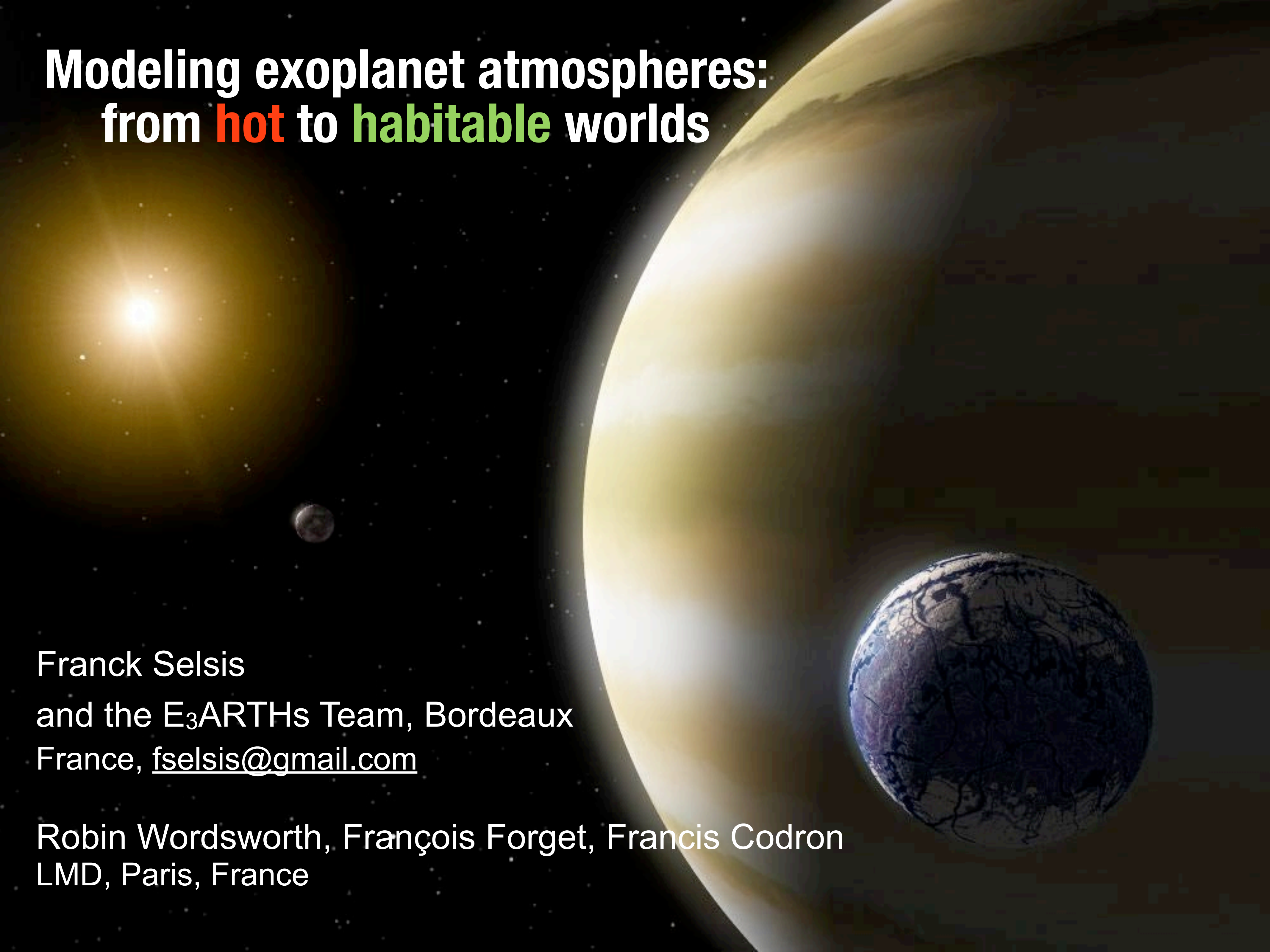
Modeling exoplanet atmospheres: from hot to habitable worlds

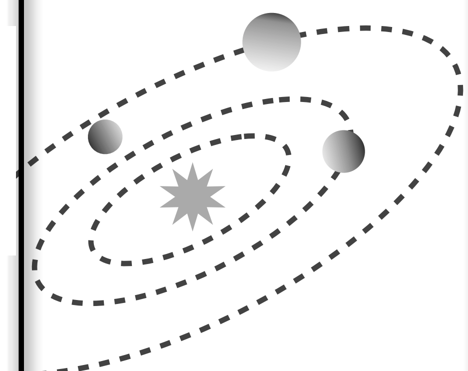


Franck Selsis
and the E$_3$ARTHs Team, Bordeaux
France, fselsis@gmail.com

Robin Wordsworth, François Forget, Francis Codron
LMD, Paris, France

Objectives:

Star
Orbit,
Planet
Atmosphere
characteristics



star *(type, age)*
Orbit *(a, e)*
Planet *(M, R, $\vec{\varpi}$)*
Surface *(H_2O/continents)*
Atmosphere
(P, % N_2, CO_2, CO, H_2, CH_4, ...)

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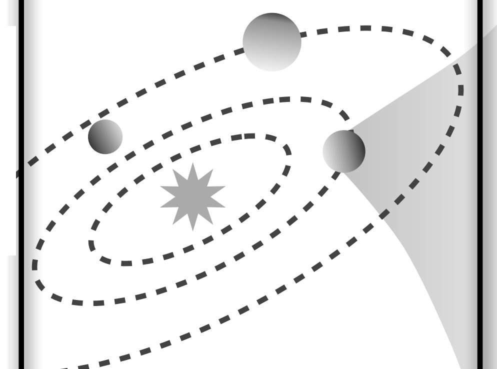

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Atmosphere modeling

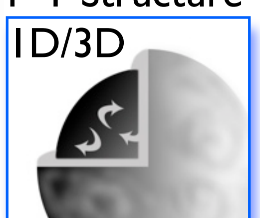
Radiative transfer (1D/3D)

Photochemistry

Molecular data

P-T Structure

1D/3D



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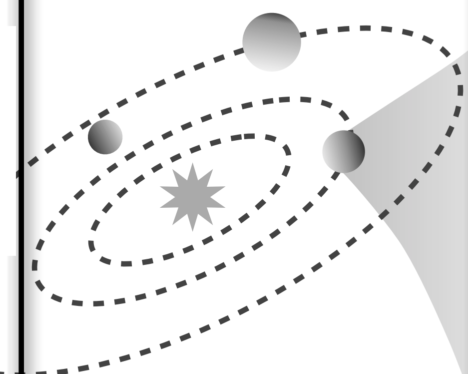

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Exploring the diversity of atmospheres

Habitability
Exotic climate
Early Earth
Prebiotic chemistry

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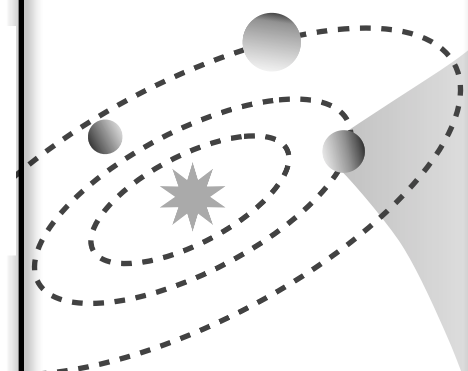

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Photochemistry

Molecular data

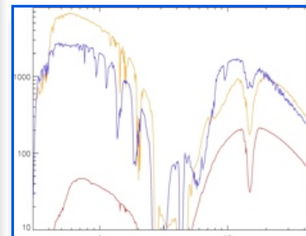
KIDA
Kinetic Database for Astrochemistry

P-T Structure

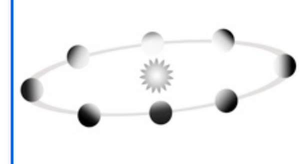
1D/3D

synthetic observables

Spectra
transit, emission, reflection



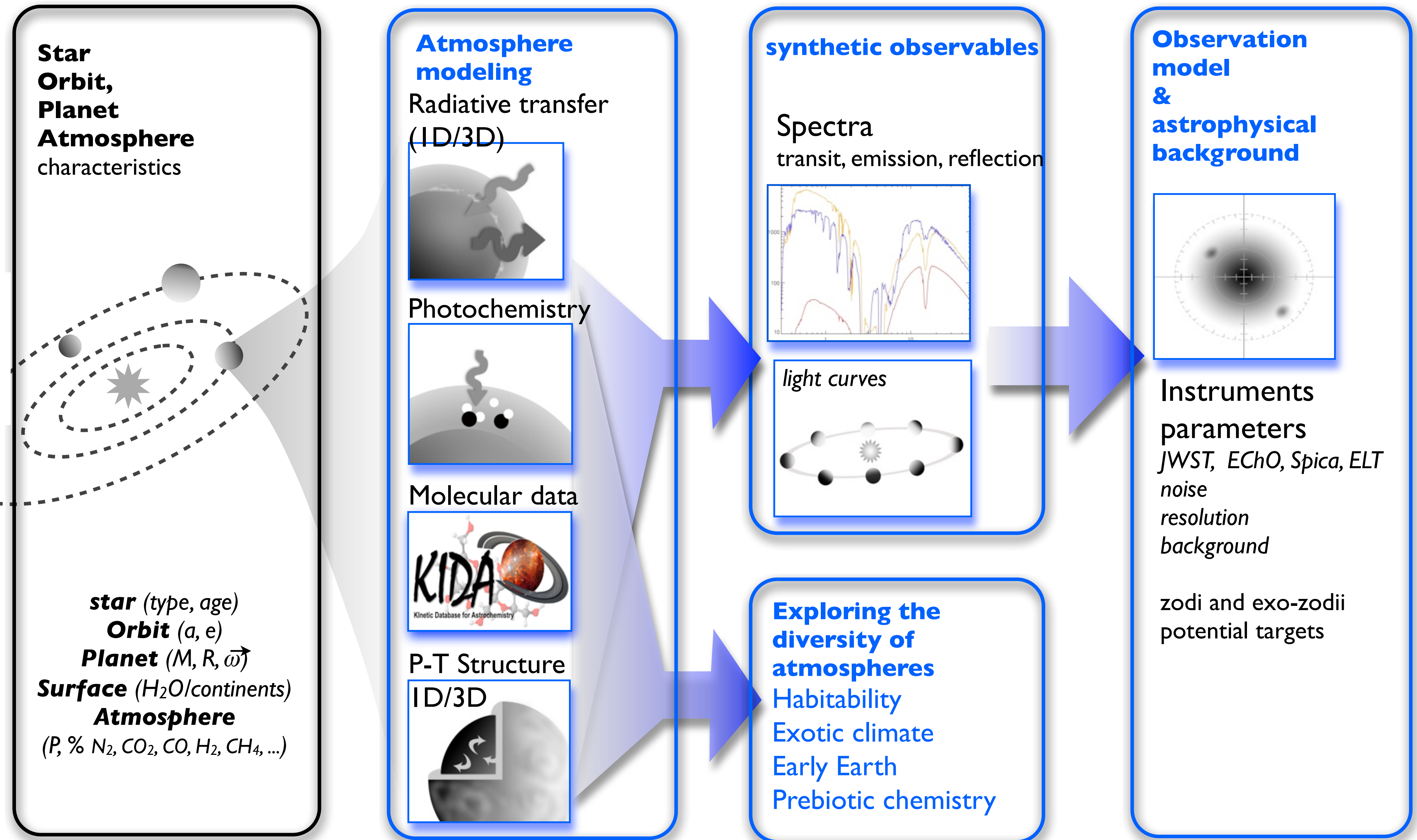
light curves



Exploring the diversity of atmospheres

Habitability
Exotic climate
Early Earth
Prebiotic chemistry

Objectives:



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Orbit,
Planet
Atmosphere
characteristics
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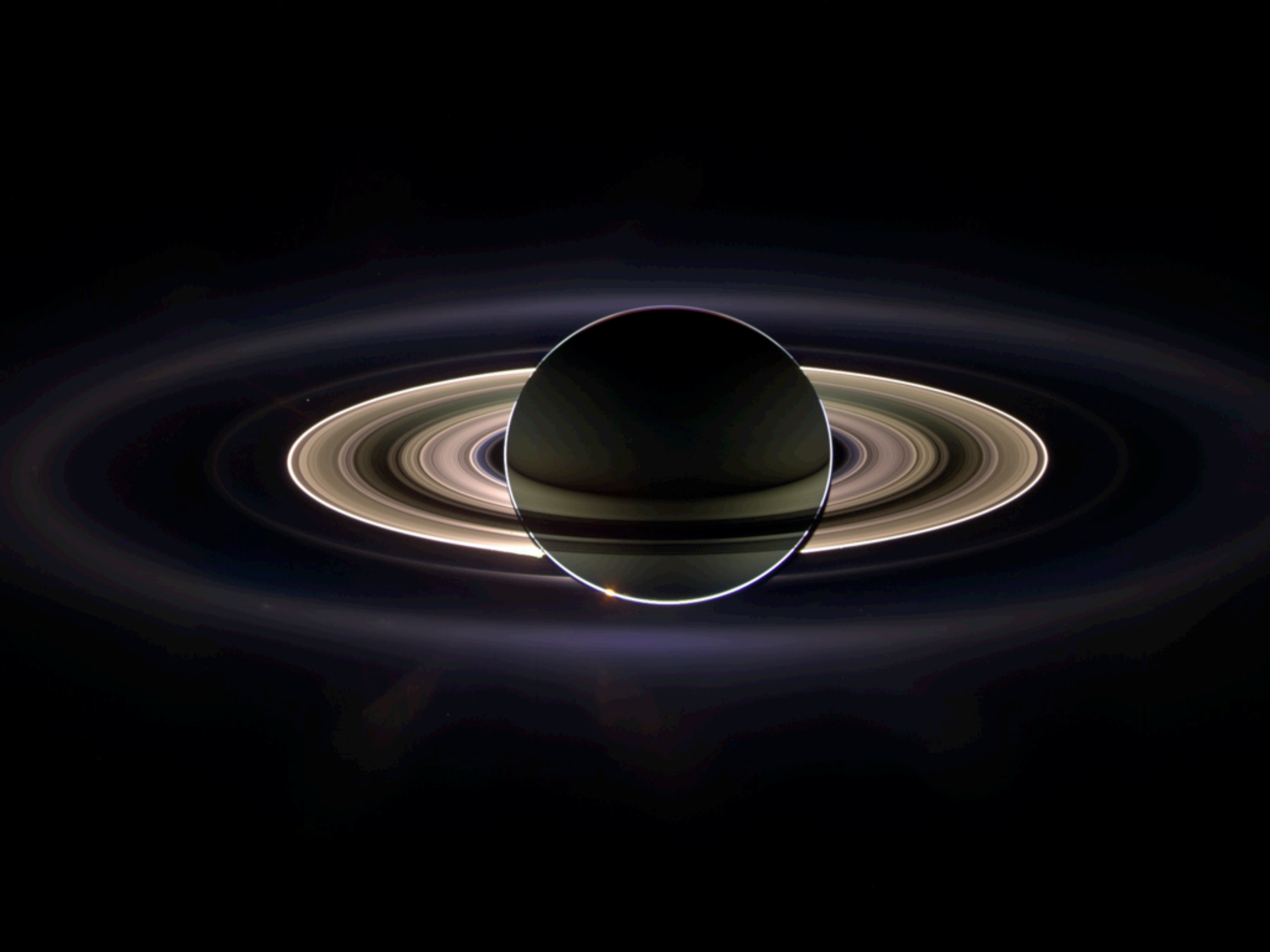
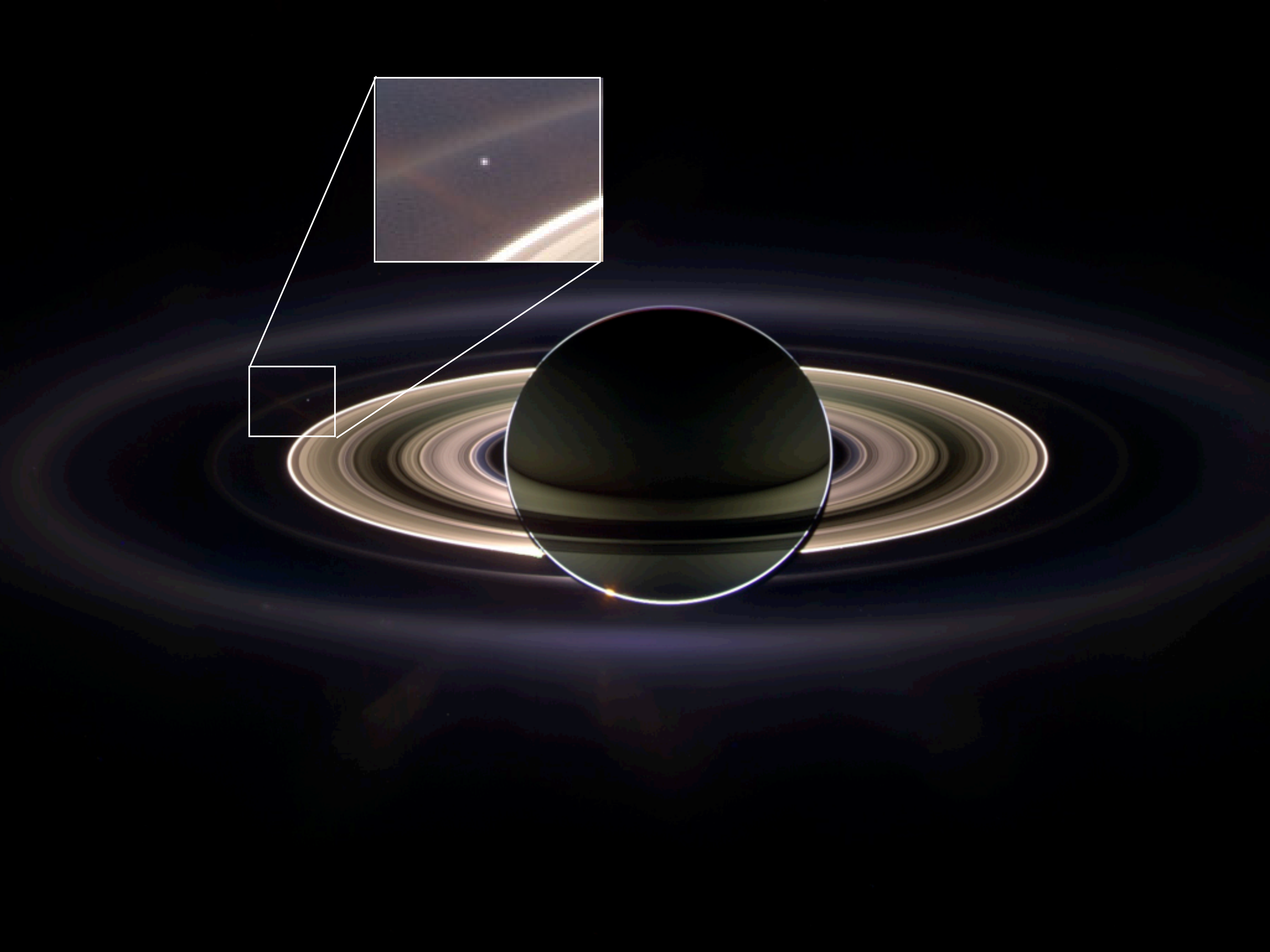
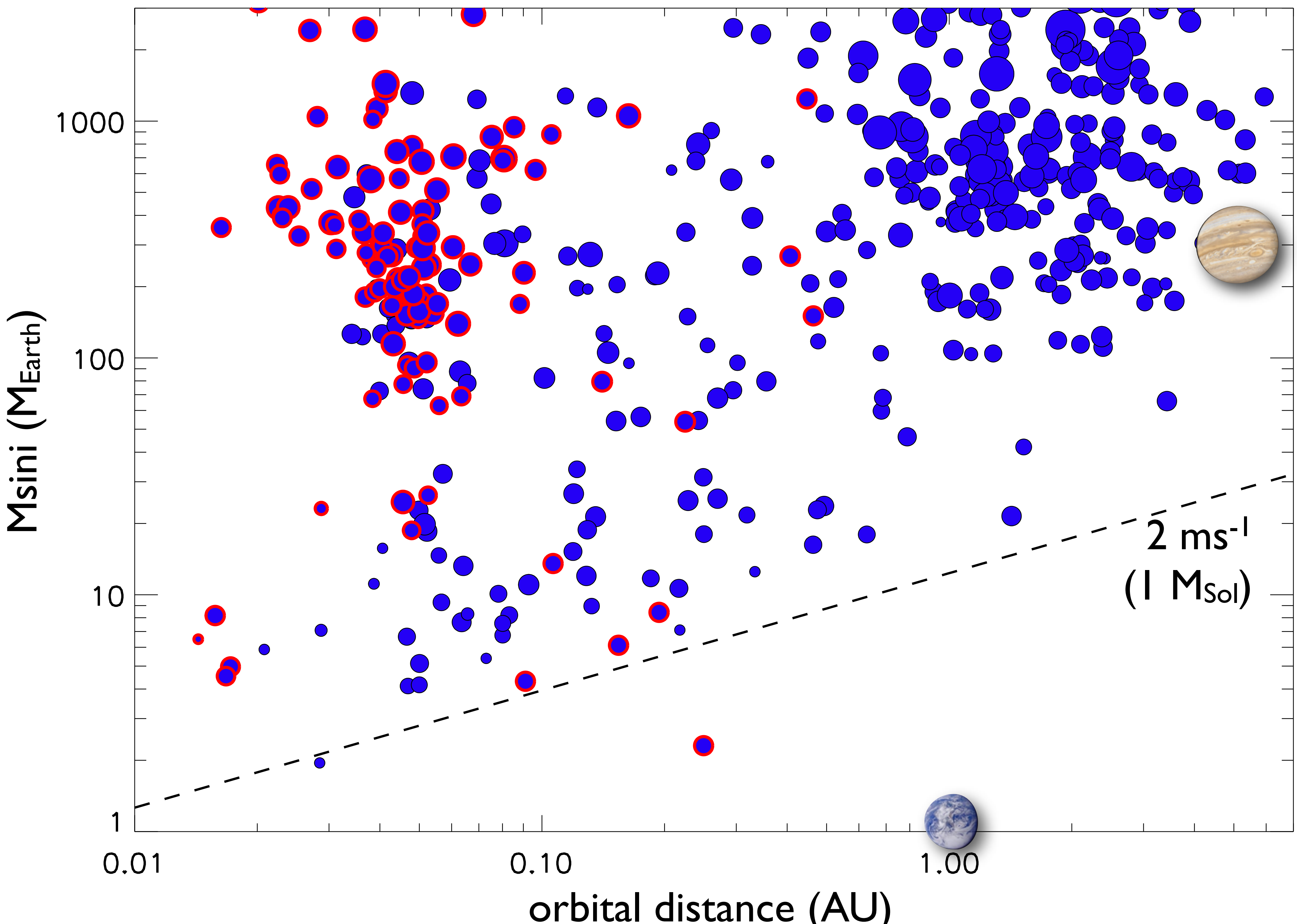
Early Earth
Prebiotic chemistry
Observation model & astrophysical background
Instruments parameters
JWST, EChO, Spica, ELT
noise
resolution
background
zodi and exo-zodii
potential targets



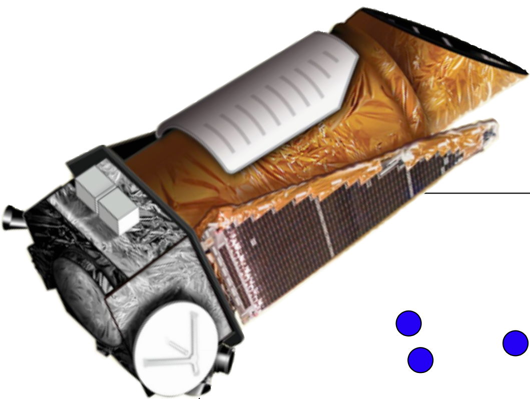


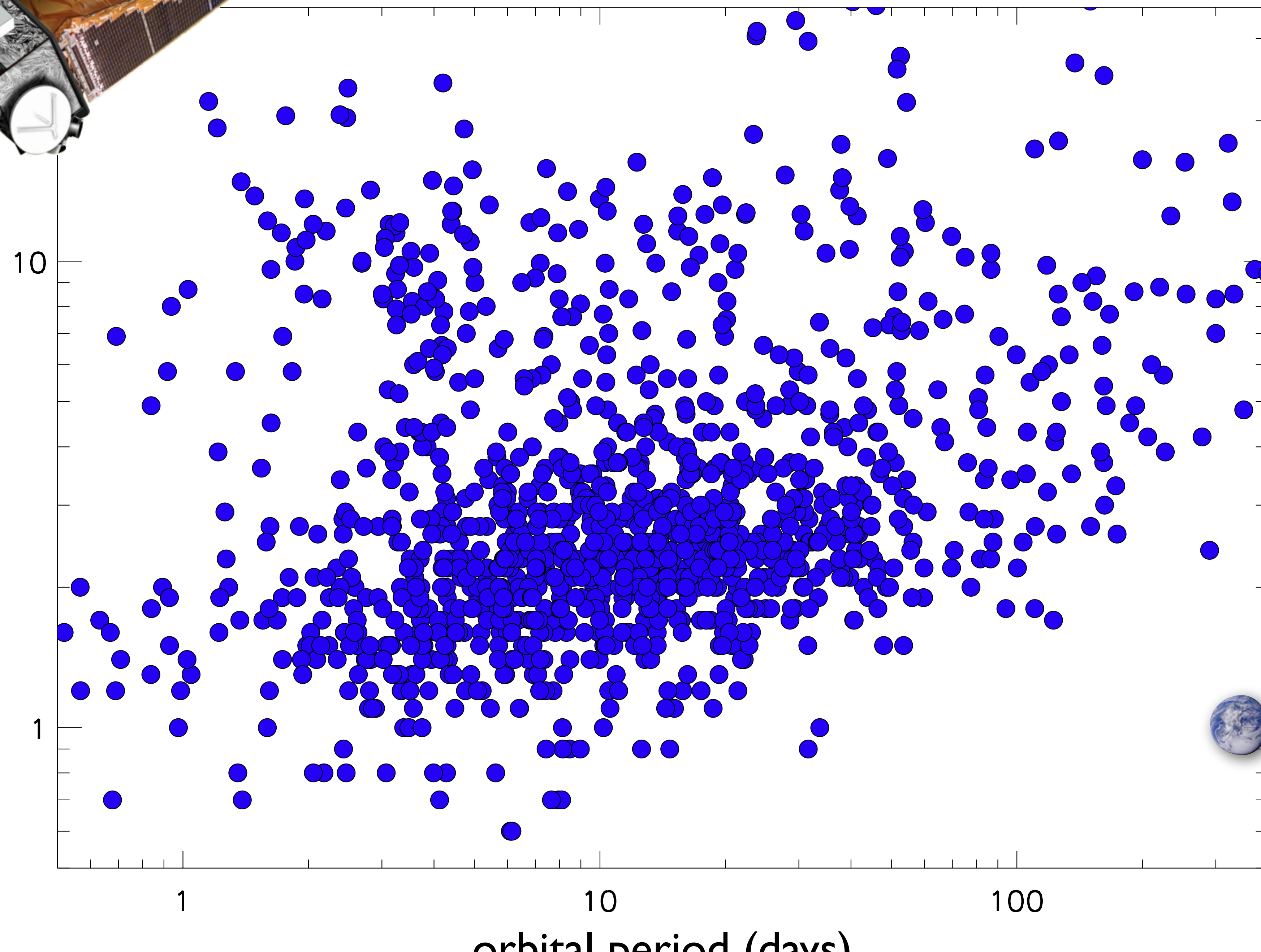
453 confirmed exoplanets, including 112 transiting ones



(data: exoplanets.org)

1235 **Kepler** candidates (*Borucki et al., 2011*)





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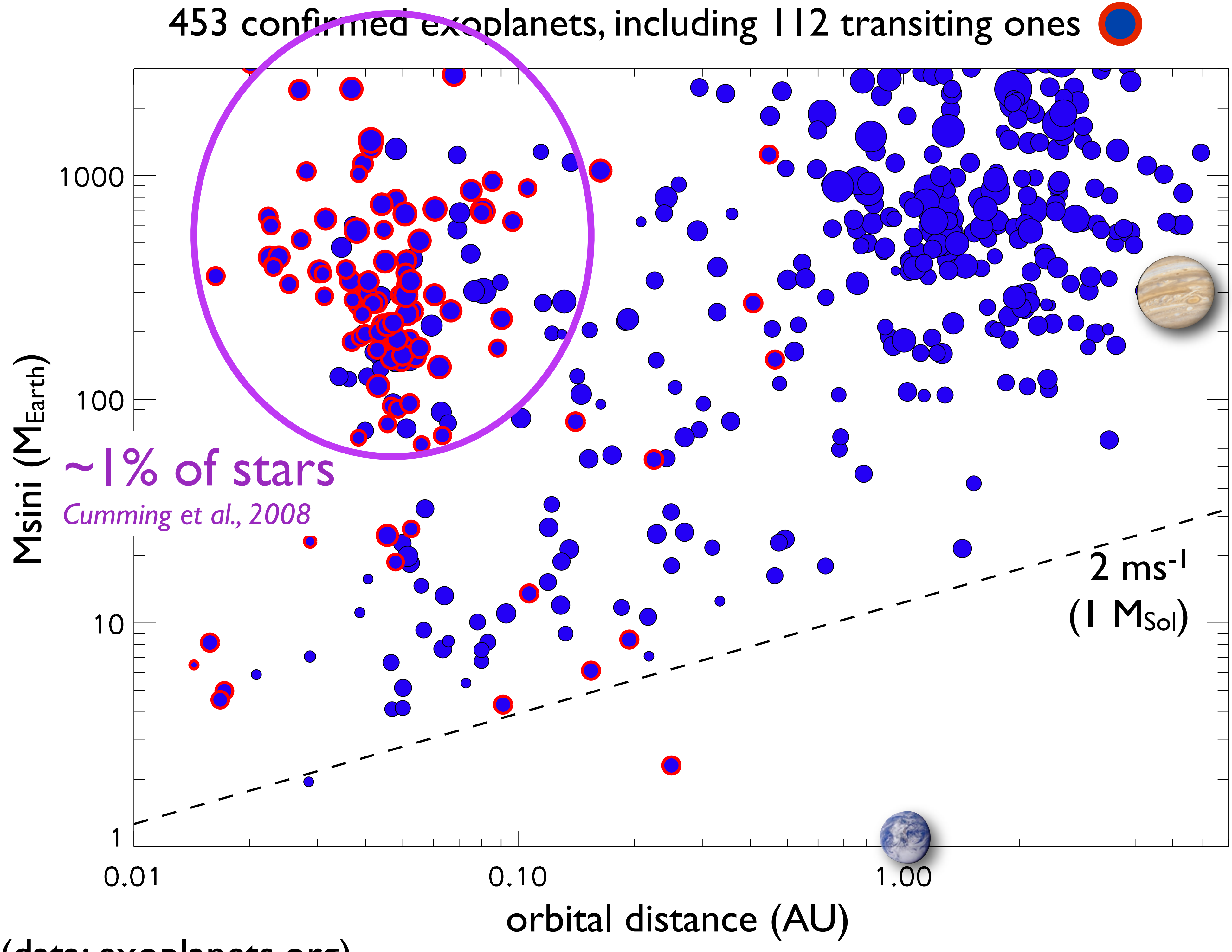

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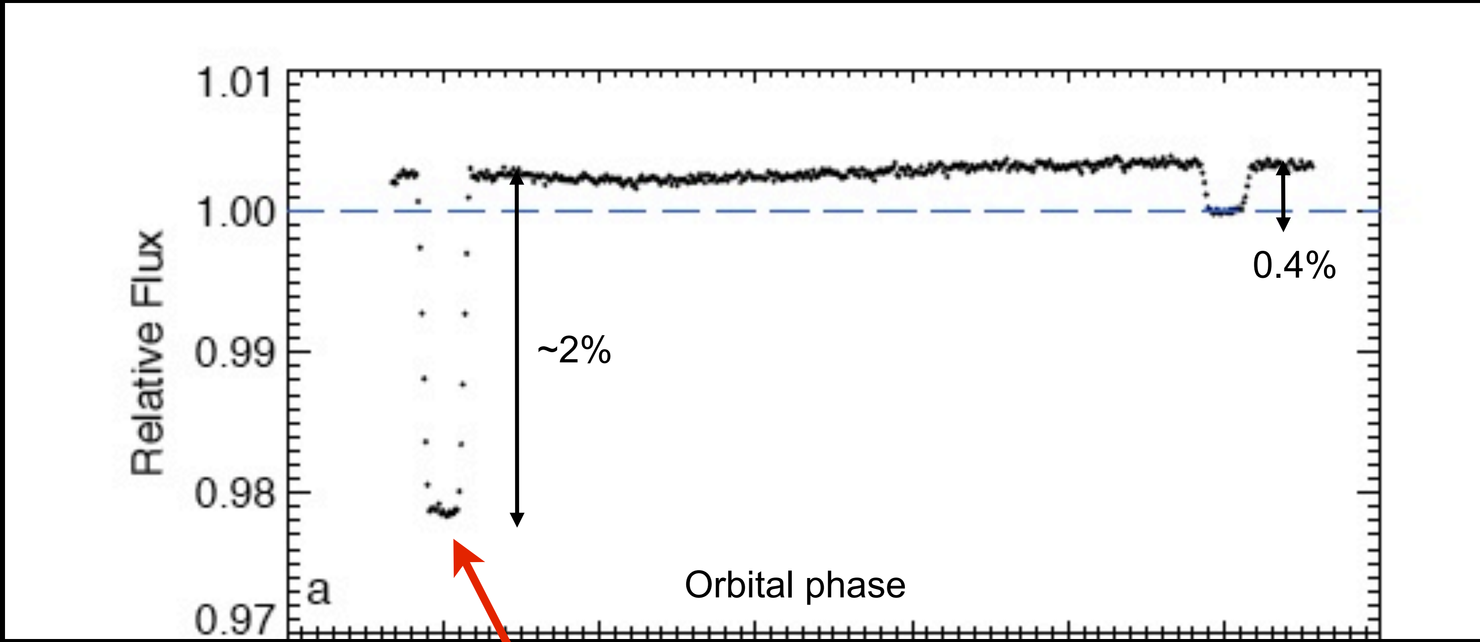
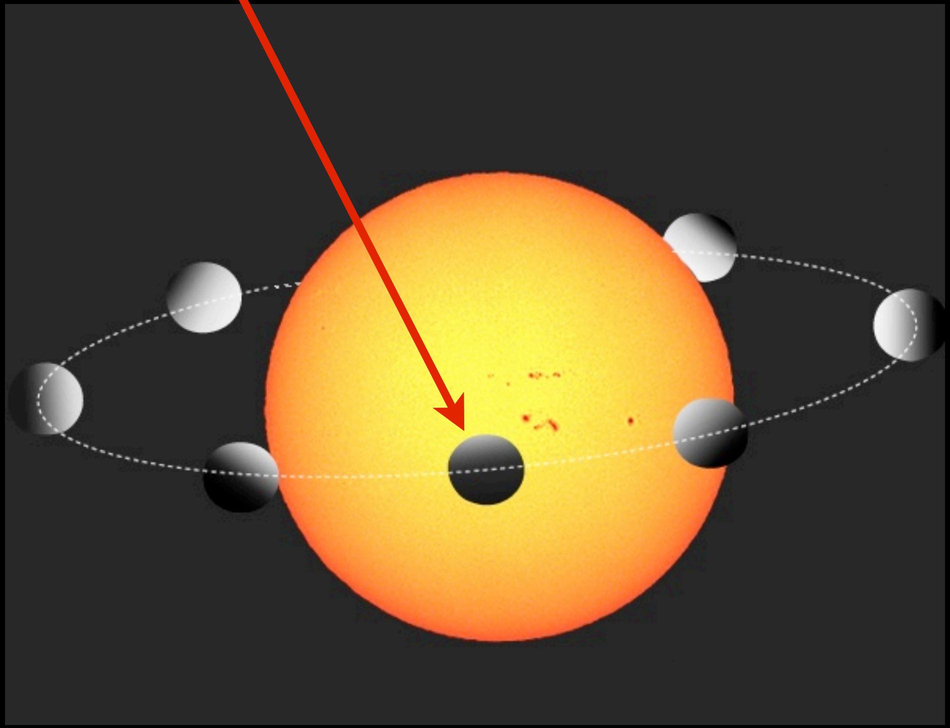
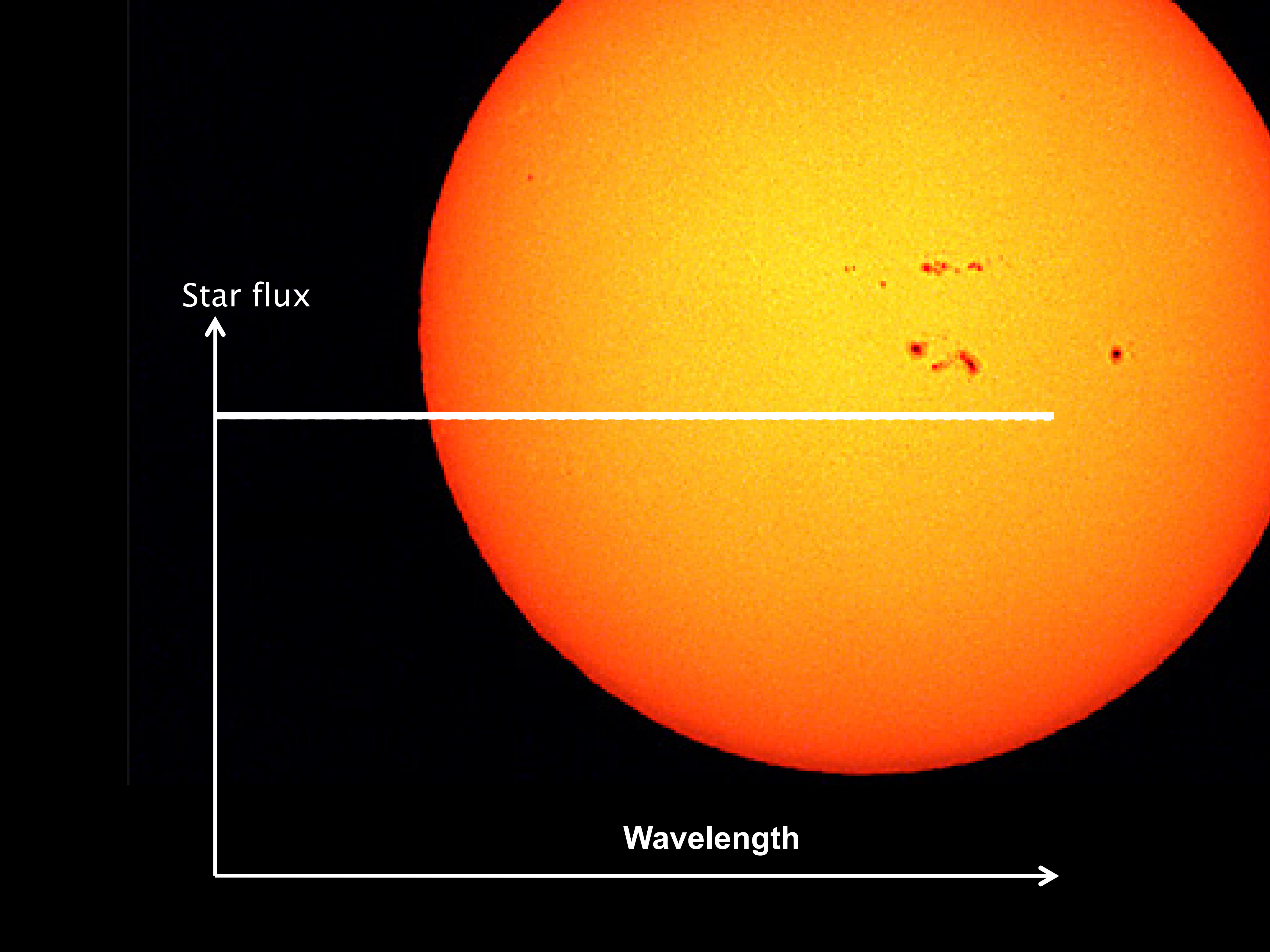
HD189733

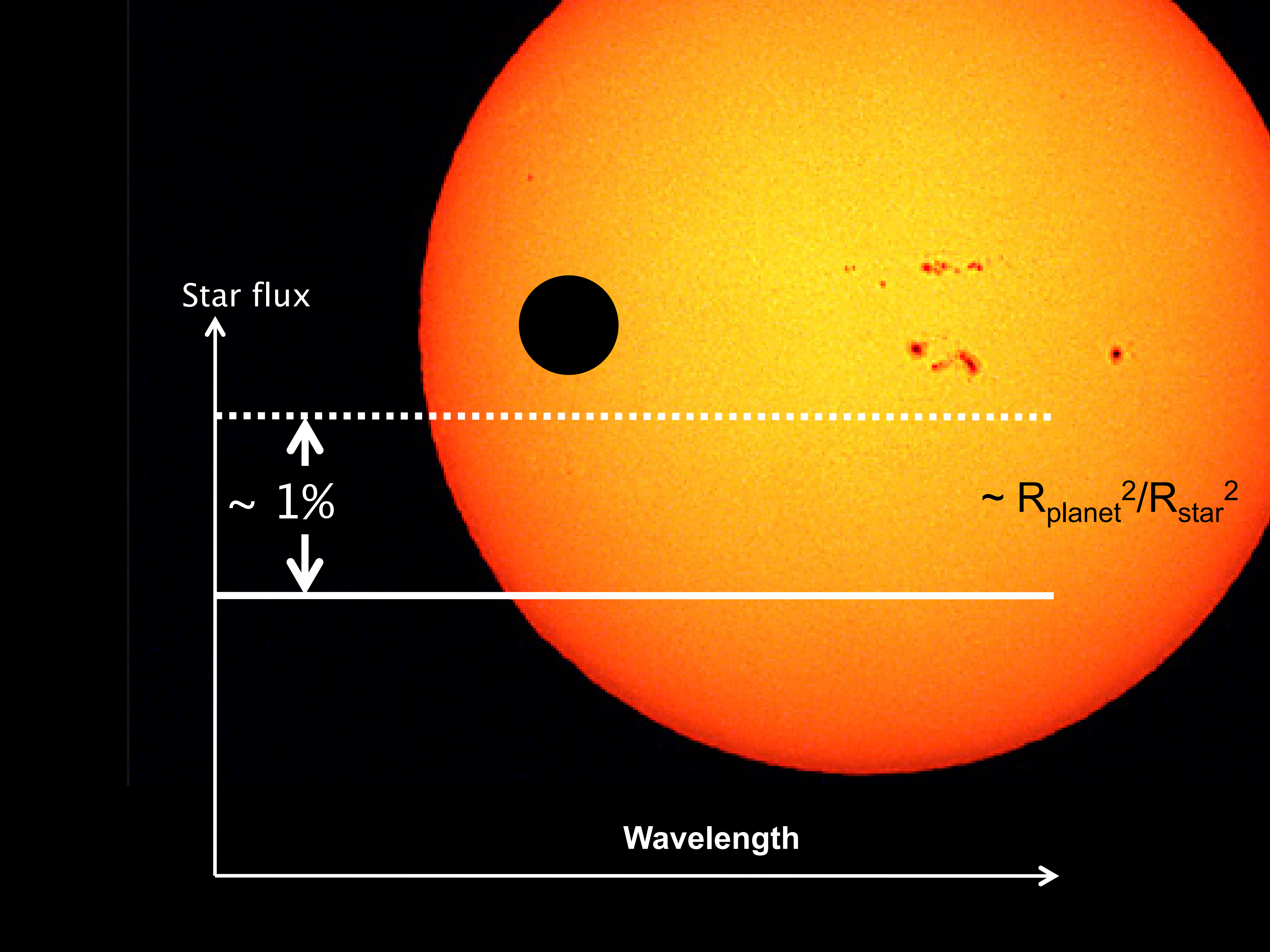
8 microns

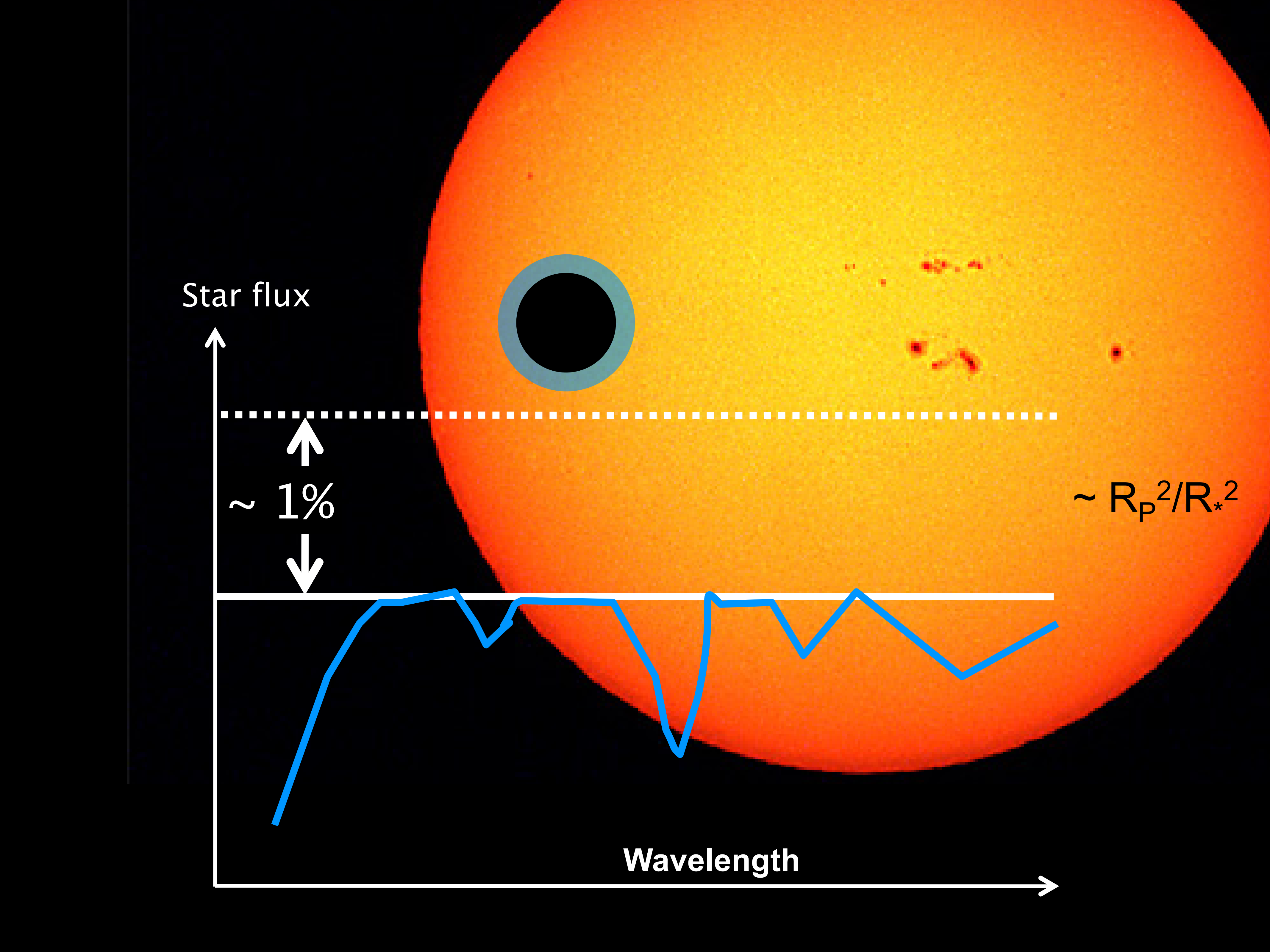
Knutson et al., 2008

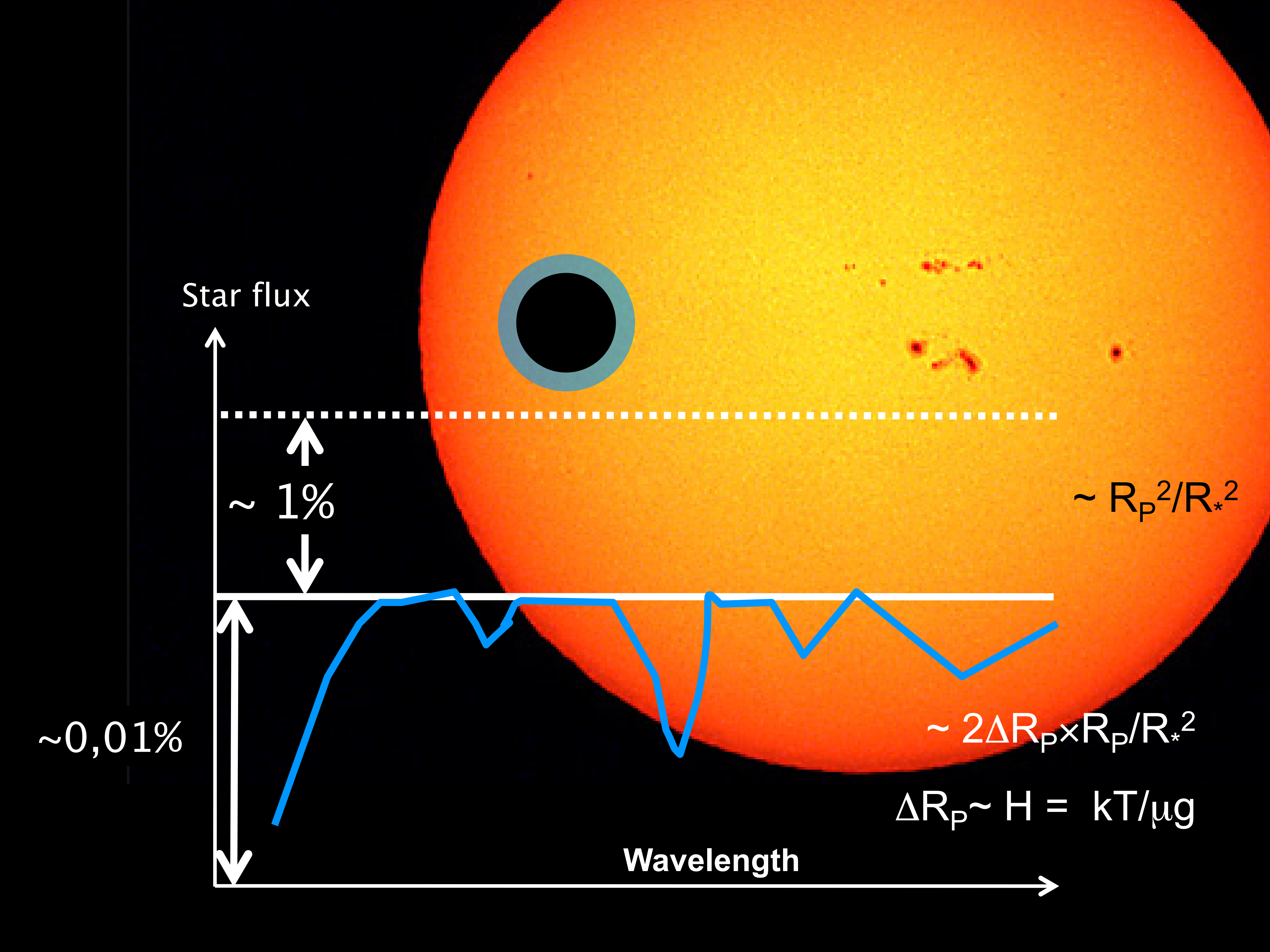





Star flux
Wavelength


Star flux
~ 1%
~ R_{planet}^2/R_{star}^2
Wavelength


Star flux
~ 1%
~ R_P^2/R_*^2
Wavelength



Star flux
~ 1%
~ R_P^2/R_*^2
~0,01%
~ $2\Delta R_P \times R_P/R_*^2$
ΔR_P ~ $H = kT/\mu g$
Wavelength

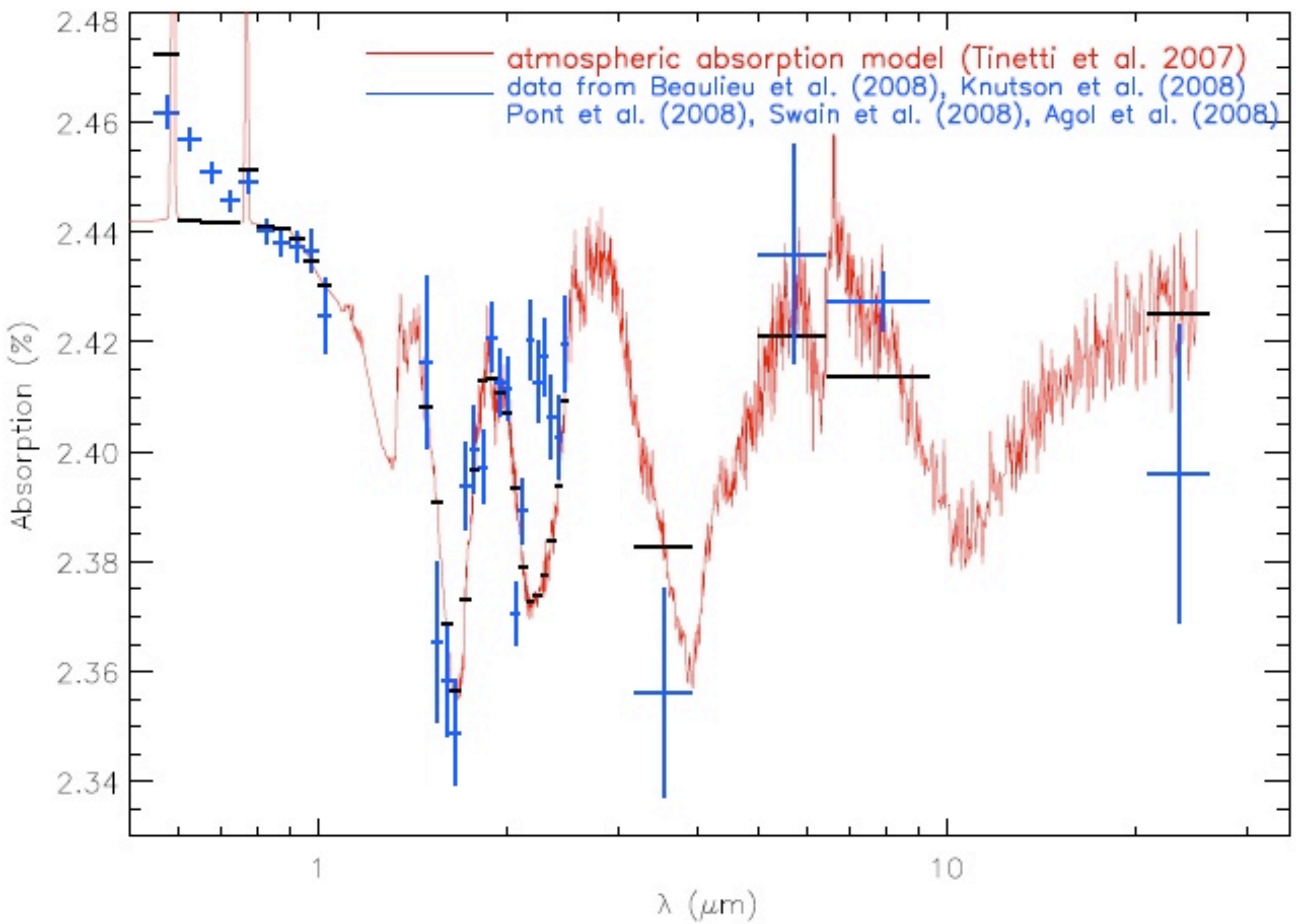


Figure 6. Compilation of data on transit depths of HD 189733. Solid (red) curve is a binned version of a model from Tinetti et al. (2007); horizontal lines (black) are the mean of this model over the bandwidths of each of the crosses (blue), which indicate 1-σ error bars.

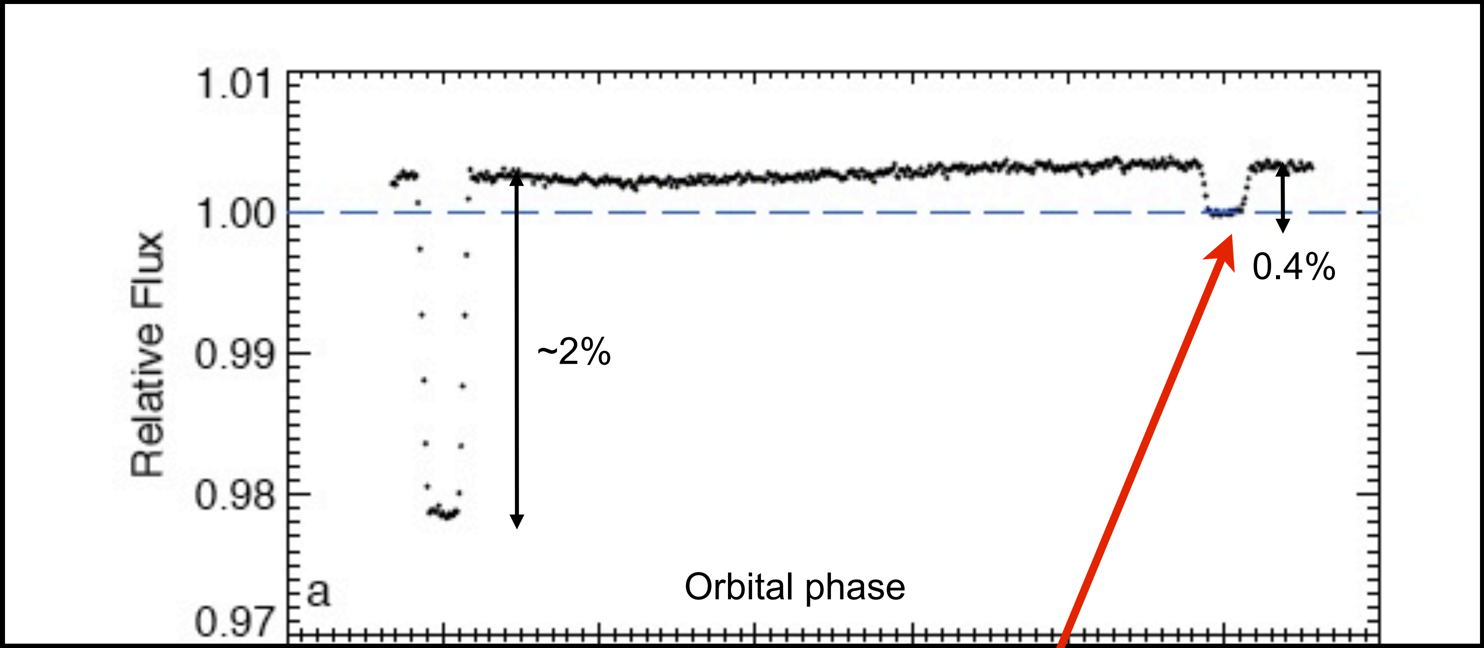
300 times smaller for a habitable planet

Agol et al., 2008

HD189733

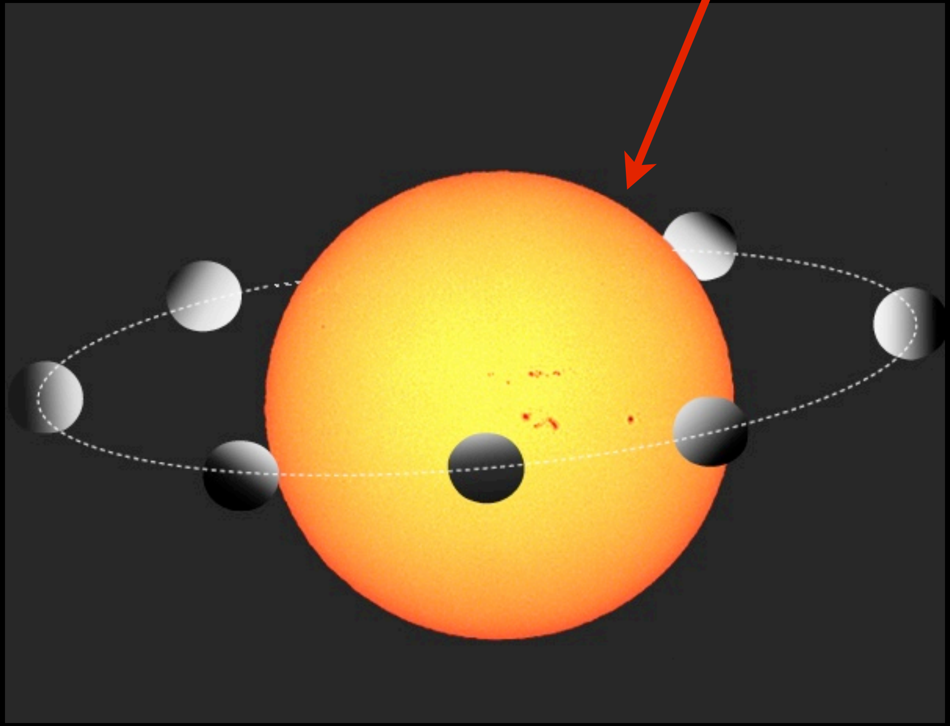
8 microns

Knutson et al., 2008



0.004 in this case

$5\ 10^{-7}$ for the Earth/Sun @ 10 microns



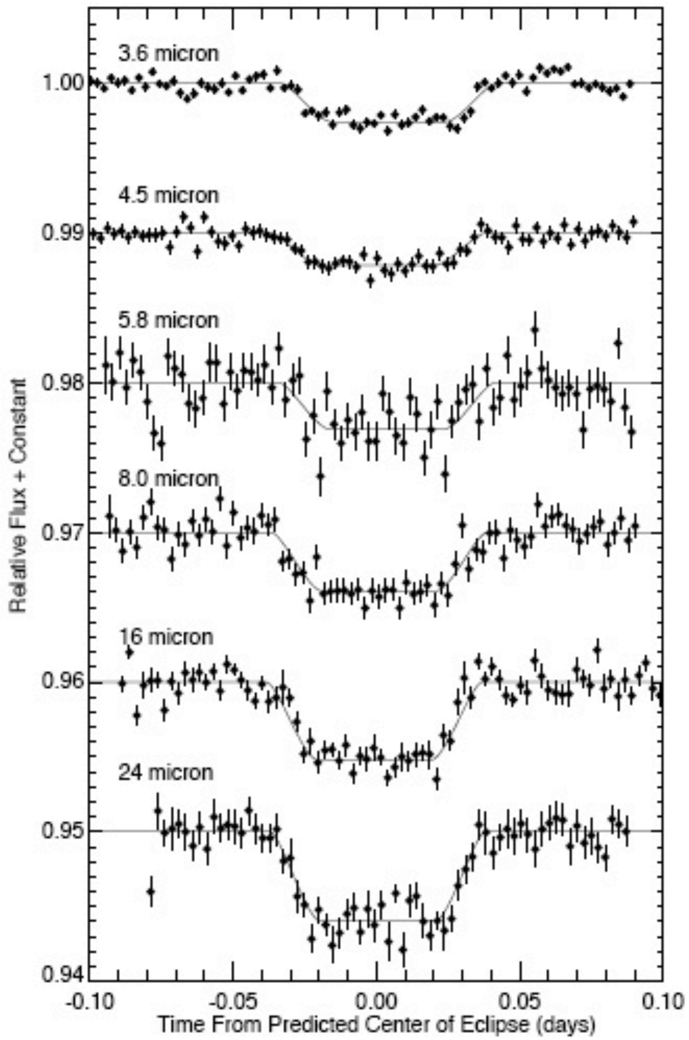
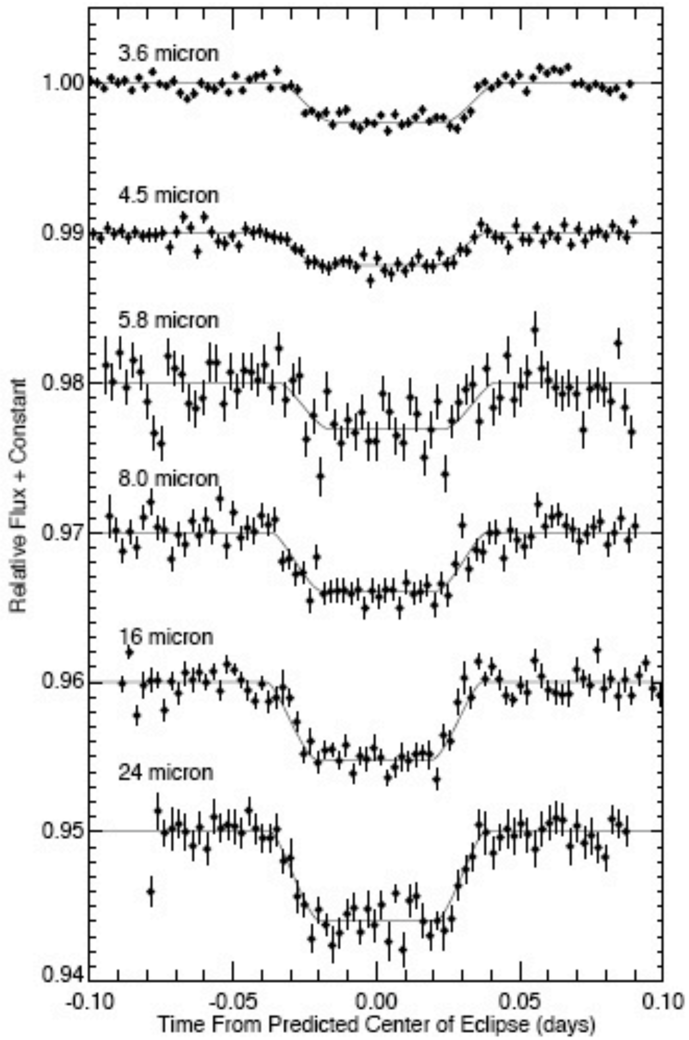


Fig. 2.— Time series observations of HD 189733b after correcting for detector effects (see §2). The central wavelength of observation for each data set is (from top to bottom) 3.6, 4.5, 5.8, 8.0, 16, and 24 μm. Each time series is binned in 3.5 minute intervals, normalized, and plotted with a distinct constant offset for clarity. The best-fit eclipse curves are overplotted.

Charbonneau et al., 2008



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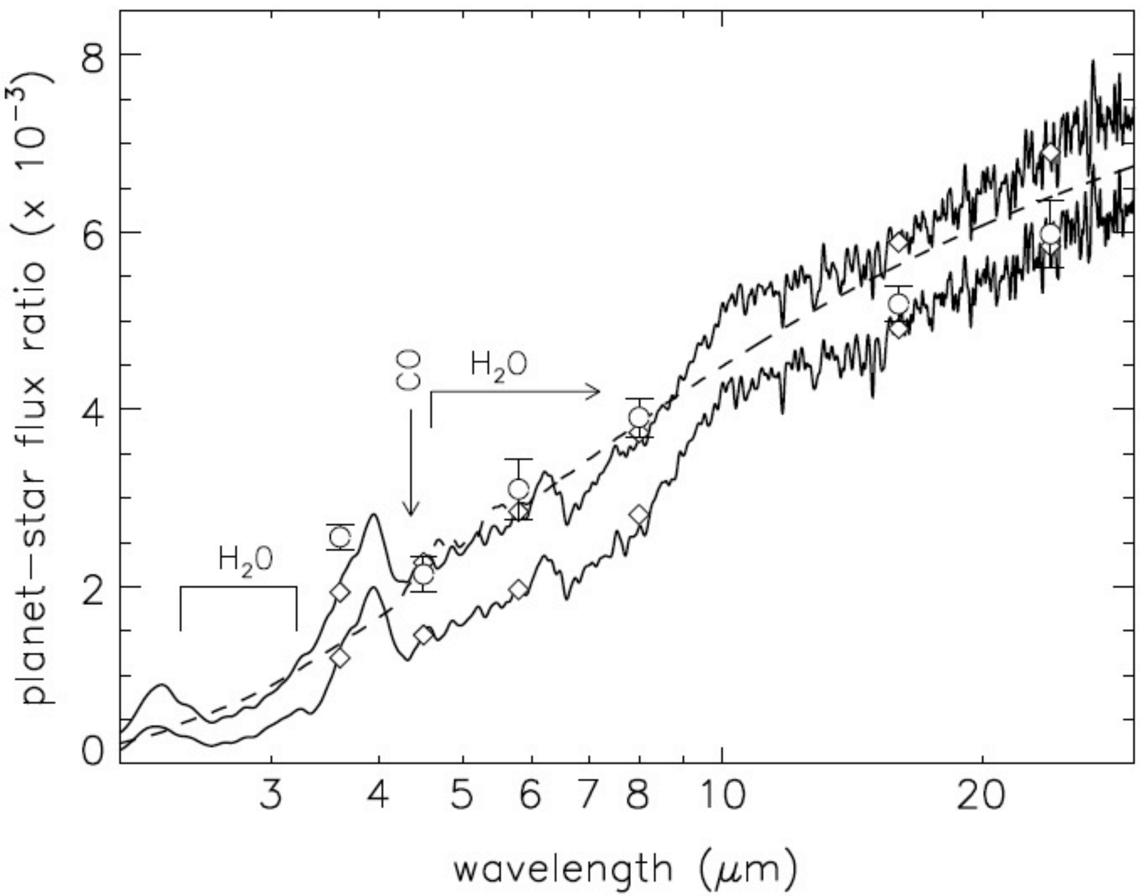
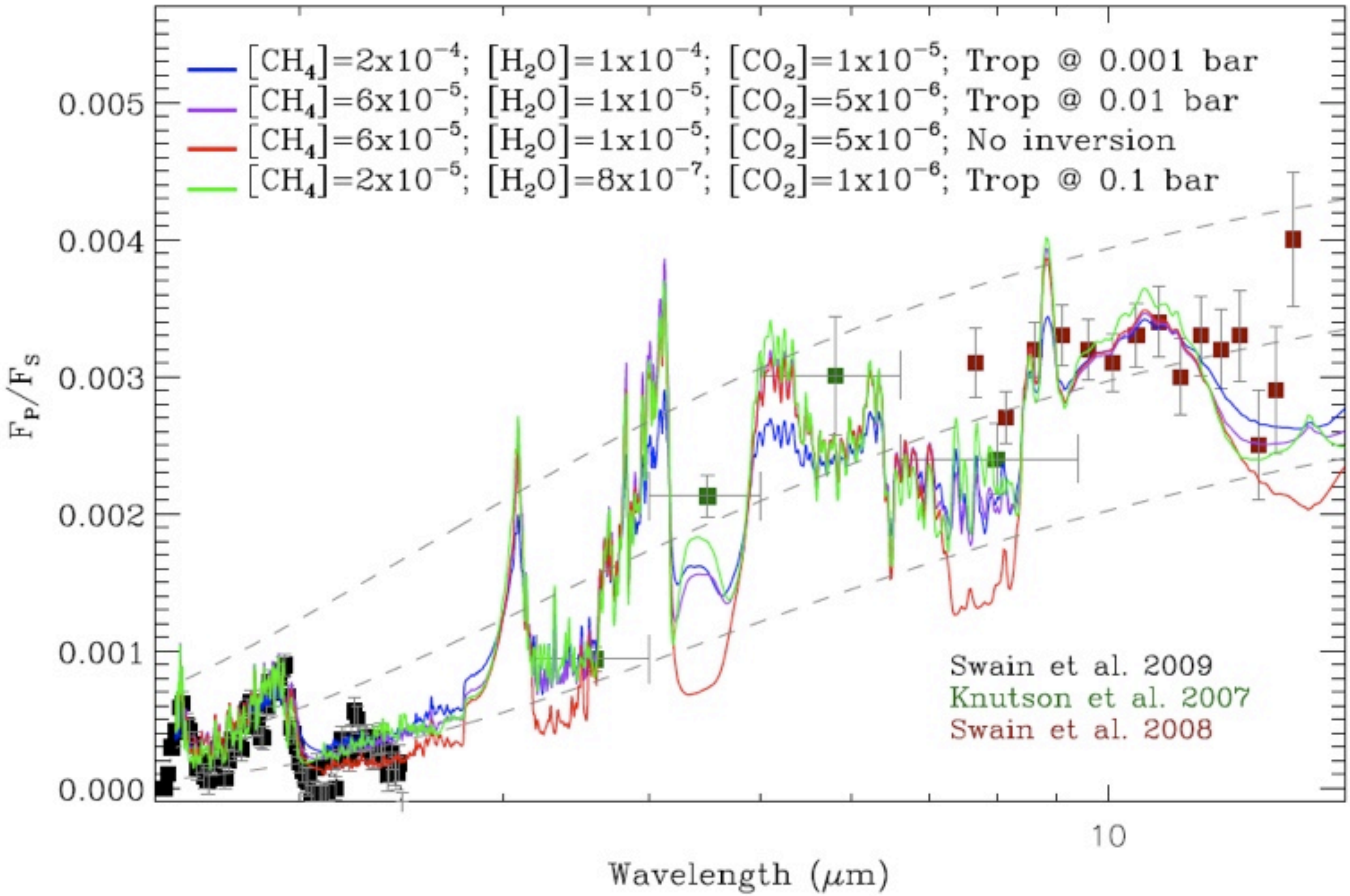


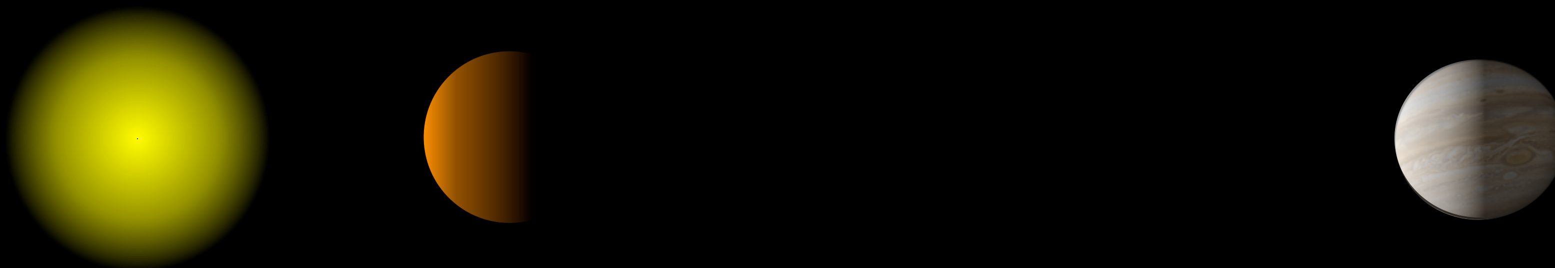
Charbonneau et al., 2008

day-side emission of HD209458b



Swain et al., 2009

Hot Jupiter (vs) Jupiter



10 × hotter
⇒ short chemical timescales

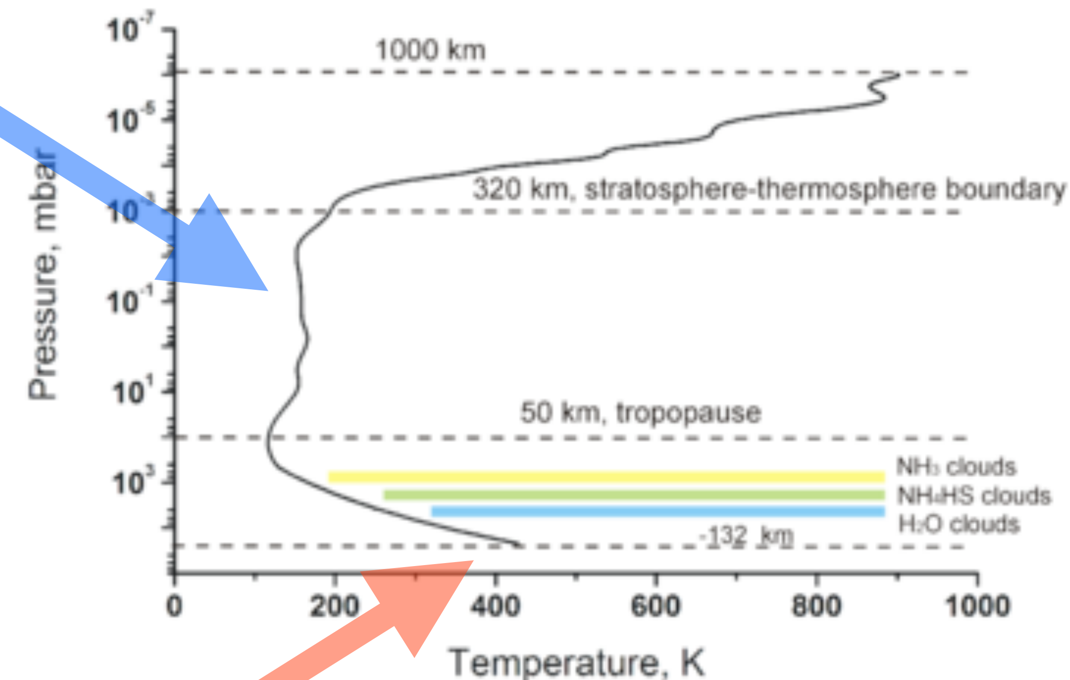
10,000 × more UV
⇒ fast photolysis in the upper atmosphere

fast radiative cooling $\propto T^3$
slower rotation (tidal synchronization)
⇒ day-night contrast

no cold trap (H_2O is a major molecule)

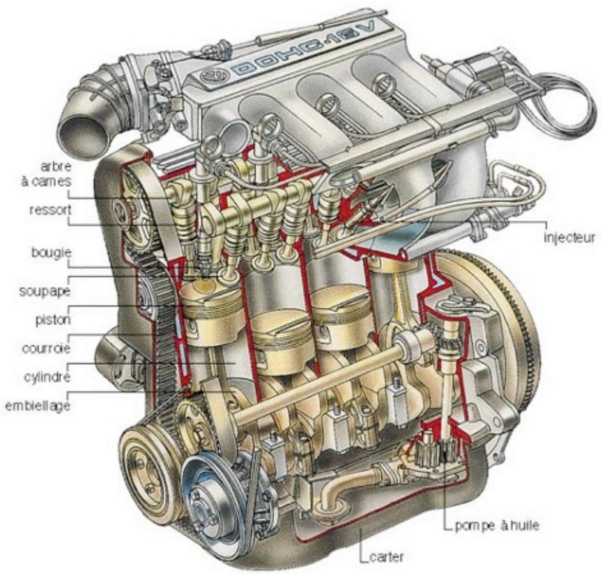
In cold atmospheres, photochemical processes are dominated by radicals produced by photolysis .
Only exothermic reactions are included.

$A + B \rightarrow C + D$

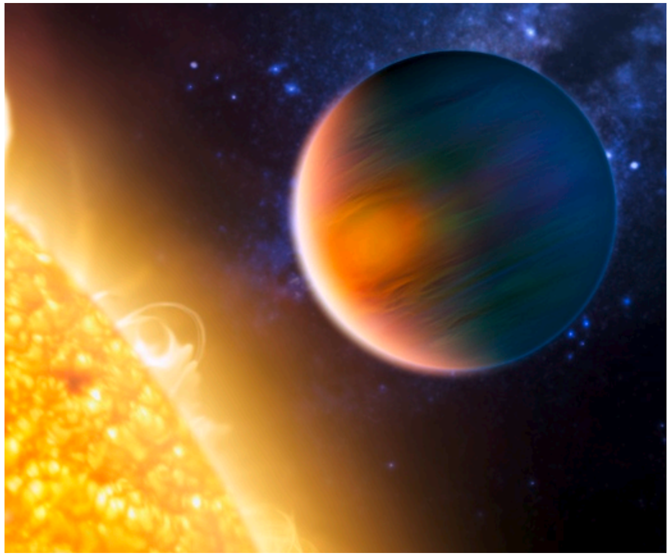


In the deep/hot layers of the giant planet atmospheres of the solar system, endothermic reactions take place but there is no UV photon.

$A + B \rightleftarrows C + D$ thermochemistry



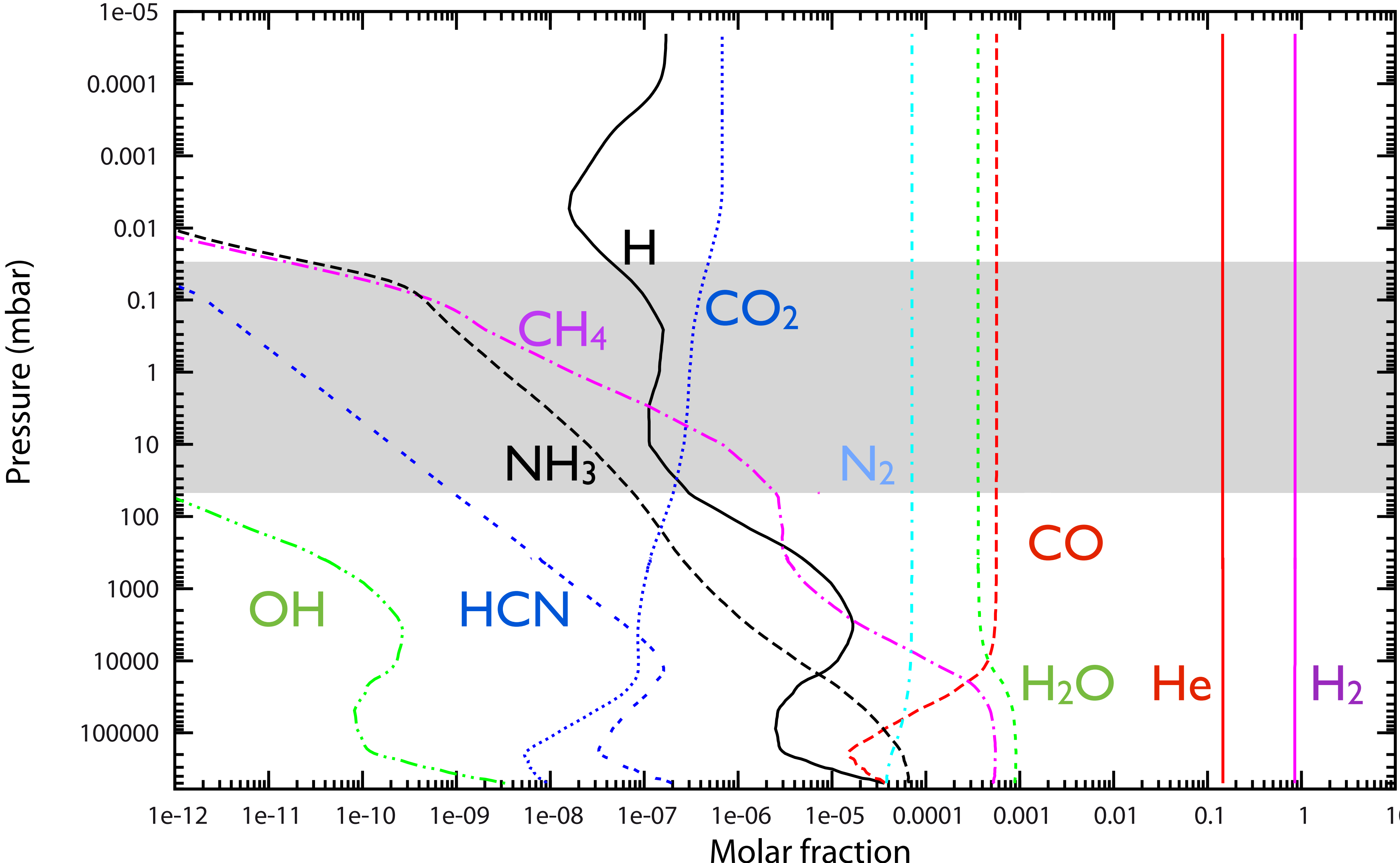
+ UV =



DCPR Network (Département de Chimie Physique des Réactions)
C0-C2 and C0-C6 (+ N, O, H, He)

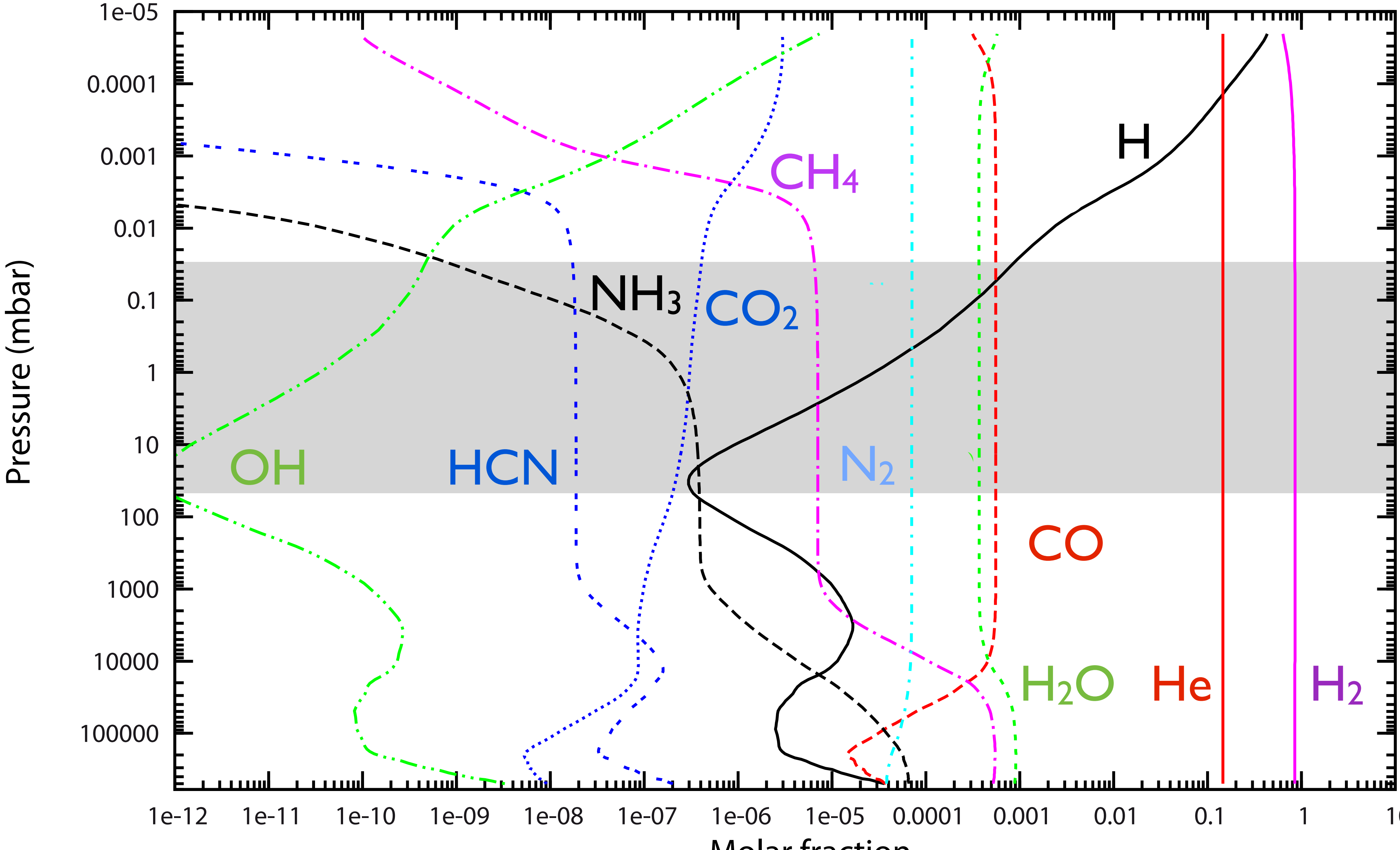
R. Bounaceur

Thermochemical equilibrium



Venot et al., in prep

1D photochemical modeling: kinetics, UV photolysis, vertical mixing and molecular diffusion



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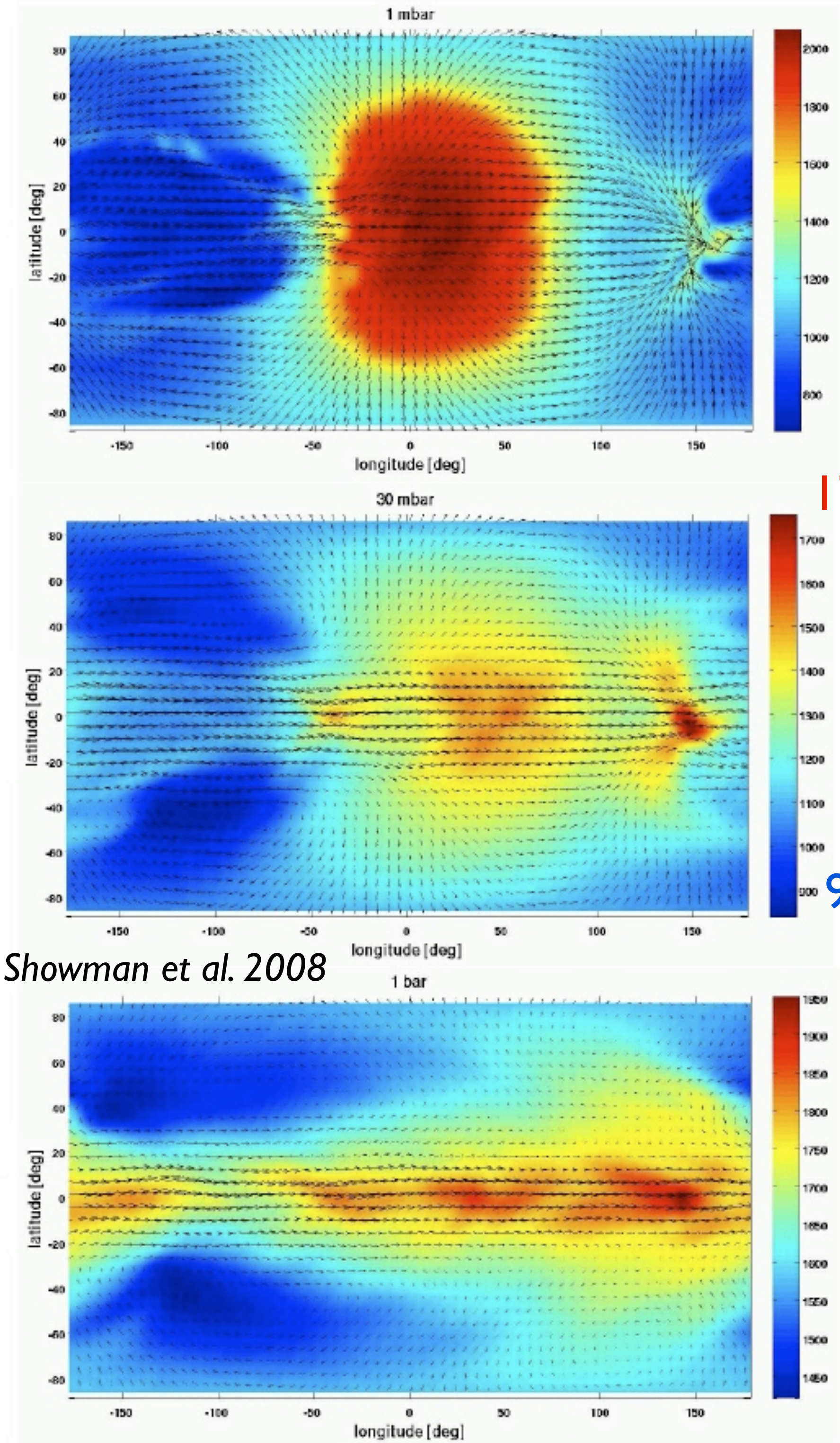
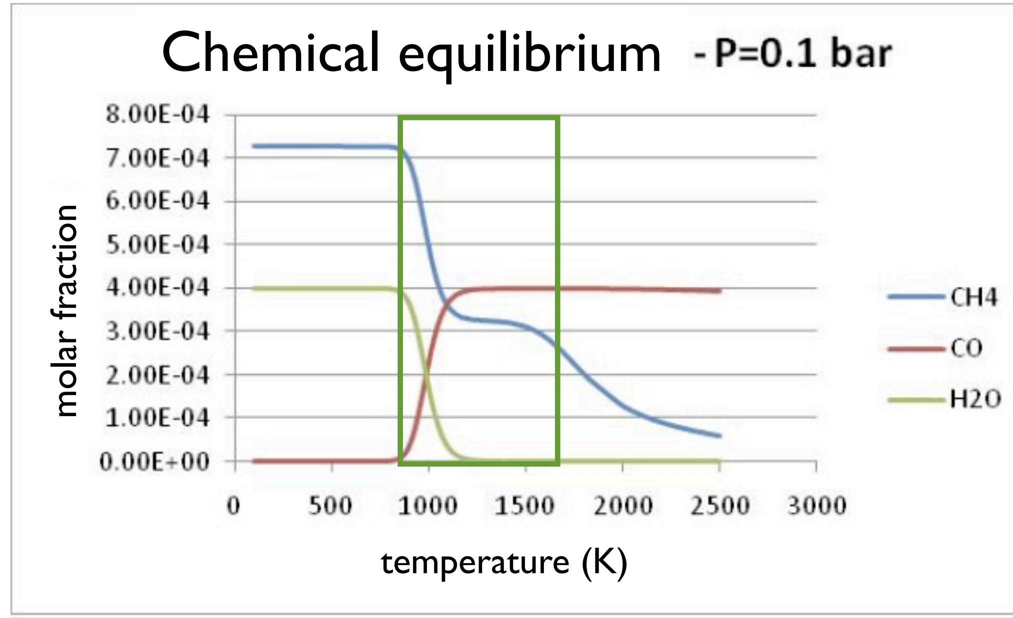


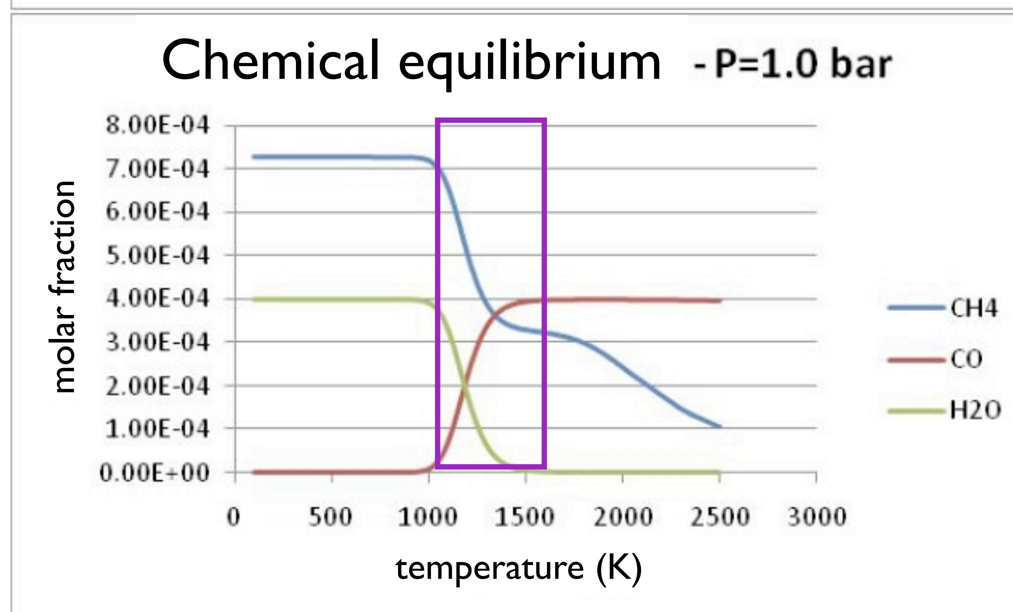
1700 K

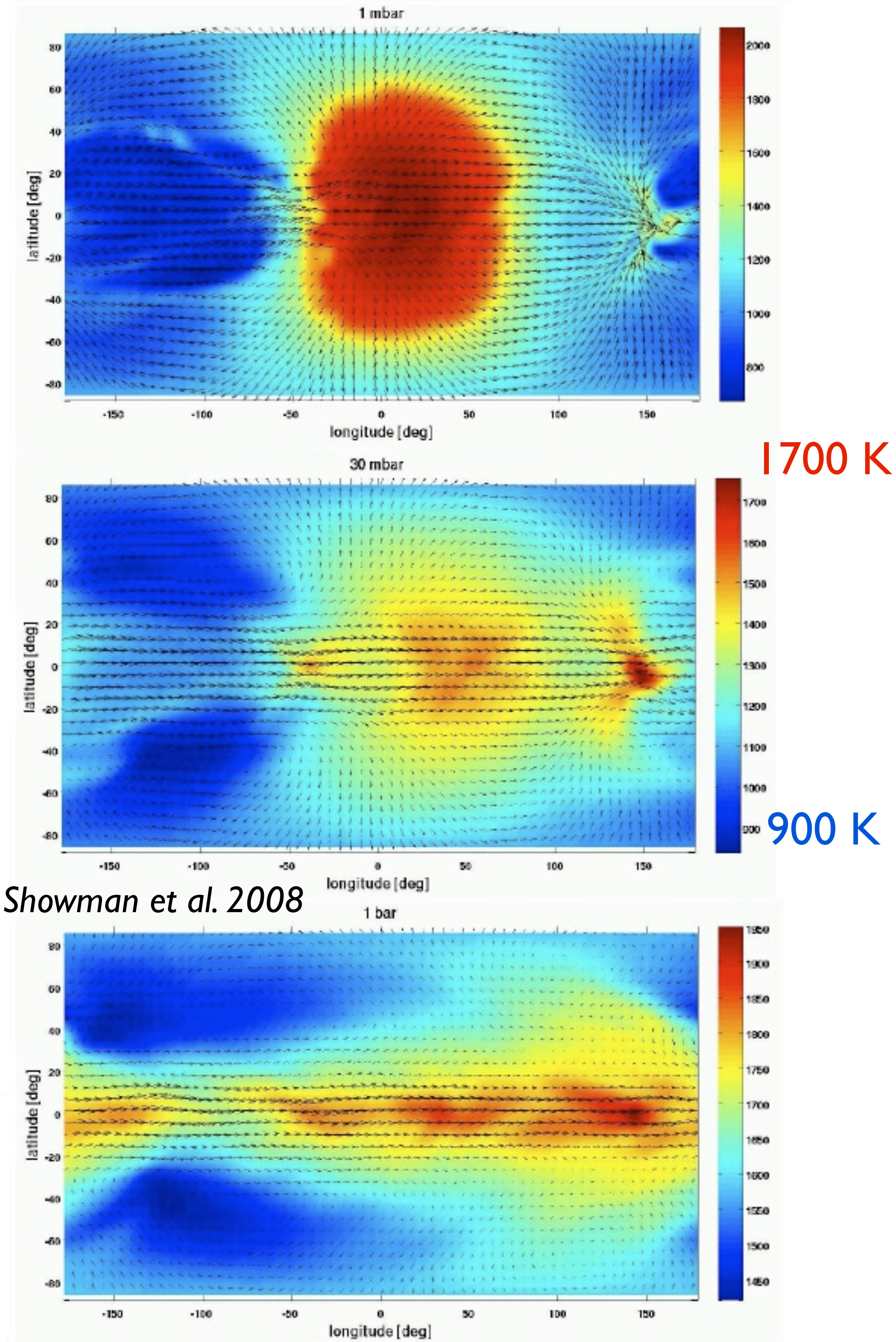
900 K

Showman et al. 2008

FIG. 16.— Temperature (colorscale, in K) and winds (arrows) for nominal HD 209458b simulation with solar abundances including TiO/VO. Panels







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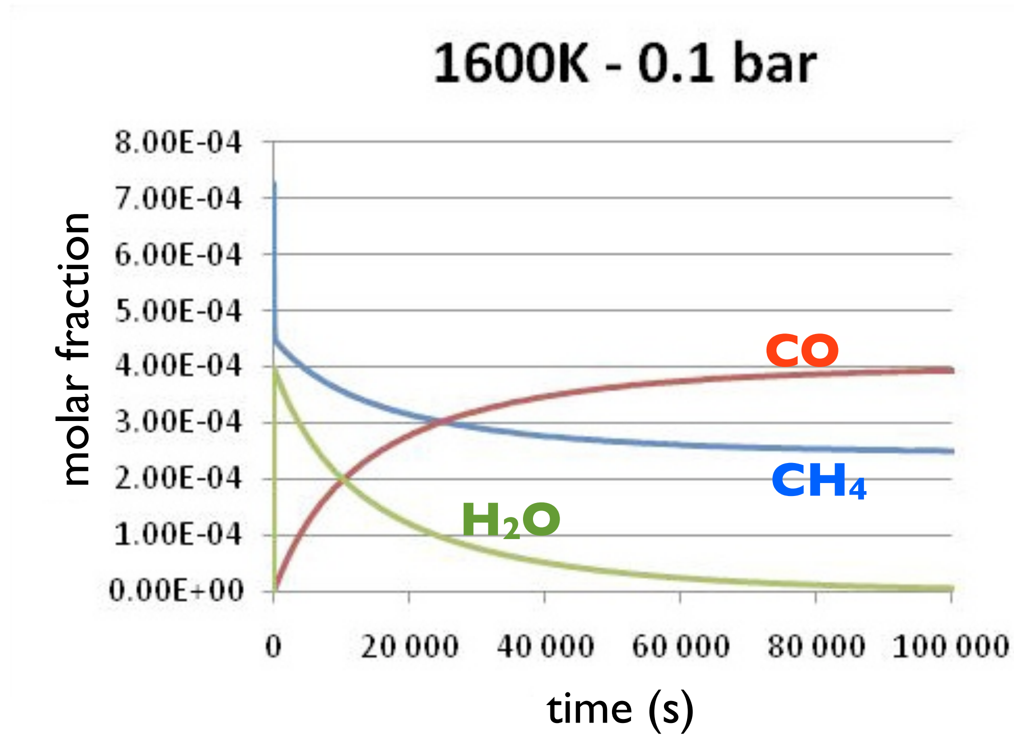

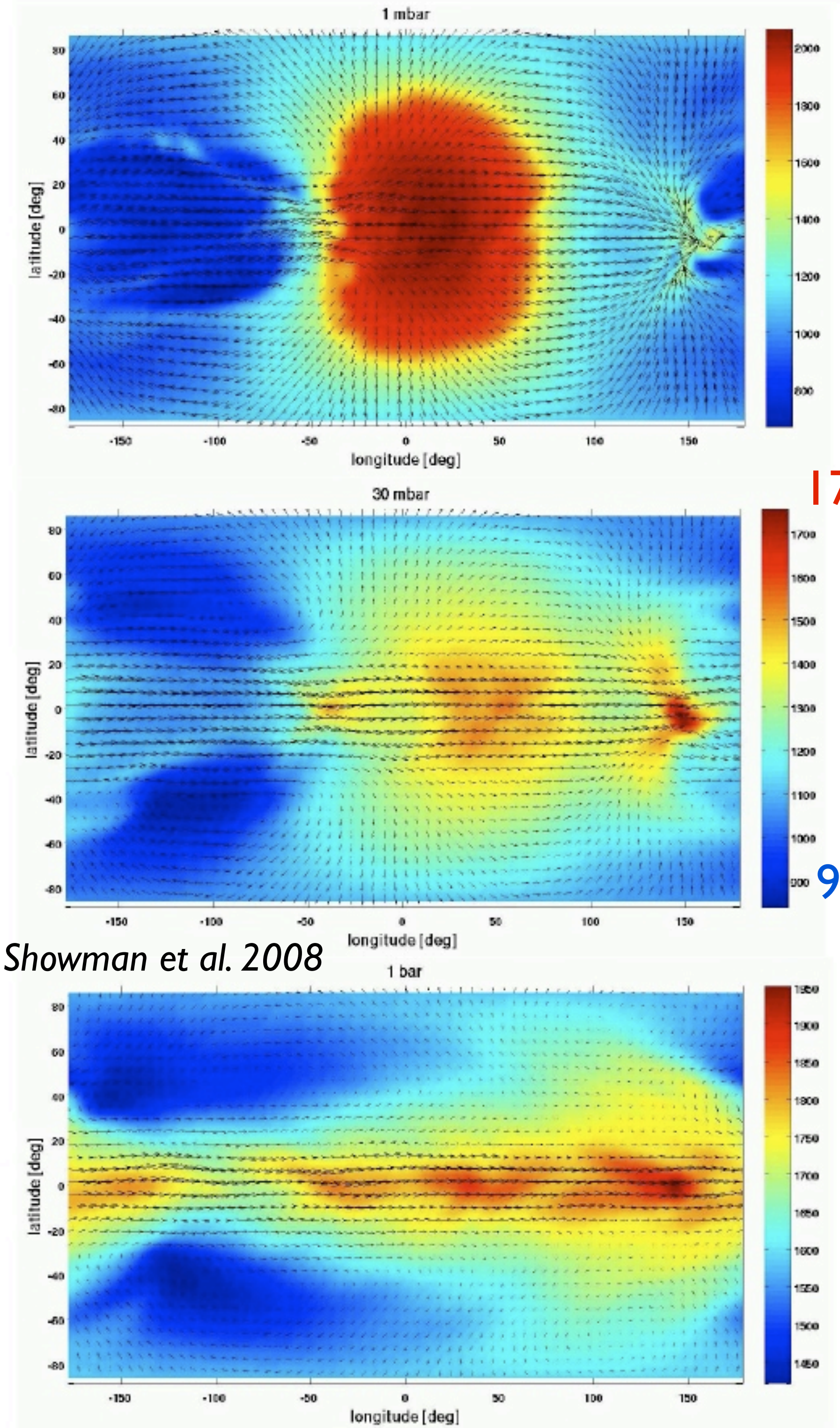

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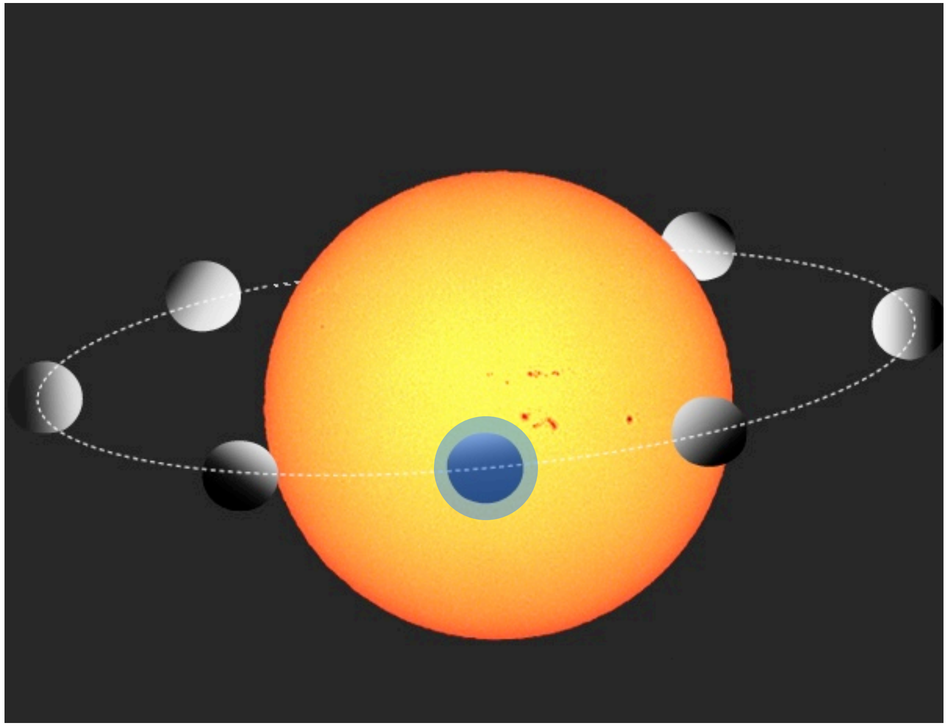

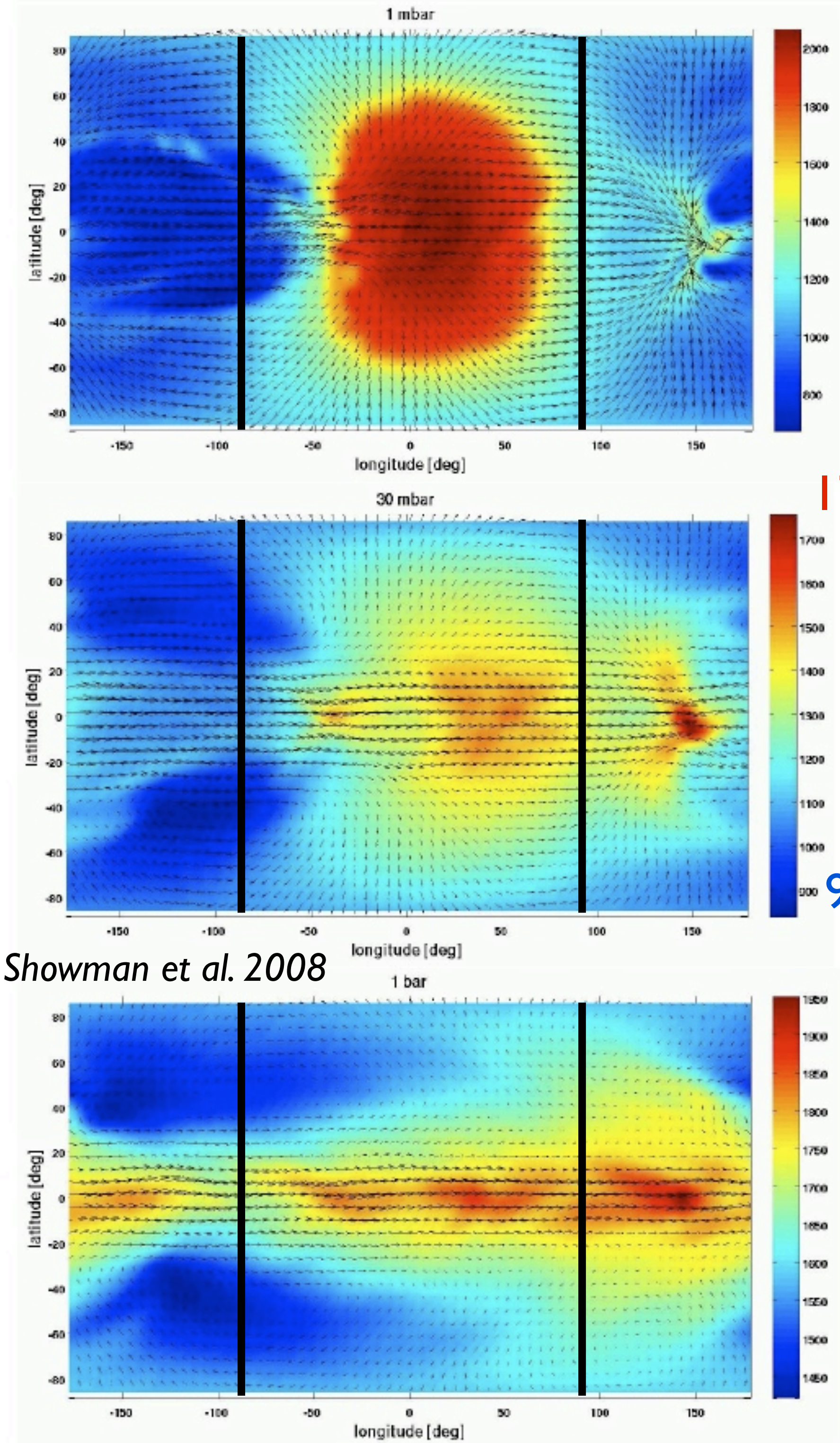

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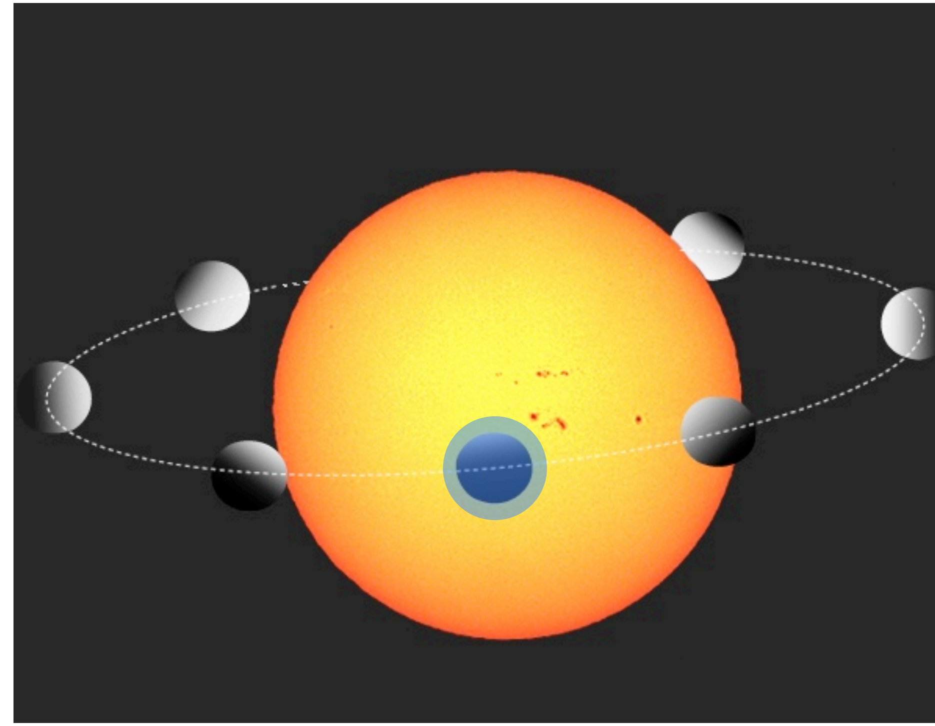

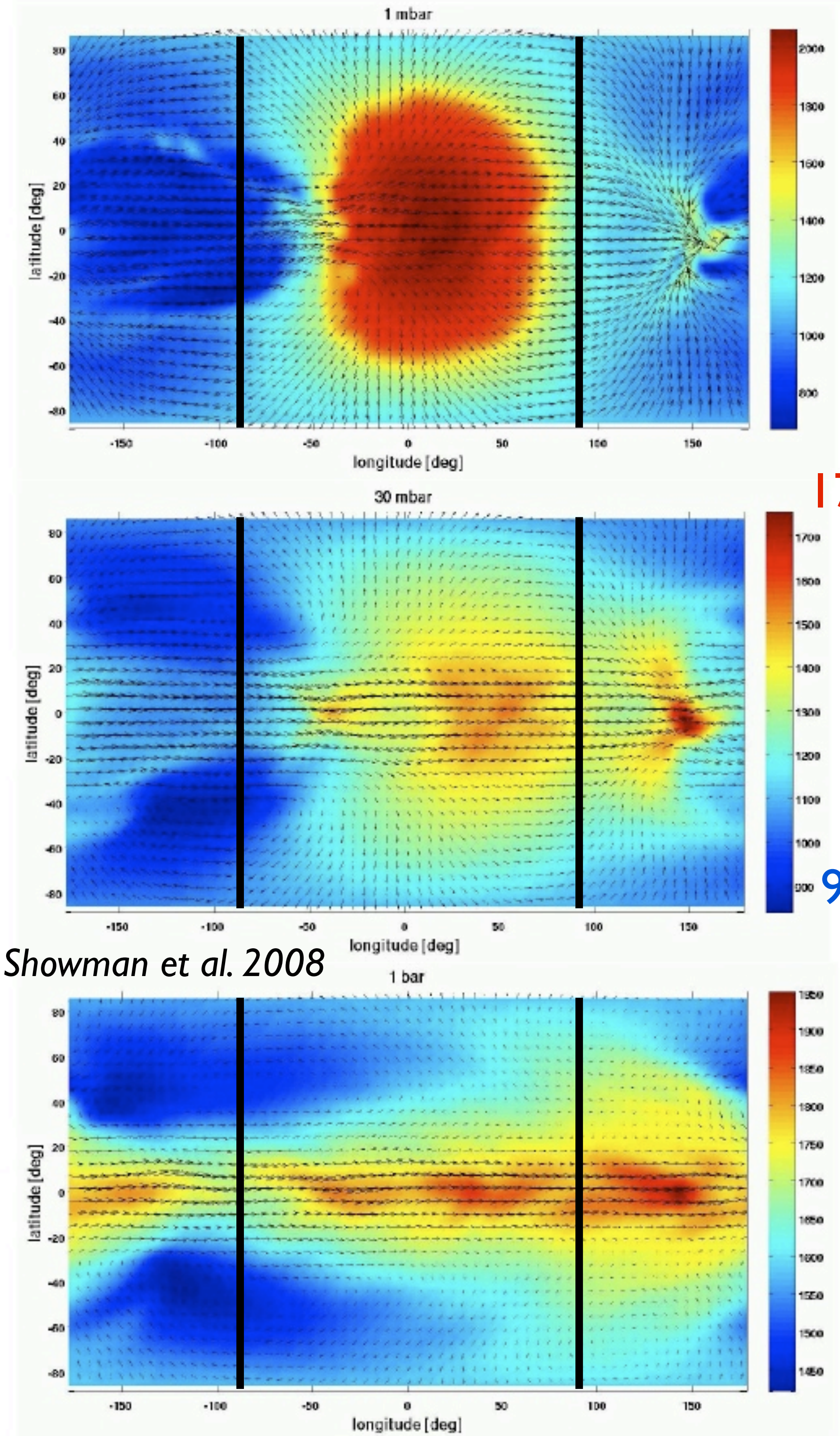

1700 K

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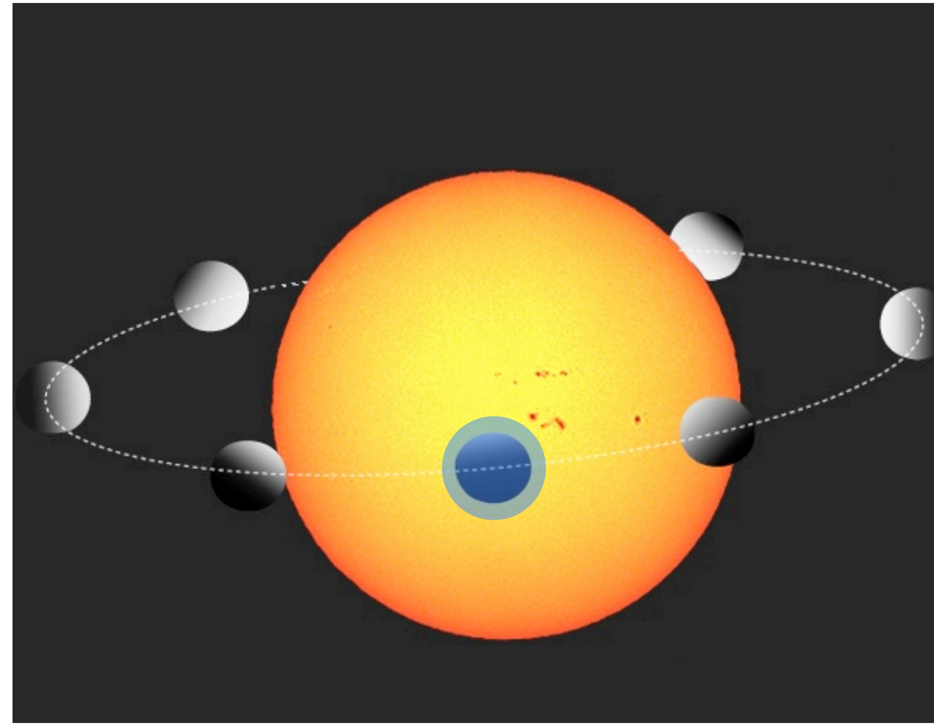
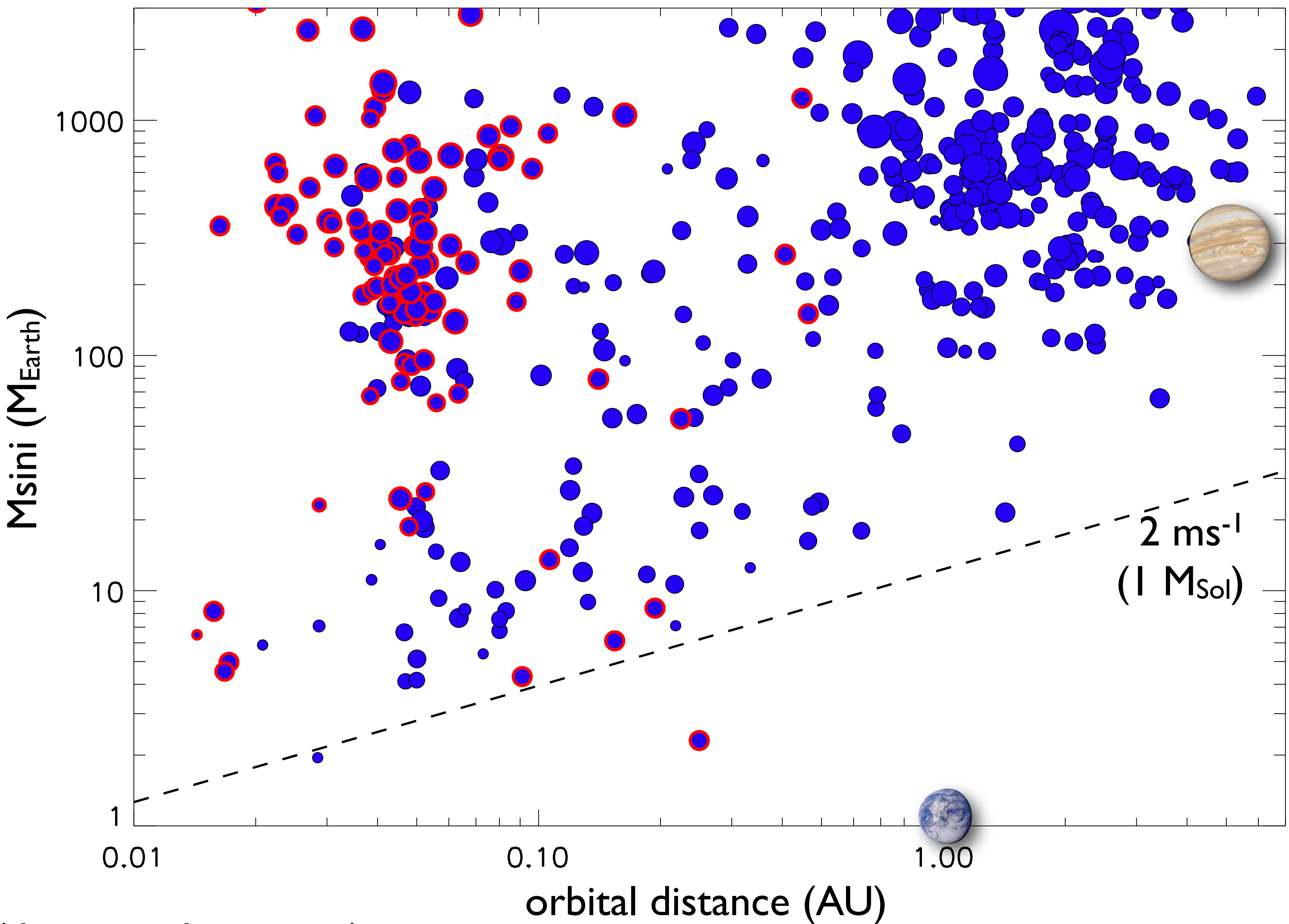


Chemistry and 3D dynamics must be coupled !

work in progress...

453 confirmed exoplanets, including 112 transiting ones



(data: exoplanets.org)

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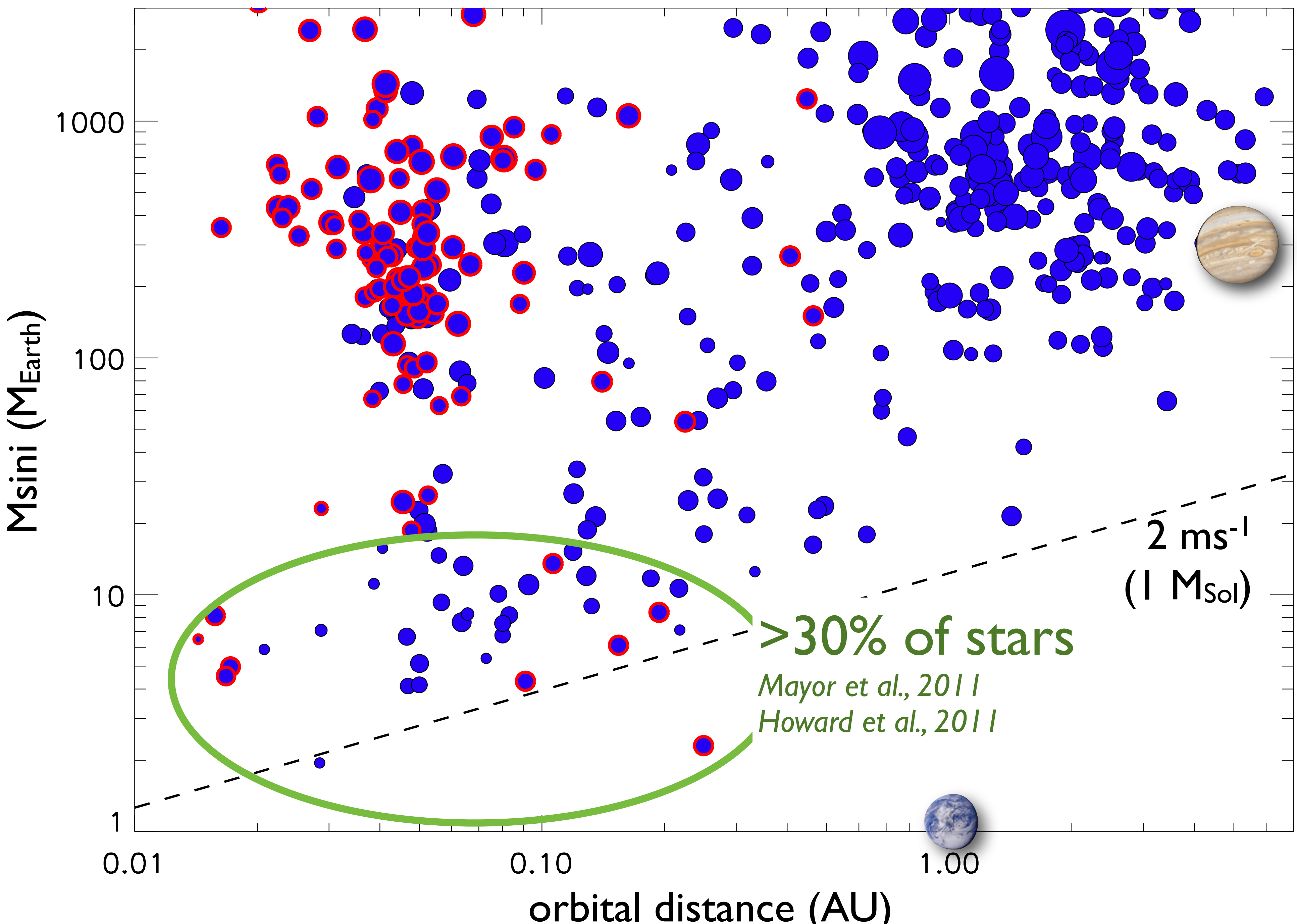

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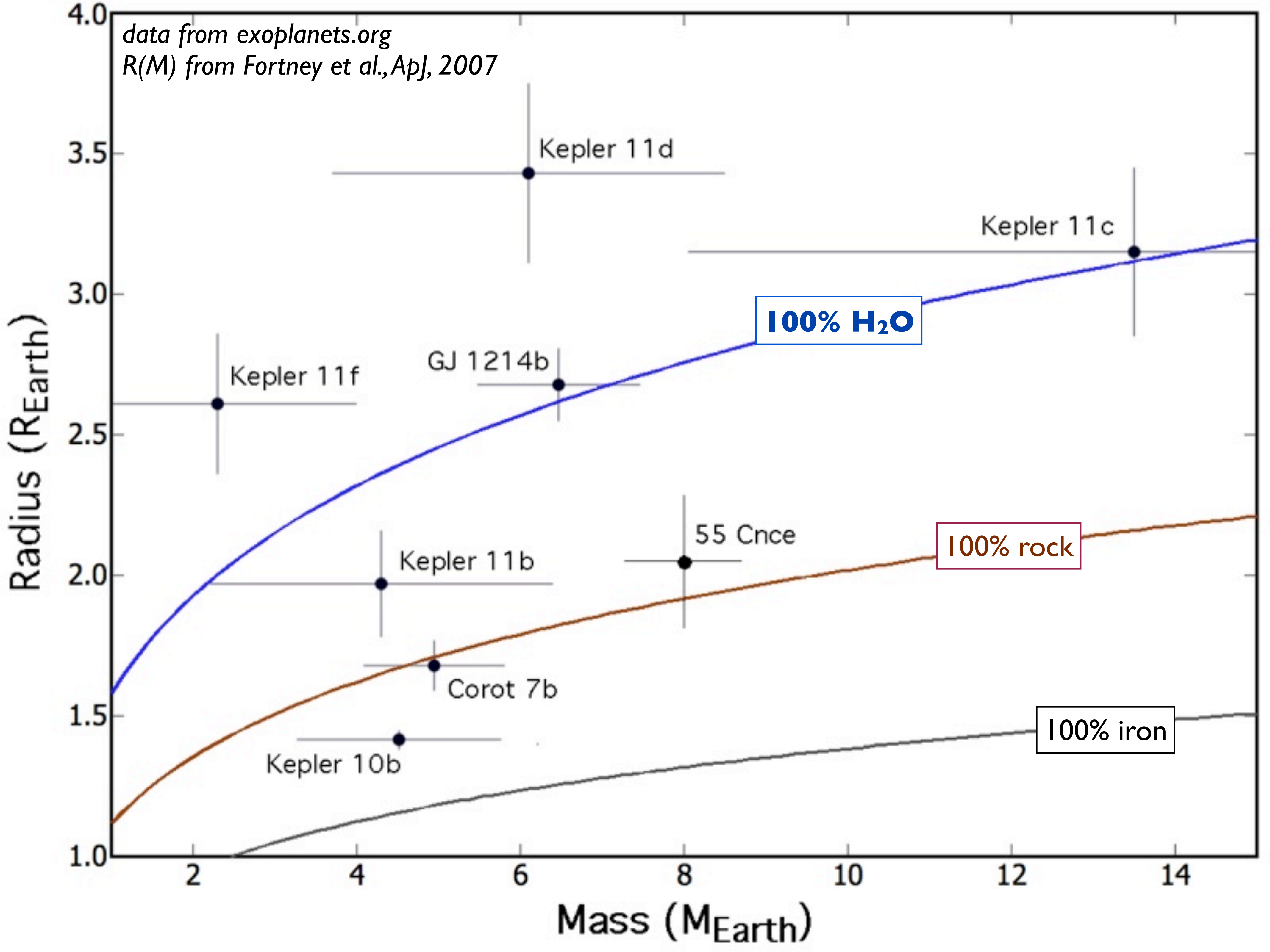
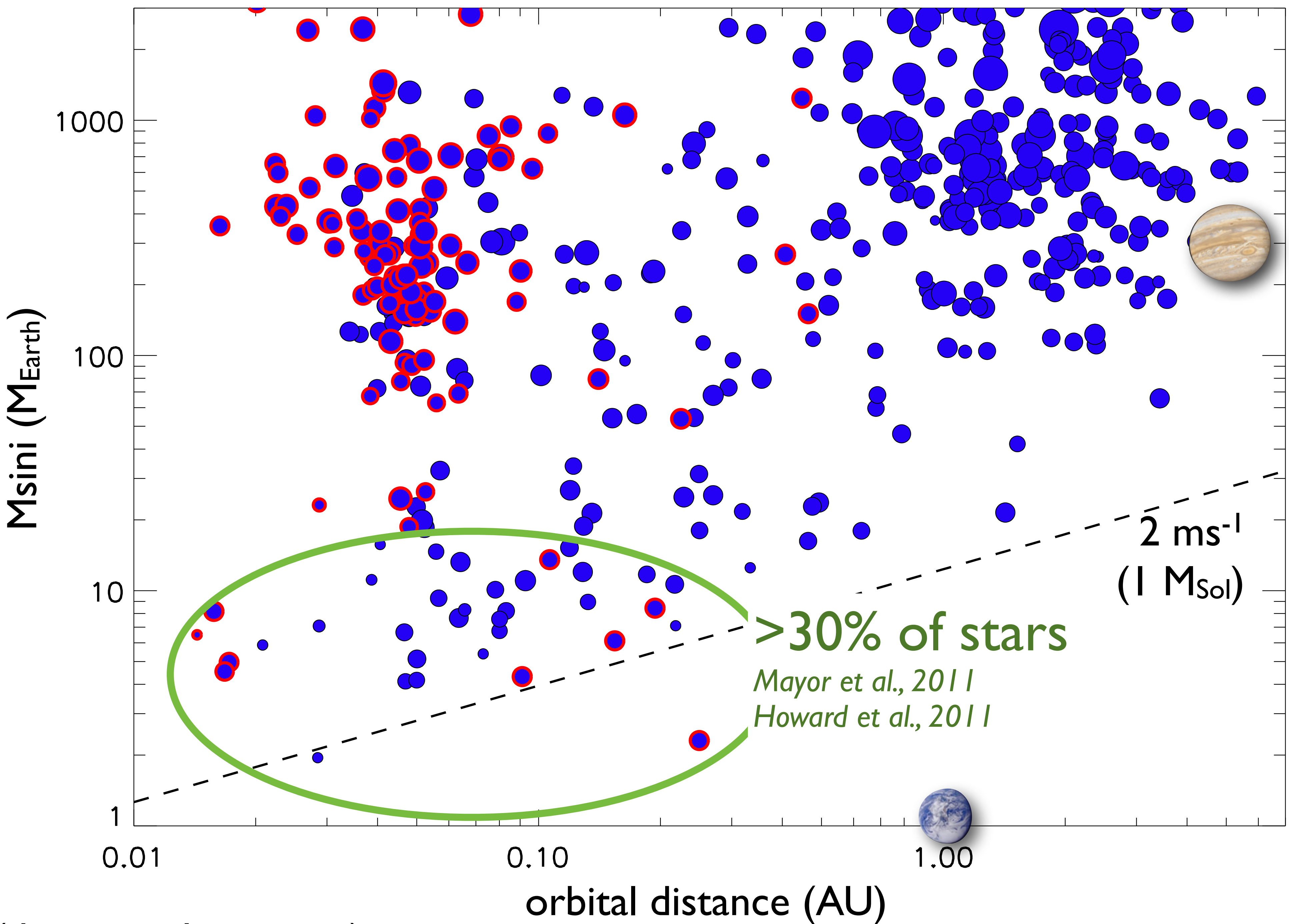

data from exoplanets.org
R(M) from Fortney et al., ApJ, 2007
Kepler 11d
Kepler 11c
100% H2O
Kepler 11f
GJ 1214b
55 Cnce
100% rock
Kepler 11b
Corot 7b
100% iron
Kepler 10b
Radius (REarth)
Mass (MEarth)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
2
4
6
8
10
12
14

453 confirmed exoplanets, including 112 transiting ones



(data: exoplanets.org)

Can we characterize the atmosphere of hot (terrestrial) non-transiting exoplanets

Transit probablity = R_*/a

Within this population of hot low-mass planets that is found around ~25% of stars, the transit probability is typically 5%

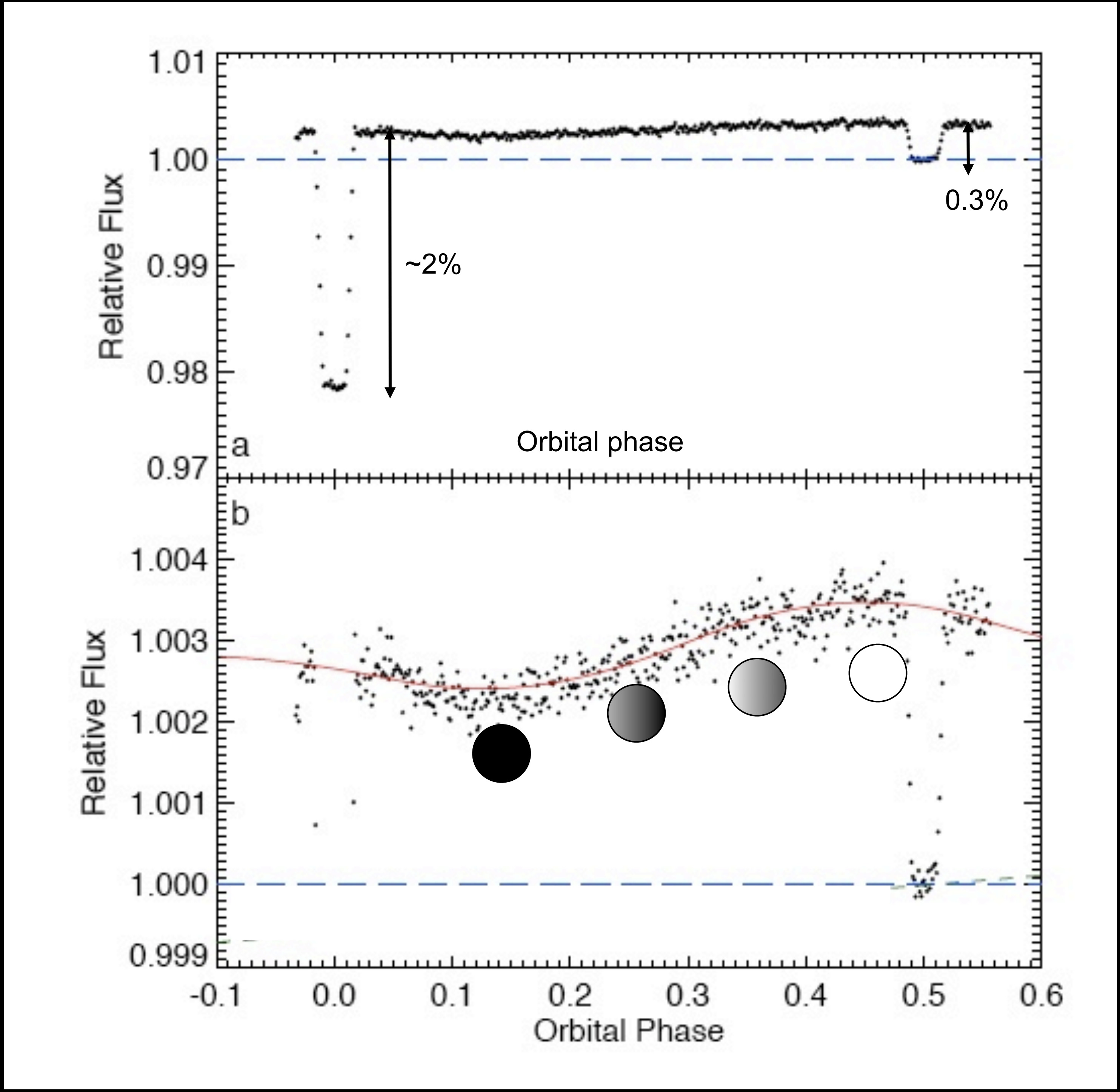
Within 10 pc there are ~300 stars, so potentially 300×0.25=75 of these planets

But only 75×0.05 = 3.75 should transit (statistically)

HD189733

8 microns

Knutson et al., 2008



This have been observed for nontransiting hot Jupiters (Cowan et al., 2007) and for one hot rocky planet (Kepler 10b, Batalha et al., 2011)

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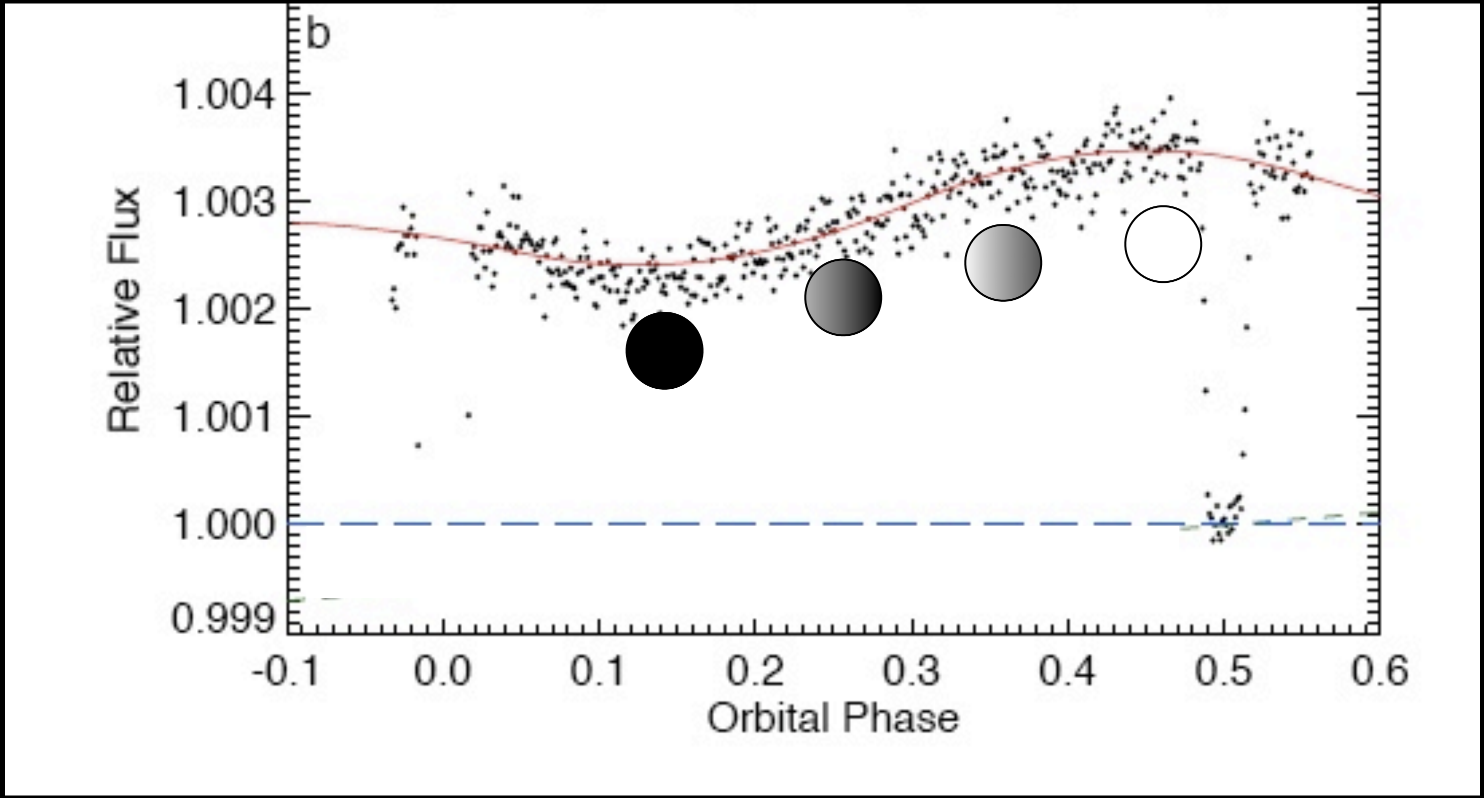
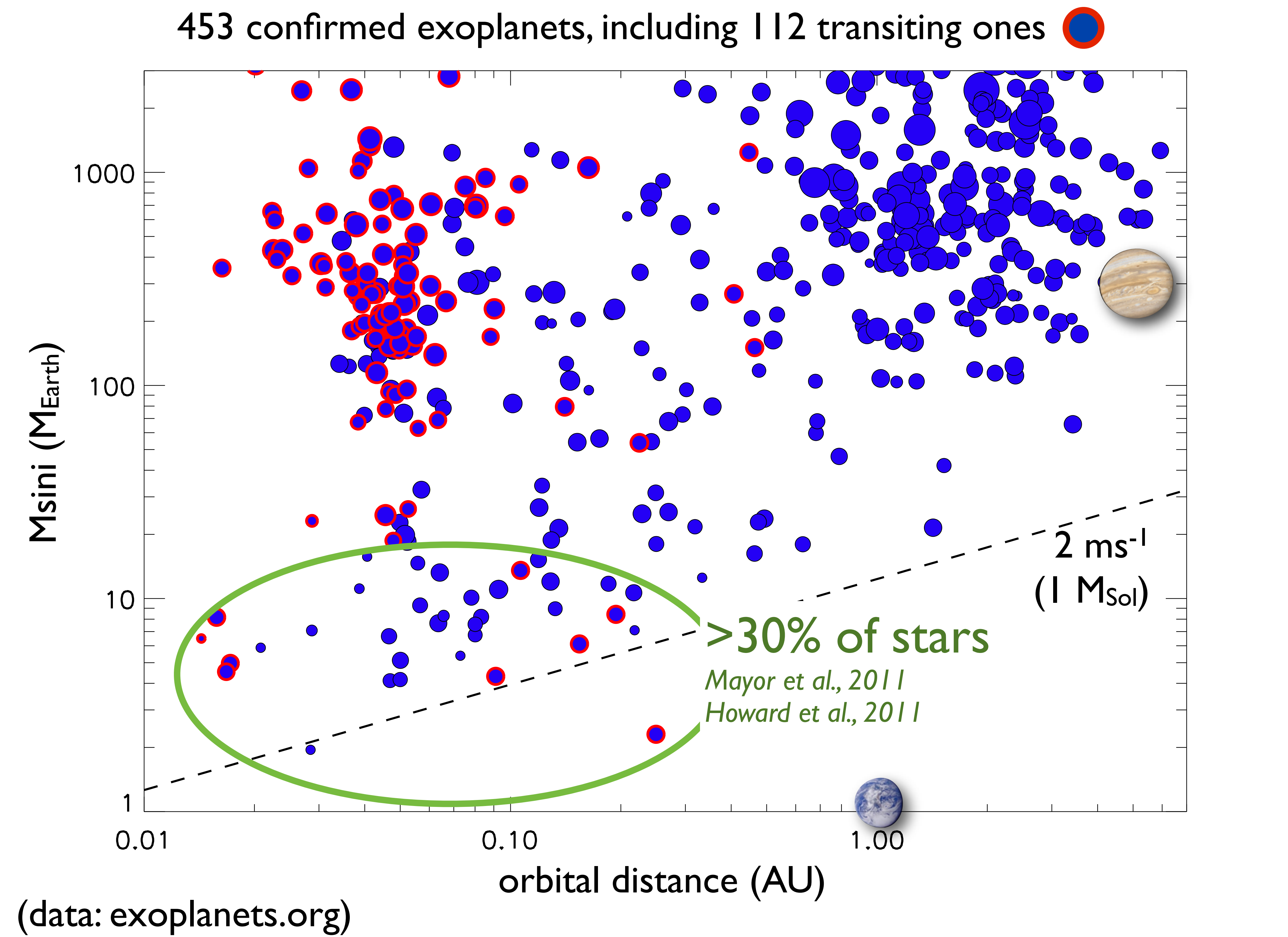
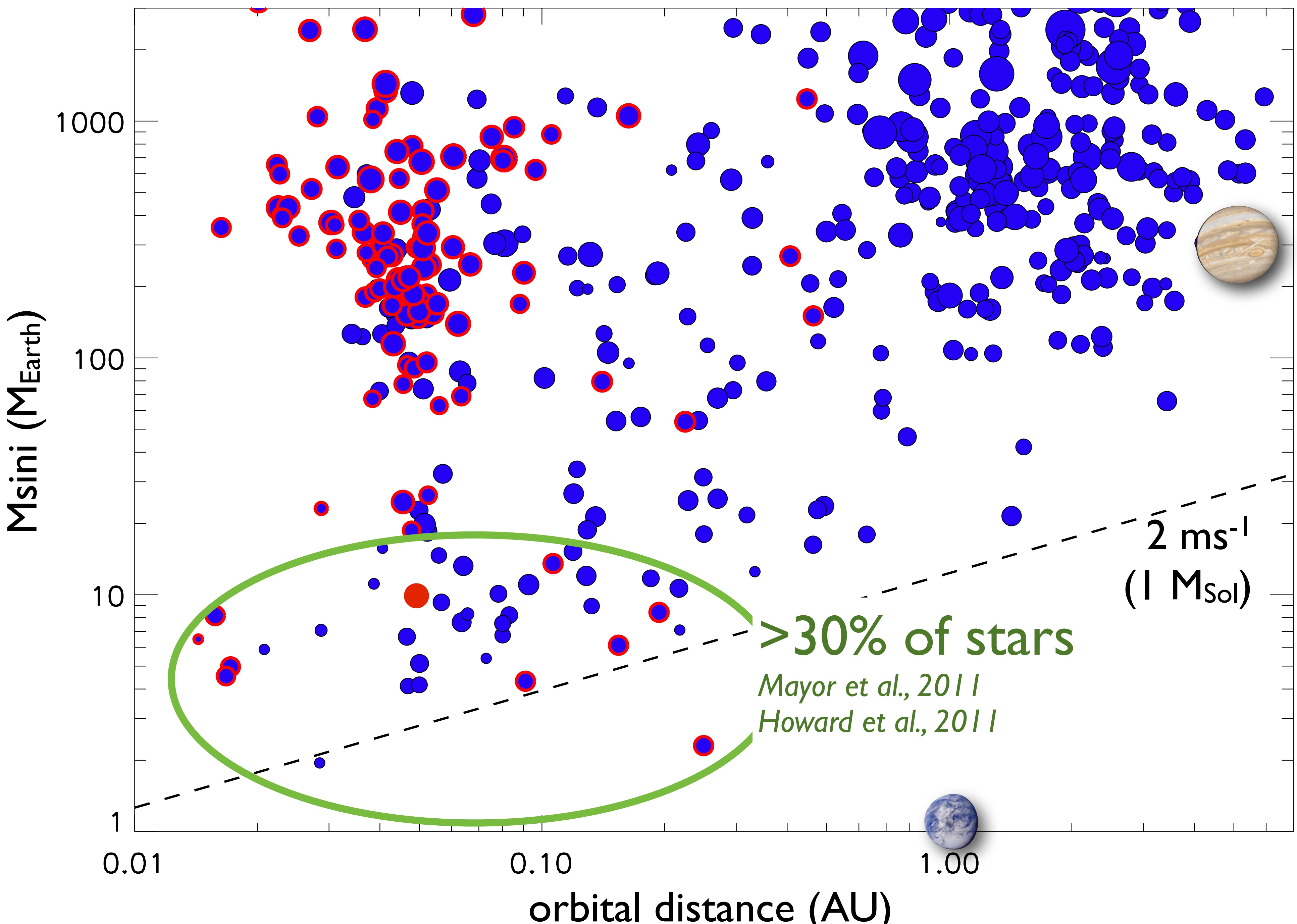


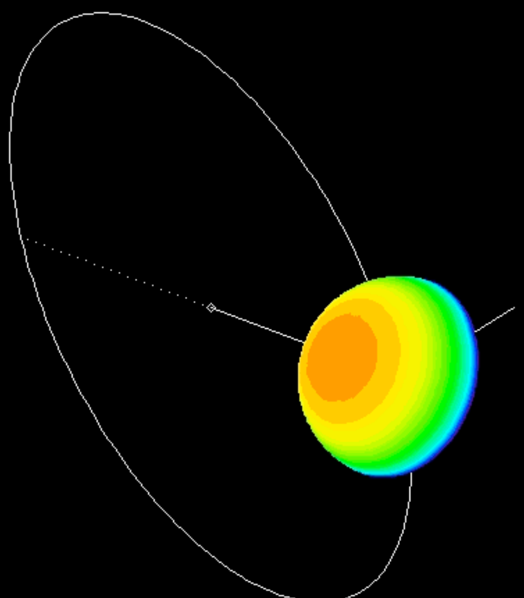

453 confirmed exoplanets, including 112 transiting ones
Msini (MEarth)
1000
100
10
1
0.01
0.10
1.00
orbital distance (AU)
2 ms-1
(1 MSol)
>30% of stars
Mayor et al., 2011
Howard et al., 2011
(data: exoplanets.org)

453 confirmed exoplanets, including 112 transiting ones



(data: exoplanets.org)

Test case



inclination = 60°

- a large rocky planet (1.8 R_{Earth}) around a low-mass star (0.3 MSun)

- 8-days period = 0.05 AU

- circular orbit

- tidally locked. Consistent with orbit.

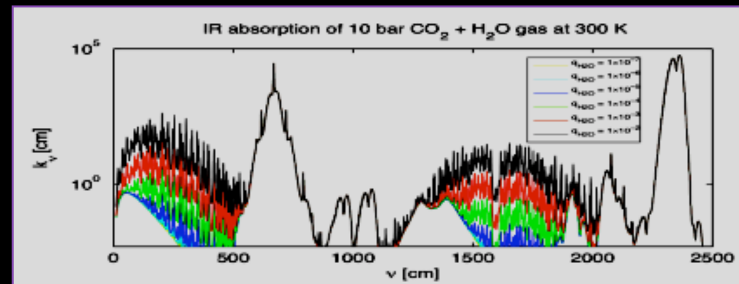
- only one atmospheric constituant : CO_2

-no cloud (too hot for CO_2 condensation, no H_2O, no dust/aerosols)

P=0, 0.1, 1, 10 bar

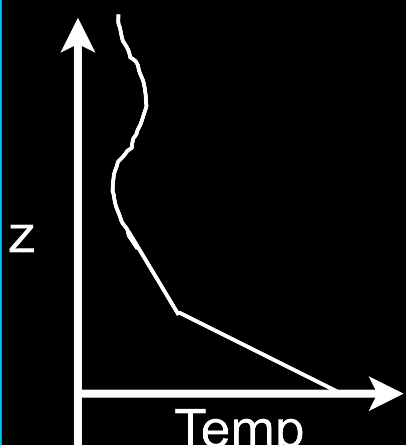
Correlated-k radiative transfer (gases + clouds) ~80 bands

Hires spectra

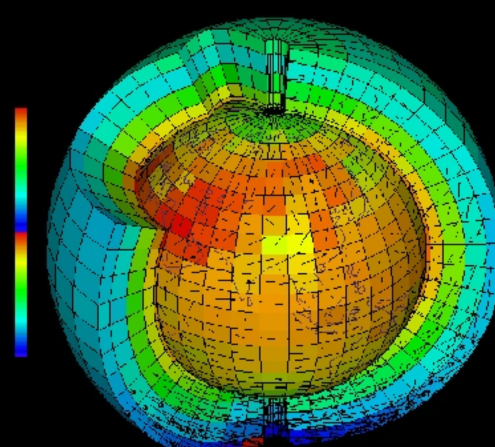


Radiative effects of gases and clouds (from UV to far IR)

1D radiative-convective model



3D dynamical core (LMDZ)

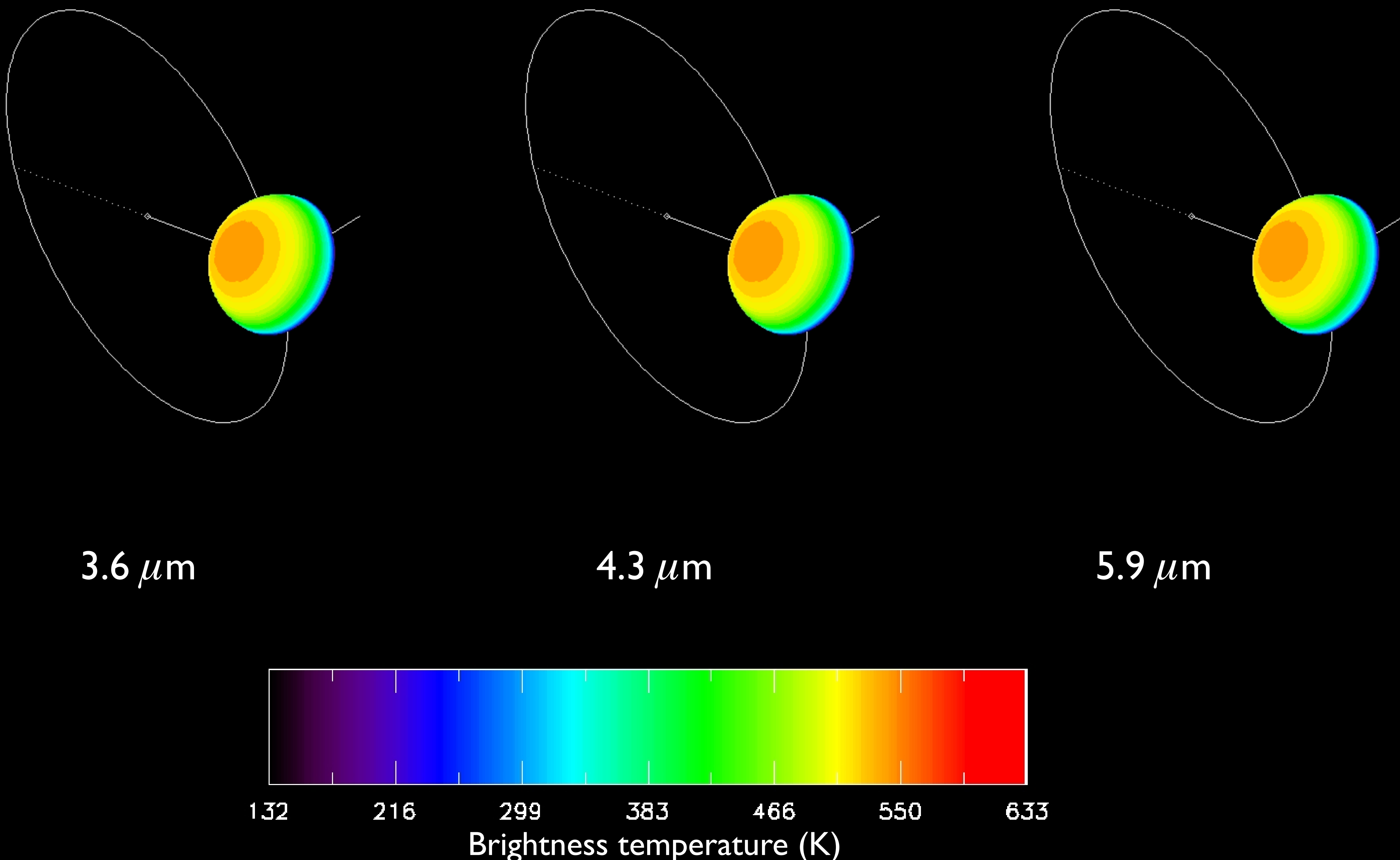


In principle, the scheme works for any atmospheric species, provided that we have the basic physical data (thermo, spectro)

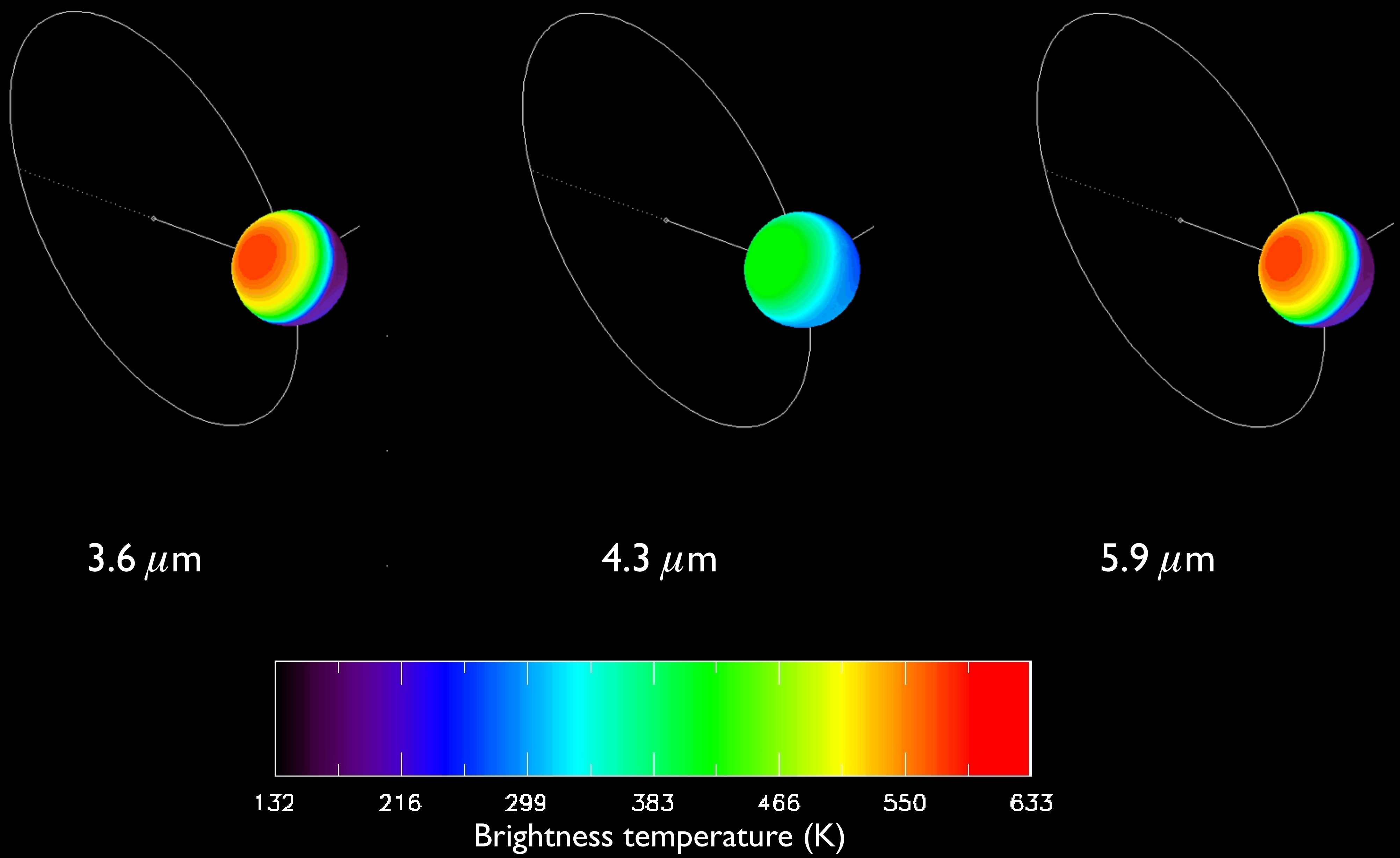
outgoing fluxes in all bands

Wordsworth et al., 2011, Selsis et al., 2011

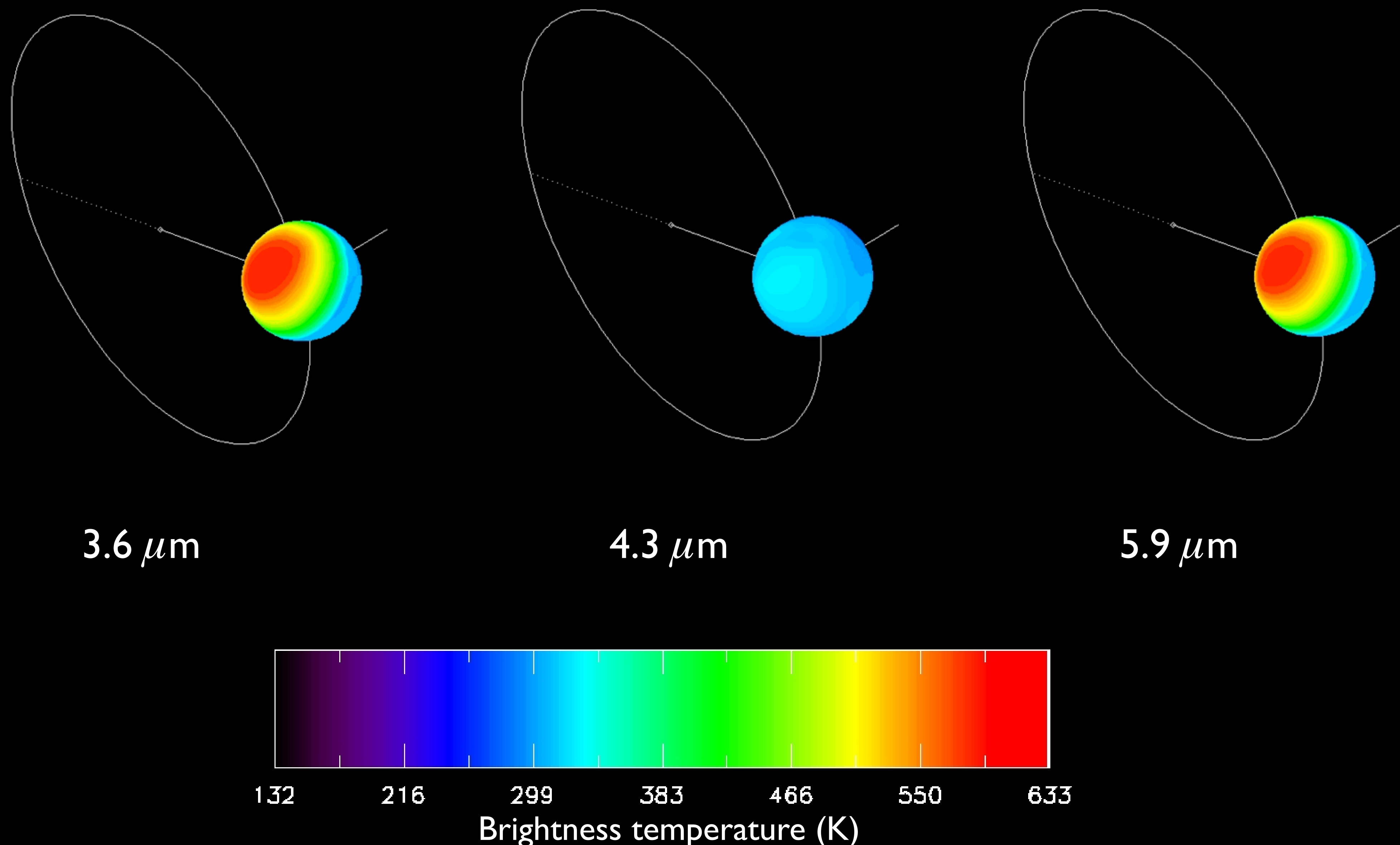
no atmosphere



0.1 bar (CO_2)

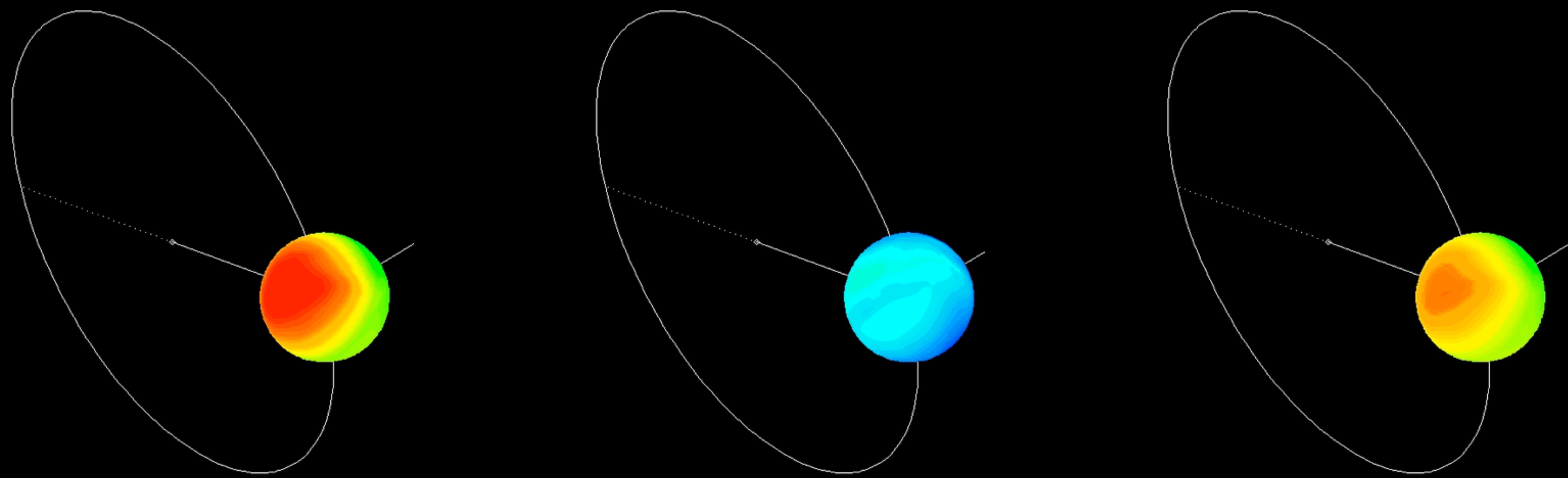

3.6 μm
4.3 μm
5.9 μm
132
216
299
383
466
550
633
Brightness temperature (K)

1 bar (CO_2)

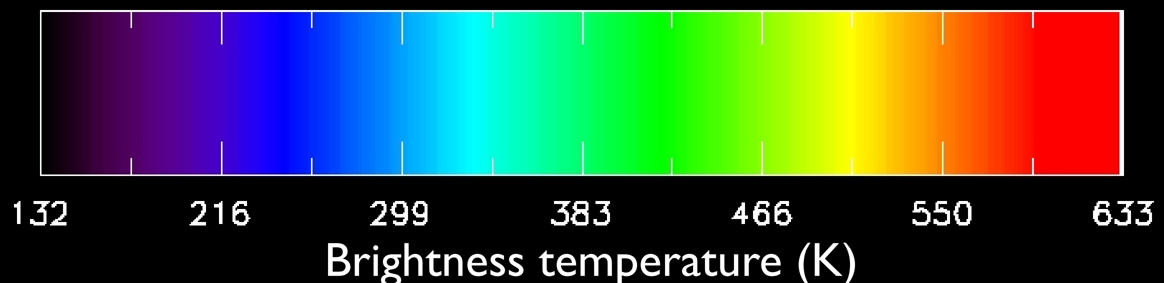


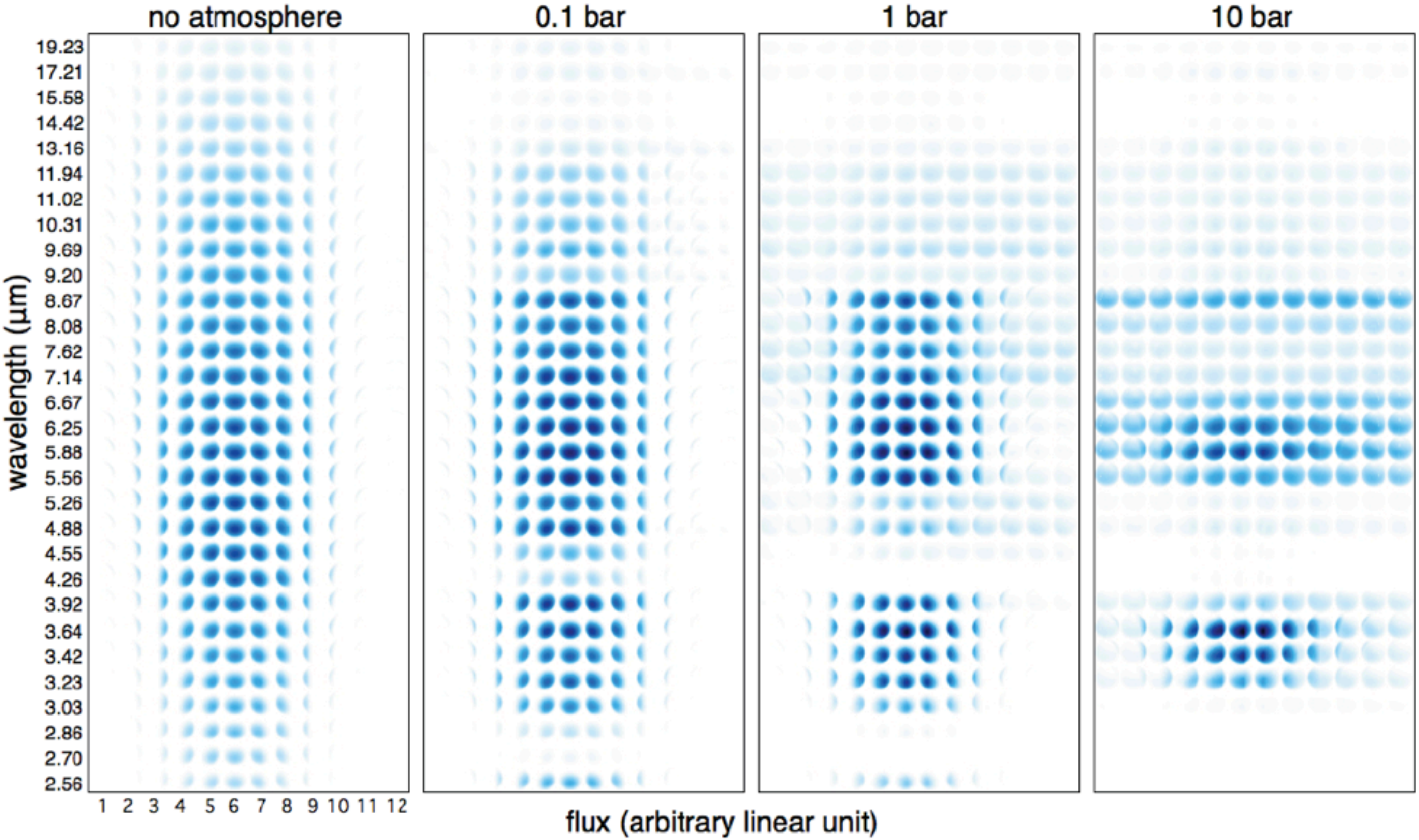
3.6 μm
4.3 μm
5.9 μm
132
216
299
383
466
550
633
Brightness temperature (K)

10 bar (CO_2)



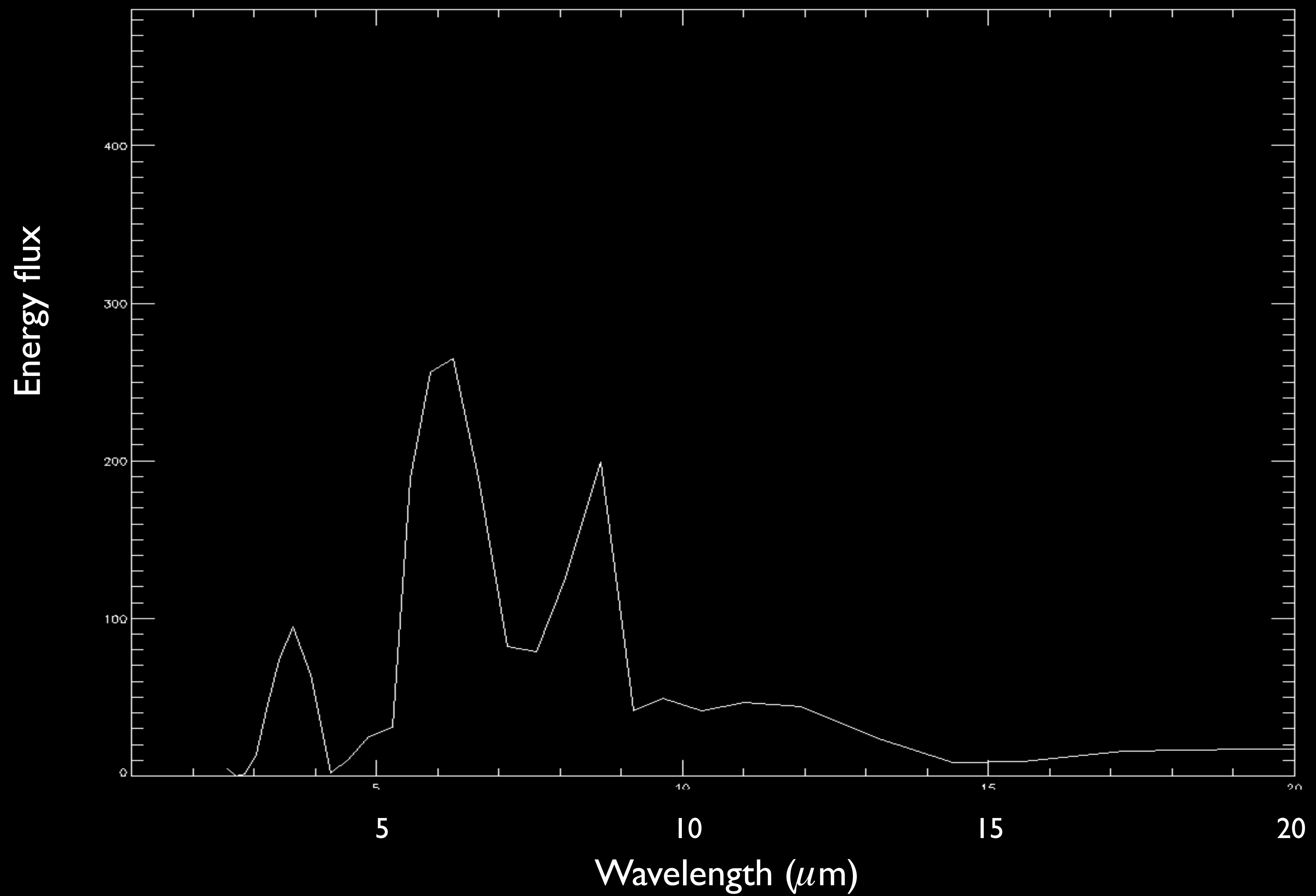
3.6 μm　　4.3 μm　　5.9 μm



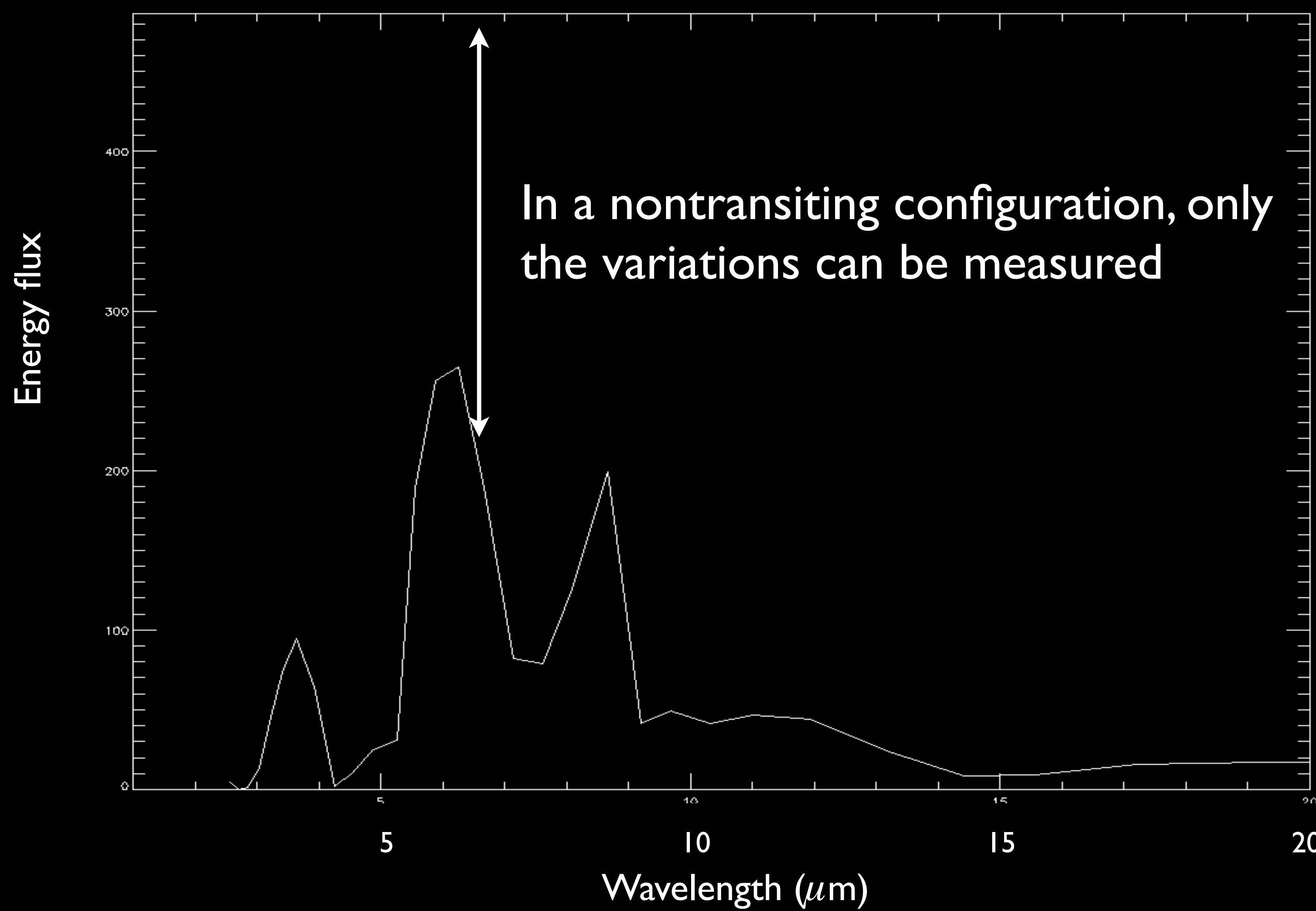


Selsis et al., 2011

10 bar CO_2

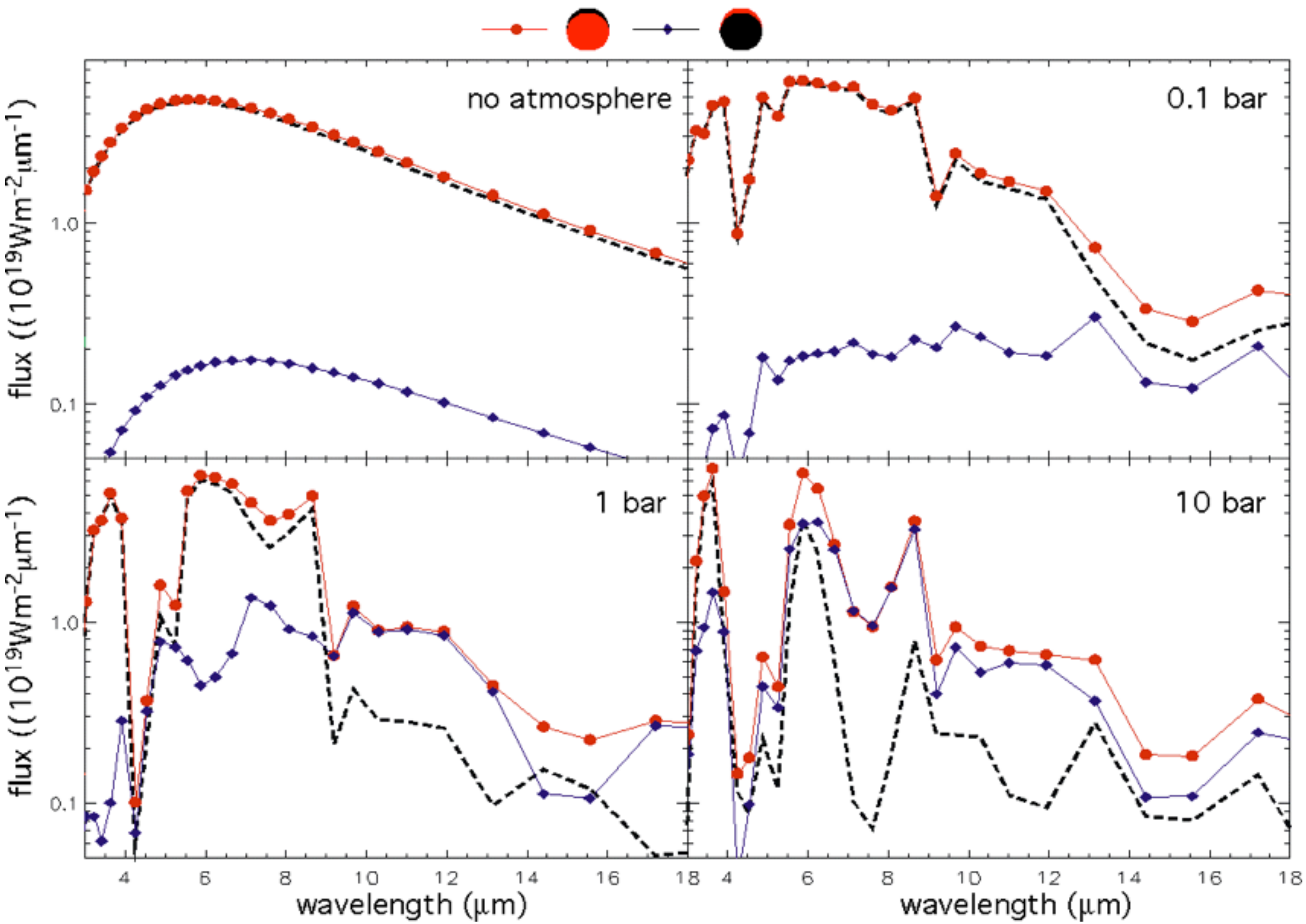


10 bar CO_2



In a nontransiting configuration, only the variations can be measured
Energy flux
400
300
200
100
0
5
10
15
20
Wavelength (μm)

Variation spectrum: amplitude of the phase variations as a function of wavelength



60° inclination

Can we characterize the atmosphere of hot (terrestrial) non-transiting exoplanets

Yes,
we can do that with **JWST**, and **EChO** (Exoplanet Characterization Observatory, pre-selected by ESA)

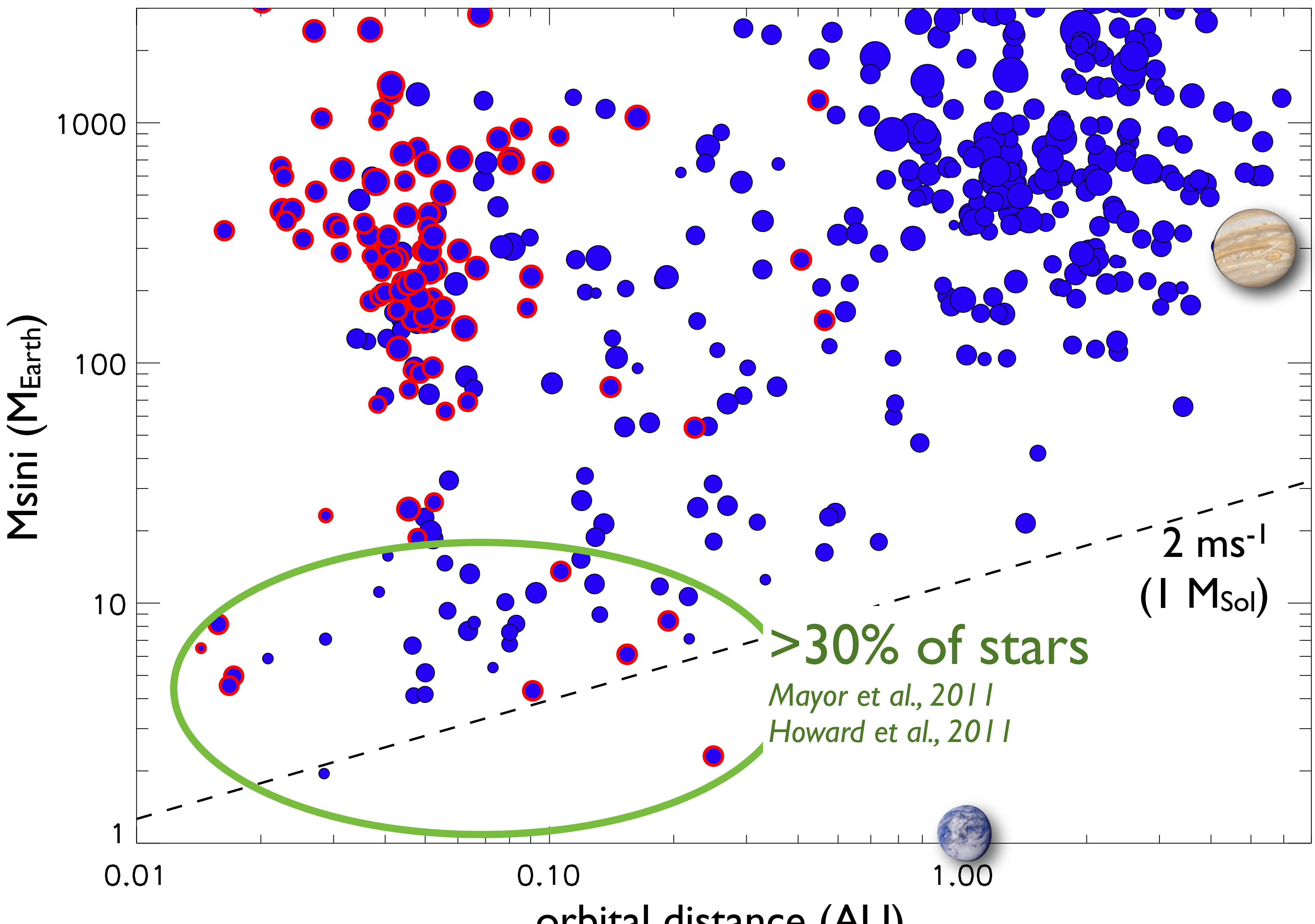
With this technique we should be able

- to distinguish planets with no atmospheres (big Mercuries) from planets with a dense atmosphere

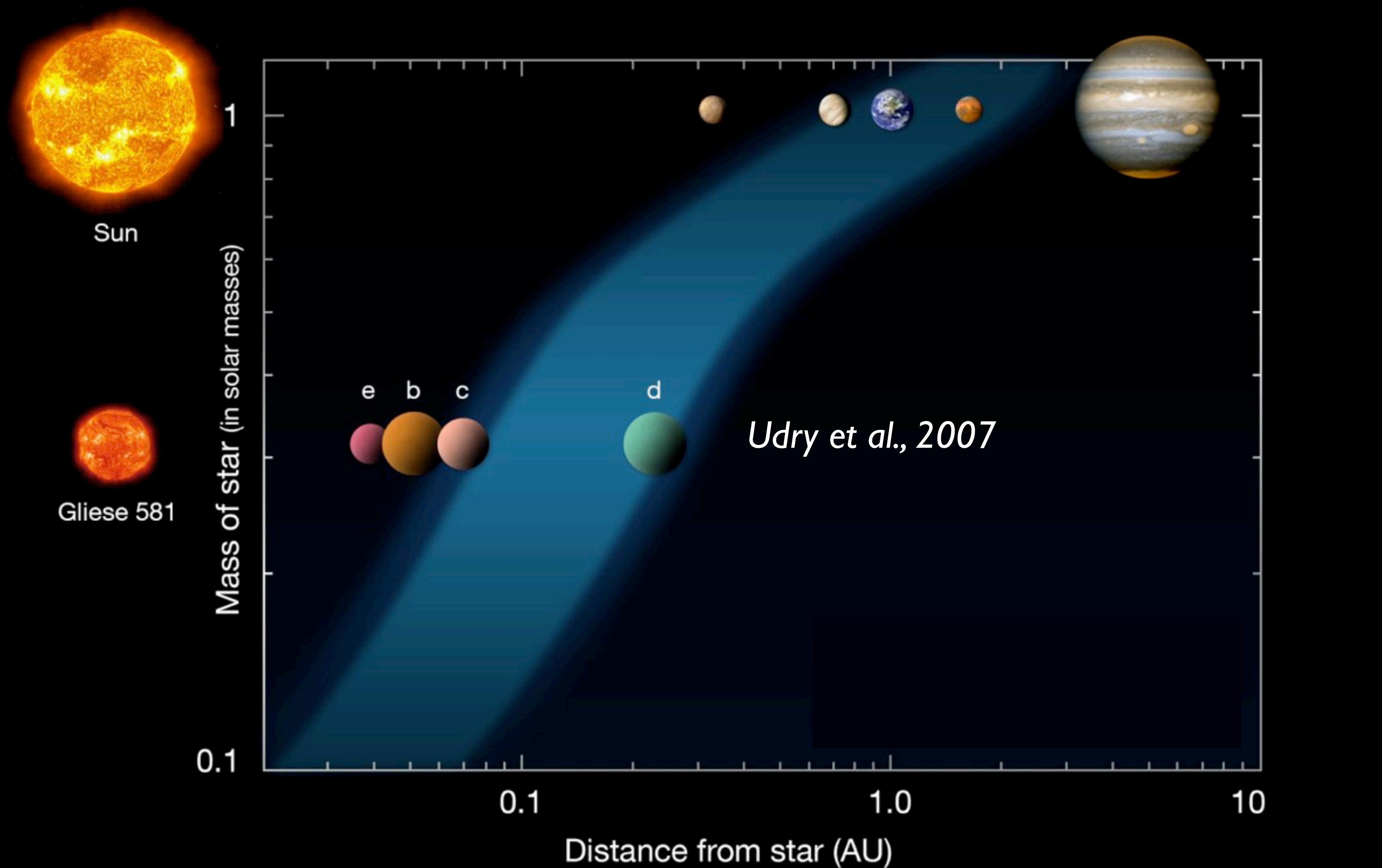
- to detect molecular features in the thermal emission

- to constrain the radius, mass and albedo of planets with no atmosphere (Maurin et al., submitted)

453 confirmed exoplanets, including 112 transiting ones

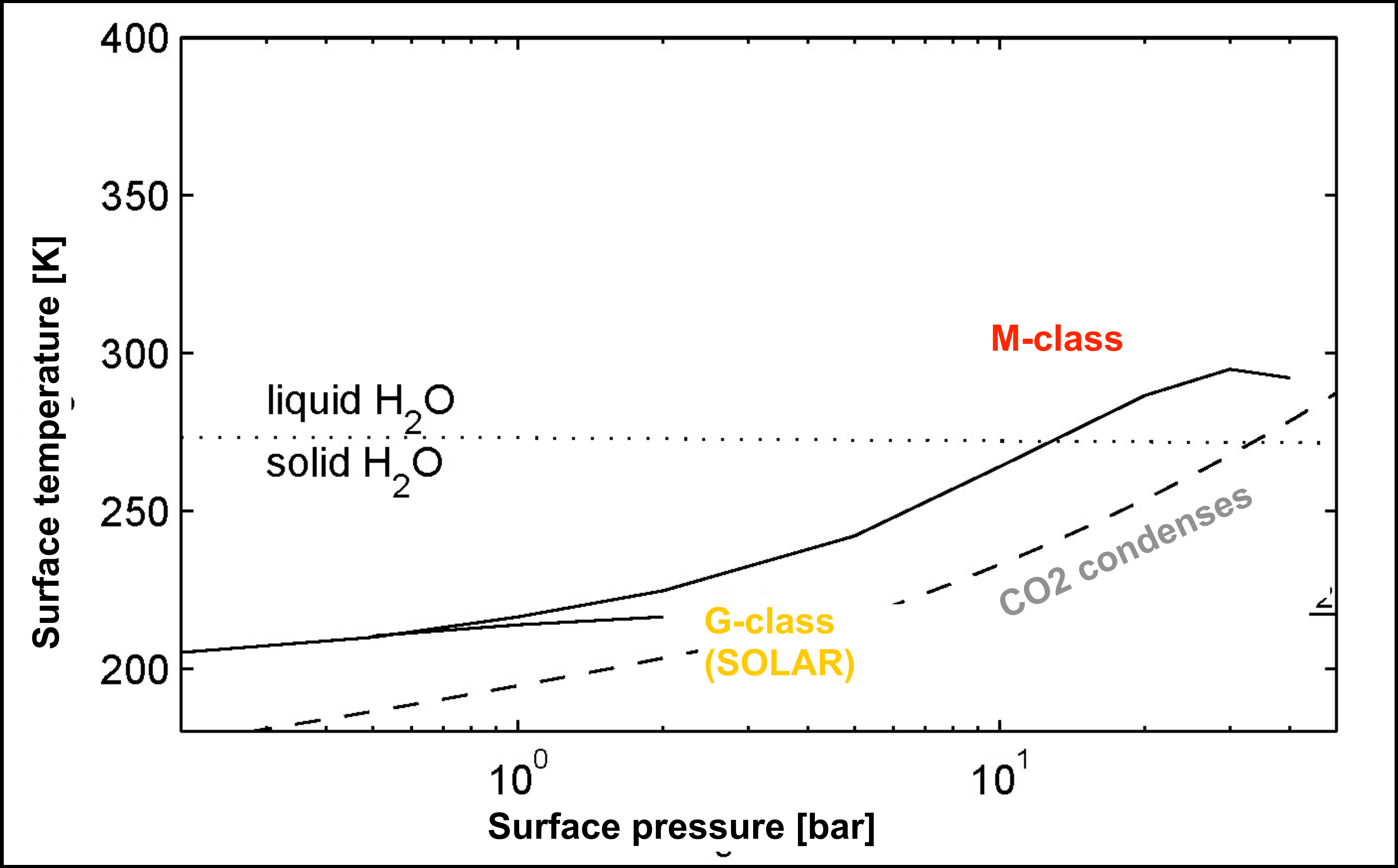


(data: exoplanets.org)



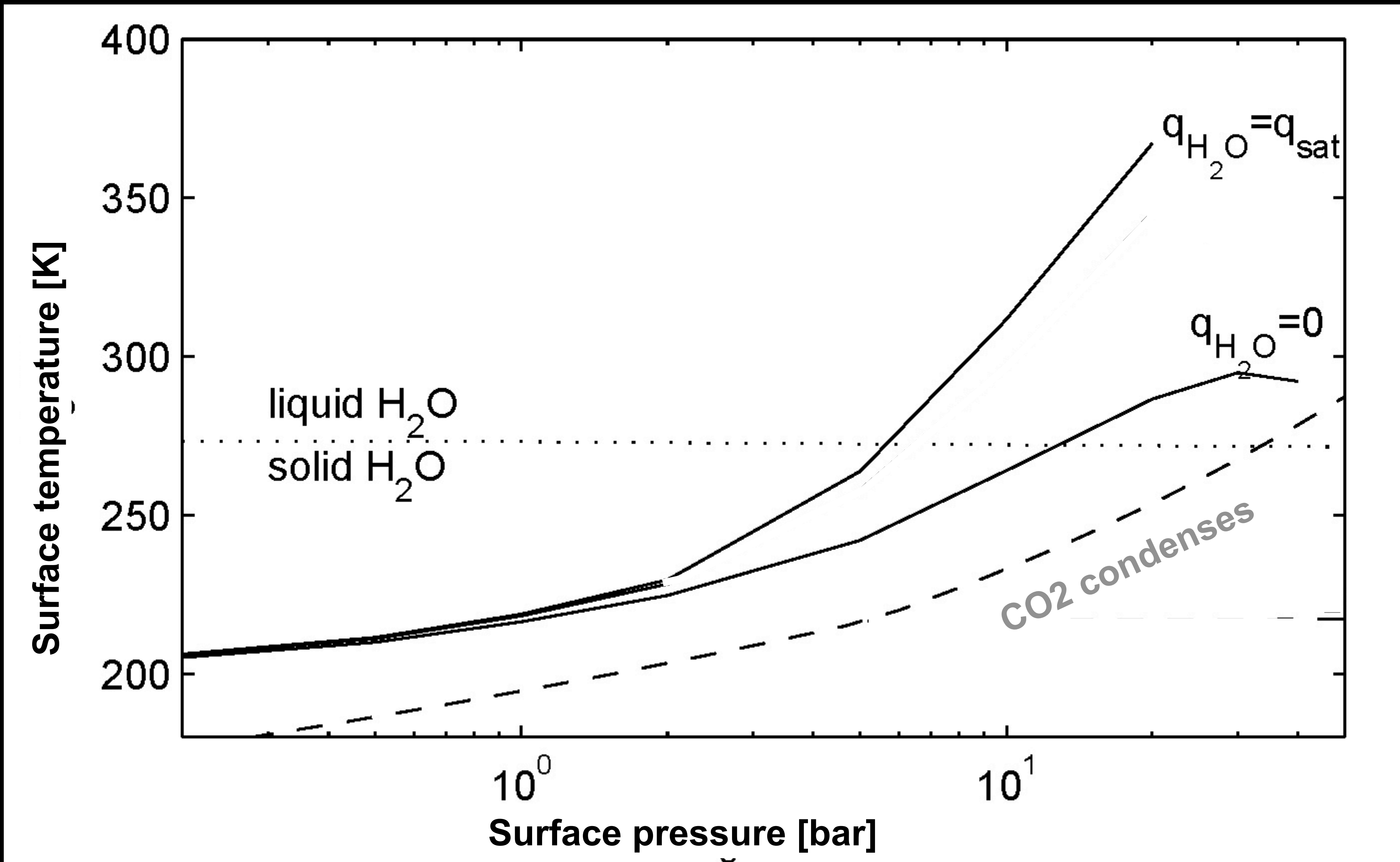
Selsis et al. 2007

Pure CO_2 atmospheres



Wordsworth et al., 2010

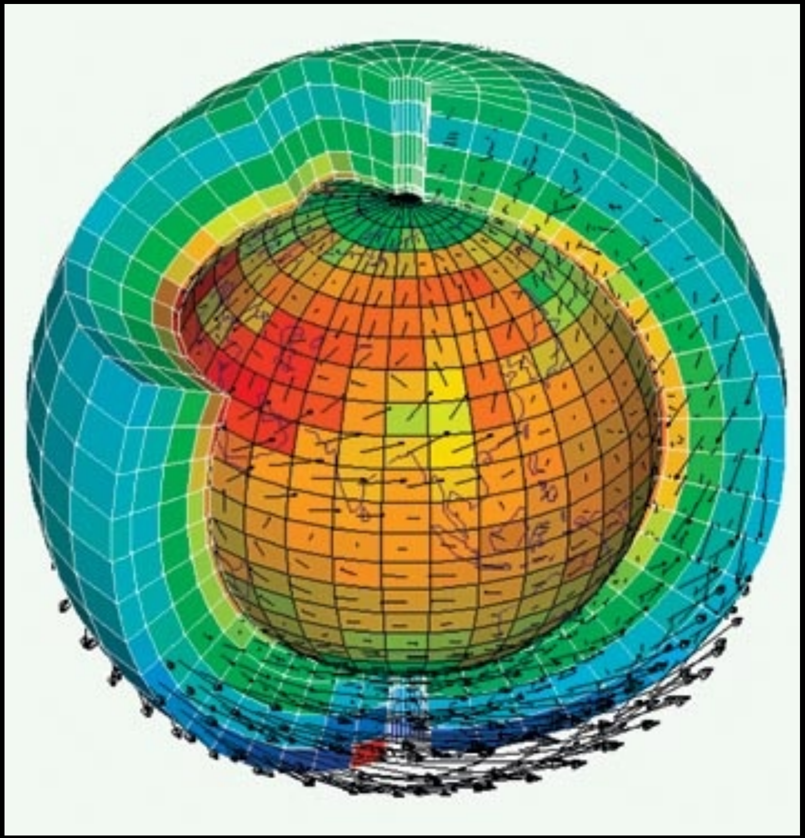
$CO_2 + H_2O$



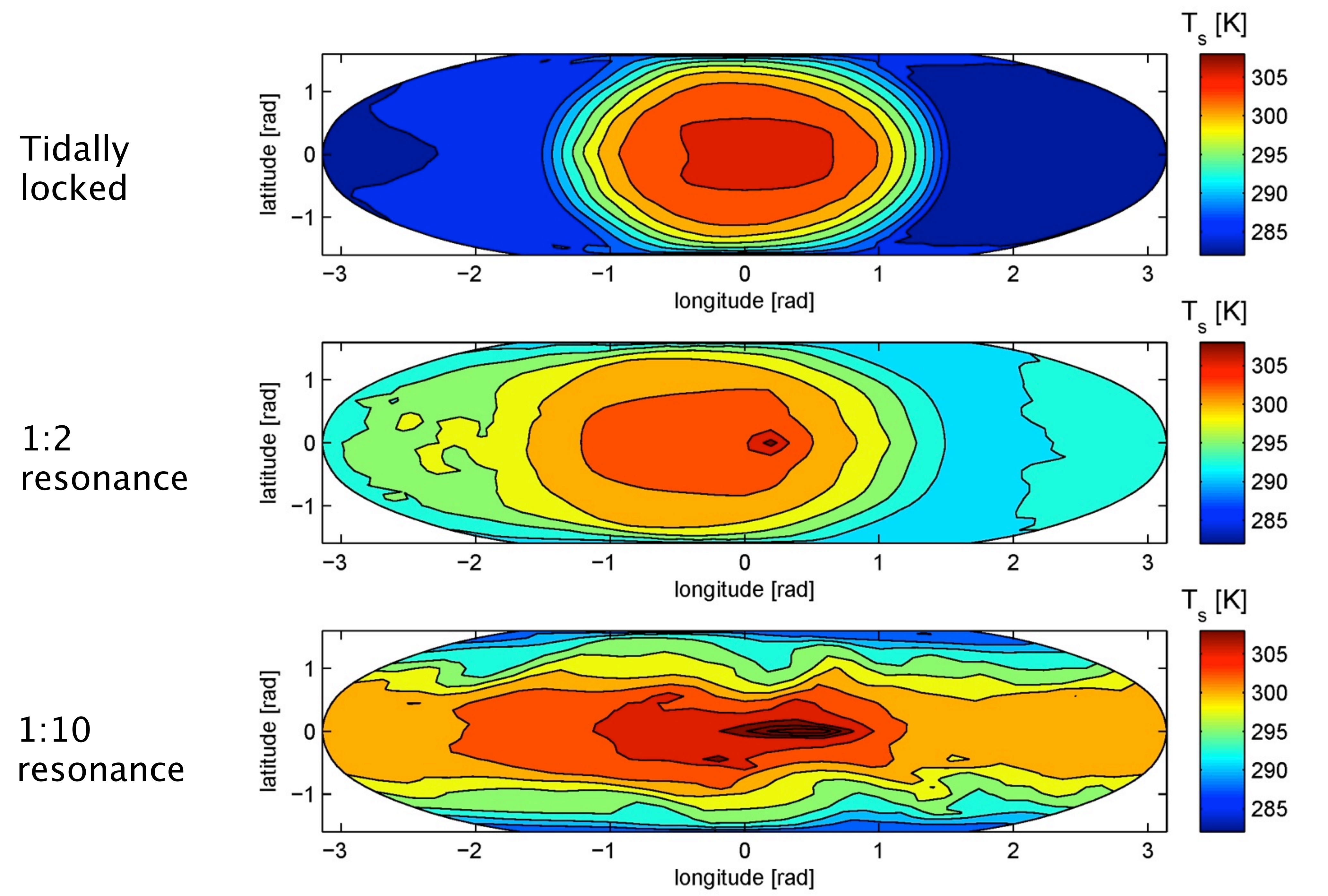
Wordsworth et al., 2010

3D work

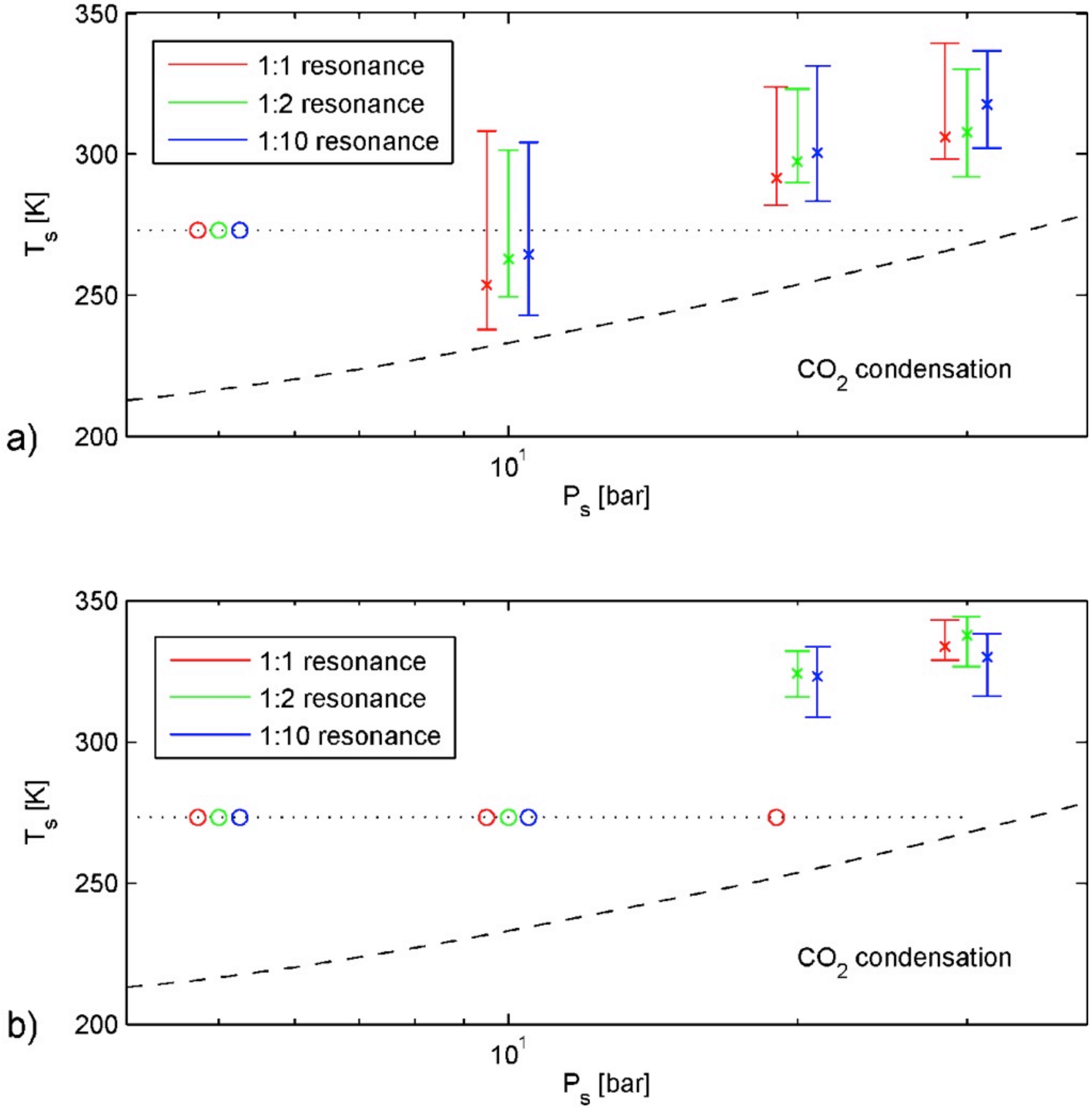
- GJ581d has undergone a strong tidal evolution.
- must be in tidal equilibrium or in spin–orbit resonance.
- obliquity = 0° is likely
- a permanent night side is possible



Would dense CO_2 atmospheres really be stable on the planet's dark side / poles?



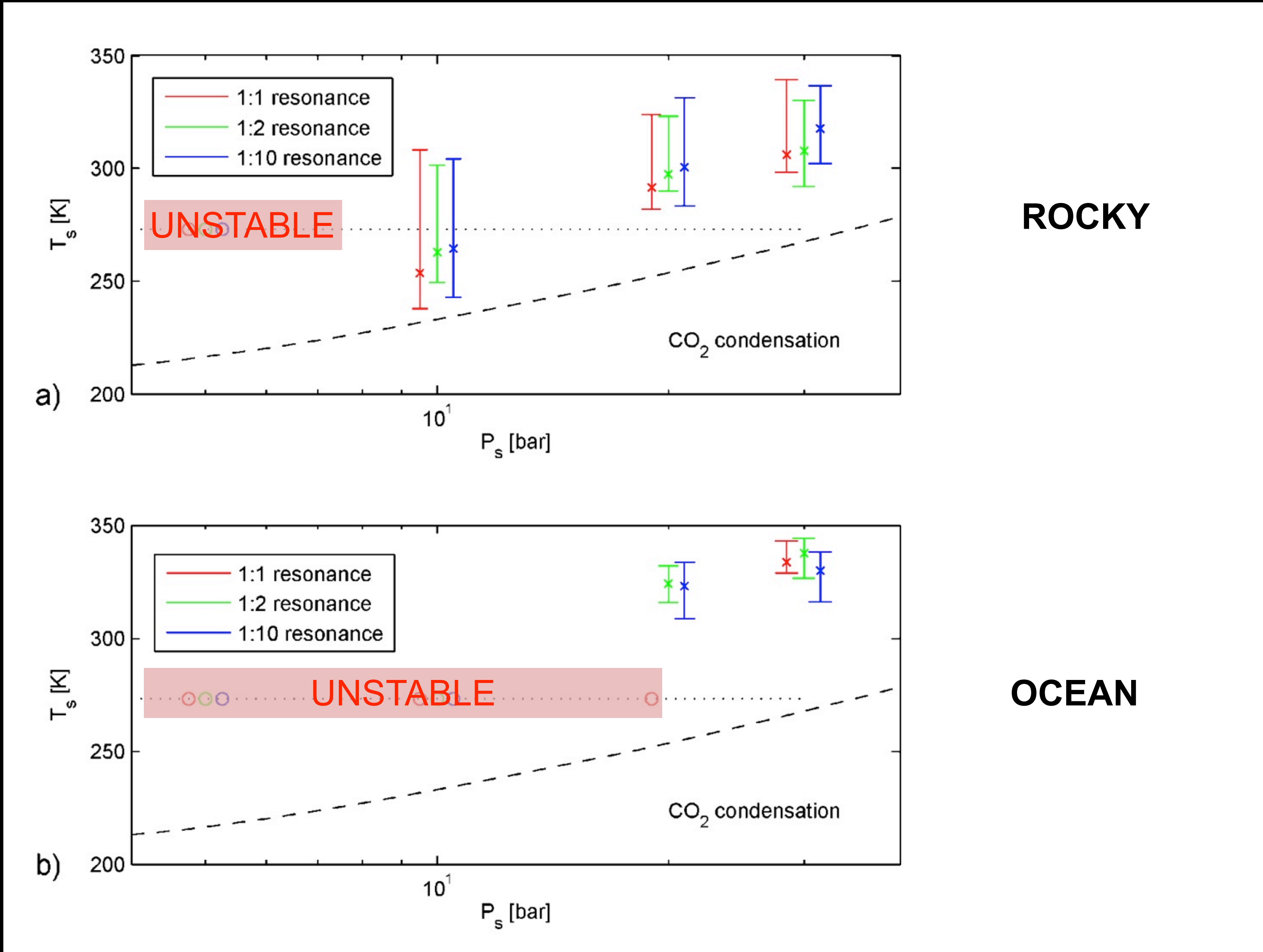
Wordsworth et al. 2011, The Astrophysical Journal Letters



ROCKY

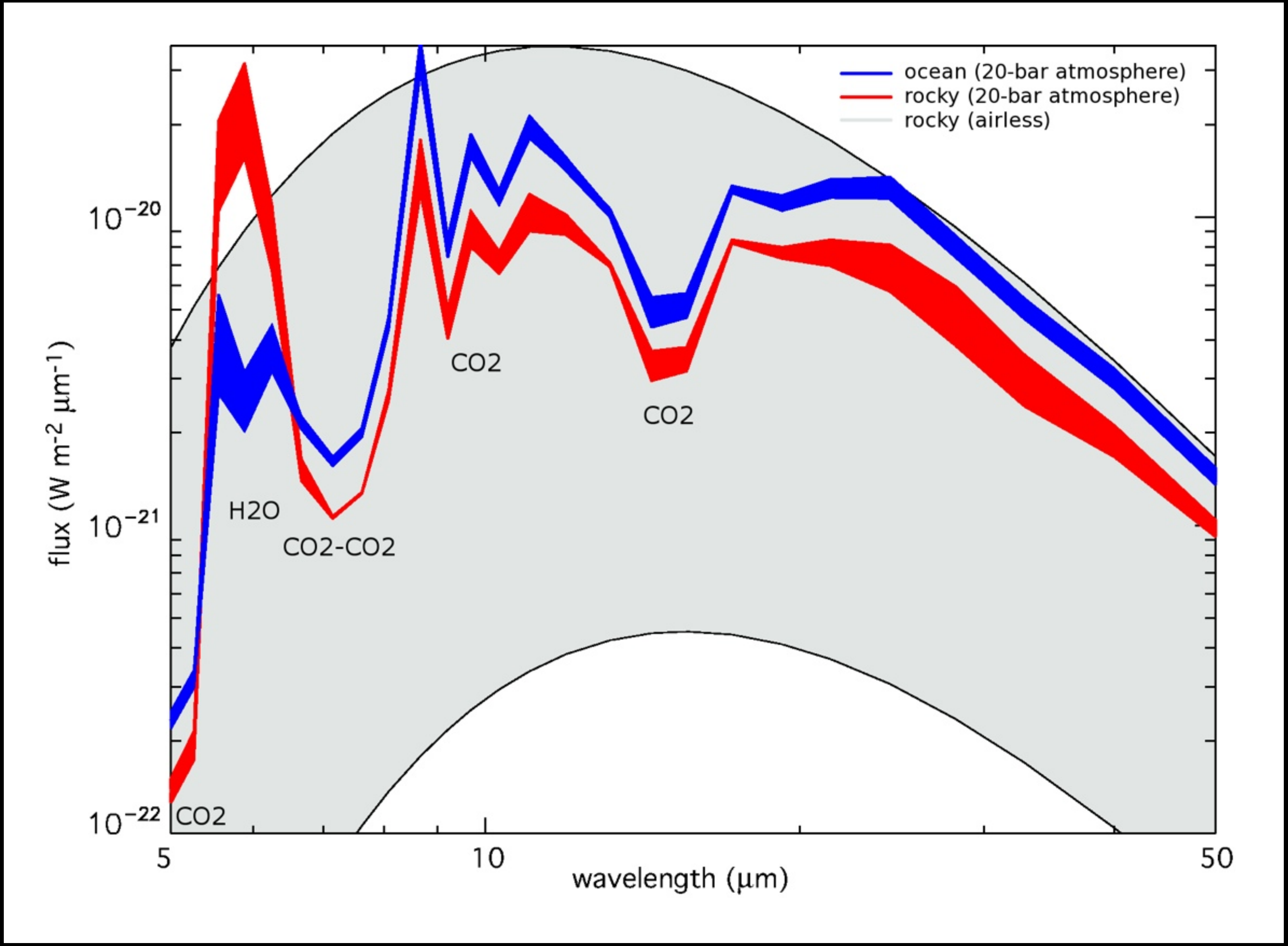
OCEAN

Wordsworth et al. 2011, The Astrophysical Journal Letters



Wordsworth et al. 2011, The Astrophysical Journal Letters

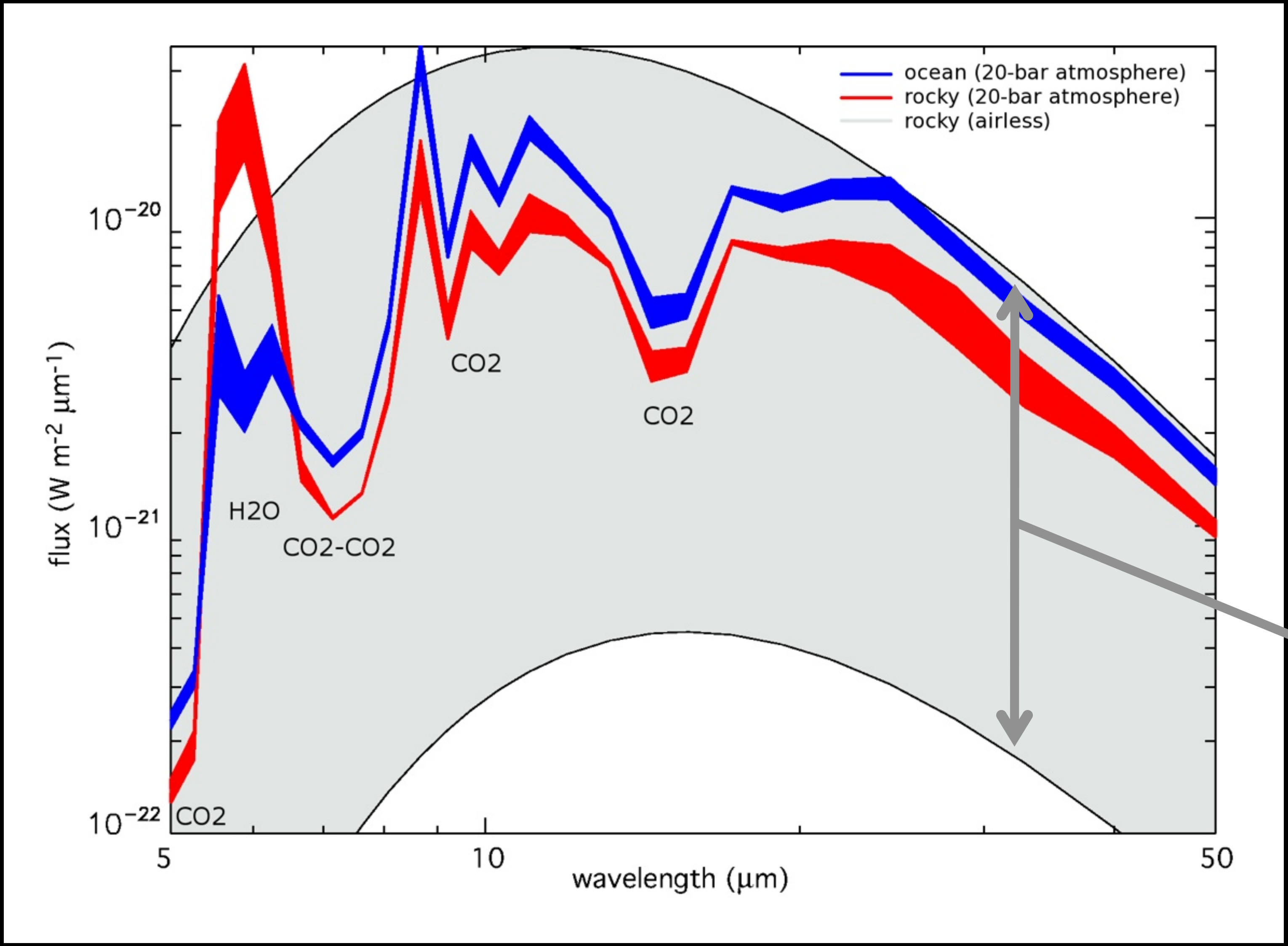
How can we distinguish the various possible cases?



Planet / star contrast ratio of order 10^{-6}
→TPF / Darwin mission required

Wordsworth et al. 2011, The Astrophysical Journal Letters

How can we distinguish the various possible cases?

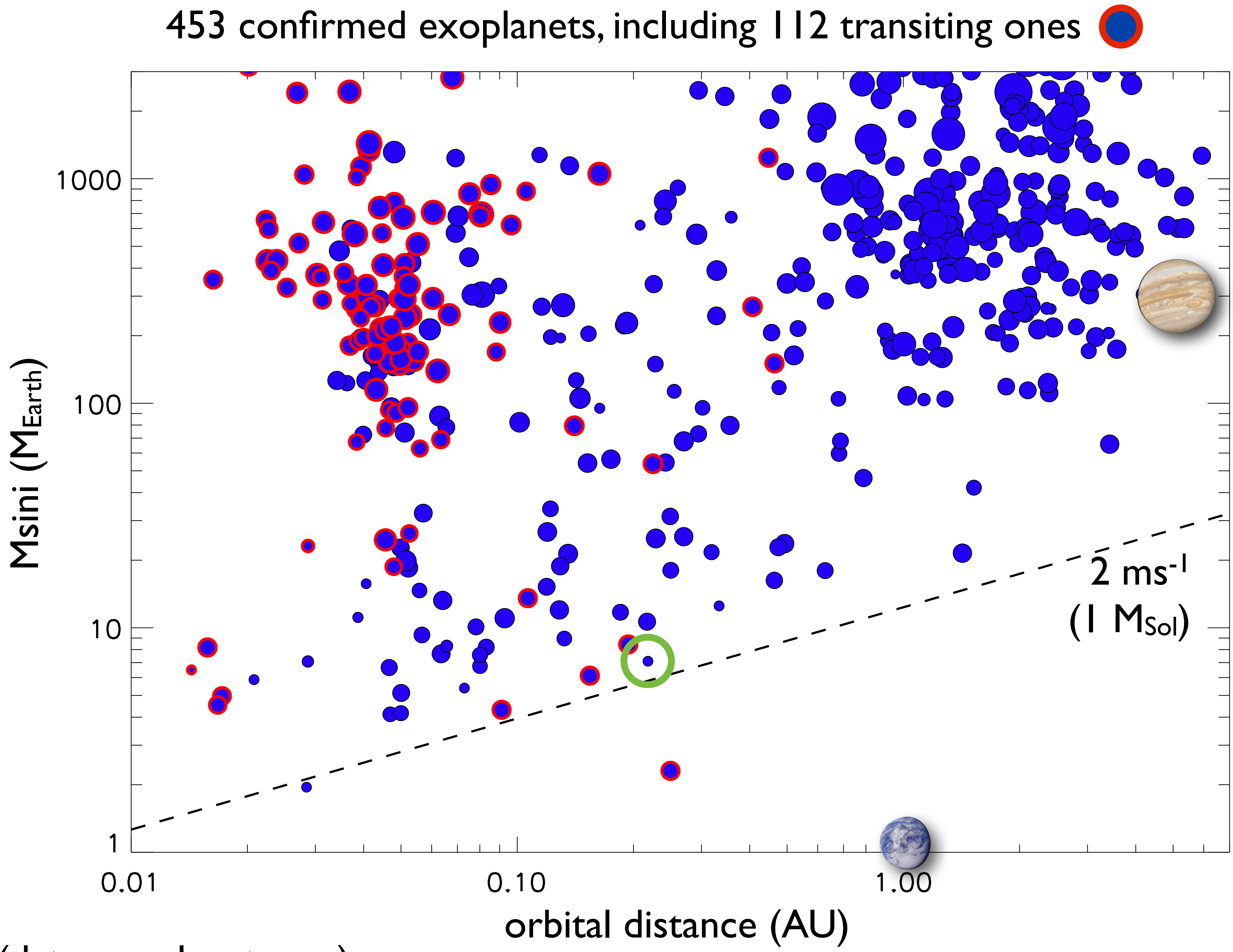


Wordsworth et al. 2011, The Astrophysical Journal Letters

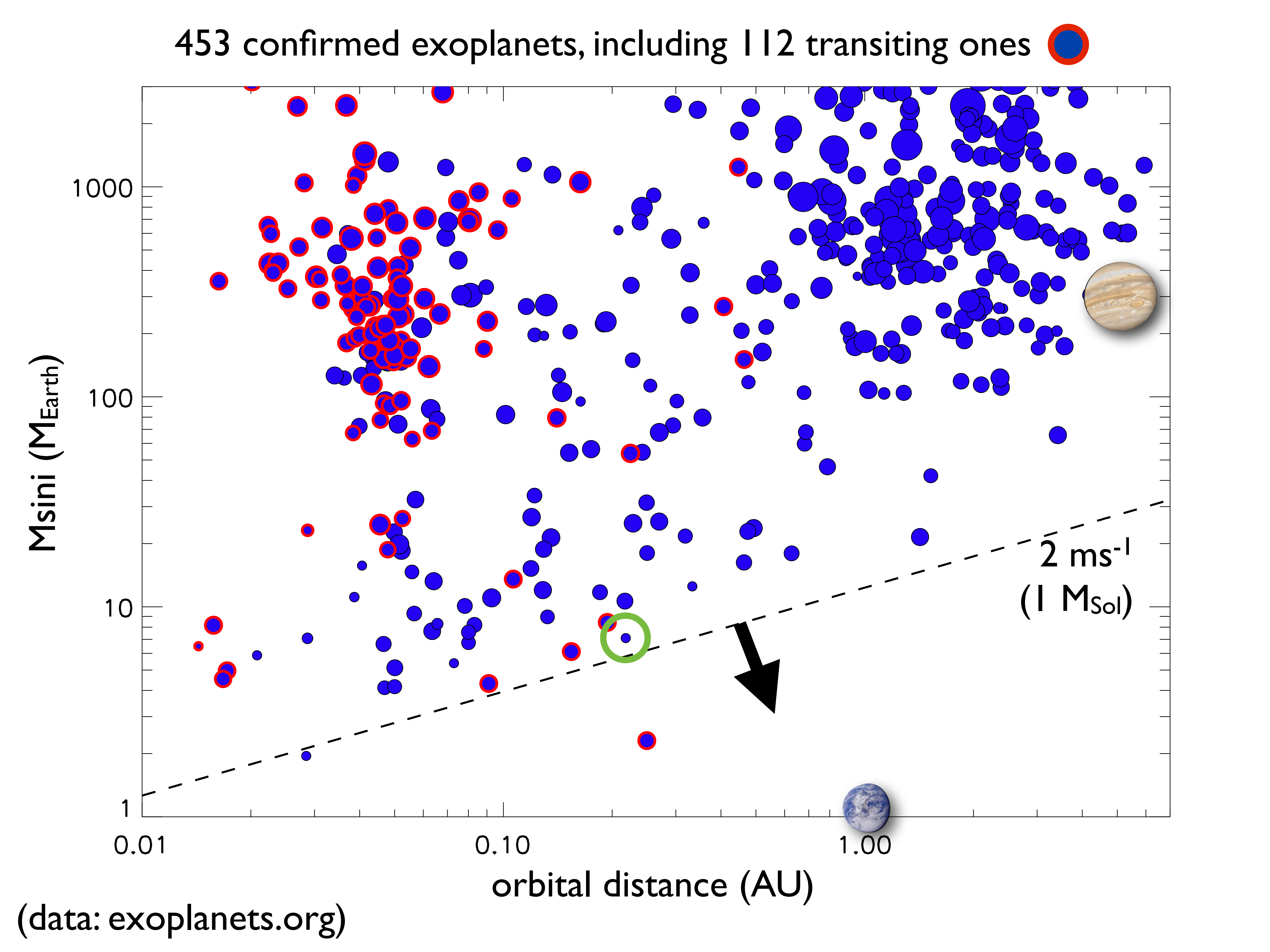
Planet / star contrast ratio of order 10^{-6}
→TPF / Darwin mission required

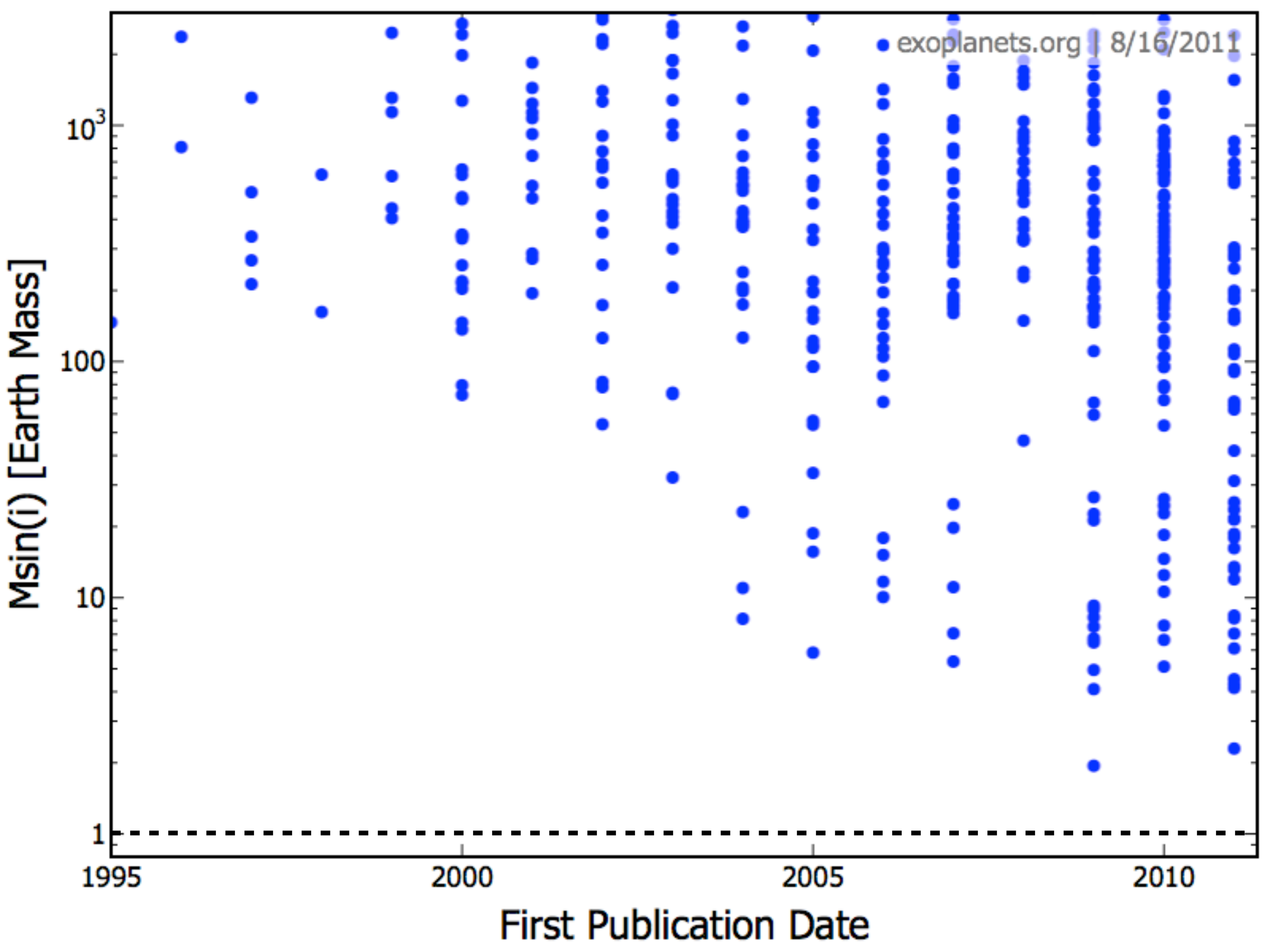
Large orbital flux variations in airless case

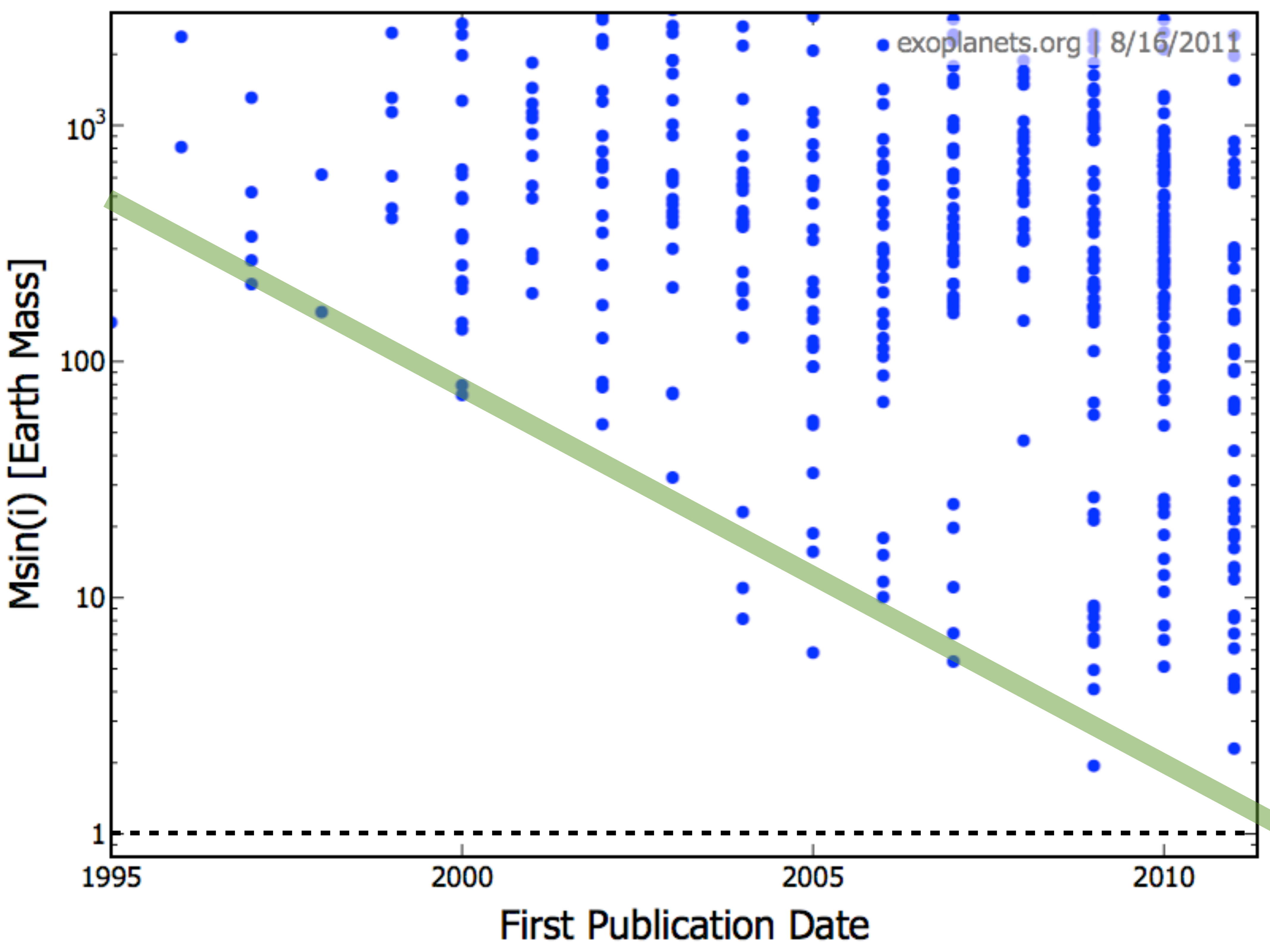
453 confirmed exoplanets, including 112 transiting ones



(data: exoplanets.org)


453 confirmed exoplanets, including 112 transiting ones
Msini (M_{Earth})
1000
100
10
1
0.01
0.10
1.00
orbital distance (AU)
2 ms^{-1}
(1 M_{Sol})
(data: exoplanets.org)


exoplanets.org | 8/16/2011
Msin(i) [Earth Mass]
10^3
100
10
1
1995
2000
2005
2010
First Publication Date



exoplanets.org | 8/16/2011
Msin(i) [Earth Mass]
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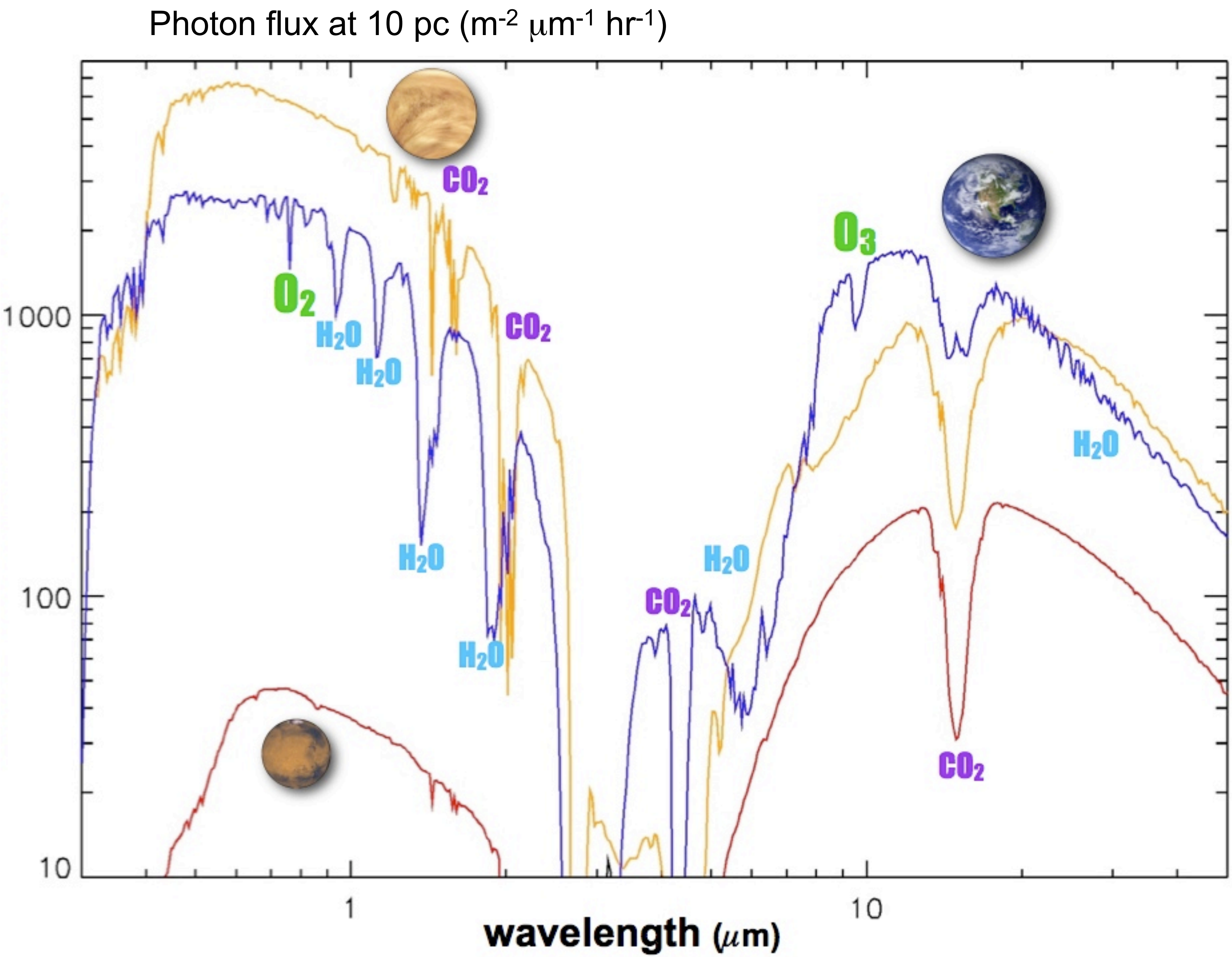
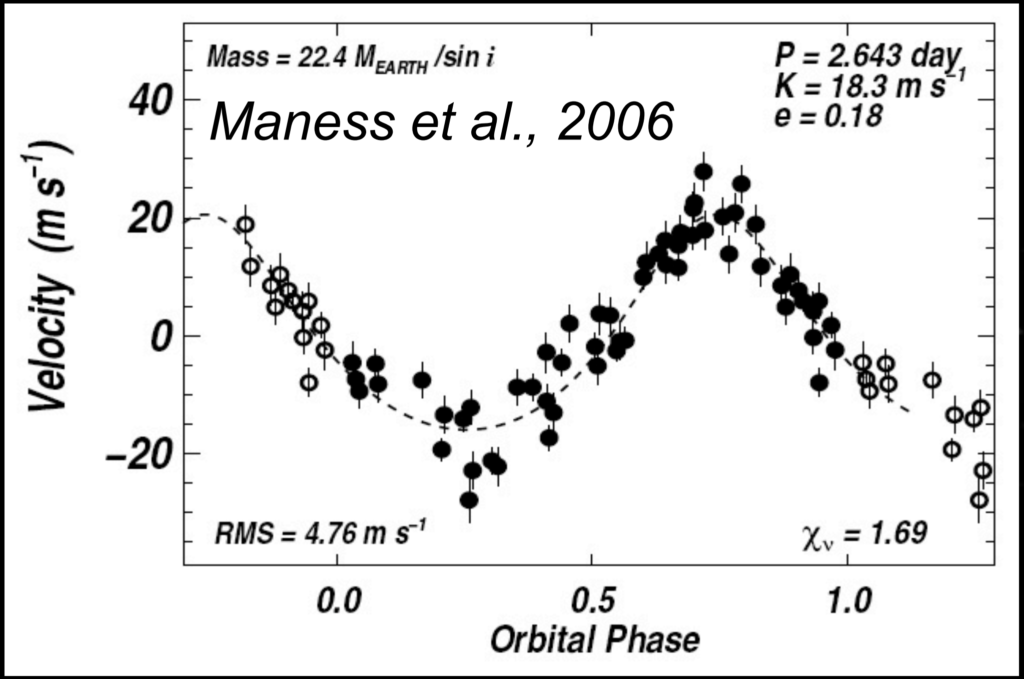
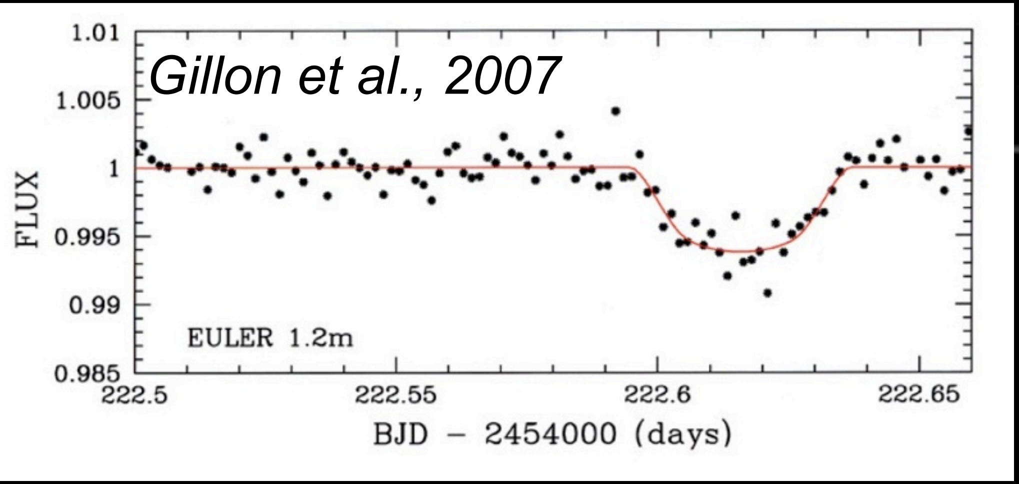


(Selsis & Tinetti, Darwin Proposal, 2007)

GJ436 b

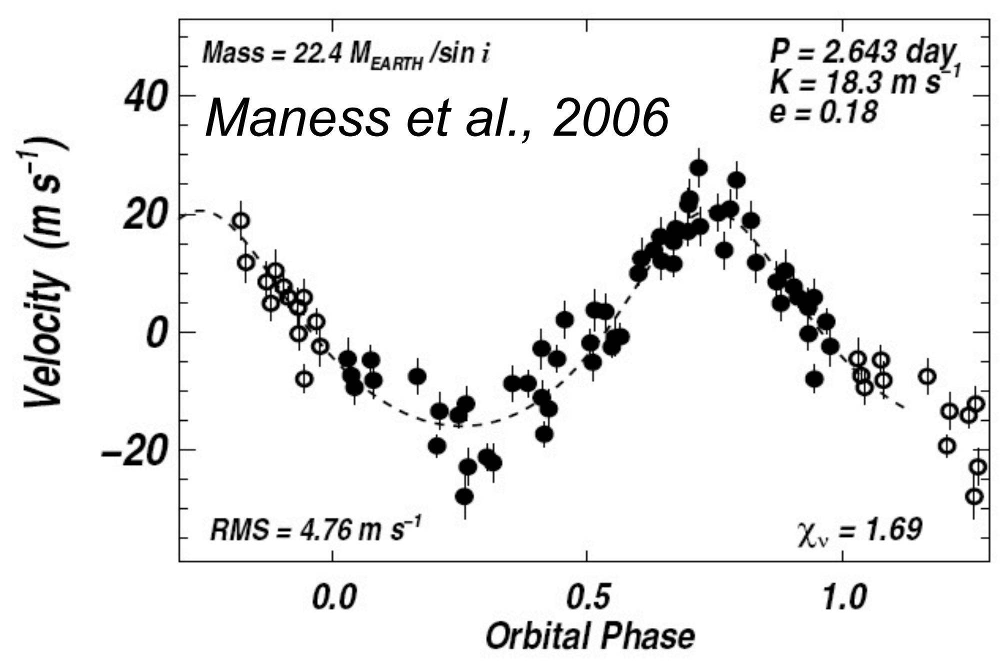


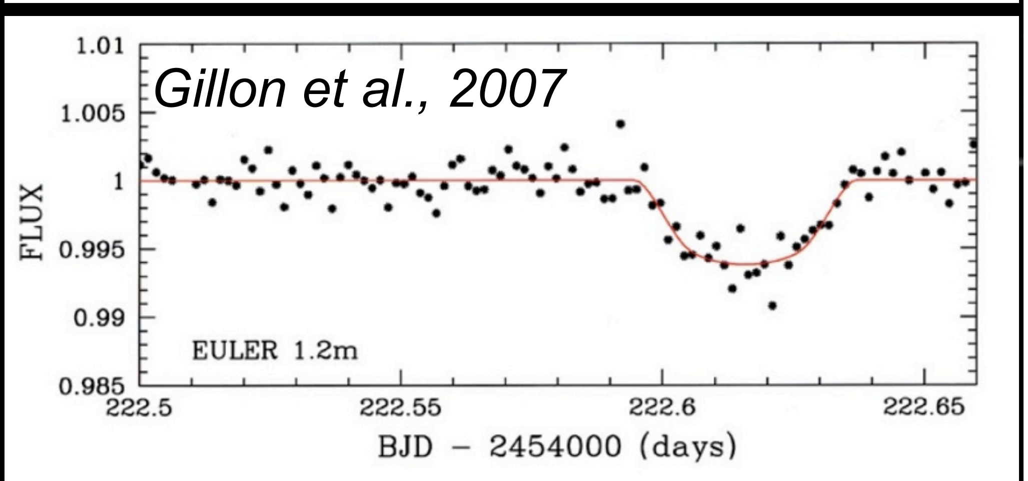
- orbital period (distance)
- eccentricity
- mass×sin(inclination)

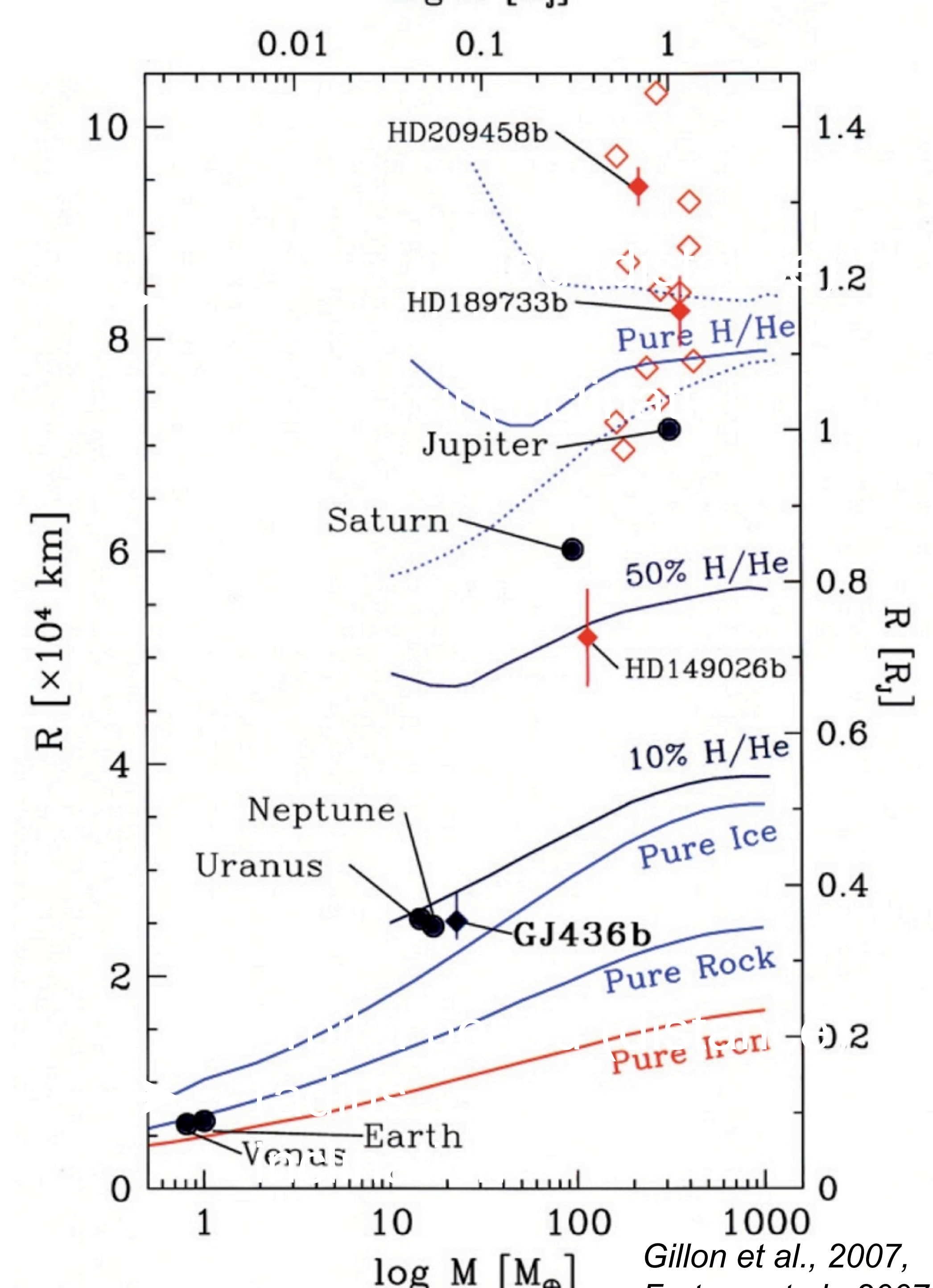


- orbital period (distance)
- radius
- inclination

GJ436 b





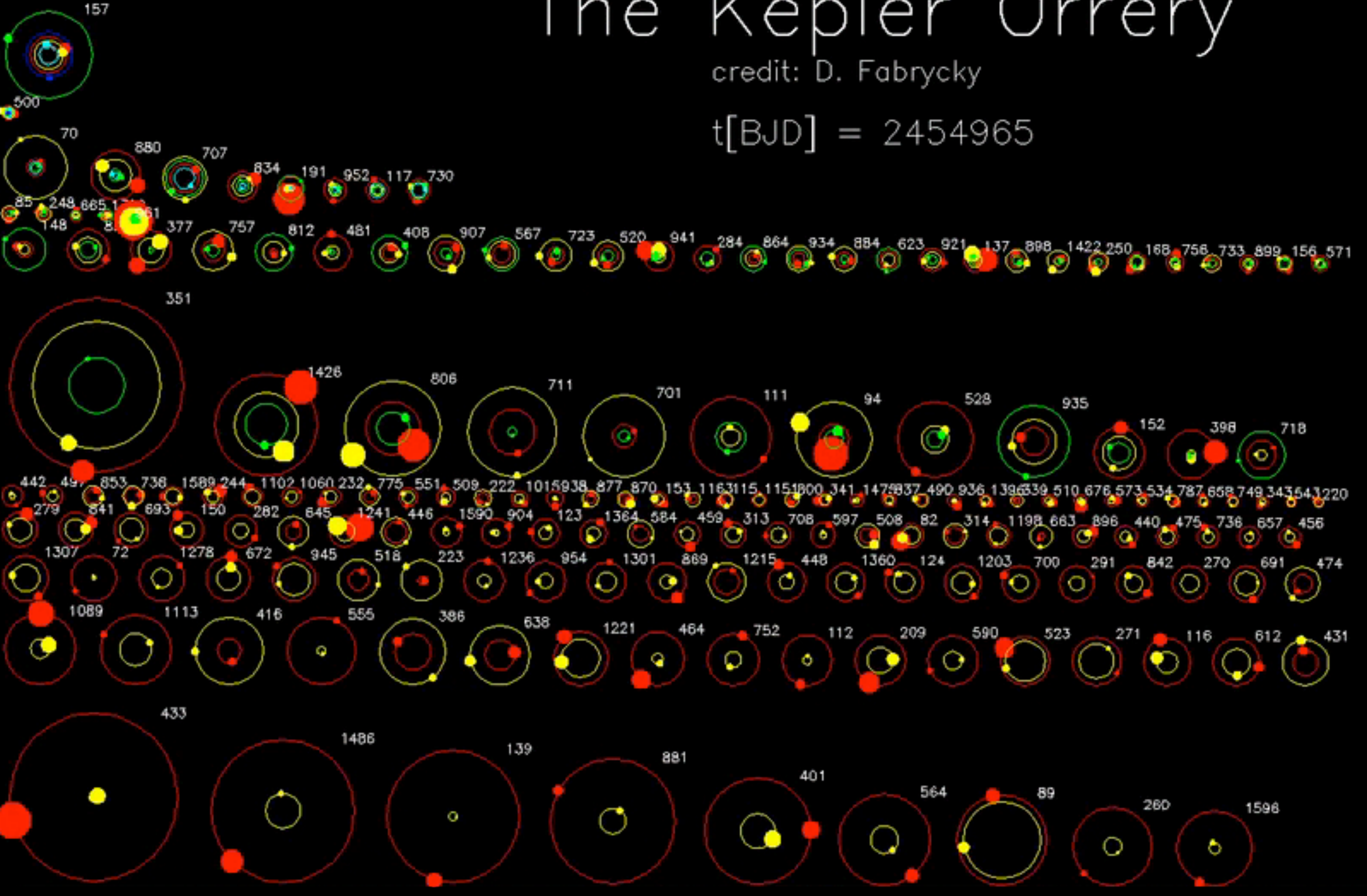


Gillon et al., 2007,
Fortney et al., 2007

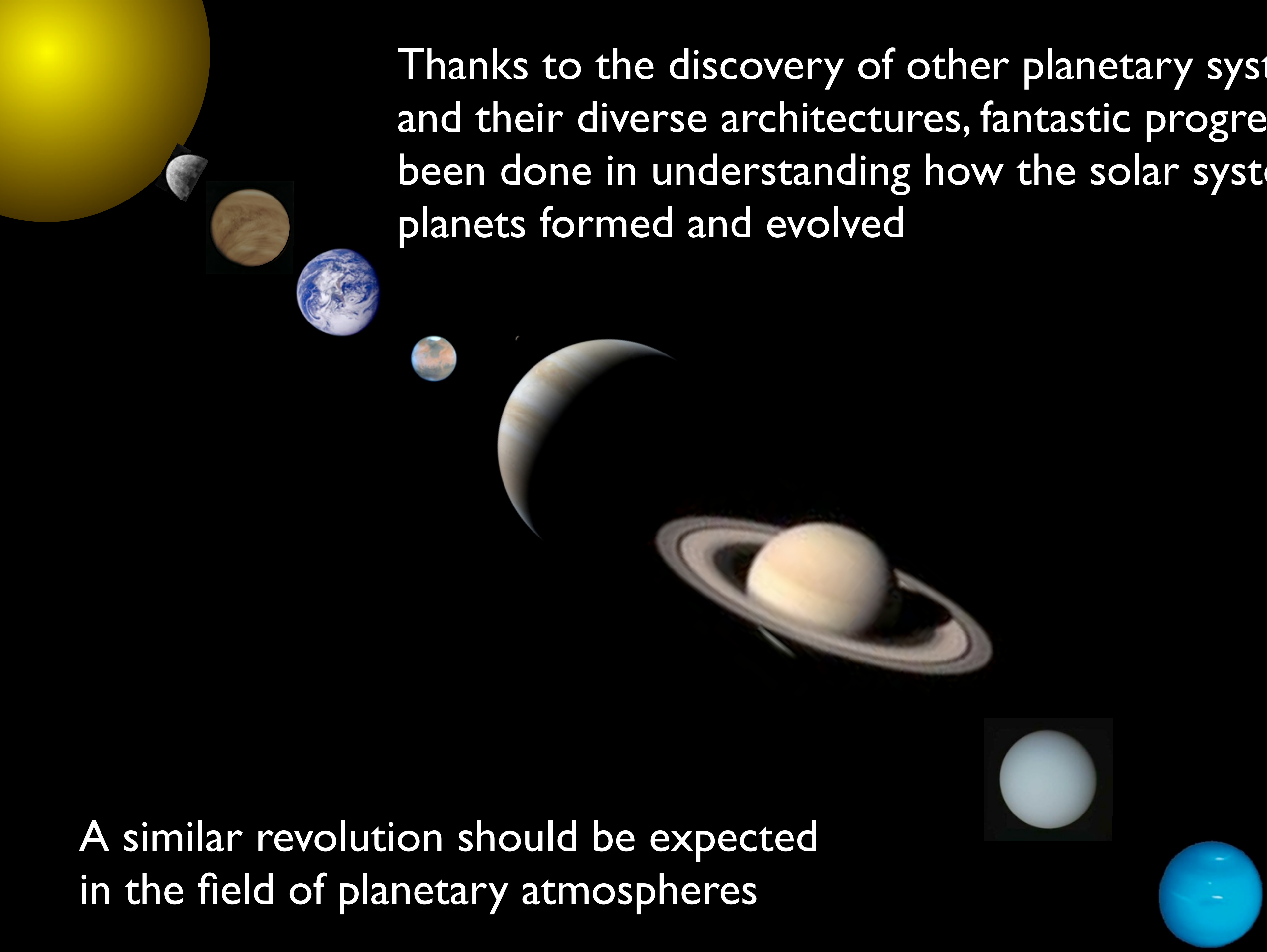
The Kepler Orrery

credit: D. Fabrycky

t[BJD] = 2454965



Thanks to the discovery of other planetary systems and their diverse architectures, fantastic progress has been done in understanding how the solar system planets formed and evolved



A similar revolution should be expected in the field of planetary atmospheres