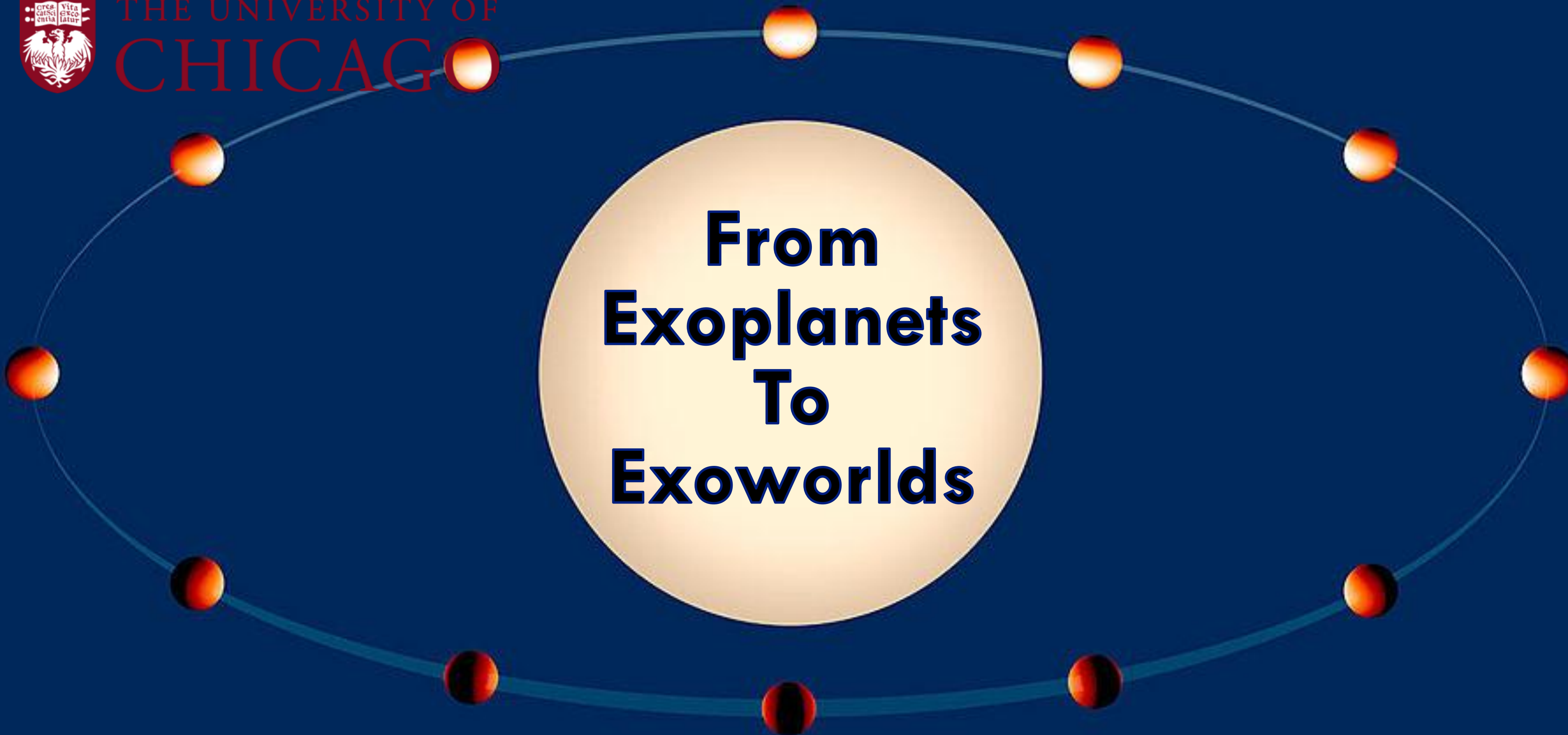
THE UNIVERSITY OF CHICAGO



From Exoplanets To Exoworlds

Kevin Stevenson

May 8th, 2015

Sagan/Michelson Fellows Symposium

Collaborators

- Jacob Bean (UChicago)
- Laura Kreidberg (UChicago)
- Jean-Michel Désert (UC-Boulder)
- Jonathan Fortney (UCSC)
- Michael Line (UCSC)
- Caroline Morley (UCSC)
- Nikku Madhusudhan (Cambridge)
- Adam Showman (LPL)
- Tiffany Kataria (Exeter)

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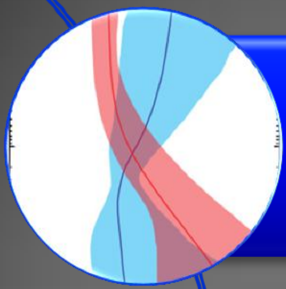
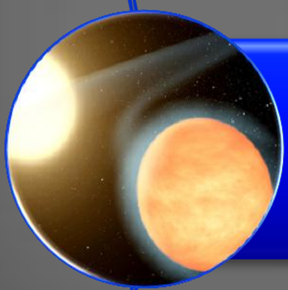
- HST
  - Part of this work was based on observations made with the NASA/ESA Hubble Space Telescope that were obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.
- Spitzer
  - Part of this work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA.

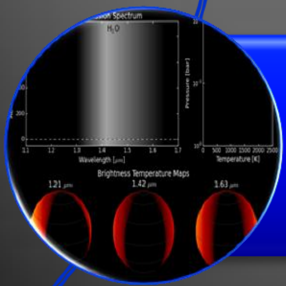
Current Questions in Exoplanet Characterization



Atmospheric thermal structure

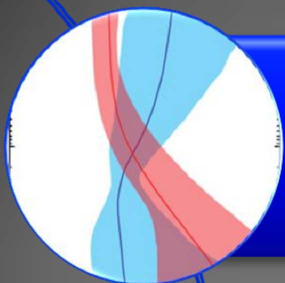


Atmospheric chemistry

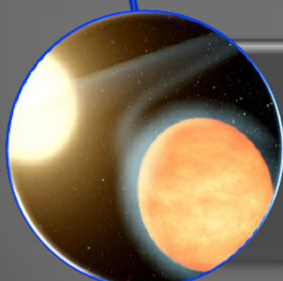


Atmospheric dynamics

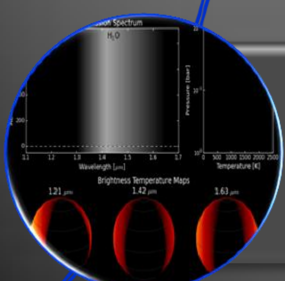
Current Questions in Exoplanet Characterization



Have we definitively detected a thermal inversion in the atmosphere of a hot-Jupiter?

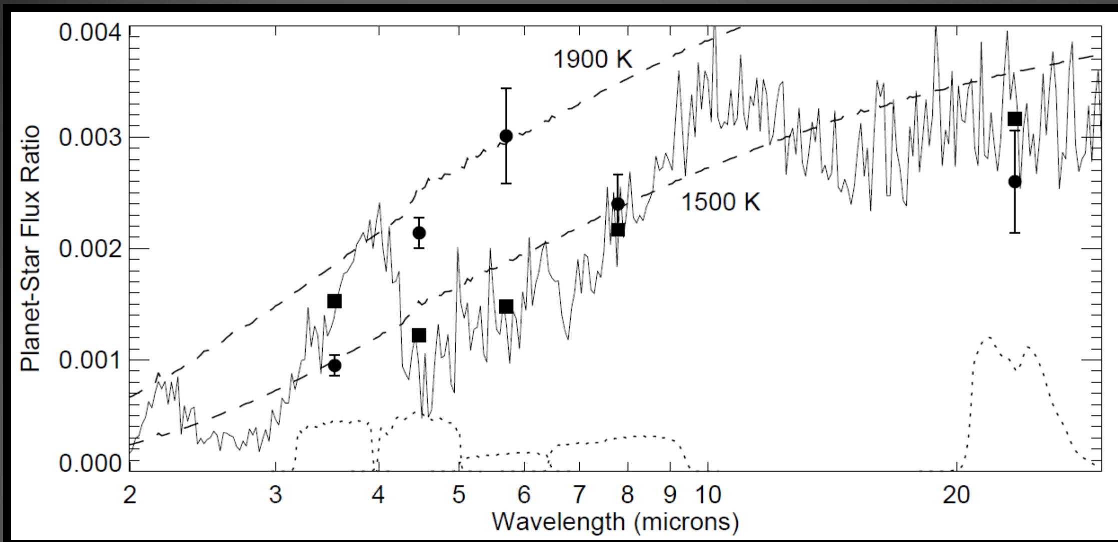


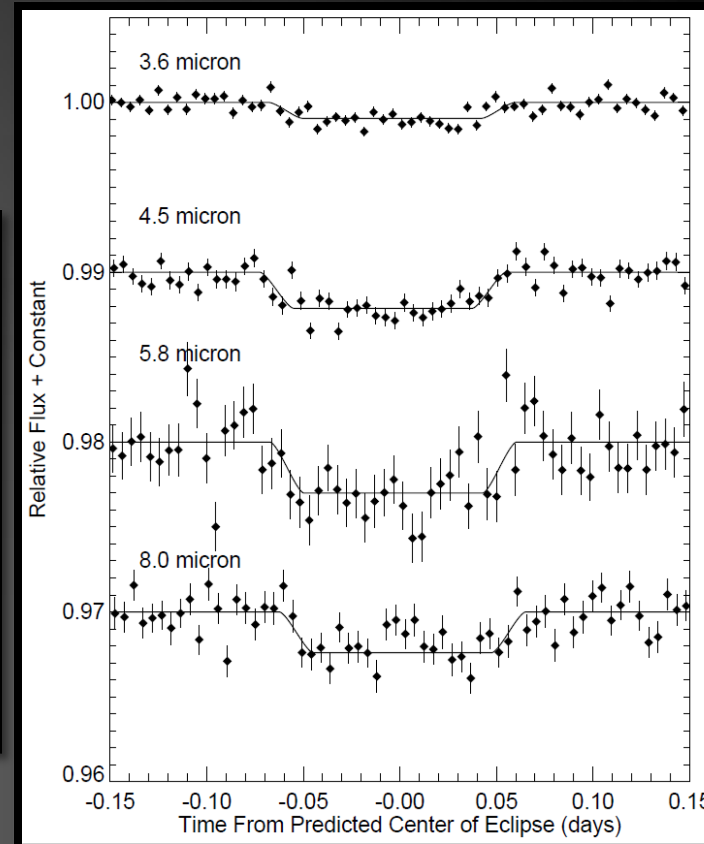
Atmospheric chemistry



Atmospheric dynamics

HD 209458b – Circa 2008

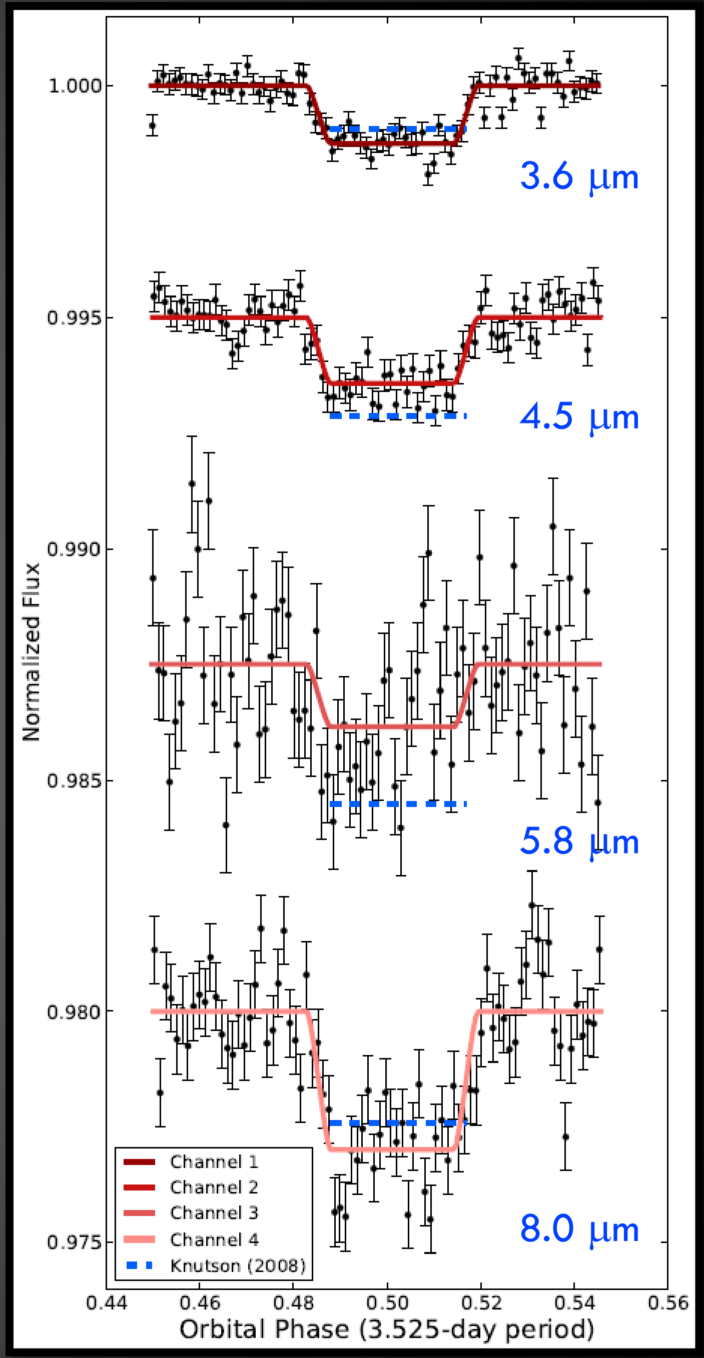




- Knutson et al. (2008) simultaneously measured one secondary eclipse in all four *Spitzer*/IRAC channels
  - Divided time between channels
  - Observing strategy was suboptimal
- Predicted emission spectrum ≠ measured Spitzer photometry points
- Prototypical exoplanet for atmospheric thermal inversions
  - Spawned numerous investigations to explain the source of purported inversion

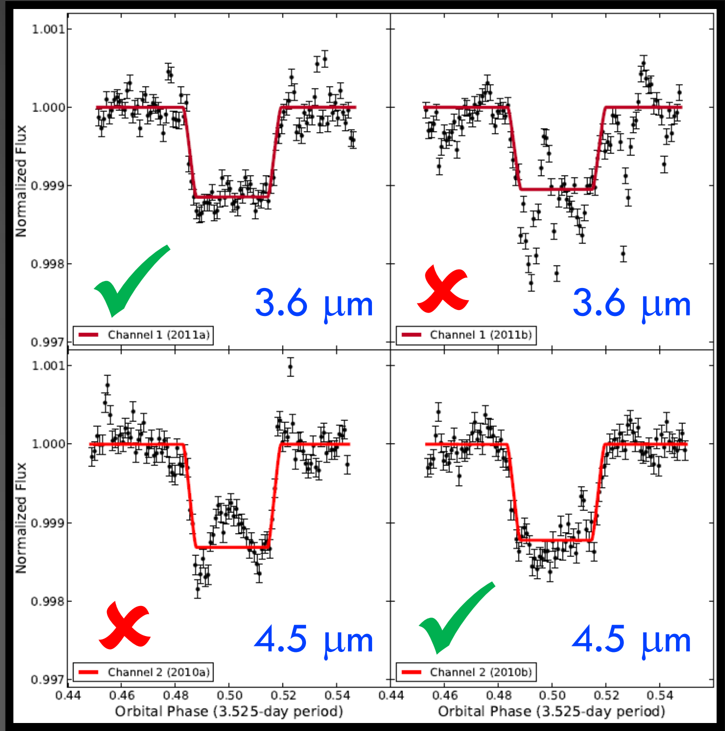
HD 209458b – Circa 2014

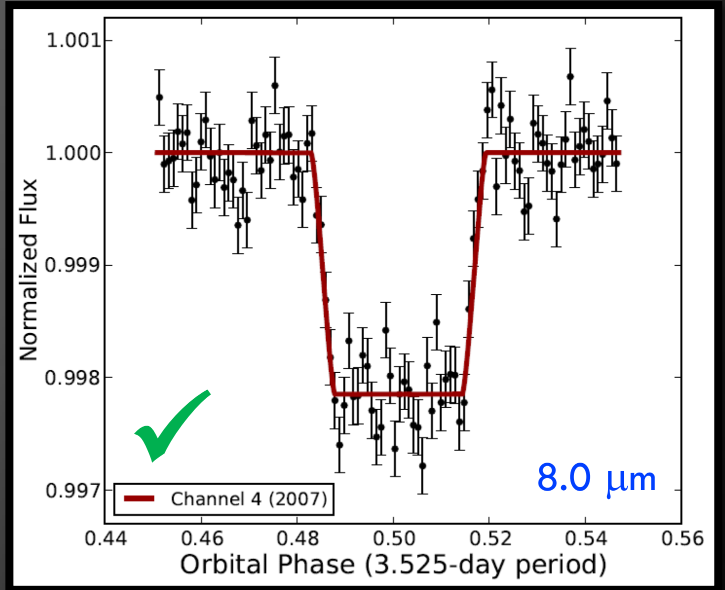
- Diamond-Lowe et al. (2014)
- Reanalysis of 2005 data
  - 4 secondary eclipses
  - State-of-the-art analysis techniques
  - BLISS mapping



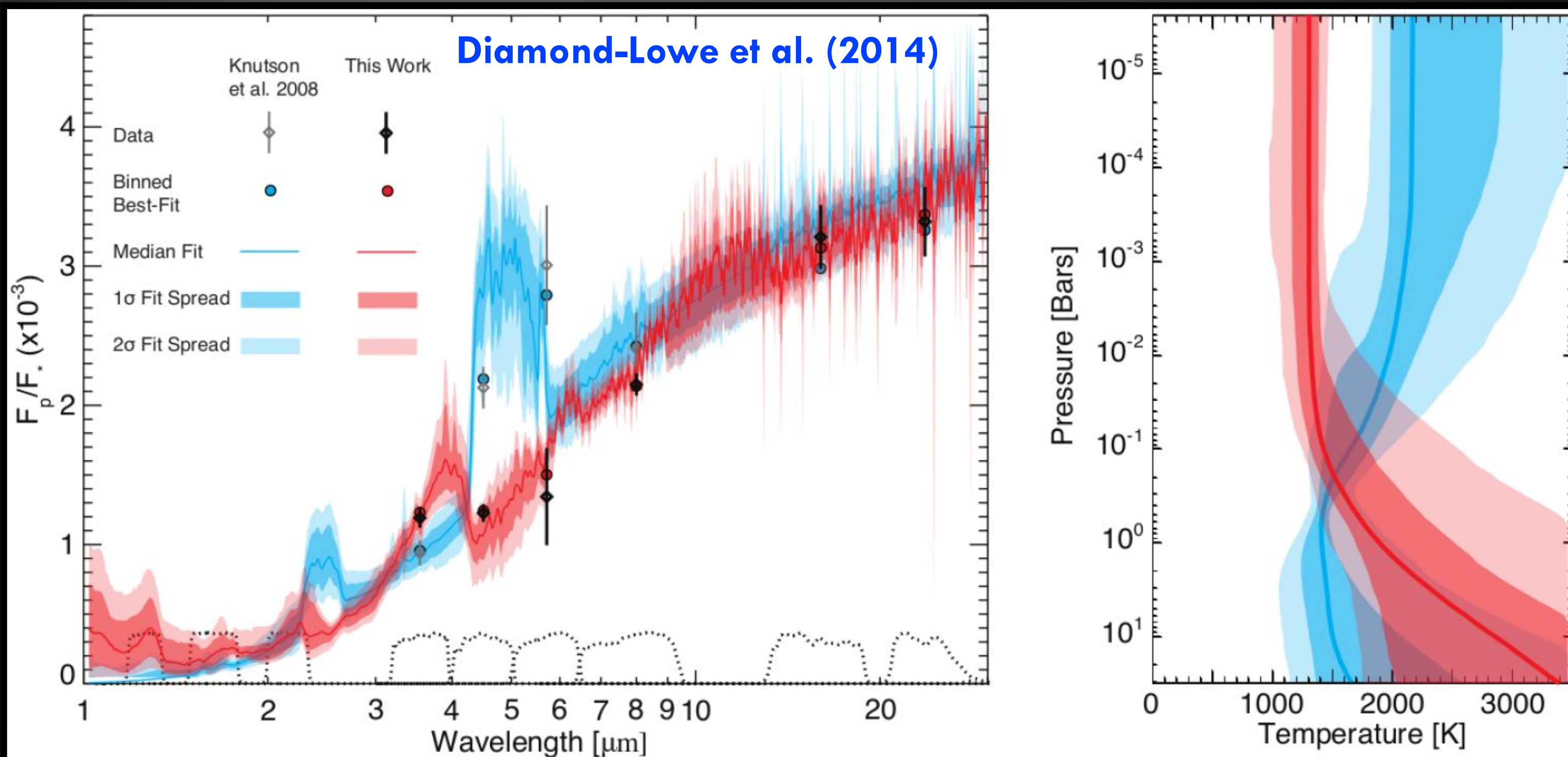
HD 209458b – Circa 2014

- Diamond-Lowe et al. (2014)
- Reanalysis of 2005 data
  - 4 secondary eclipses
  - State-of-the-art analysis techniques
  - BLISS mapping
- Analysis of previously-unpublished 2007, 2010 & 2011 data
  - 3.6, 4.5 & 8.0 μm light curves
  - More efficient observing mode



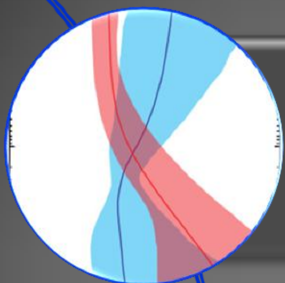


HD 209458b – Dayside Emission Spectrum



- No evidence for an atmospheric thermal inversion in HD 209458b.
- Results confirmed by Evans et al. (2015).
- No definitive detection of thermal inversion in any exoplanet.

Current Questions in Exoplanet Characterization



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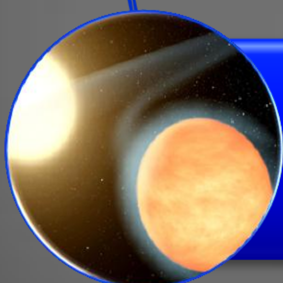
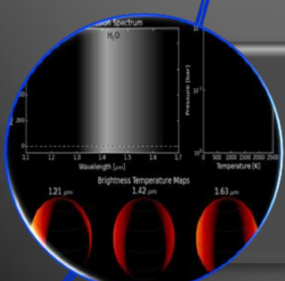


Have we definitively detected a carbon-rich atmosphere for a hot-Jupiter?



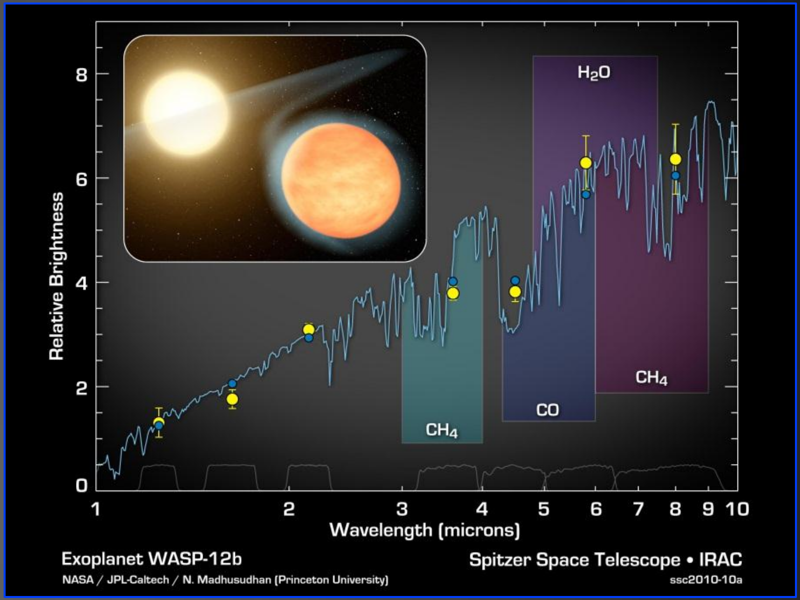
Atmospheric dynamics

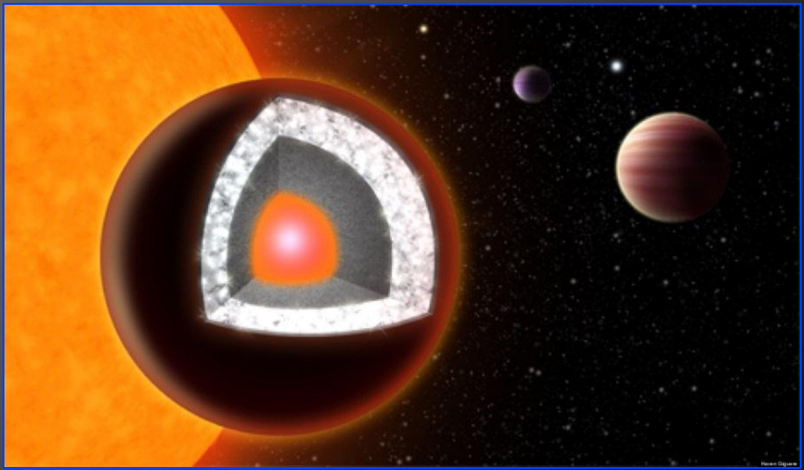
Carbon- vs Oxygen-Rich Planets

- Carbon-rich planet:
  - C/O > 1
  - Low [H_2O]
  - High [CH_4]
- Oxygen-rich planet:
  - C/O ~ 0.55 (Solar)
  - High [H_2O]
  - Low [CH_4]

- Spawned numerous investigations
  - Formation scenarios
  - Classification schemes
  - Diamond planets

Madhusudhan et al. (2011a, 2011b, 2012)





WASP-12b – Carbon-Rich Planet?

Planet

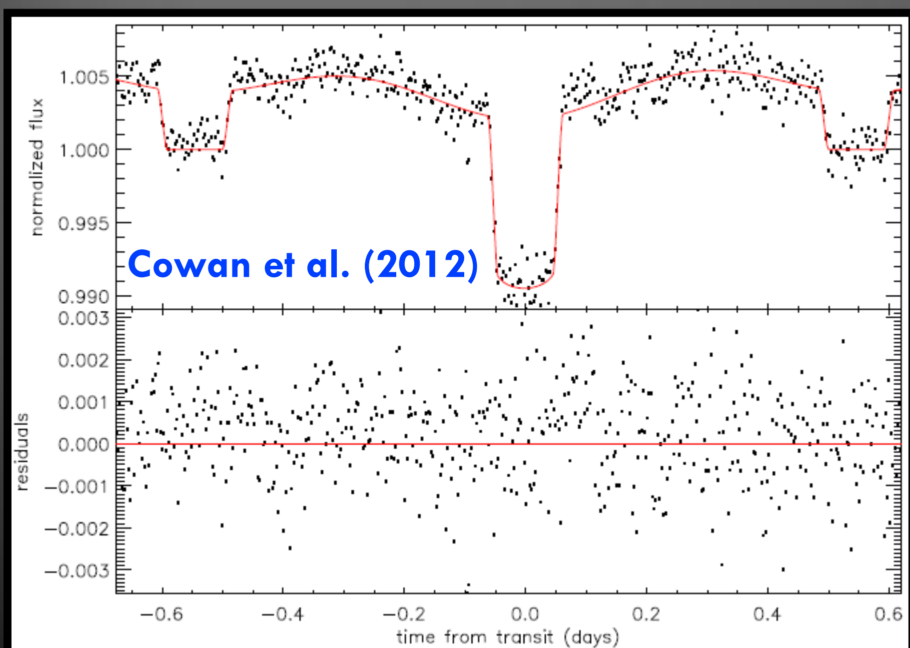
- Mass: 1.39 M_J
- Radius: 0.83 R_J
- Eq. Temperature: 2500 K
- Orbital Period: 1.09 days

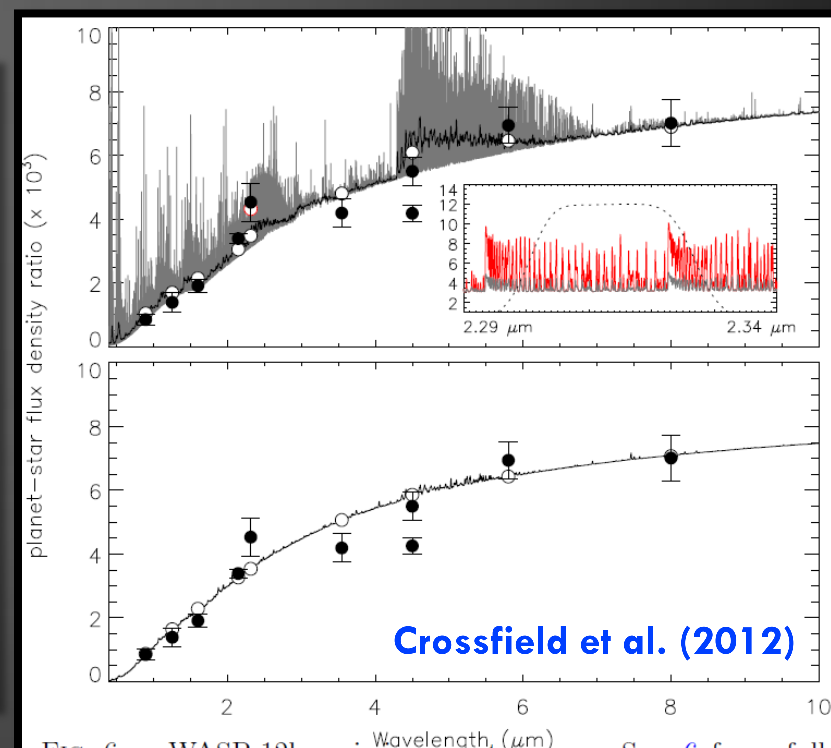
Host Star

- Mass: 1.35 $M_\odot$
- Radius: 1.57 $R_\odot$
- T_{eff}: 6300 K (G0V)
- Distance: 267 pc

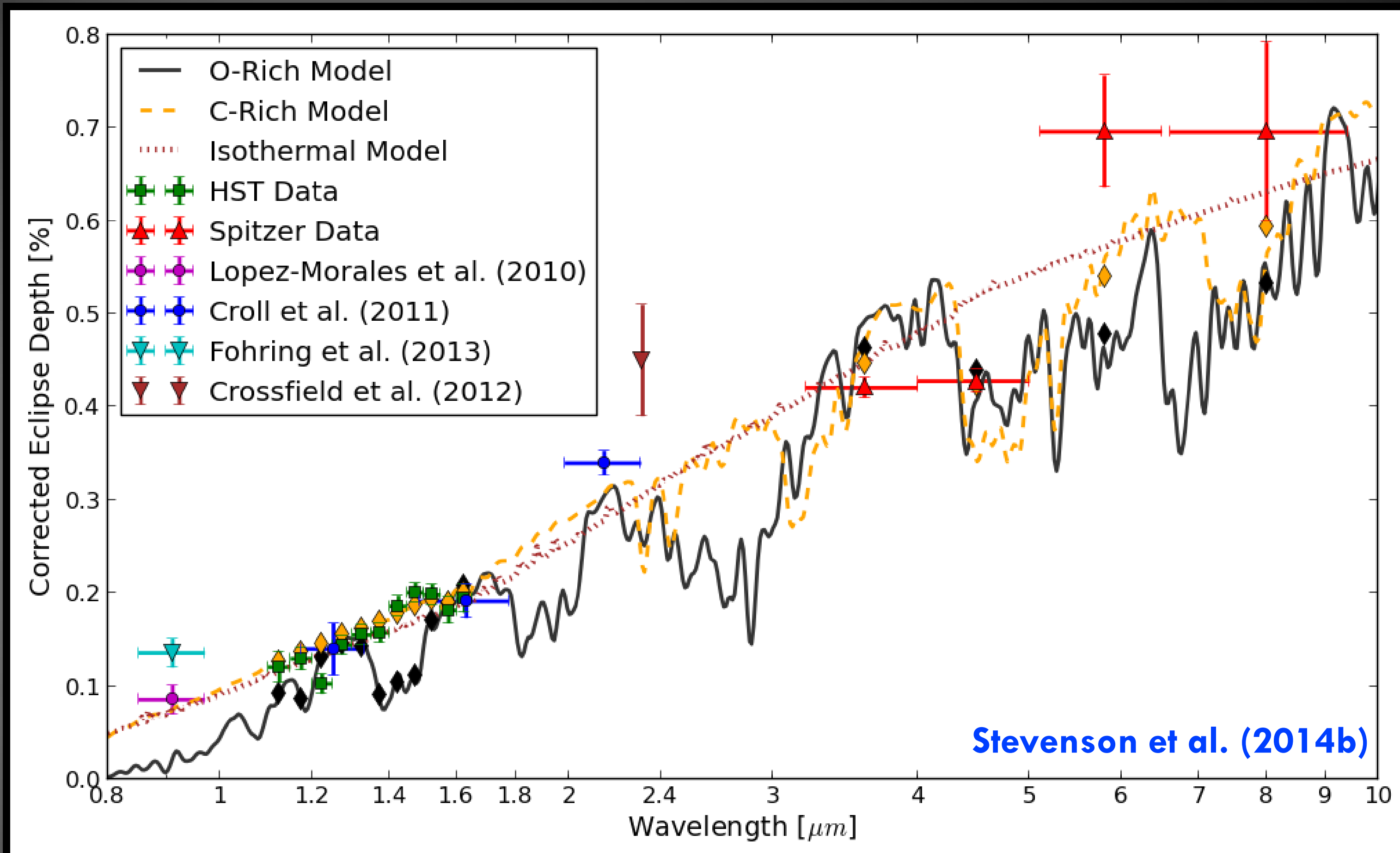
Observations

- Published and unpublished data
- *Spitzer* & *HST*
- 1.1 – 10 μm





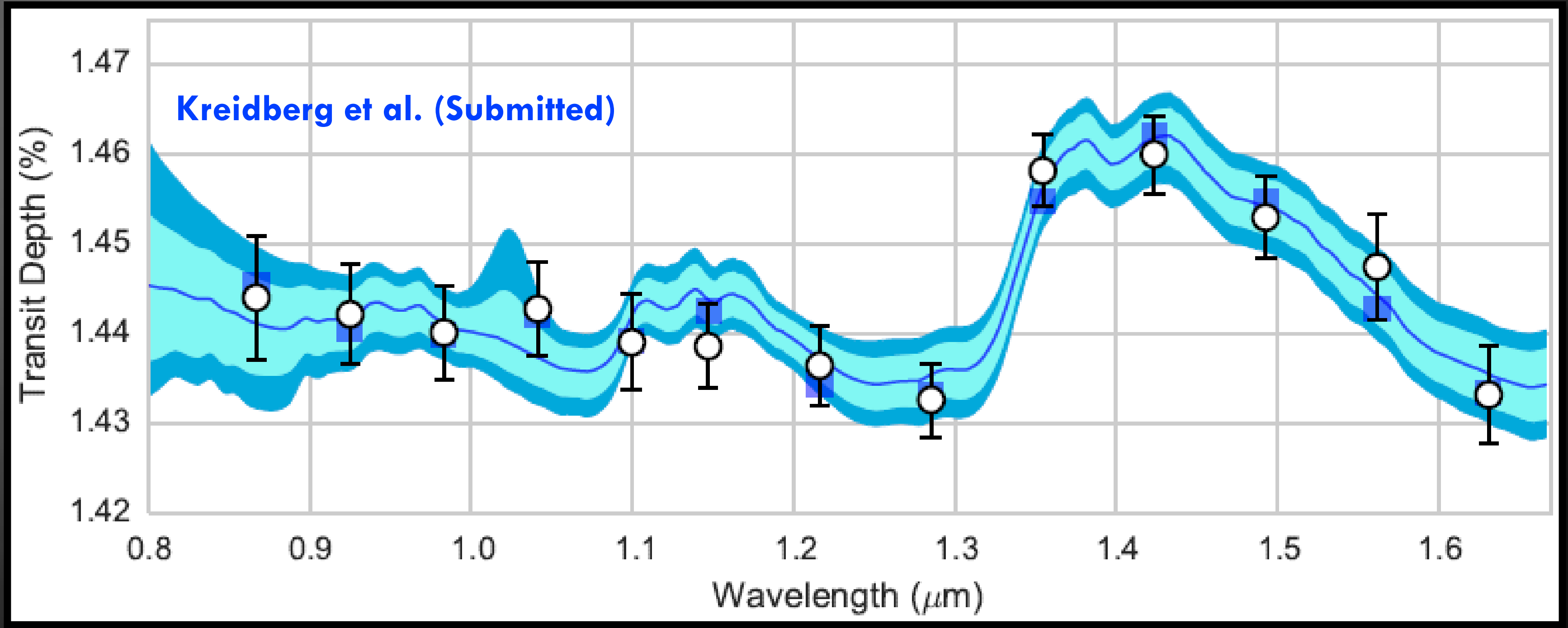
WASP-12b – Emission Spectrum

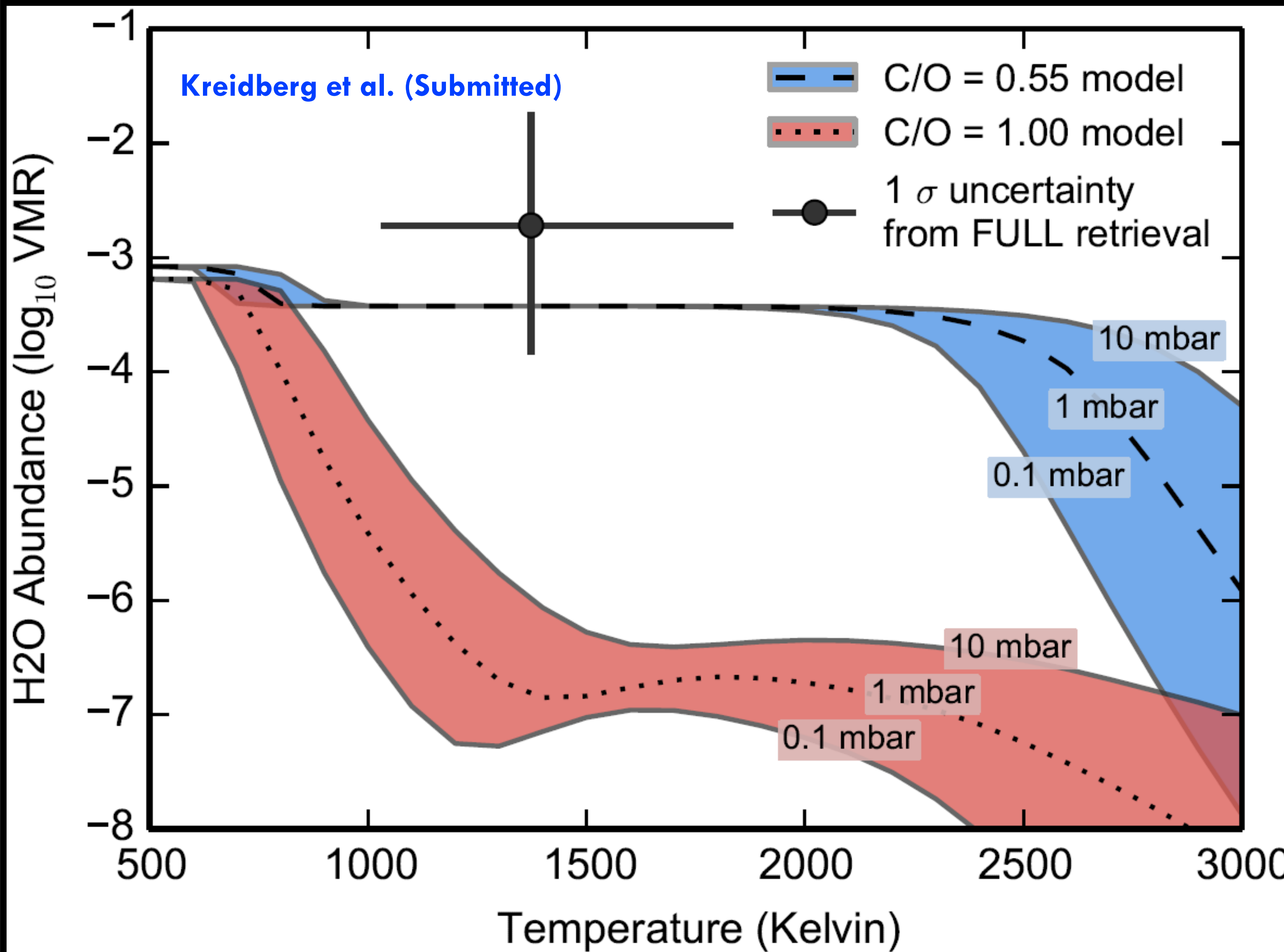


- C-Rich: Best fit to available data
- O-Rich: Poor fit assuming thermochemical equilibrium, requires 5x less H_2O and 100x more CO_2 relative to solar composition (physically implausible).
- Isothermal: 2930 K, 7.3×10^6 times less probable

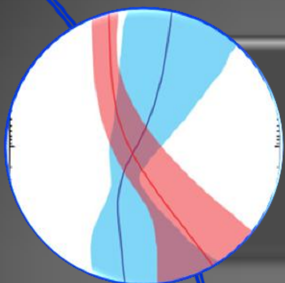
WASP-12b – Transmission Spectrum

- Observed 6 transits with HST/WFC3
  - 3 transits with G141 (1.2 – 1.7 μm)
  - 3 transits with G102 (0.8 – 1.2 μm)
- 7σ detection of H_2O at planet terminator




Kreidberg et al. (Submitted)
C/O = 0.55 model
C/O = 1.00 model
1 σ uncertainty
from FULL retrieval
10 mbar
1 mbar
0.1 mbar
10 mbar
1 mbar
0.1 mbar
H2O Abundance (log10 VMR)
−1
−2
−3
−4
−5
−6
−7
−8
500
1000
1500
2000
2500
3000
Temperature (Kelvin)

Current Questions in Exoplanet Characterization



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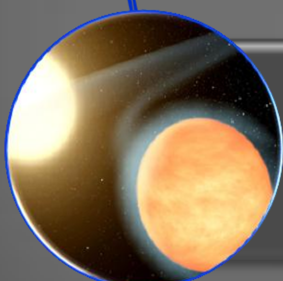

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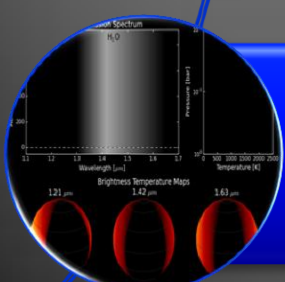
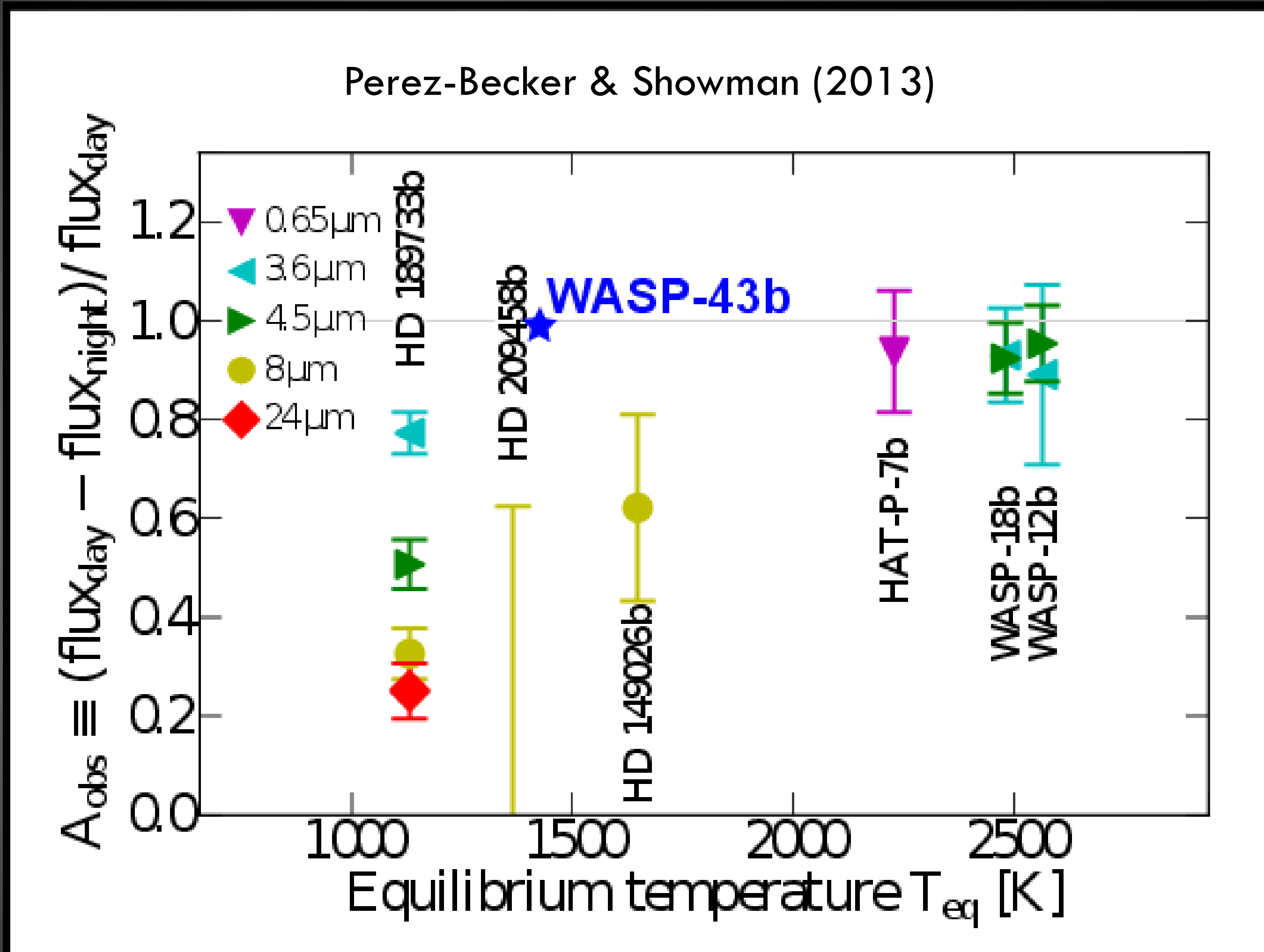
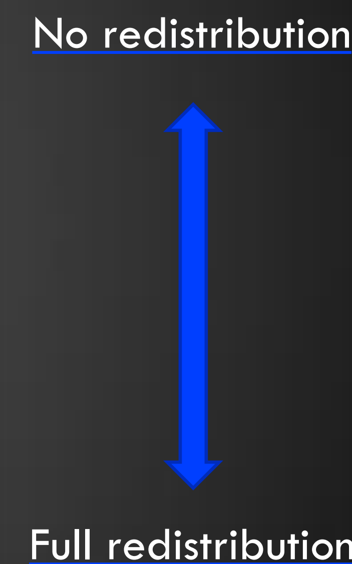


What parameters affect the heat redistribution efficiency from dayside to nightside?

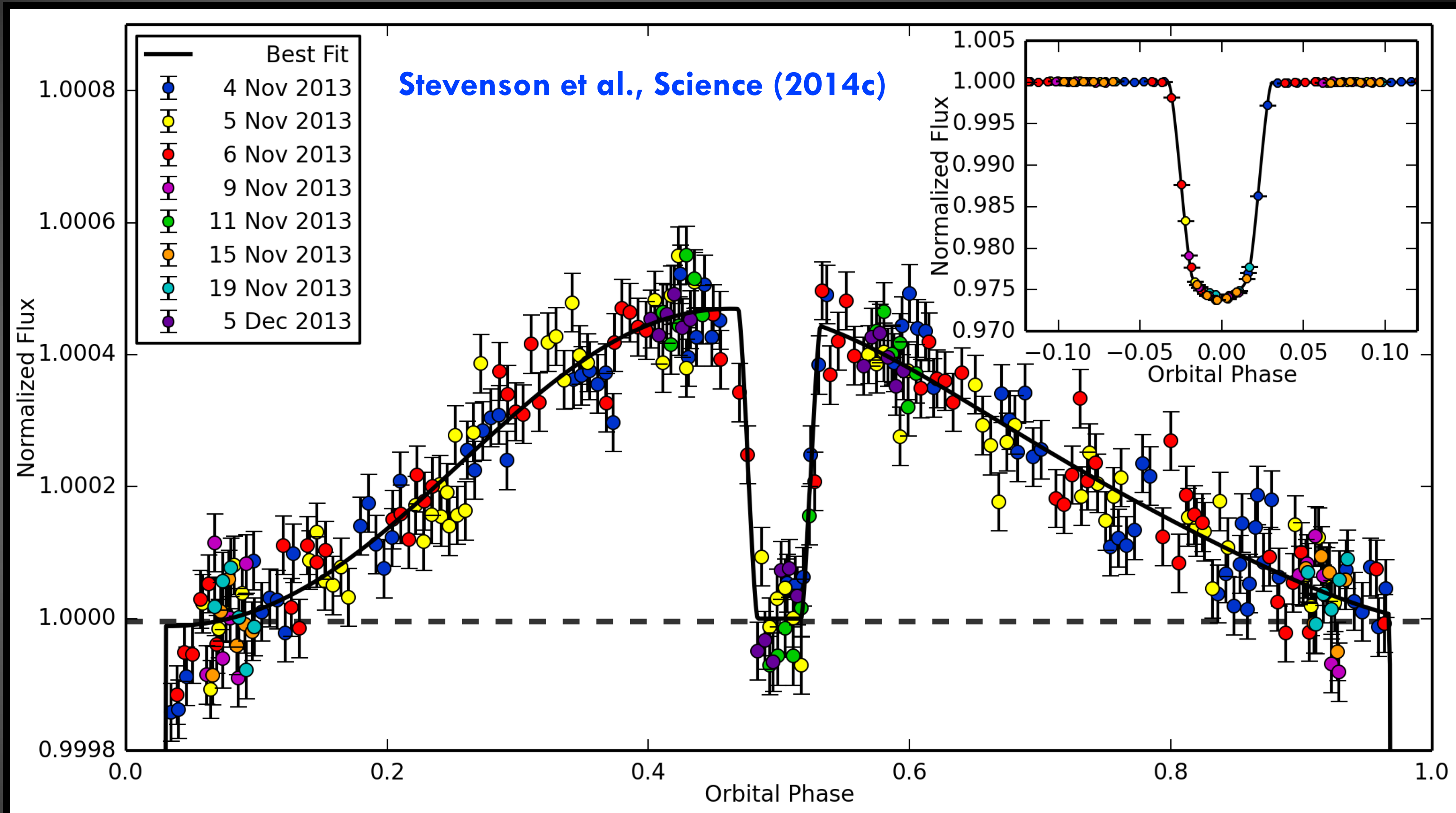
Heat Redistribution of Measured Planets



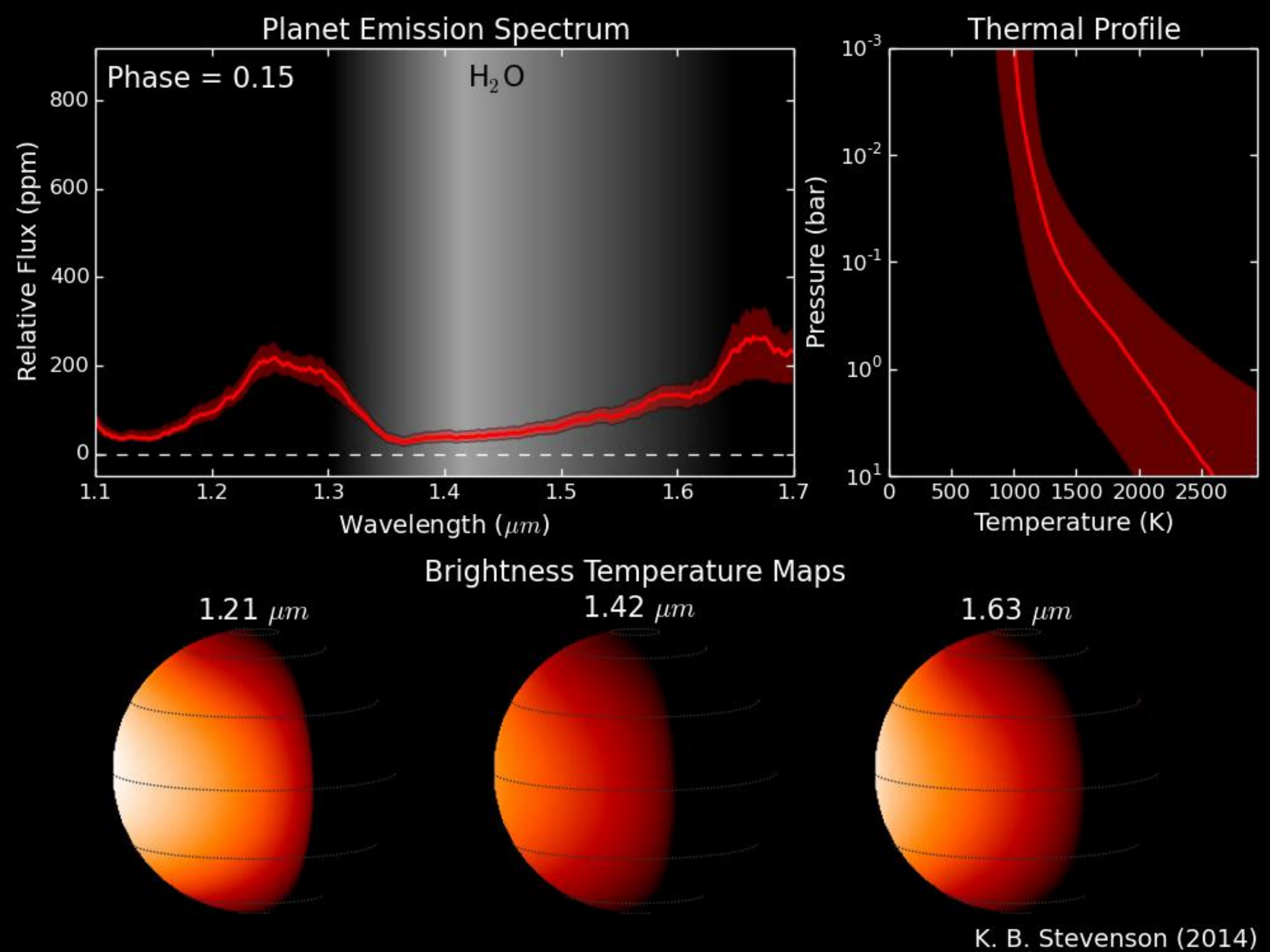


- Cooler planets typically exhibit more efficient heat redistribution
- Wavelength dependence in heat redistribution OR exoplanet dichotomy?

WASP-43b – White WFC3 Phase Curve



- PC Max. 40 ± 3 minutes before eclipse
- PC Min. 34 ± 5 minutes after transit
- Asymmetric shape (10σ confidence)
- Eclipse Depth: 461 ± 5 ppm


Planet Emission Spectrum
Phase = 0.15
H_2O
Relative Flux (ppm)
800
600
400
200
0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength (μm)
Thermal Profile
Pressure (bar)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
0
500
1000
1500
2000
2500
Temperature (K)
Brightness Temperature Maps
1.21 μm
1.42 μm
1.63 μm
K. B. Stevenson (2014)

3.6 & 4.5 μm Spitzer Phase Curves

PRELIMINARY RESULTS

Conclusions

- HD 209458b does not have a thermal inversion at the pressure levels probed by Spitzer.
  - No definitive detection of a thermal inversion in any hot-Jupiter atmosphere to date.
- Carbon-rich status of WASP-12b is debatable.
  - Secondary eclipse photometry favors C-rich scenario.
  - Primary transit spectroscopy favors O-rich scenario.
- WASP-43b *HST*/WFC3 + *Spitzer*/IRAC phase curves
  - Heat redistribution efficiency is not strictly T_{eq} dependent.