# Strict C/O Limits and Cloud Properties for 8 Hot Jupiters

from

Self-Consistent Atmospheric RetrievaL for ExoplaneTs (SCARLET)

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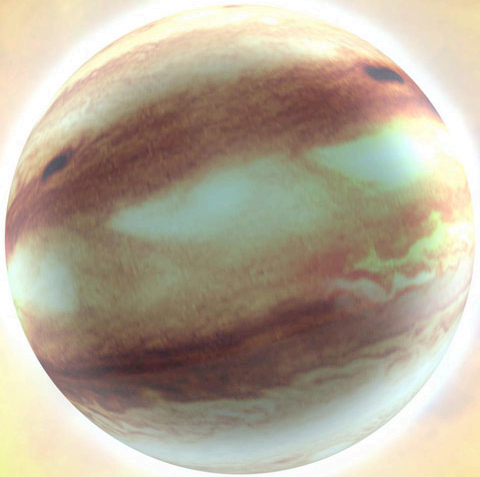
July 3rd, 2015

Benneke 2015, arXiv:1504.07655

# Fundamental Questions about Hot Jupiter Formation

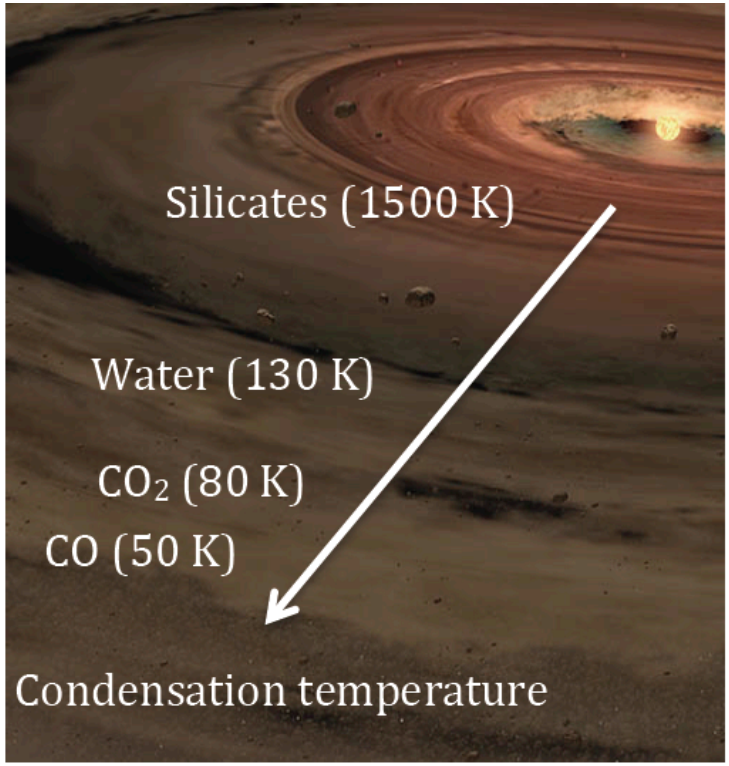
What is the origin of hot Jupiters? Where did they accrete their gas envelopes?

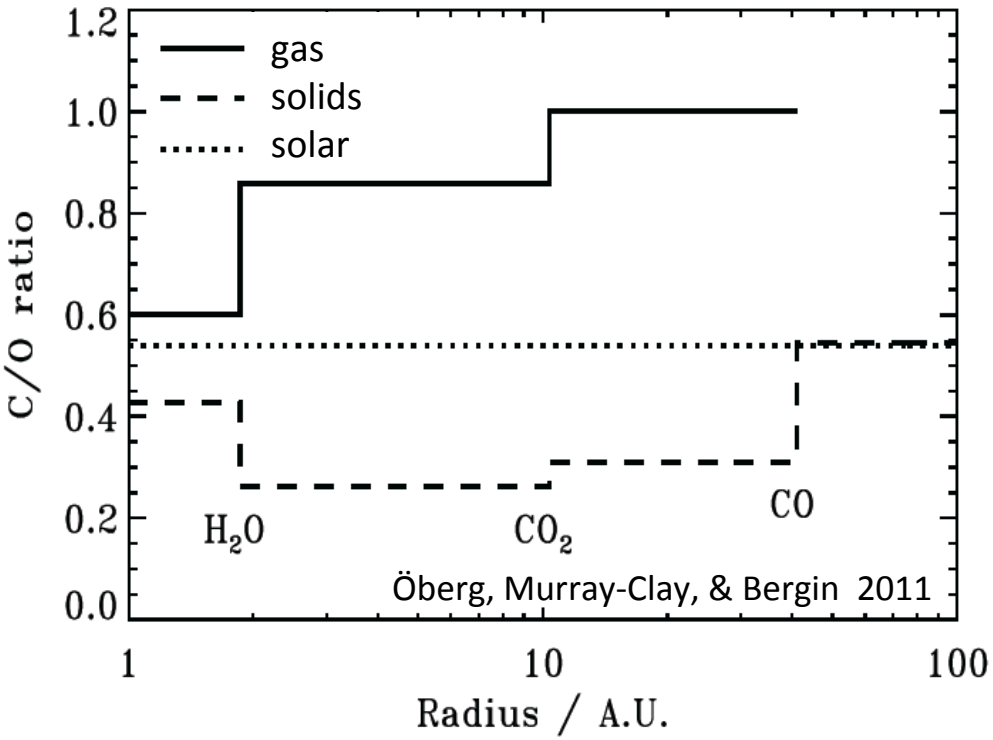
Do hot Jupiters and directly imaged giant planets have a common origin?



Do giant planets form through core accretion or disk instability? Or both?

# Metallicity and C/O as Tracers of Planet Formation and Migration

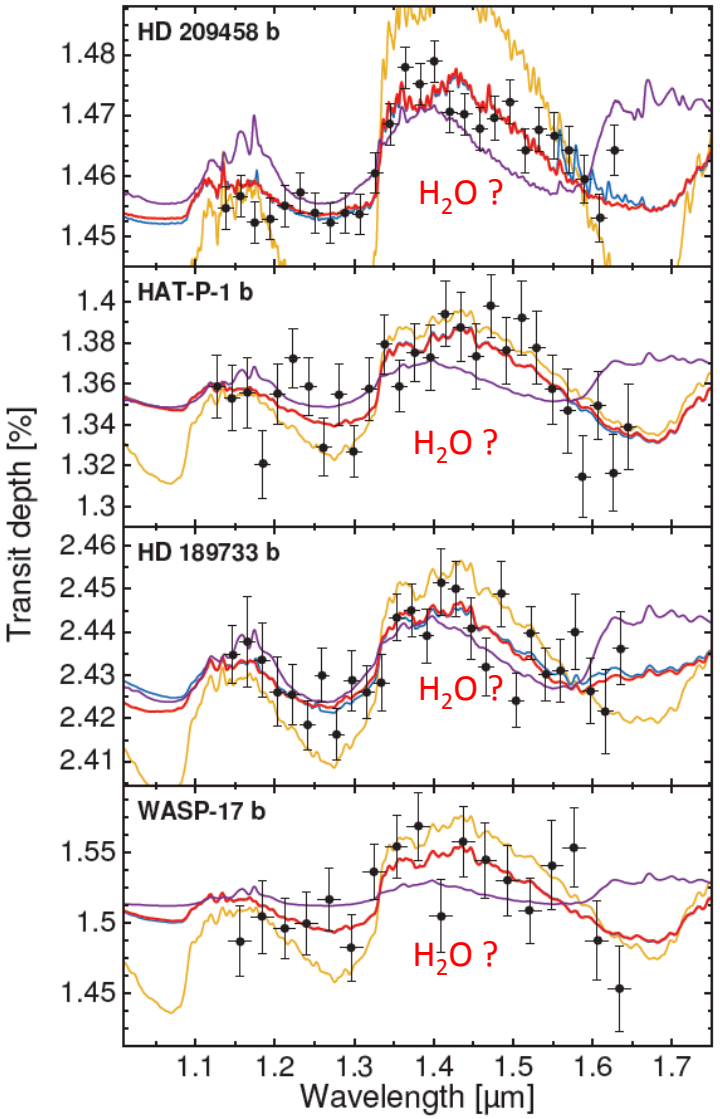


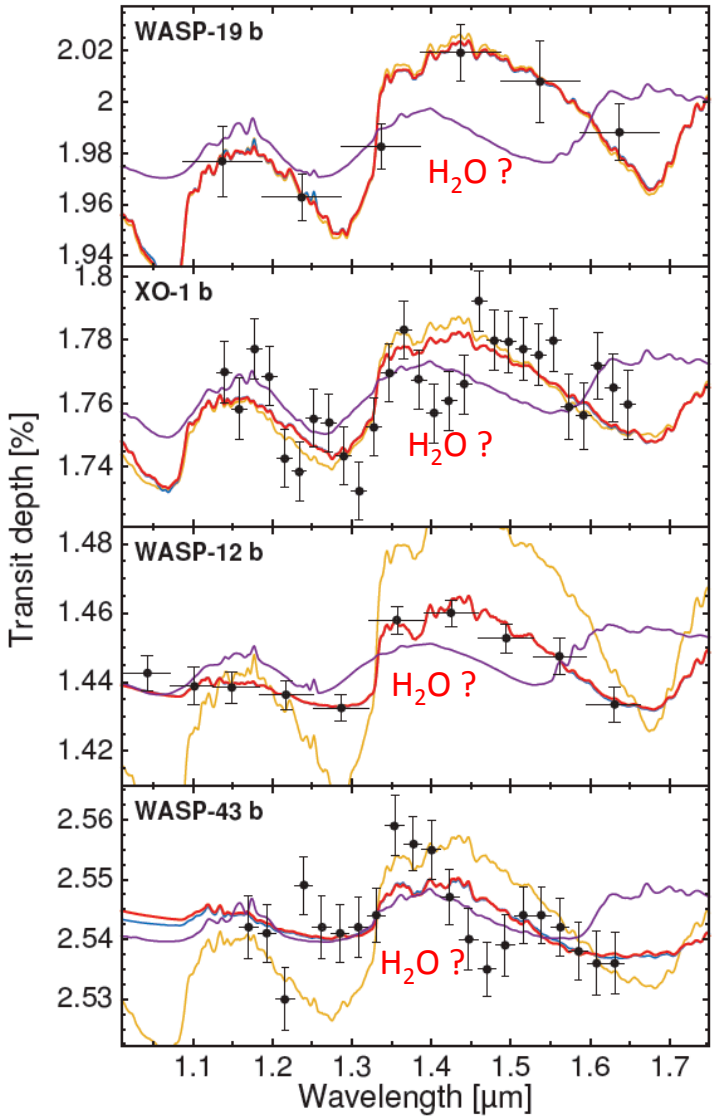




C/O ratios of gas and solids in protoplanetary disks varies with radius and time

Helling et al. 2014; Ali-Dib et al. 2014, van Boekel et al. (in prep); see summary in Benneke 2015

# *HST WFC3* Transit Surveys Show Strong Evidence of Molecular Absorption

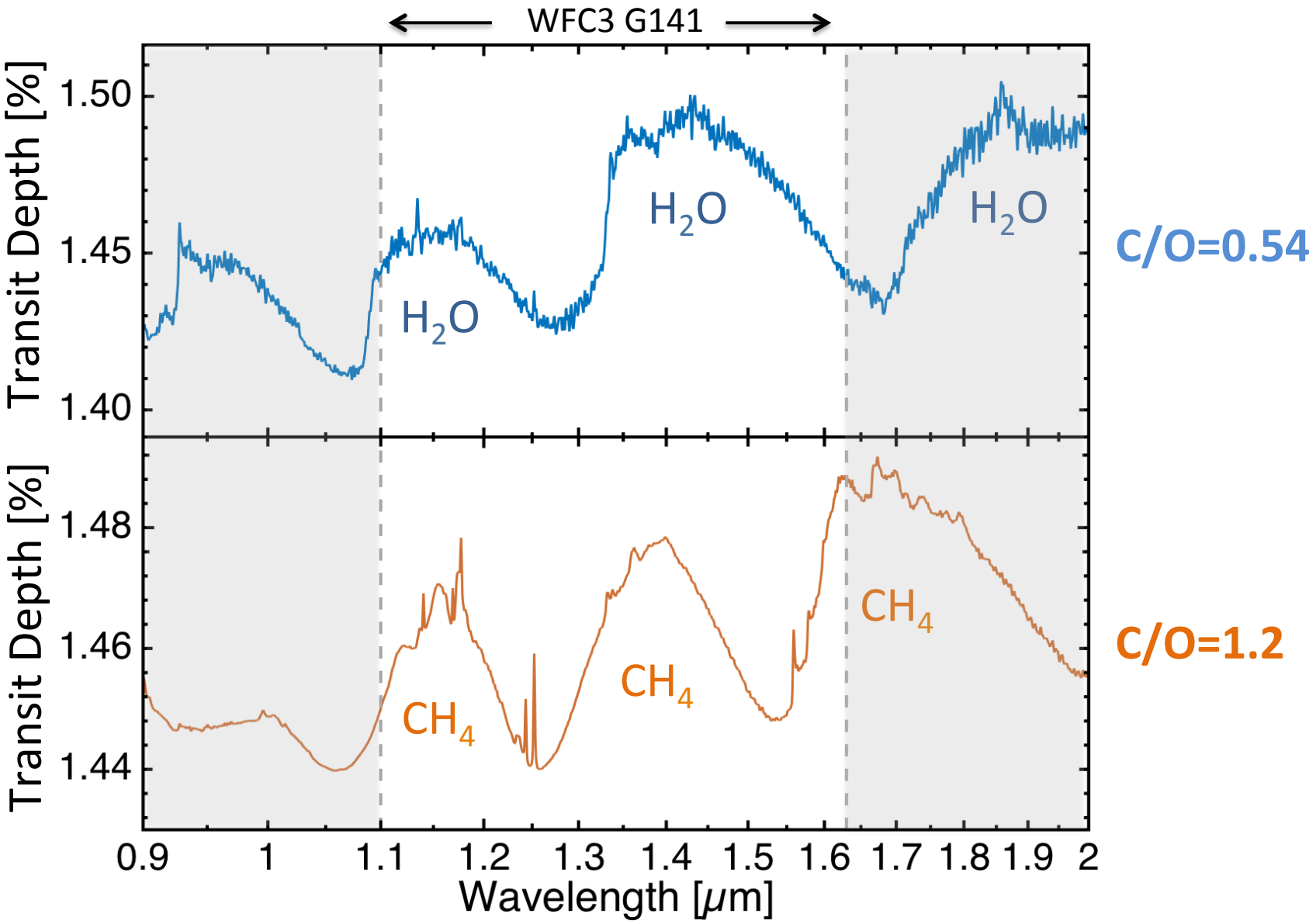



Deming+ 2013
Sing+ 2014
Huitson+ 2013
Wakeford+ 2013
McCullough+ 2014
Kreidberg+ 2015
Mandell+ 2013
Kreidberg+ 2014b

Figure from Benneke 2015

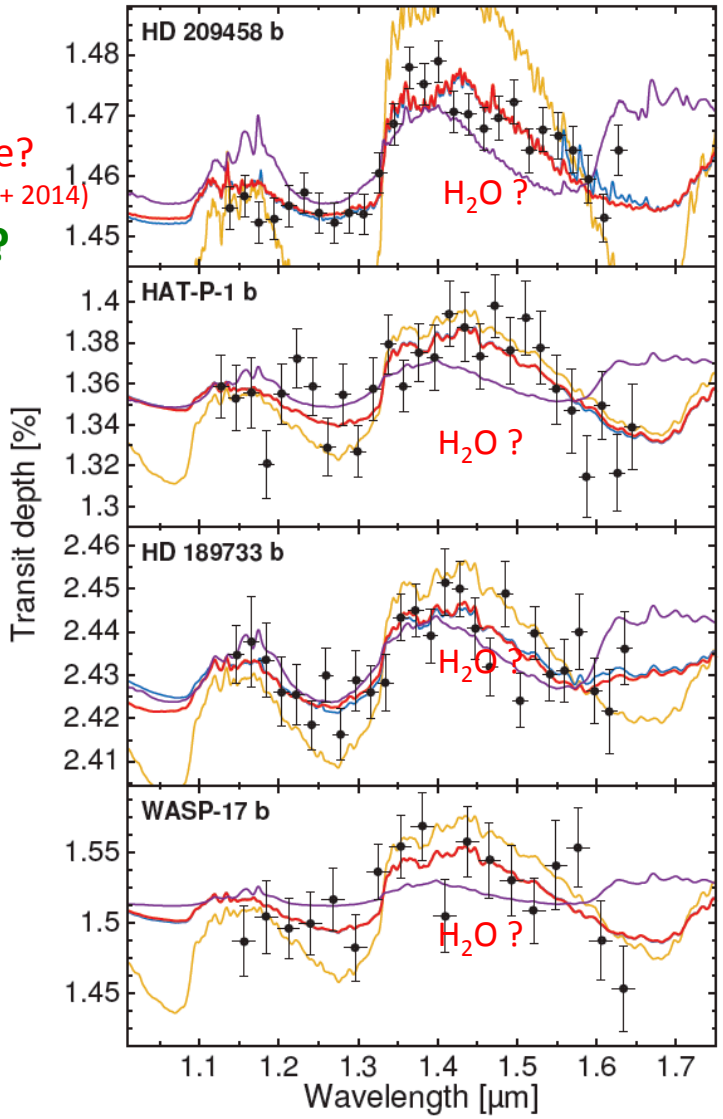
# Overlapping Water and Methane Bands in WFC3 Bandpass

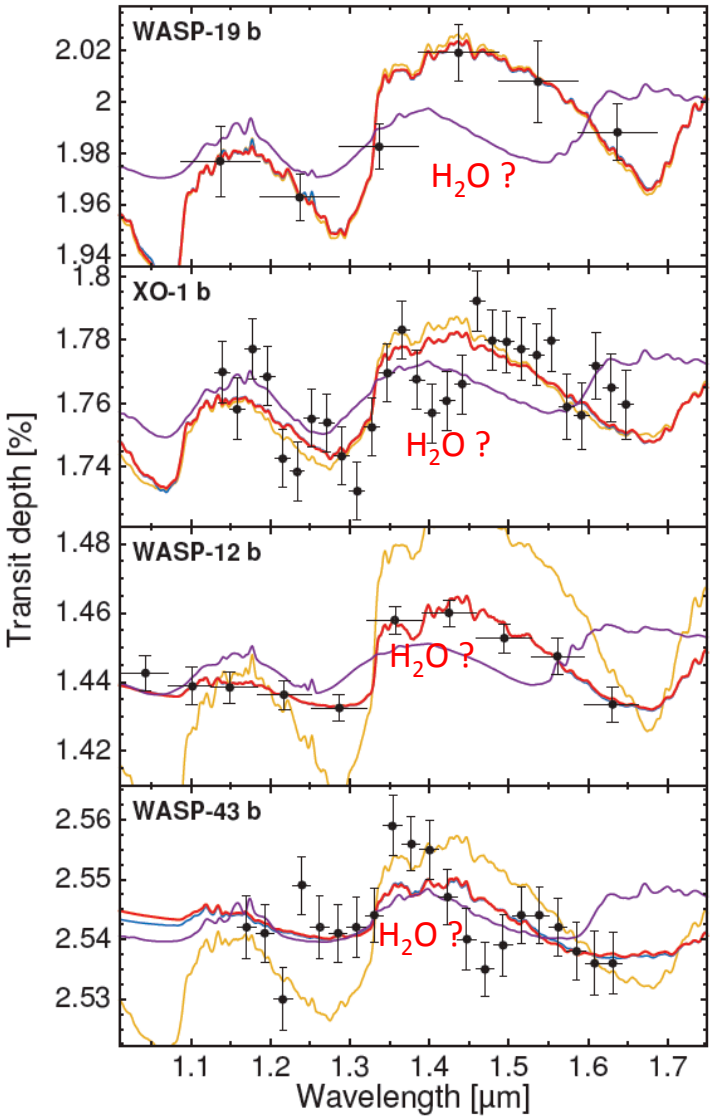


# WFC3 Transit Surveys Show Strong Evidence of Molecular Absorption

Low $H_2O$ Abundance?
(Madhusudhan+ 2014)

**Clouds?**




Deming+ 2013
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Kreidberg+ 2015
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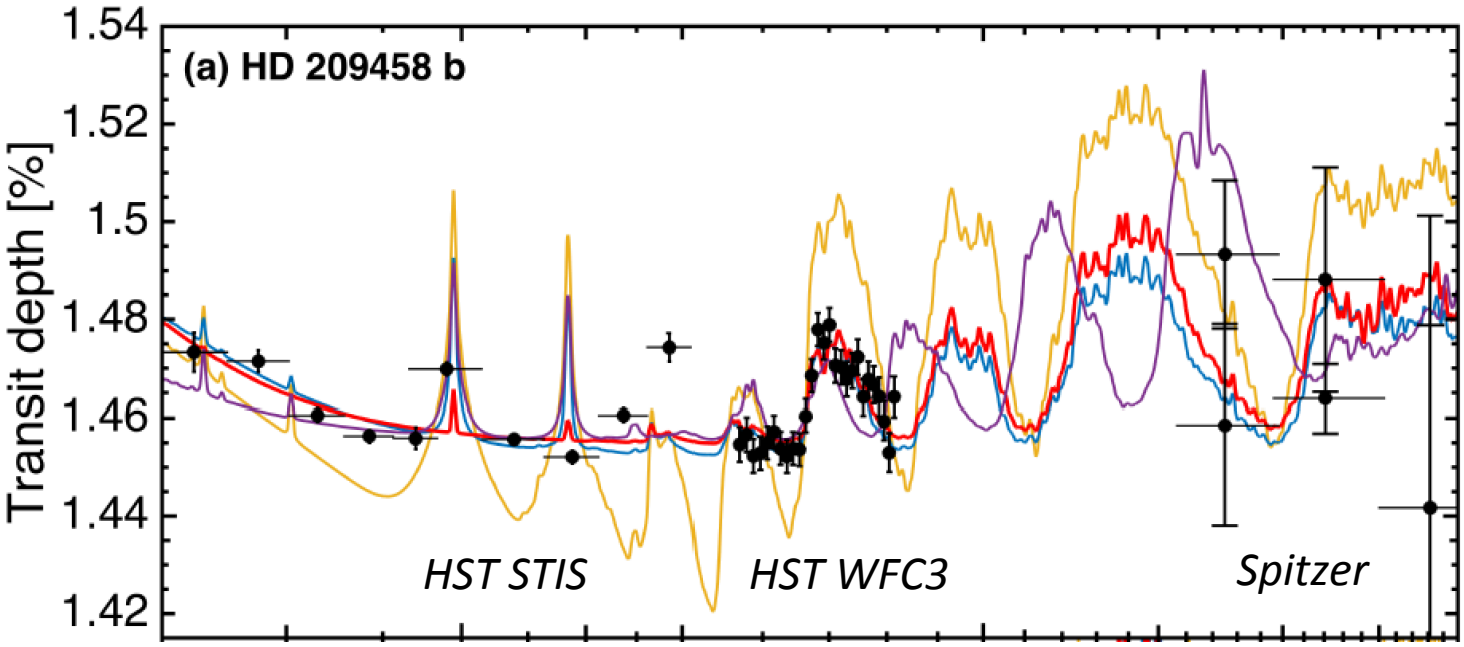
Figure from Benneke 2015

No constraints on C/O published because no carbon-bearing molecule detected

# What can we say about hot Jupiters given all information at hand?




- Philosophical divide between self-consistent forward models and atmospheric retrieval methods

## Self-Consistent Forward Models

(e.g. Fortney et al.,; Burrows et al.; Phoenix Model)

- Use prior knowledge of chemistry
- Inherently self-consistent
- **Gain physical insight!**
- Assumes all processes known without uncertainty
- Manual model "tweaking": **No robust treatment of uncertainties and degeneracies**

## Atmospheric Retrieval

(e.g. Benneke & Seager, Line et al., Madhusudhan et al.)

- Robust treatment of observational uncertainties

SCARLET (Benneke 2015)

- Ignore prior knowledge of chemistry
- Oversimplified description of atmosphere
- Provide little/no physical understanding

# Basic Concept of SCARLET

Parameterize elemental composition and atmospheric processes

**Atmospheric Retrieval**

- Molecular abundances ($CH_4$, $H_2O$, $H_2$, …)
- T-p profile

**SCARLET**

"Formation History" Parameters:

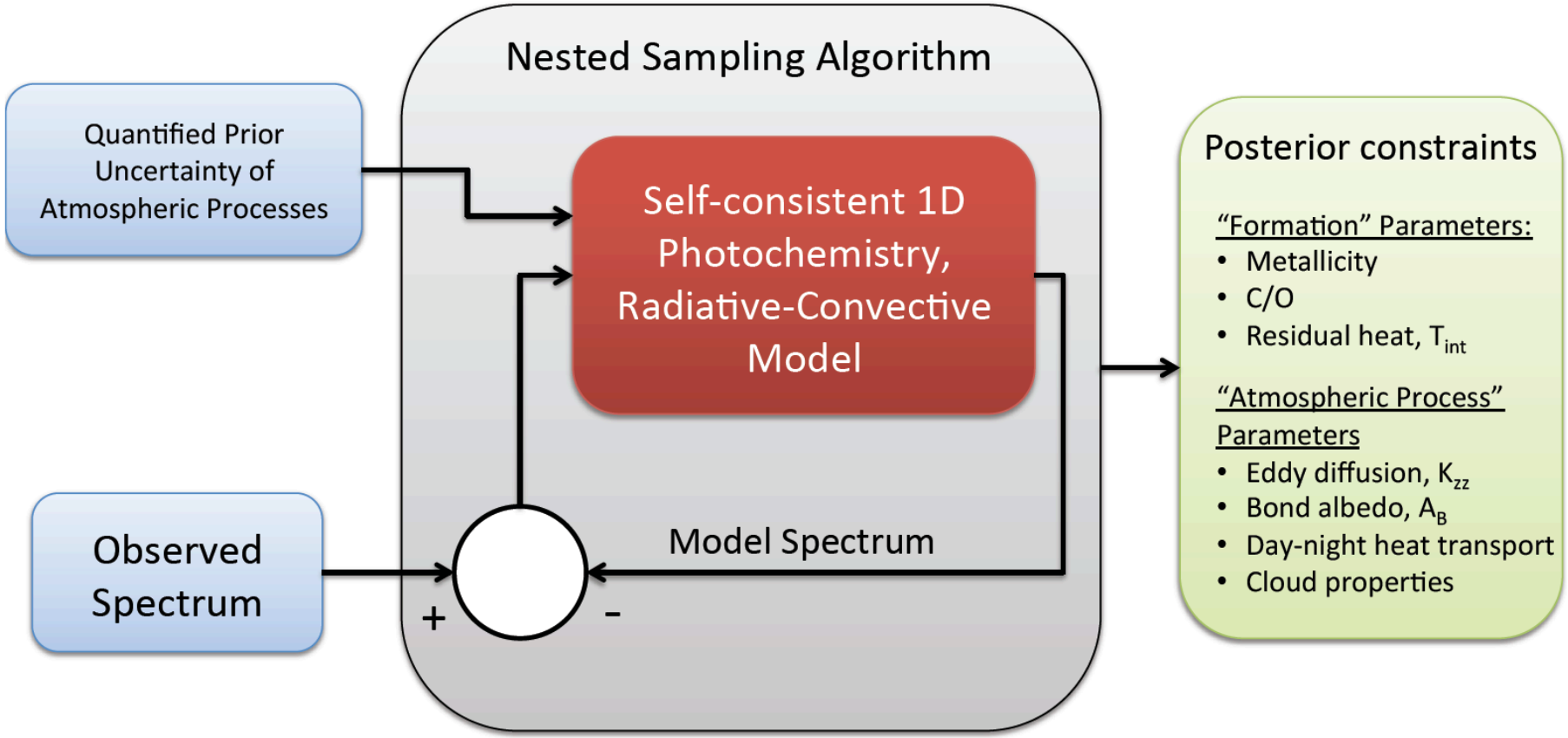
- Metallicity + C/O
- Residual accretion heat, $T_{int}$

"Atmospheric Process" Parameters

- Vertical mixing, $K_{zz}$
- Day-night heat transport
- Cloud formation
- Bond albedo, $A_B$

Gain direct insight into elemental composition and atmospheric processes!

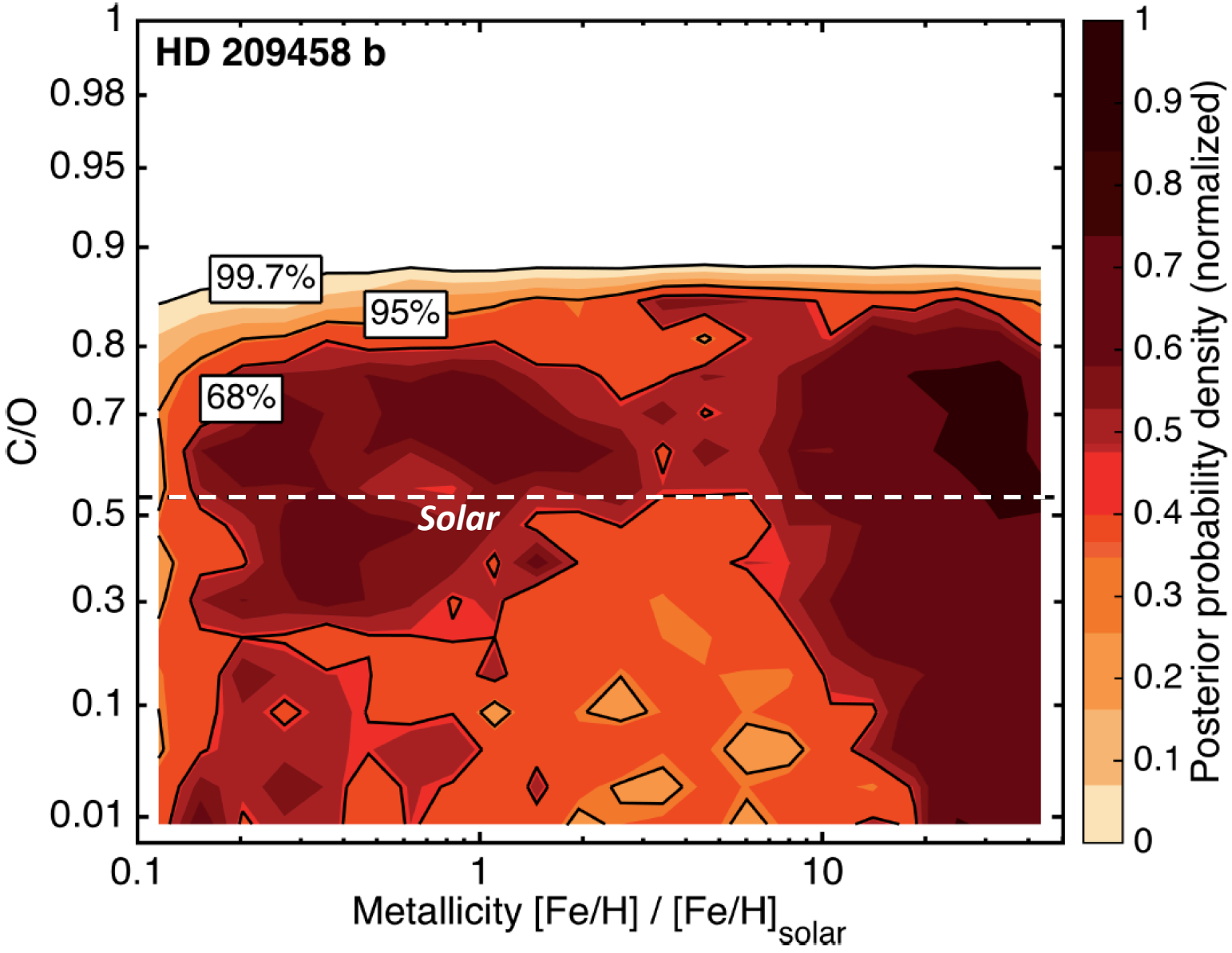
# SCARLET Framework



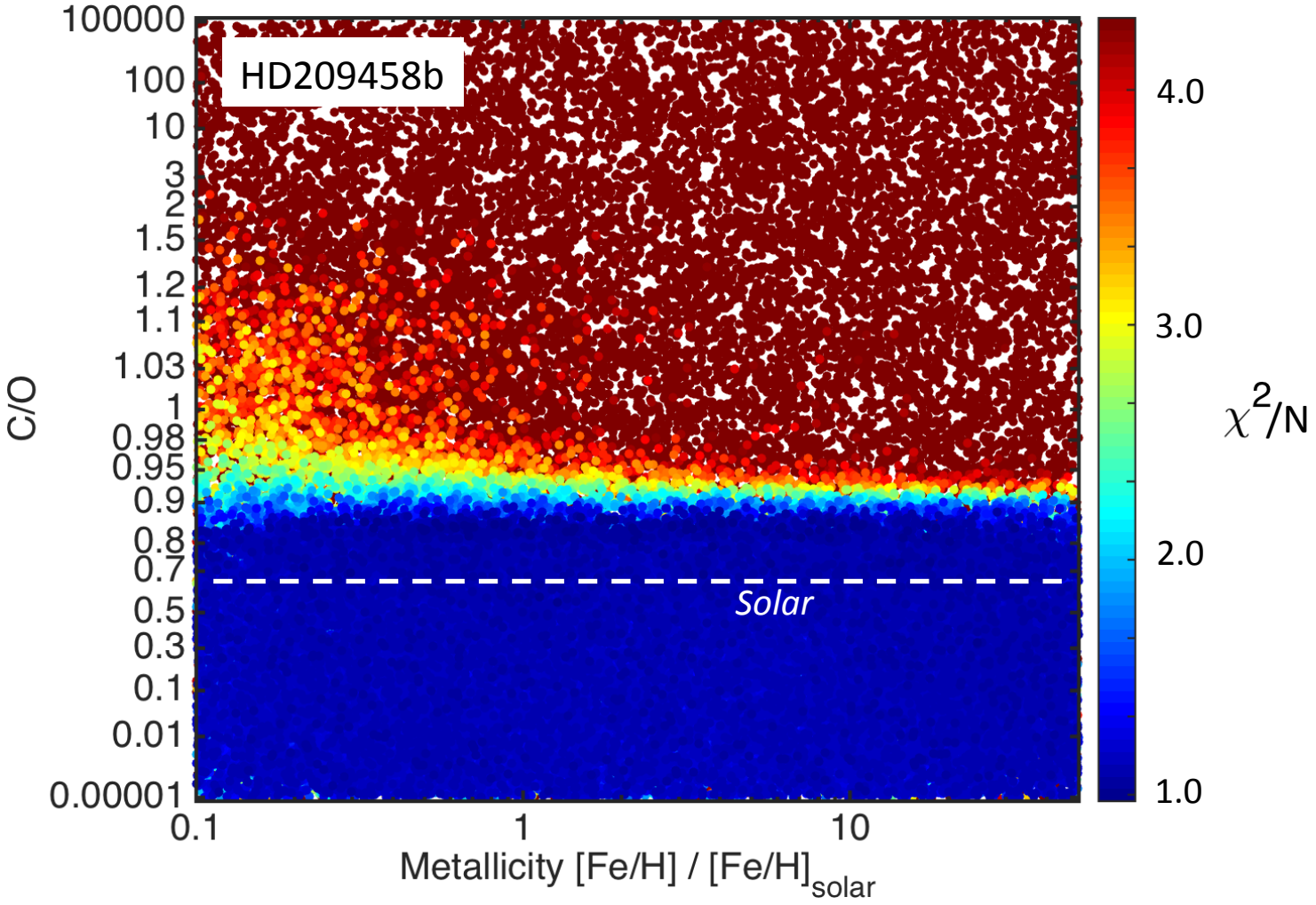

All atmospheric models are <u>self-consistent within our prior knowledge</u>

Challenge: Identify all poorly understood atmospheric processes and describe their uncertainty by assigning prior probabilities

# C/O < 0.9 for all 8 Hot Jupiters

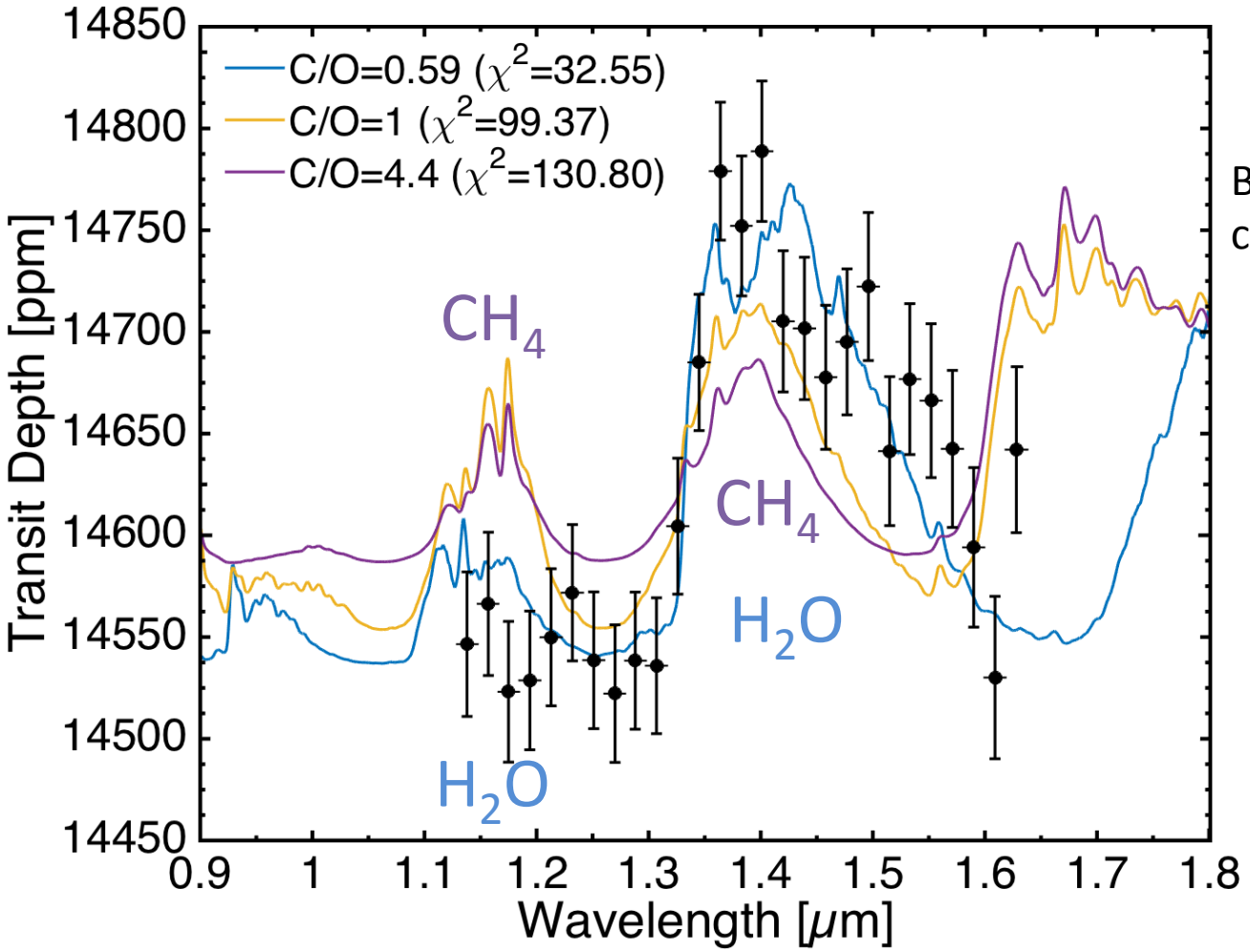


# C/O < 0.9 is a extremely robust finding




- Nested sampling explores every corner of the parameters space
- Fit to data deteriorates sharply at C/O ≥ 0.9

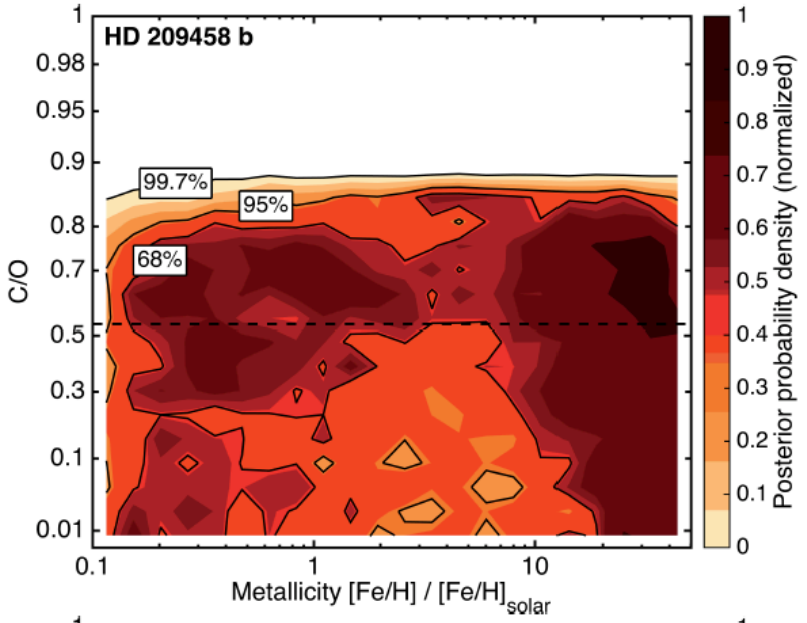
# C/O Constraints Rely Only on *HST WFC3* Transmission Spectroscopy

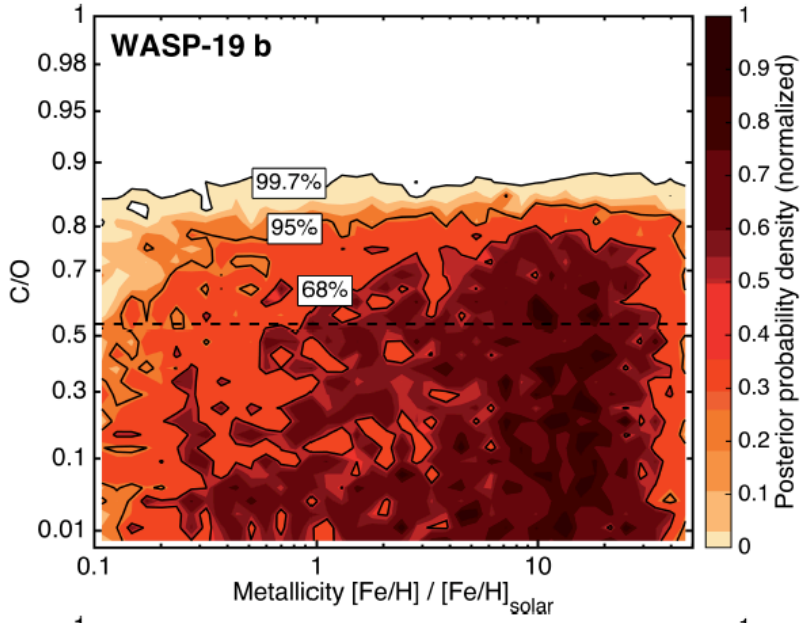



Best-fitting cloud scenarios

Methane bands at 1.15µm and 1.4µm would appear equally strong even in the presence of clouds

# C/O < 0.9 for Eight Hot Jupiters

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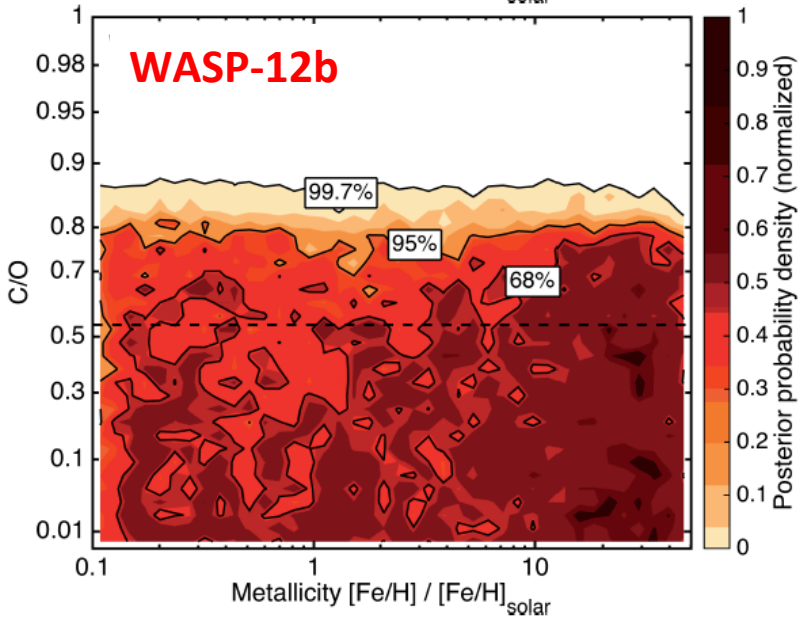
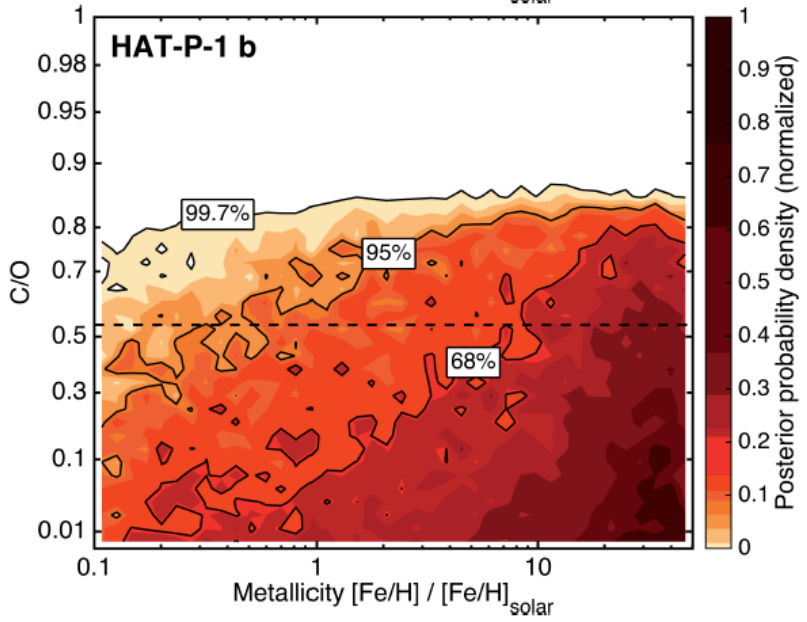
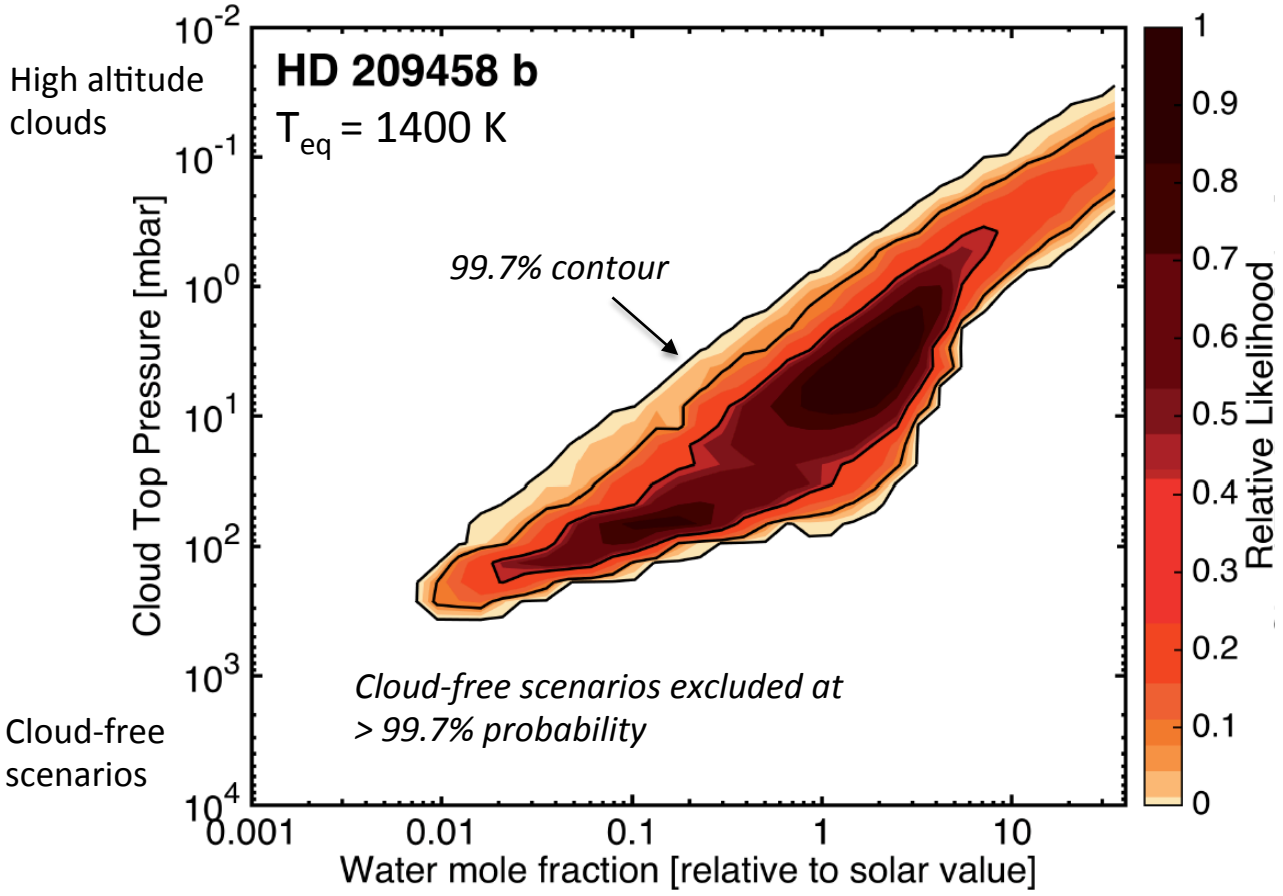
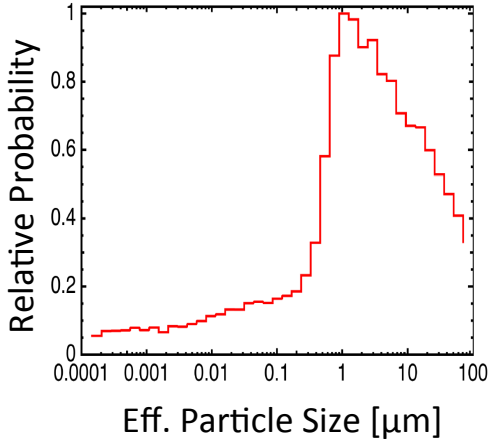


# Thick Clouds Over Wide Range of Equilibrium Temperatures

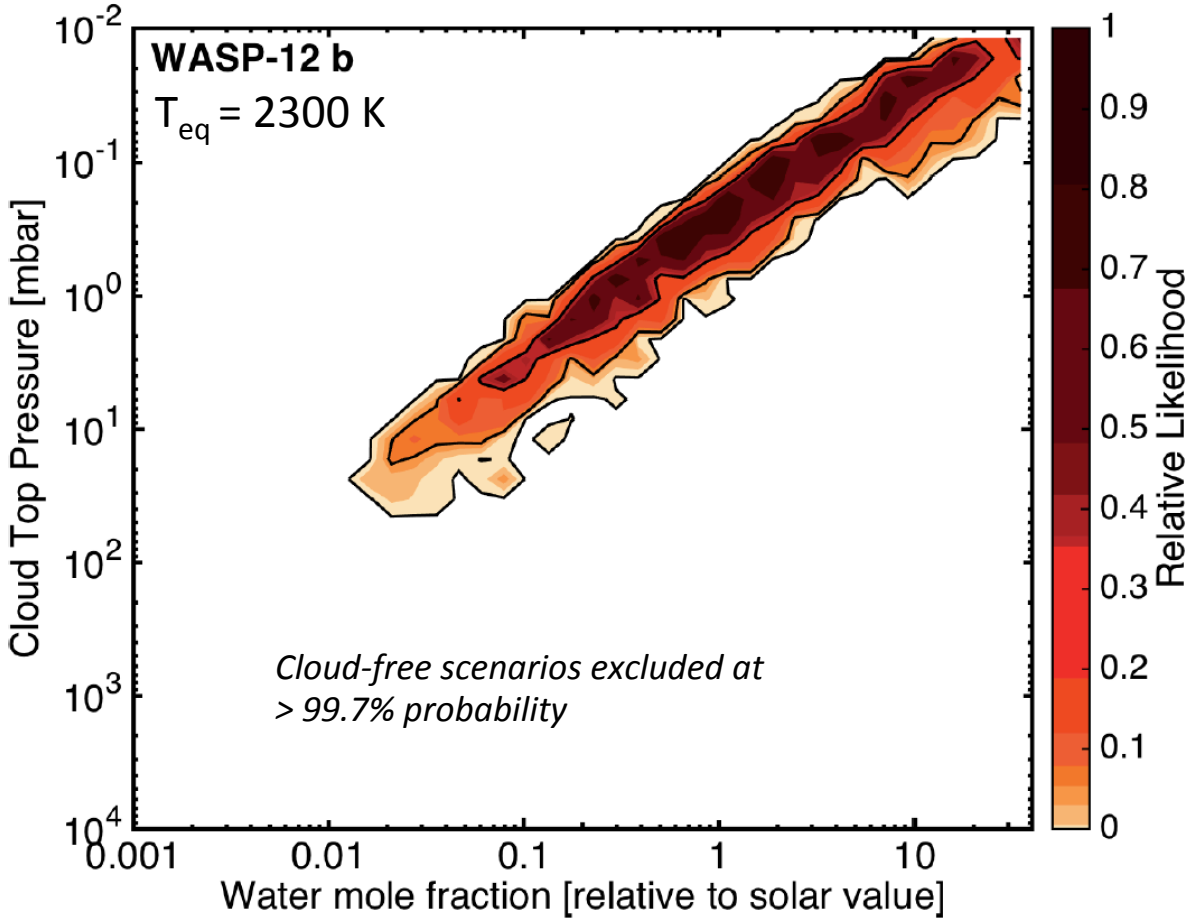



Water abundances consistent with solar composition

- Cannot confirm the sub-solar water abundance suggested

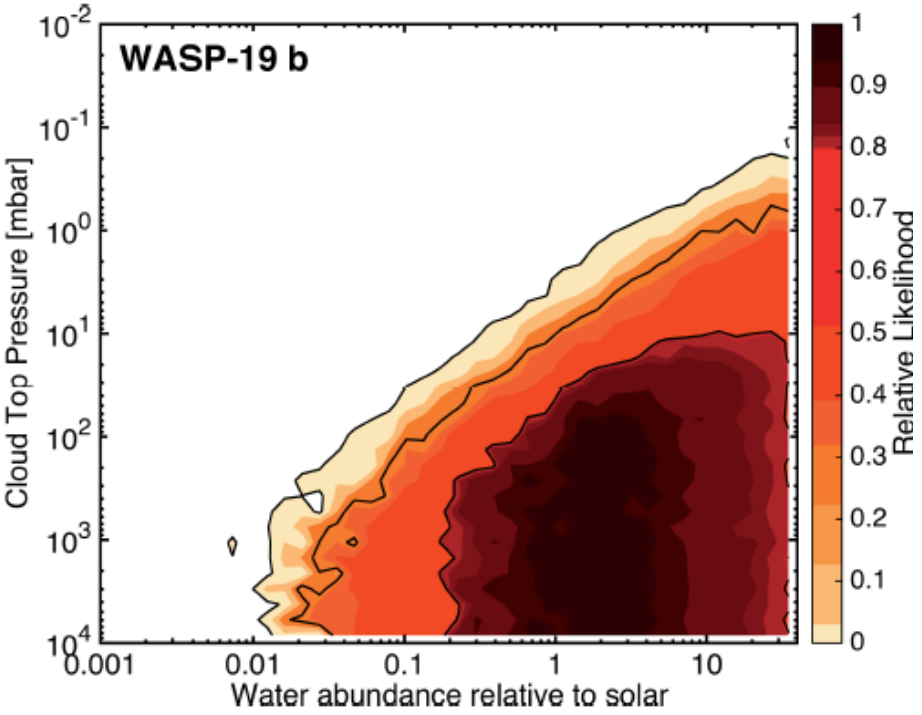
# Thick Clouds Over Wide Range of Equilibrium Temperatures

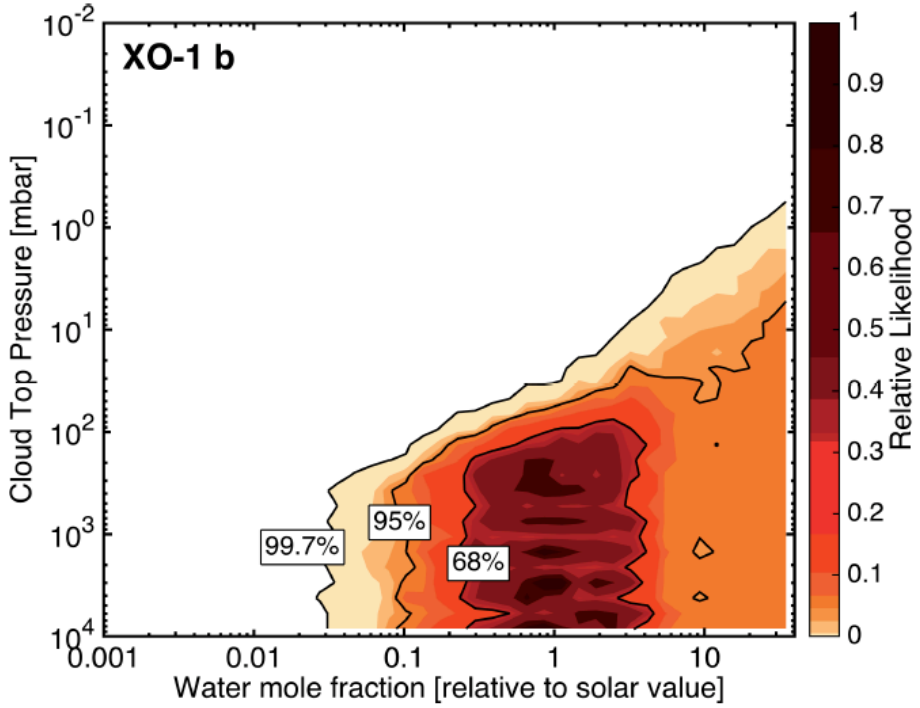



Water abundances consistent with solar composition

- Cannot confirm the sub-solar water abundance suggested

# No Direct Evidence for Clouds on WASP-19b and XO-1b




Water abundances consistent with solar composition

- Cannot confirm the sub-solar water abundance suggested

# Conclusions

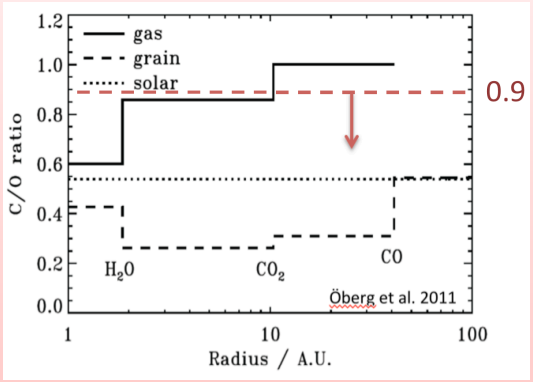
Novel interpretation framework:

- SCARLET is combines statistical robustness of atmospheric retrieval with the self-consistency and physical insight of complex forward models
- Provides direct insights into elemental composition and atmospheric processes

Hot Jupiters:

1) C/O < 0.9 for all 8 hot Jupiters

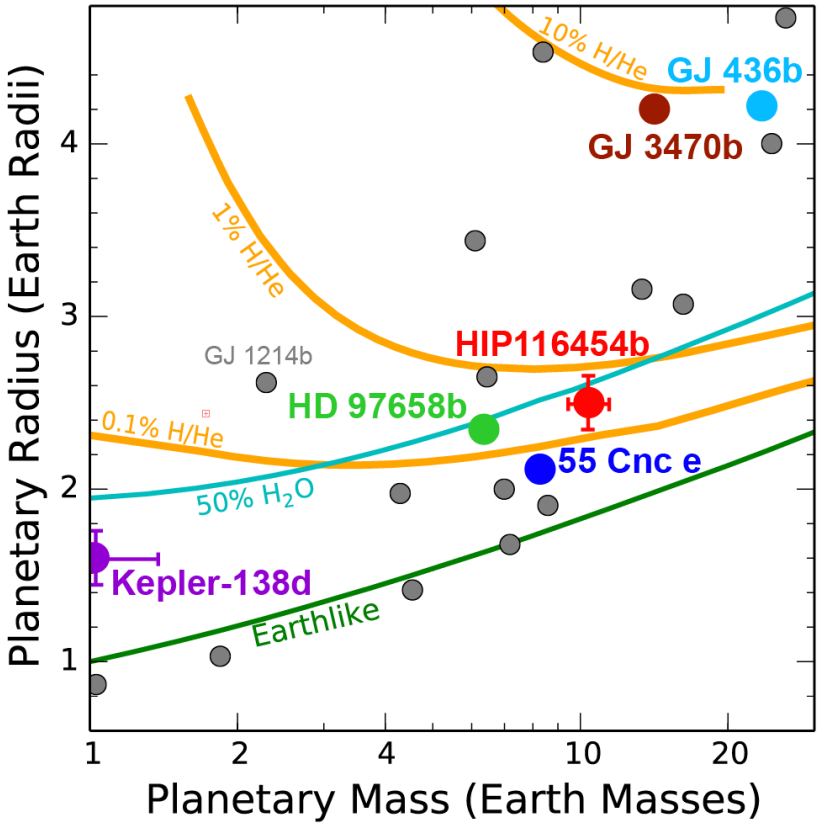
   → Hot Jupiters form inside of $CO_2$ snow line (10 AU)
   or
   Gas envelope strongly polluted by ices/planetesimals

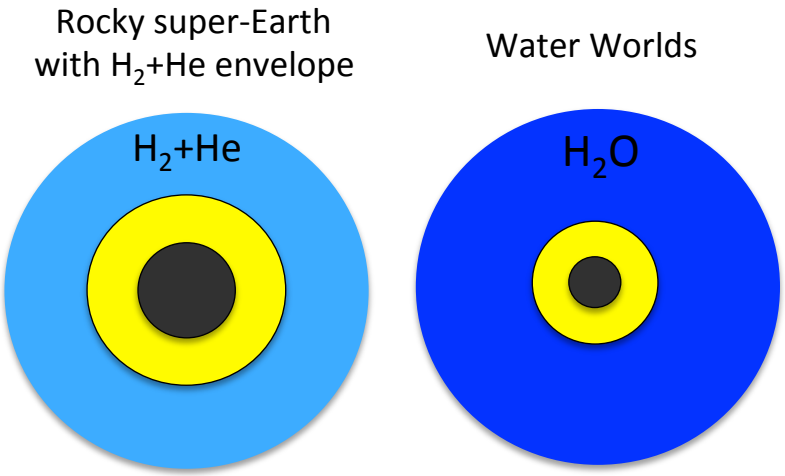



2) Water abundances consistent with solar composition for all 8 hot Jupiters

3) Thick clouds common over wide range of equilibrium temperatures (1400-2500K)

# A Large Super-Earth Survey in 2015/16 (124-orbits on *HST*)




Benneke, Crossfield, Knutson, Dragomir, Fortney, Howard, McCullough, Gilliland, Kempton, Morley

- 6 planets in the intriguing mass regime between 1 $M_{Earth}$ and 1 $M_{Neptune}$
- Uniform sample of spectra with visible and NIR coverage (0.55-1.8μm)