‘Exoplanet Models: Insights from Theory’

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Outline

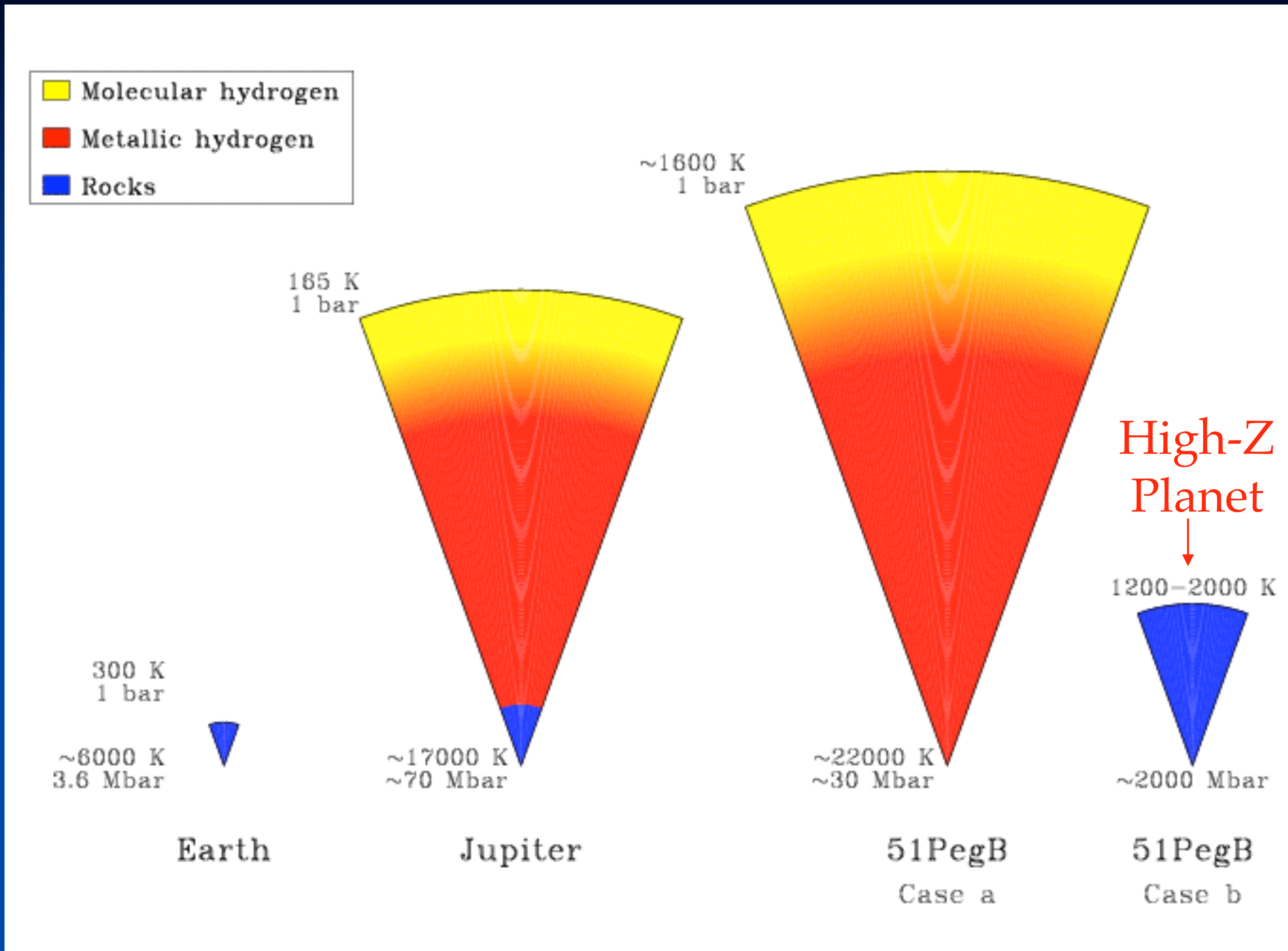
- Transit Radii
- High-Contrast Imaging of “Hot Jupiters” - Wide-Separation Direct Remote Sensing
- Secondary Eclipse Measurements and Interpretation - Thermal inversions?
- Optical “Albedo” Measurements of Hot Jupiters
- Phase Light Curves

Milestones

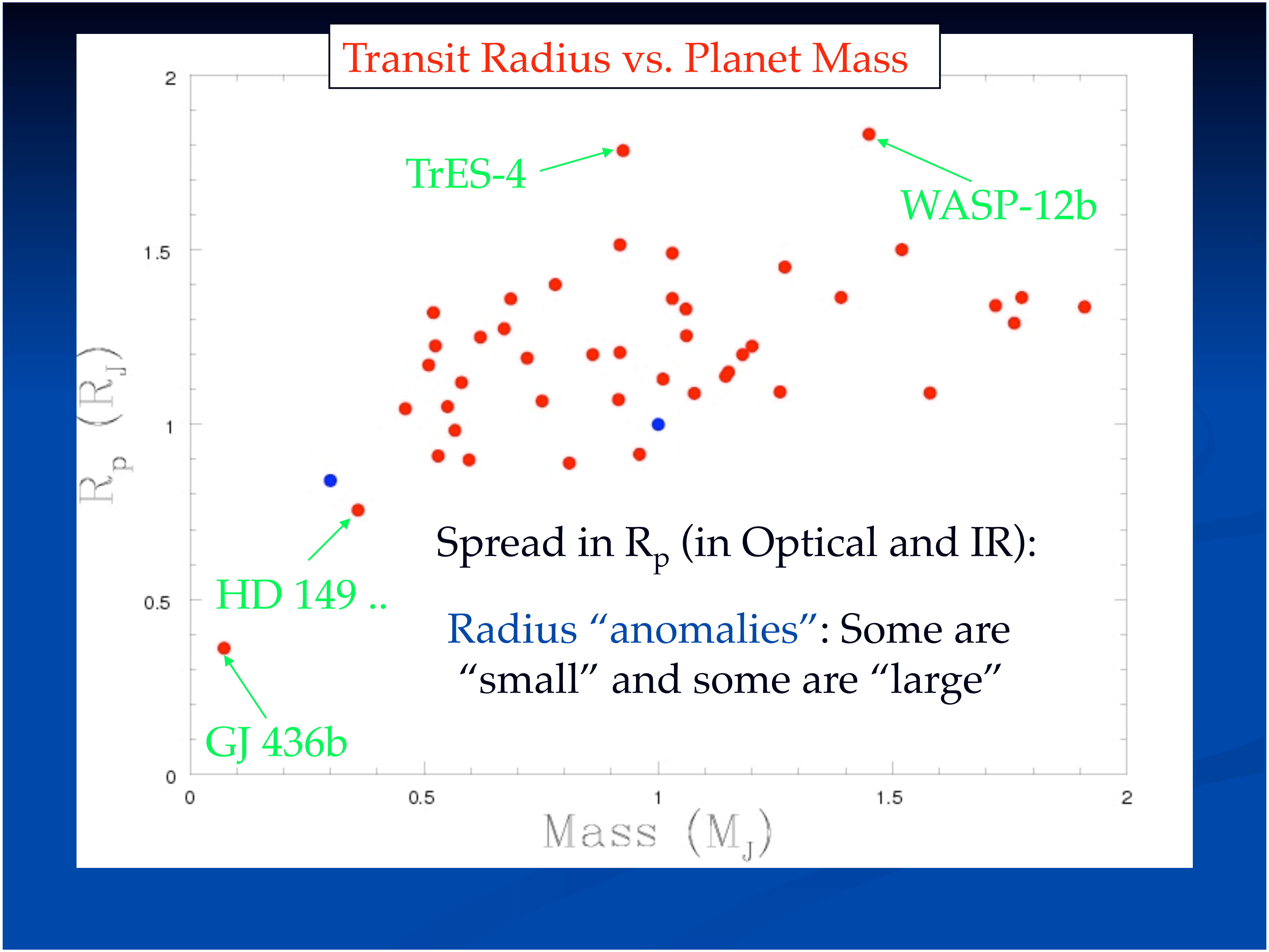
- > 60 transiting planets
- > 400 Exoplanets detected
- Detection of H_2O, CO, Na, CO_2 , CH_4
- Spitzer and NICMOS light curves and secondary eclipse measurements; brightness variations over HD 189733b
- Some EGPs show temperature inversions
- GJ 436b and HAT-P-11b: Neptunes in Transit!
- > 50 "Neptunes"
- HD 149026b with a ~80 Earth-mass core
- HD 80606 with high *e*: light curve and secondary transit!
- Evidence for cores in EGPs: Formation mechanism?
- CoRoT-7bc: ``Super Earths"; 3 Pulsar planets
- HAT-P-7b - Kepler light curve!
- **Discoveries of Fomalhaut b and HR 8799bcd, and perhaps β Pic b

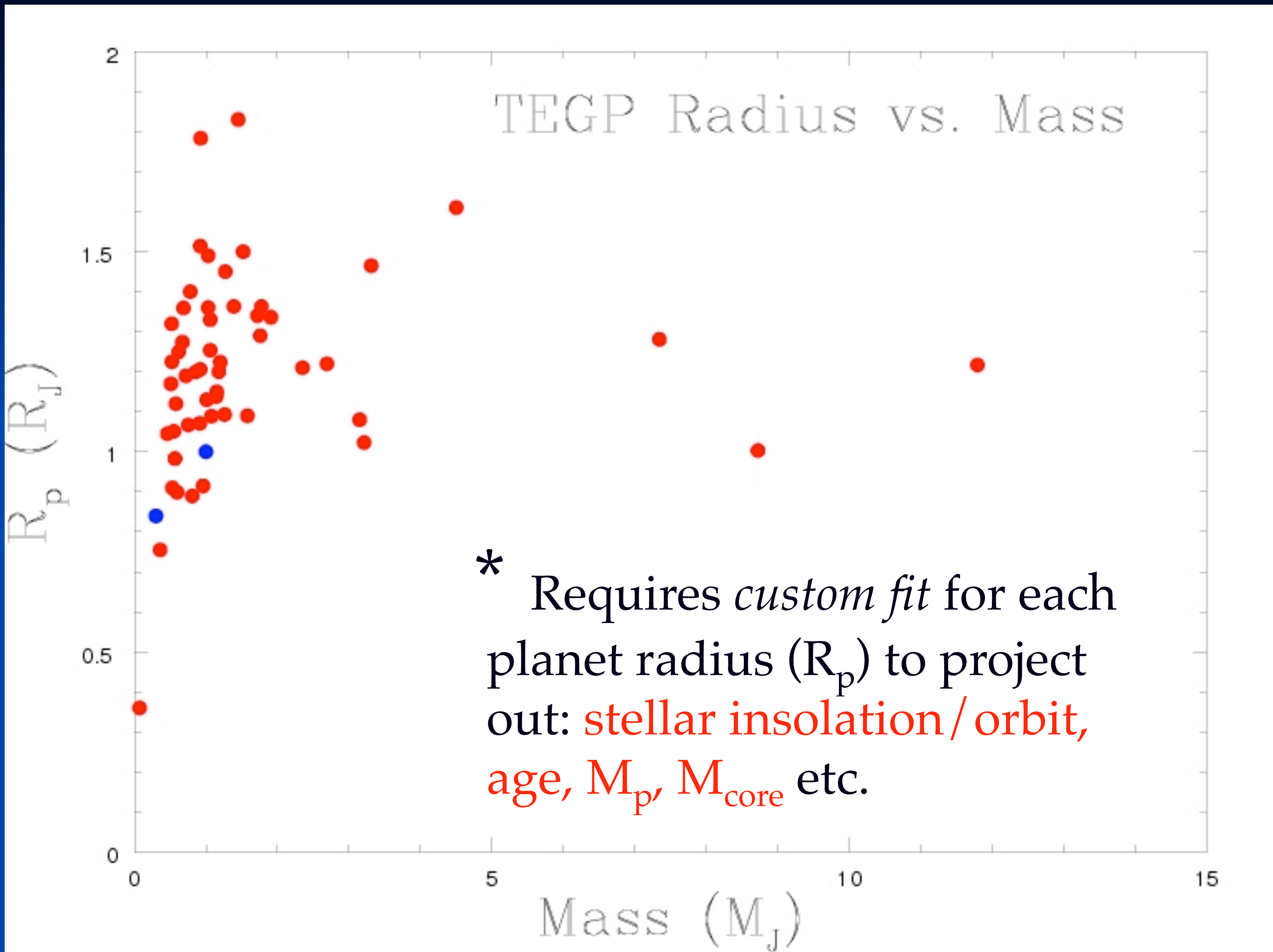
“Transiting Extrasolar Giant Planets”

Close-in (~0.02 - 0.05 AU)


Molecular hydrogen
Metallic hydrogen
Rocks
165 K
1 bar
~1600 K
1 bar
High-Z
Planet
1200–2000 K
300 K
1 bar
~6000 K
3.6 Mbar
~17000 K
~70 Mbar
~22000 K
~30 Mbar
~2000 Mbar
Earth
Jupiter
51PegB
Case a
51PegB
Case b

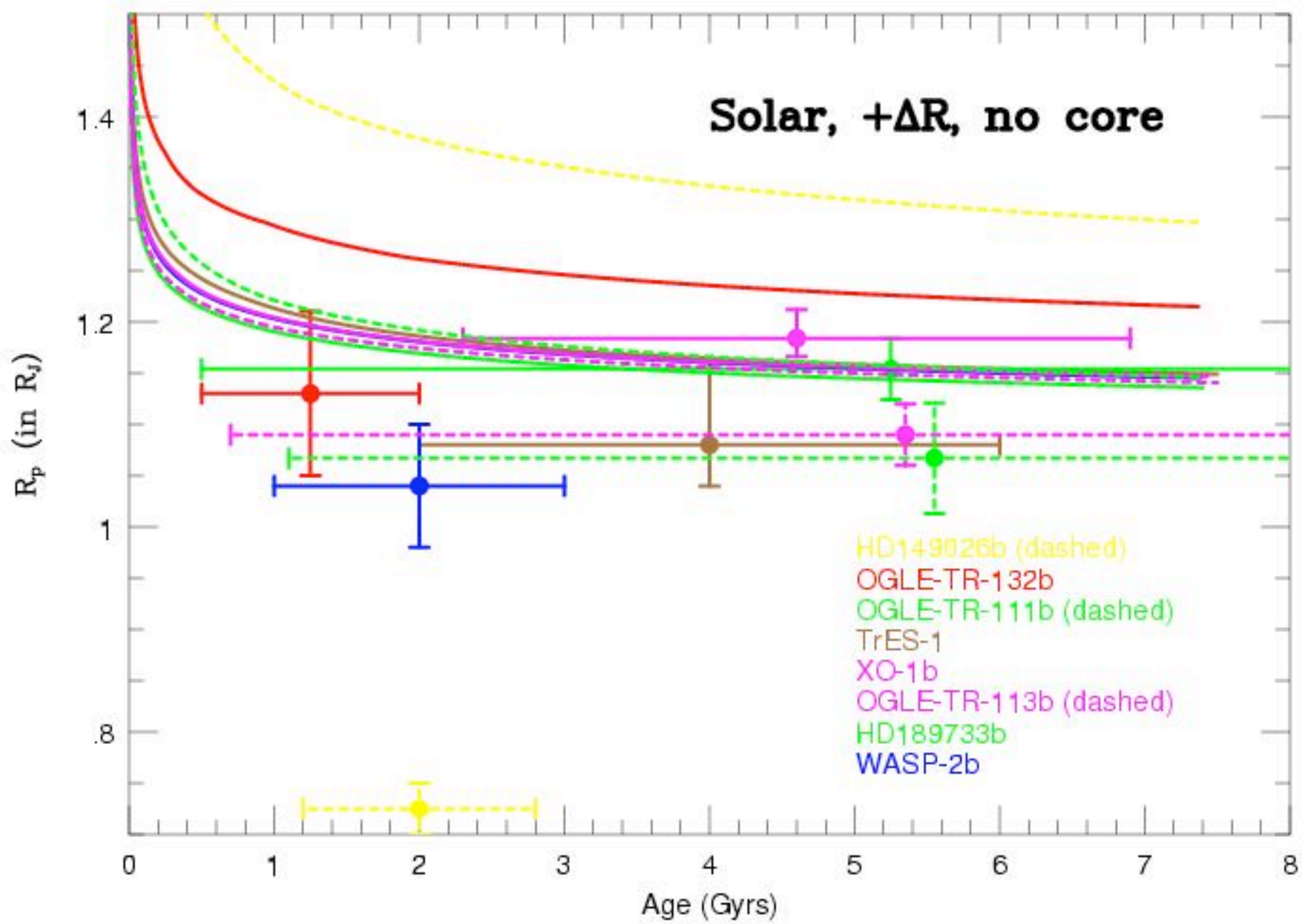
(T. Guillot)


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



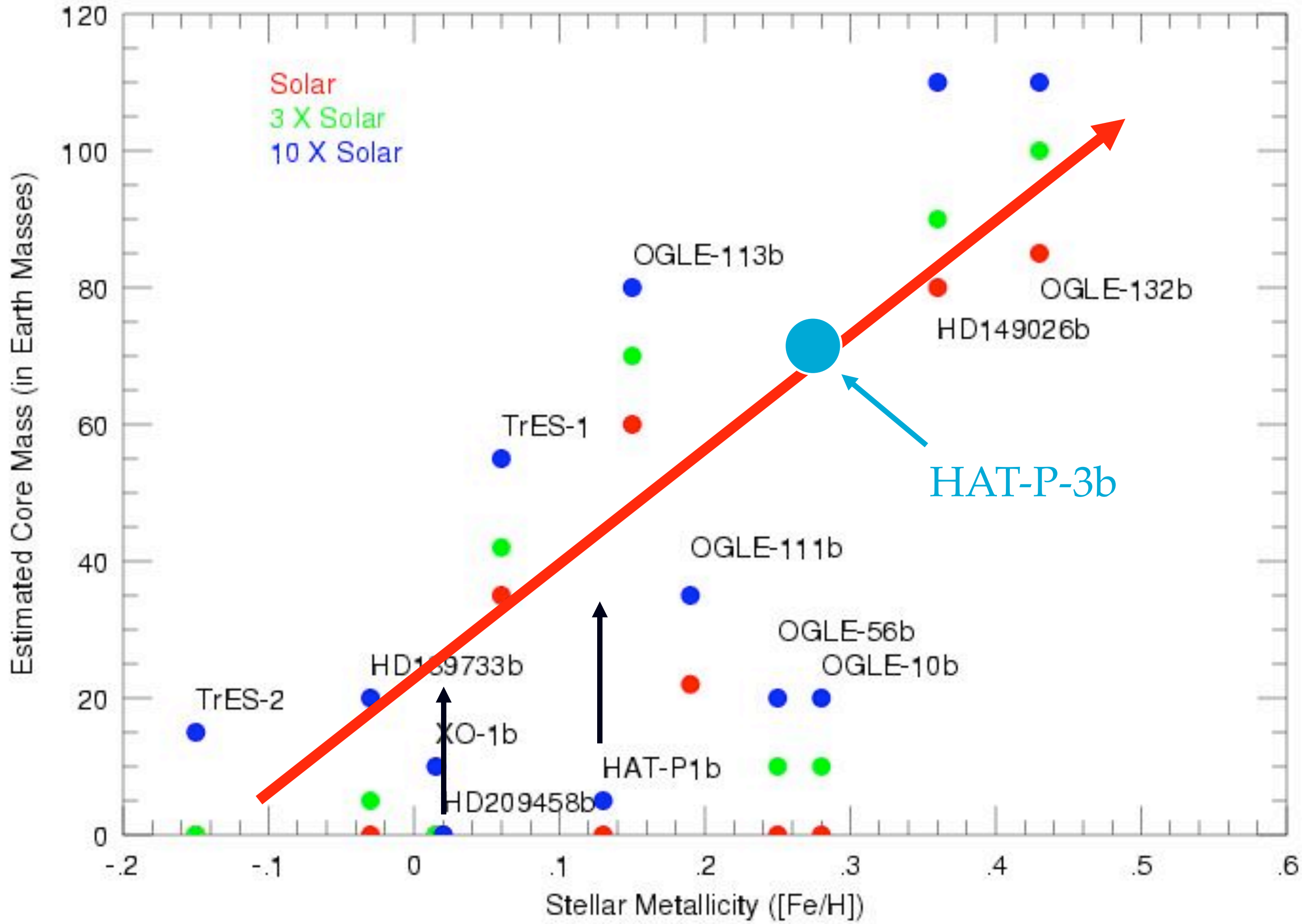
* Requires *custom fit* for each planet radius (R_p) to project out: stellar insolation/orbit, age, M_p, M_{core} etc.

Smaller EGPs: Models vs. Data



Radius Deficits: Need "ice/rock" cores?

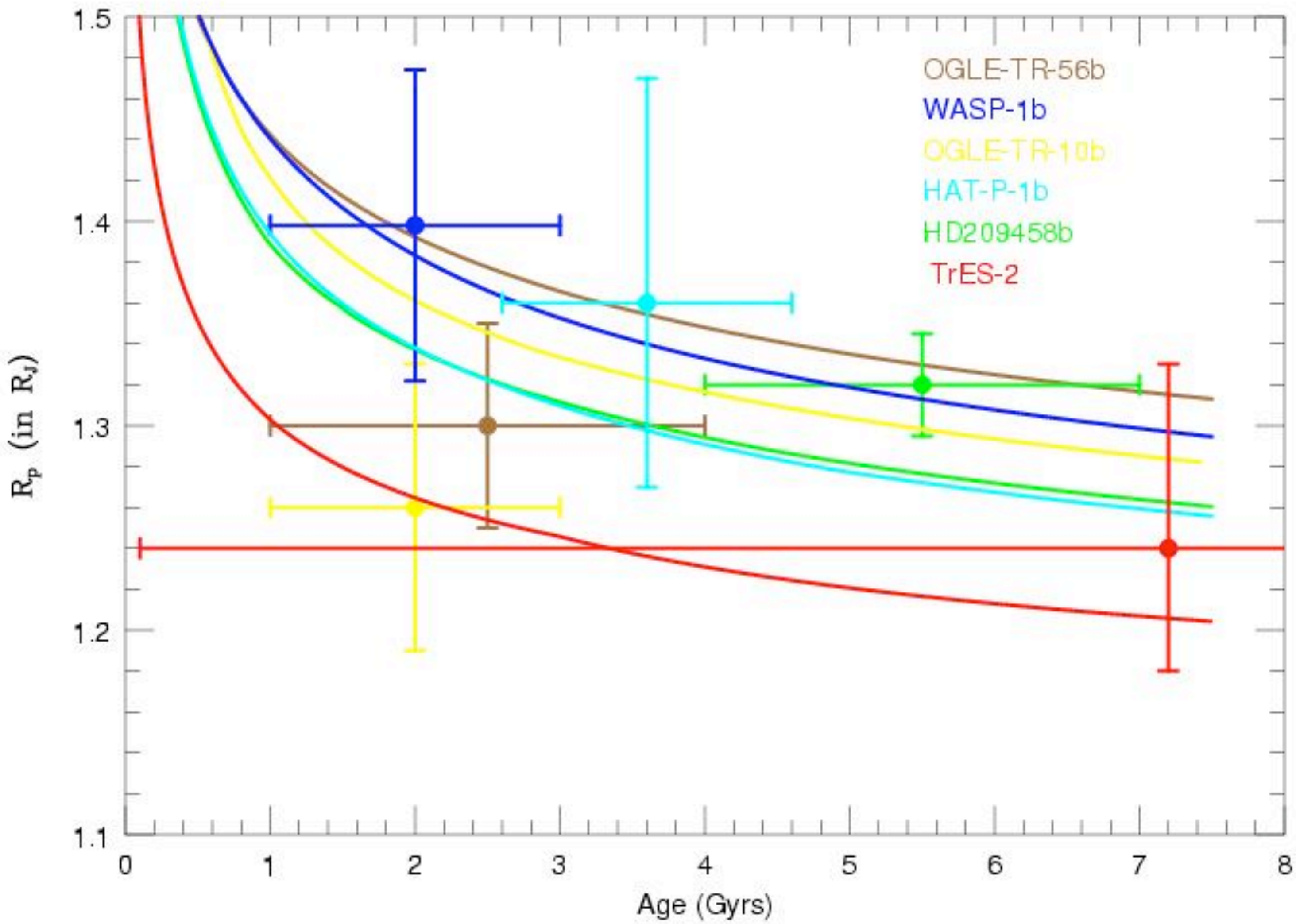
Approximate Core Mass vs. Stellar Metallicity



Note new measurement of HAT-P-1b

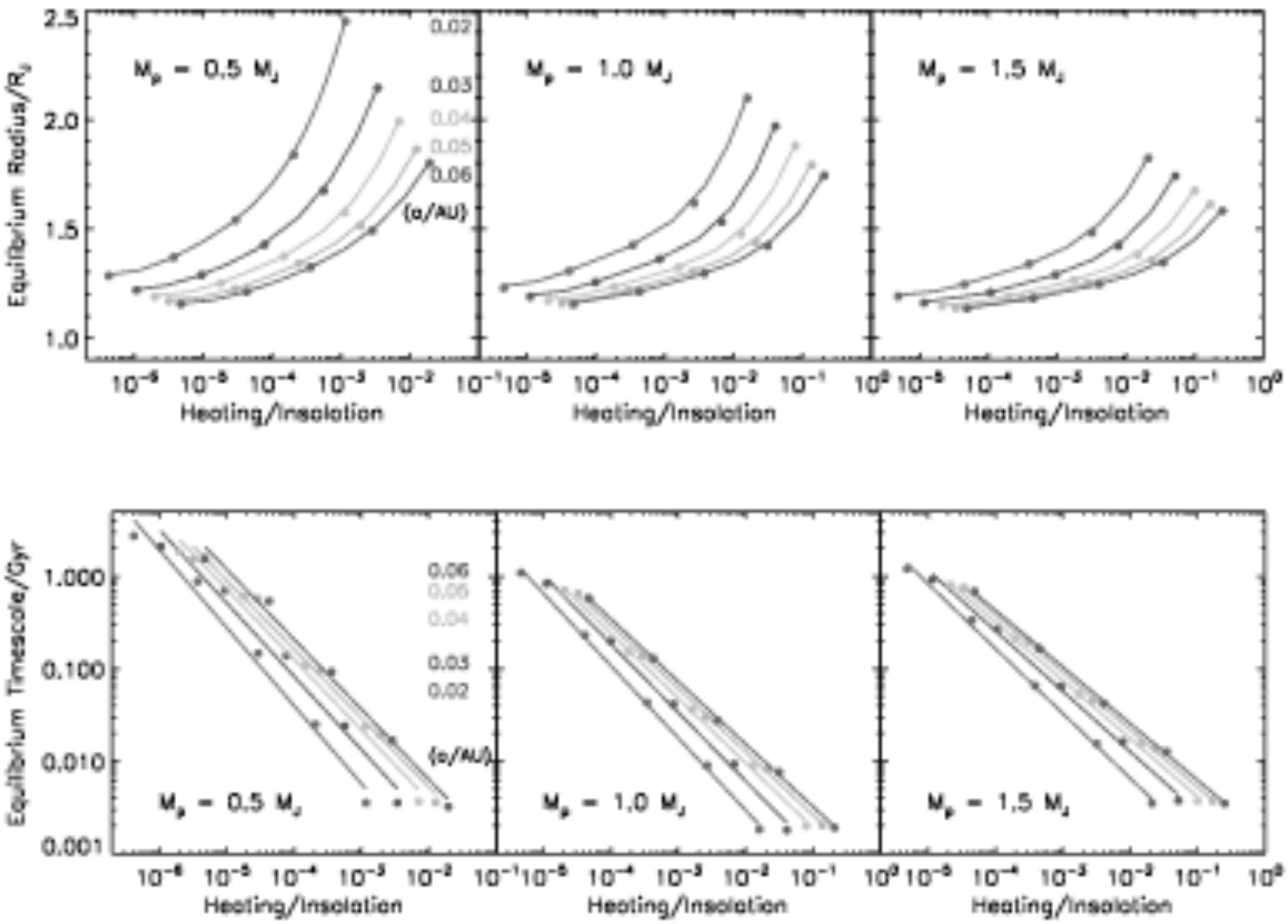
Burrows et al. 2007

Larger EGPs: Models vs. Data



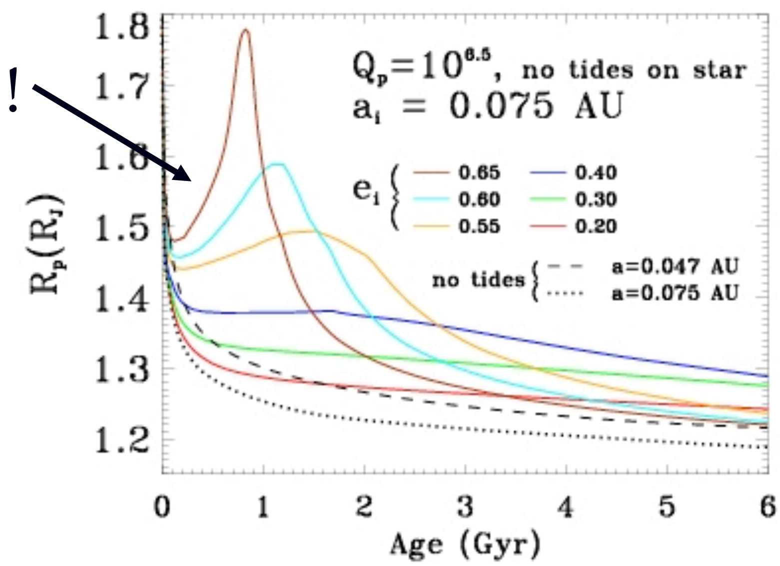
Higher Opacity/Metallicity Atmospheres increase radii

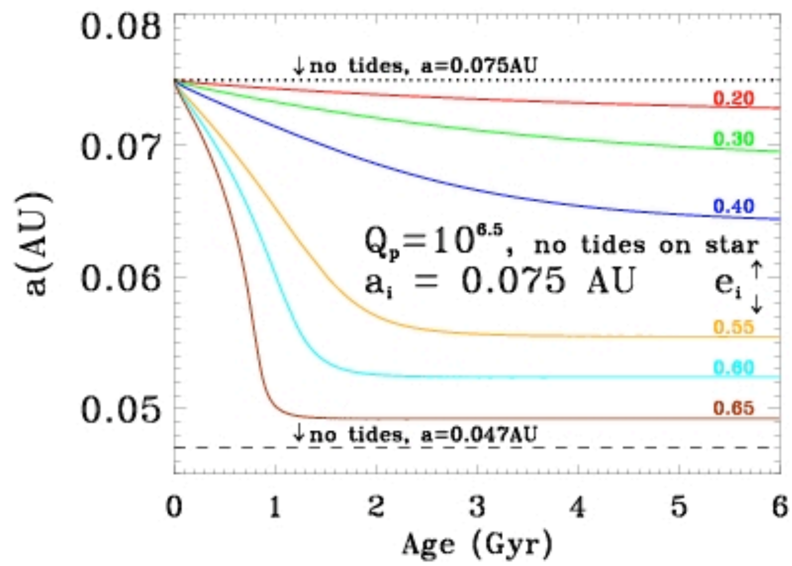
Effects of Tidal Heating on EGP Radii



et al. (2007) then the models with a nonzero heavy-element core mass are favored, considering its stellar metallicity $[Fe/H]_* =$

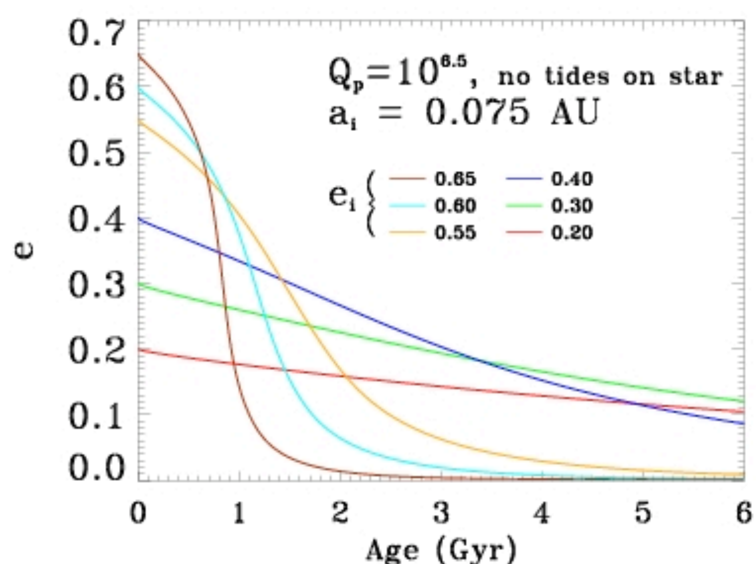
tion due to tidal heating. In this case, the Q_p parameter of XO-3b is near $\sim 10^{5.7}$, a not unreasonable value. On the other hand, the much

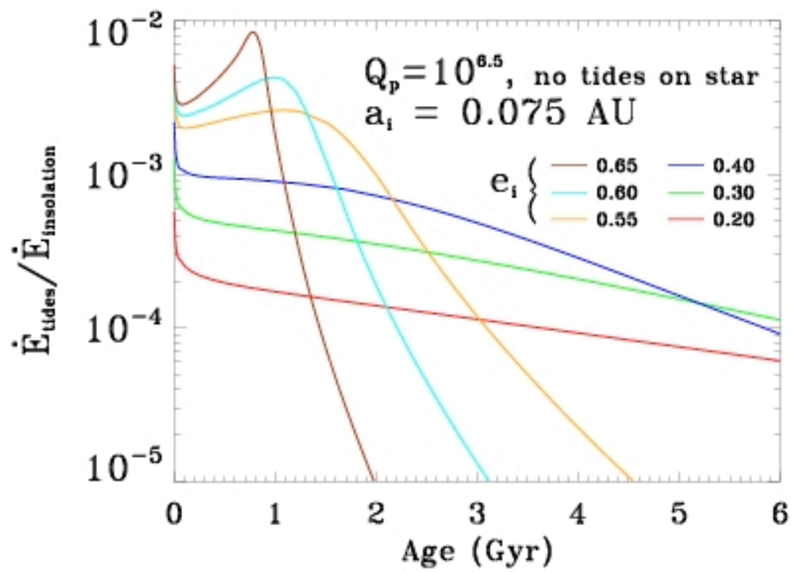




Non-monotonic R_p evolution!

Co-evolution of e, a, and R_p with tidal heating:





Ibgui & Burrows 2009

High-Contrast Imaging of Exoplanets

Wide-separation

(Direct Detection and Imaging of planetary systems)

Irradiated EGPs vs. Angular Separation

EGP	$a(1+e)/d$ ($''$)[a]	star	a (AU)	d (pc)	P	$M_p \sin(i)$ (M_J)	e
ϵ Eri b	1.61	K2V	3.3	3.2	6.85 yrs.	0.86	0.61
55 Cnc d	0.51	G8V	5.9	13.4	14.7	4.05	0.16
47 UMa c	0.31	G0V	3.73	13.3	7.10	0.76	0.1
HD 160691c	0.27	G3IV-V	2.3	15.3	3.56	$\sim$1	$\sim$0.8
υ And d	0.27	F8V	2.50	13.5	3.47	4.61	0.41
HD 39091b	0.26	G1IV	3.34	20.6	5.70	10.3	0.62
47 UMa b	0.17	G0V	2.09	13.3	2.98	2.54	0.06
γ Cephei b	0.15	K2V	1.8	11.8	2.5	1.25	$\sim$0
HD 147513b	0.15	G3V	1.26	12.9	1.48	1.0	0.52
HD 160691b	0.127	G3IV-V	1.48	15.3	1.74	1.7	0.31
HD 70642b	0.121	G5IV-V	3.3	29	4.79	2.0	0.10
HD 168443c	0.107	G5V	2.87	33	4.76	17.1	0.23
HD 10697b	0.075	G5IV	2.0	30	2.99	6.59	0.12
υ And c	0.072	F8V	0.83	13.5	241 days	2.11	0.18
GJ 876b	0.049	M4V	0.21	4.72	61.0	1.89	0.1
GJ 876c	0.036	M4V	0.13	4.72	30.1	0.56	0.27
HD 114762b	0.017	F9V	0.35	28	84.0	11.0	0.34
55 Cnc b	8.4×10^{-3}	G8V	0.12	13.4	14.7	0.84	0.02
υ And b	4.5×10^{-3}	F8V	0.059	13.5	4.62	0.71	0.034
51 Peg b	3.4×10^{-3}	G2V	0.05	14.7	4.23	0.44	0.01
τ Boo b	3.3×10^{-3}	F7V	0.05	15	3.31	4.09	$\sim$0
OGLE-TR56b	1.5×10^{-5}	G0V	0.023	$\sim$1500	1.21	1.45	$\sim$0

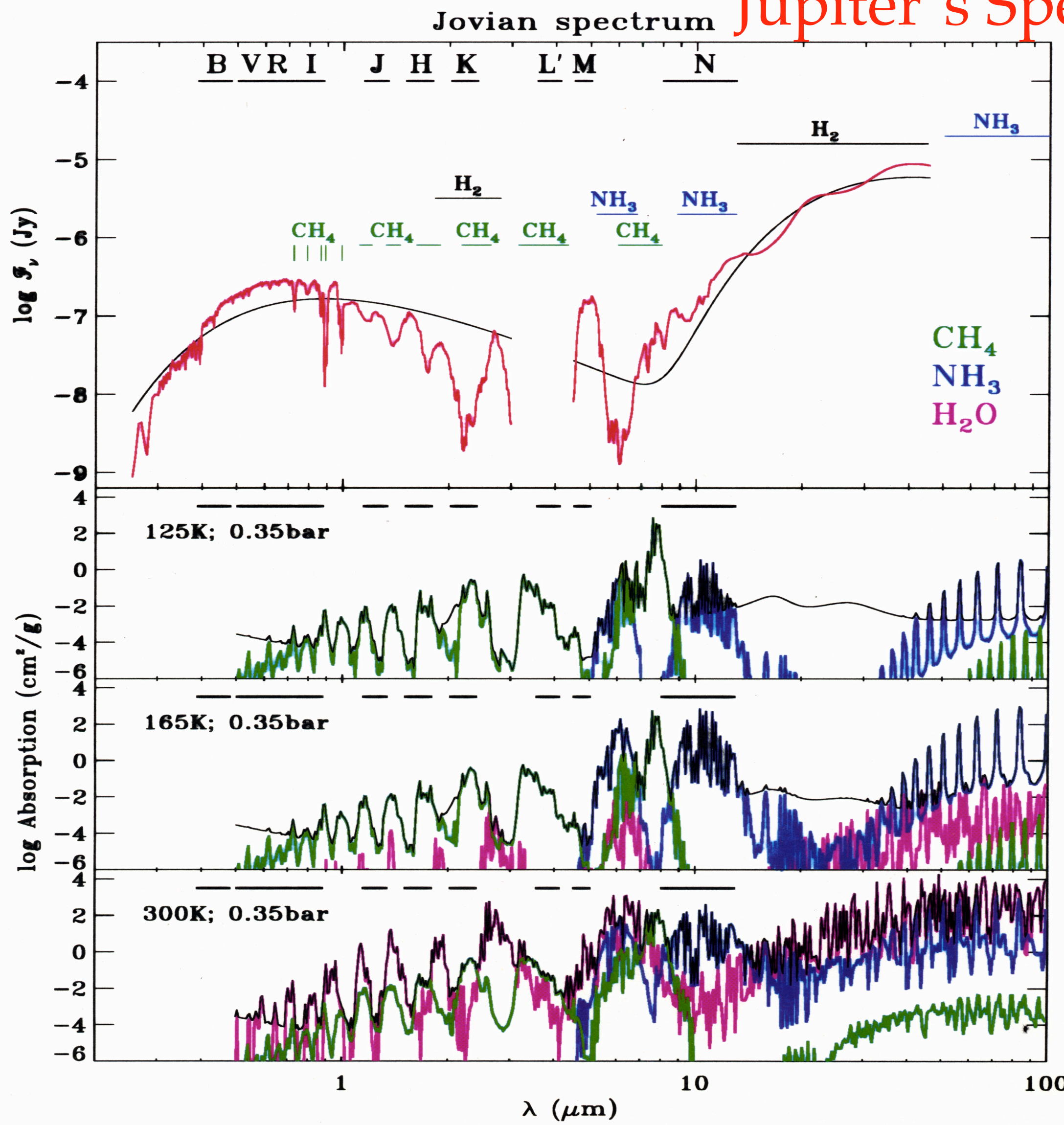
e.g., → 55 Cnc d

Hot

!

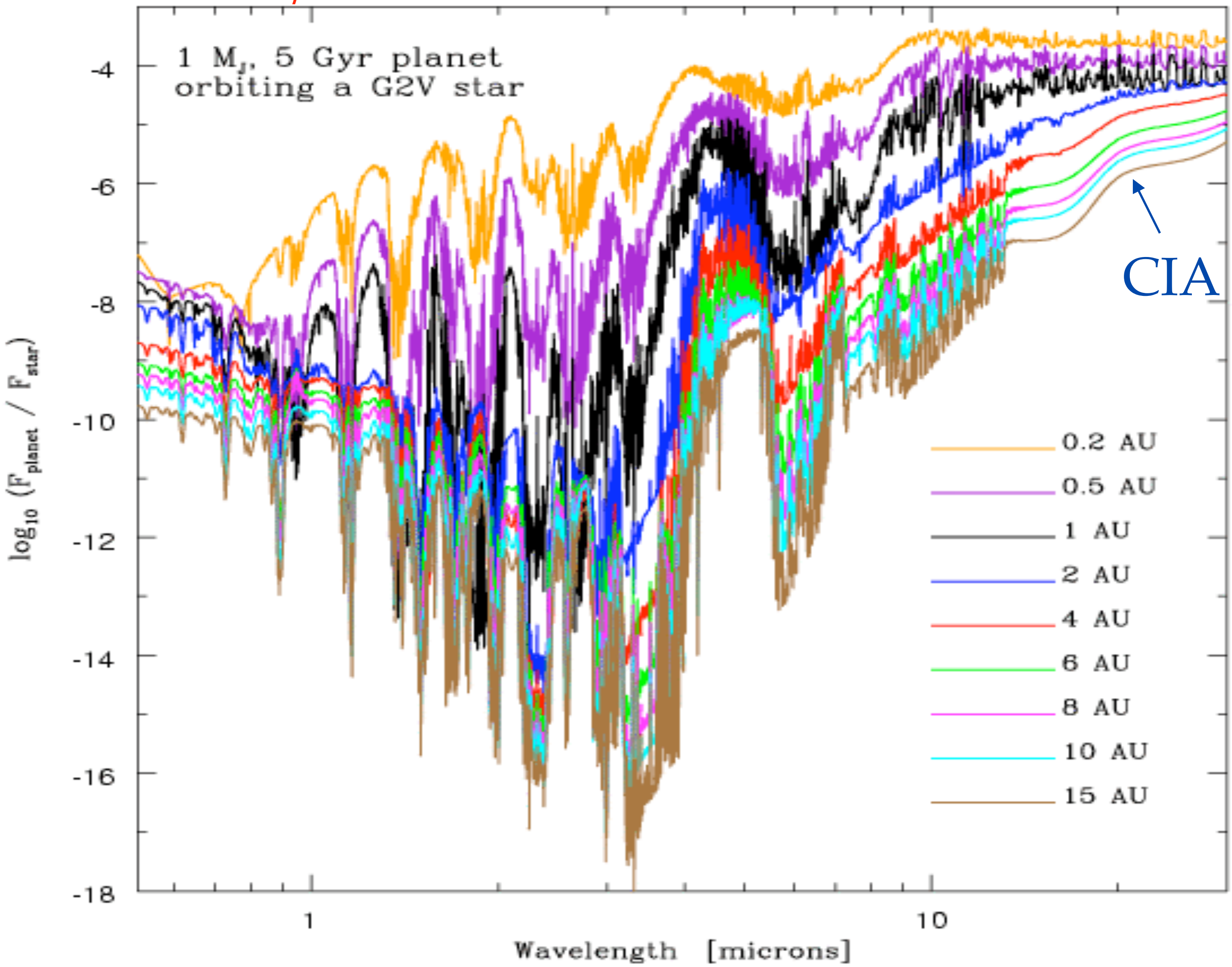
Burrows 2005; Sudarsky, Burrows, and Hubeny 2003

Jupiter's Spectrum



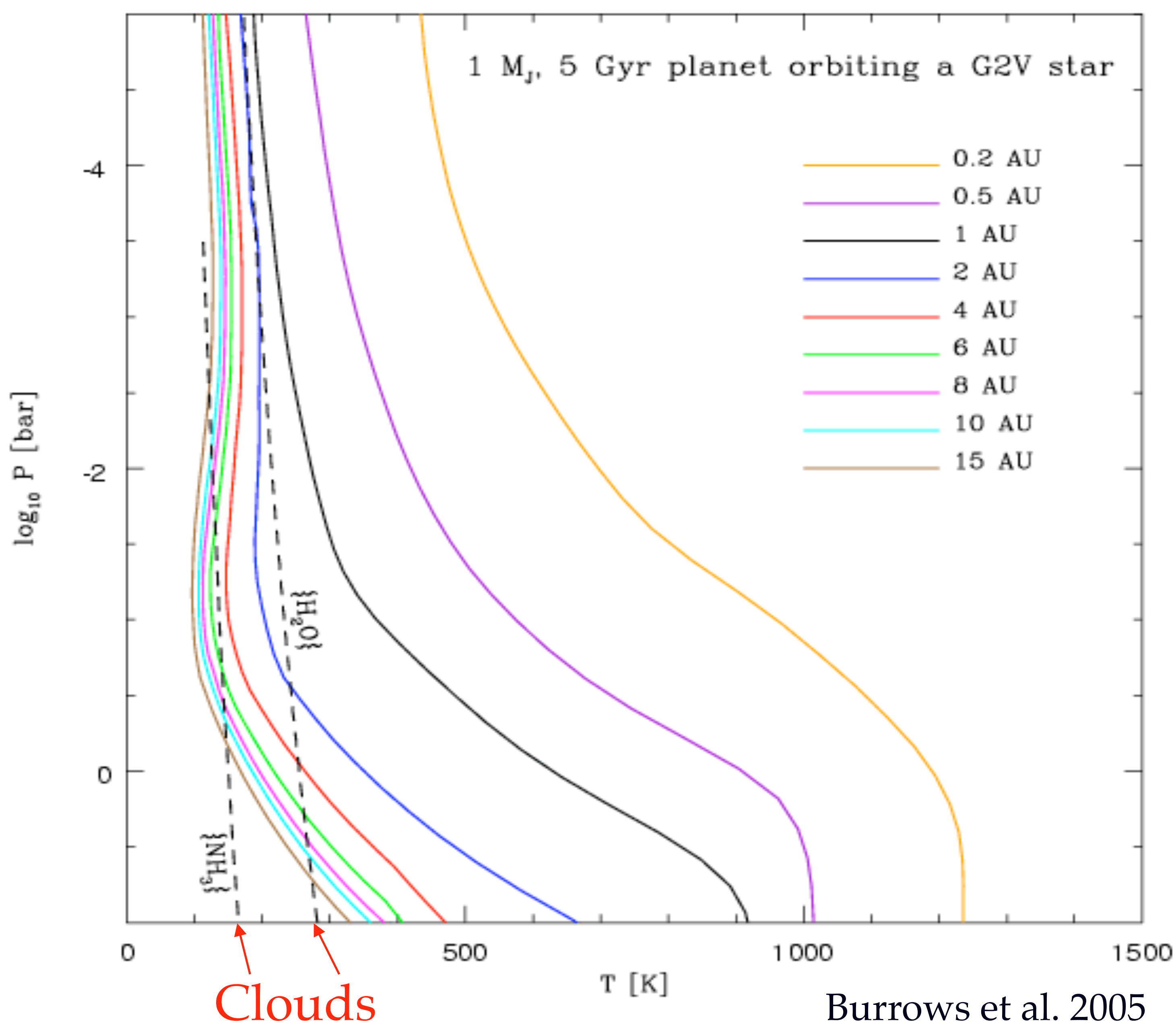
(T. Guillot)

Planet/Star Flux ratio versus Orbital Distance

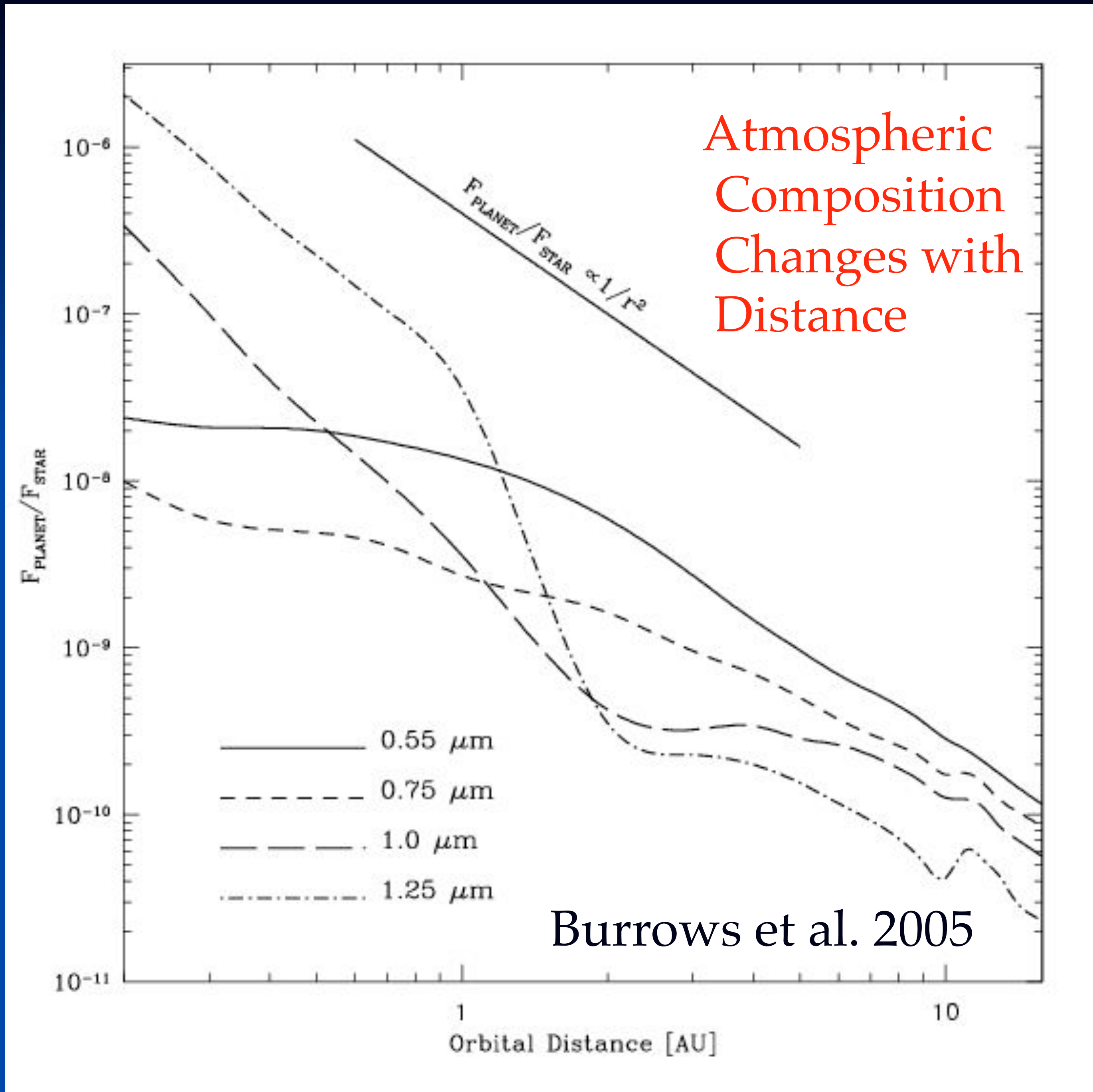


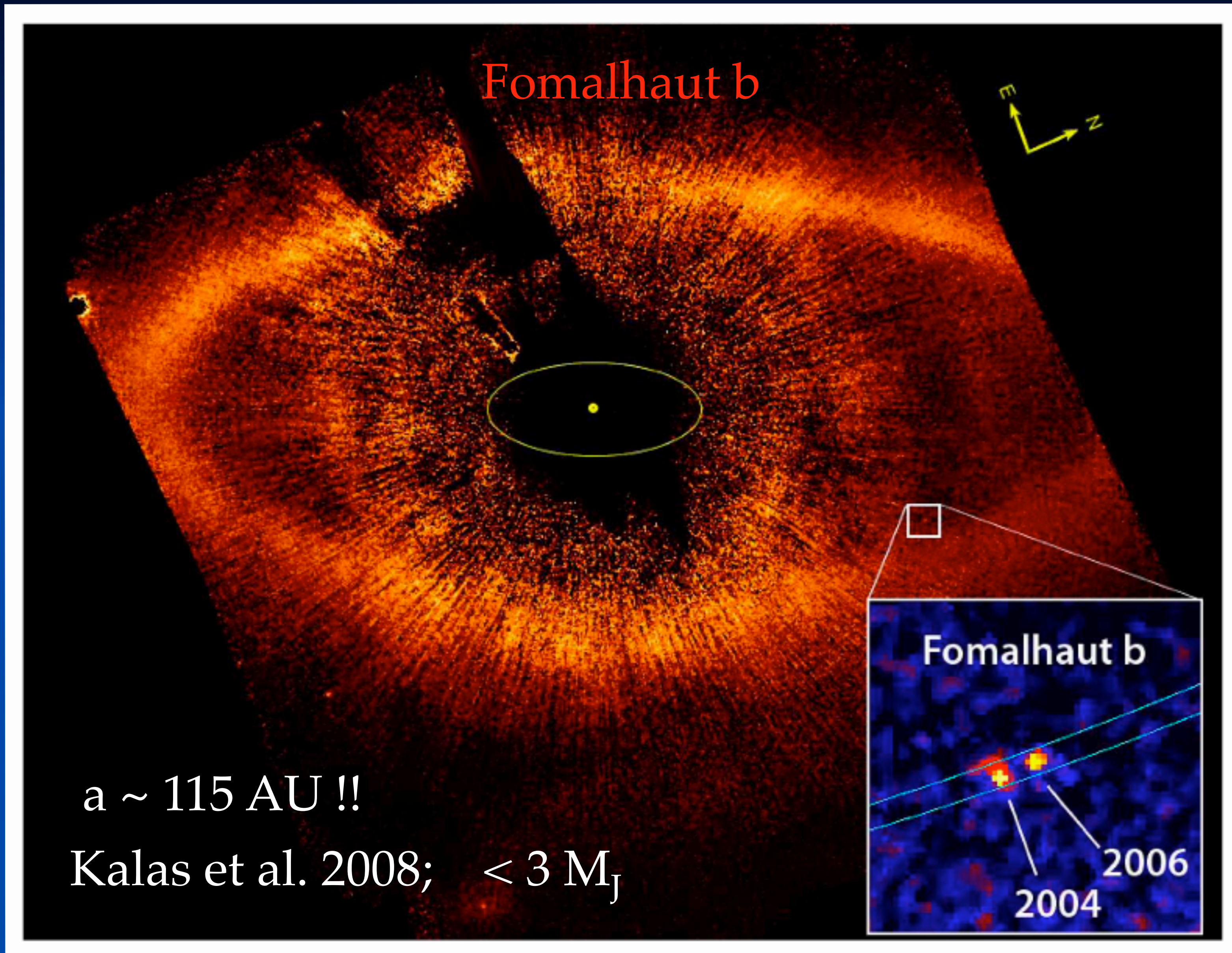
Burrows, Sudarsky, and Hubeny 2004

N.B.,Jupiter at 2 AU does not have NH_3 clouds, but does have H_2O clouds



Burrows et al. 2005

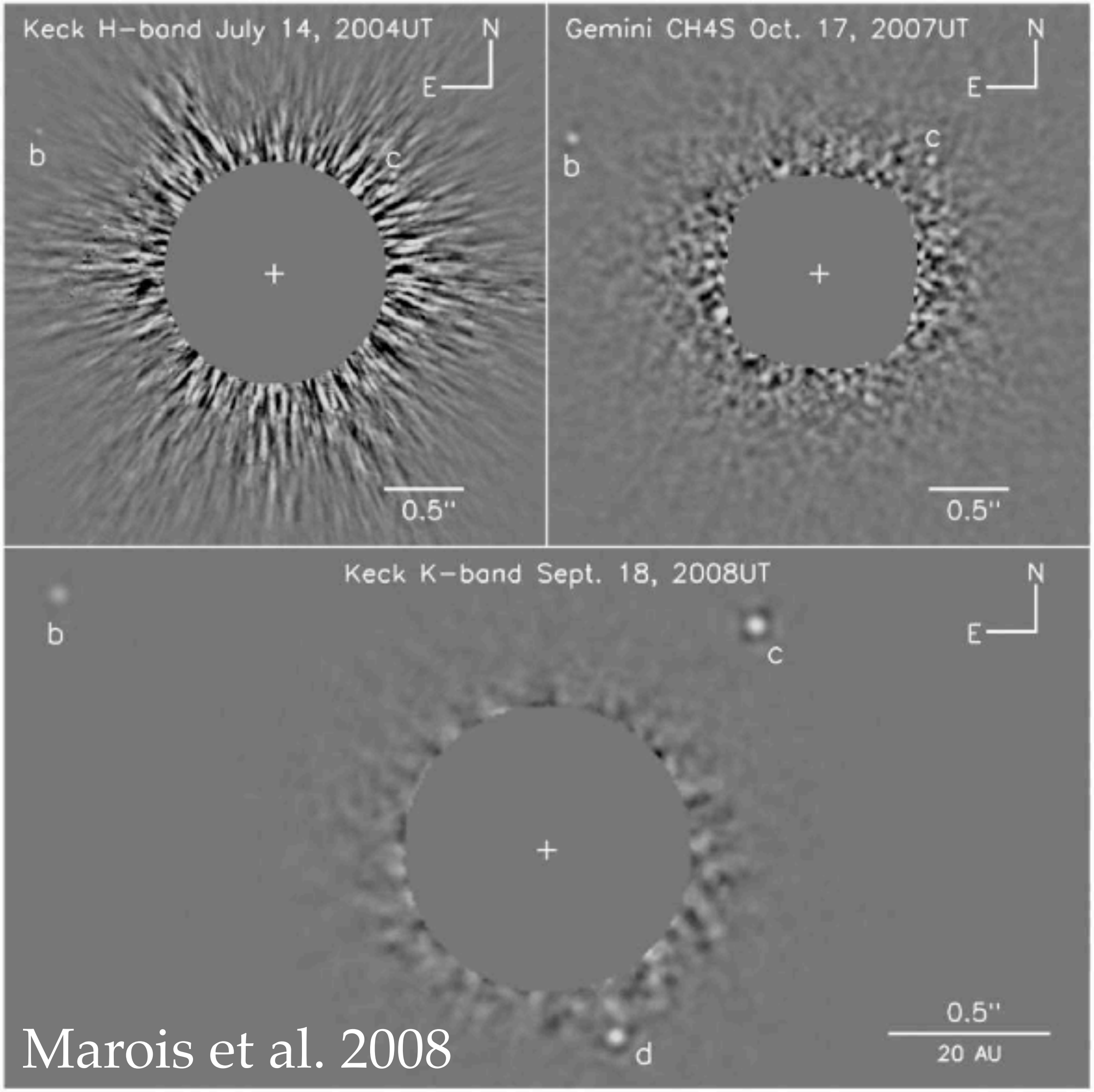

Atmospheric Composition Changes with Distance
$F_{PLANET}/F_{STAR} \propto 1/r^2$
F_{PLANET}/F_{STAR}
Orbital Distance [AU]
0.55 μm
0.75 μm
1.0 μm
1.25 μm
Burrows et al. 2005


Fomalhaut b
E
N
Fomalhaut b
2006
2004
a ~ 115 AU !!
Kalas et al. 2008; < 3 M_J

HR 8799bcd

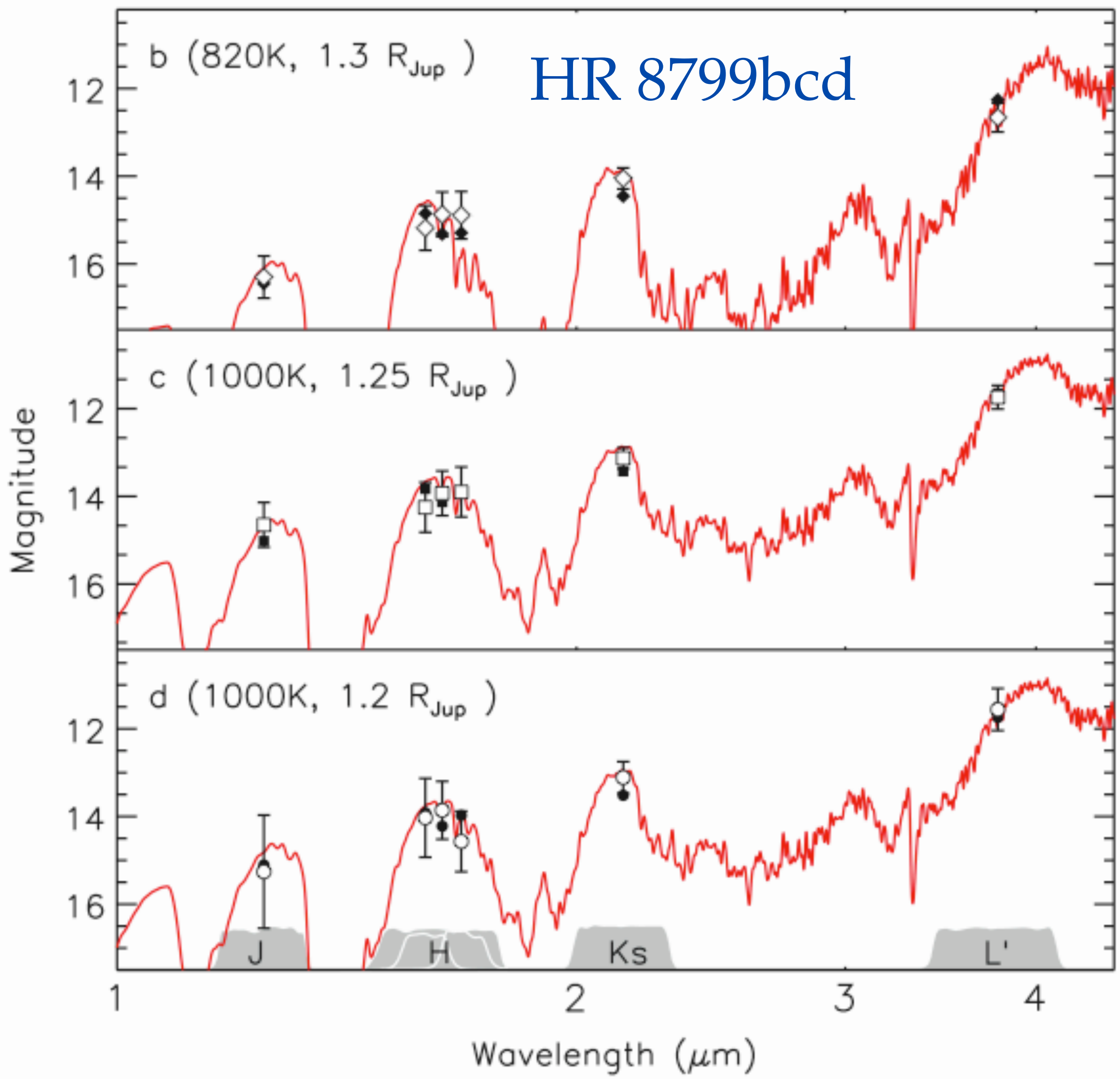
$M_b \sim 7\ M_J$
$M_c \sim 10$
M_J
$M_d \sim 10\ M_J$

D = 24, 38, 68 AU



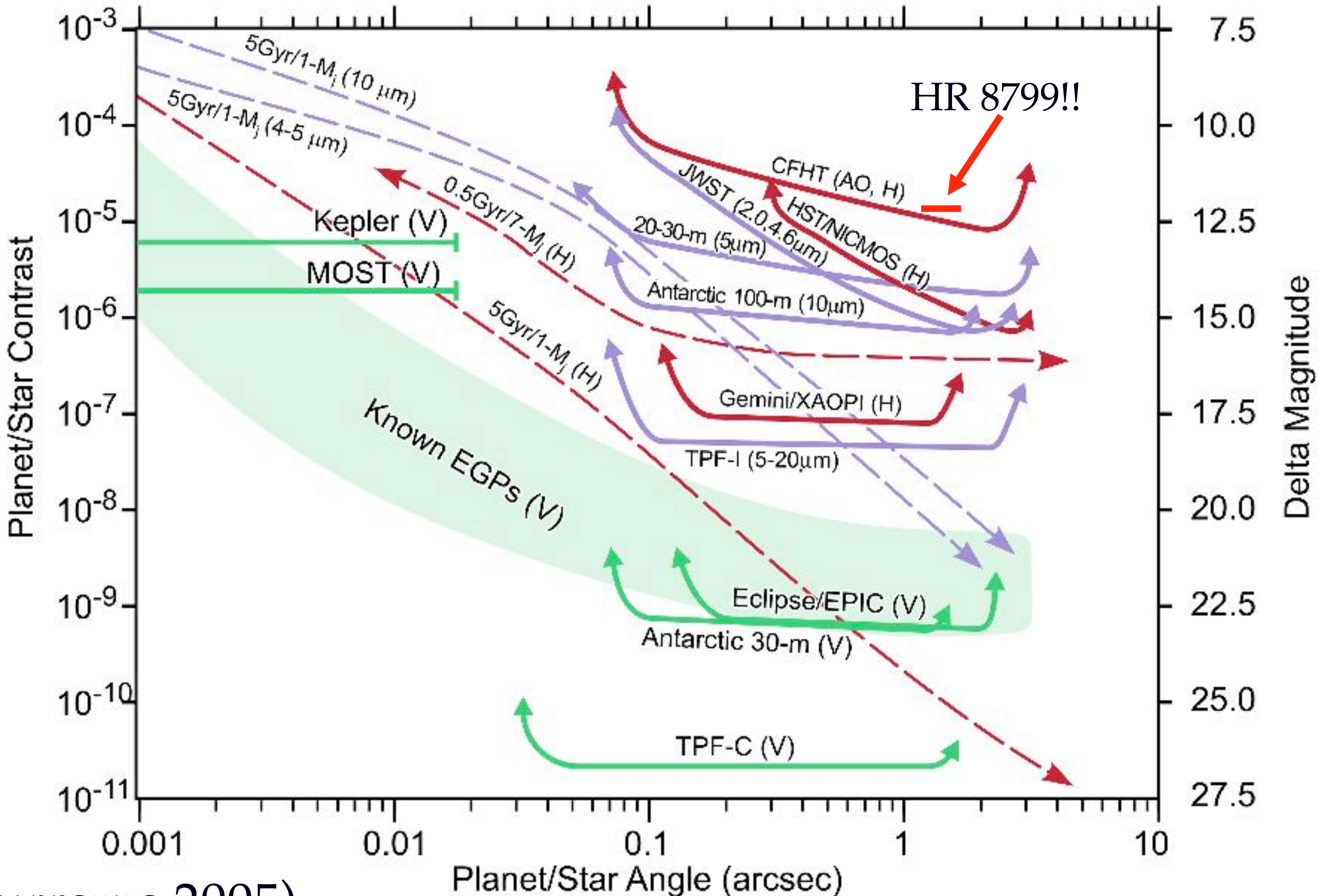
Marois et al. 2008

HR 8799bcd



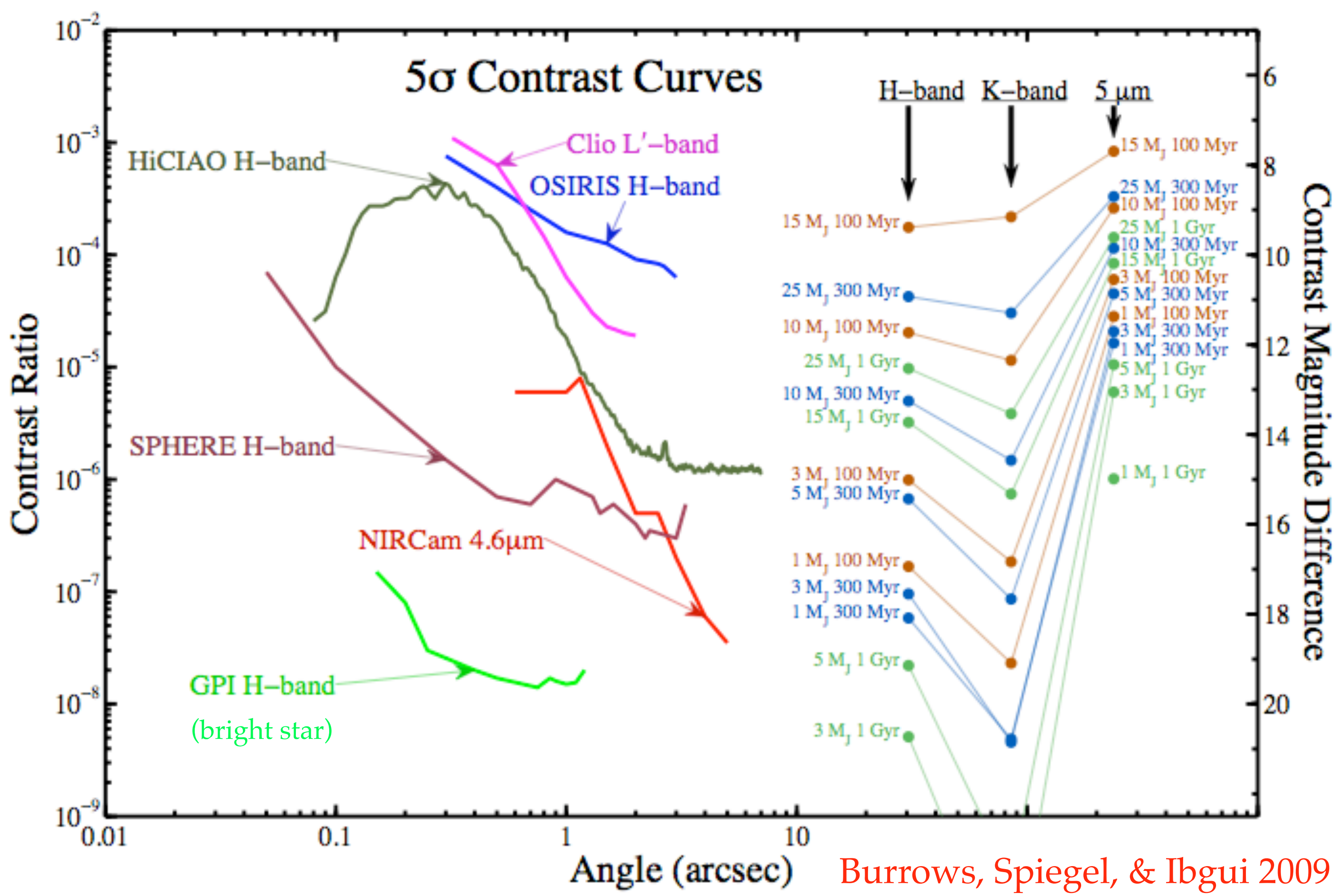
b (820K, 1.3 R_{Jup})
c (1000K, 1.25 R_{Jup})
d (1000K, 1.2 R_{Jup})
Magnitude
12
14
16
J
H
Ks
L'
1
2
3
4
Wavelength (μm)

Planet/Star *Contrast*: Theory (dashed) versus Capability



(Burrows 2005)

Red: H band (1.6 microns); Purple: Mid-IR; Green: Optical



Burrows, Spiegel, & Ibgui 2009

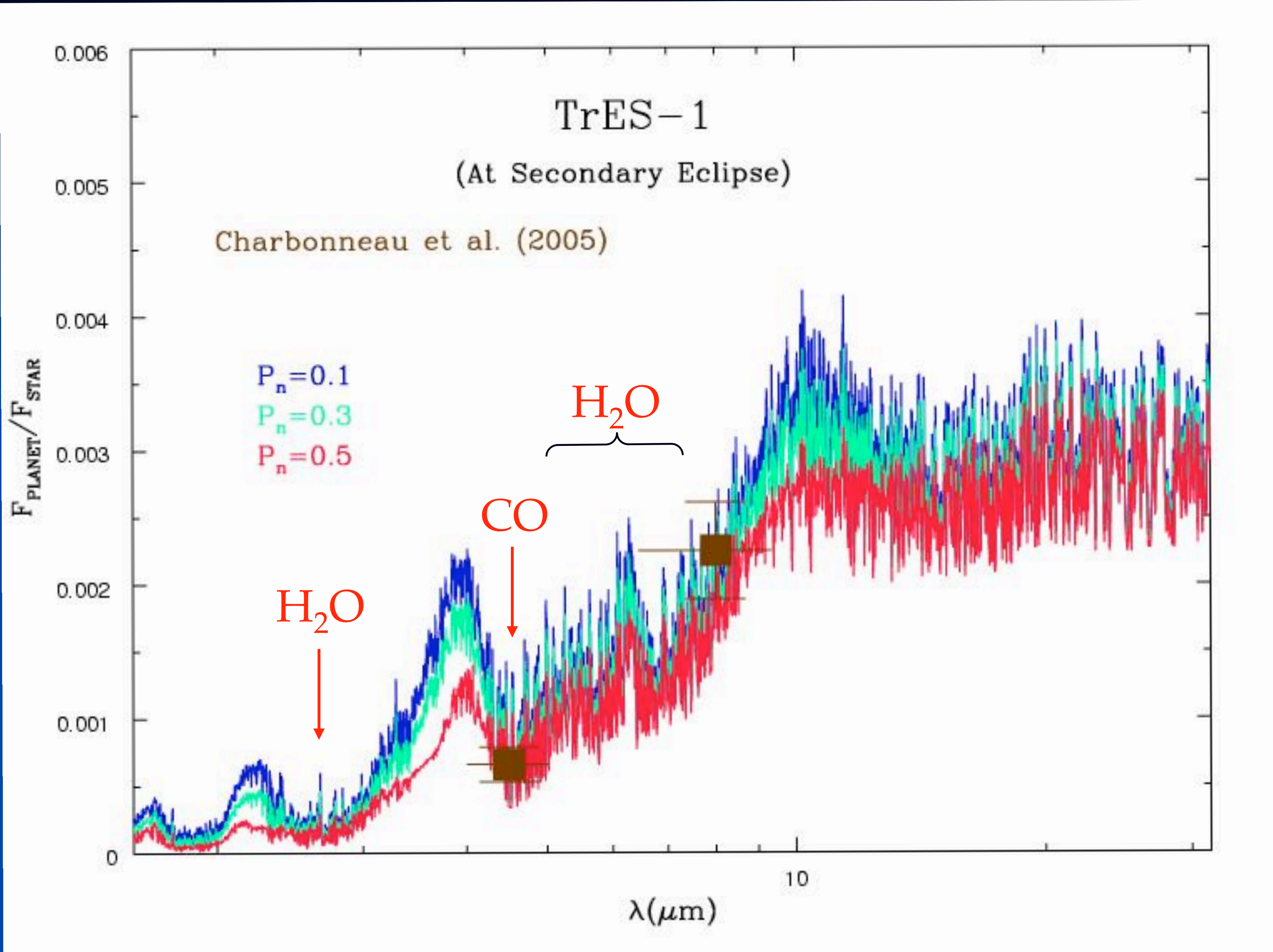
Giant Planet Transits and Secondary Eclipses

Spitzer/IRAC-MIPS!

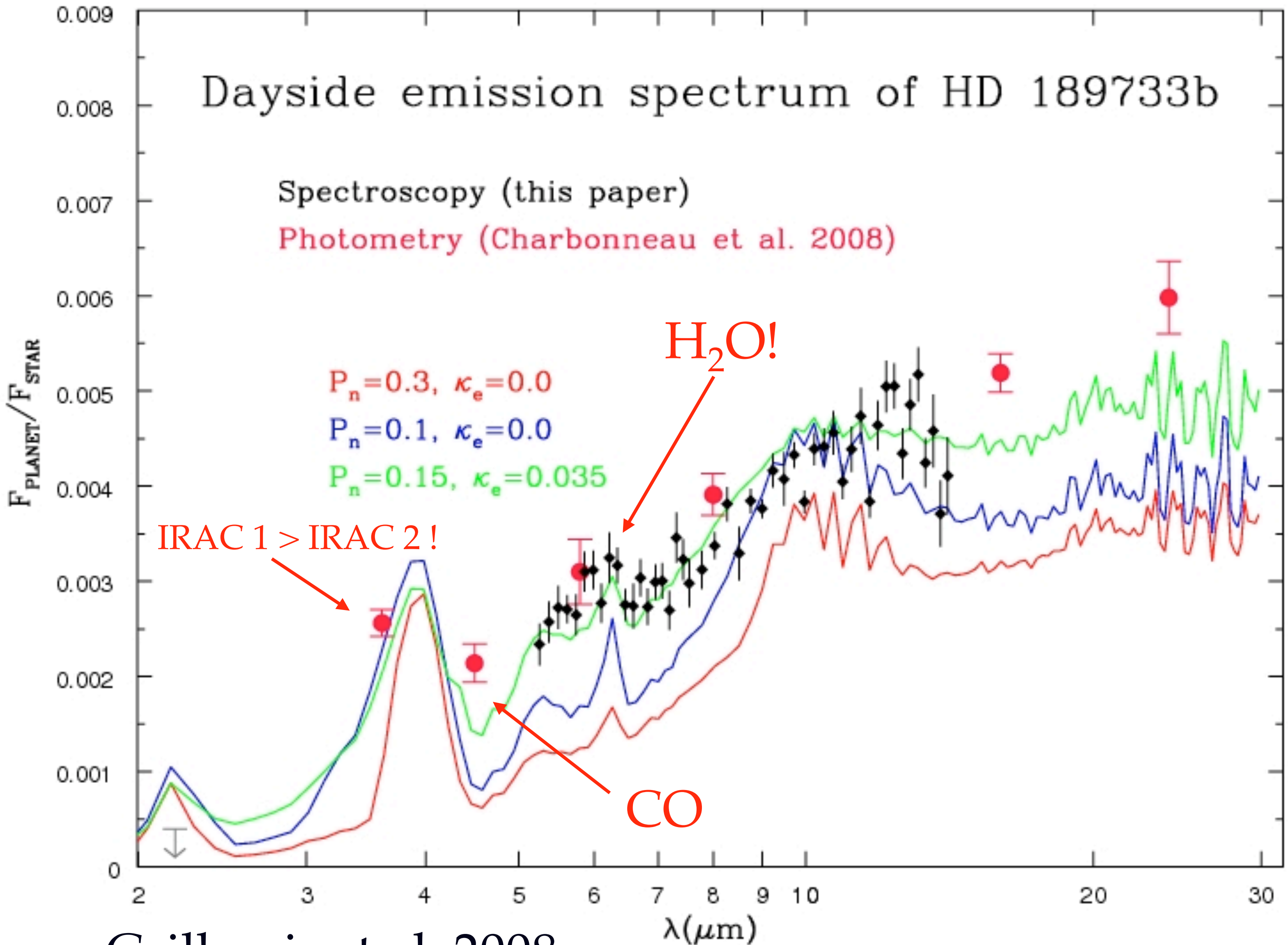
NICMOS/near-IR!

Look for variation / changes in summed light of planet and star!

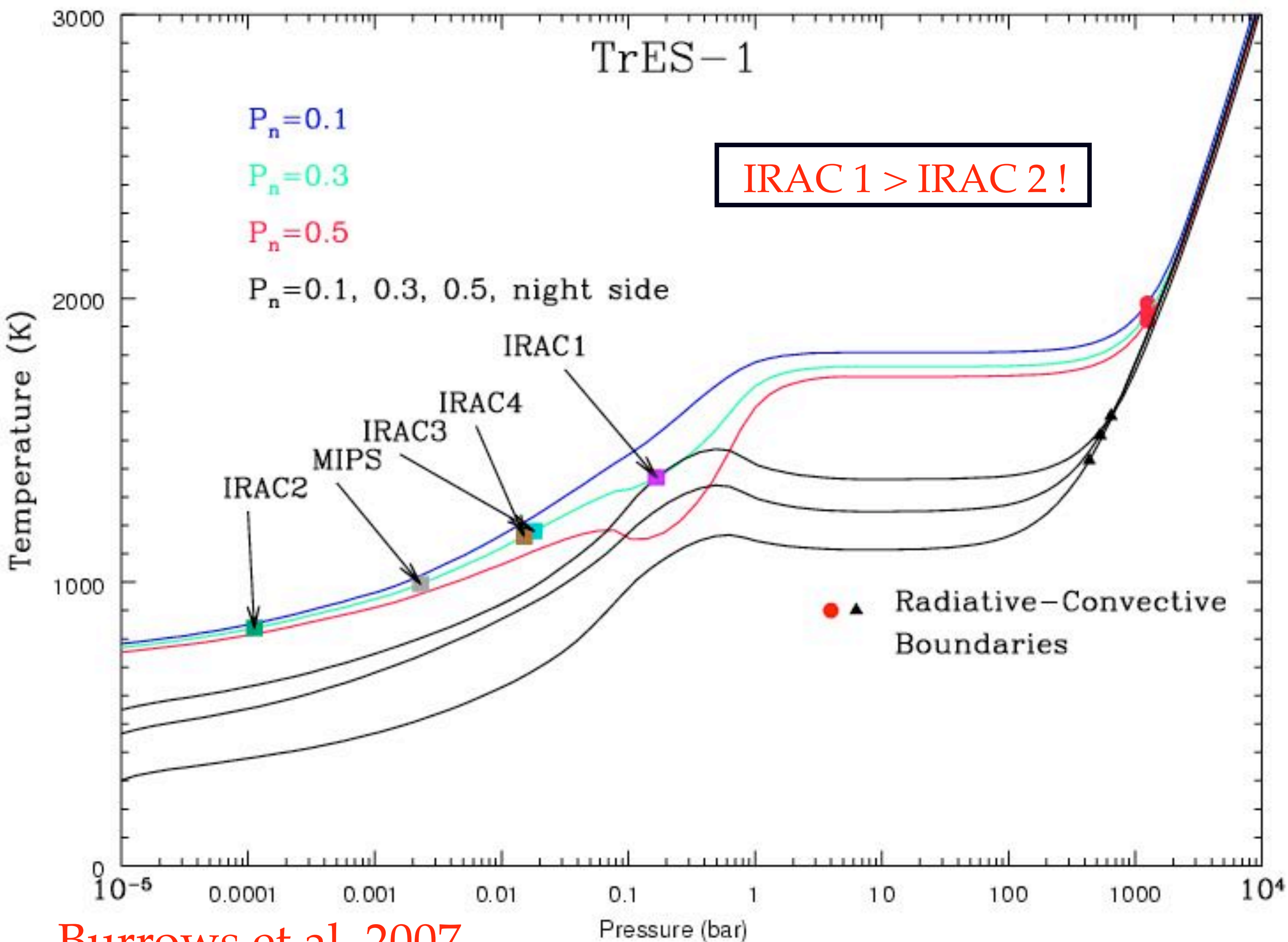
Close-in: No need for imaging!



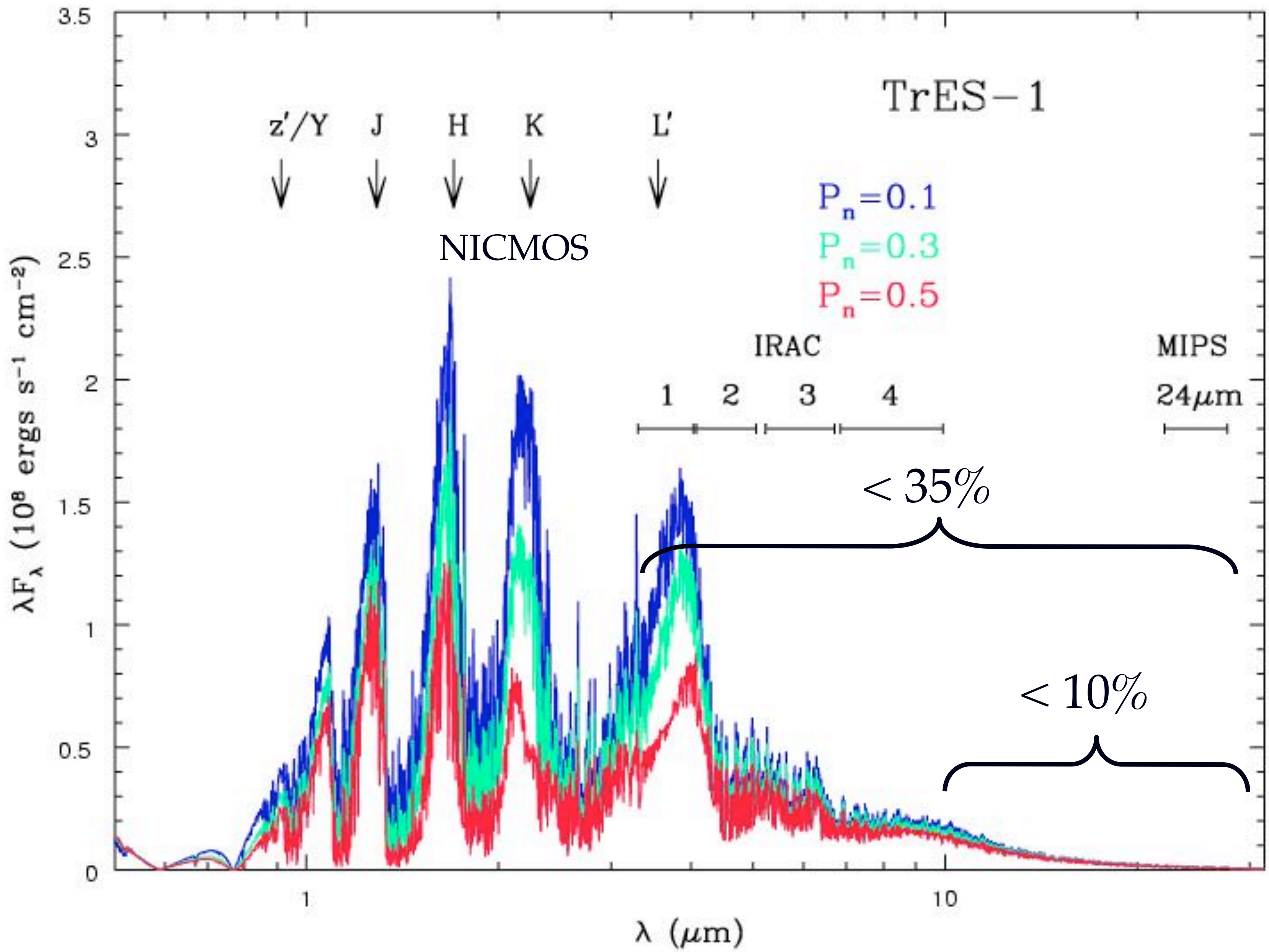
TrES−1
(At Secondary Eclipse)
Charbonneau et al. (2005)
P_n=0.1
P_n=0.3
P_n=0.5
H_2O
CO
H_2O
F_{PLANET}/F_{STAR}
0.006
0.005
0.004
0.003
0.002
0.001
0
10
λ(μm)



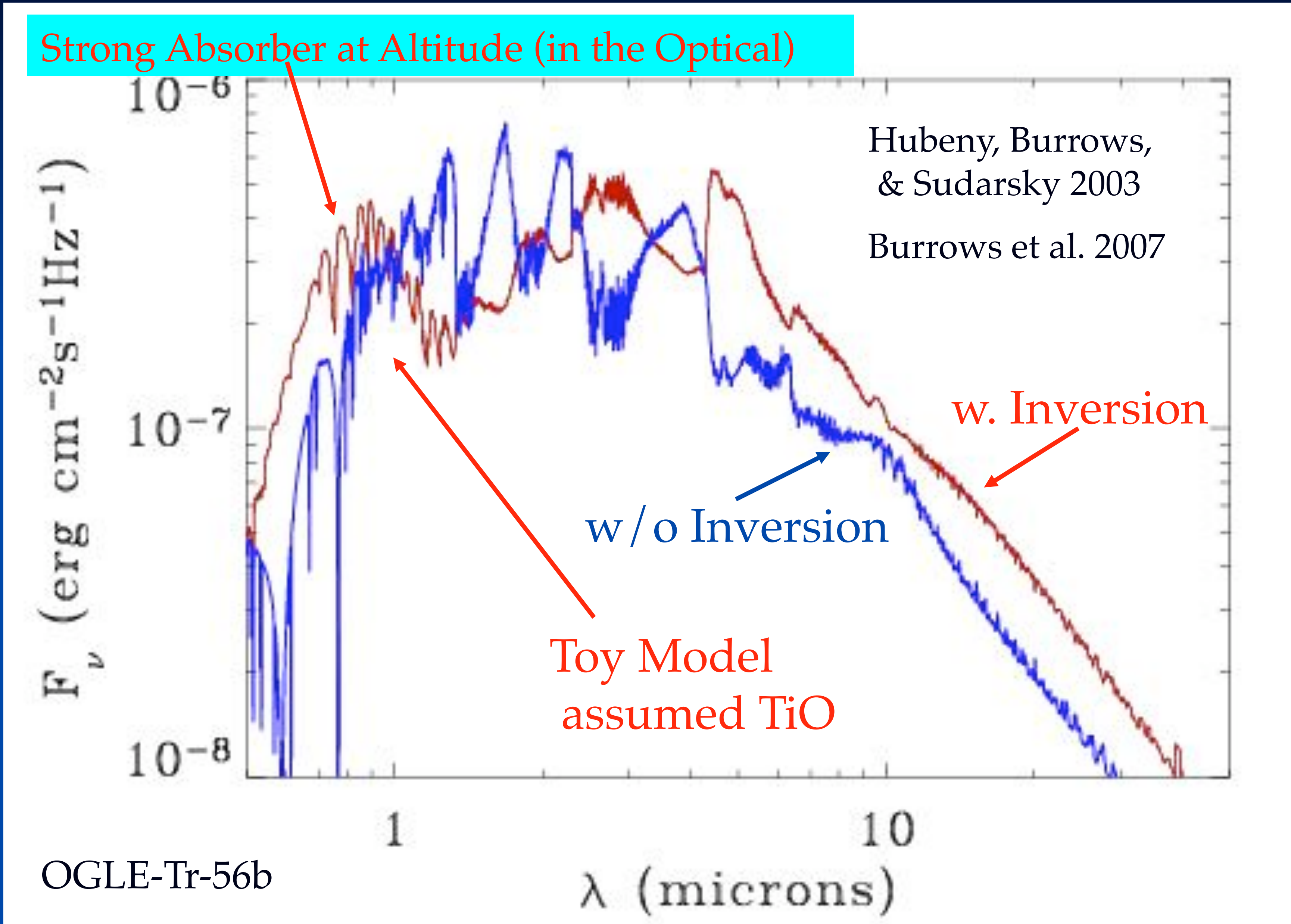
Grillmair et al. 2008

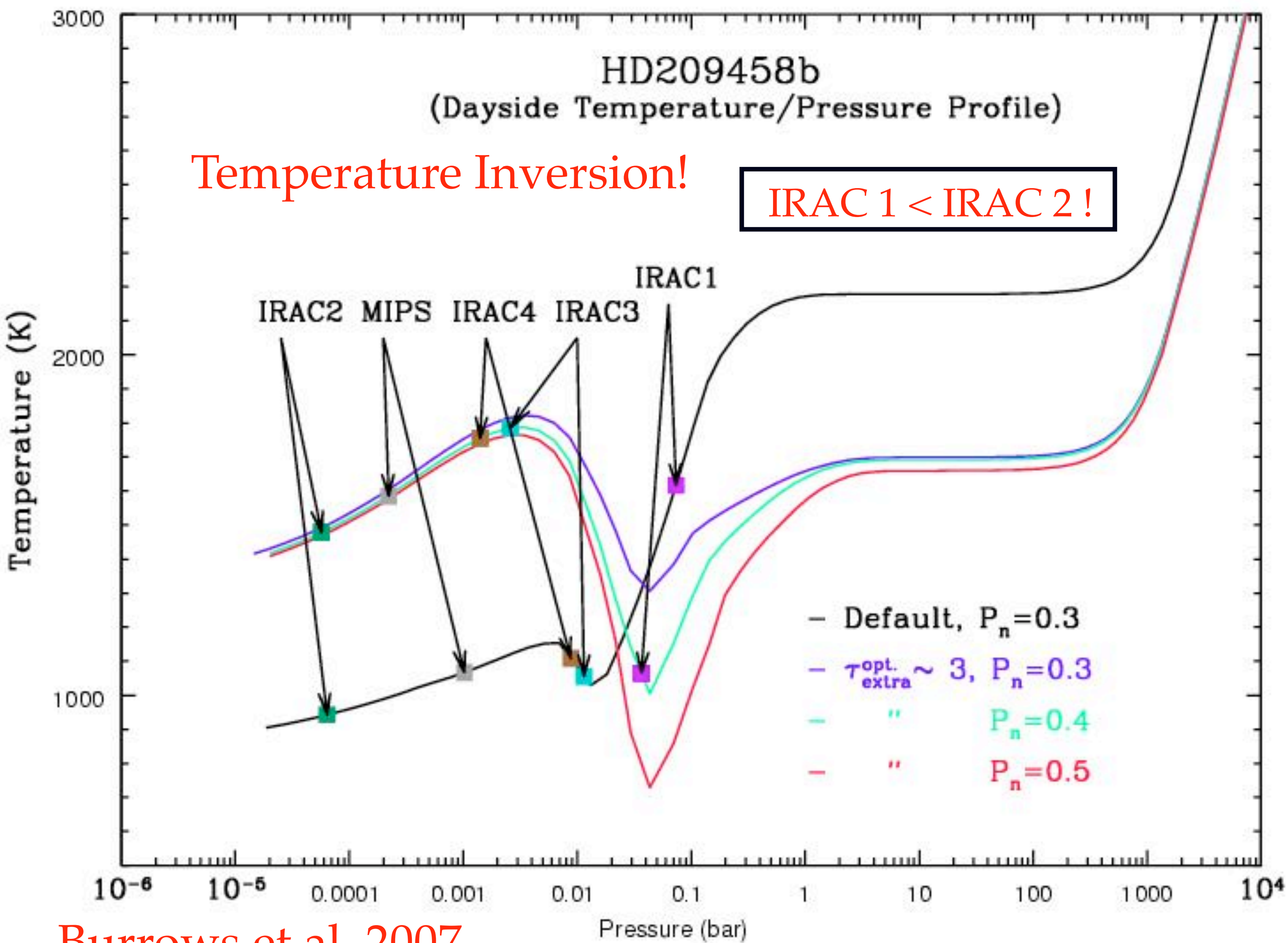


Burrows et al. 2007


TrES−1
z′/Y
J
H
K
L′
NICMOS
Pn=0.1
Pn=0.3
Pn=0.5
IRAC
1
2
3
4
MIPS
24μm
< 35%
< 10%
λFλ (10⁸ ergs s⁻¹ cm⁻²)
λ (μm)
3.5
3
2.5
2
1.5
1
0.5
0
1
10

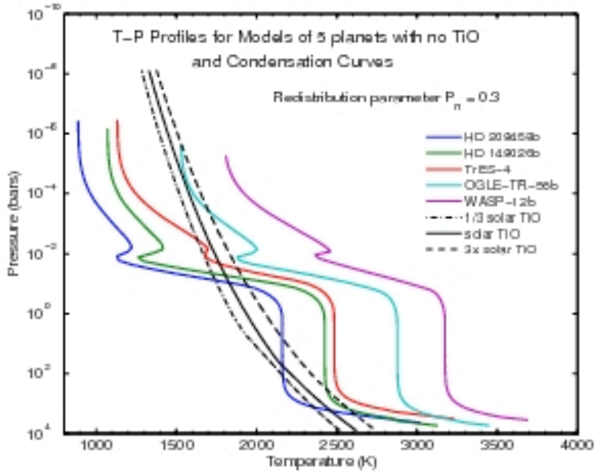
Thermal Inversions: Water (etc.) in Emission (!)

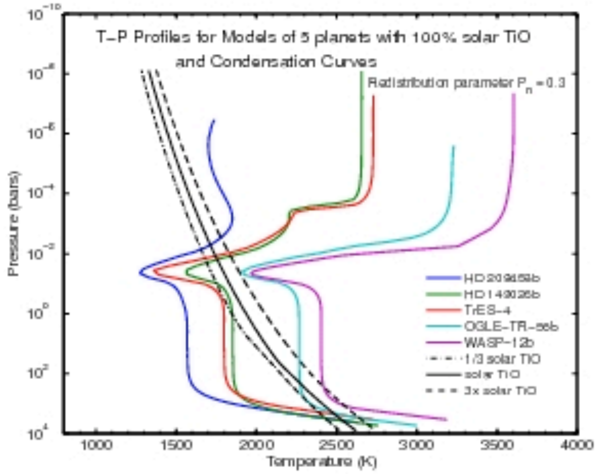




Burrows et al. 2007

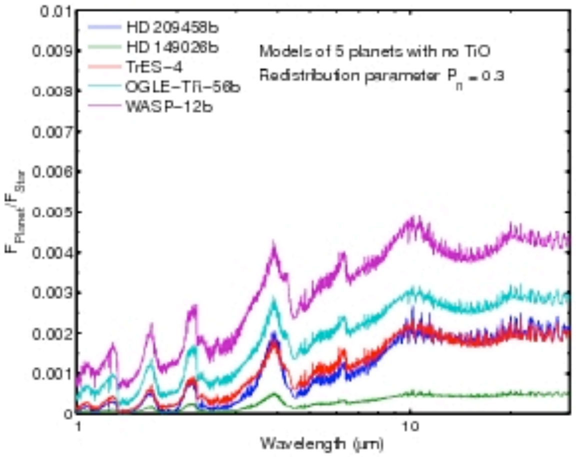
T/P Models, with and w/o TiO ($0 < X_i < 100\%$ solar)

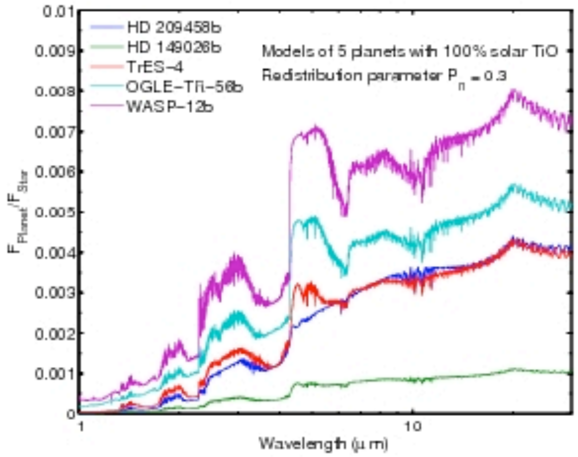




Spiegel, Silverio, & Burrows 2009

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

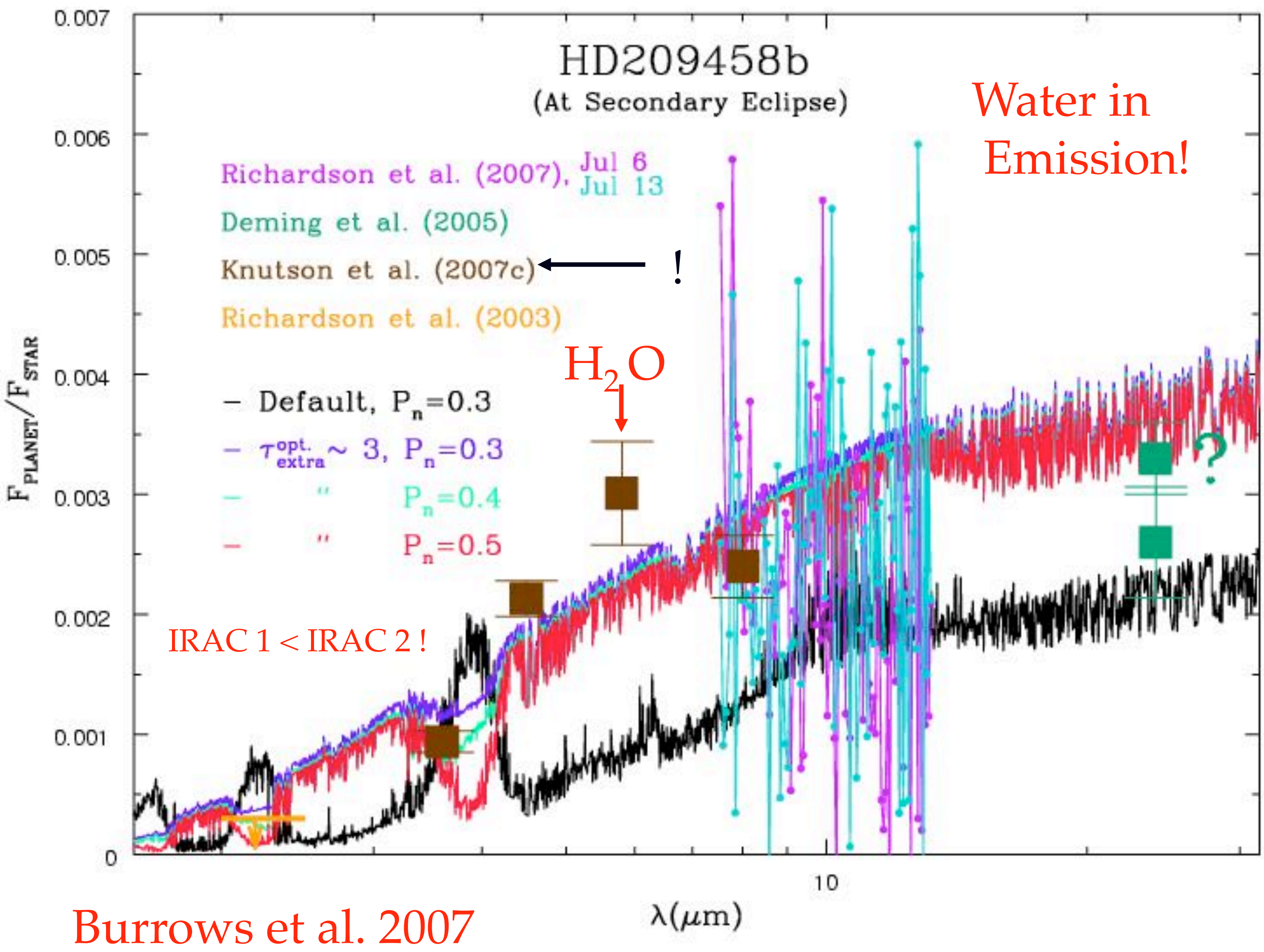




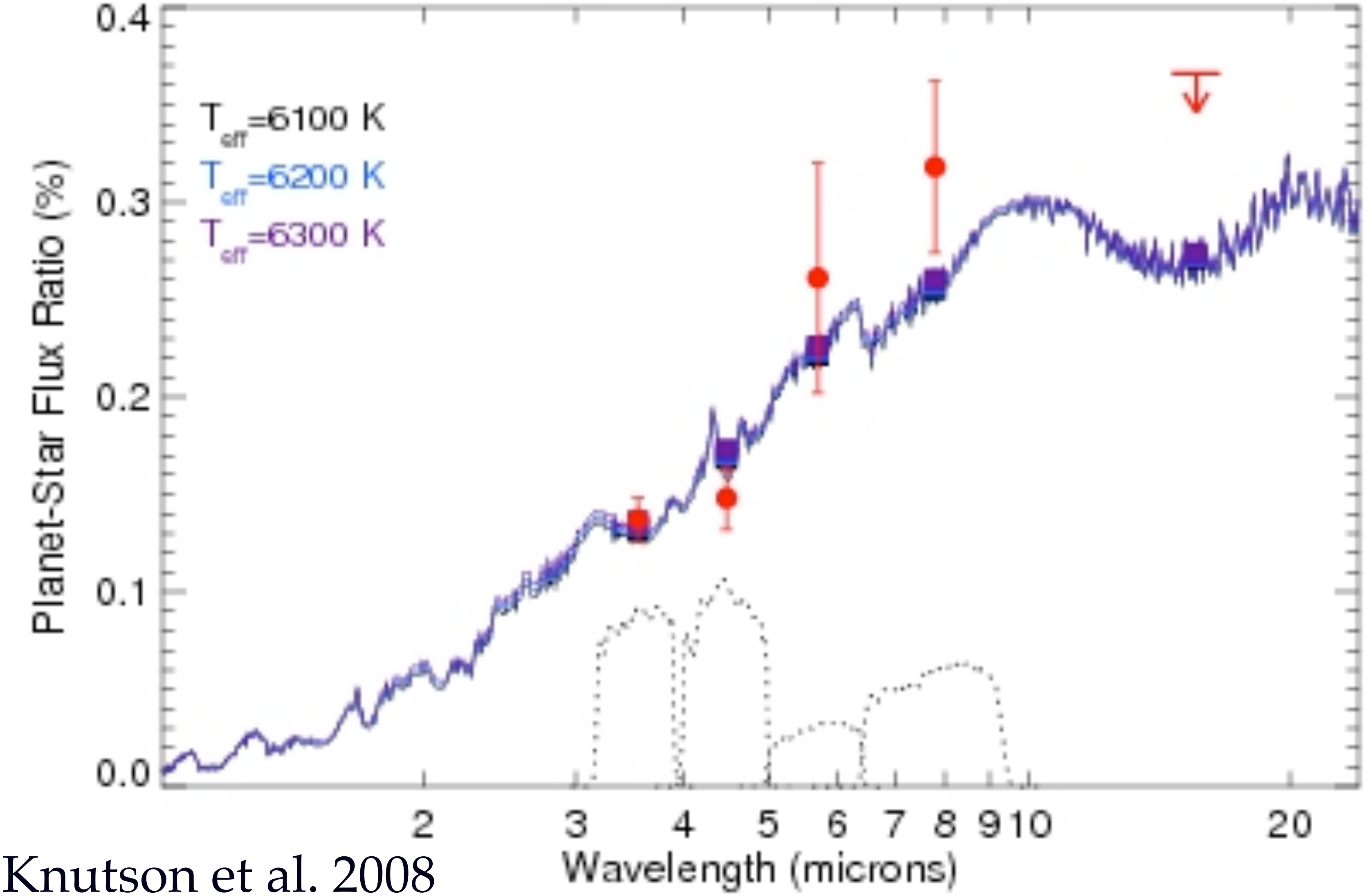
w/o TiO

with 100% solar TiO

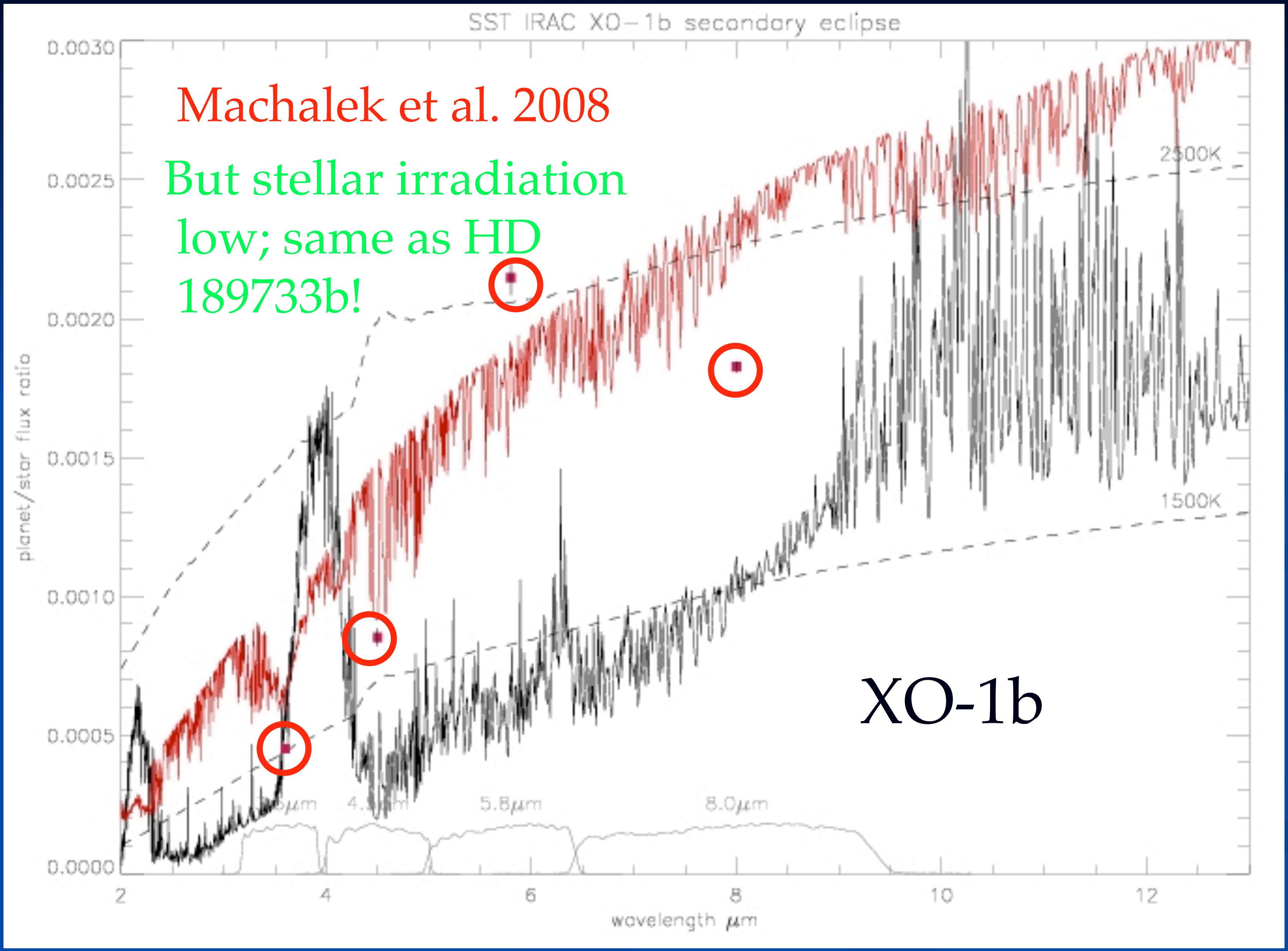
Spiegel, Silverio, & Burrows 2009

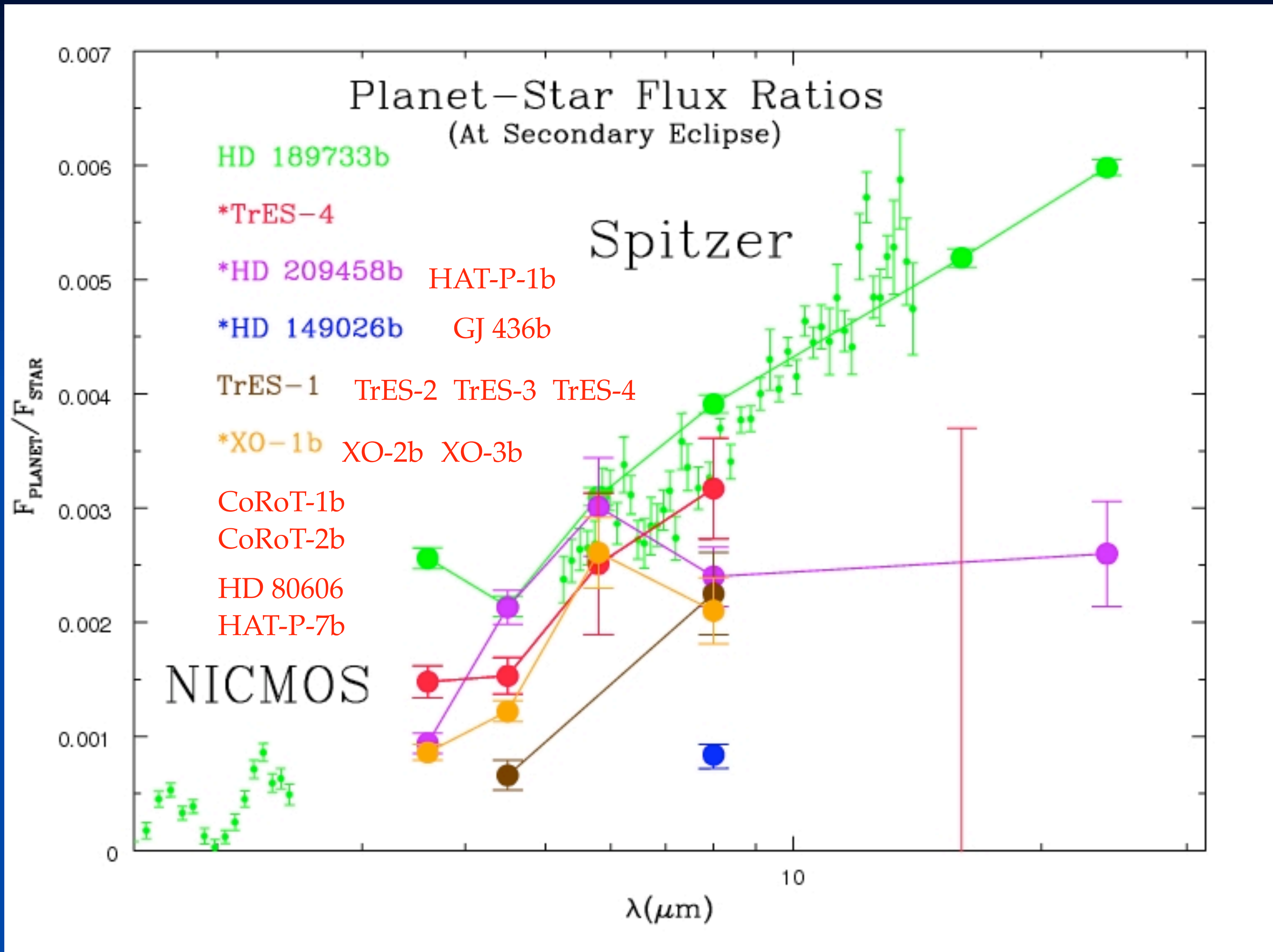

HD209458b
(At Secondary Eclipse)
Water in Emission!
Richardson et al. (2007), Jul 6 Jul 13
Deming et al. (2005)
Knutson et al. (2007c)
!
Richardson et al. (2003)
H2O
– Default, Pn=0.3
– τ extra opt. ~ 3, Pn=0.3
– " Pn=0.4
– " Pn=0.5
?
IRAC 1 < IRAC 2 !
FPLANET/FSTAR
λ(μm)
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
10
Burrows et al. 2007

TrES-4: A thermal inversion

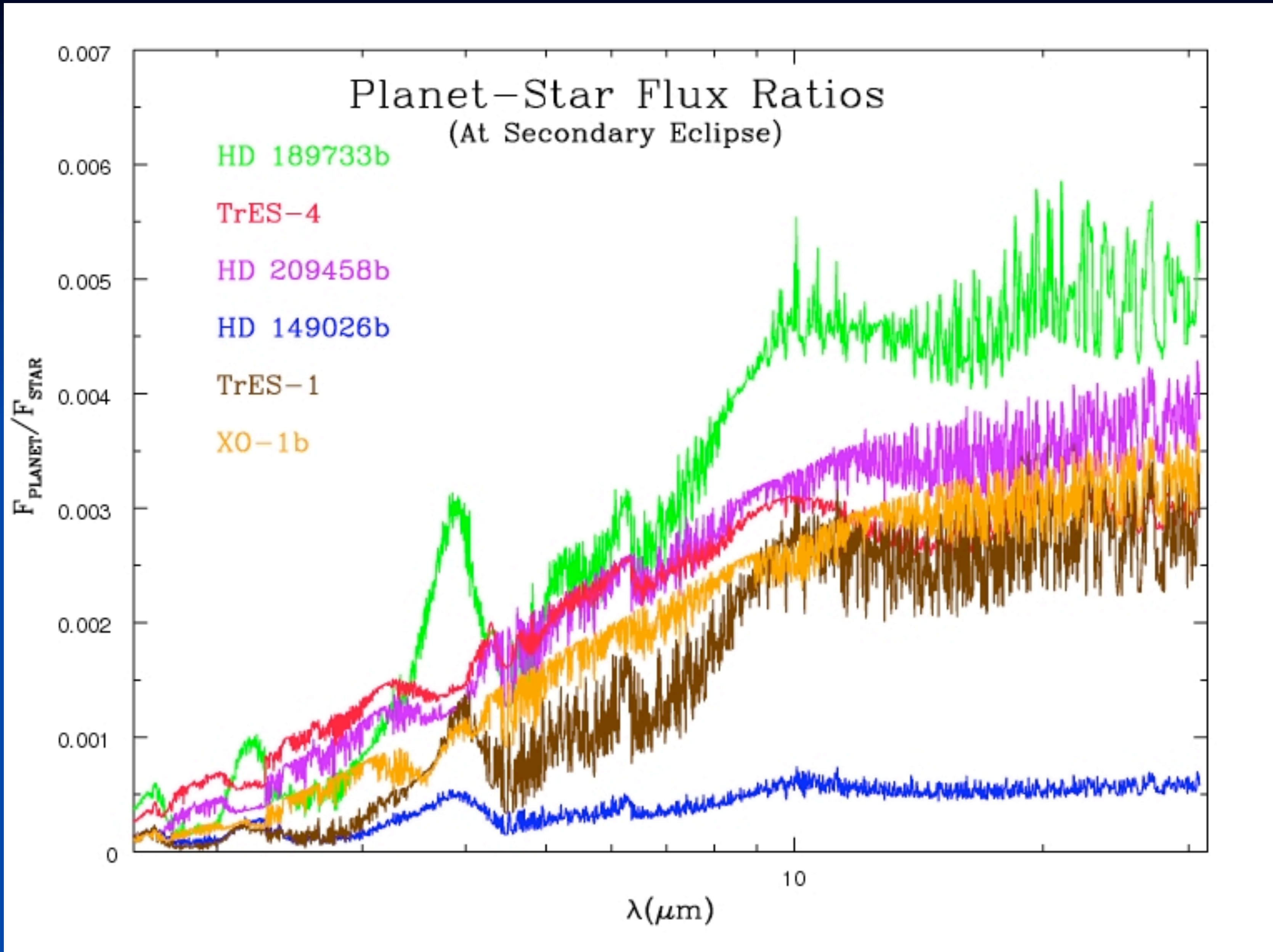


Knutson et al. 2008

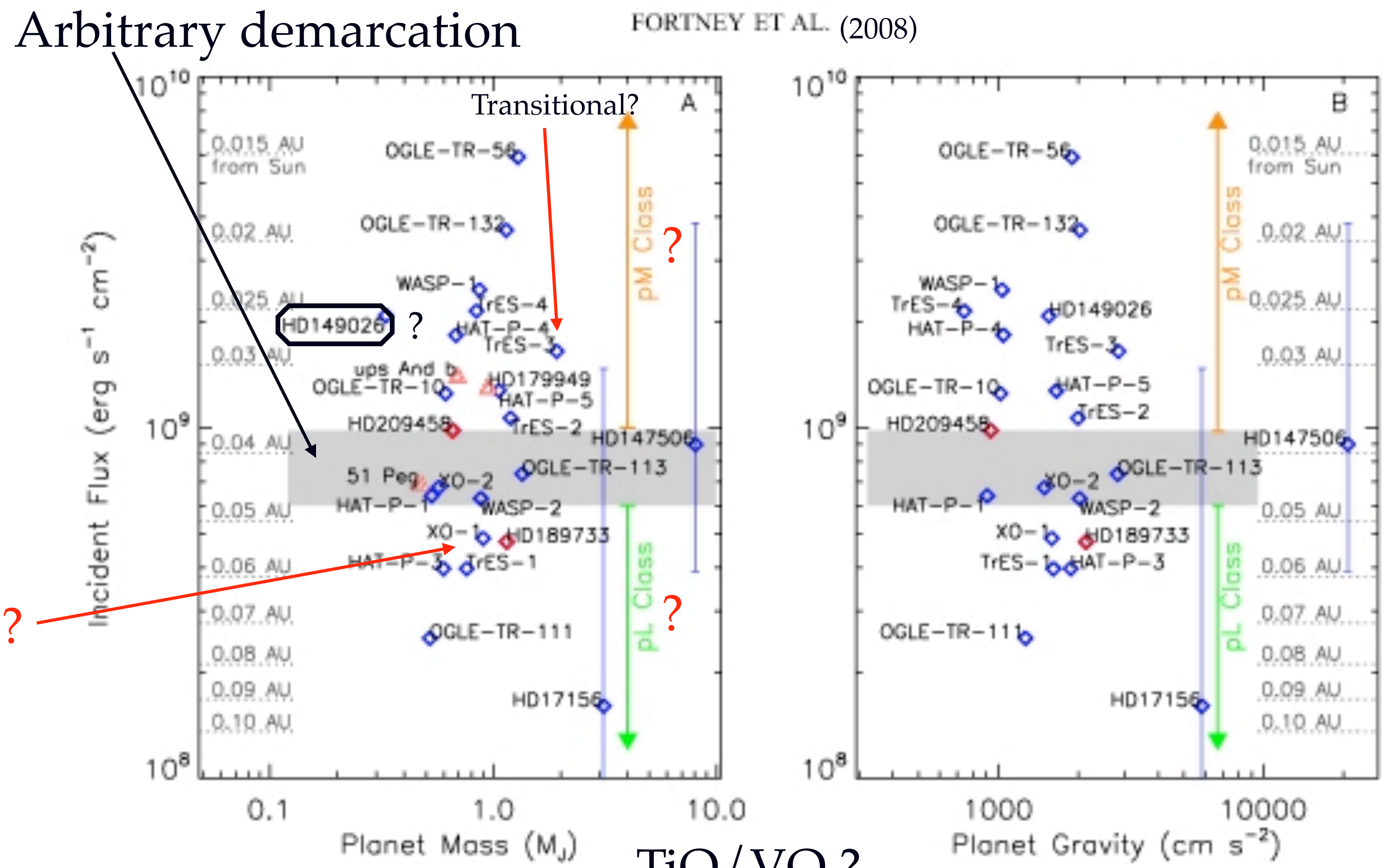

SST IRAC XO−1b secondary eclipse
Machalek et al. 2008
But stellar irradiation low; same as HD 189733b!
XO-1b
2500K
1500K
3.6μm
4.5μm
5.8μm
8.0μm
planet/star flux ratio
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
wavelength μm
2
4
6
8
10
12



Planet–Star Flux Ratios
(At Secondary Eclipse)
HD 189733b
*TrES–4
*HD 209458b
*HD 149026b
TrES–1
*XO–1b
HAT-P-1b
GJ 436b
TrES-2 TrES-3 TrES-4
XO-2b XO-3b
CoRoT-1b
CoRoT-2b
HD 80606
HAT-P-7b
Spitzer
NICMOS
F_{PLANET}/F_{STAR}
$\lambda(\mu m)$
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
10



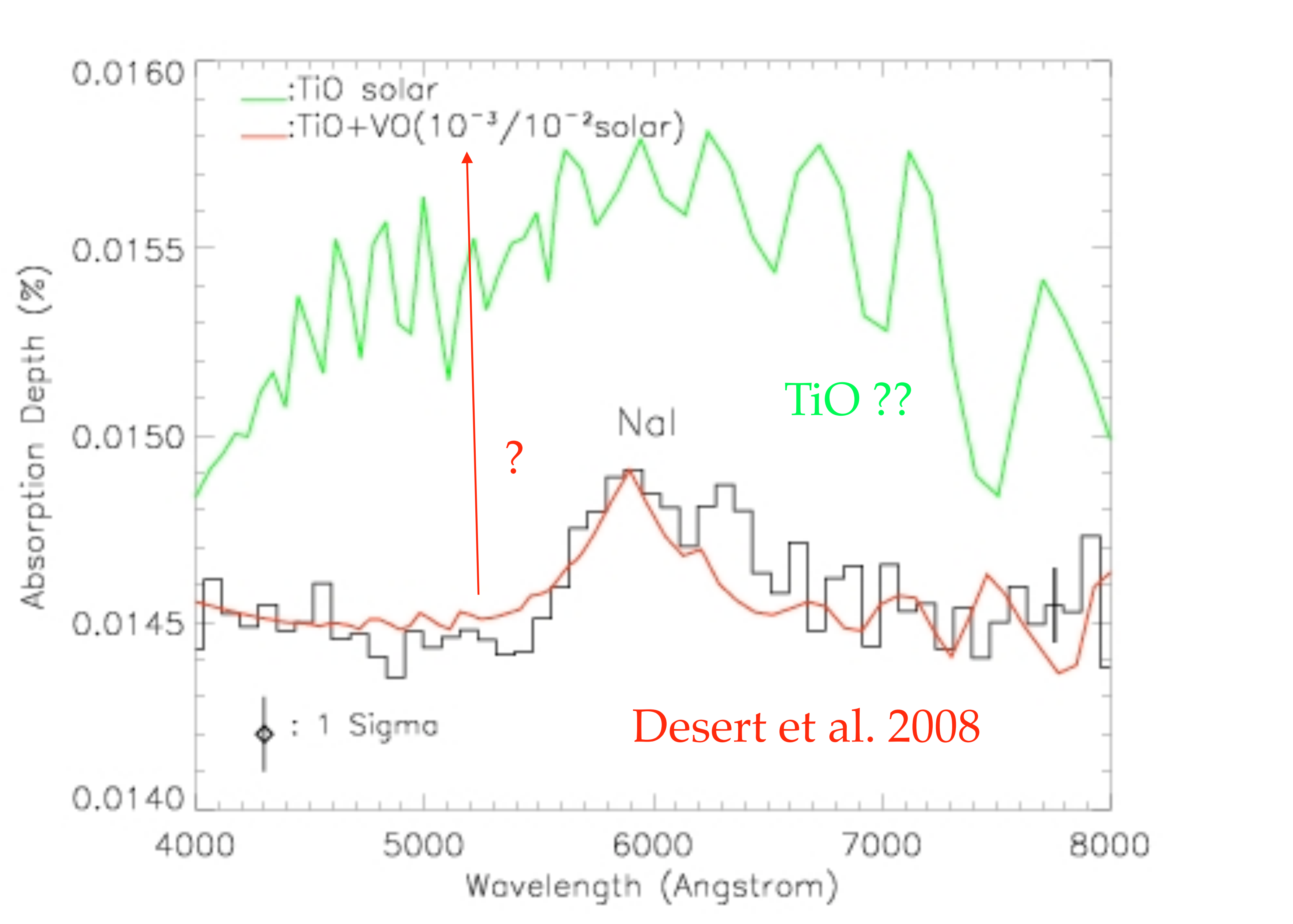
Planet−Star Flux Ratios
(At Secondary Eclipse)
HD 189733b
TrES−4
HD 209458b
HD 149026b
TrES−1
XO−1b
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
F_{PLANET}/F_{STAR}
10
$\lambda(\mu m)$



pM, pL ??; F_p correlation?? - Burrows, Budaj, & Hubeny 2008

TiO/VO? : Hubeny, Burrows, & Sudarsky 2003

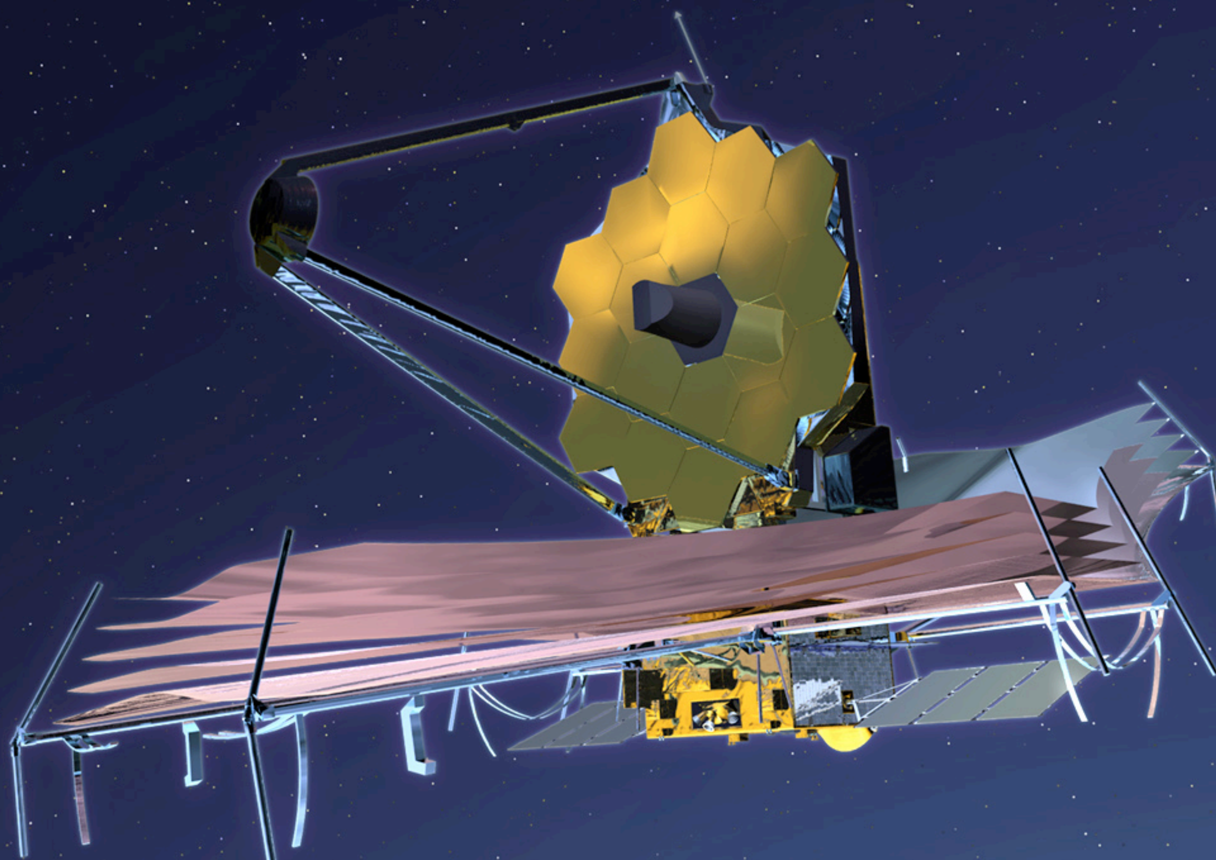
HD 209458b in Transit: Optical



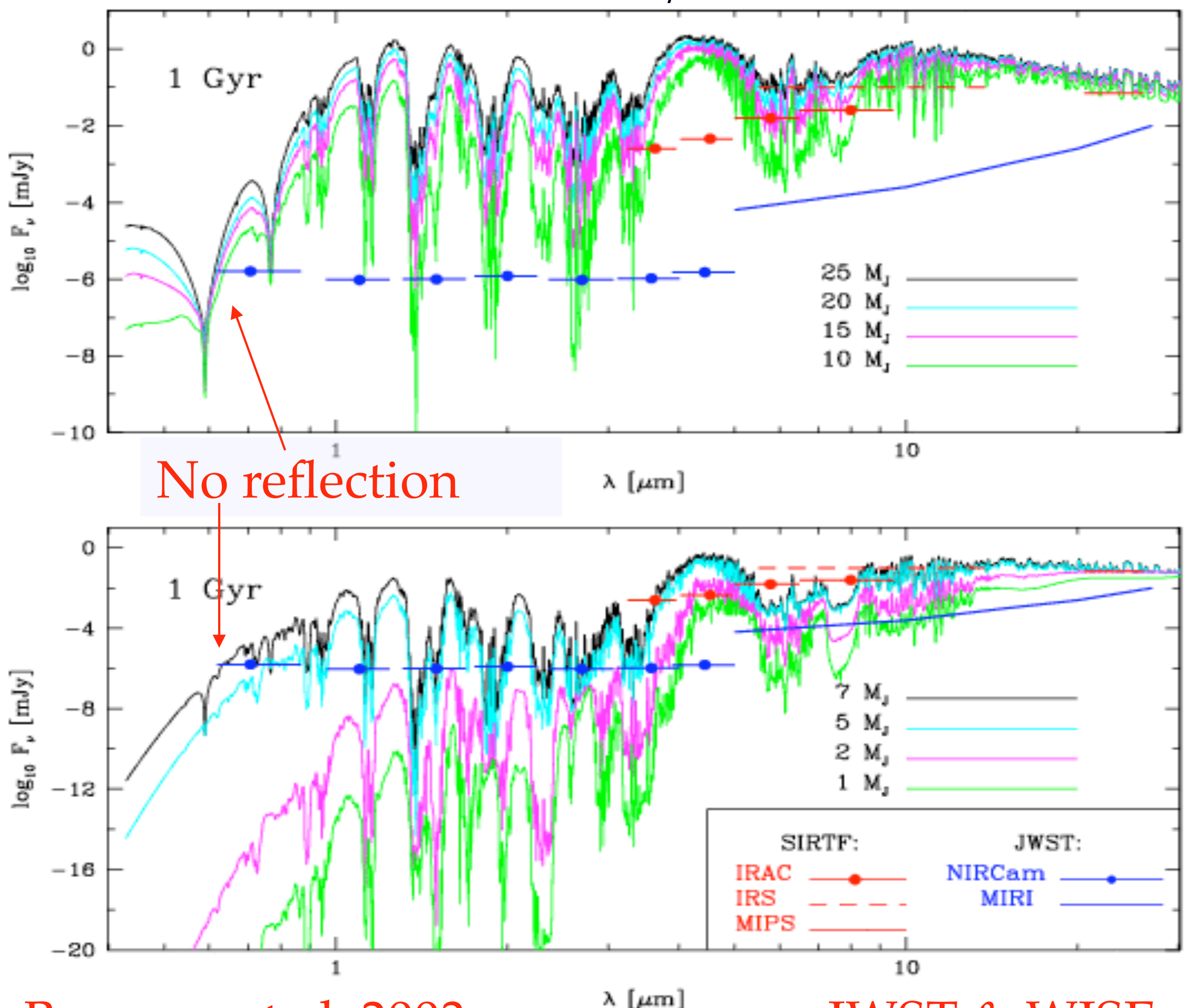
Cause of Thermal Inversion?

- 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: HS, allotropes of S (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 & credible 3D GCMs
- Observation: Need better and more definitive optical spectra

JWST - Successor to Spitzer



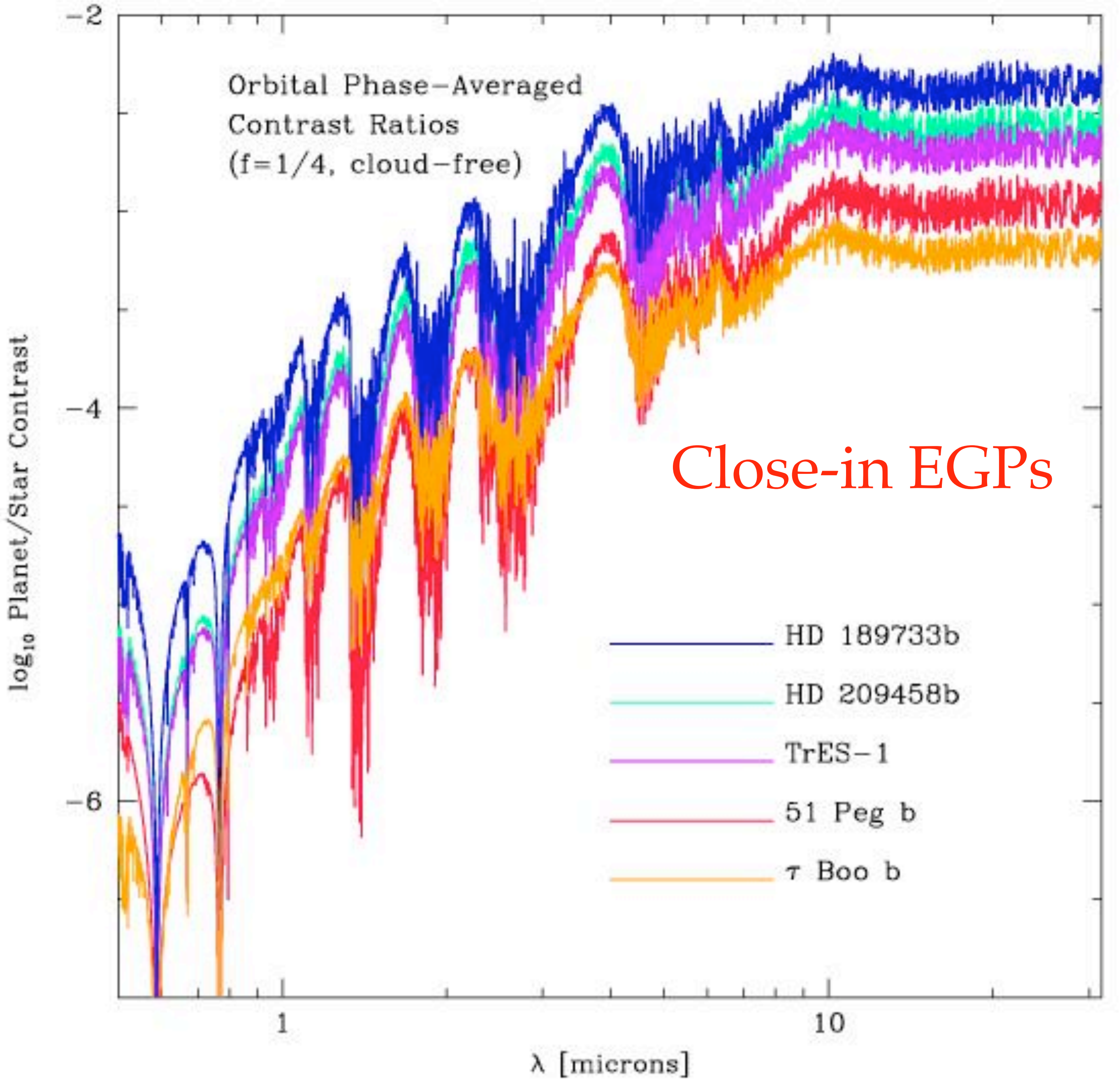
Isolated BDs / EGPs



Burrows et al. 2003

JWST & WISE

Optical Albedos of "Hot Jupiters"



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
log10 Planet/Star Contrast
λ [microns]
-2
-4
-6
1
10

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

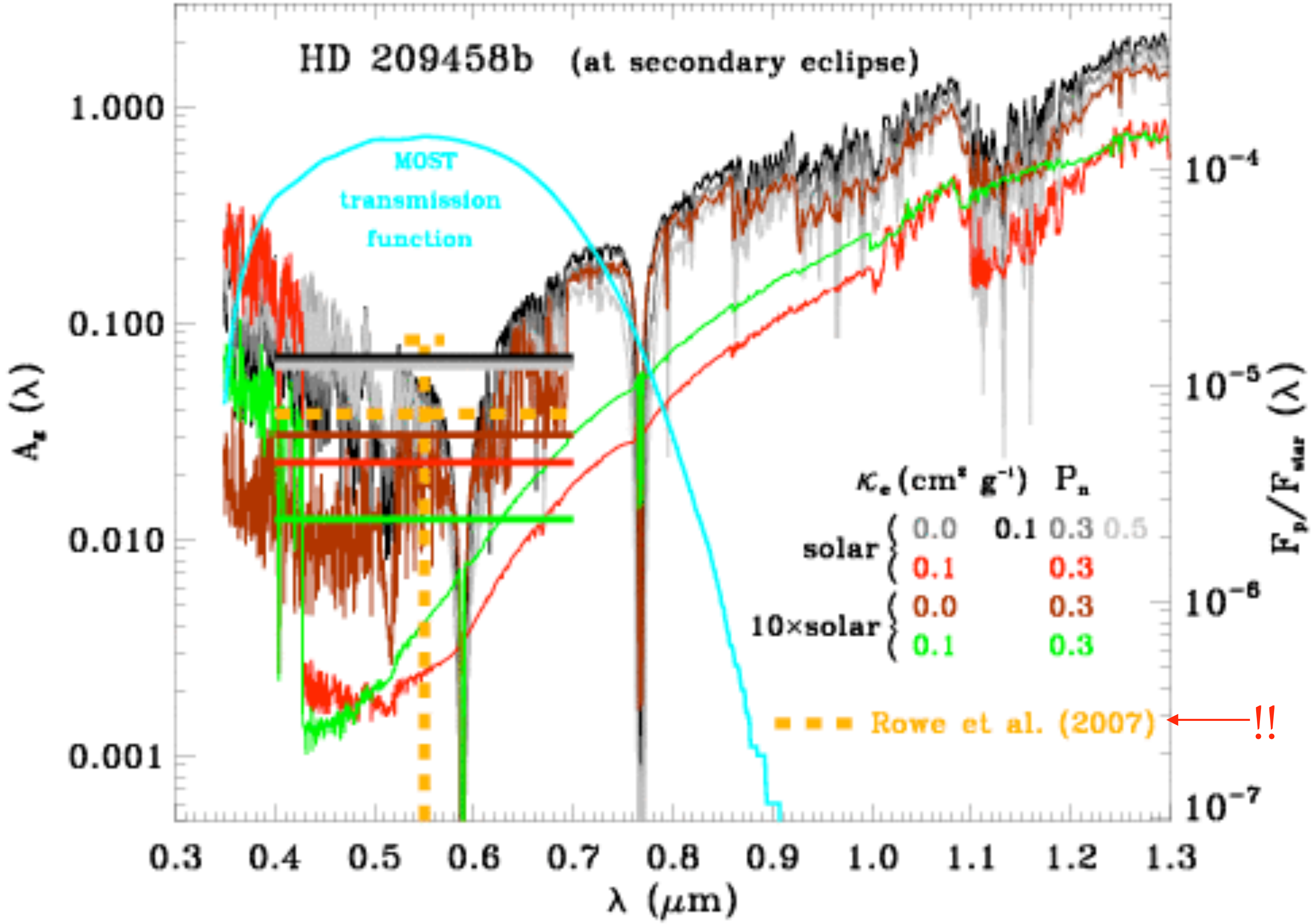
CoRoT-Exo-2b: Snellen/Alonso et al. 2009; Rogers et al. 2009
"Albedo"/thermal measurement - $F_p/F_* \sim 1.3 \times 10^{-4}$ (CoRoT red)
$\sim 1.6 \times 10^{-4}$ (CoRoT white); Bond albedo ~ 0.075 (?)

CoRoT-Exo-1b: Snellen et al. 2009; Gillon et al 2009; Alonso et al. 2009; Rogers et al. 2009 - F_p/F_* (K band) $\sim 3.0 \times 10^{-3}$; F_p/F_* (opt) $\sim 1.3\text{-}1.6 \times 10^{-4}$

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

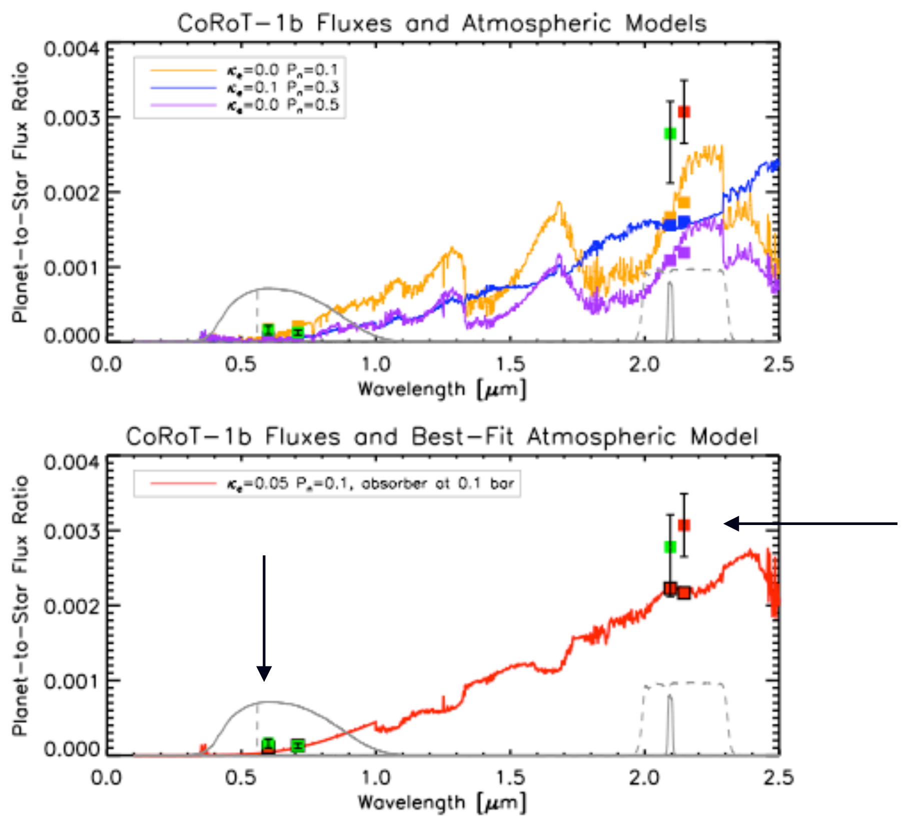
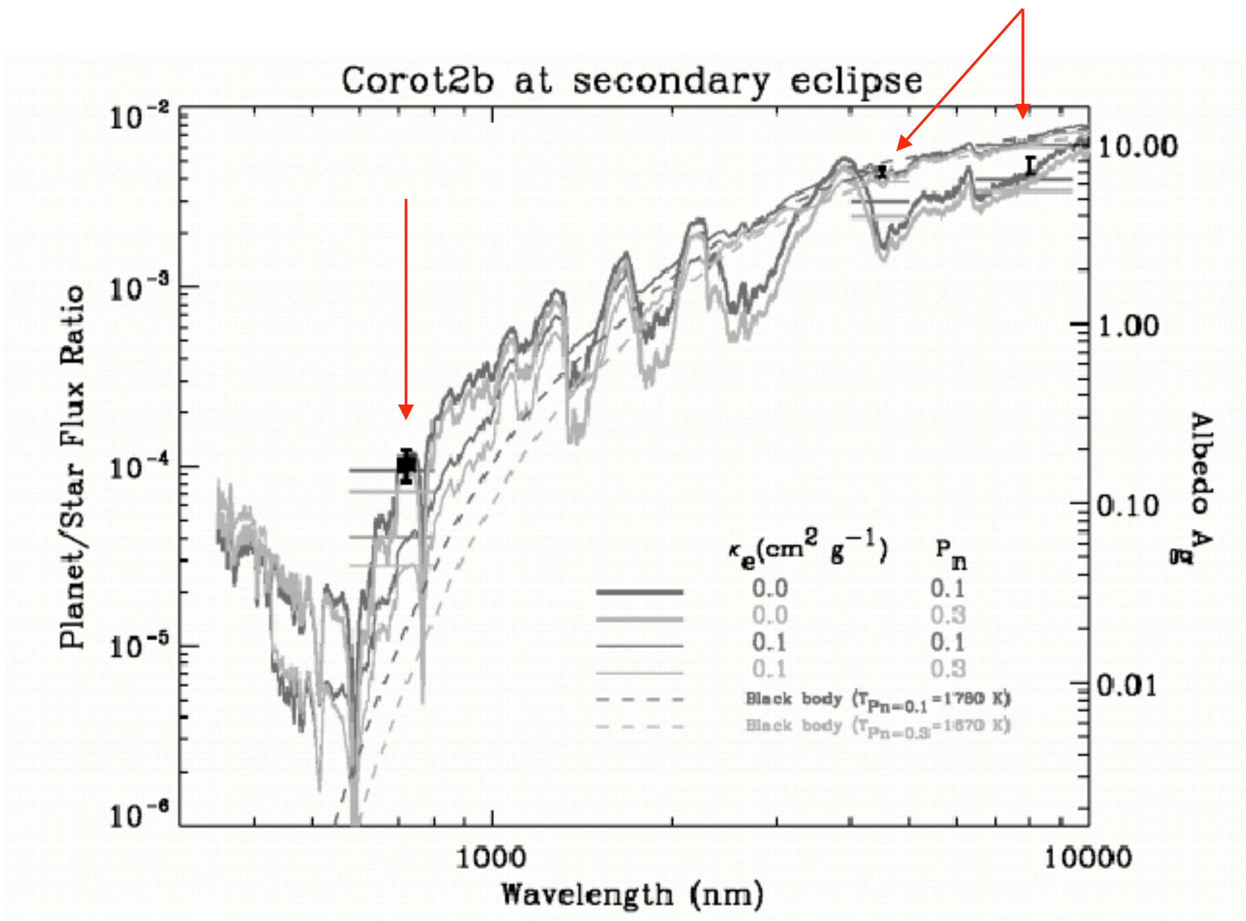


Fig. 7.— Top Panel: The measured planet-to-star flux ratios compared to the band-averaged ratios from atmospheric models that incorporate extra optical absorbers placed near the 0.01 bar level. Three models shown here in orange, blue, and purple, have absorber opacities $_e$ = 0.0, 0.1, and 0.0 cm^2 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 (Close-in)

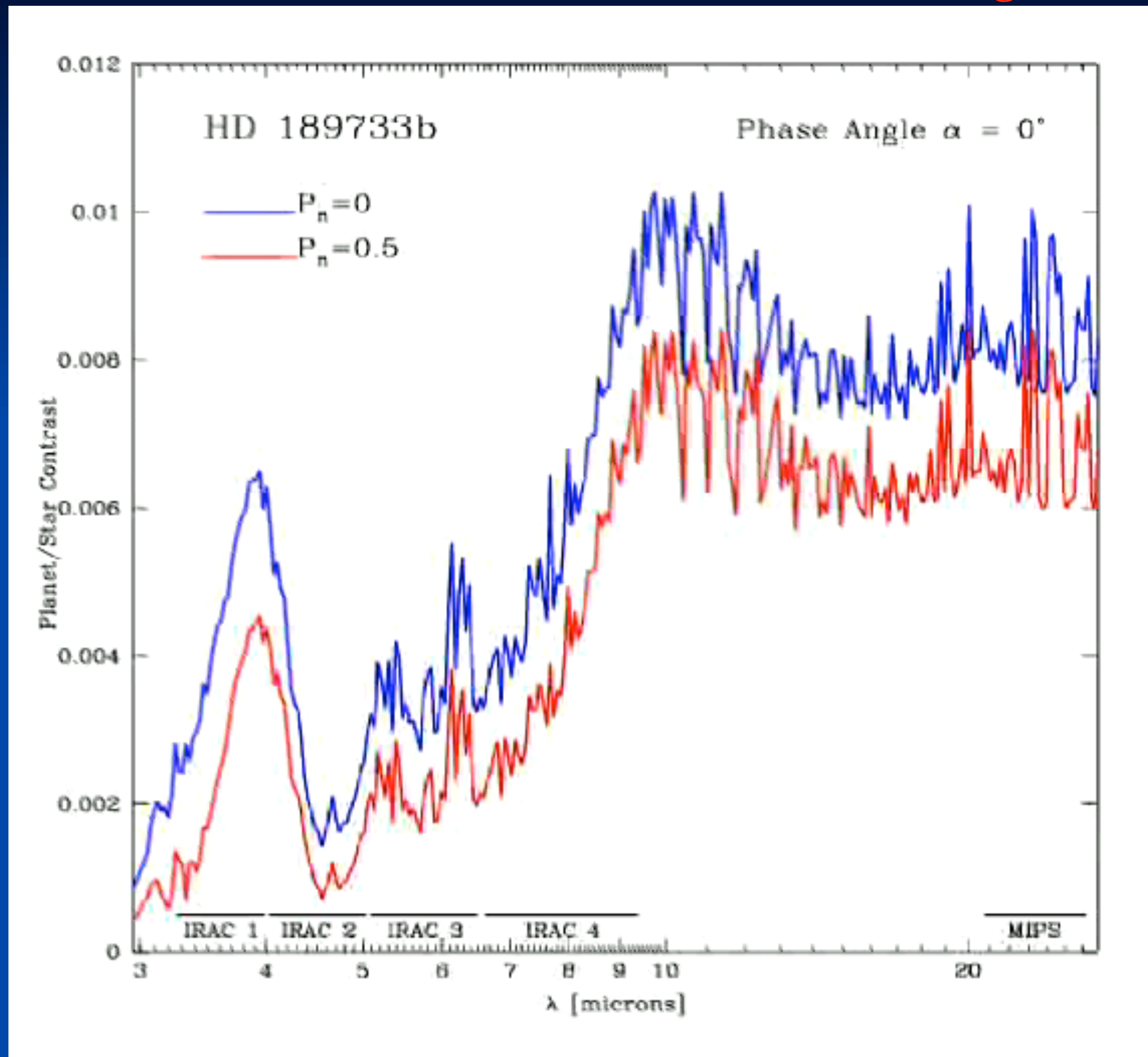
Effect of Fe / silicateClouds?

Day/Night contrasts;

Global Atmospheric Dynamics determines Dayside brightness!

Radius?!

Contrast vs. Phase and Wavelength



Burrows et al. 2006

Ups And b Phase Curve at 24 μm

Contrast does NOT imply weak day-night coupling:

Thermal inversion

Future: Kepler, JWST

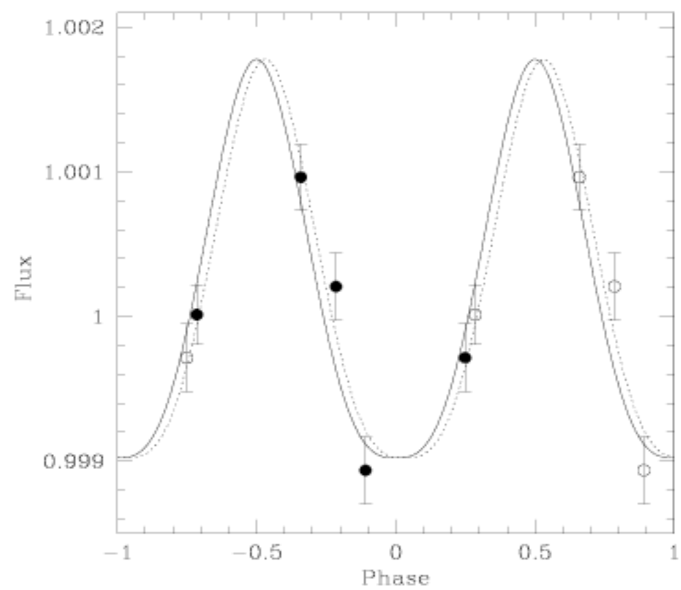
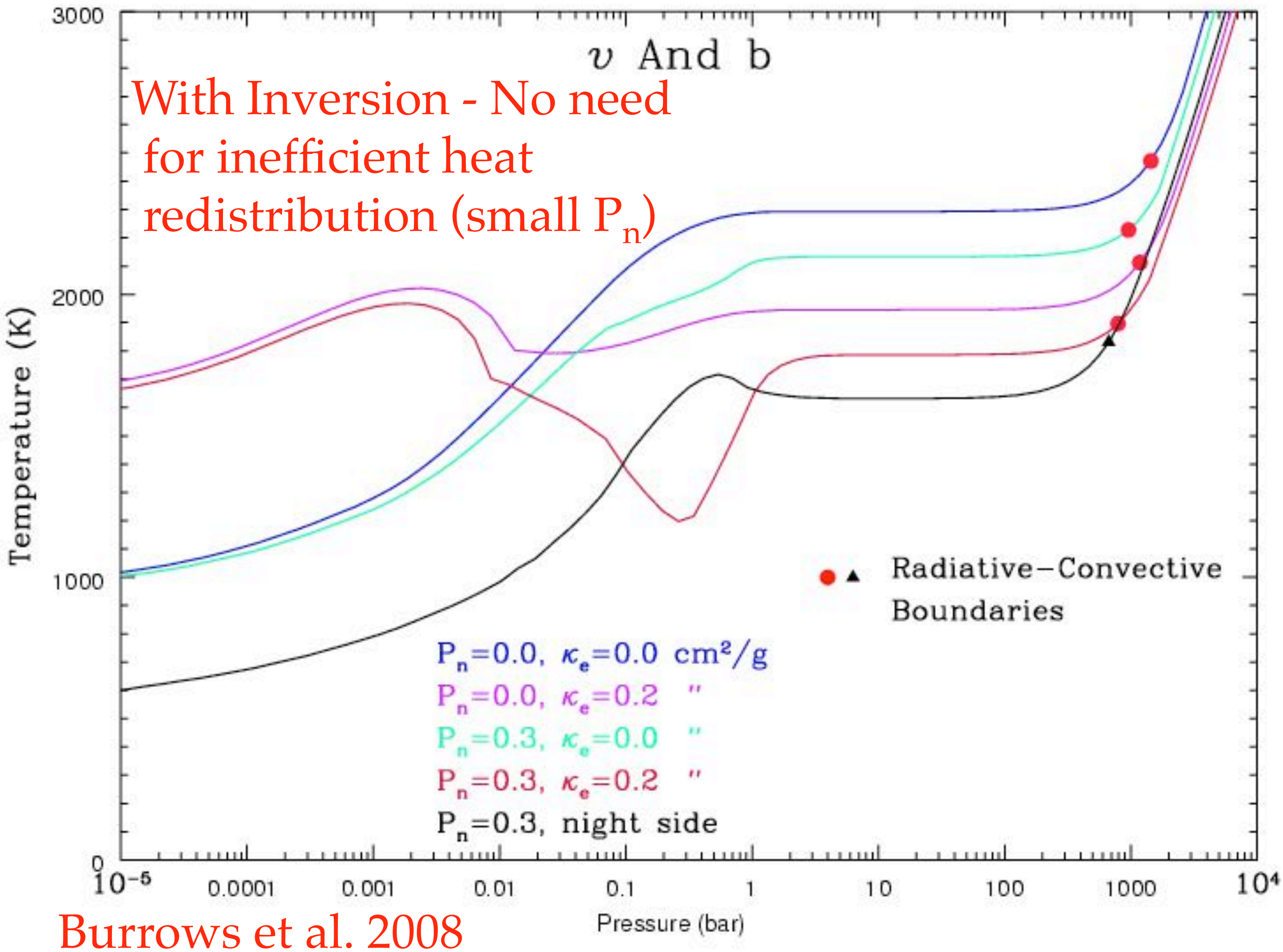
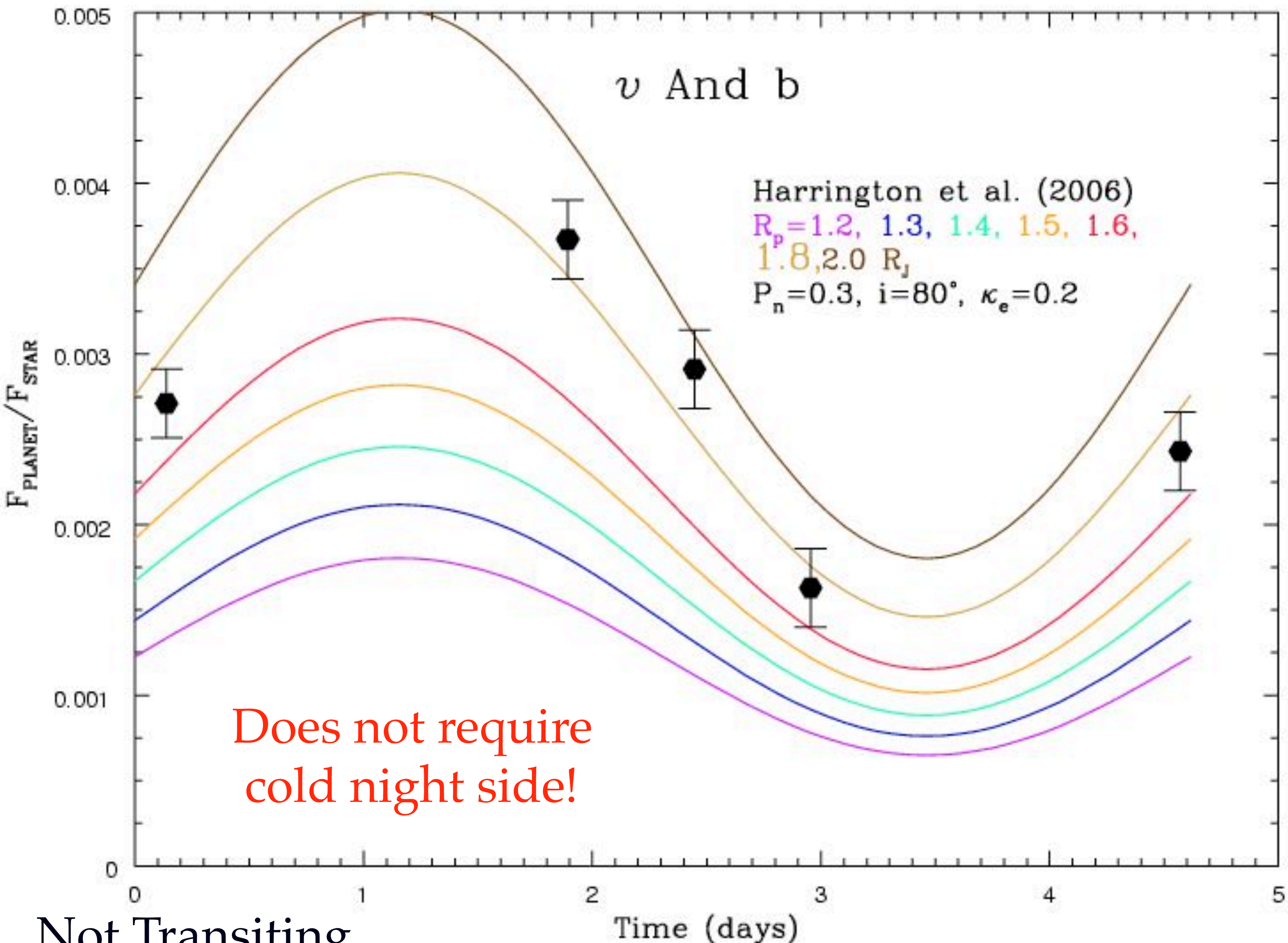


Figure 2: Comparison of the phase curve and the No-Redistribution Model. The solid points show our final phase curve, after applying calibrations, in time order from left to right. The open points are repetitions of these, displaced horizontally by one orbit, to better illustrate the phase coverage over 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.

Harrington et al. 2006

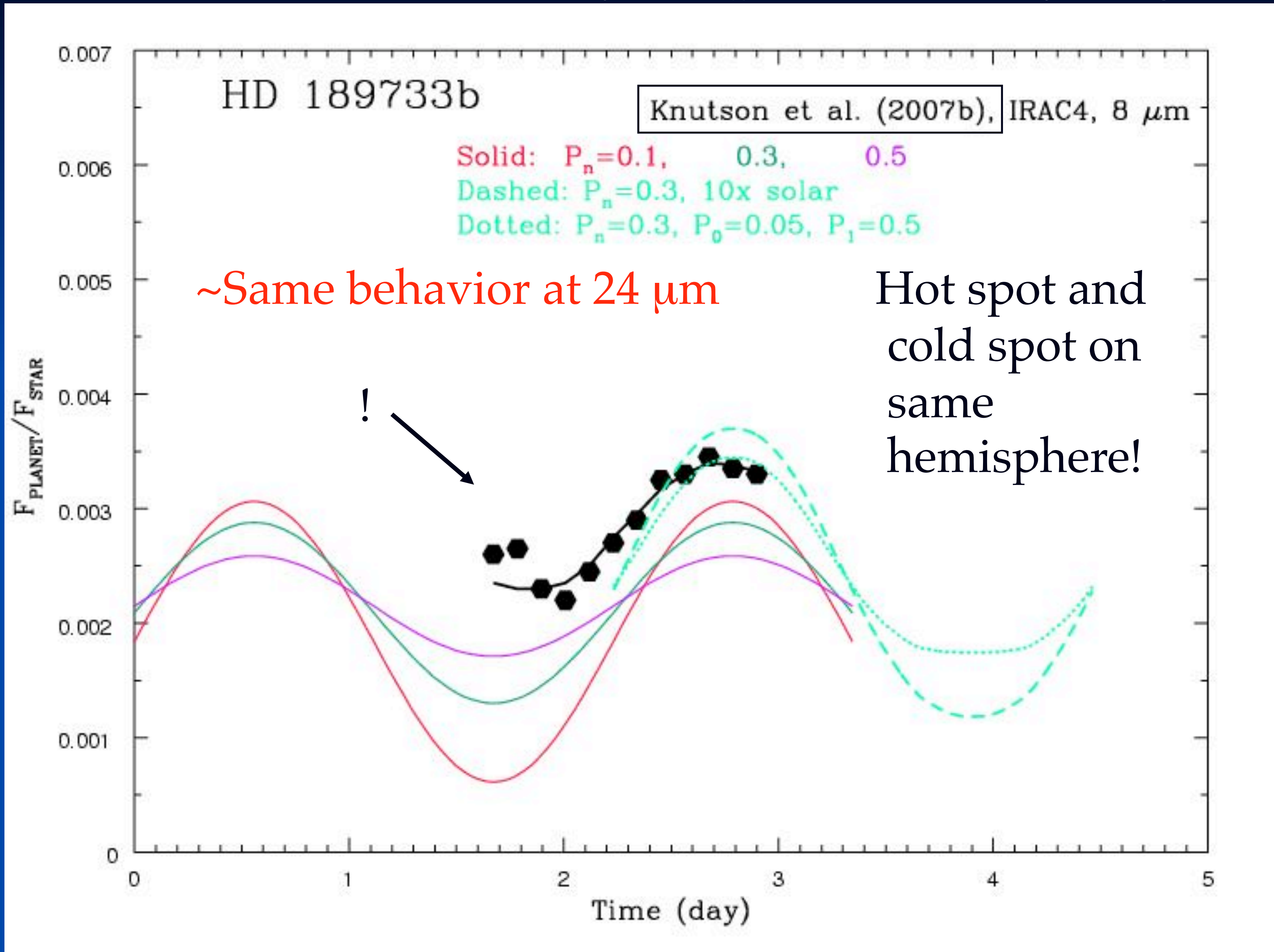


υ And b
With Inversion - No need for inefficient heat redistribution (small P_n)
Temperature (K)
Pressure (bar)
3000
2000
1000
0
10⁻⁵
0.0001
0.001
0.01
0.1
1
10
100
1000
10⁴
Radiative−Convective Boundaries
P_n=0.0, κ_e=0.0 cm²/g
P_n=0.0, κ_e=0.2 "
P_n=0.3, κ_e=0.0 "
P_n=0.3, κ_e=0.2 "
P_n=0.3, night side
Burrows et al. 2008



Not Transiting

Multi-D models do not yet improve fits to anything!



Cho et al. 2003

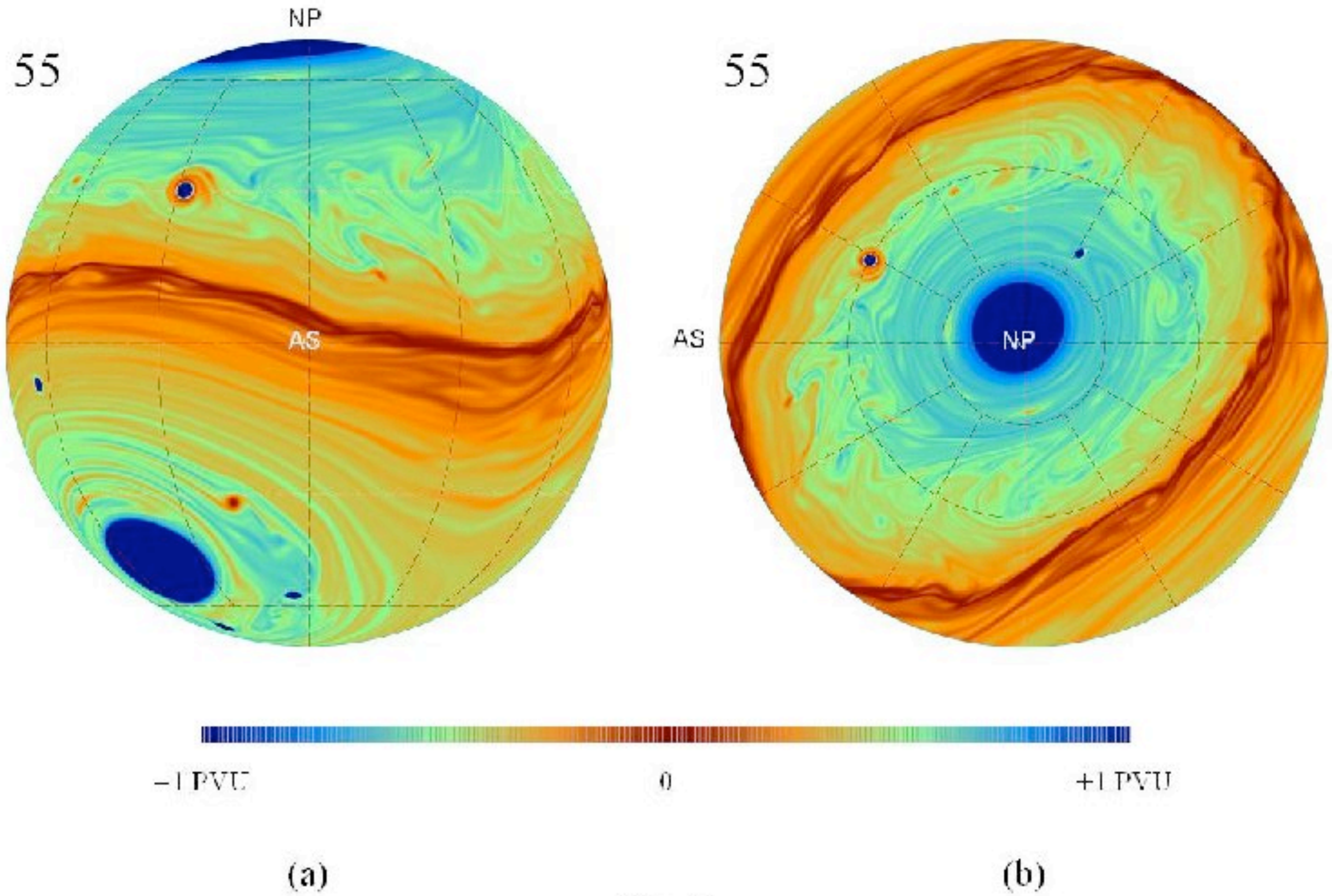
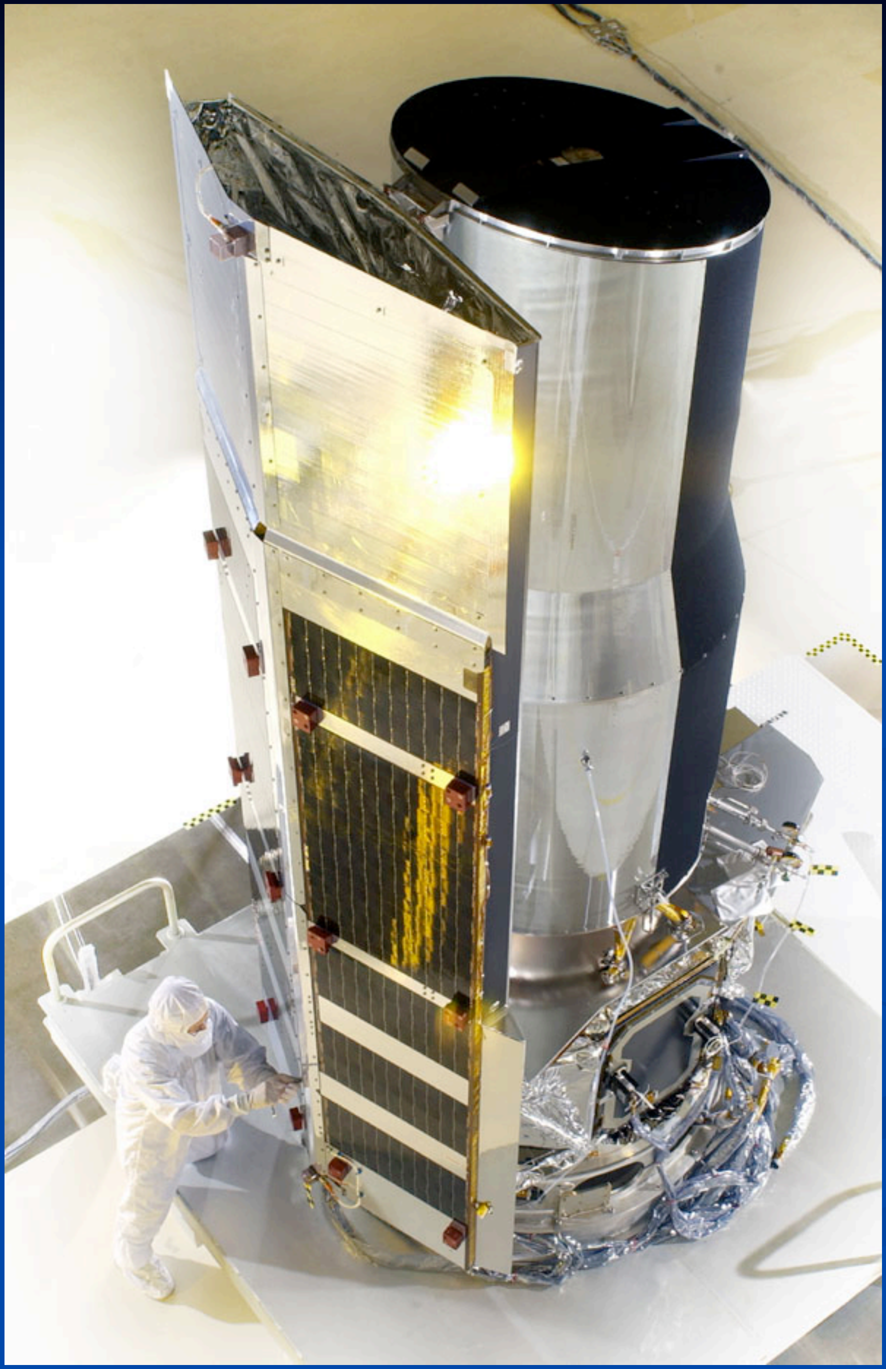


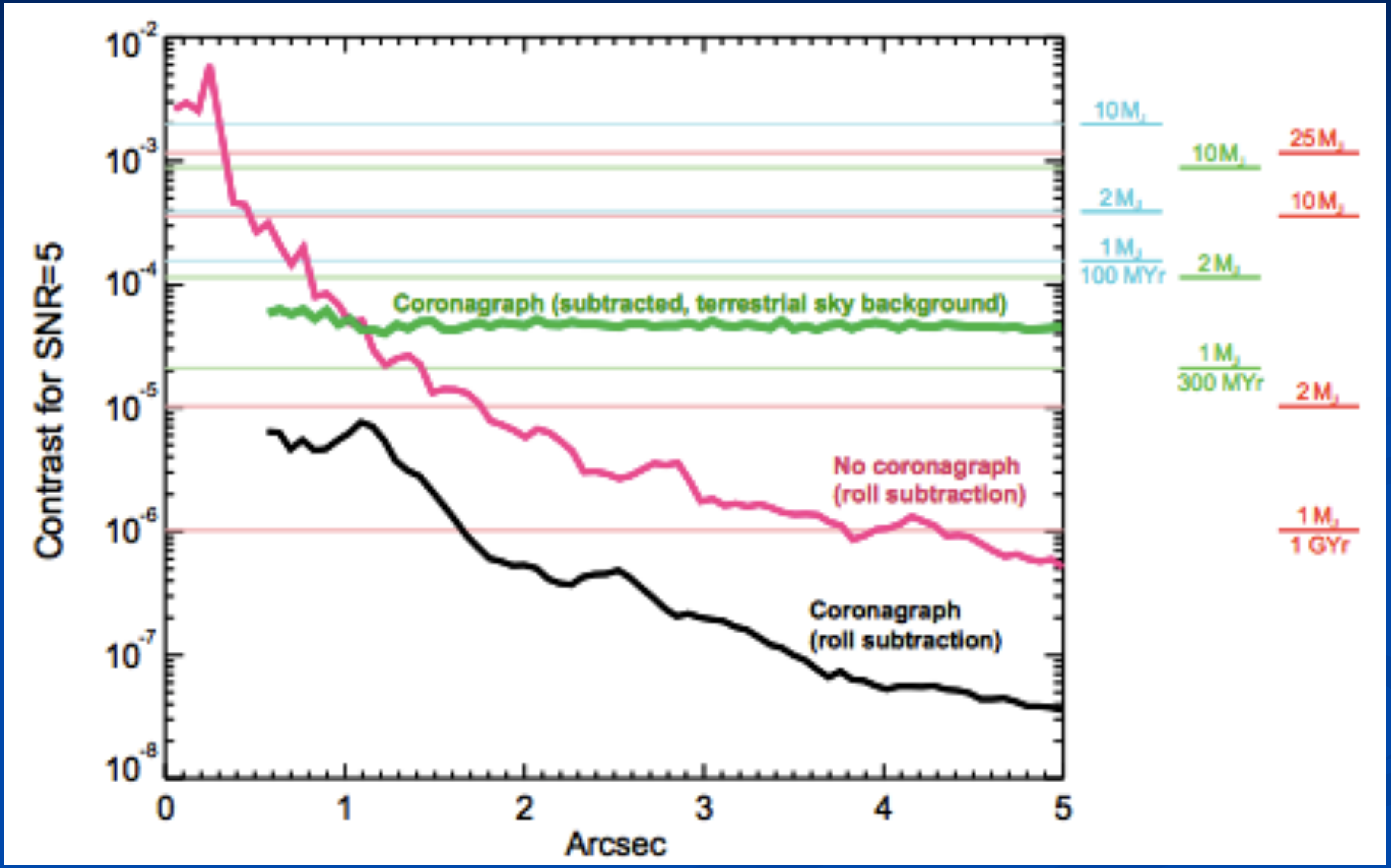
Fig. 1

3D GCMs??? - Have not to date been useful, but in the future ...

“The Beginning”

Spitzer:





Contrast for SNR=5
Arcsec
Coronagraph (subtracted, terrestrial sky background)
No coronagraph
(roll subtraction)
Coronagraph
(roll subtraction)
10M
2M
1M
100 MYr
10M
2M
1M
300 MYr
25M
10M
2M
1M
1 GYr

Table 1 – Log_{10} of planet/star contrast at 4.6 μm (TFI Coronagraph)[1]

Sp	M_m	0.01 Gyrs			0.10 Gyrs			1 Gyrs			5 Gyrs		
		1 M_J	5 M_J	10 M_J	1 M_J	5 M_J	10 M_J	1 M_J	5 M_J	10 M_J	1 M_J	5 M_J	10 M_J
A0	0.78	-5.09	-4.16	-3.78	-5.96	-4.94	-4.47	-7.67	-5.83	-5.33	-8.87	-6.95	-5.97
F0	2.27	-4.49	-3.56	-3.18	-5.37	-4.35	-3.88	-7.07	-5.24	-4.74	-8.27	-6.36	-5.38
G2	3.58	-3.97	-3.04	-2.66	-4.84	-3.82	-3.35	-6.55	-4.71	-4.21	-7.75	-5.83	-4.85
K0	4.29	-3.68	-2.76	-2.38	-4.56	-3.54	-3.07	-6.26	-4.43	-3.93	-7.46	-5.55	-4.59
K5	4.69	-3.52	-2.60	-2.22	-4.40	-3.38	-2.91	-6.10	-4.27	-3.77	-7.30	-5.39	-4.41
M0	5.15	-3.34	-2.41	-2.03	-4.22	-3.20	-2.72	-5.92	-4.08	-3.58	-7.12	-5.20	-4.22
M5	7.98	-2.21	-1.28	-0.9	-3.08	-2.06	-1.59	-4.79	-2.95	-2.45	-5.99	-4.07	-3.09
L0	10.15	-1.34	-0.41	-0.03	-2.22	-1.20	-0.72	-3.92	-2.08	-1.58	-5.12	-3.22	-2.22
L5	10.98	-1.01	-0.08	0.30	-1.88	-0.86	-0.39	-3.59	-1.75	-1.25	-4.79	-2.88	-1.89
T0	11.40	-0.84	0.09	0.48	-1.72	-0.70	-0.22	-3.42	-1.58	-1.08	-4.62	-2.70	-1.72
T5	12.38	-0.45	0.48	0.86	-1.33	-0.31	0.16	-3.03	-1.20	-0.70	-4.23	-2.31	-1.34

[green] Contrast exceeds the 10σ sensitivity beyond 1". [2]
[orange] Contrast exceeds the 10σ sensitivity beyond 5". [2]
[blue] Contrast exceeds the 10σ sensitivity beyond 1" *without* coronagraph and no PSF calibration.

[1] Evolutionary models from Barraffe *et al* 2003.
[2] Contrast threshold assuming the 2" (FWHM) occulting spot and a speckle noise attenuation factor ~10x.

Instrument	Channel/Mode	λ (μm)	R ($\lambda/\delta\lambda$)
NIRCam	Short λ Lyot Coronagraph	0.6 - 2.3	4, 10, 100
NIRCam	Long λ Lyot Corongagraph	2.4 - 5.0	4, 10, 100
TFI	Multi-λ coronagraph	1.6 - 2.5	100
TFI	Multi-λ coronagraph	3.2 - 4.9	100
TFI	Non-redundant mask	1.6 - 2.5	100
TFI	Non-redundant mask	3.2 - 4.9	100
MIRI	Quadrant Phase Coronagraph	10.65	20
MIRI	Quadrant Phase Coronagraph	11.4	20
MIRI	Quadrant Phase Coronagraph	15.5	20
MIRI	Lyot Coronagraph	23	5
MIRI	Integral field spectrograph	5.86 - 7.74	3000
MIRI	Integral field spectrograph	7.43 - 11.84	3000
MIRI	Integral field spectrograph	11.44 - 18.20	3000
MIRI	Integral field spectrograph	17.53 - 28.75	2250
NIRSpec	Integral field spectrograph	0.7 - 5.0	2700

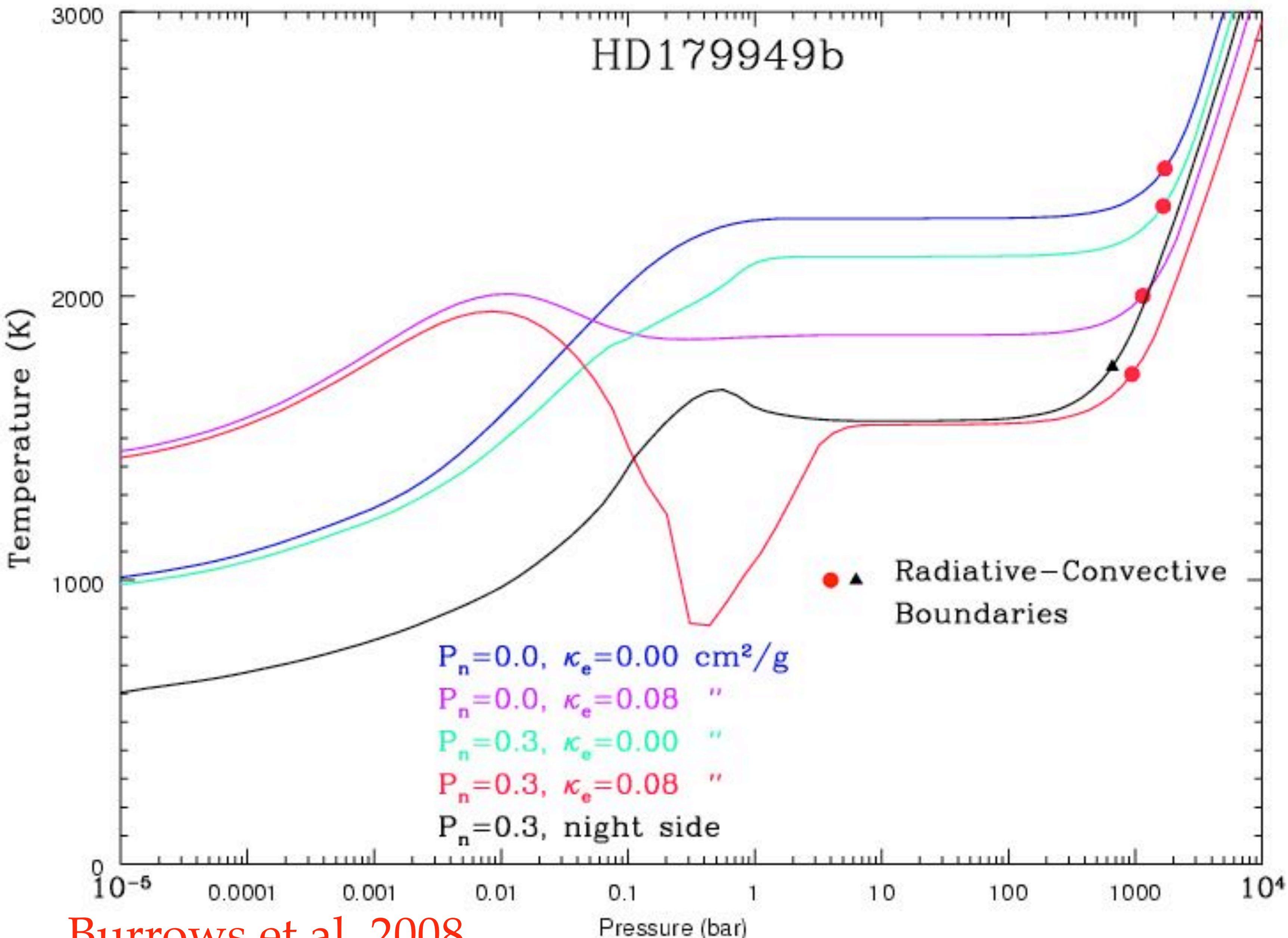
SI	λ (μm)	Spectral Resolution (λ/δλ)	FOV	Mode	Comments	Application
NIRCam	0.6 - 2.3 2.4 - 5.0	4, 10, 100 4, 10, 100	2 x (2.2' x 2.2') 2 x (2.2' x 2.2')	Imaging Imaging	Photometric Imaging	High precision light curves of transits from photometry of point source images. Wavelength coverage permits photometric monitoring of primary or secondary eclipses.
NIRCam	0.6 – 2.3	4, 10, 100	2 x (2.2' x 2.2')	Phase diversity imaging	Defocusing of images to 57 or 114 pixel diameters	High precision light curves of transits associated with bright objects which need to be defocused to avoid saturation within the minimum integration time
NIRCam	2.4 – 5.0	2000	2 x (2.2' x 2.2')	Long-λ Grism	Backup capability for WFSC. Used with F277W, F322W, F356W, F410M or F444W	Emission spectroscopy of hot gas giant transiting planets
NIRSpec	1.0 – 5.0	100, 1000, 2700	0.1" x 2.0", 0.2" x 3.5", 0.4"x 4.0"	Spectroscopy	Fixed long slits	Low and intermediate resolution transmission and emission spectroscopy of transiting planets.
NIRSpec	0.7 - 5.0	2700	3" x 3"	Spectroscopy	Integral Field Unit	Intermediate resolution, transmission and emission spectroscopy of transiting planets.
MIRI	5 – 29	4-6	1.9' x 1.4'	Imaging	Photometric Imaging	
MIRI	5 - 11	100	5" x 0.2"	Spectroscopy	Fixed Slit or Slitless	Light curves of transits from photometry of point source images.
MIRI	5.9 – 7.7 7.4 – 11.8 11.4 – 18.2 17.5 – 28.8	3000 3000 3000 3000	3.7" x 3.7" 4.7" x 4.5" 6.2"x 6.1" 7.1"x7.7"	Spectroscopy	Integral field unit	Intermediate resolution, emission spectroscopy of transiting planets.
TFI	1.6 – 2.5	100	2.2' x 2.2'	Imaging	Selectable central λ	High precision light curves of transits from photometry of point source images. Wavelength coverage permits photometric monitoring of primary eclipses.
TFI	3.2 – 4.9	100	2.2' x 2.2'	Imaging	Selectable central λ	High precision light curves of transits from photometry of point source images. Wavelength coverage permits photometric monitoring of secondary eclipses.

TABLE X

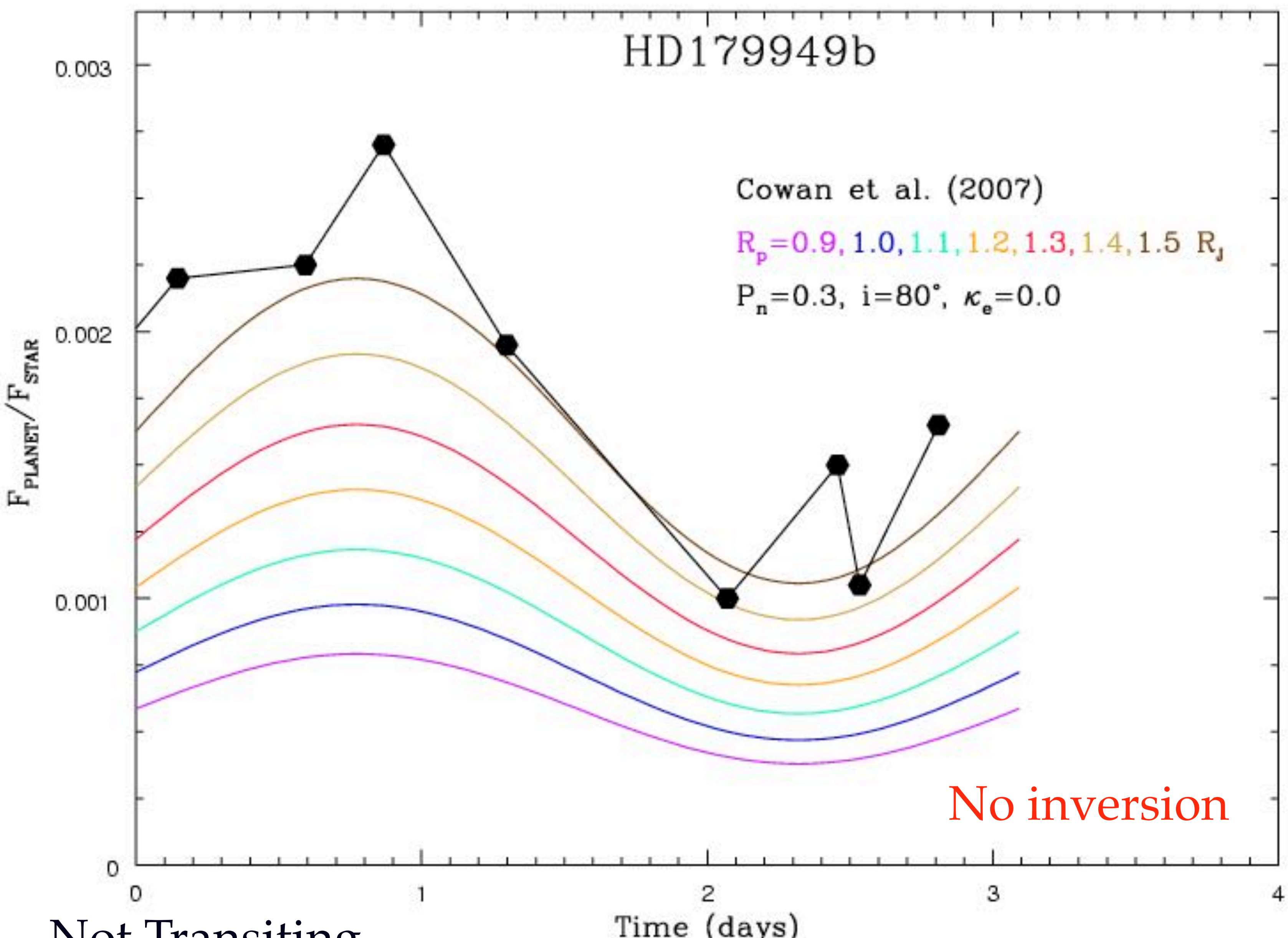
Instrument sensitivities

Instrument/mode	λ (μm)	Bandwidth	Sensitivity
NIRCam	2.0	$R = 4$	11.4 nJy, AB = 28.8
TFI	3.5	$R = 100$	126 nJy, AB = 26.1
NIRSpec/Low Res.	3.0	$R = 100$	132 nJy, AB = 26.1
NIRspec/Med. Res.	2.0	$R = 1000$	1.64×10^{-18} erg s^{-1} cm^{-2}
MIRI/Broadband	10.0	$R = 5$	700 nJy, AB = 24.3
MIRI/Broadband	21.0	$R = 4.2$	8.7 μJy, AB = 21.6
MIRI/Spect.	9.2	$R = 2400$	1.0×10^{-17} erg s^{-1} cm^{-2}
MIRI/Spect.	22.5	$R = 1200$	5.6×10^{-17} erg s^{-1} cm^{-2}

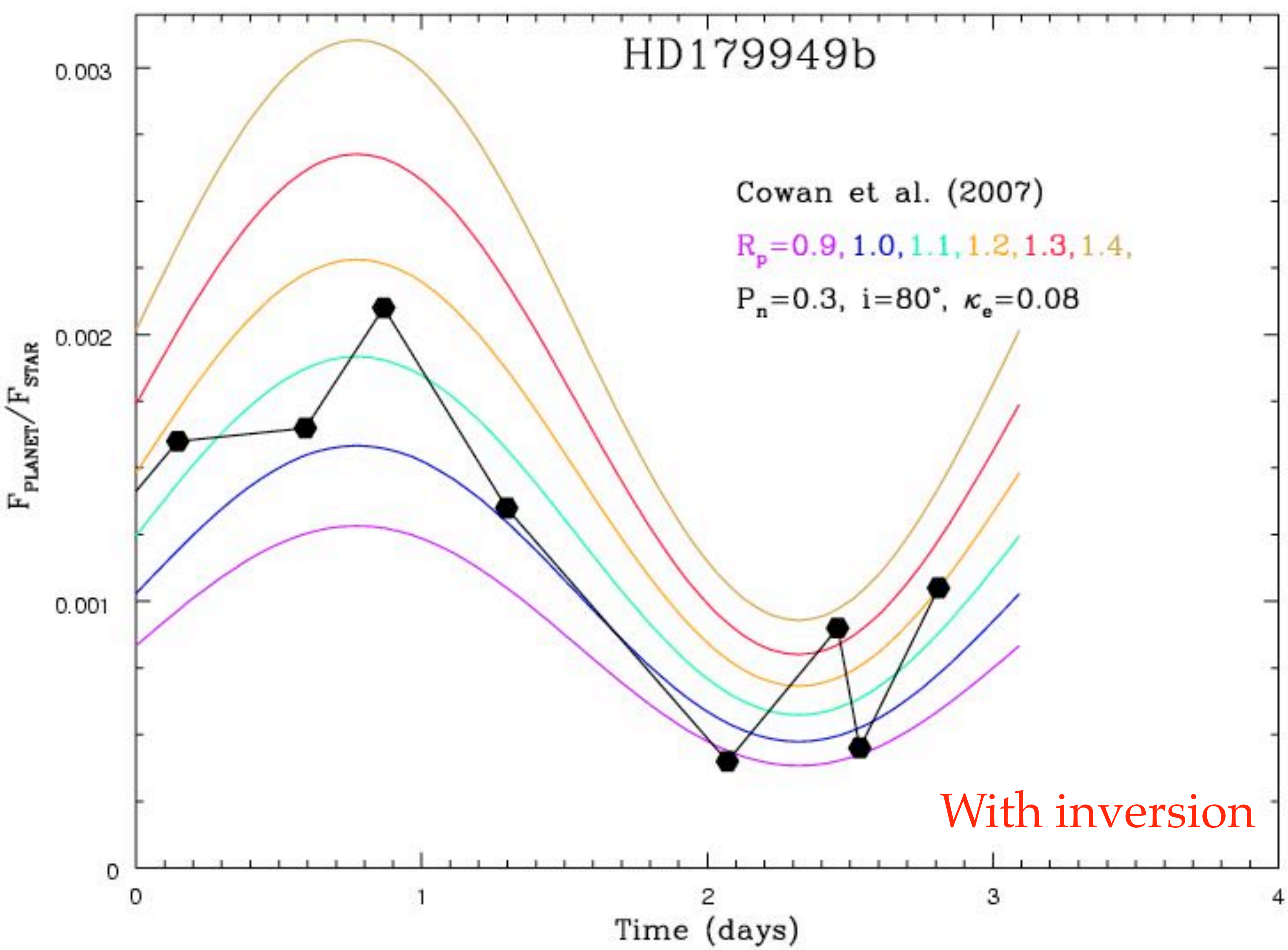
Note. Sensitivity is defined to be the brightness of a point source detected at 10σ in 10,000 s. Longer or shorter exposures are expected to scale approximately as the square root of the exposure time. Targets at the North Ecliptic Pole are assumed. The sensitivities in this table represent the best estimate at the time of submission and are subject to change.



Burrows et al. 2008

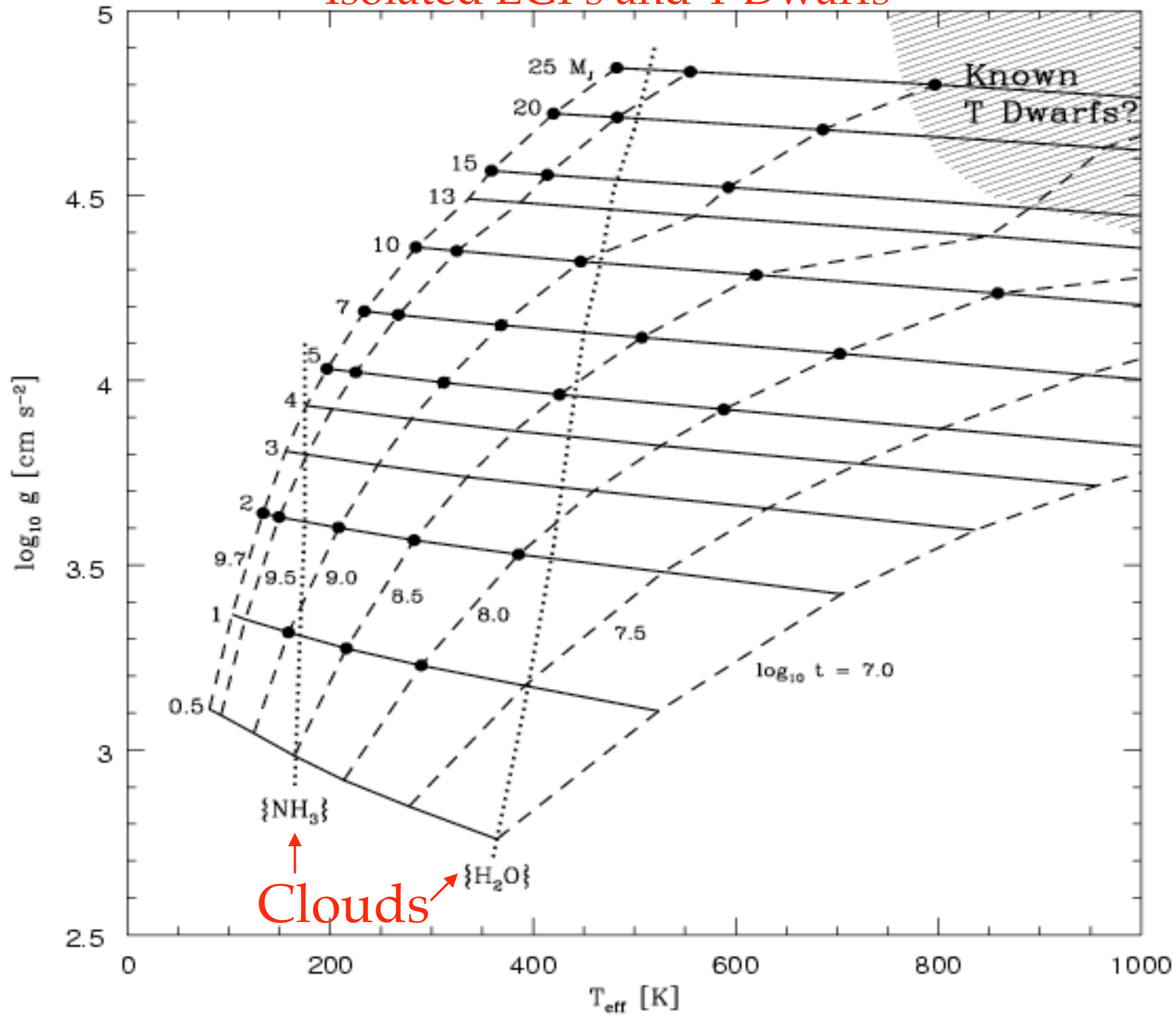


Not Transiting

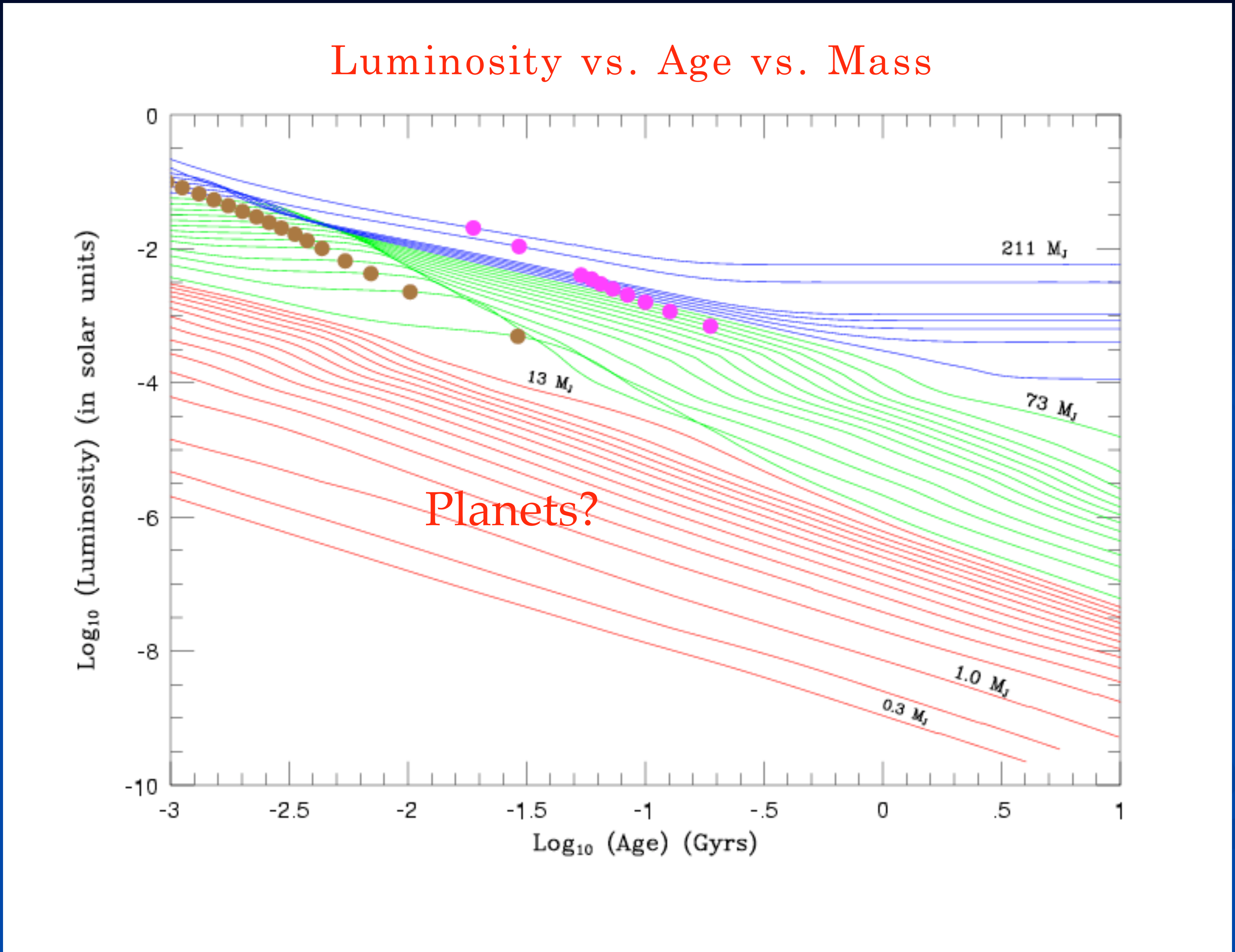


HD179949b
Cowan et al. (2007)
R_p=0.9, 1.0, 1.1, 1.2, 1.3, 1.4,
P_n=0.3, i=80°, κ_e=0.08
With inversion
F_{PLANET}/F_{STAR}
0.003
0.002
0.001
0
0
1
2
3
4
Time (days)

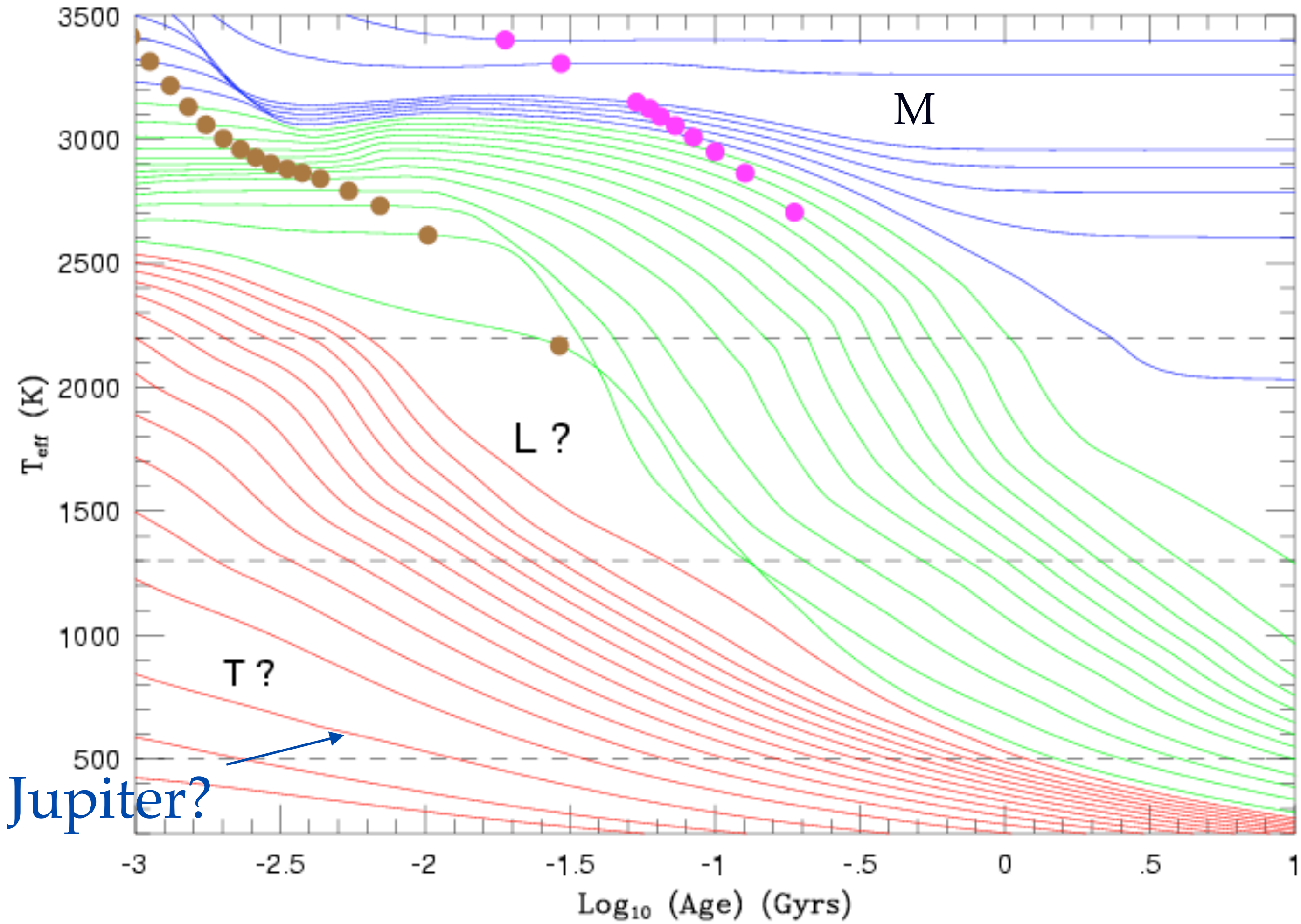
Isolated EGPs and Y Dwarfs



Burrows, Sudarsky, and Lunine 2003



Burrows et al. 1997; Burrows et al. 2001



Burrows et al. 2001

Future of Direct and Indirect Detection of Exoplanets

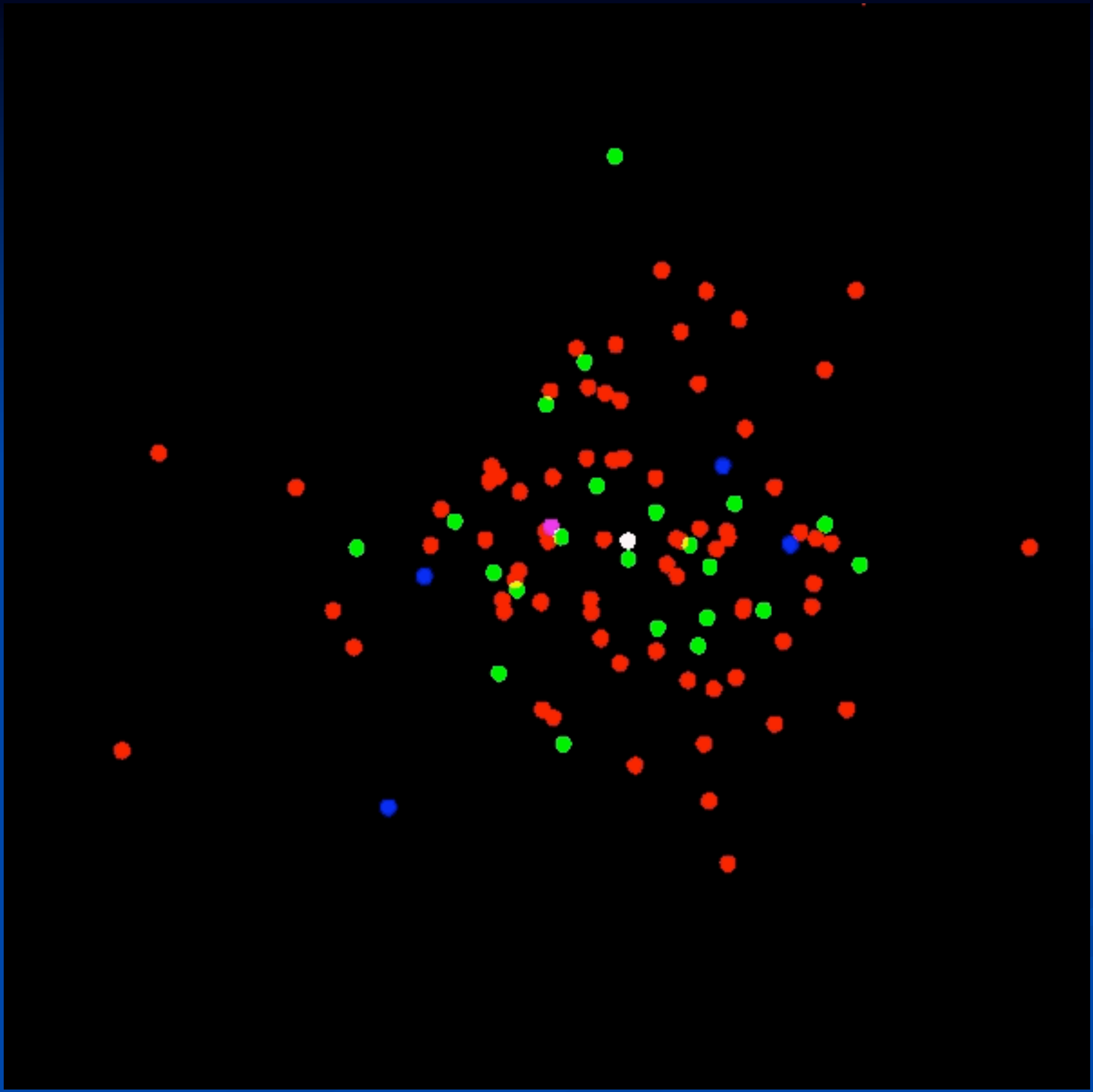
From the Ground:

- 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:

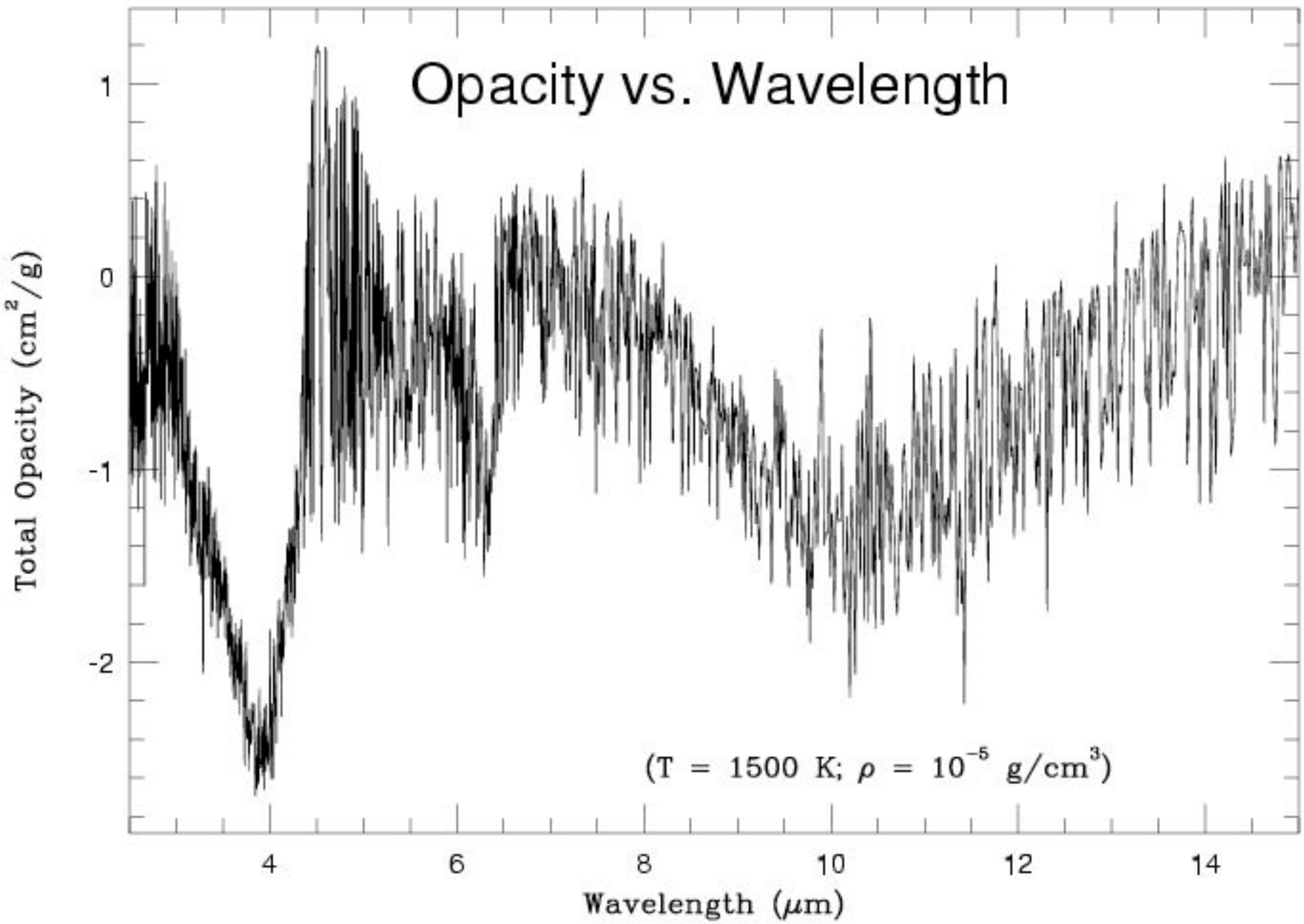
- HST - NICMOS/ACS/STIS
- EPOXI
- Spitzer - Warm Spitzer
- JWST (MIRI, NIRCam)
- SIM(?)/GAIA
- "Eclipse/TOPS" (coronagraph); PIAA?
- Kepler/CoRoT !
- WISE !
- TPF-C; TPF-I/Darwin, TPF-O??

Colors:
Metallicity



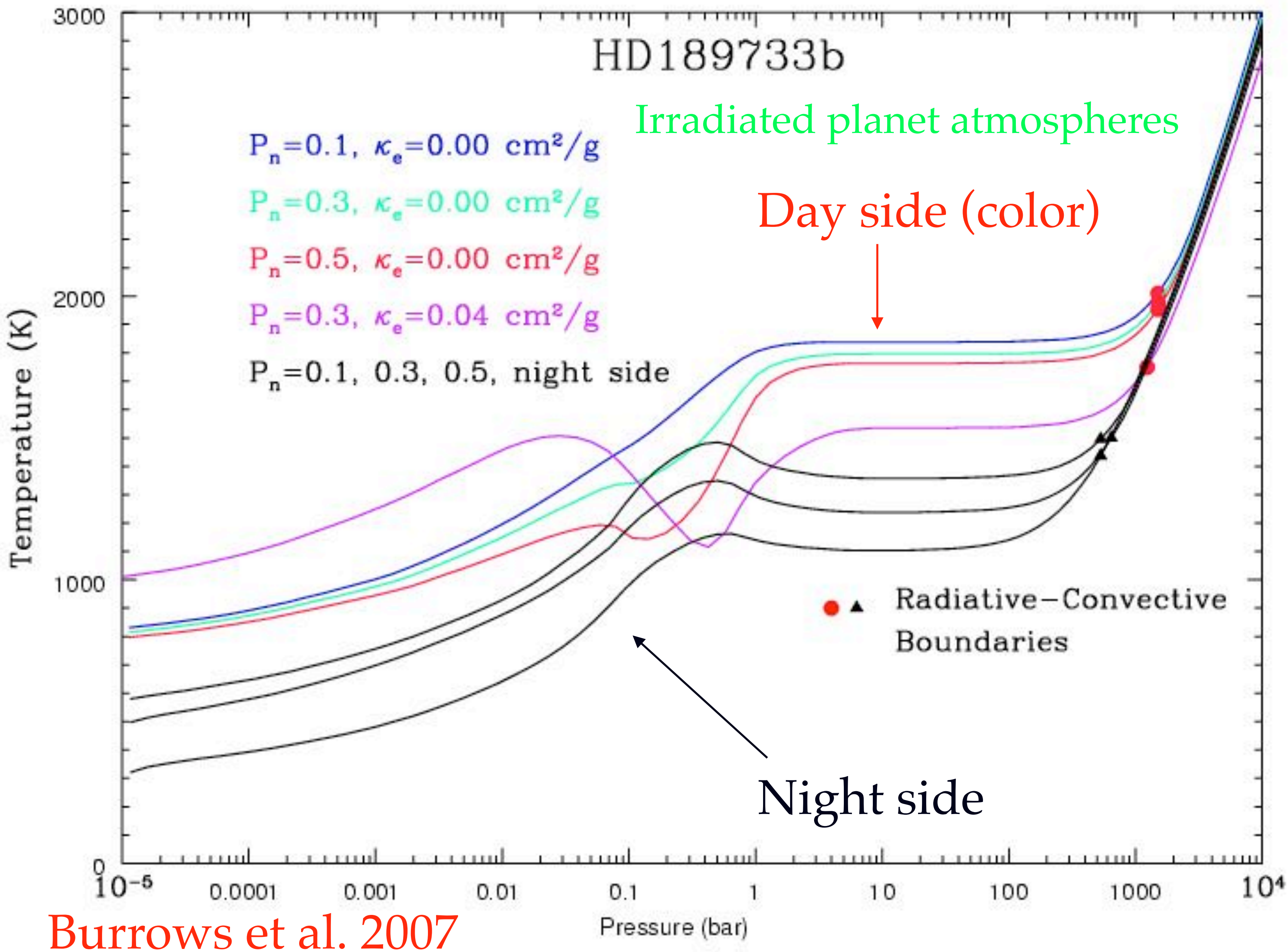
Circa 2002

Jason Young:



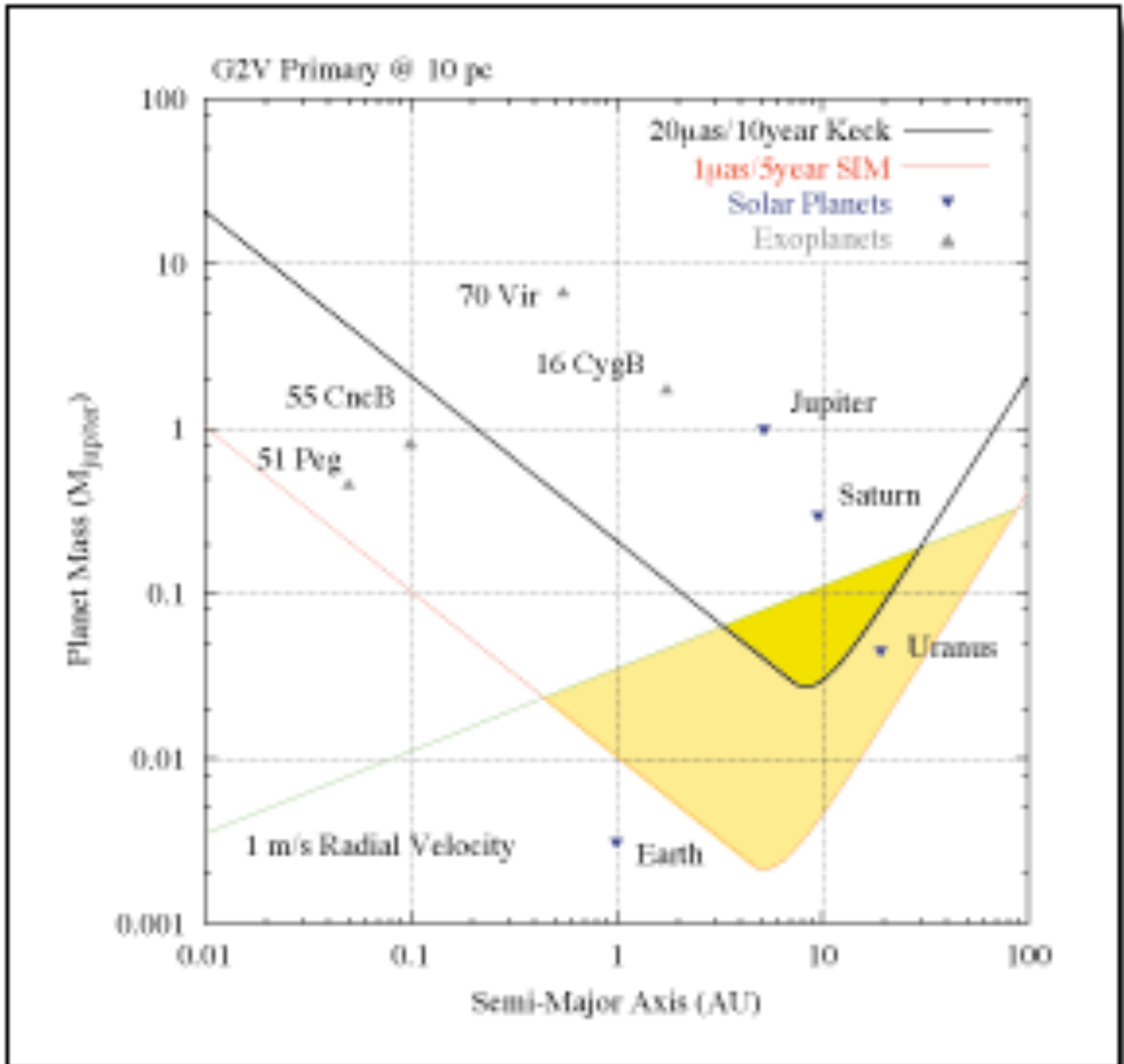
Opacity vs. Wavelength
Total Opacity (cm^2/g)
1
0
-1
-2
4
6
8
10
12
14
Wavelength (μm)
(T = 1500 K; ρ = 10^{-5} g/cm^3)

Mostly H_2O



Burrows et al. 2007

SIM:



SIM's discovery space for planets.