"Theoretical Frontiers of Exoplanet Research"

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With collaborators D. Spiegel, I. Hubeny, J. Budaj, L. Ibgui, ….

Outline

- Transits of Giant planets (EGPs): R_p vs. M
- Wavelength-Dependence of Transit Radius

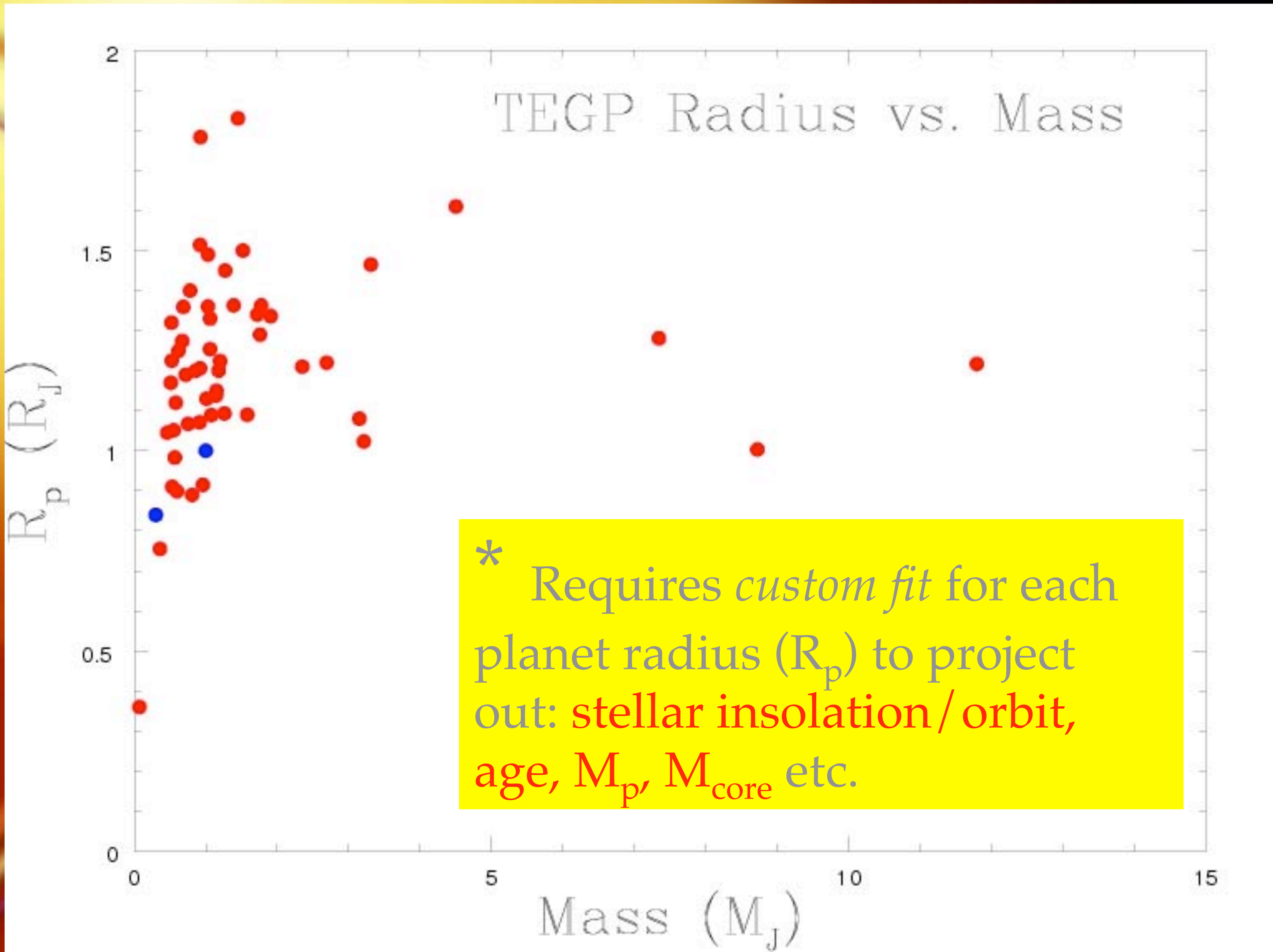
- "Hot Jupiter" Secondary Eclipse Spectra
  Temperature-Pressure Profiles
- Optical Albedos

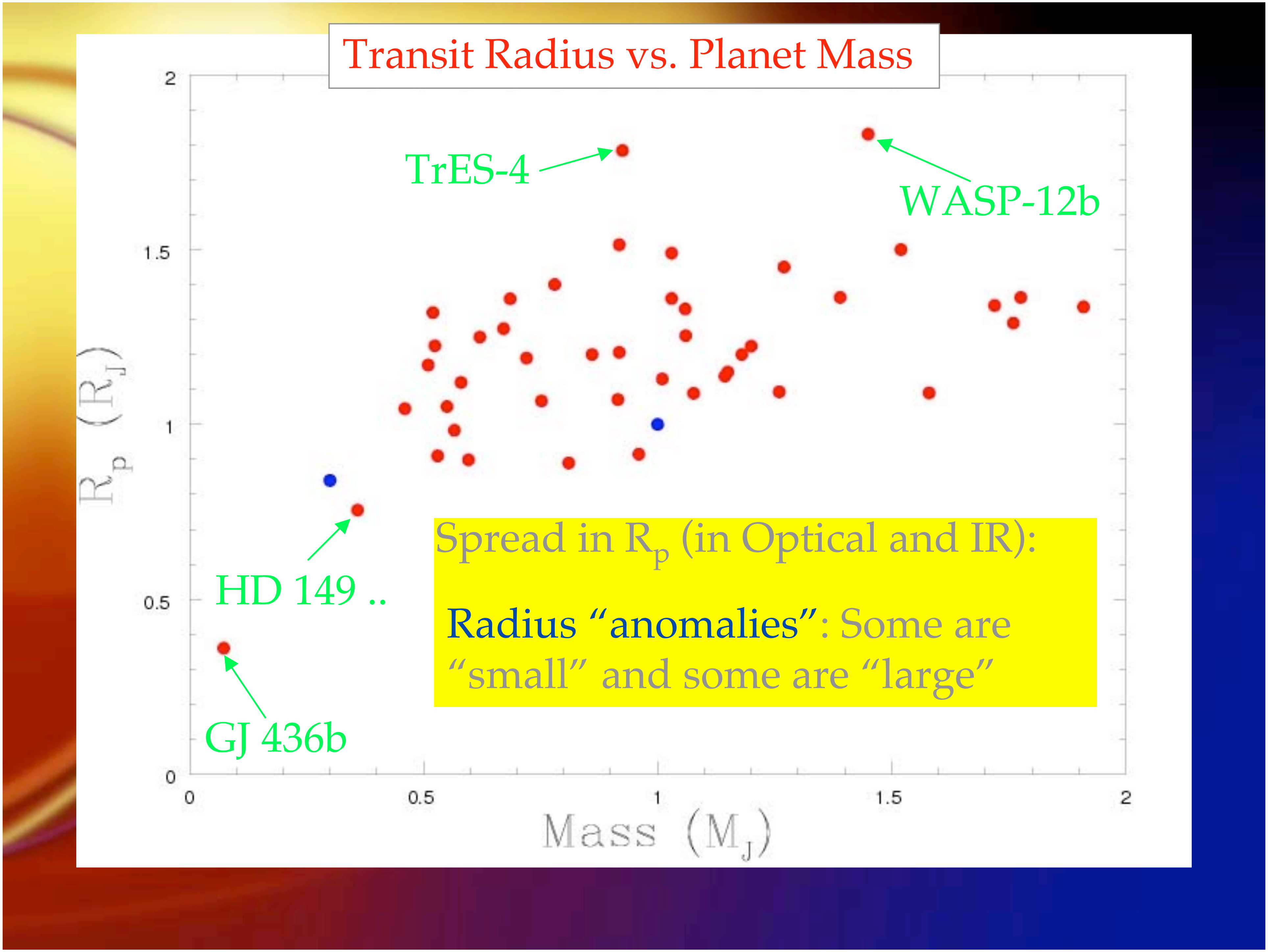
- Photometric Light Curves
- Variation of Spectra with Planetary Phase
- Planet thermal, composition, brightness Maps

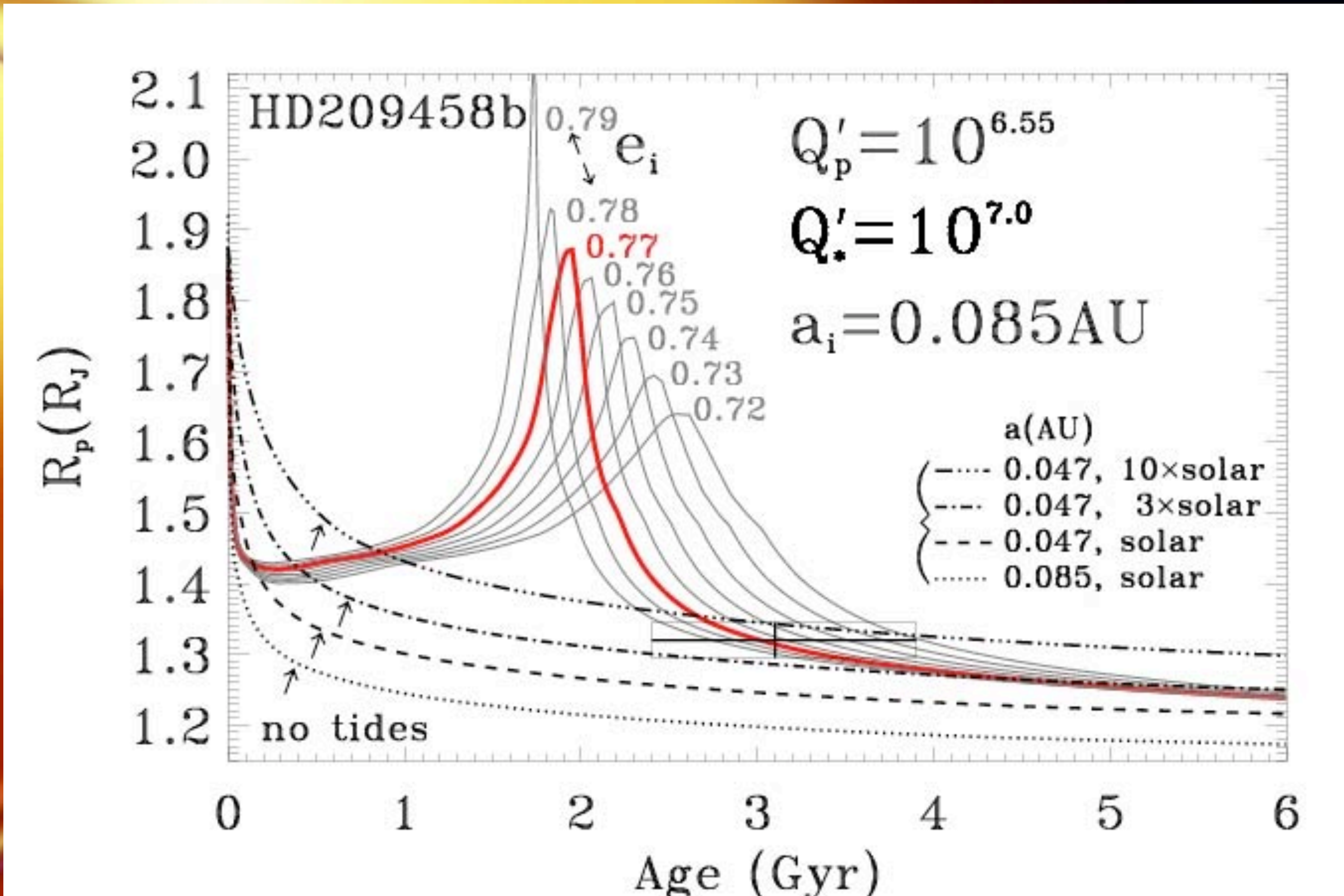
- Future ...

Radius-Mass Relationship for Irradiated EGPs ("Hot Jupiters")

(dependence on age, star,
semi-major axis distance,
planet mass, "core mass,"
atmospheric opacities)

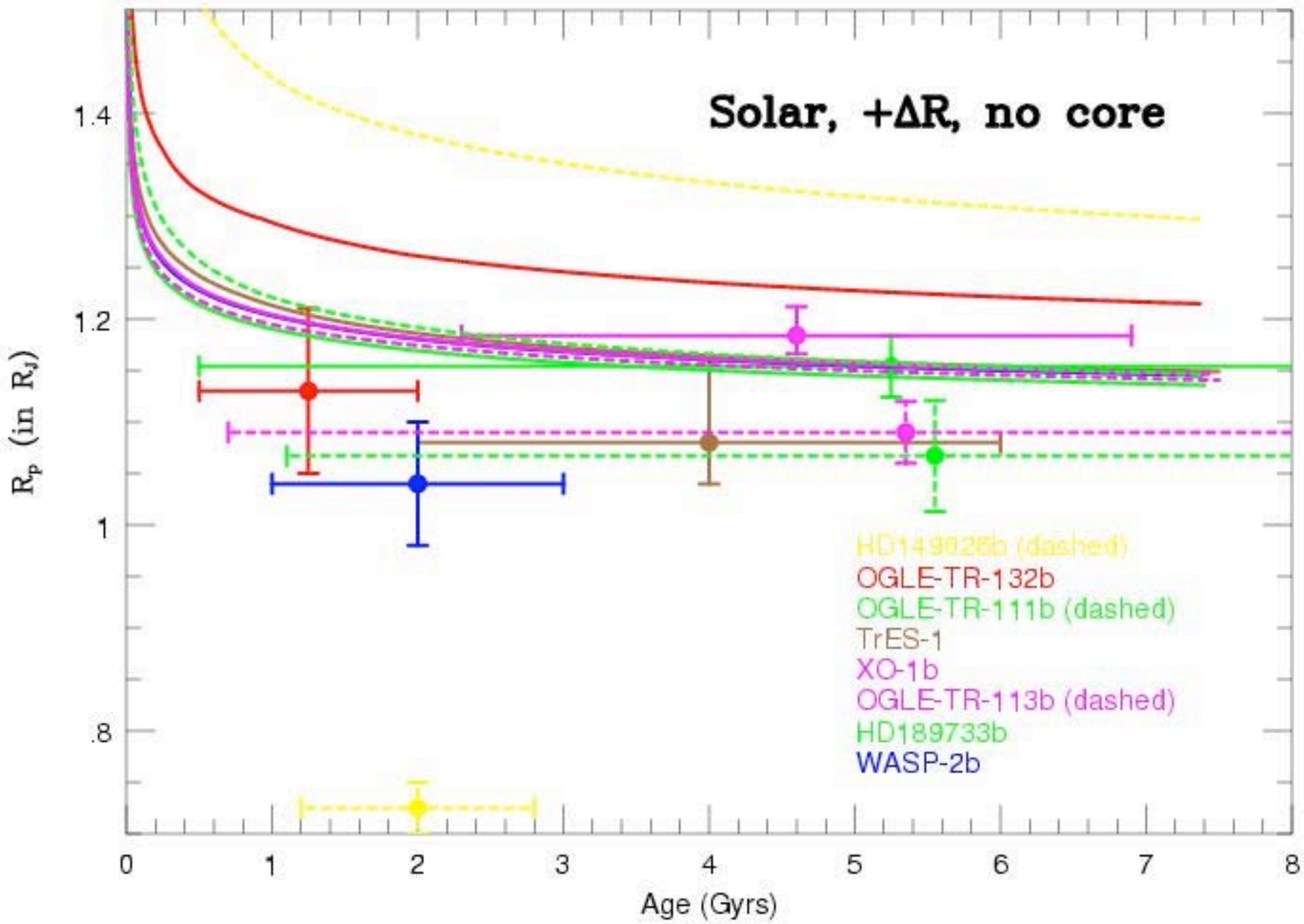

TEGP Radius vs. Mass
R_p (R_J)
Mass (M_J)
0
0.5
1
1.5
2
0
5
10
15
* Requires *custom fit* for each planet radius (R_p) to project out: stellar insolation/orbit, age, M_p, M_{core} etc.


Transit Radius vs. Planet Mass
TrES-4
WASP-12b
HD 149 ..
GJ 436b
Spread in R_p (in Optical and IR):
Radius "anomalies": Some are "small" and some are "large"
R_p (R_J)
Mass (M_J)
0
0.5
1
1.5
2



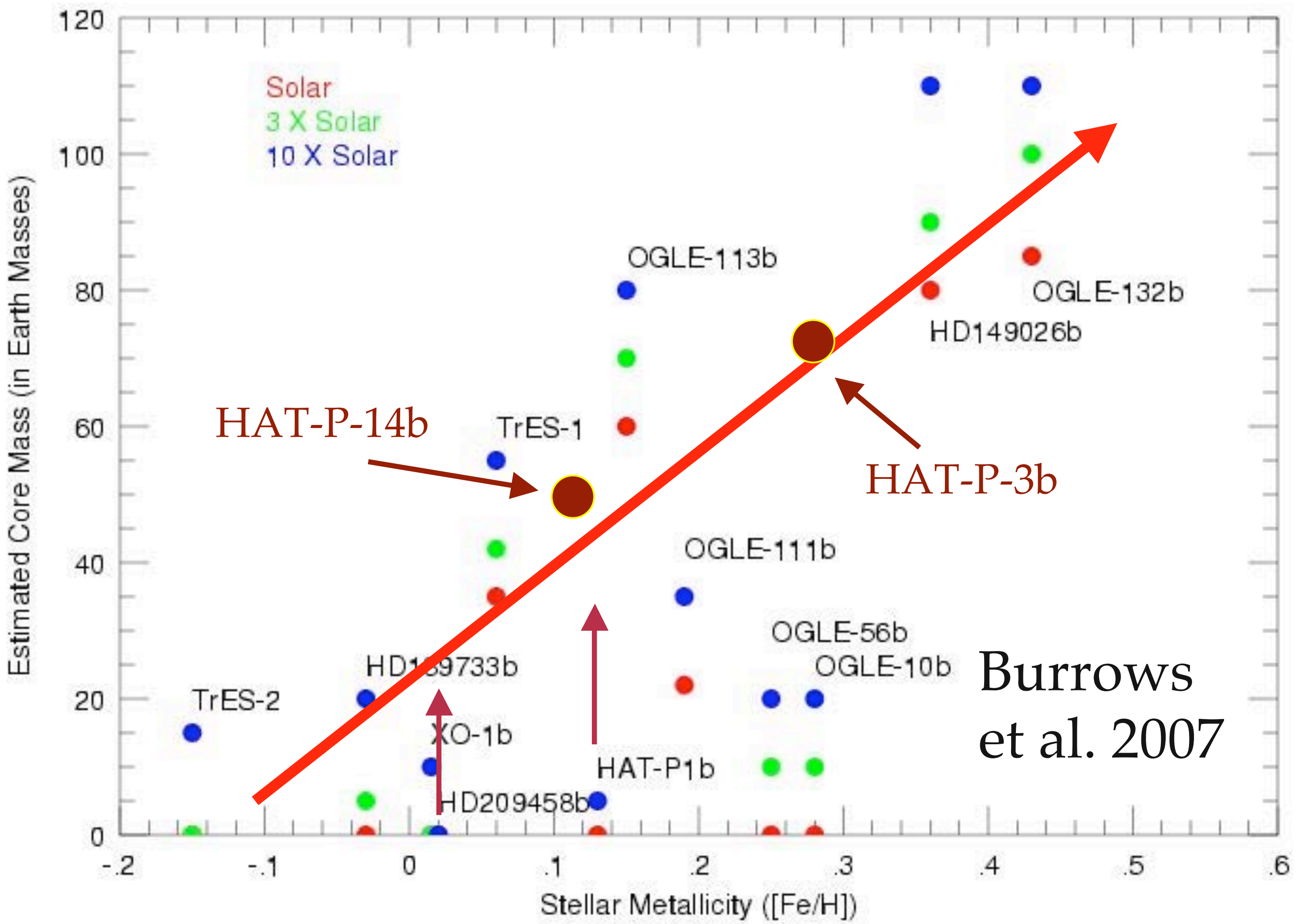
3 x solar opacity atmosphere - fits HD 209458b

Smaller EGPs: Models vs. Data



Radius Deficits: Need “ice/rock” cores?

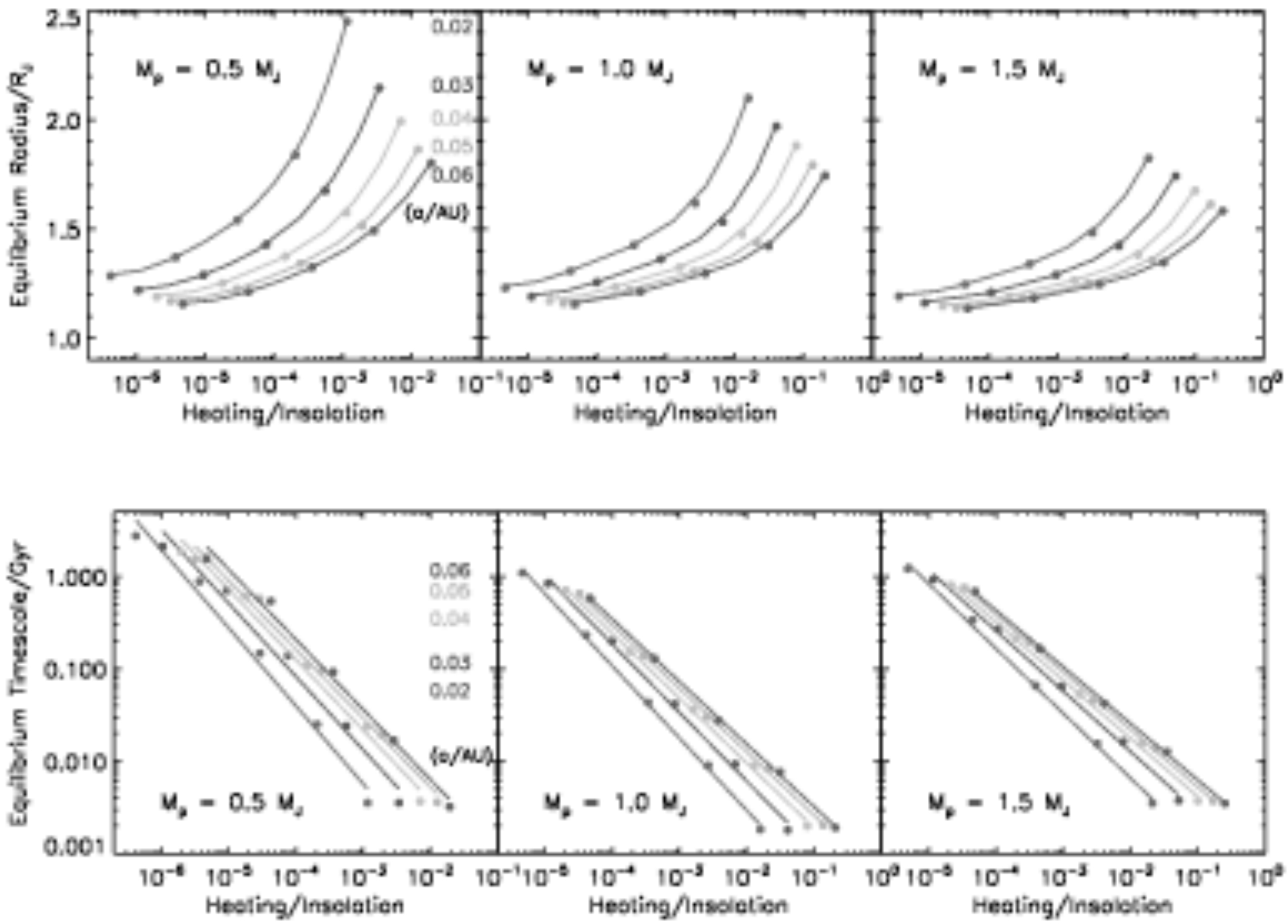
Approximate "Core" Mass vs. Stellar Metallicity



Note new measurement of HAT-P-1b

See also Guillot et al. 2006

Effects of Tidal Heating on EGP Radii

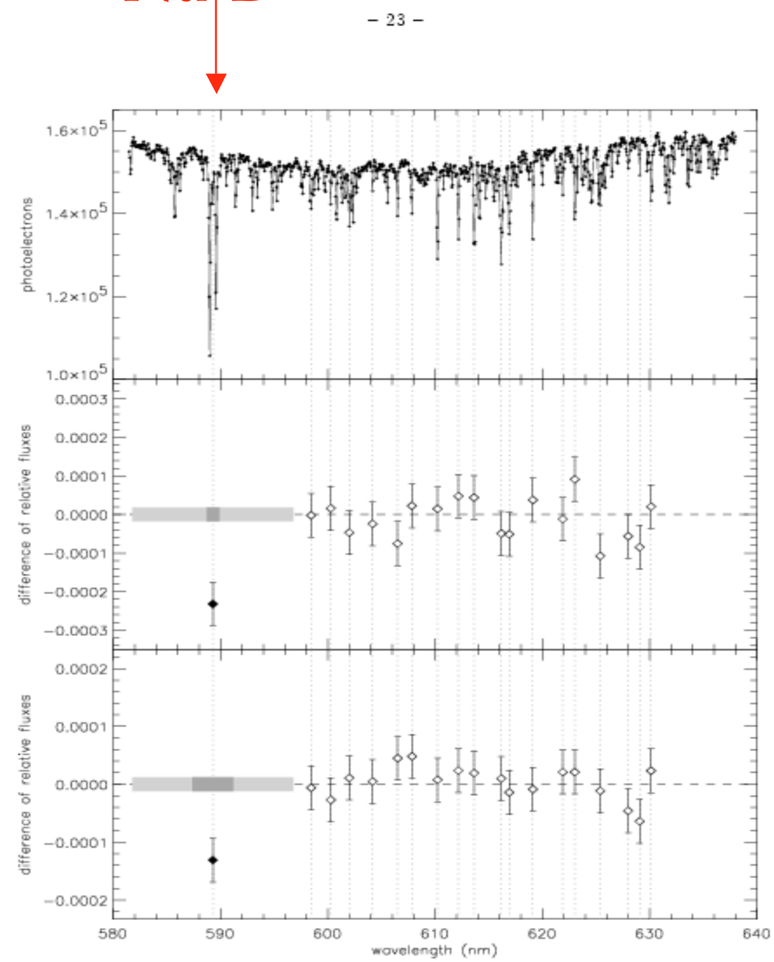


Wavelength-Dependence of the Transit Radius

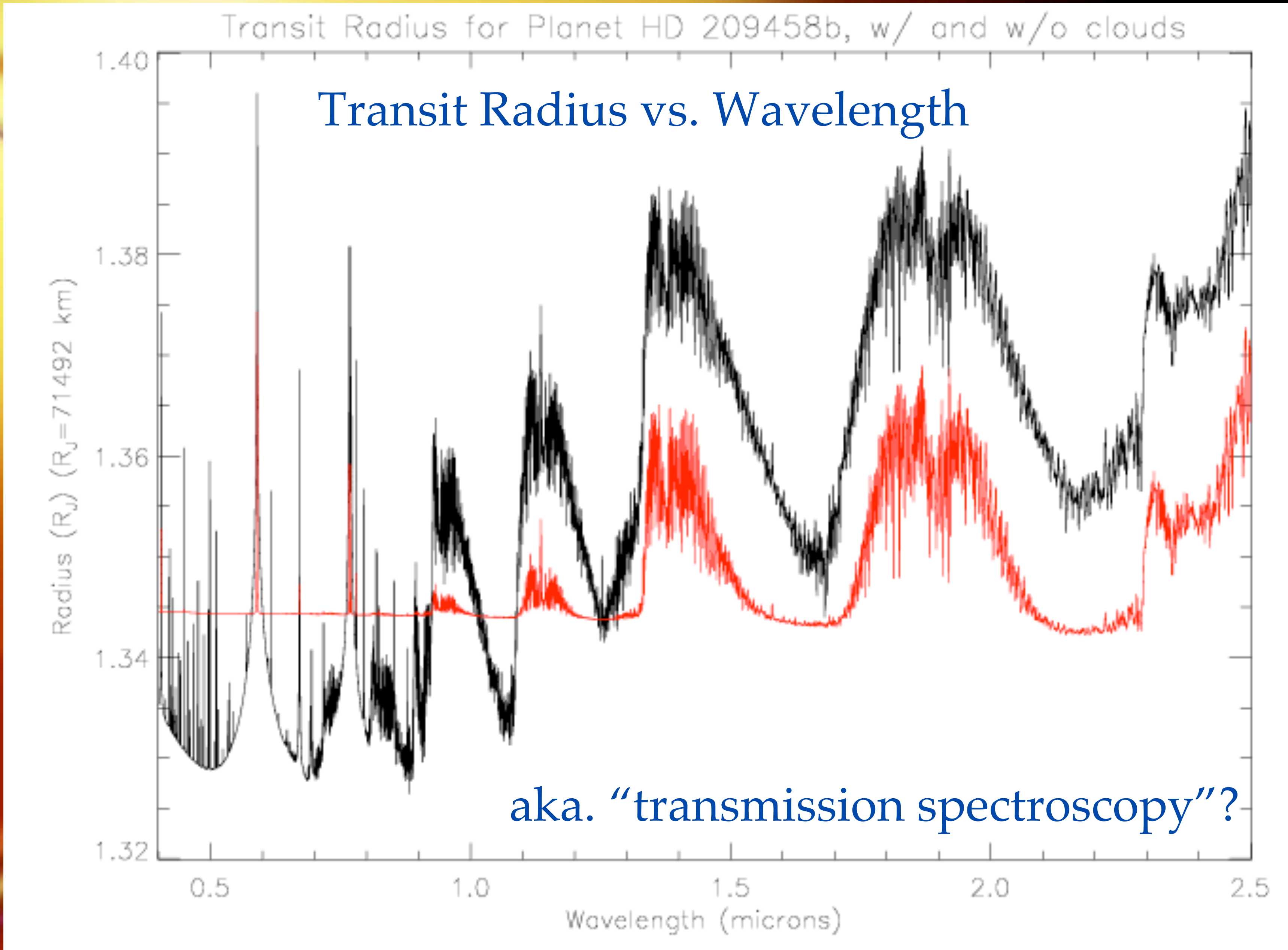
"Transmission Spectroscopy"

HD209458b:

Na-D



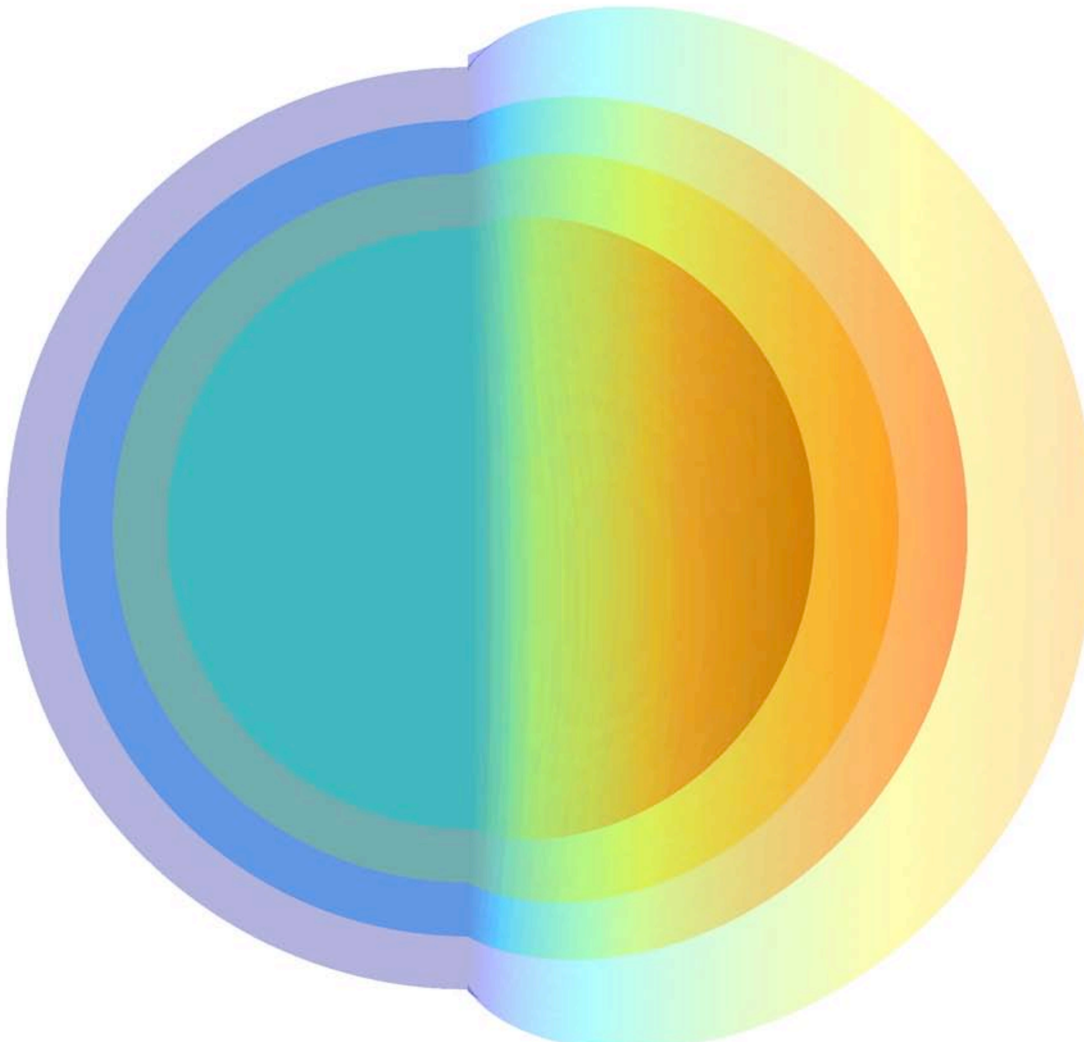
Radius is Larger in Na-D!
Na detection: Charbonneau et al. 2003



Fortney et al. 2003

With upper-atmosphere optical absorber

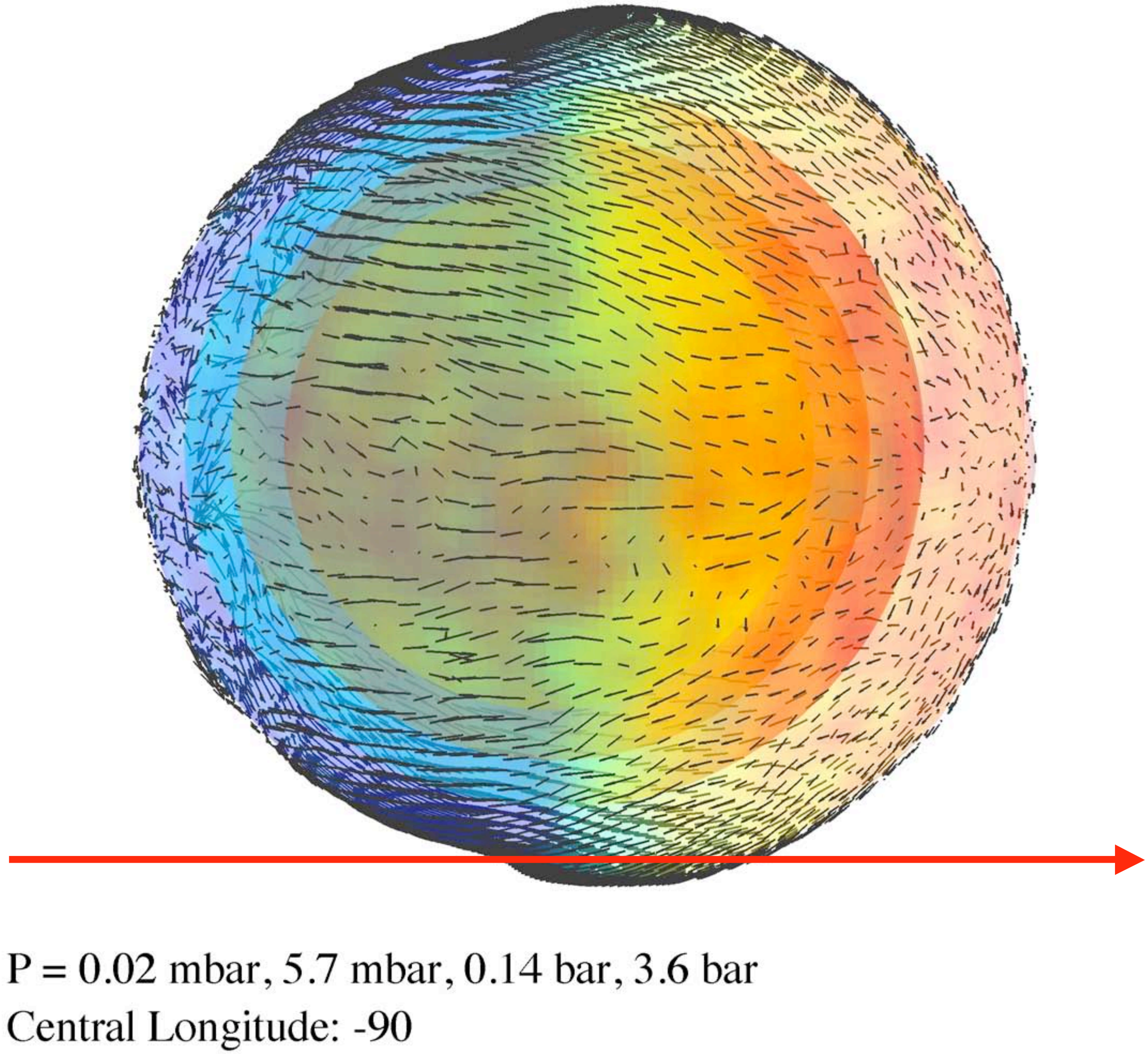
Burrows, Rauscher, Spiegel, & Menou 2010



P = 0.02 mbar, 5.7 mbar, 0.14 bar, 3.6 bar

Central Longitude: -90

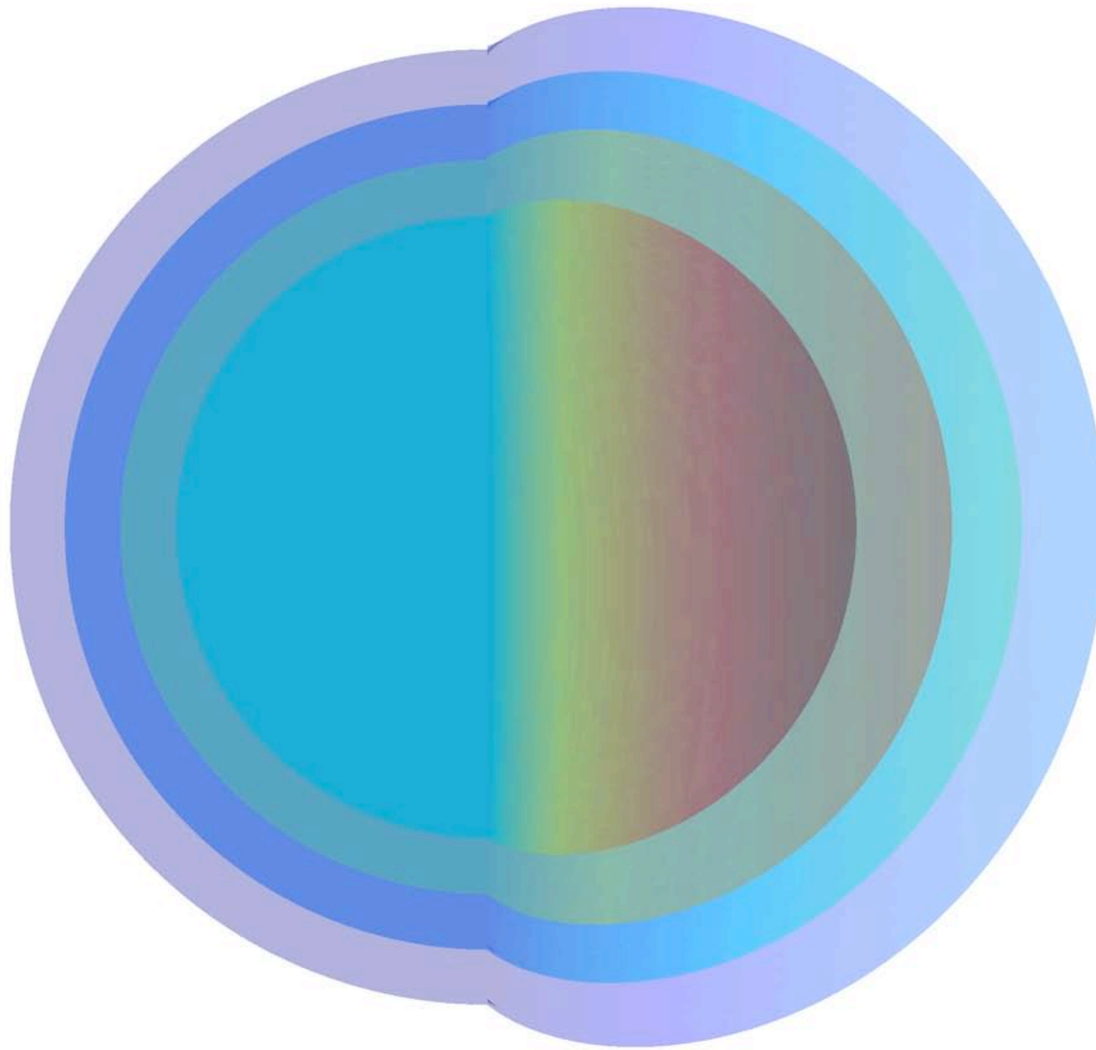
With upper-atmosphere optical absorber



Transit chord

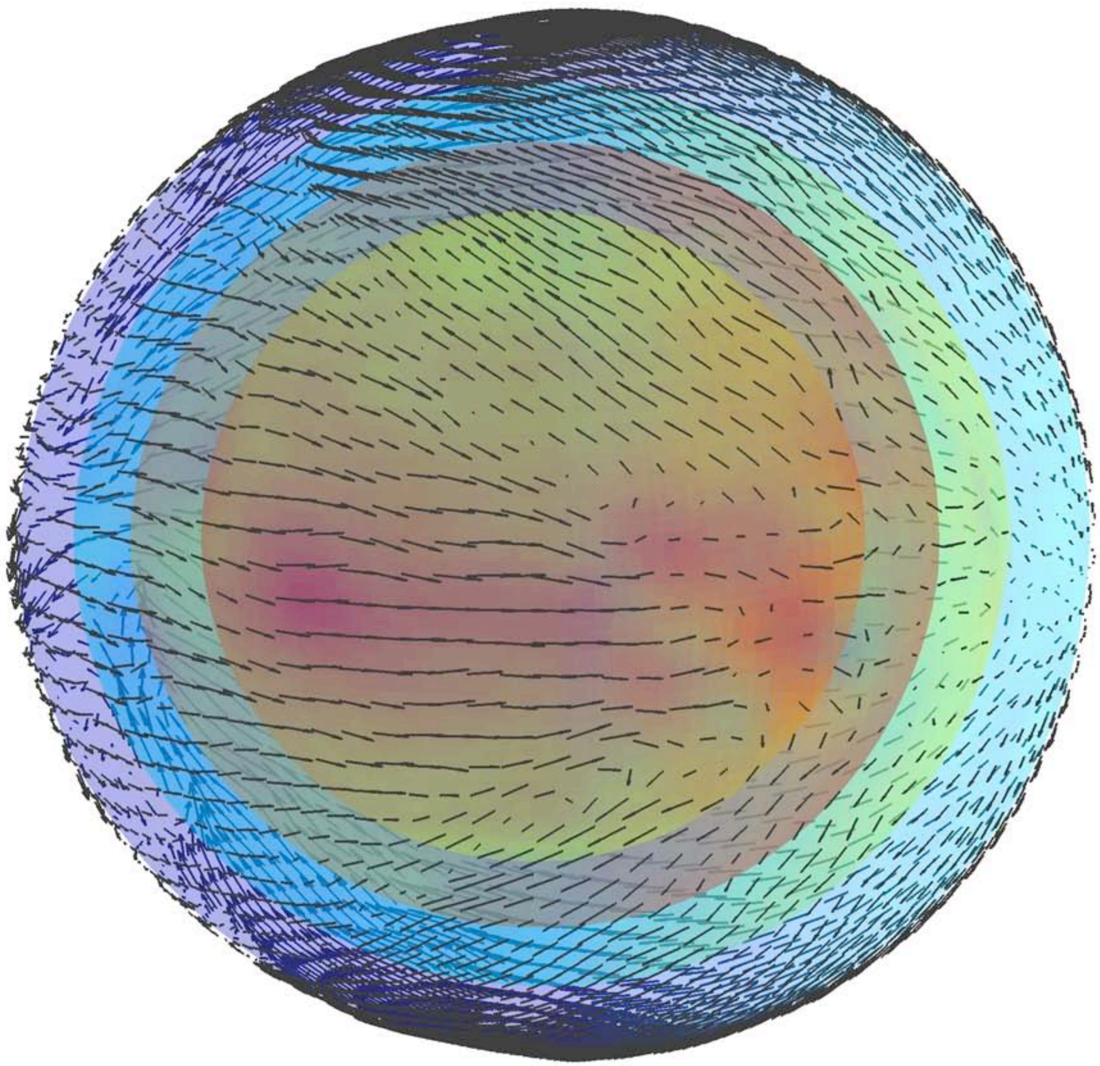
Graphics by D. Spiegel

Without upper-atmosphere optical absorber

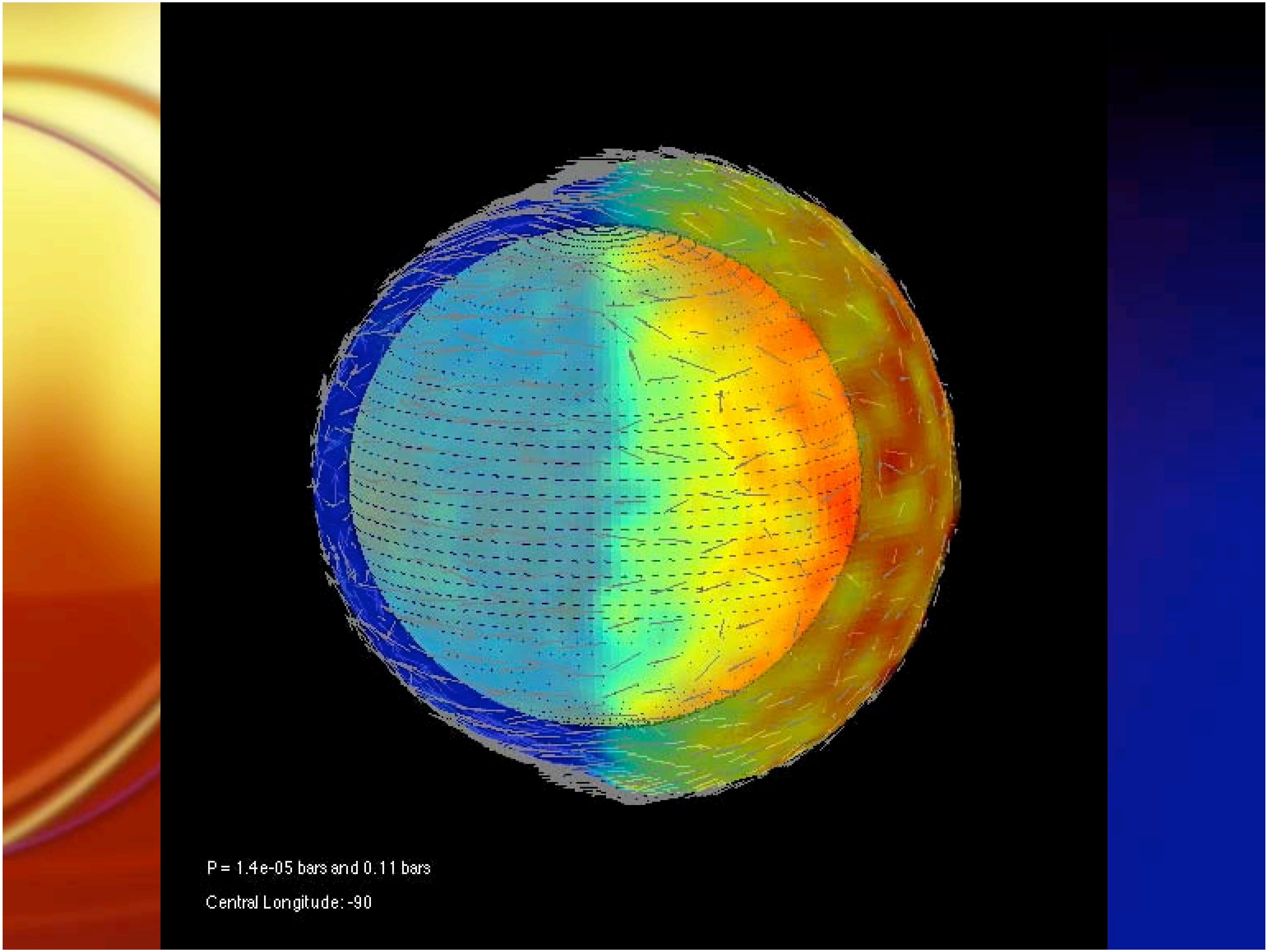


P = 0.02 mbar, 5.7 mbar, 0.14 bar, 3.6 bar
Central Longitude: -90

Without upper-atmosphere optical absorber

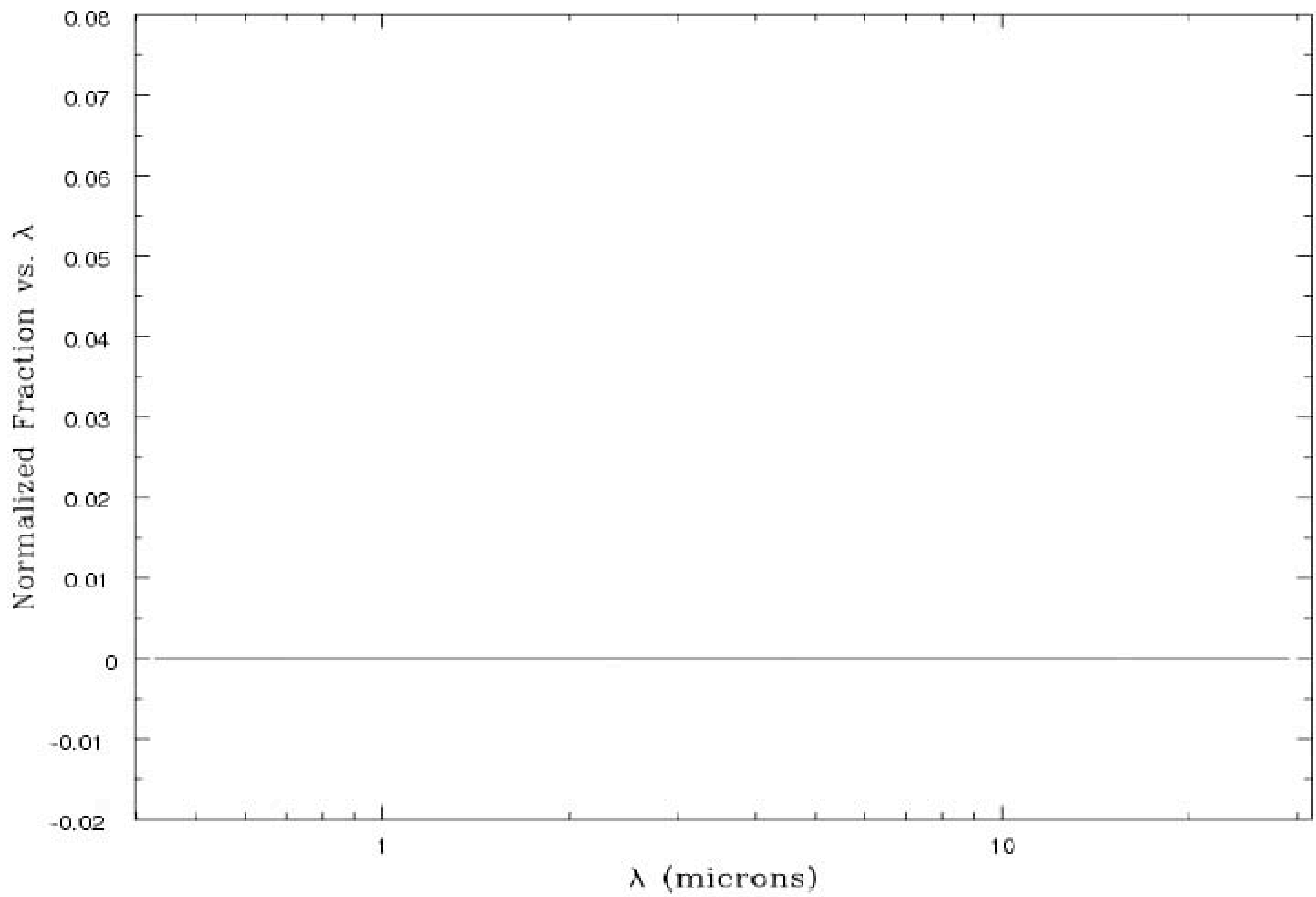


P = 0.02 mbar, 5.7 mbar, 0.14 bar, 3.6 bar
Central Longitude: -90



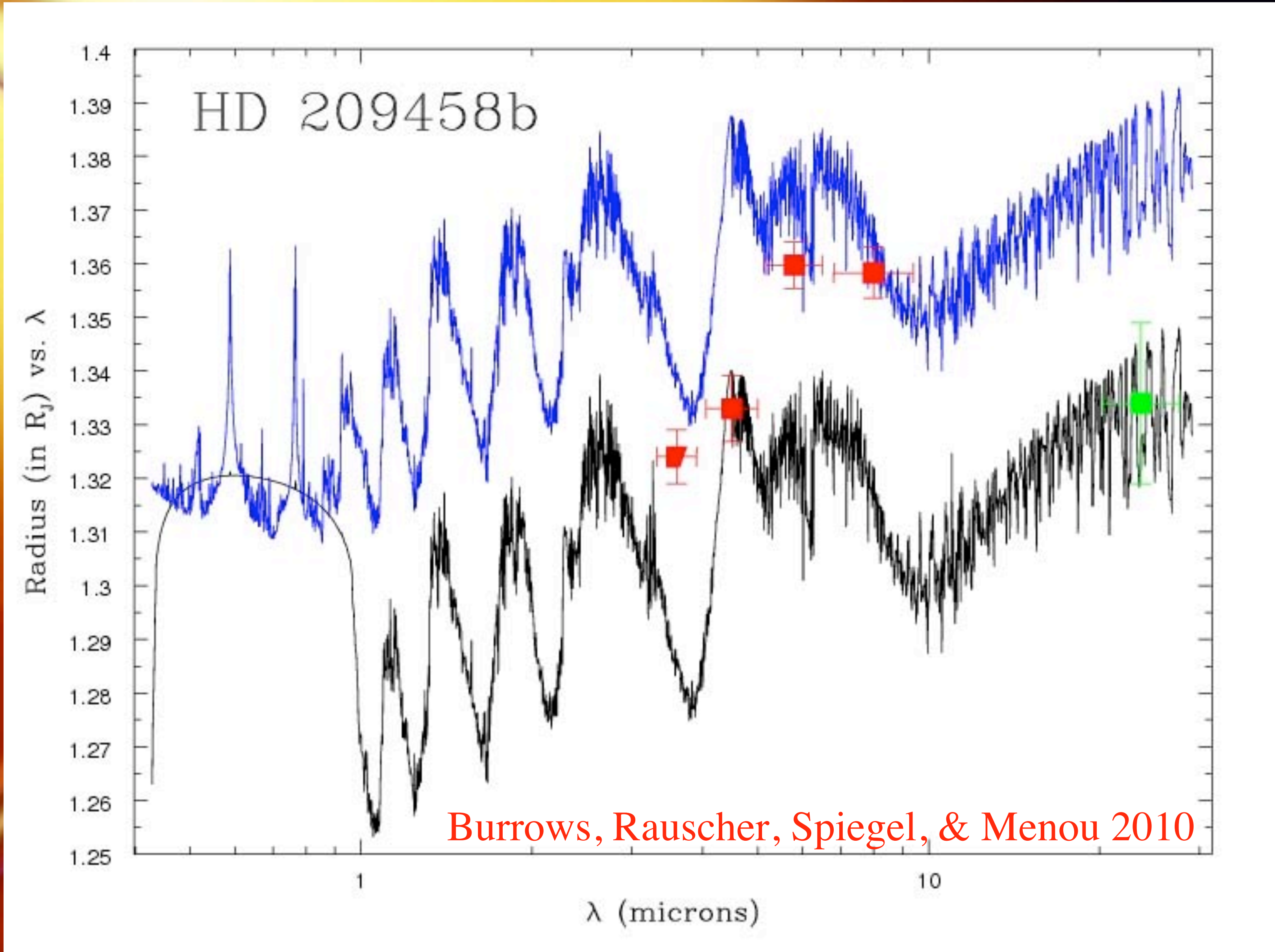
P = 1.4e-05 bars and 0.11 bars
Central Longitude: -90

Fractional Atmosphere vs. Wavelength



Burrows, Rauscher, Spiegel, & Menou 2010

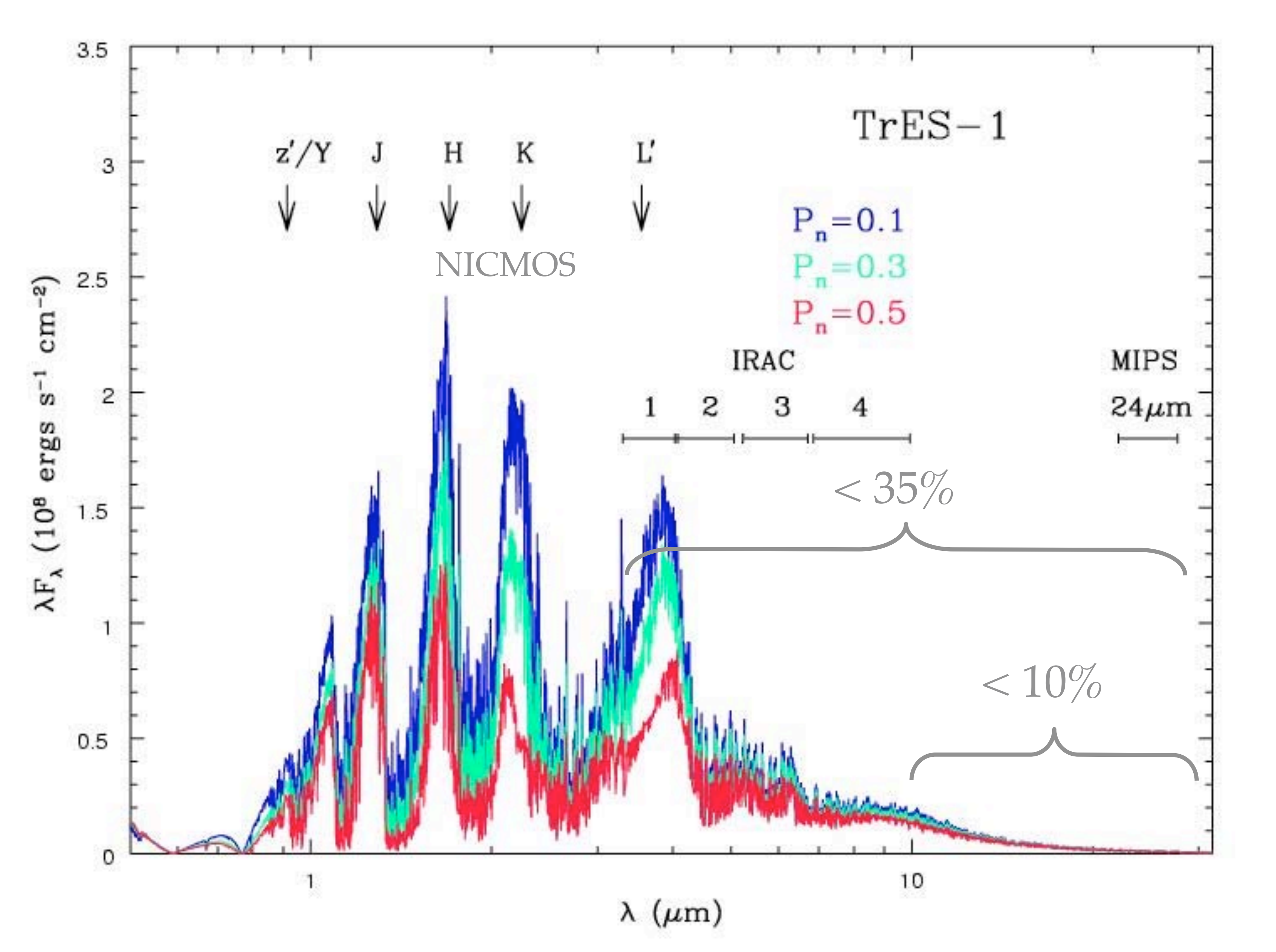
HD 209458b: Transit Radius vs. Wavelength



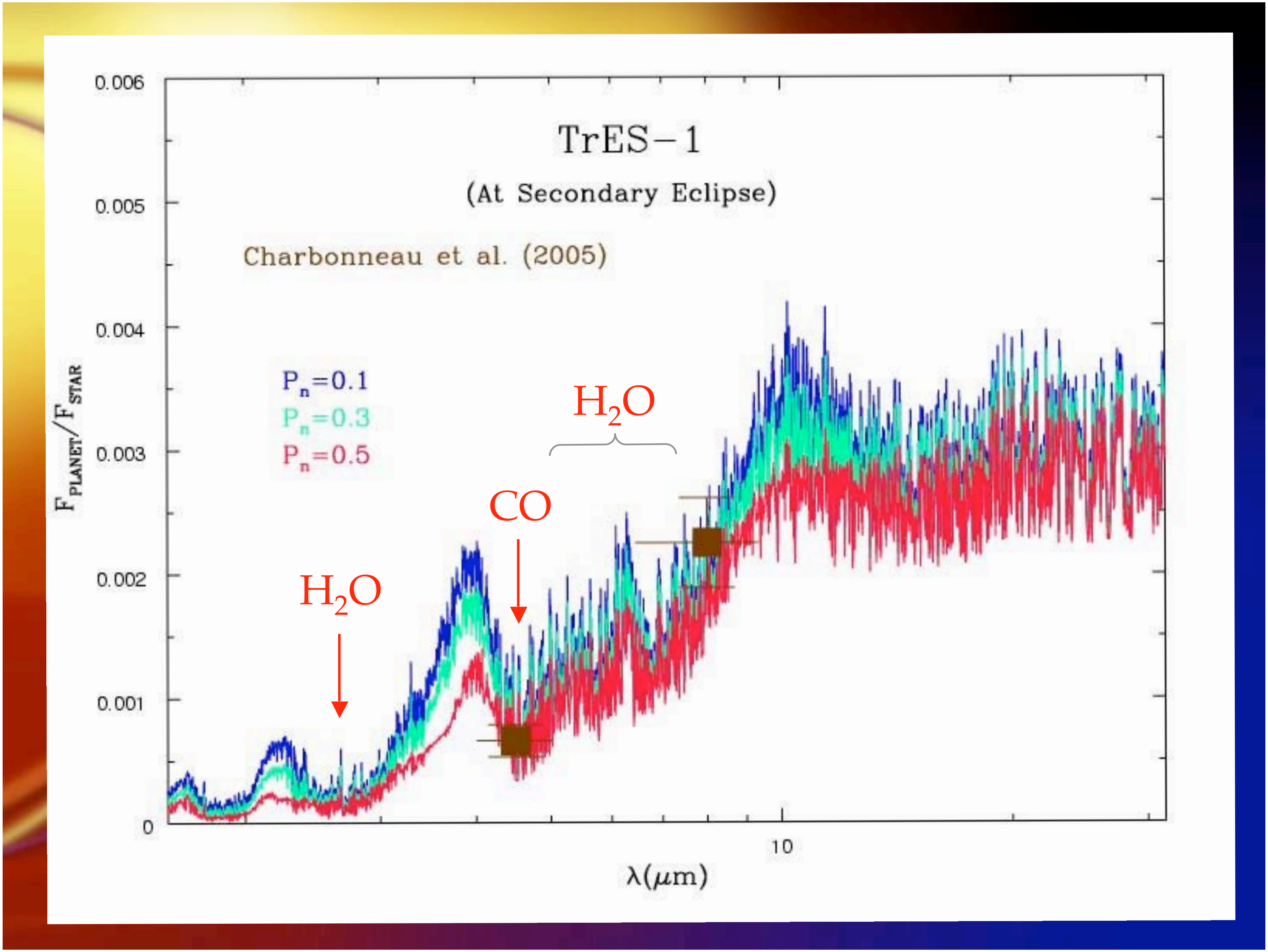
see also Fortney et al. 2010

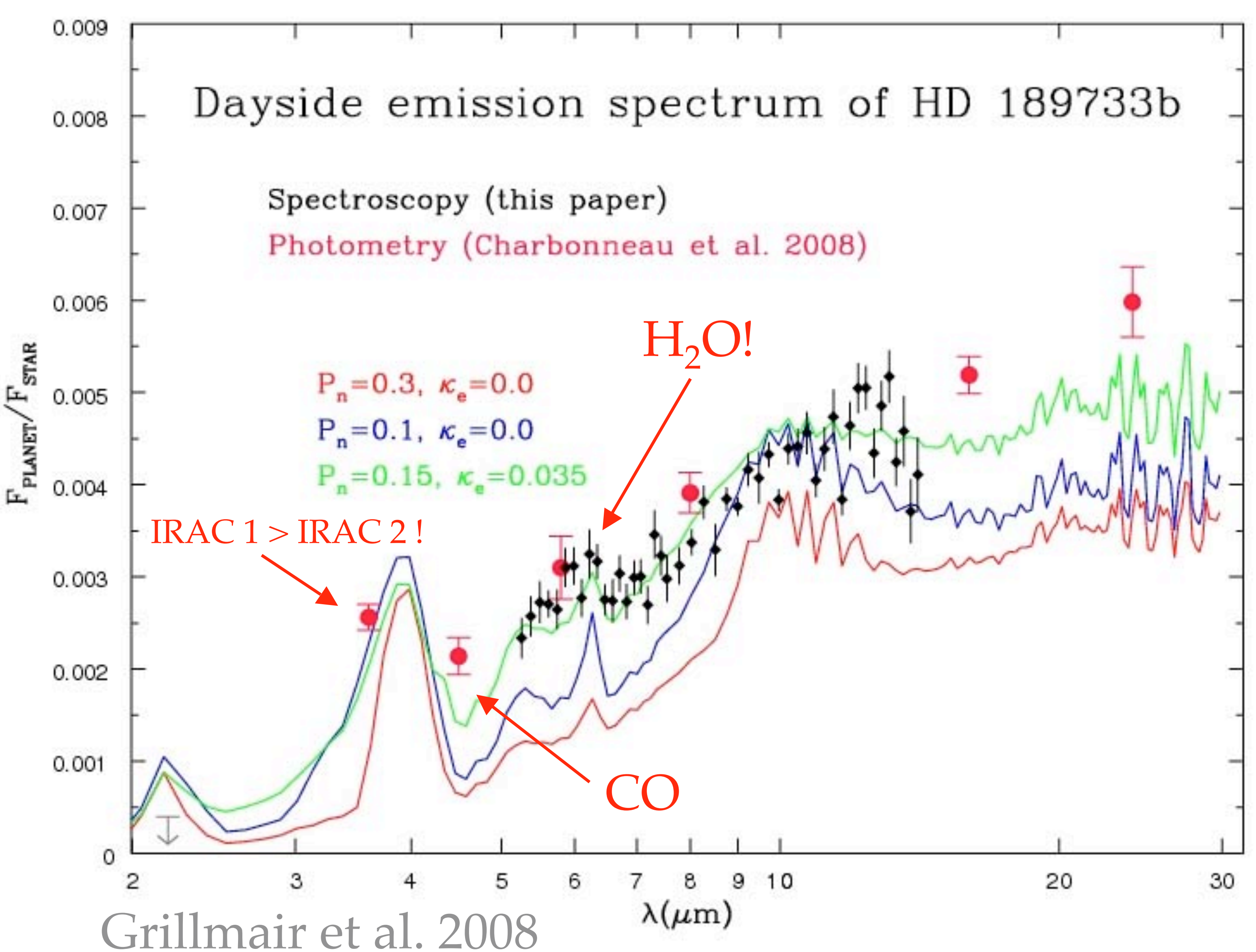
“Hot Jupiter” Spectra and Temperature-Pressure Profiles

Secondary Eclipses

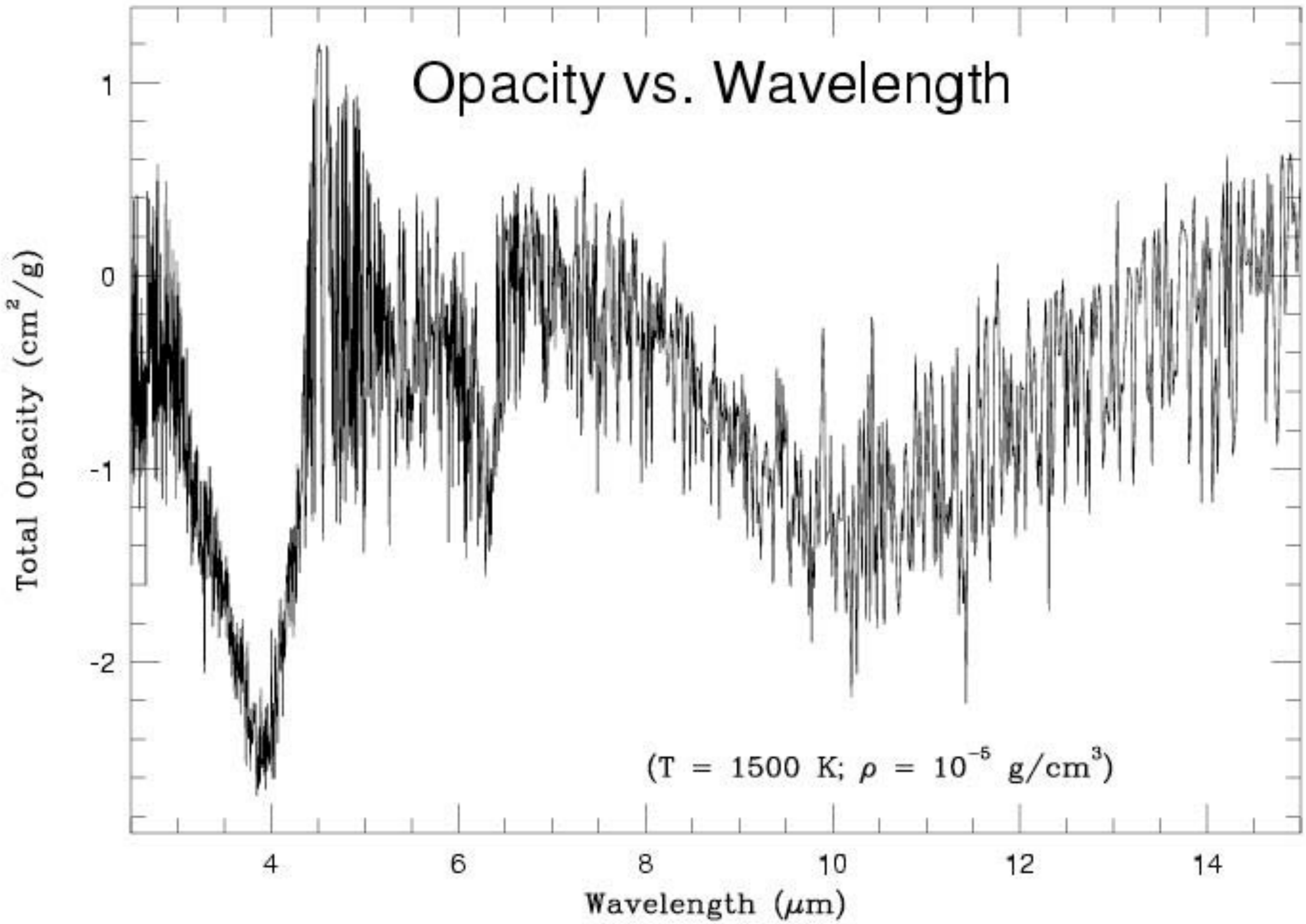


TrES−1
z′/Y
J
H
K
L′
NICMOS
P_n=0.1
P_n=0.3
P_n=0.5
IRAC
1
2
3
4
MIPS
24μm
< 35%
< 10%
λF_λ (10^8 ergs s^{-1} cm^{-2})
λ (μm)
0
0.5
1
1.5
2
2.5
3
3.5
1
10

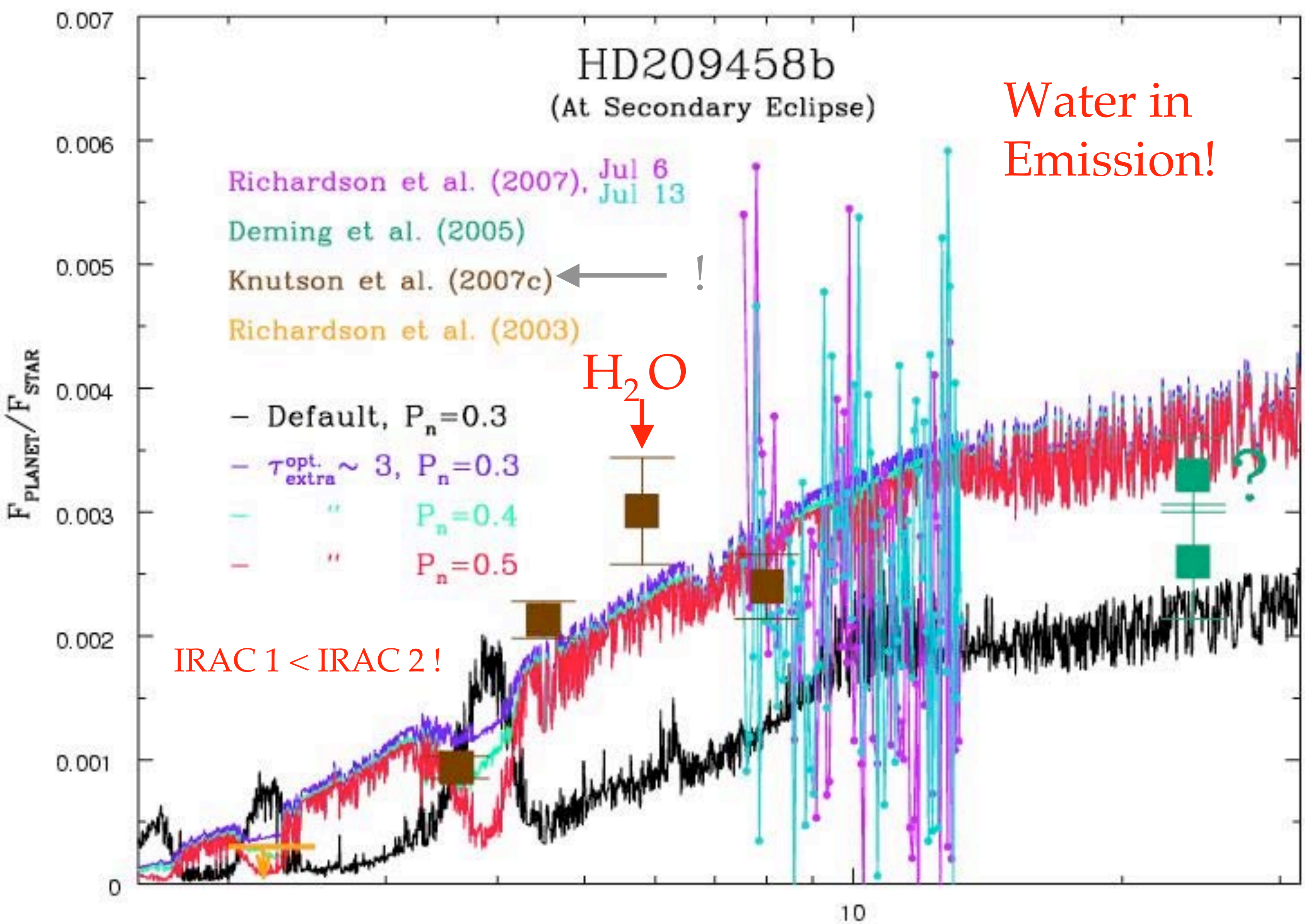

TrES−1
(At Secondary Eclipse)
Charbonneau et al. (2005)
P_n=0.1
P_n=0.3
P_n=0.5
H_2O
CO
H_2O
F_{PLANET}/F_{STAR}
$\lambda(\mu m)$
0.006
0.005
0.004
0.003
0.002
0.001
0
10



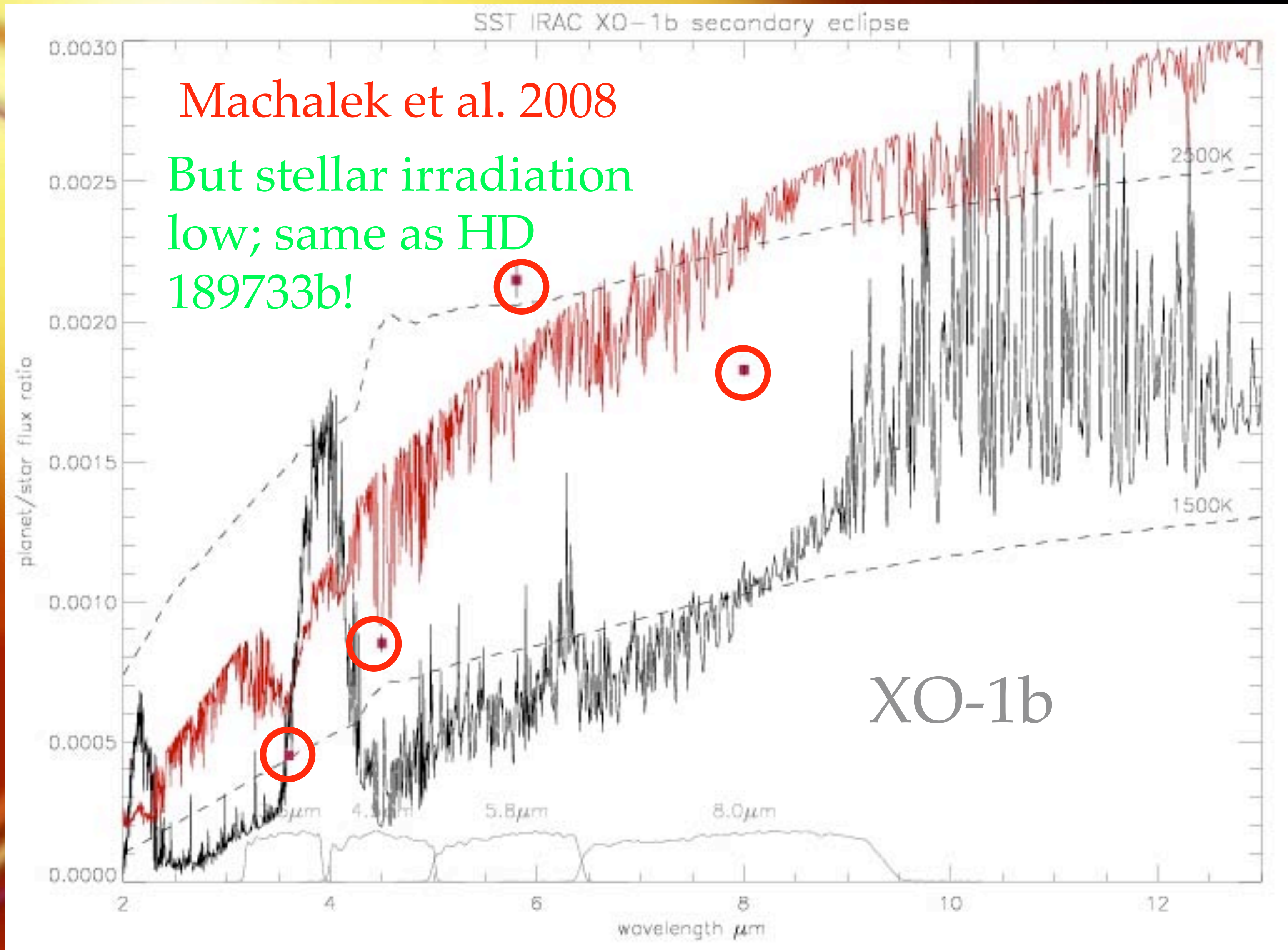
Grillmair et al. 2008


Opacity vs. Wavelength
Total Opacity (cm^2/g)
1
0
-1
-2
4
6
8
10
12
14
Wavelength (μm)
(T = 1500 K; ρ = 10^{-5} g/cm^3)

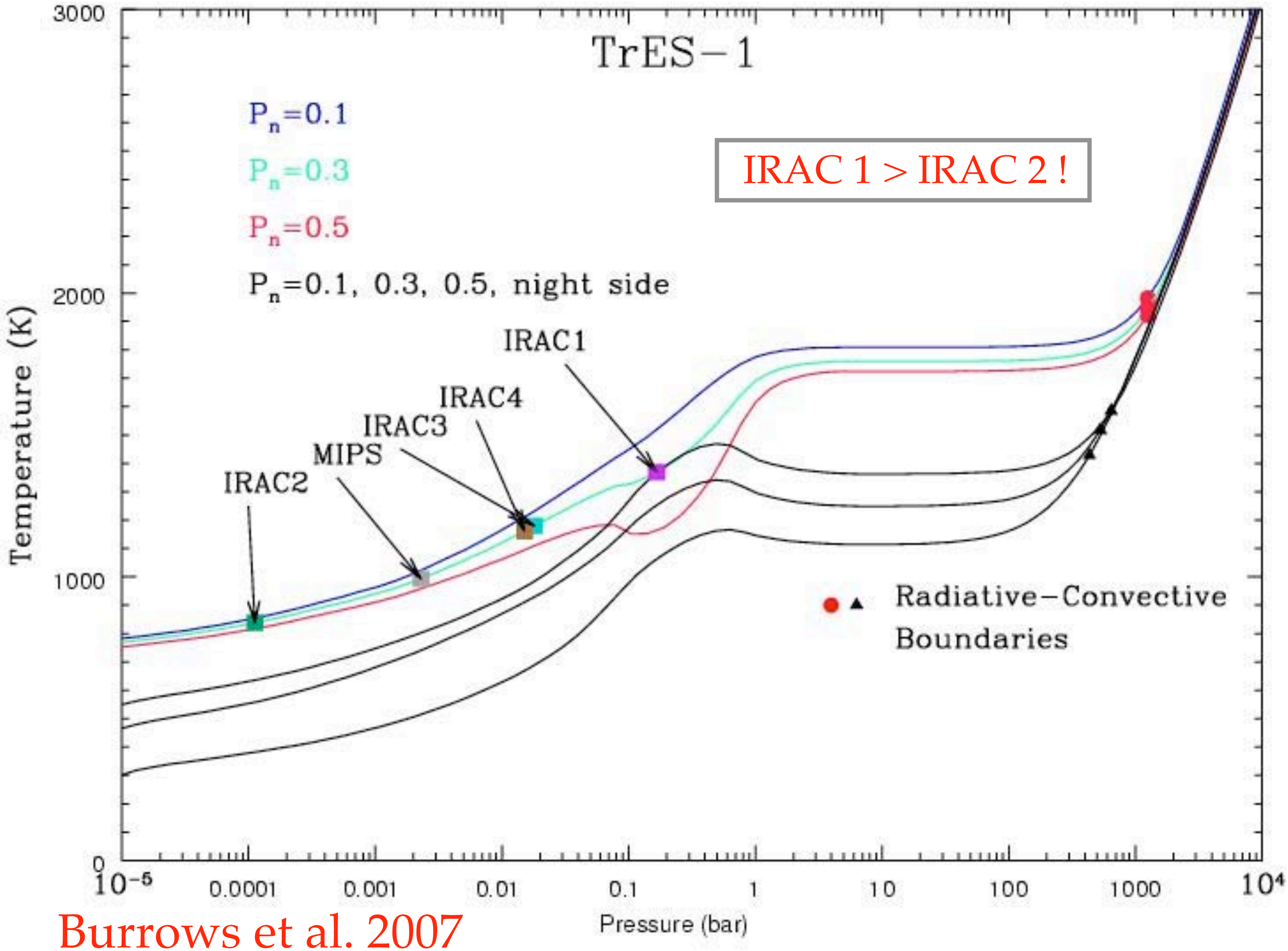
Mostly H_2O



Burrows et al. 2007

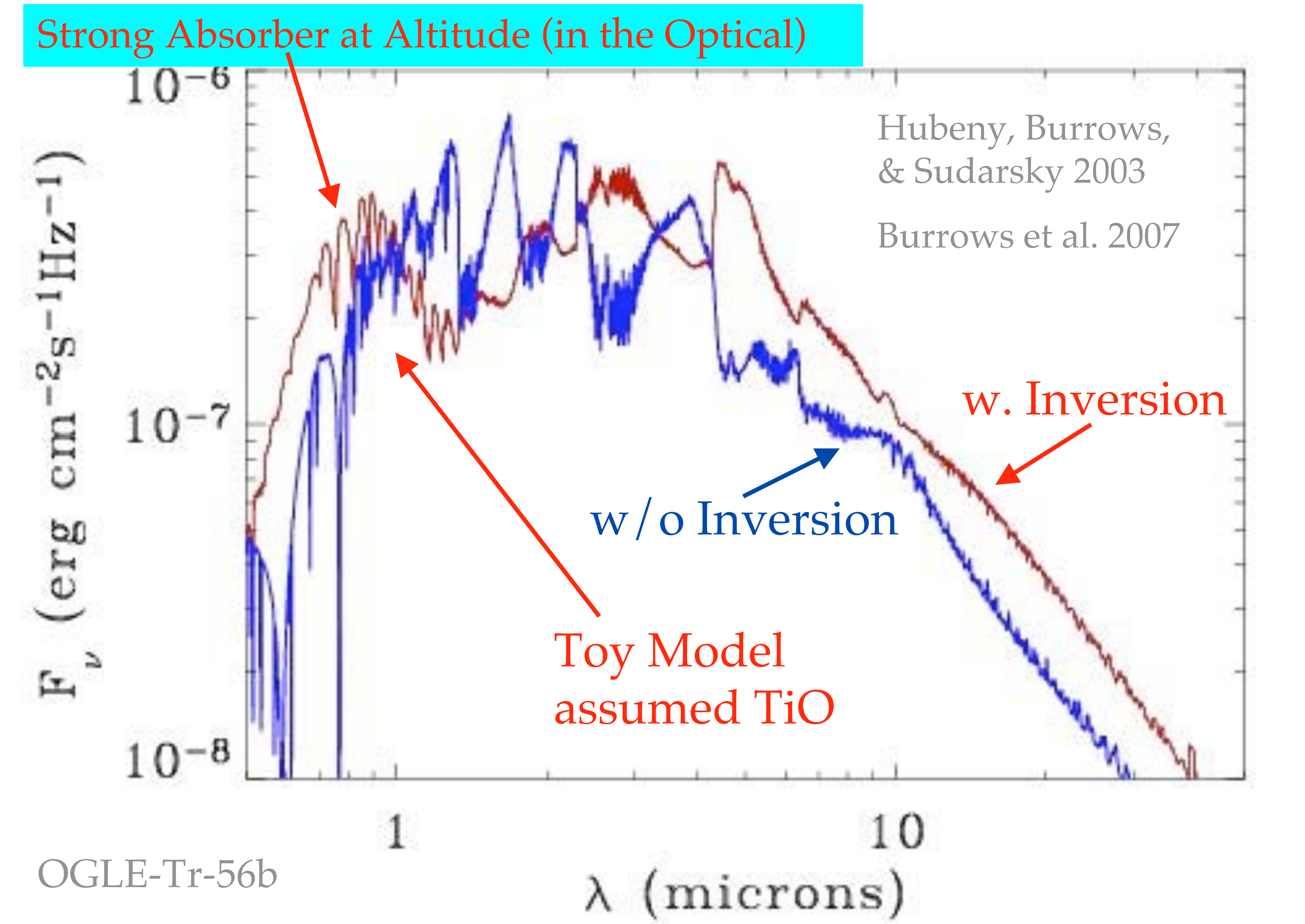


SST IRAC XO-1b secondary eclipse
Machalek et al. 2008
But stellar irradiation low; same as HD 189733b!
2500K
1500K
XO-1b
5.8μm
8.0μm
planet/star flux ratio
wavelength μm



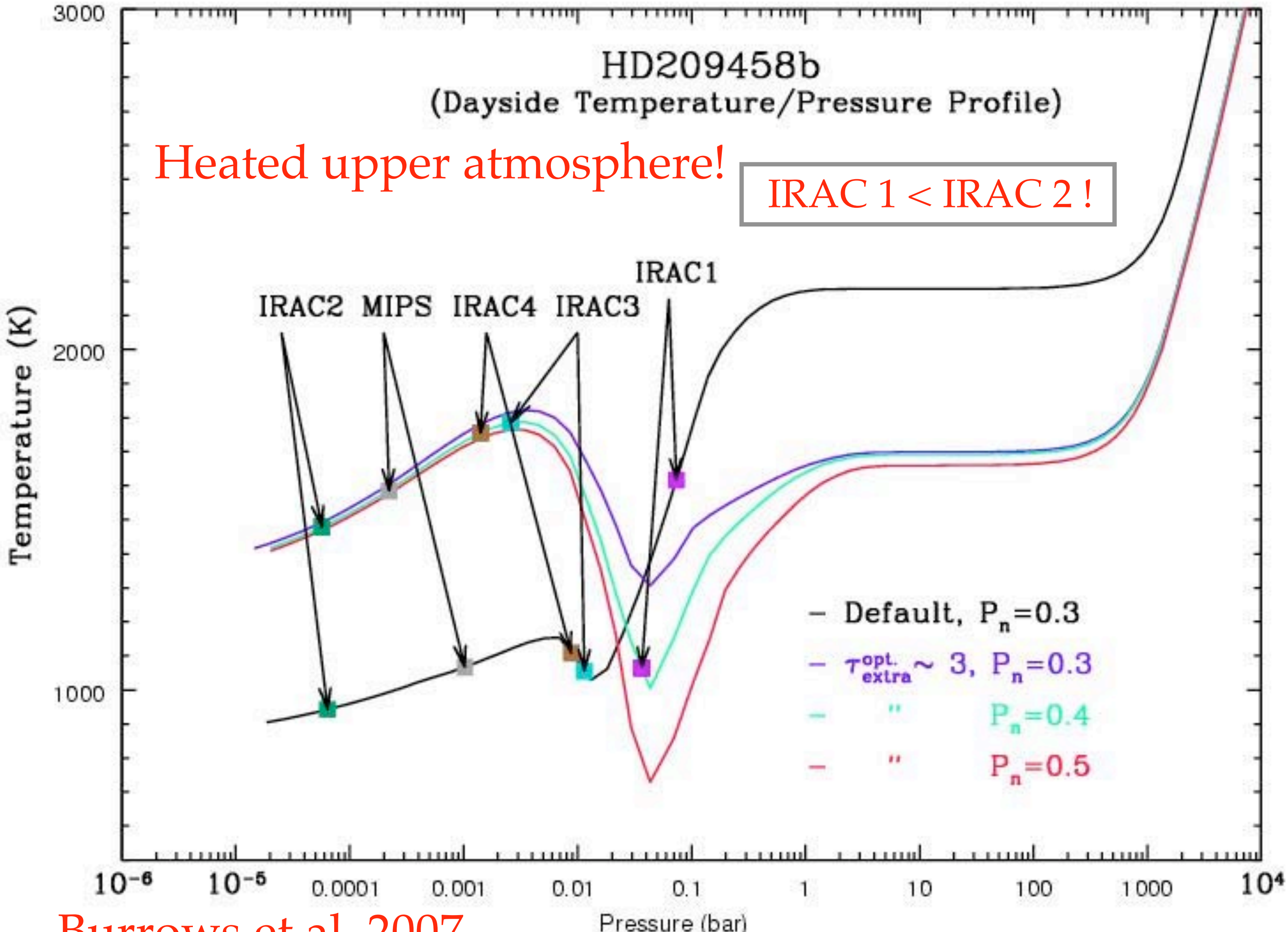
Burrows et al. 2007

Thermal Inversions: Water (etc.) in Emission (!)



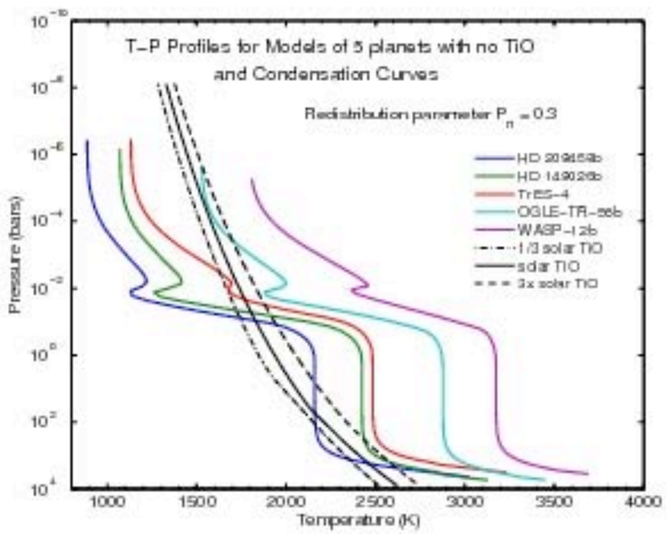
Heated upper atmosphere!

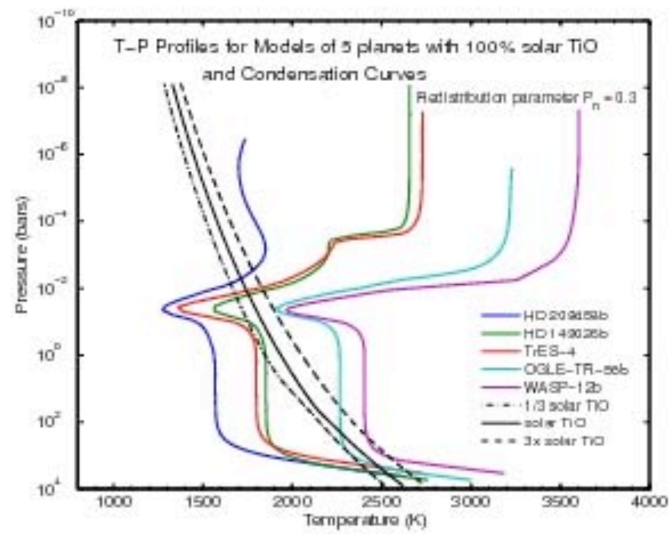
IRAC 1 < IRAC 2 !



Burrows et al. 2007

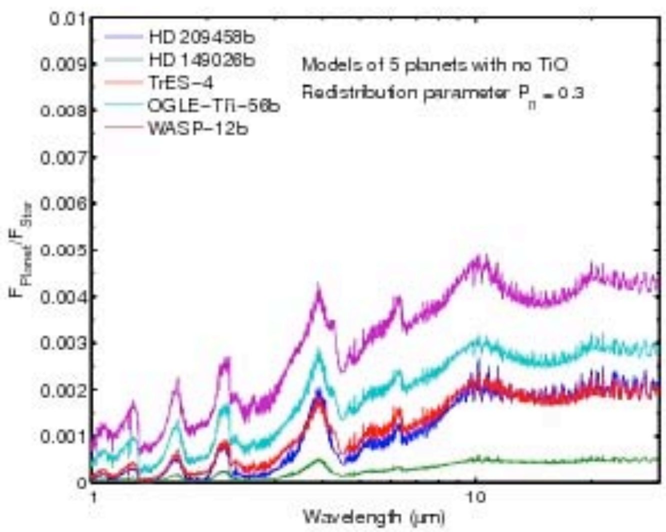
T/P Models, with and w/o TiO ($0 < X_i < 100\%$ solar)

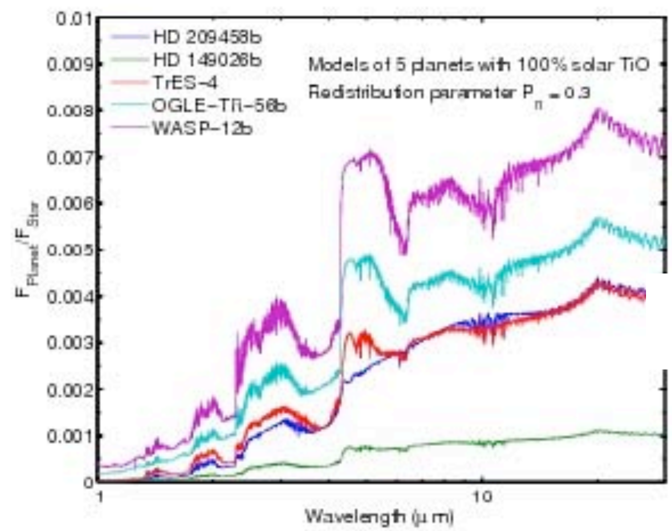




Spiegel, Silverio, & Burrows 2009

T/P Models, with and w/o TiO ($0 < X_i < 100\%$ solar)





w/o TiO

with 100% solar TiO

Spiegel, Silverio, & Burrows 2009

Indices of Upper-Atmosphere Heating and Inversion:

- **Inversion: IRAC 2/IRAC1 - High "Bump" at IRAC3 (water in emission?) - "other" emission features**

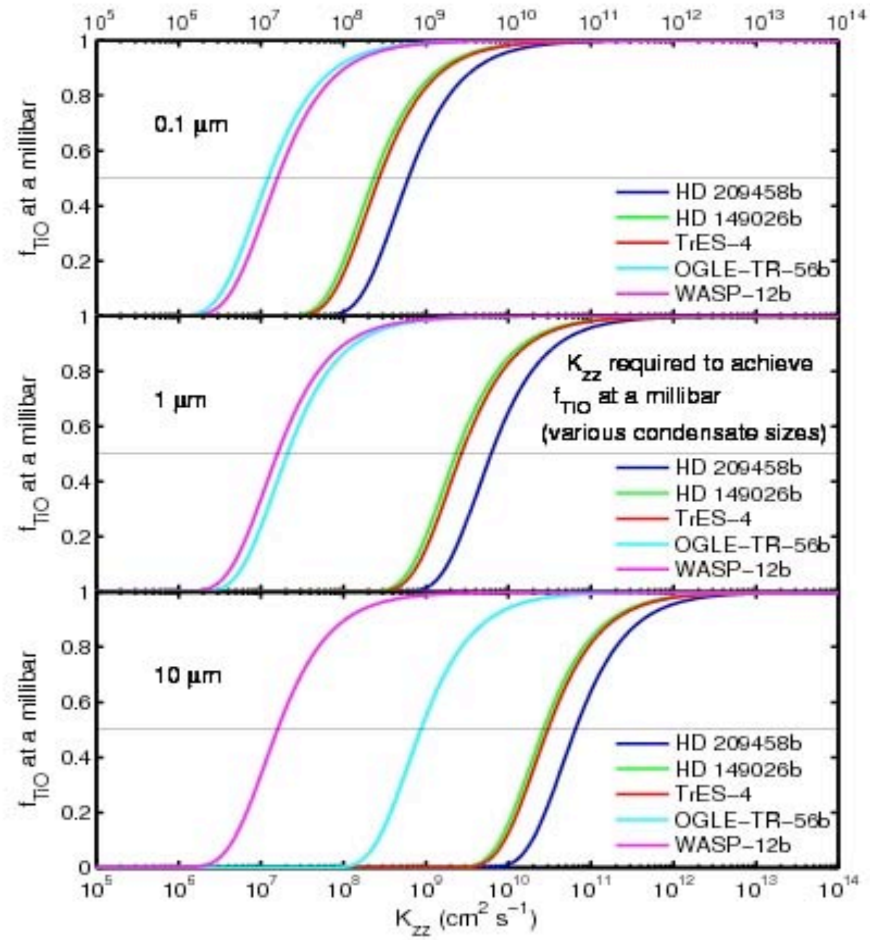
- **Hot Upper Atmosphere: "High" planet-star flux ratios in IRAC 2, IRAC 3, and IRAC 4 bands (and at 24 microns?)**

- **What is absorbing in the optical at altitude?**

Cold trap!

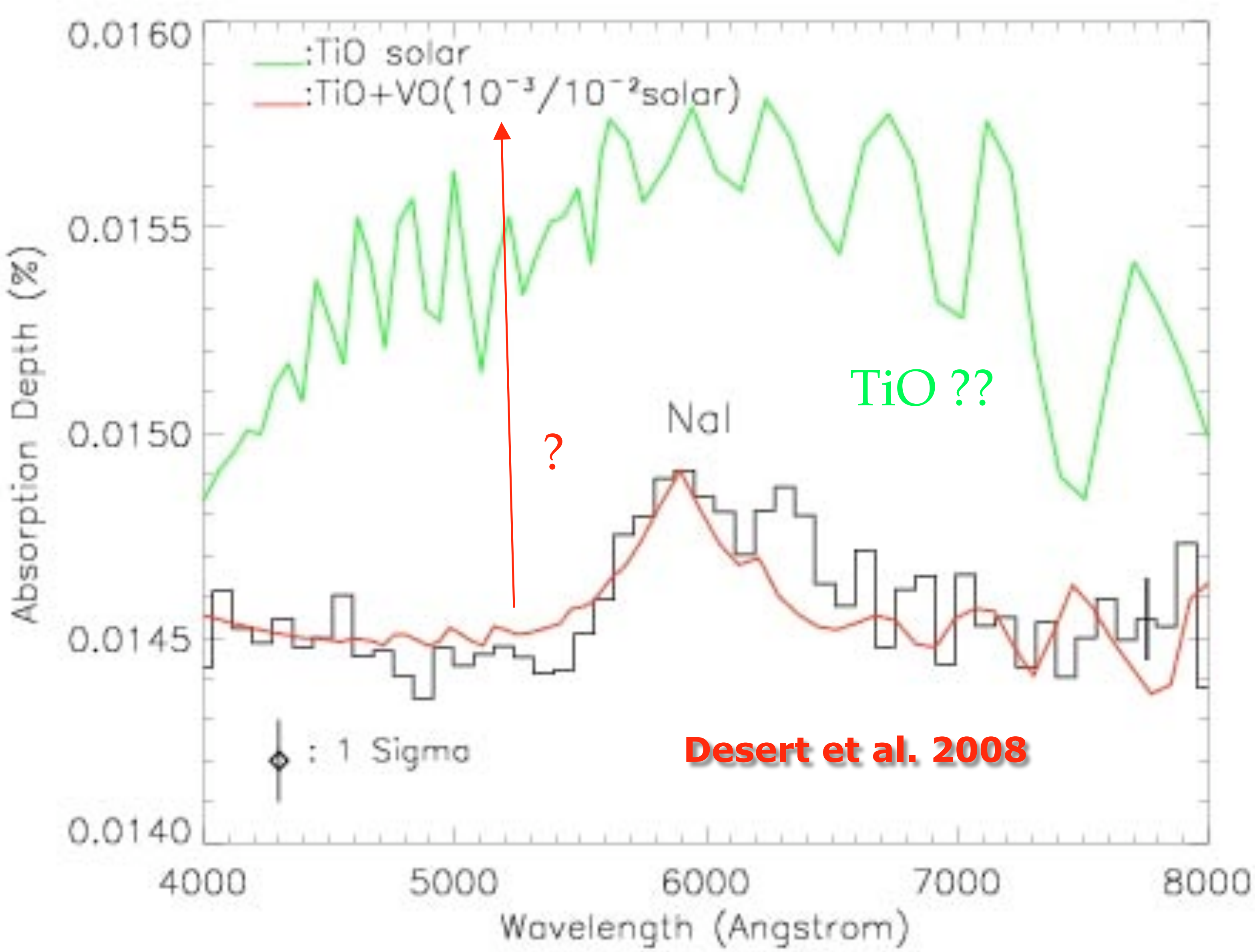
K_{zz} (mixing coefficient) required vs. particle size (a)

Strong Mixing Required



Spiegel, Silverio, & Burrows 2009

HD 209458b in Transit: Optical



Cause of Heating in Upper Atmosphere?

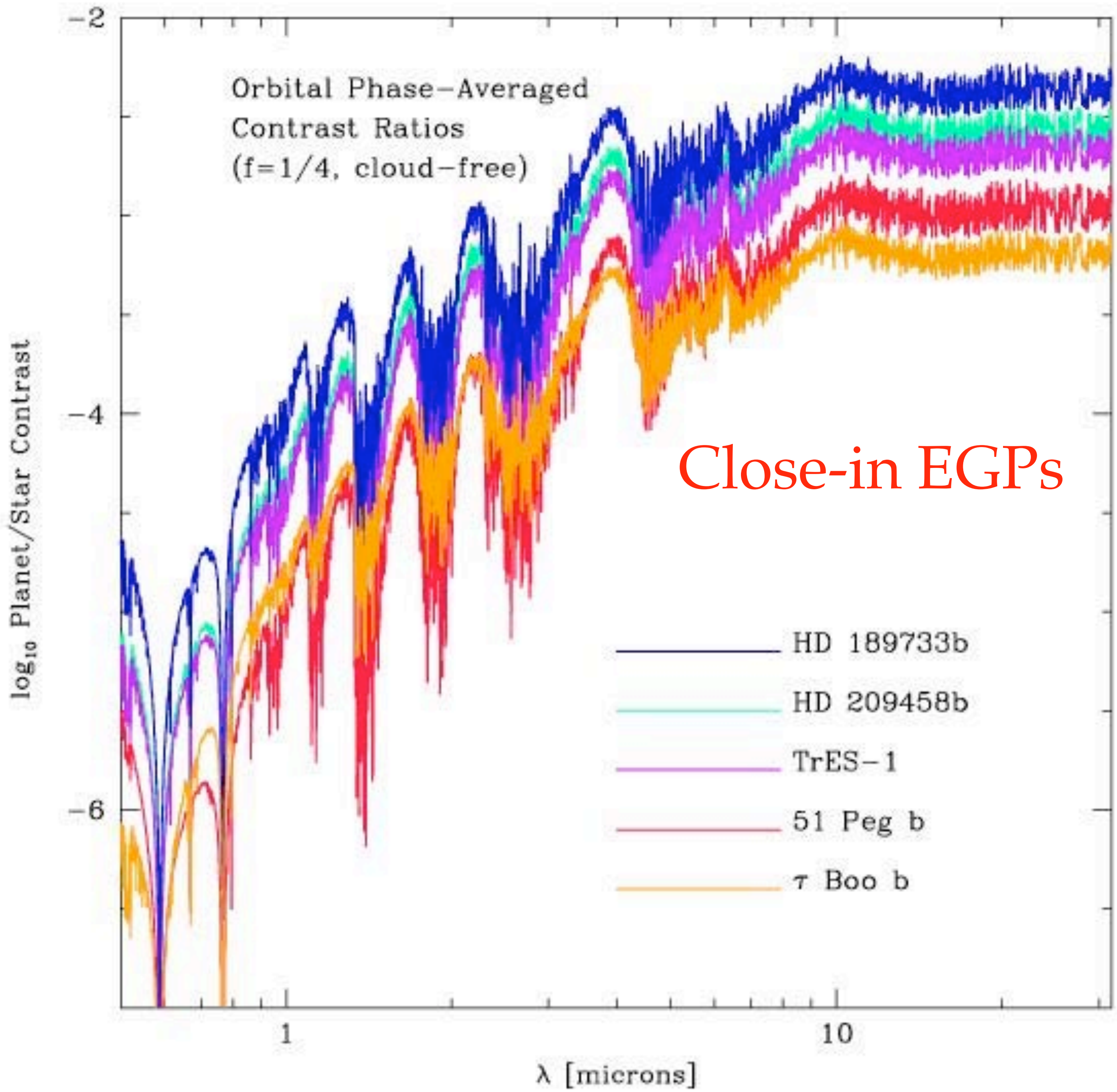
- Extra absorber in the Optical at Altitude (low pressures)?
- Can it be TiO/VO (Hubeny et al. 2003; Burrows et al. 2008; Fortney et al. 2008)?

-"Can't" be at equilibrium abundances (Fortney et al.): cold trap (condenses out), day-night circulation sink; Heavies settle; Needs vigorous vertical mixing to work (Spiegel et al. 2009!) - problematic? - Desart et al. (?): < ~10^{-2} - 10^{-3} solar (HD 209458b)

- Photolytic products? Polyacetyenes? Tholins?
- Sulfur chemistry and photolysis: Thiozone (S_3), allotropes of S, HS (Zahnle et al. 2009) - metallicity dependence (XO-2b)?
- Only weakly correlated with stellar insolation (e.g., XO-1b and HD 189733b!) - no simple parametrization!
- Wave heating??
- Theory: Need non-equilibrium chemistry & 3D GCM to resolve?
- Observation: Need better and more definitive optical spectra

Secondary Eclipses in the Optical: MOST, Kepler, and CoRoT

“Albedos”



Orbital Phase-Averaged
Contrast Ratios
(f=1/4, cloud-free)
Close-in EGPs
HD 189733b
HD 209458b
TrES-1
51 Peg b
τ Boo b
-2
-4
-6
1
10
log10 Planet/Star Contrast
λ [microns]

Optical "Reflection" / "Albedo" / Thermal Measurements of "Hot Jupiters"

MOST HD 209458b Albedo Limit: Rowe et al. 2008; $A_g < 0.085$ - Burrows, Ibgui, & Hubeny 2008

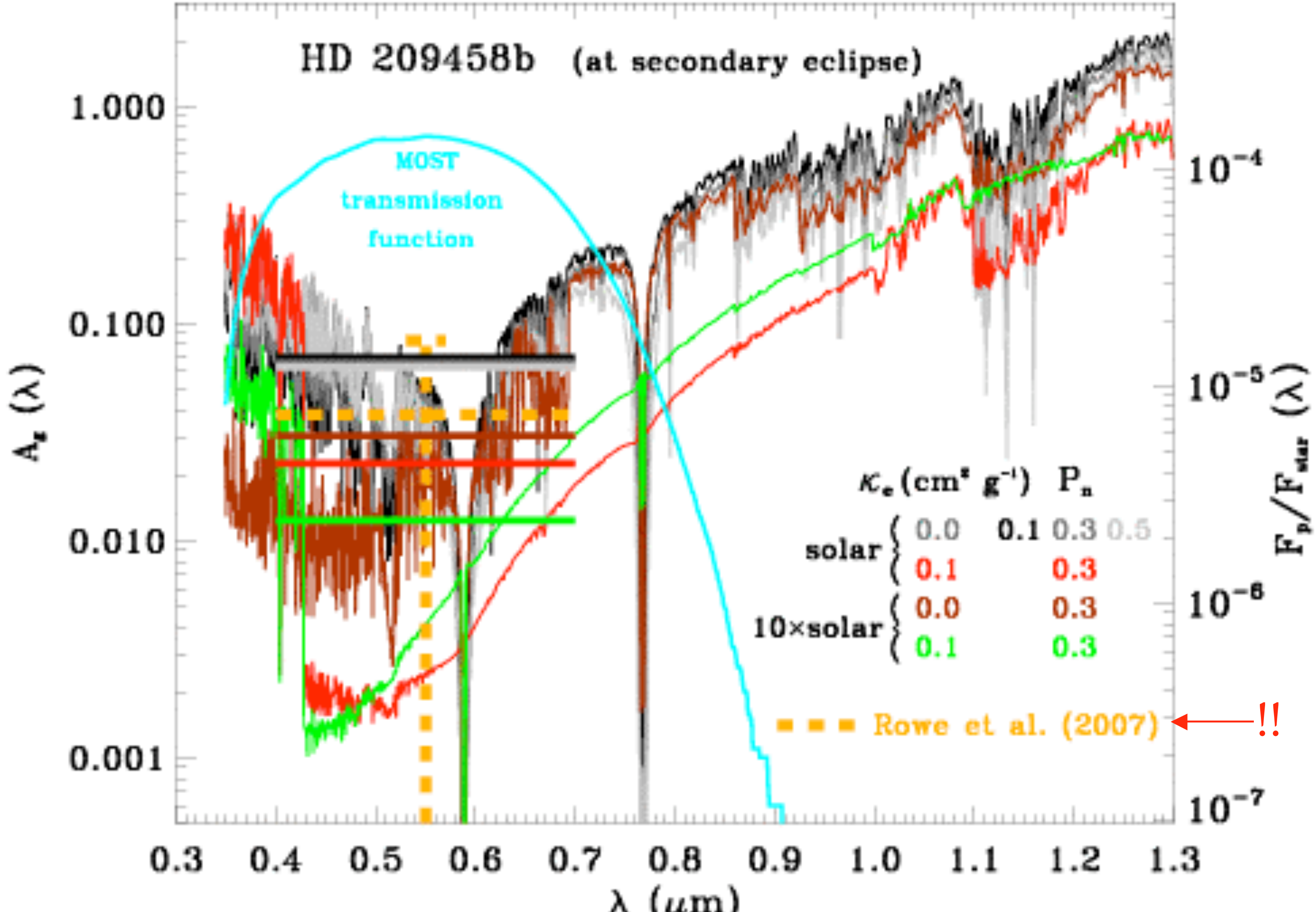
CoRoT-Exo-1b: Snellen / Alonso et al. 2009; Rogers et al. 2009 "Albedo" / thermal measurement - $F_p / F_* \sim 1.3 \times 10^{-4}$ (CoRoT red) $\sim 1.6 \times 10^{-4}$ (CoRoT white); Bond albedo ~ 0.075 (?)

CoRoT-Exo-2b: Snellen et al. 2009b; "Albedo" / thermal measurement - $F_p / F_* \sim 1.0 \times 10^{-4}$

KEPLER HAT-P-7b: Borucki et al. 2009 et al. 2009b; $F_p / F_* \sim 1.3 \times 10^{-4}$ ←—!!

MOST HD 209458b Albedo: Burrows, Ibgui, & Hubeny 2008

Rowe et al. 2007



CoRoT-1b(Optical and K band): Rogers et al. 2009

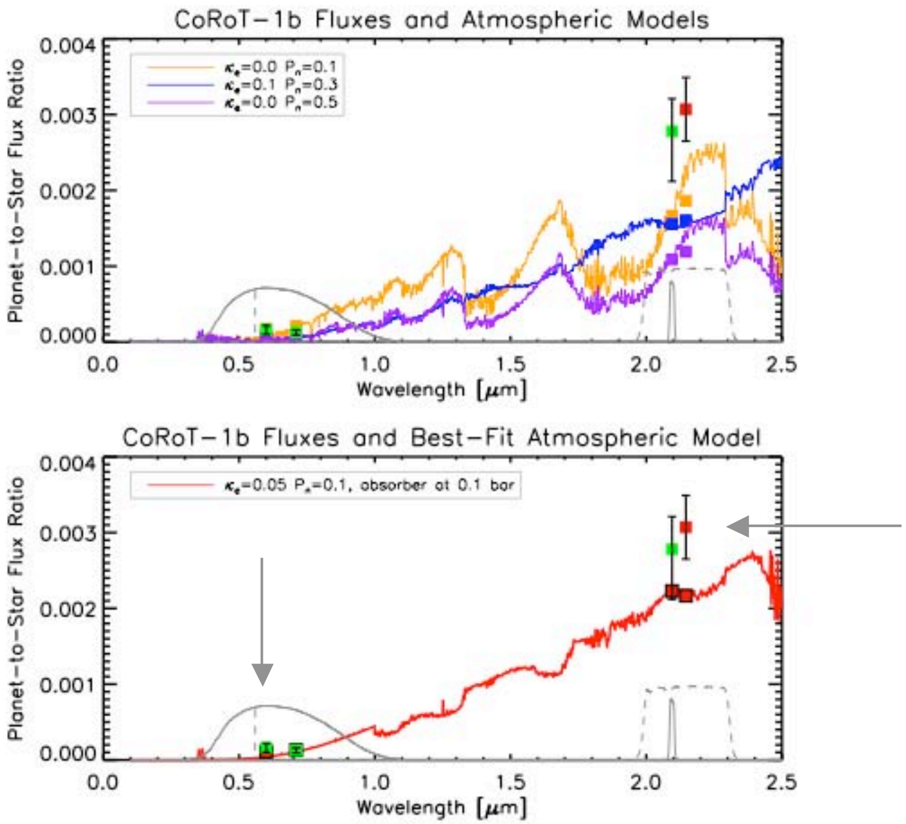
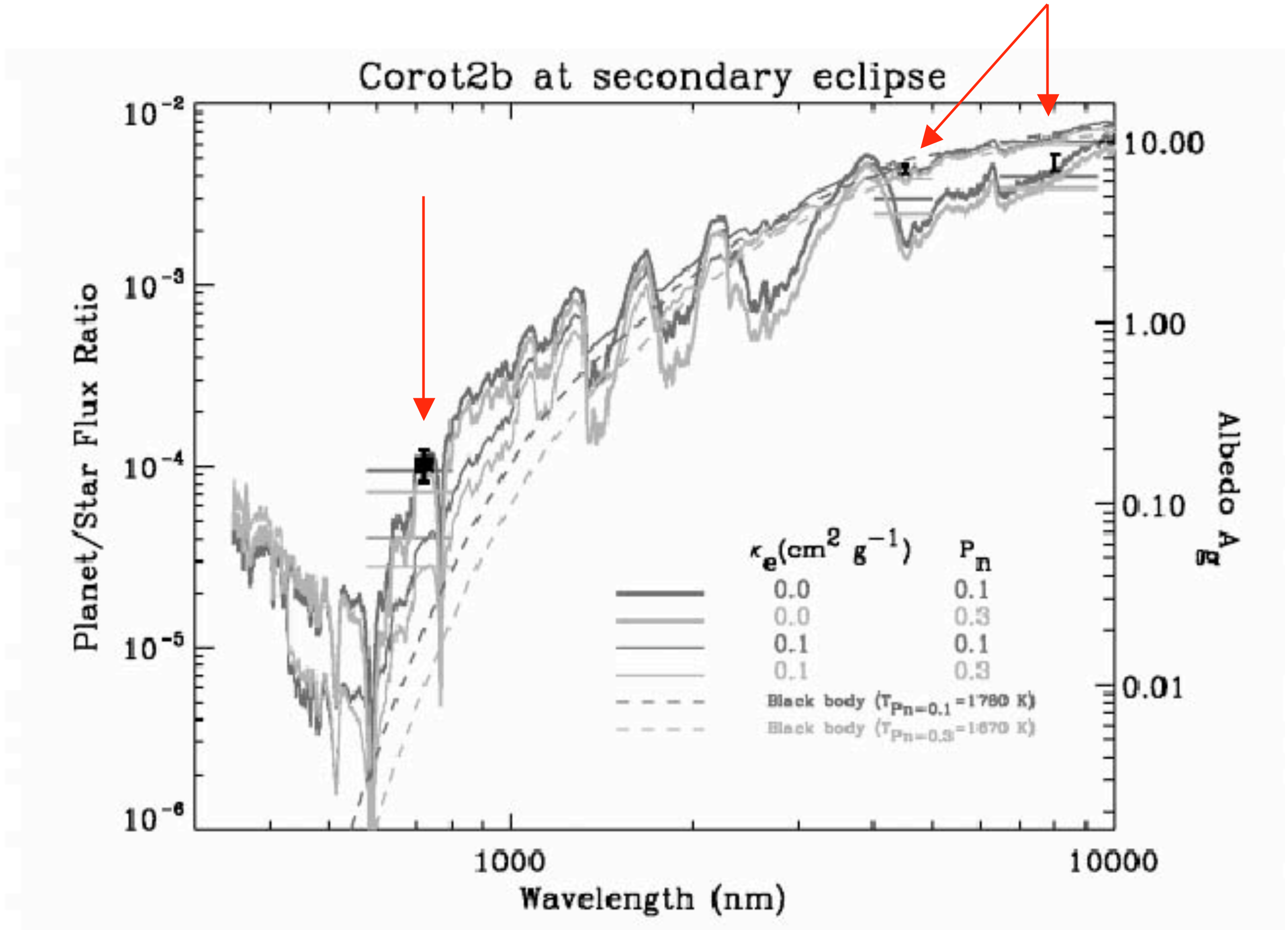


Fig. 7.— Top Panel: The measured planet-to-star flux ratios compared to the band-averaged ratios from atmospheric models that incorporate extra optical absorbers placed near the 0.01 bar level. Three models shown here in orange, blue, and purple, have absorber opacities $_e$ = 0.0, 0.1, and 0.0 $cm^2\ g^{-1}$, and redistribution parameters P_n = 0.1, 0.3, and 0.5, respectively. Bottom Panel: The measured flux ratios compared to the predicted ratios from the best-fit atmospheric model, with =0.05 $cm^2\ g^{-1}$ and P_n = 0.1, and the absorber placed near the 0.1 bar level, deeper in the atmosphere than for the other models.

CoRoT-2b(Optical and IRAC): Snellen et al. 2009



Planetary (Phase) Light Curves
(Close-in)

(Photometric Variations)

Ups And b Phase Curve at 24 μm

Contrast does NOT imply weak day-night coupling:

Thermal inversion

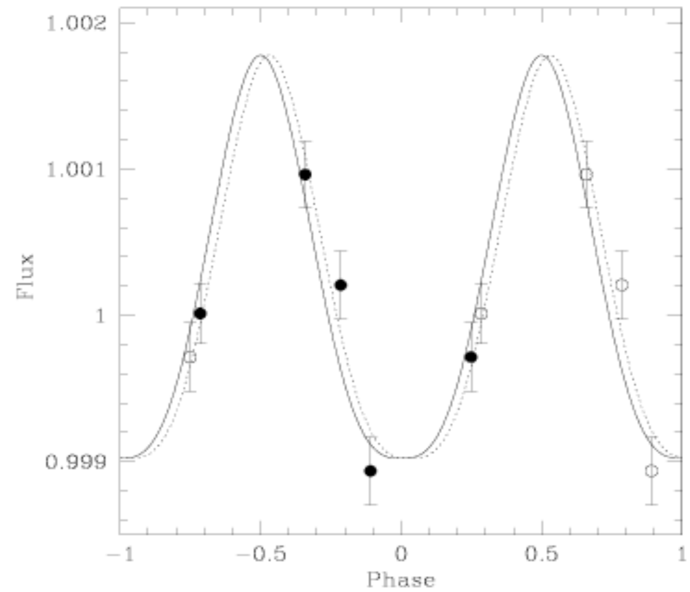
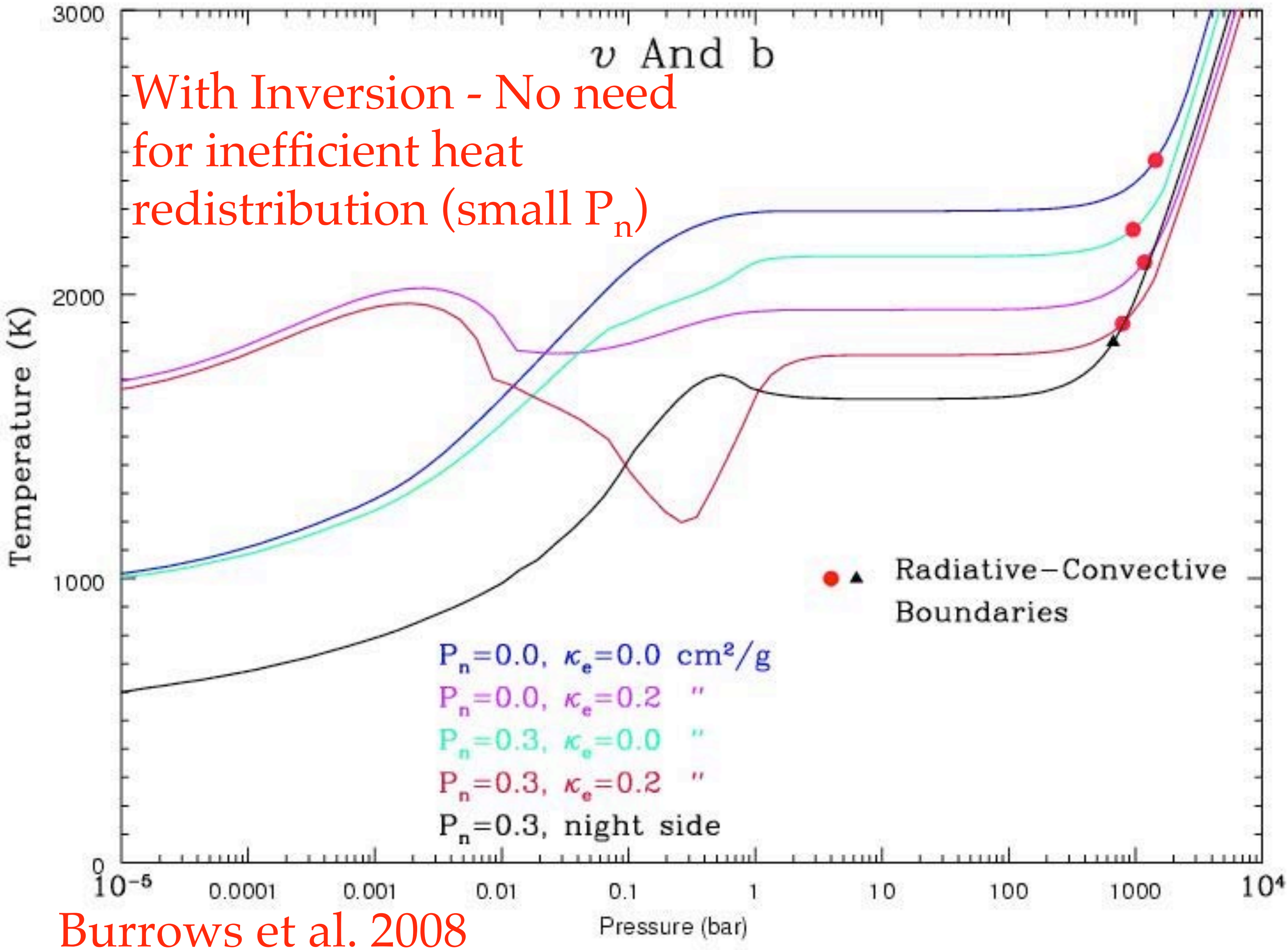


Figure 2: Comparison of the phase curve and the No-Redistribution Model. The solid points show our final phase curve, after applying calibrations, in time order from left to right. The open points are repetitions of these, displaced horizontally by one orbit, to better illustrate the phase coverage over two cycles. The solid line is an analytic model for the planetary emission in which energy absorbed from the star is reradiated locally on the day side with no heat transfer across the surface of the planet, the so-called No-Redistribution model (and in excellent agreement with the more detailed version in (*18*)). The assumed inclination in this case is 80° from pole-on, and the relative planet/star amplitude is 2.9×10^{-3}. If we allow for a phase shift relative to the radial velocity curve, we obtain a slightly better fit, as shown by the dotted curve. The best fit is obtained with a phase lag of 11°, but zero lag is excluded only at the 2.5σ level.

8

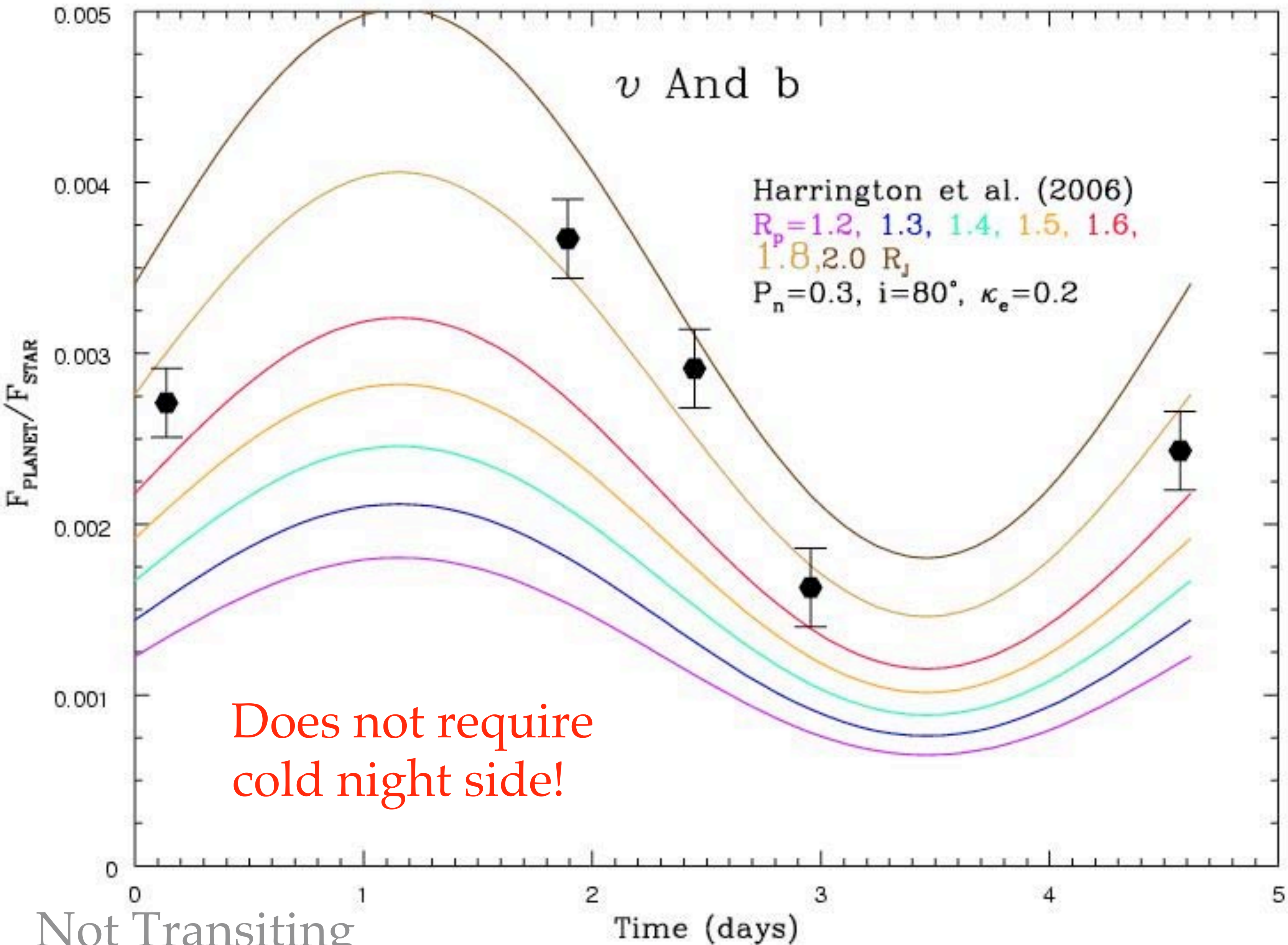
Harrington et al. 2006

Future: Kepler, JWST



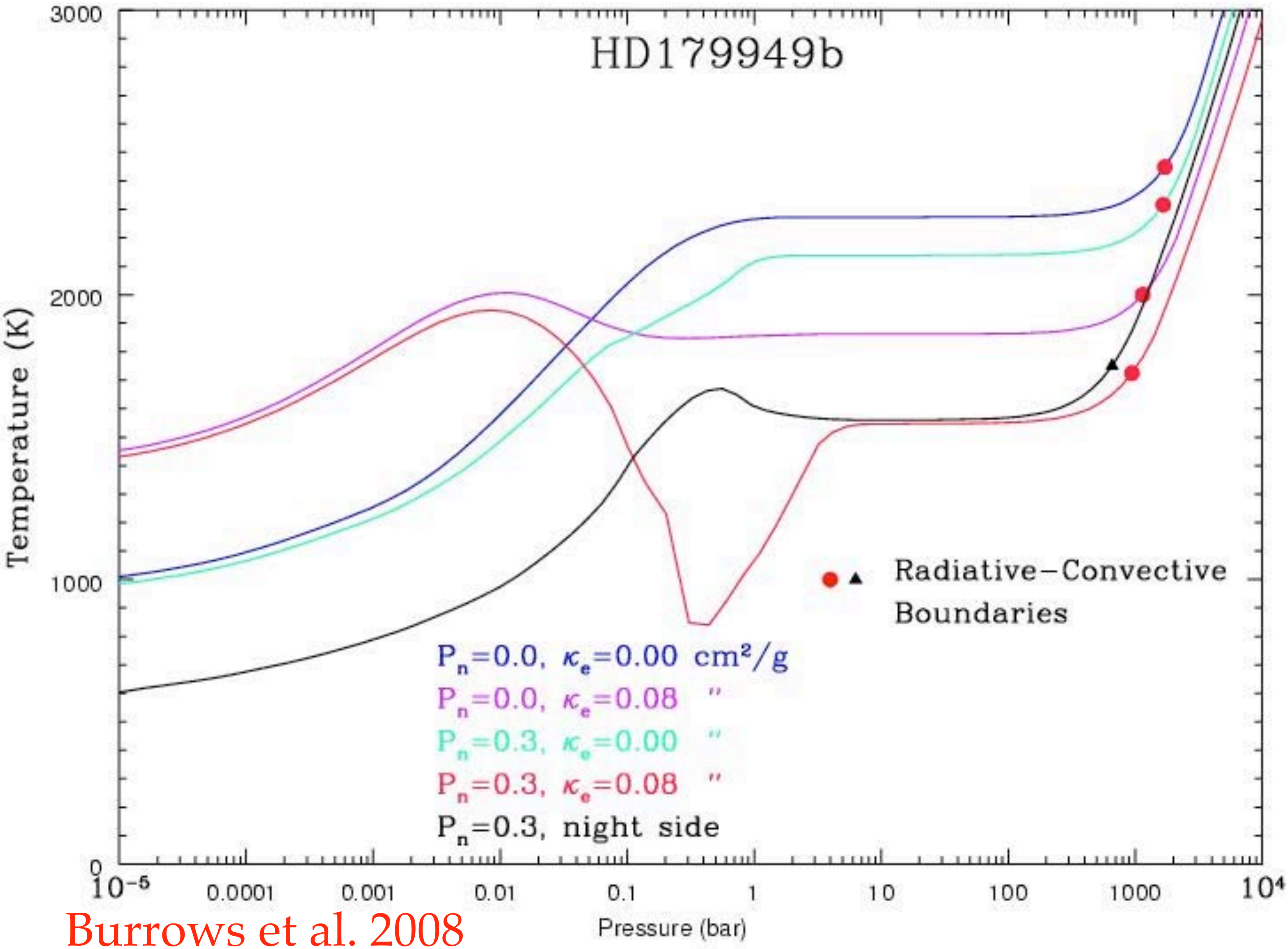
With Inversion - No need for inefficient heat redistribution (small P_n)

Burrows et al. 2008

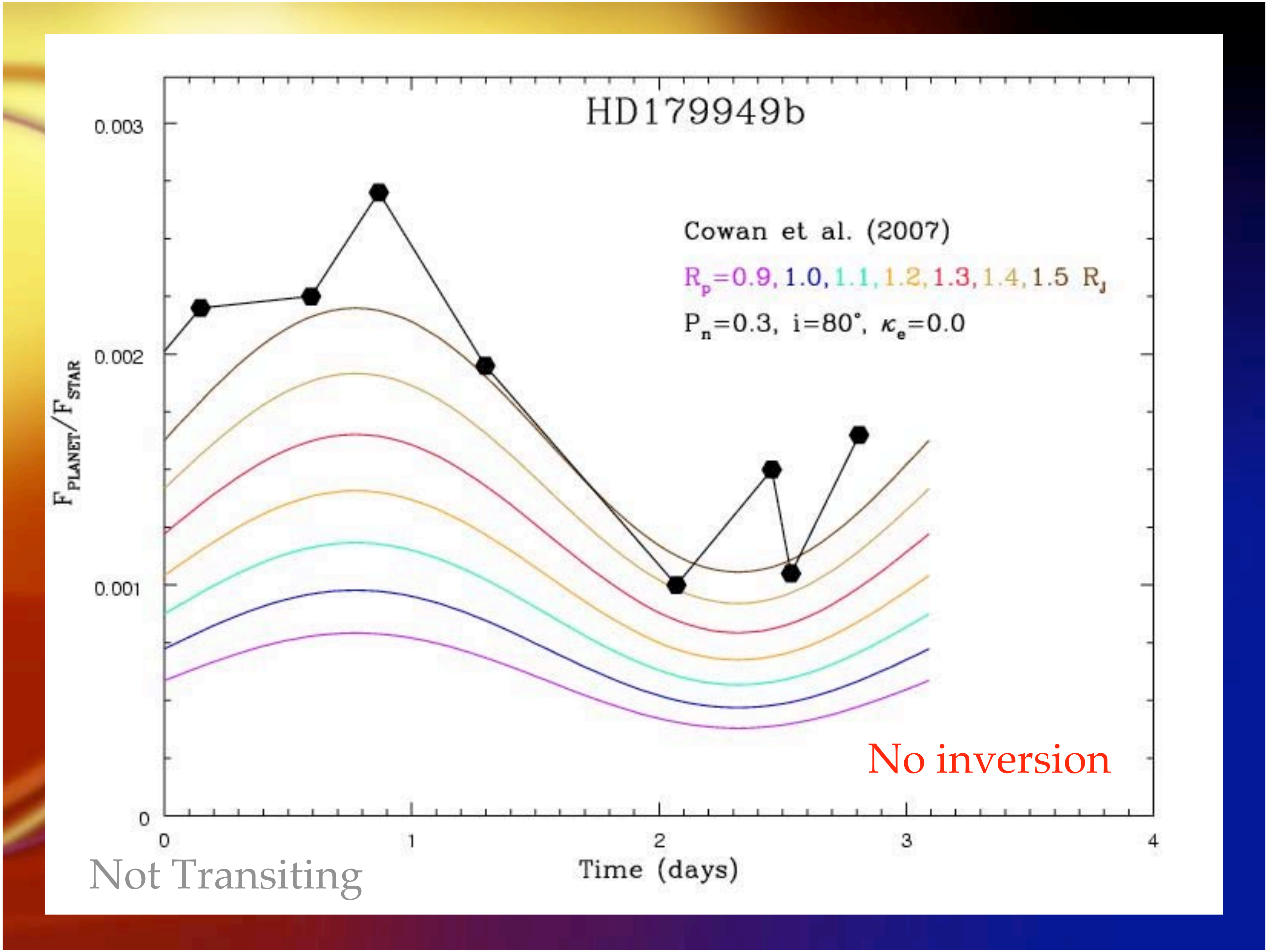


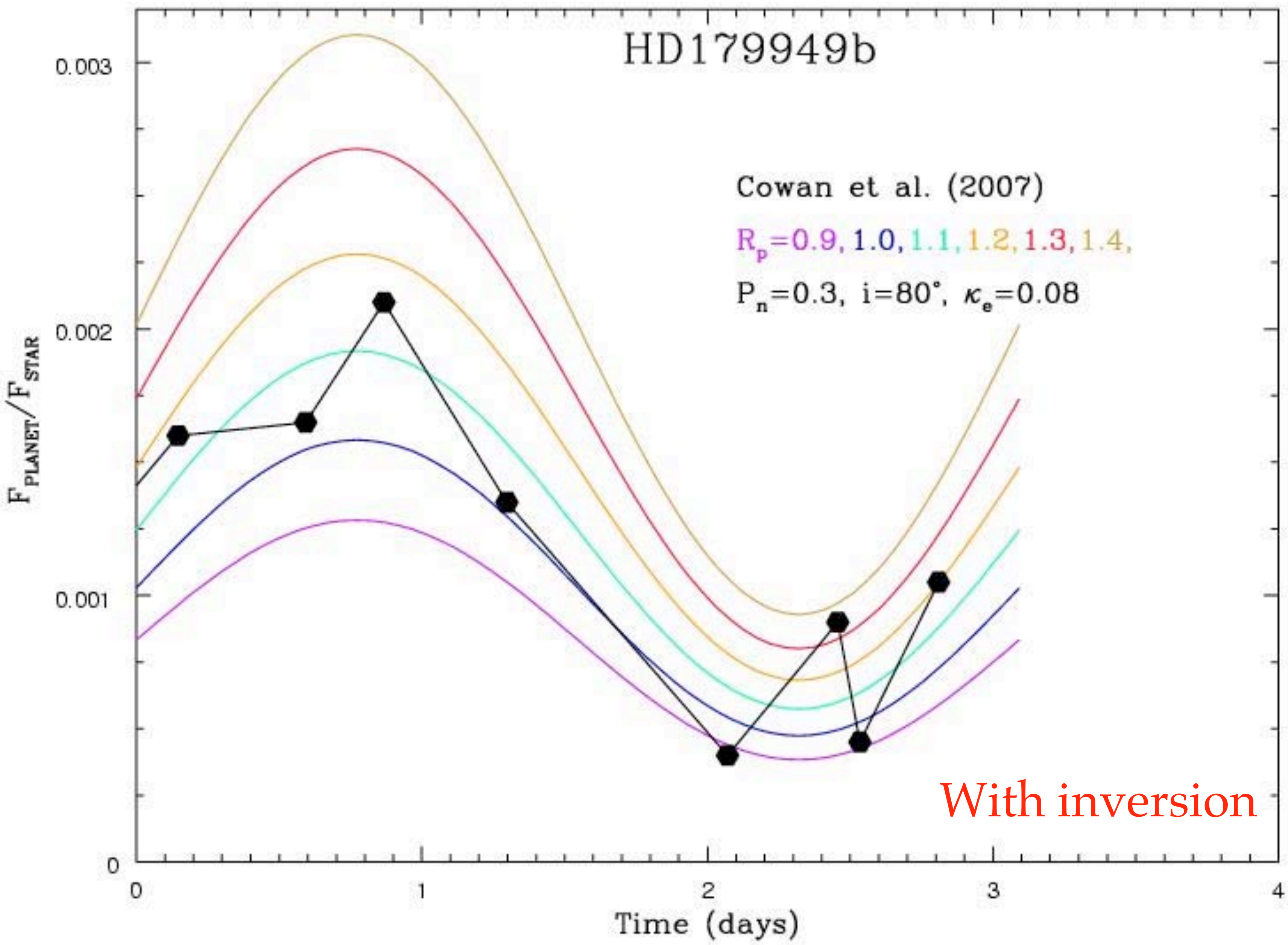
Does not require cold night side!

Not Transiting

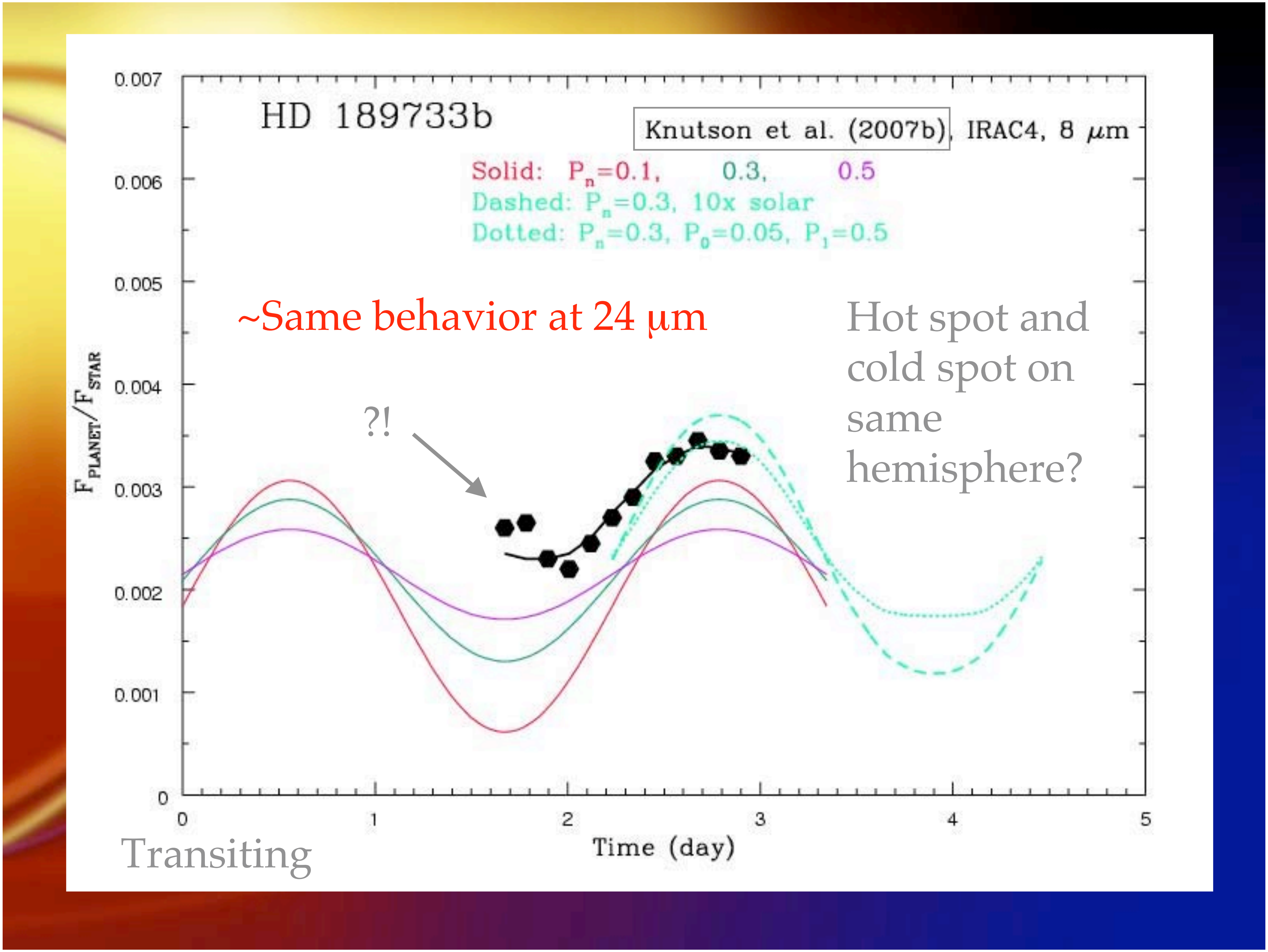


Burrows et al. 2008


HD179949b
Cowan et al. (2007)
R_p=0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5 R_J
P_n=0.3, i=80°, κ_e=0.0
No inversion
F_PLANET/F_STAR
0.003
0.002
0.001
0
0
1
2
3
4
Time (days)
Not Transiting



HD179949b
Cowan et al. (2007)
R_p=0.9, 1.0, 1.1, 1.2, 1.3, 1.4,
P_n=0.3, i=80°, κ_e=0.08
F_{PLANET}/F_{STAR}
Time (days)
With inversion

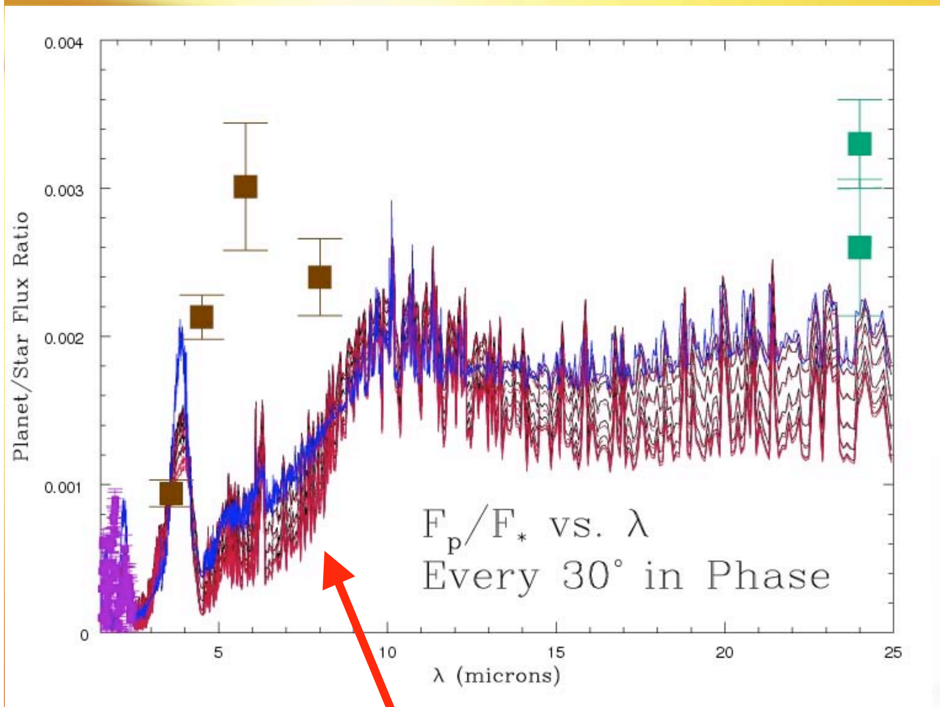


HD 189733b
Knutson et al. (2007b), IRAC4, 8 μm
Solid: Pn=0.1, 0.3, 0.5
Dashed: Pn=0.3, 10x solar
Dotted: Pn=0.3, P0=0.05, P1=0.5
~Same behavior at 24 μm
?!
Hot spot and cold spot on same hemisphere?
FPLANET/FSTAR
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
0
1
2
3
4
5
Time (day)
Transiting

Variation of Spectra with Planetary Phase

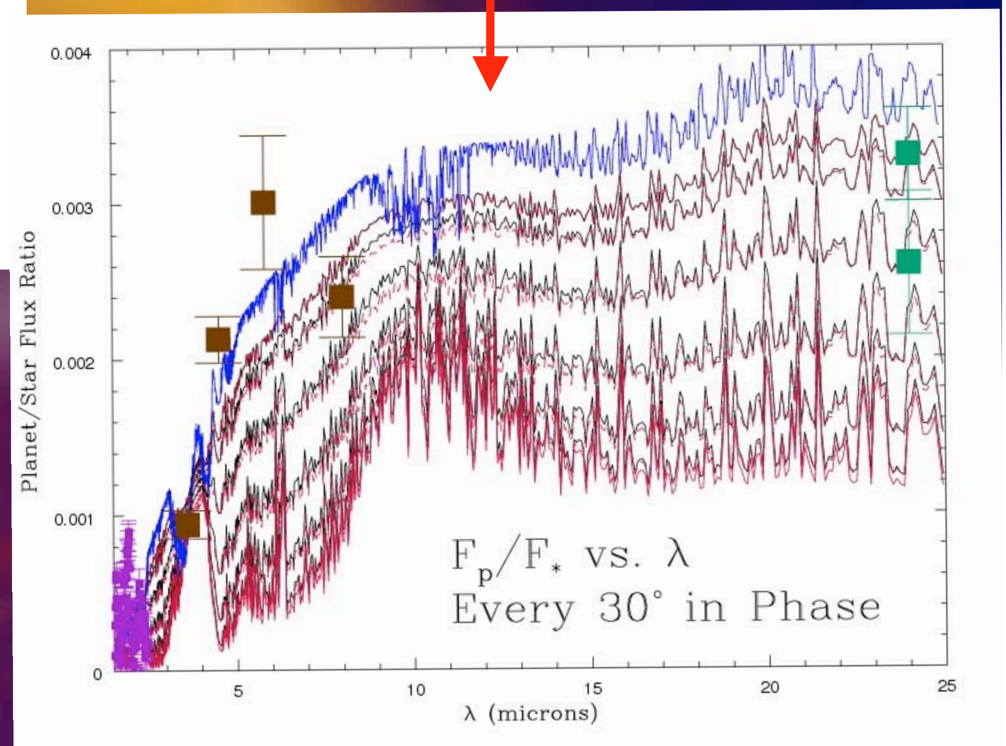
("Light Curves")

HD 209458b: Full-orbit Phase Light Curves



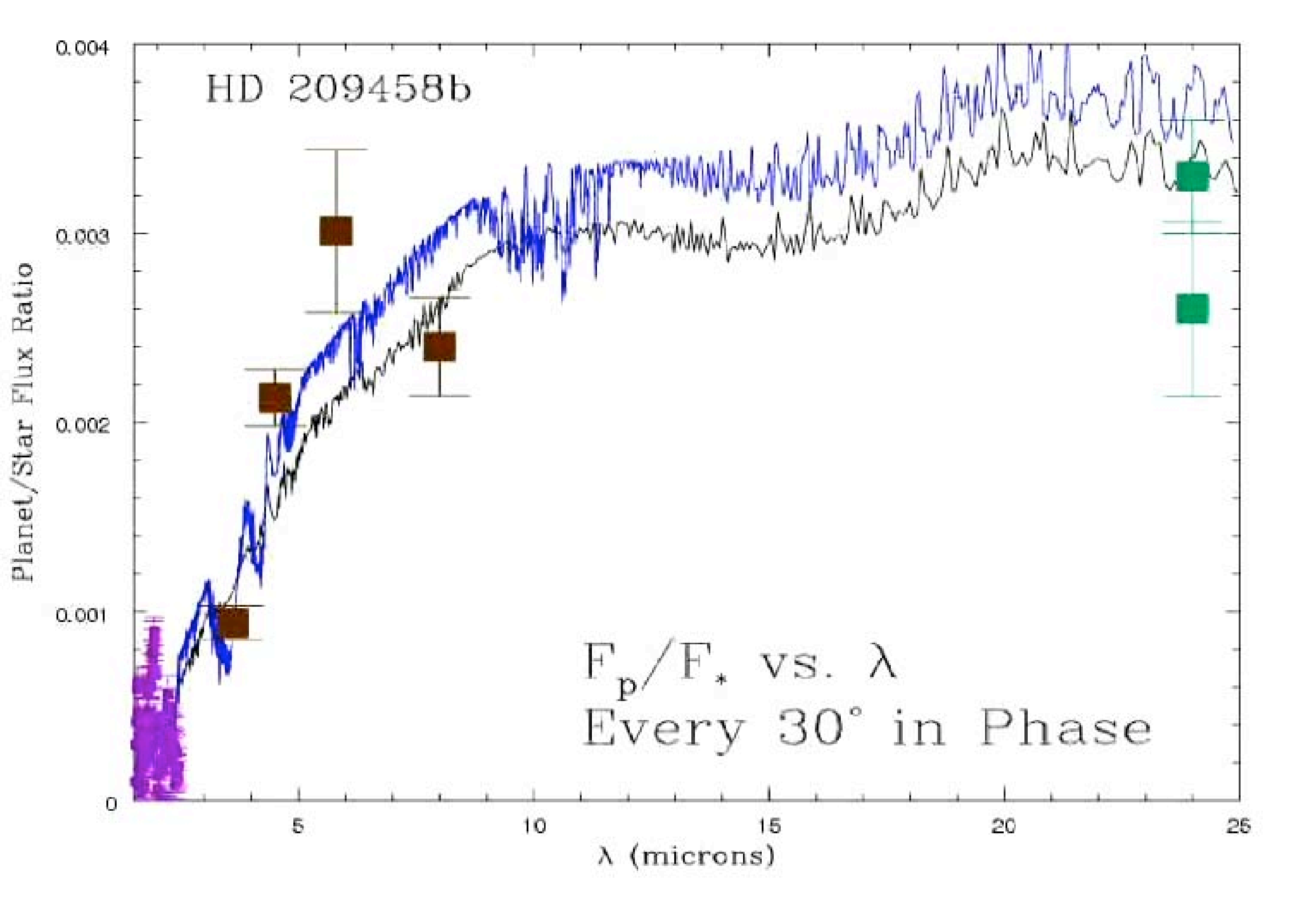
Without extra absorber

With Inversion / Hot upper atmosphere



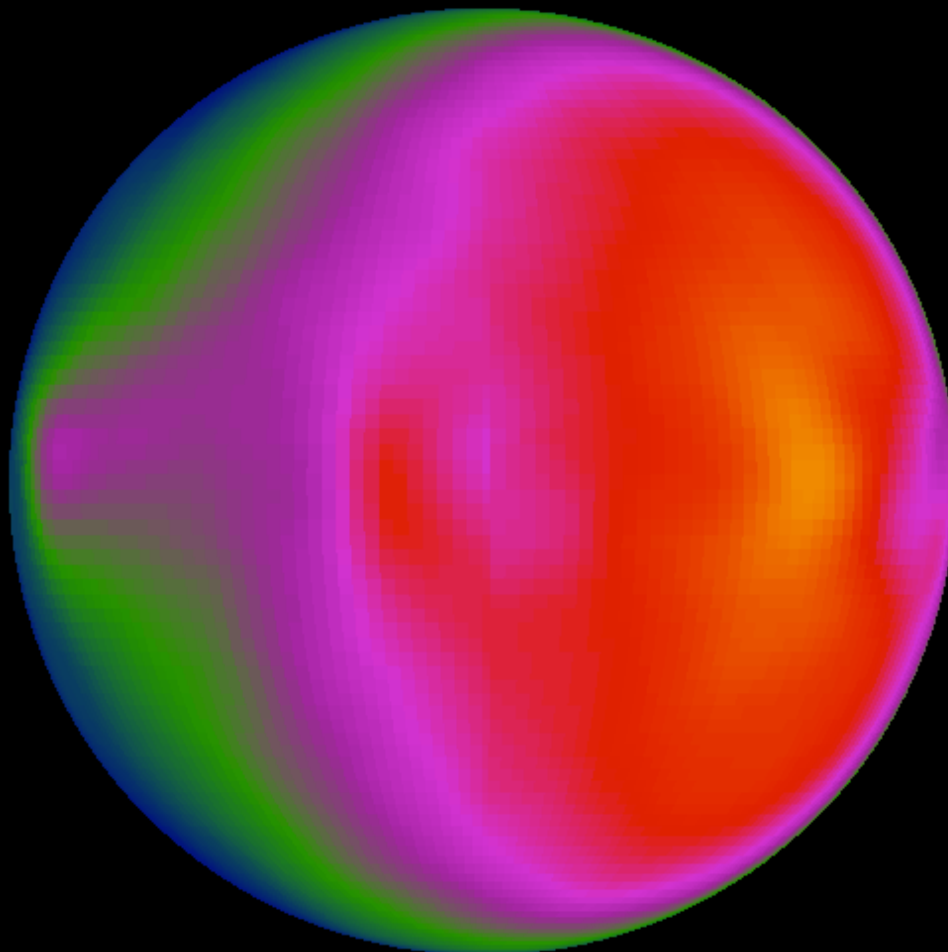
Burrows, Rauscher, Spiegel, & Menou 2010

Planet/Star Flux Ratio vs. Wavelength and Phase

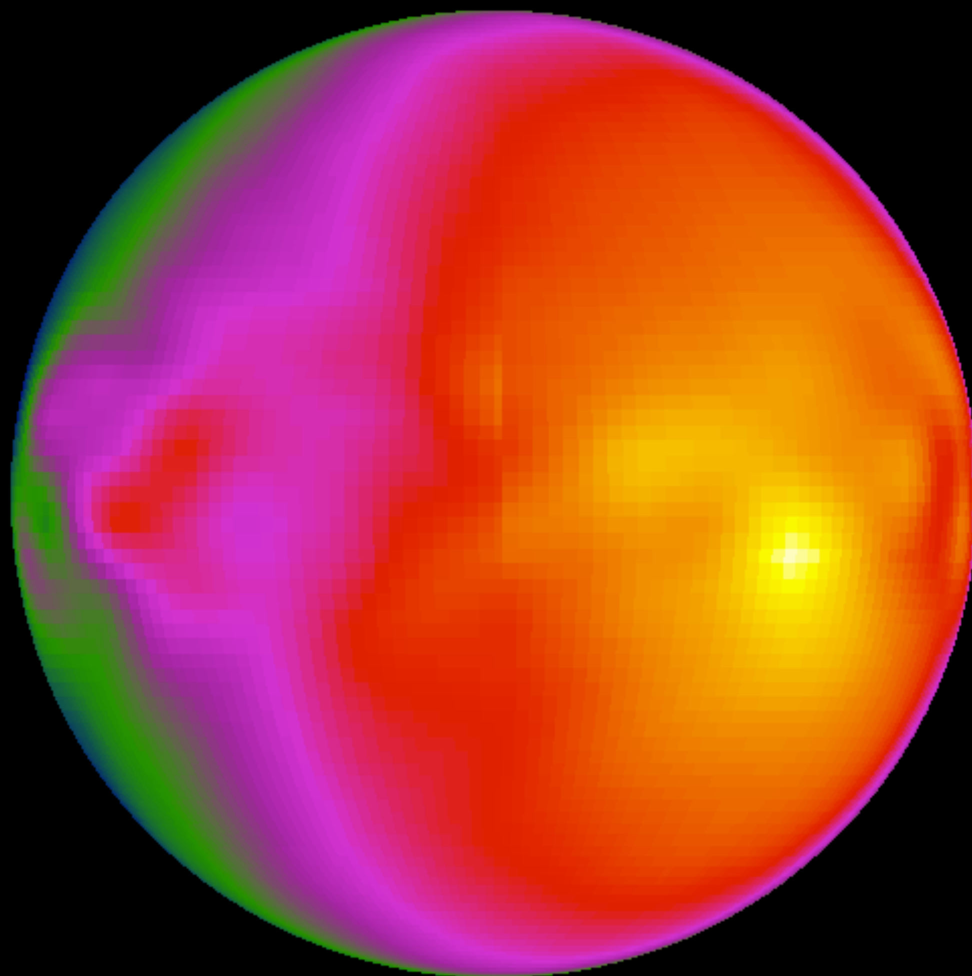


Burrows, Rauscher, Spiegel, & Menou 2010

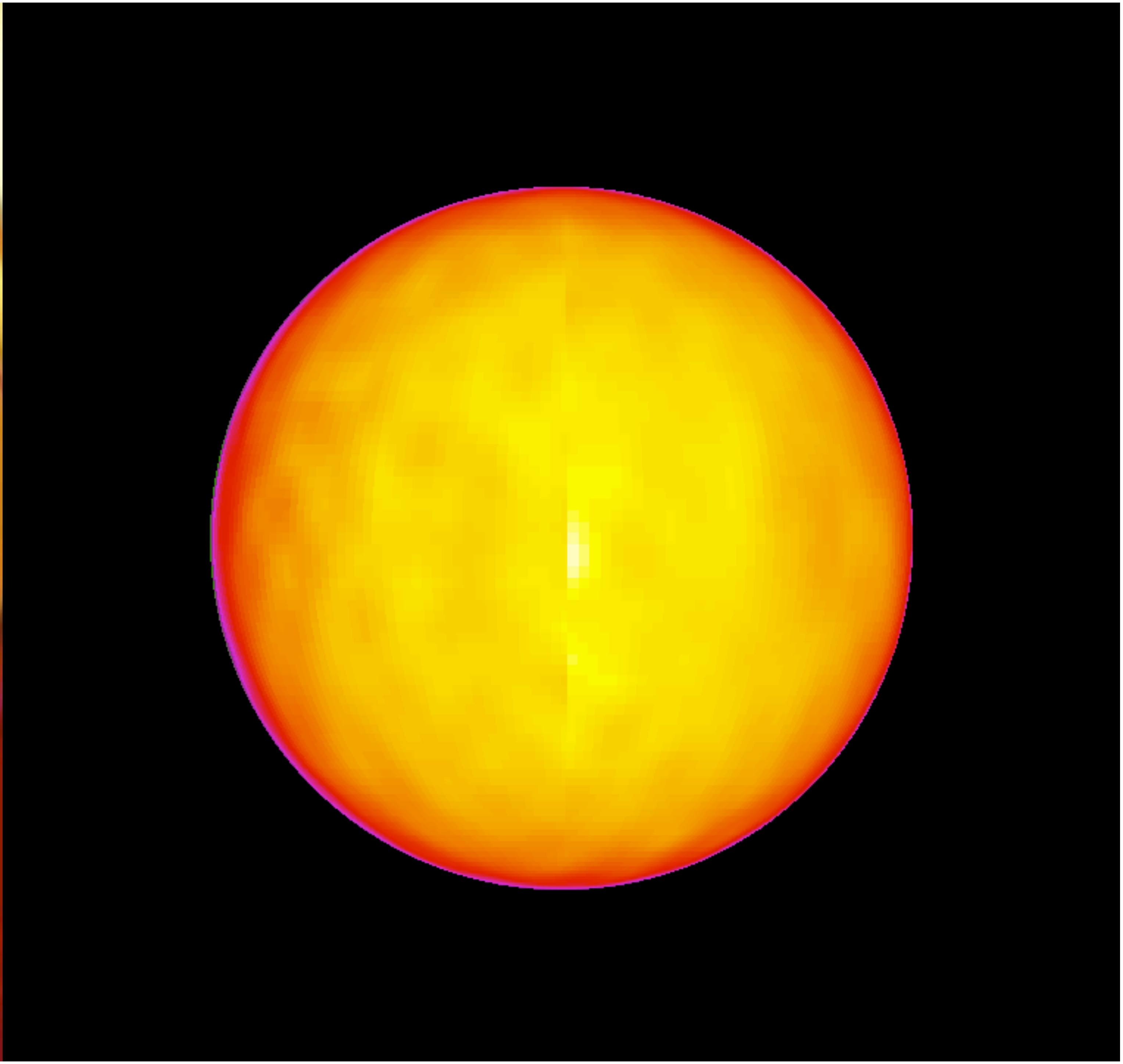
J-band HD 209458b Map (model a03)



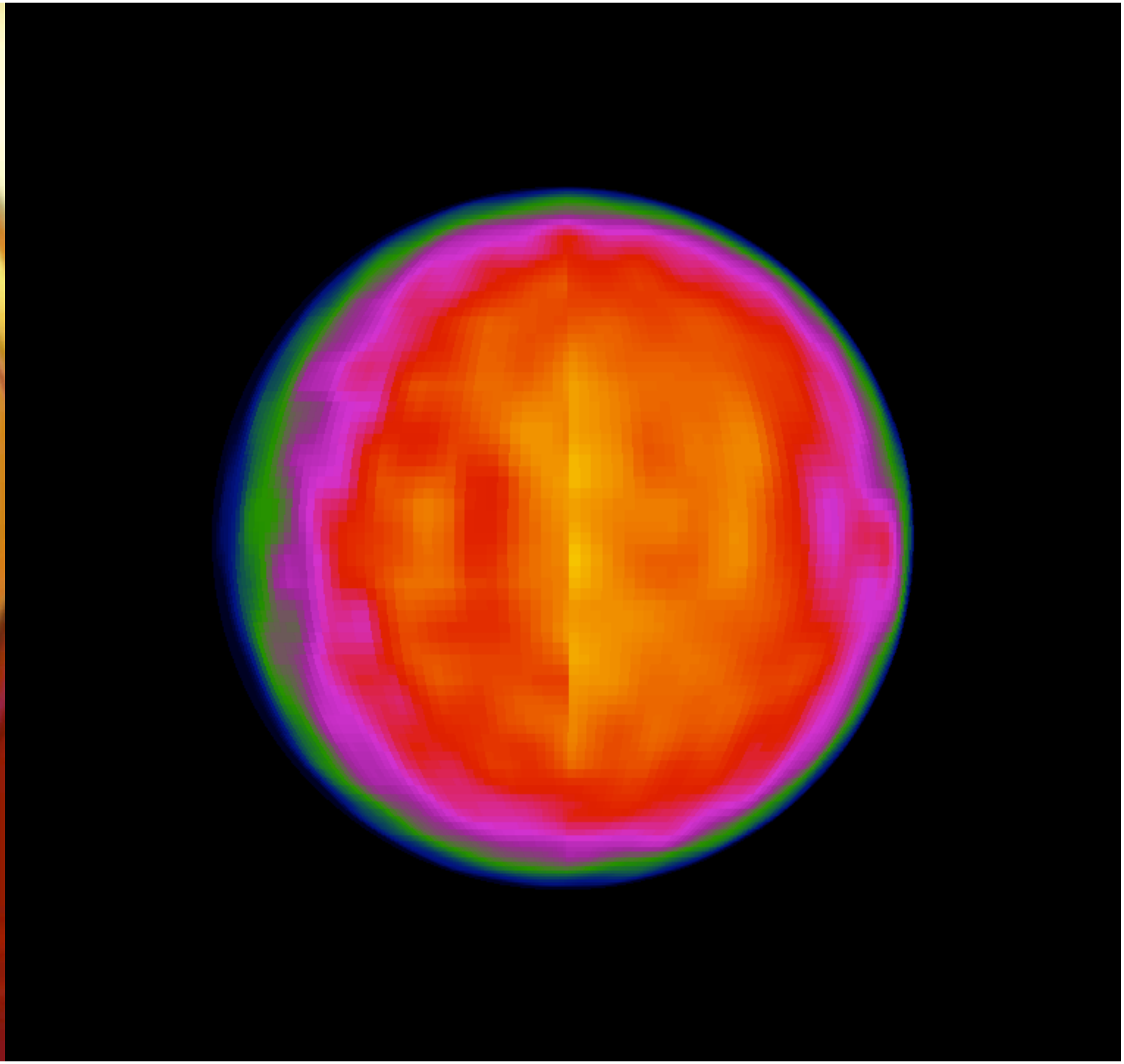
J band HD 209458b Map (model a00)



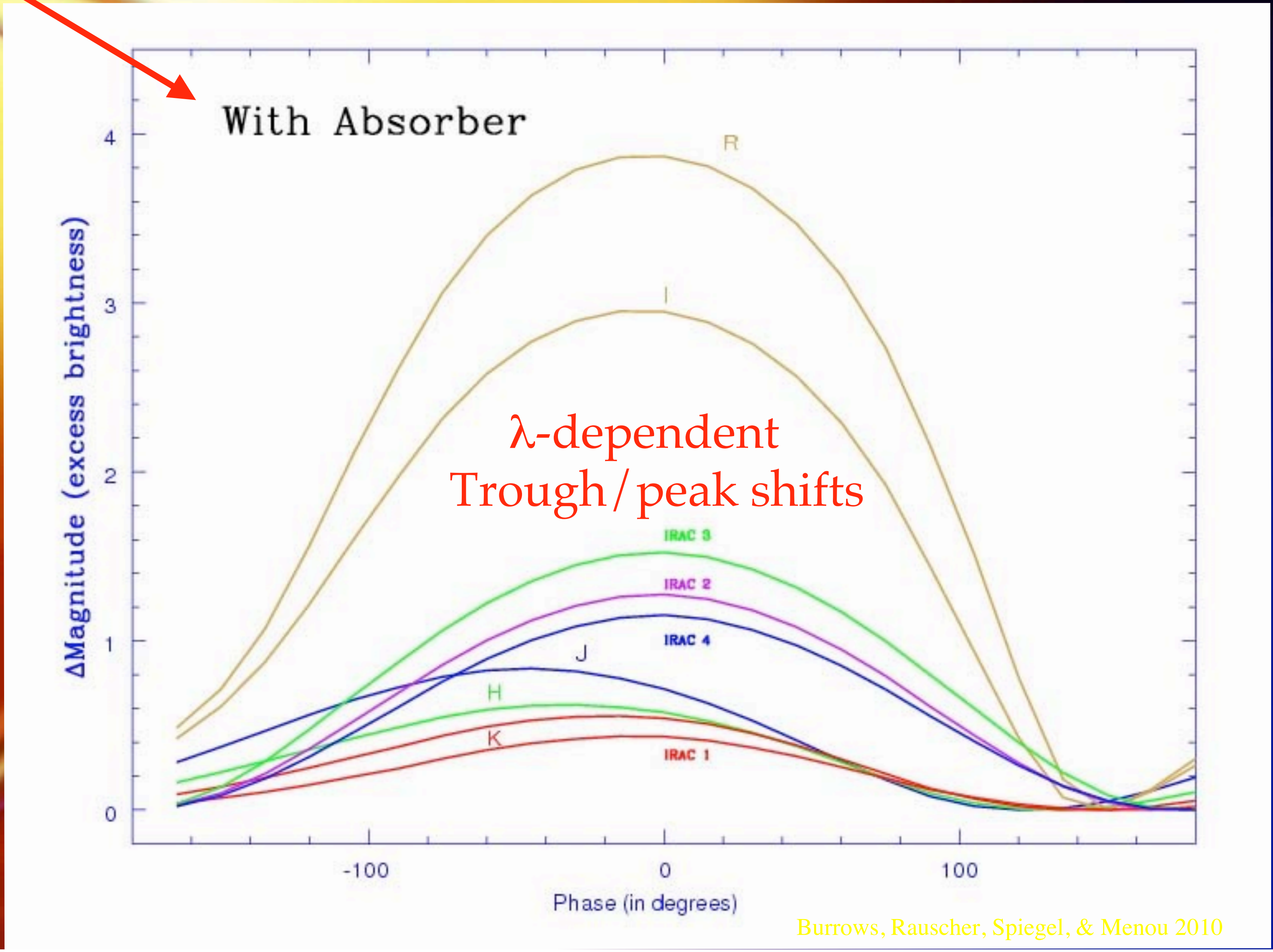
IRAC3 band HD 209458b Map (model a03)



I band HD 209458b Map (model a03)

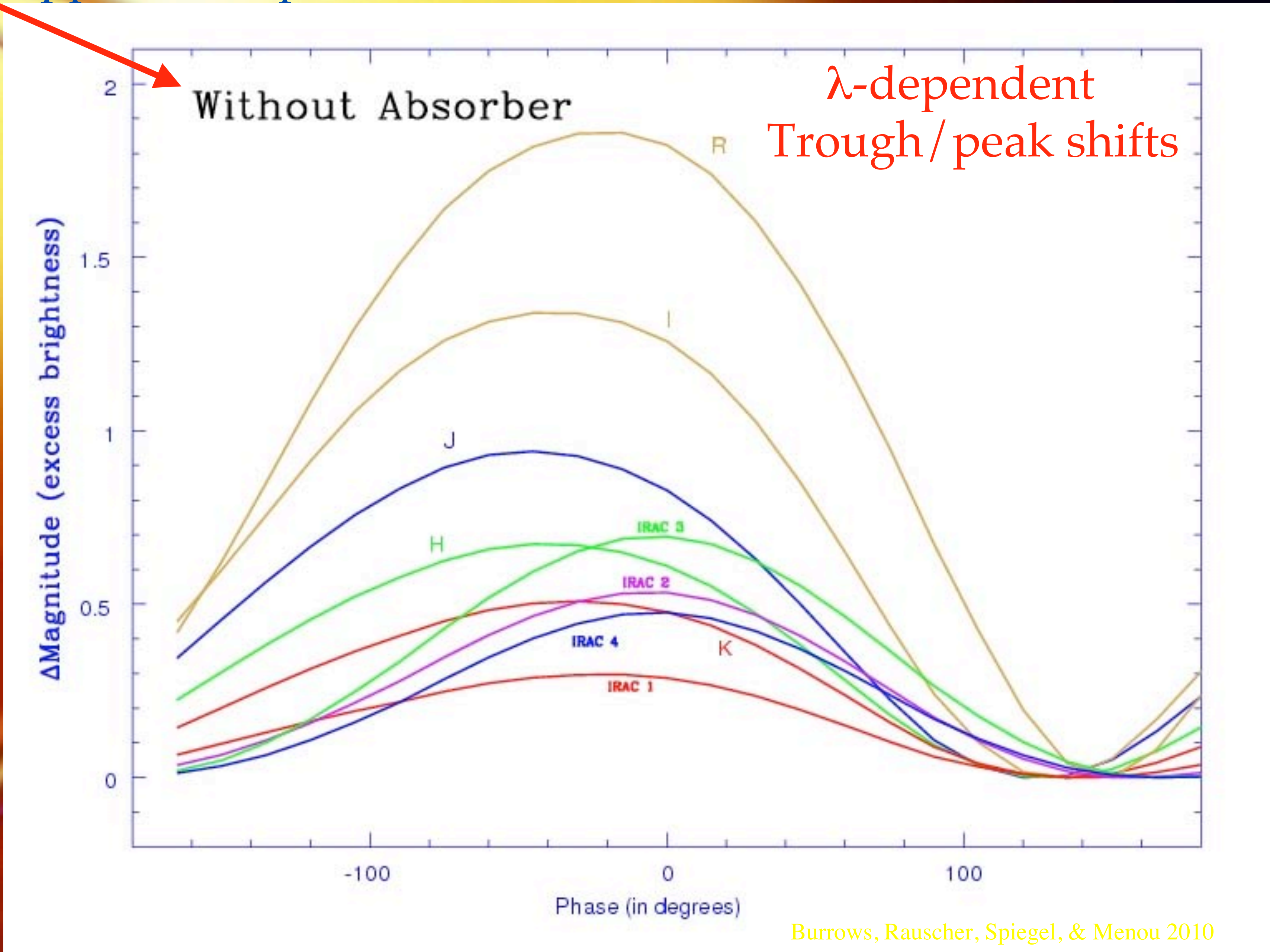


HD 209458b: Integrated Phase Light Curves: With inversion/hot upper atmosphere



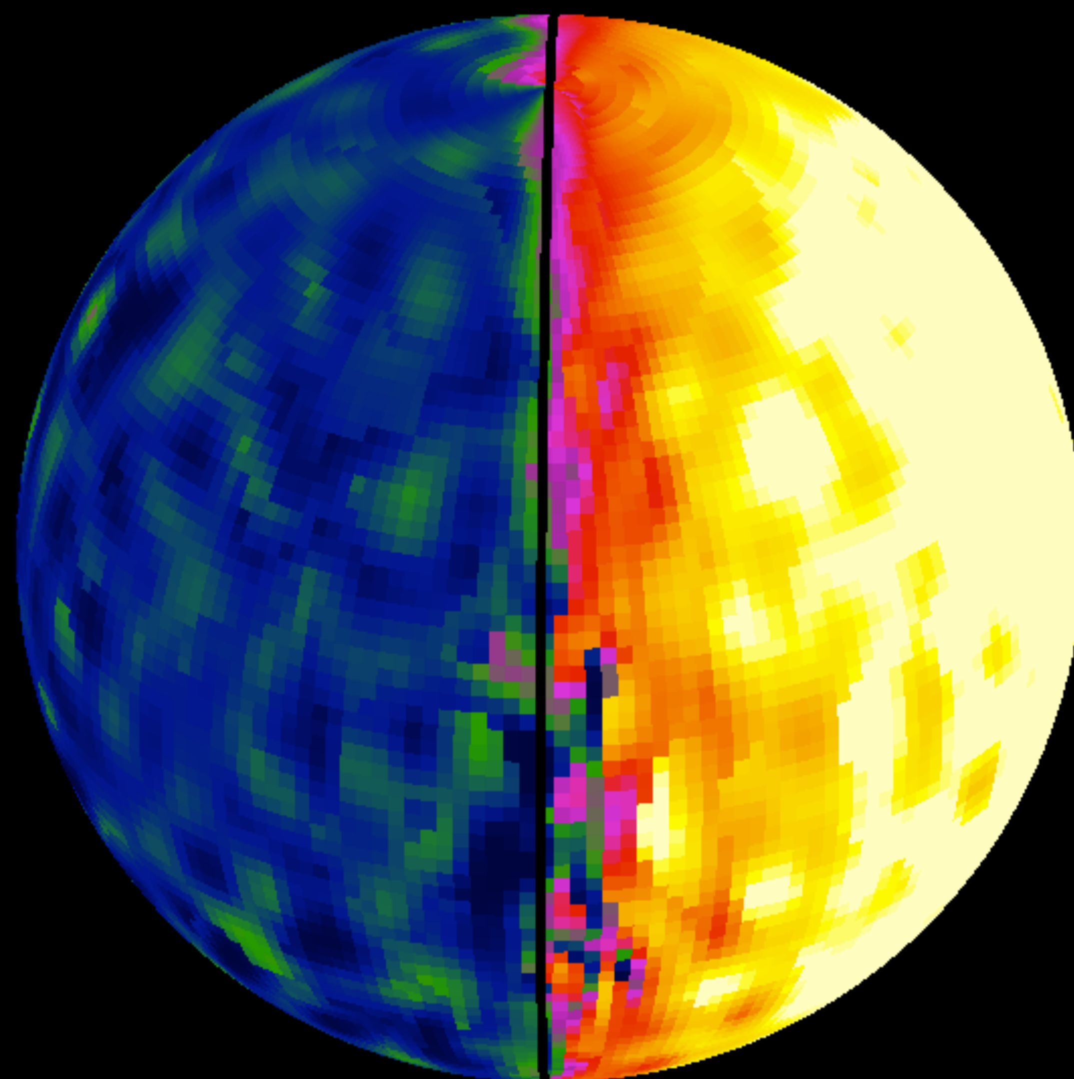
Burrows, Rauscher, Spiegel, & Menou 2010

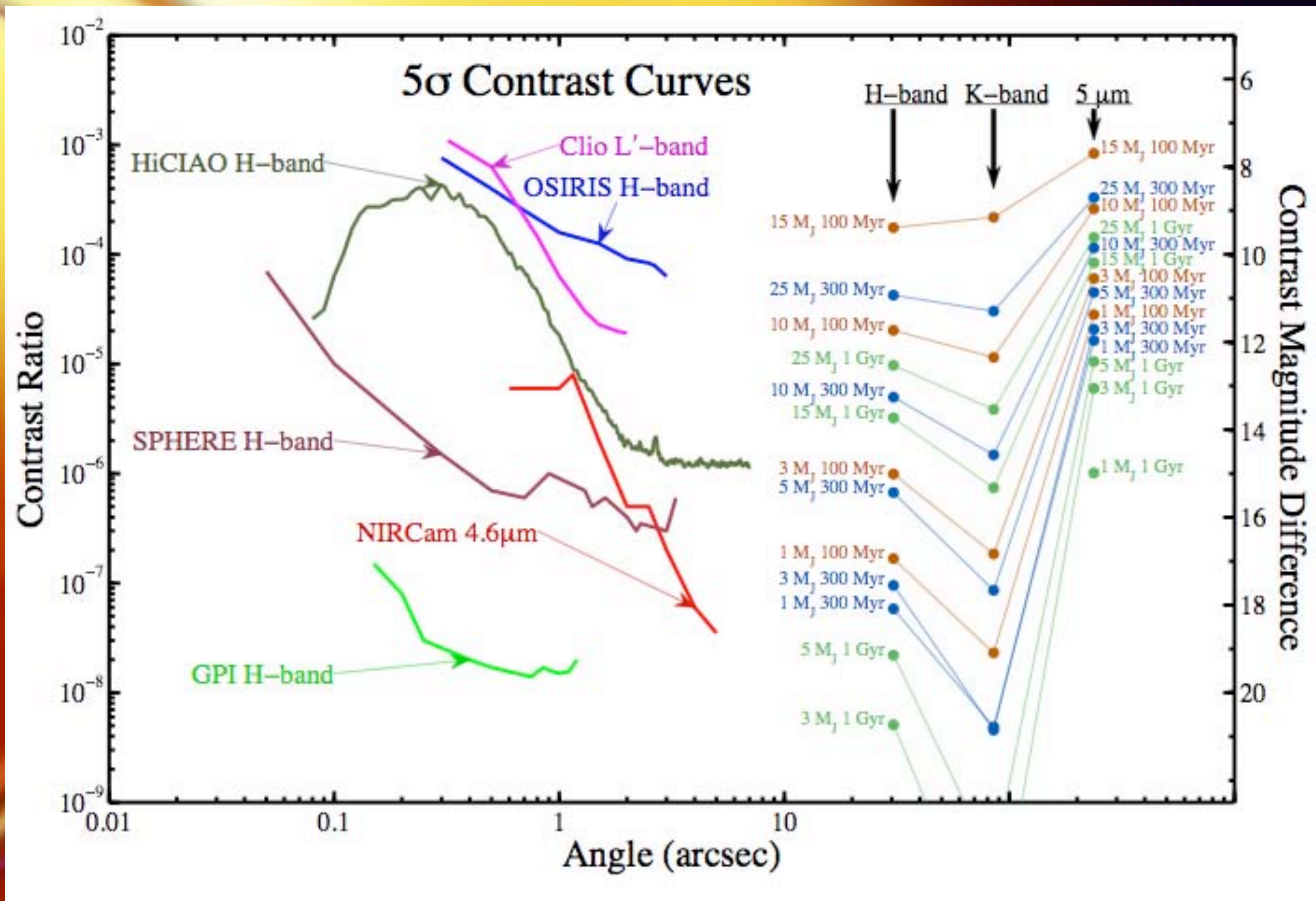
HD 209458b: Integrated Phase Light Curves: No upper atmosphere absorber



Burrows, Rauscher, Spiegel, & Menou 2010

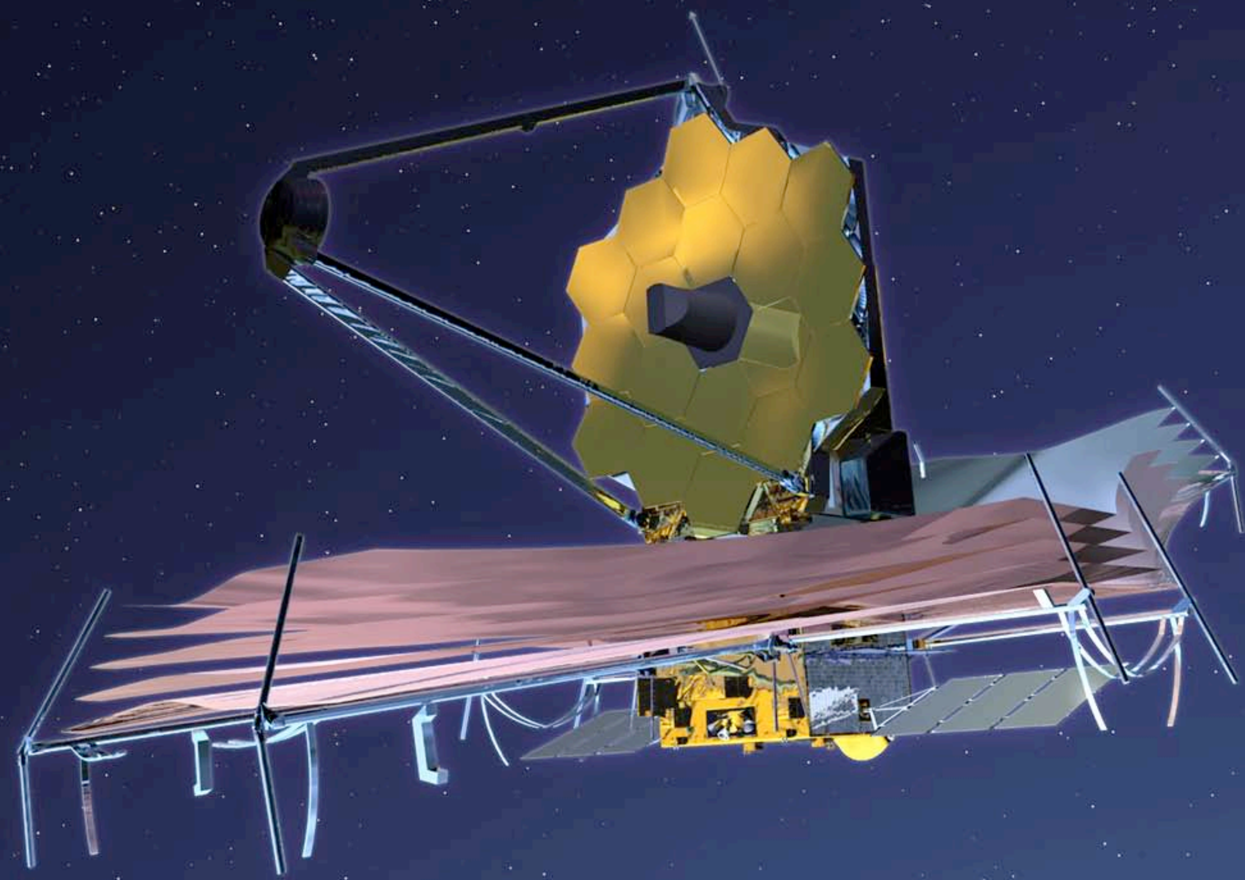
Methane Map: with Upper Atmos. heating





5σ Contrast Curves
Contrast Ratio
Angle (arcsec)
Contrast Magnitude Difference
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0.01
0.1
1
10
6
8
10
12
14
16
18
20
HiCIAO H–band
Clio L′–band
OSIRIS H–band
SPHERE H–band
NIRCam 4.6μm
GPI H–band
H–band
K–band
5 μm
15 M_J 100 Myr
25 M_J 300 Myr
10 M_J 100 Myr
25 M_J 1 Gyr
10 M_J 300 Myr
15 M_J 1 Gyr
3 M_J 100 Myr
5 M_J 300 Myr
1 M_J 100 Myr
3 M_J 300 Myr
1 M_J 300 Myr
5 M_J 1 Gyr
3 M_J 1 Gyr
1 M_J 1 Gyr

JWST



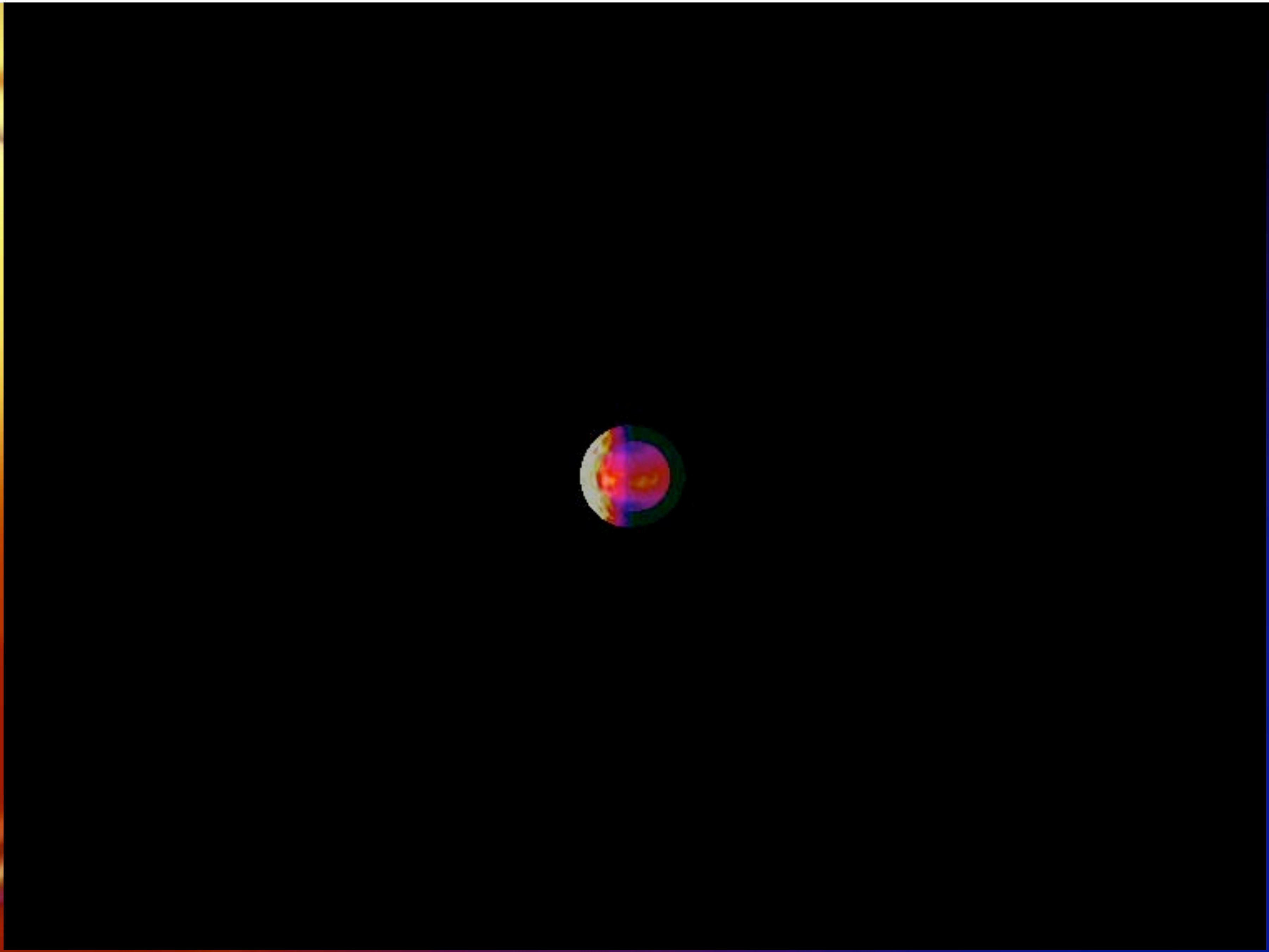
Future of Direct and Indirect Detection of Extrasolar Planets

From the Ground:

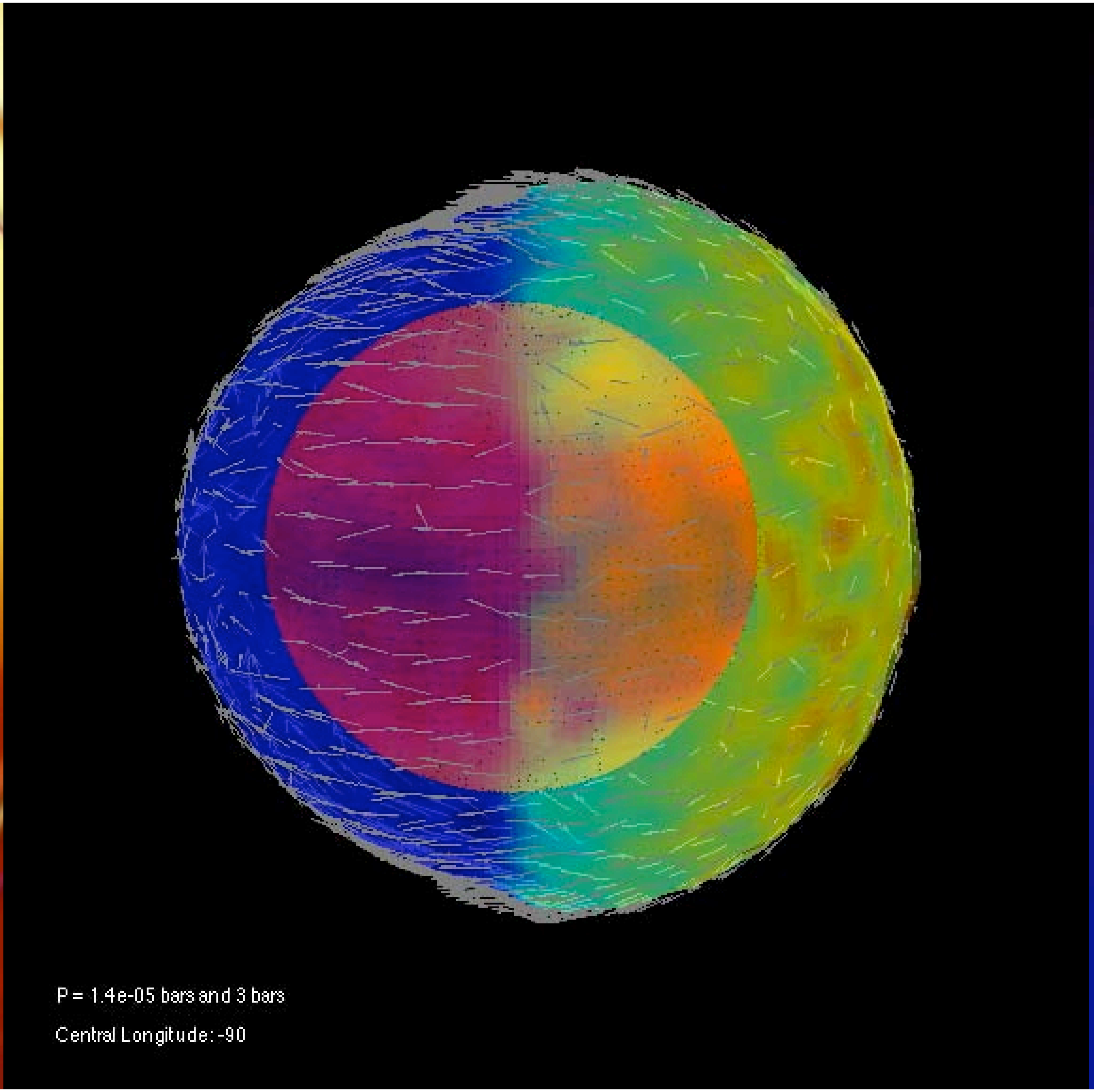
- Precision Radial Velocity
- Precision photometry ?
- Transit searches (many)
- Interferometry (LBT, VLTI, Keck, PTI): Imaging (Fizeau) and Astrometry (Michelson)
- Extreme Adaptive Optics (Gemini Planet Imager)
- Microlensing
- Coronagraphic Imaging (Gemini NICI; SEEDS)

From Space:

- HST - NICMOS/ACS/STIS
- EPOXI
- Spitzer - Warm Spitzer
- JWST (MIRI, NIRCam)
- SIM(?)/GAIA
- Eclipse/TOPS (coronagraph); PIAA?
- Kepler/COROT
- WISE
- TPF-C; TPF-I/Darwin, TPF-O??



Graphic by D. Spiegel


P = 1.4e-05 bars and 3 bars
Central Longitude: -90

Methane Map: w/o Upper Atmos. heating