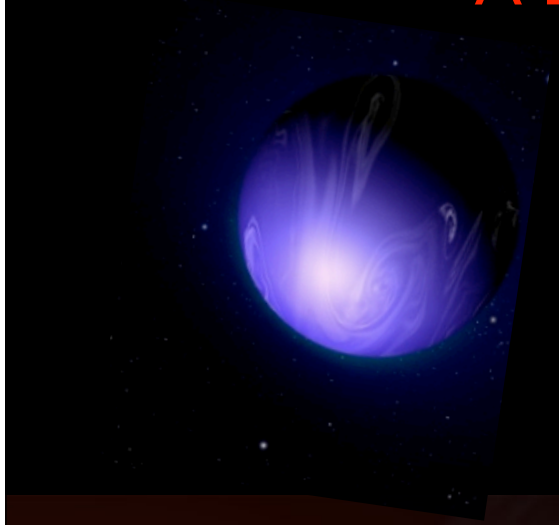
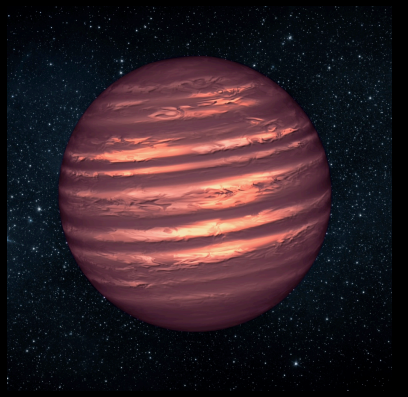
# Exoplanet Atmospheres

## A Decade of Intriguing Observations

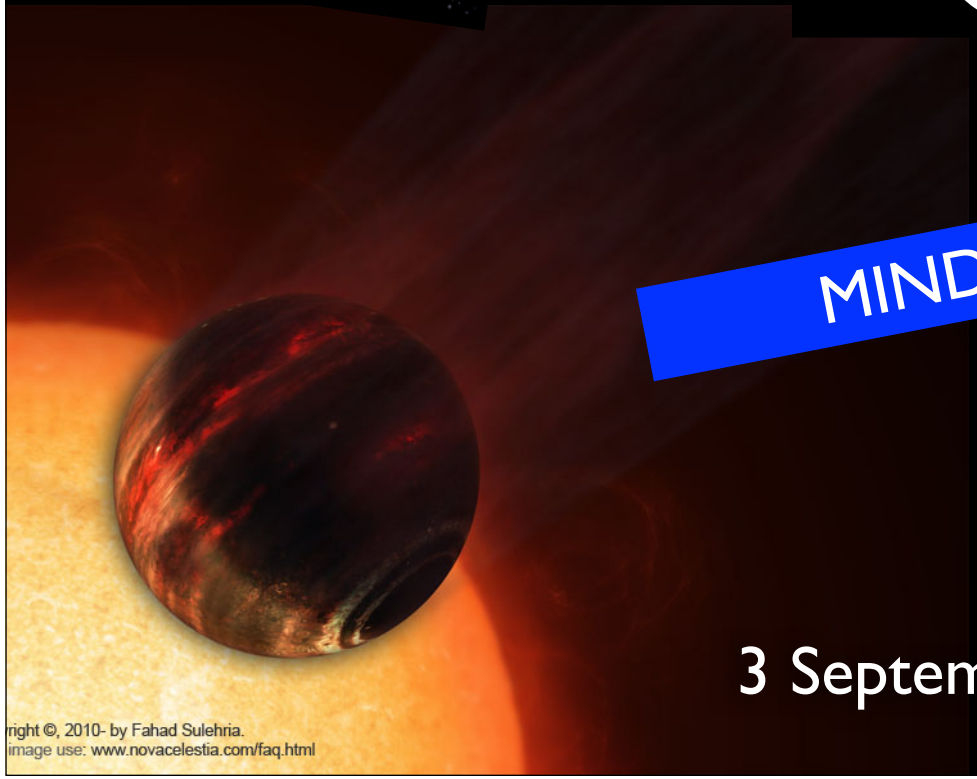


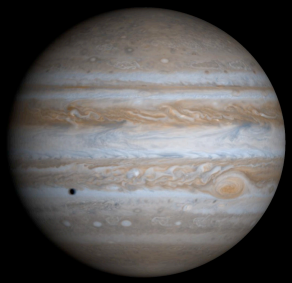
David K. Sing

UNIVERSITY OF EXETER



MIND THE GAP



3 September 2013

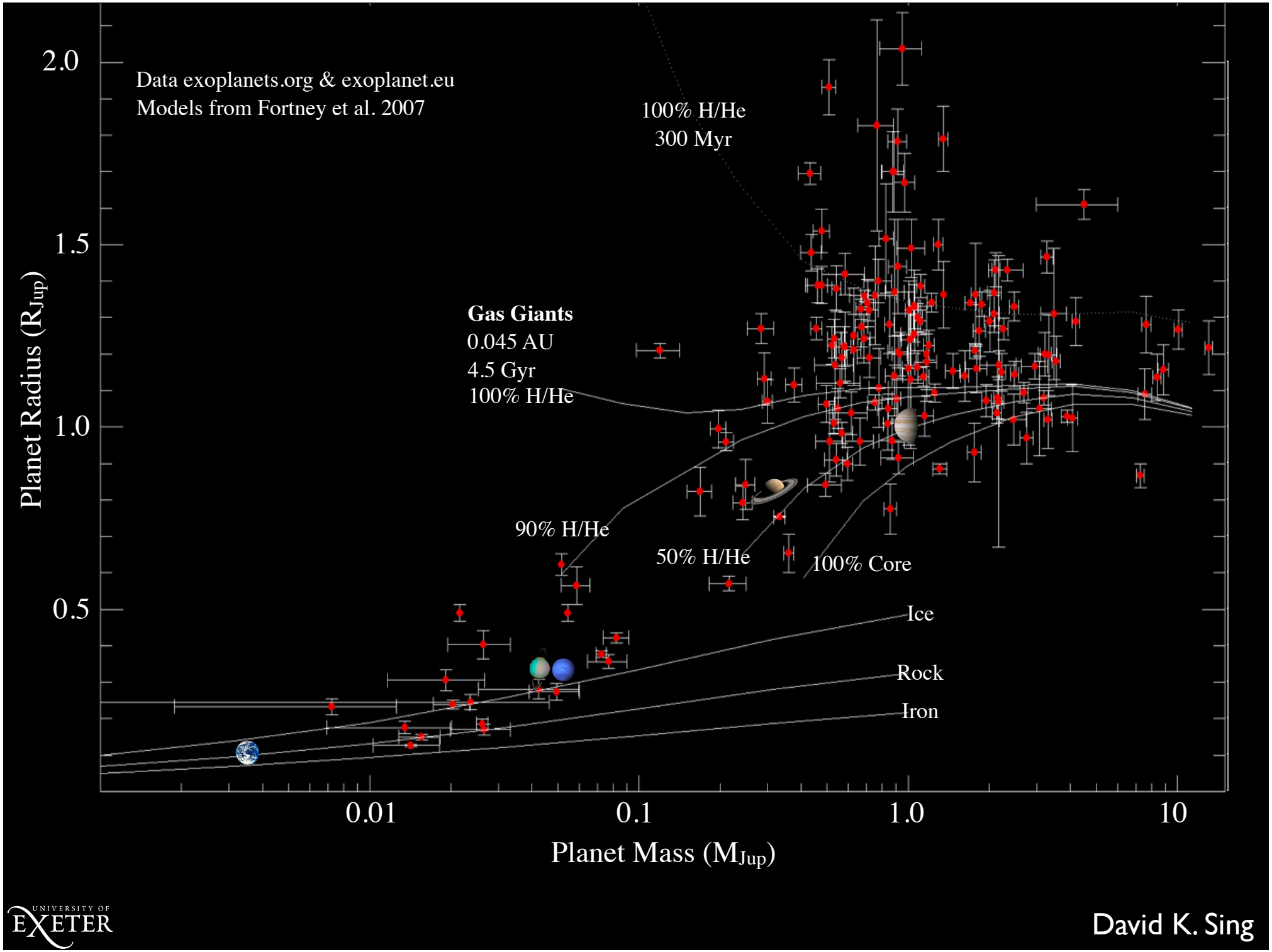
# Outline

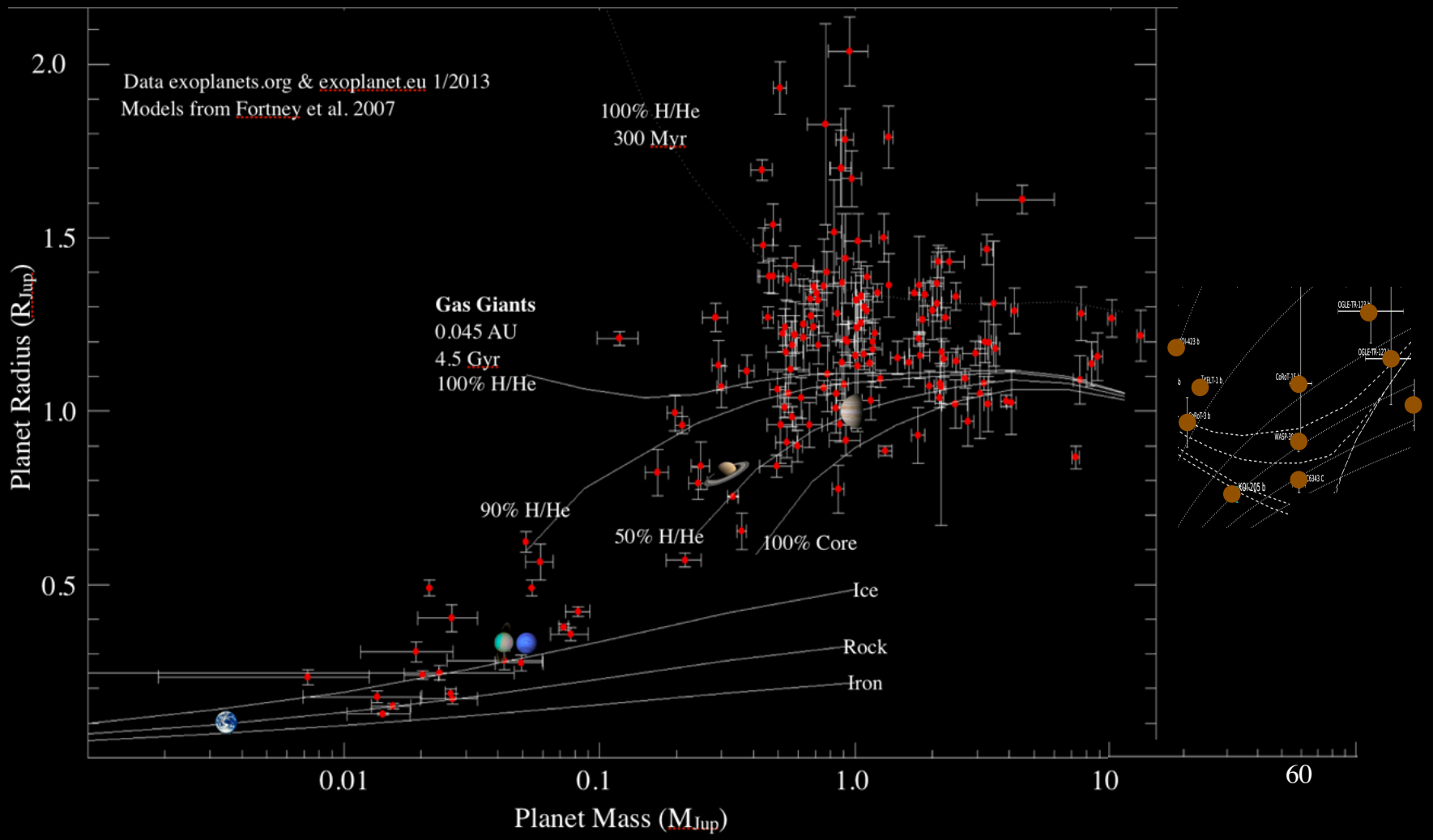
- Introduction Exoplanets
- Transiting Exoplanet Atmospheres
- What's been discovered, outstanding questions

  Clouds & Hazes

  Stratospheres

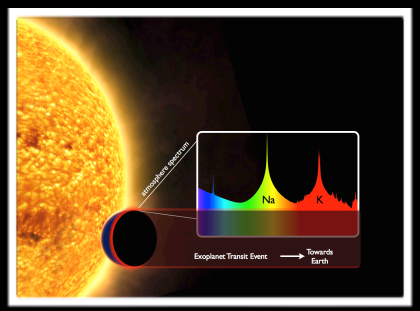
- Prototypes - HD189733b, HD209458b
- Latest HST Results
- Comparisons to Brown Dwarfs

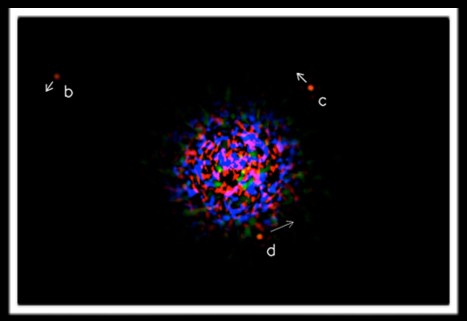

Data exoplanets.org & exoplanet.eu
Models from Fortney et al. 2007
100% H/He
300 Myr
Gas Giants
0.045 AU
4.5 Gyr
100% H/He
90% H/He
50% H/He
100% Core
Ice
Rock
Iron
Planet Radius (RJup)
Planet Mass (MJup)
2.0
1.5
1.0
0.5
0.01
0.1
1.0
10
UNIVERSITY OF EXETER
David K. Sing

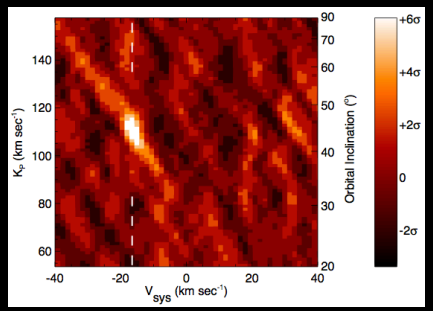

Data exoplanets.org & exoplanet.eu 1/2013
Models from Fortney et al. 2007
100% H/He
300 Myr
Gas Giants
0.045 AU
4.5 Gyr
100% H/He
90% H/He
50% H/He
100% Core
Ice
Rock
Iron
Planet Radius (R_Jup)
Planet Mass (M_Jup)
2.0
1.5
1.0
0.5
0.01
0.1
1.0
10
60

# Exoplanet Atmosphere Characterisation by Spectra

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



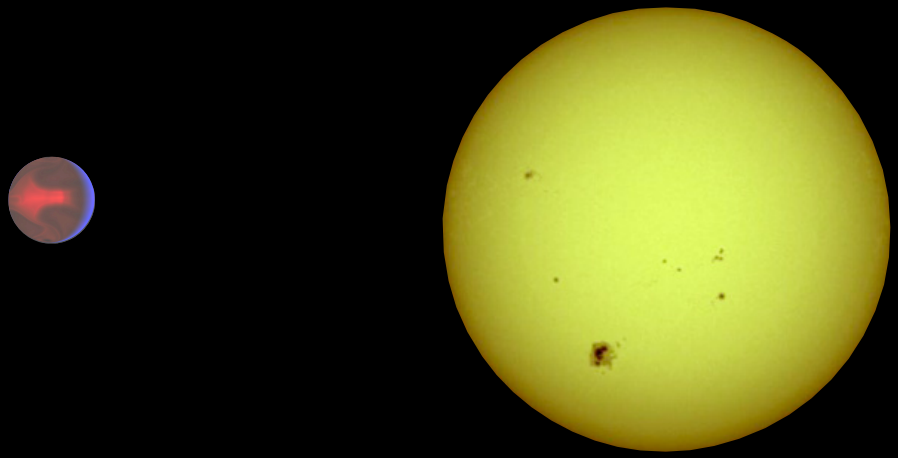



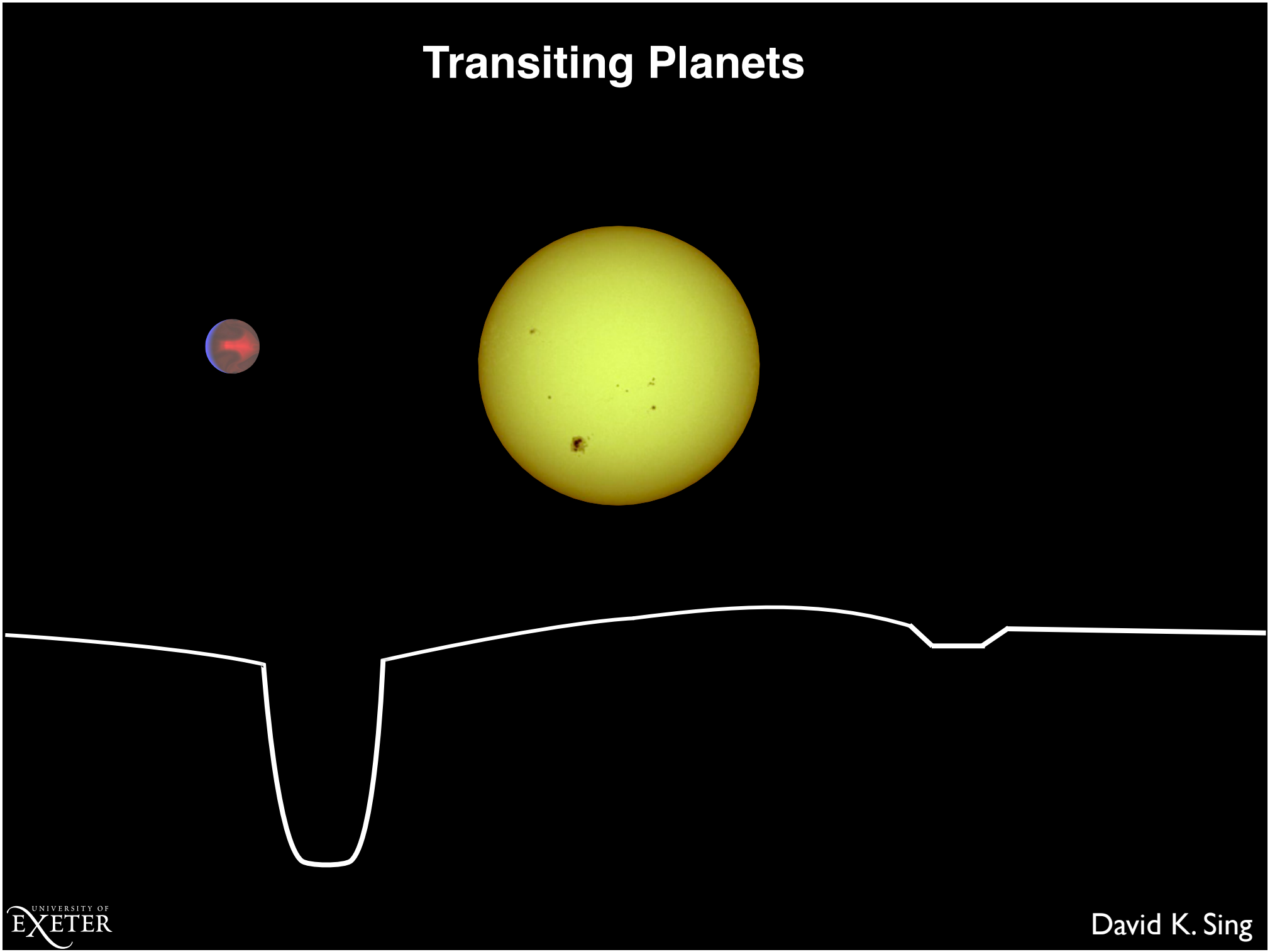

UNIVERSITY OF EXETER

David K. Sing

# Transiting Planets



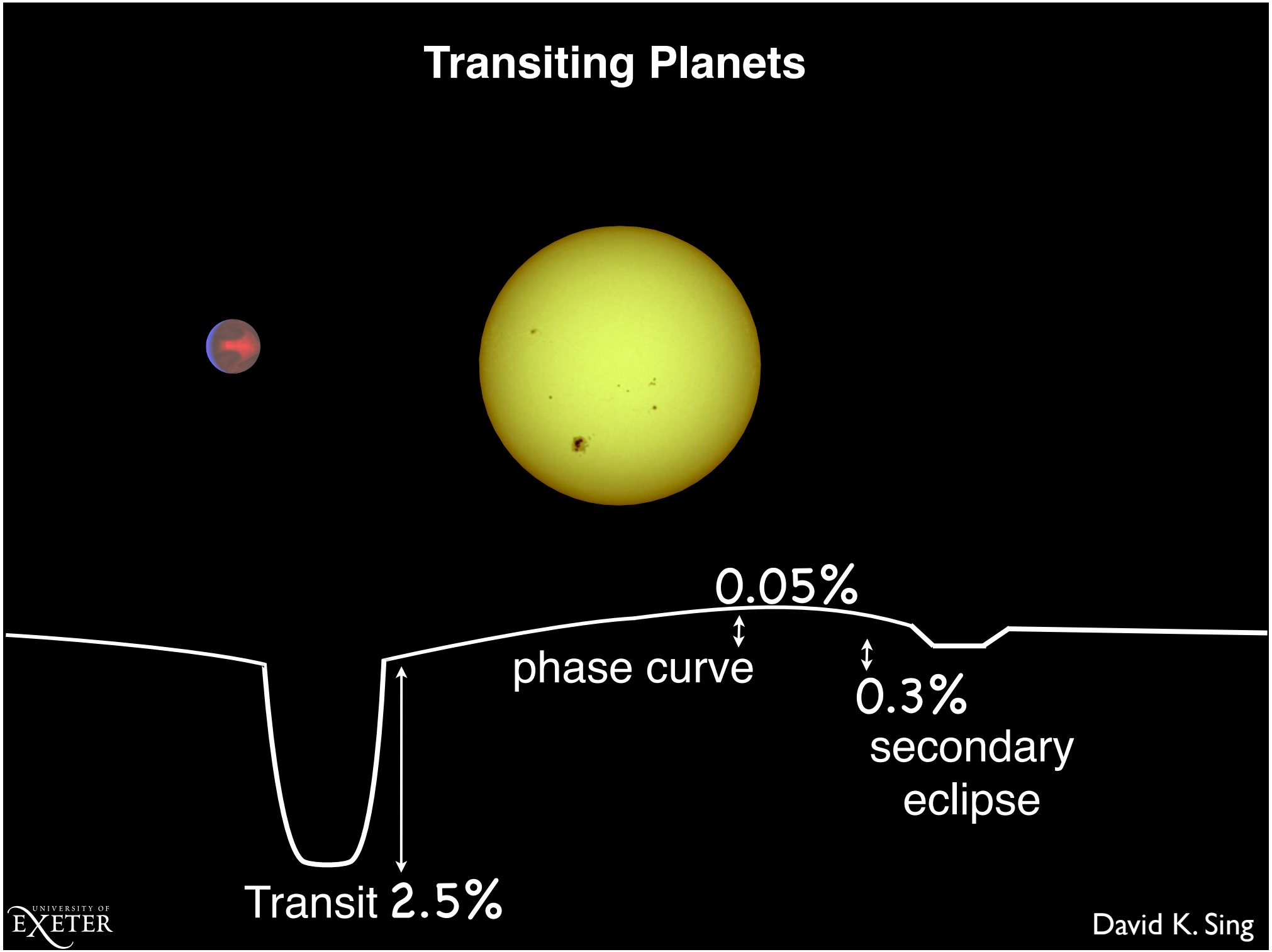
# Transiting Planets



UNIVERSITY OF EXETER

David K. Sing

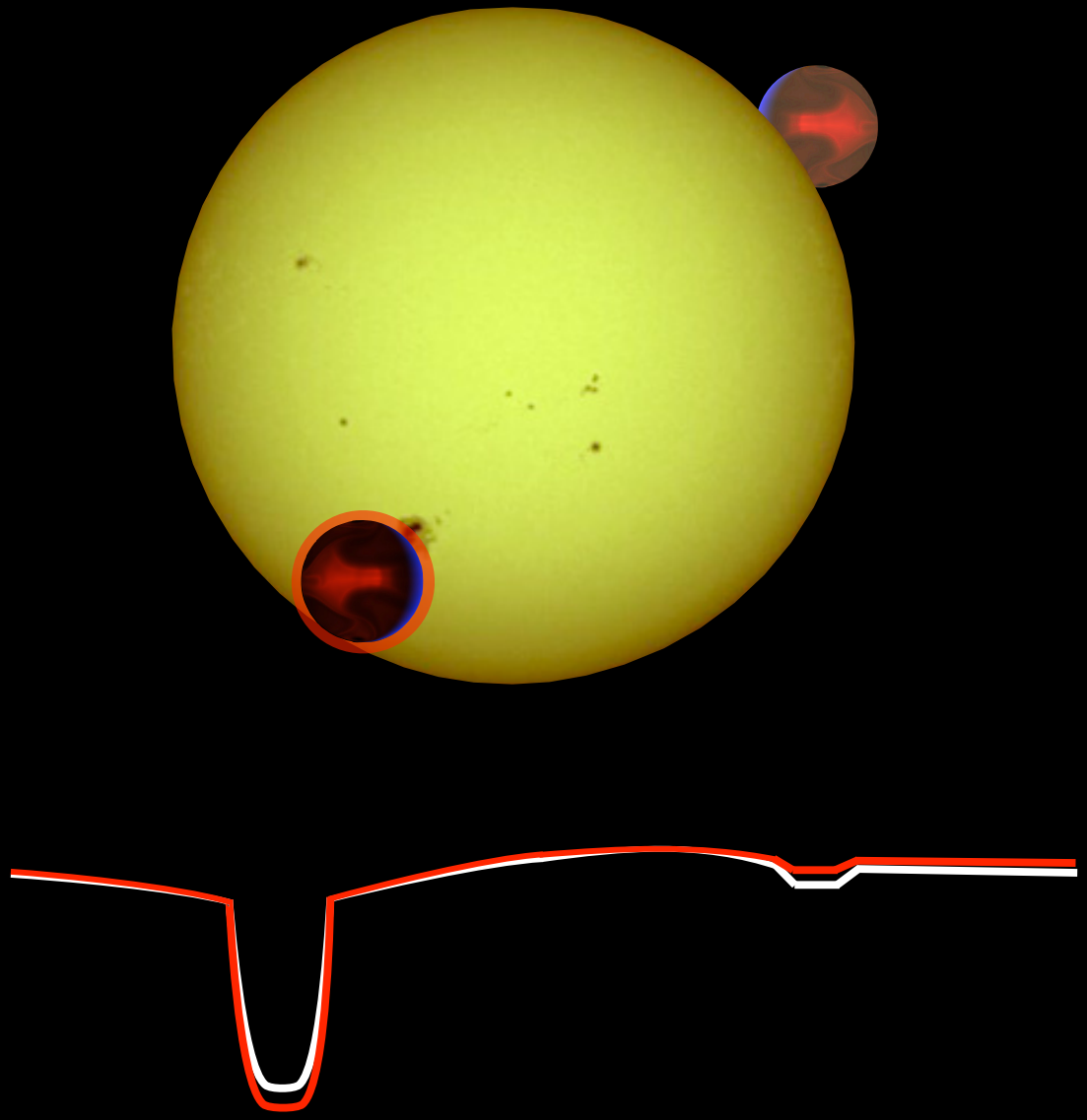
# Transiting Planets




UNIVERSITY OF EXETER

David K. Sing

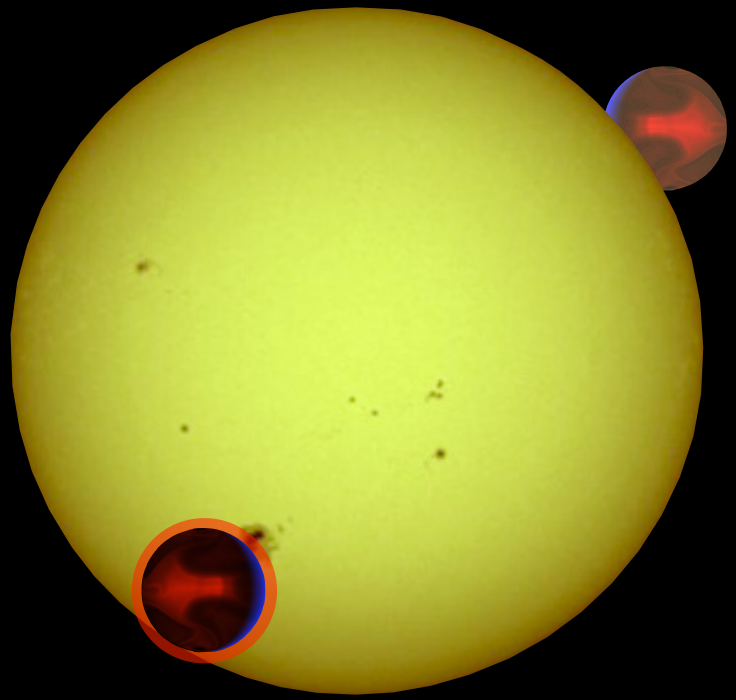
# Exoplanet Spectra

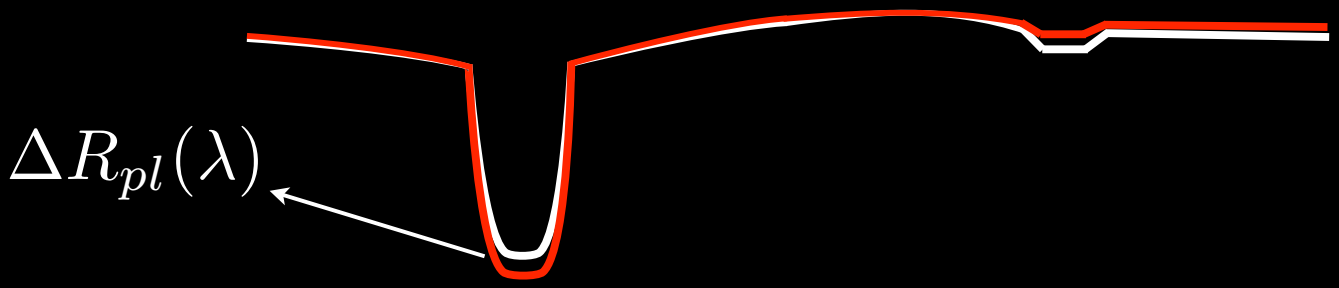


UNIVERSITY OF EXETER

David K. Sing

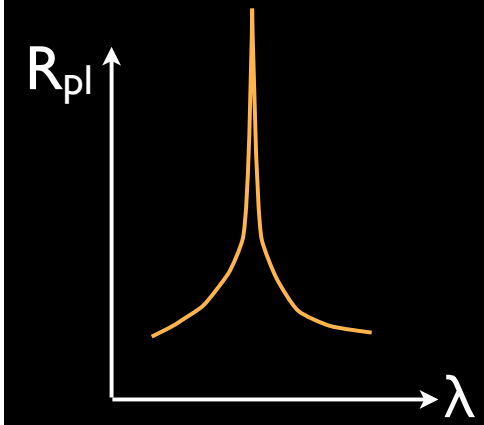
# Exoplanet Spectra

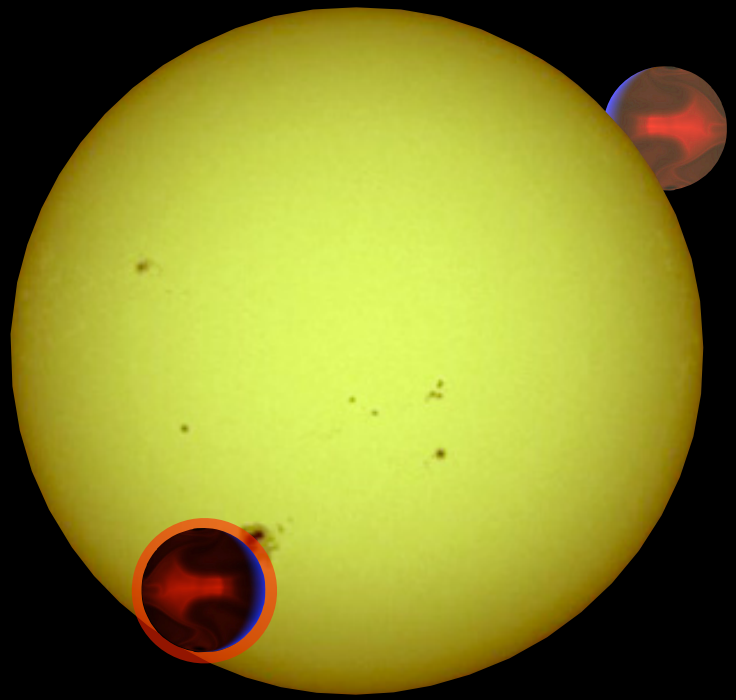


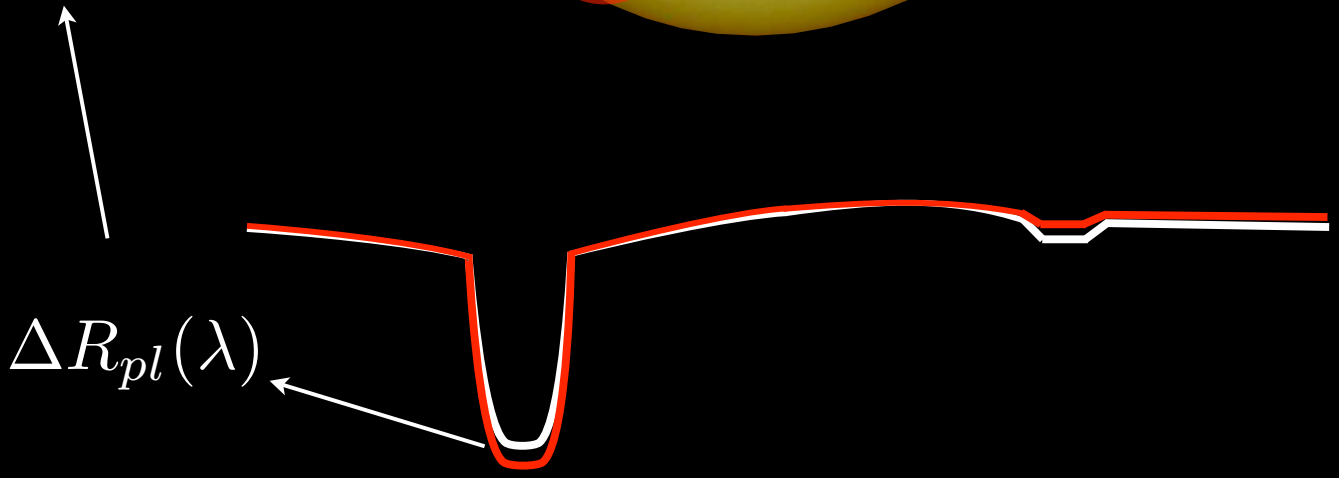


# Exoplanet Spectra

Transmission spectrum

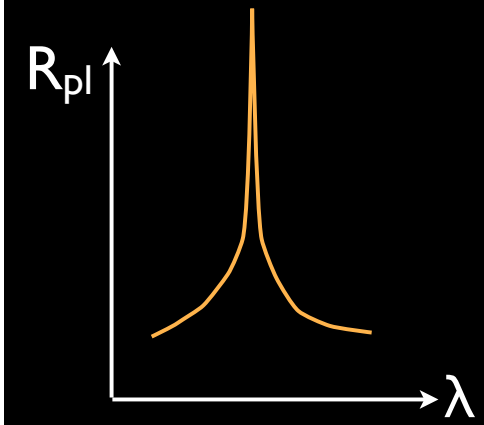


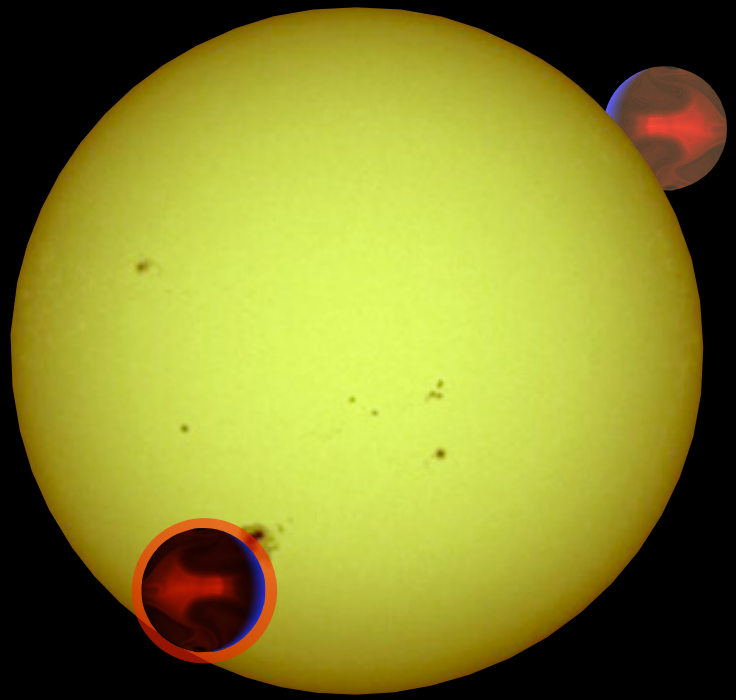





# Exoplanet Spectra

Transmission spectrum

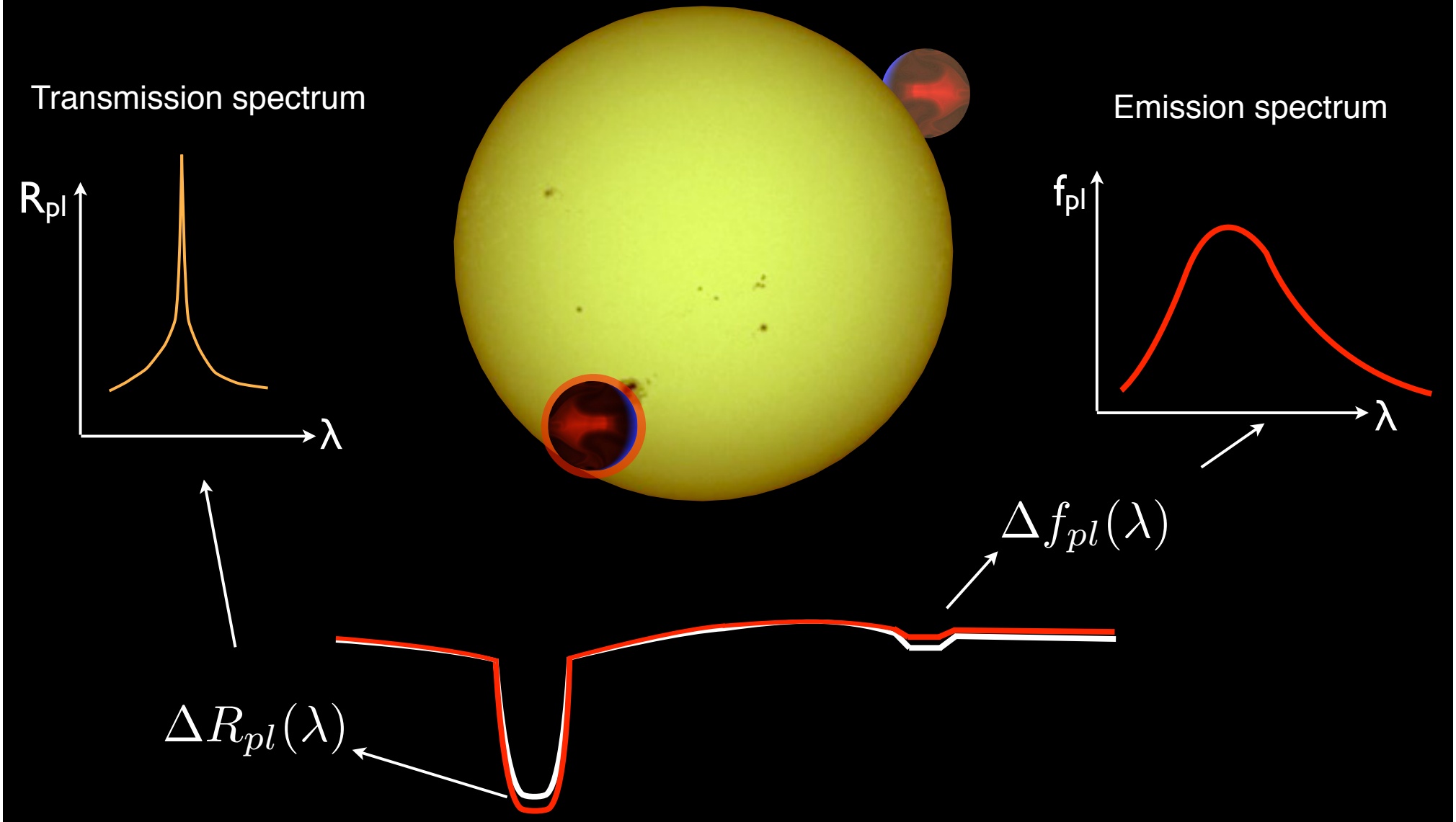


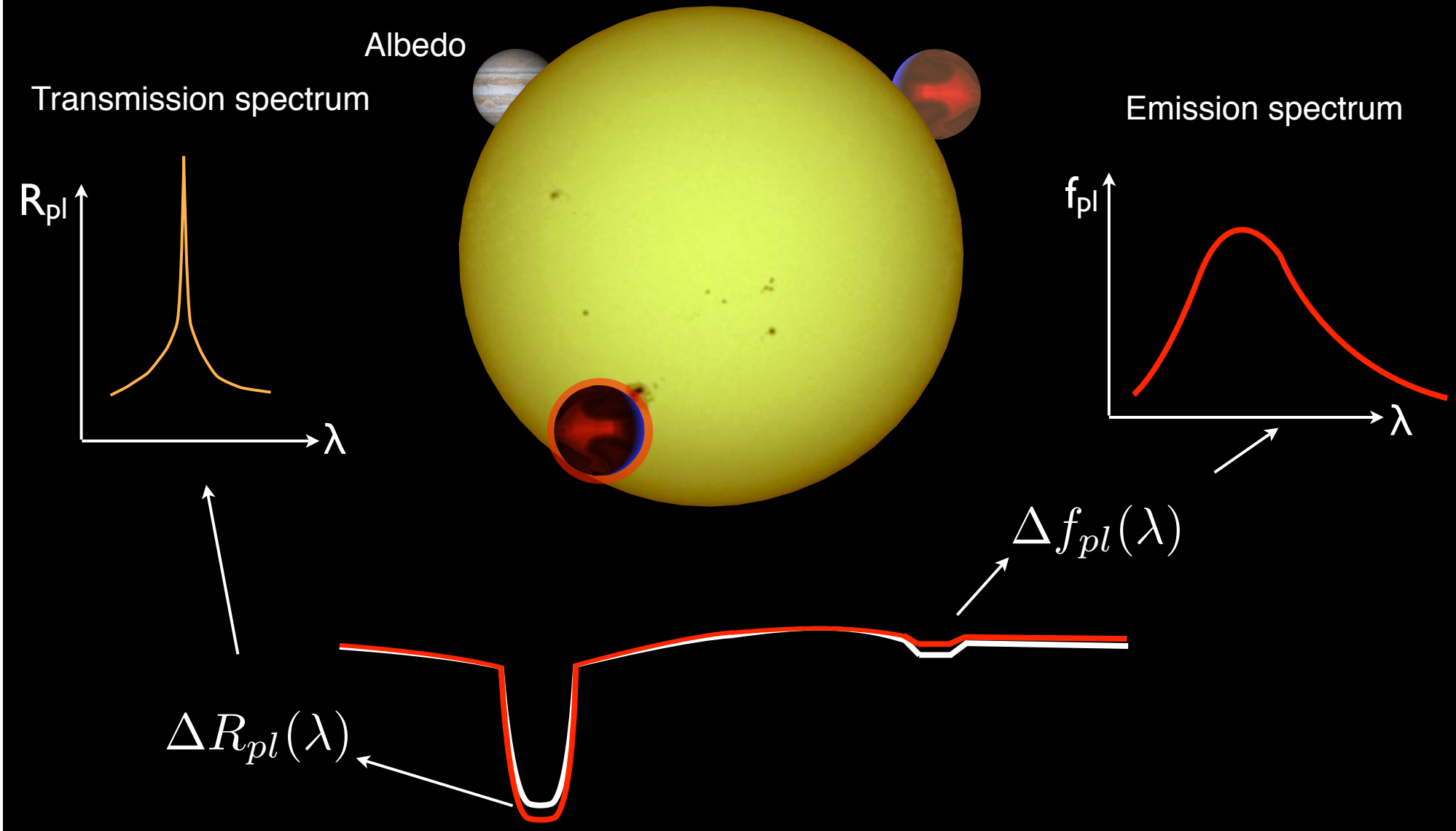
$\Delta f_{pl}(\lambda)$

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

# Exoplanet Spectra



# Exoplanet Spectra



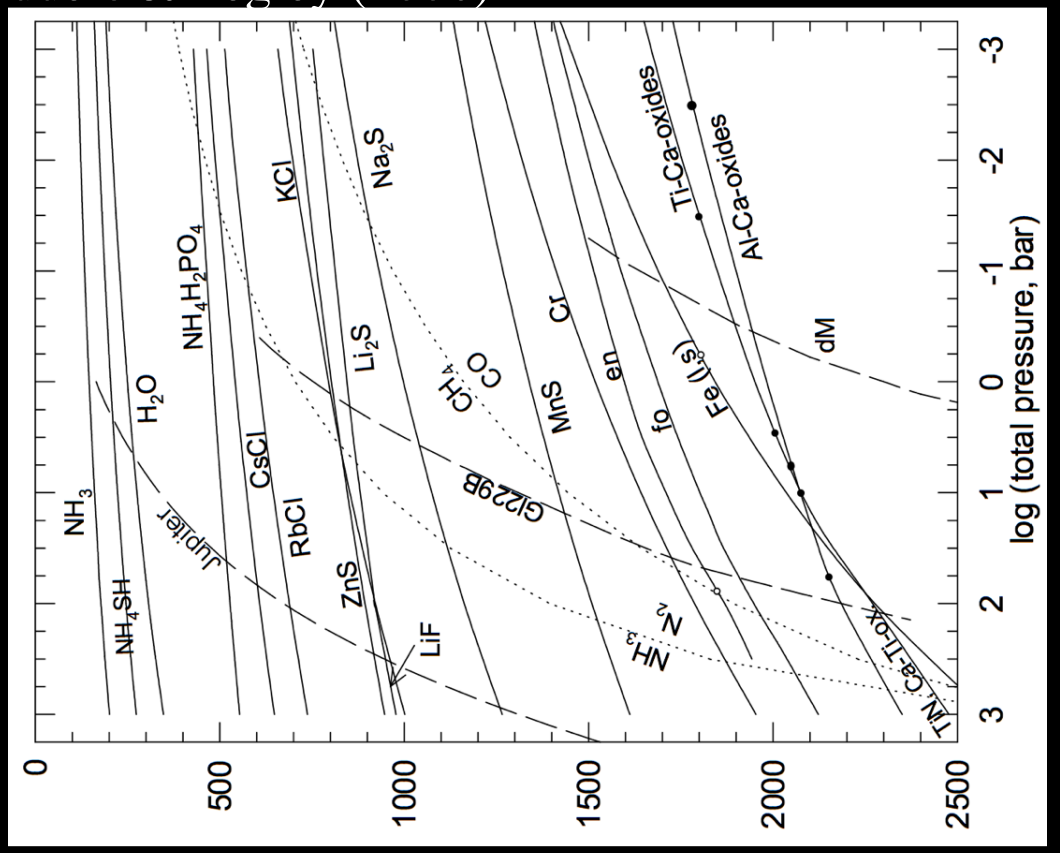

UNIVERSITY OF EXETER

David K. Sing

# Hot Jupiter models

## What should these planets look like?

Lodders & Fegley (2006)




Temperature (K)

## Early Atmosphere Models

Inspired by Brown Dwarfs

Solar Composition

Chemical Equilibrium

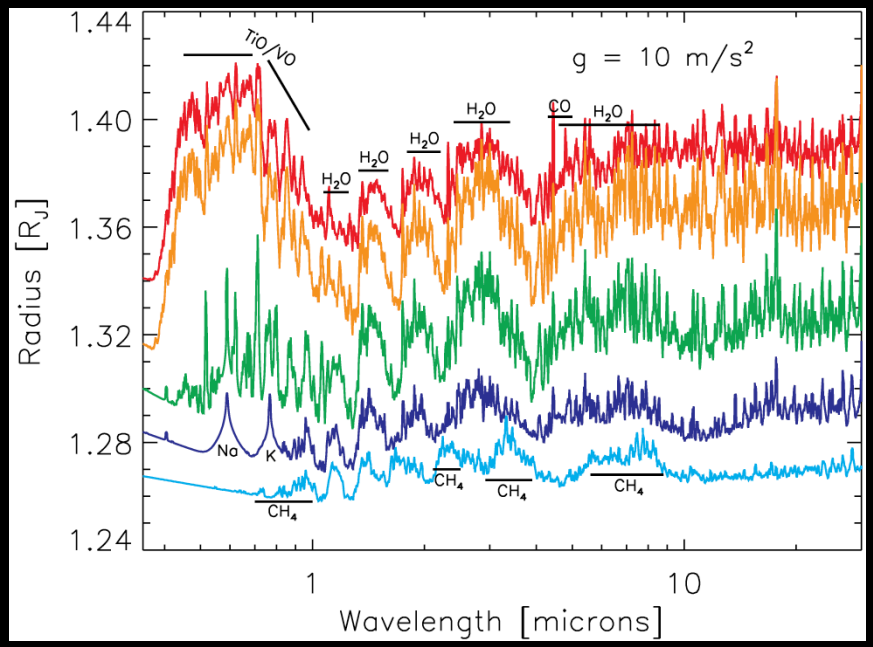
Radiative Transfer

- $H_2$ Na K
- $H_2O$ - Dominant
- CO - hotter atmospheres
- $CH_4$ - cooler atmospheres
- TiO - for the hotter planets - could lead to thermal inversion layers
- Clouds - likely to be seen depending on T-P profiles

# Hot Jupiter models

## What should these planets look like?

Fortney et al. 2010




Early Atmosphere Models

Inspired by Brown Dwarfs

Solar Composition

Chemical Equilibrium

Radiative Transfer

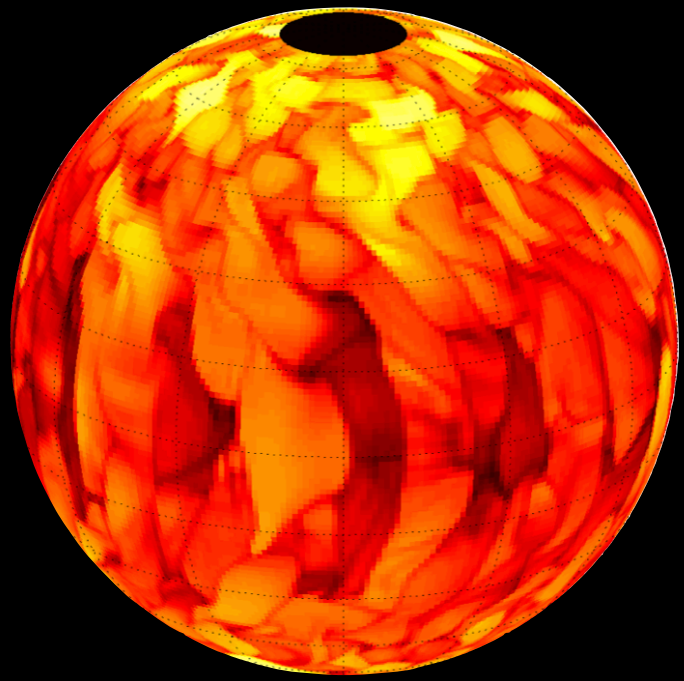
$H_2$ Na K
$H_2O$ - Dominant
CO - hotter atmospheres
$CH_4$ - cooler atmospheres
TiO - for the hotter planets - could lead to thermal inversion layers
Clouds - likely to be seen depending on T-P profiles

# Hot Jupiter models

## What should these planets look like?

Atmosphere Models

Dynamics play a **crucial** role



Brown Dwarfs
Rapidly Rotating
Convection Dominated

Showman & Kaspi (2013)

# Hot Jupiter models

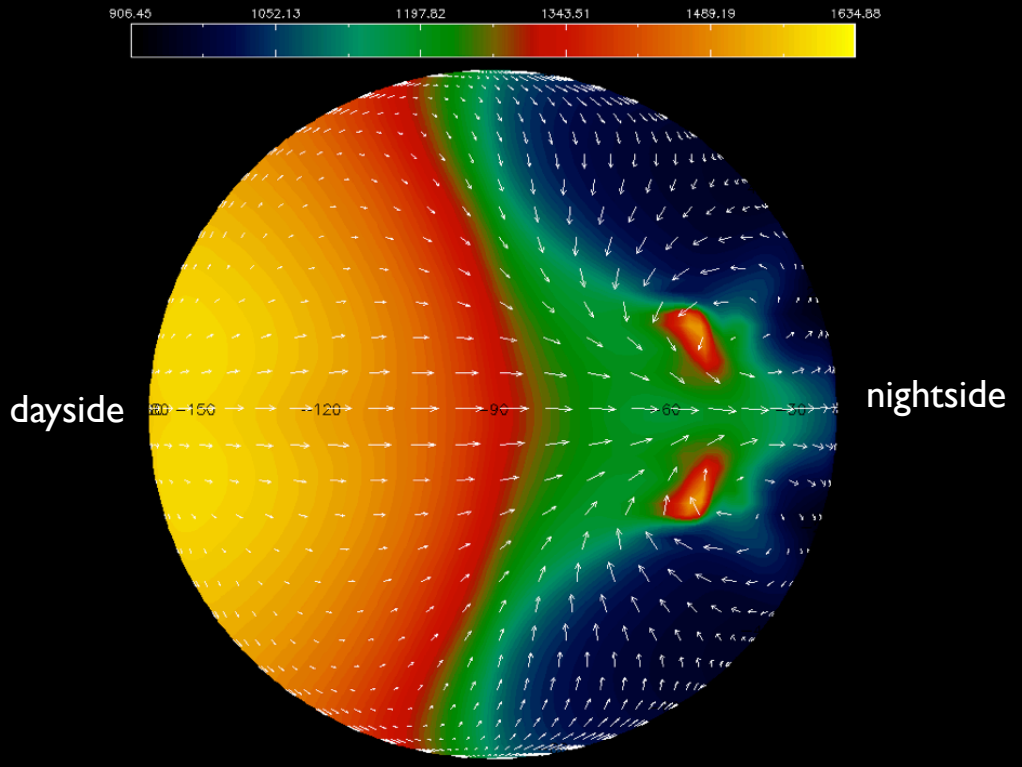
## What should these planets look like?

<u>Atmosphere Models</u>

Dynamics play a **crucial** role

Large Temp range over short time scales

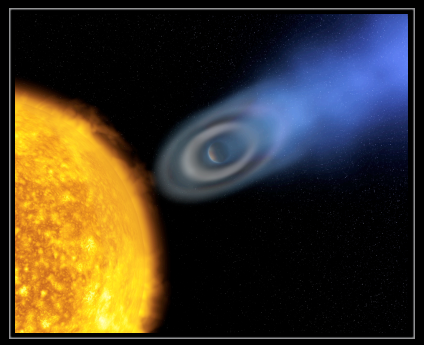
Large vertical mixing expected too

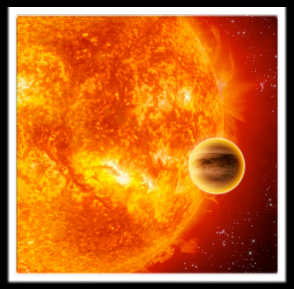


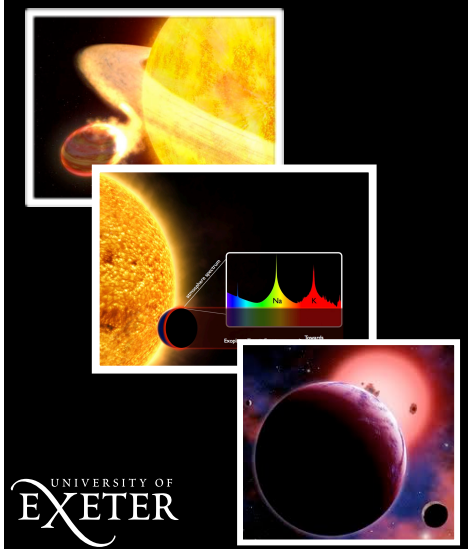

<u>Hot Jupiters</u>
Tidally Locked
Advection Dominated

UM Endgame, Mayne et al. (2013)

# Identified Transit Atmospheric Constituents

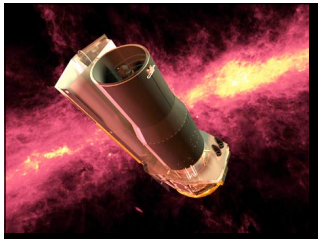




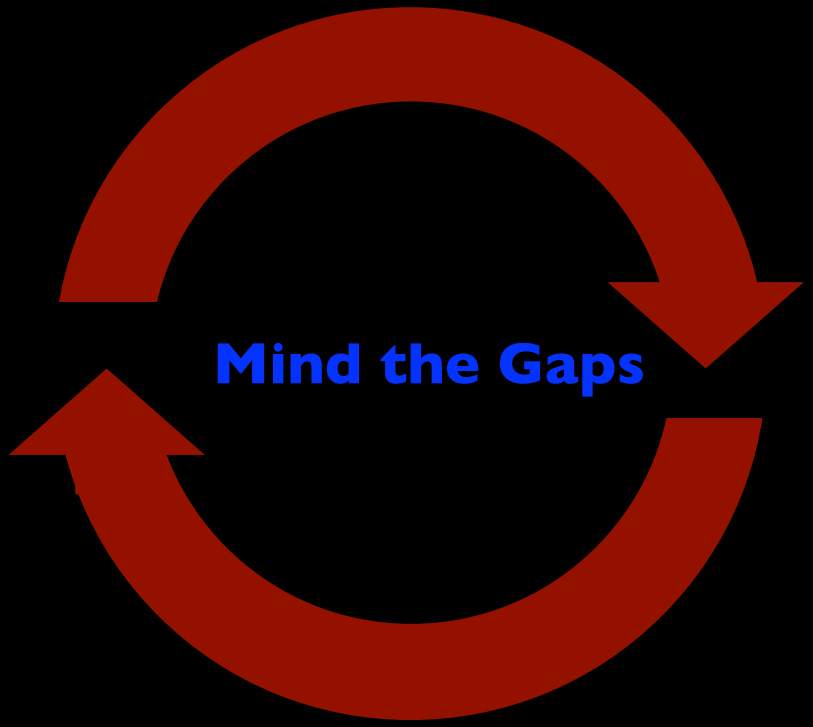


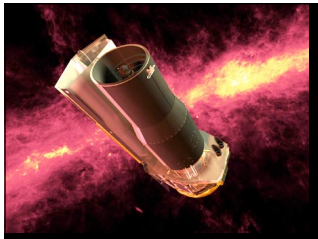
| | | | |
|---|---|---|---|
| HD209458b | | | |
| **Na** | Confirmed: | HST & Subaru | |
| **C II** | Confirmed: | HST | ’02,’08 |
| $H_2$,TiO/VO | initial: | HST | ‘04,’10 |
| CO | initial: | VLT-(RV) | ’03,’07,’09 |
| H I, O I, Si III | initial: | HST | ’10 |
| $H_2O$ | Confirmed: | HST, Spitzer | ‘03,’10,’13 |
| | | | ’10,’13 |
| HD189733b | | | |
| **Na** | Confirmed: | HET & HST | |
| **Rayleigh-haze** | Confirmed: | HST | ’08,’12 |
| $H_2O$, CO | Confirmed: | Spitzer, RV | ’07,’11,’13 |
| $CO_2$, H I | initial: | Spitzer; HST | ’08 |
| | | | ’09,’10 |
| Wasp-12b | | | |
| Mg II, Metals | initial: | HST | ’11 |
| ~~Molecules high C/O~~ | ~~initial:~~ | ~~VLT, CFHT, Spitzer~~ | (Mdwarf) |
| Wasp-17b: Na | confirmed: | VLT, Magellen | ’11,’12 |
| XO-2b: K, Na | initial: | GTC | ’11,’12 |
| GJ1214: | | | ’11,’12 |
| flat/metal-rich/haze | confirmed: | VLT, HST, CFHT, Spitzer... | |
| GJ436: Molecules | initial: | Spitzer | ’10,’11 |
| Hat-P-1b: $H_2O$, Na | initial: | HST | ’13 |
| Wasp-19b: $H_2O$ | initial: | HST | ’13 |
| GJ3470b: flat/not flat? | initial: | Keck, LBT | ’13,’13 |

UNIVERSITY OF EXETER



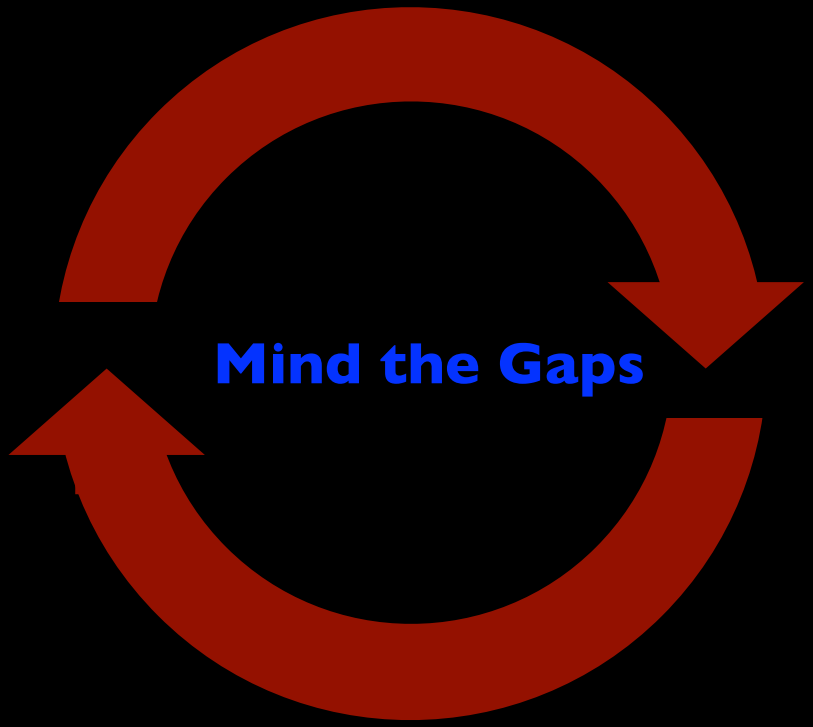
# Current State of the Exoplanet Atmosphere Field Observations

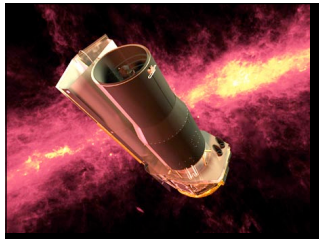




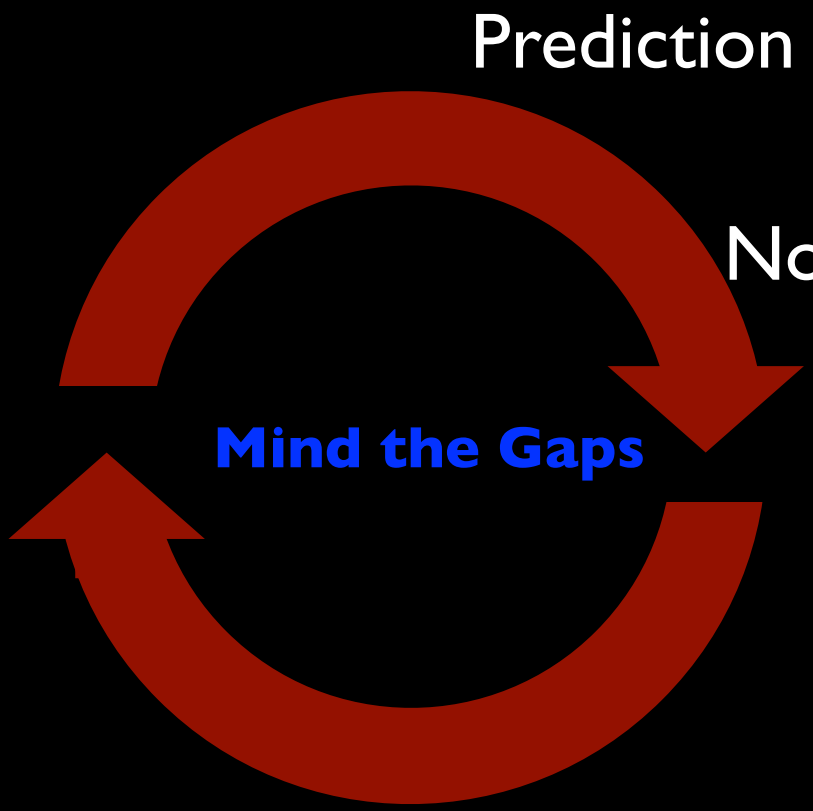
# Current State of the Exoplanet Atmosphere Field Observations

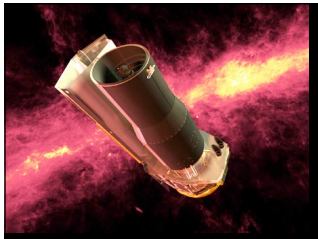
Prediction



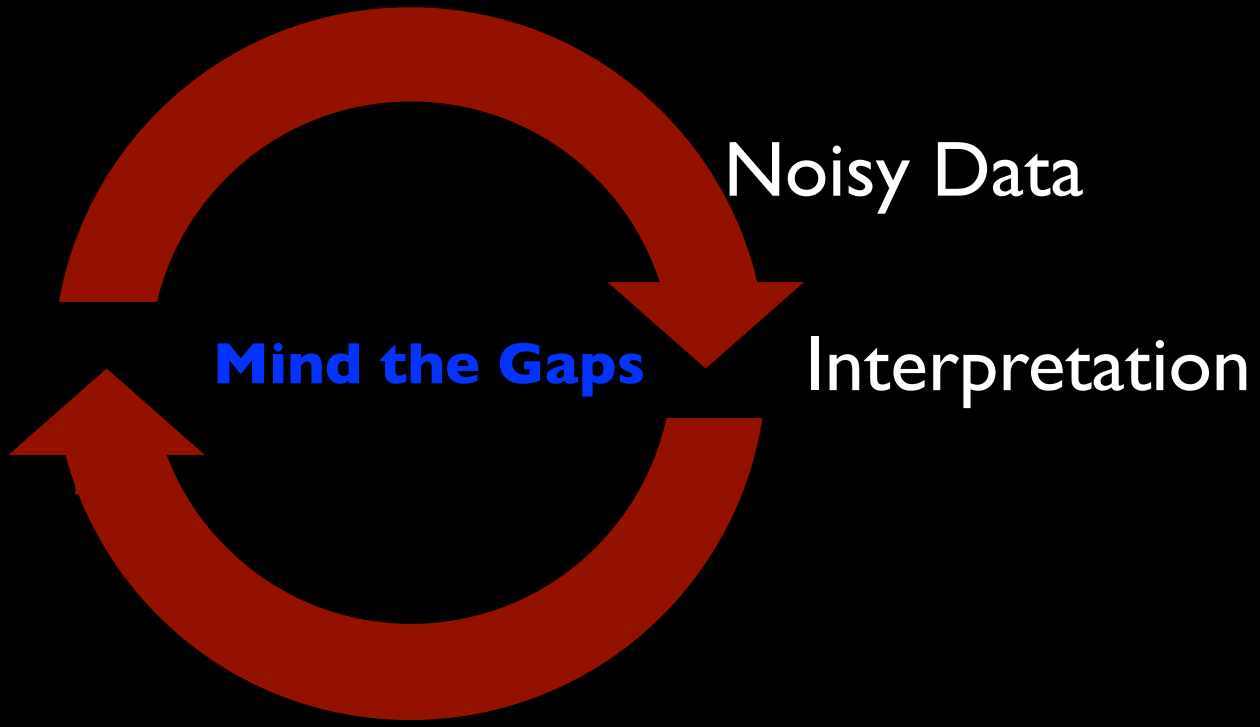


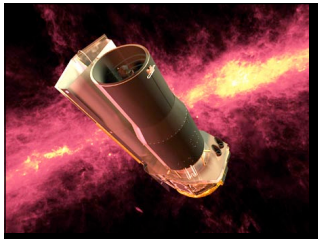
# Current State of the Exoplanet Atmosphere Field Observations



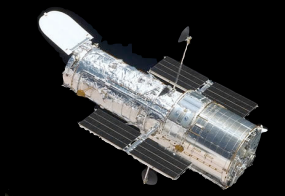


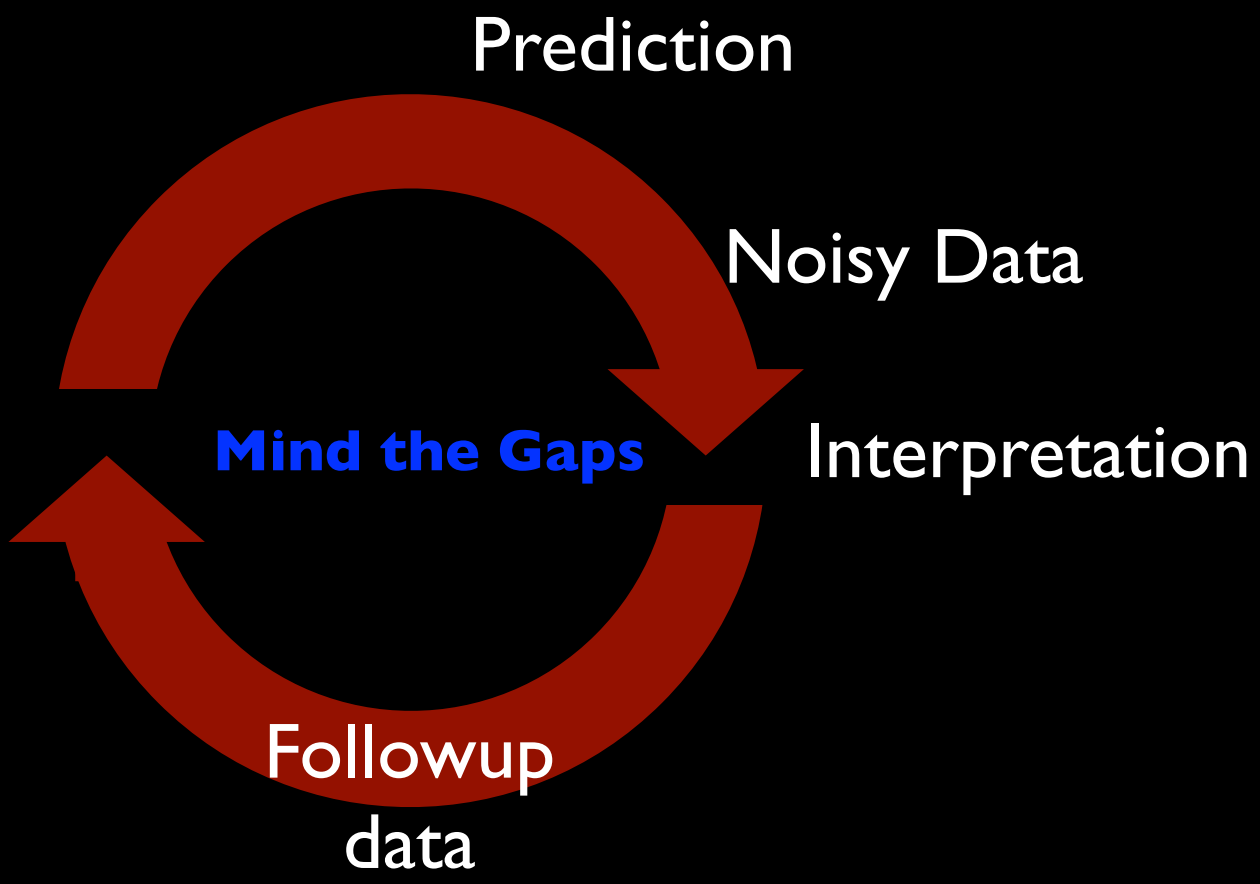
# Current State of the Exoplanet Atmosphere Field Observations

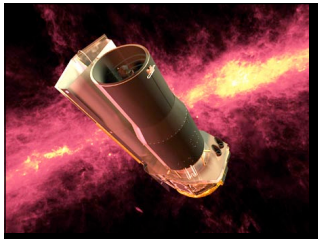




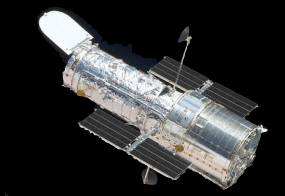
# Current State of the Exoplanet Atmosphere Field Observations

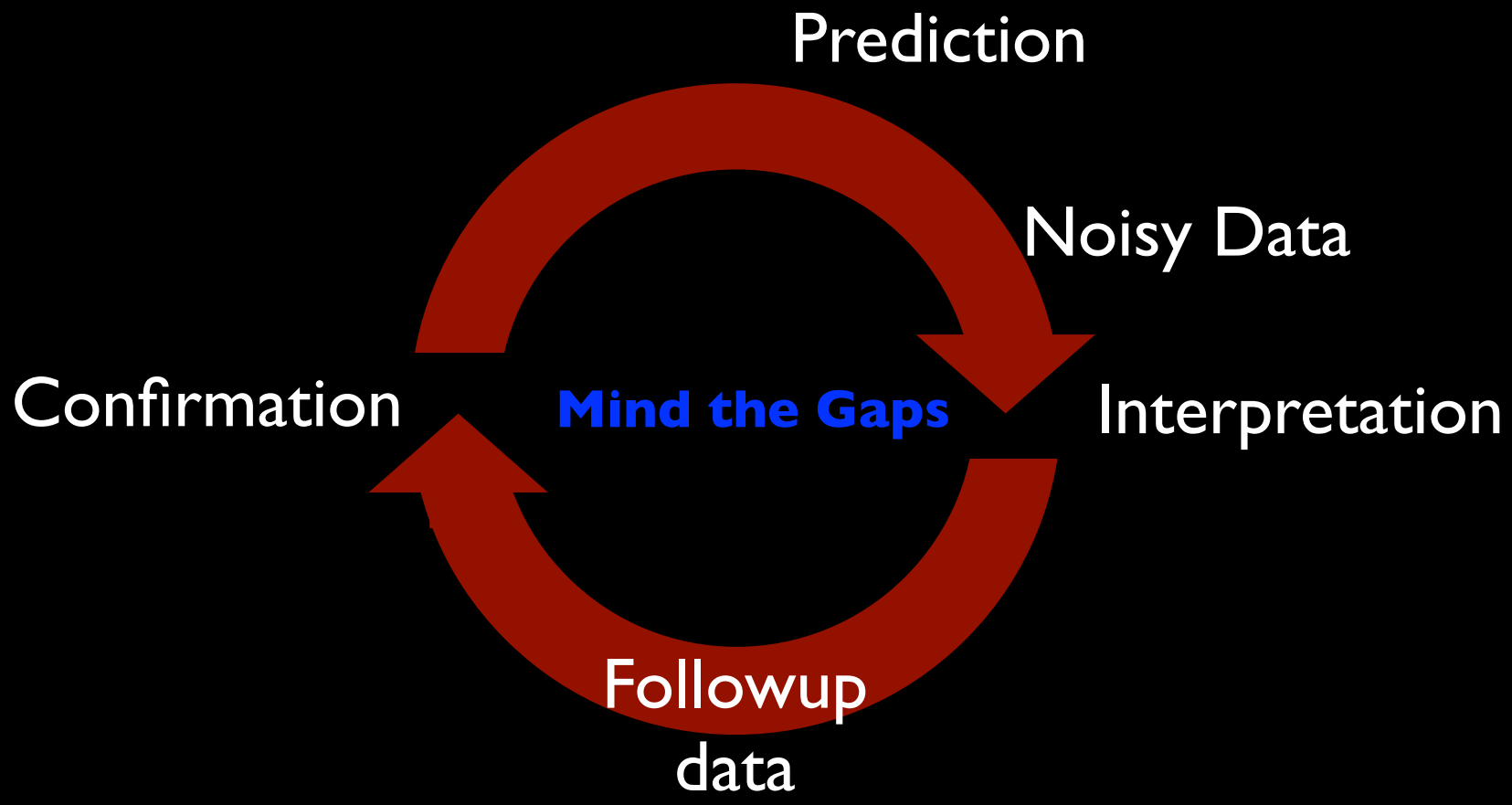


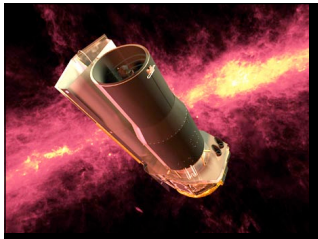




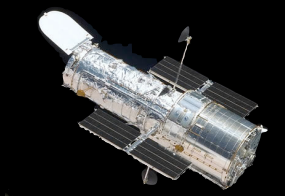
# Current State of the Exoplanet Atmosphere Field Observations

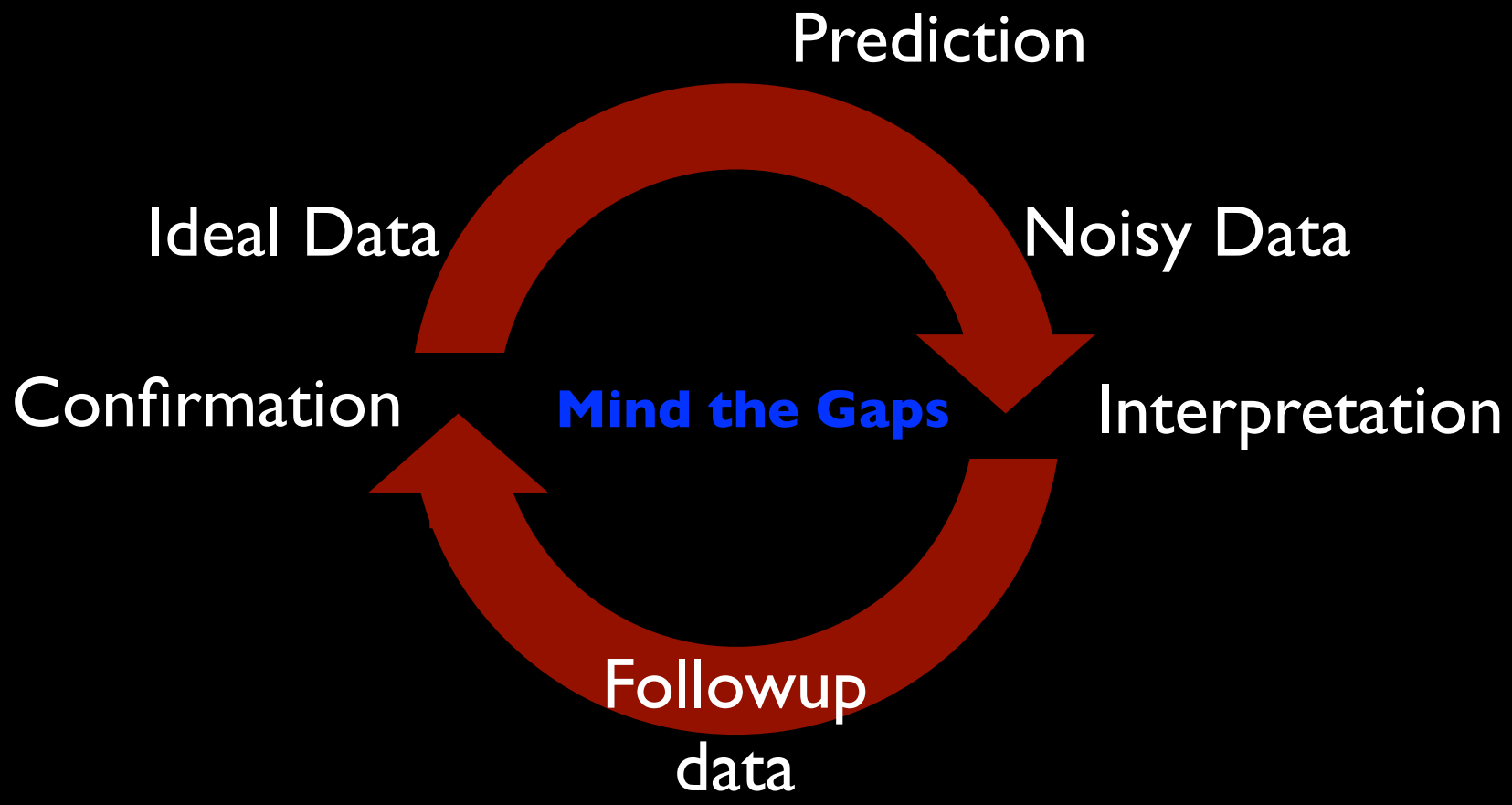


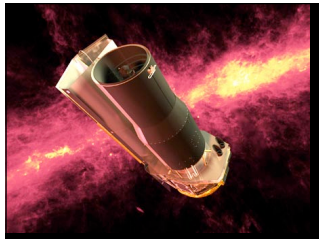




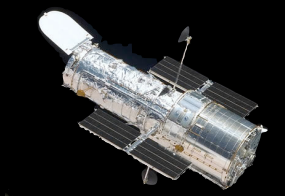
# Current State of the Exoplanet Atmosphere Field Observations

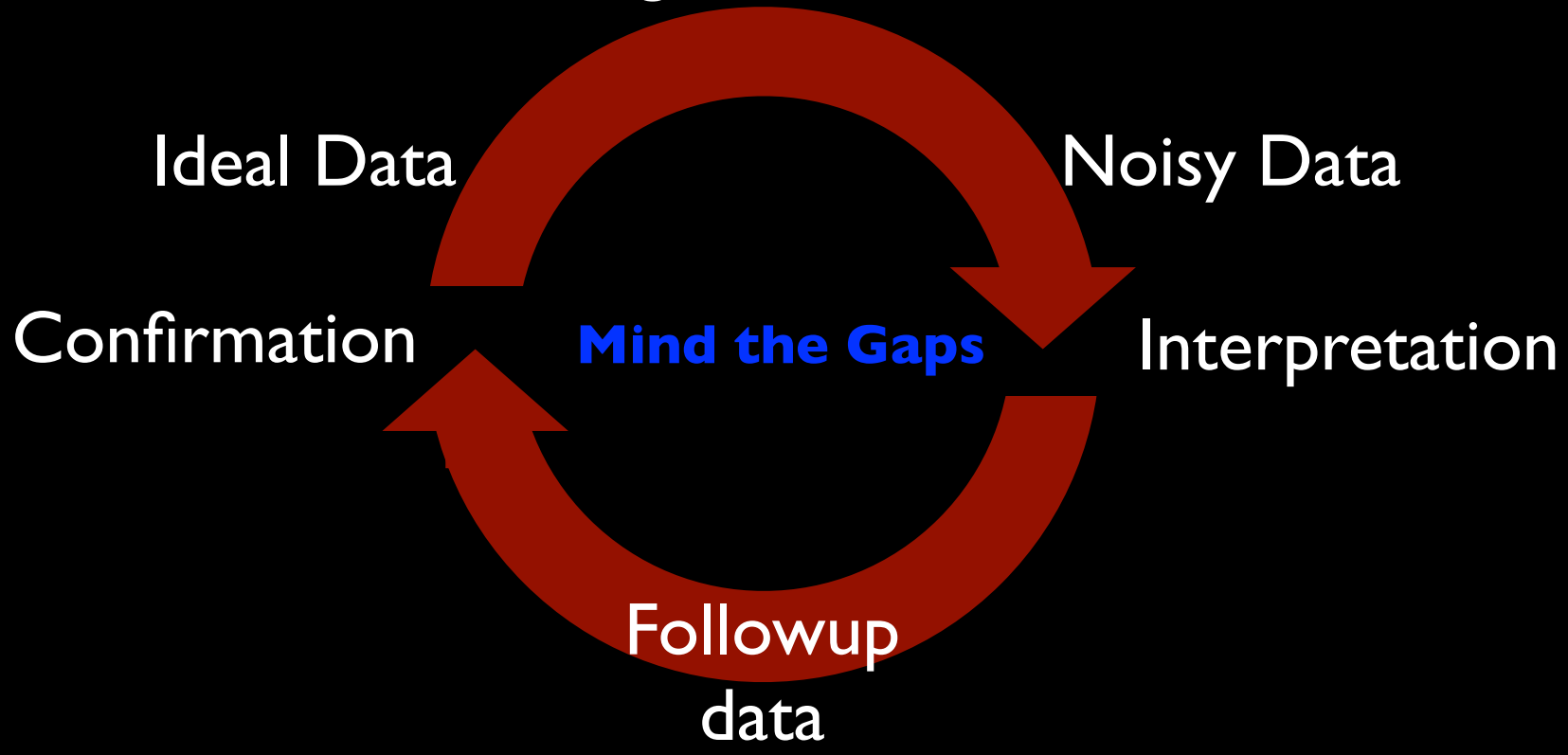


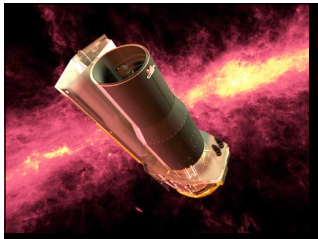




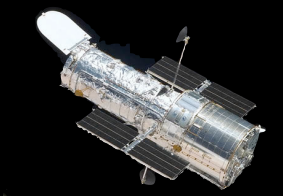
# Current State of the Exoplanet Atmosphere Field Observations



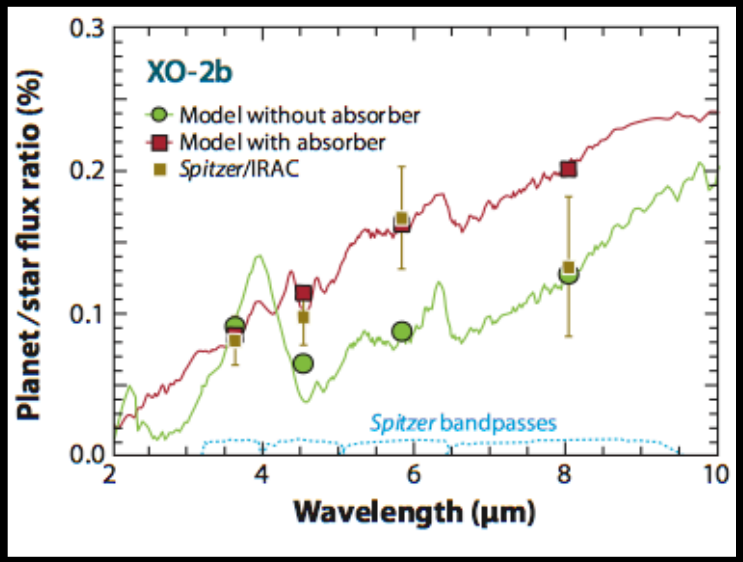




# Current State of the Exoplanet Atmosphere Field Observations



few observational constraints




Seager & Deming (2010)

- Lots of Photometry (35+ planets)
- Major degeneracies in composition & thermal structure
- Very Little *Spectroscopy* (2 or so planets)

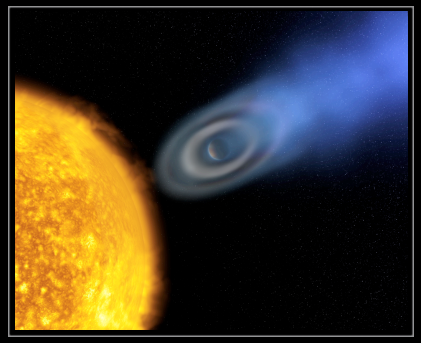
# ‘209 and ‘189

Almost everything we know about hot Jupiters has comes from just *two* planets.

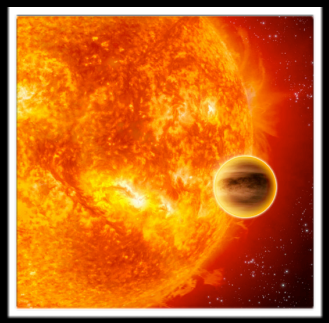
A few prototype HJs will always dominate

transit+emission+phase curve spectroscopy is ‘highly’ constraining

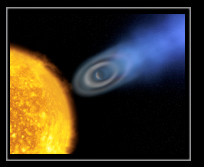
very few planets can be measured with all 3



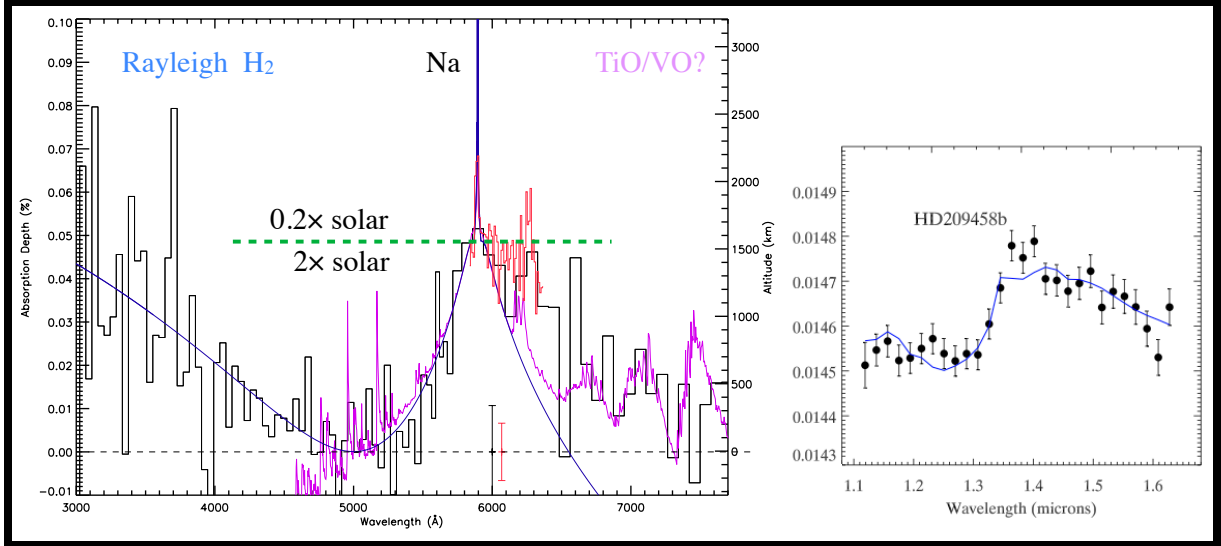
‘189
‘209
Wasp-12
Wasp-19



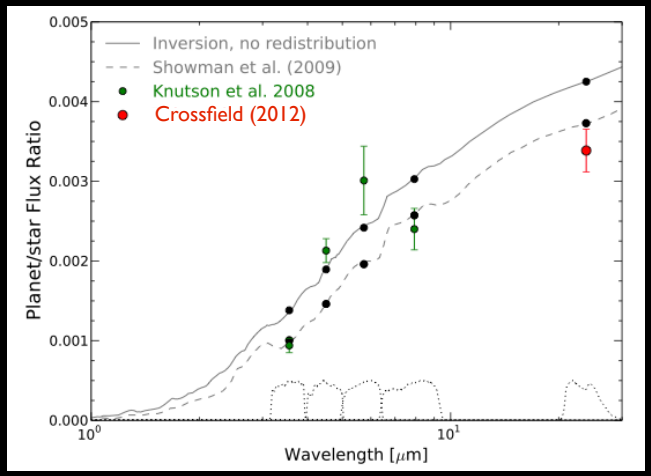
# HD 209458b: our first characterised exoplanet



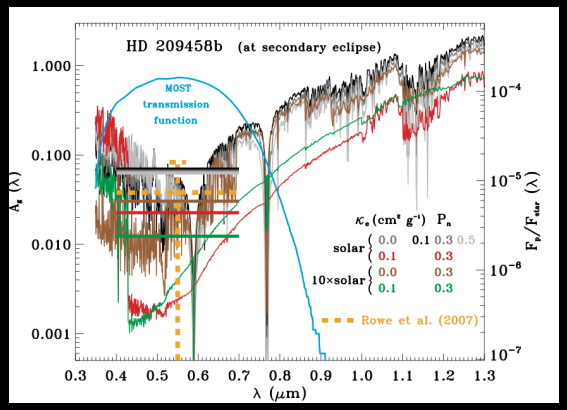
## Transmission




## Emission




## Albedo




**Na, H2O, CO, Rayleigh**

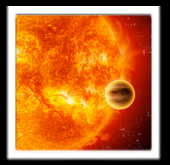
**Low albedo - few %**

**Possible Stratosphere**

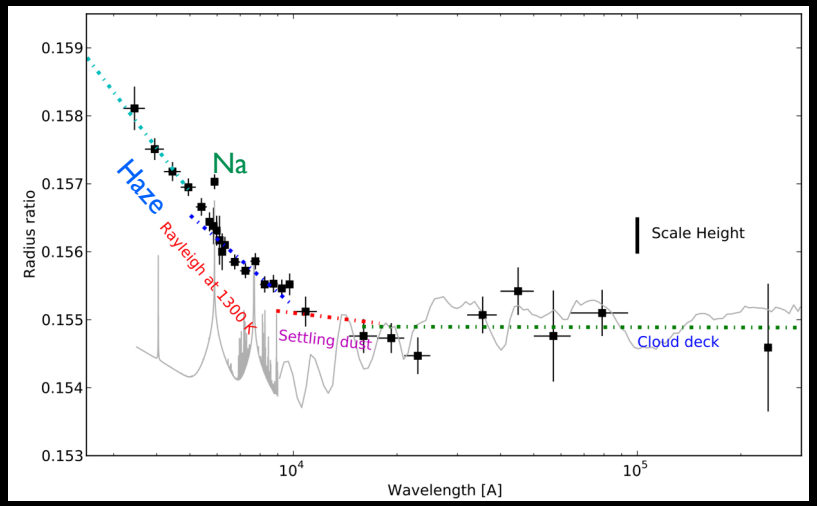
**Possible Thermosphere**

Charbonneau et. al. (2002)
Sing et al. ('08a,'08b)
Desert et al. (0209)
Agol et al. (2010)
Lecavelier et al. (2008)
Rowe et al. (2008)
Burrows et al. (2008)
Crossfield et al. (2012)
Knutson et al. ('07,'08)
Deming et al. (2013)
Vidal-Madjar (2011)

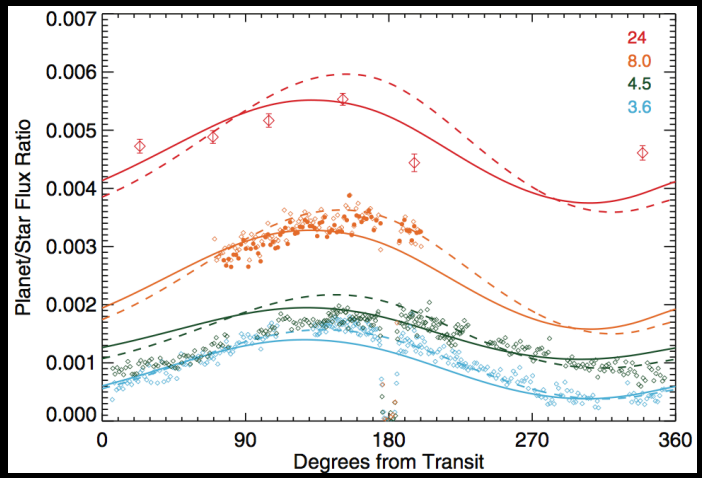
# HD 189733b: our best characterised exoplanet



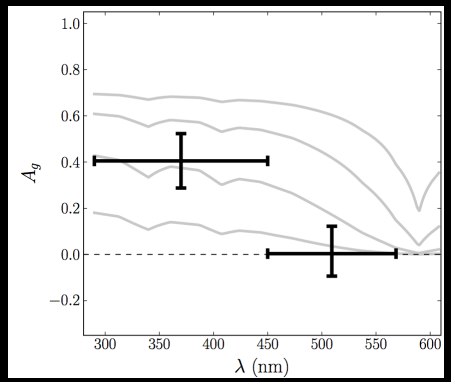
## Transmission




## Phase Curve




## Albedo




**Optical Haze**

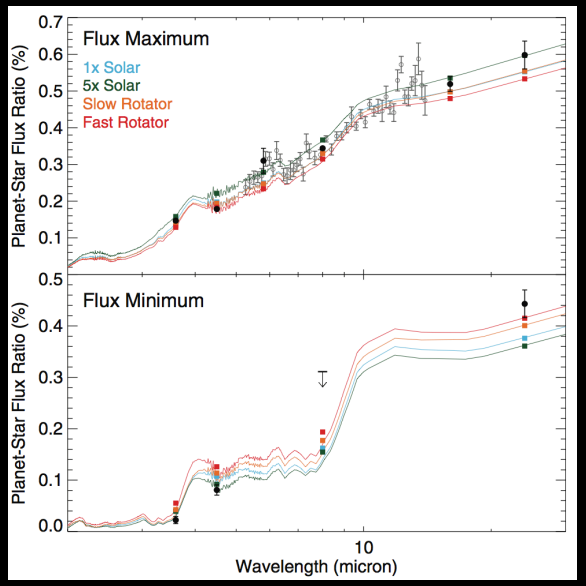
**'blue planet'**

**offset Hot Spot - 'Jets'**

**Na, Hα, $H_2O$ and CO present**

**Efficient heat re-distribution**

## Emission

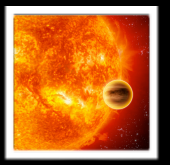



Charbonneau et al. (2008)
Grillmair et al. (2007)
**Knutson** et al. ('07,'09,**'12**)
**Pont** et al. ('07,**'13**)
Sing et al. ('09, '12)
de Kok et al. (2013)
Birkby et al. (2013)
Desert et al. ('09,'11)
Agol et al. (2010)
Gibson et al. ('11,'12)
Huitson et al. (2012)
**Evans** et al. (**2013**)
Jensen et al. (2012)

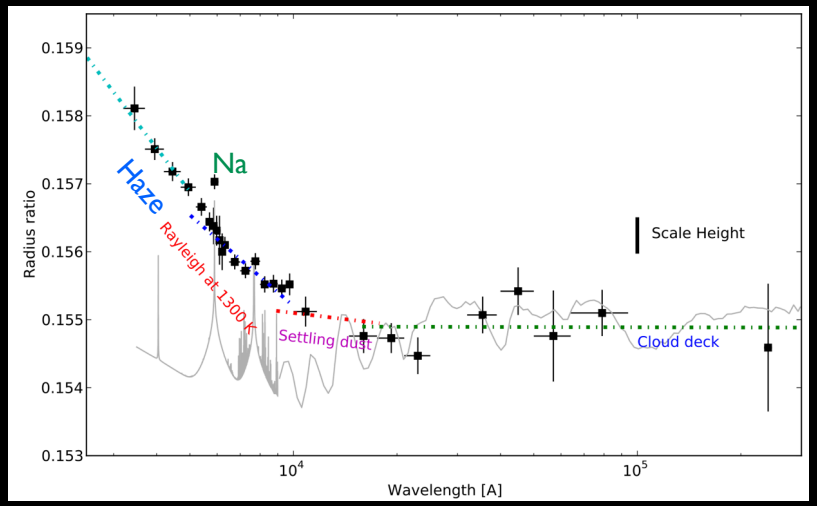
UNIVERSITY OF EXETER

David K. Sing

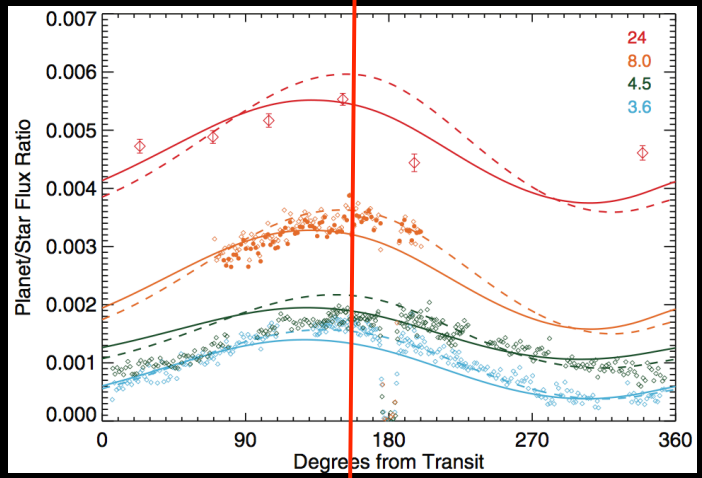
# HD 189733b: our best characterised exoplanet



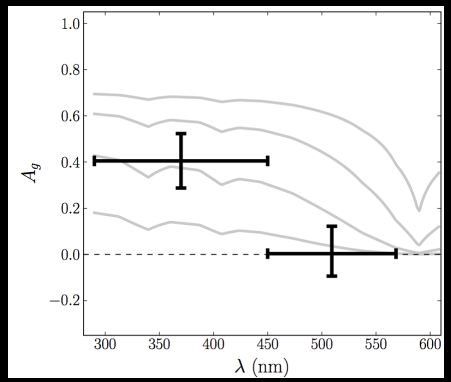
## Transmission




## Phase Curve



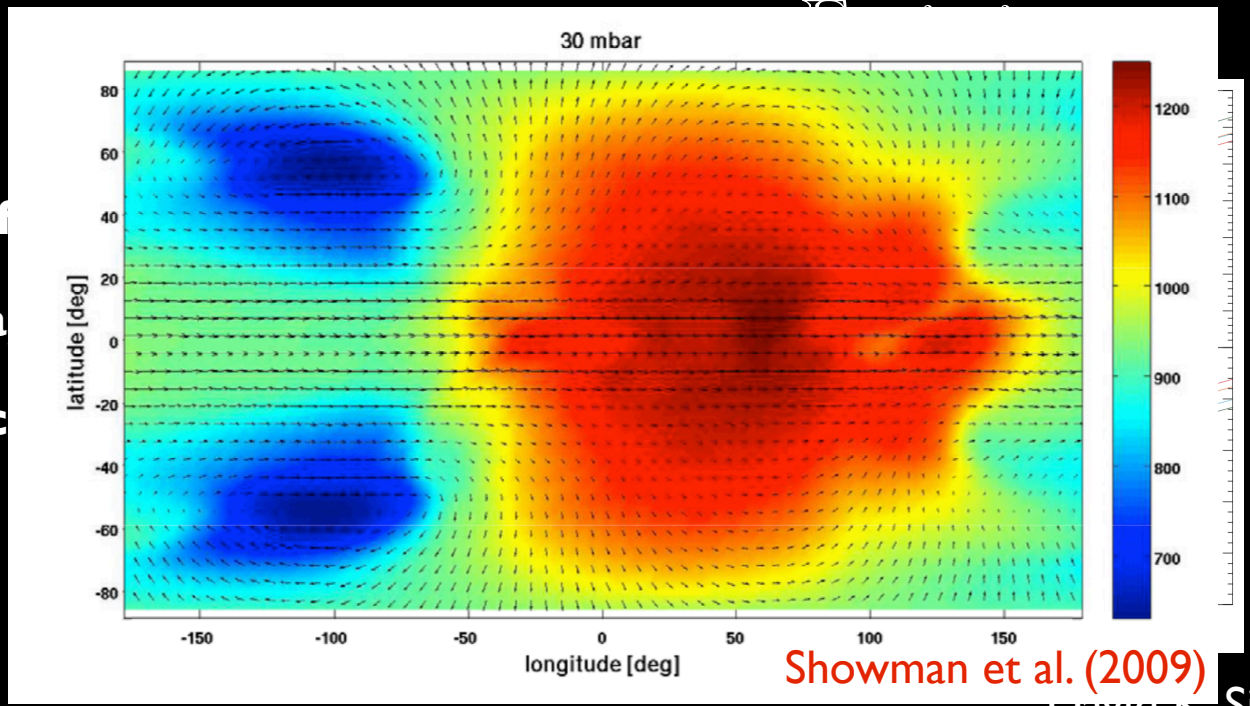

## Albedo




**of**

**Na**

**Effic**




Showman et al. (2009)

Charbonneau et al. (2008)
Grillmair et al. (2007)
**Knutson** et al. ('07,'09,**'12**)
**Pont** et al. ('07,**'13**)
Sing et al. ('09, '12)
de Kok et al. (2013)

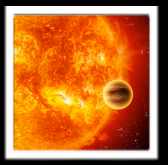
**Evans** et al. (**2013**)

Jensen et al. (2012)

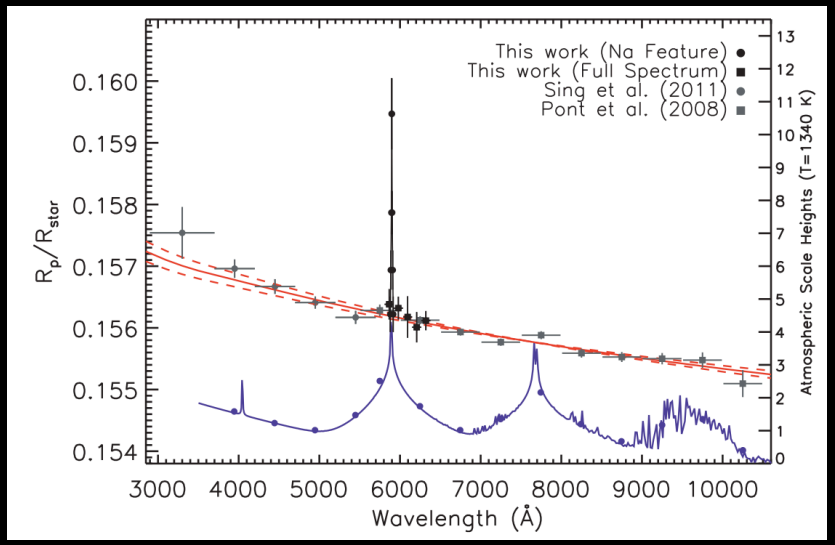
UNIVERSITY OF EXETER

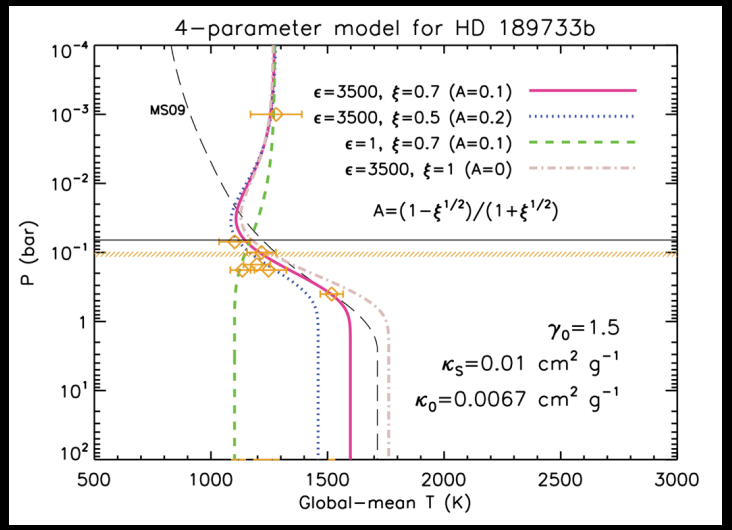
David K. Sing

# HD 189733b: a condensate 'haze'?

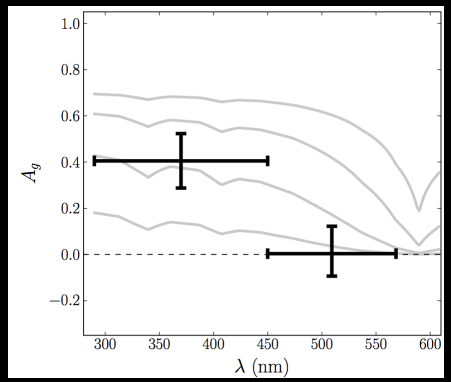


## Transmission




## Albedo

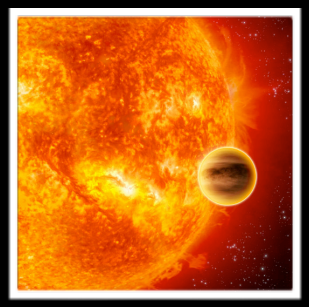



**'blue planet'**

**Condensates vs. Photochemical Haze**

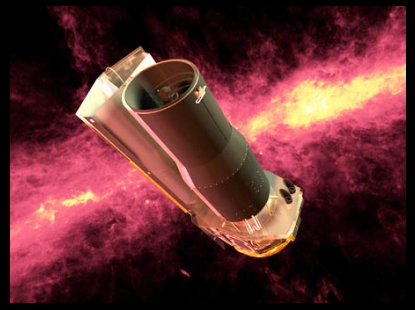
**$MgSiO_3$** **Polycyclic Aromatic Hydrocarbons**
**soot - big PAHs**

Sing et al. (2012)
Lecavelier et al. (2008)
Huitson et al. (2012)
Evans et al. (2013)
Heng et al. (2012)
Zahnle et al. (2009)



# Emission spectrum

## *Temperatures & Albedo*

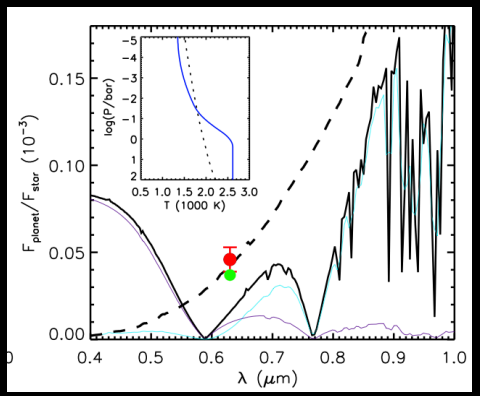


- Thermal Emission flux from planet probes temperature; Optical the Albedo
- Hot-Js often have low albedos (*but not always*)

  Tres-2b is Dark (Ag=0.025+/-0.007)

  Kepler-7b is Bright

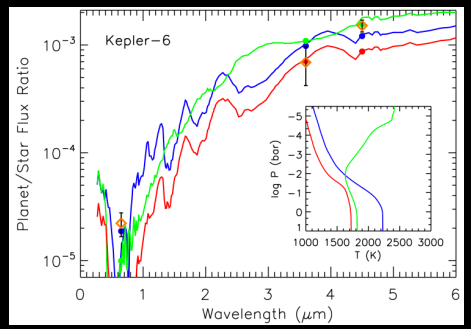
Kepler




Demory et al. (2011)

(Ag=0.32+/-0.03)

Kepler + Spitzer




Desert et al. (2011)

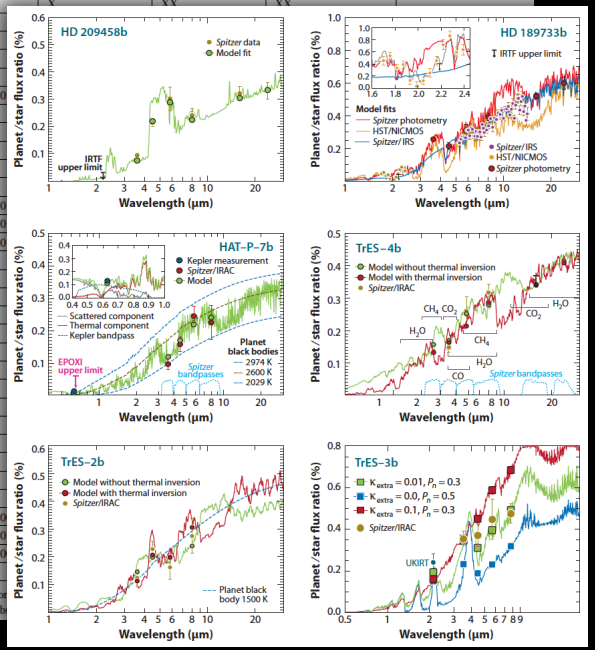
$A_B = 11\%$

$T = 1660$ K

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

| ID | 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 |
| HAT-2 | X | X | XX | XX | |
| HAT-3 | X | | | | |
| HAT-4 | X | | | | |
| HAT-5 | XX | | | | |
| HAT-6 | X | | | | |
| HAT-7 | 0.098% ± 0.0 | | | | |
| HAT-8 | X | | | | |
| HAT-10 | X | | | | |
| HAT-11 | X | | | | |
| HAT-12 | X | | | | |
| TrES-1 | XX | | | | |
| TrES-2 | 0.135% ± 0.0 | | | | |
| TrES-3 | 0.346% ± 0.0 | | | | |
| TrES-4 | 0.137% ± 0.0 | | | | |
| WASP-1 | XX | | | | |
| WASP-2 | XX | | | | |
| WASP-3 | XX | | | | |
| WASP-4 | XX | | | | |
| WASP-5 | XX | | | | |
| WASP-6 | XX | | | | |
| WASP-7 | X | | | | |
| WASP-8 | | | | | |
| WASP-10 | X | | | | |
| WASP-12 | XX | | | | |
| WASP-14 | X | | | | |
| WASP-17 | | | | | |
| WASP-18 | XX | | | | |
| WASP-19 | XX | | | | |
| XO-1 | 0.086% ± 0.0 | | | | |
| XO-2 | 0.081% ± 0.0 | | | | |
| XO-3 | 0.101% ± 0.0 | | | | |
| XO-4 | XX | | | | |

[a]Tabulation of the exoplanet secon
under way. A single X refers to ob

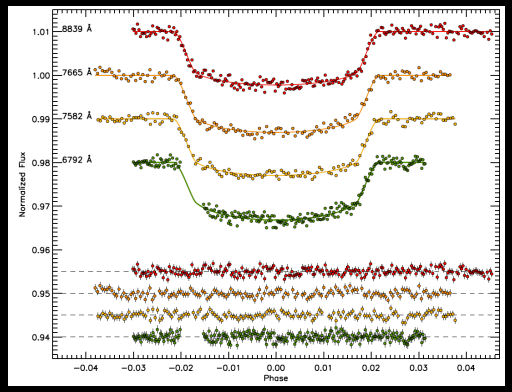


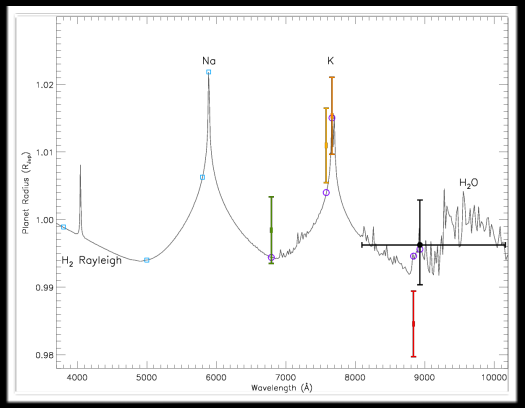

Seager & Deming (2010)

Cowan & Agol (2011)

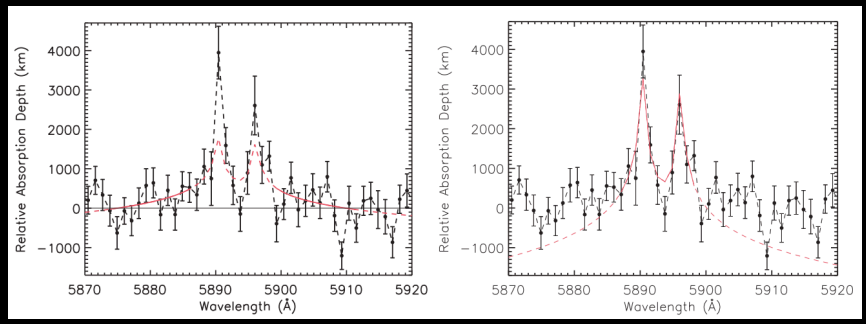
Kipping & Spiegel (2011)

# Hot Jupiters: A story of Alkali Metals

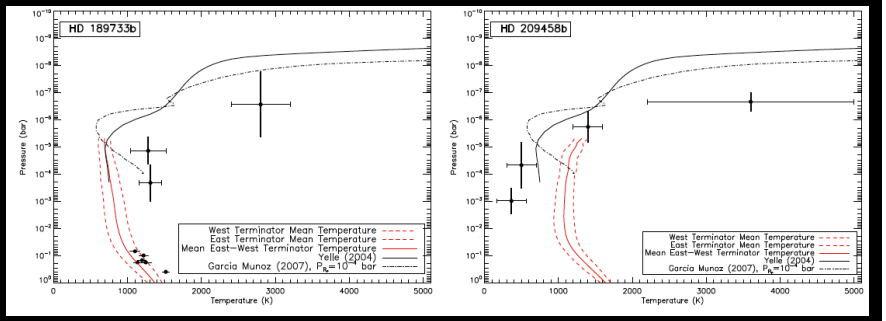



| | |
|---|---|
| XO-2b | Na & K |
| Hat-P-1b | Na |
| Wasp-17 | Na |
| ‘189 | Na |
| **‘209** | **Na** |




Huitson et al. 2012




Na line is narrow (no press. broad)

Strong core indicates Thermosphere

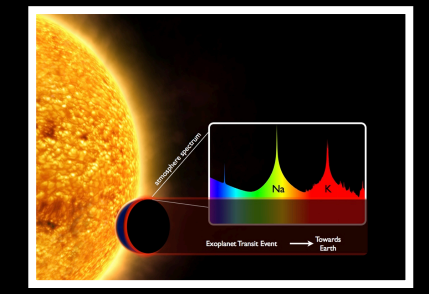
**Narrow vs. Wide Alalki Wings?**

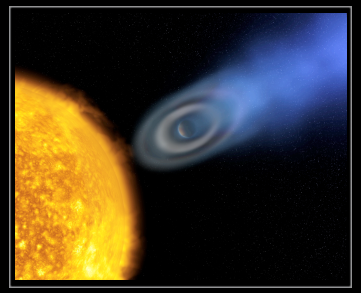
Most Hot Jupiter Alkali Metals seem to have Narrow Alkali Line profile

... but wide wings lead to low albedos which most HJs

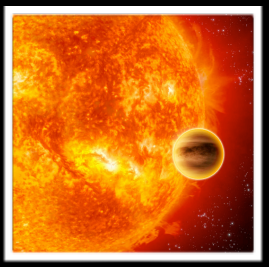
Brown Dwarfs have wide line wings

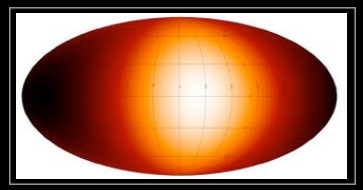
# What Do we know about hot-Jupiters atmospheres??

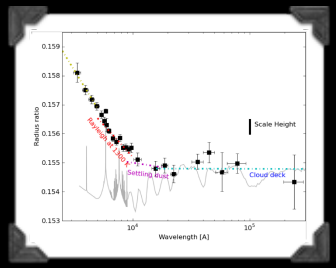


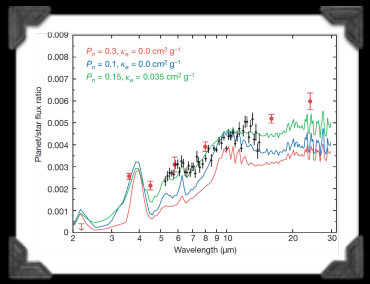



- Most hot Jupiters are very dark
  theory: Na & K absorb optical light
- Alkali metals
- hot Jupiters have escaping atmospheres
- hot Jupiters really are *HOT* (up to 3000 K)
  possible break-down of re-distribution >2000K
- offset dayside hot-spots
  theory: large equatorial jets
- Haze
- Molecules: CO & $H_2O$





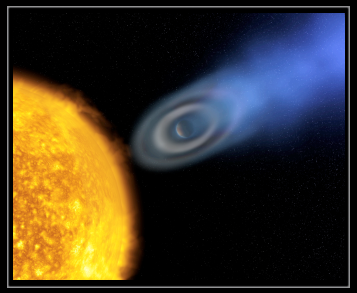


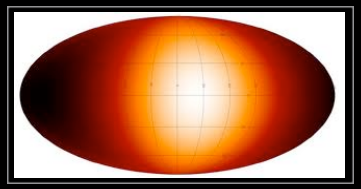




UNIVERSITY OF EXETER

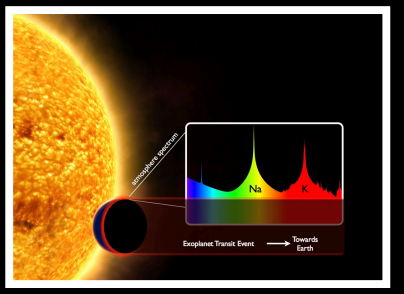
David K. Sing

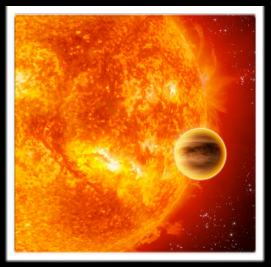
# What Do we know about hot-Jupiters atmospheres??

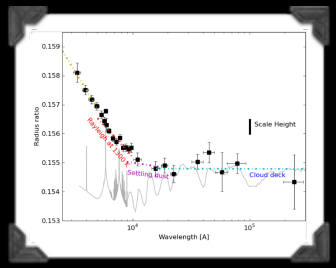


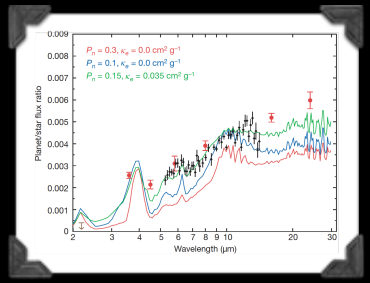


- Most hot Jupiters are very dark
  - theory: Na & K absorb optical light
- Alkali metals
- hot Jupiters have escaping atmospheres
- hot Jupiters really are *HOT* (up to 3000 K)
  - possible break-down of re-distribution >2000K
- offset dayside hot-spots
  - theory: large equatorial jets
- Haze
- Molecules: CO & $H_2O$





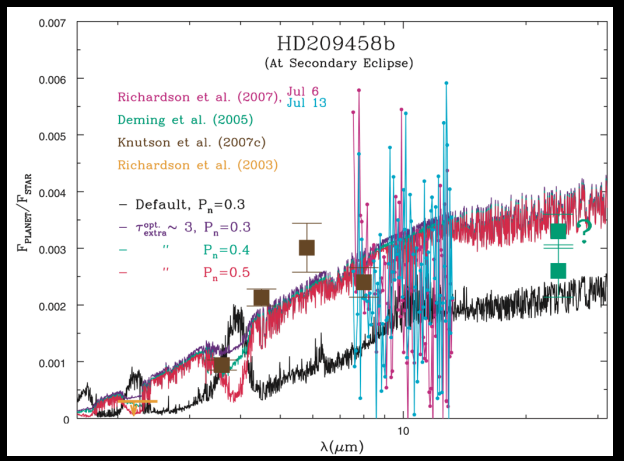

**Have bits and pieces of puzzle**
**no comprehensive theory of H-Js**

UNIVERSITY OF EXETER

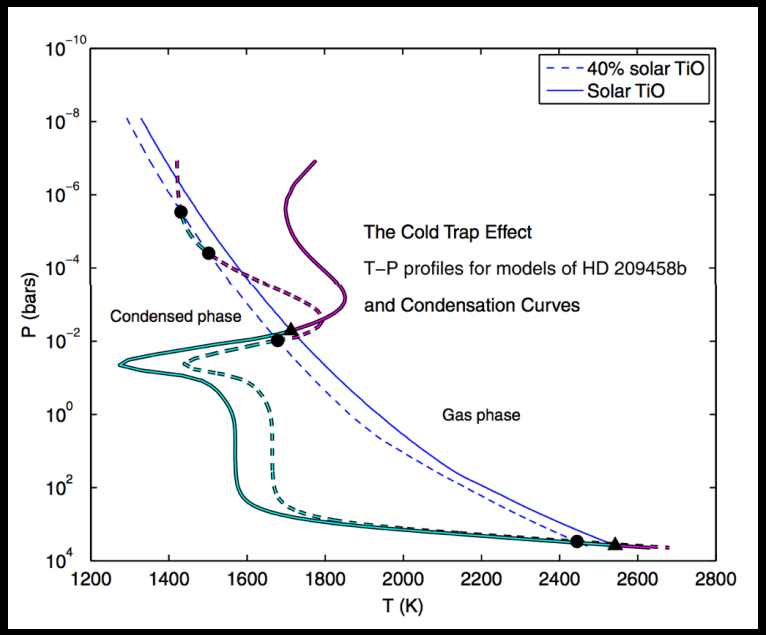
David K. Sing

# Outstanding questions?

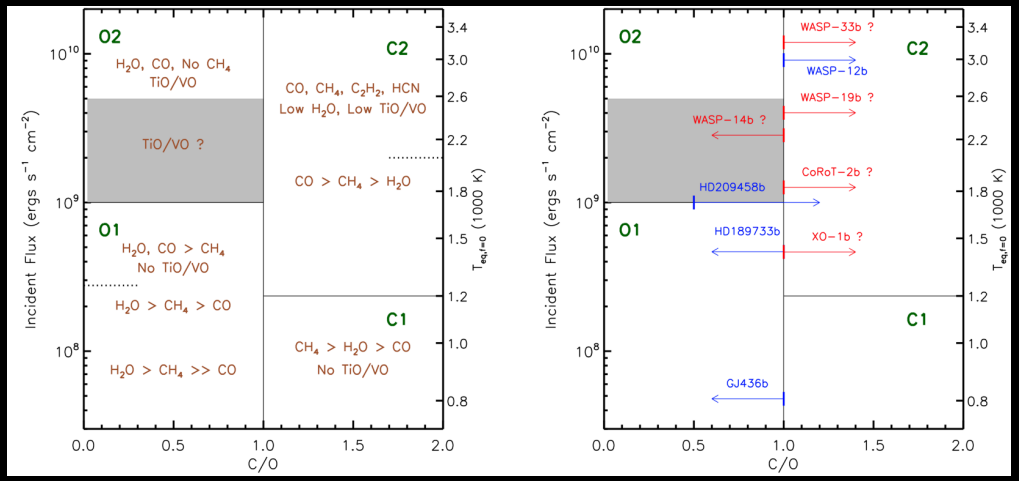
The presence of Thermal inversions




Role of TiO?




high C/O ratios?

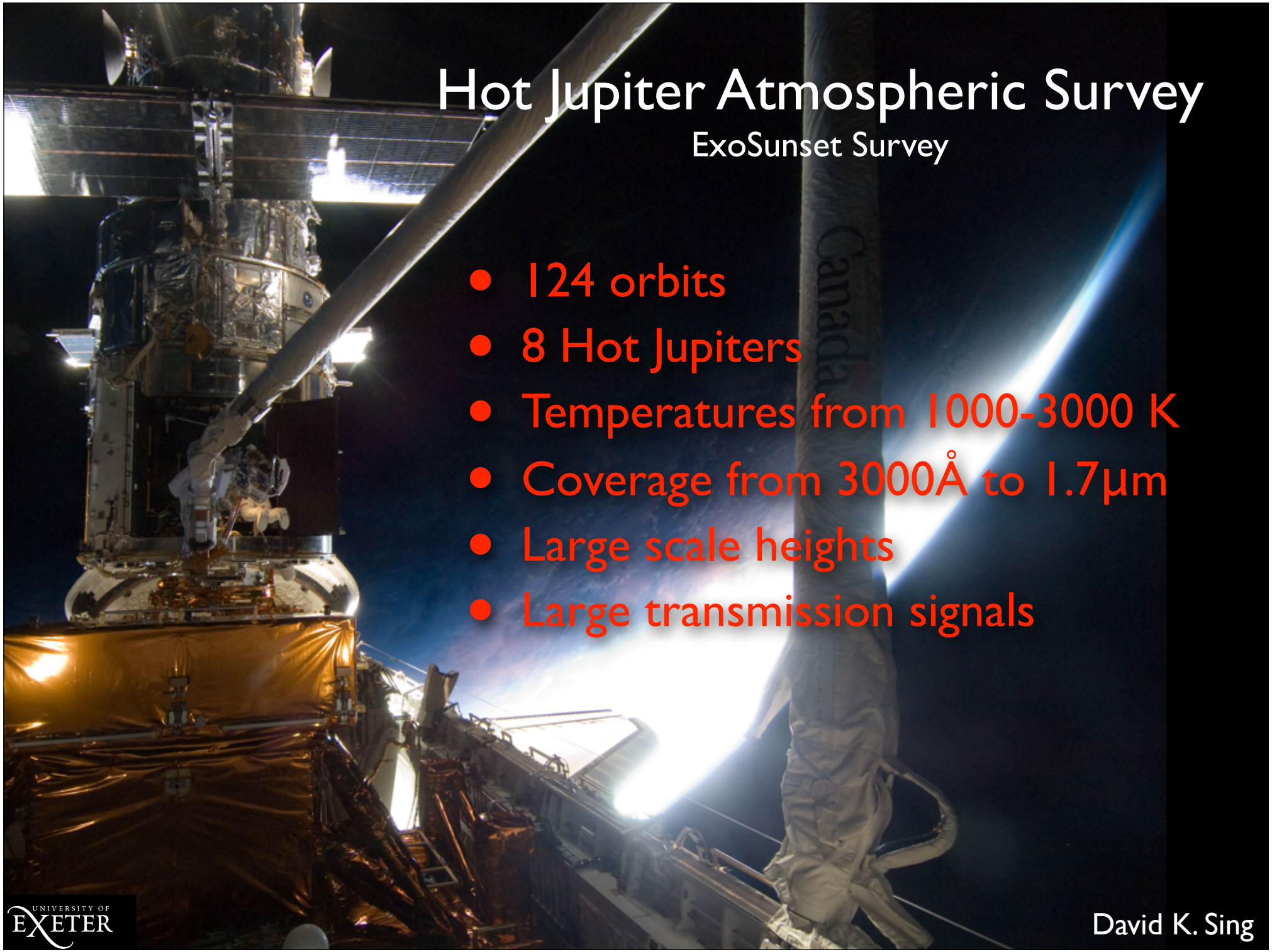



Cold Traps?

Stellar Activity?

Clouds?

Knutson et al. 2008, 2010; Burrows et al. 2008; Fortnety et al. 2008; Spiegel et al. (2009) Madhusudhan et al. 2012)

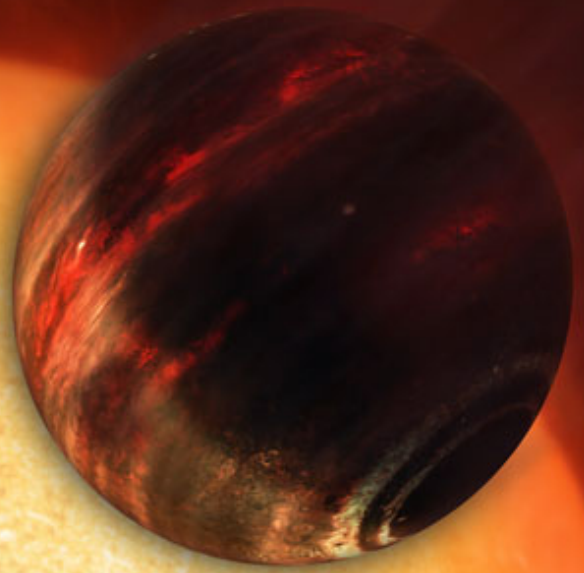

Hot Jupiter Atmospheric Survey
ExoSunset Survey
• 124 orbits
• 8 Hot Jupiters
• Temperatures from 1000-3000 K
• Coverage from 3000Å to 1.7μm
• Large scale heights
• Large transmission signals
UNIVERSITY OF EXETER
David K. Sing

# Hot Jupiter Atmospheric Survey

Key H-J Facts: Most hot Jupiters are dark
hot Jupiters really are *HOT* (up to 3000 K)

atmosphere is *dominated* by stellar irradiation

Fate of incoming starlight essential to understanding the overall atmosphere





<u>Constraints needed</u>

*optical opacities*

altitude of absorption

*infrared opacities*

altitude of emission

Optical-near-IR transmission spectra

# Large HST STIS/WFC3 Optical-NIR Program

## Science Goals

- Hot Jupiter sub-classes
- Identify Stratosphere Absorbers (TiO, HS)
- Clouds & Hazes
- Measure abundances, constrain T-P profile

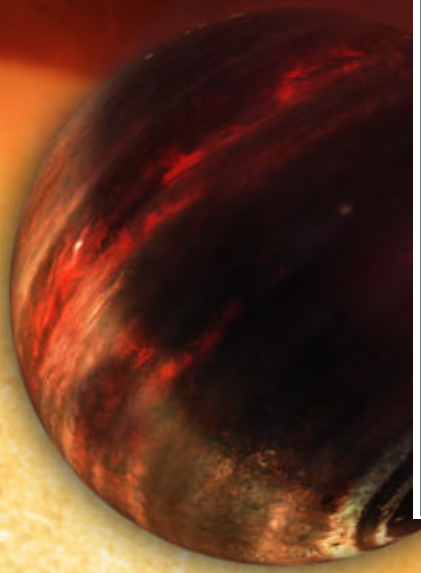


**Table 1. Hot-Jupiter Target List** ($T_{eff}$ is estimated equilibrium temperature)

| Target | Period (days) | $R_{planet}$ (Jup) | $M_{planet}$ (Jup) | $T_{eff}$ (K) | g ($m/s^2$) | Irradiation ($ergs/s/cm^2$) | $V_{mag}$ | H (km) |
|---|---|---|---|---|---|---|---|---|
| Hat-P-12b | 3.21 | 0.96 | 0.21 | 1080 | 5.7 | 2.2E+08 | 12.8 | 680 |
| Wasp-6b | 3.36 | 1.22 | 0.50 | 1340 | 8.3 | 5.2E+08 | 11.9 | 580 |
| Wasp-39b | 4.05 | 1.27 | 0.28 | 1360 | 4.3 | 5.00E+08 | 12.1 | 1140 |
| Hat-P-1b | 4.46 | 1.20 | 0.53 | 1500 | 9.1 | 7.3E+08 | 10.4 | 580 |
| Wasp-31b | 3.4 | 1.54 | 0.48 | 1800 | 5.02 | 1.50E+09 | 11.7 | 1280 |
| Wasp-17b | 3.74 | 1.74 | 0.49 | 1860 | 4.0 | 1.9E+09 | 11.6 | 1670 |
| Wasp-19b | 2.15 | 1.15 | 1.31 | 2319 | 16.6 | 4.10E+09 | 12.3 | 501 |
| Wasp-12b | 1.09 | 1.79 | 1.41 | 2800 | 11.0 | 1.0E+10 | 11.69 | 930 |

observations complete

# Wasp-19b

G5V 5590K very active star

0.016AU (3.7R★)
0.8 days
Rroche ~ 1.5 Rpl

1.31 MJup, 1.15 RJup planet

Teq = 2581K
Tday ~ 2677 K *Spitzer*
Tnight ~ ?*
(Anderson et al. 2011)
Cowan and Agol 2011)

*upcoming HST *WFC3*
(Huitson et al.)
*Spitzer* (Knutson et al.)

A very-hot Jupiter ($T_{eq}$~2600 K)

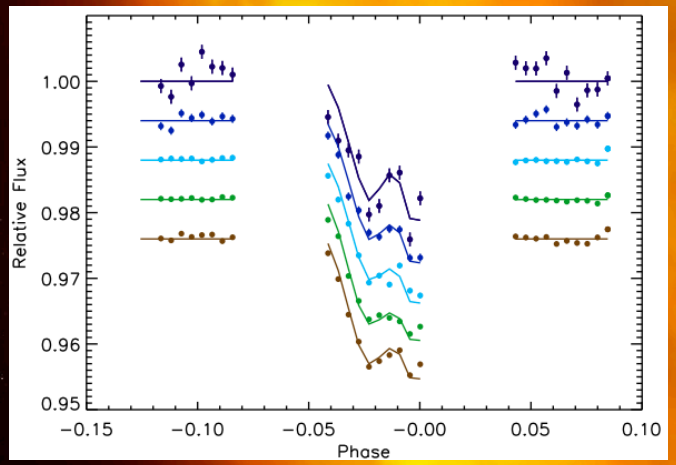
orbiting a very active star

at only 0.016 AU (3.7R★)

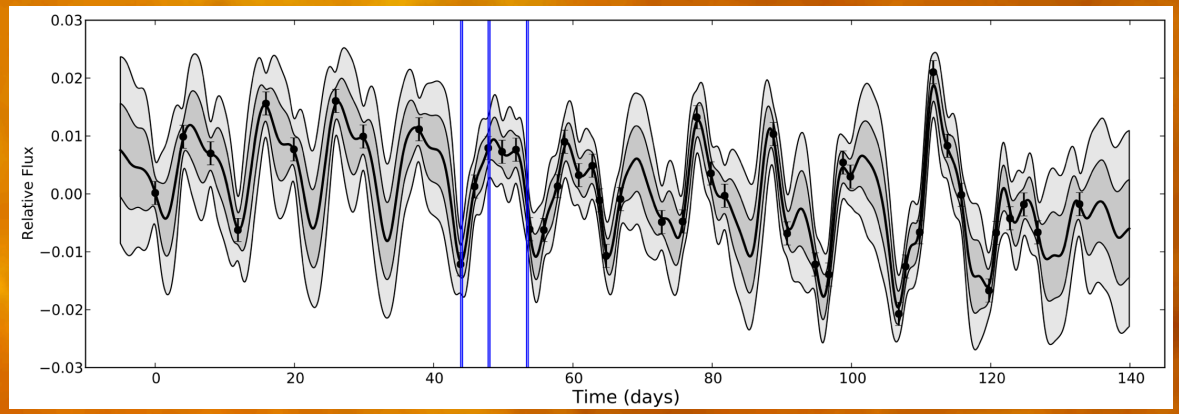
in 19 hours.

(Knutson et al. 2010)

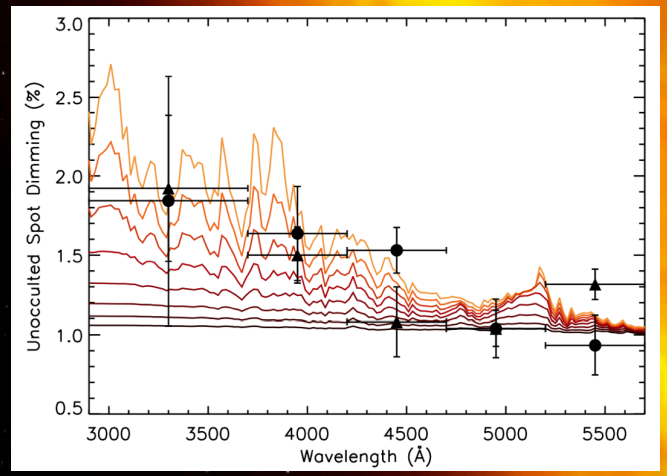
# Wasp-19b




## Activity Monitoring of All HST Targets




$P_{rotation}$ = 10.5±0.2 days




Constrain Spot Temp

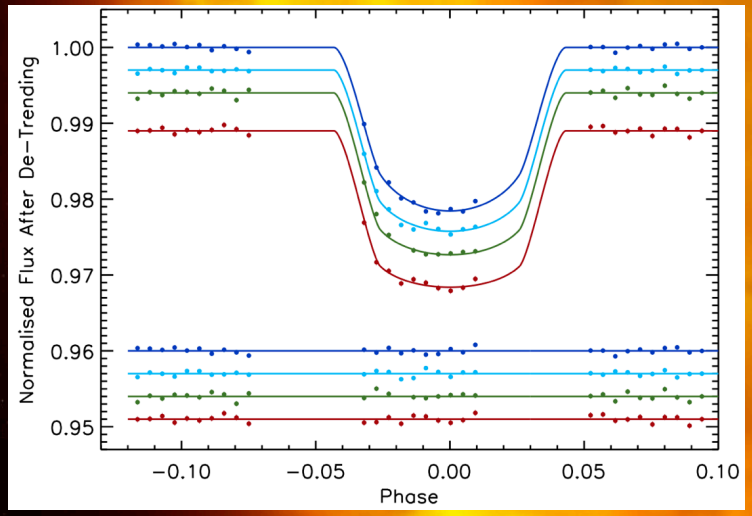
Correct Transmission Spectra for Occulted and Unocculted Spots

5500 K Teff

Activity Correlates with Thermal Inversions (Knutson et al. 2010)

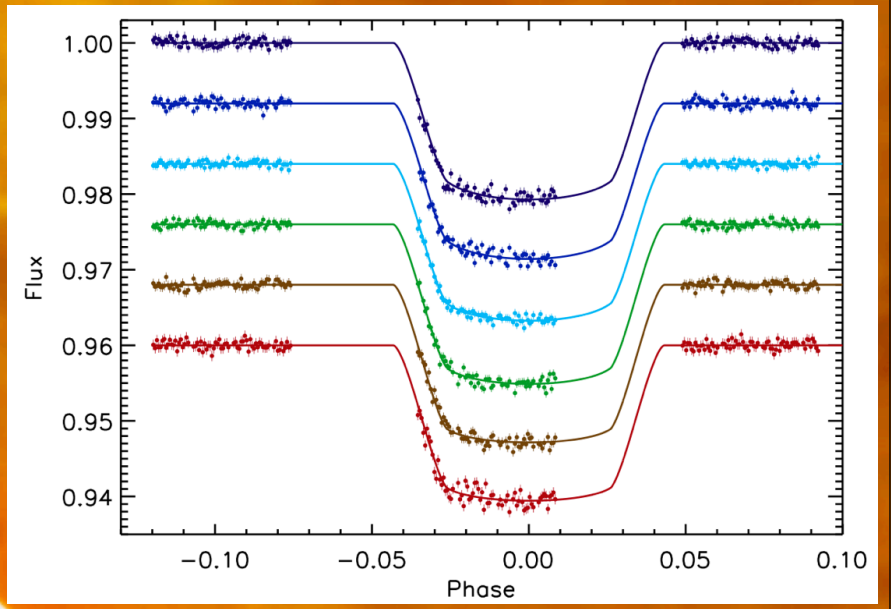
# Wasp-19b

## STIS optical-red




~300 ppm

## WFC3 near-IR



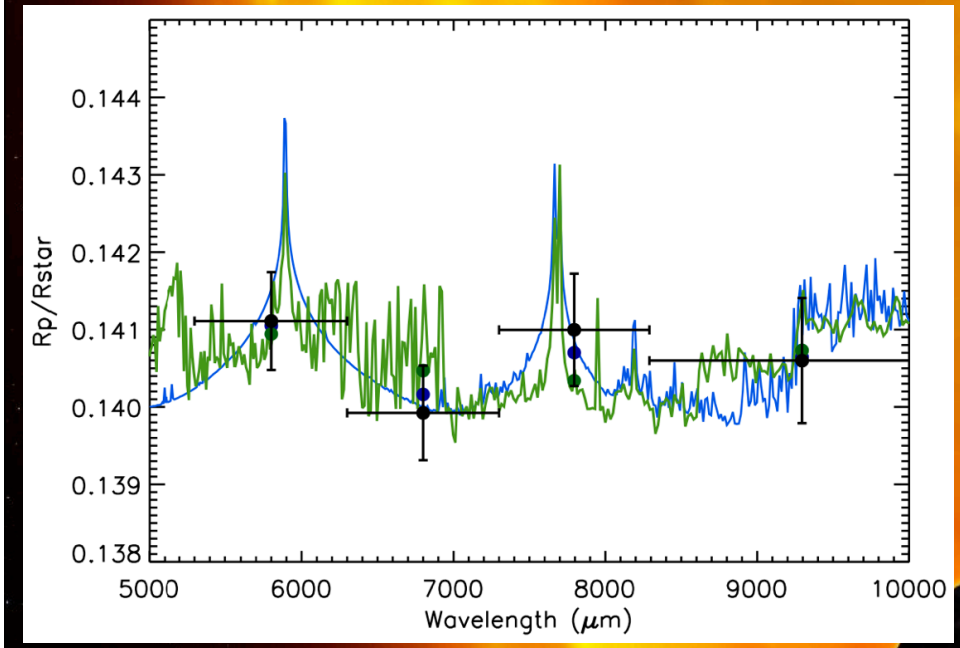

~500 ppm

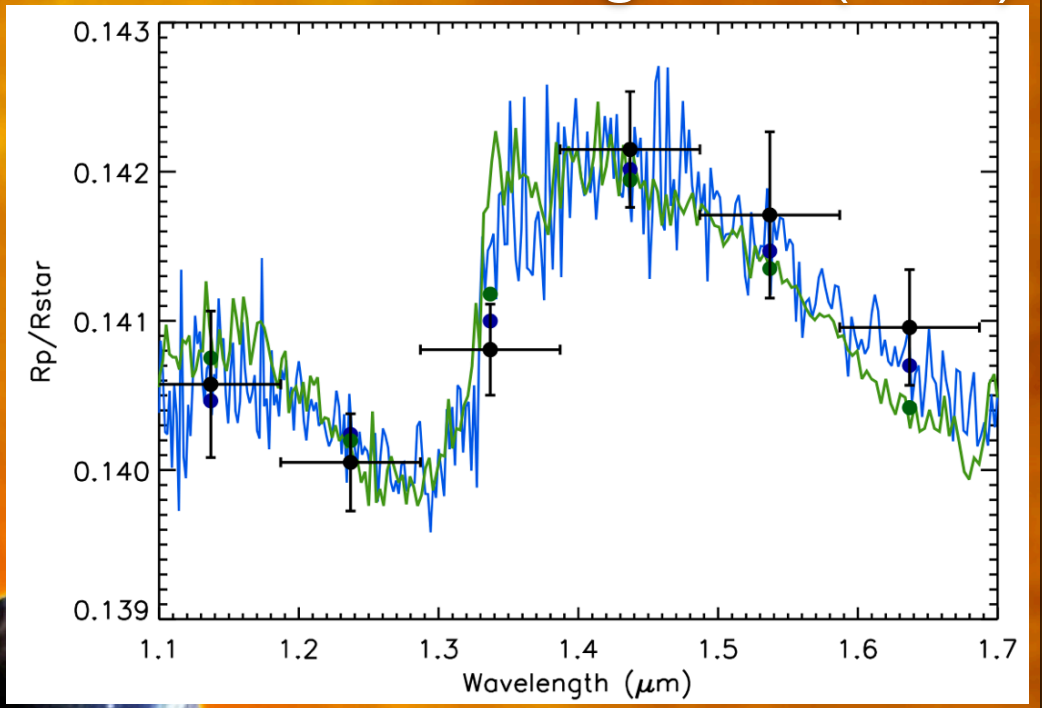
Put together red-Optical with near-IR

Huitson, Sing, et al. (2013)

# Wasp-19b

Huitson, Sing, et al. (2013)




Detect $H_2O$ - amazing consistency with standard models

TiO ruled out despite 2300 K temp

no thermal inversion - activity??

- insufficient mixing??

- high C/O unlikely with $H_2O$ detection

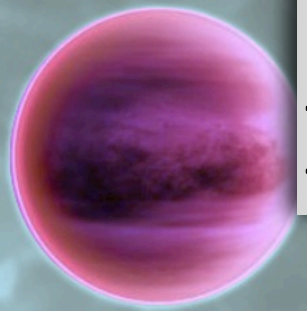
# Wasp-12b

F6V 6300K

0.023AU (3.1R★)
1.1 days
Rroche ~ 1.24 Rpl

1.42 MJup, 1.84 RJup

Tday ~ 2928 K *Spitzer*
Tnight ~ 983 K *Spitzer*

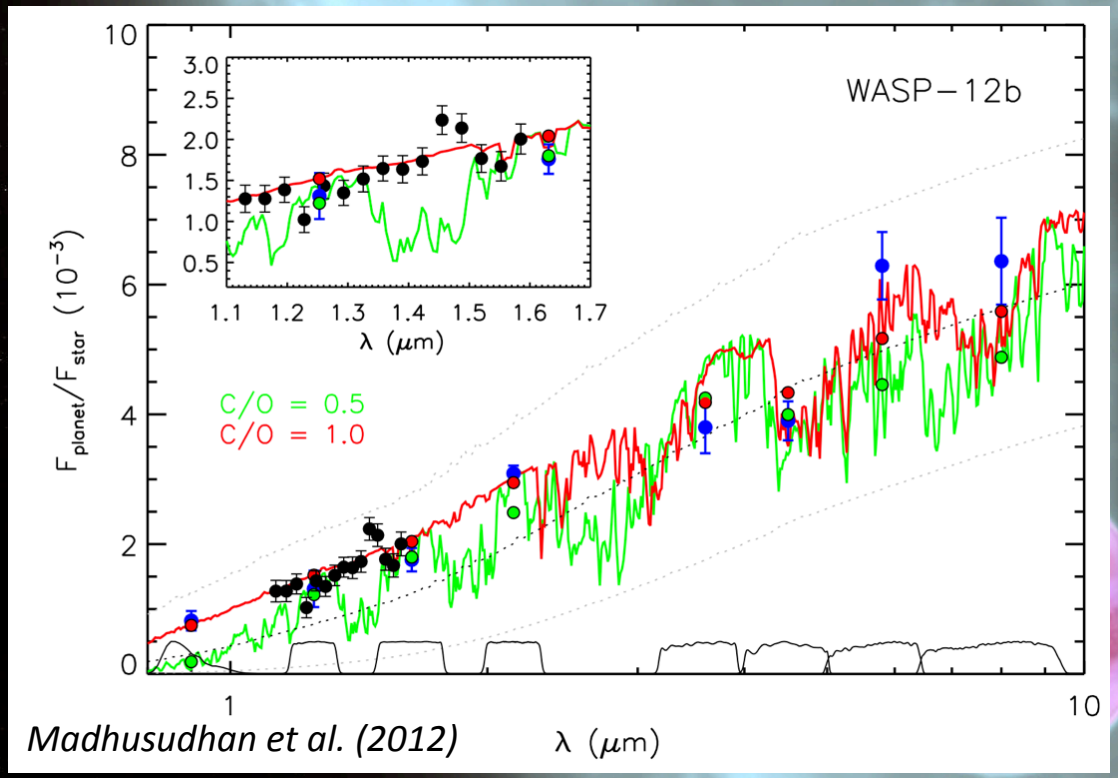


**One of the hottest (Teq~3200K) at 0.023 AU (3.1R★) from hot (but not active) star.**

**Roche lobe radius ~ 1.24 Rpl !**

**This is the potential carbon-rich "diamond planet" with C/O > 1, the tidally-disrupting planet, the bow-shock planet.**

# Wasp-12b




*Madhusudhan et al. (2012)*

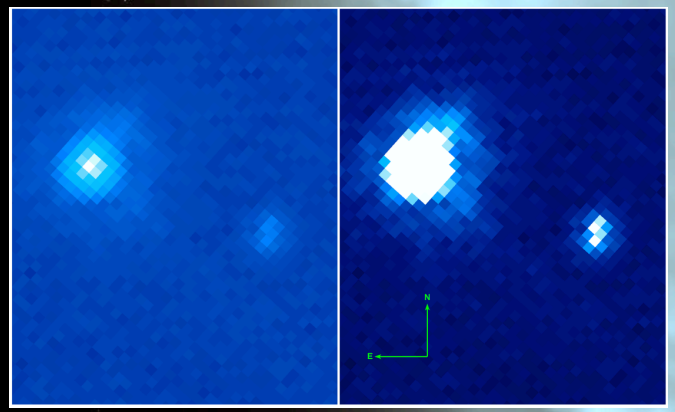
**One of the hottest (Teq~3200K) at 0.023 AU (3.1R★) from hot (but not active) star.**

**Roche lobe radius ~ 1.24 Rpl !**

**This is the potential carbon-rich "diamond planet" with C/O > 1, the tidally-disrupting planet, the bow-shock planet.**

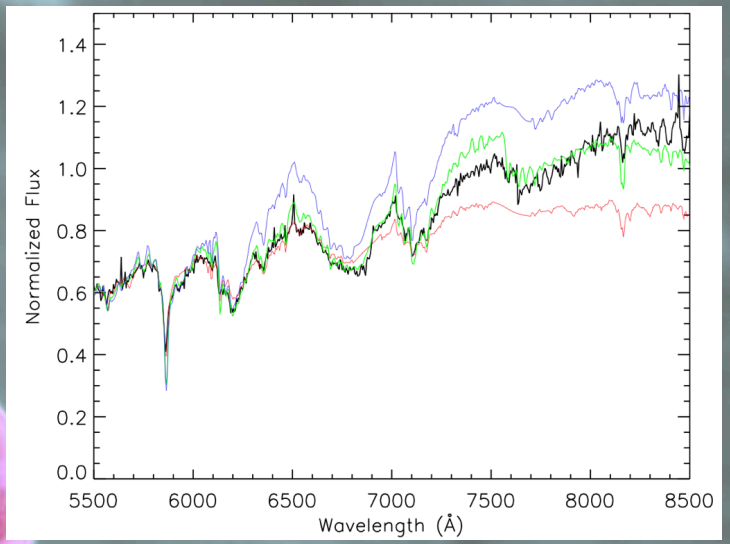
# Wasp-12b

## Wasp-12 is Triple System

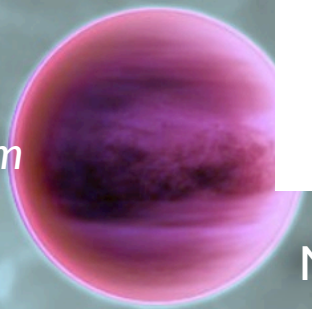


HST acquisition image

M0V equal mass binary (21 AU separation)
Physically associated with Wasp-12A (450 AU separation)




*Implications for Stellar Kozai Migration Mechanism*



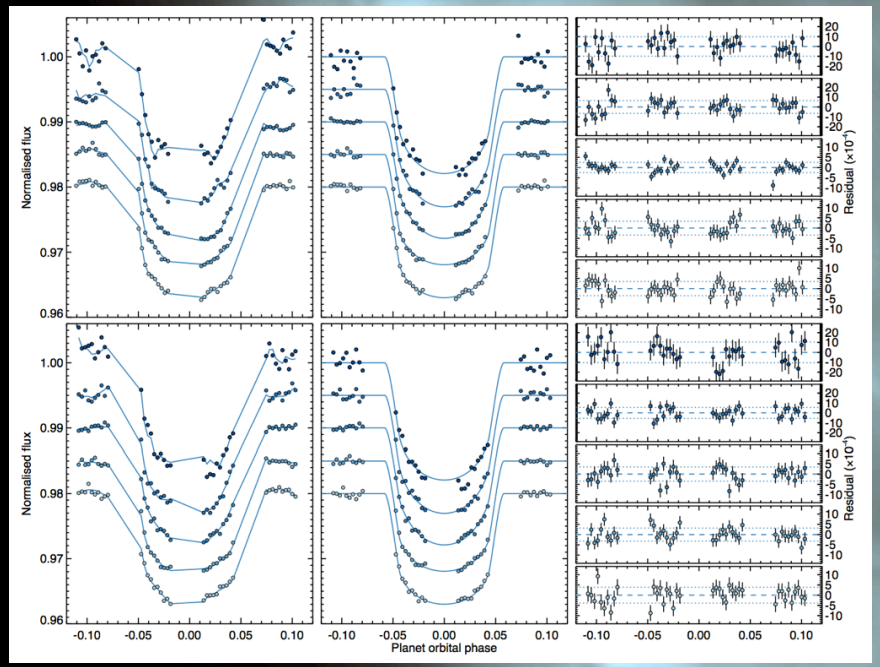
Predicted Spin-orbit misalignment for Kozai migrated planets (Fabrycky & Tremaine 2007)
$59^{+20}_{-15}$ deg for Wasp-12 (Albrecht et al. 2012)

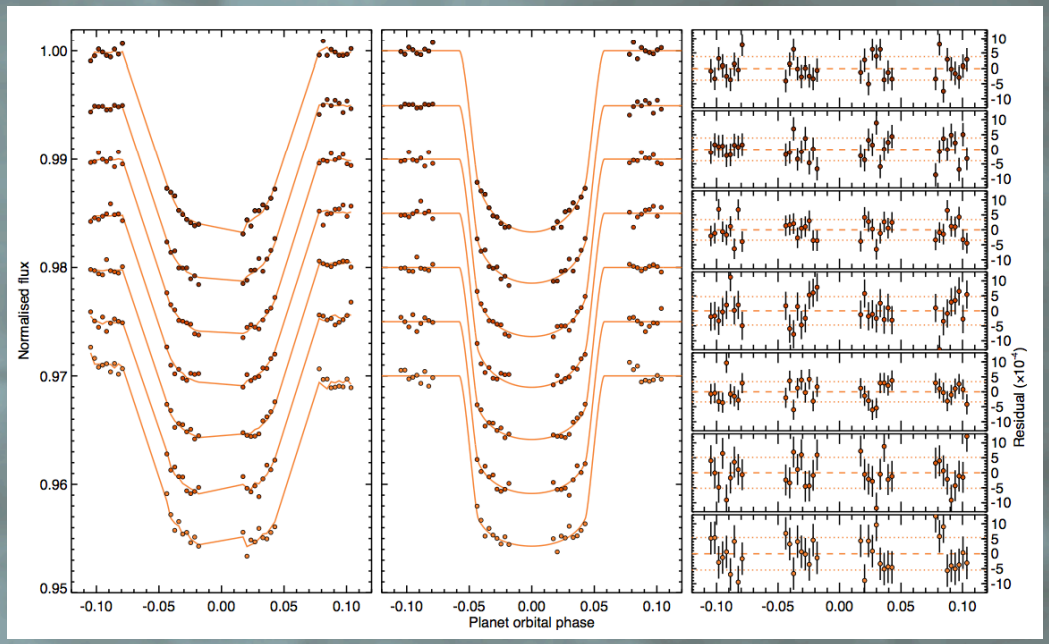
M-dwarf spectral type Teff= 3660 K

Bergfors et al. (2011;2013)
Crossfield et al. (2012)
Sing et al. (2013, submitted)
Bechter et al. (2013)

**Emission spectrum is consistent with Black Body at 3000 K**

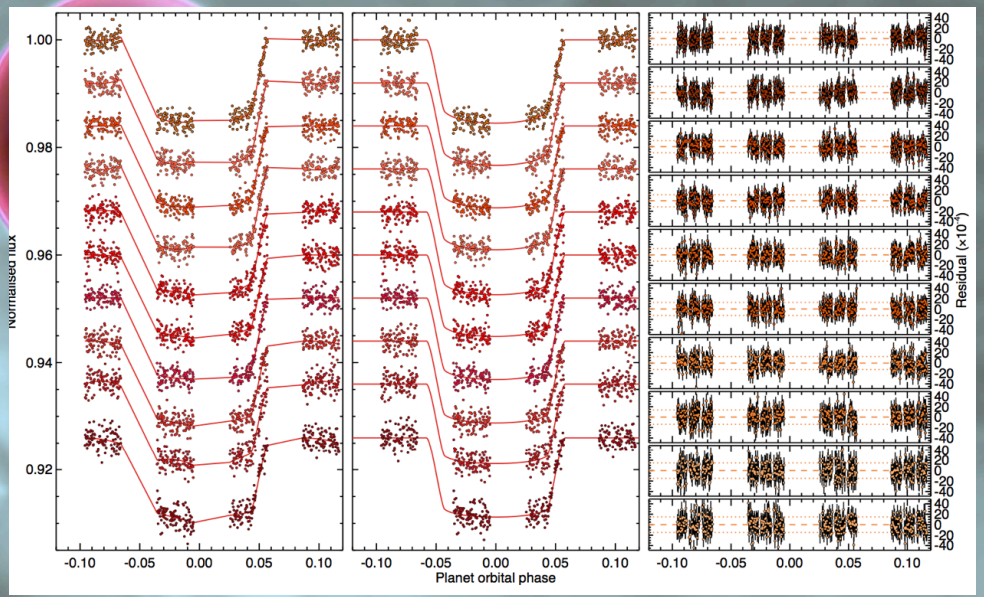
# Wasp-12b



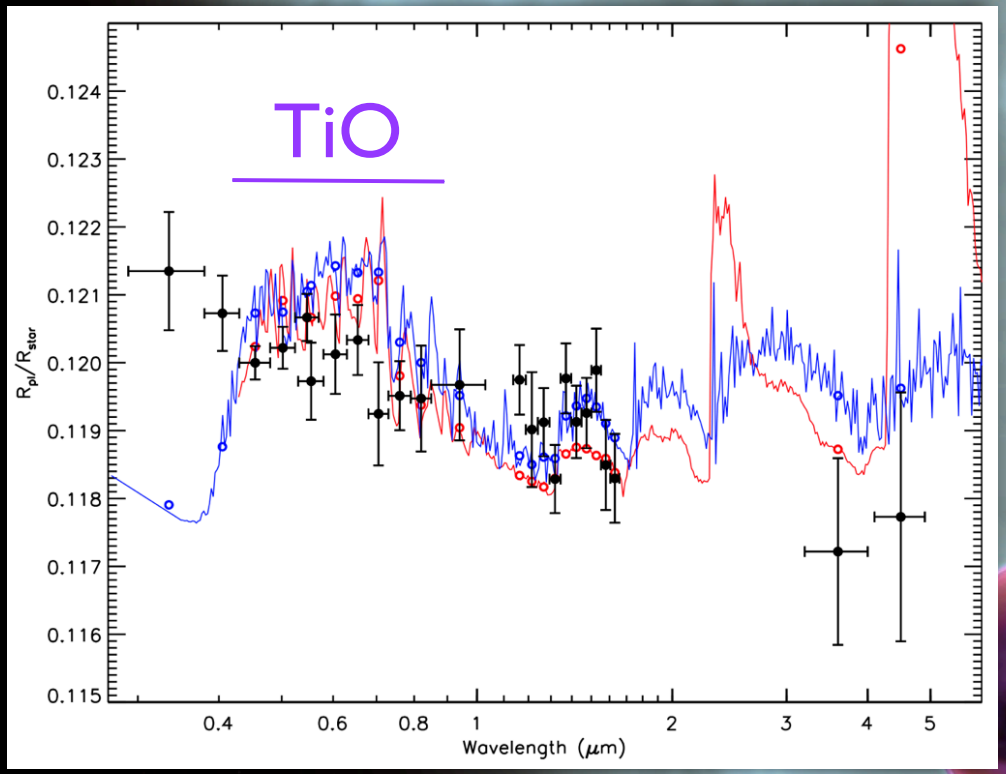




Optical & near-IR

Sing et al. (2013; submitted)



# Wasp-12b



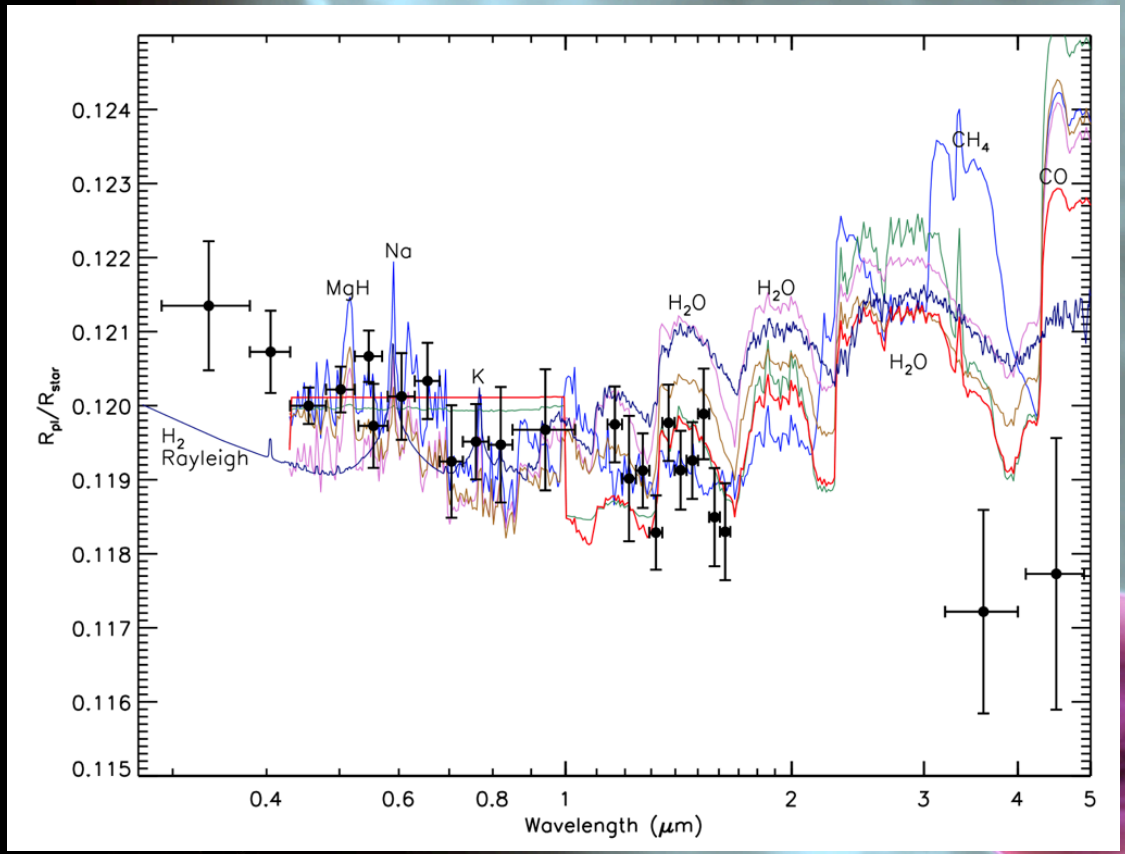

**Muted 1.4 μm water-band absorption (already known; Swain et al. 2013)**

**Optical shows no agreement with CLEAR, solar abundance atmospheric models**

**TiO ruled out**

Sing et al. (2013; submitted)

# Wasp-12b




**Muted 1.4 µm water-band absorption (already known; Swain et al. 2013)**

**Clear Atmospheric models ruled out (variety of C/O & Metallicities)**

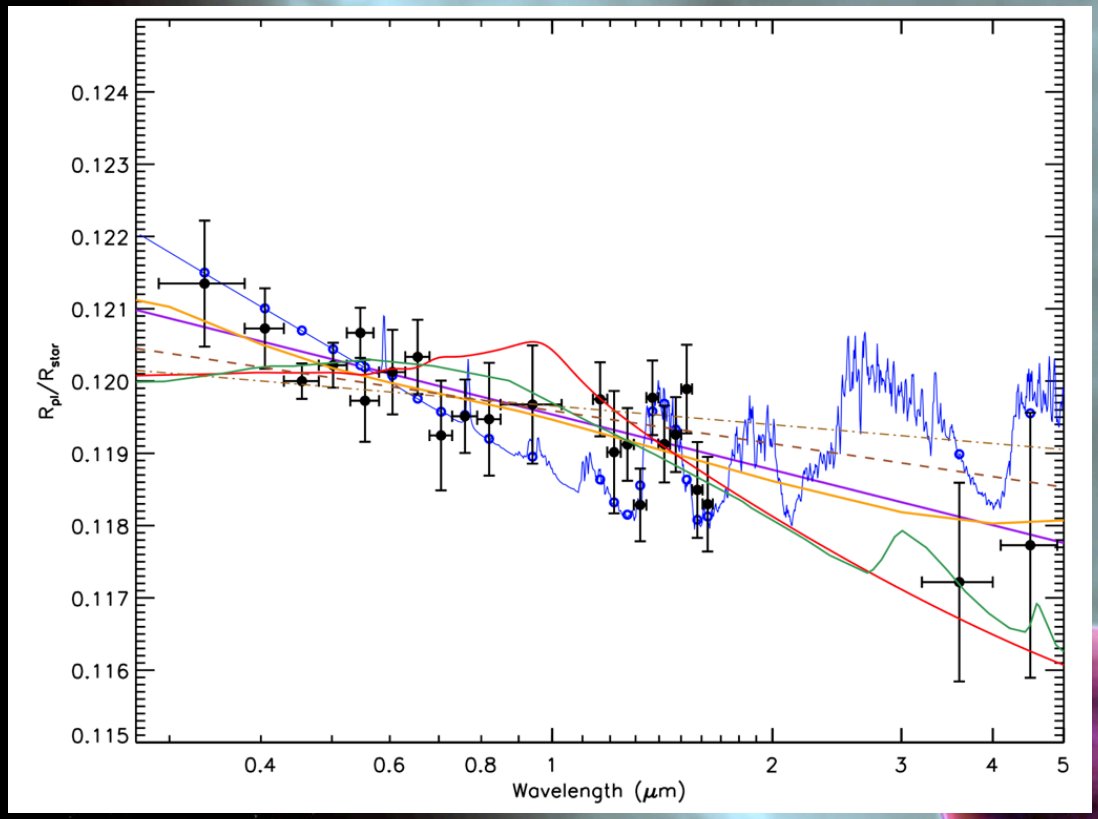
**No metal oxides**

**No metal hydrides**

**No Na or K**

Sing et al. (2013; submitted)

# Wasp-12b




**Best fits Mie scattering $Al_2O_3$ T=1000-3100 K.**

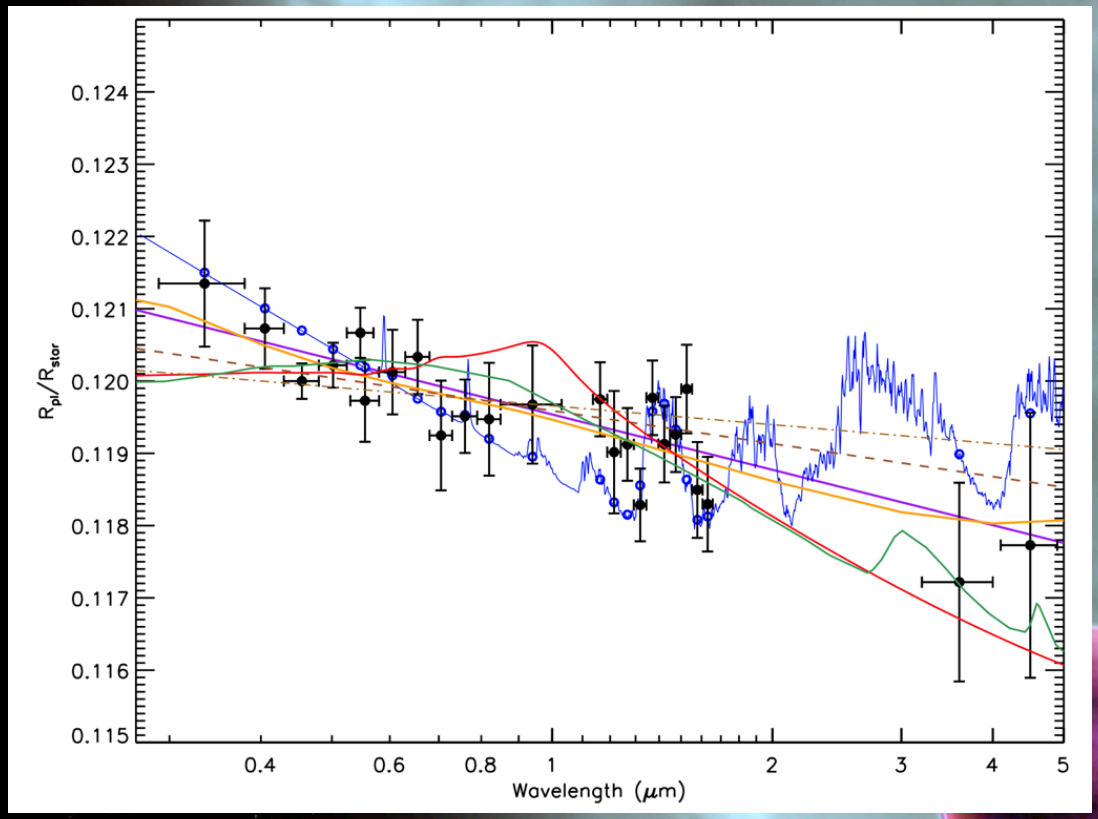
**Rayleigh scattering good fit - but needs a low Temp of 880 K**

**Variety of cloudy/hazy models are acceptable fits**

- Aerosols needed for Transmission
- Helps explain Modest albedo ($A_B$=25%)
- Helps explain black body emission spectrum

Sing et al. (2013; submitted)

# Wasp-12b




**Best fits Mie scattering $Al_2O_3$ T=1000-3100 K.**

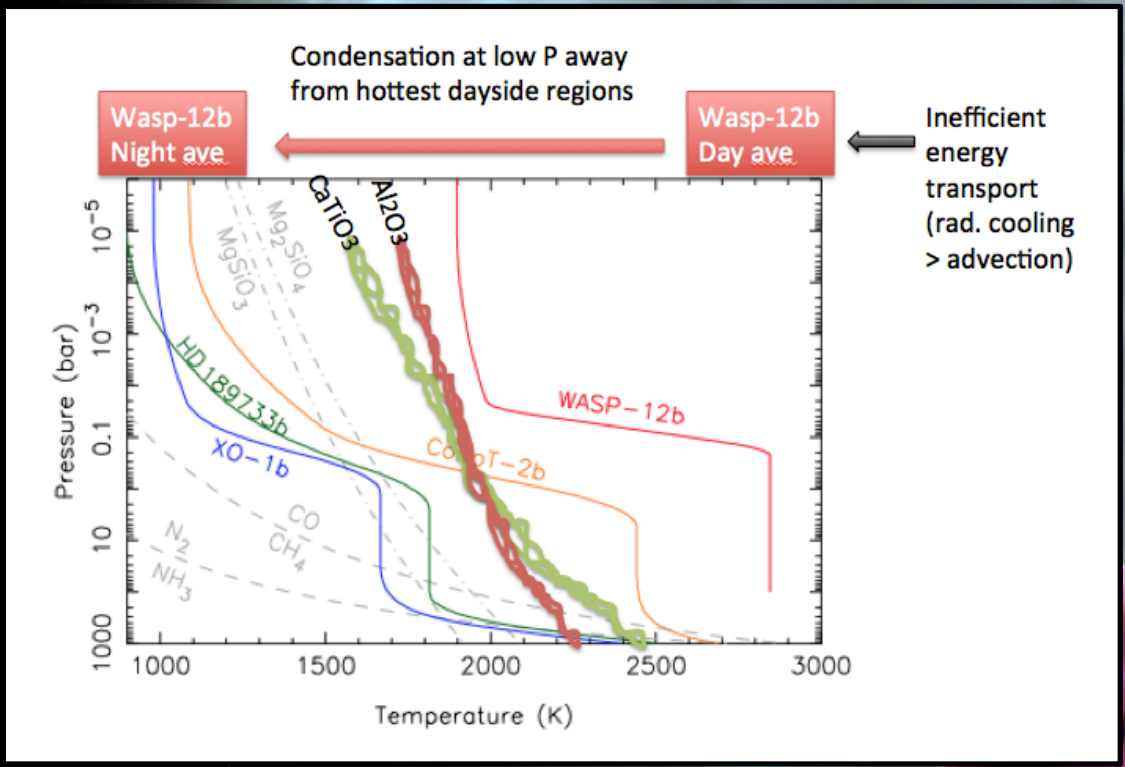
**Rayleigh scattering good fit - but needs a low Temp of 880 K**

**Variety of cloudy/hazy models are acceptable fits**

- Aerosols needed for Transmission
- Helps explain Modest albedo ($A_B$=25%)
- Helps explain black body emission spectrum

Sing et al. (2013; submitted)

# Wasp-12b




day-to-night (condensation)
cold trap?


night-to-day transport and uplifting of finer grains (large effective Kzz) ?

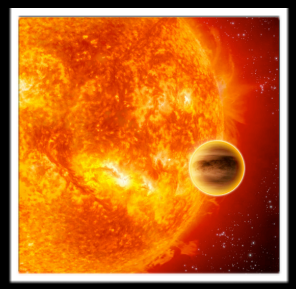
Is this cold-trapping the TiO?

But there are many many unknowns…

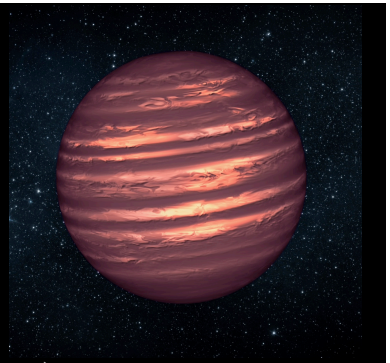
(Spiegel et al. 2009;
Parmentier, Showman& Lian 2013)

- Night Side Cold Trap is leading way to deplete TiO
- May not see TiO in any hot Jupiters

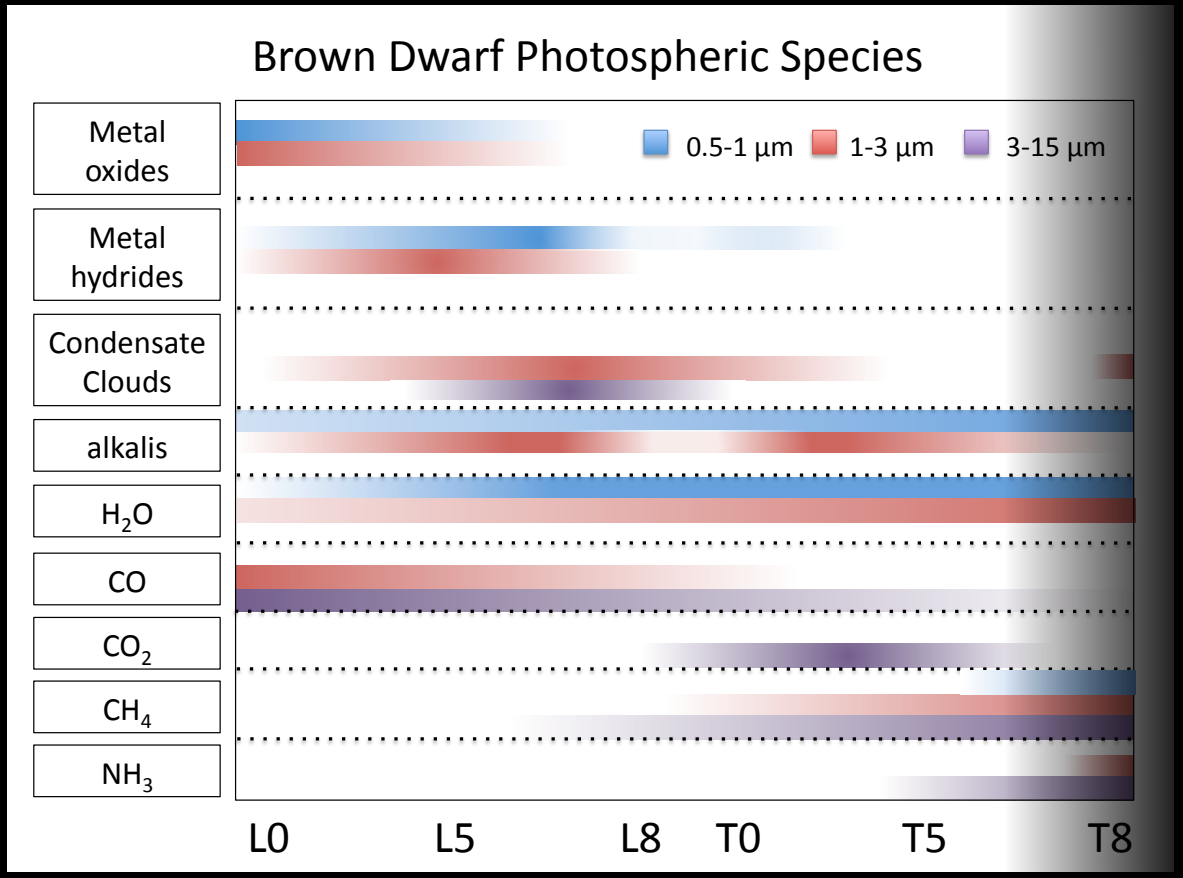
Sing et al. (2013; submitted)



# Hot Jupiter vs. Brown Dwarf Atmospheres

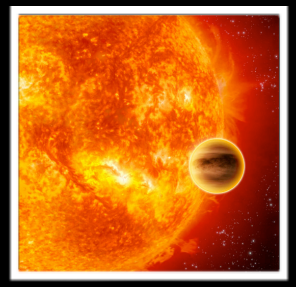


Adapted from Burgasser (2012, ExoMol conference)

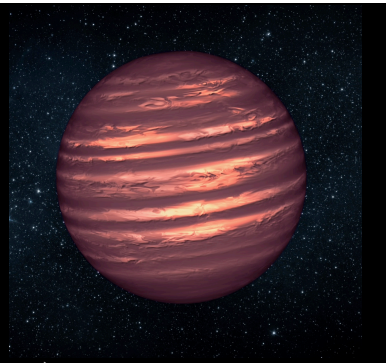



$T_{eq}$ 2400 1800 1500 1200 1000

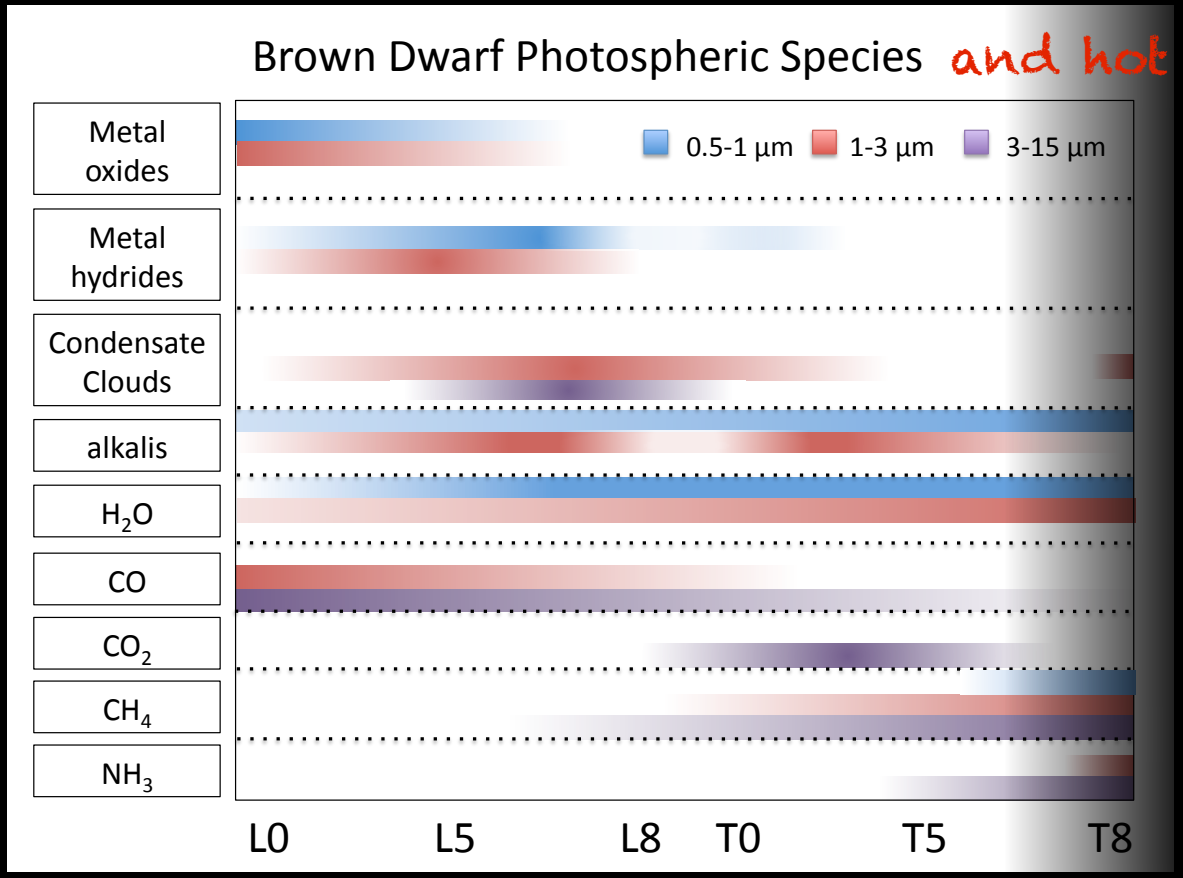
Lodders (1999)
Visscher et al. 2006; 2010)



# Hot Jupiter vs. Brown Dwarf Atmospheres

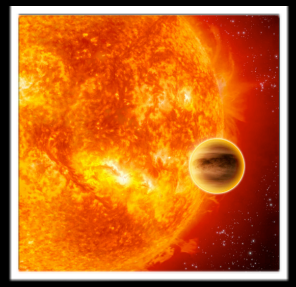


Adapted from Burgasser (2012, ExoMol conference)

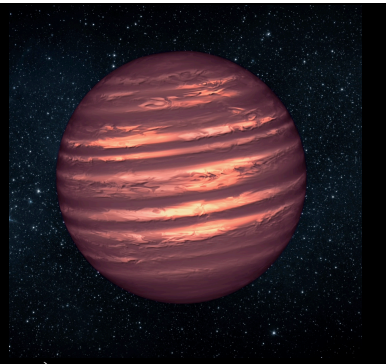



$T_{eq}$ 2400 1800 1500 1200 1000

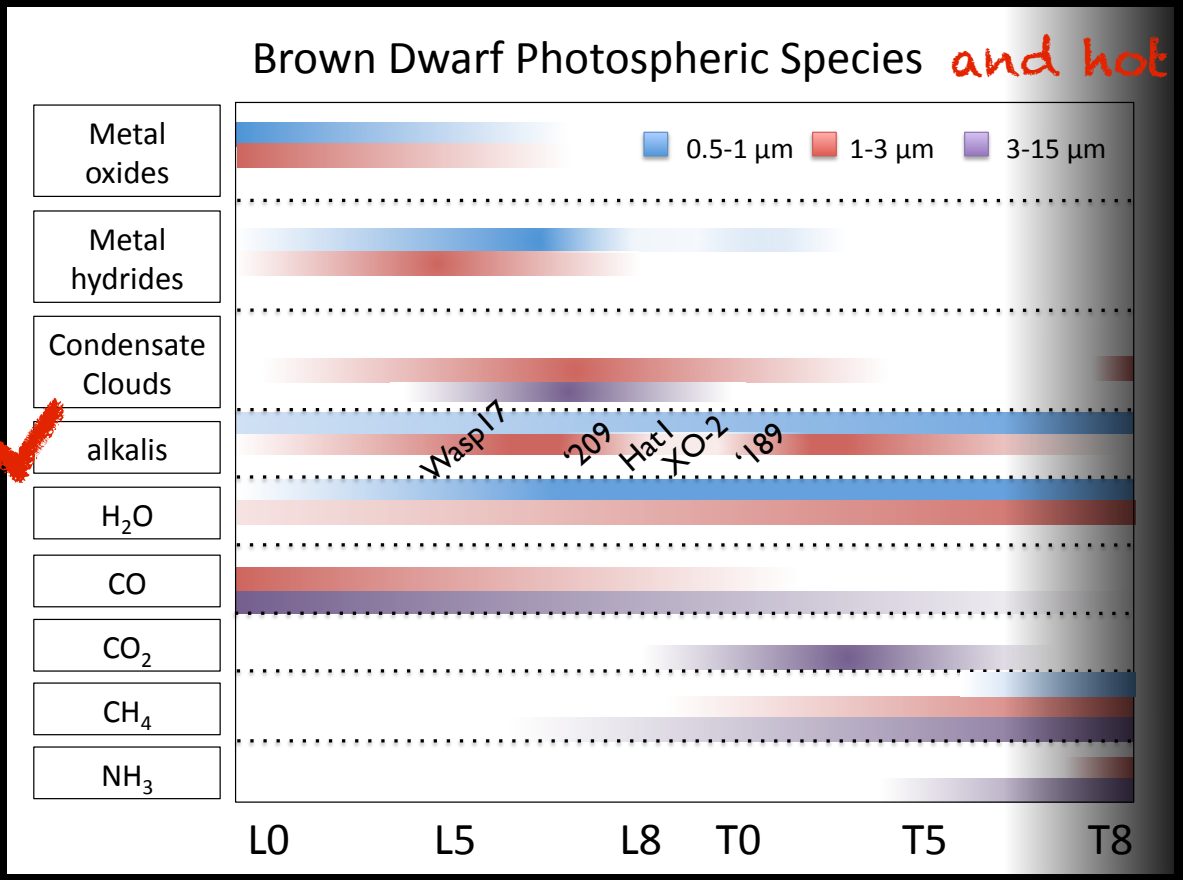
Lodders (1999)
Visscher et al. 2006; 2010)



# Hot Jupiter vs. Brown Dwarf Atmospheres

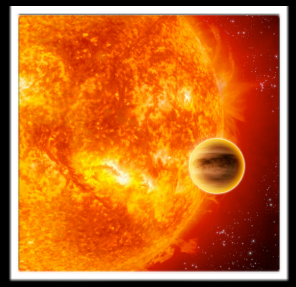


Adapted from Burgasser (2012, ExoMol conference)

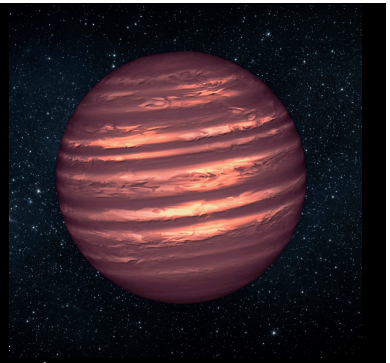



$T_{eq}$ 2400 1800 1500 1200 1000

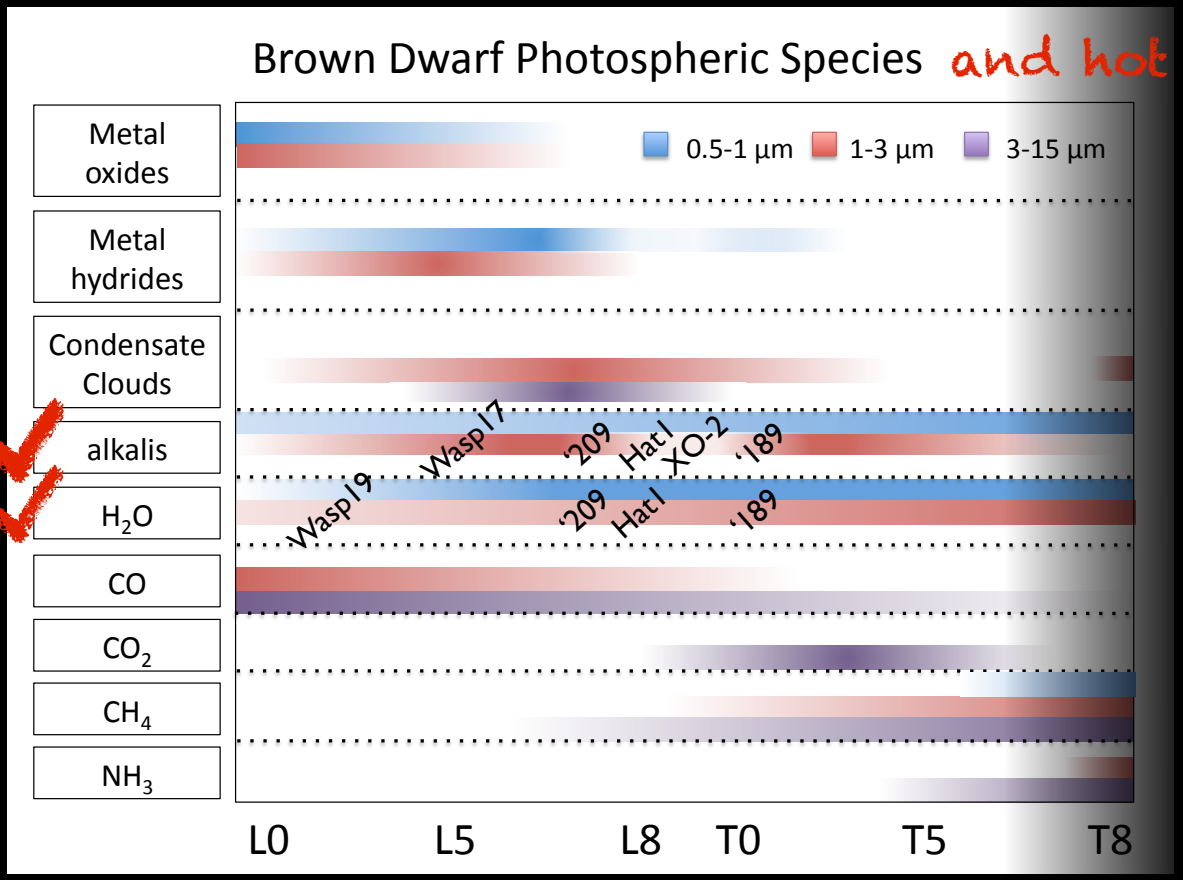
Lodders (1999)
Visscher et al. 2006; 2010)



# Hot Jupiter vs. Brown Dwarf Atmospheres

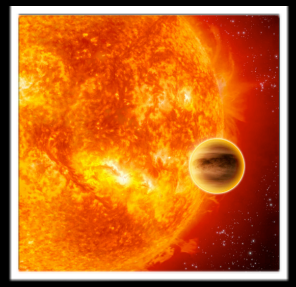


Adapted from Burgasser (2012, ExoMol conference)

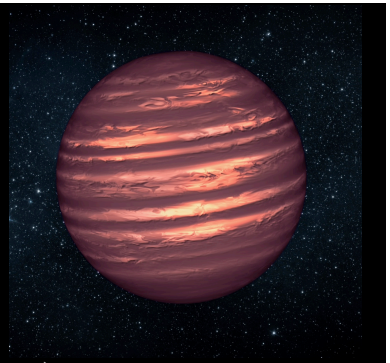



$T_{eq}$ 2400 1800 1500 1200 1000

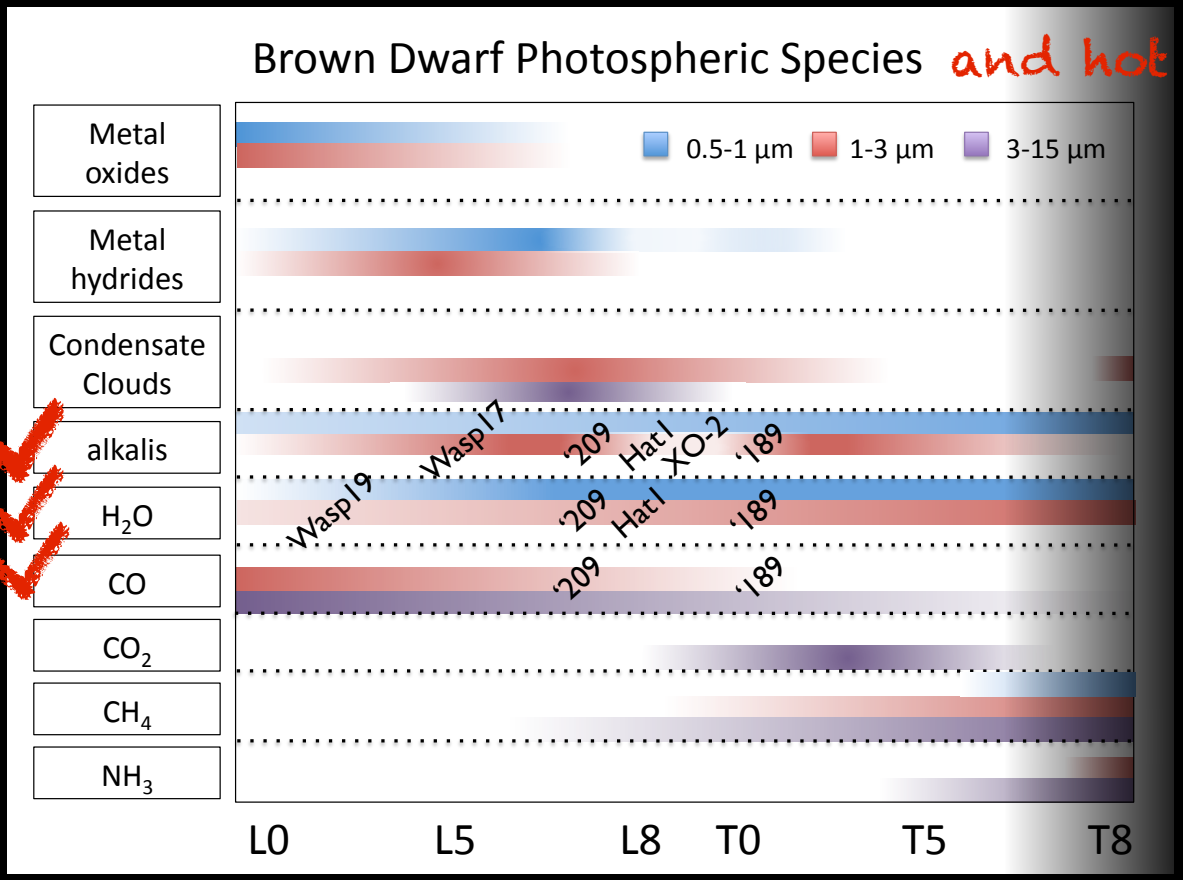
Lodders (1999)
Visscher et al. 2006; 2010)



# Hot Jupiter vs. Brown Dwarf Atmospheres

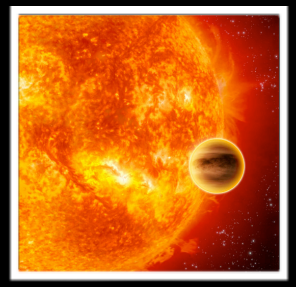


Adapted from Burgasser (2012, ExoMol conference)

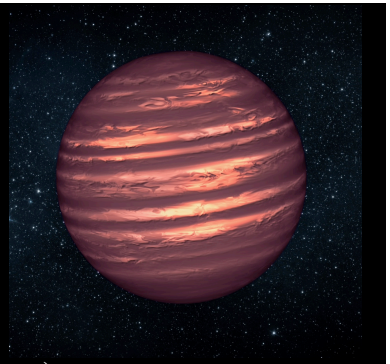



$T_{eq}$ 2400 1800 1500 1200 1000

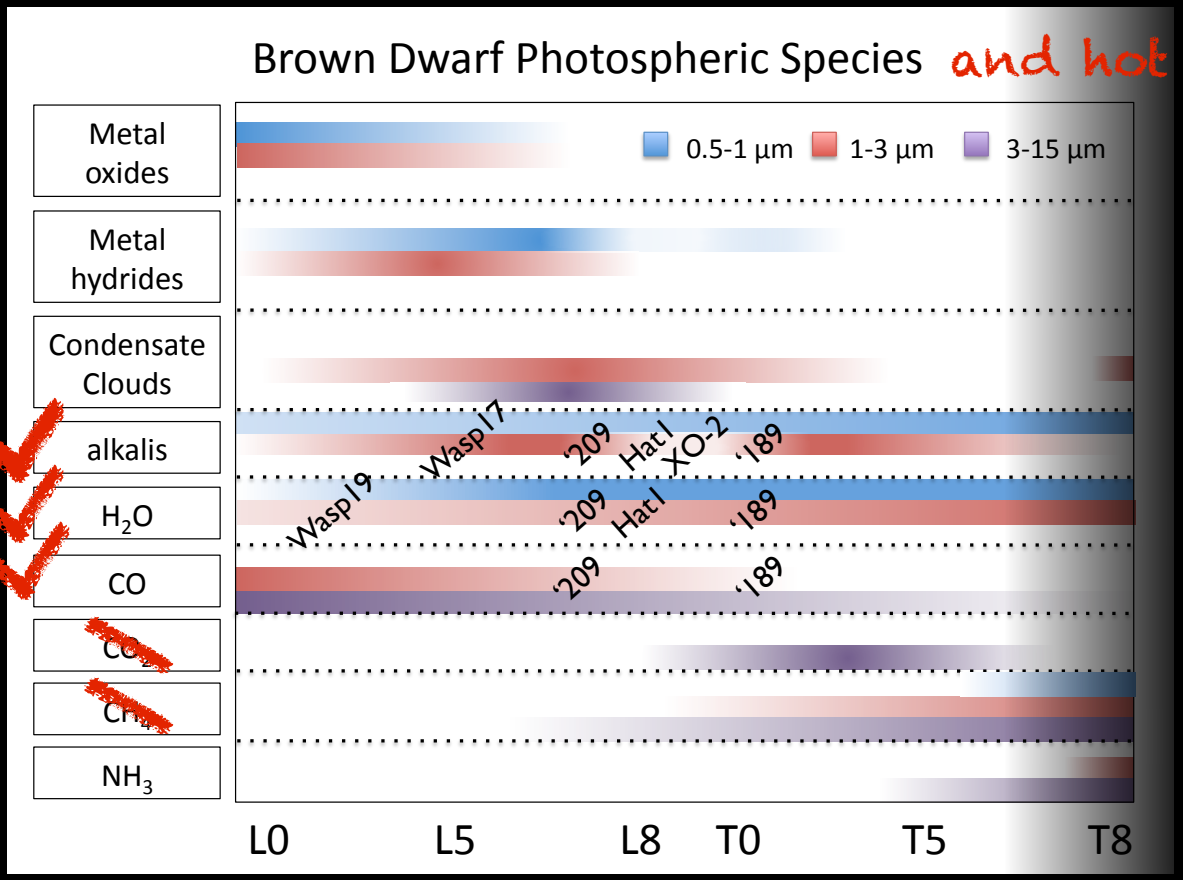
Lodders (1999)
Visscher et al. 2006; 2010)



# Hot Jupiter vs. Brown Dwarf Atmospheres

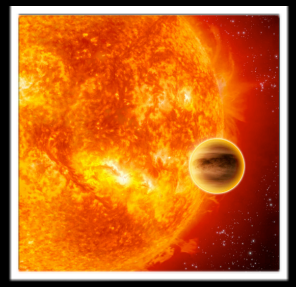


Adapted from Burgasser (2012, ExoMol conference)

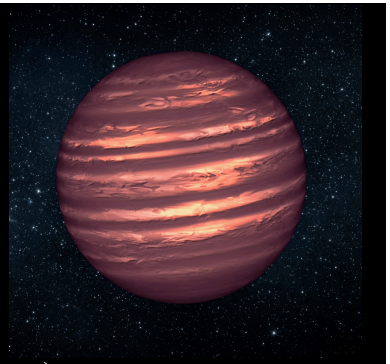



$T_{eq}$ 2400 1800 1500 1200 1000

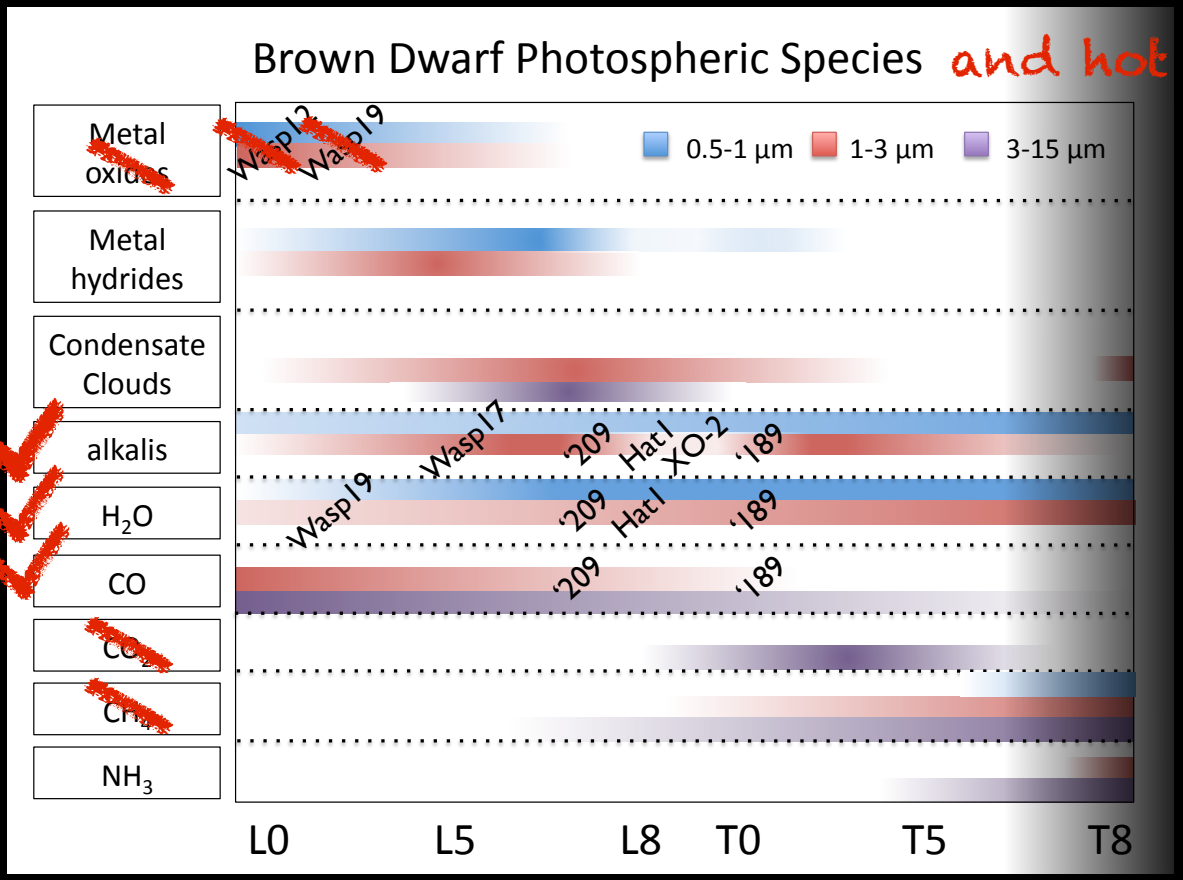
Lodders (1999)
Visscher et al. 2006; 2010)



# Hot Jupiter vs. Brown Dwarf Atmospheres

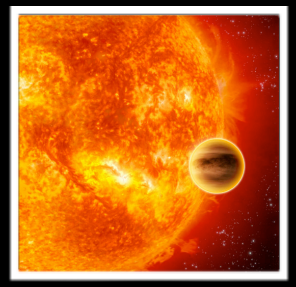


Adapted from Burgasser (2012, ExoMol conference)

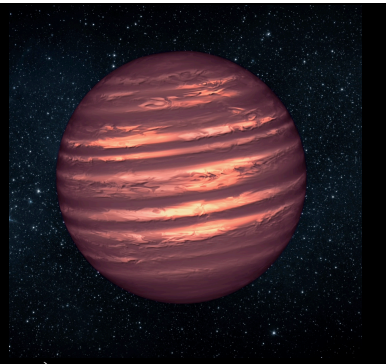



$T_{eq}$ 2400 1800 1500 1200 1000

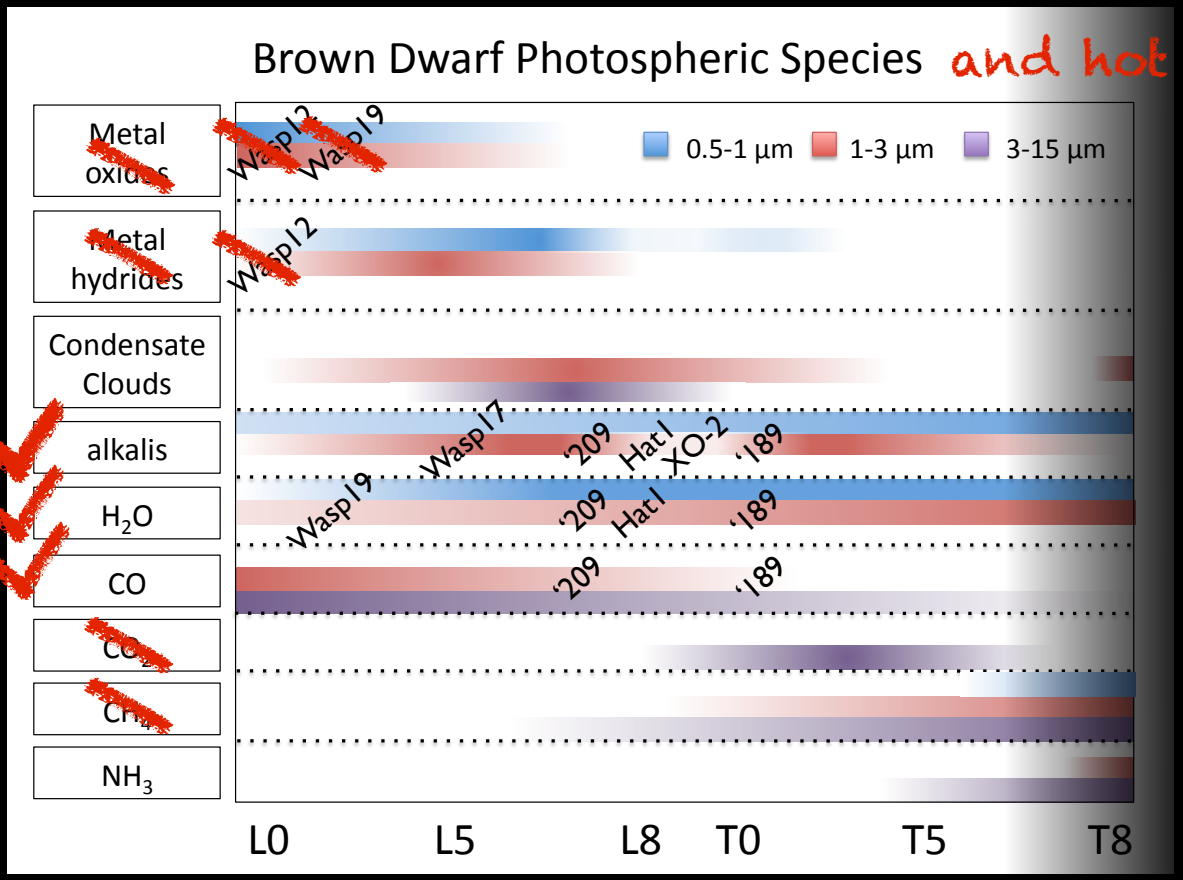
Lodders (1999)
Visscher et al. 2006; 2010)



# Hot Jupiter vs. Brown Dwarf Atmospheres

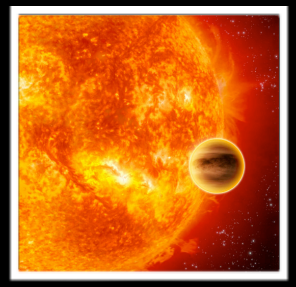


Adapted from Burgasser (2012, ExoMol conference)

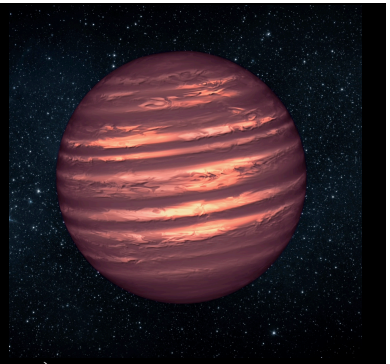



$T_{eq}$ 2400 1800 1500 1200 1000

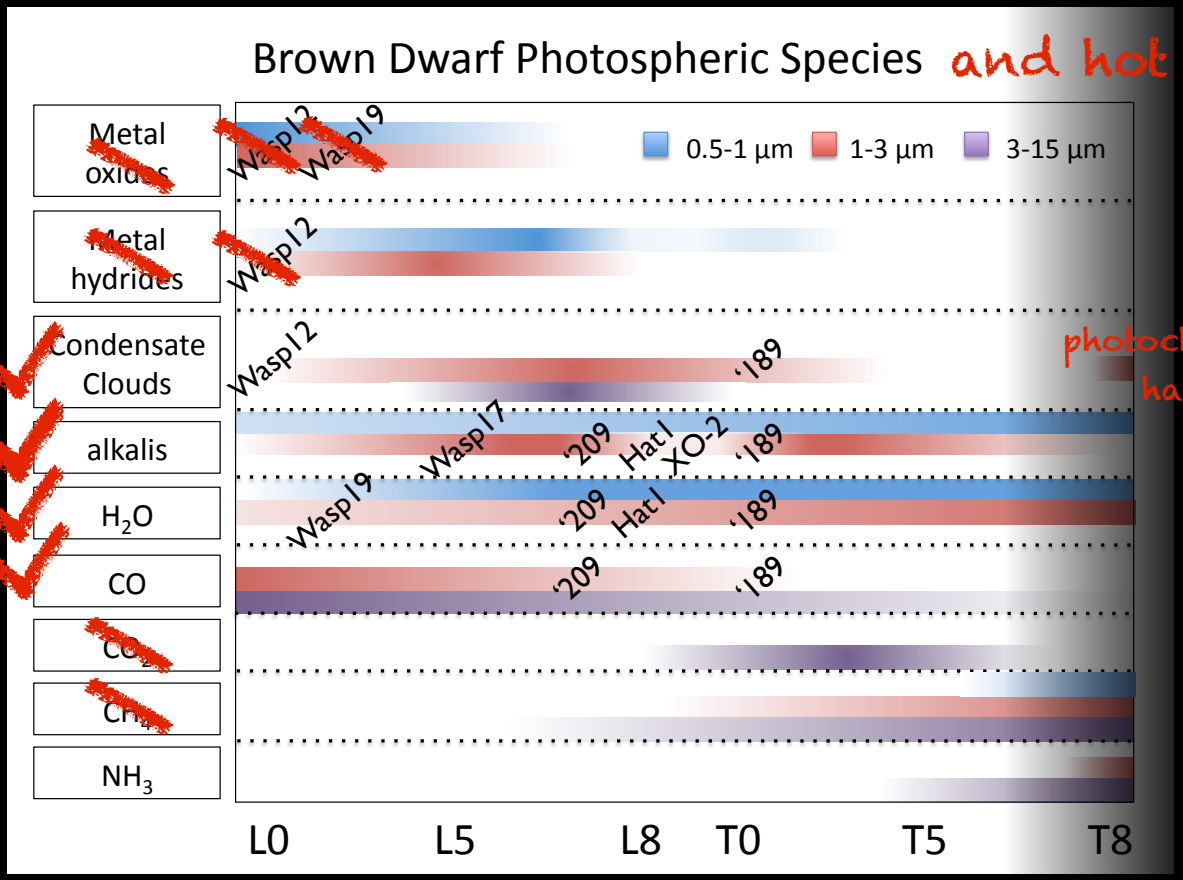
Lodders (1999)
Visscher et al. 2006; 2010)



# Hot Jupiter vs. Brown Dwarf Atmospheres



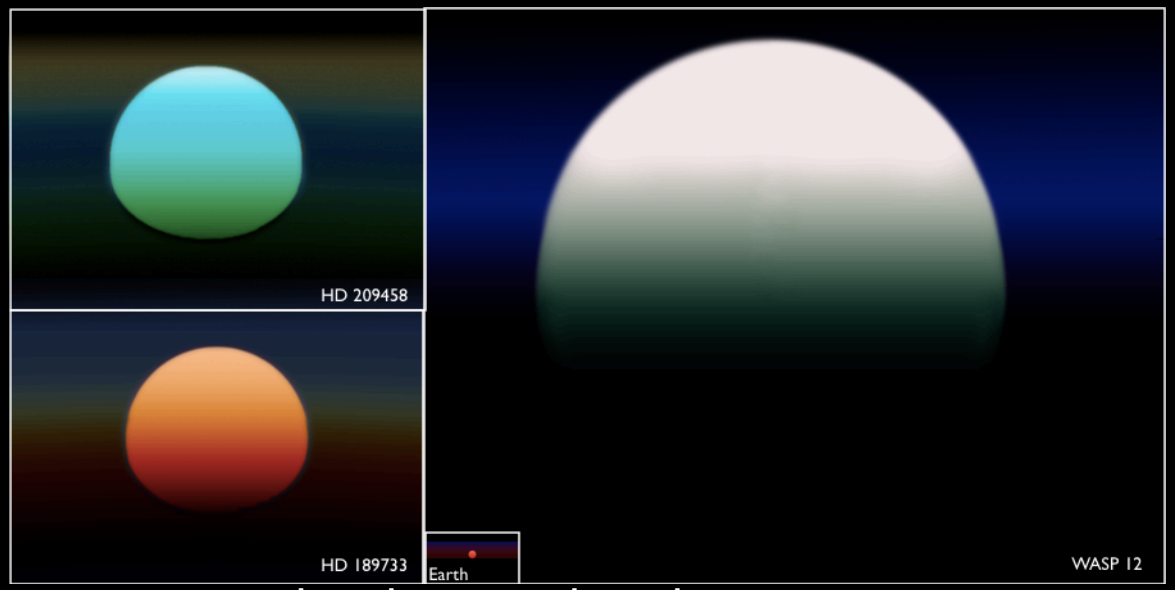
Adapted from Burgasser (2012, ExoMol conference)




$T_{eq}$ 2400 1800 1500 1200 1000

Lodders (1999)
Visscher et al. 2006; 2010)

# Conclusions




exoclimes.com

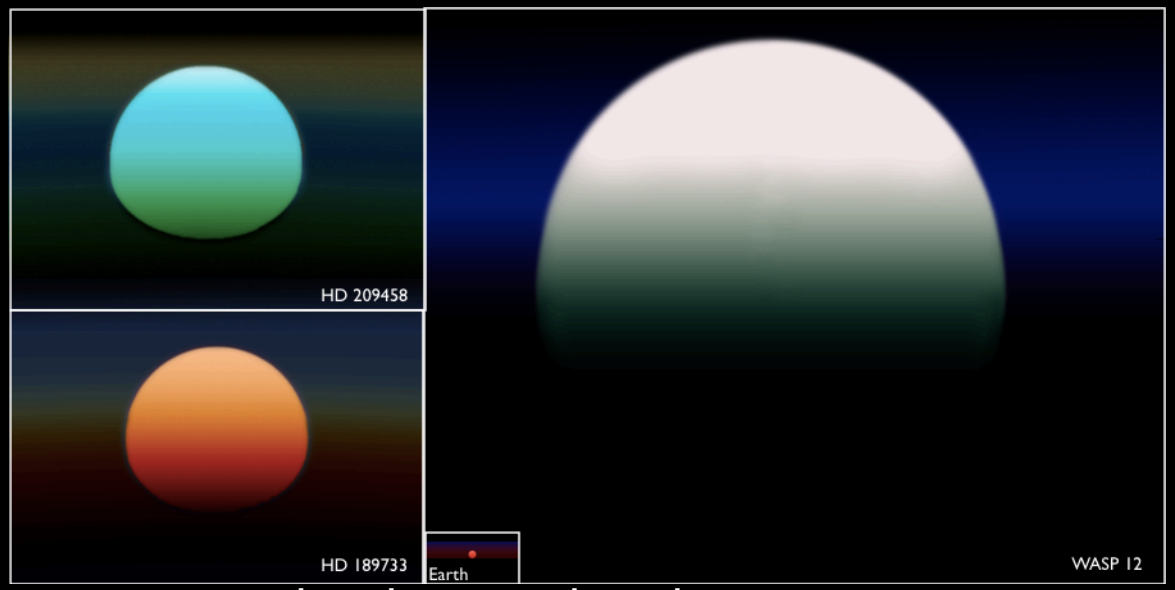
rendered sunsets based on transmission spectra

Hot Jupiter**s** do have strong water features detectable via broadband transmission spectroscopy

TiO hypothesis is in trouble (high C/O too)

Clouds Can Not be neglected in ANY exoplanet

# Job add




exoclimes.com

rendered sunsets based on transmission spectra

2 ERC funded postdocs at Exeter (5 yrs)

- observer
- theorist/modeller

Oct. add in AAS job register