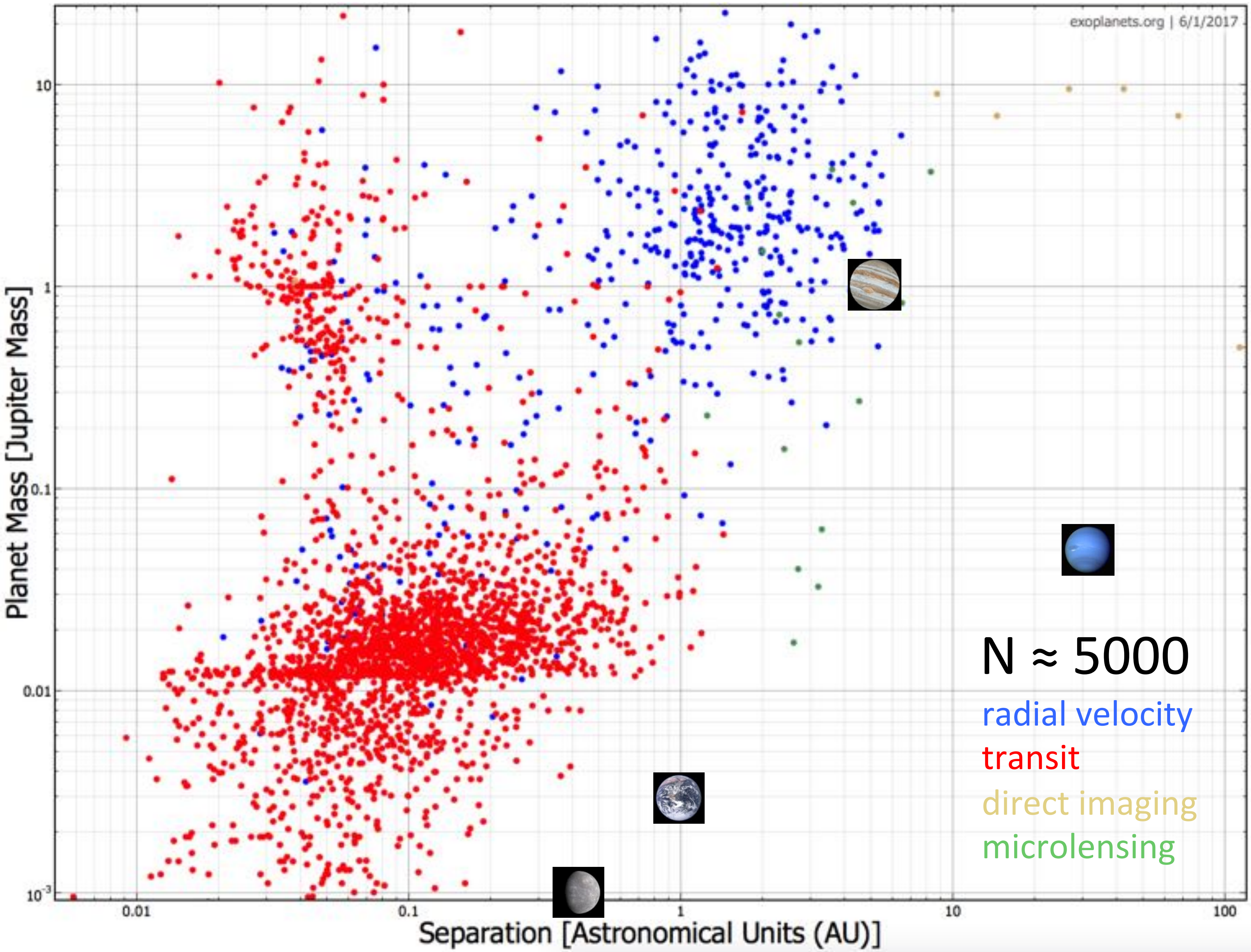
Comparative Exoplanetology in the Era of the Great Observatories, JWST, and Beyond

Jacob Bean
University of Chicago

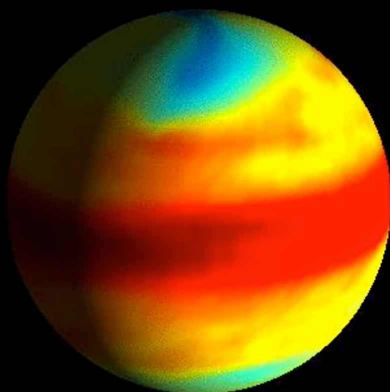
University of Chicago Group – January 2017

University of Chicago Group – January 2017

Known exoplanets as of June 2017



Fundamental Themes for Exoplanet Atmosphere Characterization

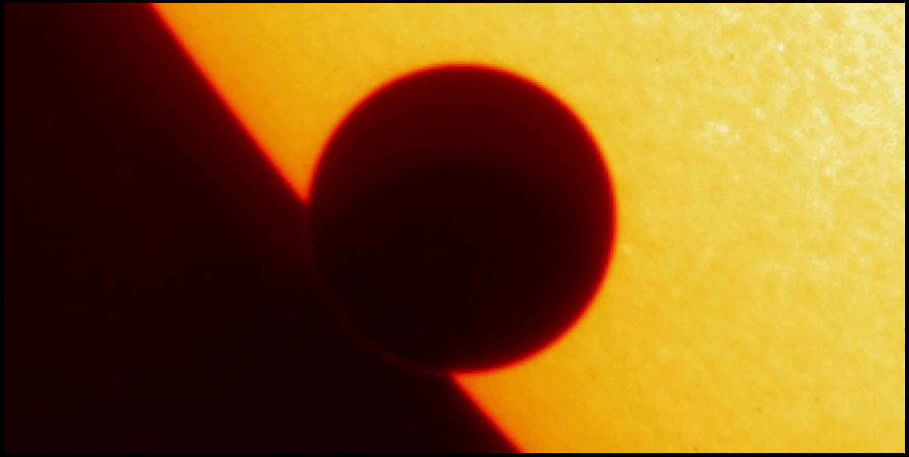


Determining thermal structures, energy budgets, and dynamics to understand planetary physics.

Measuring compositions to trace planet formation and evolution.

Connected questions motivates holistic studies.

The "Small Black Shadow" vs. "The Pale Blue Dot"



Strengths:

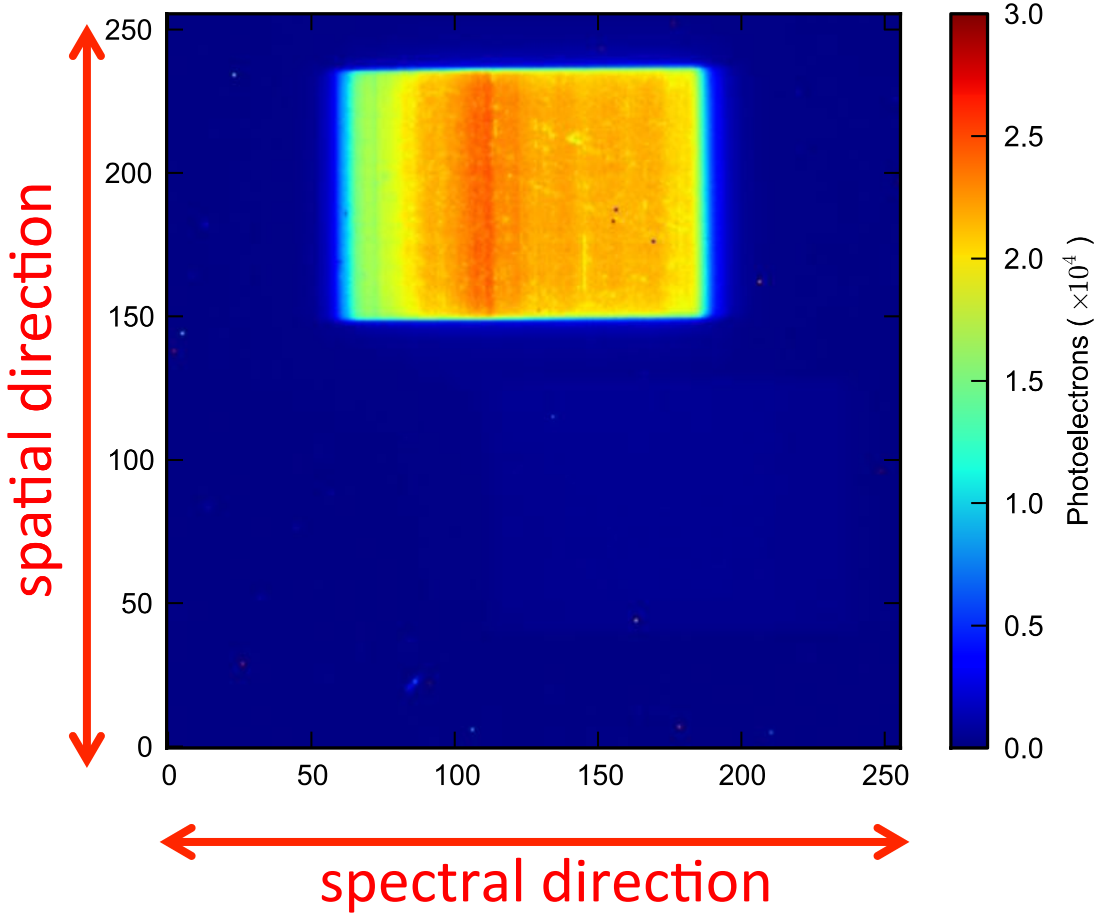
- Know the mass and radius of the planet
- Multiple probes of the atmosphere
- Can study planets close-in to their host stars
- Rapidly advancing field

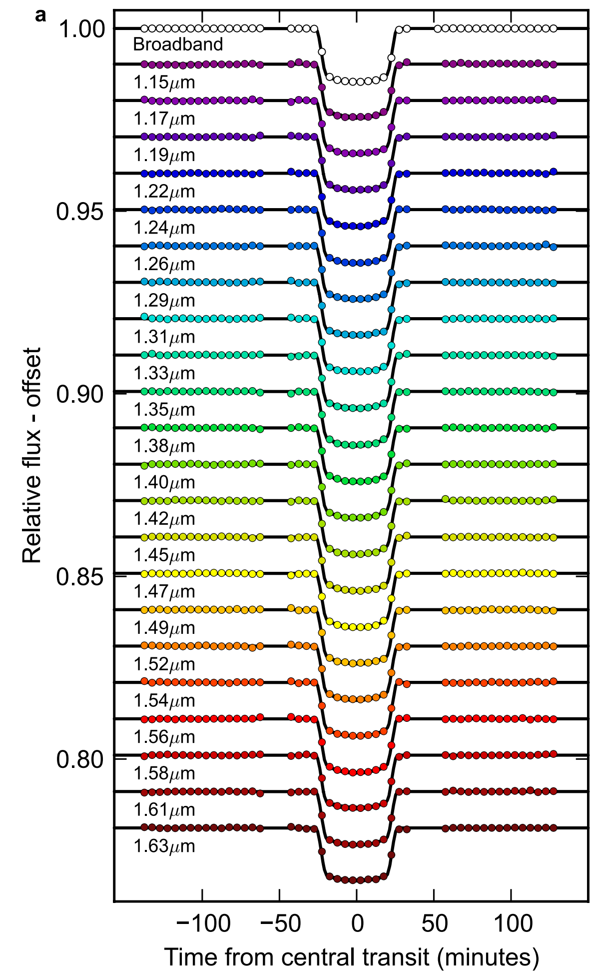
Weaknesses:

- Measure planets relative to their stars
- Limited (for the most part) to planets that are transiting
- Limited to close-in planets (a << 1 AU)

Astronaut Andrew Feustel installs the **Wide Field Camera 3** (May 14, 2009)

Using an instrument designed for faint galaxies to look at bright, nearby stars

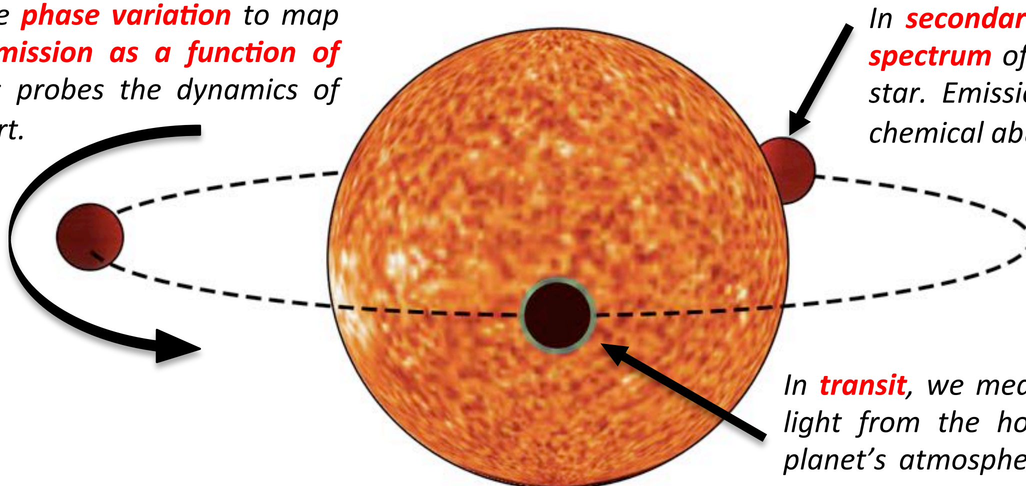




Probing Exoplanet Atmospheres With Transits

We observe the ***phase variation*** *to map the planet's* ***emission as a function of longitude****. This probes the dynamics of energy transport.*

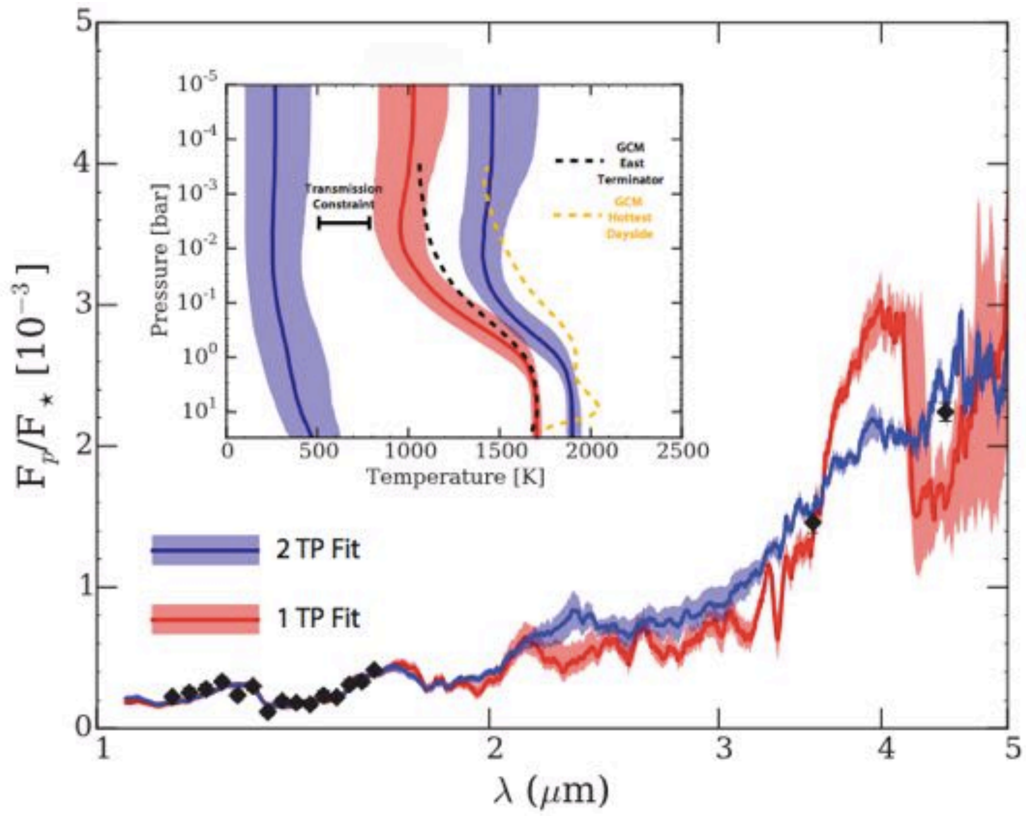
In ***secondary eclipse****, we measure the dayside* ***emission spectrum*** *of the planet as its light is blocked by the host star. Emission spectroscopy is sensitive to the absolute chemical abundances and the thermal structure.*

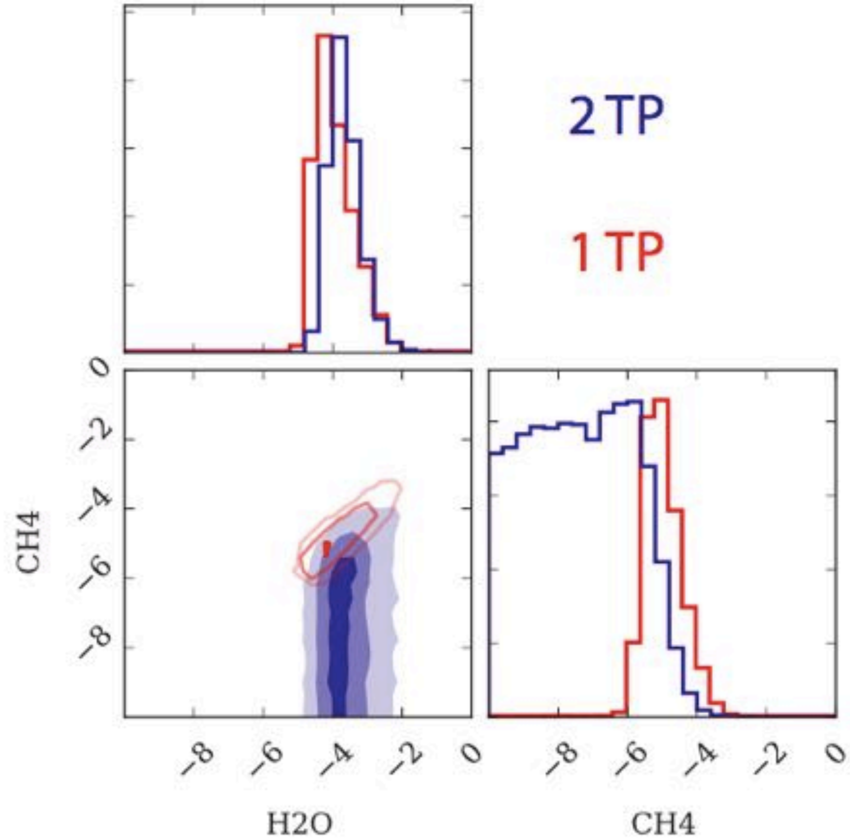


In ***transit****, we measure the* ***transmission spectrum*** *of the planet as light from the host star is absorbed by chemical species in the planet's atmosphere. These data are most sensitive to the relative chemical abundances and the presence of cloud or haze particles.*

Robust modeling is critical!

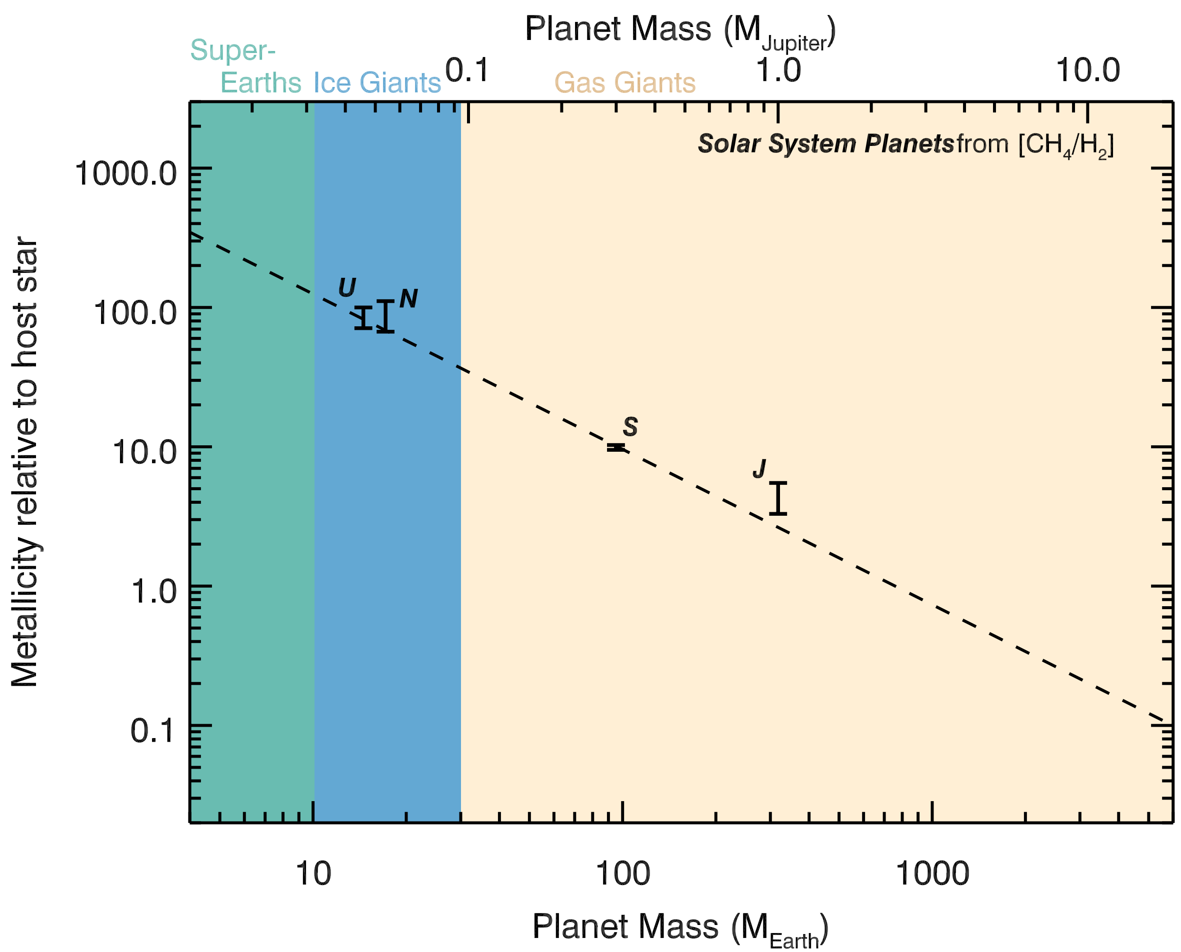
phase 0.25 of WASP-43b



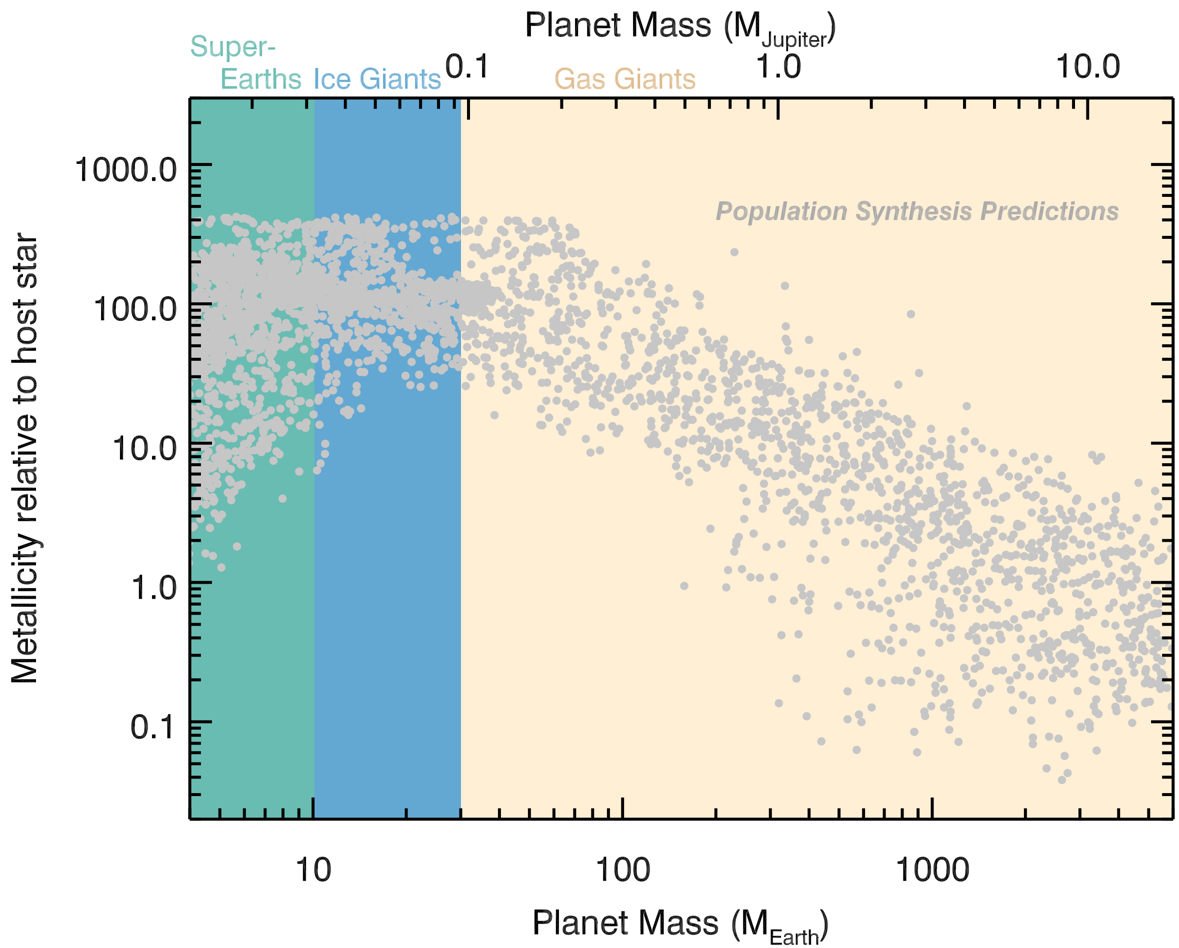


Feng+ 2016

Key Question #1: **What are the metallicities of planetary atmospheres?**

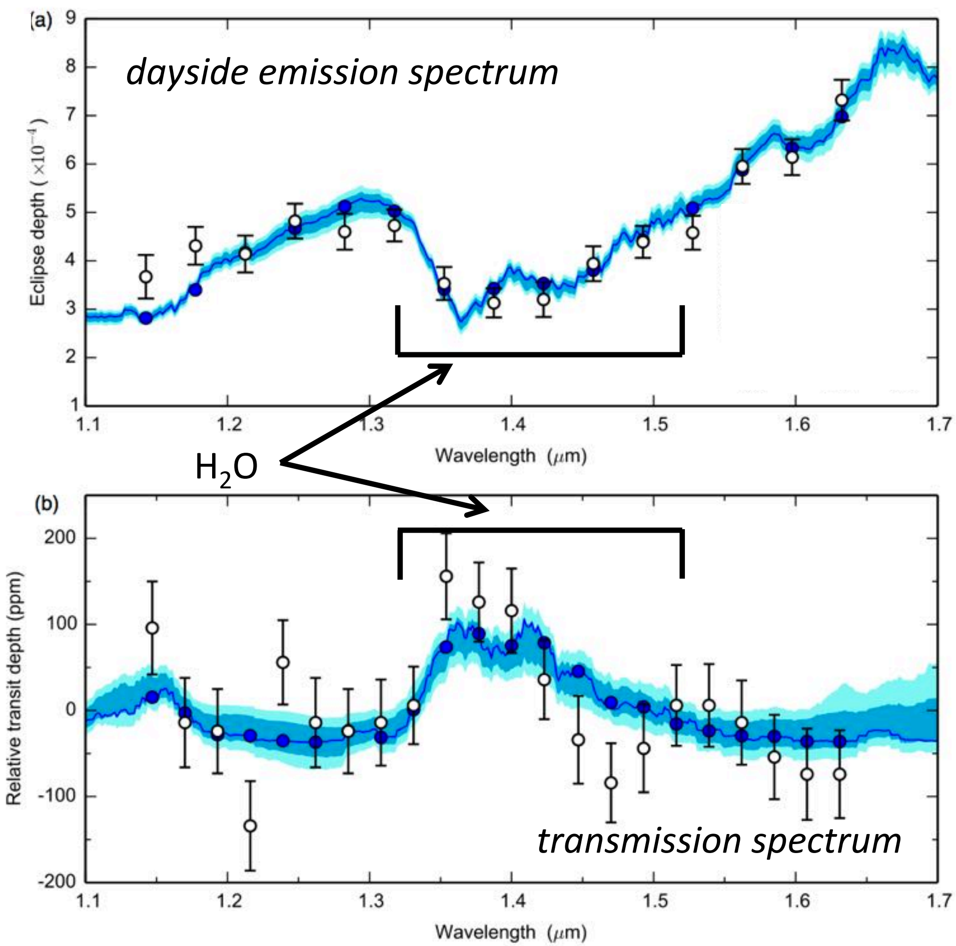


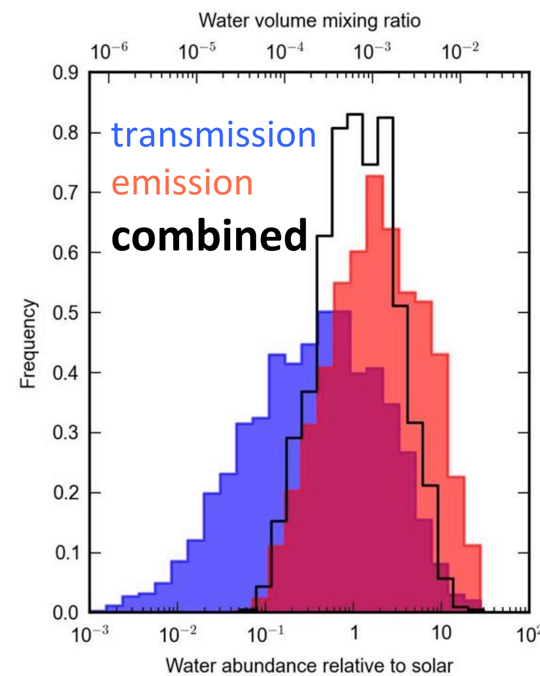
Key Question #1: **What are the metallicities of planetary atmospheres?**



Fortney+ 2013, 100km planetesimals

Precise Water Abundance for WASP-43b





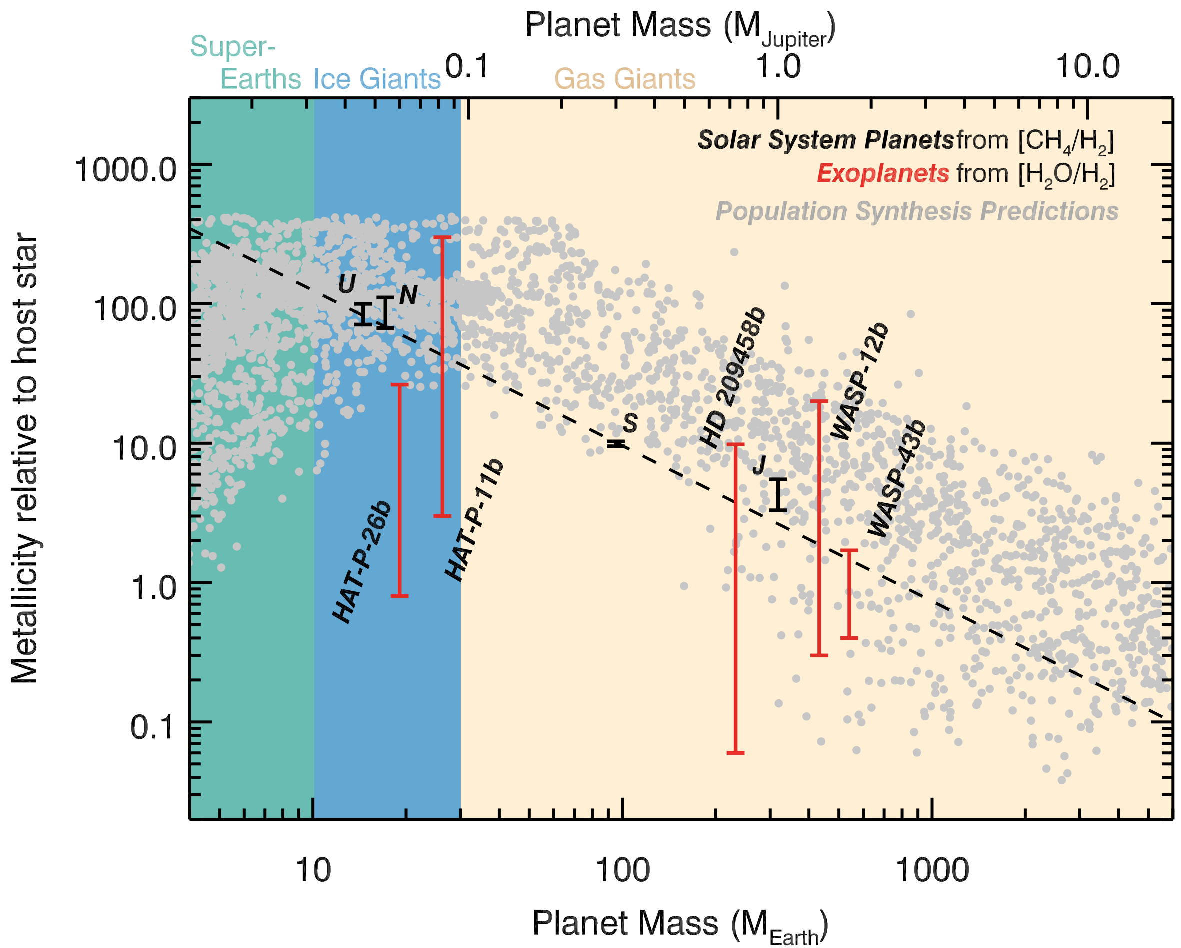
combined result gives (1σ):

O/H = 0.4 – 3.5 x solar!

(assuming solar abundance ratios)

Kreidberg+ 2014b

Key Question #1: **What are the metallicities of planetary atmospheres?**



Exoplanet data: Kreidberg+ 2014b, Fraine+ 2014, Kreidberg+ 2015, Line+ 2016, Stevenson+ 2017, Wakeford+ 2017

Key Question #1: **What are the metallicities of planetary atmospheres?**

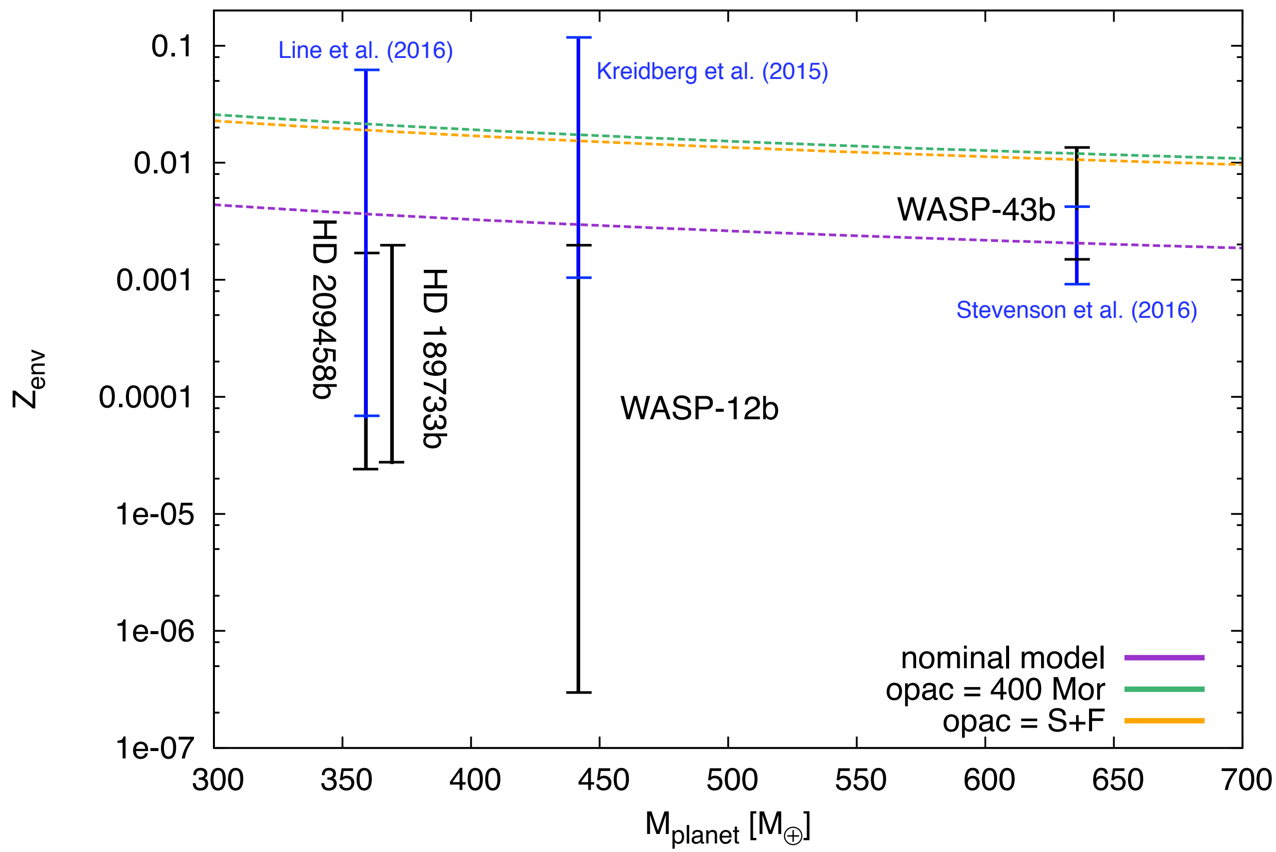
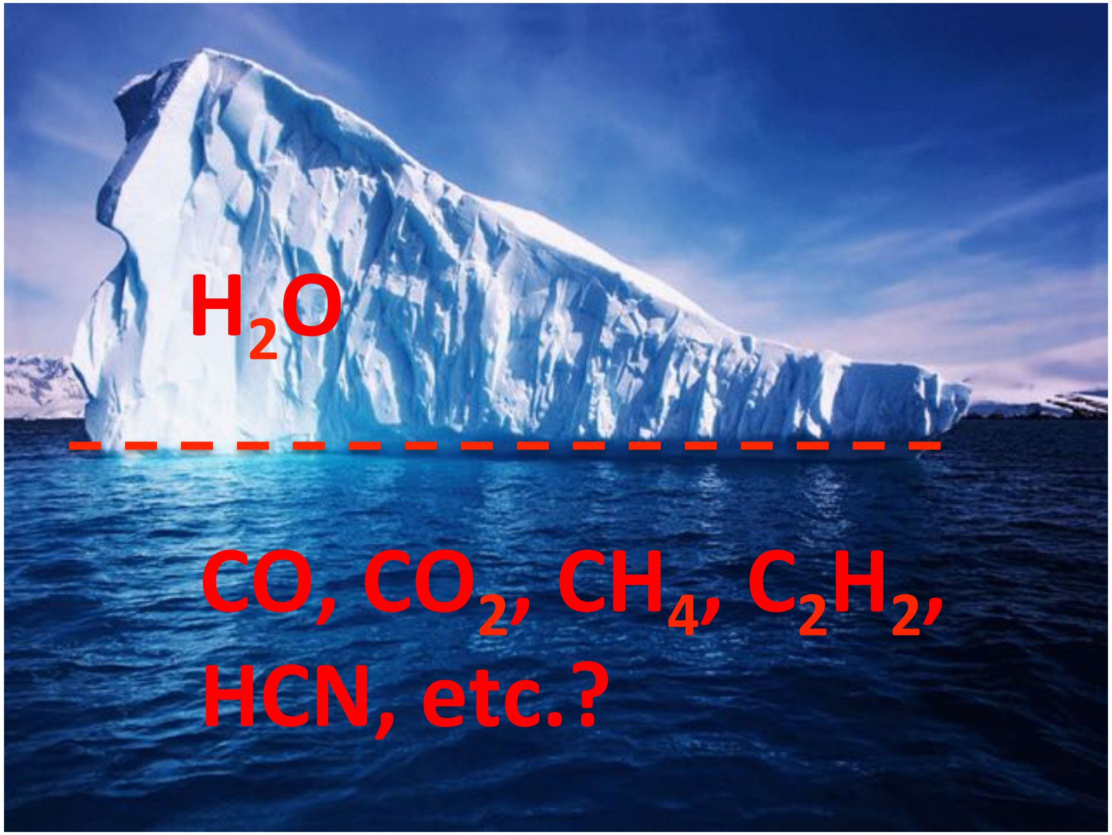
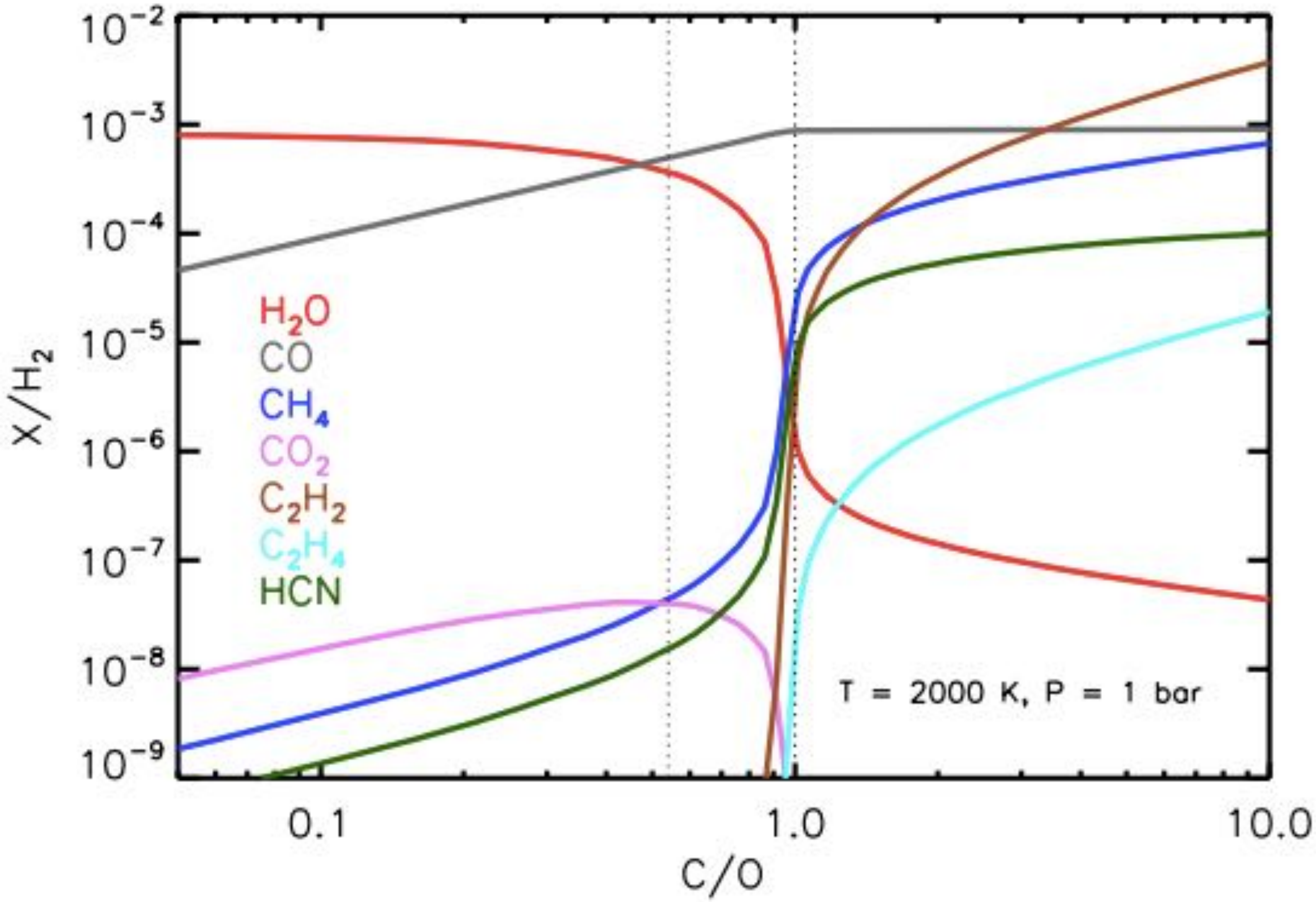


Figure from Julia Venturini
based on Venturini+ 2016

Key Question #2: **What are the carbon-to-oxygen ratios (C/O) in planetary atmospheres?**



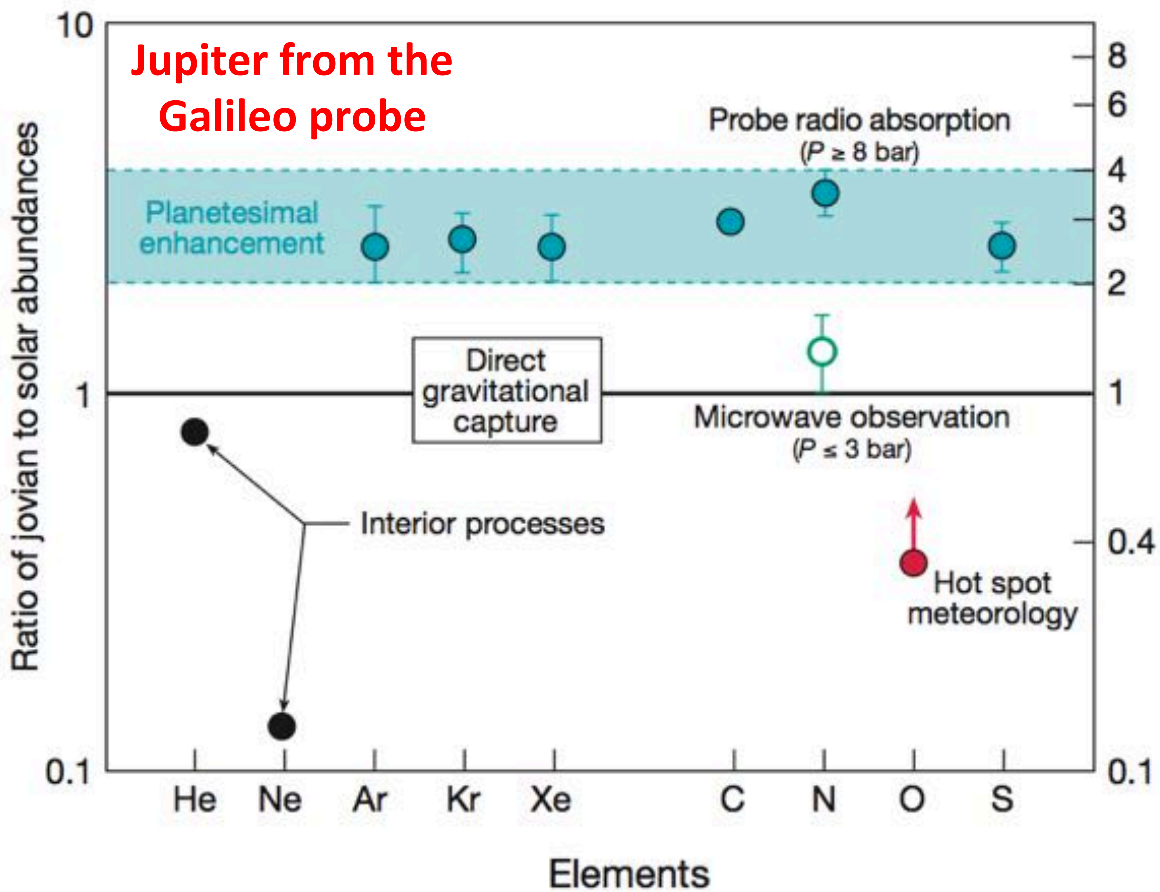
Key Question #2: **What are the carbon-to-oxygen ratios (C/O) in planetary atmospheres?**



Note this depends strongly on temperature, pressure, and metallicity.

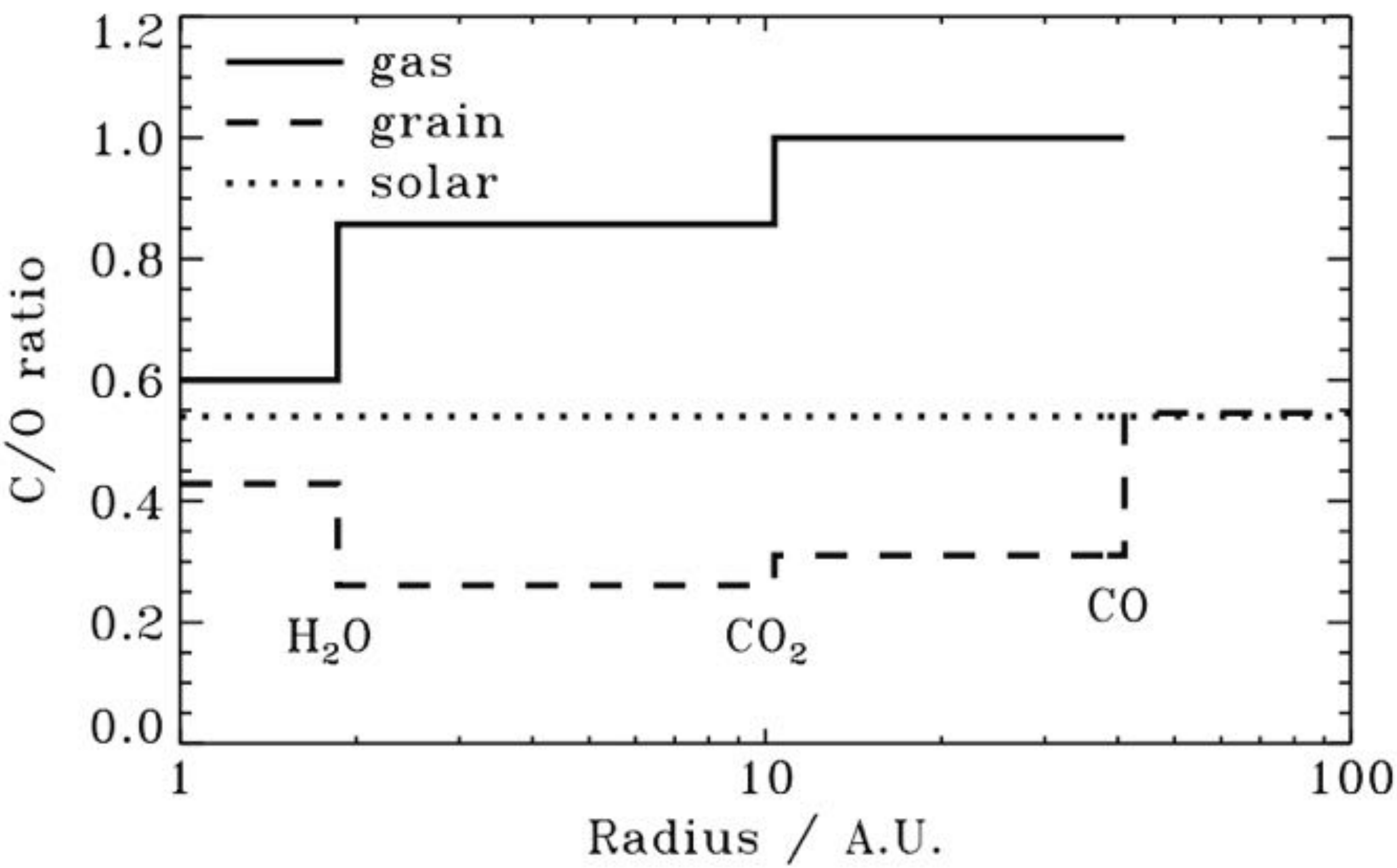
Madhusudhan 2012

Key Question #2: **What are the carbon-to-oxygen ratios (C/O) in planetary atmospheres?**



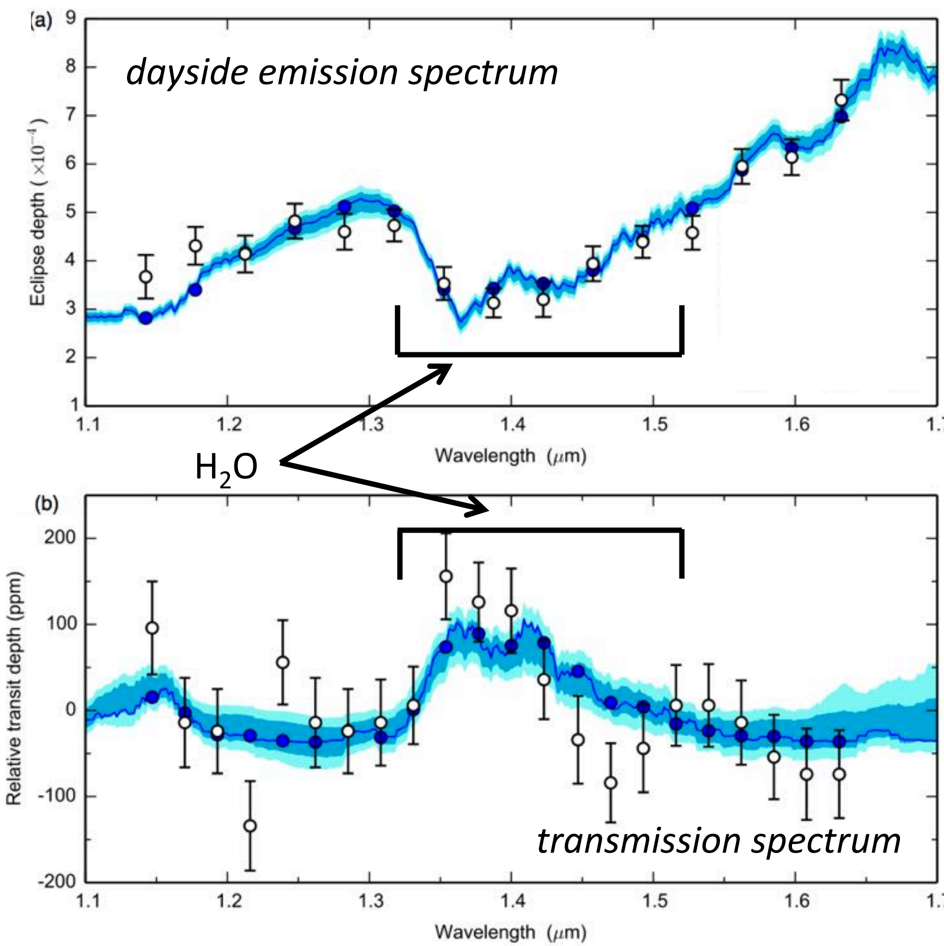
Owen+ 1999

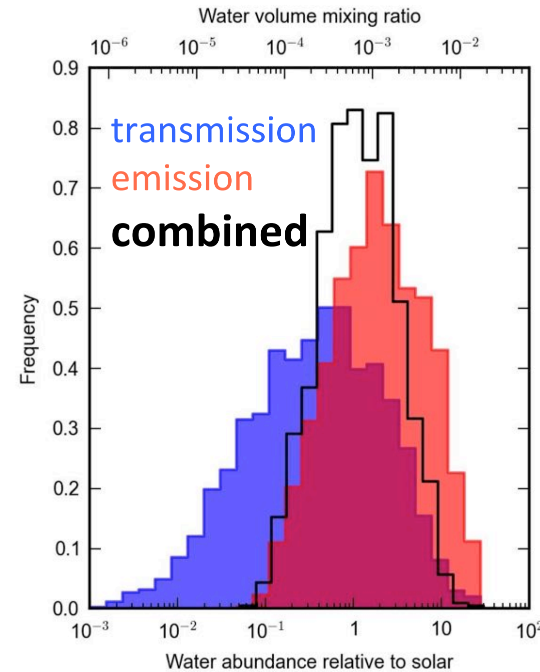
Key Question #2: **What are the carbon-to-oxygen ratios (C/O) in planetary atmospheres?**



Öberg+ 2011
See also Madhusudhan+ 2014

Precise Water Abundance for WASP-43b





combined result gives (1σ):

O/H = 0.4 – 3.5 x solar!

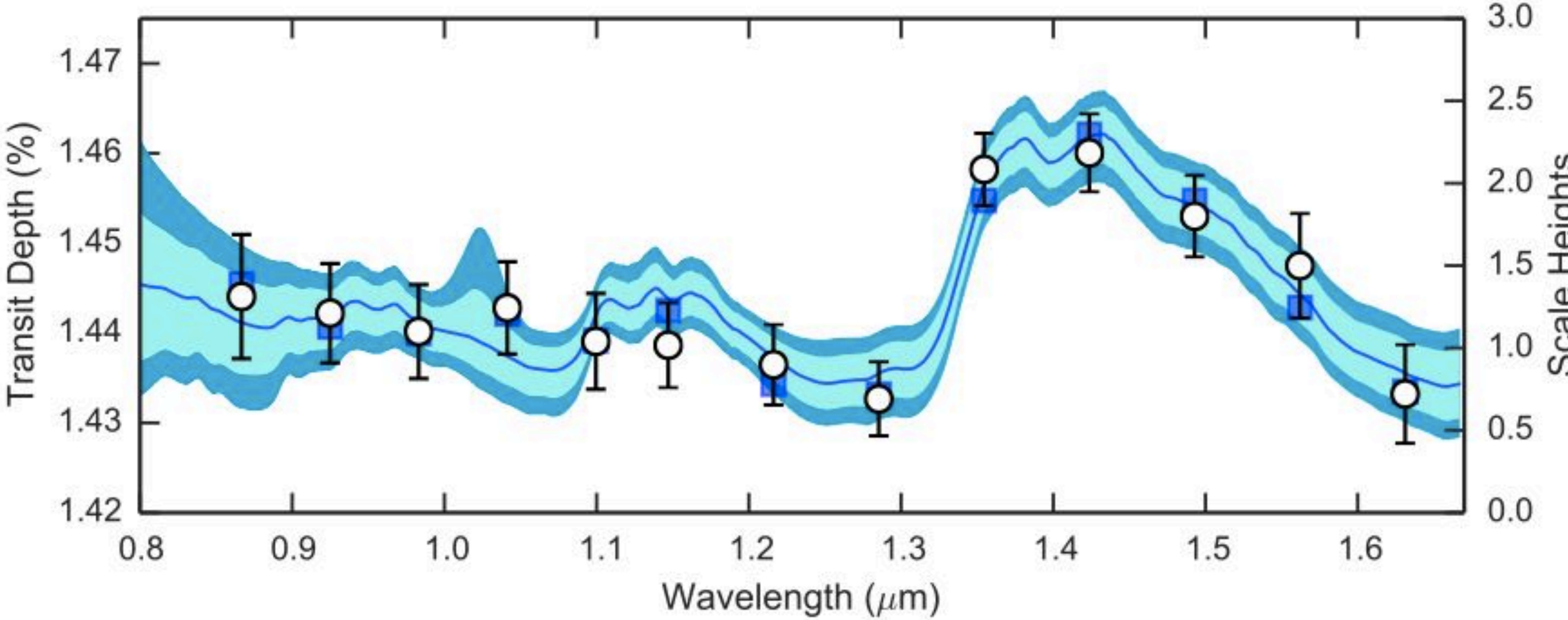
(assuming solar abundance ratios)

Kreidberg+ 2014b

Water detection for WASP-12b

model fit by Mike Line

transmission spectrum



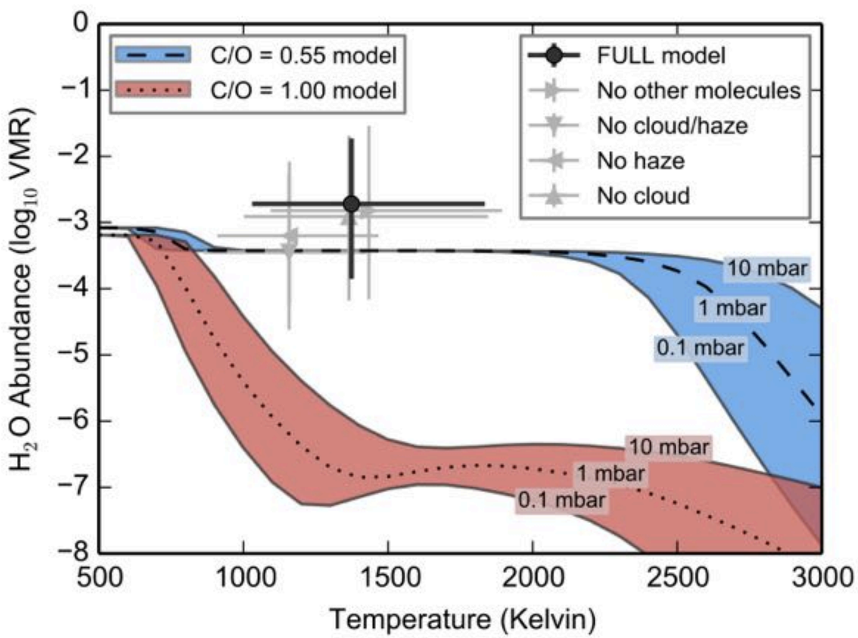
7σ detection of water absorption

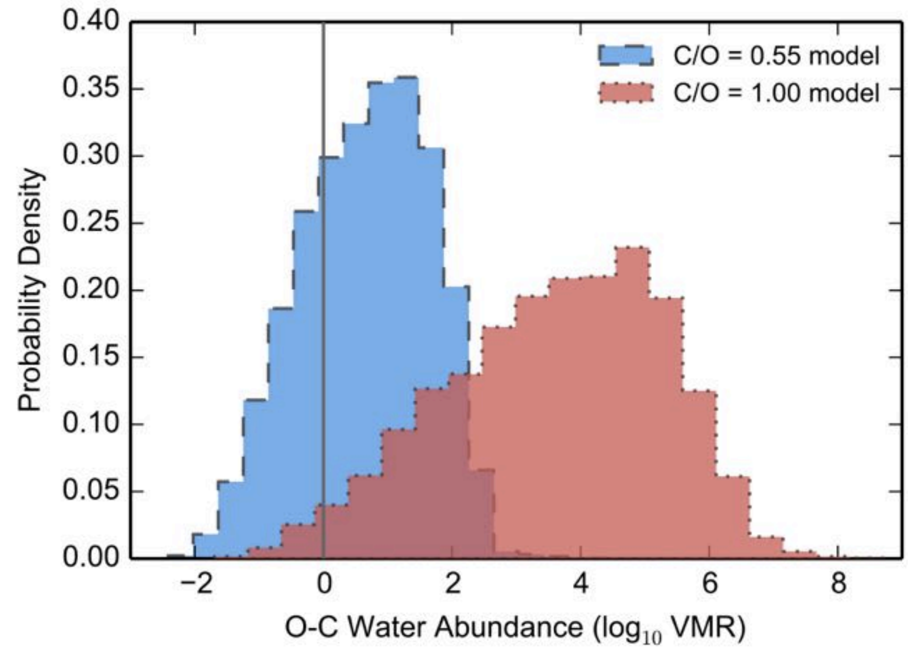
First use of the G102 grism for exoplanets

Kreidberg+ 2015

Key Question #2: **What are the carbon-to-oxygen ratios (C/O) in planetary atmospheres?**

WASP-12b





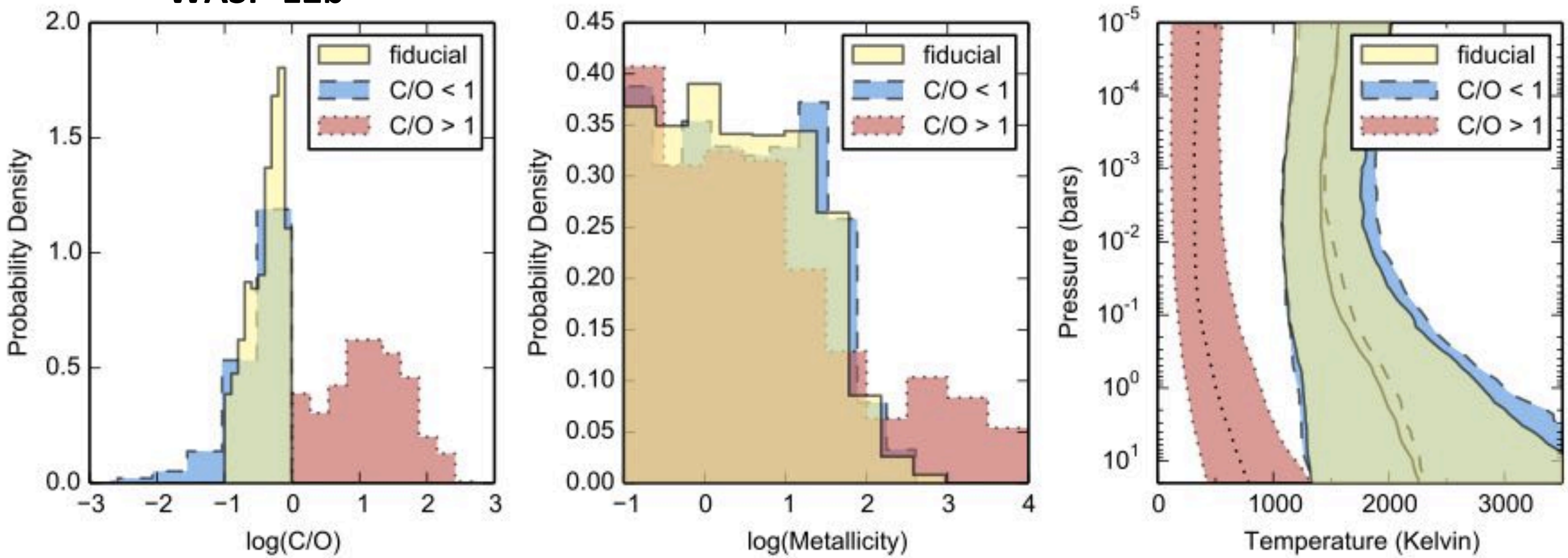
Results disfavor high C/O at 2σ confidence

(assuming solar metallicity, chemical equilibrium, & 1D)

Kreidberg+ 2015

Key Question #2: **What are the carbon-to-oxygen ratios (C/O) in planetary atmospheres?**

WASP-12b



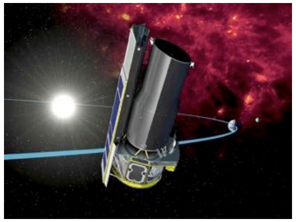
Results disfavor high C/O at >3σ confidence

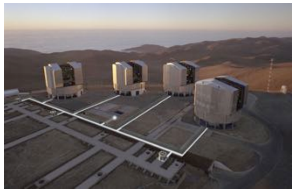
(still assuming chemical equilibrium & 1D)

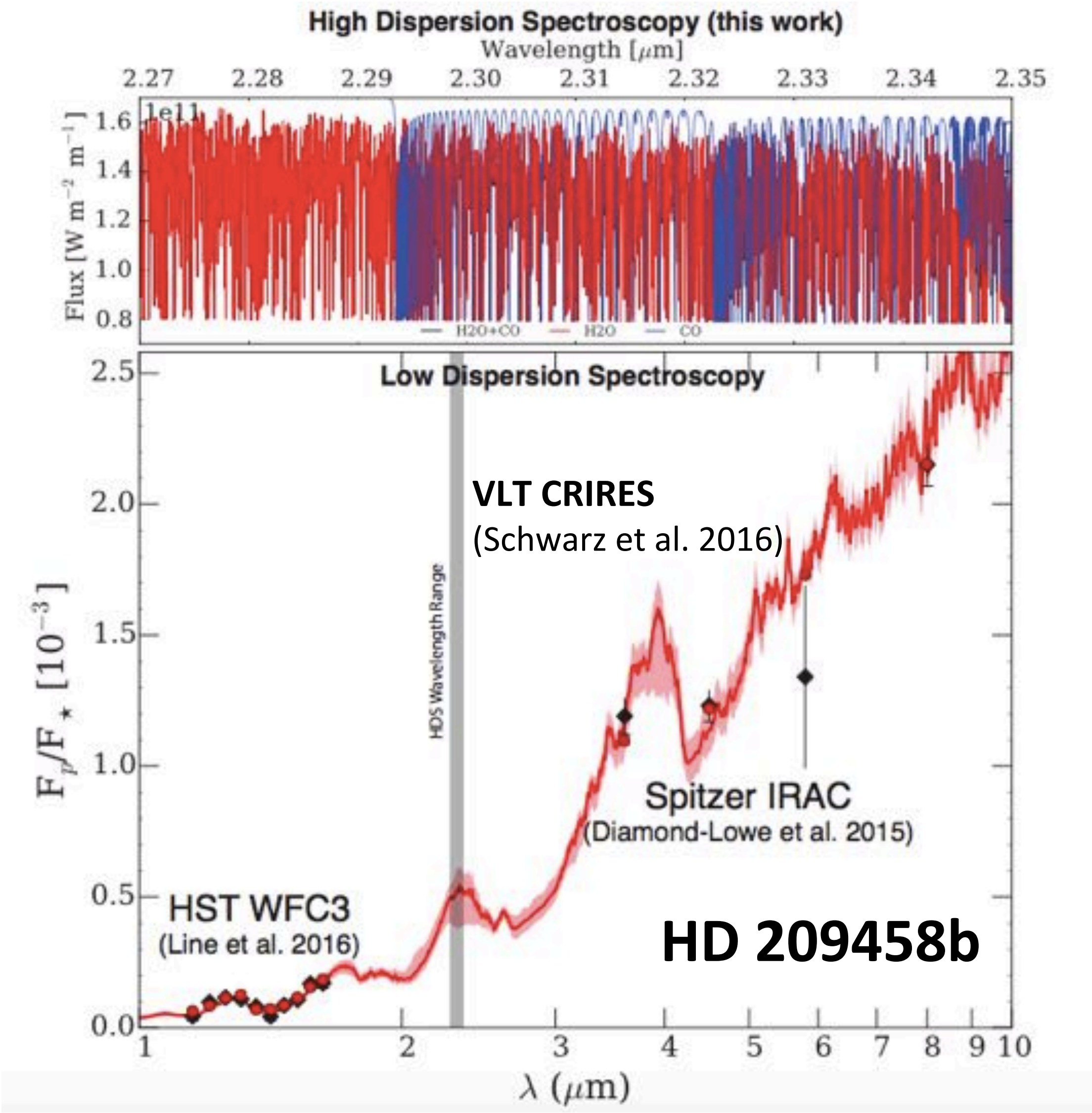
Kreidberg+ 2015

See also Benneke arXiv:1504.07655

Combining high- and low-resolution spectroscopy

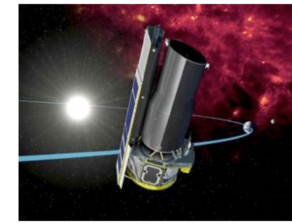


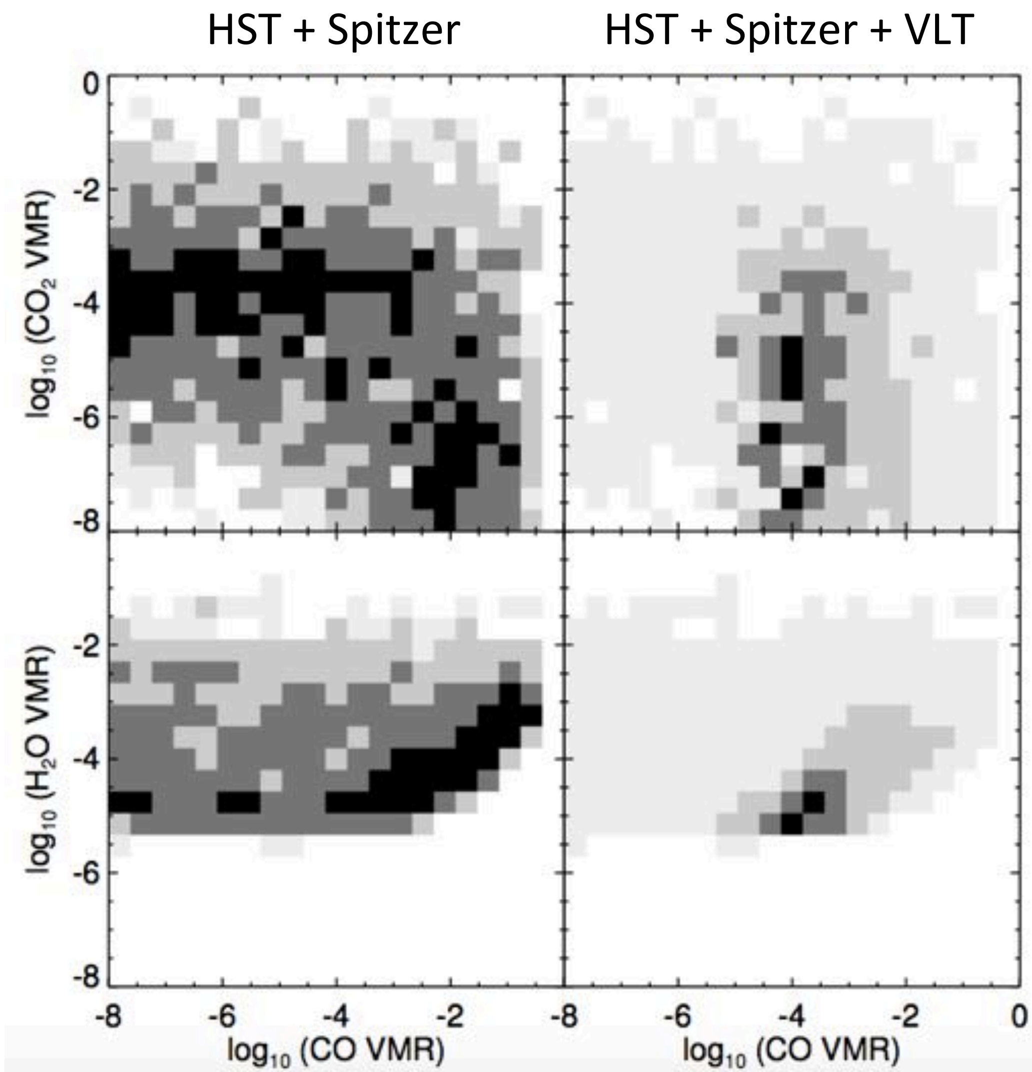




Brogi+ 2017

Combining high- and low-resolution spectroscopy

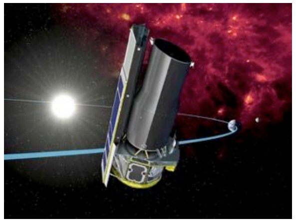


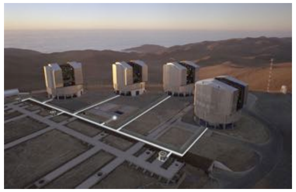


HD 209458b

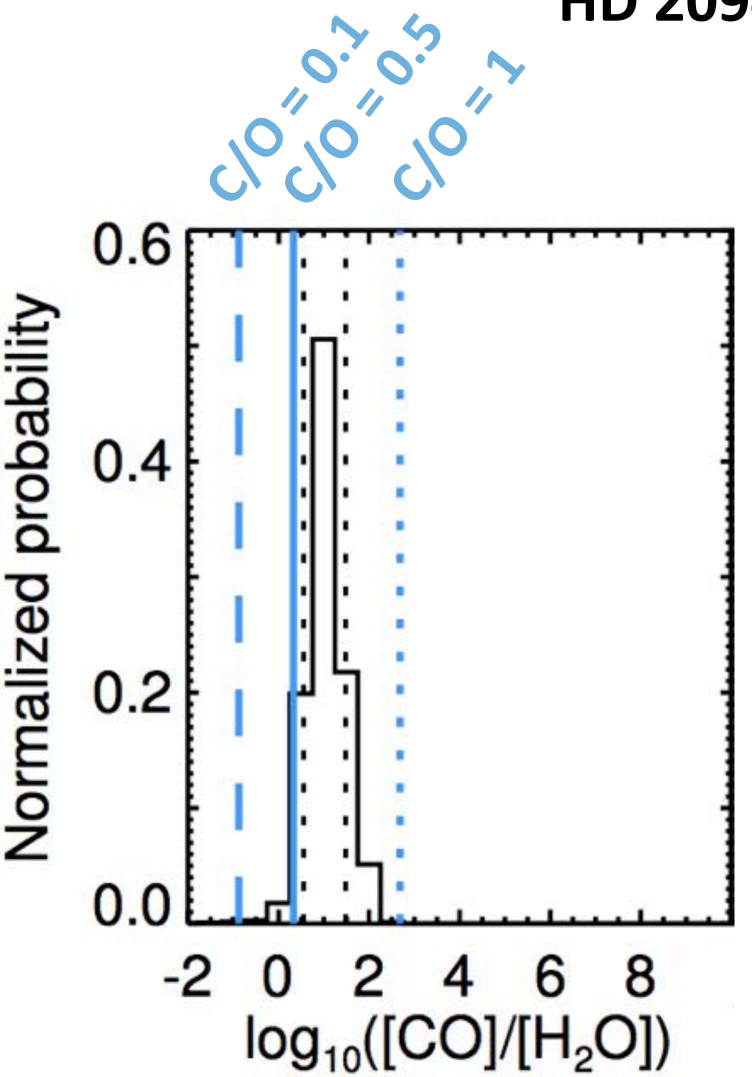
Brogi+ 2017

Combining high- and low-resolution spectroscopy





HD 209458b



Results in a nutshell:

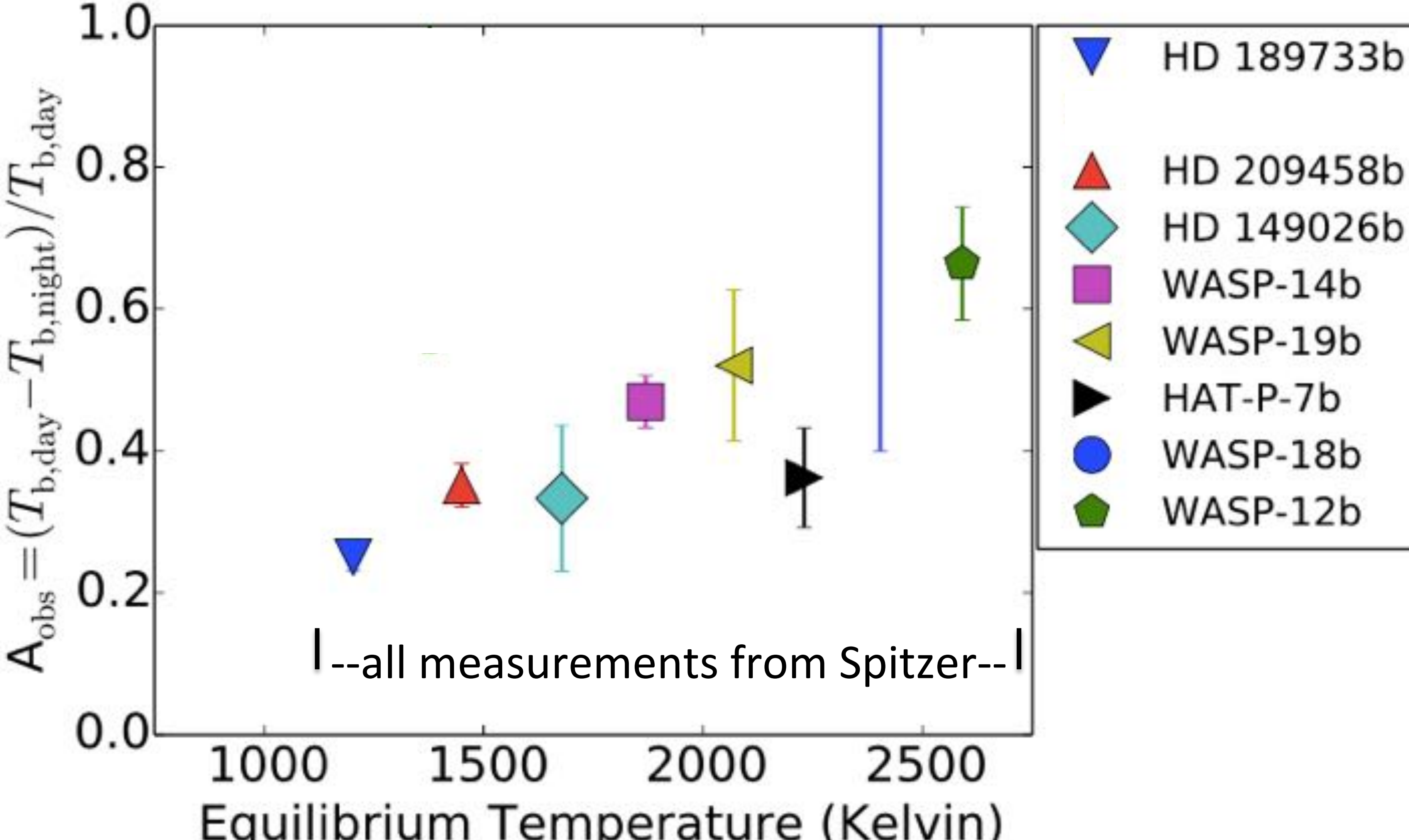
C/O < 1 at more than 3σ confidence

C/O likely super-stellar

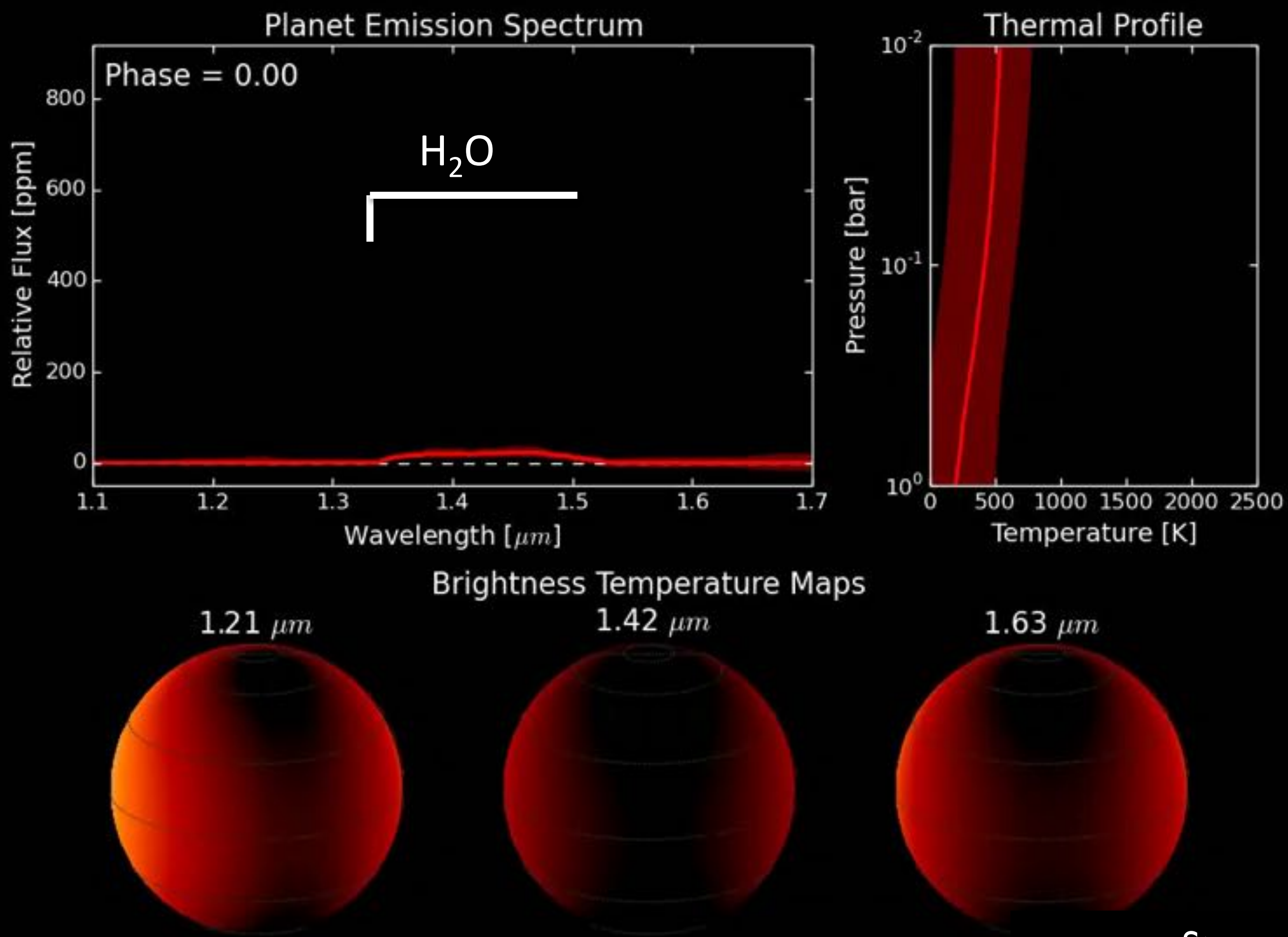
Brogi+ 2017

Key Question #3: **How do planetary atmospheres transport heat?**

Komacek & Showman 2016



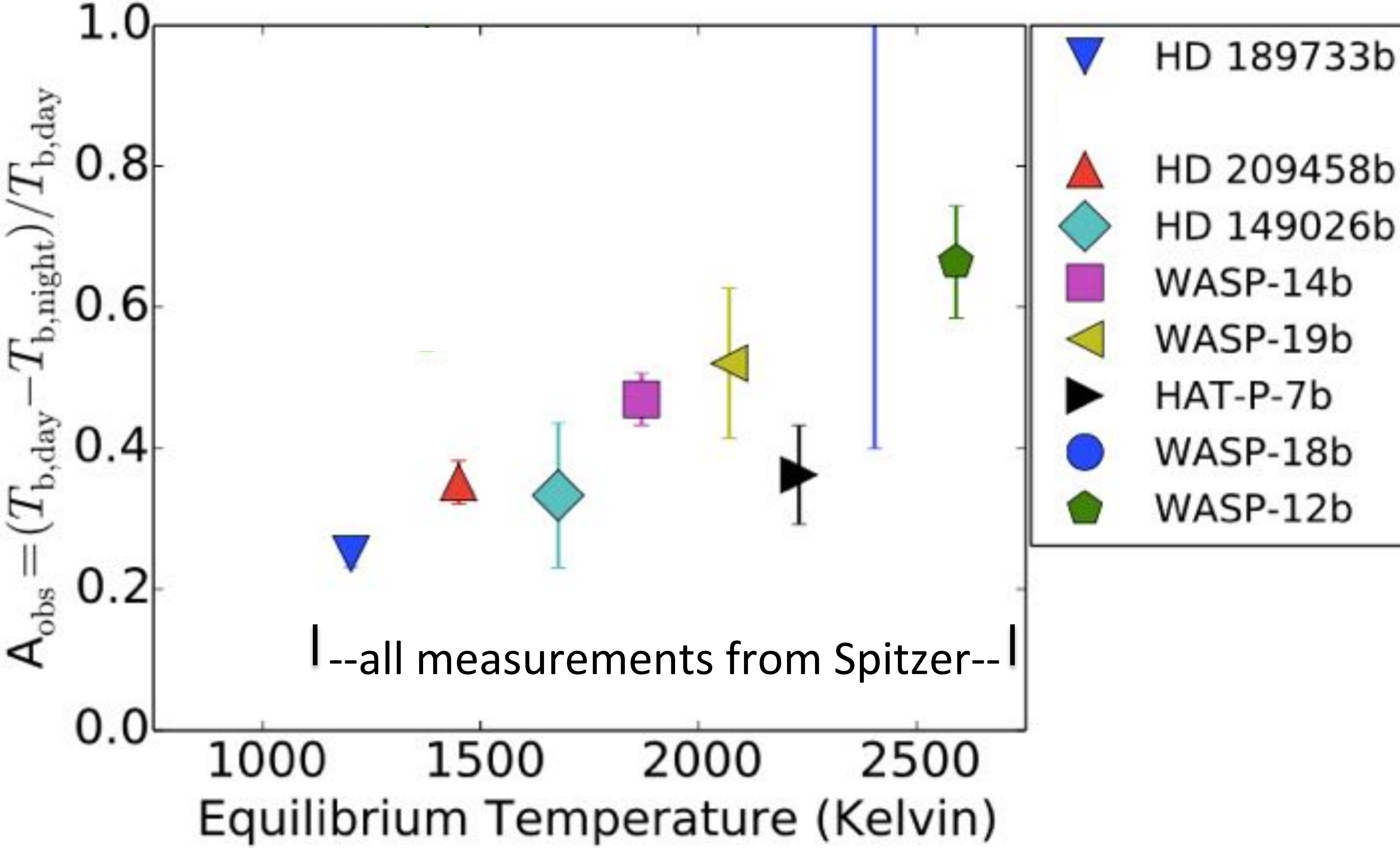
The Global Thermal Structure of WASP-43b



Stevenson+ 2014b

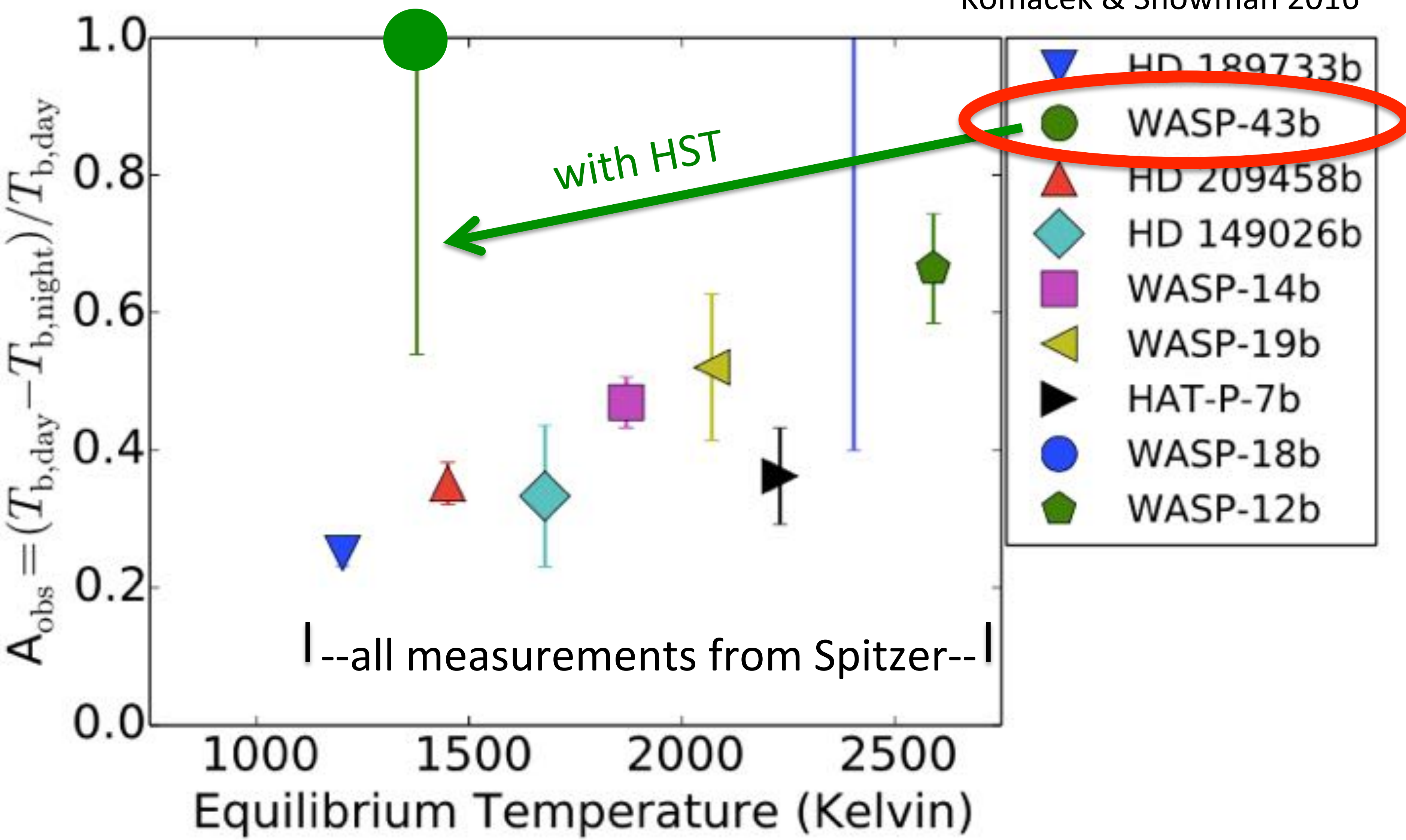
Key Question #3: **How do planetary atmospheres transport heat?**

Komacek & Showman 2016



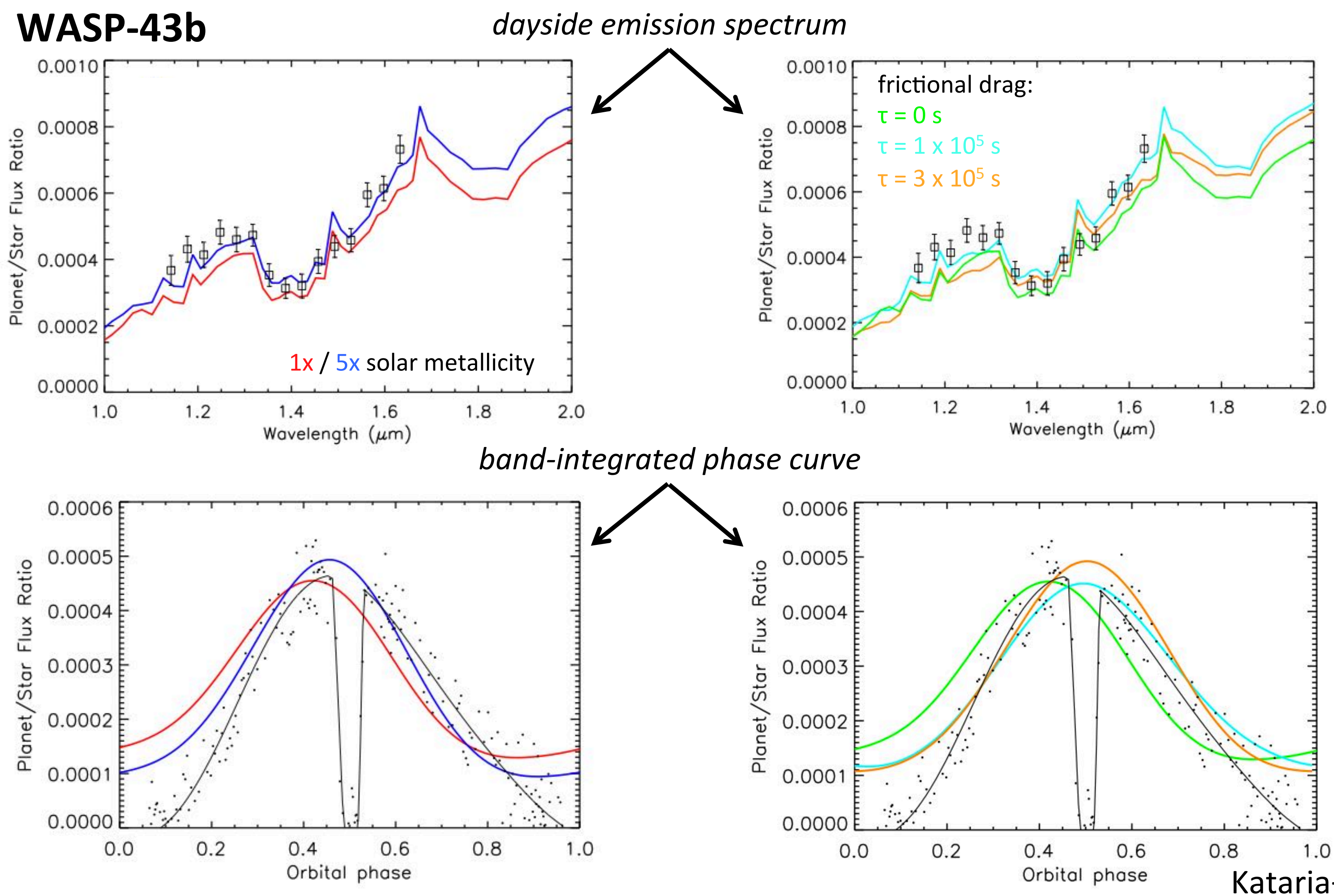
Key Question #3: **How do planetary atmospheres transport heat?**

Komacek & Showman 2016



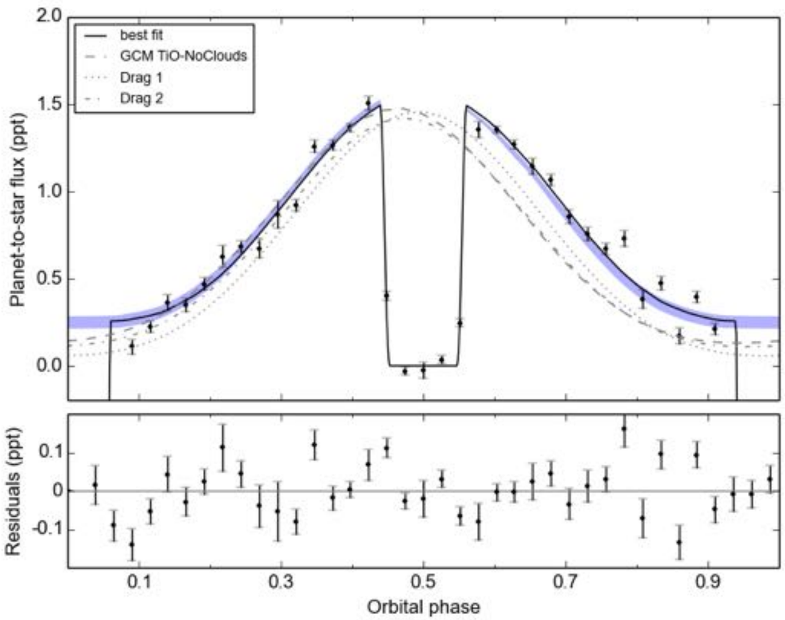
Key Question #3: **How do planetary atmospheres transport heat?**

WASP-43b



Kataria+ 2015

New HST/WFC3 Phase Curves



WASP-103b

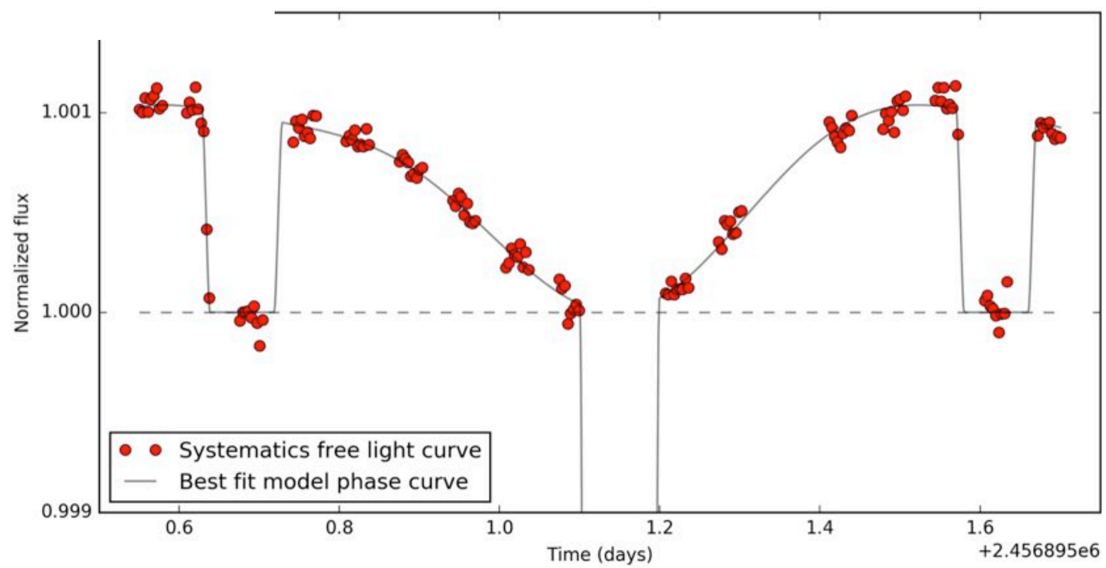
Similar gravity and rotation rate as WASP-43b, but much hotter (3000 vs 1700 K)

Project led by Laura Kreidberg (Harvard CfA)

WASP-18b

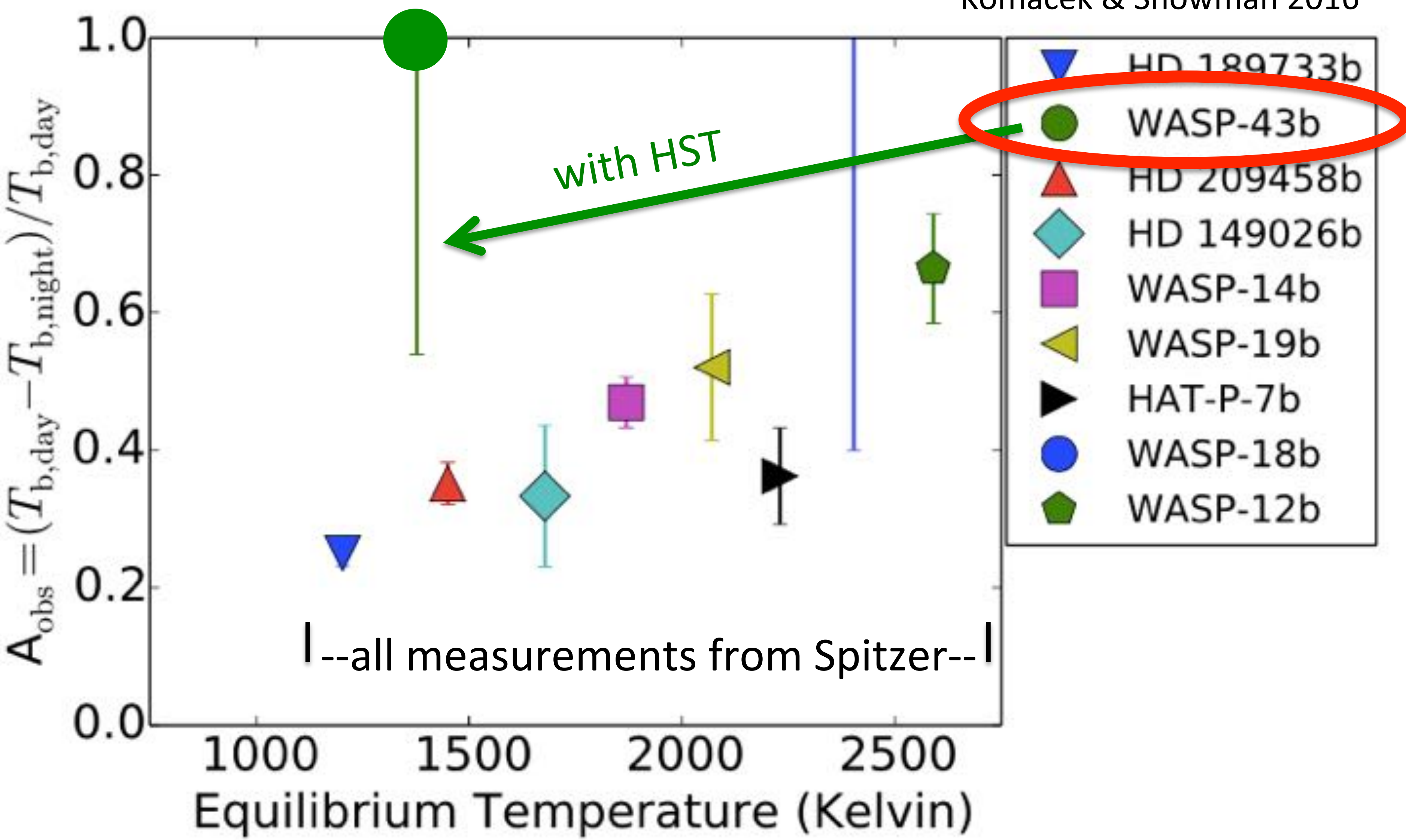
Similar T as WASP-103b, but much higher gravity (10 vs 1.5 M_{jup})

Analysis led by Jacob Arcangeli (U. Amsterdam)



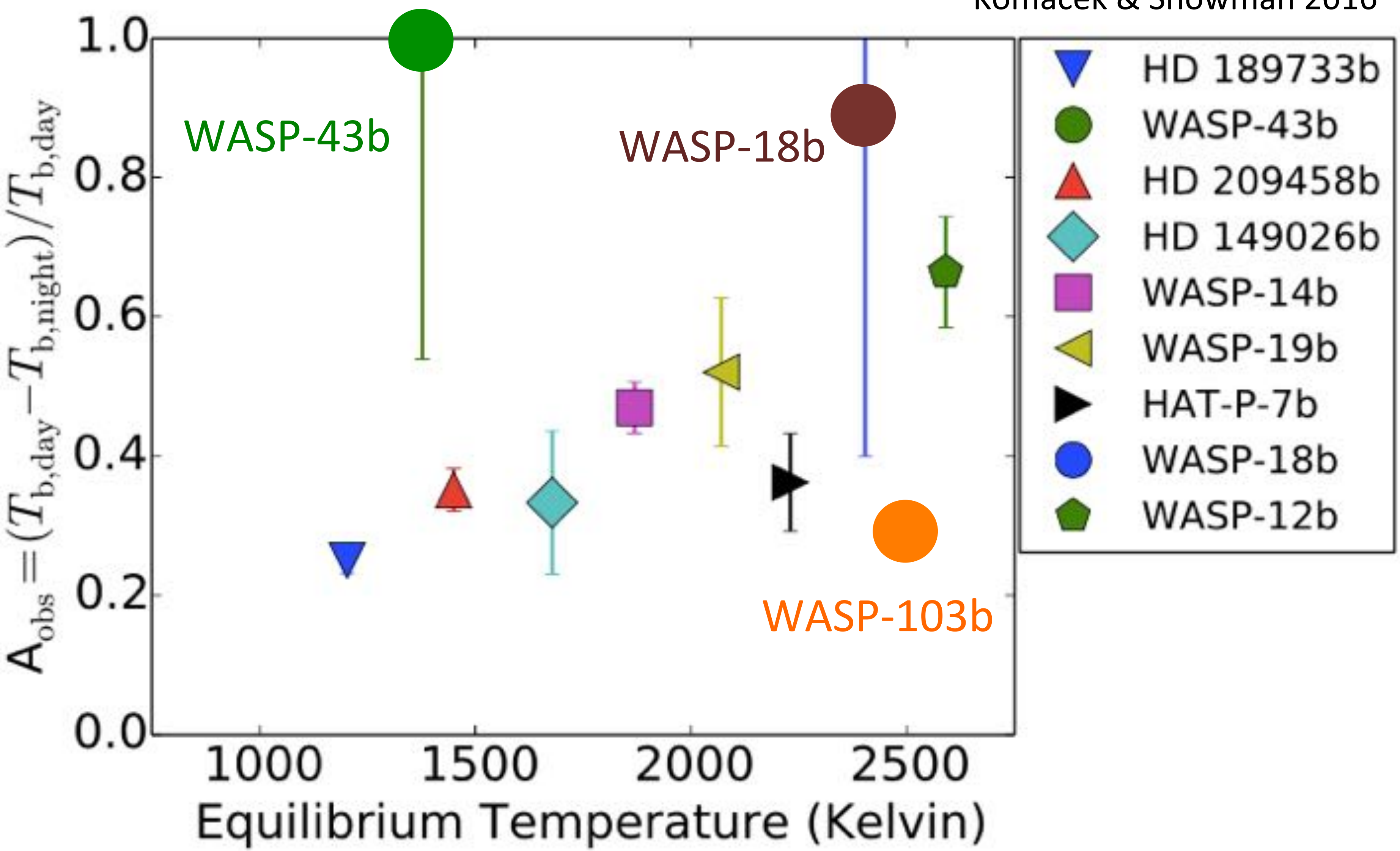
Key Question #3: **How do planetary atmospheres transport heat?**

Komacek & Showman 2016

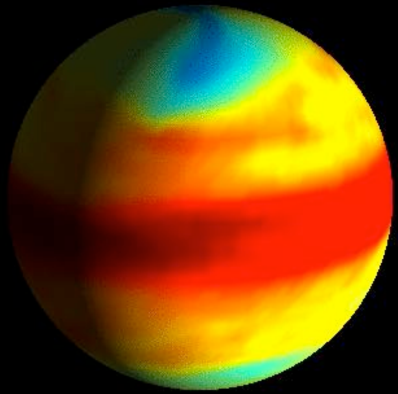


Key Question #3: **How do planetary atmospheres transport heat?**

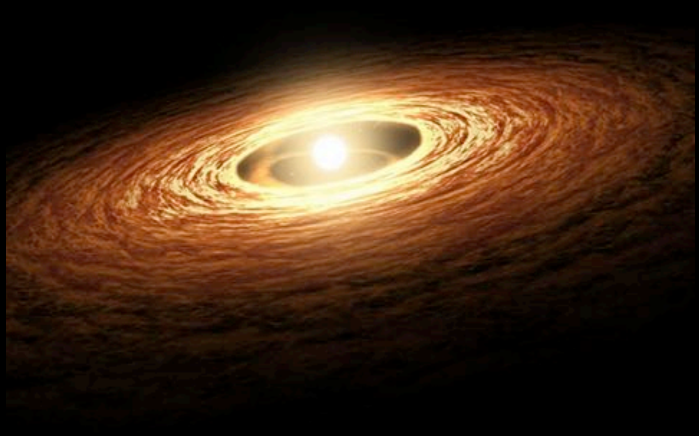
Komacek & Showman 2016



Fundamental Questions for Exoplanet Atmospheres



What are they like?

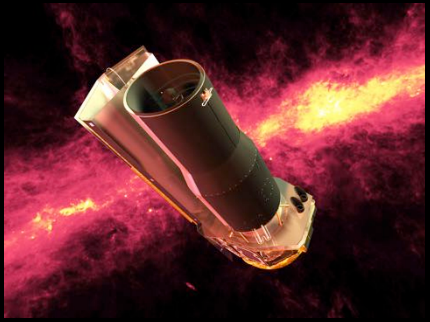


Where did they come from?

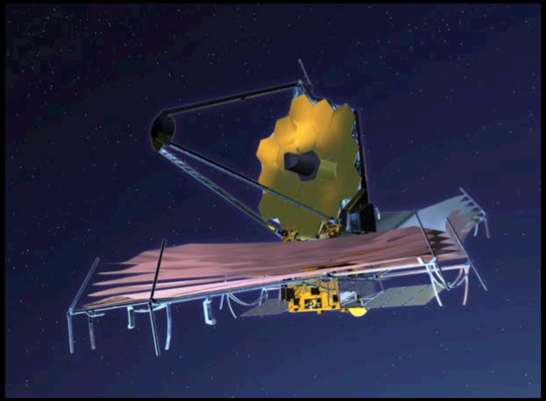
Comparative planetology is the next step

A bright future for comparative exoplanetology!

HST & Spitzer: now

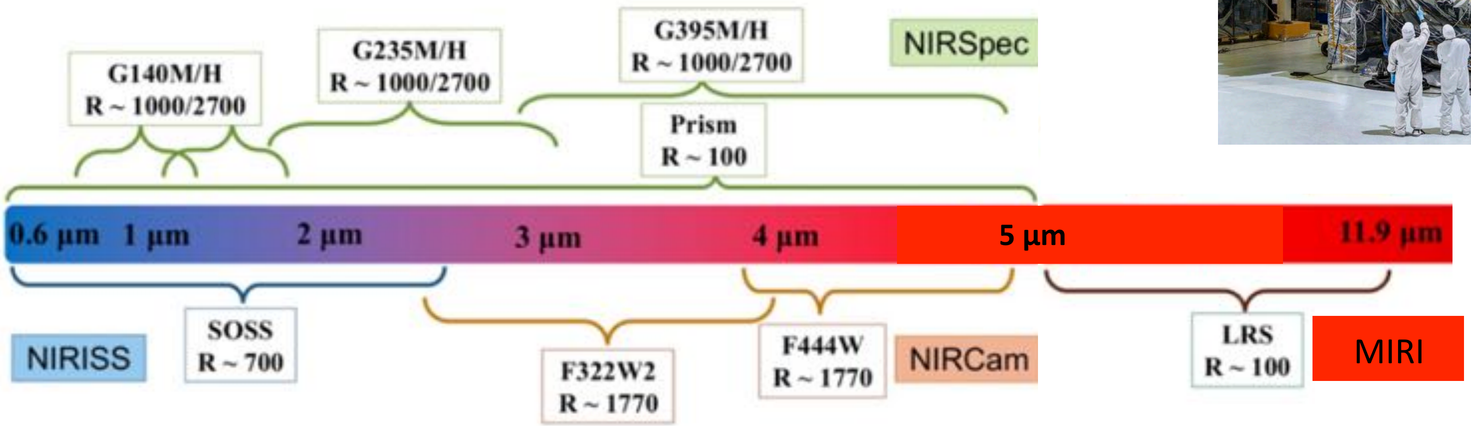


JWST: 2018+

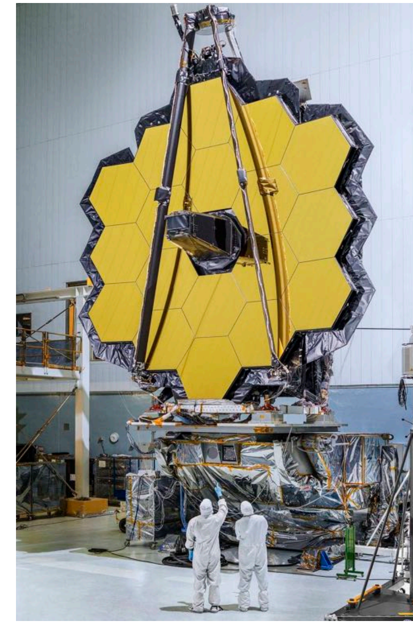


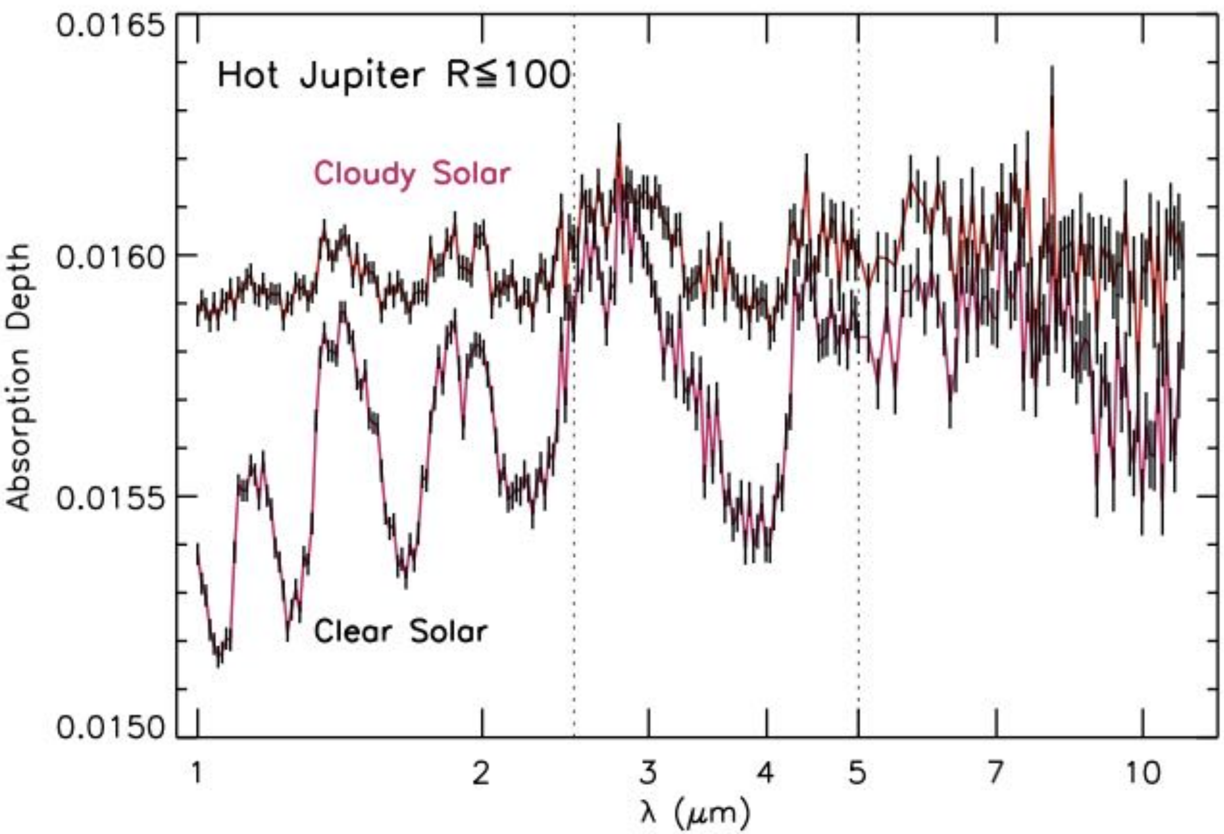
FINESSE: 2020s

The potential of *JWST* for transit spectroscopy



The potential of *JWST* for transit spectroscopy





Greene+ 2016

FINESSE Fast Infrared Exoplanet Spectroscopy Survey Explorer

Exploring the Diversity of New Worlds Around Other Stars

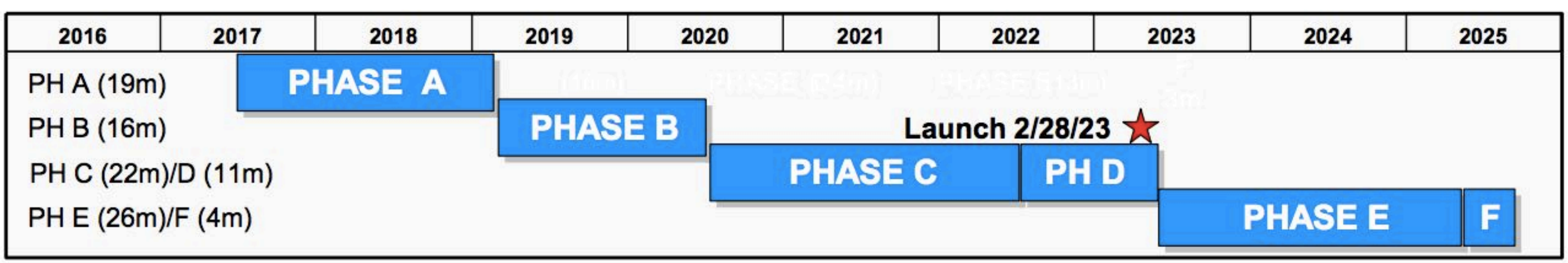
Proposal for the NASA MIDEX AO Dec 15, 2016

Objective

FINESSE will test theories of planetary origins and climate, transform comparative planetology, and open up exoplanet discovery space by performing a comprehensive, statistical, and uniform survey of exoplanet atmospheres.

Strategy

- Transmission spectroscopy of 500 planets
- Phase-resolved emission spectroscopy of 100 planets
- Focus on synergistic science with *JWST*



FINESSE Fast Infrared Exoplanet Spectroscopy Survey Explorer

Exploring the Diversity of New Worlds Around Other Stars

Proposal for the NASA MIDEX AO Dec 15, 2016

People

- PI: Mark Swain
- Mission Development & Operations: Robert Green, Edward Wright, Gautam Vasisht
- Science Team: Jacob Bean, Nicholas Cowan, Jonathan Fortney, Caitlin Griffith, Tiffany Kataria, Eliza Kempton, Laura Kreidberg, David Latham, Michael Line, Suvrath Mahadevan, Jorge Melendez, Julianne Moses, Gael Roudier, Evgenya Shkolnik, Adam Showman, Kevin Stevenson, Yuk Yung, Robert Zellem

FINESSE Fast Infrared Exoplanet Spectroscopy Survey Explorer

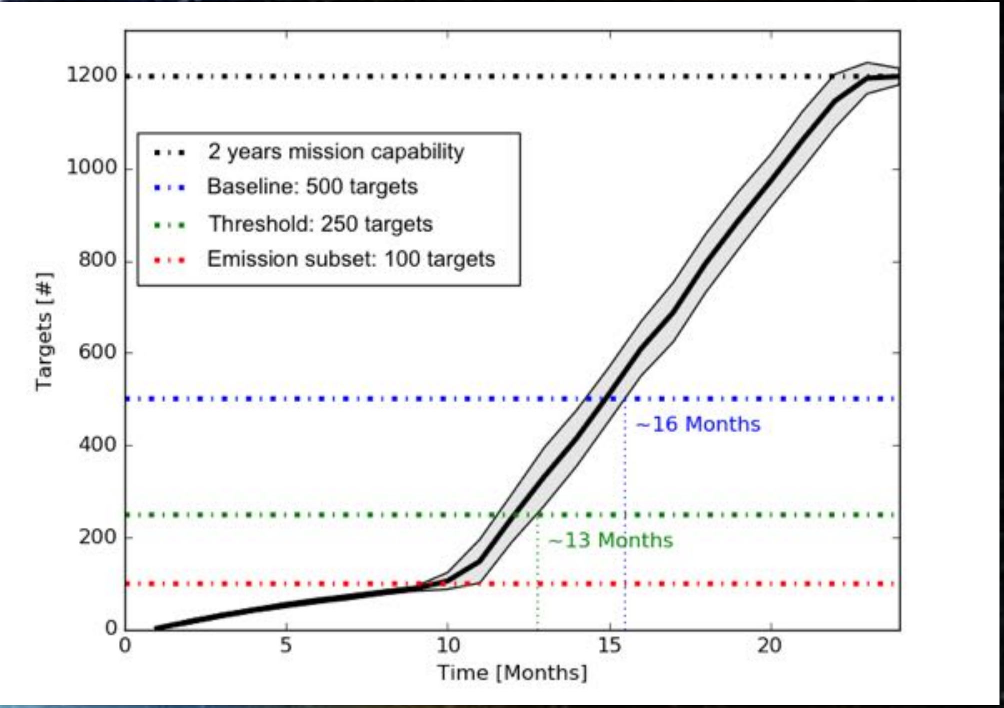
Exploring the Diversity of New Worlds Around Other Stars

Mission Overview

- Earth-Sun L2 (Heliocentric) orbit
- 2016 MIDEX Standard LV compatible
- Near-unrestricted launch period (better than 95% launch availability)
- DSN stations for downlink (one eight-hour pass/week during Science Operations)
- Two-year Baseline Science Mission duration
- Full-sky coverage every four months

Payload

- Telescope, 75 cm Cassegrain
  - All-aluminum, IR surface figure
  - Passively cooled to 125 K
- Spectrometer, 0.5–5.0 μm,
  - $\lambda/\Delta\lambda \cong 80$ @ 1.2 μm, 300 @ 3 μm
  - Passively cooled to 90 K
  - Single observing mode, high stability
- Payload in the loop fine guidance
  - Integrated with spectrometer
  - Uses separate window on science detector for guiding
- Single detector, HgCdTe, JWST/NIRSpec copy
  - Passively cooled to 70 K



FINESSE Fast Infrared Exoplanet Spectroscopy Survey Explorer

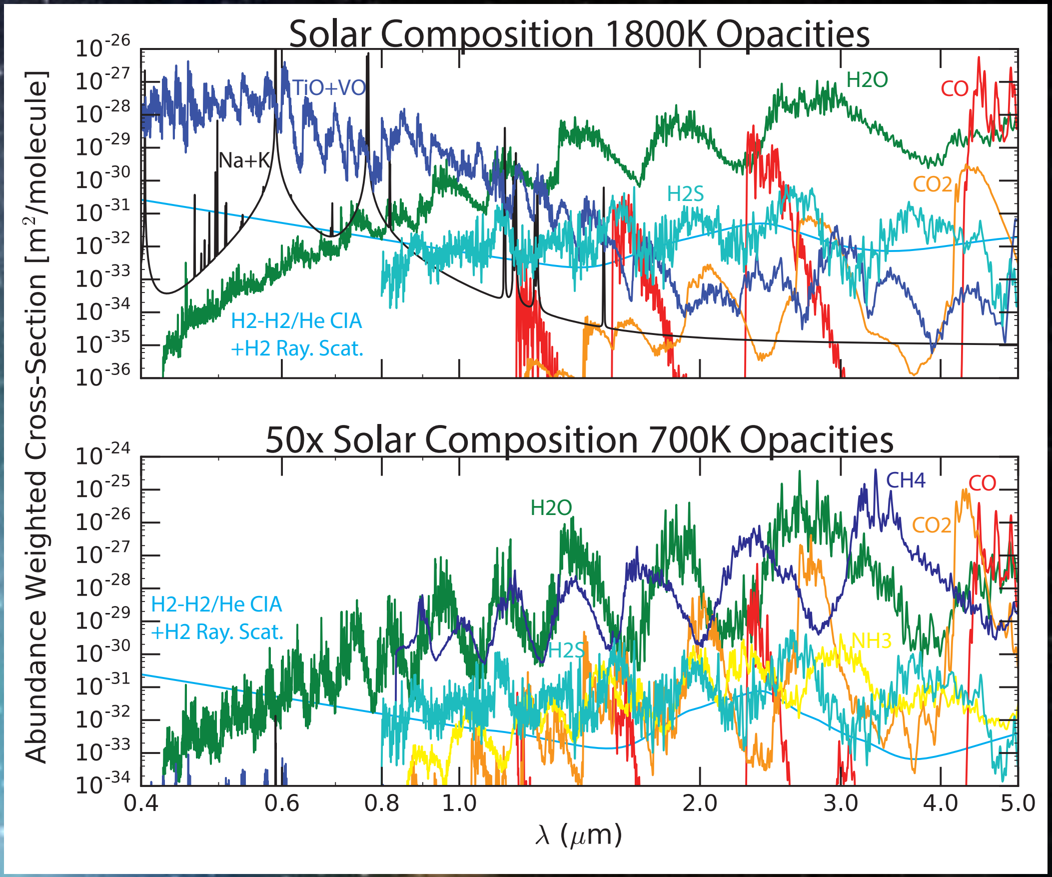
Exploring the Diversity of New Worlds Around Other Stars

Mission Overview

- Earth-Sun L2 (Heliocentric) orbit
- 2016 MIDEX Standard LV compatible
- Near-unrestricted launch period (better than 95% launch availability)
- DSN stations for downlink (one eight-hour pass/week during Science Operations)
- Two-year Baseline Science Mission duration
- Full-sky coverage every four months

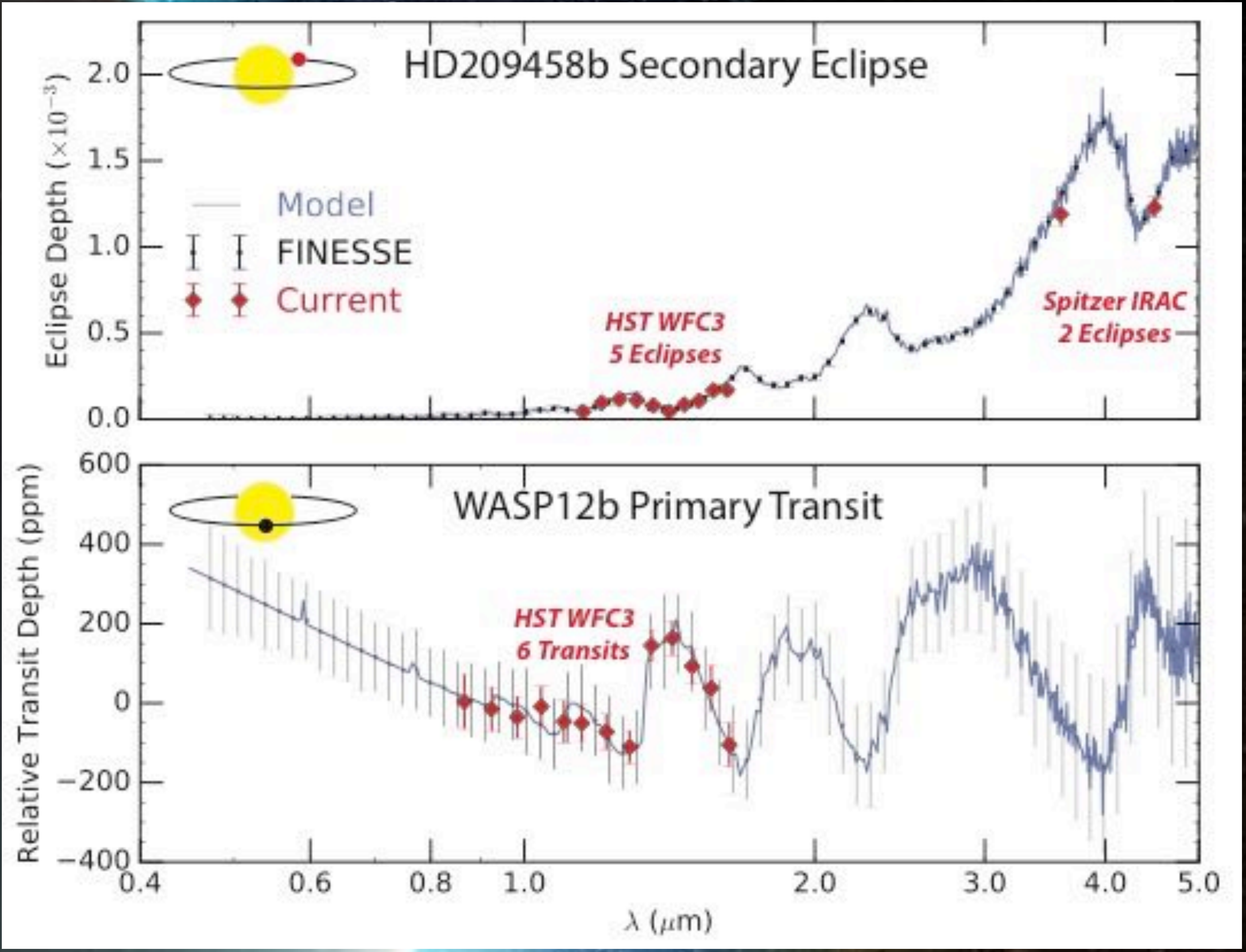
Payload

- Telescope, 75 cm Cassegrain
  - All-aluminum, IR surface figure
  - Passively cooled to 125 K
- Spectrometer, 0.5–5.0 μm,
  - λ/Δλ ≅ 80 @ 1.2 μm, 300 @ 3 μm
  - Passively cooled to 90 K
  - Single observing mode, high stability
- Payload in the loop fine guidance
  - Integrated with spectrometer
  - Uses separate window on science detector for guiding
- Single detector, HgCdTe, JWST/NIRSpec copy
  - Passively cooled to 70 K



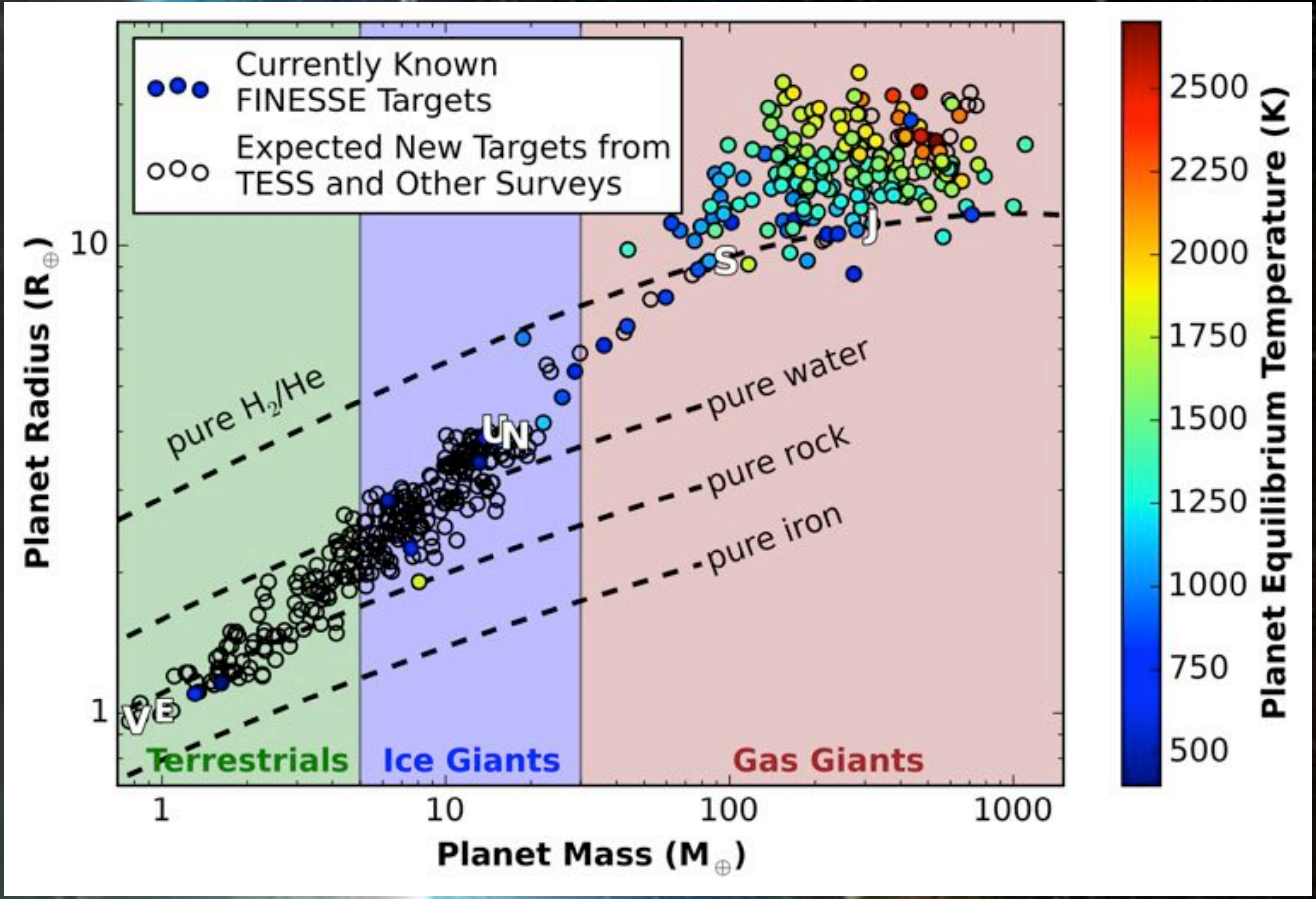
FINESSE Fast Infrared Exoplanet Spectroscopy Survey Explorer

Exploring the Diversity of New Worlds Around Other Stars



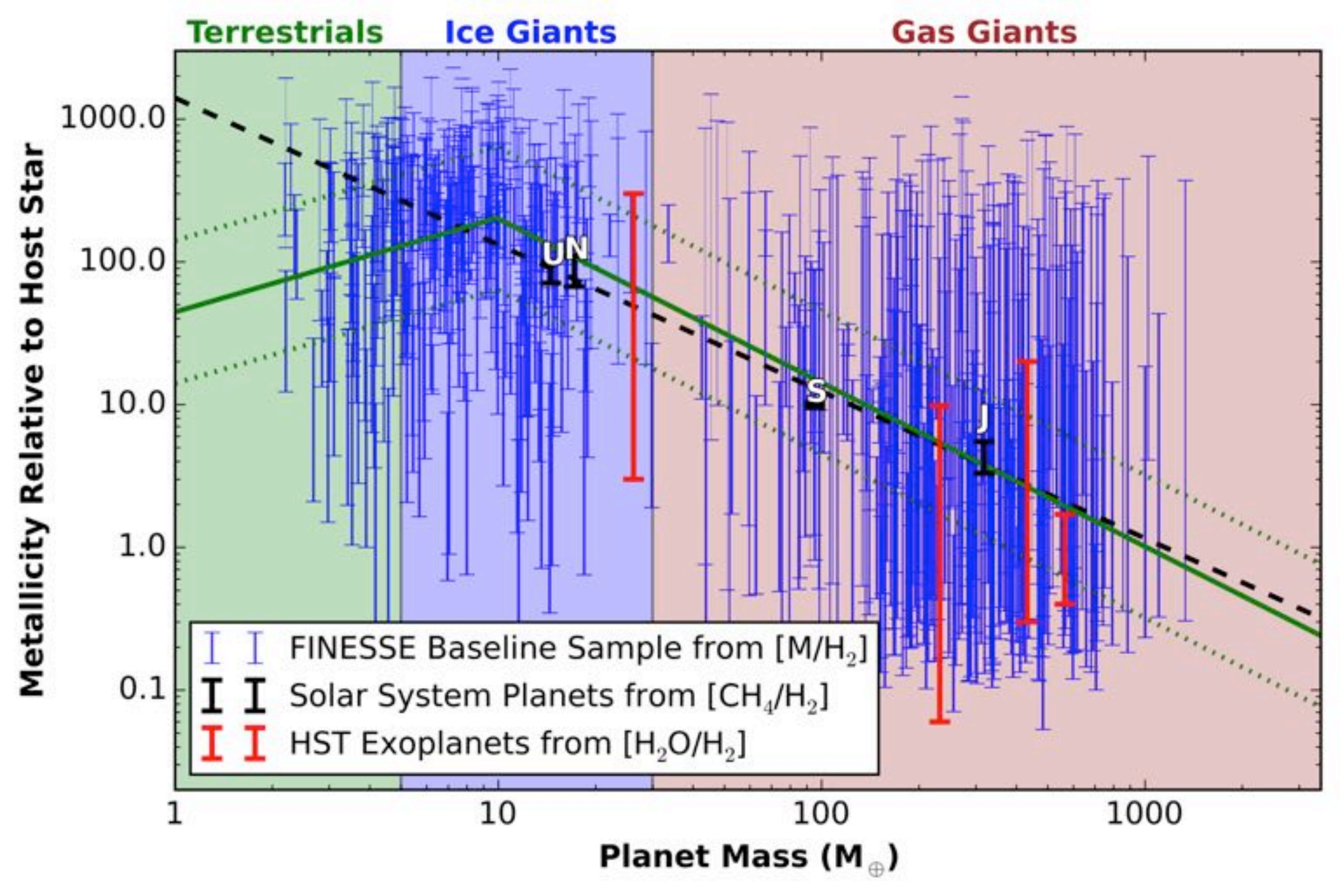
FINESSE Fast Infrared Exoplanet Spectroscopy Survey Explorer

Exploring the Diversity of New Worlds Around Other Stars



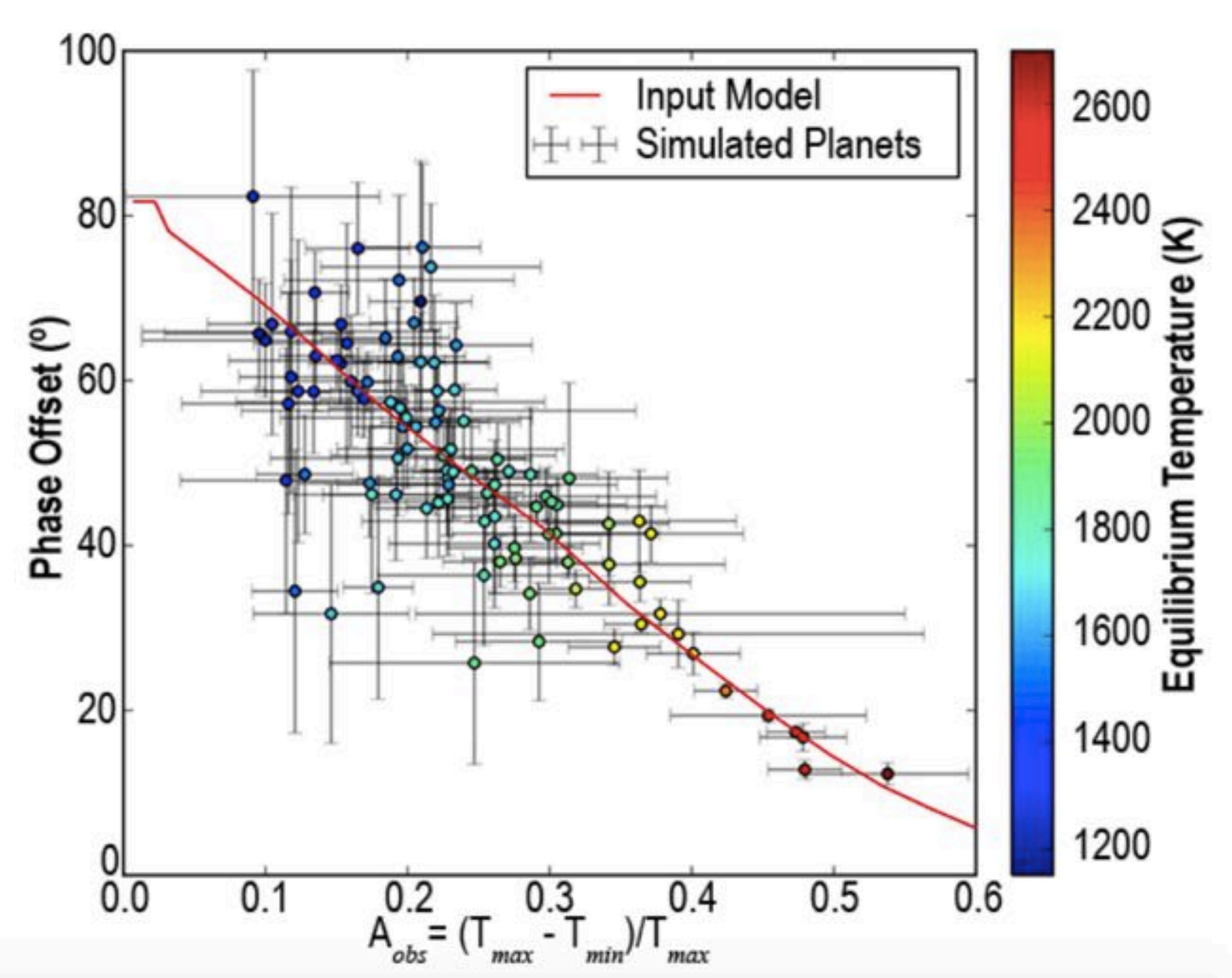
FINESSE Fast Infrared Exoplanet Spectroscopy Survey Explorer

Exploring the Diversity of New Worlds Around Other Stars

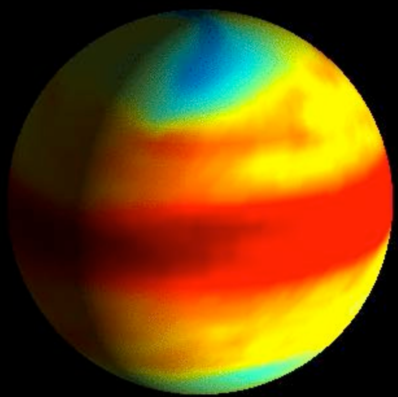


FINESSE
Fast Infrared Exoplanet Spectroscopy Survey Explorer

Exploring the Diversity of New Worlds Around Other Stars



Fundamental Questions for Exoplanet Atmospheres



What are they like?

Where did they come from?

Are any of them **habitable?**

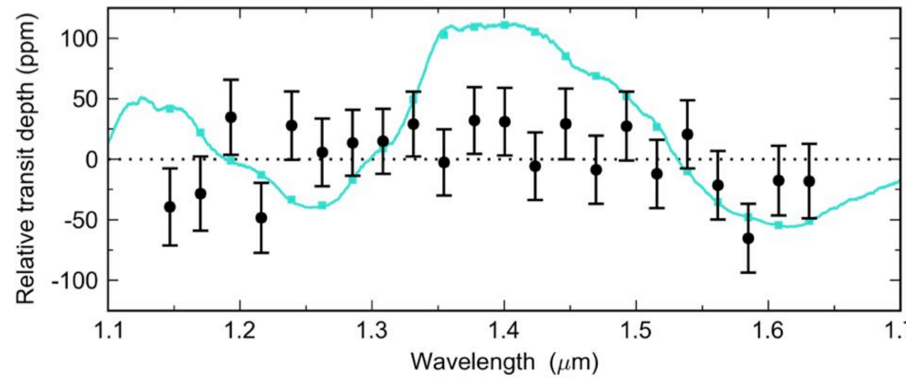
Towards Other Earths with Transit Spectroscopy

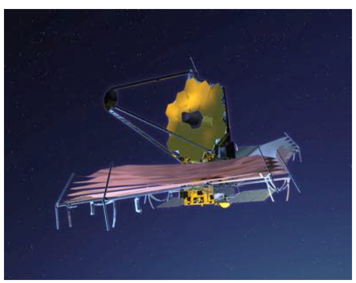
GJ 1214b

$R_p = 2.7\ R_E$
$T = 580$ K

2014
Kreidberg+ (2014a)
precision = 30 ppm

REAL DATA!



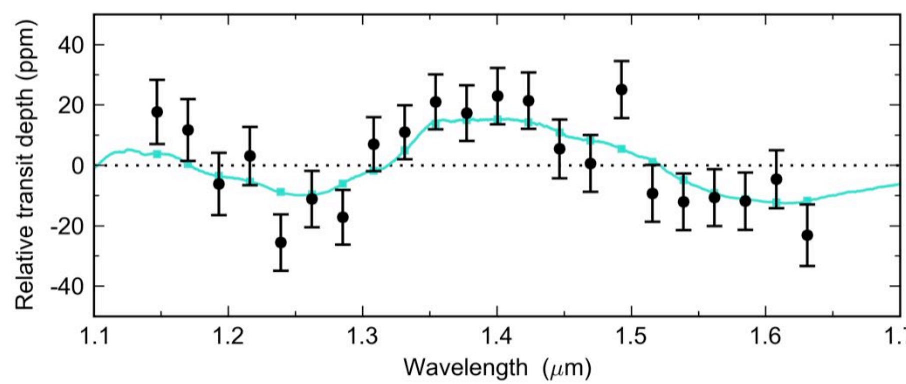


Earth 2.0

$R_p = 1.0\ R_E$
$T = 300$ K

2019
precision = 10 ppm

SIMULATED DATA



N_2-rich, trace H_2O atmosphere