Exoplanetary Atmospheres

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Protostars & Planets VI, Heidelberg, Germany

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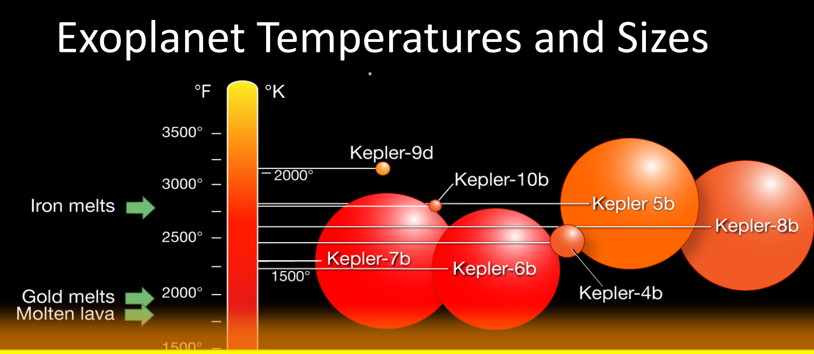
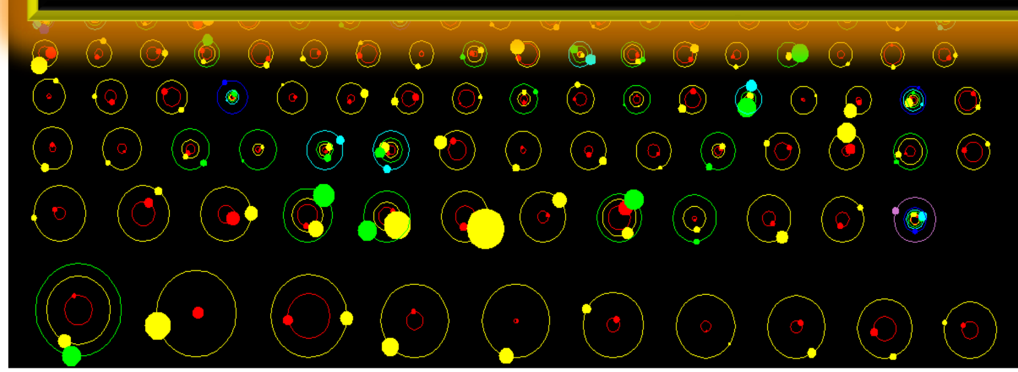
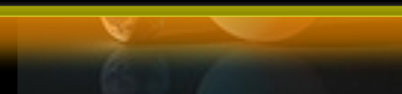
Exoplanets are extremely diverse in their physical characteristics



Question at the new frontier:

How diverse are the chemical compositions and physical processes in exoplanets?





Hot Jupiter! Super-Earth!

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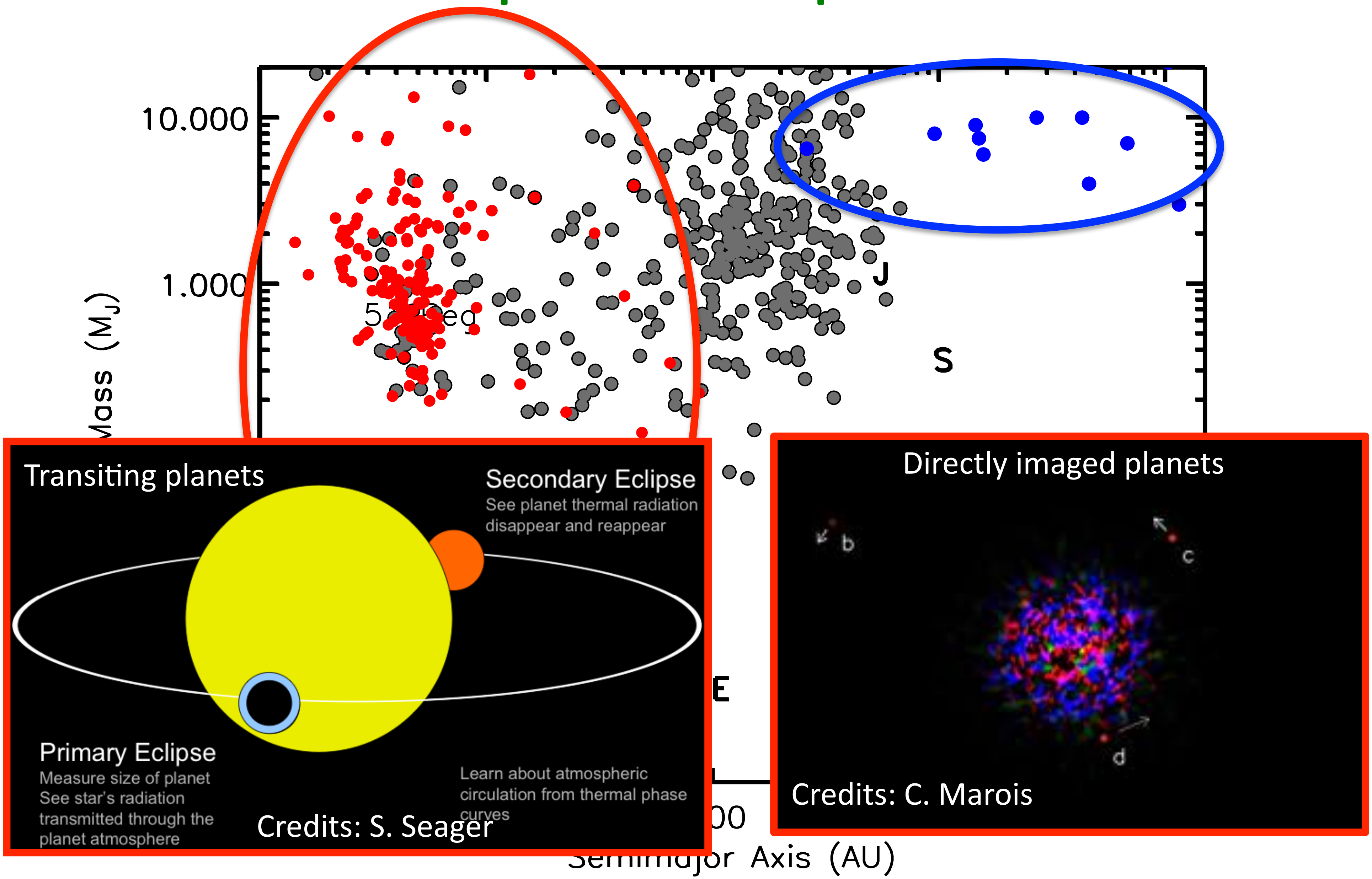
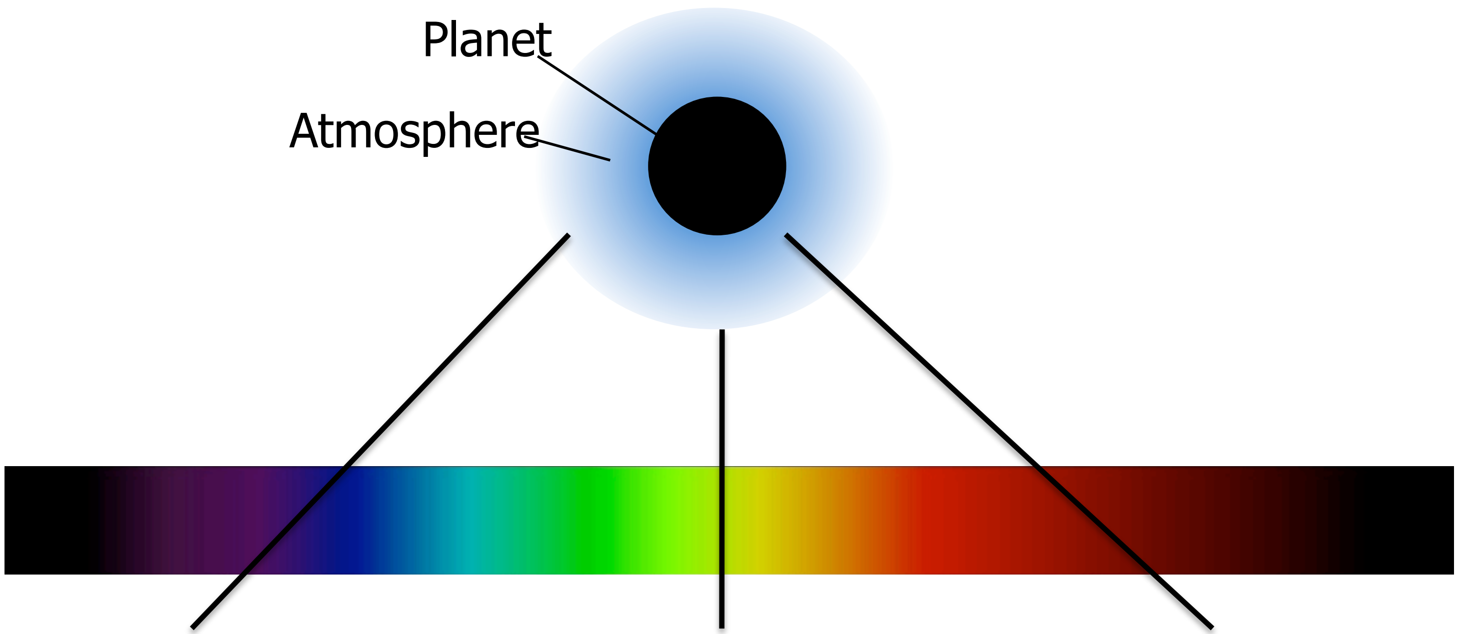
Exoplanet Population



What Do We Learn From Transmission Spectroscopy?



Wavelength	UV	Visible	Infrared
What do we measure?	Lyman alpha, ionized metals	Sodium, potassium, TiO, VO	Water, methane, CO, CO_2
What do we learn?	Atmospheric mass loss	Clouds/hazes or transparent? Other absorbers?	Is the chemistry in equilibrium?

Outline

- ✧ Theory of Exoplanetary Atmospheres
- ✧ Atmospheres of Hot Jupiters
- ✧ Atmospheres of Directly-imaged Planets
- ✧ Atmospheres of Hot Neptunes
- ✧ Atmospheres of Super-Earths
- ✧ Frontier Problems and Future Outlook

Models of Exoplanetary Atmospheres

1-D Equilibrium models of exoplanetary atmospheres

$$\frac{dP}{dr} = -\rho g$$

$$\frac{dI_\lambda}{d\tau_\lambda} = -(1 + \frac{\sigma_\lambda}{\kappa_\lambda})I_\lambda + \frac{j_\lambda}{\kappa_\lambda}$$

$$\int_0^\infty \kappa_\lambda [J_\lambda - B_\lambda]\, d\lambda = 0$$

$$\frac{dT}{dr} = -\frac{\gamma - 1}{\gamma}\frac{\mu g}{k_B}$$

$$P = \frac{\rho k_B T}{\mu}$$

Boundary Conditions

- Stellar Irradiation (Kurucz Model)
- Intrinsic Energy source

Chemical Equilibrium

$$[X] = f_z \times [X]_{solar}$$

$$\frac{G(T)}{RT} = \sum_{i=1}^{m} \left\{ n_{\phi i} \left[\frac{\Delta G_{\phi i}(T)}{RT} + \ln P + \ln\left(\frac{n_{\phi i}}{N}\right) \right] \right\}_{\phi=1} + \frac{1}{RT} \sum_{\phi=2}^{s+1} [n_{\phi i} \Delta G_{\phi i}(T)]_{i=1}$$

$$\sum_{i=1}^{m} [v_{\phi i j} n_{\phi i}]_{\phi=1} + \sum_{\phi=2}^{s+1} [v_{\phi i j} n_{\phi i}]_{i=1} = b_j \quad \text{for } j = 1 \rightarrow k$$

$$B_{CO} = A_C + A_O + \frac{P_{H_2}^2}{2K_1(T)} - \sqrt{\left[A_C + A_O + \frac{P_{H_2}^2}{2K_1(T)}\right]^2 - 4A_C A_O}$$

Model Parameters

- Day-night redistribution: P_n, P_1, P_2
- Extra absorber: $P_{abs}, (\lambda_0, \lambda_1), \kappa_e$
- Composition (f_z) + clouds, etc.

Caveats

- Parameters
- Chemical equilibrium and compositions
- Computation time
- Artificial sources and sinks

Marley et al. 1996; Seager & Sasselov 1998; Allard et al. 2001; Sudarsky et al. 2003; Seager et al. 2005; Barman et al. 2005; Fortney et al. 2006; Burrows et al. 2007

Models of Exoplanetary Atmospheres

1-D parametric models of exoplanet atmospheres

$$\frac{dP}{dr} = -\rho g$$

$$\frac{dI_\lambda}{d\tau_\lambda} = -(1 + \frac{\sigma_\lambda}{\kappa_\lambda})I_\lambda + \frac{j_\lambda}{\kappa_\lambda}$$

$$\int_0^\infty \kappa_\lambda [J_\lambda - B_\lambda]\, d\lambda = 0$$

$$P = P(T)$$

$$\frac{dT}{dr} = -\frac{\gamma - 1}{\gamma}\frac{\mu g}{k_B}$$

$$P = \frac{\rho k_B T}{\mu}$$

Boundary Conditions

- Stellar Irradiation (Kurucz Model)
- Intrinsic Energy source

Chemical Equilibrium

$$[X] = f_z \times [X]_{solar}$$

Perturbations to equilibrium or uniform mixing

$$B_{CO} = A_C + A_O + \frac{P_{H_2}^2}{2K_1(T)} - \sqrt{\left[A_C + A_O + \frac{P_{H_2}^2}{2K_1(T)}\right]^2 - 4A_C A_O}$$

Model Parameters

- Day-night redistribution: P_n, P_1, P_2
- Extra absorber: $P_{abs}, (\lambda_0, \lambda_1), \kappa_e$
- Composition (f_z) + clouds, etc.

Caveats

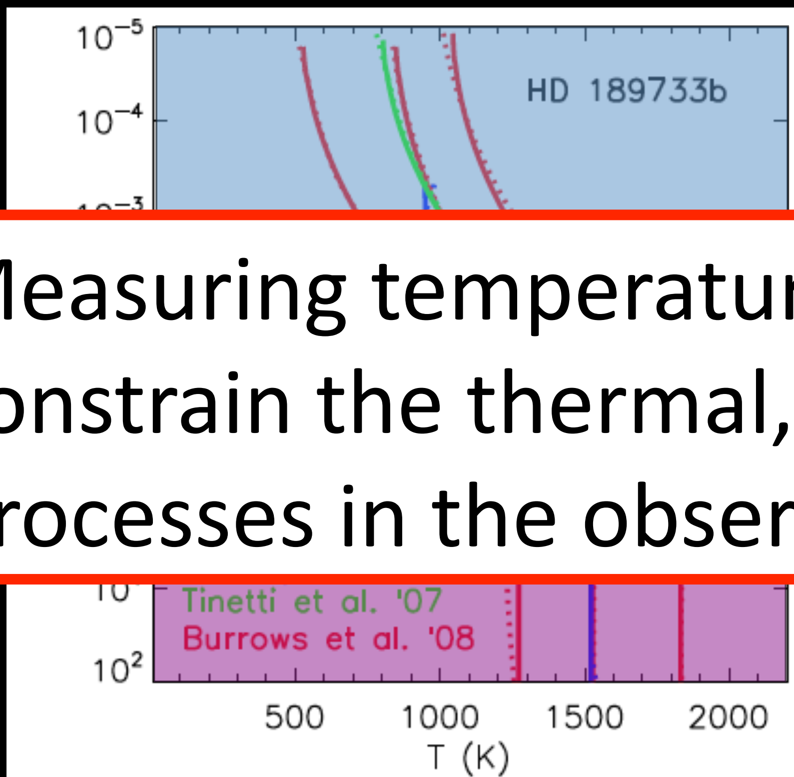
- Parameters
- Chemical equilibrium and compositions
- Computation time
- Artificial sources and sinks

Madhusudhan & Seager 2009; Miller-Ricci et al. 2009; Lee et al. 2012, Line et al. 2012; Benneke et al. 2012

Theory of Exoplanetary Atmospheres

- Equilibrium and non-Equlibrium chemistry (Burrows & Sharp 1999; Lodders & Fegley 2002; Moses et al. 2011)
- Temperature structures in irradiated atmospheres (Hansen et al. 2008; Spiegel et al. 2009; Guillot et al. 2010; Heng et al. 2011)
- Clouds, hazes, condensates (Helling et al. 2008; Lecavelier des Etangs 2008; Marley et al. 2013; Morley et al. 2013)
- Atmospheric dynamics (Cho et al. 2008; Showman et al. 2008,2009; Heng et al. 2011; Rauscher & Menou 2012)
- Exospheres and atmospheric escape (Vidal Madjar et al. 2003; Murray-Clay et al. 2009; Koskinen et al. 2012)
- Statistical retrieval codes (Madhusudhan & Seager 2009; Madhusudhan et al. 2011; Line et al. 2012; Lee et al. 2012; Benneke et al. 2012)
- Carbon-rich atmospheres (Madhusudhan et al. 2011; Madhusudhan 2012)
- Terrestrial-size exoplanets (Kaltenegger et al. 2011; Schaffer et al. 2011)
- High-Temperature opacity linelists (Rothman et al. 2005,2008; Freedman et al. 2008; Tennyson & Yurchenko 2012; ExoMol Project) – Most important inputs!

Temperature Structures in Highly Irradiated Atmospheres



Low optical depth limit

$$T(\tau) = T_{\rm eff}\left[\frac{3\tau}{4} + \frac{1}{2}\right]^{1/4}$$

Measuring temperature structures allows us to constrain the thermal, chemical, and radiative processes in the observable atmosphere

Diffusion approximation

Large optical depth limit

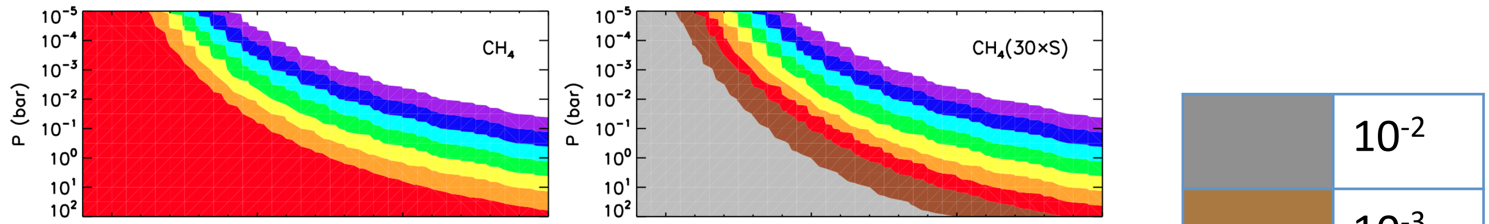
$$F = -\frac{16}{3}\frac{\sigma T^3}{\kappa\rho}\frac{dT}{dz} = \frac{16\sigma T^3}{3}\frac{dT}{d\tau}$$

Two stream gray model (Hansen, 2008; Guillot 2010; Heng et al. 2011)

$$T^4 = \frac{3}{4}T_{\rm eff}^4\left[\tau + \frac{2}{3}\right] + \mu_0 T_0^4\left[1 + \frac{3}{2}\left(\frac{\mu_0}{\gamma}\right)^2 - \frac{3}{2}\left(\frac{\mu_0}{\gamma}\right)^3 \ln\left(1 + \frac{\gamma}{\mu_0}\right) - \frac{3}{4}\left(\frac{\mu_0}{\gamma}\right)e^{-\gamma\tau/\mu_0}\right]$$

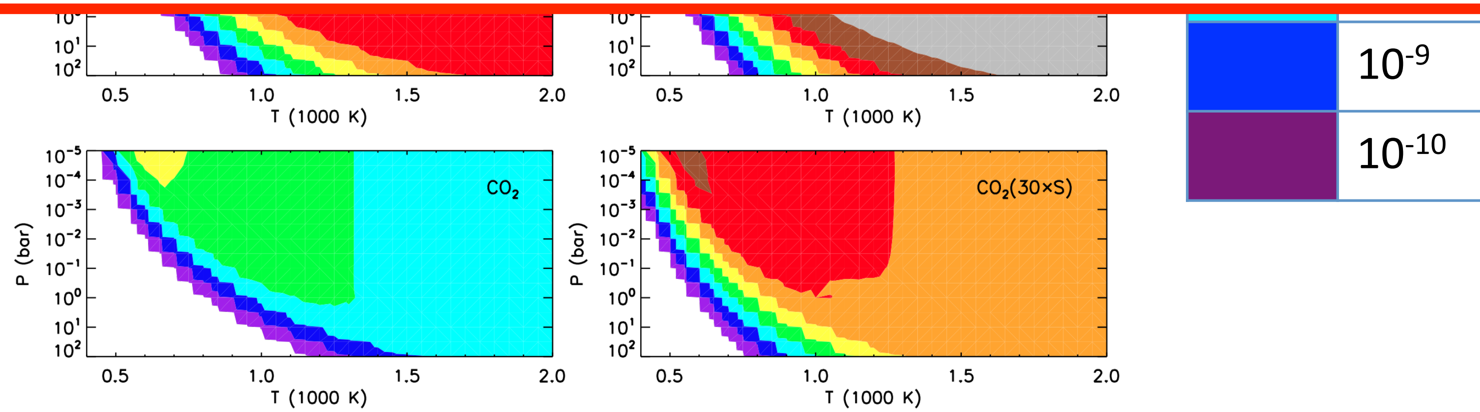
Chemistry in H_2-rich Atmospheres

(Molecular mixing ratios assuming chemical equilibrium)



For solar composition atmospheres:

1. H_2O should be dominant O carrier at all T
2. CO should be dominant C carrier at high T
3. CH_4 should be dominant C carrier at low T



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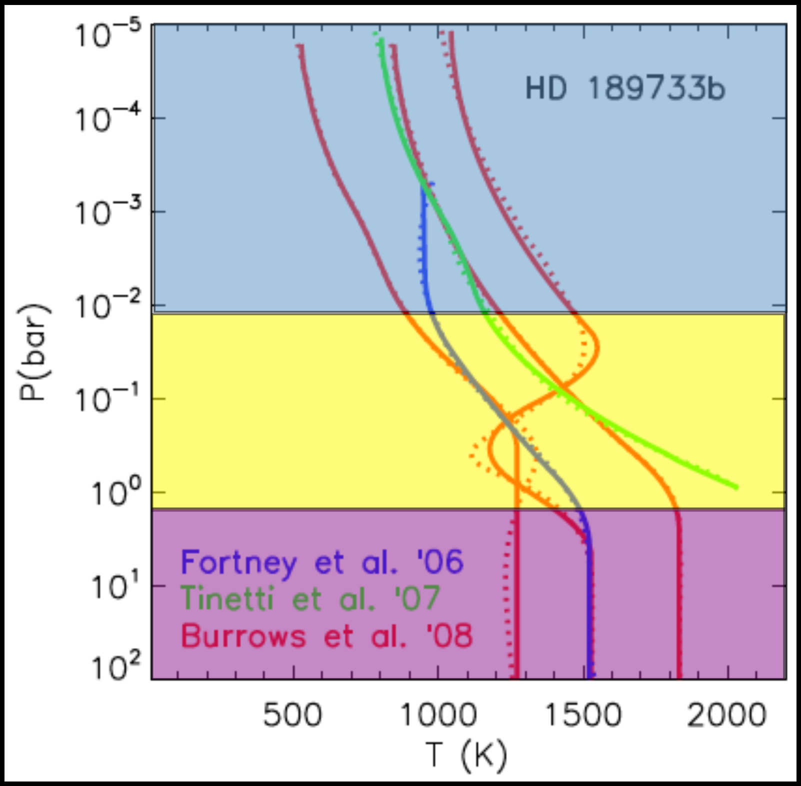
Advances in hot Jupiter Atmospheres

- Temperature structures and thermal inversions
- Molecular and Atomic abundances
- Phase curves and atmospheric dynamics
- Hazes and clouds
- Two distinct observational advances
  - Ground-based spectroscopy
  - HST WFC3 spectroscopy
- Atmospheric detections of radial velocity planets
- Exospheres and atmospheric escape
- Inferences of Polarization

Temperature Structures in Highly Irradiated Atmospheres



Low optical depth limit

$$T(\tau) = T_{\text{eff}} \left[\frac{3\tau}{4} + \frac{1}{2} \right]^{1/4}$$

Function of several parameters
(molecular species, UV/visible absorbers,
atmospheric dynamics, etc.)

Diffusion approximation
Large optical depth limit

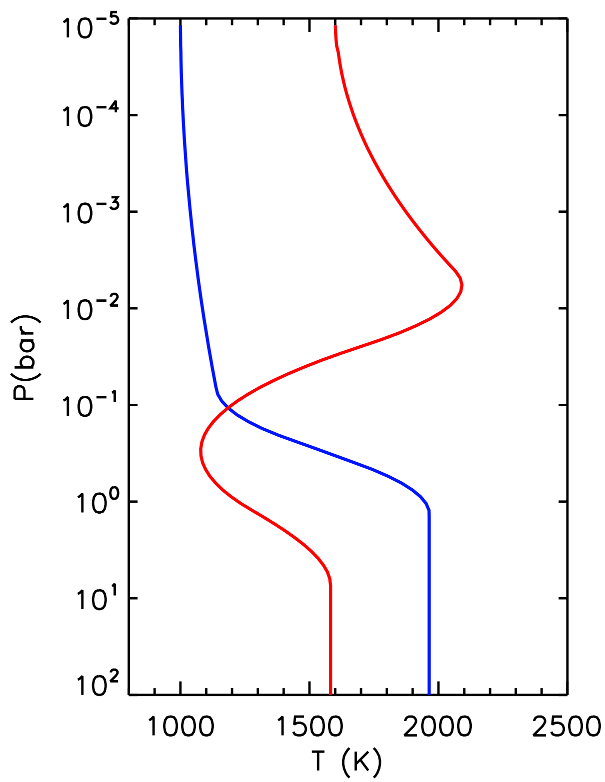
$$F = -\frac{16}{3} \frac{\sigma T^3}{\kappa \rho} \frac{dT}{dz} = \frac{16 \sigma T^3}{3} \frac{dT}{d\tau}$$

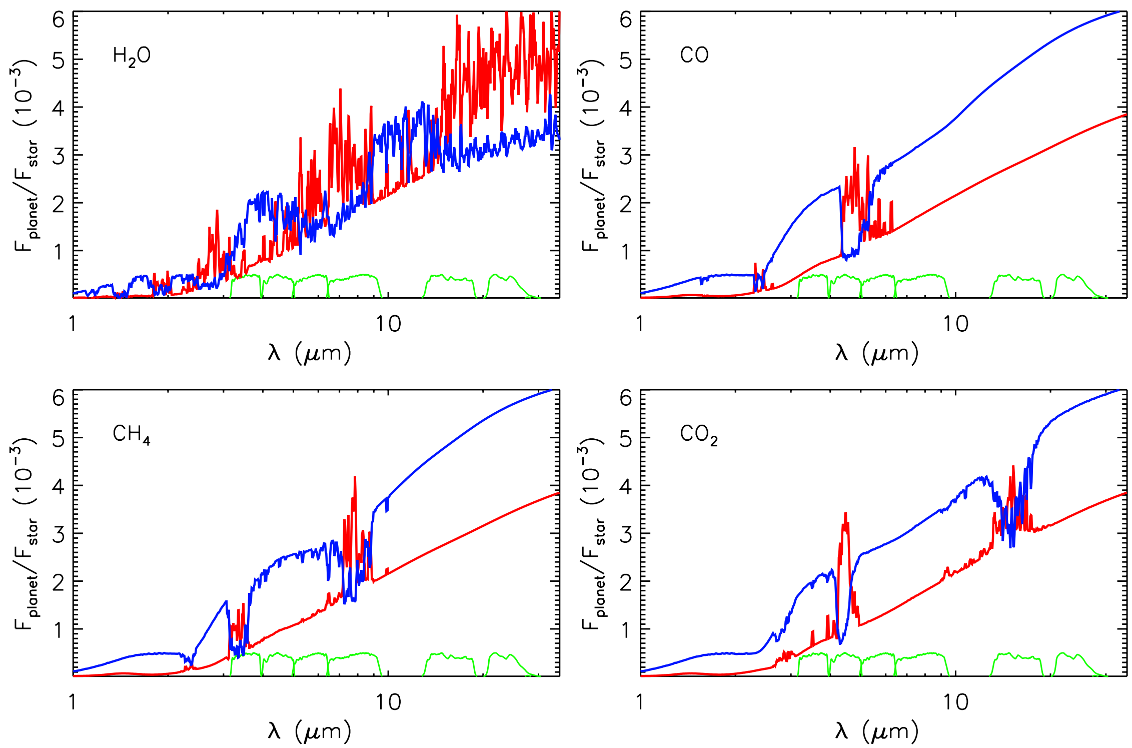
Thermal inversions in hot Jupiters

(The TiO/VO Hypothesis)

TiO and VO can be very strong absorbers of incident stellar irradiation in the visible high in the atmospheres of hot Jupiters, and can hence cause thermal inversions.

Hubeny, I. et al. 2003, ApJ, 594, 1011
Fortney et al 2006, ApJ, 642, 495

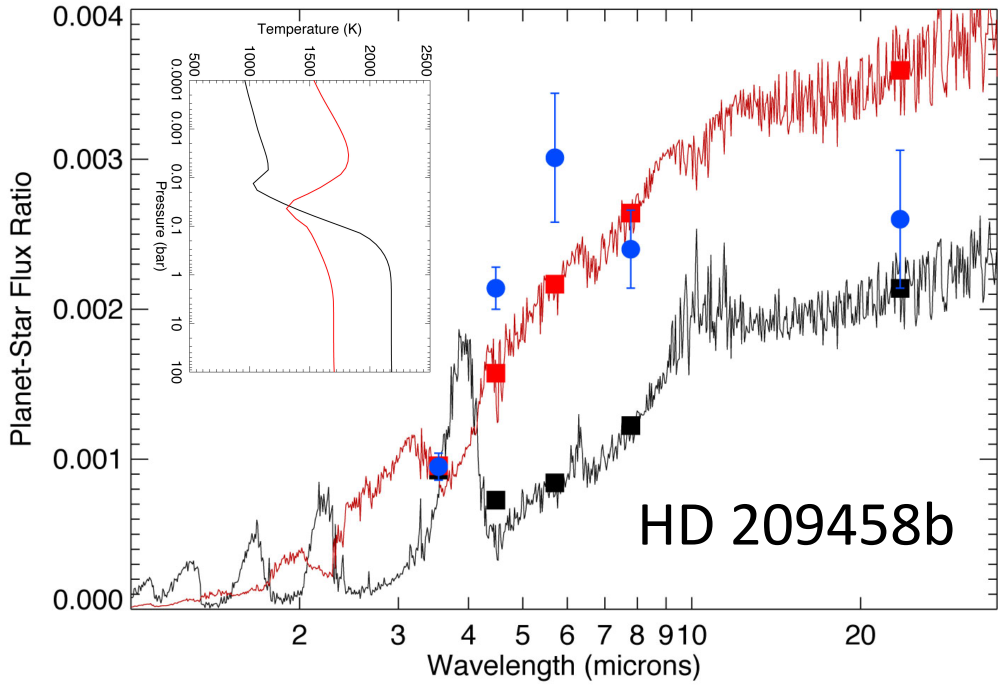




Madhusudhan & Seager 2010

Thermal inversions in hot Jupiters

Classification of hot Jupiter atmospheres

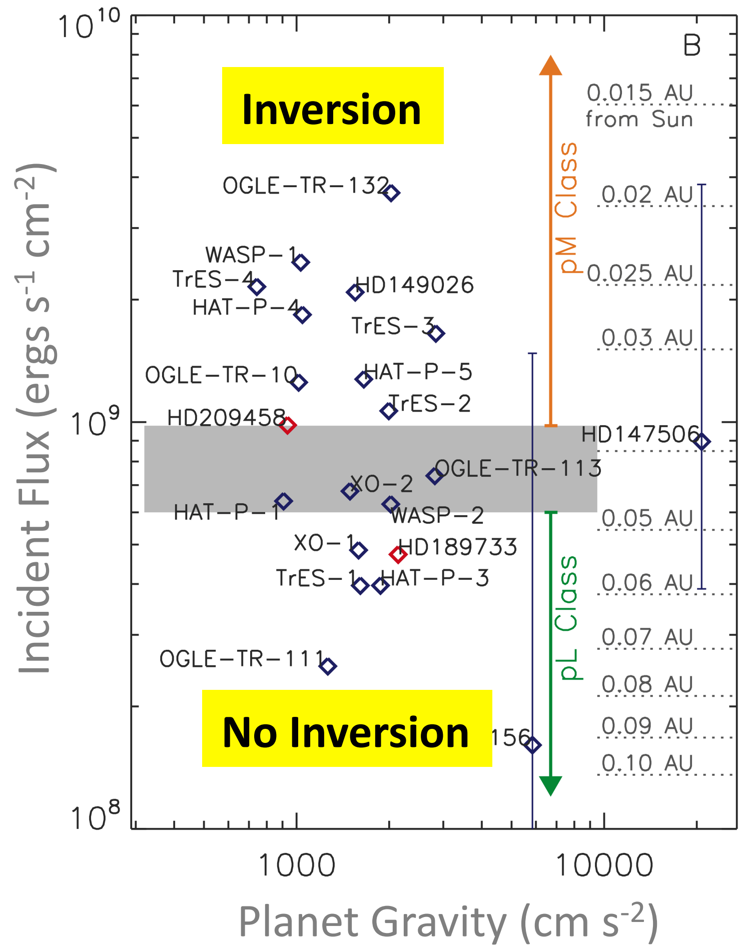


Data: *Knutson et al. 2008, ApJ, 673, 526*

Models: *Burrows et al. 2007, ApJ, 668, L171*

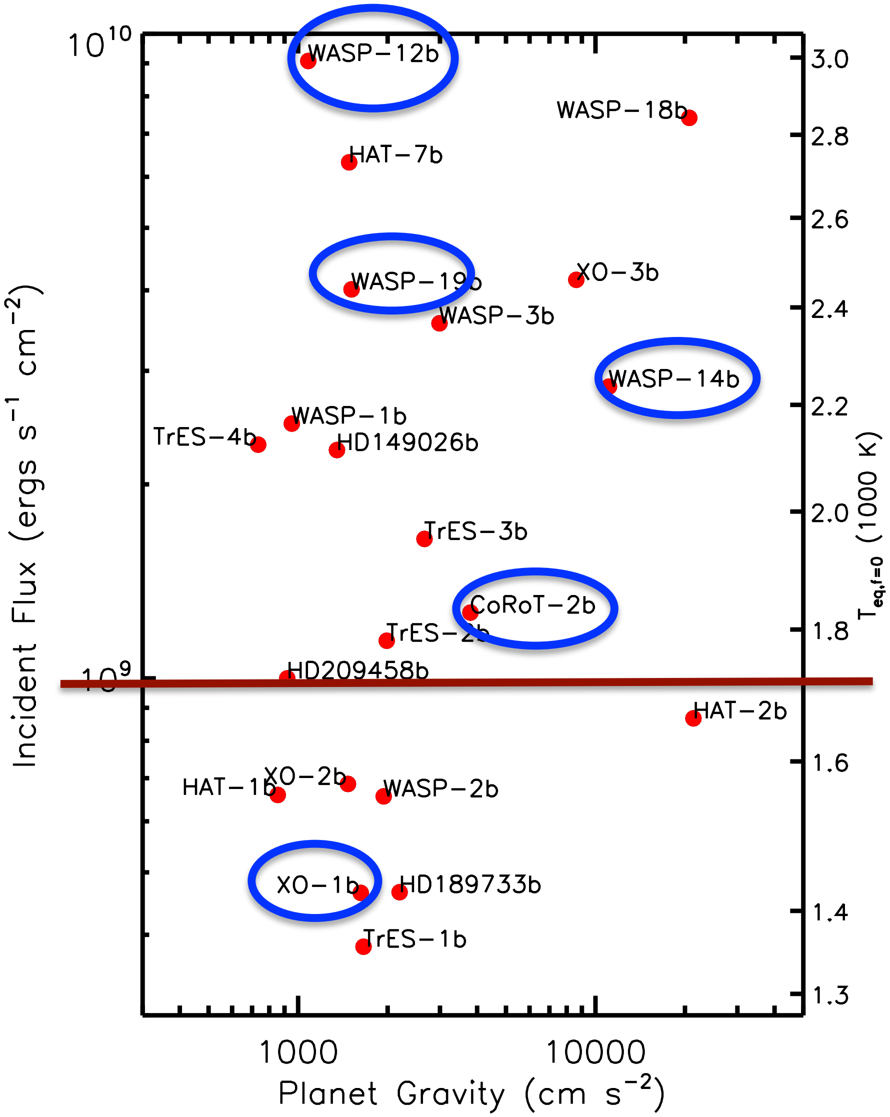
But, TiO and VO may be depleted due to gravitational settling and condensation

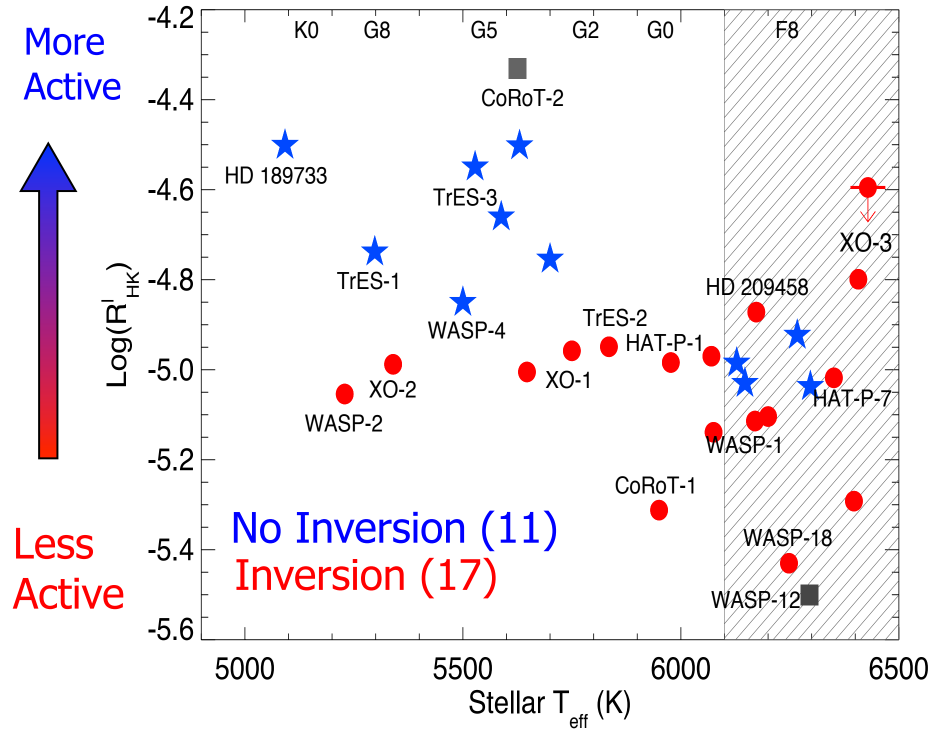
Spiegel et al. 2009, ApJ, 699, 1487



Fortney et al. 2008, ApJ, 678, 1419

Classifications of hot Jupiters



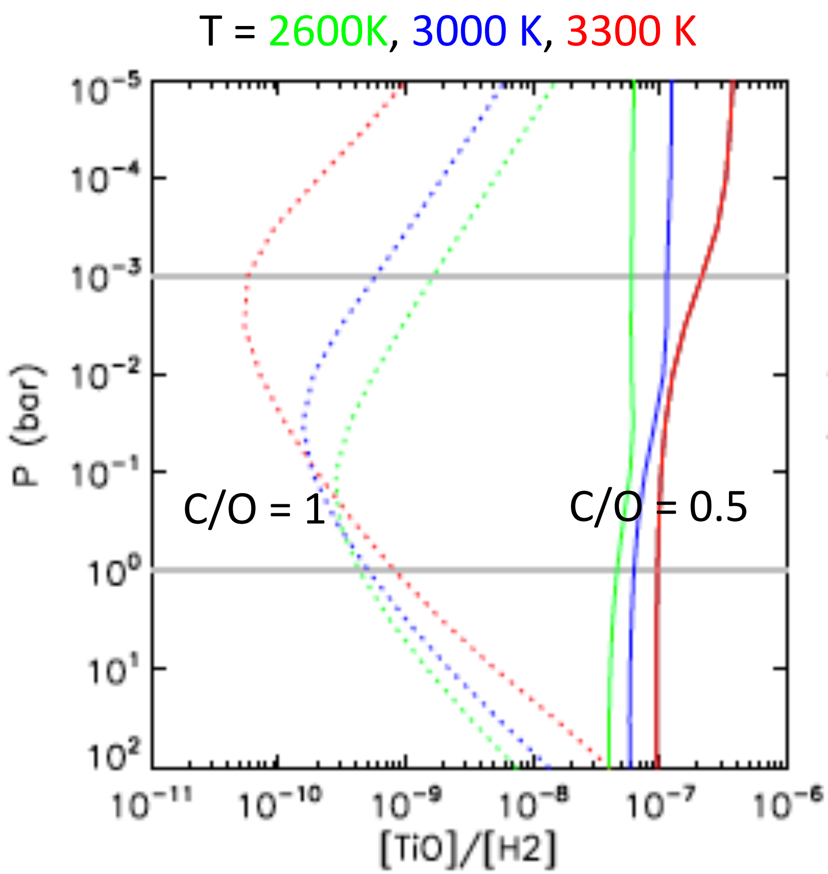


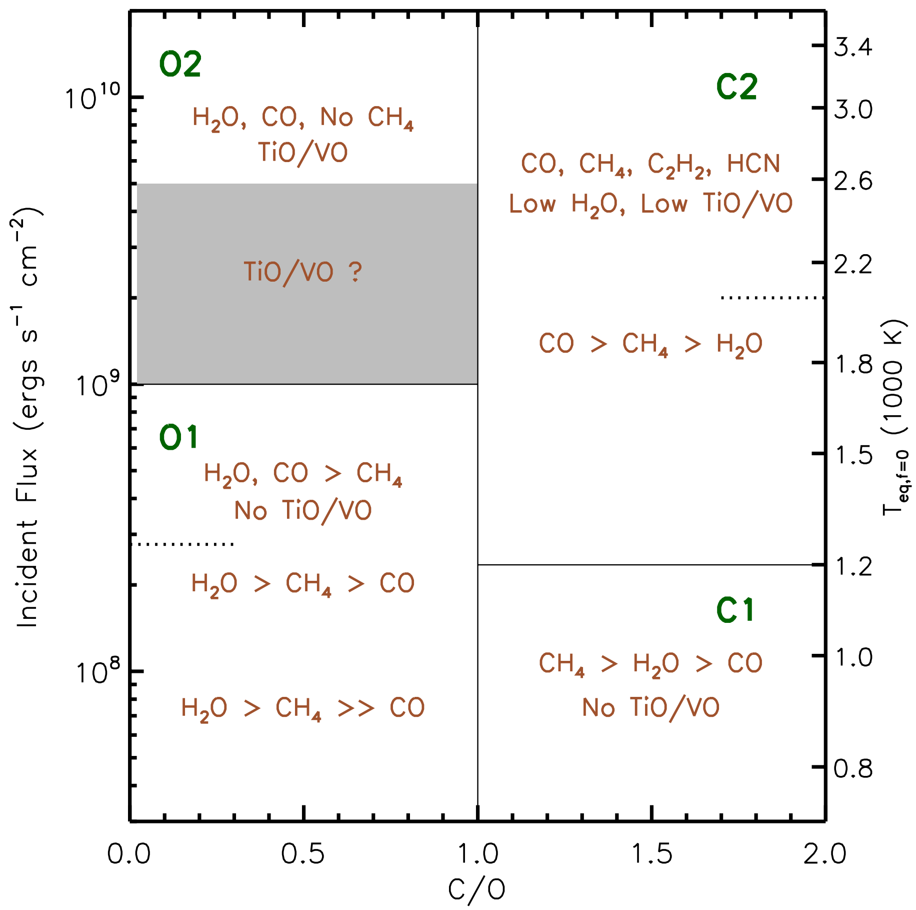
Correlation Between Stellar Activity and Temperature Inversions

Knutson et al. 2010, ApJ, 720, 1569

Machalek et al. 2008; Fressin et al. 2010; Deming et al. 2010; Anderson et al. 2012; Blecic et al. 2013

Classifications of hot Jupiters





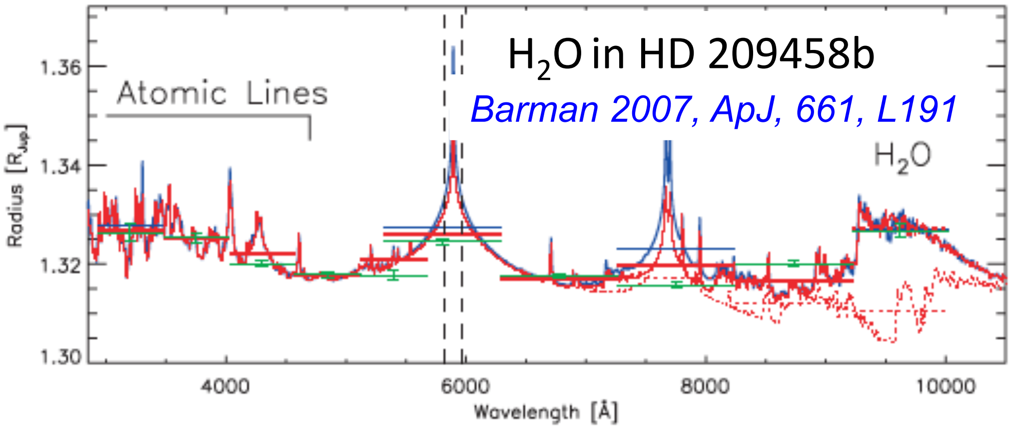
TiO and VO can be 100x lower for C/O ≥ 1.

Madhusudhan et al. 2011, ApJ, 743, 191

2-D classification scheme with C/O ratio as second dimension

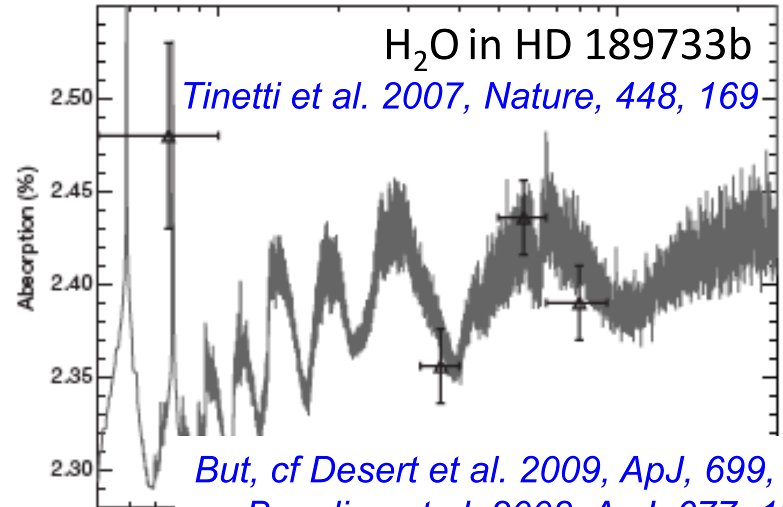
Madhusudhan 2012, ApJ, 758, 36

Molecular inferences in hot Jupiter Atmospheres



H$_2$O in HD 209458b

Barman 2007, ApJ, 661, L191

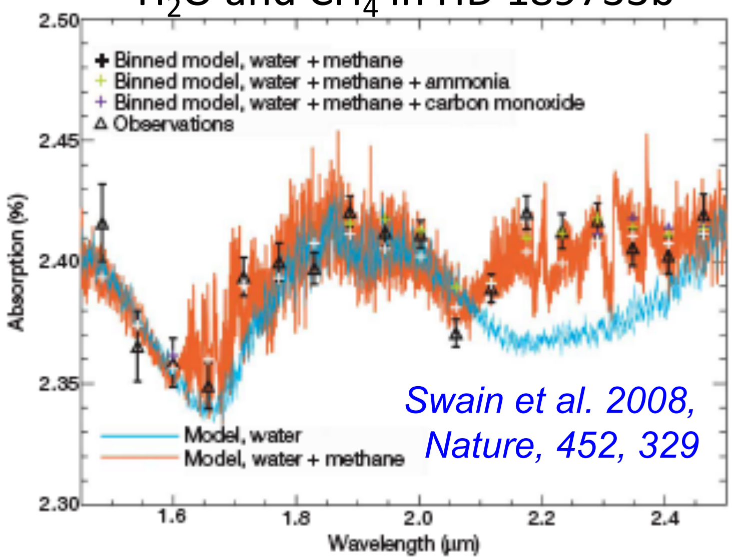


H$_2$O in HD 189733b

Tinetti et al. 2007, Nature, 448, 169

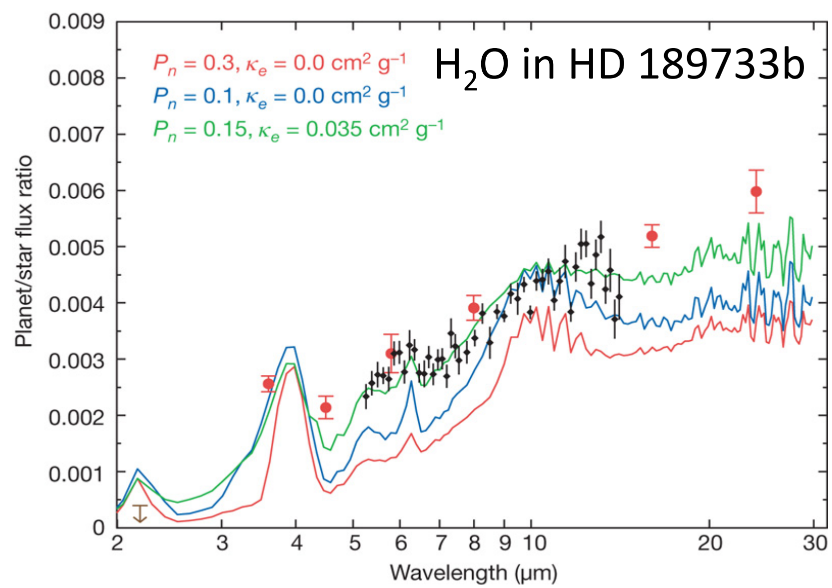
But, cf Desert et al. 2009, ApJ, 699, 478
Beaulieu et al. 2008, ApJ, 677, 1343

H$_2$O and CH$_4$ in HD 189733b



Swain et al. 2008, Nature, 452, 329

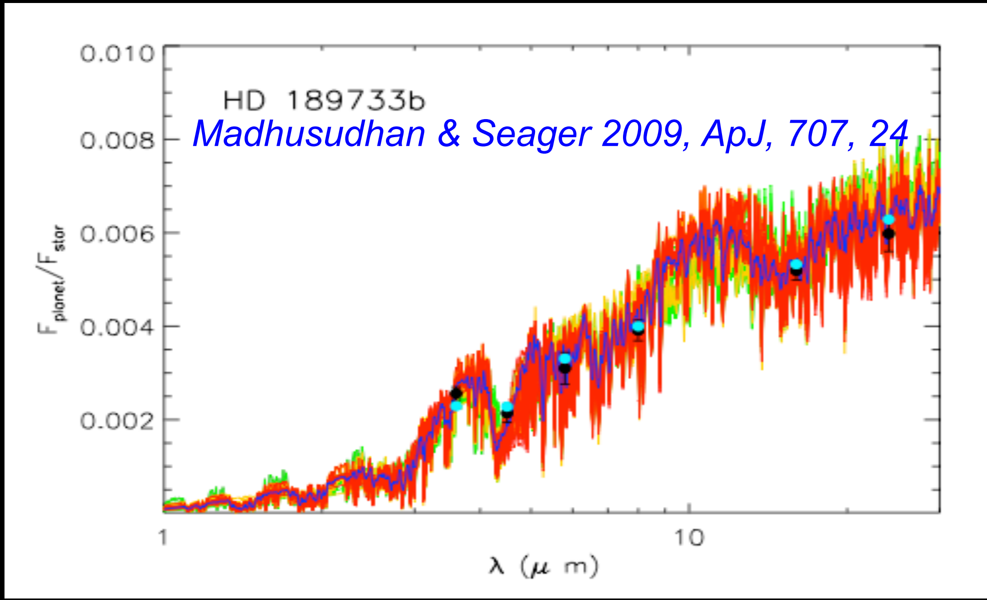
But, cf Gibson et al. 2011, MNRAS, 411, 2199
Crouzet et al. 2012, ApJ, 761, 7



H$_2$O in HD 189733b

Grillmair et al. 2008, Nature, 456, 767

Atmospheric Retrieval for Exoplanets



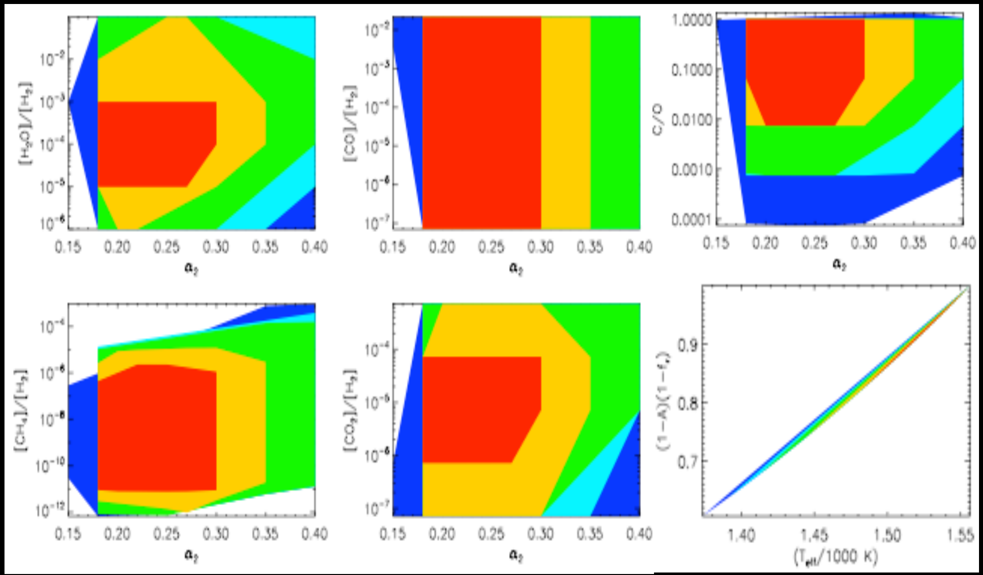
$$\xi^2 = \frac{1}{N_{obs}} \sum_{i=1}^{N_{obs}} \left(\frac{f_{i,obs} - f_{i,model}}{\sigma_i} \right)^2$$

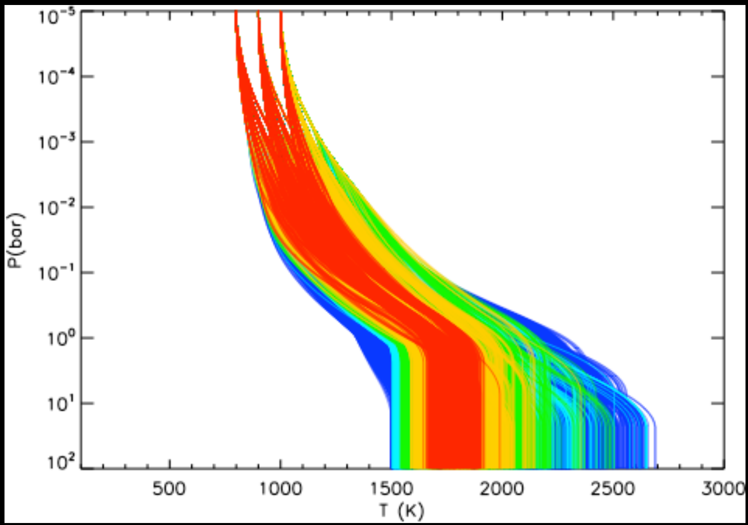
0 - 1

1 - 2

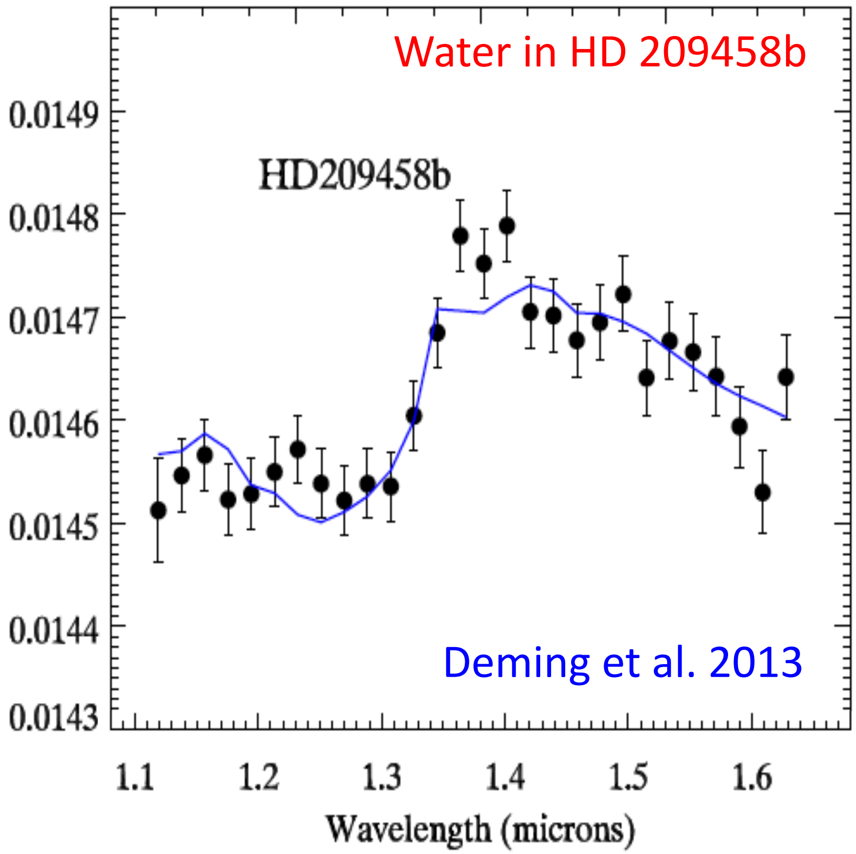
2 - 3

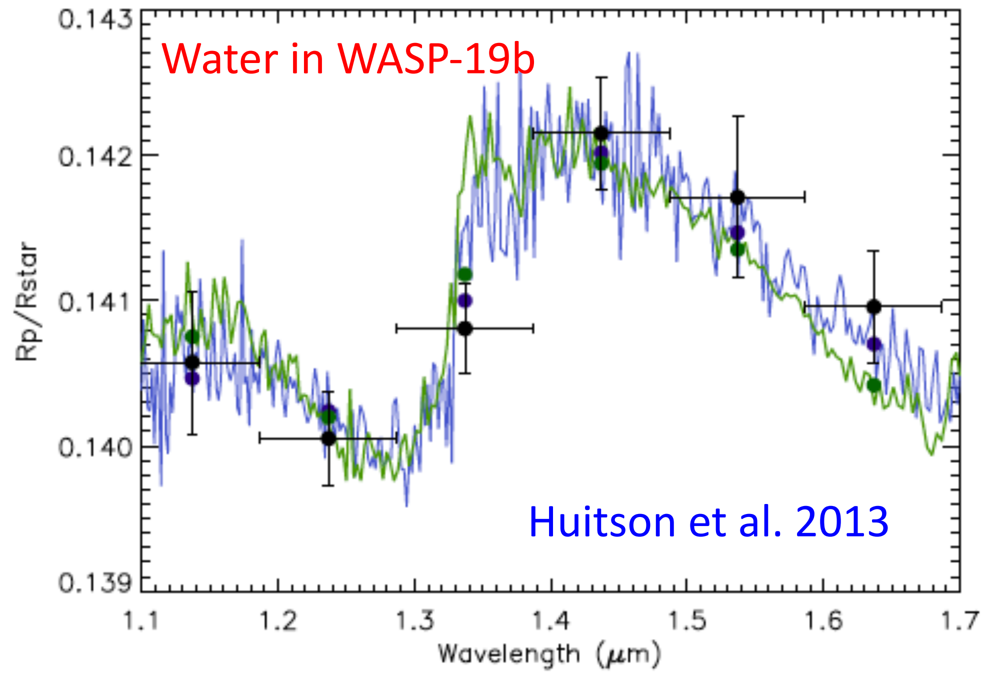
Statistical constraints on H_2O, CO, CH_4, and CO_2 in HD 189733b & HD 209458b





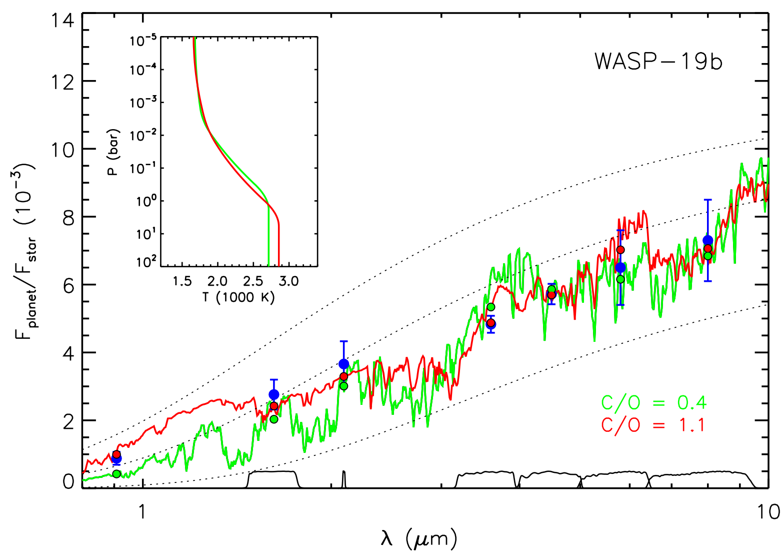
Other Examples of Molecular Inferences



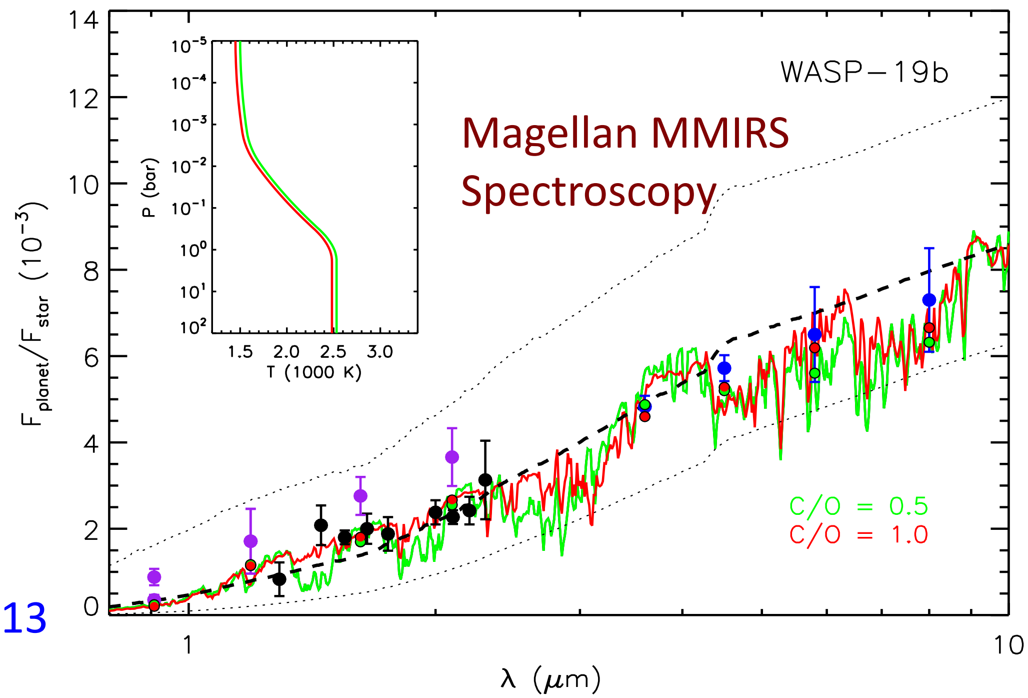


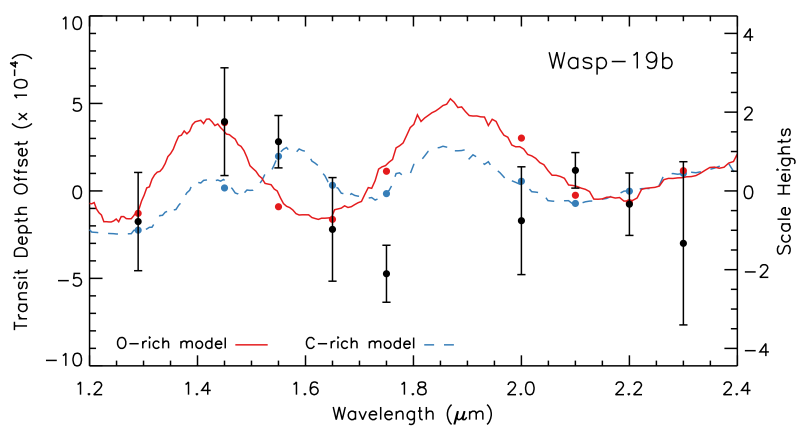
Also see Desert et al. 2009; Madhusudhan & Seager 2009; Swain et al. 2008, 2009; Tinetti et al. 2011; Madhusudhan & Seager 2011; Line et al. 2012; Lee et al. 2012; de Kok et al. 2013; Swain et al. 2013

Ground-based Photometry and Spectra of hot Jupiters



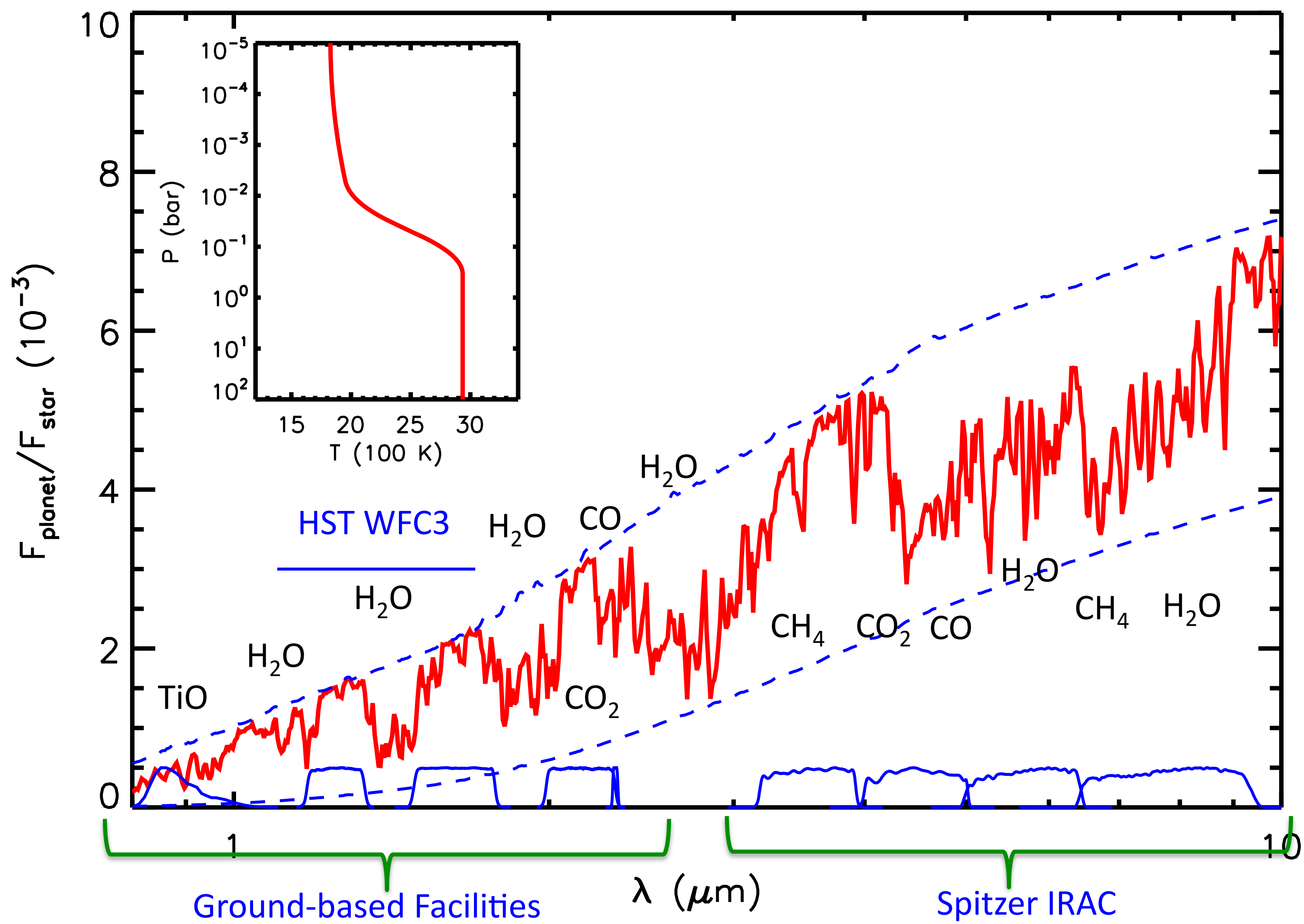
Anderson et al. 2012; Lendl et al. 2013



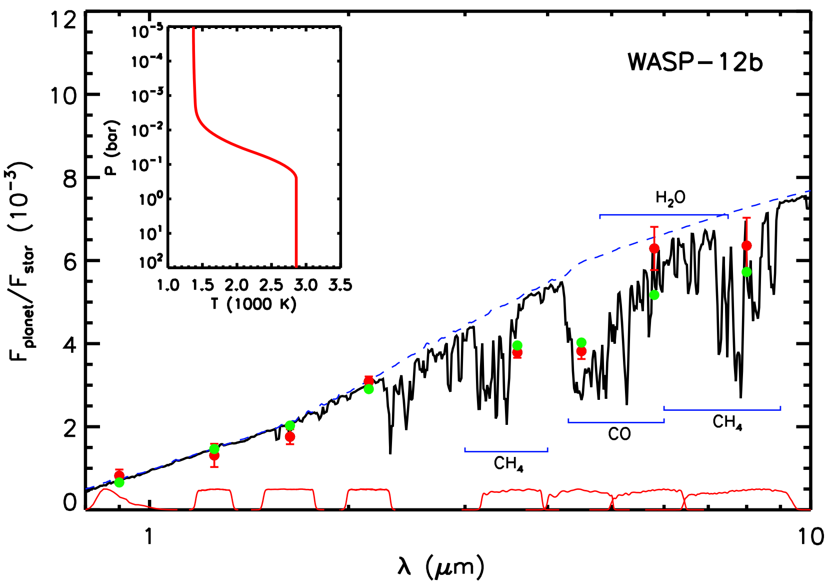


Bean et al. 2013

Spectral Signatures of hot Jupiter Atmospheres



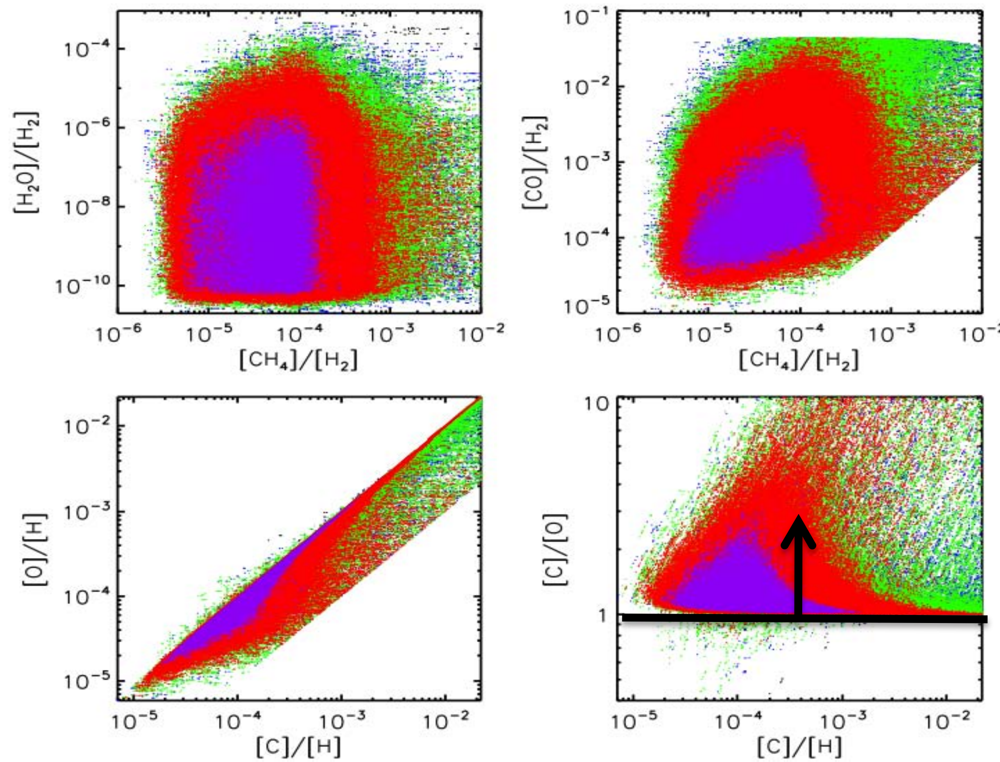
First measurement of atmospheric C/O in a giant planet



Key Molecular Constraints

- $H_2O/H_2 \leq 6 \times 10^{-6}$
- $CH_4/H_2 \geq 8 \times 10^{-6}$

C/O ≥ 1

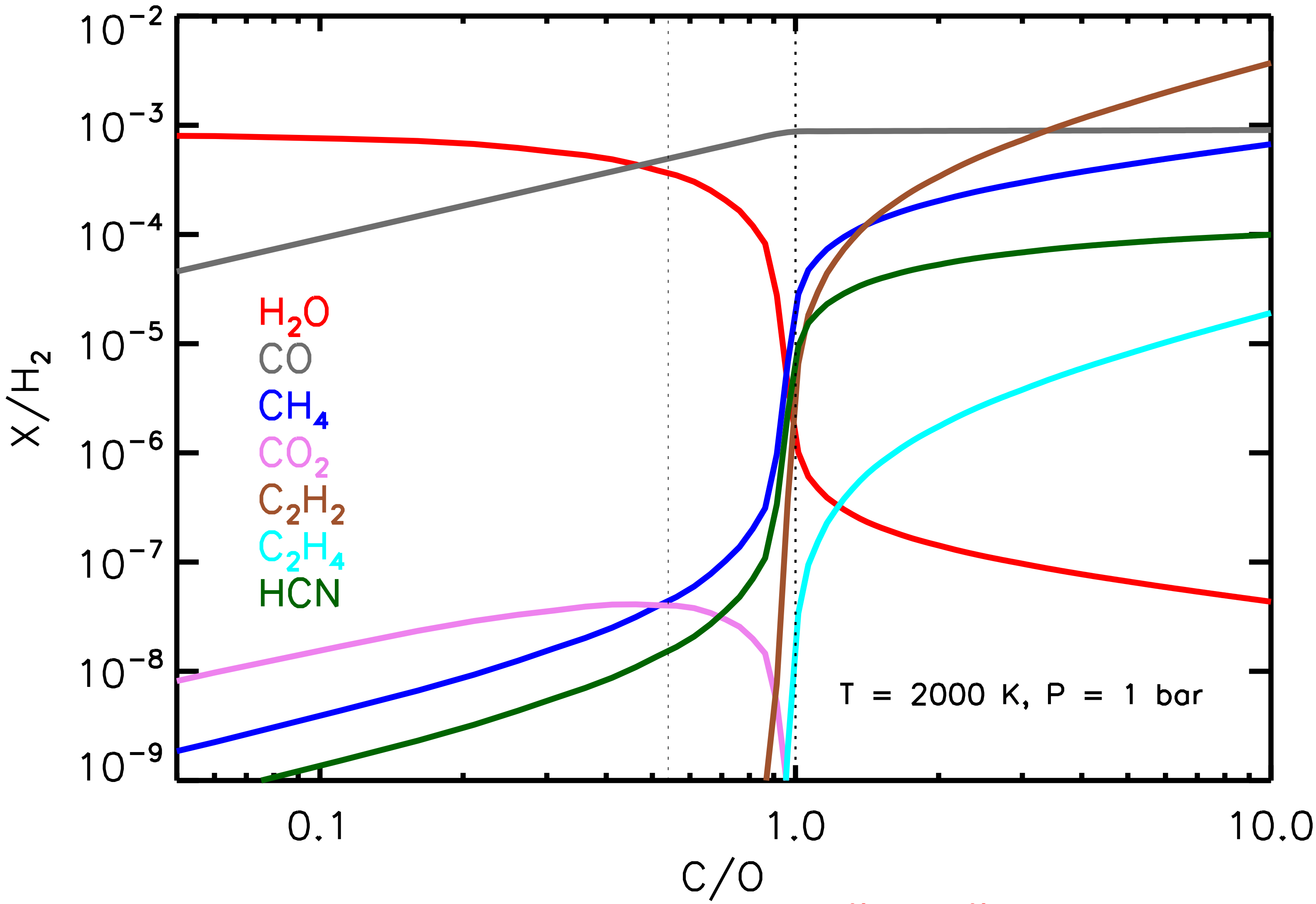


Adapted from Madhusudhan et al. 2011, Nature, 469, 64

Data from Lopez-Morales et al. 2010; Croll et al. 2010; Campo et al. 2011

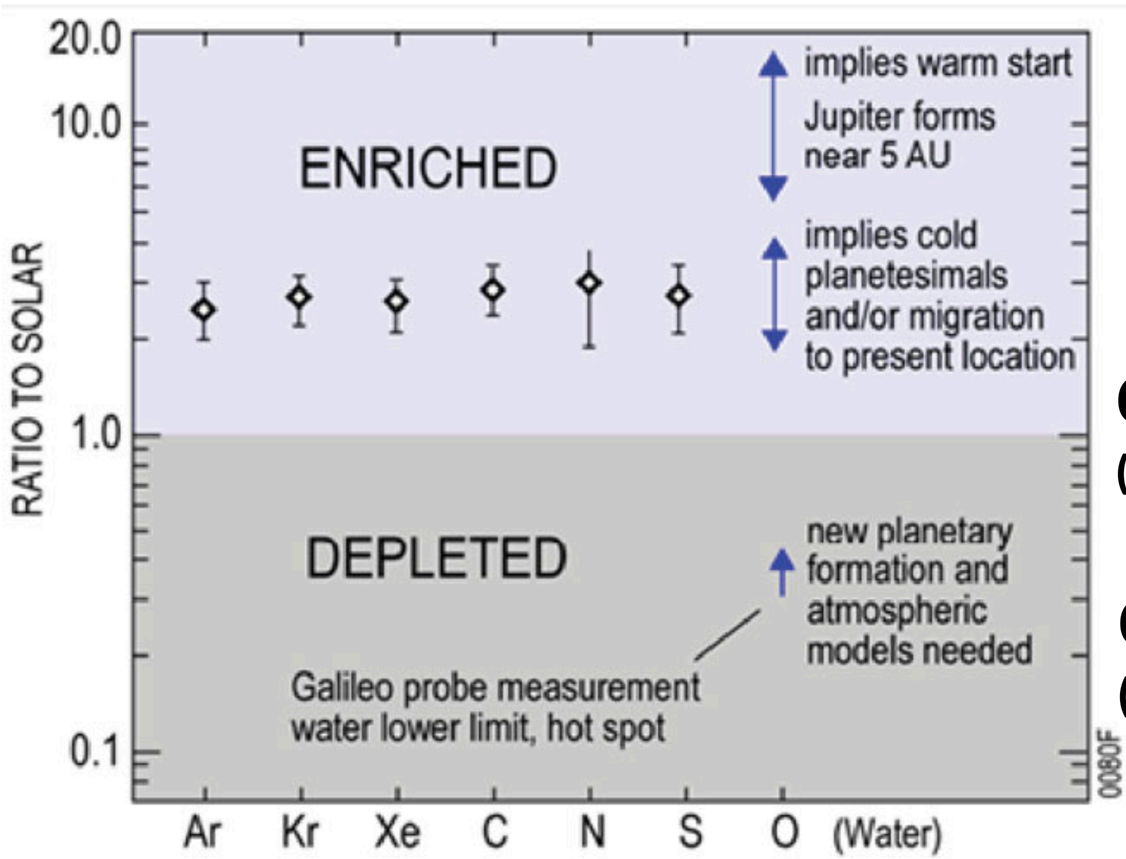
But cf Crossfield et al. 2012, Cowan et al. 2012, Swain et al. 2012, Stevenson et al. 2013

Influence of C/O on Atmospheric Chemistry

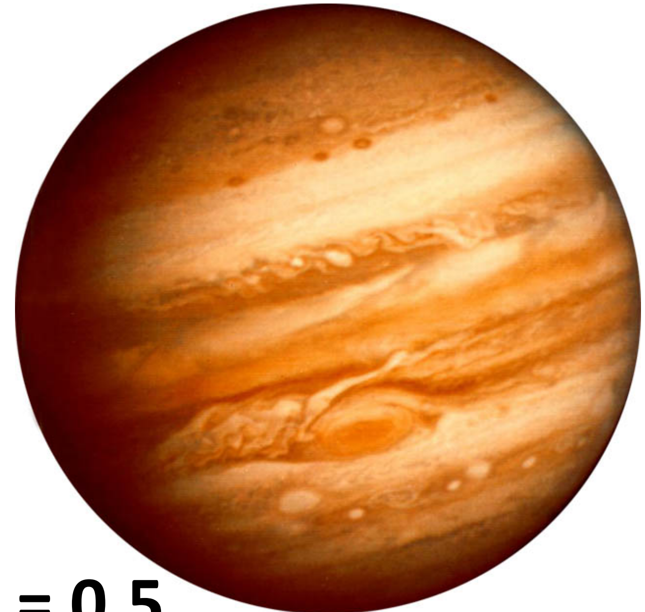


Madhusudhan 2012, ApJ, 758, 36

Atmospheric abundances in Jupiter



Owen et al 1999; Bolton et al. 2010



C/O = 0.5

(Working Hypothesis)

C/O ≥ 1

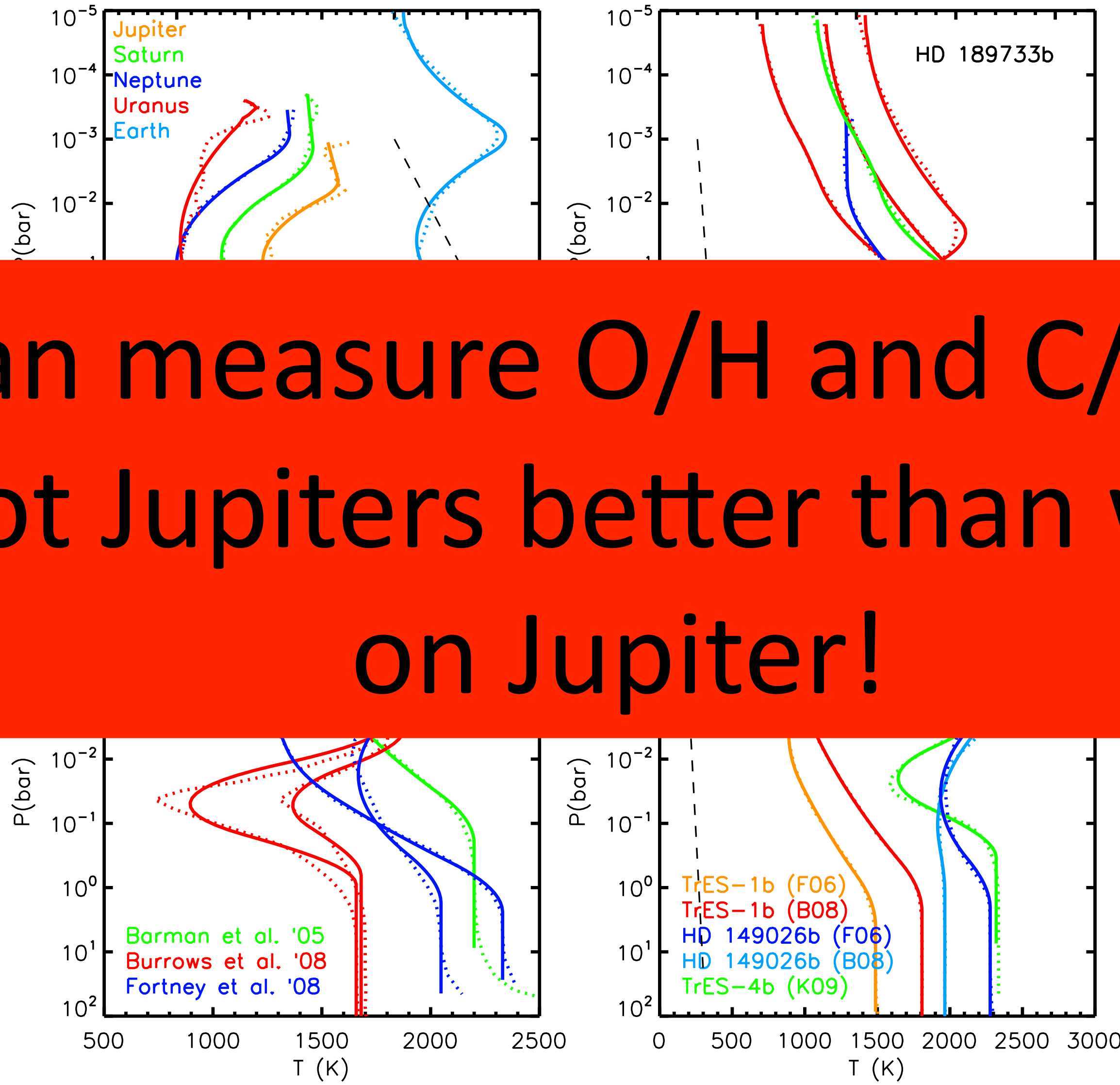
(Strange Territory)

Lodders 2004; Kuchner & Seager 2005; Mousis et al. 2012.

Key Message: We don't know the O/H and C/O ratios in the giant planets in the solar system

The Juno mission (@ Jupiter in 2016) aims to determine the water content, and hence O/H, in Jupiter's atmosphere.

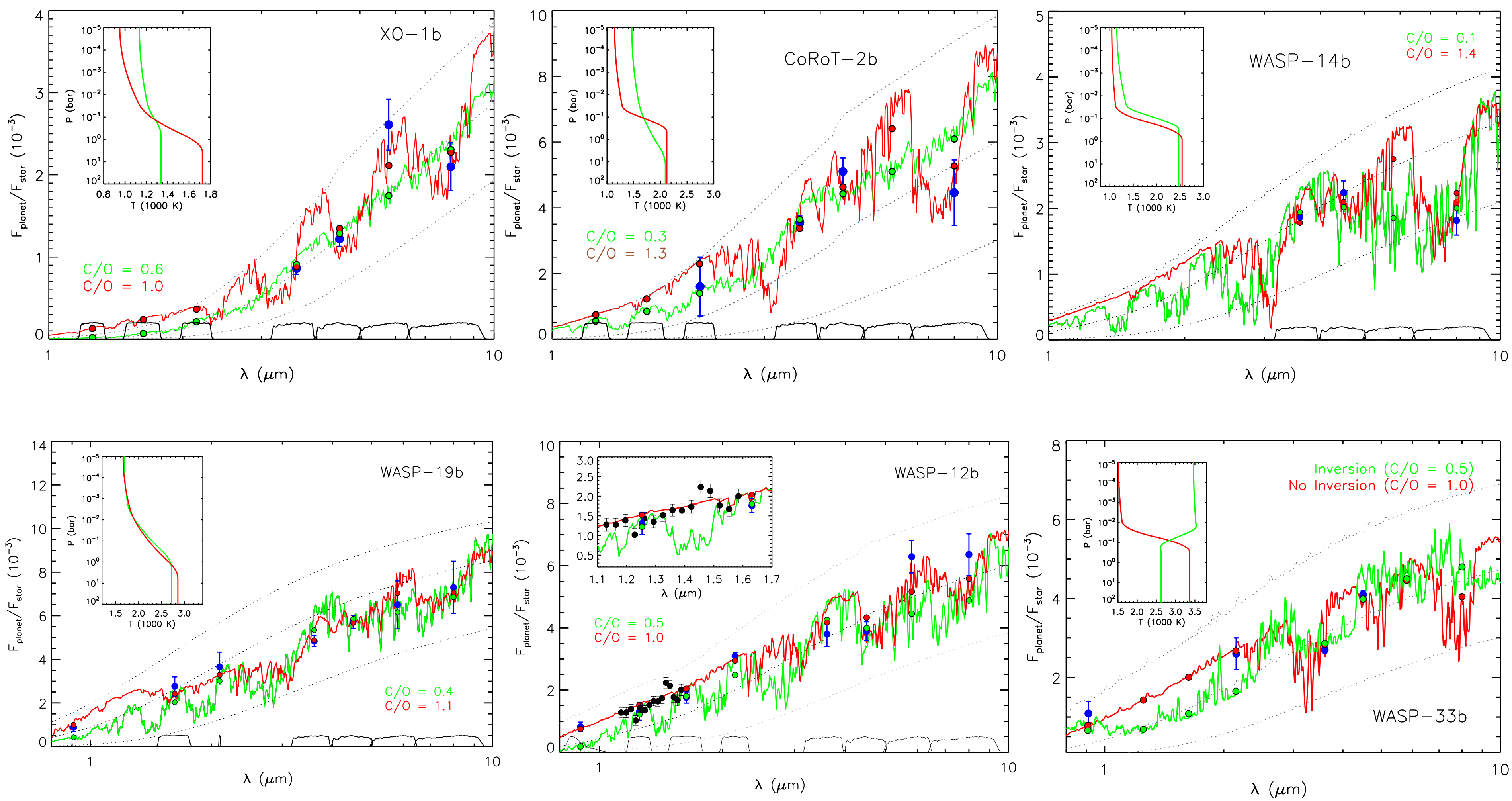
Temperature Profiles of Planetary Atmospheres



We can measure O/H and C/O ratios in hot Jupiters better than we can on Jupiter!

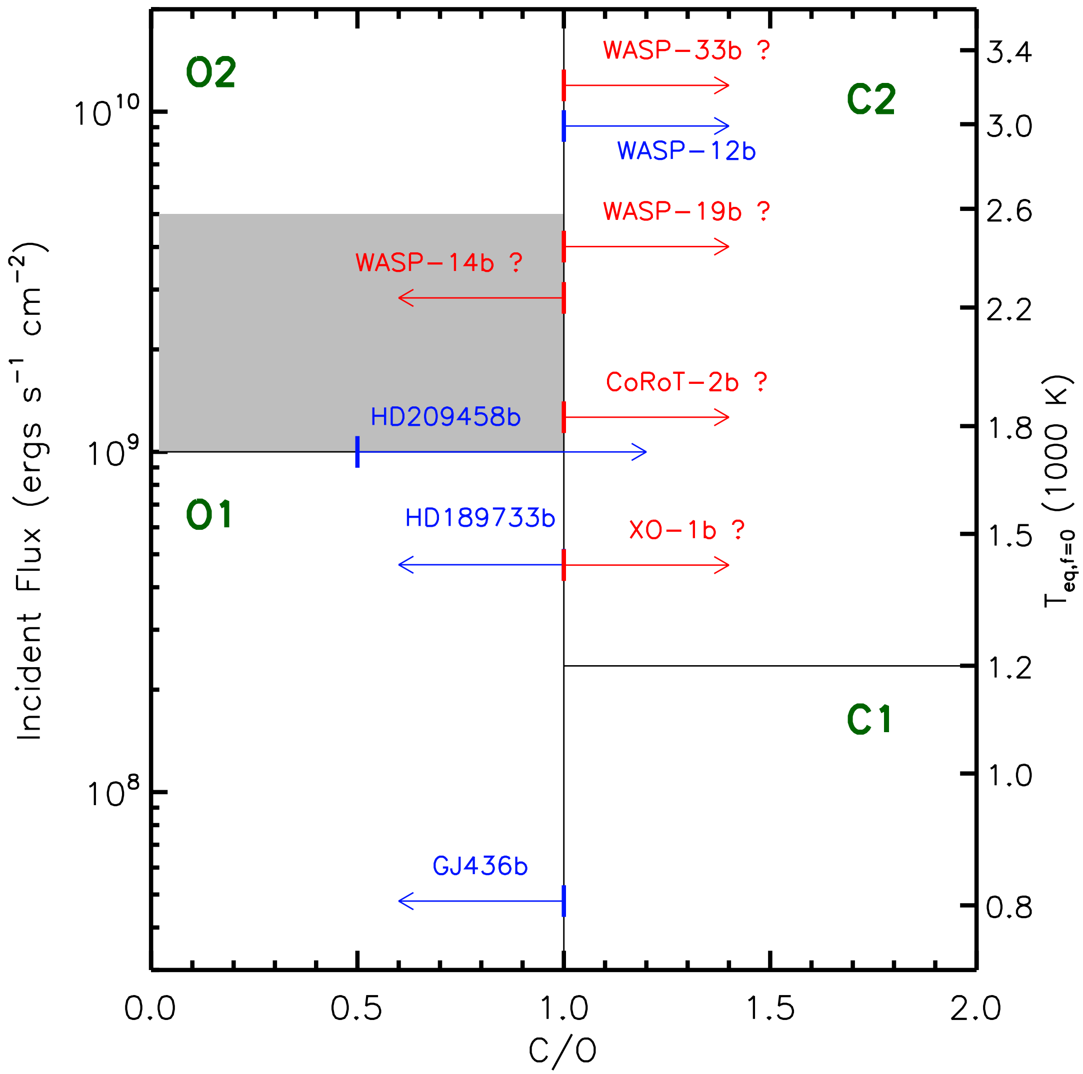
Madhusudhan & Seager 2009

C/O ratios in Exoplanetary Atmospheres



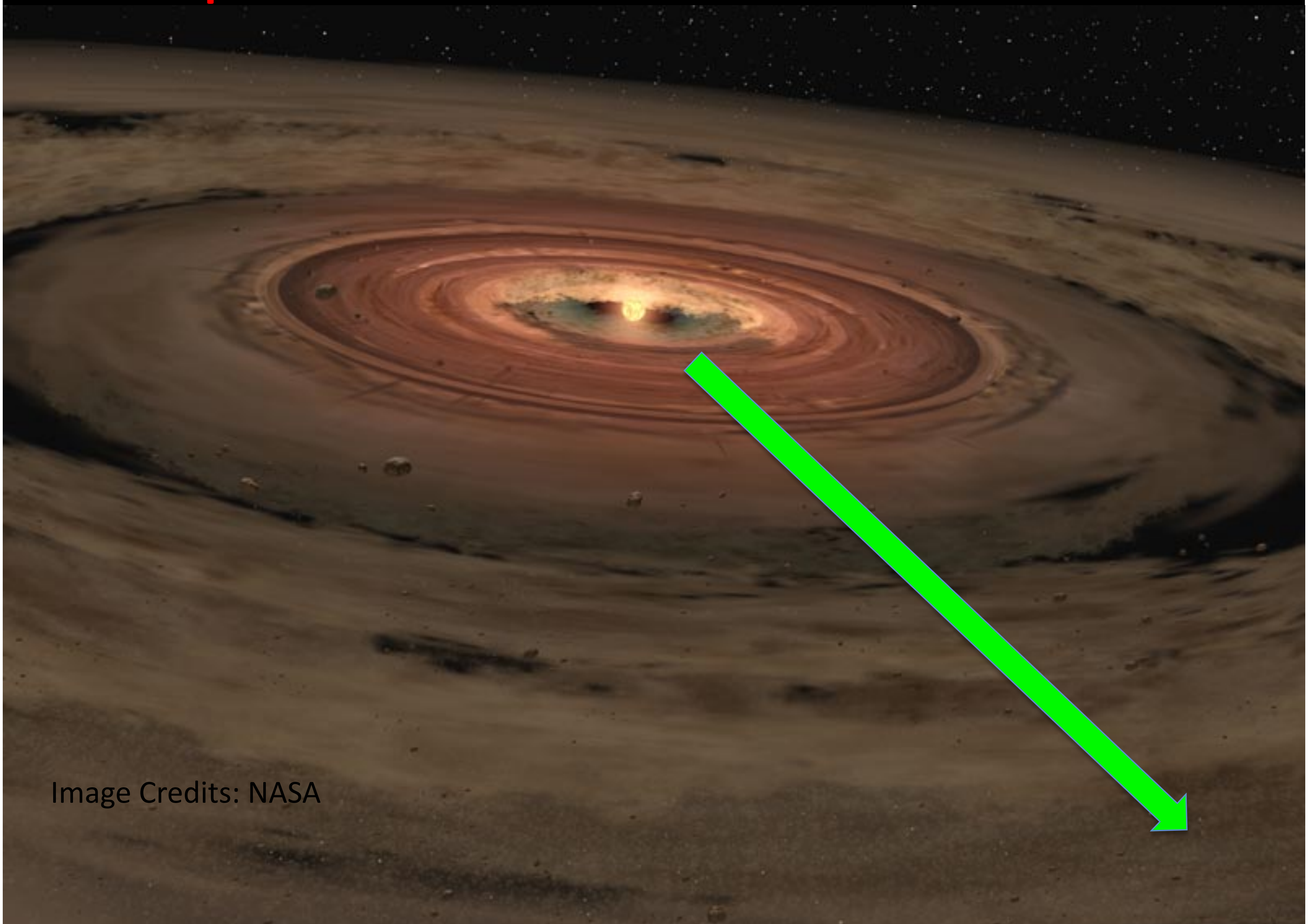
Madhusudhan 2012, ApJ, 758, 36

C/O Ratios in Hot Jupiter Atmospheres

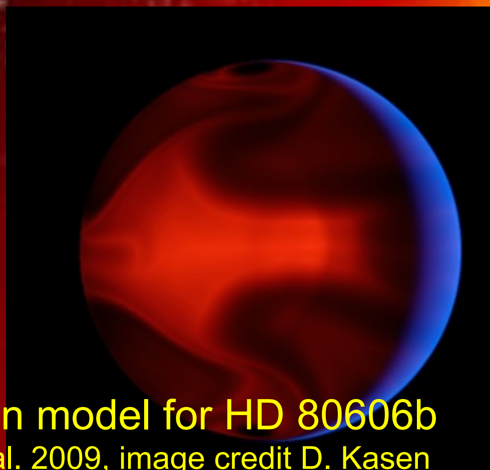


Madhusudhan 2012, ApJ, 758, 36

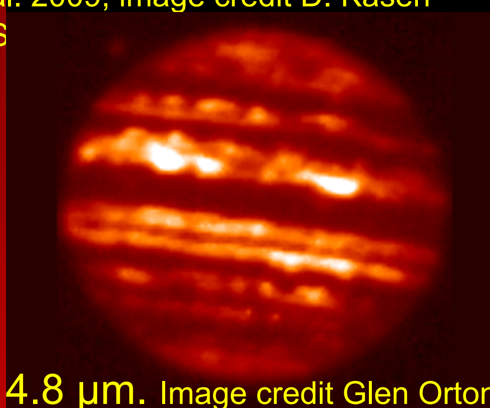
Implications for Planet Formation



Atmospheric Circulation on Hot Jupiters



Circulation model for HD 80606b
Laughlin et al. 2009, image credit D. Kasen (UCSC)/NAS



Jupiter at 4.8 μm. Image credit Glen Orton

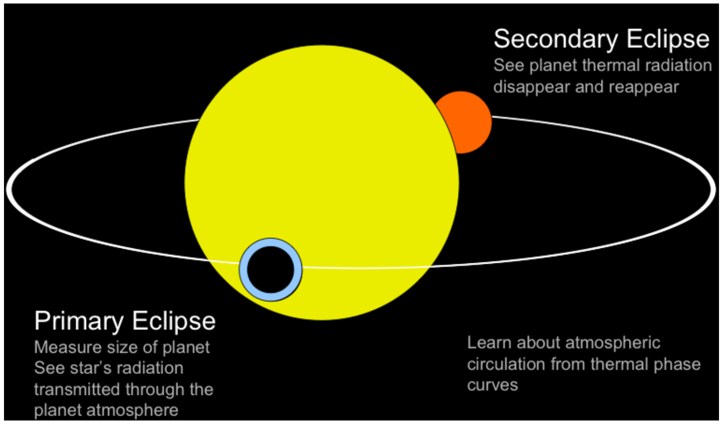
Hot Jupiters should be **tidally locked**, may have large thermal and/or chemical gradients between the two hemispheres.

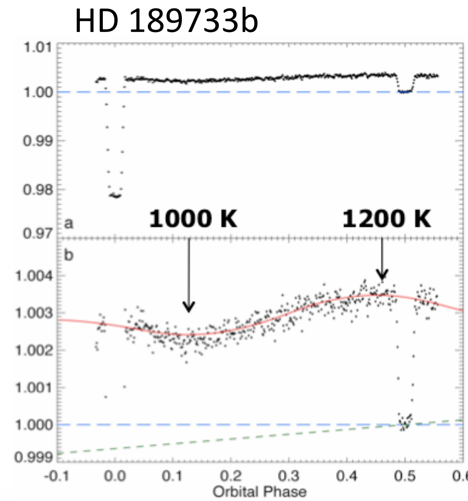
Planet's slow rotation means that the circulation should be **global in scale** (broad jets, large vortices).

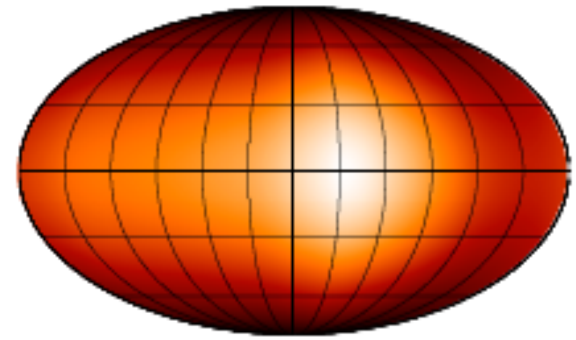
Cho et al. 2008
Laughlin et al. 2009
Showman et al. 2009
Heng et al. 2011
Rauscher & Menou 2012
Dobbs-Dixon et al. 2012

Image credit: ESA/C. Carreau

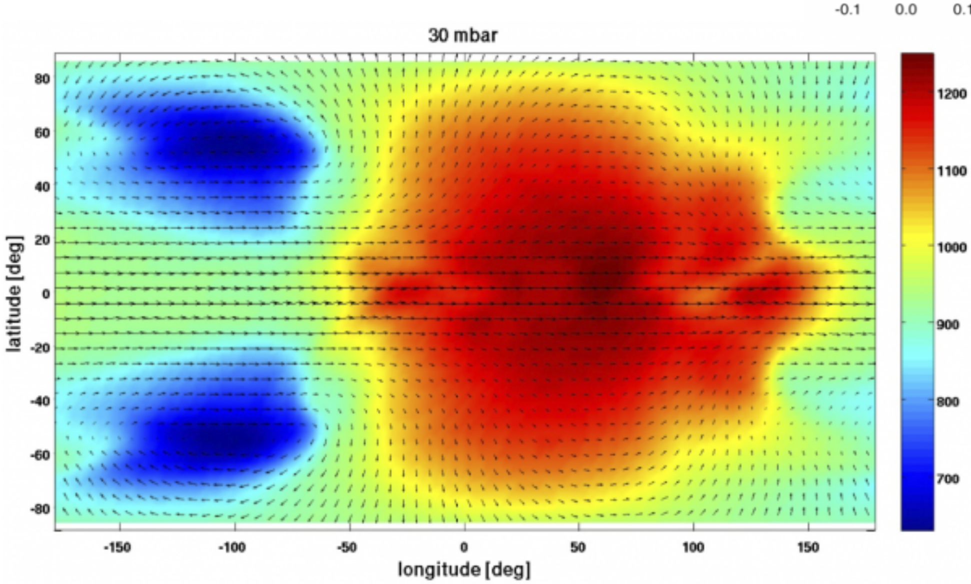
Thermal Phase Curves and Atmospheric Dynamics

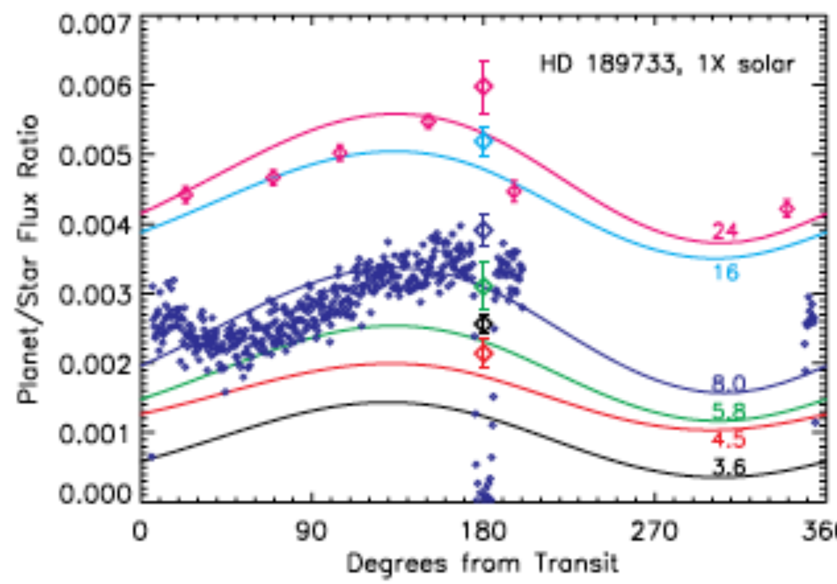






Knutson et al. 2007, 447, 183
Knutson et al. 2009, 690, 822
Cowan & Agol 2008, ApJ, 678, L129





Showman et al. 2009, ApJ, 678, 1419

3D GCM Models predict eastward shift of the hot spot away from the sub-stellar point, consistent with observations of phase curves.

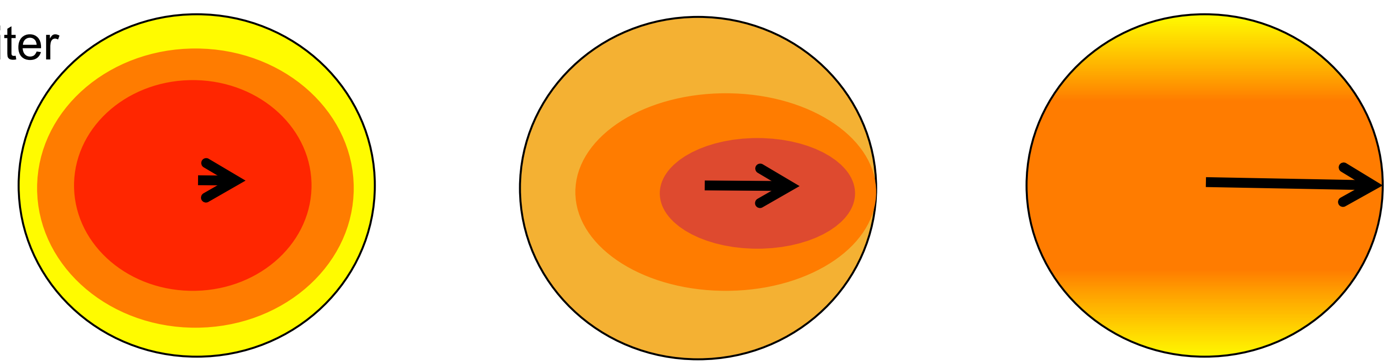
Atmospheric Circulation Models 101

To 0th order, response of atmosphere to radiative forcing depends on two parameters:

- *Radiative* time scale t_R set by atmospheric opacity (metallicity, chemistry)
- *Advective* time scale t_A set by wind speed, rotation rate

Day-night temperature gradient on tidally locked planets depends on ratio of *radiative* to *advective* time scales at photosphere

Hot Jupiter Dayside



$t_R/t_A << 1$ | $t_R/t_A \sim 1$ | $t_R/t_A >> 1$

Hot Planets Have Hotter Day Sides

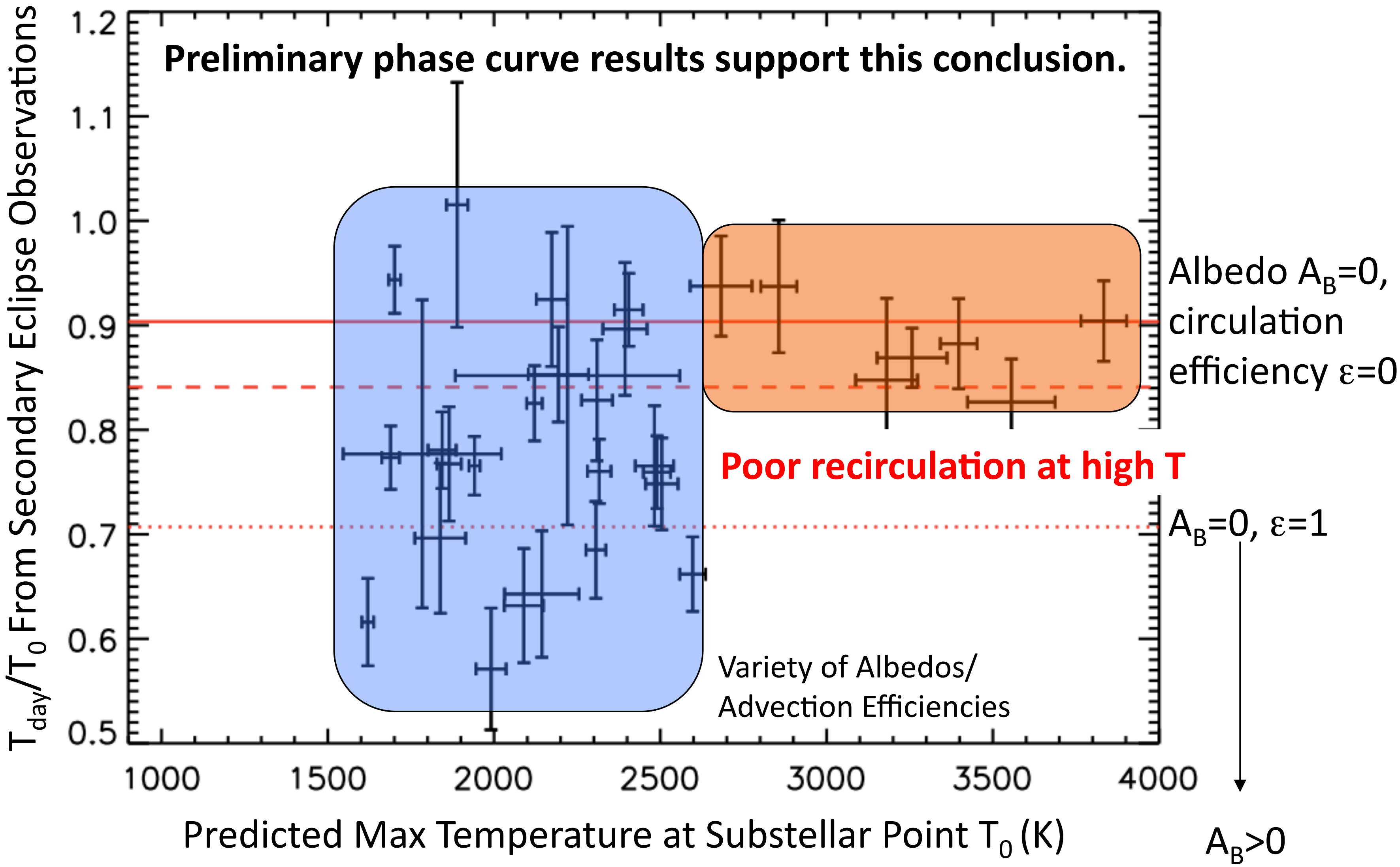
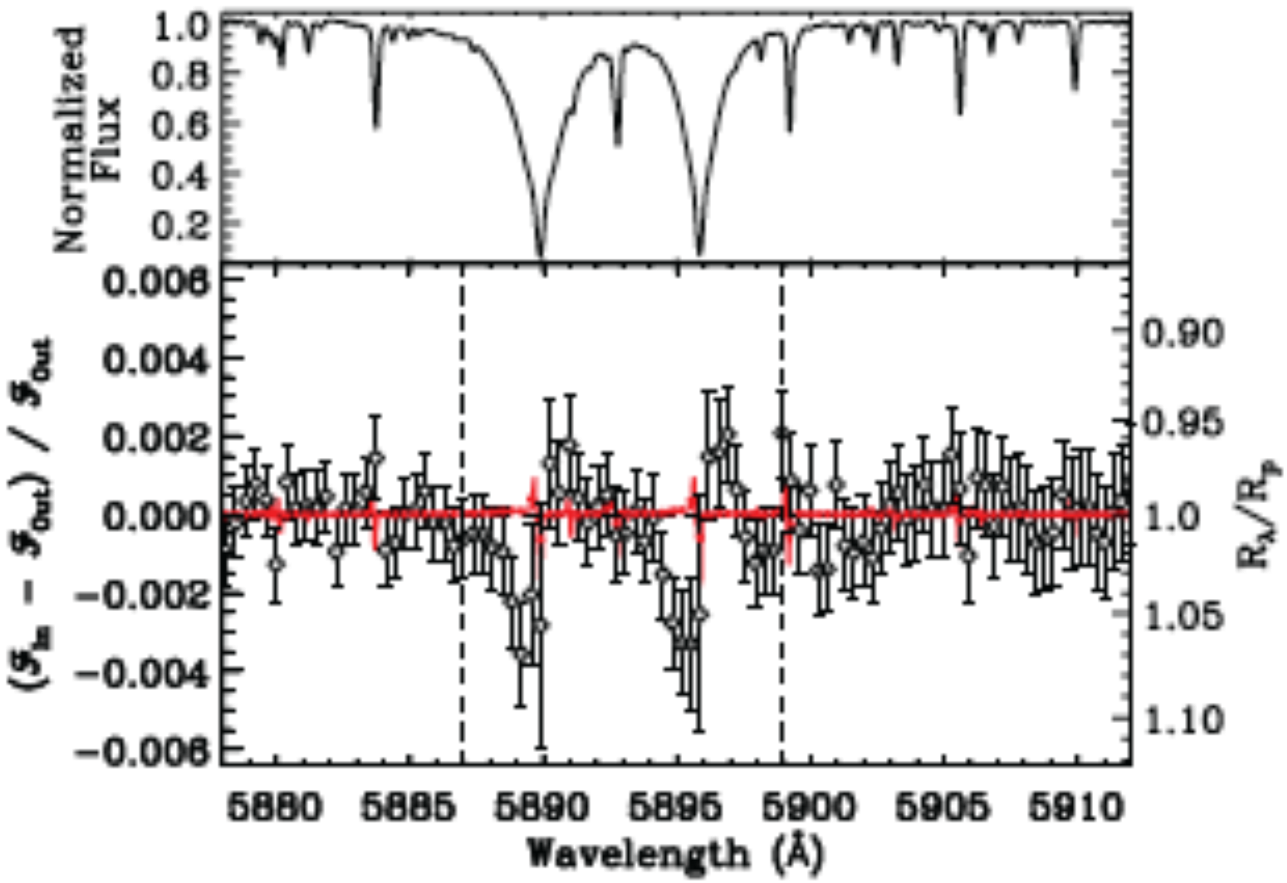


Figure courtesy N. Cowan, updated from Cowan & Agol (2011b)

Inferences of Atomic Species in hot Jupiters

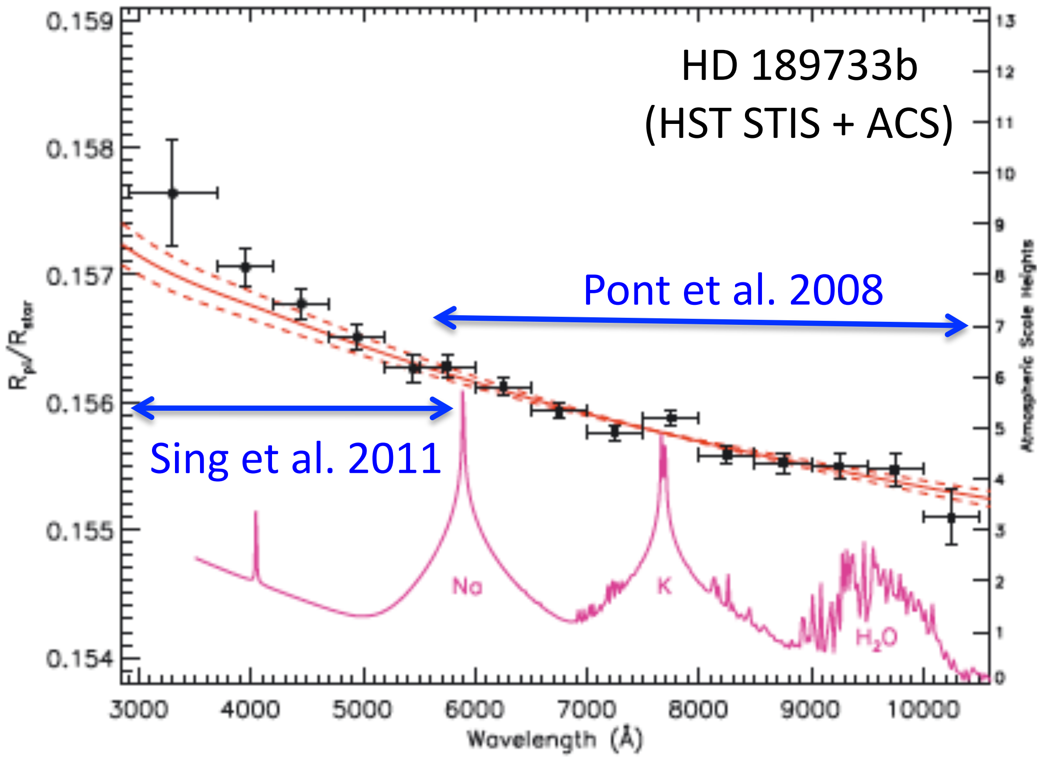
Na I detection in optical from ground

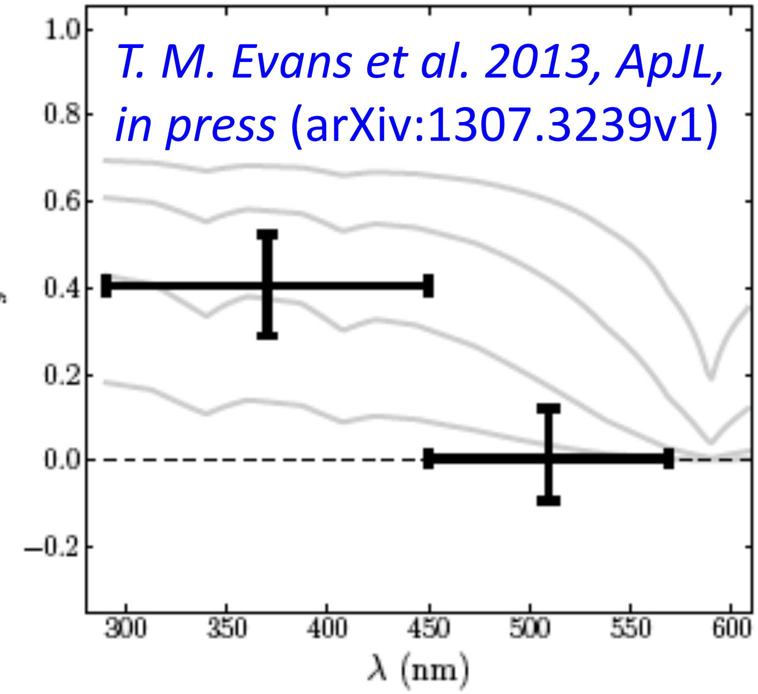


Redfield et al. 2008, ApJ, 673, L87

Charbonneau et al. 2002; Vidal-Madjar et al. 2003,3004; Redfield et al. 2008; Snellen et al. 2008; Des Etangs et al. 2010; Wood et al. 2011; Colon et al. 2010; Sing et al. 2011.

Hazes and Clouds in hot Jupiter Atmospheres





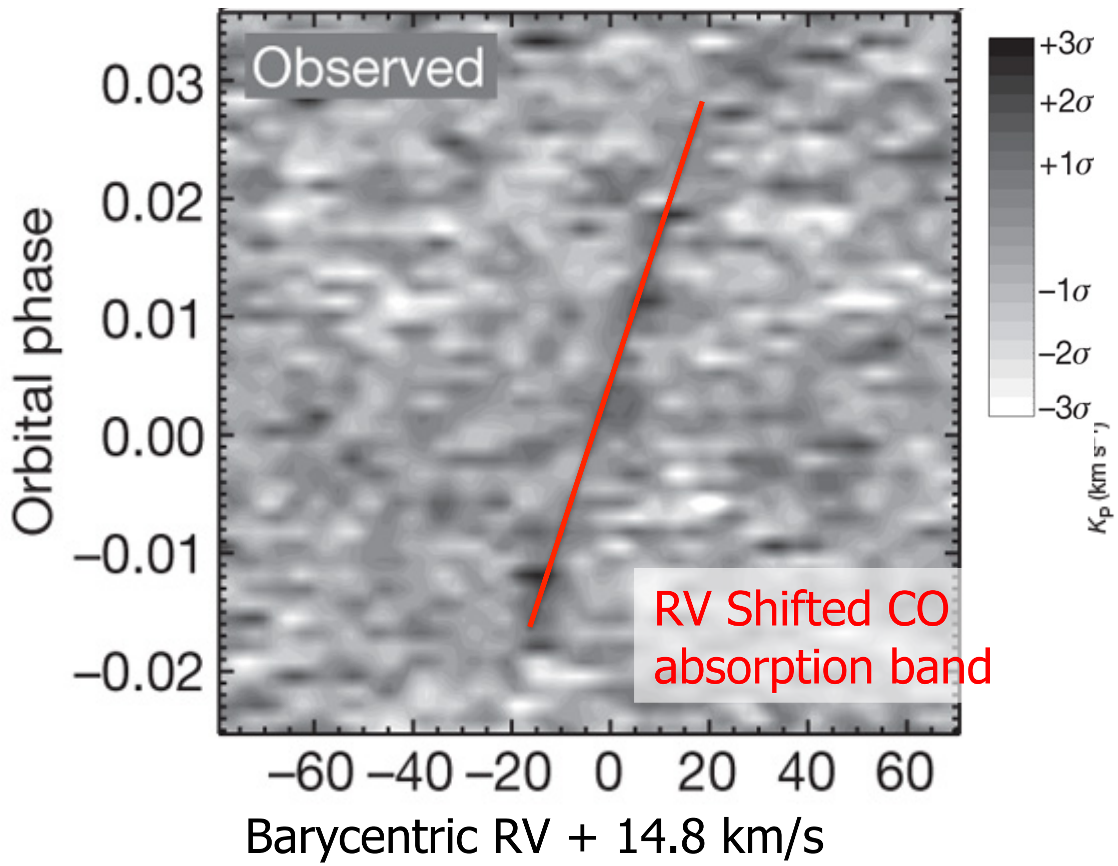
F. Pont et al. 2008, MNRAS, 385, 109
D. K. Sing et al. 2011, MNRAS, 416, 1443

Modeling and Theory:
Lecavelier Des Etangs et al. 2008, A&A, 481, L83
Helling et al. 2008, A&A, 485, 547

Other results indicating high geometric albedos for some hot Jupiters using Kepler:
Kepler-7b (Demory et al. 2011, ApJ, 735, 12)
HAT-7b (Christiansen et al. 2010, ApJ, 710, 97)

Cross-correlation Technique

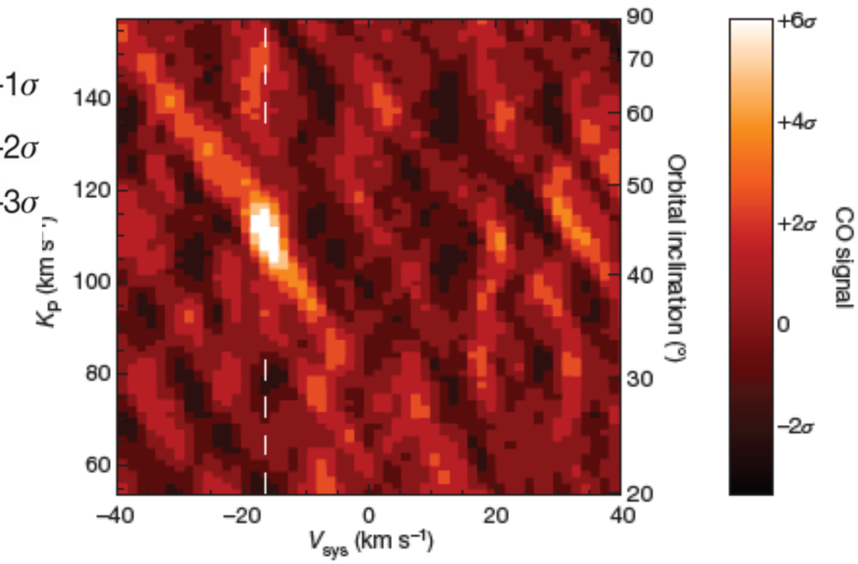
RV-Shifted Absorption from HD 209458b During Transit



Snellen et al. (2010)

CO absorption detected at 5.6σ

CO detection in the non-transiting planet τ Bootis



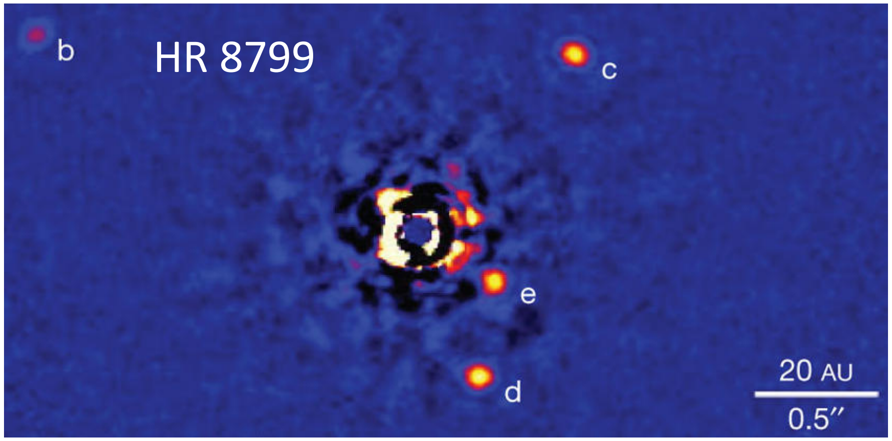
Brogi et al. (2012)

Also see Rodler et al. (2013)

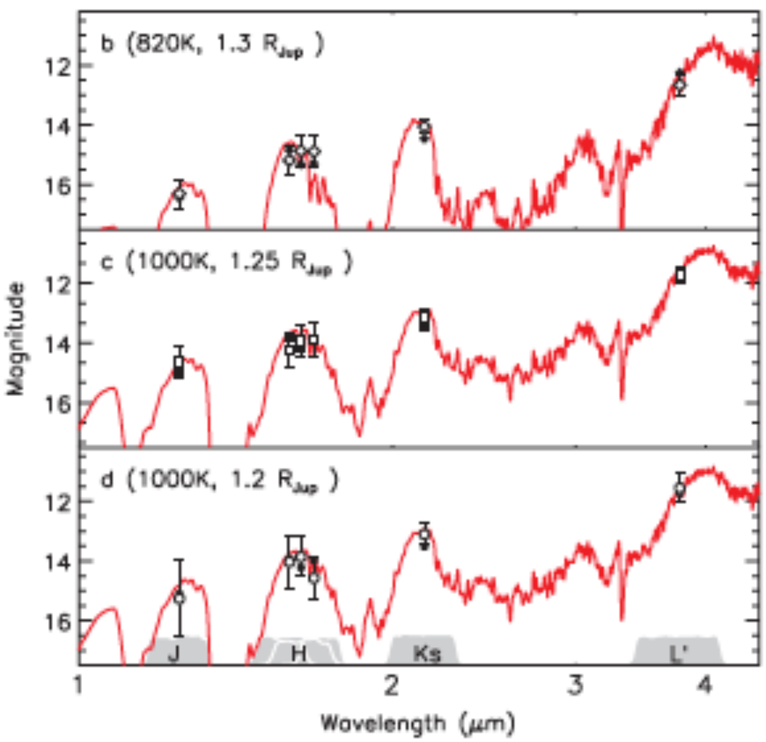
Outline

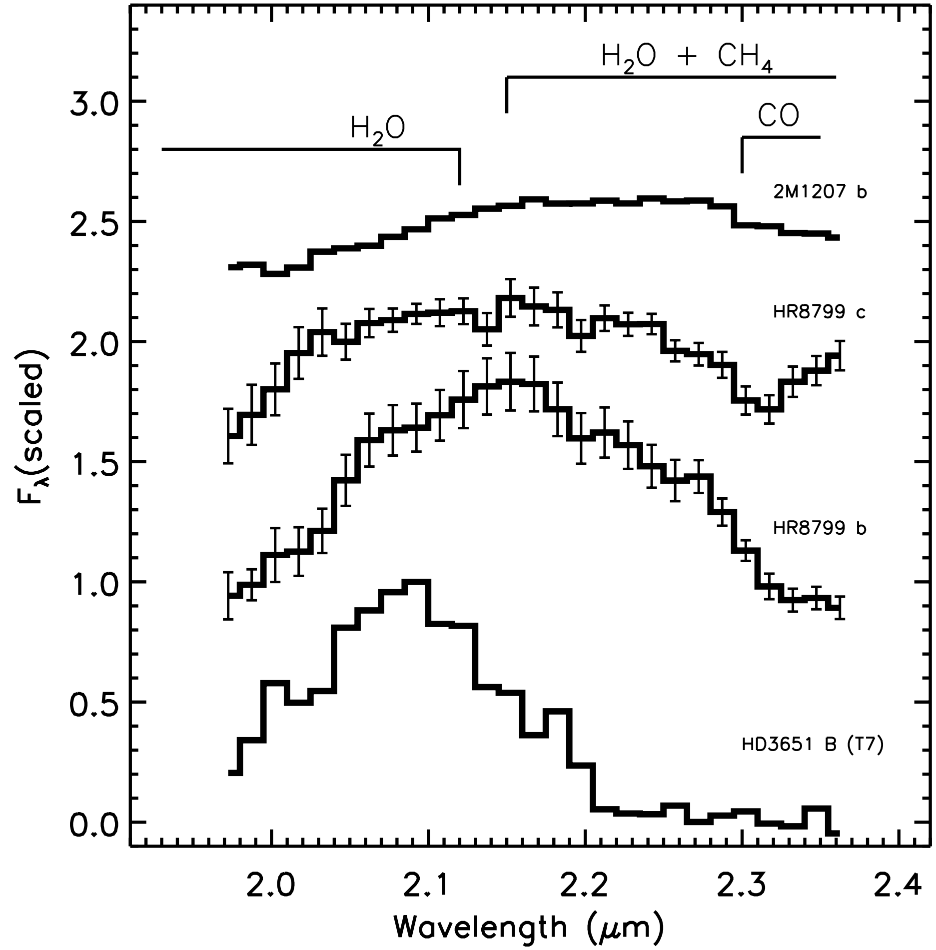
- ✧ Theory of Exoplanetary Atmospheres
- ✧ Atmospheres of Hot Jupiters
- ✧ Atmospheres of Directly-imaged Planets
- ✧ Atmospheres of Hot Neptunes
- ✧ Atmospheres of Super-Earths
- ✧ Frontier Problems and Future Outlook

Atmospheres of Directly-imaged Exoplanets



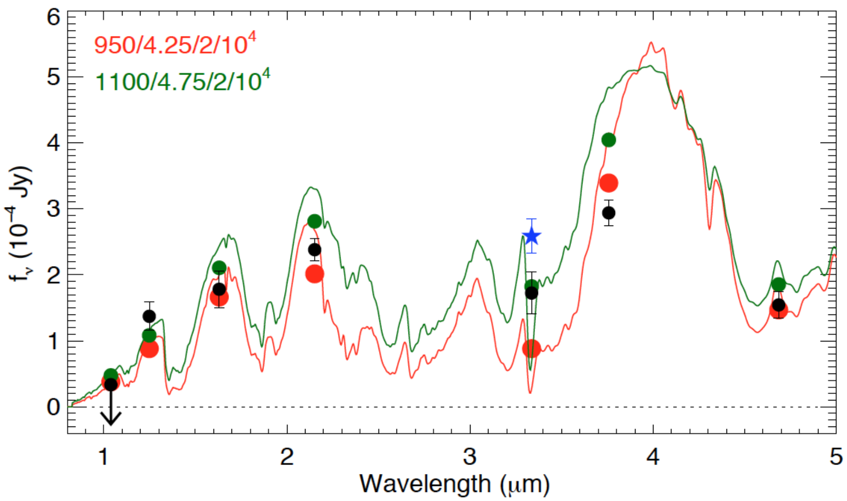
Marois et al. 2008,2010

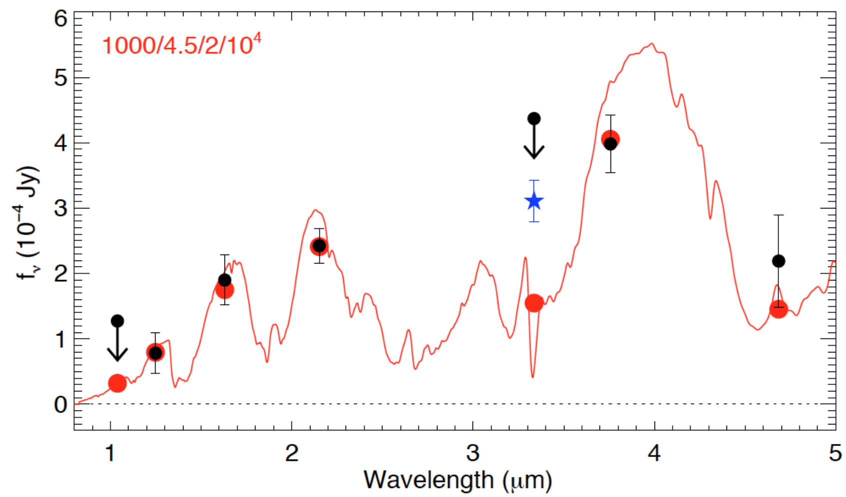




Barman et al. (2011)

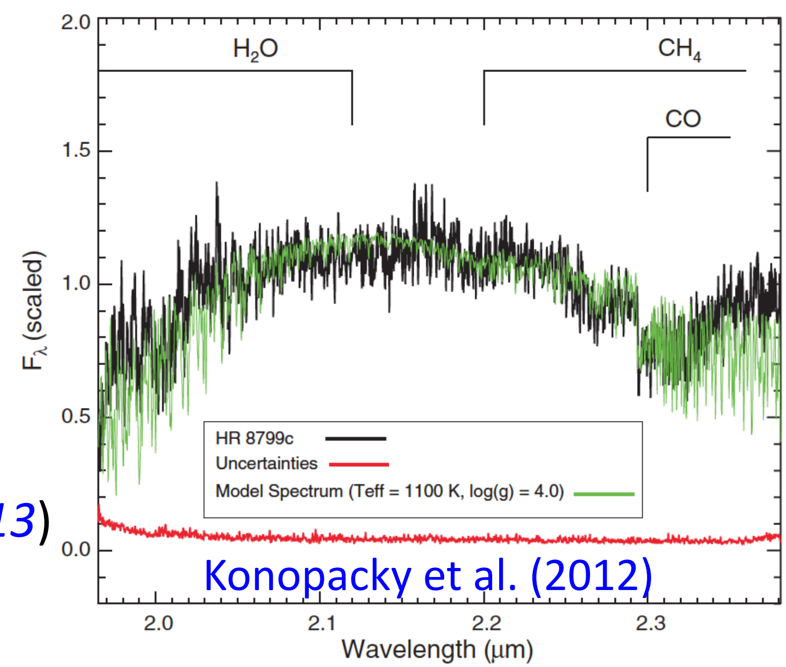
Inferences for the HR 8799 system





Marley et al. (2012)

- Non-equilibrium chemistry (*Bowler et al. 2010; Barman et al. 2011*)
- Thick clouds (*Barman et al. 2011; Currie et al. 2011; Madhusudhan et al. 2011; Marley et al. 2012*)
- High-resolution spectroscopy (*Janson et al. 2010; Barman et al. 2011; Konopacky et al. 2012; Oppenheimer et al. 2013*)
- Atmospheric Retrieval (*Lee et al. 2013*)



Konopacky et al. (2012)

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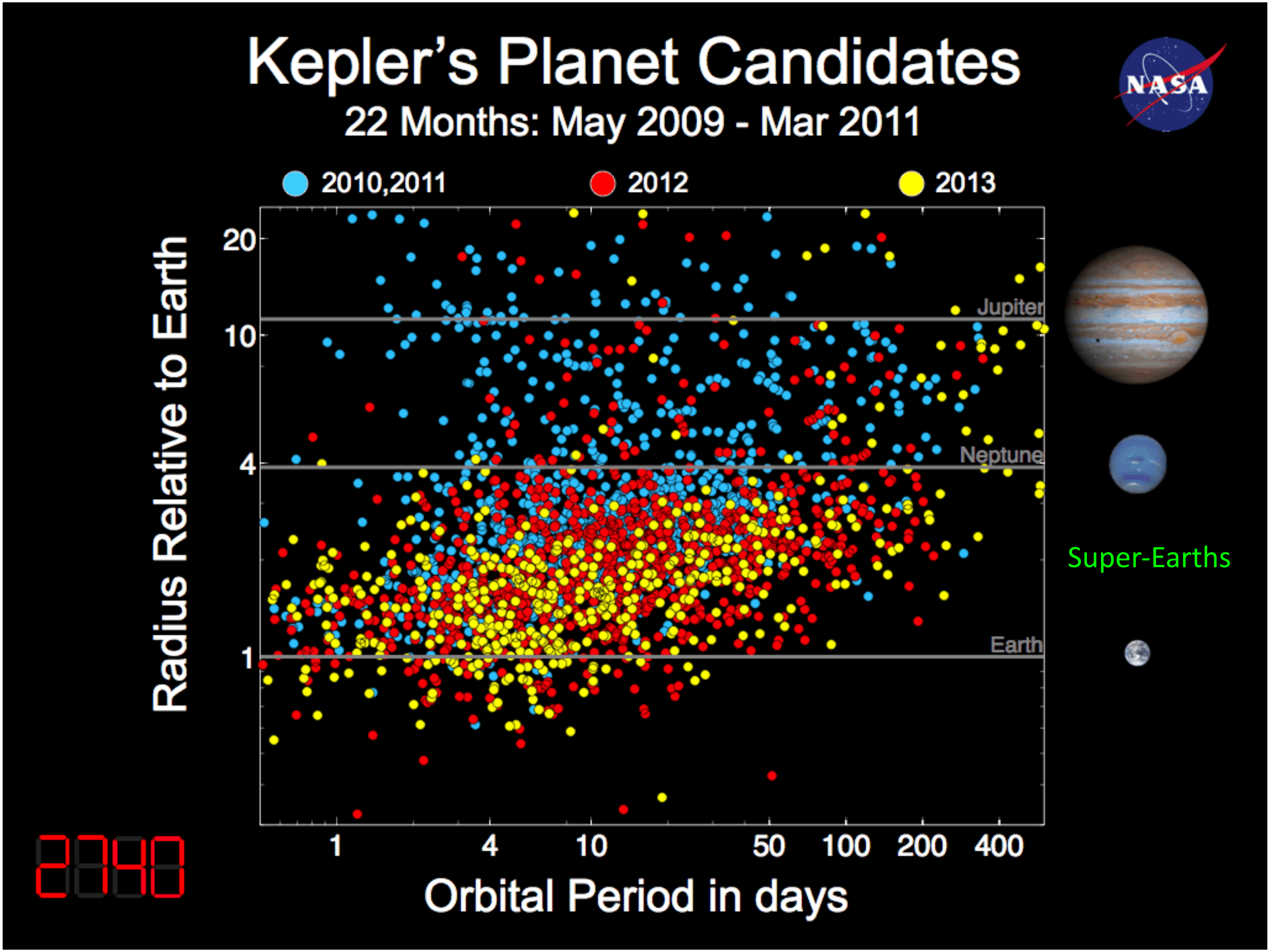
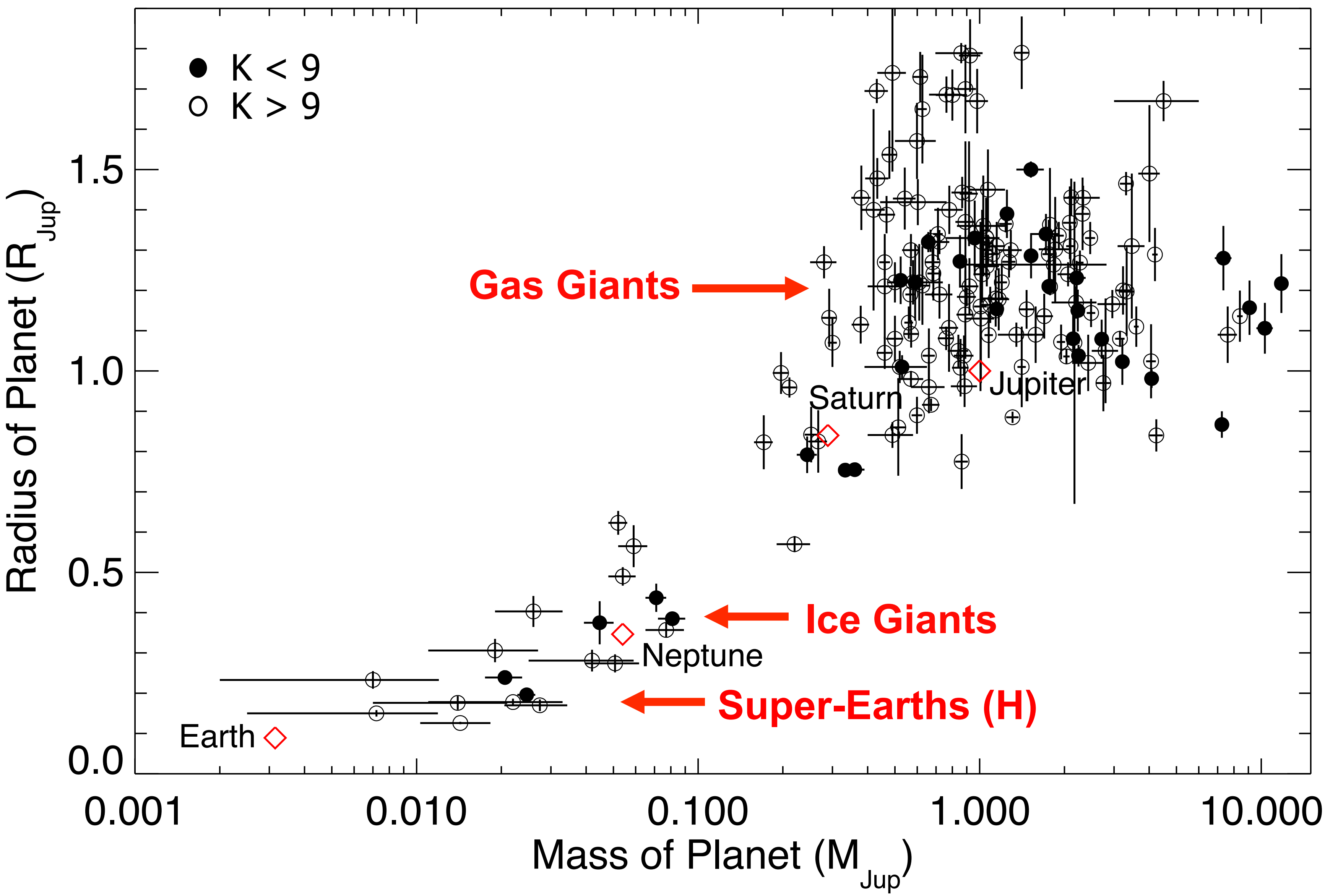
- ✧ Frontier Problems and Future Outlook


Kepler's Planet Candidates
22 Months: May 2009 - Mar 2011
2010,2011
2012
2013
Radius Relative to Earth
20
10
4
1
Jupiter
Neptune
Earth
1
4
10
50
100
200
400
Orbital Period in days
Super-Earths
2740

Prospects for Surveying Sample of Smaller Planets



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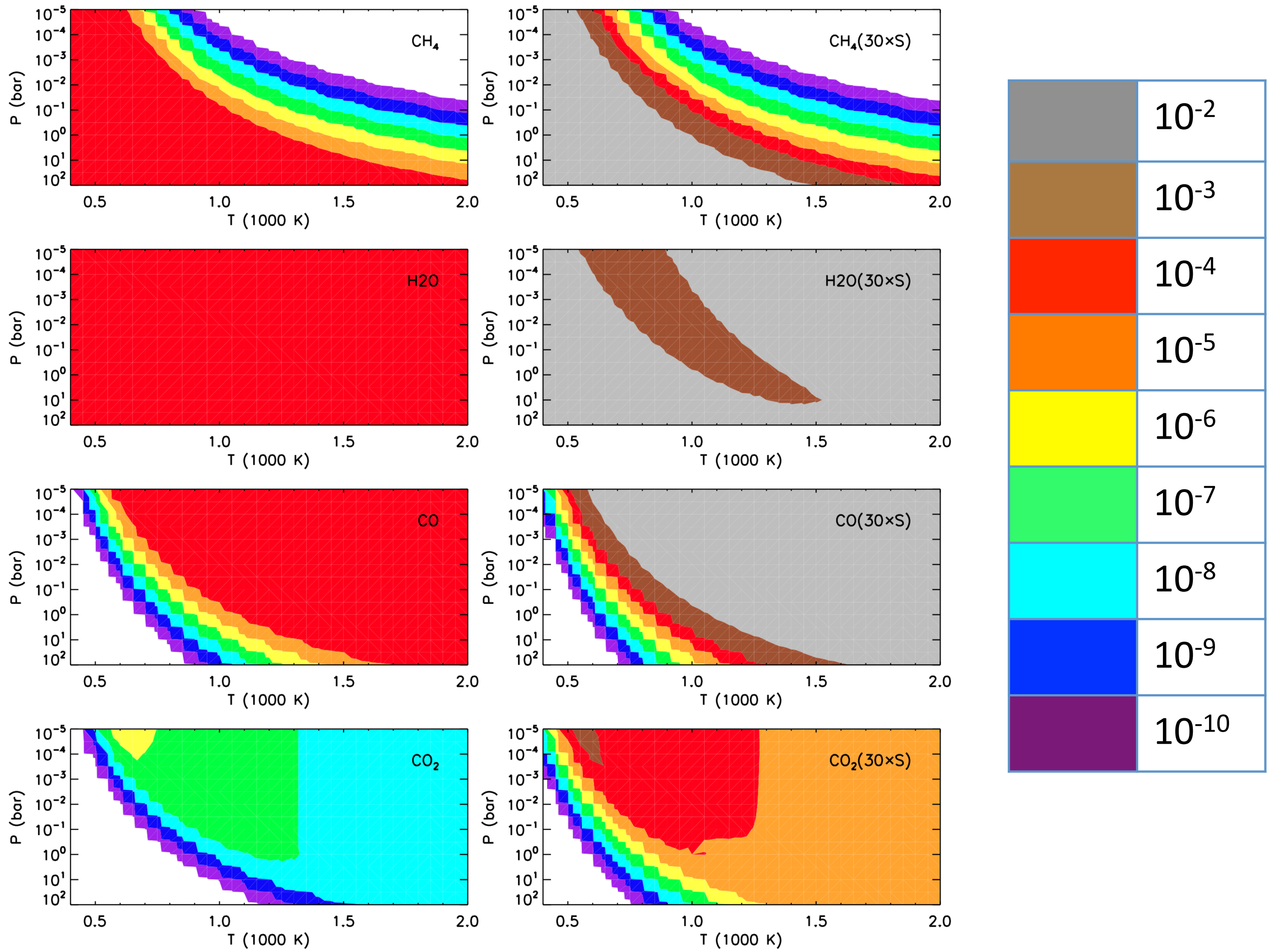
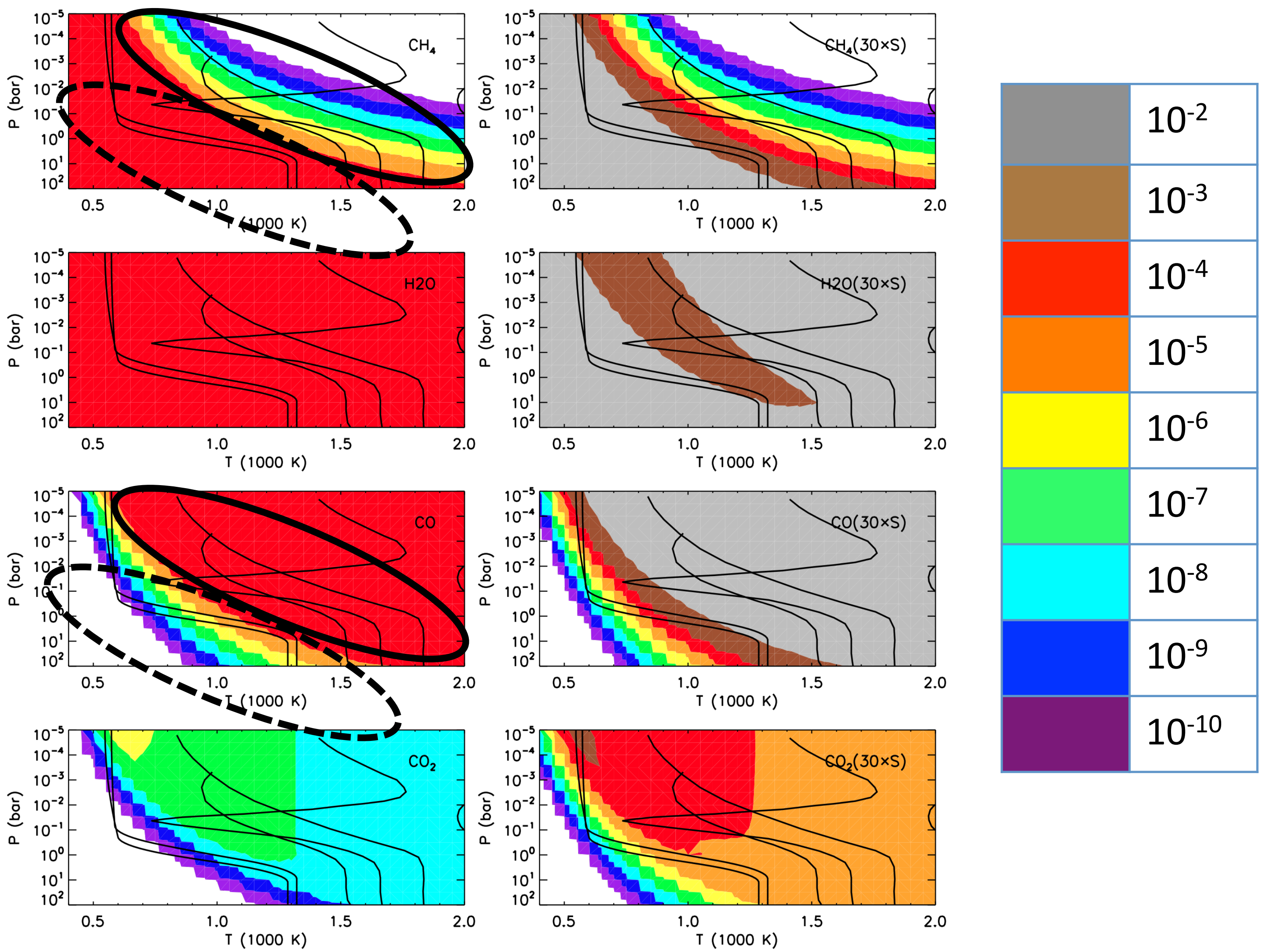
Chemistry in H_2-rich Atmospheres

(Molecular mixing ratios assuming chemical equilibrium)

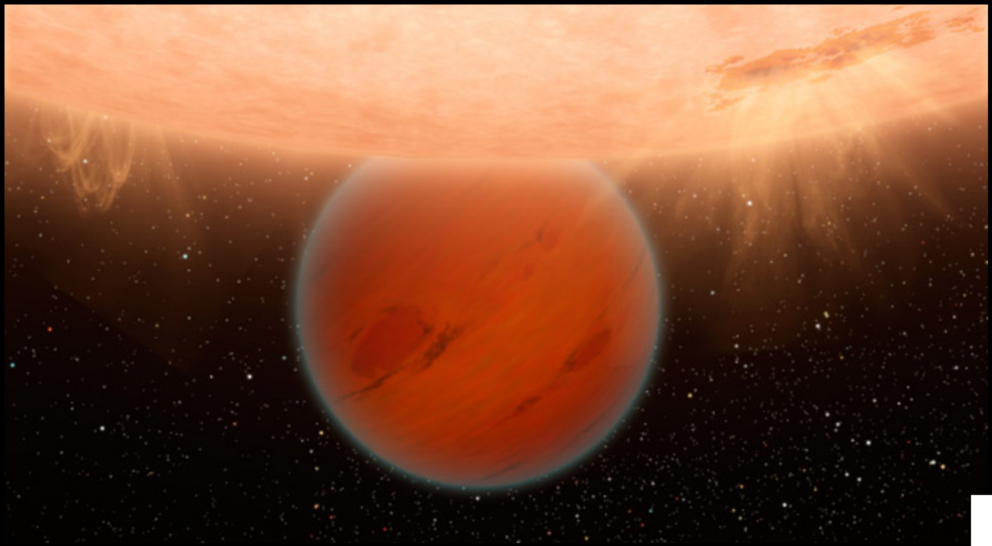


Chemistry in H_2-rich Atmospheres

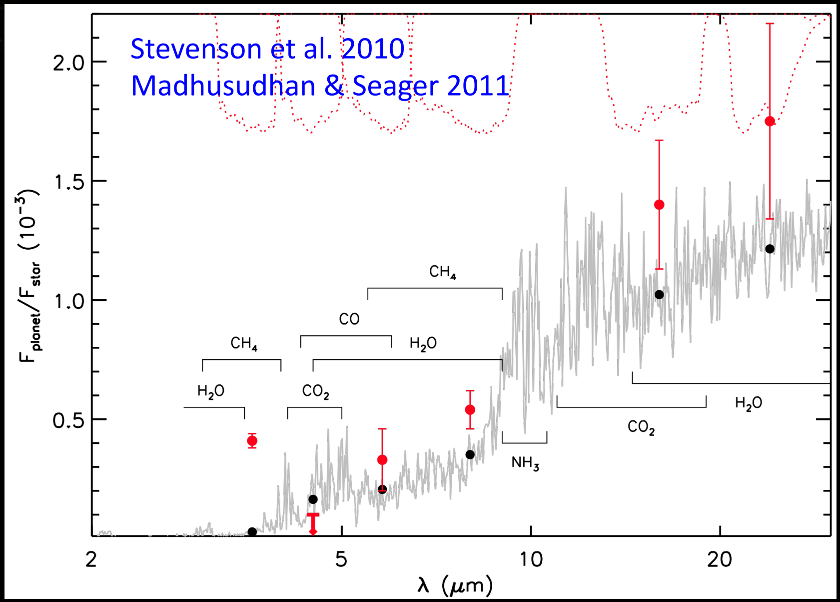
(Molecular mixing ratios assuming chemical equilibrium)



The hot Neptune GJ 436b



Credits: NASA/JPL/Caltech



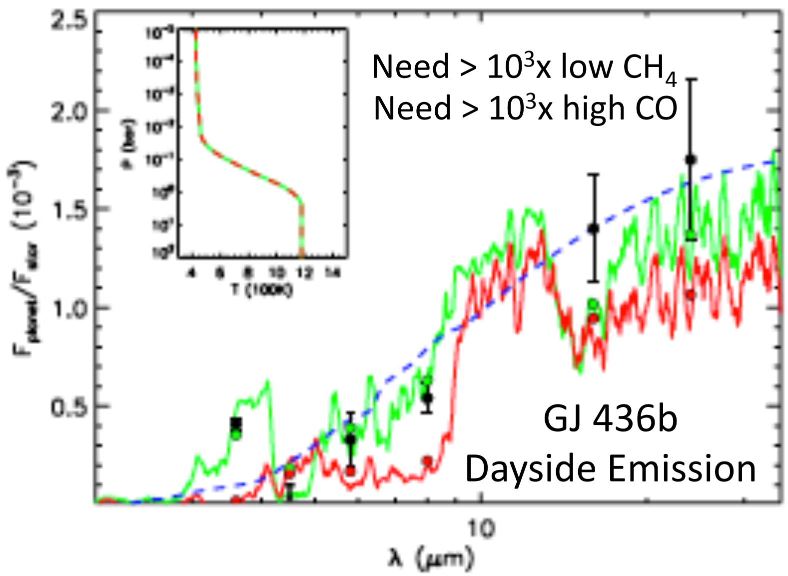
$M_s = 0.4\ M_\odot$, $R_s = 0.5\ M_\odot$, $T_{eff} = 3500$ K, M3 V

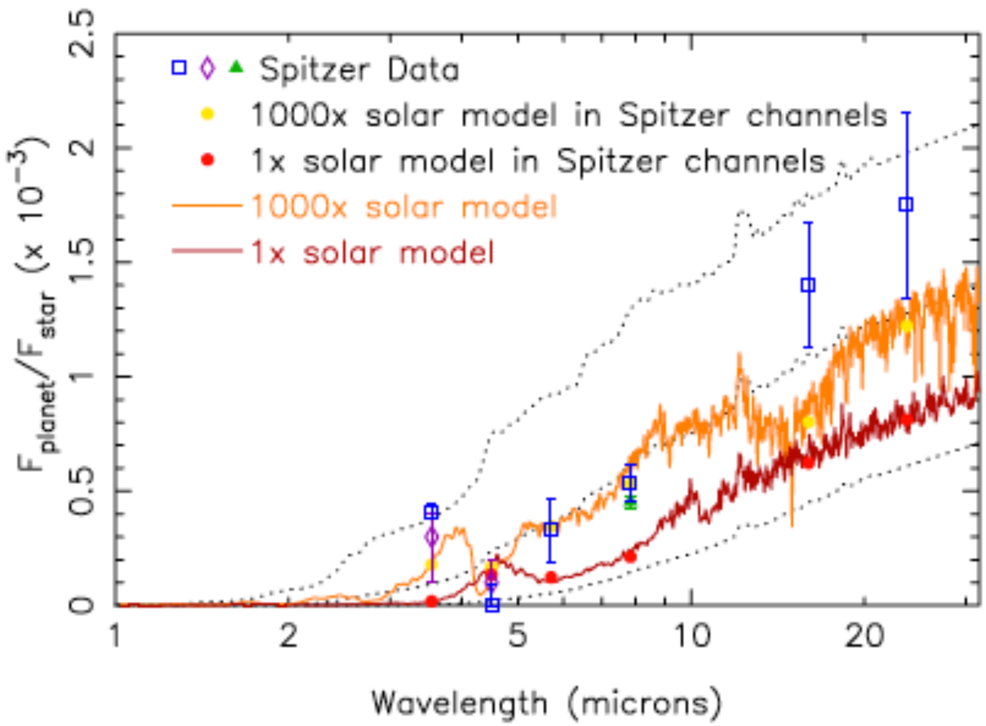
$M_p = 22.2\ M_E$, $R_p = 4.3\ R_E$, $T_{eq} \sim 750$ K

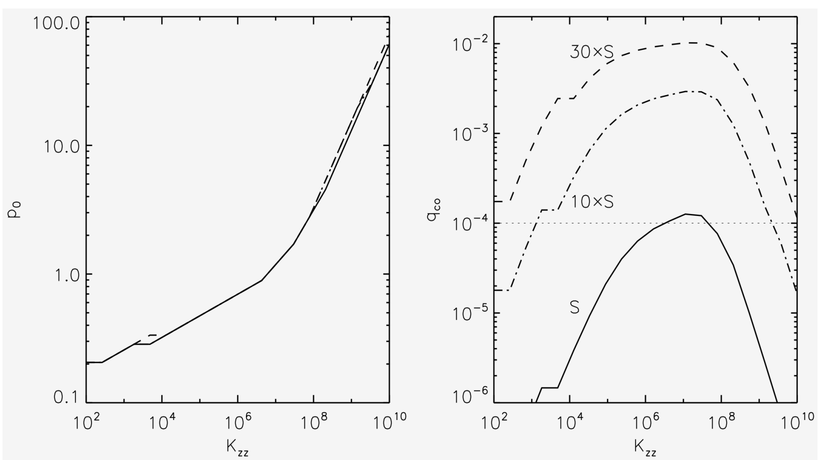
$a = 0.03$ AU, $d = 10.2$ pc, $P = 2.6$ days, $e = 0.15$

Butler et al. 2004; Gillon et al. 2007; Manness et al. 2007

Non-Equilibrium Chemistry and High Metallicity in GJ 436b







- First atmospheric detection (*Demory et al. 2009*)
- Grid of equilibrium models (*Spiegel et al. 2010*)
- General circulation model (*Lewis et al. 2010*)
- Transmission Models (*Shabram et al. 2011*)
- Non-equilibrium and very high metallicity models (*Moses et al. 2013*)

Stevenson et al. 2010
Madhusudhan & Seager 2011
But cf Beaulieu et al. 2011; Knutson et al. 2011

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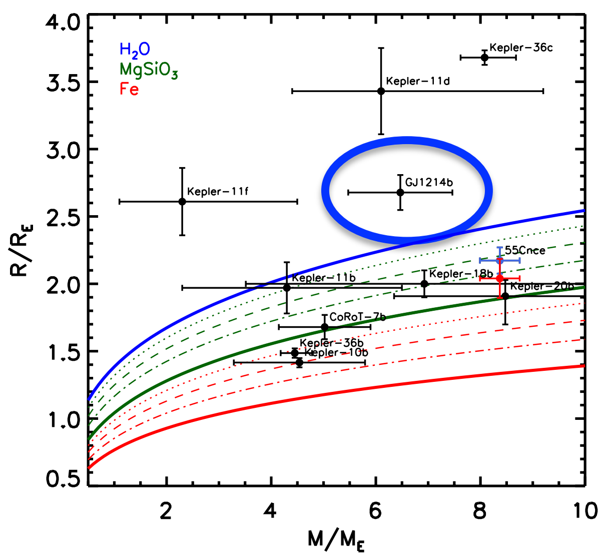
The Atmosphere of super-Earth GJ 1214b

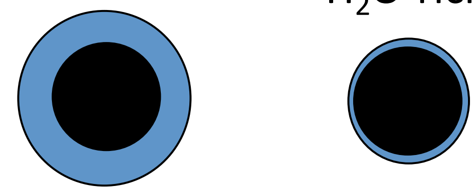


Scale Height

$$H = \frac{kT}{g\mu}$$

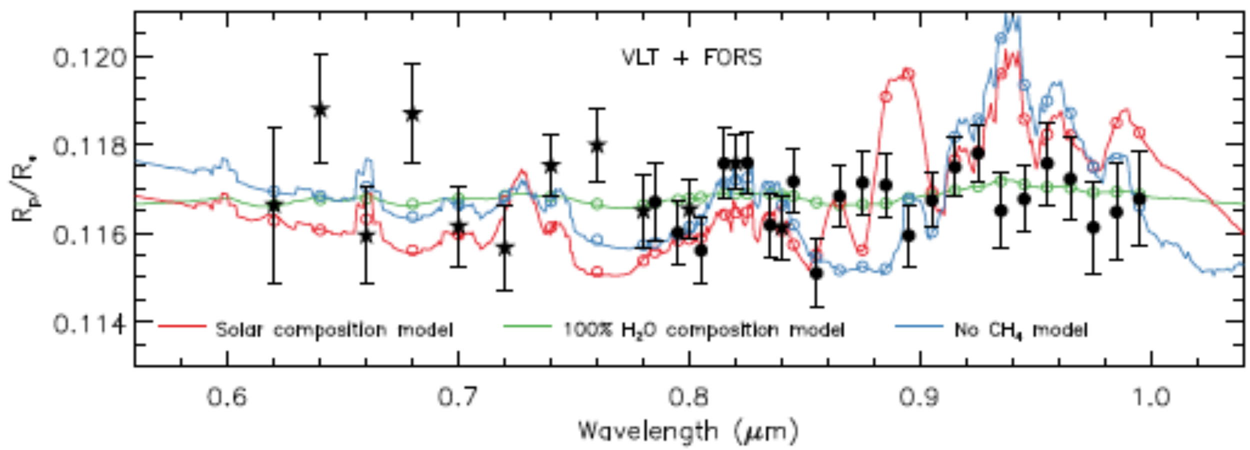
H_2-rich

H_2O-rich

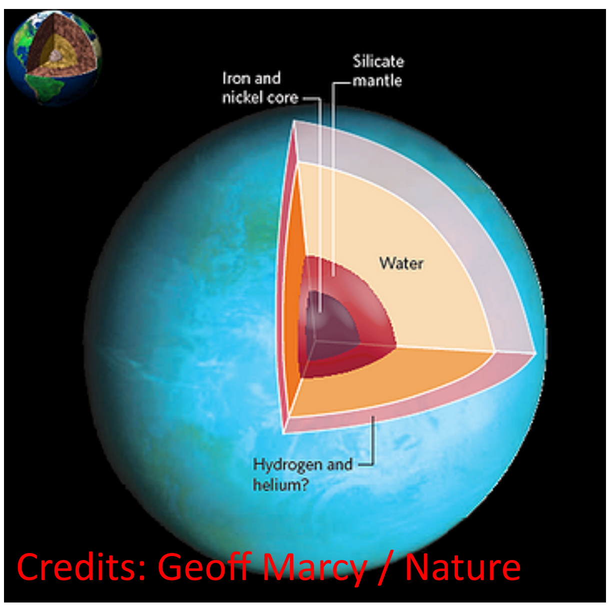


Large scale height

Small scale height

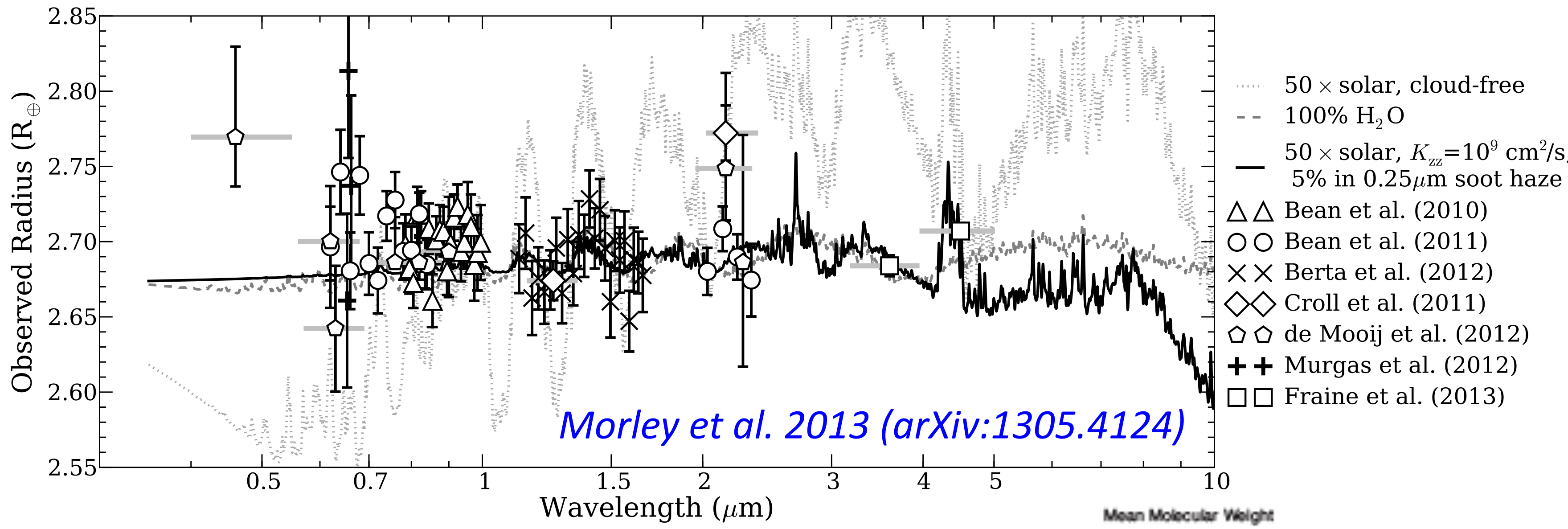


Bean et al. 2010, Nature, 468, 669;
Bean et al. 2011, ApJ, 743, 92

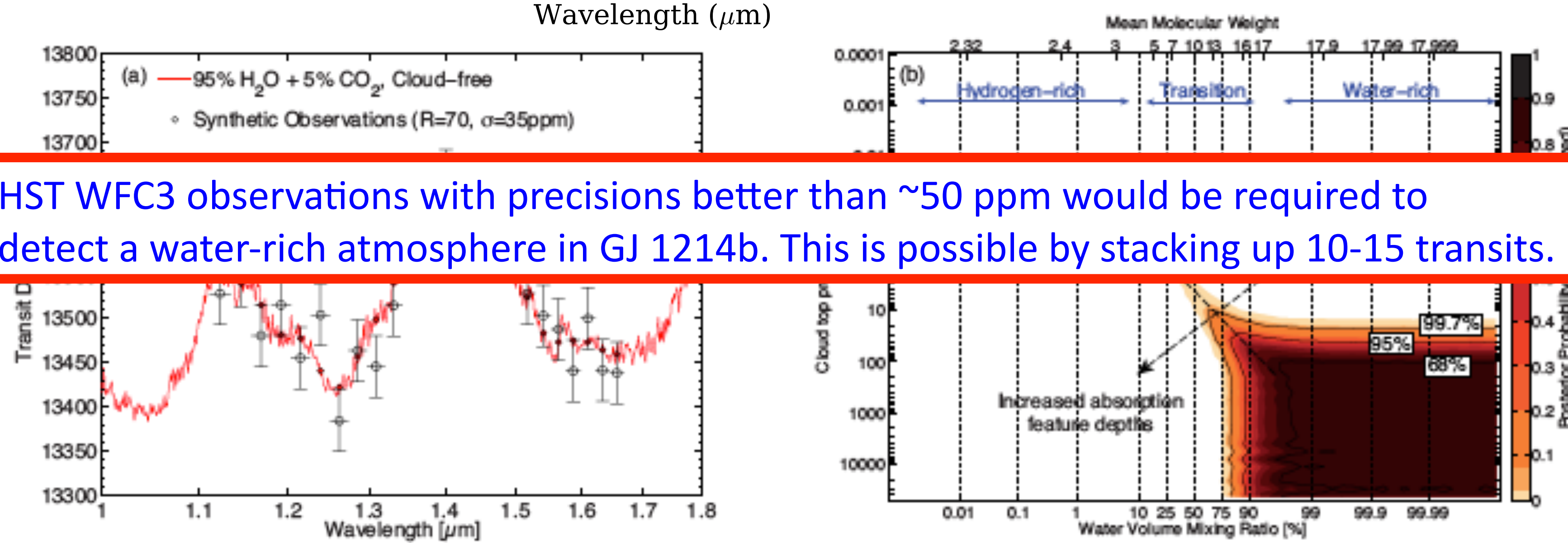


Charbonneau et al. 2009; Rogers & Seager 2009,2010;
Miller-Ricci & Fortney 2011; Kempton et al. 2011; Desert et al. 2011;
Berta et al. 2011; Croll et al. 2011; de Mooij et al. 2012; Murgas et al. 2012;
Benneke & Seager 2013; Howe & Burrows 2012; Fraine et al. 2013

Distinguishing Between Cloudy and Metal-rich Atmosphere in GJ 1214b



Morley et al. 2013 (arXiv:1305.4124)



HST WFC3 observations with precisions better than ~50 ppm would be required to detect a water-rich atmosphere in GJ 1214b. This is possible by stacking up 10-15 transits.

Benneke & Seager 2013 (arXiv:1306.6325)

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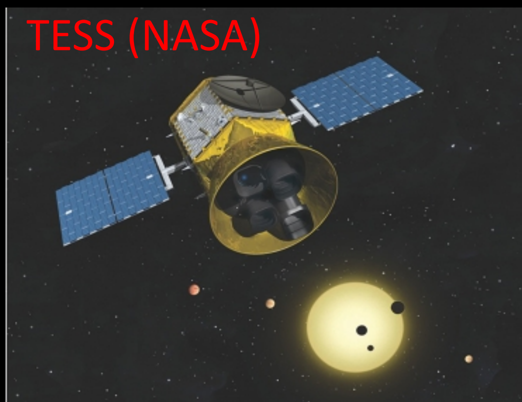
The Future of Exoplanet Science

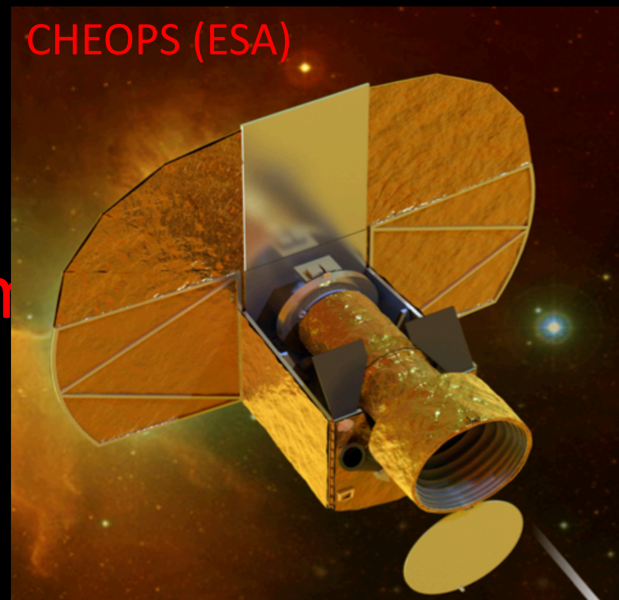
- Detection of small planets orbiting nearby stars
- Characterization of atmospheres of exoplanets
  - To understand physical and chemical processes in exoplanetary atmospheres and interiors
  - To place constraints on planet formation and evolution

The Future of Exoplanet Science

TESS (NASA)

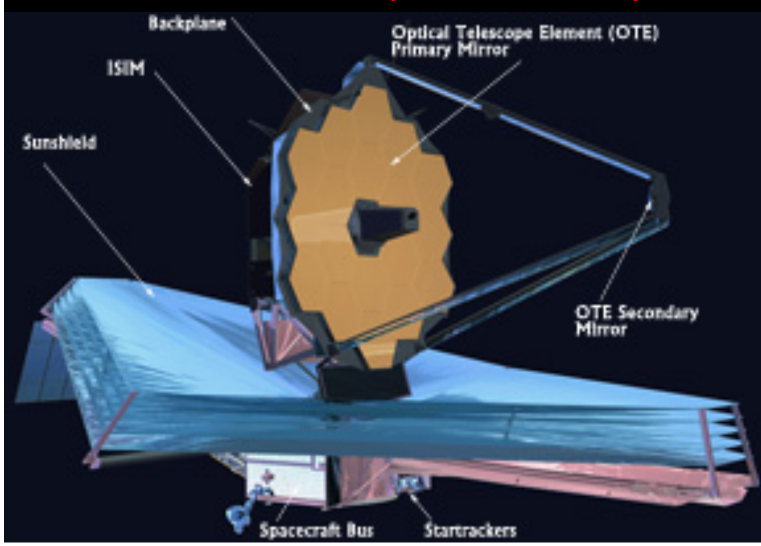


CHEOPS (ESA)



NEXT-GENERATION TRANSIT SURVEY

The James Webb Space Telescope



EChO (ESA Mission)

The future from ground
E-ELT, GMT, TMT