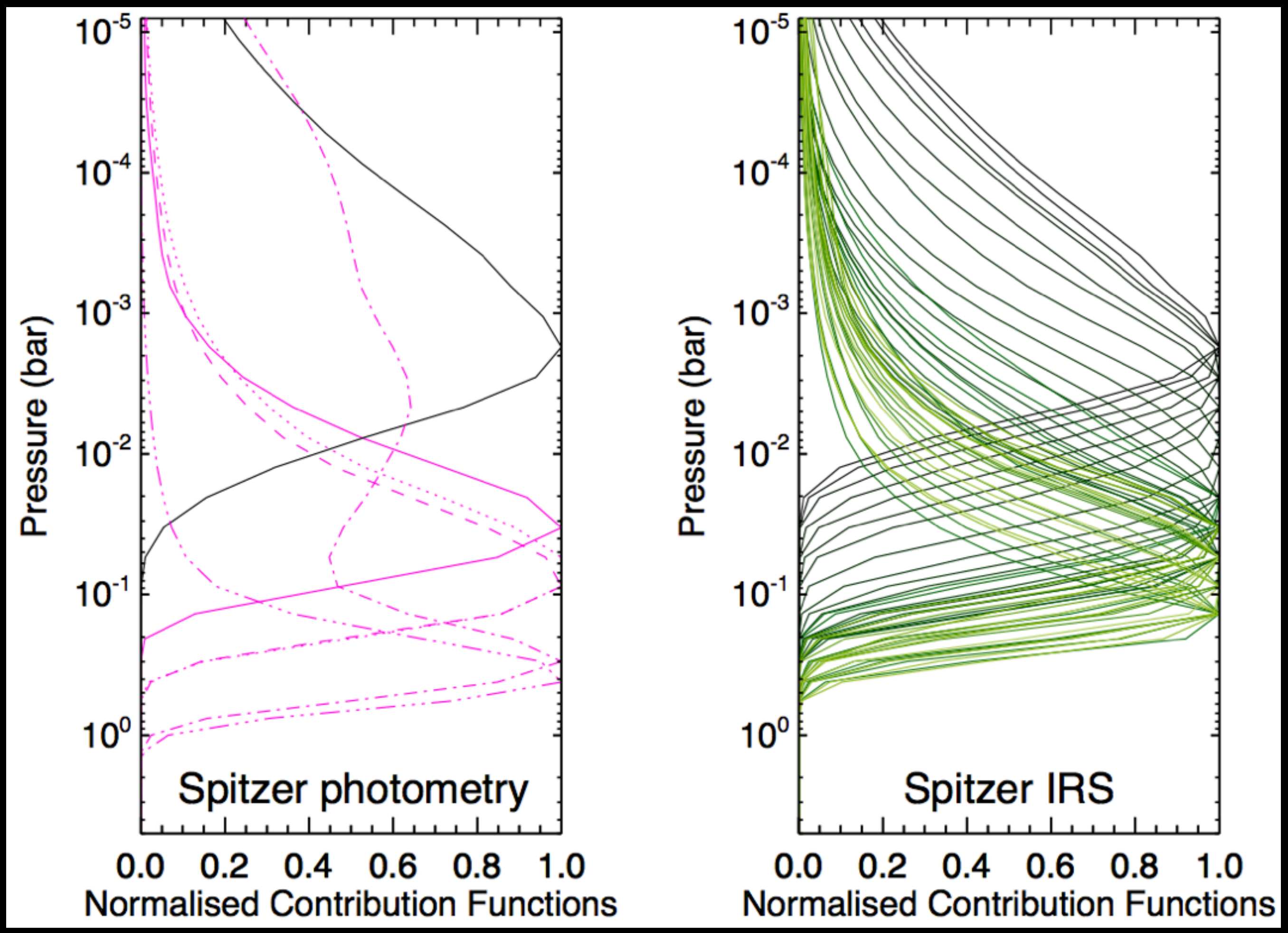
Thermal Structure

Huitson et al. submitted



Transmission

Lee et al. (2011)



Emission

Temp. via scale height

Press. via altitude

Na: $T_{z=2000\ km} = 2800$ K

Rayleigh: $T_{z=0\ km} = 1340$ K

Press. via contribution function

Degeneracy Temp. & Abundances

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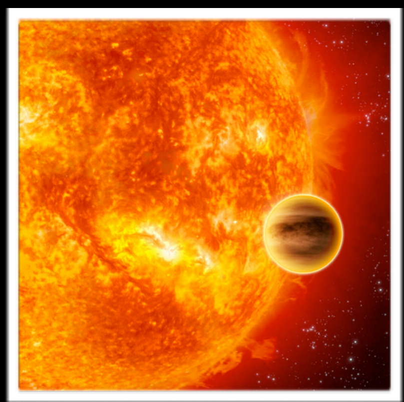
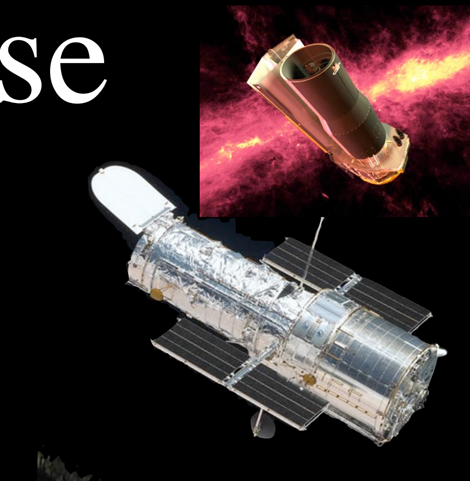
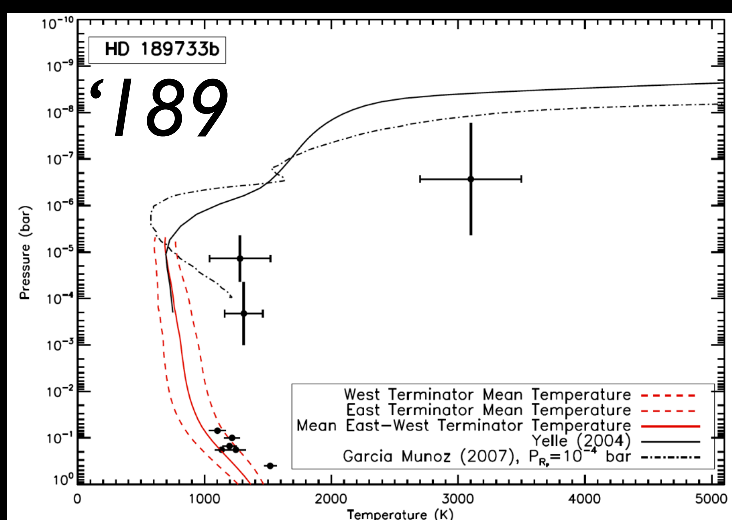
Emission + Transmission + Phase

Thermal Structure

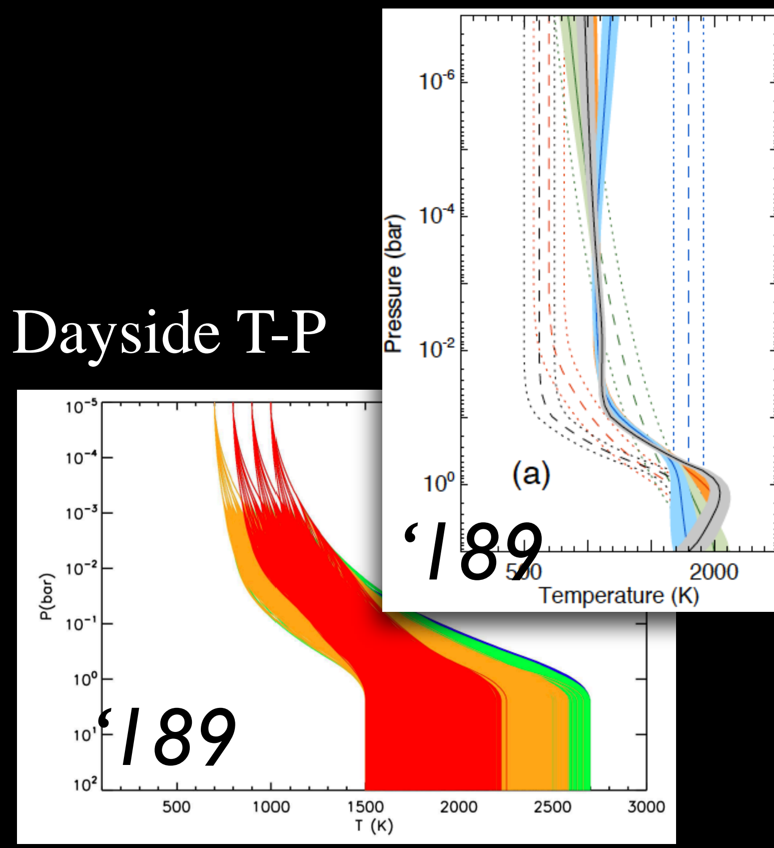




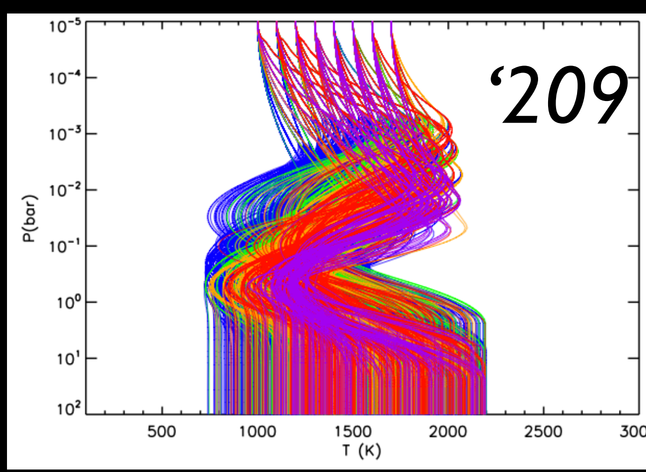
Limb T-P



Dayside T-P



Dayside T-P



'189 NO Stratosphere

'209 YES Stratosphere

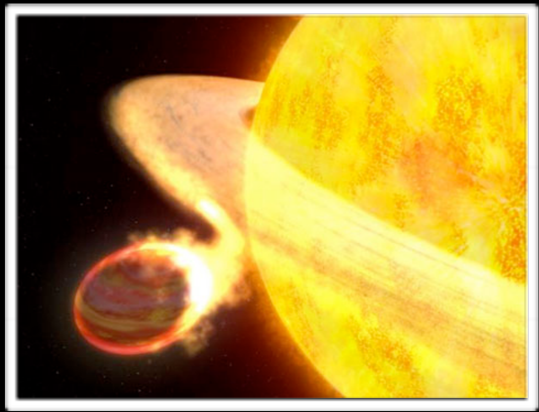
'189 YES Thermosphere

'209 YES Thermosphere

Huitson et al. (submitted)
Vidal-Madjar et al. (2011a,b)

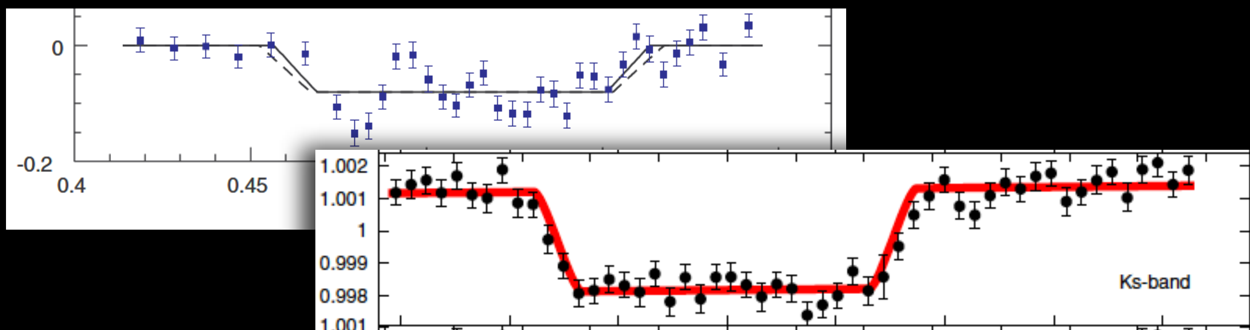
Charbonneau et al. (2008)
Madhusudhan & Seager (2009)
Lee et al. (2011)

Burrows et al. (2007)
Knutson et al. (2008)



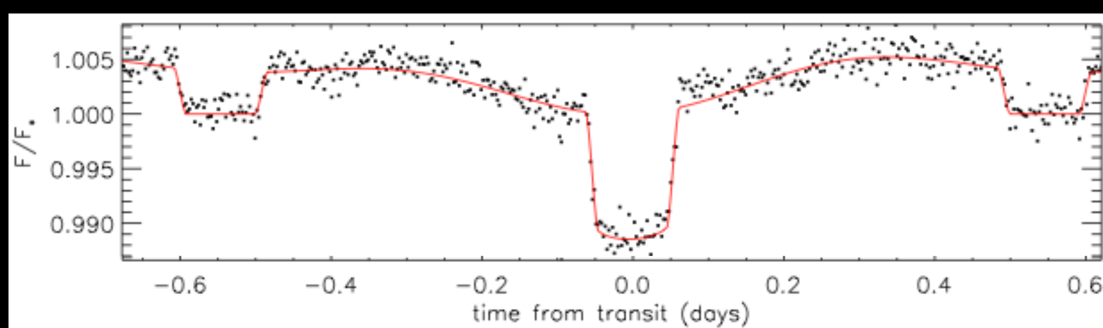
Transmission+Emission+Phase

Wasp-12b: Hottest of the Hot Jupiters



Lopez-Morales et al. (2010)

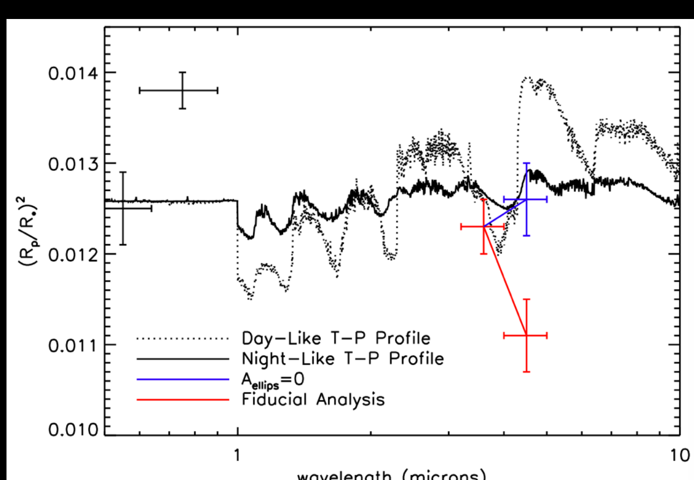
Croll et al. (2011)



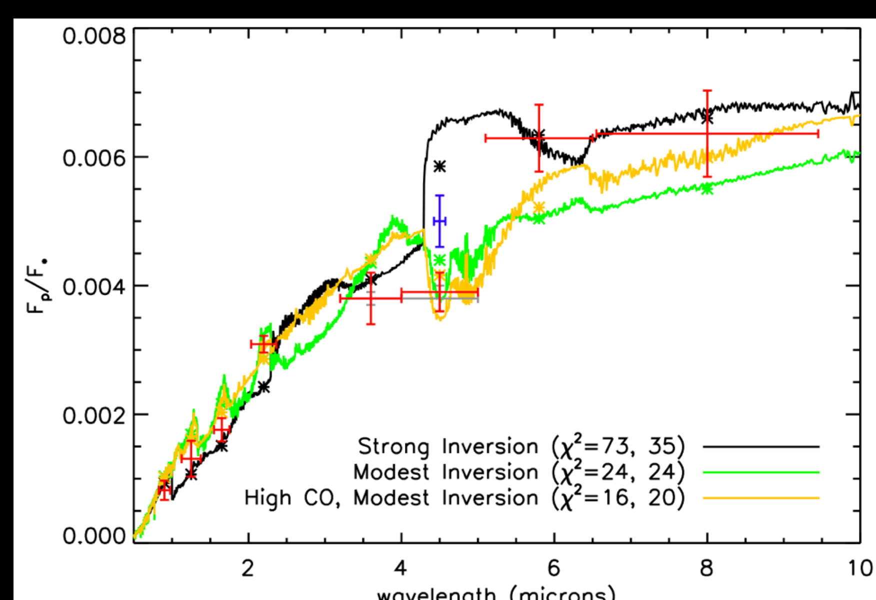
Phase Curve

Campo et al. (2011)
Cowan et al. (2011)

- Large Day/Night Contrast
  3000 K Days
  1000 K Nights
- Solar or high C/O?



Transmission



Emission

Madhusudhan et al. (2011)
Crossfield et al. (2012)

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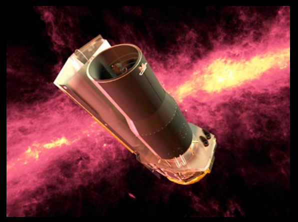
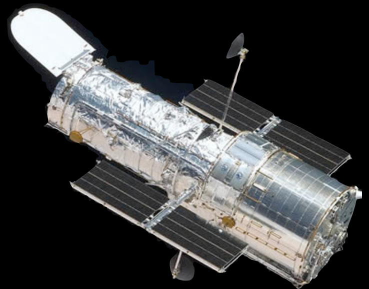
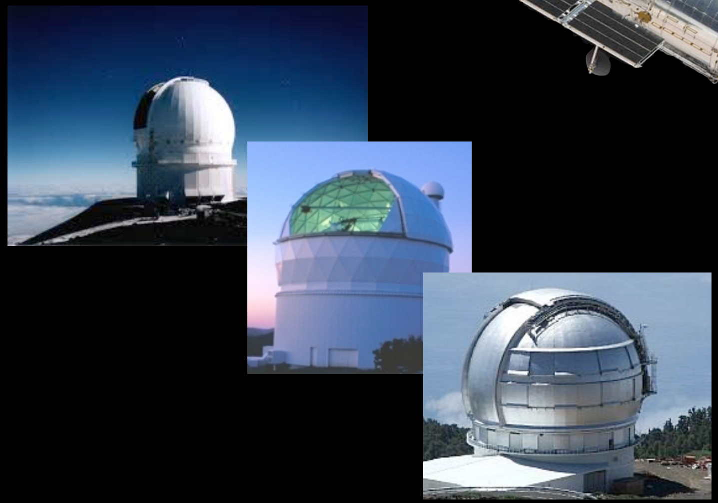


Era of hot-Jupiter Atmo Surveys





Ground

- emission (**nIR**; e.g. Croll; Snellen)
- transmission
  Optical (e.g Jensen et al. 2011; Sing et al. 2011)

Space

- *Spitzer* emission+phase (PI Harrington;Knutson; Krick)
- *HST* WFC3 transmission+emission (PI Deming)
- *HST* STIS transmission (PI Sing)

see poster Swain

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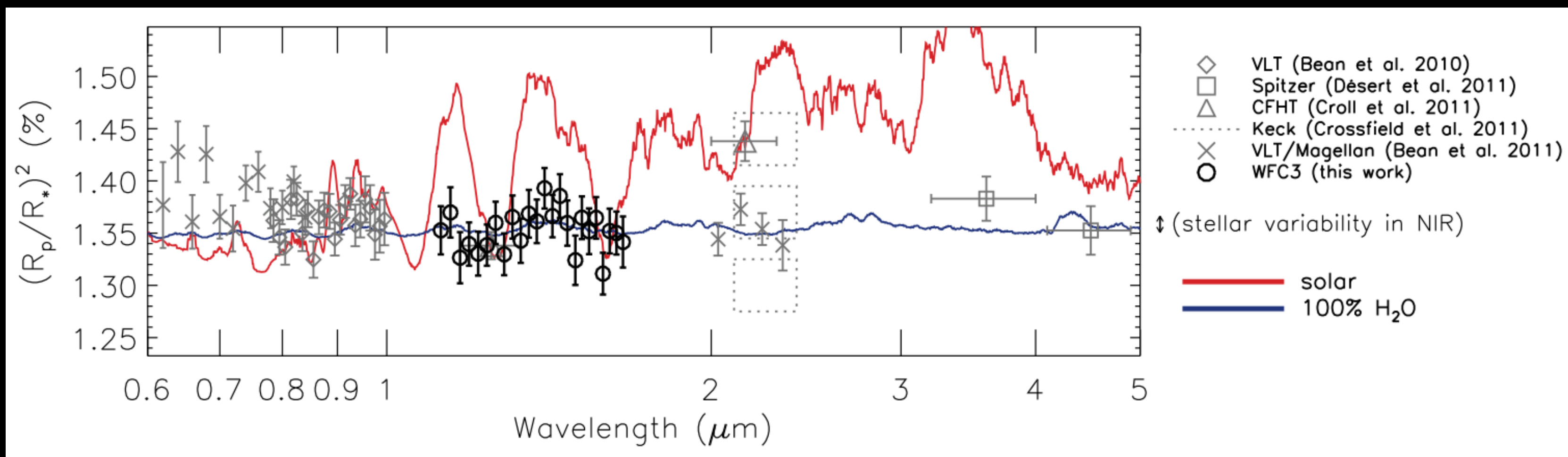
Beginning Era of hot-Neptunes & super-Earths

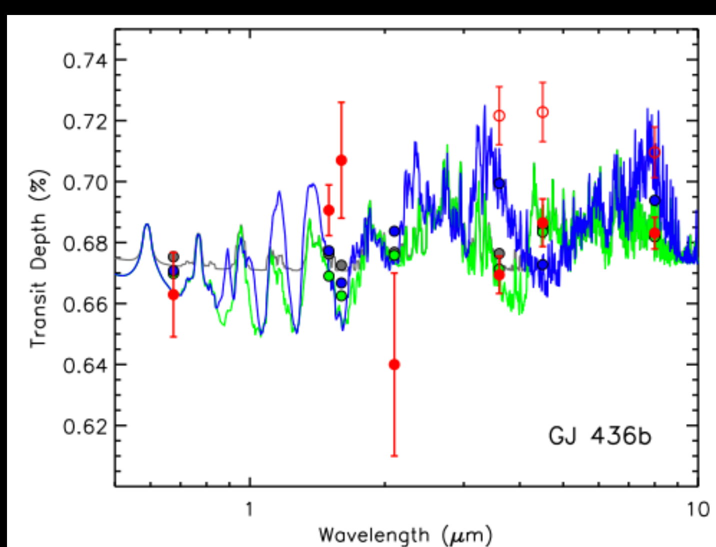


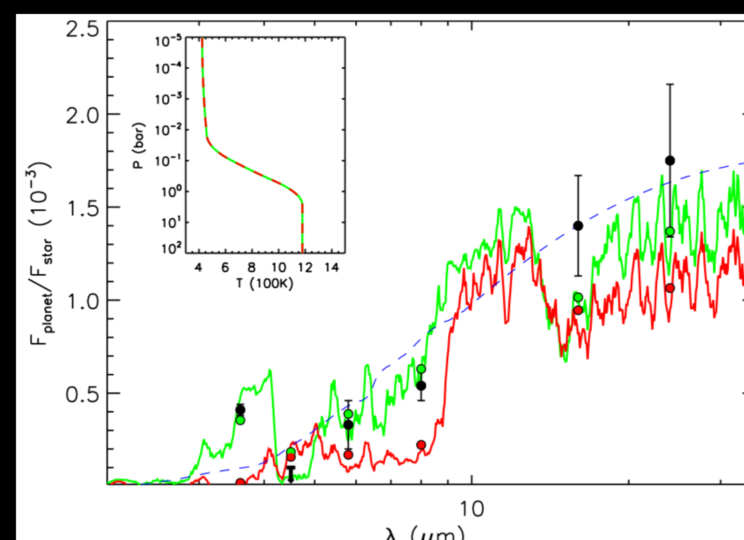
GJ1214b

Flat-*ish* spectra

Small Signals

- small scale heights
- clouds/hazes covering signatures





Transmission Emission

GJ436

- enhanced CO, reduced CH_4
- issues with stellar variability

Berta et al. (2011)
Knutson et al. (2011)
Stevenson et al. (2010)
Madhusudhan & Seager (2011)

Future → M-dwarfs & Very Bright Transits

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Conclusions

- Now have increasingly "good" constraints for a couple hot-Jupiter atmos
- Era of comparative exoplanets has started with hot Jupiters
- Beginning era for super-Earth & hot-Neptune atmosphere studies

Postdoctoral position on Large HST program

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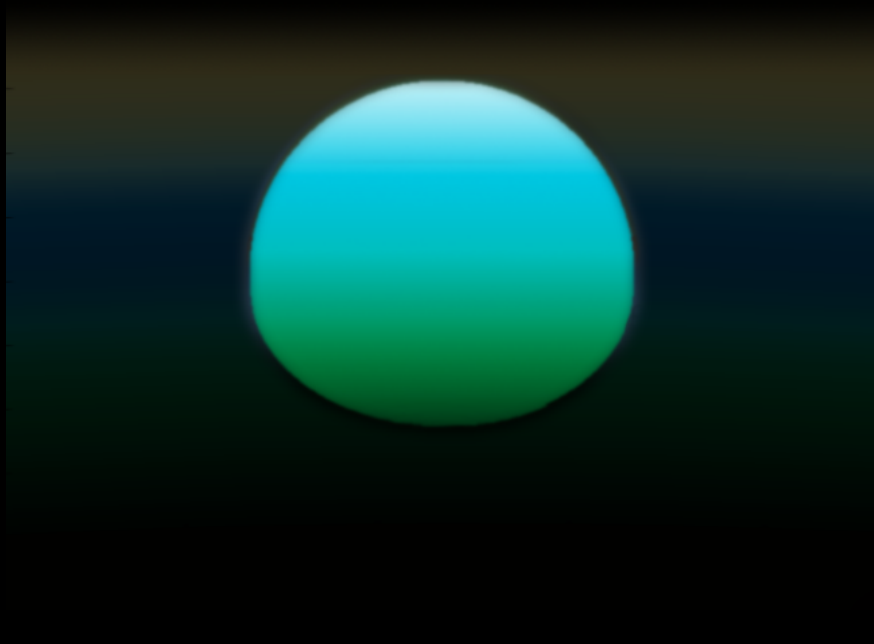

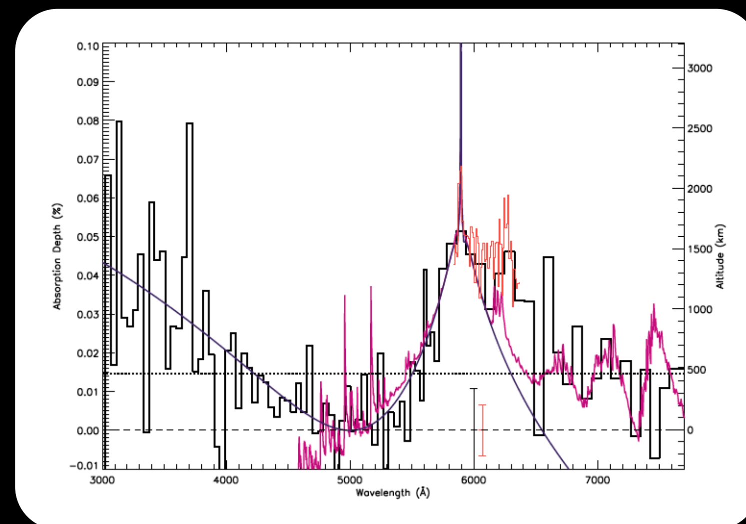

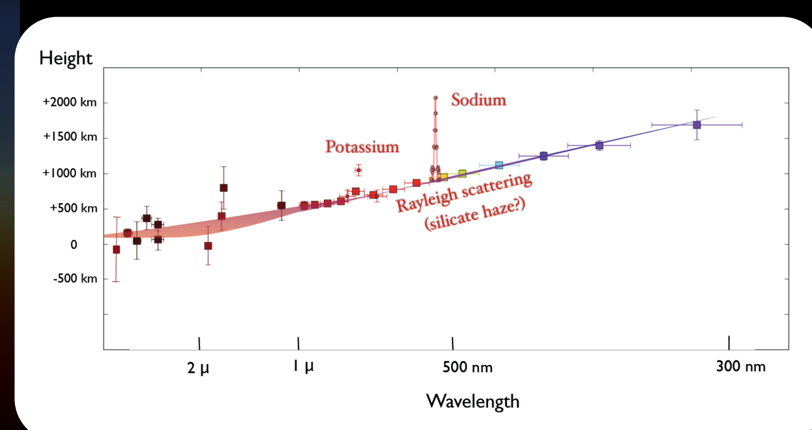

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G. Ballester	UofA
A. Showman	UofA
A. Burrows	Princeton
A. Lecavelier	IAP
A. Vidal-Madjar	IAP
D. Deming	Maryland
K. Zahnle	Nasa Ames
S. Aigrain	Oxford
G. Henry	Tennessee

- 124 Orbits
- 8 hot-Jupiters (1000 to 3000 K)
- Full high quality optical+nIR spectra from 3000 Å to 1.6μm

Email D. Sing for details

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