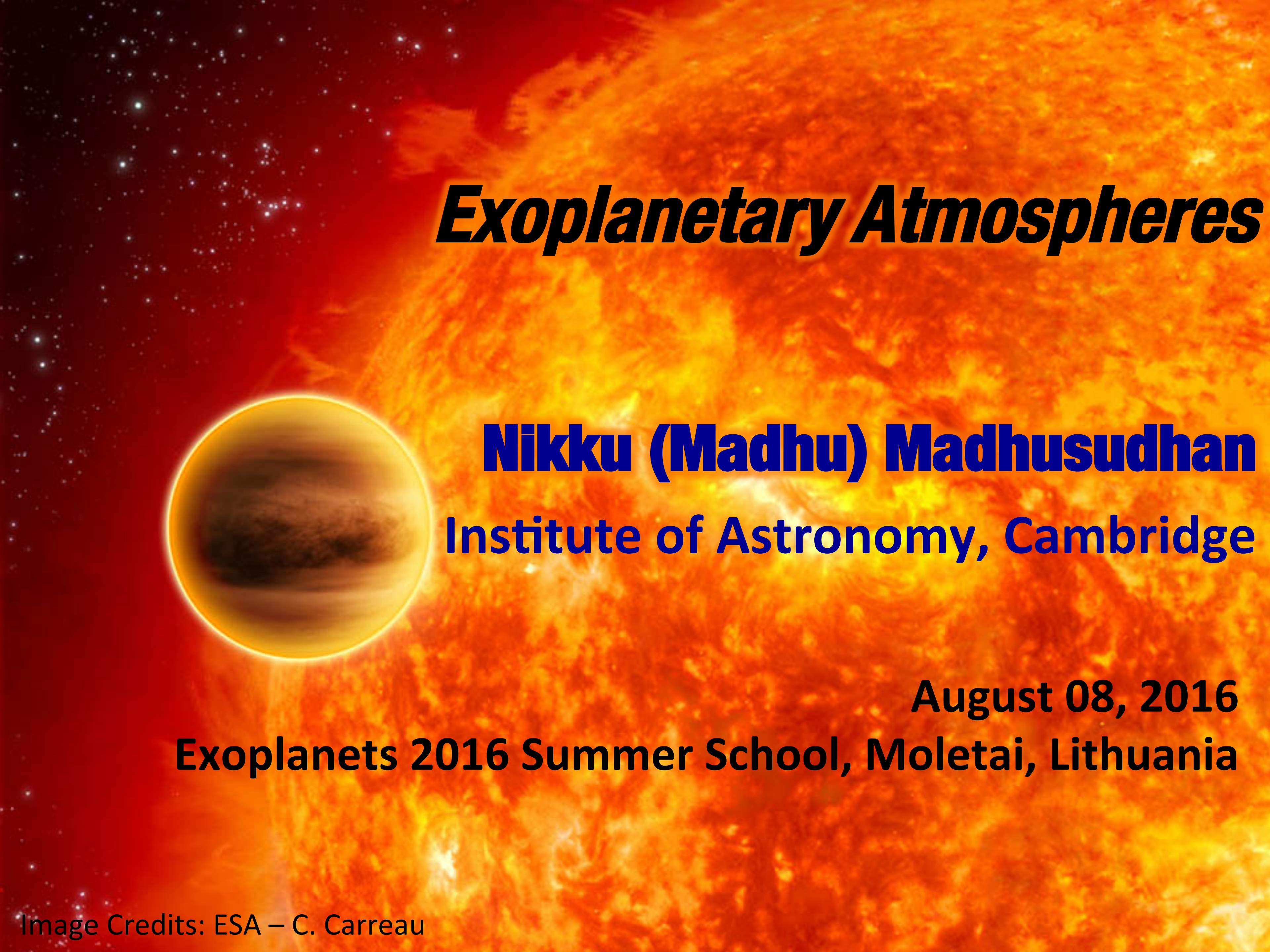
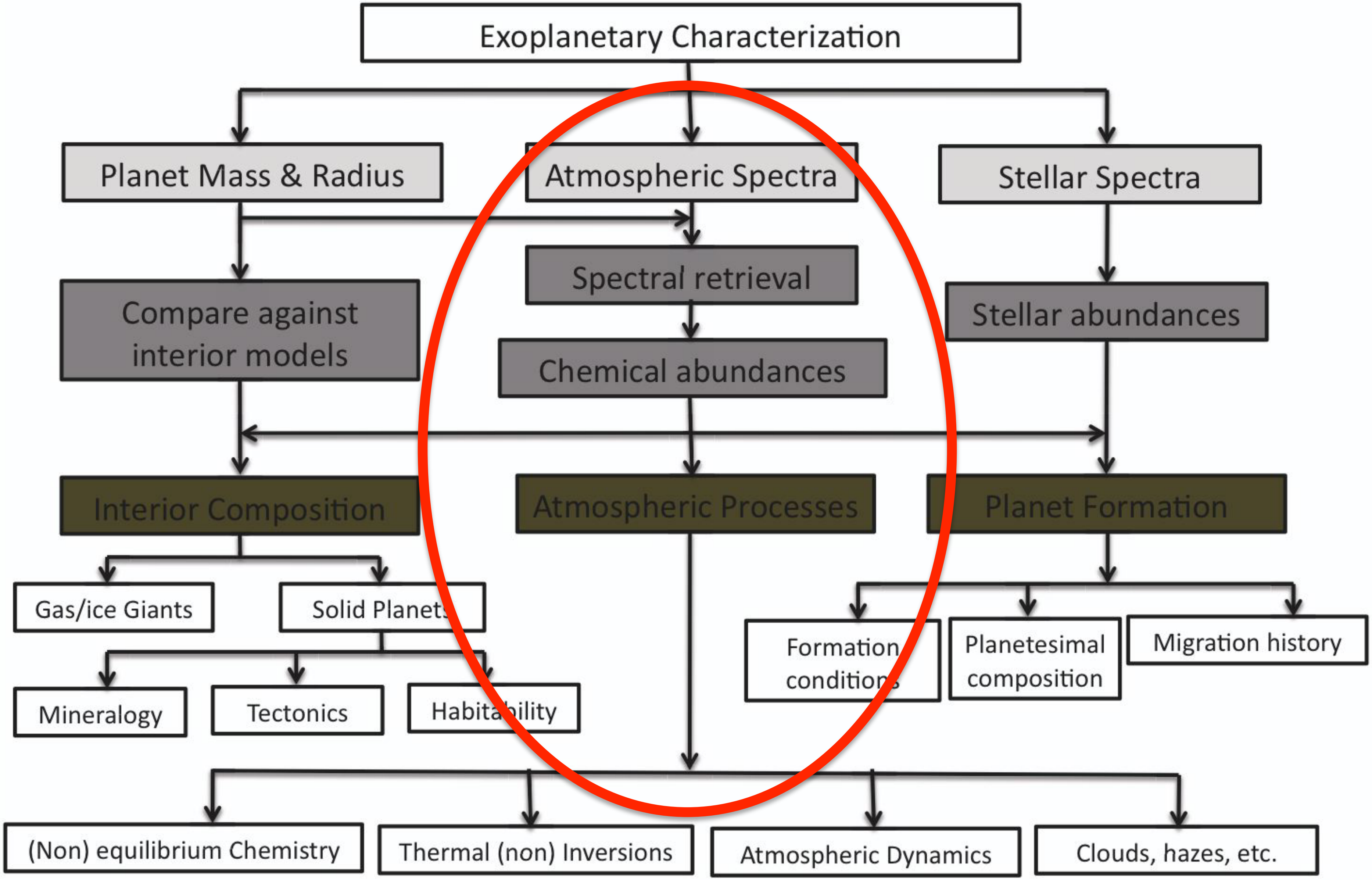


Exoplanetary Atmospheres

Nikku (Madhu) Madhusudhan
Institute of Astronomy, Cambridge

August 08, 2016
Exoplanets 2016 Summer School, Moletai, Lithuania

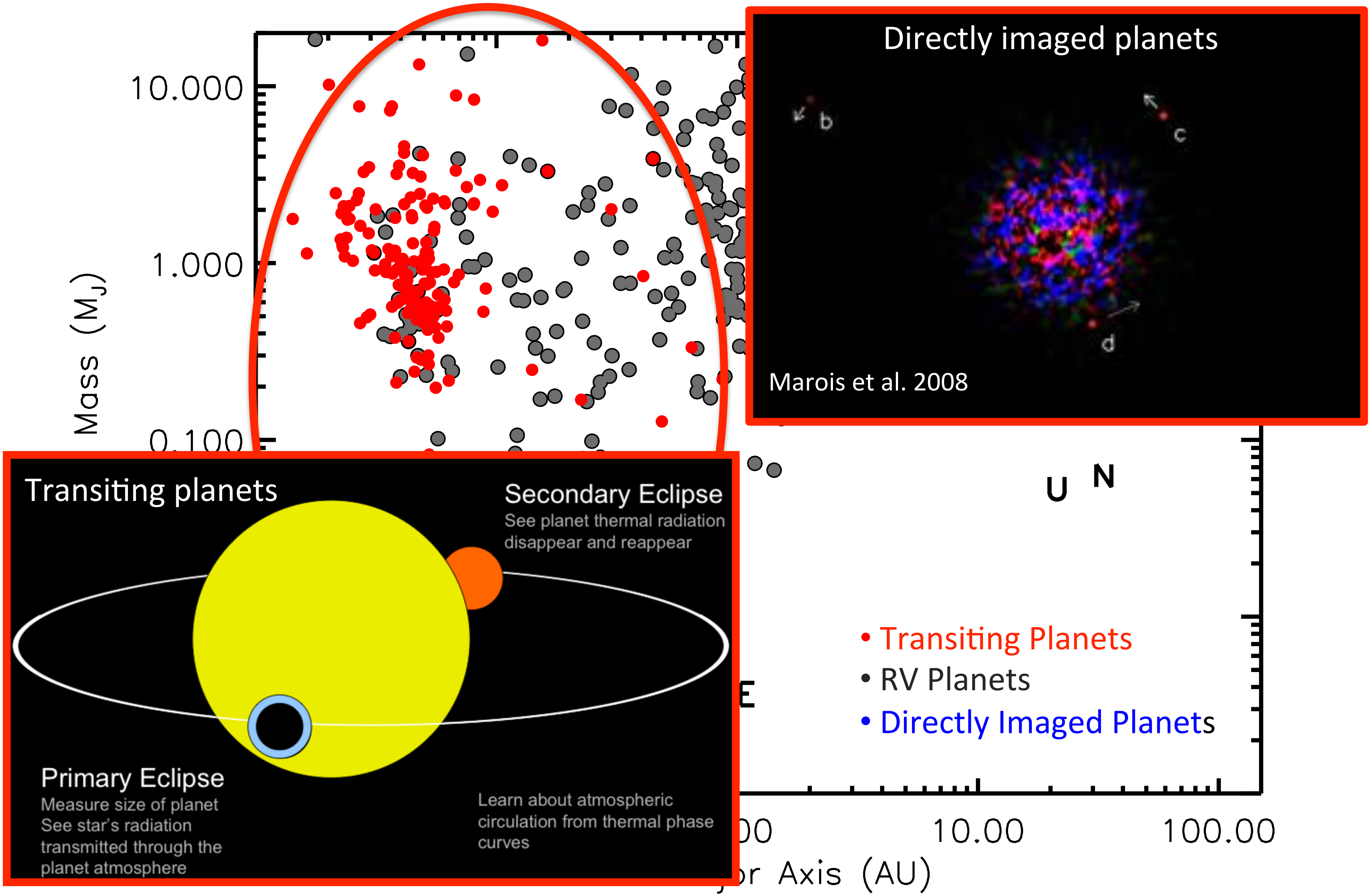
Image Credits: ESA – C. Carreau



Madhusudhan, Knutson, Fortney, and Barman, 2014,
`Exoplanetary Atmospheres' , Protostars and Planets VI (arXiv:1402.1169)

Observing Exoplanetary Atmospheres

Exoplanets Conducive for Atmospheric Characterization



Directly imaged planets

Marois et al. 2008

Transiting planets

Secondary Eclipse

See planet thermal radiation disappear and reappear

Primary Eclipse

Measure size of planet

See star's radiation transmitted through the planet atmosphere

Learn about atmospheric circulation from thermal phase curves

The Transit Method

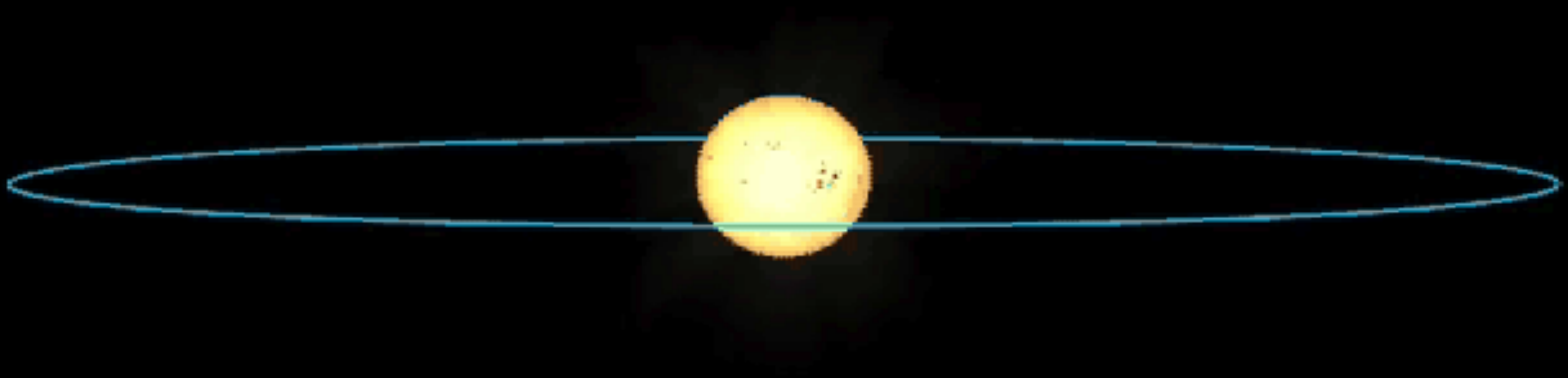
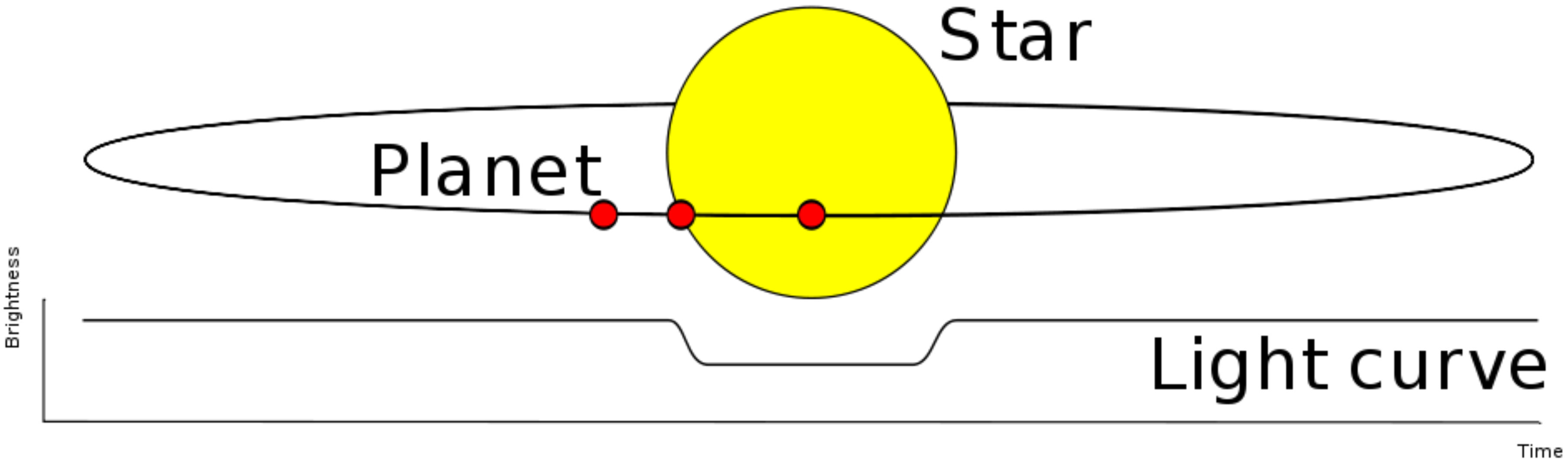
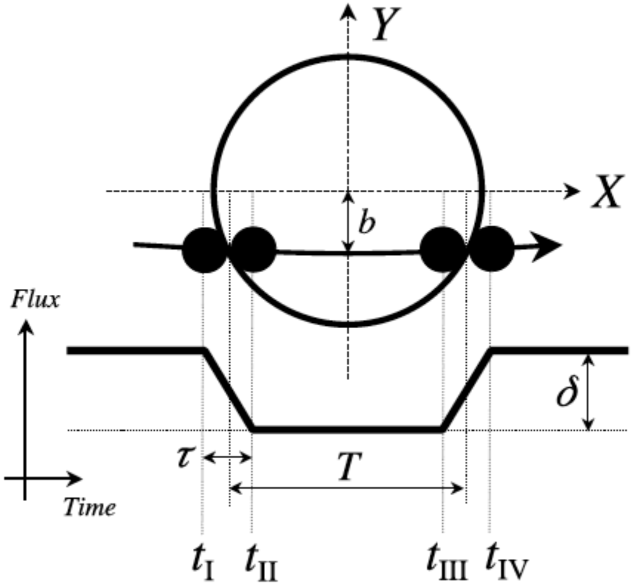


Image credits: NASA Kepler Team

The Transit Method

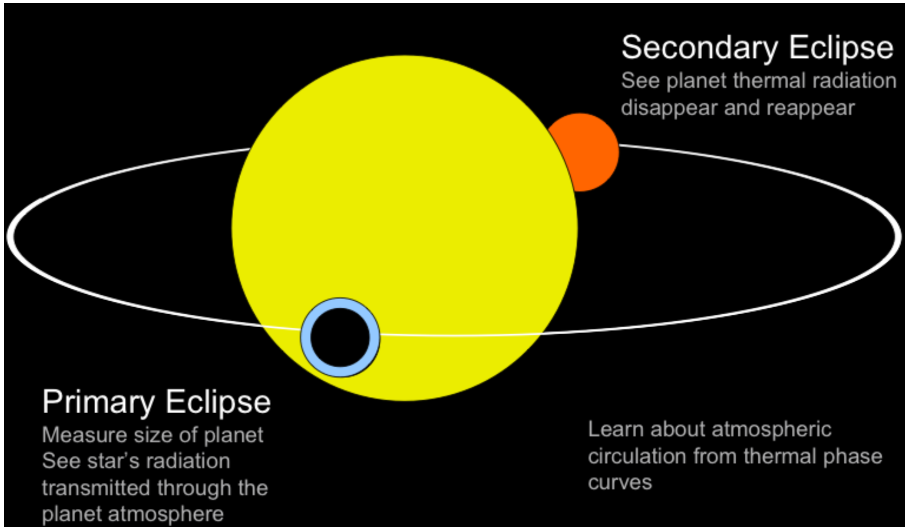




$$\delta_{transit} = \left(\frac{R_p}{R_s}\right)^2$$

$$\delta_{occultation} \approx \frac{B_\lambda(T_p)}{B_\lambda(T_s)}\left(\frac{R_p}{R_s}\right)^2$$

Atmospheric Spectra of Transiting Planets



Secondary Eclipse
See planet thermal radiation disappear and reappear

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Measure size of planet
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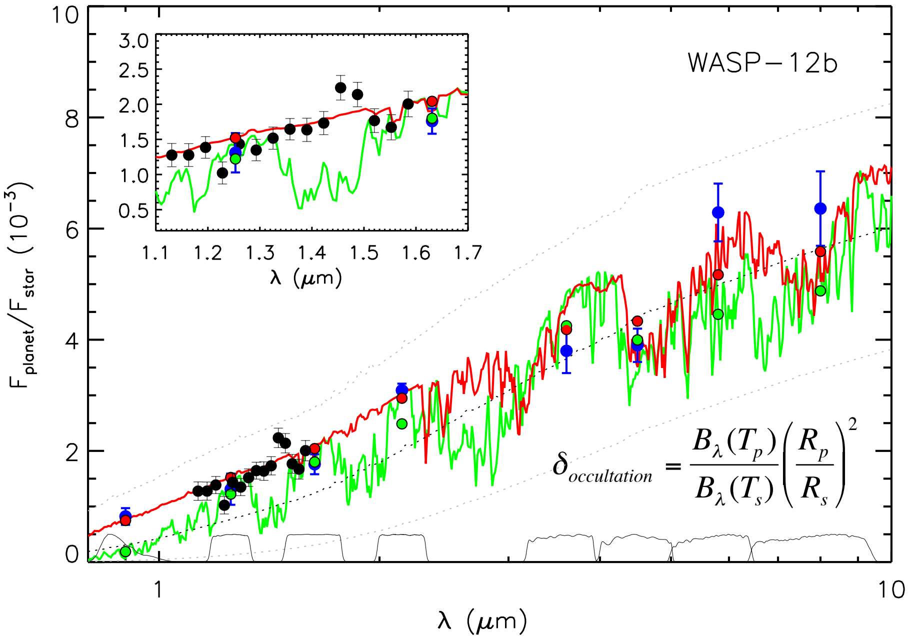
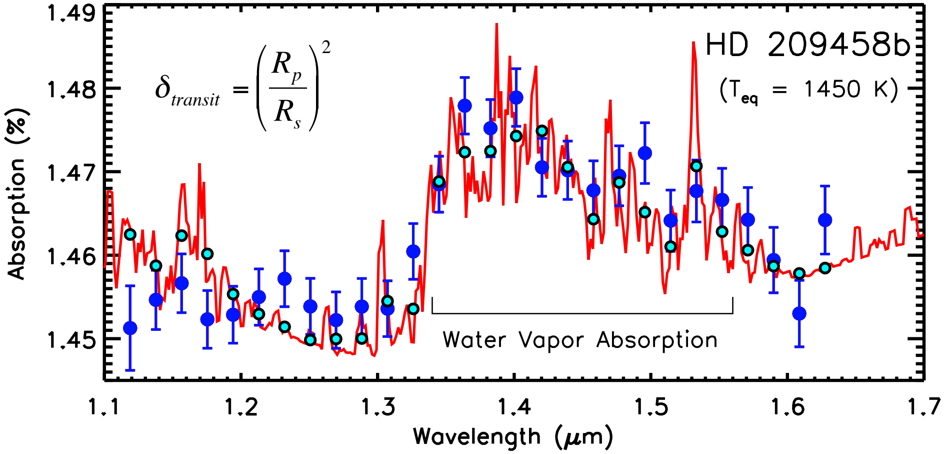


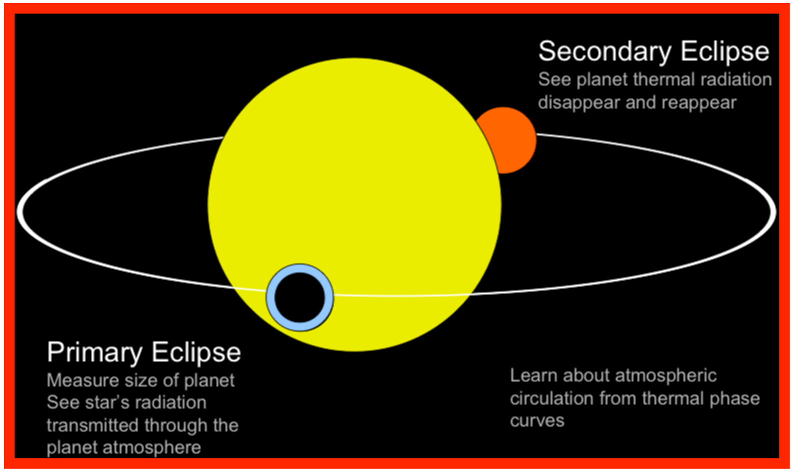


$$\delta_{occultation} \approx \frac{B_\lambda(T_p)}{B_\lambda(T_s)}\left(\frac{R_p}{R_s}\right)^2$$

$$\delta_{transit} = \left(\frac{R_p}{R_s}\right)^2$$

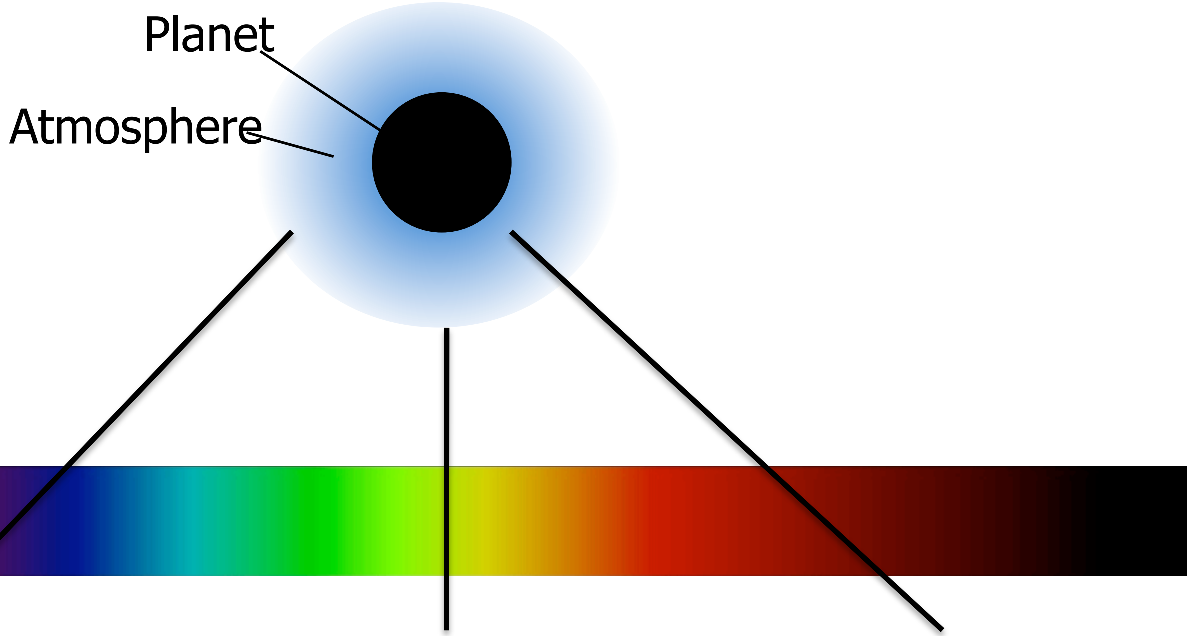
Design Considerations for Transit Spectroscopy

$$\Delta_{transit} = \left(\frac{R'_p}{R_s}\right)^2 \qquad \Delta_{occultation} \approx \frac{B_\lambda(T_p)}{B_\lambda(T_s)}\left(\frac{R_p}{R_s}\right)^2 \qquad H \sim 10H_{sc}, H_{sc} = \frac{kT}{g\mu}$$



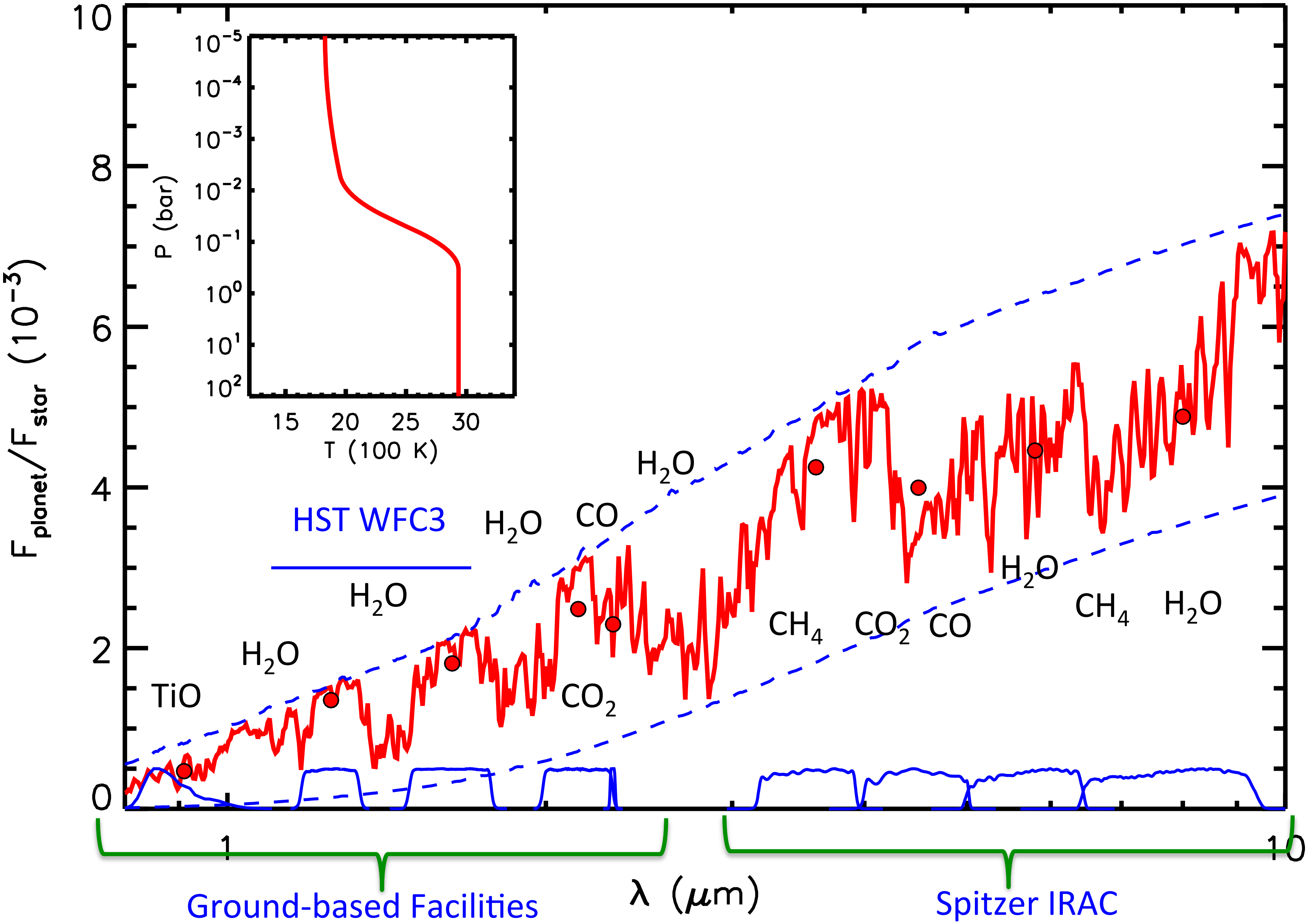
- Large Signal:
  - Large and/or hot planets
  - Small and/or cool stars
- High Precision:
  - Bright host star (but not too bright!)
  - Good comparison stars (for ground-based)
- Optimal (and available) spectral bands.

What Do We Learn From Transmission Spectroscopy?

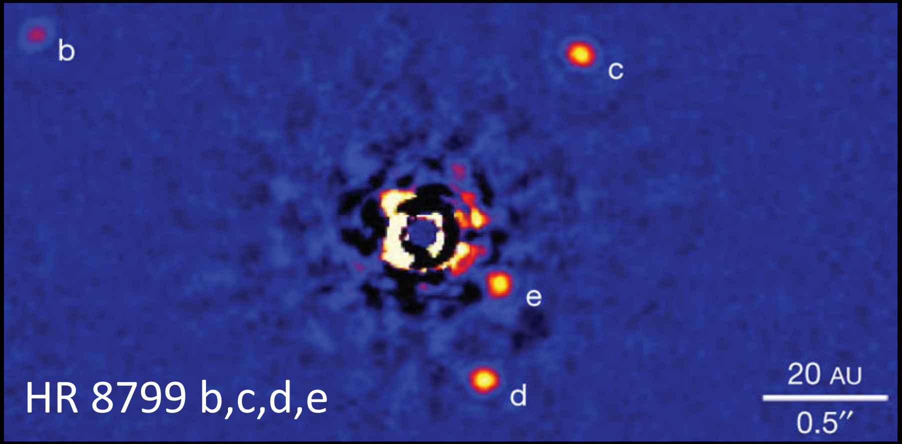


Wavelength	**UV**	**Visible**	**Infrared**
What do we measure?	Lyman alpha, ionized metals	Sodium, potassium, TiO, VO	Molecular chemistry
What do we learn?	Atmospheric mass loss	Clouds/hazes?	

Spectral Bands available for Transit Spectroscopy

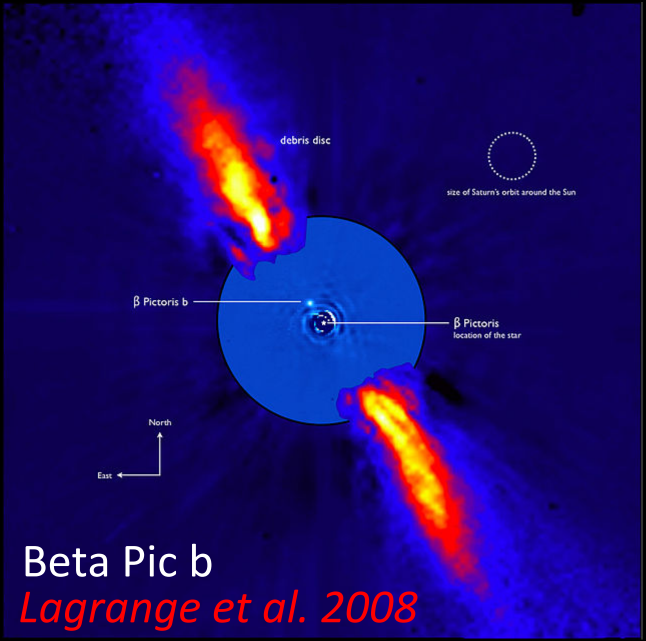


Direct Imaging



HR 8799 b,c,d,e

Marois et al. 2008,2010

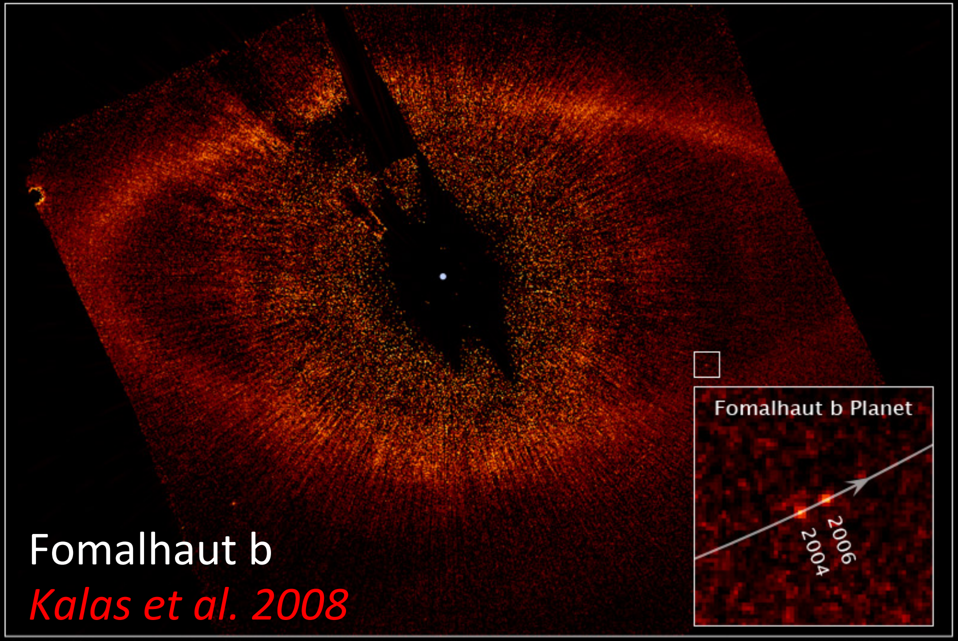


Beta Pic b

Lagrange et al. 2008

Fomalhaut System

Hubble Space Telescope • ACS/HRC



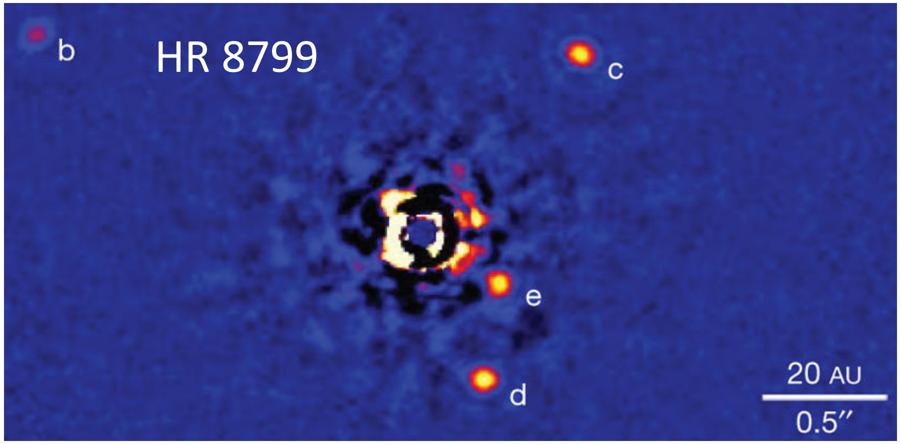
Fomalhaut b

Kalas et al. 2008

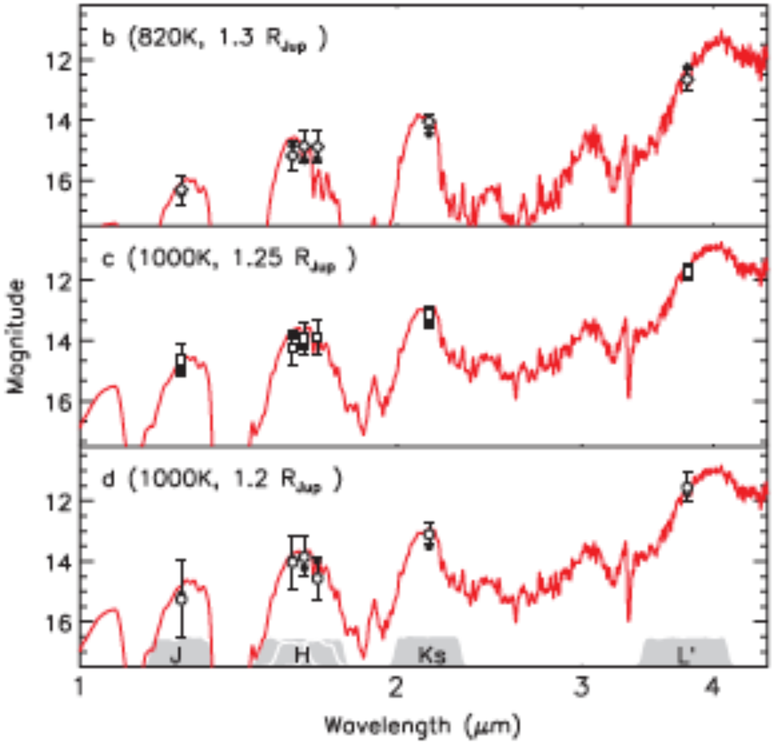
NASA, ESA, and P. Kalas (University of California, Berkeley)

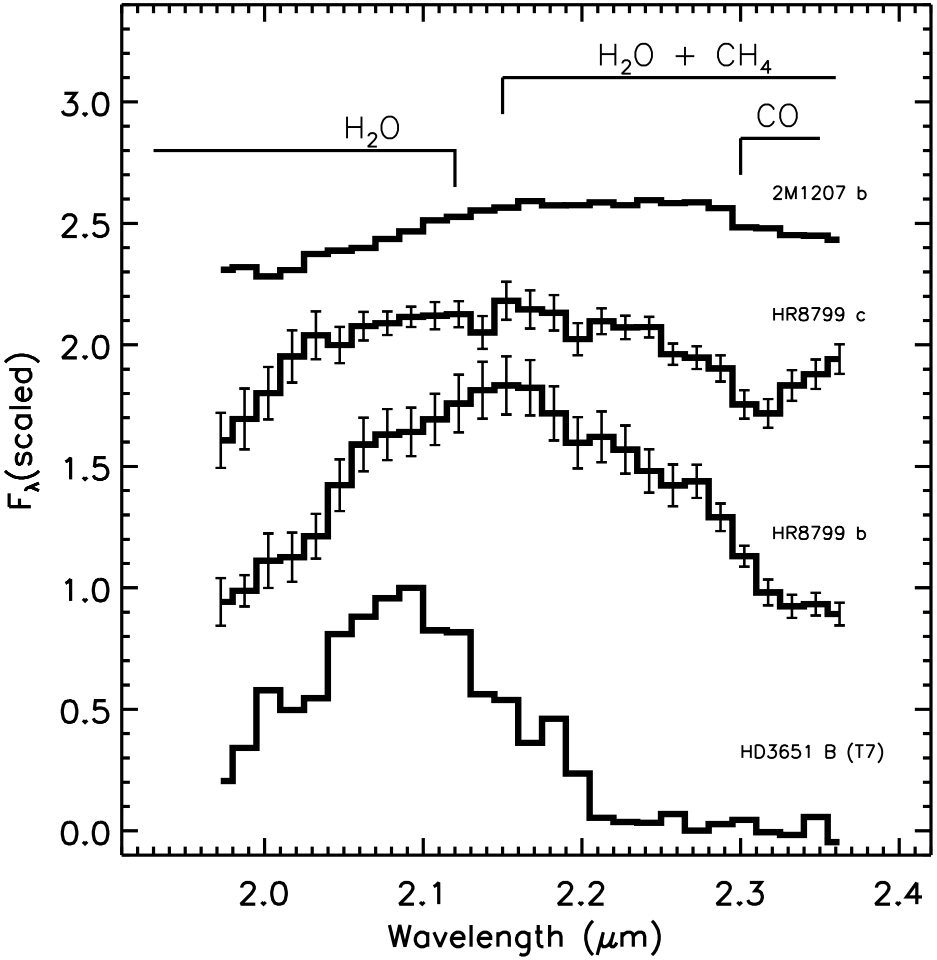
STScI-PRC08-39a

Atmospheric Spectra of Directly-Imaged Planets



Marois et al. 2008,2010

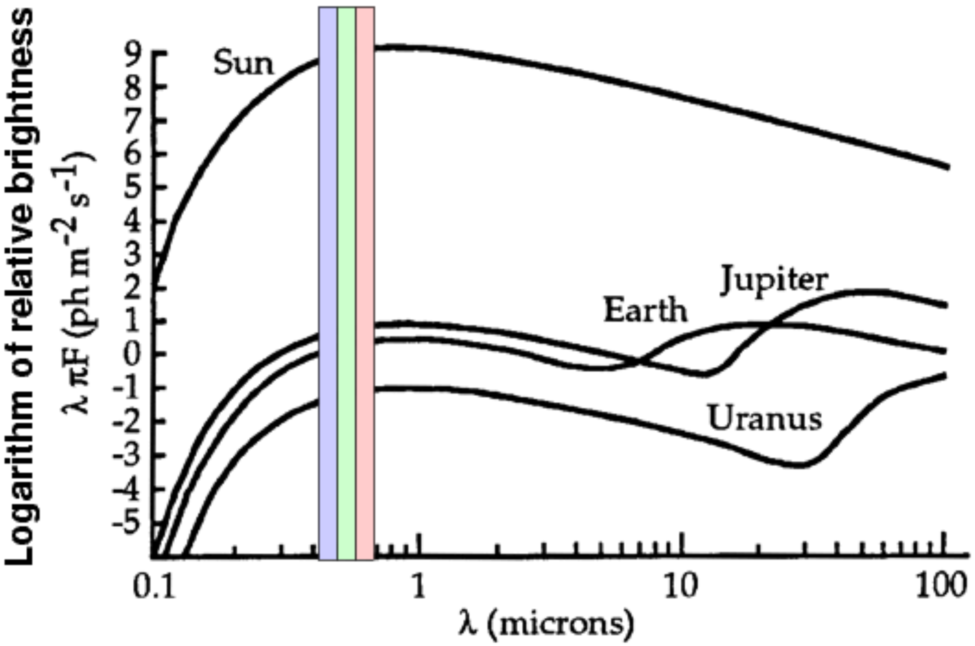


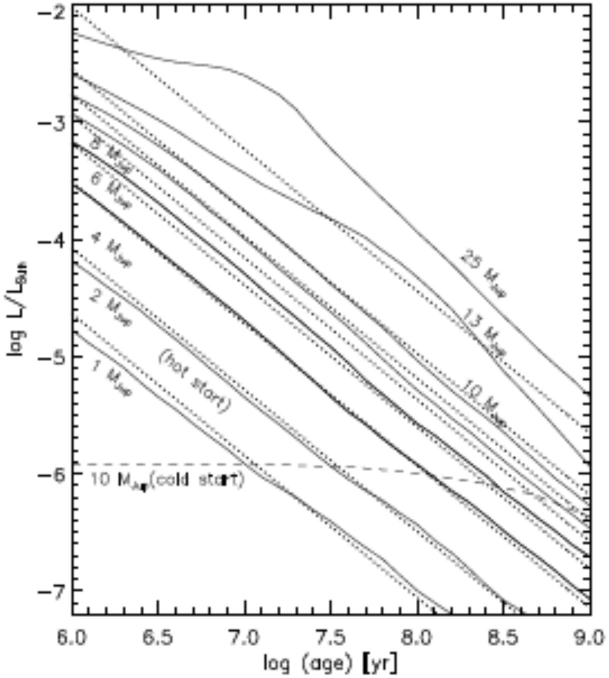


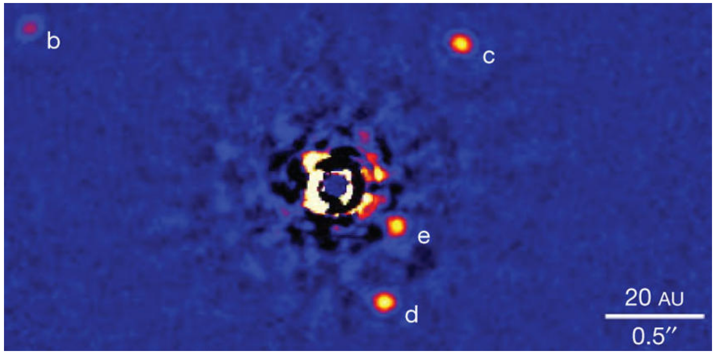
Barman et al. (2011)

Design Considerations for Directly Imaged Planets

Young, Giant, and Wide orbits

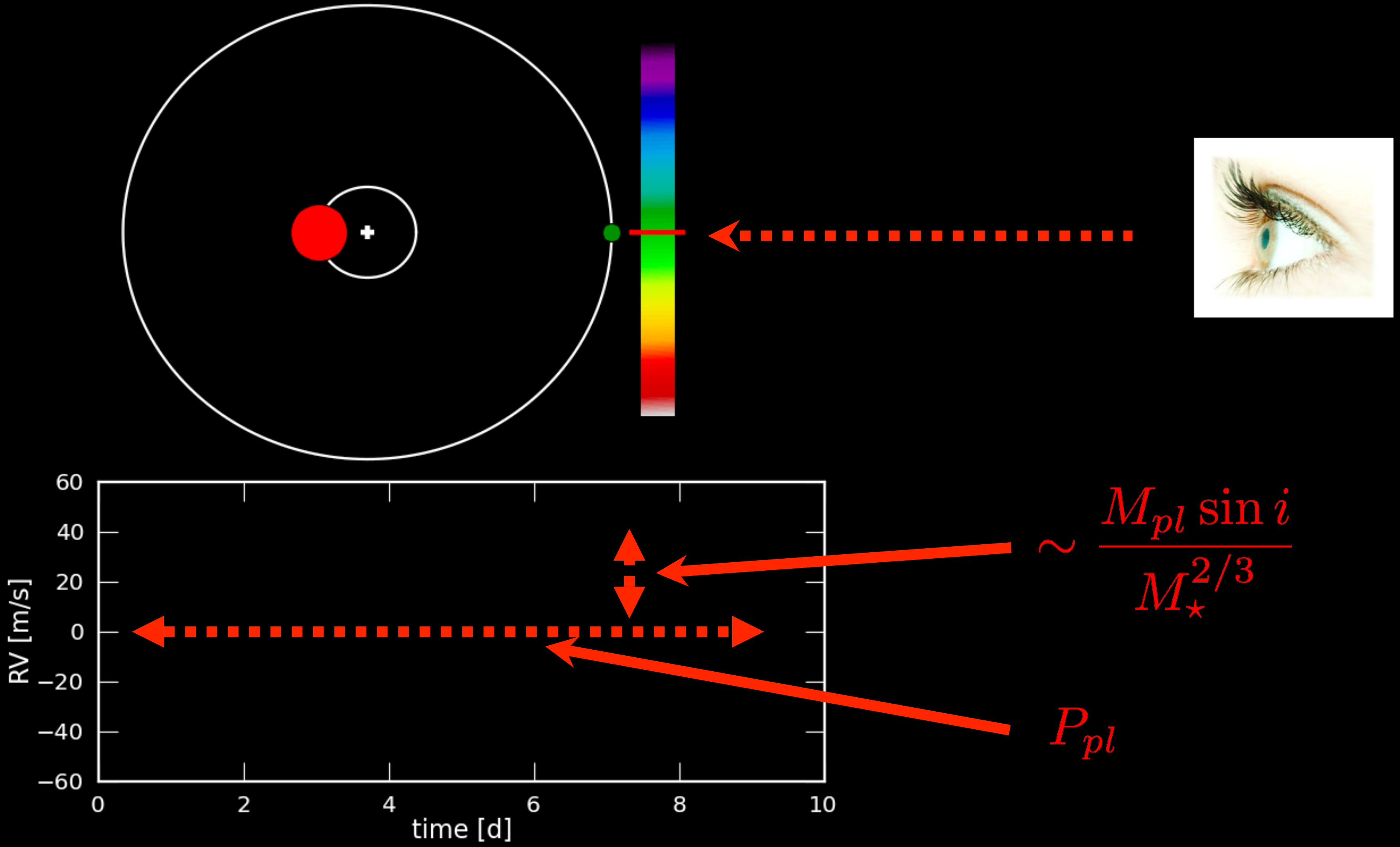






Marois et al. 2008,2010

The Radial Velocity (Doppler) Method



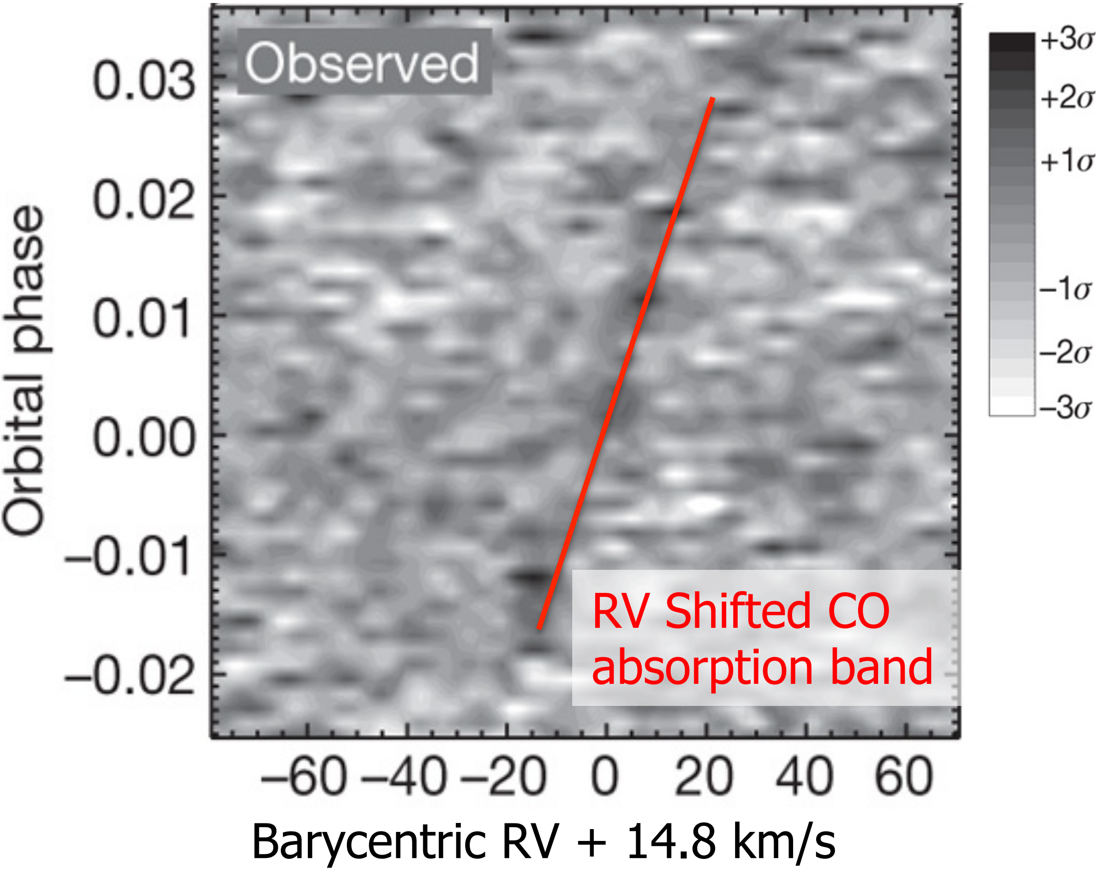
$$\sim \frac{M_{pl} \sin i}{M_{\star}^{2/3}}$$

$$P_{pl}$$

Courtesy: Xavier Dumusque

Ultra high resolution spectroscopy of RV planets

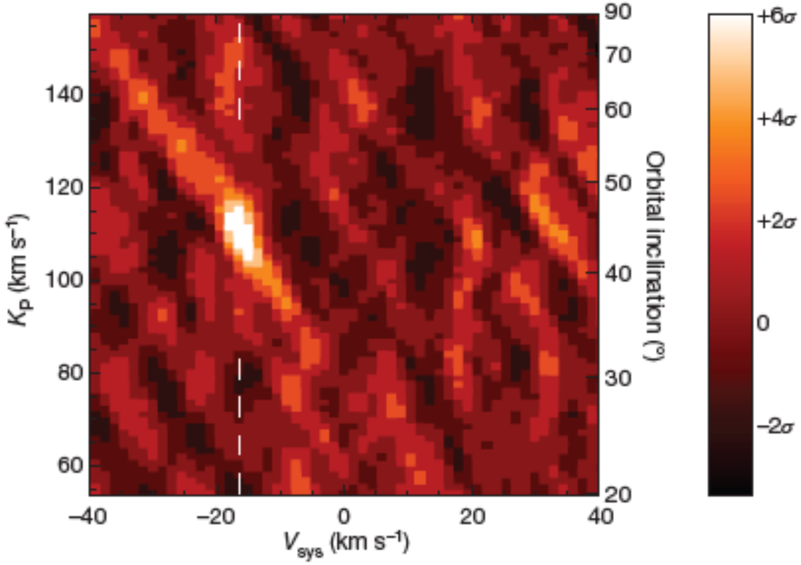
RV-Shifted Absorption from HD 209458b During Transit



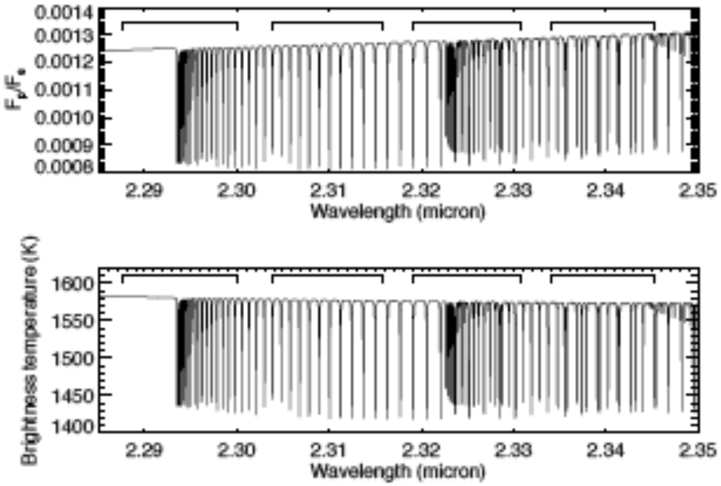
Snellen et al. (2010)

CO absorption detected at 5.6σ

CO detection in hot Jupiters

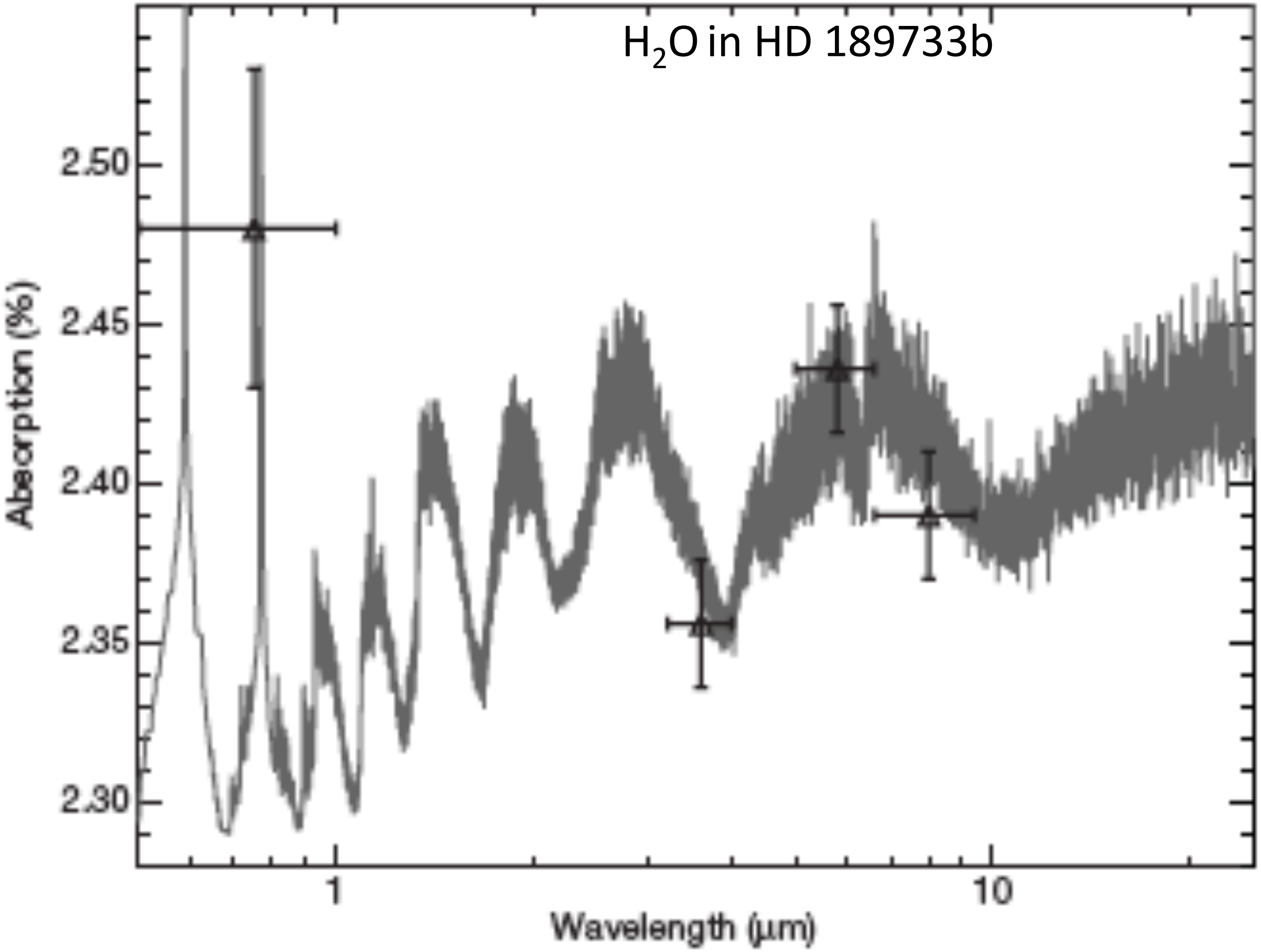


Brogi et al. (2012), de Kok et al. (2013)



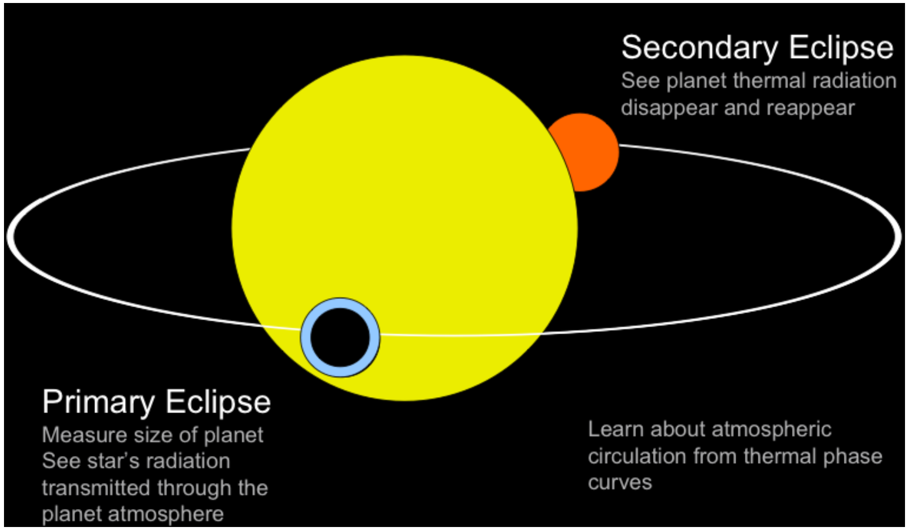
Atmospheric Characterization

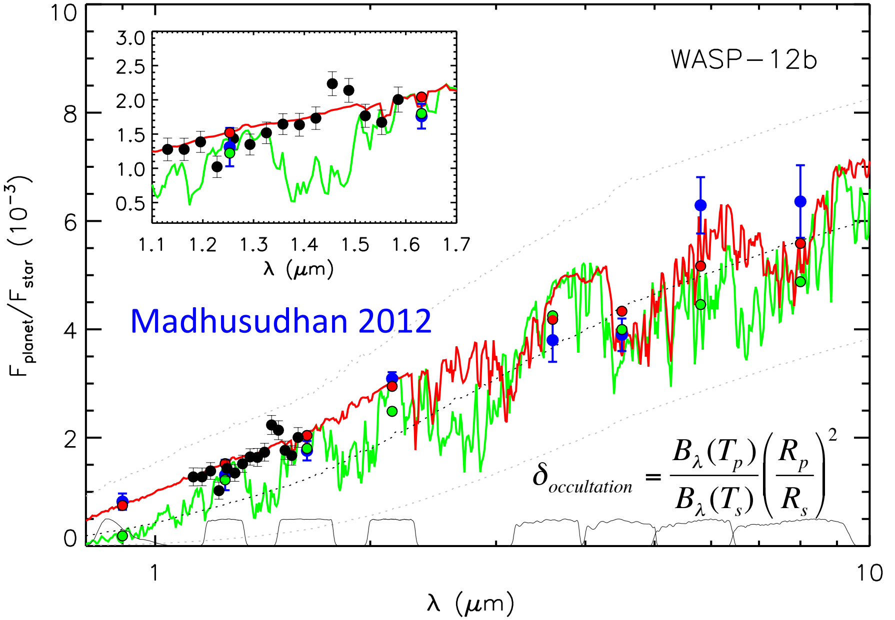
Early Molecular Inferences



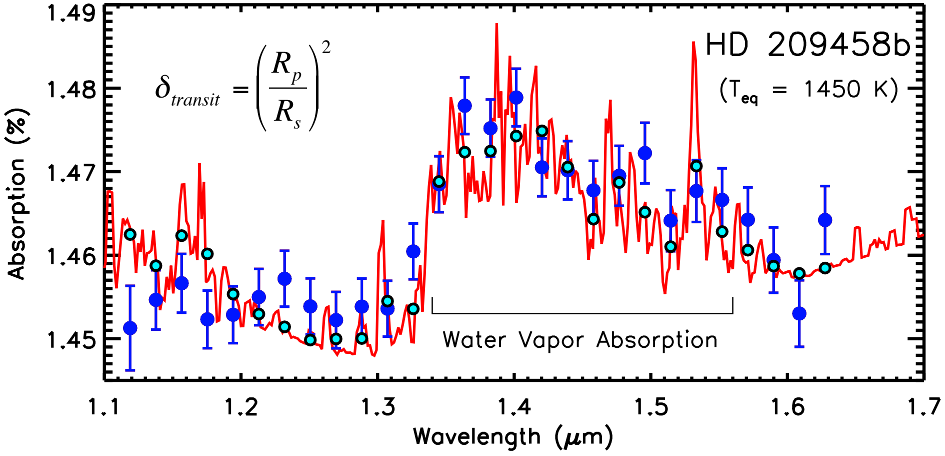
Tinetti et al. 2007, Nature, 448, 169

Atmospheric Spectroscopy of Exoplanets

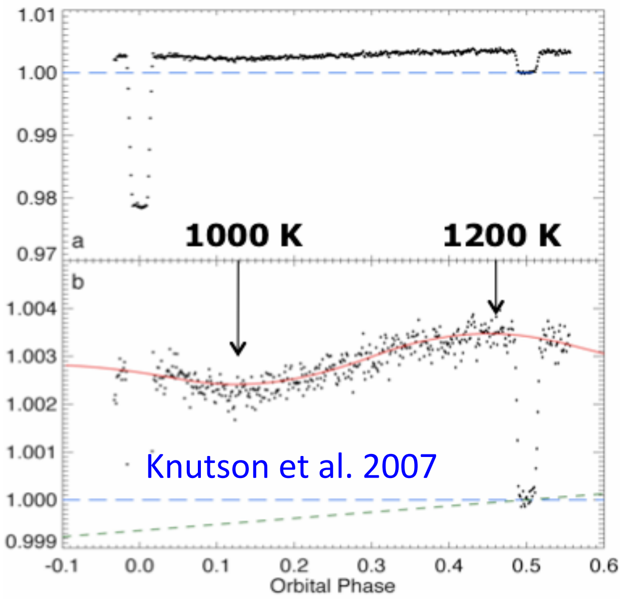




Madhusudhan 2012



Deming et al. 2013, Madhusudhan et al. 2014



Knutson et al. 2007

Exoplanetary Atmosphere Models

1-D models of irradiated atmospheres with line-by-line radiative transfer

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

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

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

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

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

Boundary Conditions

- Stellar Irradiation (Kurucz Model)
- Intrinsic Energy source

Chemical Equilibrium

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

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

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

$$B_{\mathrm{CO}} = A_{\mathrm{C}} + A_{\mathrm{O}} + \frac{P_{\mathrm{H}_2}^2}{2K_1(T)} - \sqrt{\left[A_{\mathrm{C}} + A_{\mathrm{O}} + \frac{P_{\mathrm{H}_2}^2}{2K_1(T)}\right]^2 - 4A_{\mathrm{C}}A_{\mathrm{O}}}$$

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

Seager & Sasselov 1998, Sudarsky et al. 2003
Fortney et al. 2006, Burrows et al. 2007

Atmospheric Retrieval

$$Steady\ state : \{\rho, P, T, \tau | r, z\}$$

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

$$-\frac{dI_\lambda}{d\tau_\lambda} = -I_\lambda + B_\lambda$$

$$\left| \begin{array}{rl} P_0 < P < P_1 : & P = P_0 e^{\alpha_1 (T - T_0)^{\beta_1}} \\ P_1 < P < P_3 : & P = P_2 e^{\alpha_2 (T - T_2)^{\beta_2}} \\ P > P_3 : & T = T_3 \end{array} \right.$$

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

Parameters

- $T_0, P_1, P_2, P_3, \alpha_1, \alpha_2$
- $f_i : \{i = H_2O, CO, CH_4, CO_2\}$
- clouds, etc.

Boundary Conditions

- Global Energy Balance (Kurucz Model)
- Intrinsic Energy source (negligible)

Perturbations to Chemical Equilibrium

$$[B_i] = f_i \times [B_i]_{solar}$$

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

$$B_{\rm CH_4} = 2A_{\rm C} - B_{\rm CO} \qquad B_{\rm H_2O} = 2A_{\rm O} - B_{\rm CO}$$

$$K_1(T) = \exp\,[(a_1/T + b_1 + c_1 T + d_1 T^2 + e_1 T^3)/RT]$$

$$B_{\rm N_2} = A_{\rm N} + \frac{P_{\rm H_2}^2}{8K_2(T)} - \sqrt{\left[A_{\rm N} + \frac{P_{\rm H_2}^2}{8K_2(T)}\right]^2 - A_{\rm N}^2} \qquad B_{\rm NH_3} = 2(A_{\rm N} - B_{\rm N_2})$$

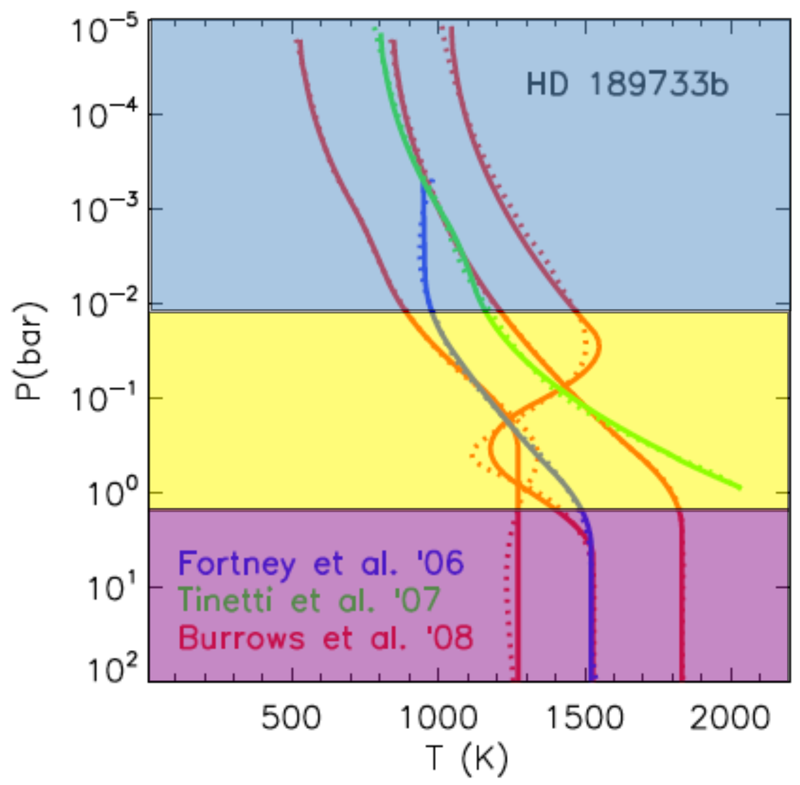
Features

- Computationally fast (can explore parameter space)
- Can explore non-equilibrium concentrations
- Day-night energy redistribution as output

Madhusudhan & Seager 2009; Madhusudhan et al. 2011

Also see Lee et al. 2012, Line et al. 2012, Benneke et al. 2012

P-T structure of Irradiated Atmospheres



Gray atmosphere
Low optical depth limit

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

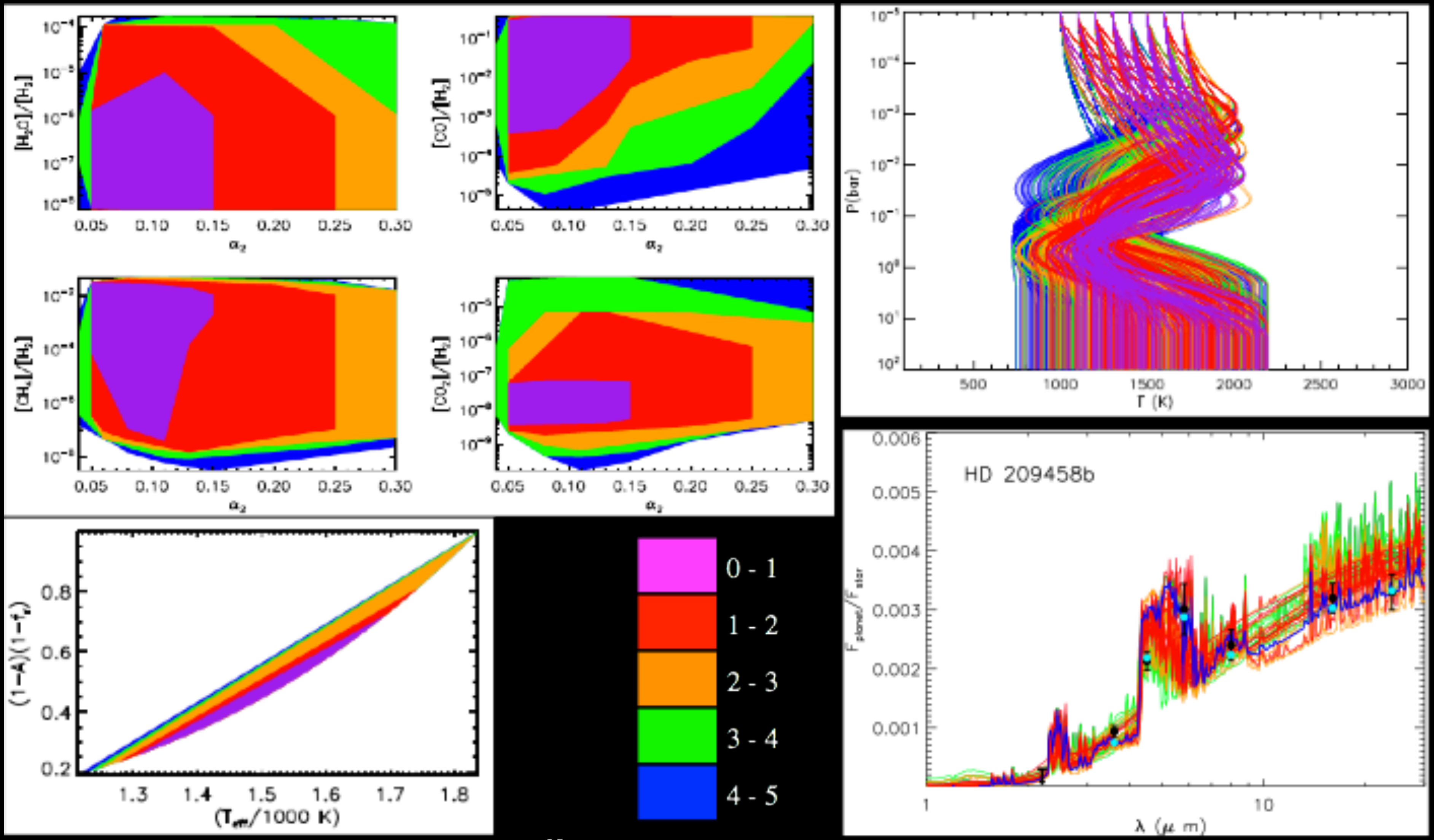
Diffusion approximation
Large optical depth limit

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

Two stream gray model (Guillot 2010)

$$T^4 = \frac{3T_{\rm int}^4}{4}\left[\frac{2}{3}+\tau\right] + \frac{3T_{\rm irr}^4}{4} f\left[\frac{2}{3}+\frac{1}{\gamma\sqrt{3}}+\left(\frac{\gamma}{\sqrt{3}}-\frac{1}{\gamma\sqrt{3}}\right)e^{-\gamma\tau\sqrt{3}}\right]$$

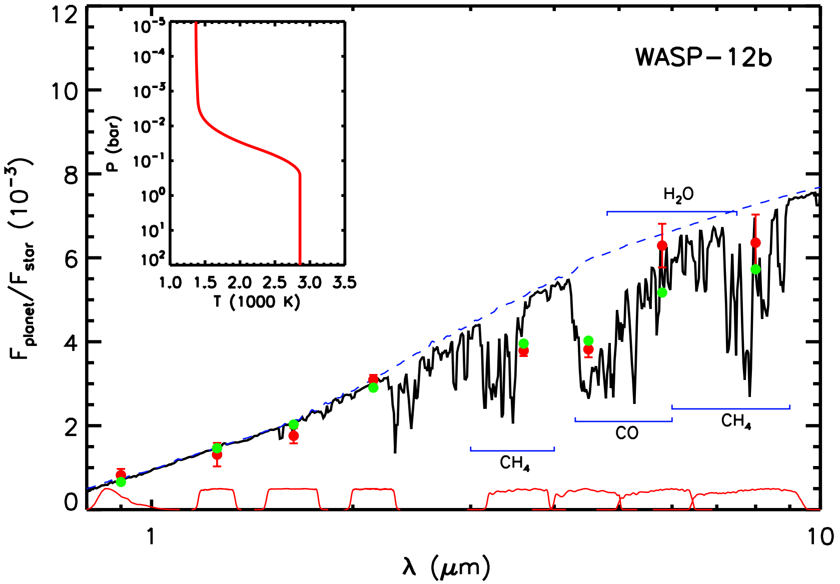
Atmospheric Retrieval for Exoplanets



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

Madhusudhan and Seager (2009)

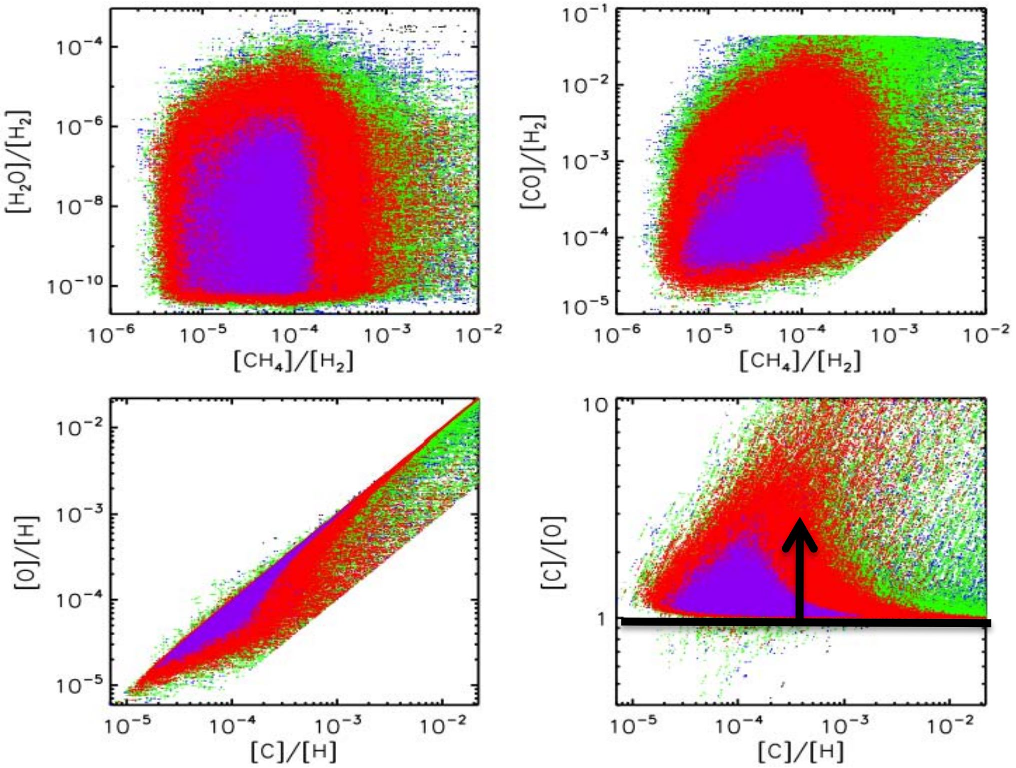
First measurement of atmospheric C/O in a giant planet



Key Molecular Constraints

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

$$C/O \geq 1$$



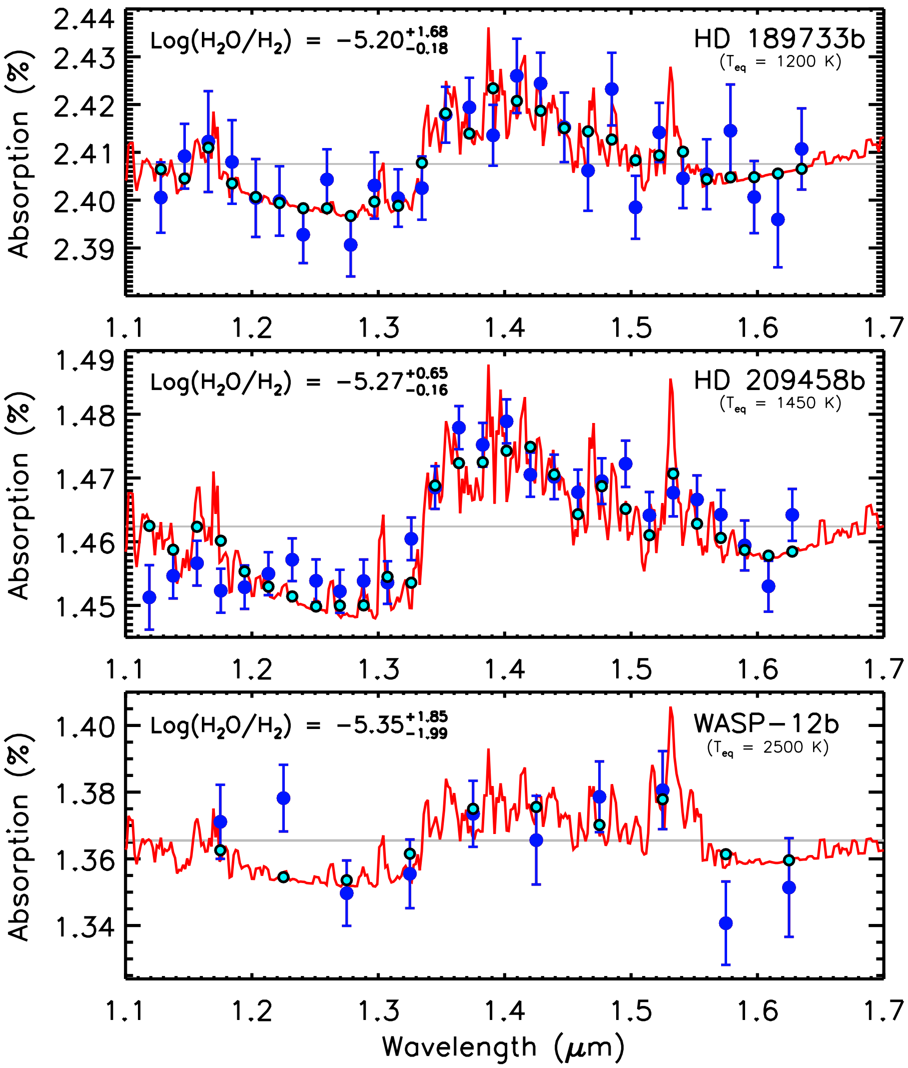
Adapted from Madhusudhan et al. 2011, Nature, 469, 64

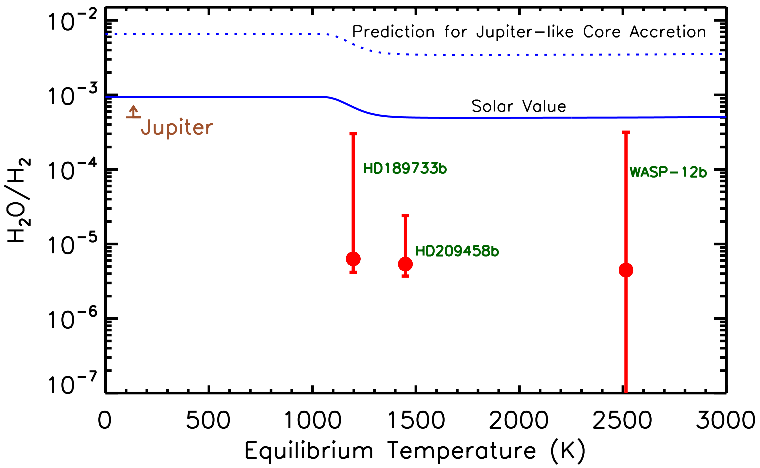
Data from Lopez-Morales et al. 2010; Croll et al. 2010; Campo et al. 2011

But cf Crossfield et al. 2012, Cowan et al. 2012, Swain et al. 2012, Stevenson et al. 2014

New Advances with HST Transit Spectroscopy

(HST WFC3 Large pilot program: 115 HST Orbits, ~10 planets, PI: Drake Deming)

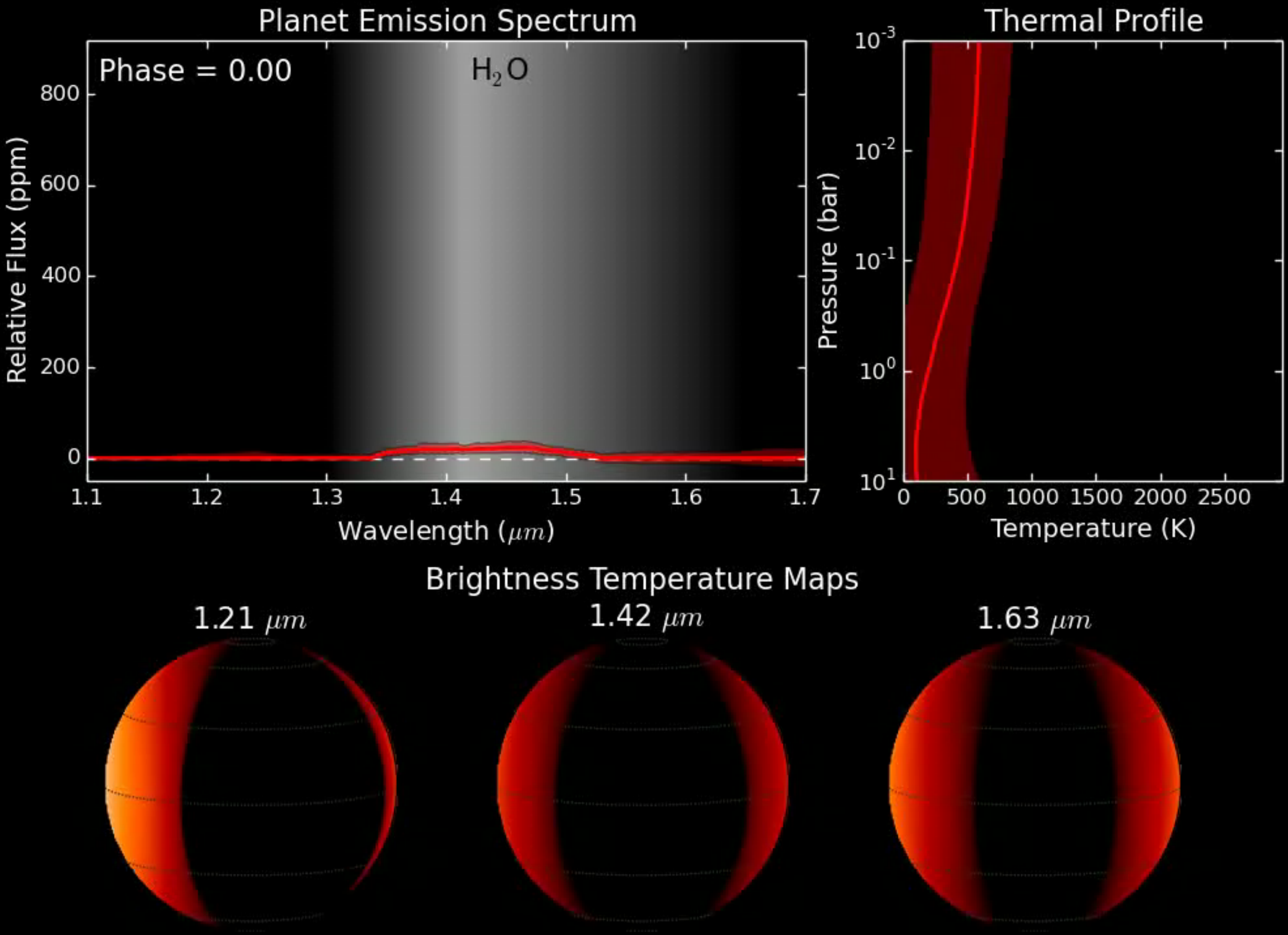




Hubble Telescope

Madhusudhan et al. 2014a

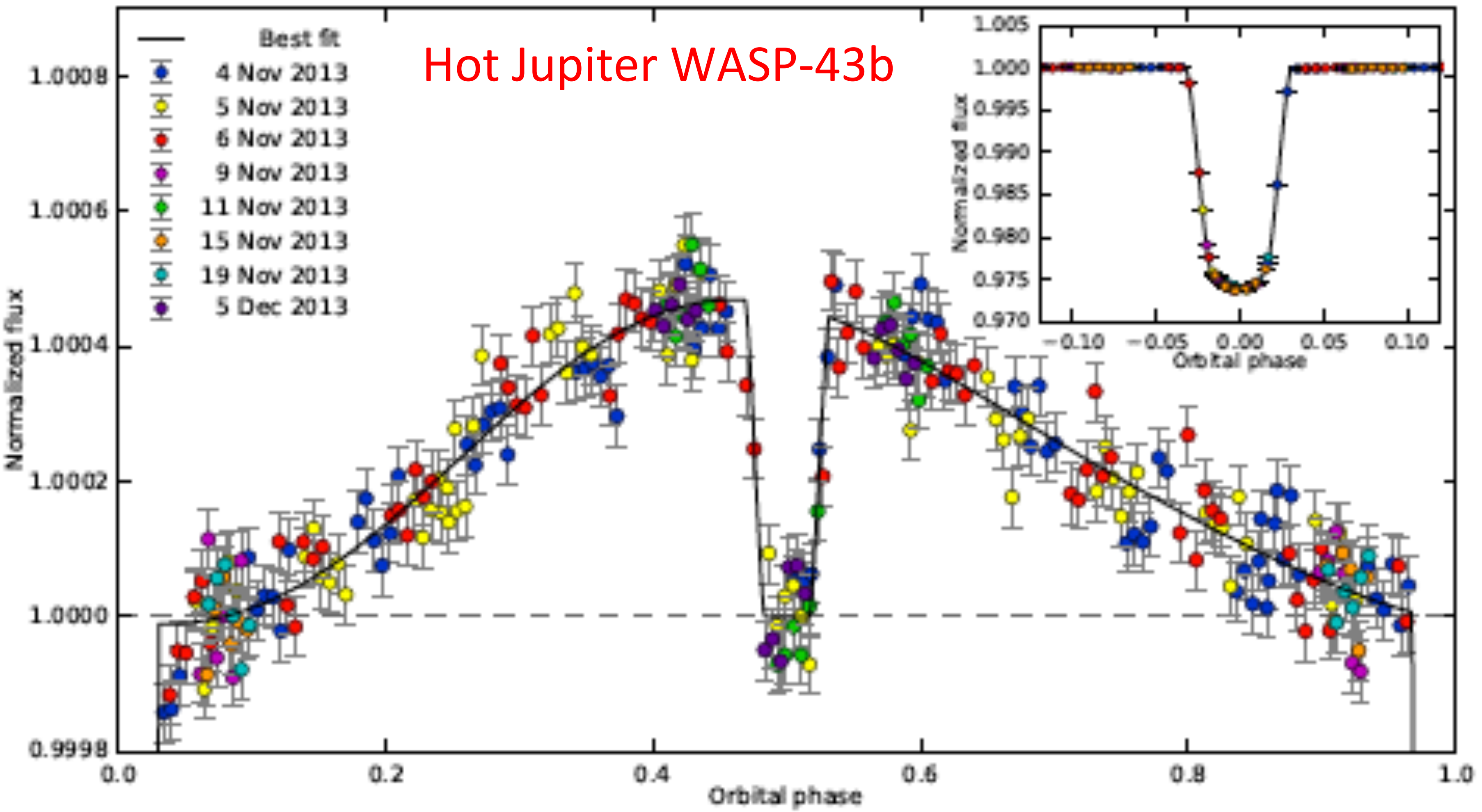
A Hot Jupiter in High Definition



K. B. Stevenson (2014)

Multi-visit ‘Deep’ HST Observations

(HST WFC3 Treasury program: 150 HST Orbits, 4 planets, PI: Jacob Bean)

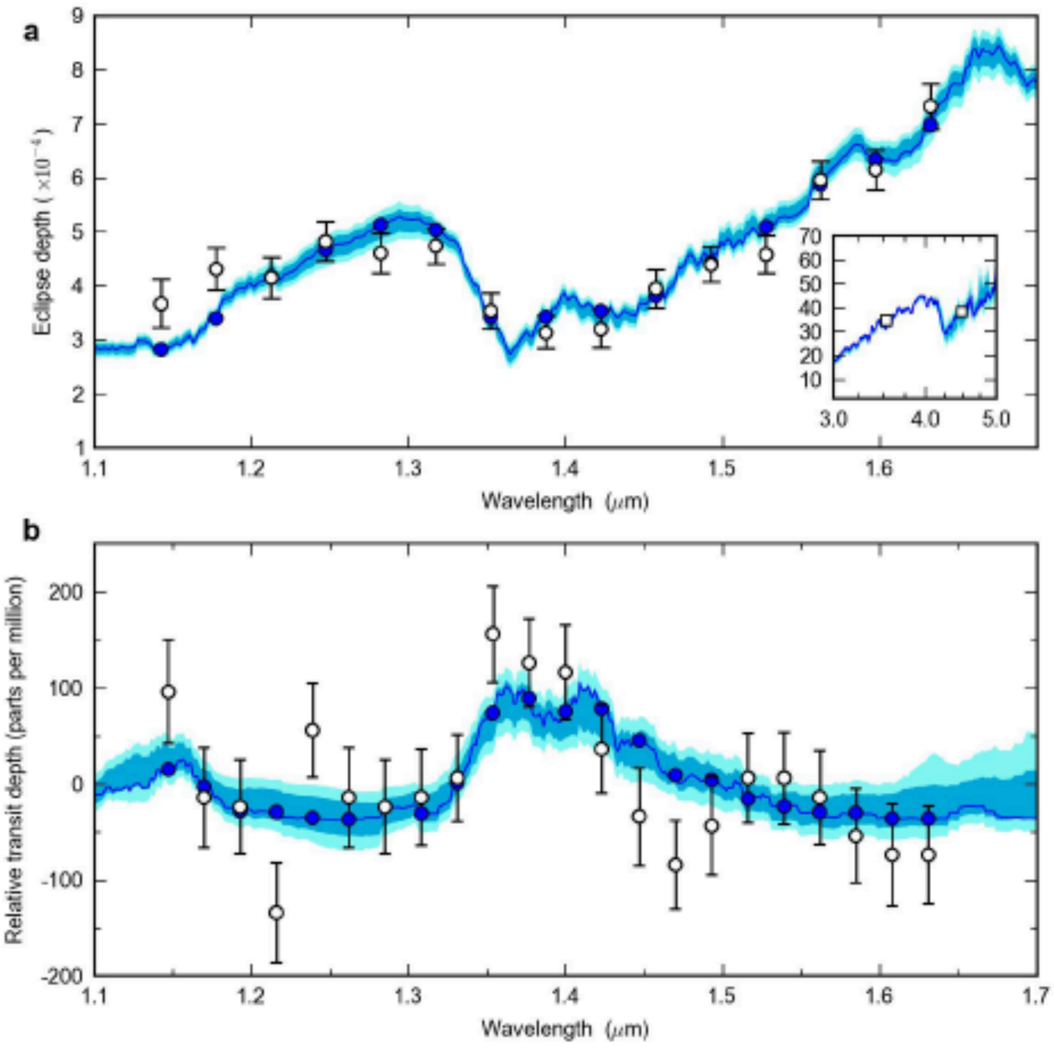


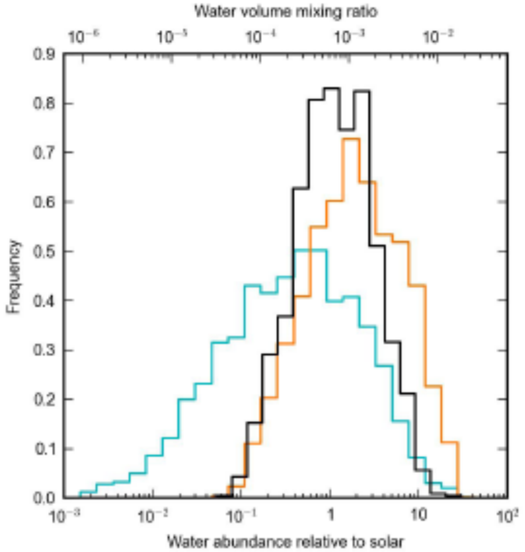
Hot Jupiter WASP-43b

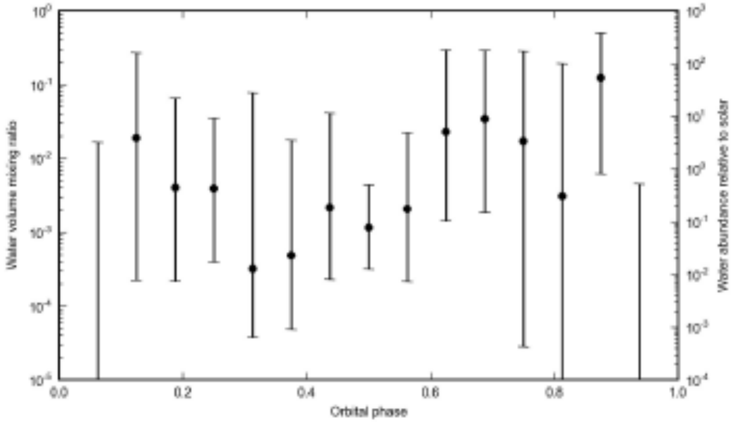
61 HST Orbits, 6 Transits, 5 Occultations
3 full planetary orbits

Stevenson et al. 2014, Nature

H_2O in the atmosphere of WASP-43b



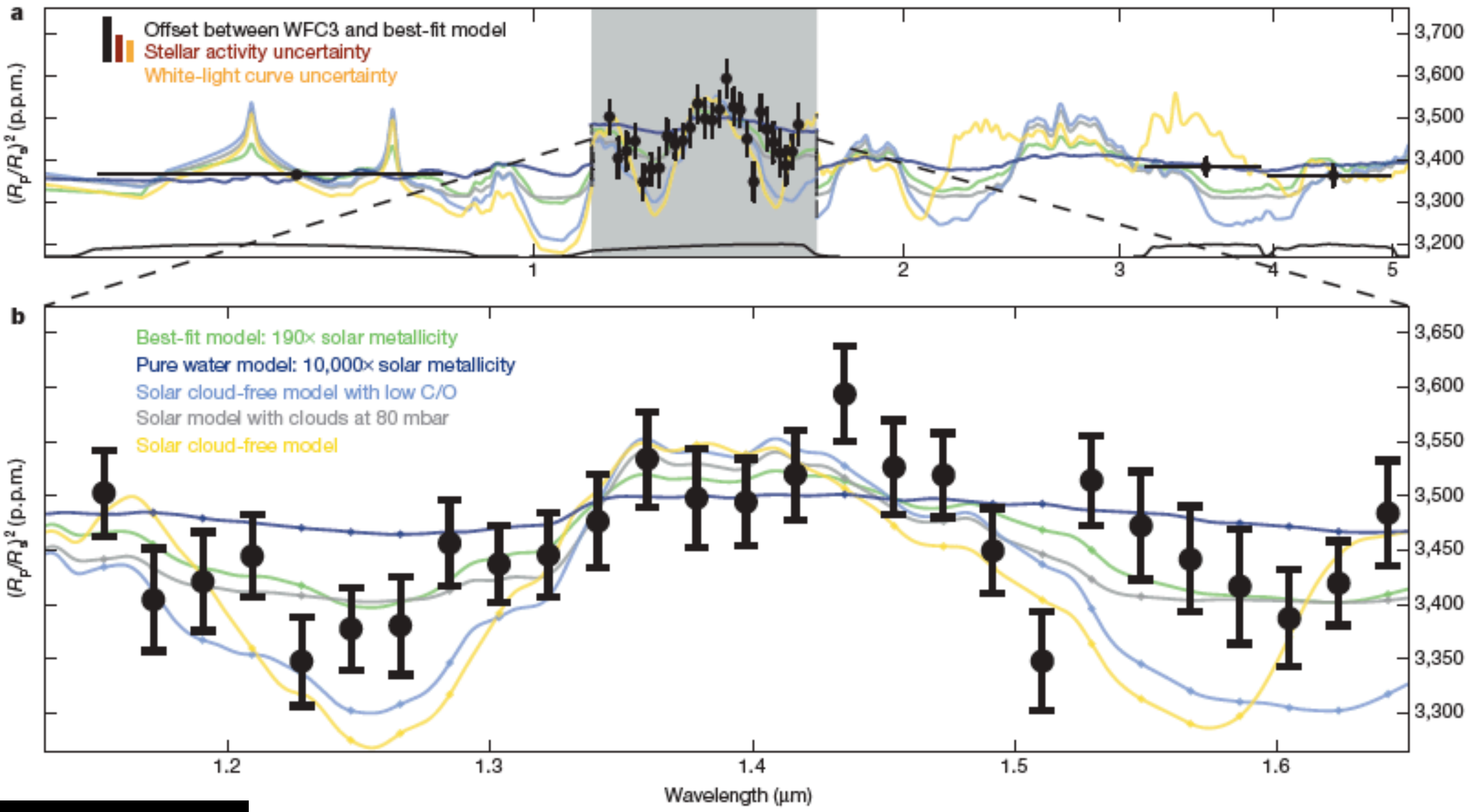


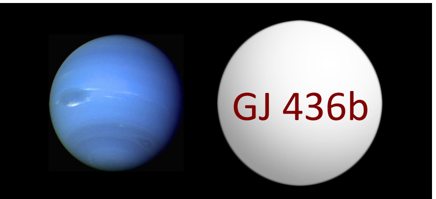


Kriedberg et al. 2014, ApJ

First Detection of H_2O in an Exo-Neptune

Transmission Spectrum of HAT-P-11b

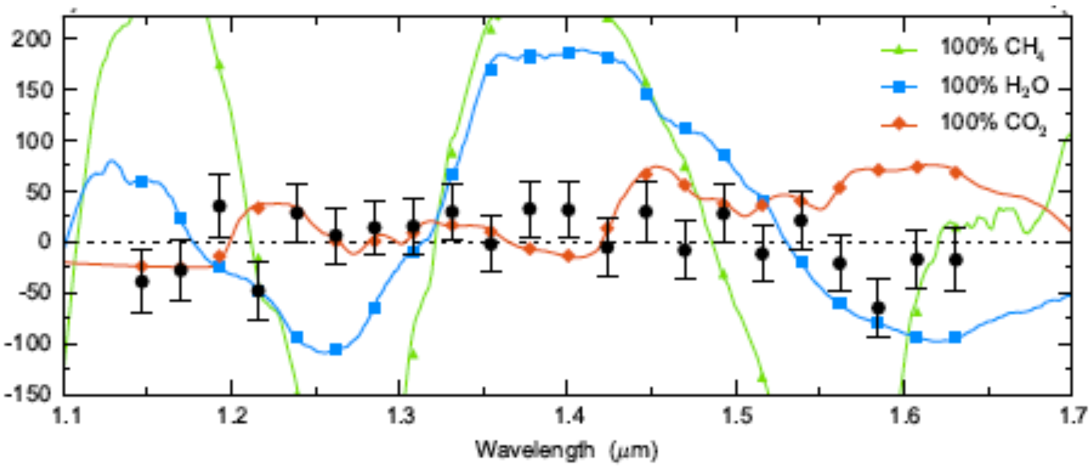




Fraine et al. 2014, Nature

Spectra of Super-Earths

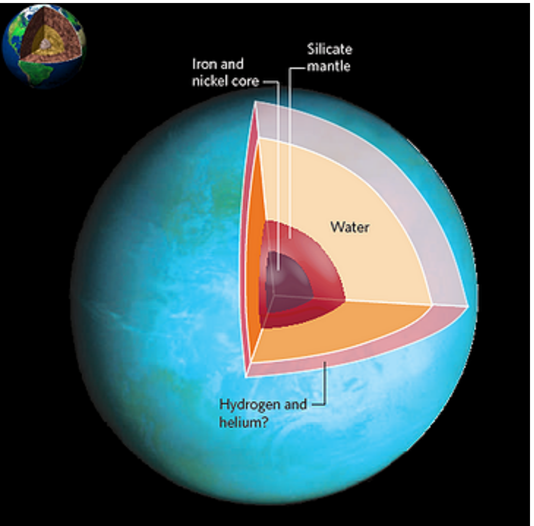
Clouds in the super-Earth GJ 1214b (T ≈ 550 K)



M_p = 6.55 ± 0.98 M_E
R_p = 2.678 ± 0.13 R_E
T_{eq} = 400 - 550 K

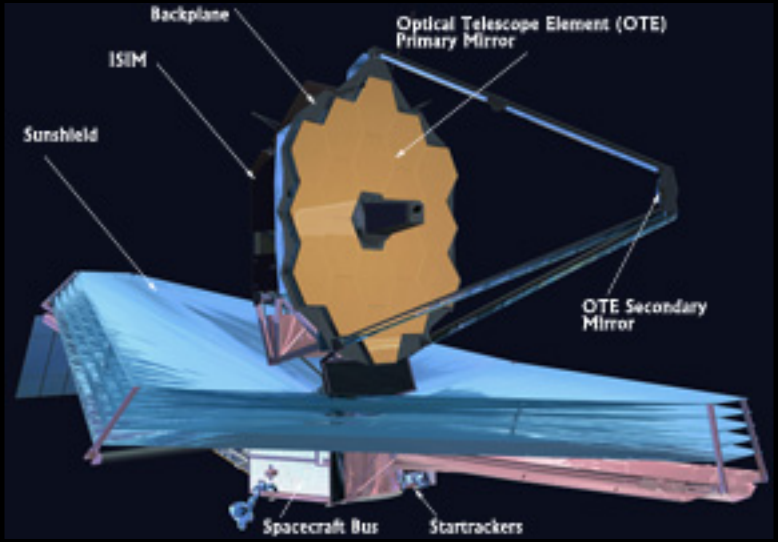
Key Merit: Orbits an M Dwarf
(M = 0.16 M_s, R = 0.2 R_s)

60 HST orbits Kreidberg et al. 2014

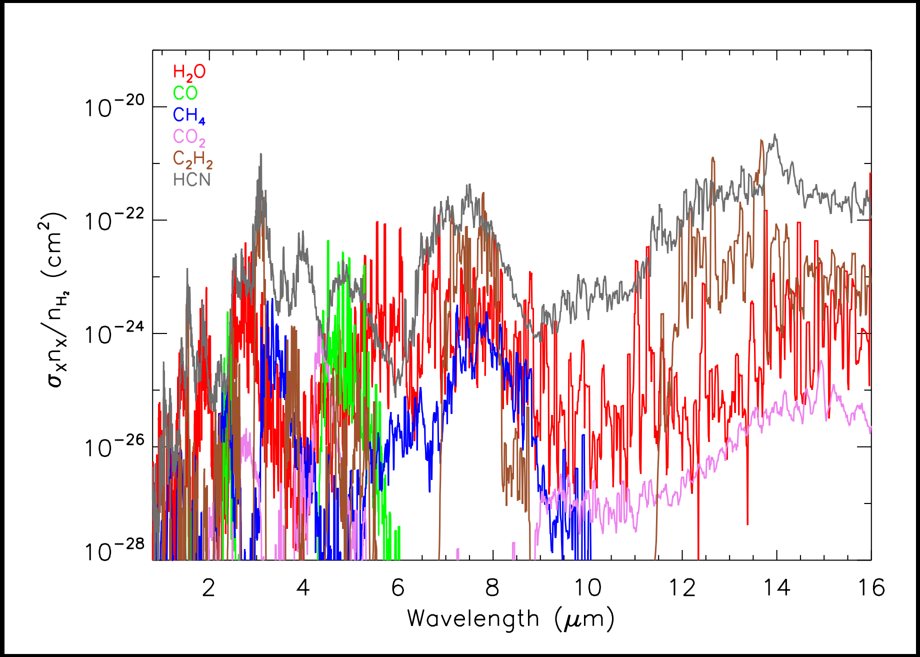


Future Observational Facilities

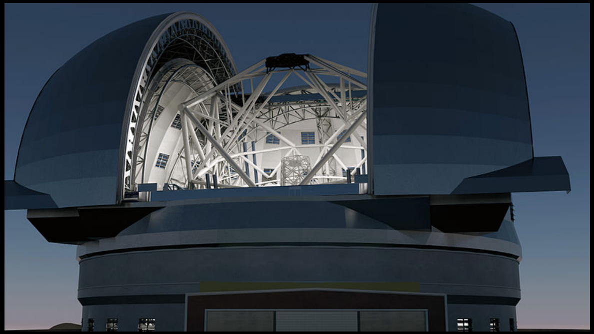
The James Webb Space Telescope



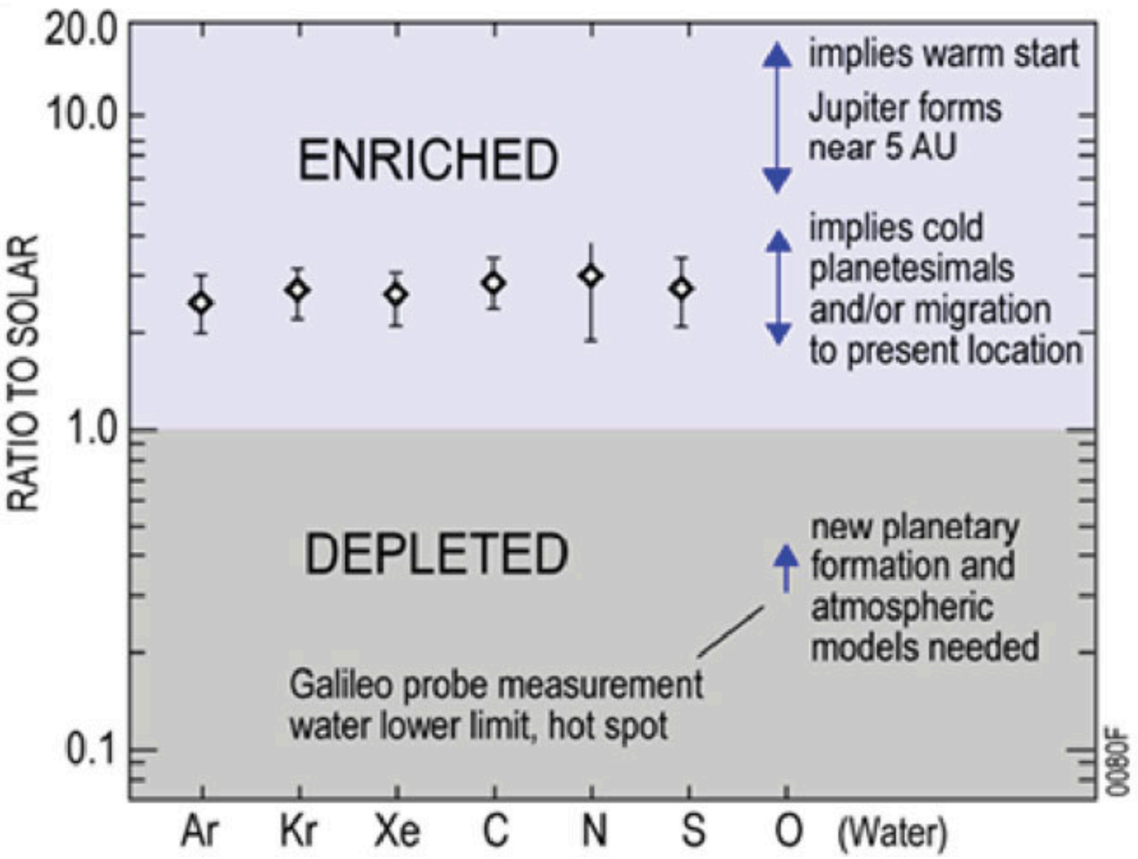
- JWST: NIRSpec and MIRI (0.6-24 μm), R~3000
- E-ELT: METIS (2.9-5.3 μm) R -> 10^5 + N-band



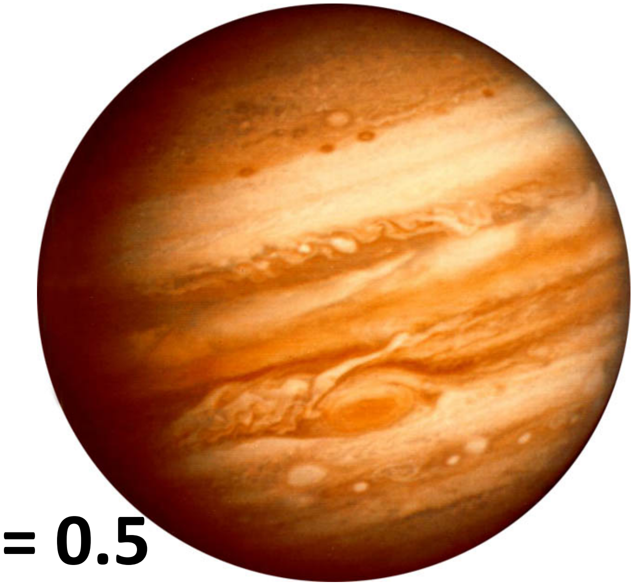
The Future from Ground: European – Extremely Large Telescope



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; Madhusudhan et al. 2011b, Mousis et al. 2012.

H_2O abundance is not known for Jupiter

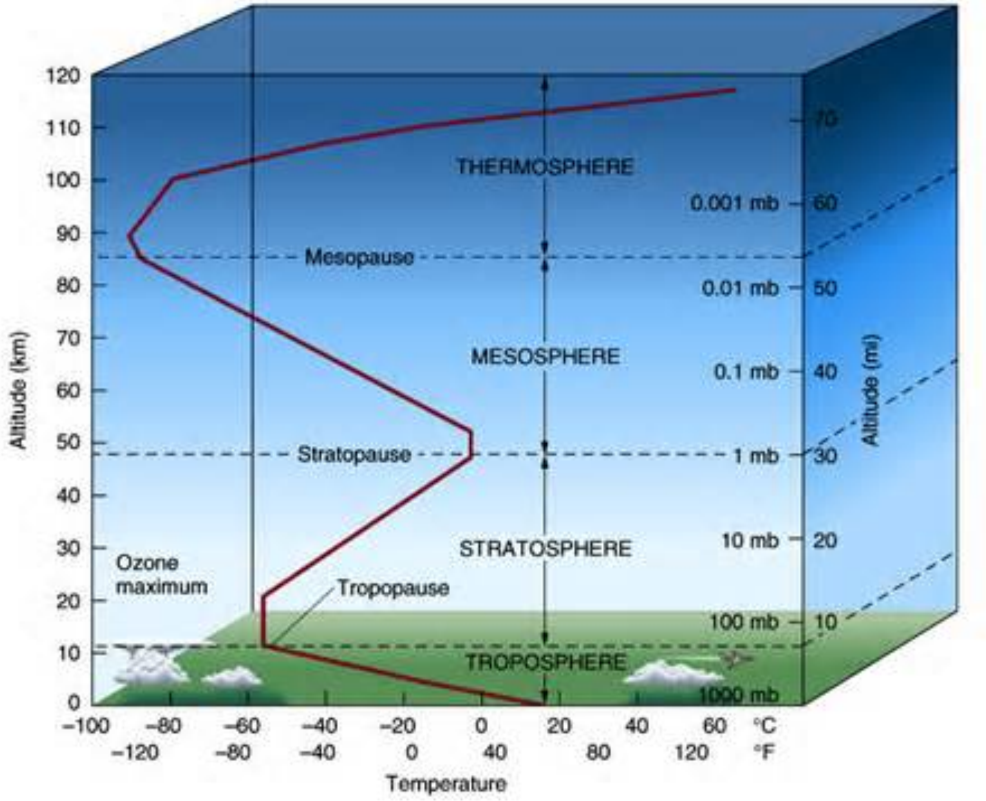
Atmospheric Theory

Theory of Exoplanetary Atmospheres

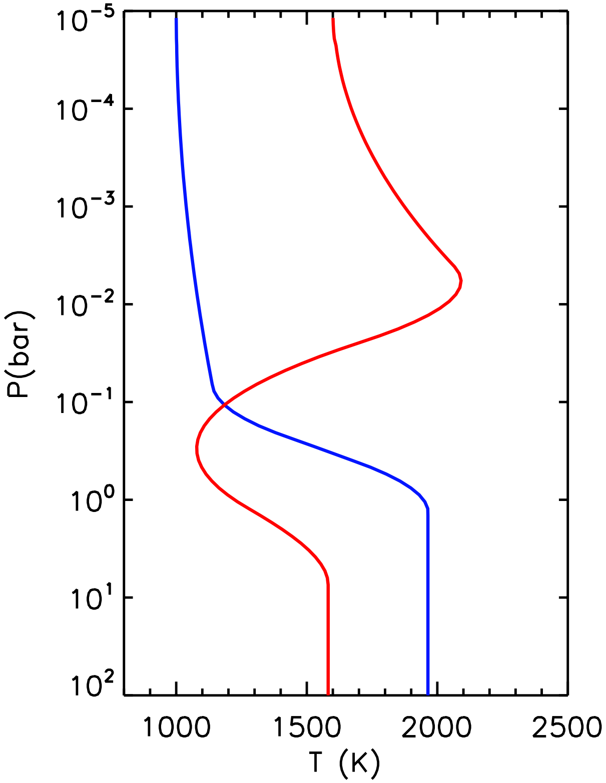
- Equilibrium and non-Equlibrium chemistry (Burrows & Sharp 1999; Lodders & Fegley 2002; Moses et al. 2011)
- Temperature structures in irradiated atmospheres (Hansen et al. 2008; Spiegel et al. 2009; Guillot et al. 2010; Heng et al. 2011)
- Clouds, hazes, condensates (Helling et al. 2008; Lecavelier 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!

1. Theory of Temperature Profiles and Thermal Inversions

Some Context



Earth's Atmosphere:
U. S. Standard Atmosphere



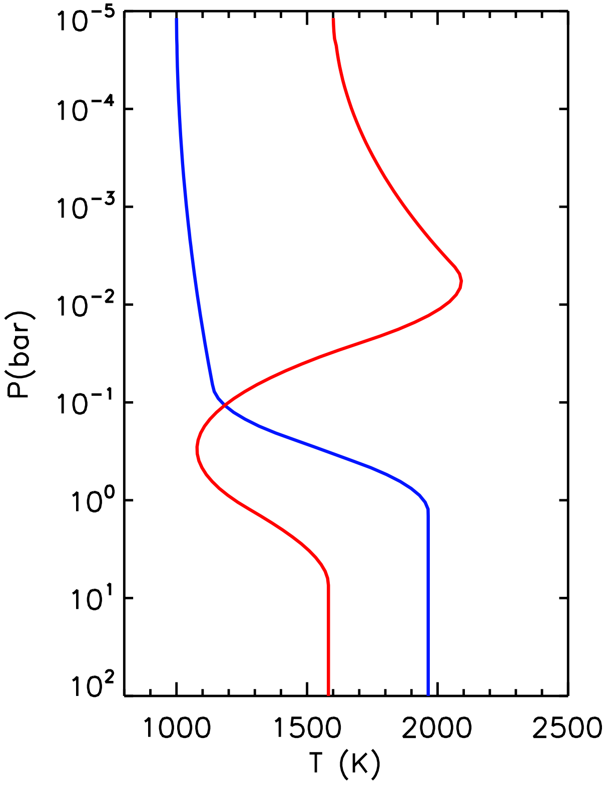
Typical model temperature profiles of highly irradiated planets

Stratosphere caused by Ozone

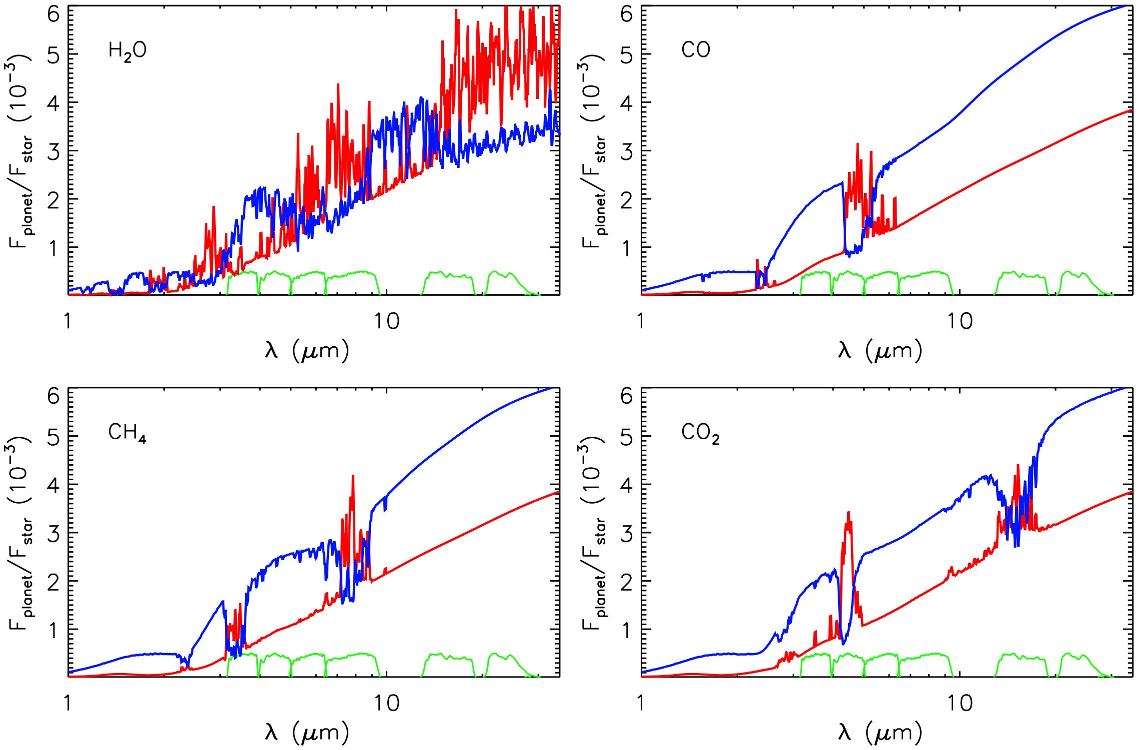
Theory of Thermal inversions in hot Jupiters
(The TiO/VO Hypothesis)

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

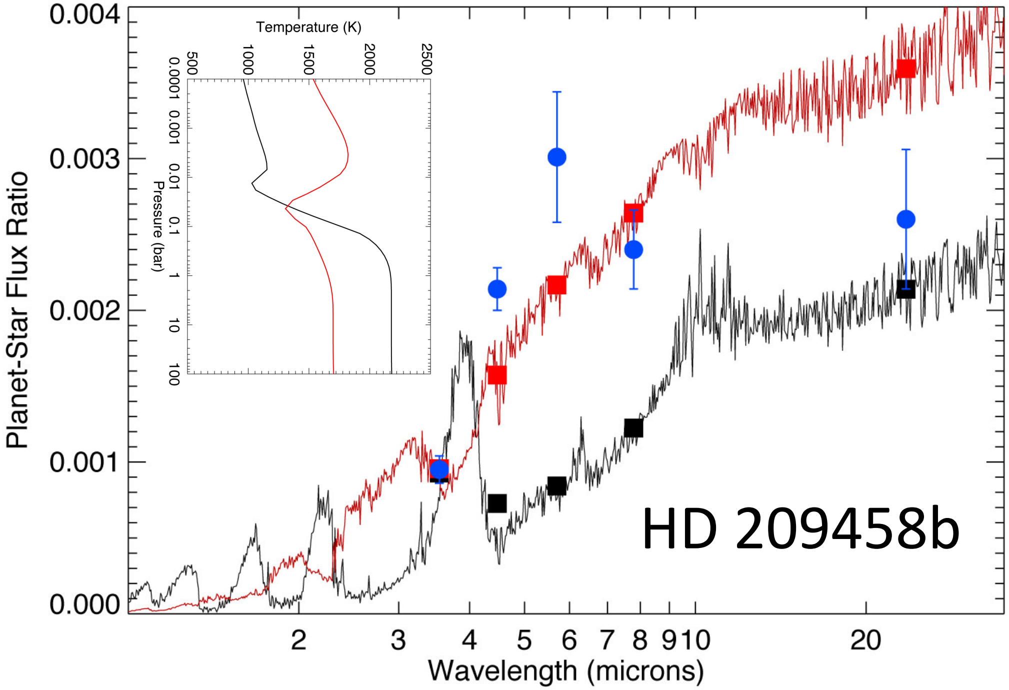


Madhusudhan & Seager 2010



Thermal inversions in hot Jupiters

Classification of hot Jupiter atmospheres

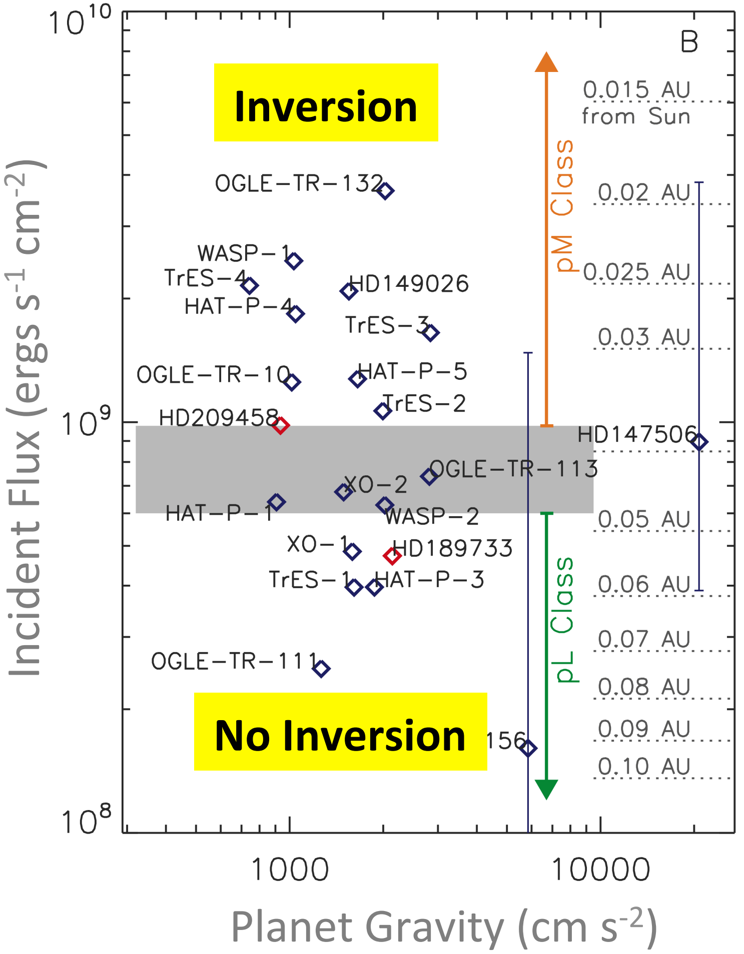


Data: *Knutson et al. 2008, ApJ, 673, 526*

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

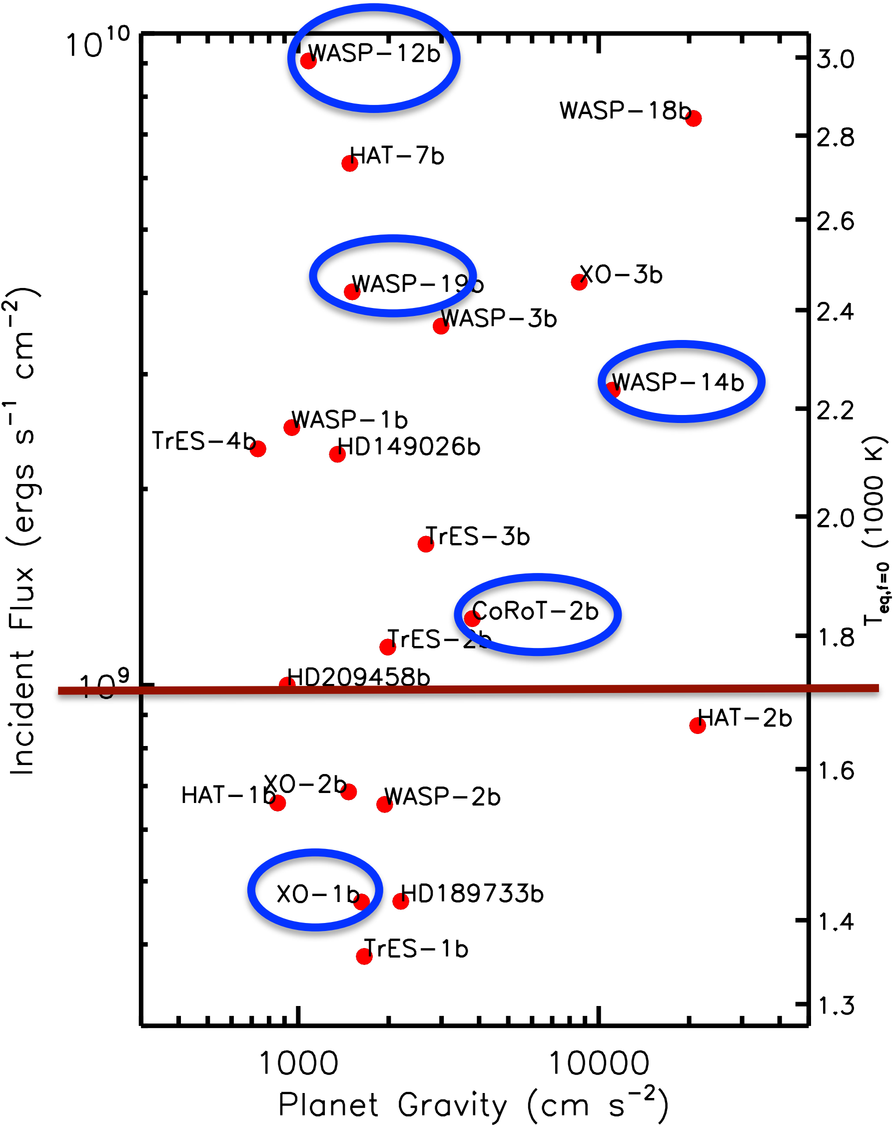
But, TiO and VO may be depleted due to gravitational settling and condensation

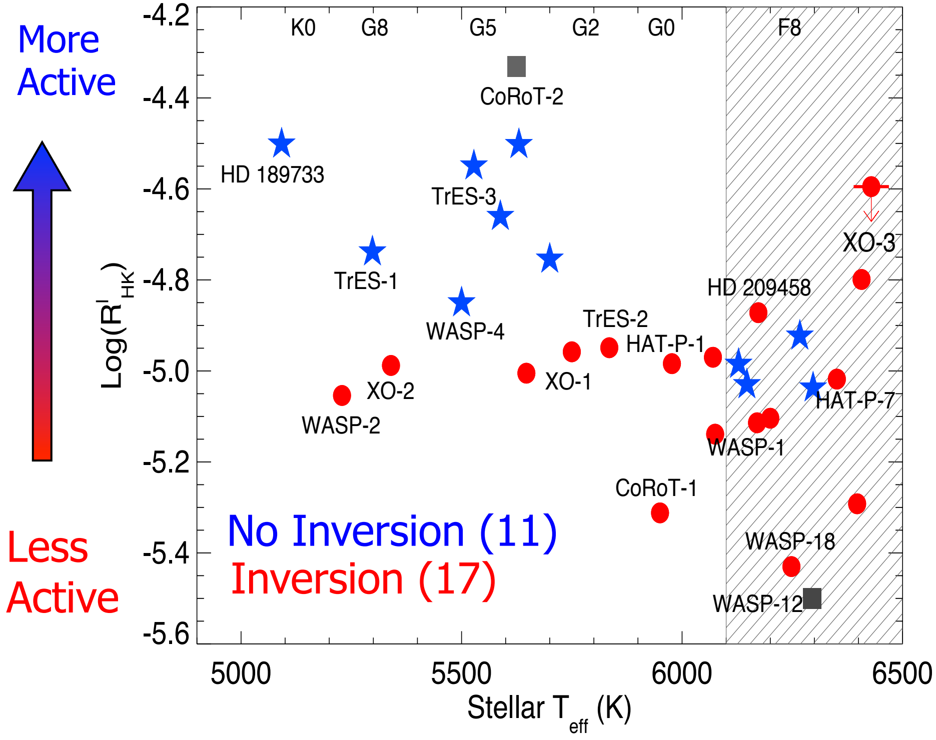
Spiegel et al. 2009, ApJ, 699, 1487



Hubeny et al. 2003
Fortney et al. 2008, ApJ, 678, 1419

Classifications of hot Jupiters





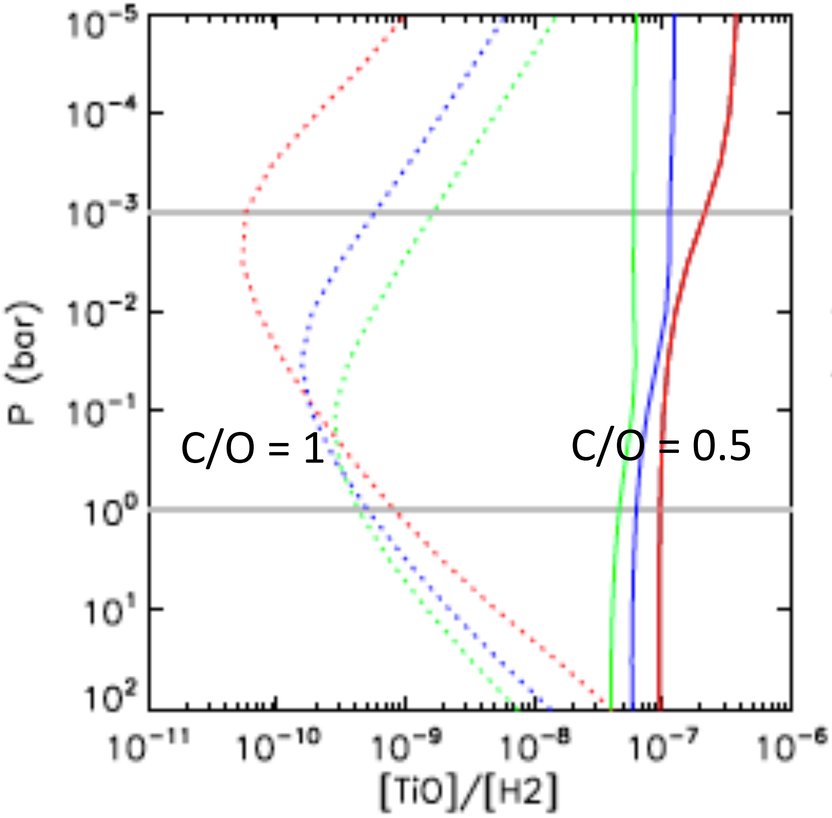
Correlation Between Stellar Activity and Temperature Inversions

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

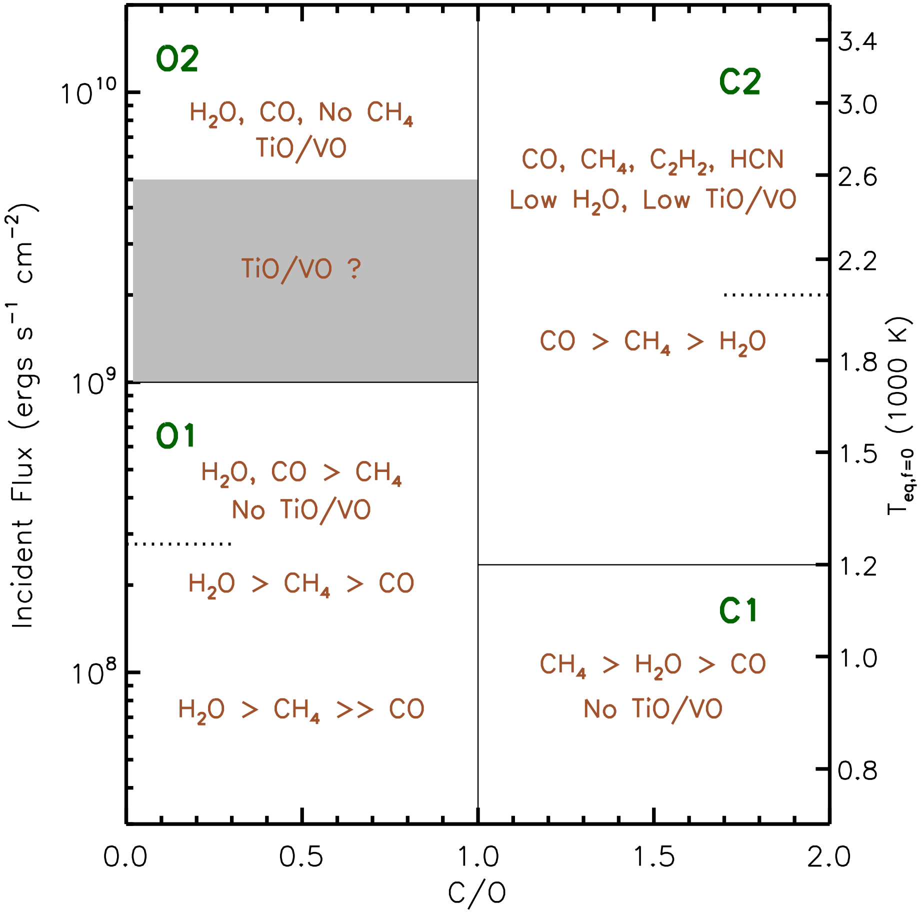
Classifications of hot Jupiters

T = 2600K, 3000 K, 3300 K



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

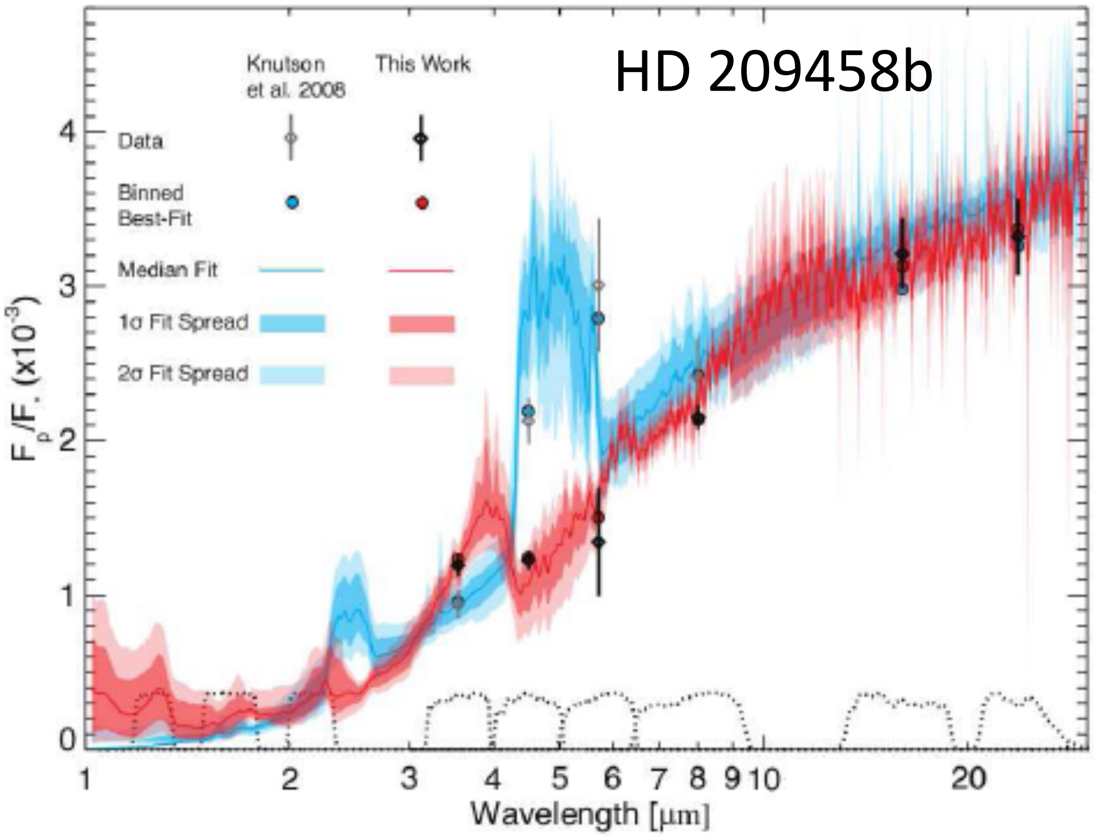
Madhusudhan et al. 2011, ApJ, 743, 191

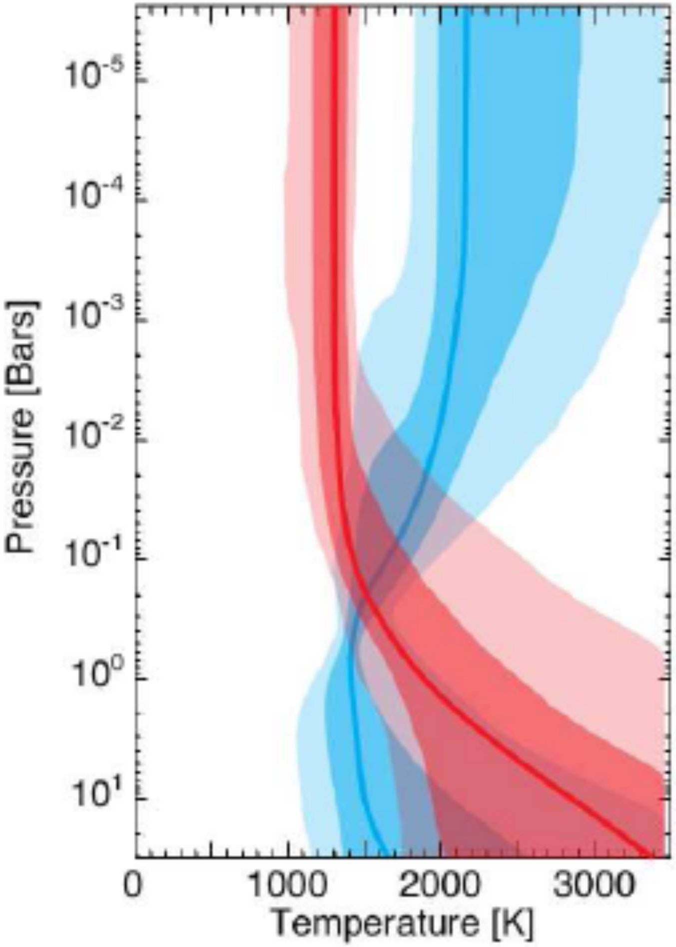


2-D classification scheme with C/O ratio as second dimension

Madhusudhan 2012, ApJ, 758, 36

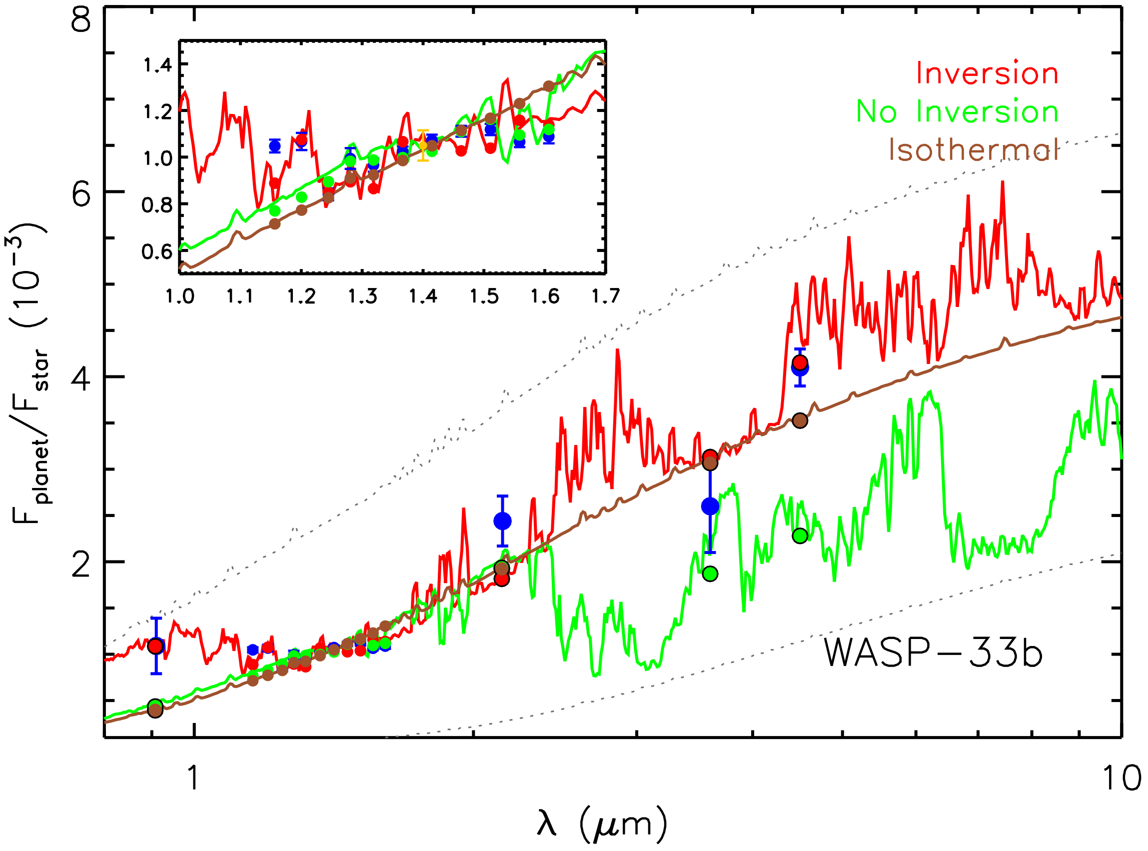
No Thermal Inversion in HD 209458b

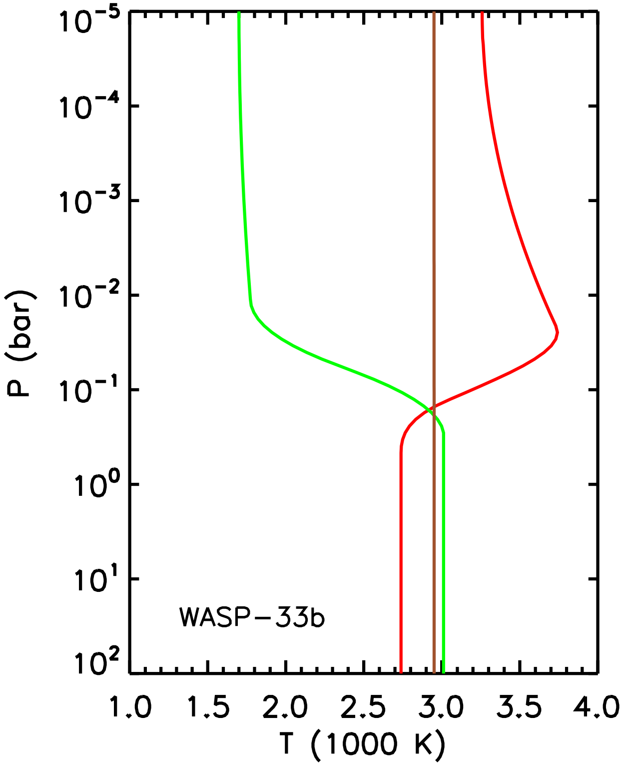




Diamond-Lowe et al. 2014

First Spectroscopic Evidence for a Thermal Inversion



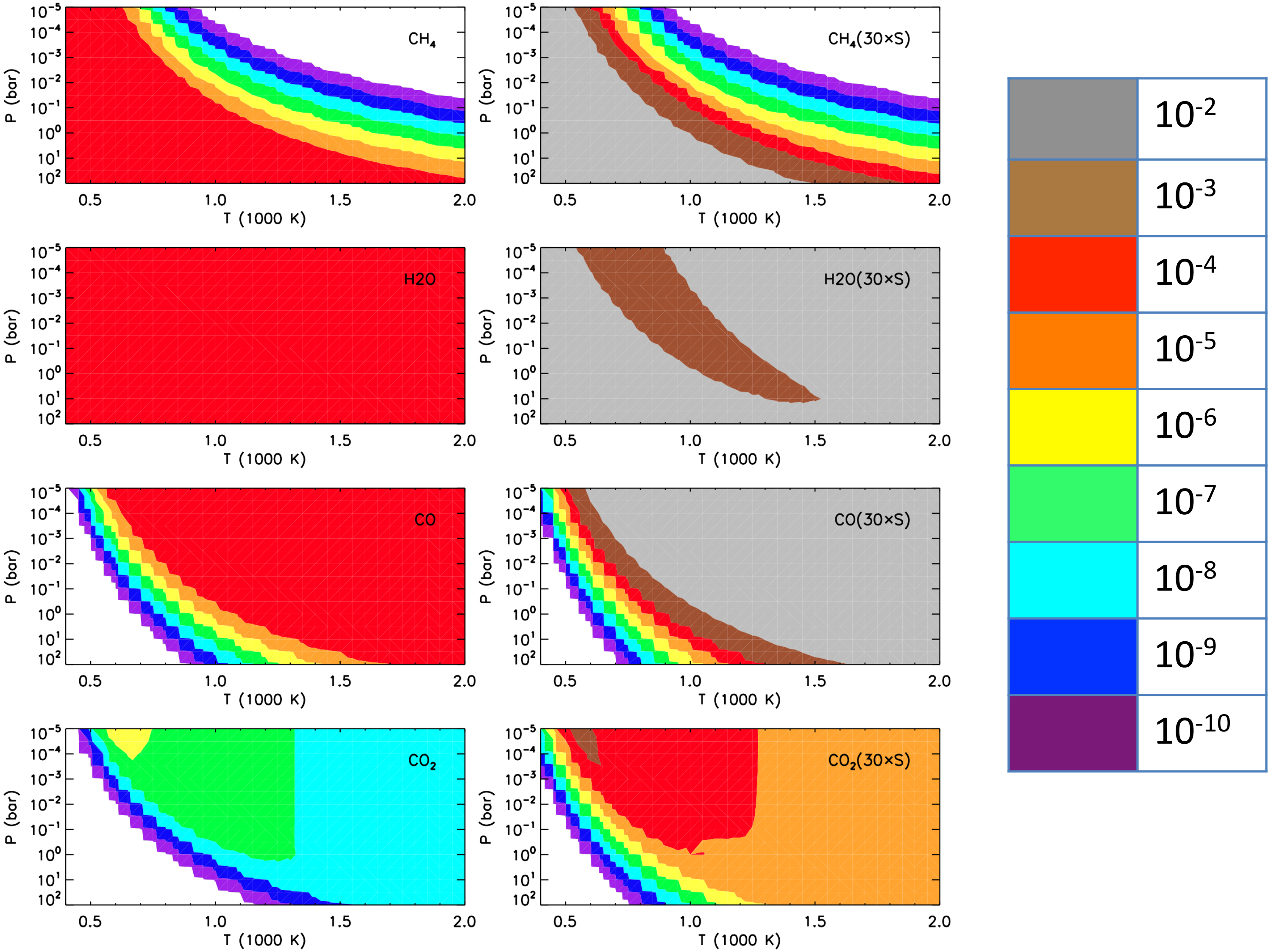


Haynes et al. 2015

2. Theory of Atmospheric Chemistry

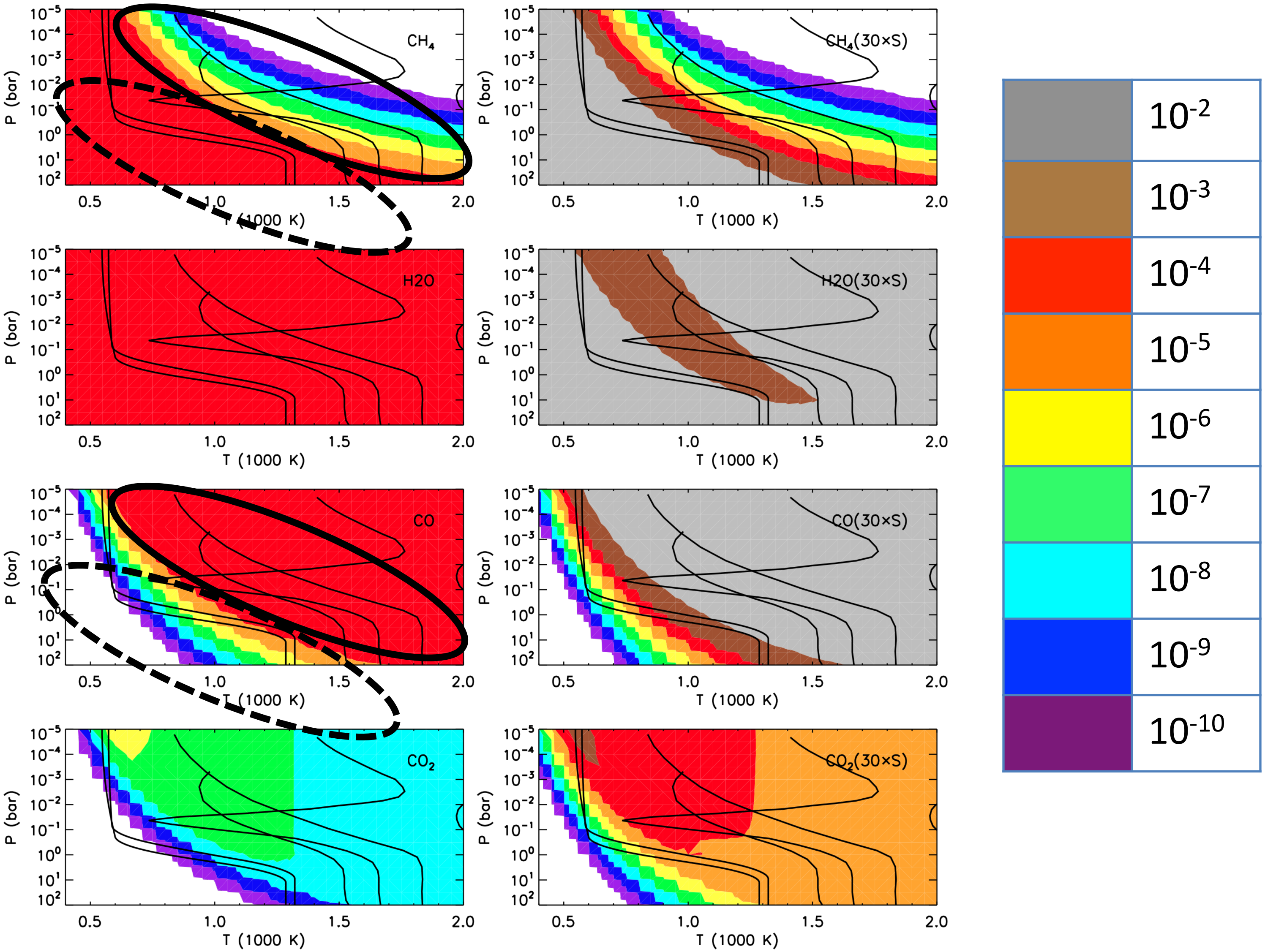
Chemistry in H_2-rich Atmospheres

(Molecular mixing ratios assuming chemical equilibrium)



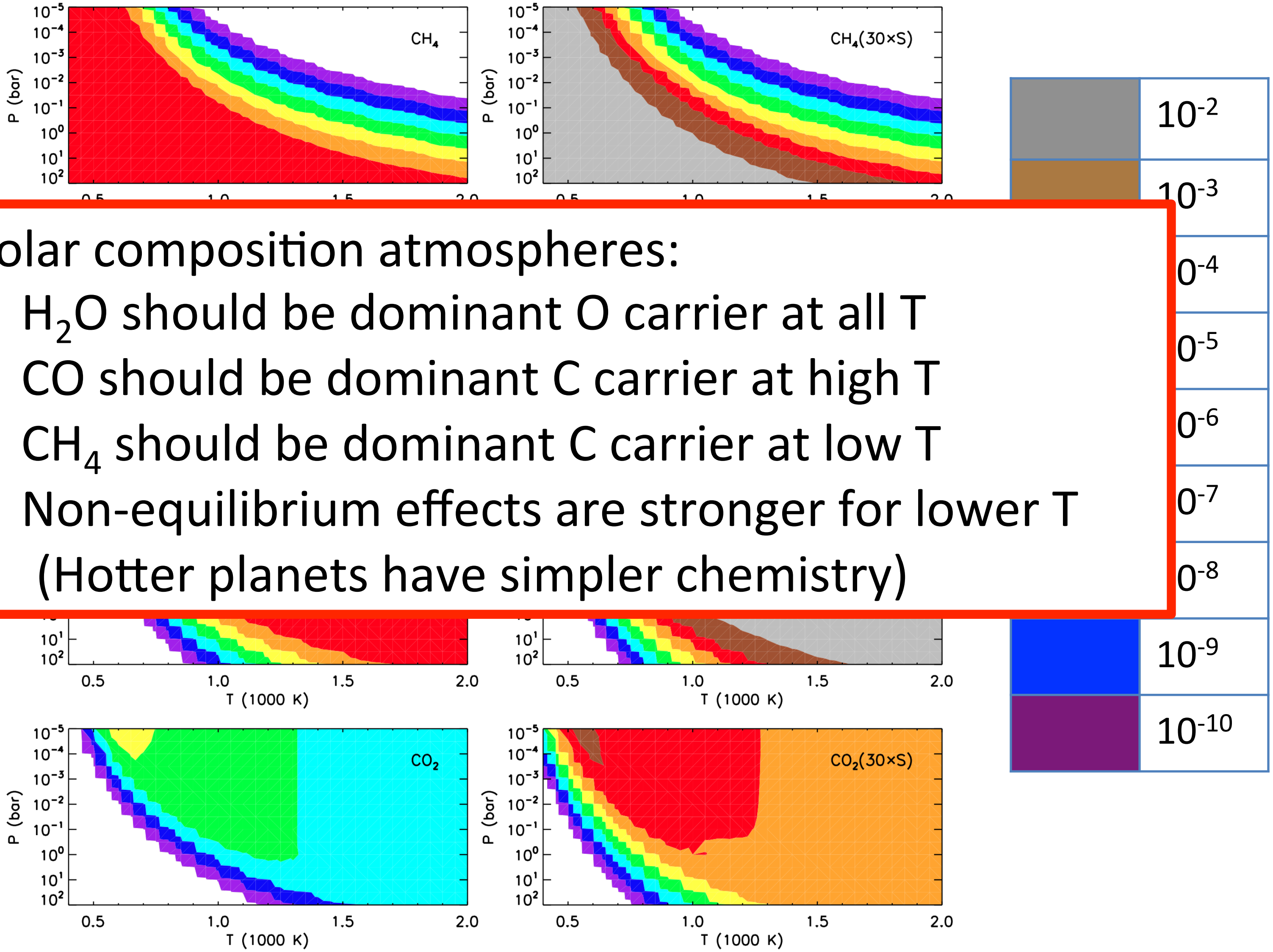
Chemistry in H_2-rich Atmospheres

(Molecular mixing ratios assuming chemical equilibrium)



Chemistry in H_2-rich Atmospheres

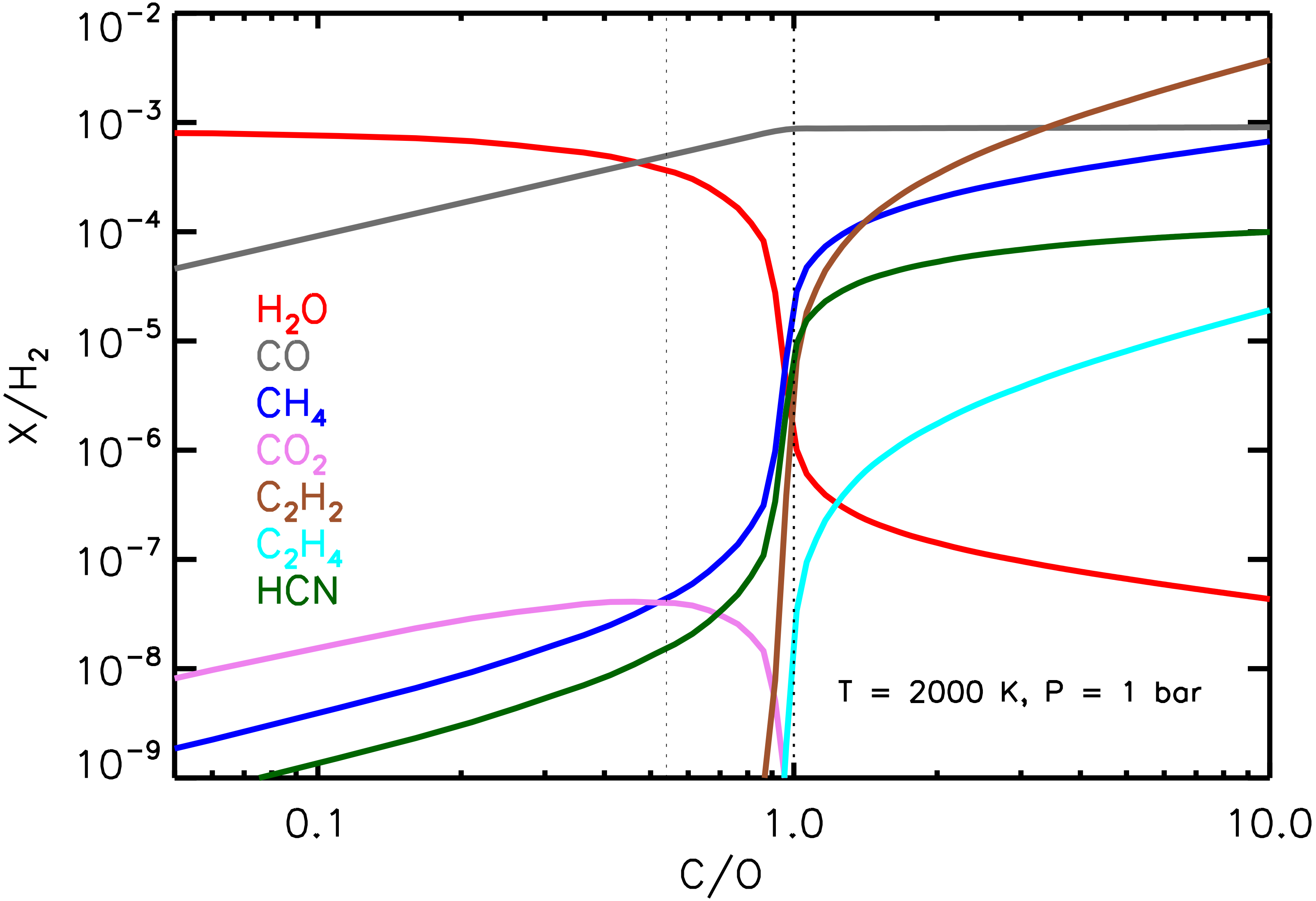
(Molecular mixing ratios assuming chemical equilibrium)



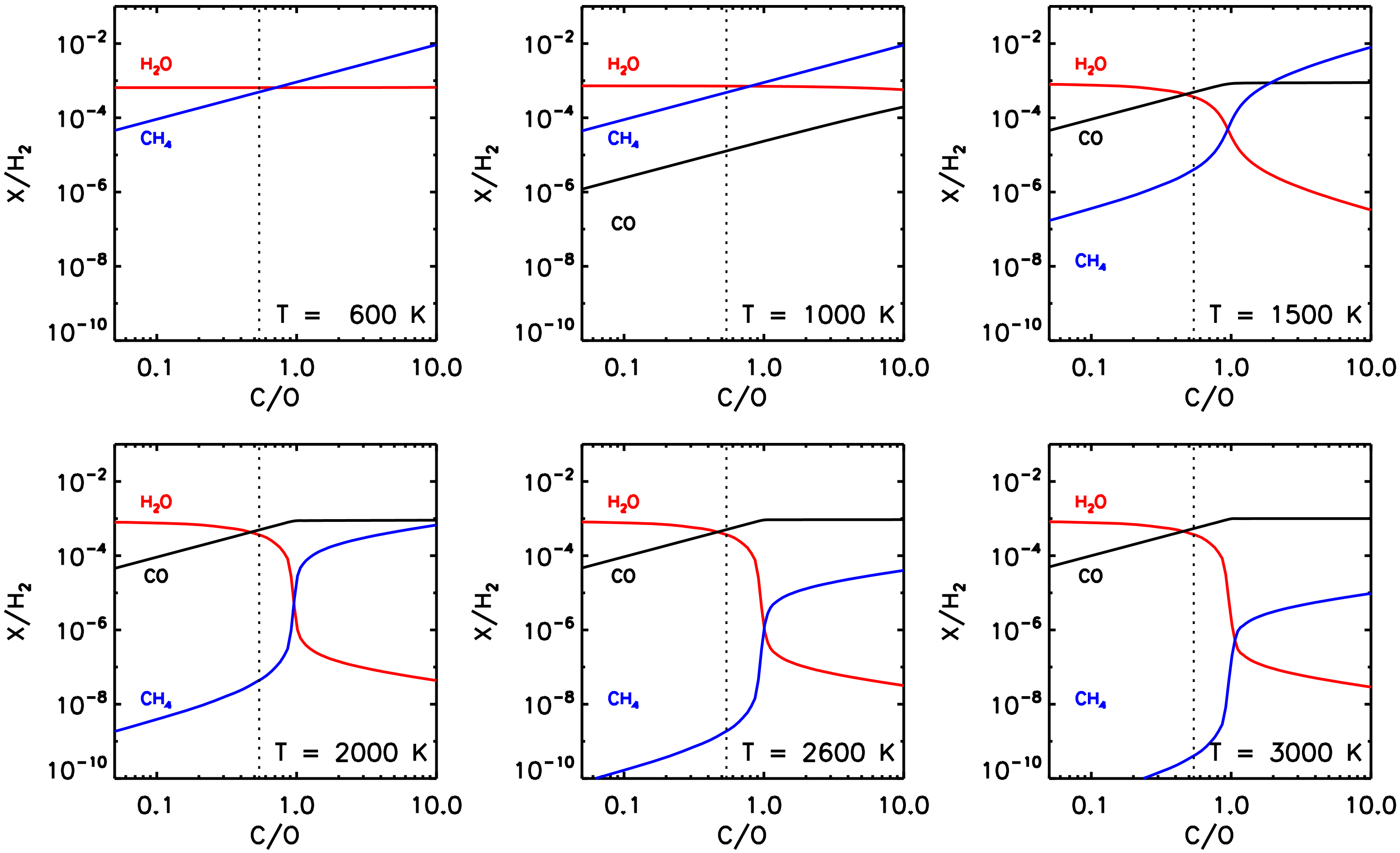
For solar composition atmospheres:

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
4. Non-equilibrium effects are stronger for lower T
   (Hotter planets have simpler chemistry)

Influence of C/O on Atmospheric Chemistry

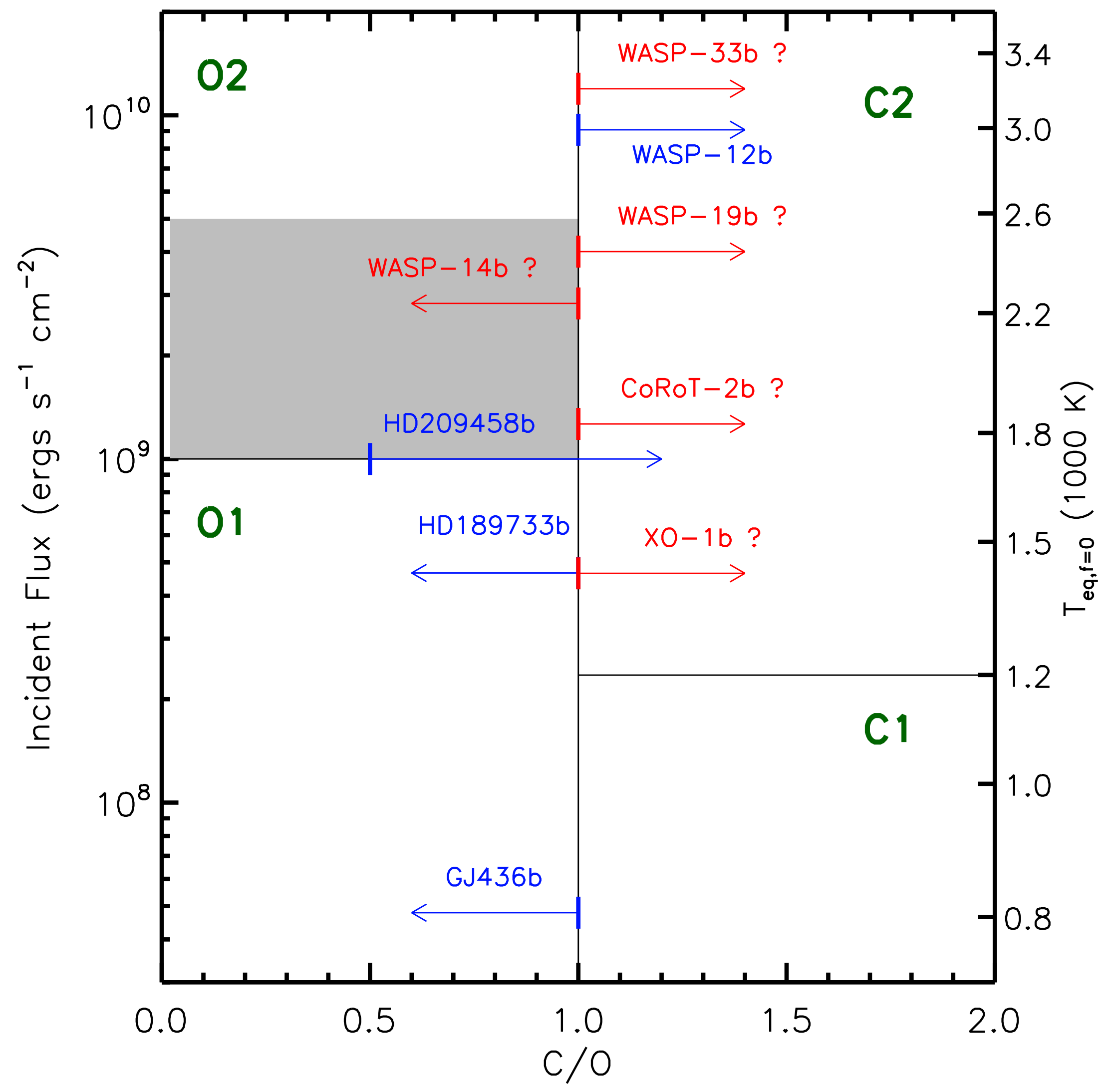


Influence of C/O on Atmospheric Chemistry



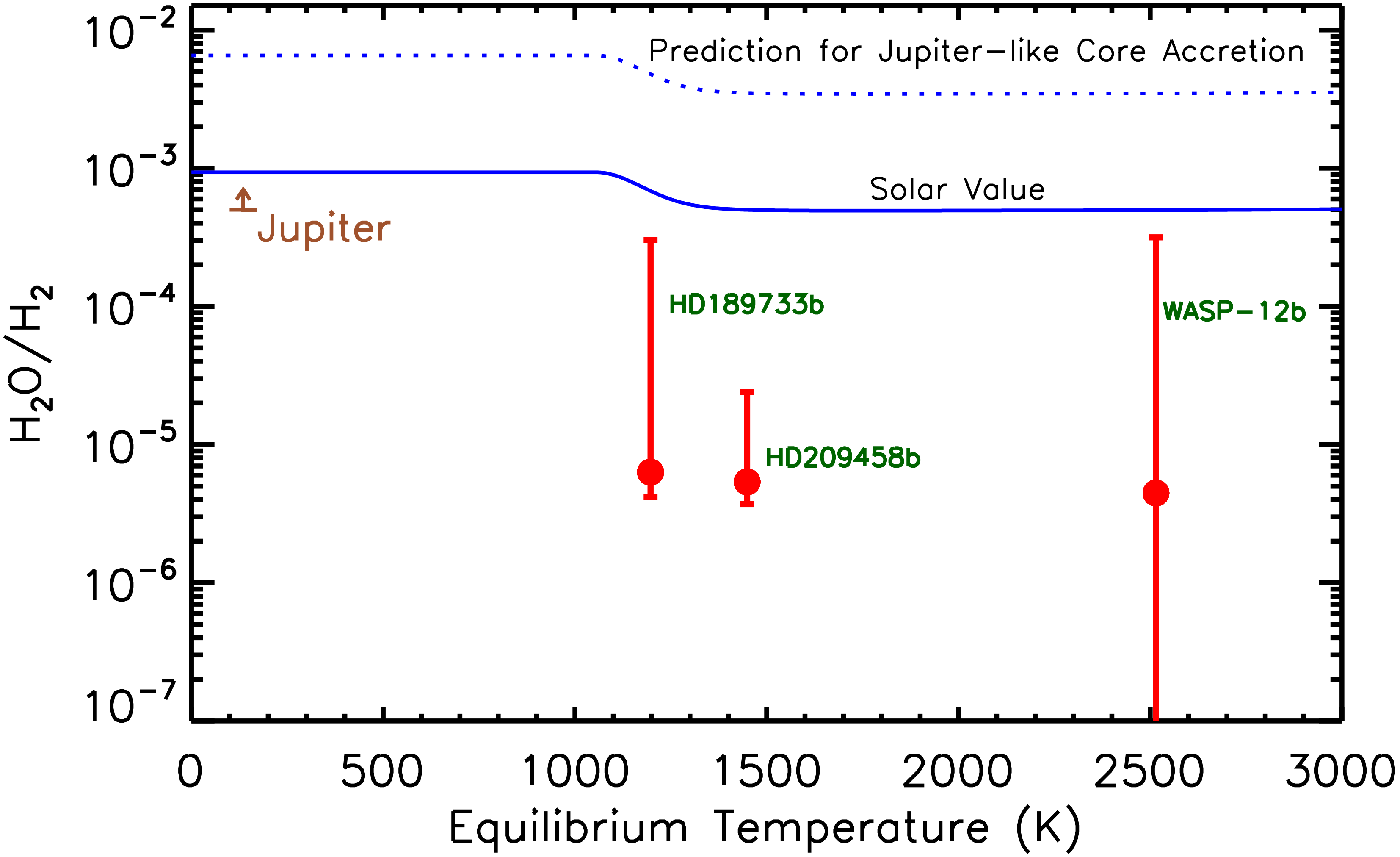
Madhusudhan 2012

C/O Ratios in Hot Jupiter Atmospheres



Madhusudhan 2012, ApJ, 758, 36

High-precision H_2O Measurements



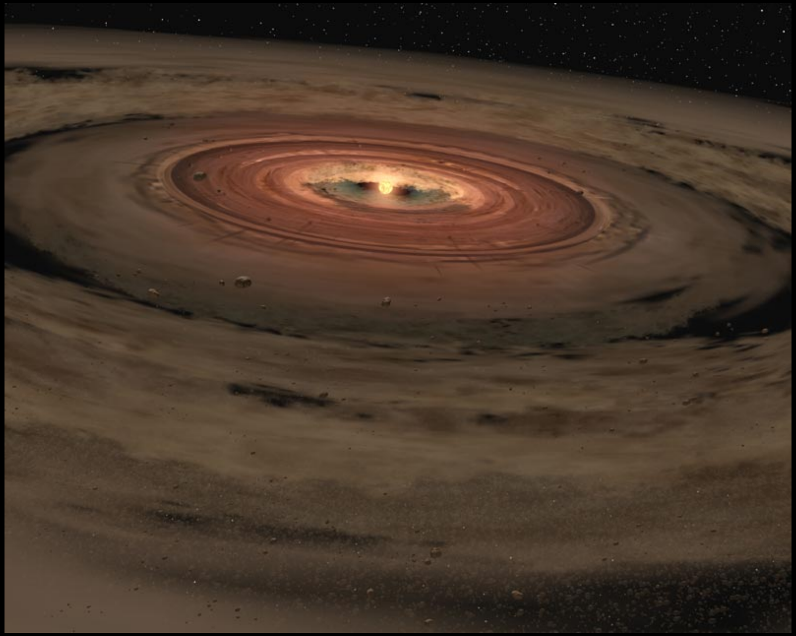
Madhusudhan et al. 2014a

What is causing the low H_2O abundances in hot Jupiters?

What is causing the Low H_2O Abundances?

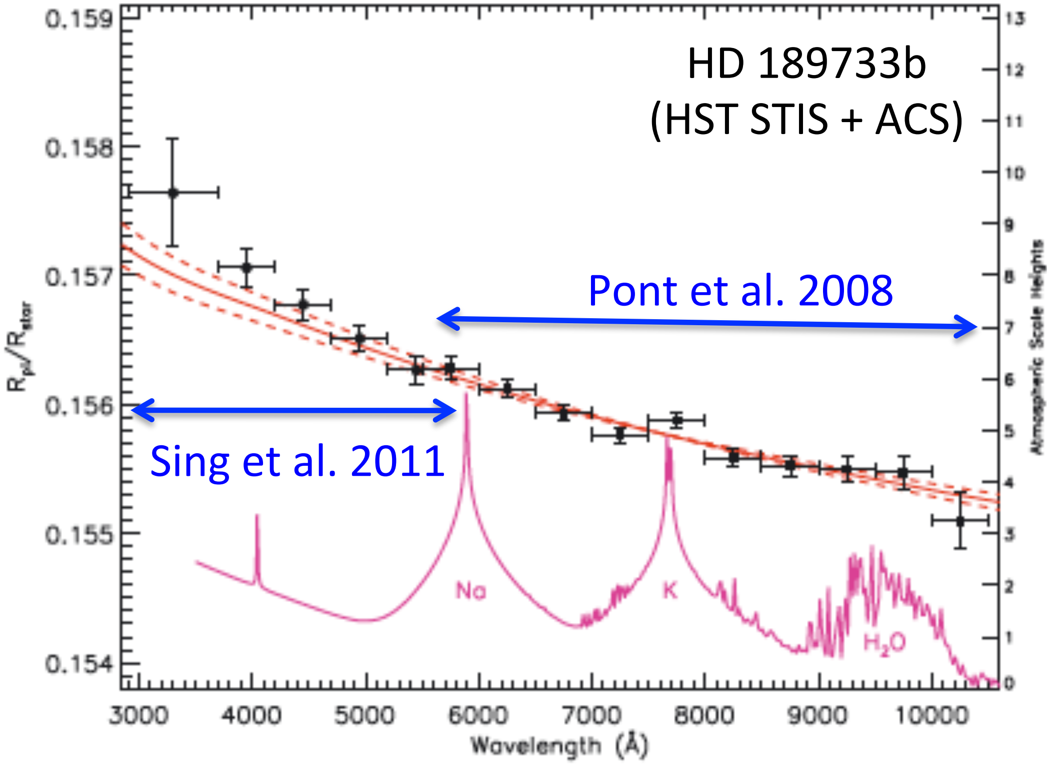
Clouds/Hazes?

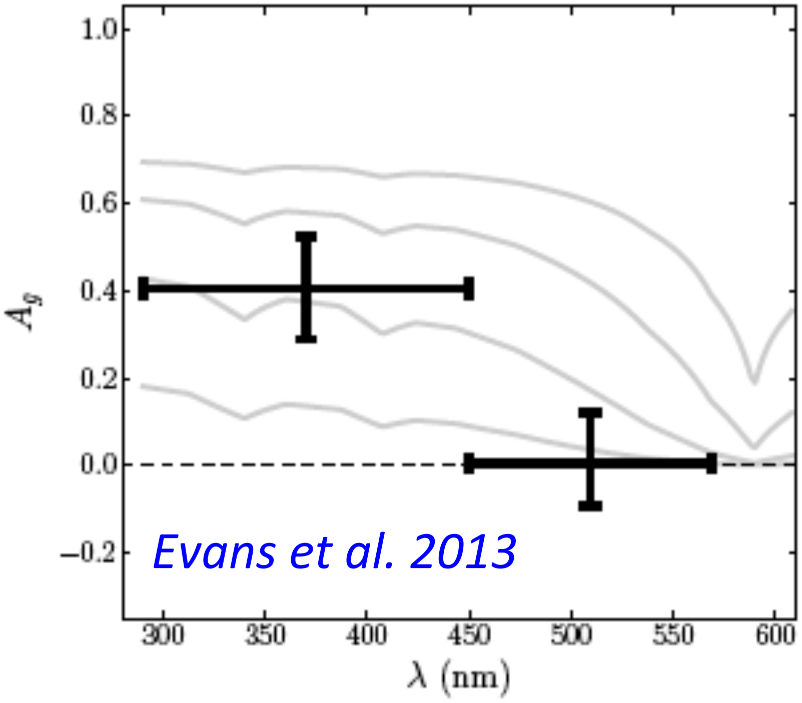
Low O/H?



3. Clouds and Hazes

Hazes and Clouds in hot Jupiter Atmospheres





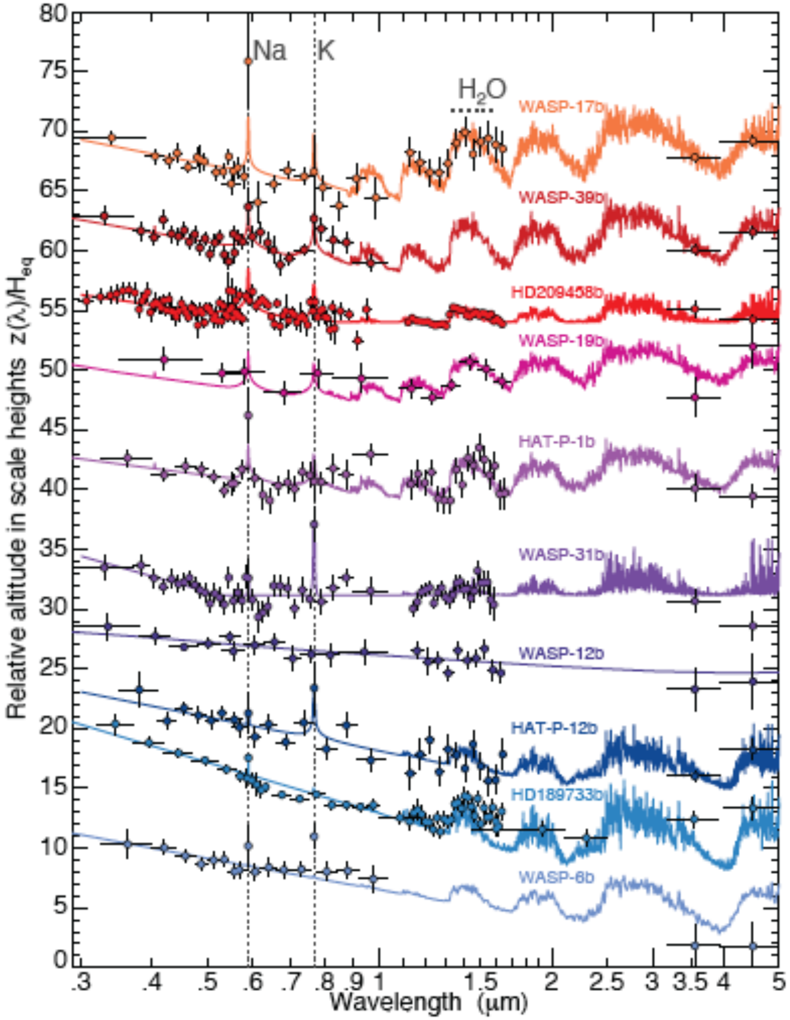
Evans et al. 2013

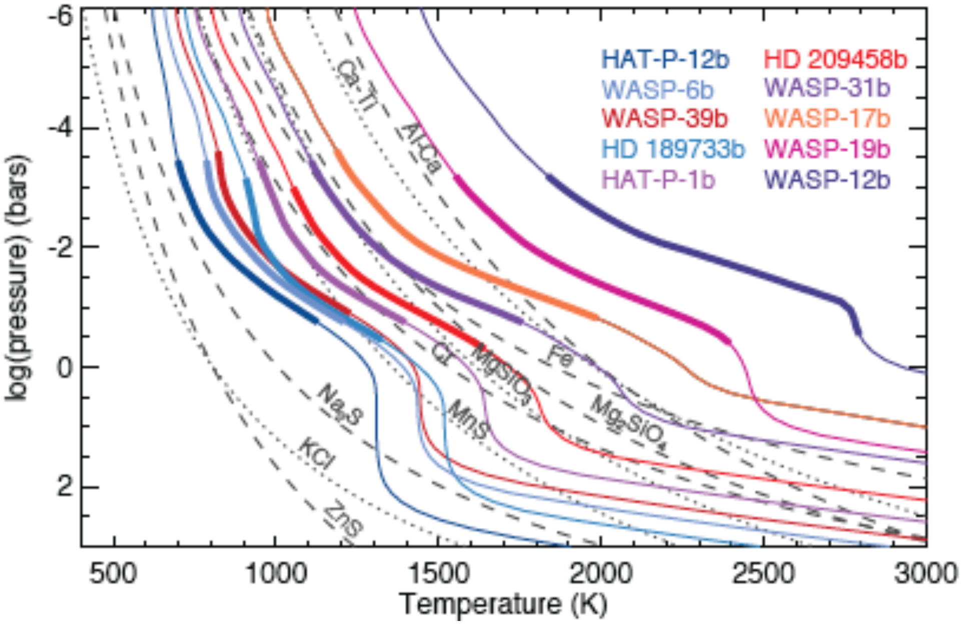
F. Pont et al. 2008, MNRAS, 385, 109
D. K. Sing et al. 2011, MNRAS, 416, 1443

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)

Clouds/Hazes





Sing et al. 2016, Nature

4. Signatures of Planet Formation in Atmospheric Abundances

Signatures of Planet Formation

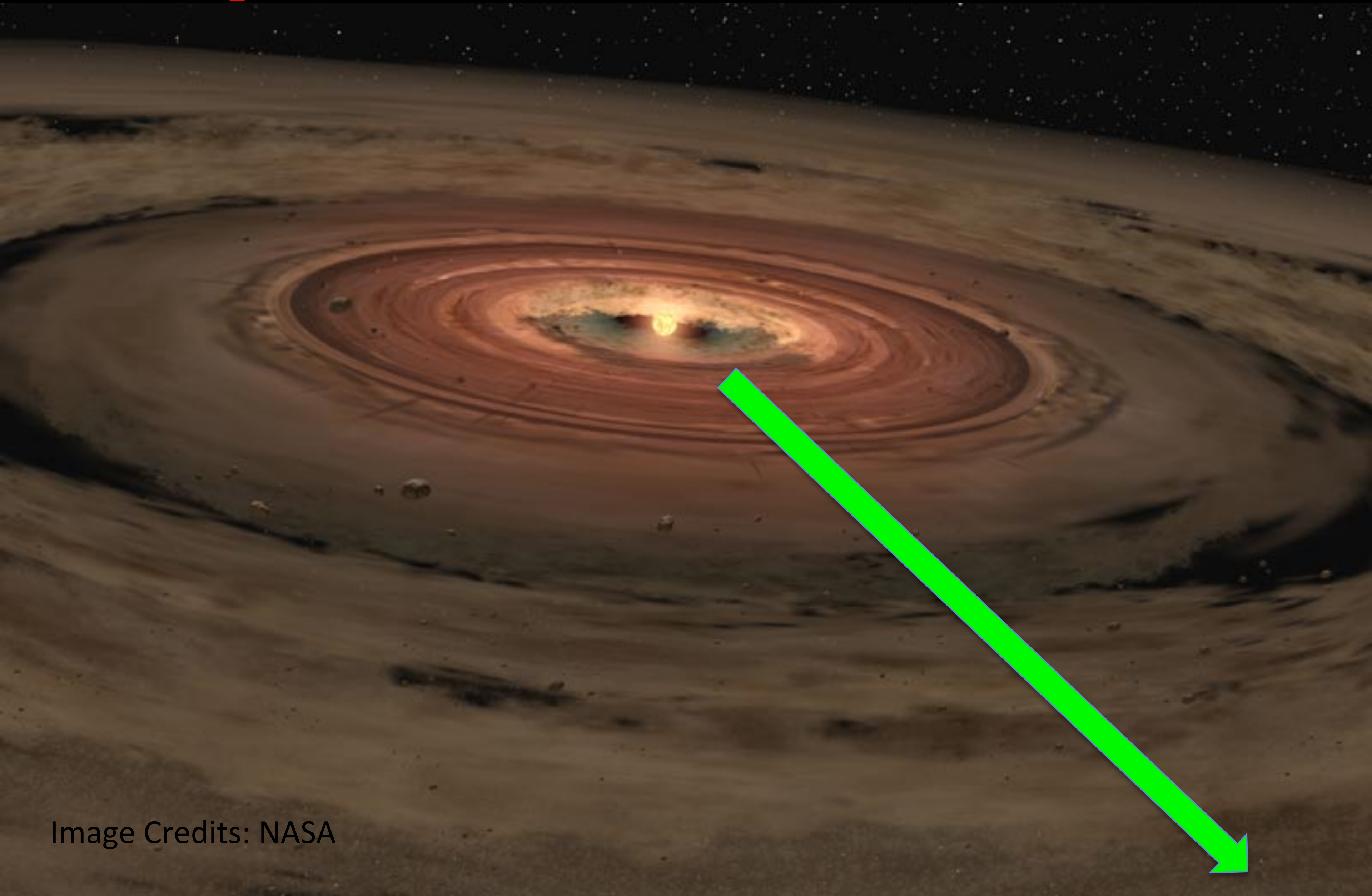
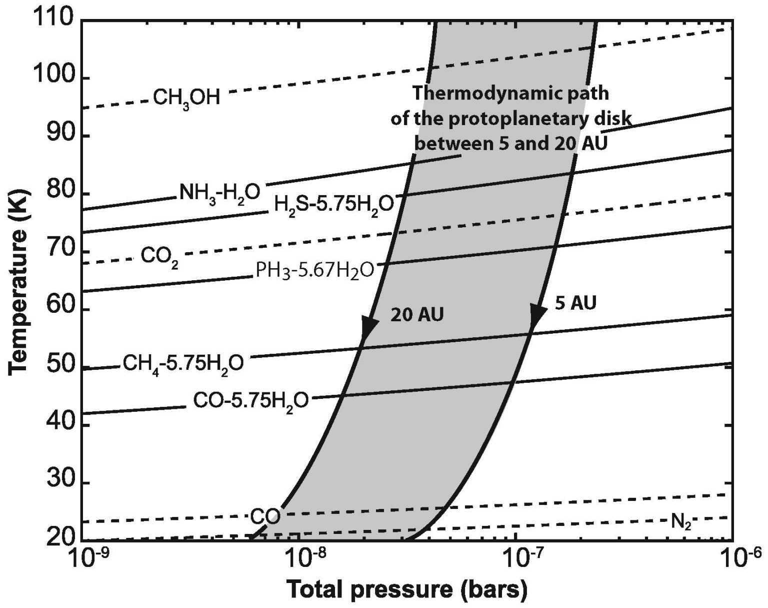
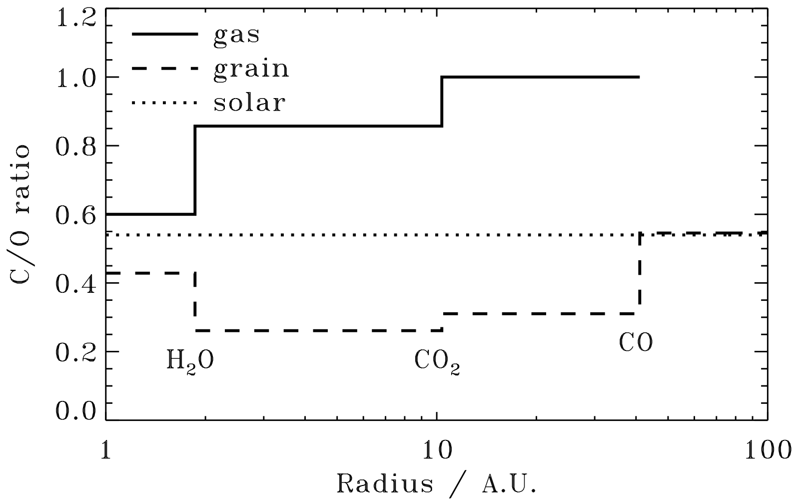


Image Credits: NASA

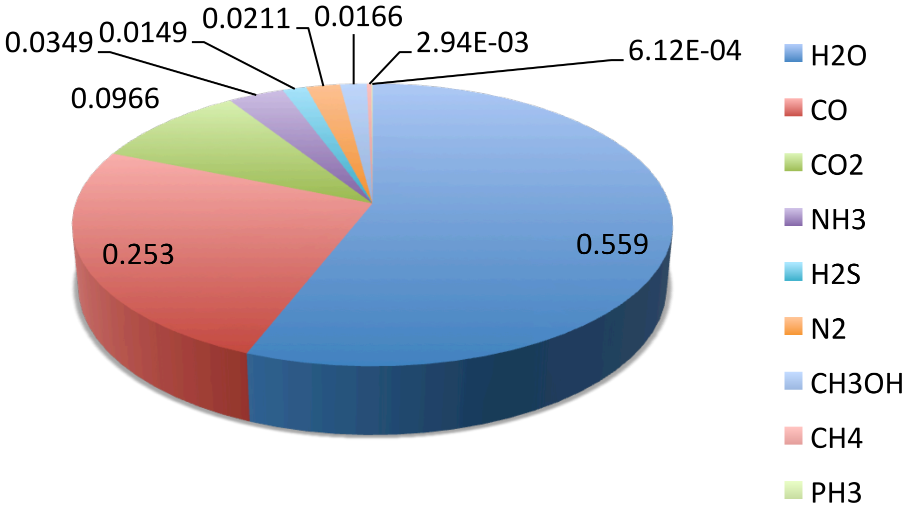
Constraints on Formation Conditions





Oberg et al. 2011

Mousis et al. 2009; Madhusudhan et al. 2011b



Other recent studies:

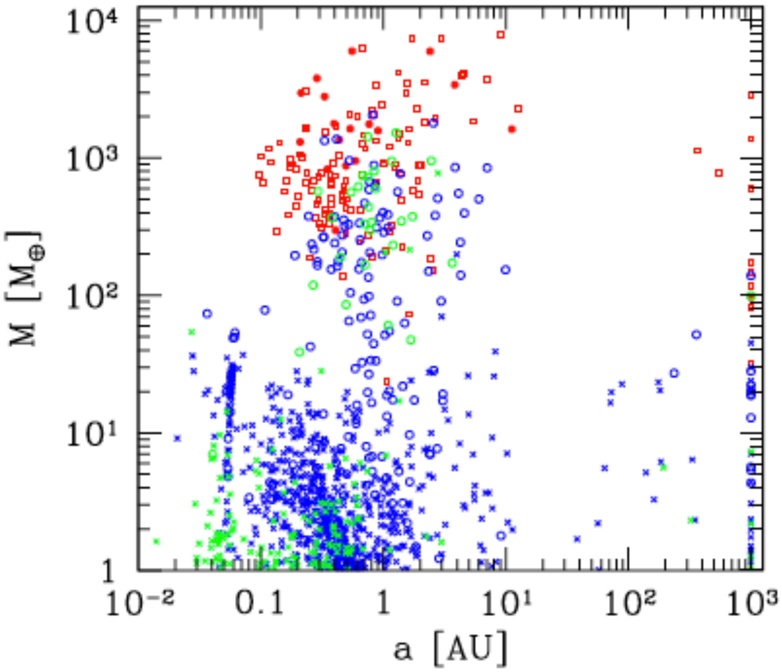
Moses et al. 2013

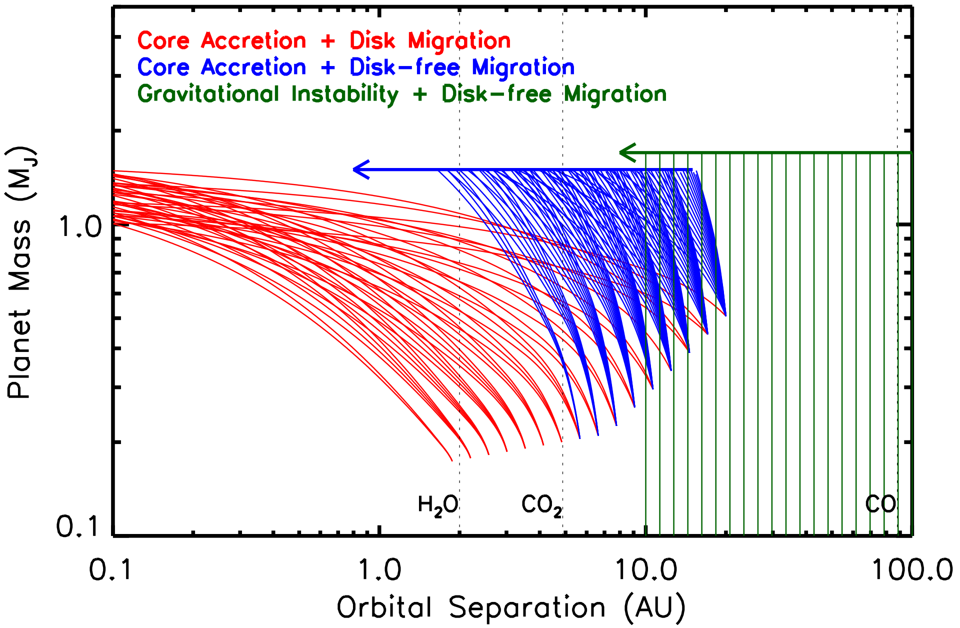
Ali-Dib et al. 2014

Marboeuf et al. 2014a,b

Madhusudhan et al. 2014b

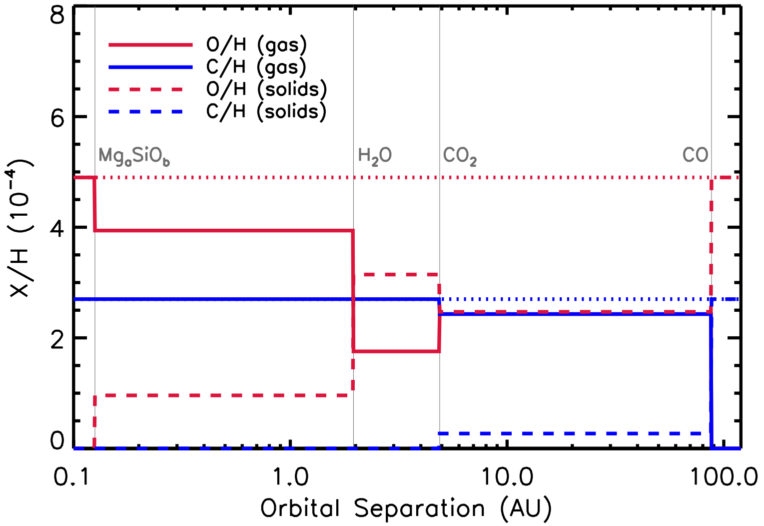
Chemical Constraints on hot Jupiter Migration



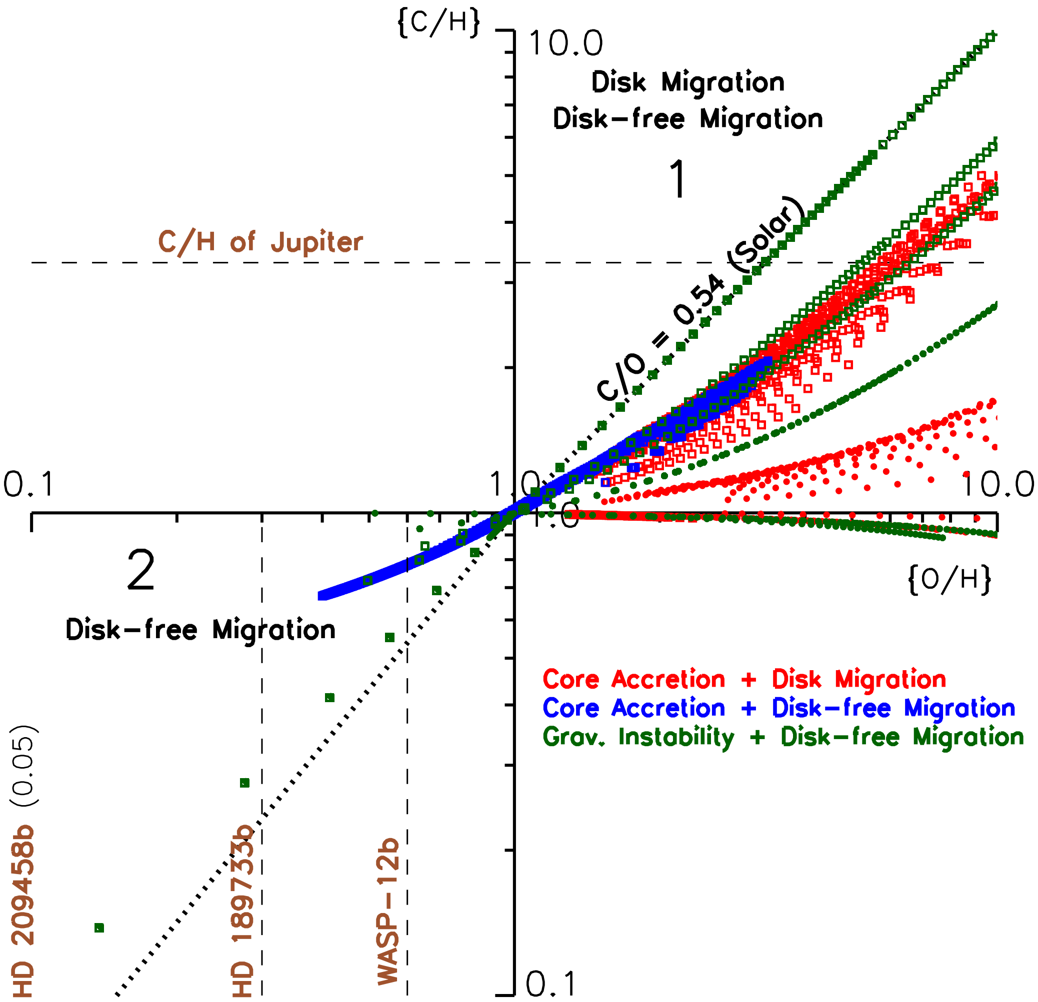


Benz et al. 2014

Madhusudhan et al. 2014b



Chemical Constraints on hot Jupiter Migration



Madhusudhan et al. 2014b

5. Habitable Exoplanets and Biosignatures

Exoplanetary Habitability

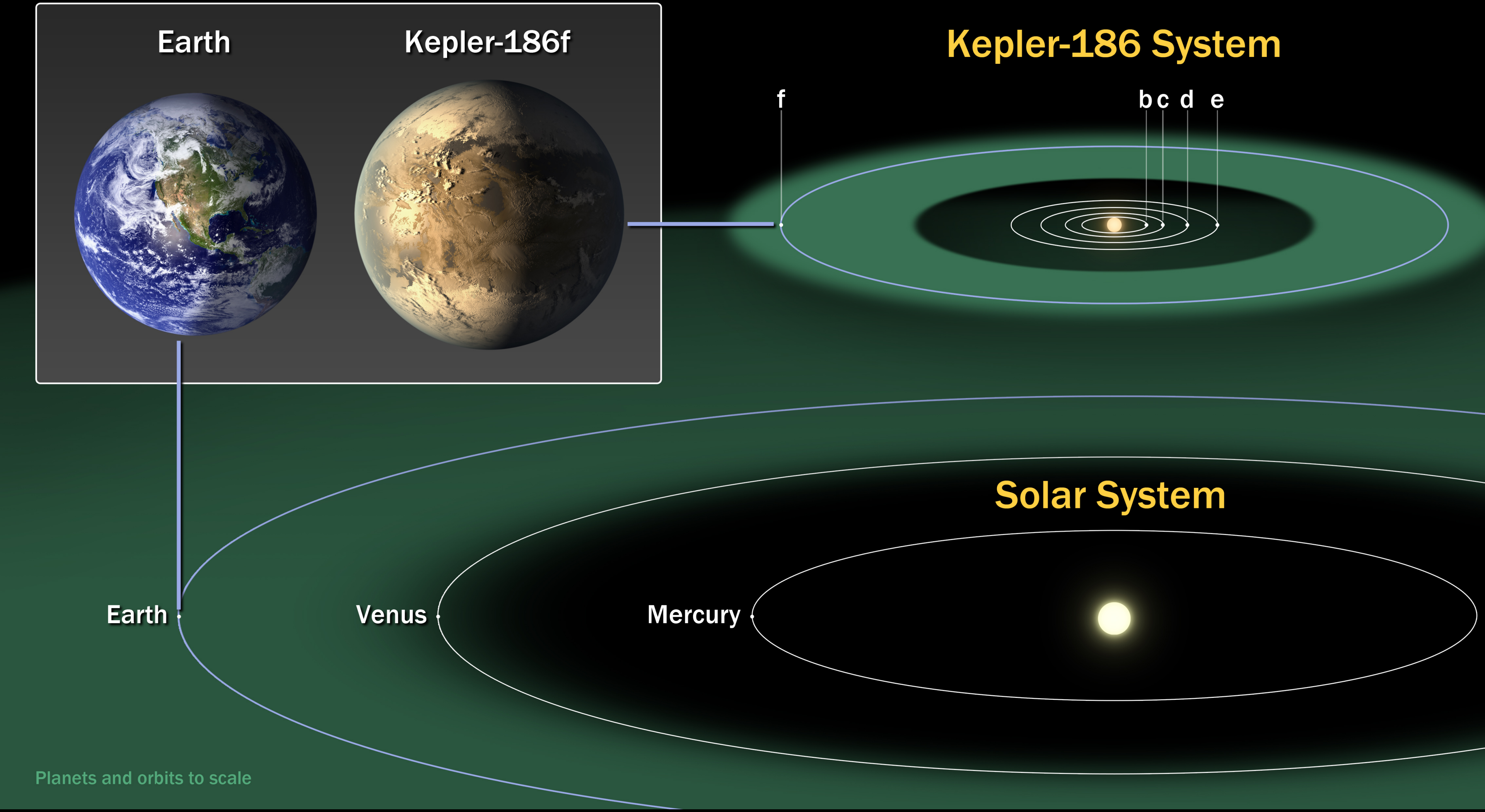
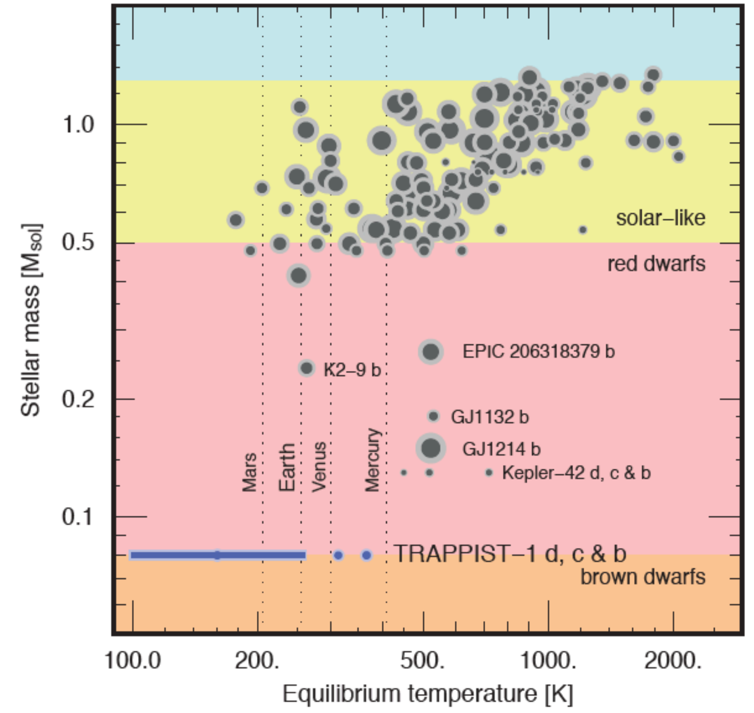


Image credits: NASA Kepler Team

Quintana et al. 2014

Trappist-1abc



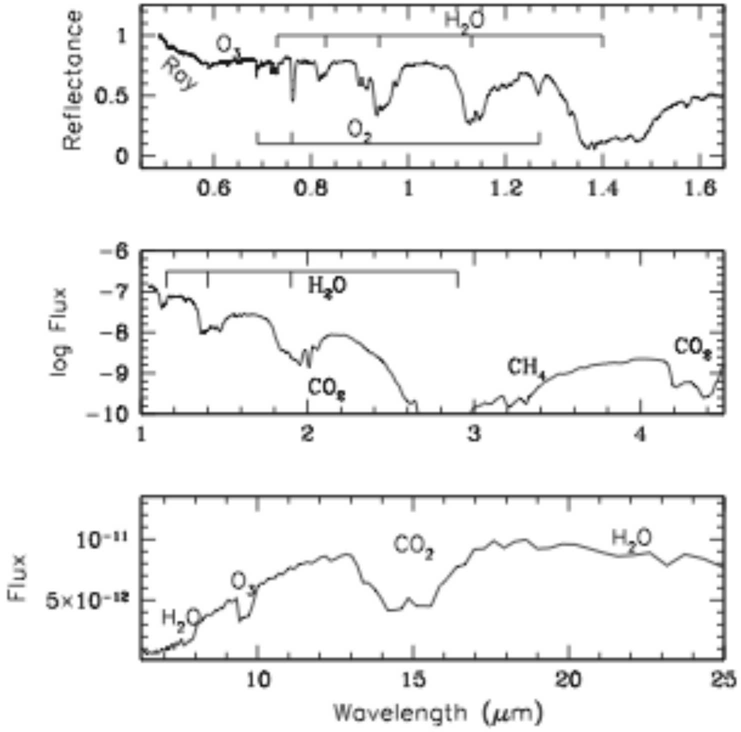
Gillon et al. 2016

What is a Biosignature?

Characteristics of a biosignature gas

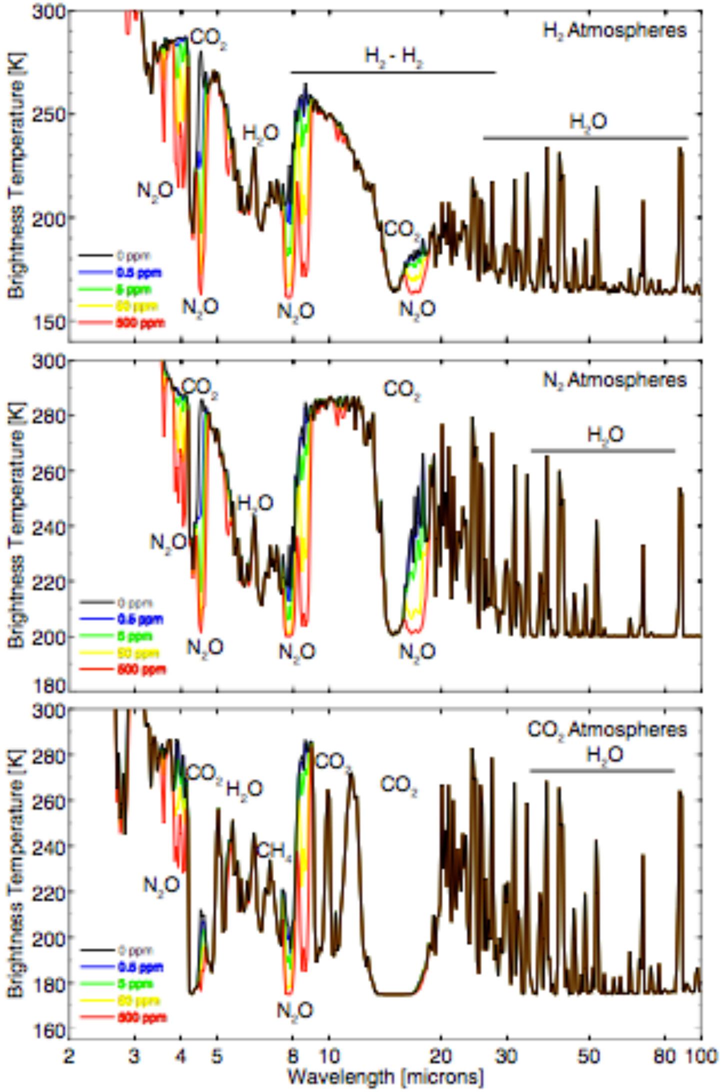
- Primary metabolic byproduct
- Abundant enough to be detectable
- Strong spectral signature
- No false positives

Telluric Biosignatures: N_2O, O_2 (O_3)



Turnbull et al. 2006; Robinson et al. 2011; Seager et al. 2012

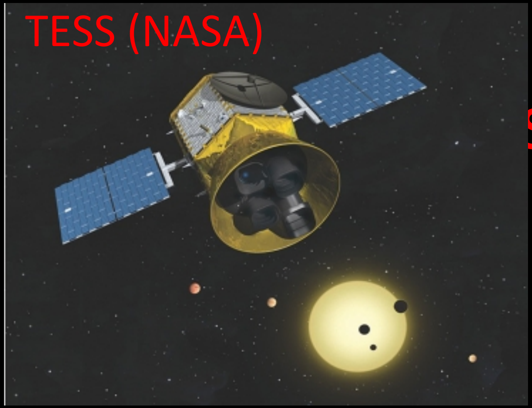
Model Spectra of Habitable Super-Earths



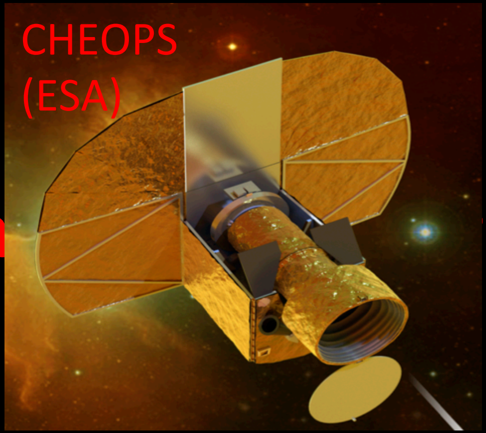
Seager et al. 2013

5. The Future of Exoplanet Science

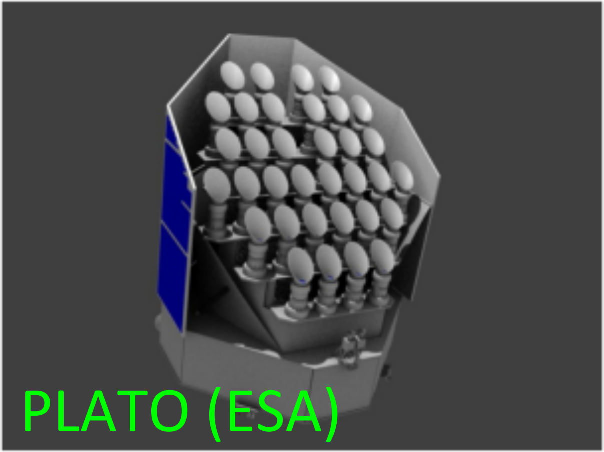
NGTS
NEXT-GENERATION TRANSIT SURVEY


TESS (NASA)

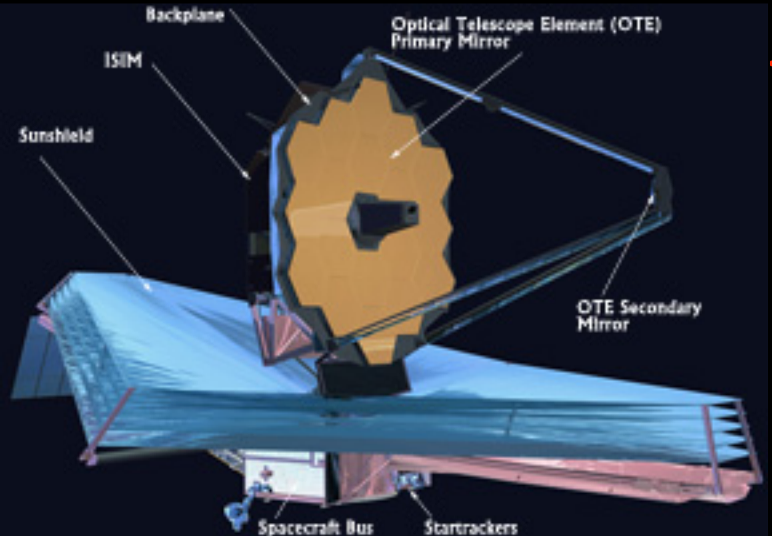
sn


CHEOPS (ESA)

biti

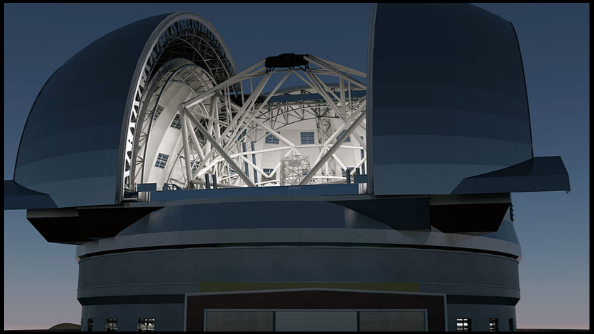

PLATO (ESA)

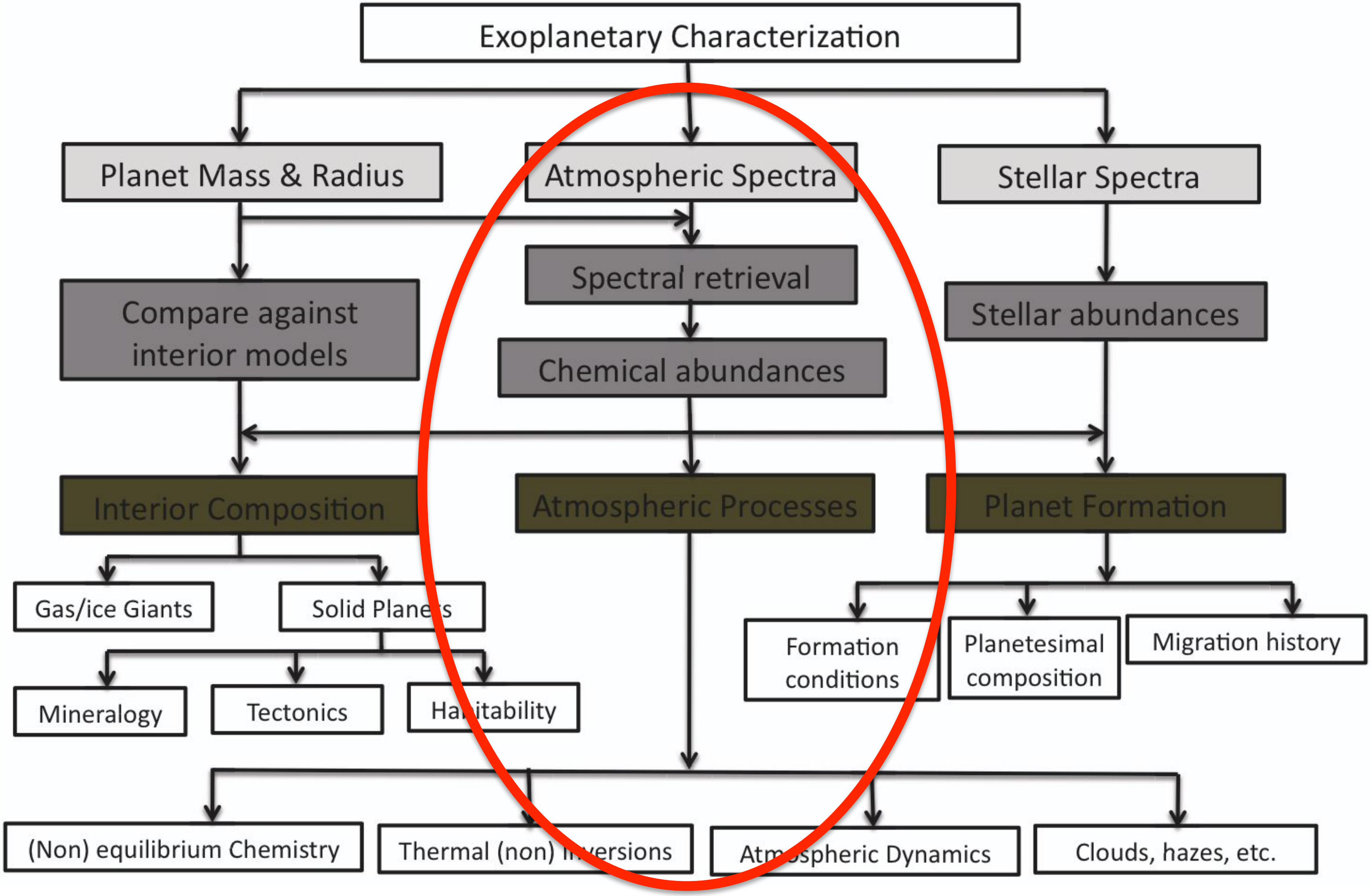
The James Webb Space Telescope



f atmospheres a

The future from ground
E-ELT, GMT, TMT





Exoplanetary Characterization

Planet Mass & Radius

Atmospheric Spectra

Stellar Spectra

Compare against interior models

Spectral retrieval

Chemical abundances

Stellar abundances

Interior Composition

Atmospheric Processes

Planet Formation

Gas/ice Giants

Solid Planets

Mineralogy

Tectonics

Habitability

Formation conditions

Planetesimal composition

Migration history

(Non) equilibrium Chemistry

Thermal (non) inversions

Atmospheric Dynamics

Clouds, hazes, etc.

Madhusudhan, Knutson, Fortney, and Barman, 2014,
`Exoplanetary Atmospheres' , Protostars and Planets VI