# "Spectra and Photometry: Windows into Exoplanet Atmospheres"

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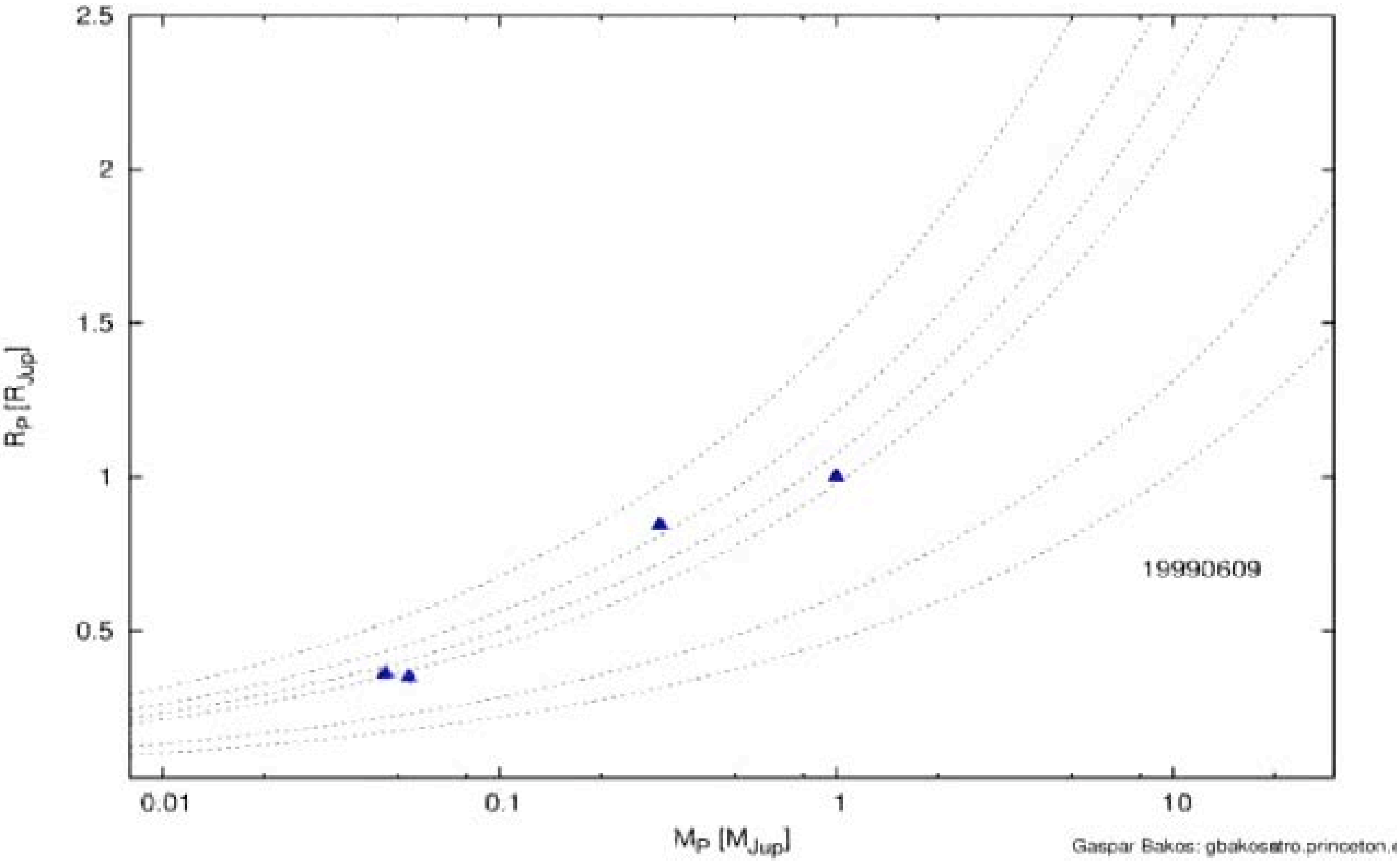
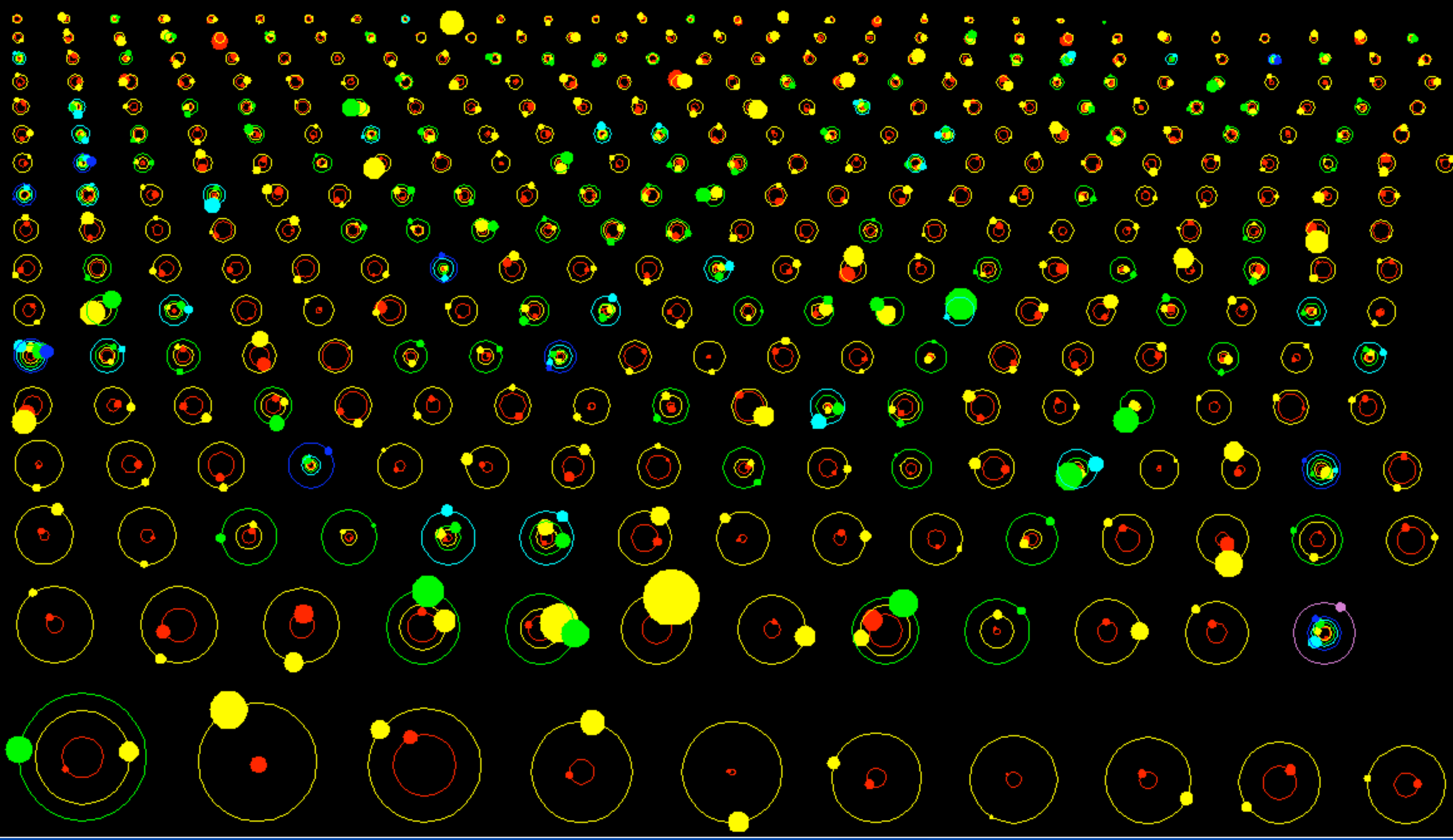
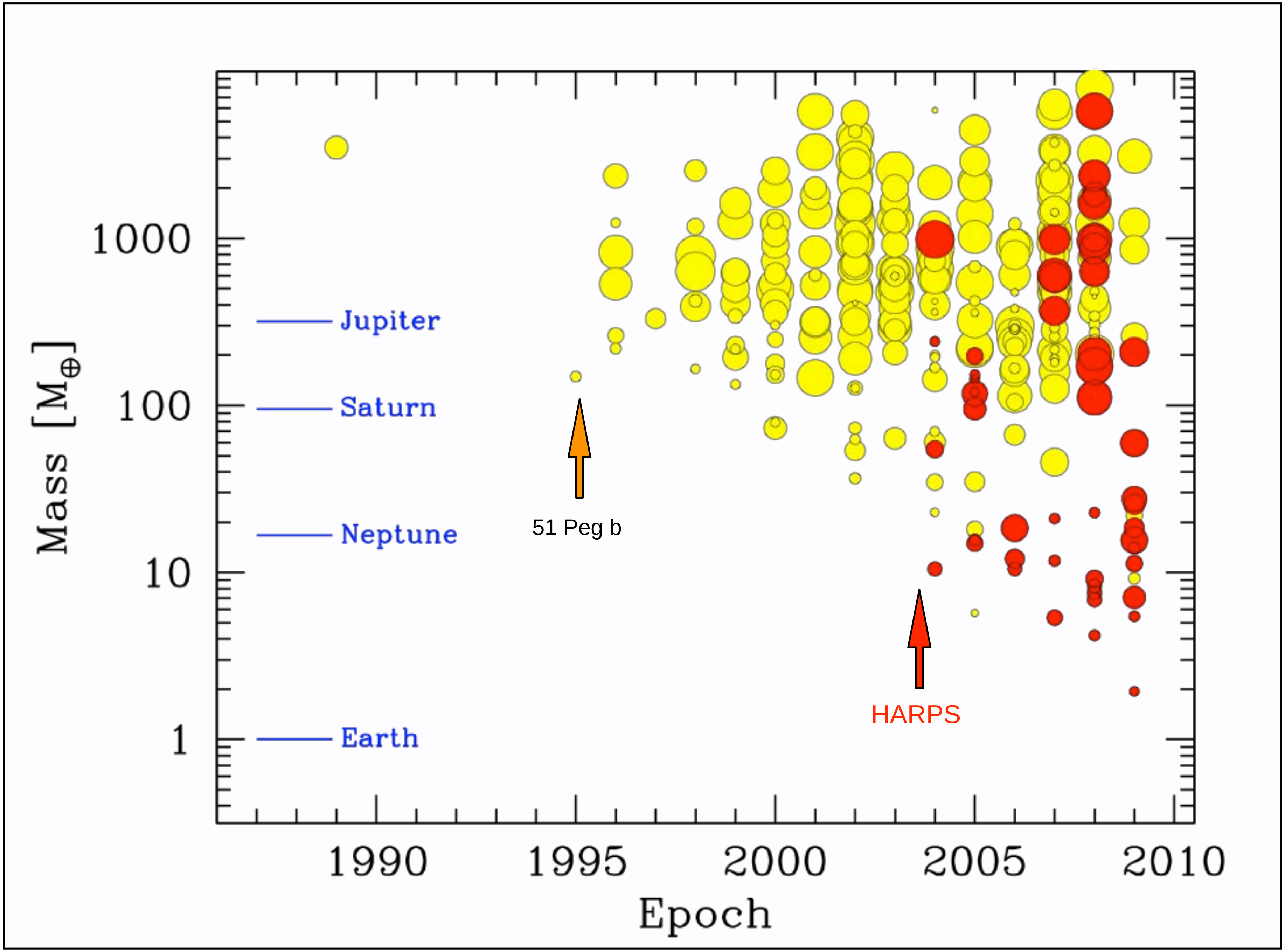
Our Solar System


2.5
2
1.5
1
0.5
0.01
0.1
1
10
$R_P$ [$R_{Jup}$]
$M_P$ [$M_{Jup}$]
19990609
Gaspar Bakos: gbakosatro.princeton.e

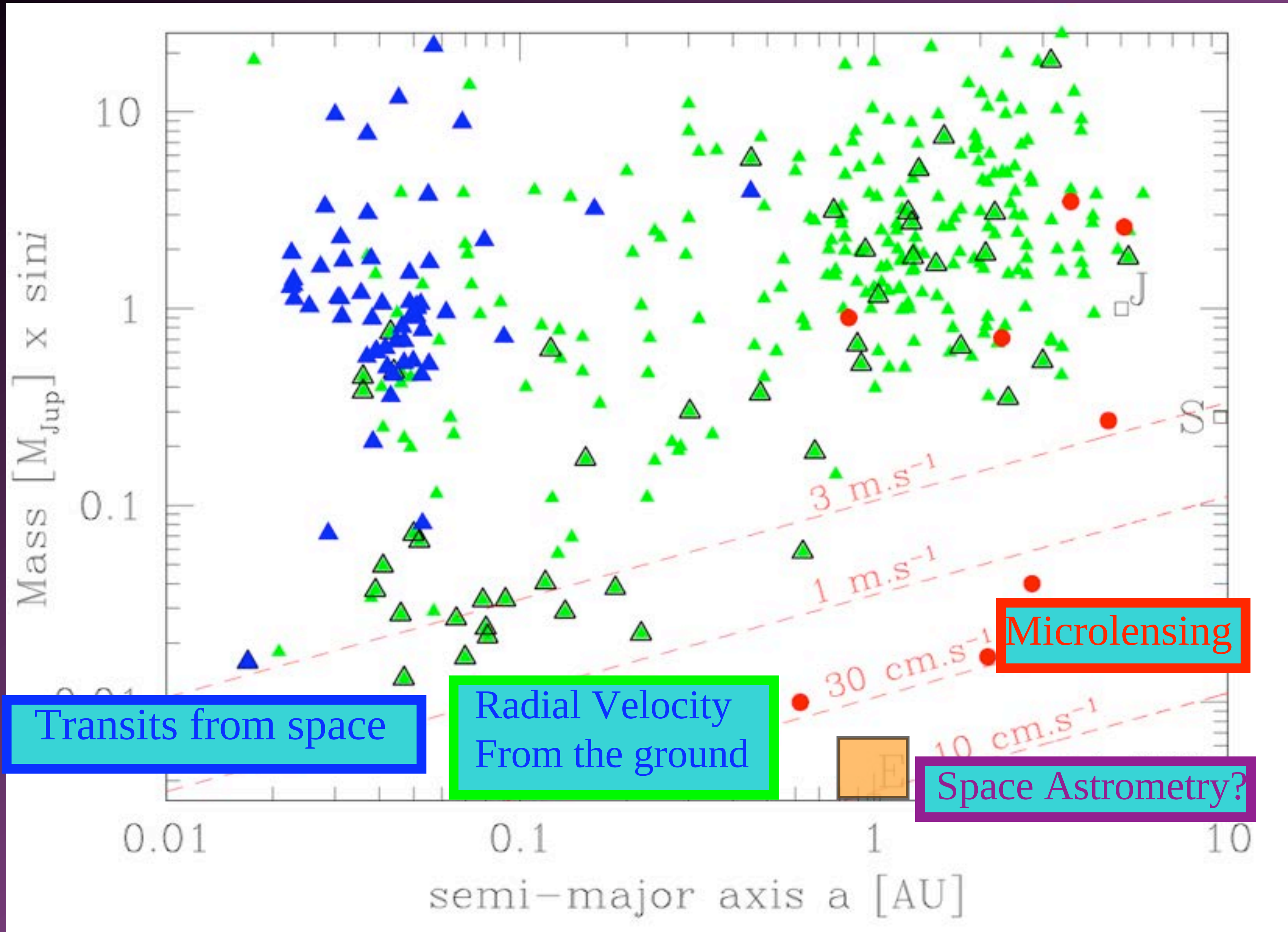
# The Kepler Orrery II

t[BJD] = 2455879          D. Fabrycky 2012

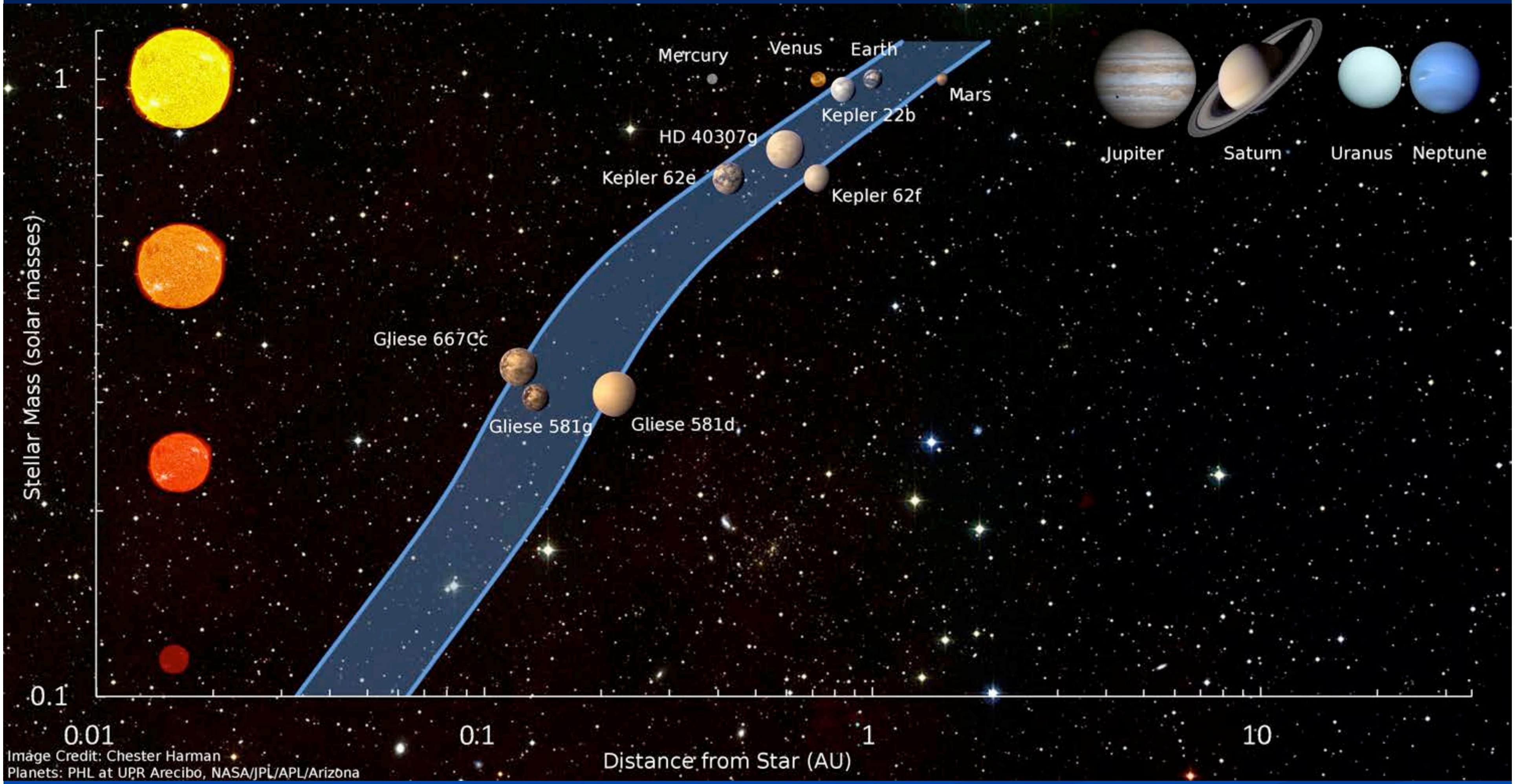




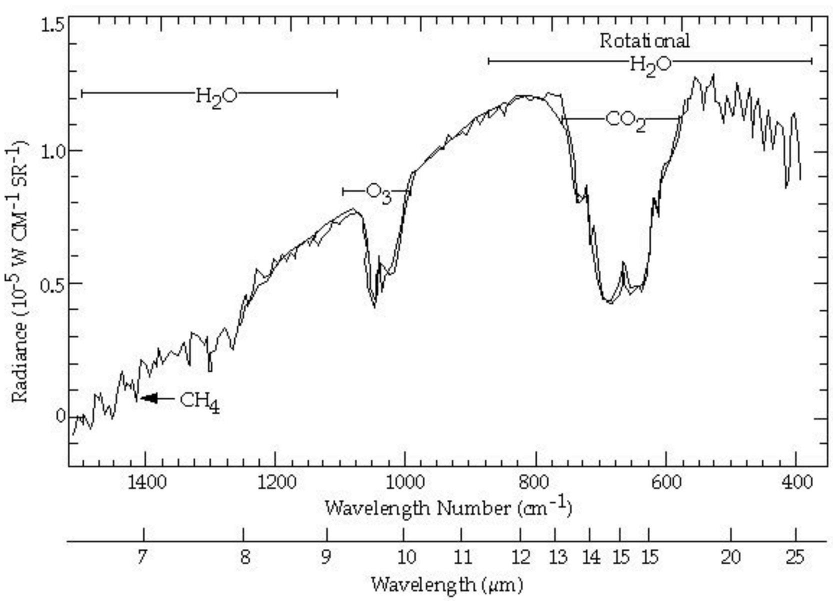
Mass [M⊕]
1000
100
10
1
Jupiter
Saturn
Neptune
Earth
51 Peg b
HARPS
1990
1995
2000
2005
2010
Epoch



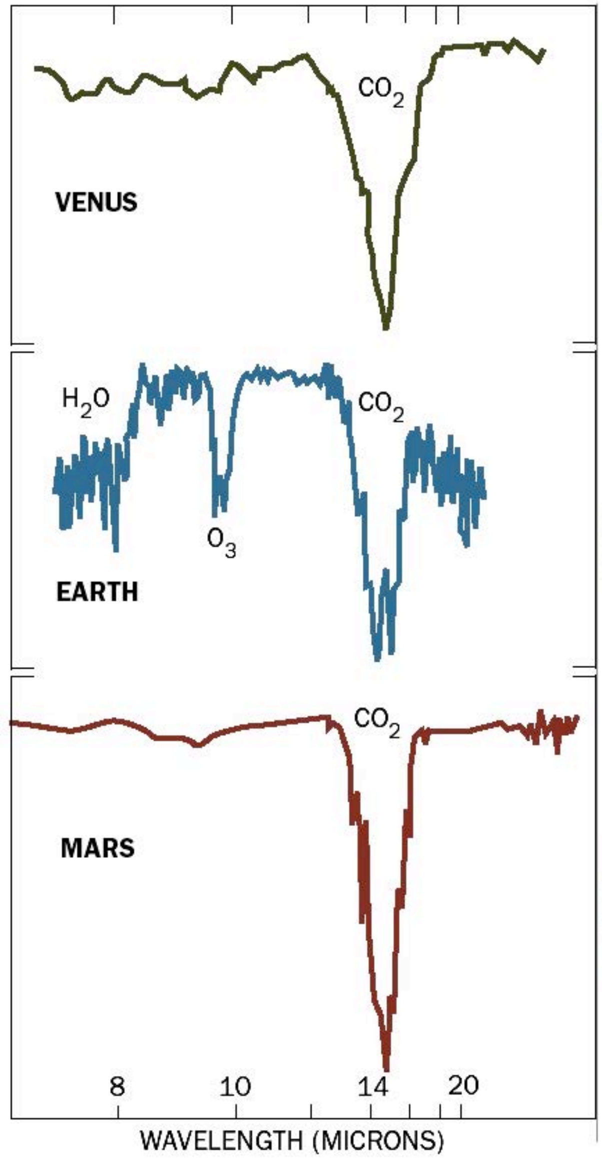
Mass [M_Jup] x sini
10
1
0.1
0.01
0.01
0.1
1
10
semi−major axis a [AU]
3 m.s-1
1 m.s-1
30 cm.s-1
10 cm.s-1
J
S
E
Transits from space
Radial Velocity
From the ground
Microlensing
Space Astrometry?



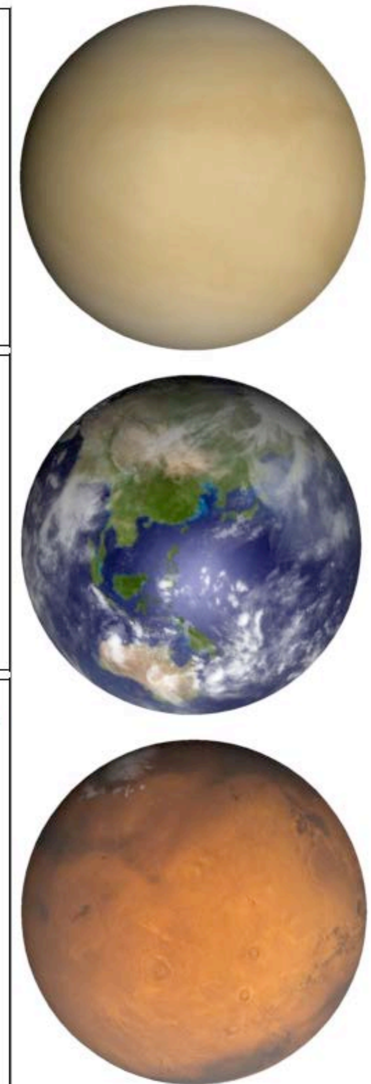

Kasting and Harman 2013



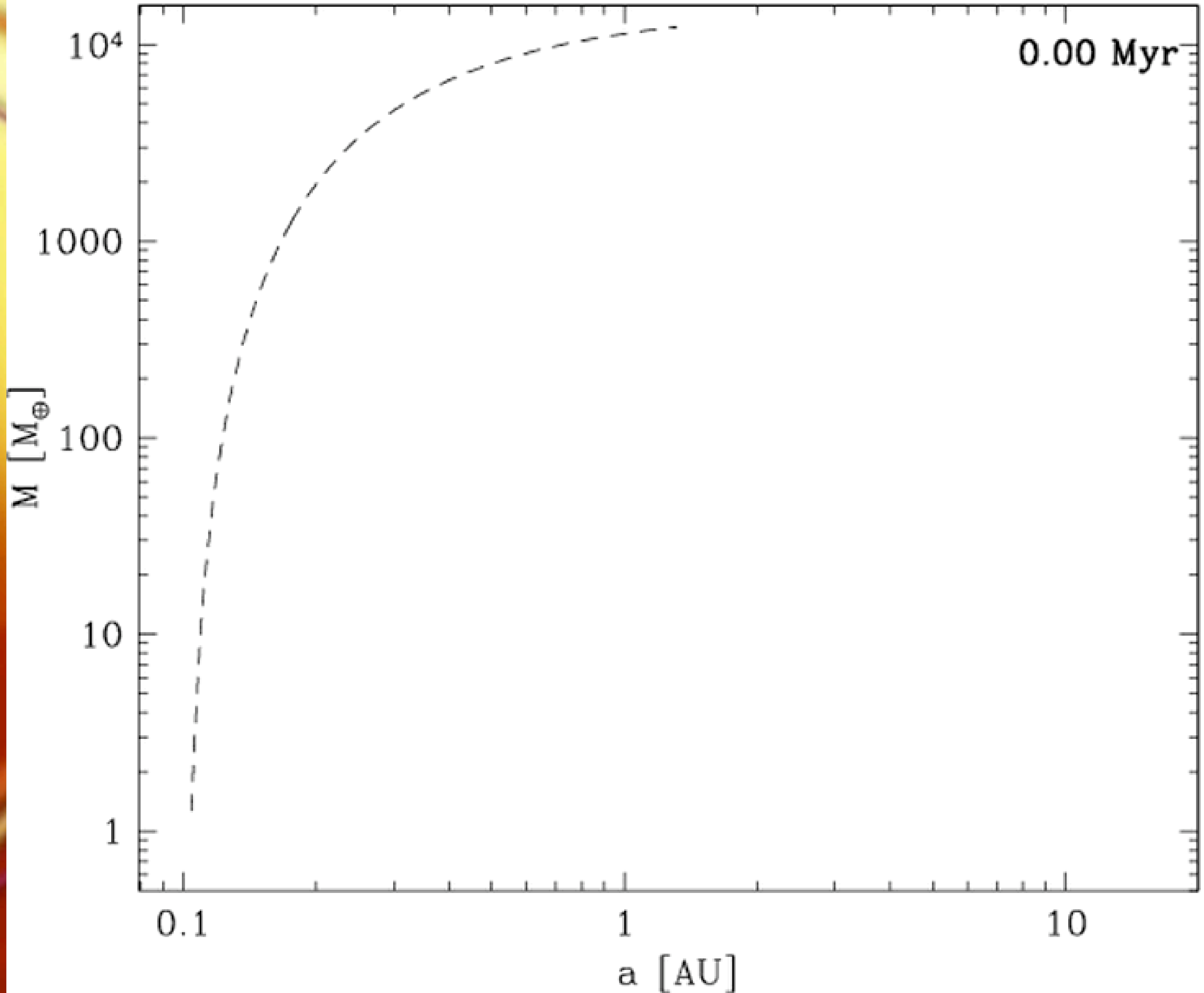
1.5
1.0
0.5
0
Radiance (10-5 W CM-1 SR-1)
Rotational
H2O
H2O
O3
CO2
CH4
1400
1200
1000
800
600
400
Wavelength Number (cm-1)
7
8
9
10
11
12
13
14
15
15
20
25
Wavelength (μm)

VENUS
CO2
EARTH
H2O
O3
CO2
MARS
CO2
8
10
14
20
WAVELENGTH (MICRONS)

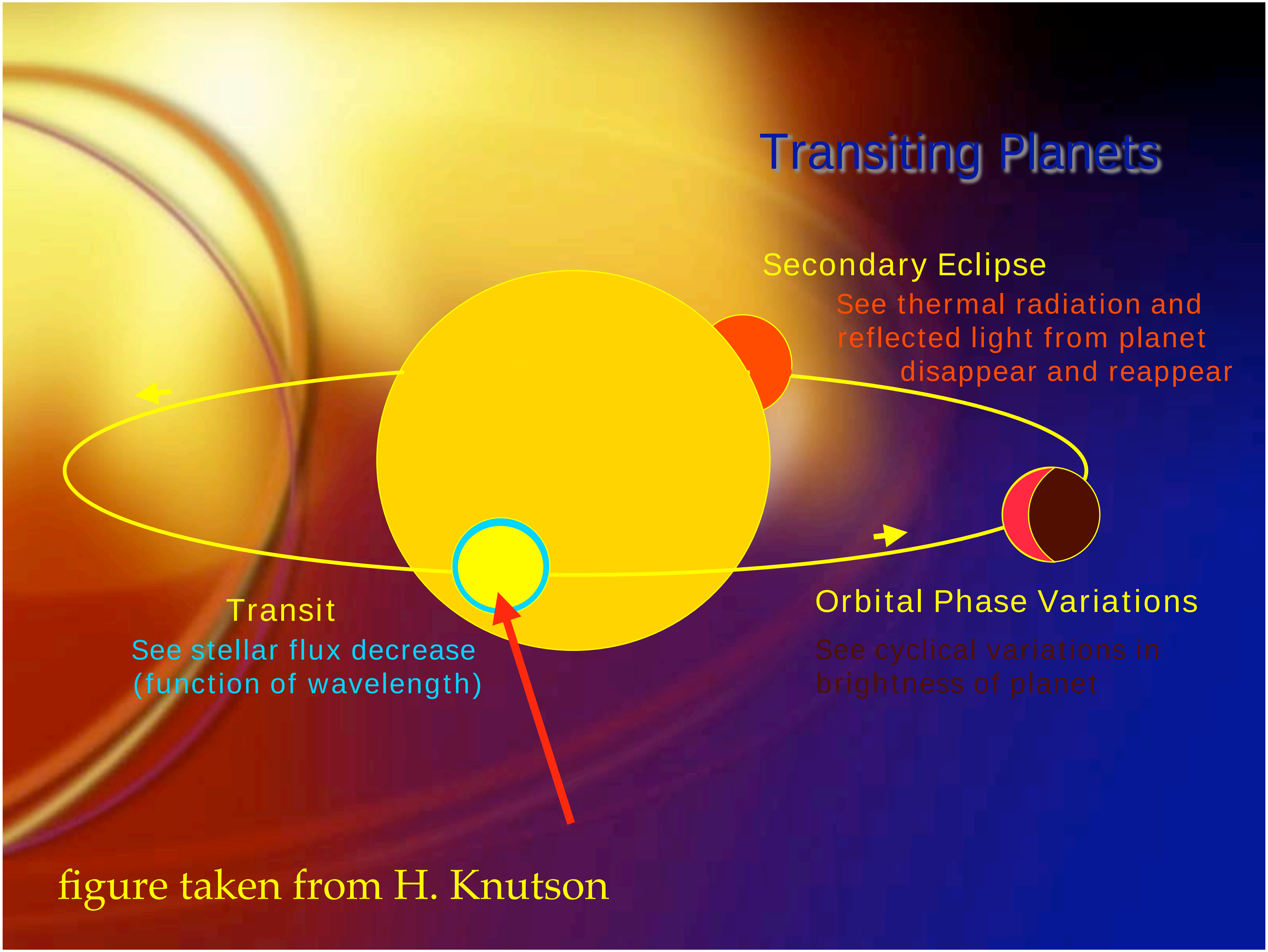



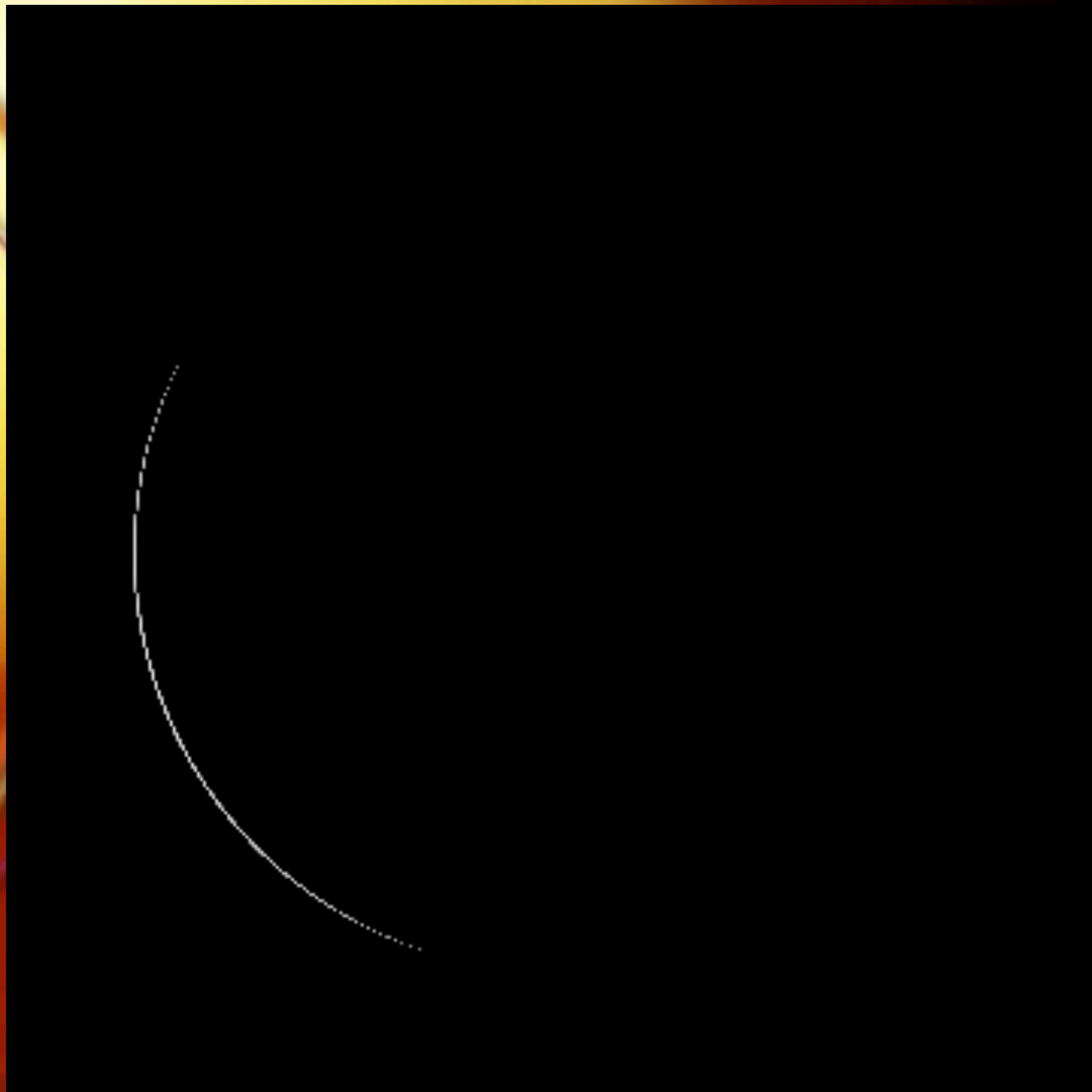
# Population Synthesis




Mordasini, Alibert, Benz

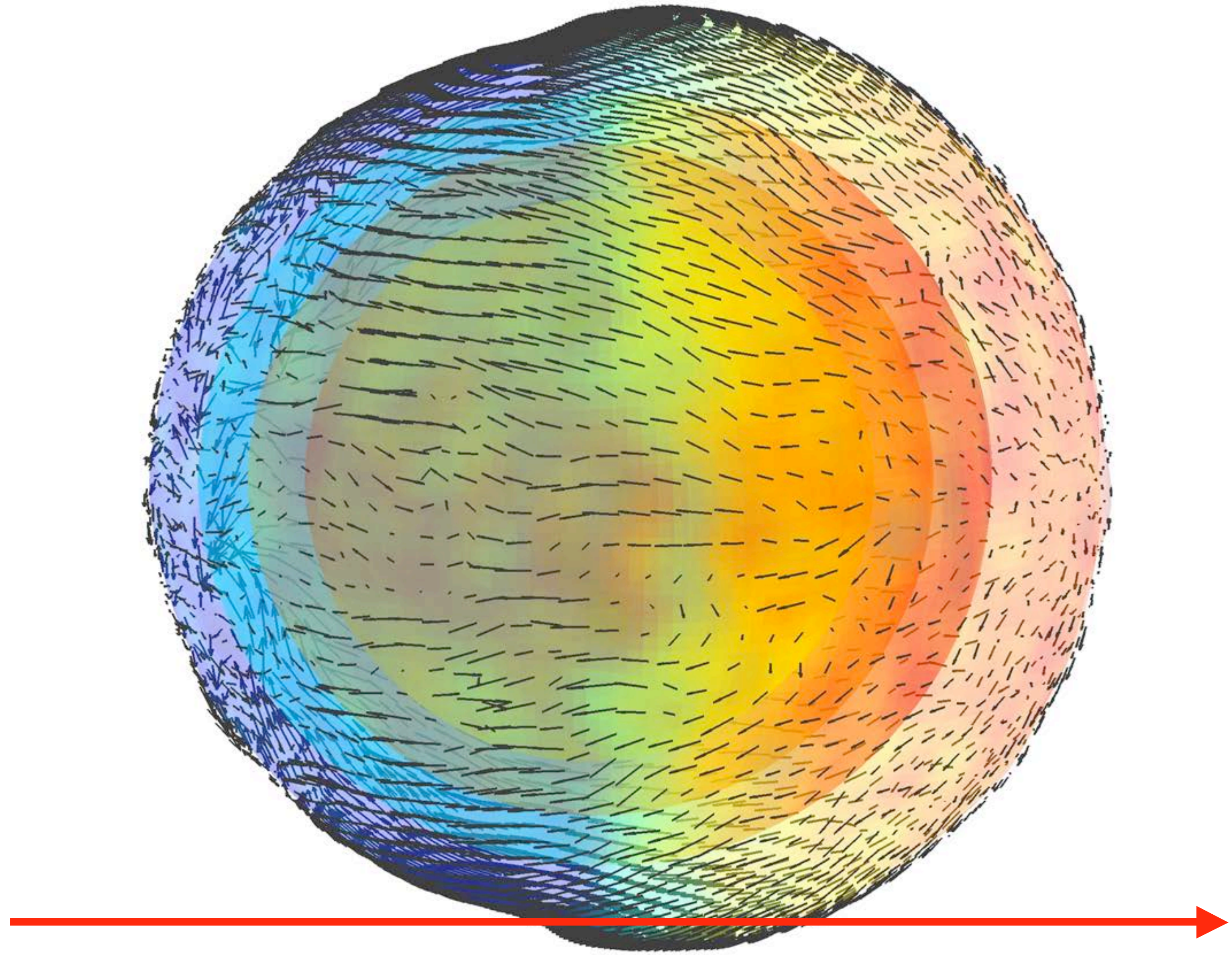
Univ. Bern


Transiting Planets
Secondary Eclipse
See thermal radiation and
reflected light from planet
disappear and reappear
Transit
See stellar flux decrease
(function of wavelength)
Orbital Phase Variations
See cyclical variations in
brightness of planet
figure taken from H. Knutson



With upper-atmosphere optical absorber

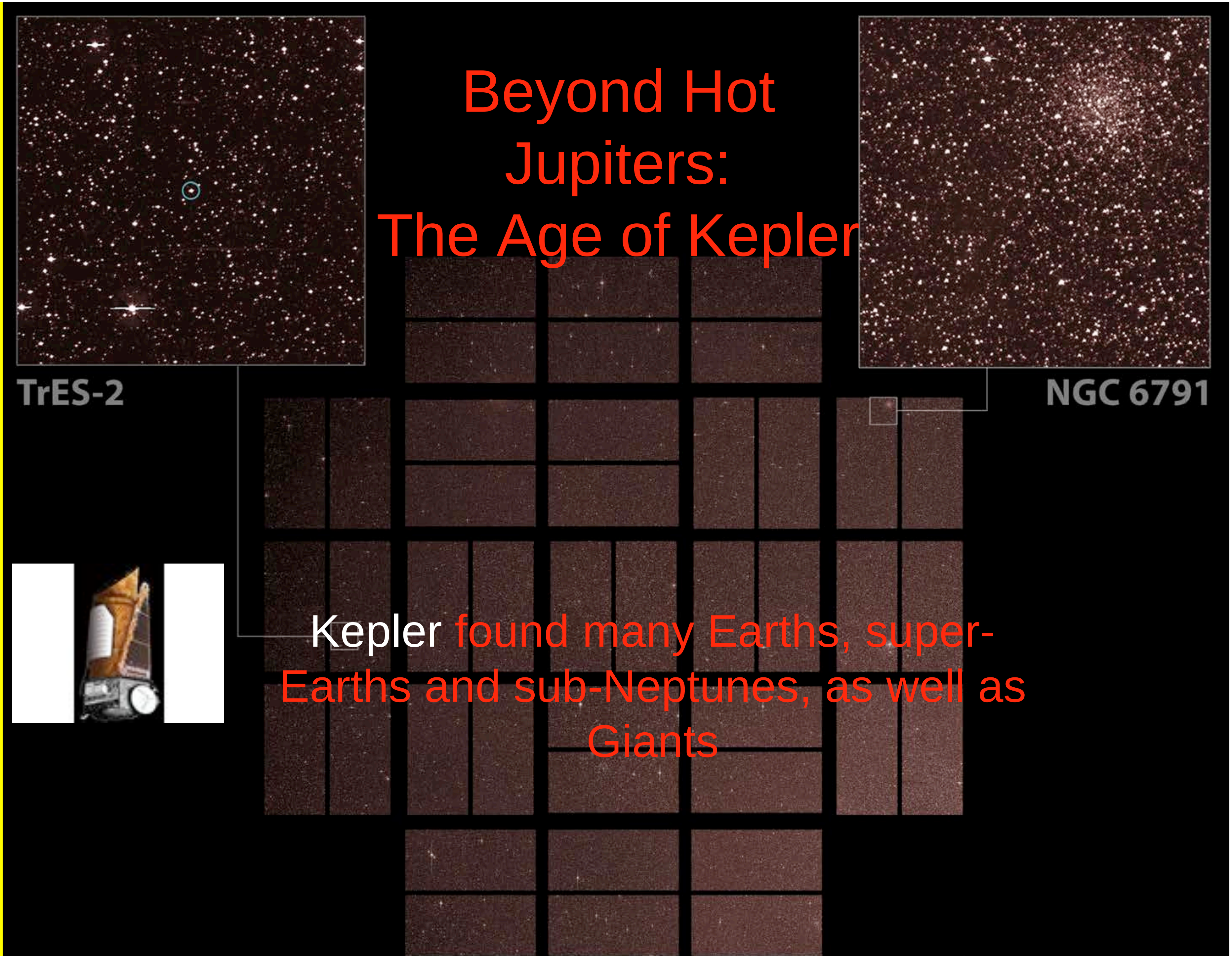
**Transit chord**



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

Graphics by D. Spiegel

# Beyond Hot Jupiters: The Age of Kepler

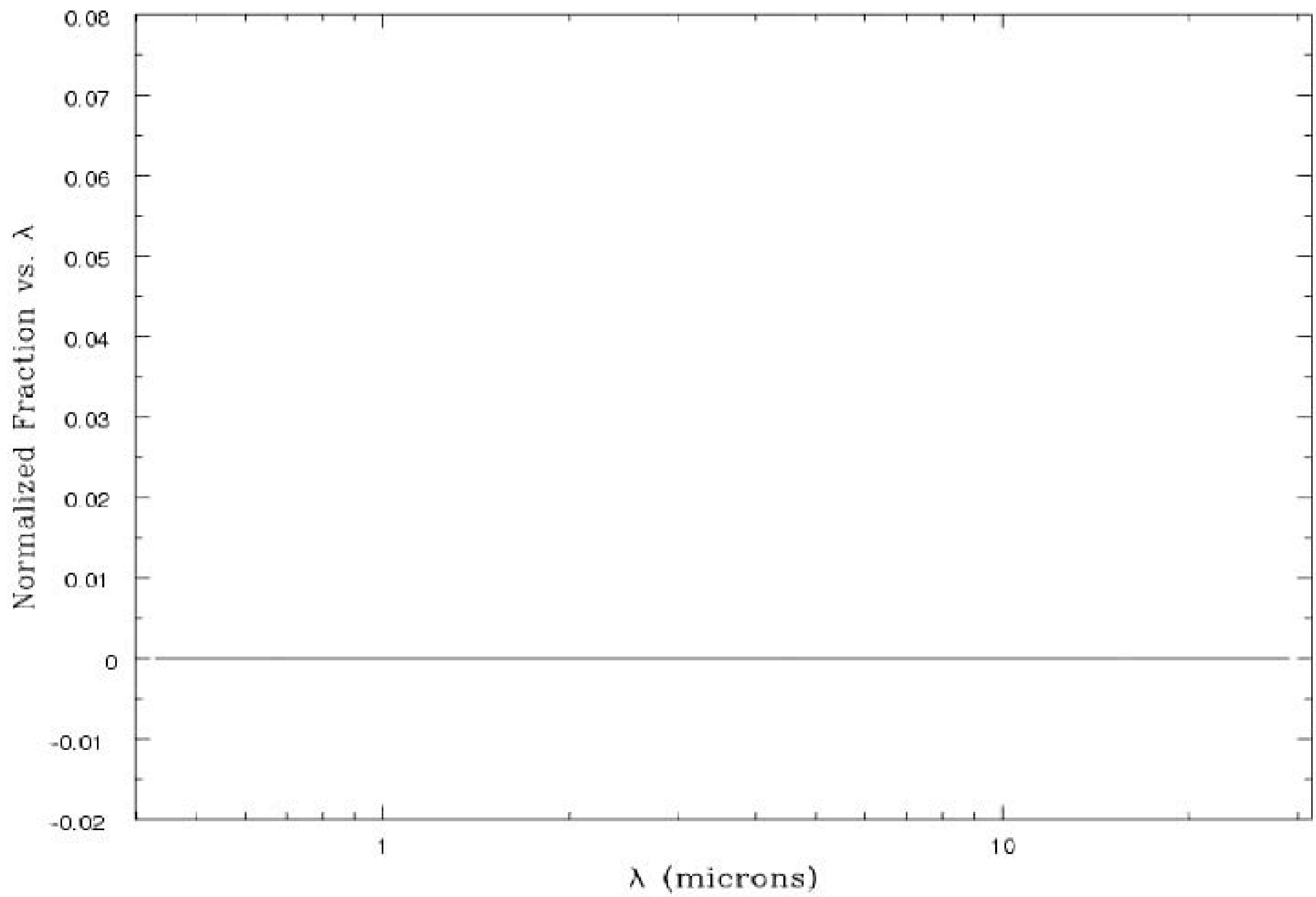



Kepler found many Earths, super-Earths and sub-Neptunes, as well as Giants

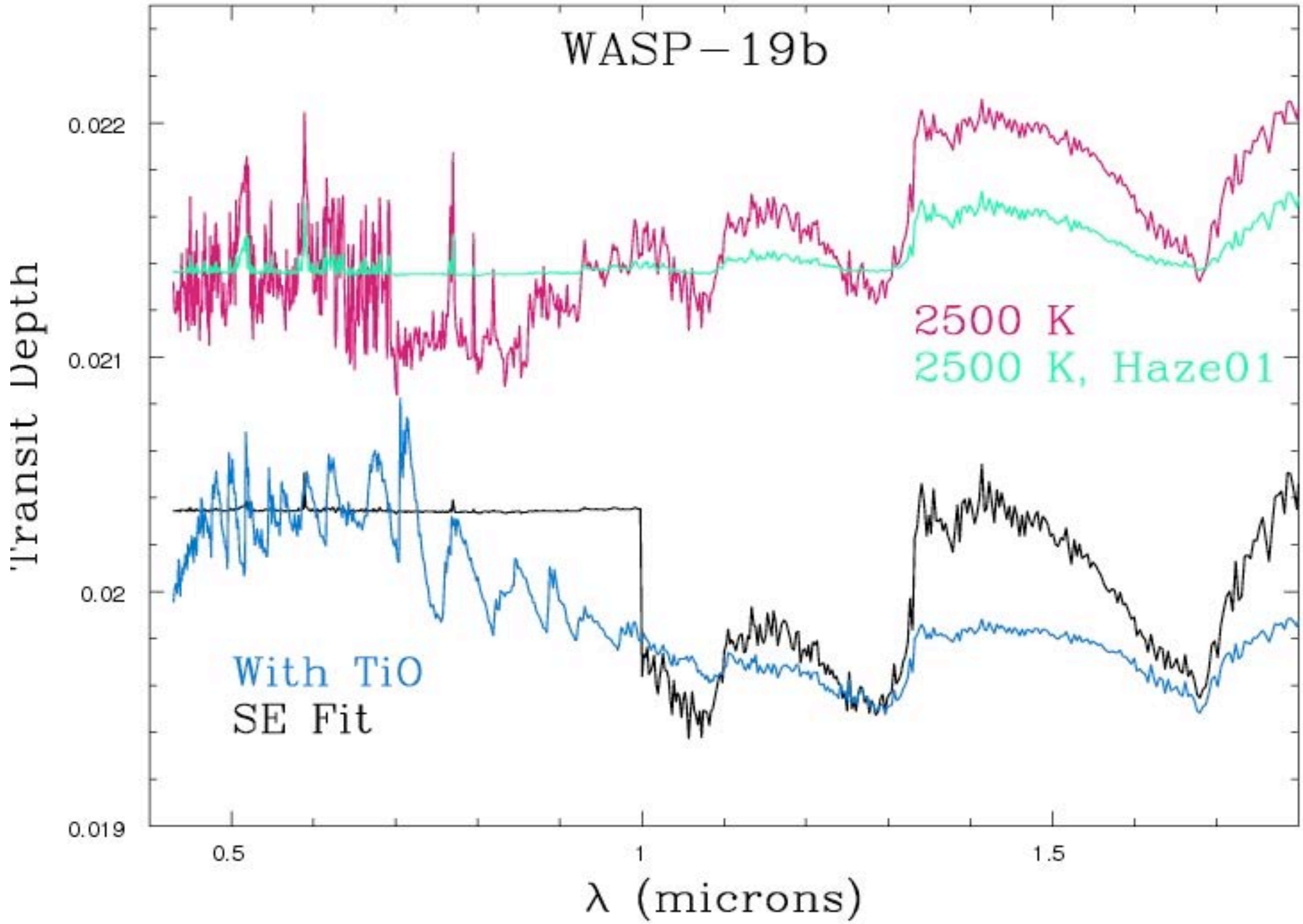
# Transit Spectra

- At terminator - couples aspects of day and night
- Chemistry at transition?
- Day/night temperatures
- Ingress/Egress asymmetry

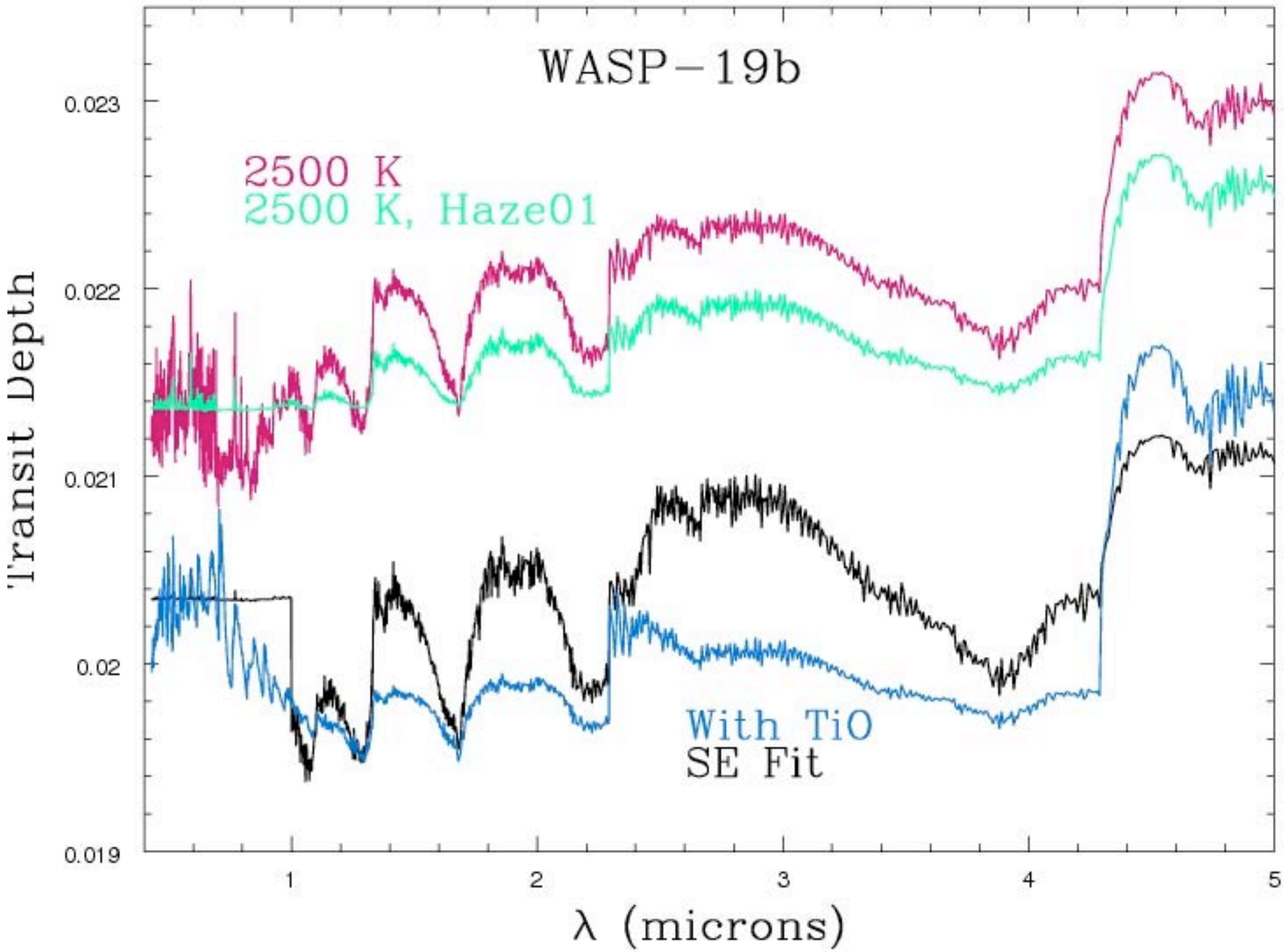
# Fractional Atmosphere vs. Wavelength




Burrows, Rauscher, Spiegel, & Menou 2010

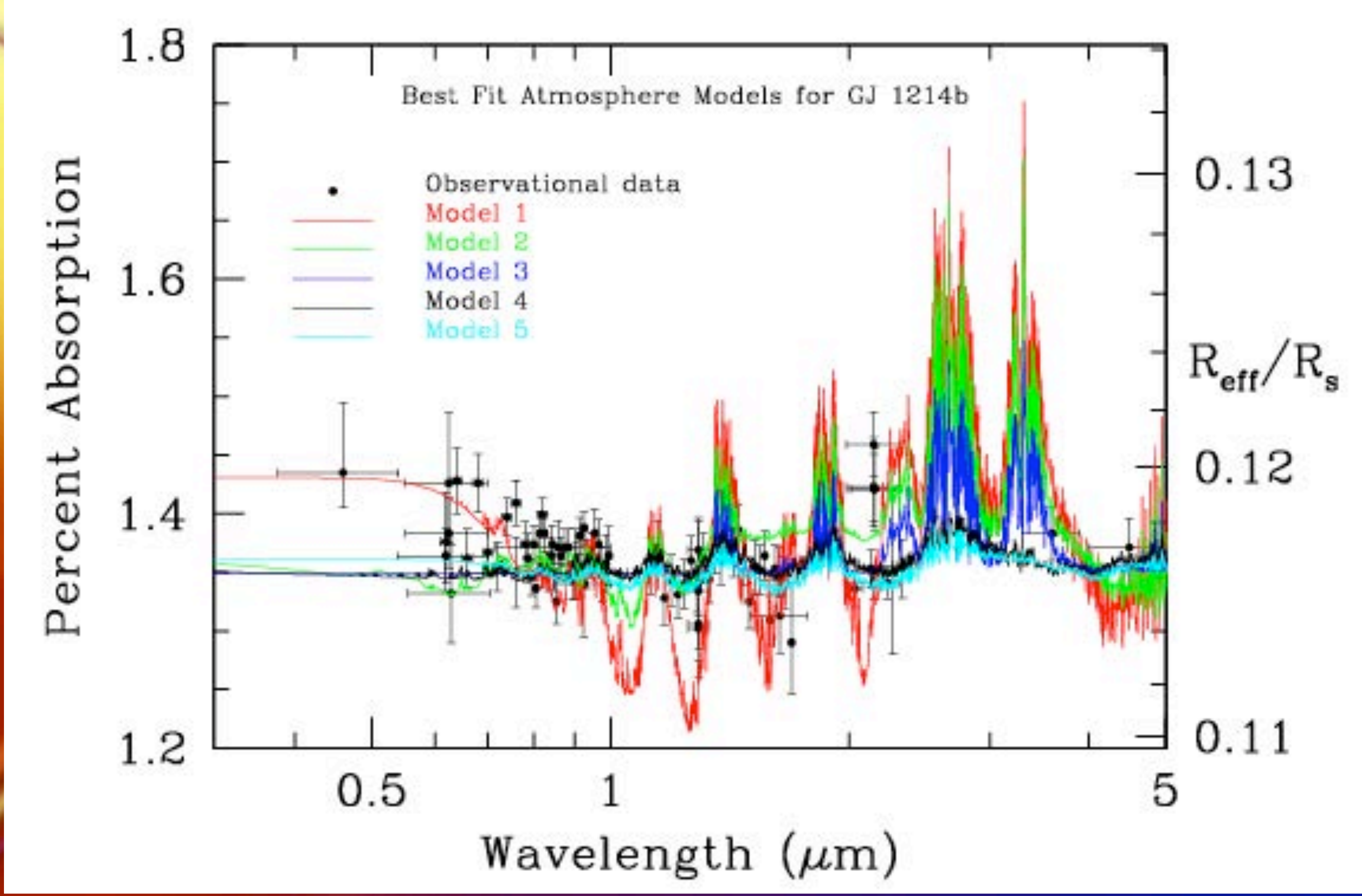


WASP−19b
2500 K
2500 K, Haze01
With TiO
SE Fit
Transit Depth
0.022
0.021
0.02
0.019
0.5
1
1.5
λ (microns)



WASP−19b
2500 K
2500 K, Haze01
With TiO
SE Fit
Transit Depth
λ (microns)
0.023
0.022
0.021
0.02
0.019
1
2
3
4
5

# GJ 1214b: Transit Radius vs. Wavelength




Howe & Burrows 2012, in press

# Haze on HD 189733b

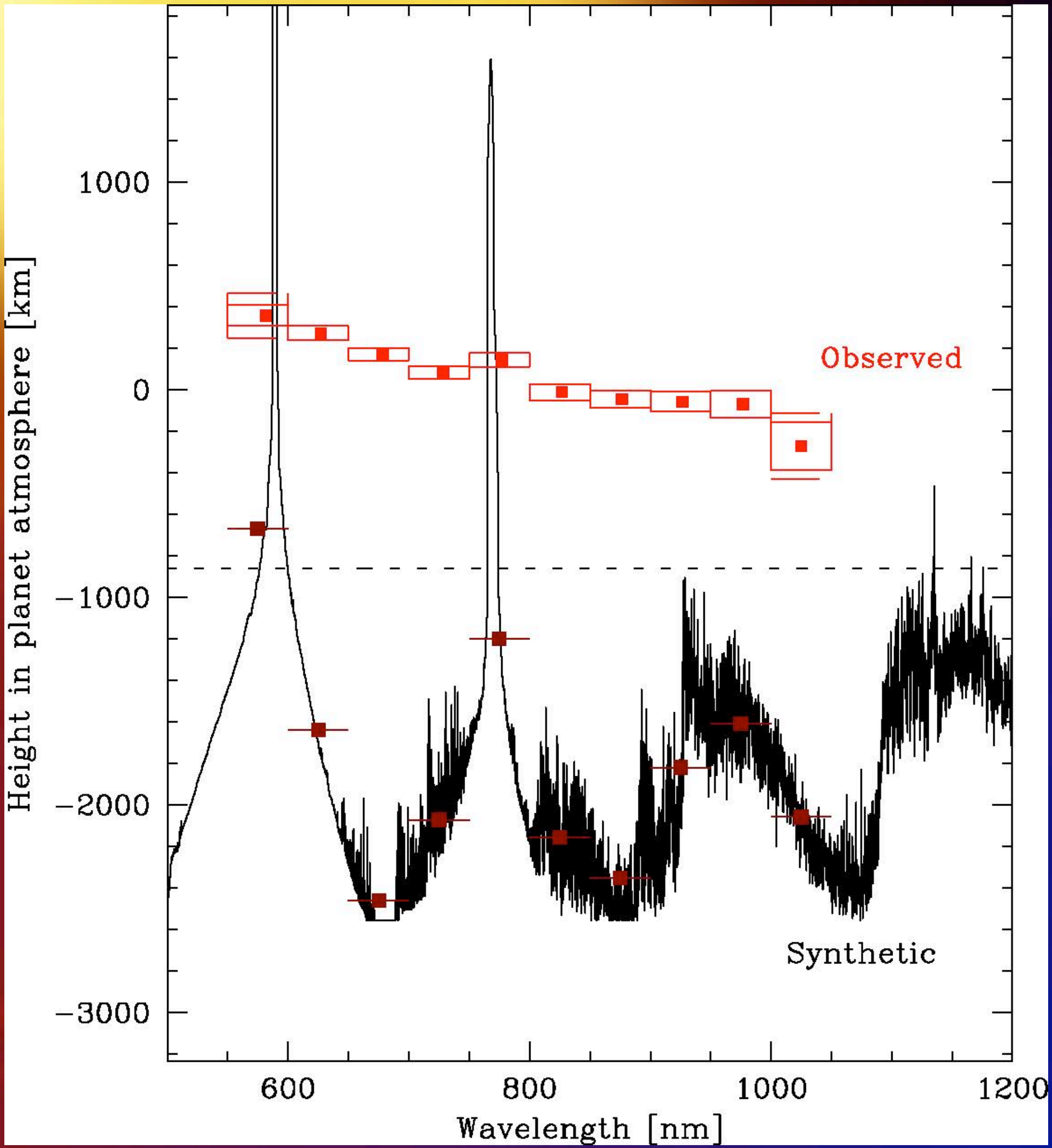
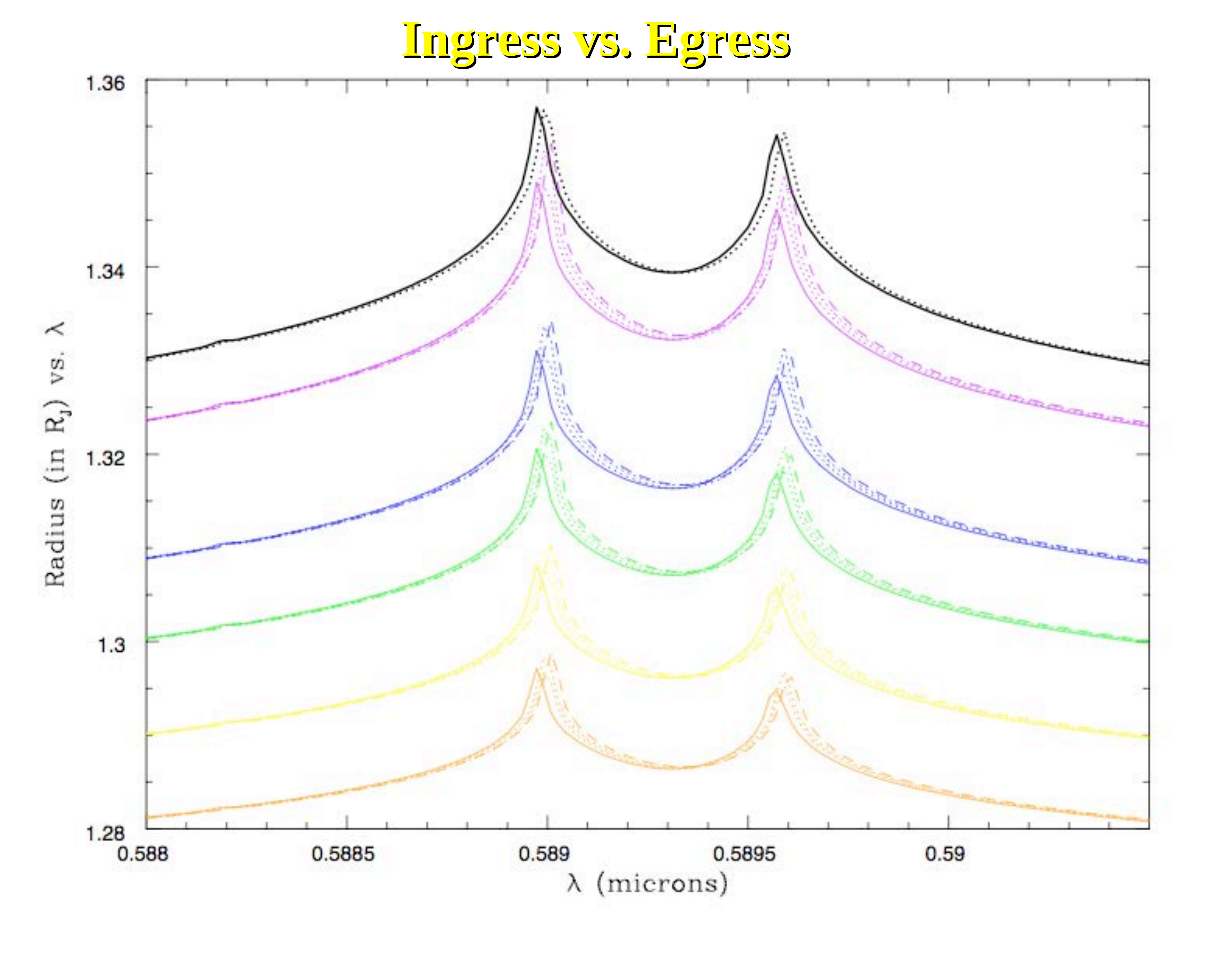



Figure from Pont, Knutson et al. (2007) showing atmospheric transmission function derived from HST ACS measurements between 600-1000 nm

# HD 209458b: Transit Radius vs. Wavelength - Measuring Orbit and Wind Speeds?

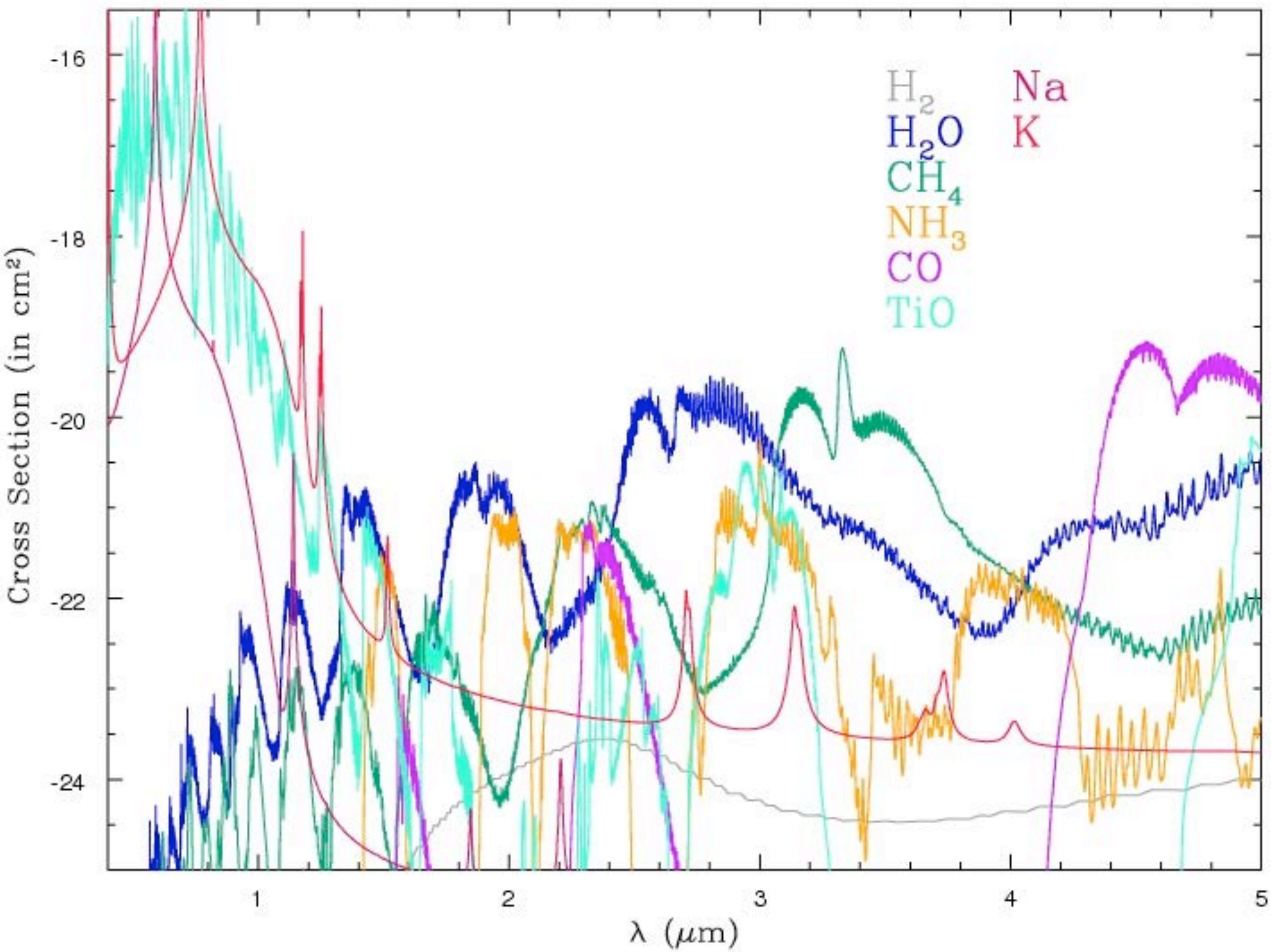


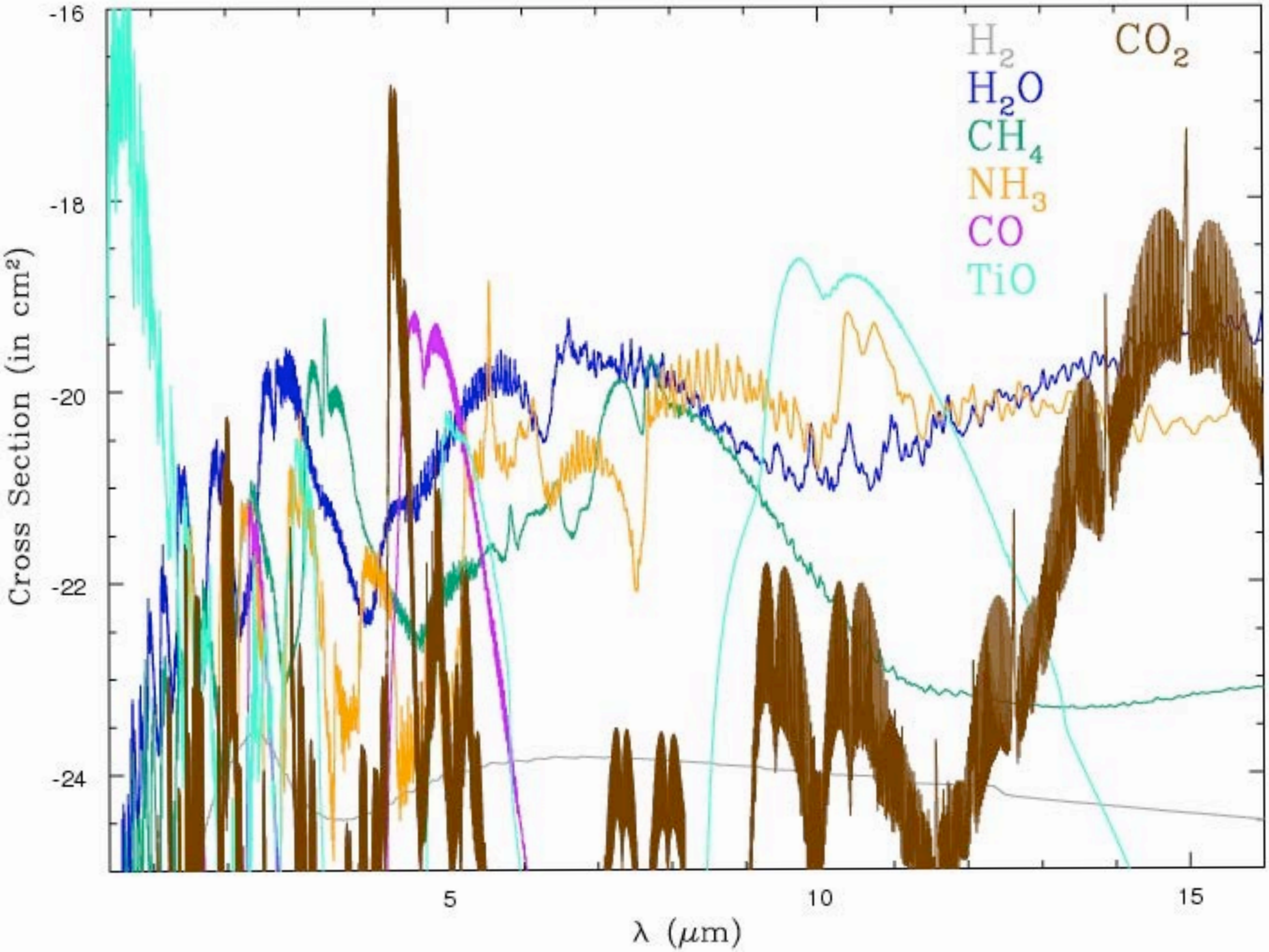

Using Burrows, Rauscher, Spiegel, & Menou 2010

**Also, re tau Boo B**

# Atmospheric Clouds/Hazes

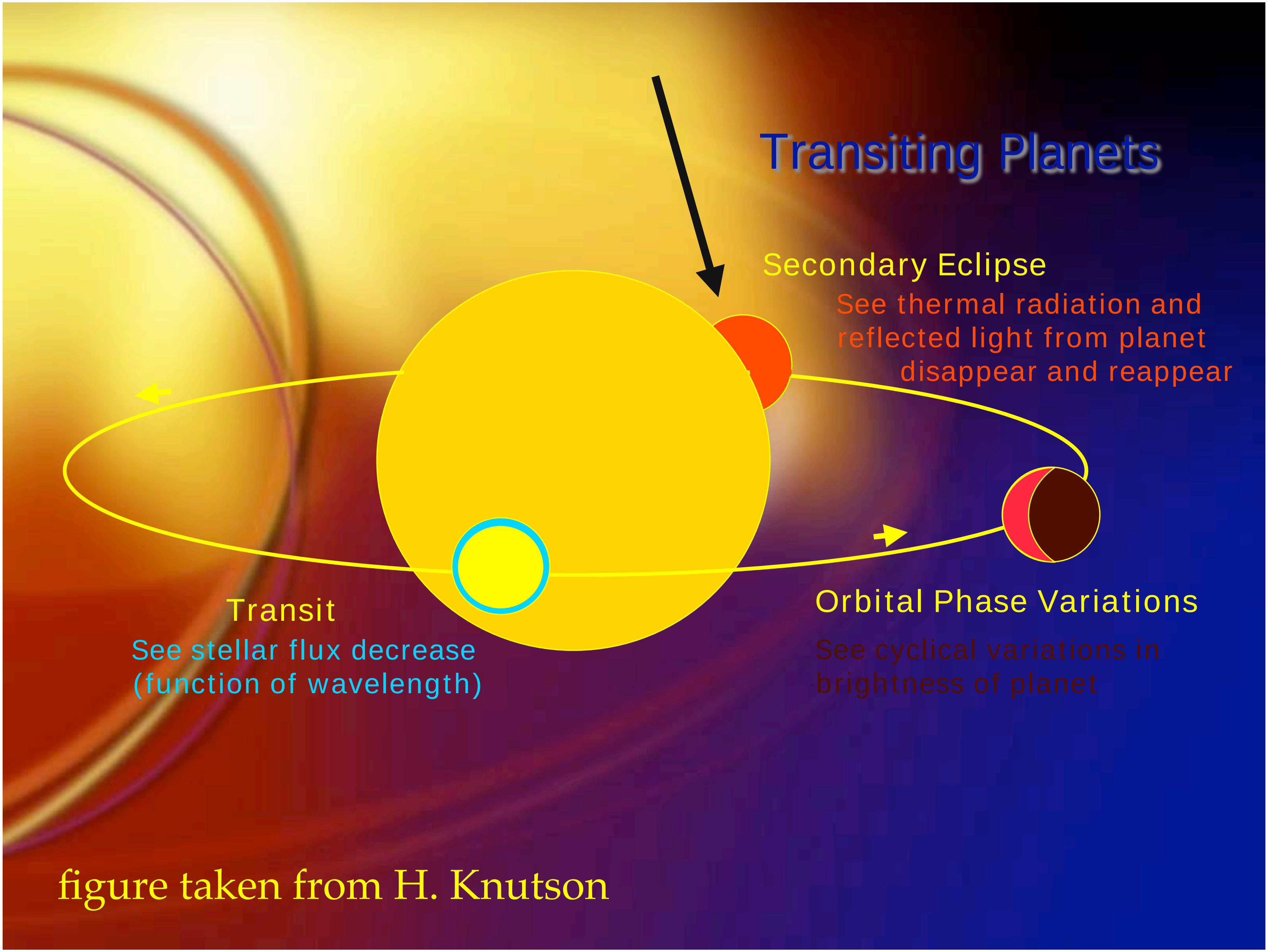
- Opacities
- Physical extent
- More important for transit spectra than secondary eclipse or light curve spectra, but …
- HD 189733b (e.g., Pont et al.)


H$_2$
Na
H$_2$O
K
CH$_4$
NH$_3$
CO
TiO
Cross Section (in cm$^2$)
-16
-18
-20
-22
-24
1
2
3
4
5
λ (μm)

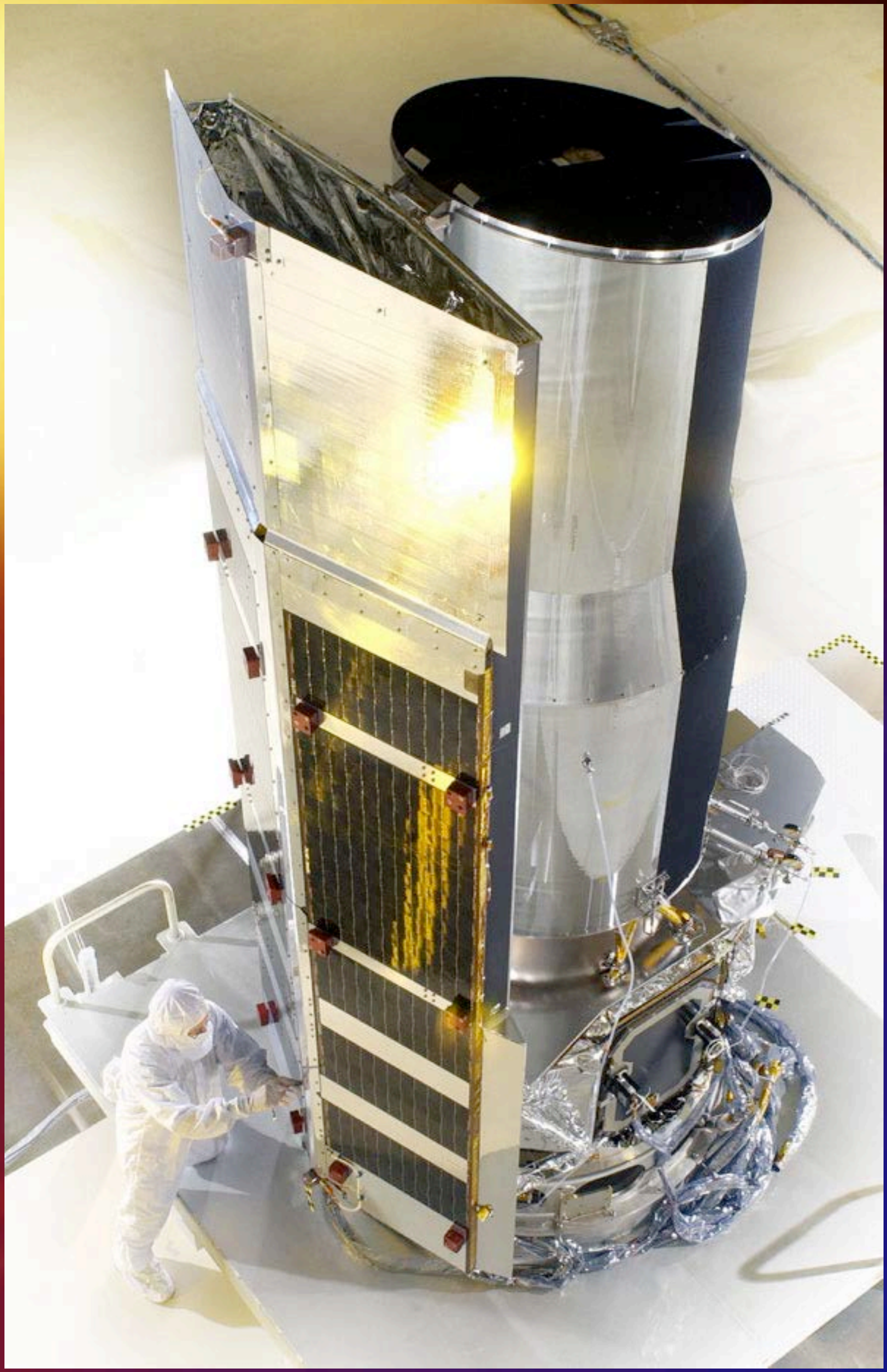


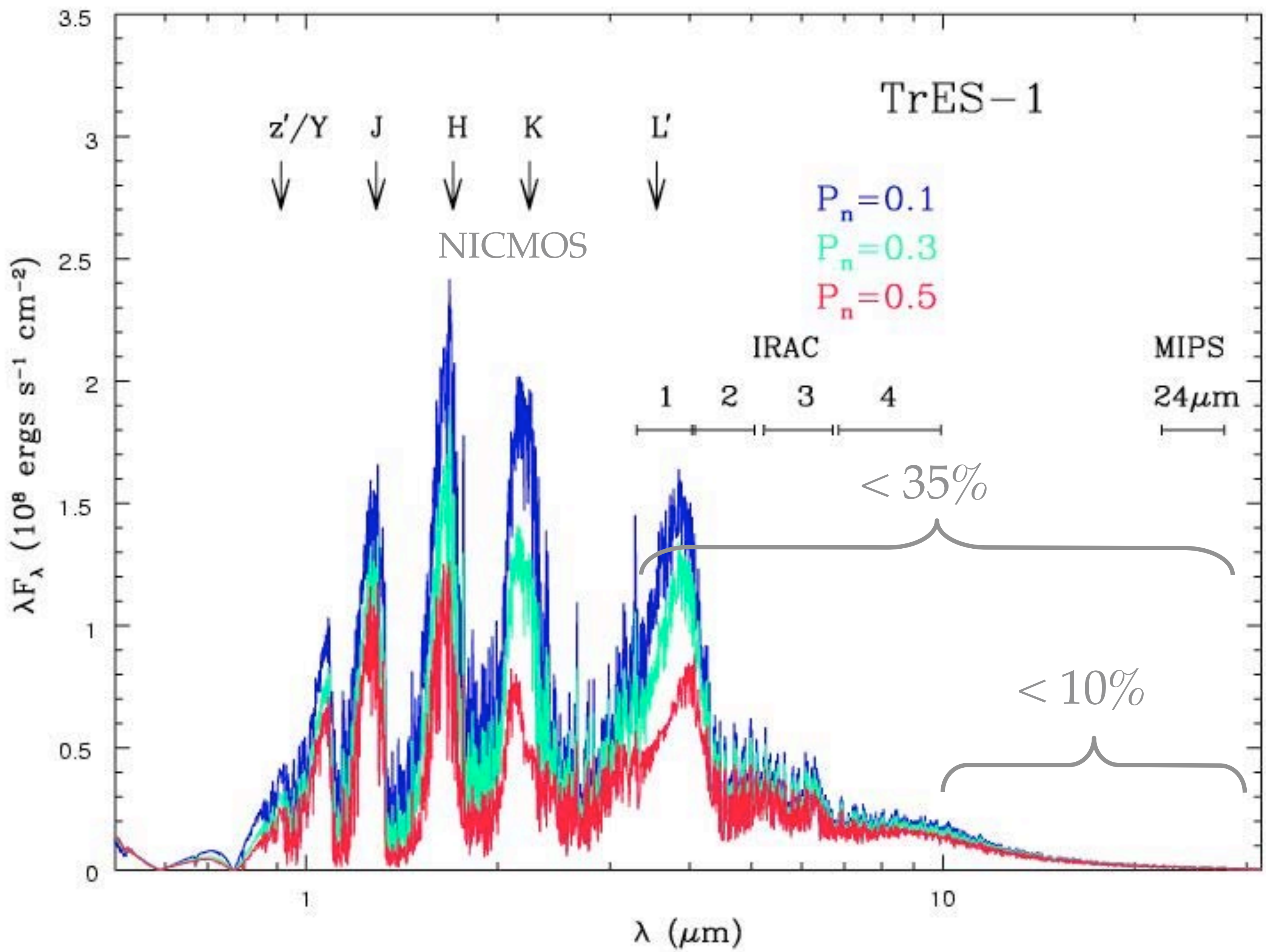
H2
H2O
CH4
NH3
CO
TiO
CO2
Cross Section (in cm²)
-16
-18
-20
-22
-24
5
10
15
λ (μm)

# Secondary Eclipse - Emission Spectra, Hot Upper Atmospheres, and Inversions

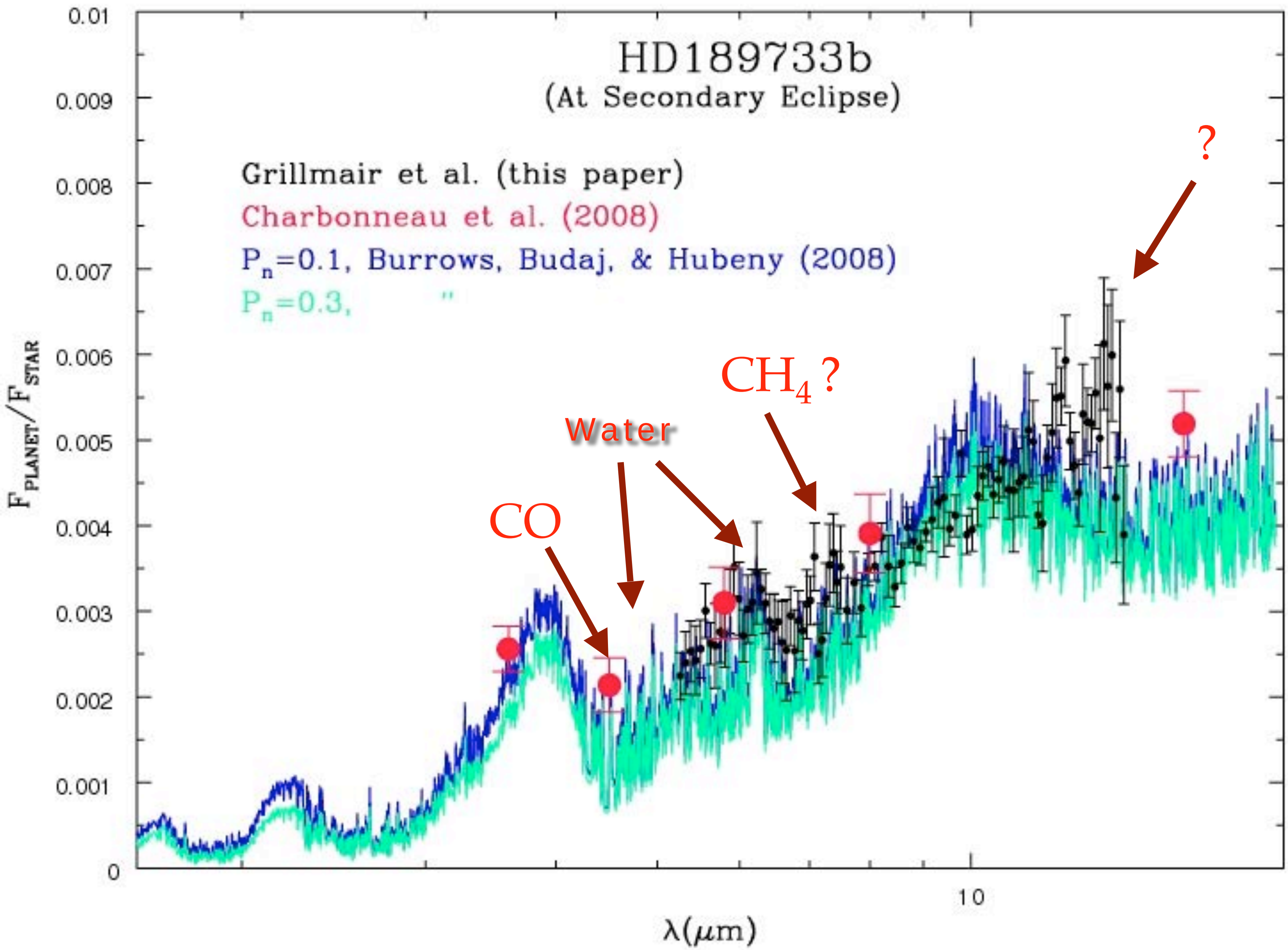

Transiting Planets
Secondary Eclipse
See thermal radiation and
reflected light from planet
disappear and reappear
Transit
See stellar flux decrease
(function of wavelength)
Orbital Phase Variations
See cyclical variations in
brightness of planet
figure taken from H. Knutson

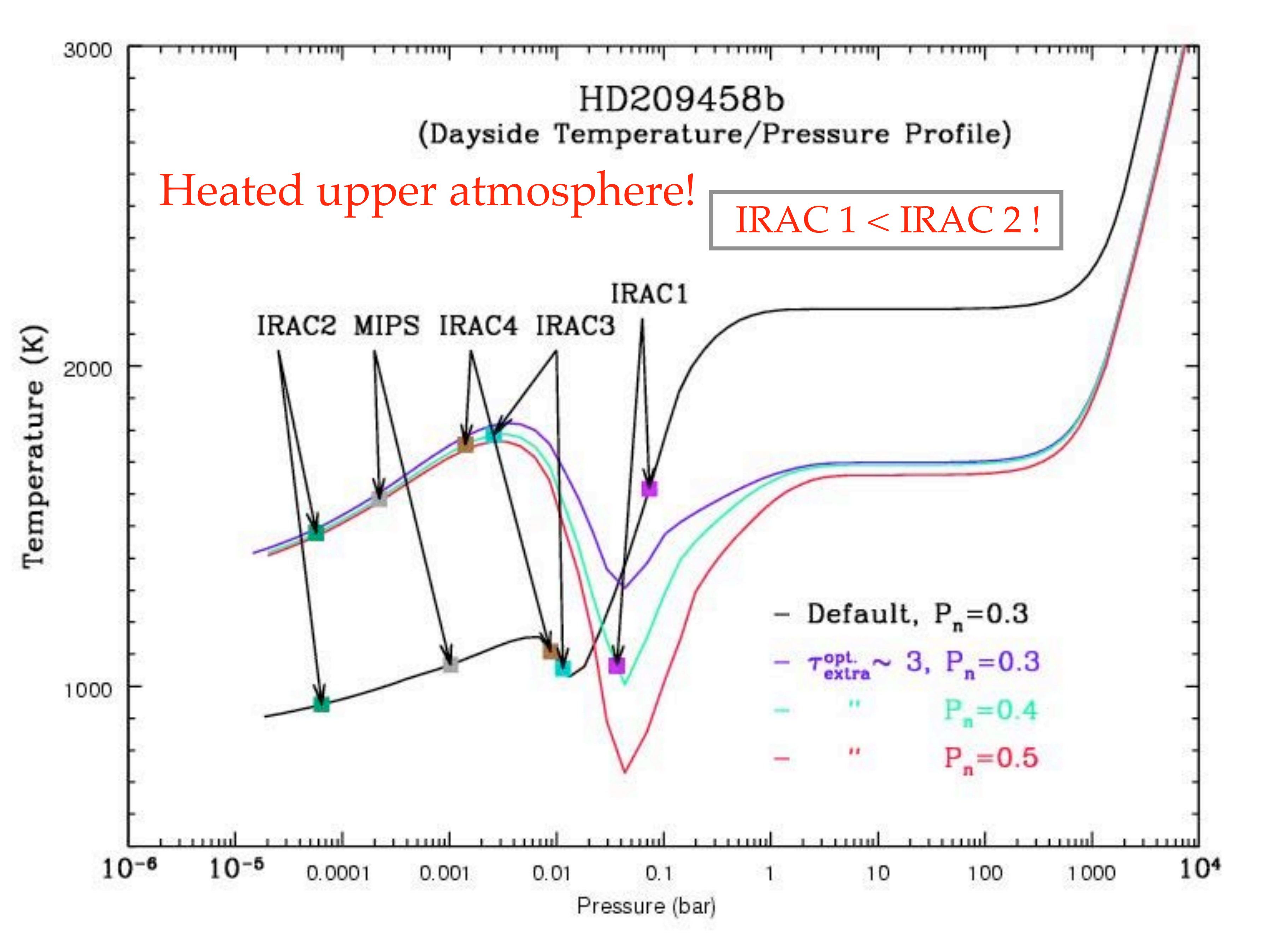
Spitzer ST:

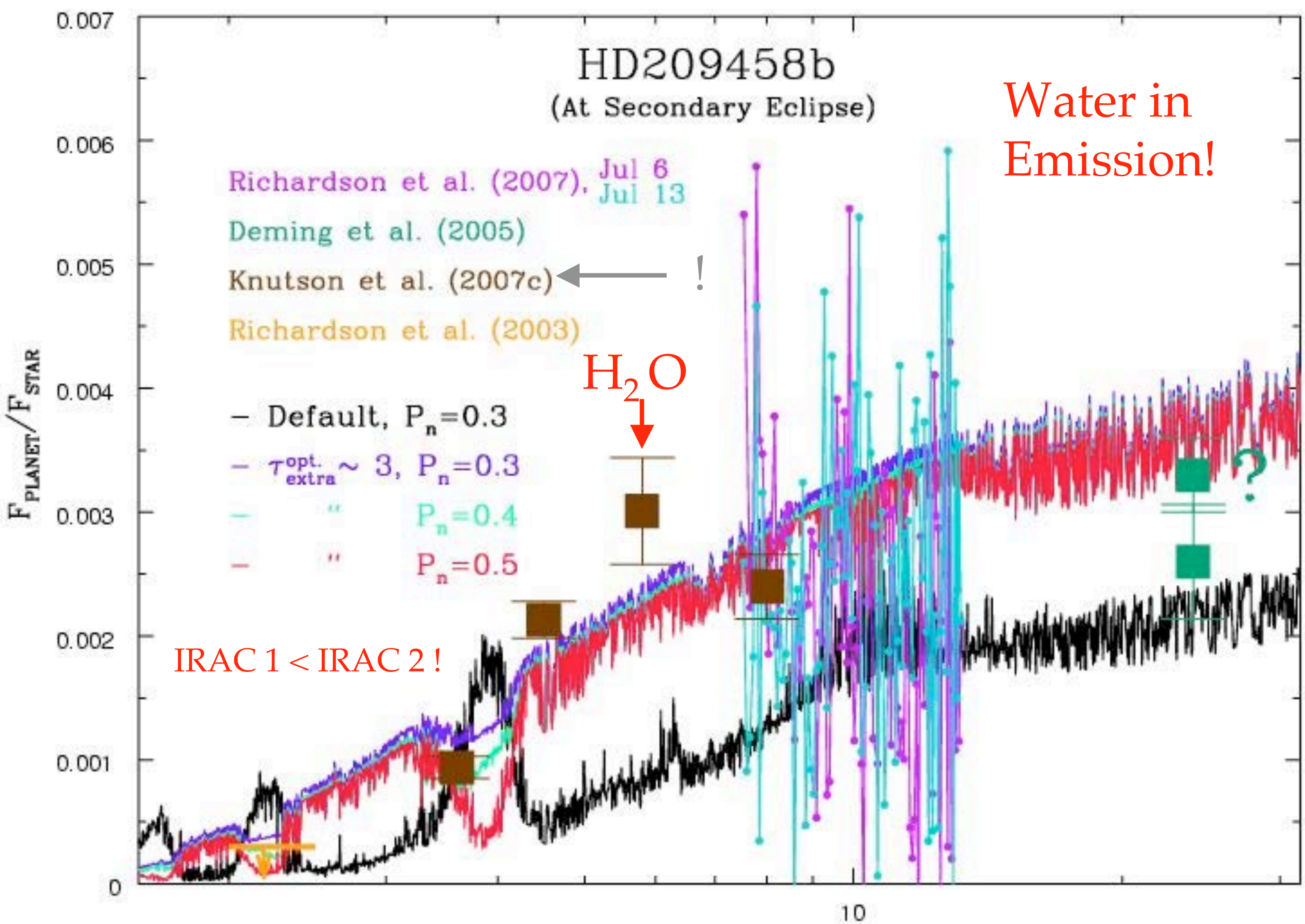




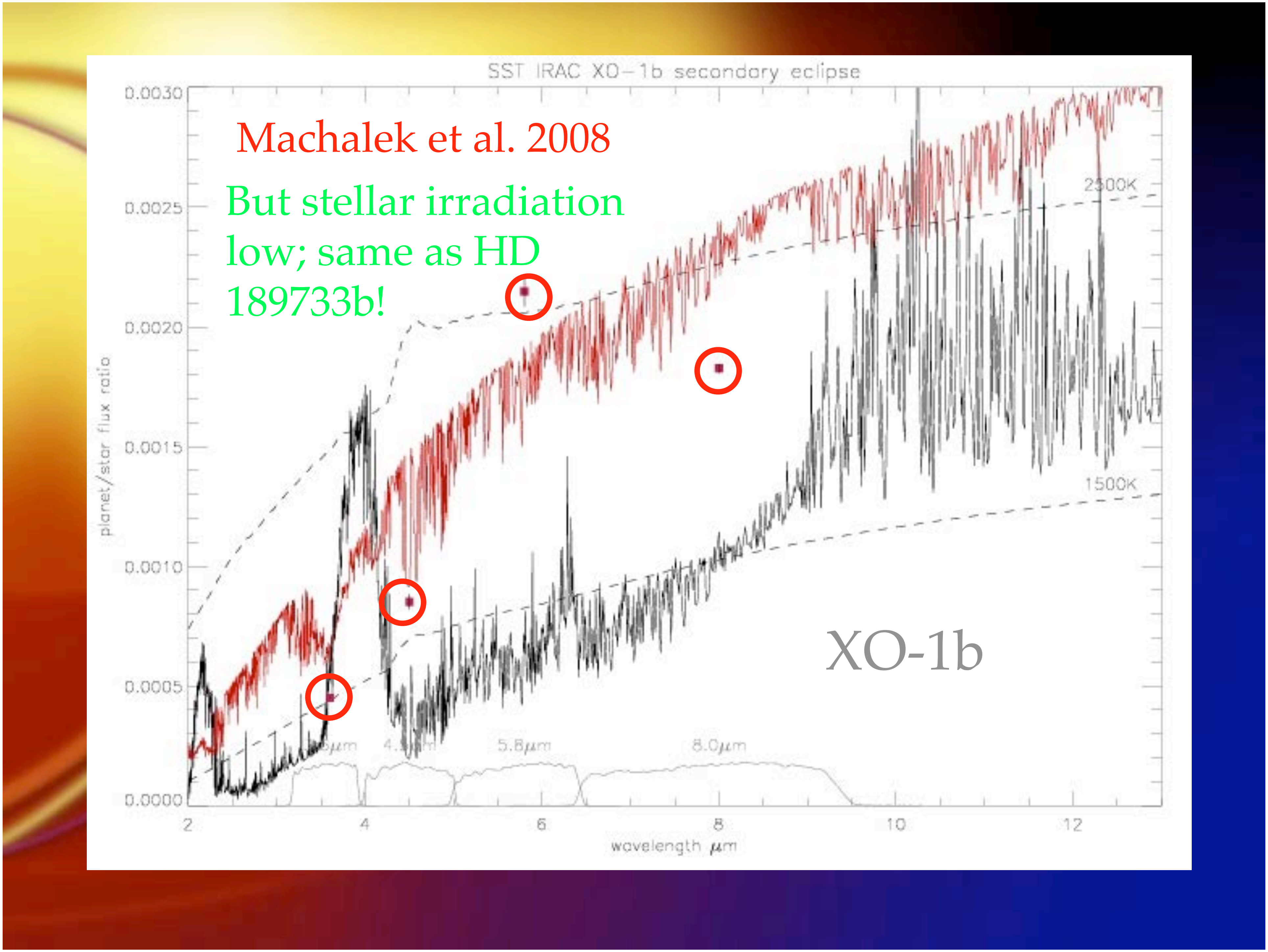
TrES−1
z′/Y
J
H
K
L′
NICMOS
P_n=0.1
P_n=0.3
P_n=0.5
IRAC
1
2
3
4
MIPS
24μm
< 35%
< 10%
λF_λ (10^8 ergs s^-1 cm^-2)
λ (μm)
0
0.5
1
1.5
2
2.5
3
3.5
1
10


HD189733b
(At Secondary Eclipse)
Grillmair et al. (this paper)
Charbonneau et al. (2008)
$P_n$=0.1, Burrows, Budaj, & Hubeny (2008)
$P_n$=0.3, "
$F_{PLANET}/F_{STAR}$
0.01
0.009
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
10
λ(μm)
CO
Water
$CH_4$ ?
?


HD209458b
(Dayside Temperature/Pressure Profile)
Heated upper atmosphere!
IRAC 1 < IRAC 2 !
IRAC2 MIPS IRAC4 IRAC3
IRAC1
Default, $P_n$=0.3
$\tau^{opt.}_{extra}$ ~ 3, $P_n$=0.3
" $P_n$=0.4
" $P_n$=0.5
Temperature (K)
Pressure (bar)
3000
2000
1000
$10^{-6}$
$10^{-5}$
0.0001
0.001
0.01
0.1
1
10
100
1000
$10^4$




Burrows et al. 2007



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

# Indices of Upper-Atmosphere Heating and Inversion:

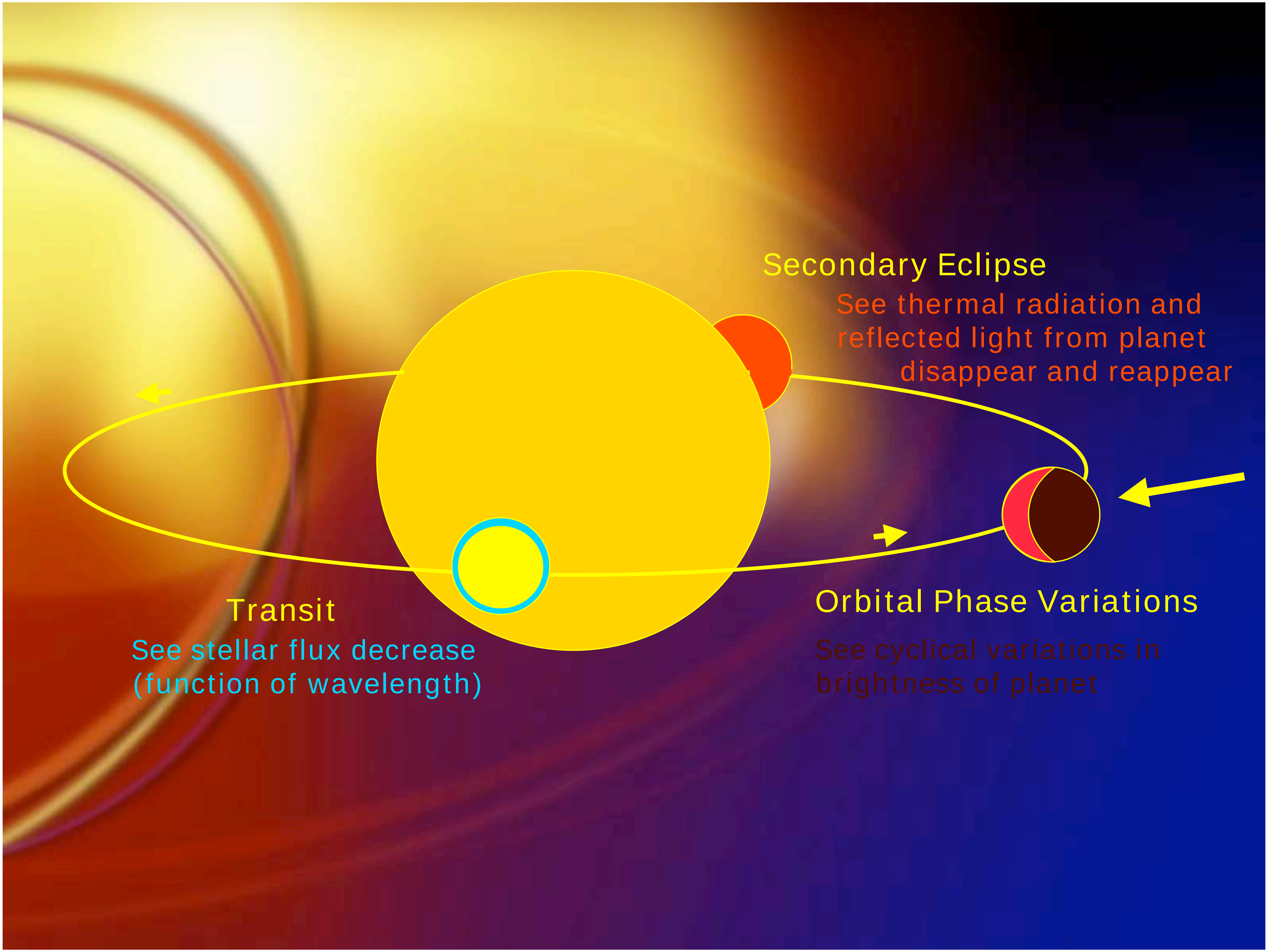
- **Inversion: IRAC 2/IRAC1 - High "Bump" at IRAC3 (water in emission?) - "other" emission features**

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

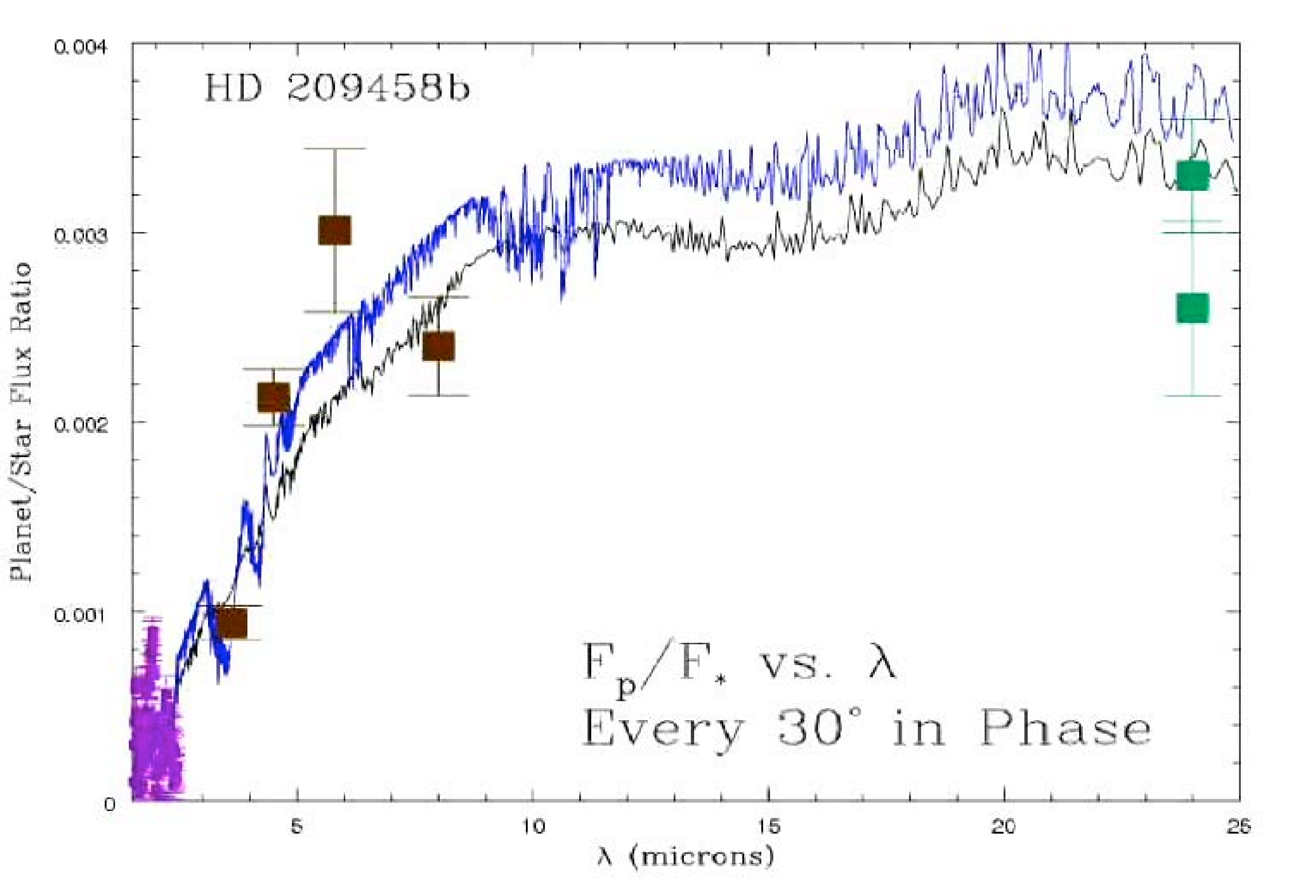
- **Hot Spot advection??**

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

# Light Curves

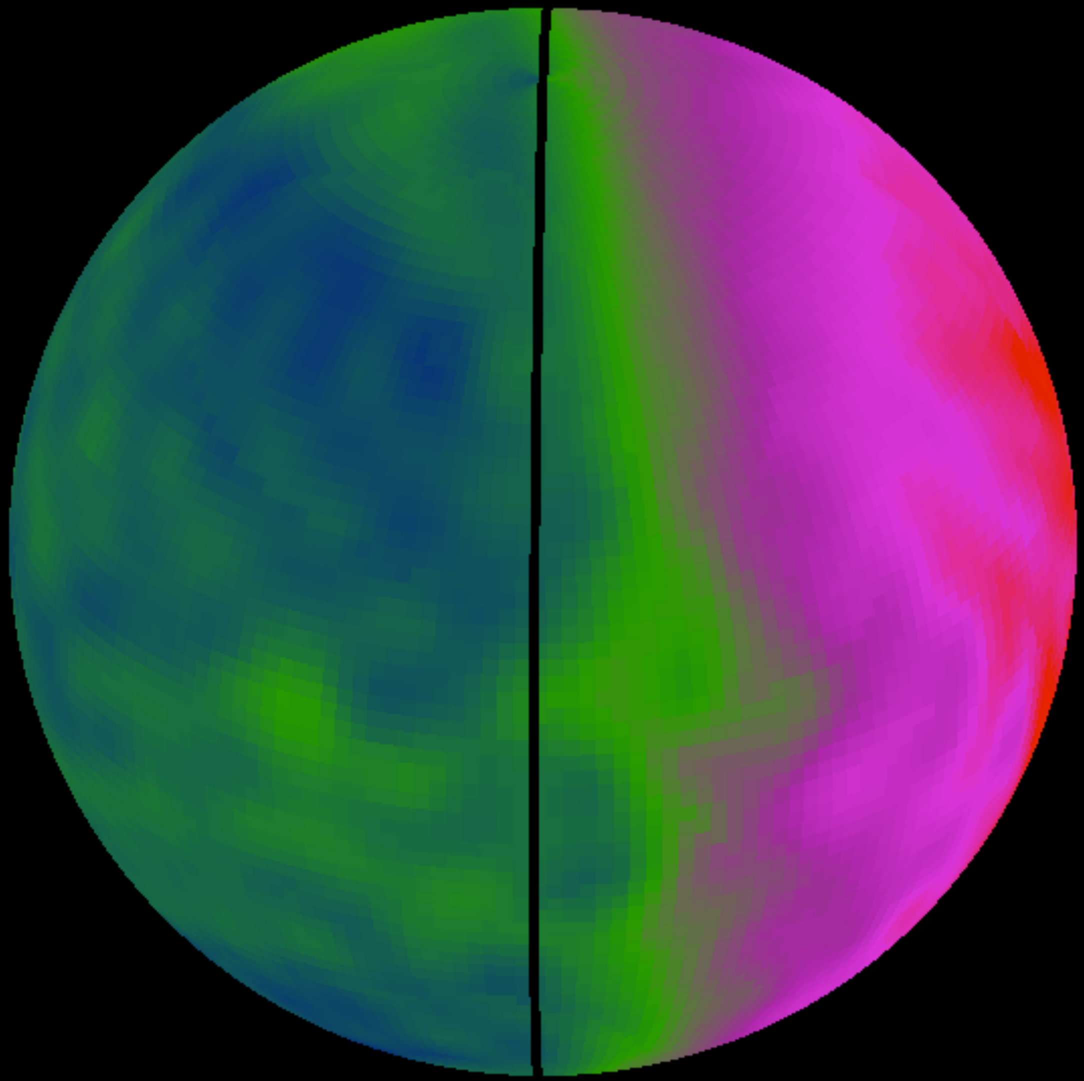

Secondary Eclipse
See thermal radiation and
reflected light from planet
disappear and reappear
Transit
See stellar flux decrease
(function of wavelength)
Orbital Phase Variations
See cyclical variations in
brightness of planet

# Planet/Star Flux Ratio vs. Wavelength and Phase

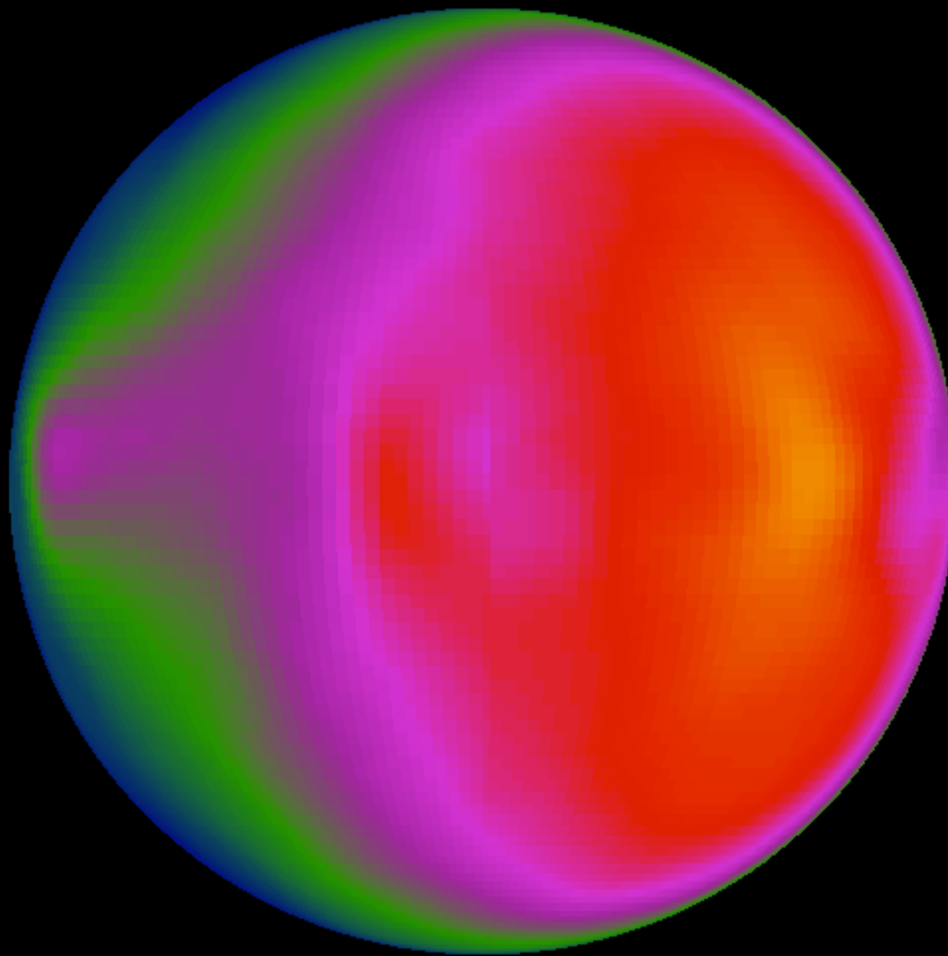



Burrows, Rauscher, Spiegel, & Menou 2010

Methane Map: w/o Upper Atmos. heating

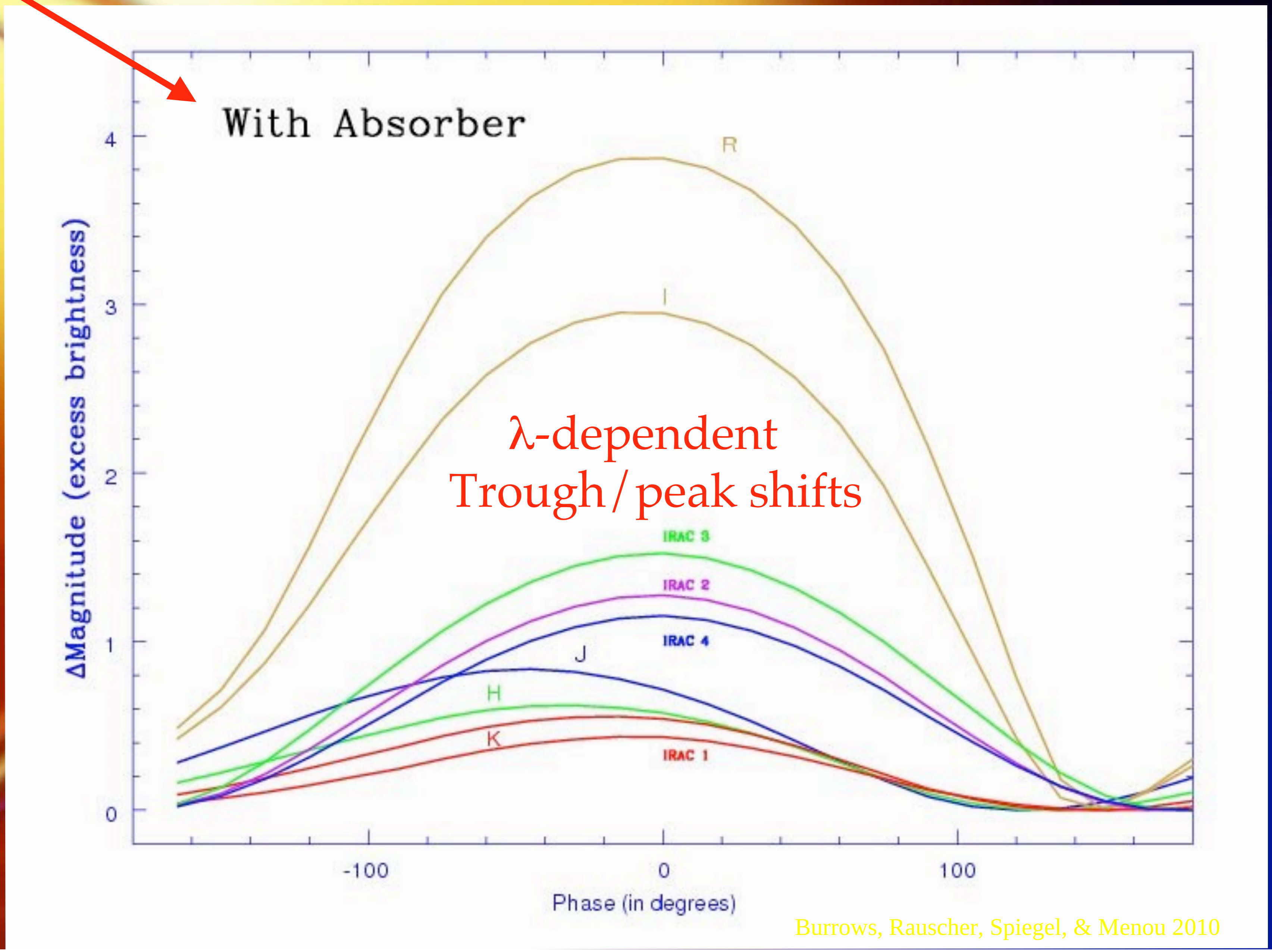


J-band HD 209458b Map (model a03)

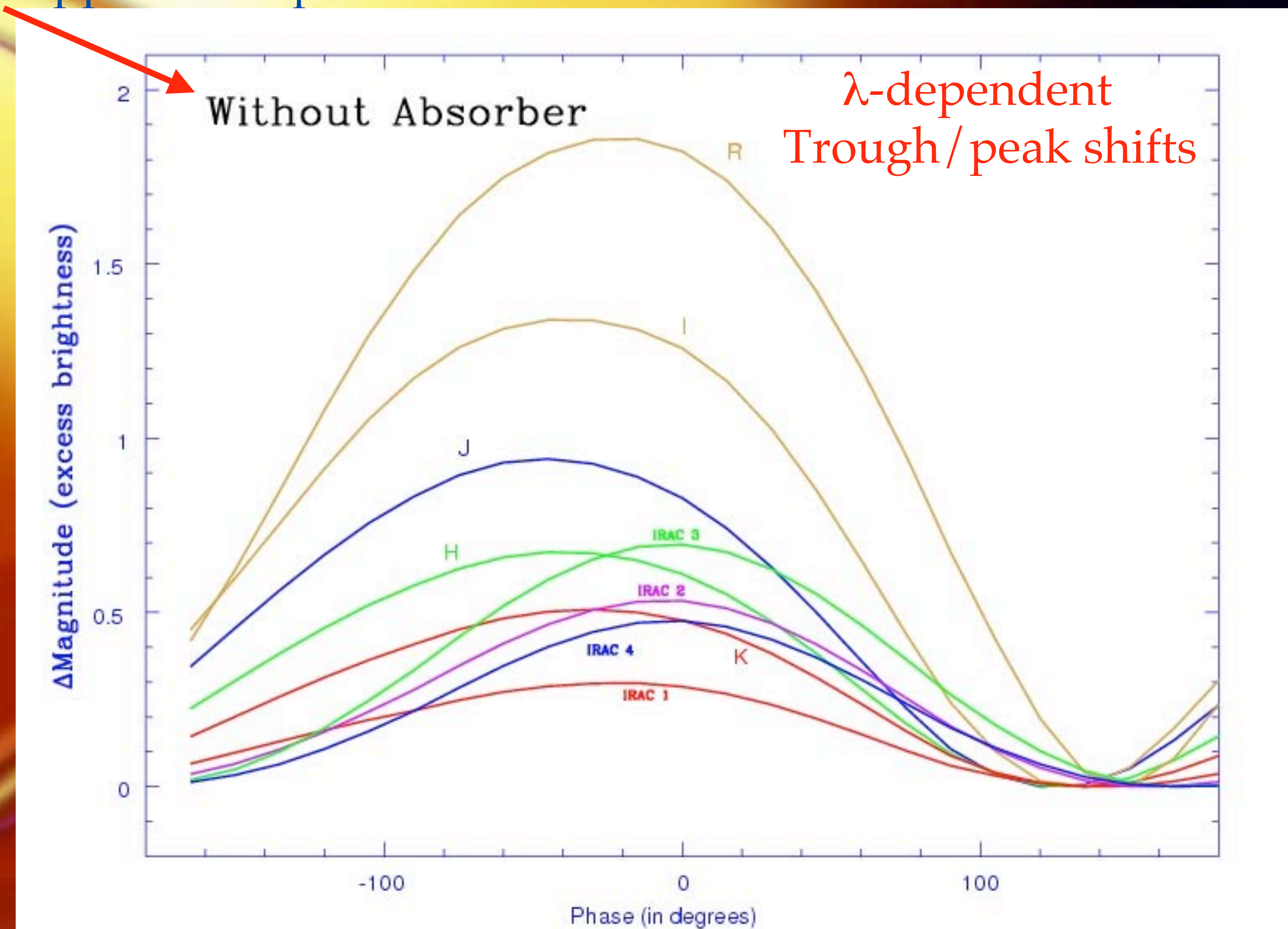


**Burrows et al. 2010**

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

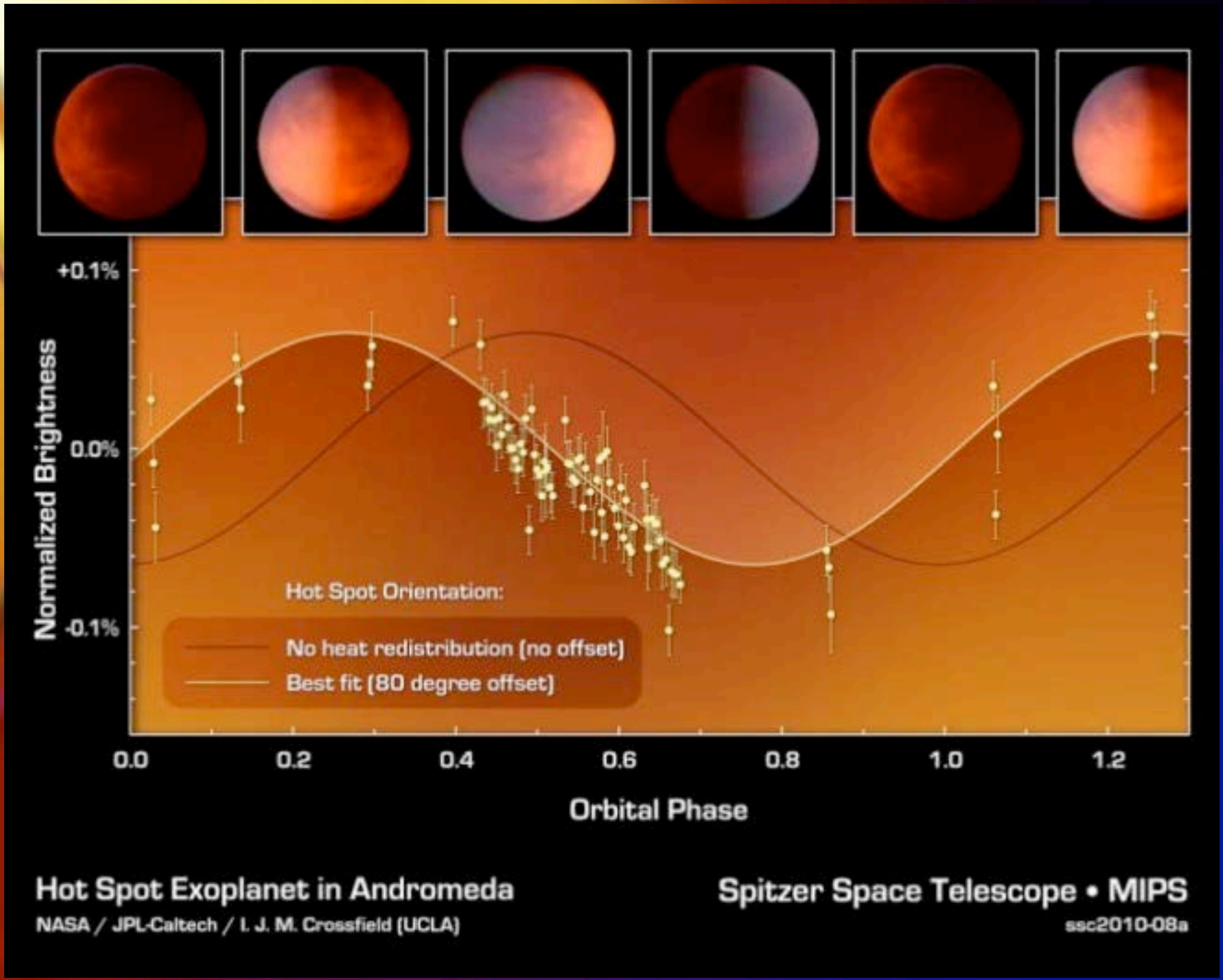


# HD 209458b: Integrated Phase Light Curves: No upper atmosphere absorber




Burrows, Rauscher, Spiegel, & Menou 2010

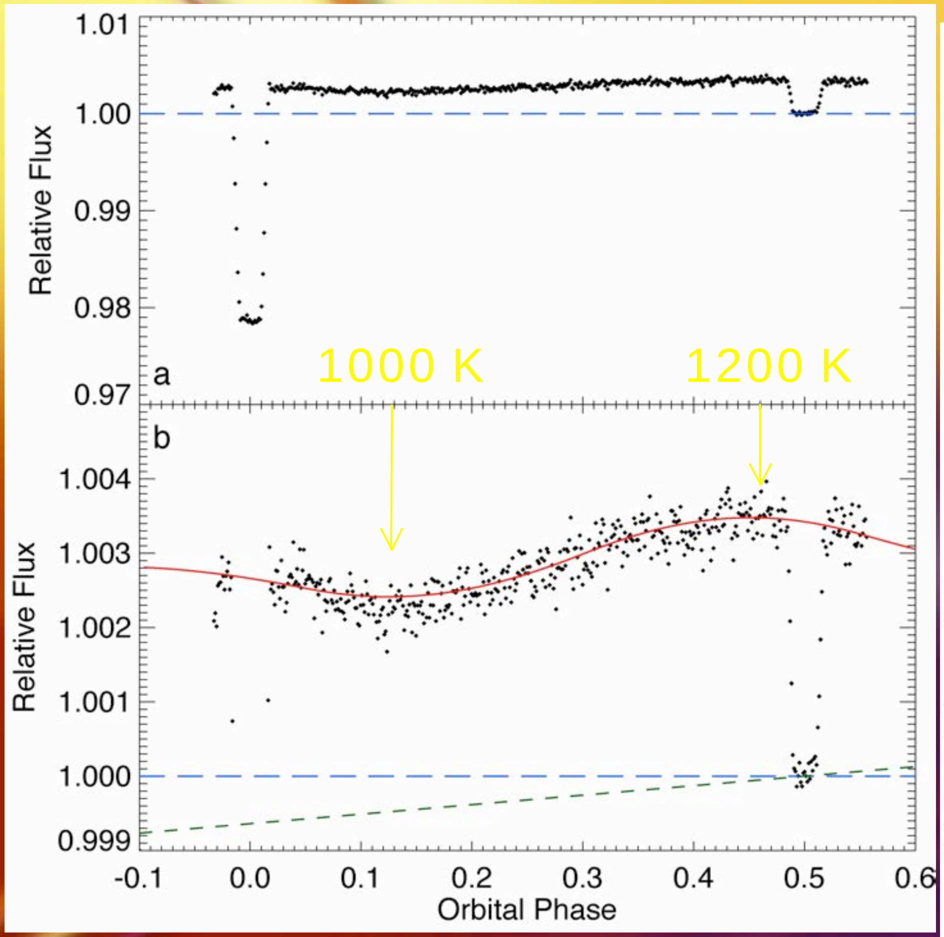
# New Ups And b Phase Curve at 24 μm

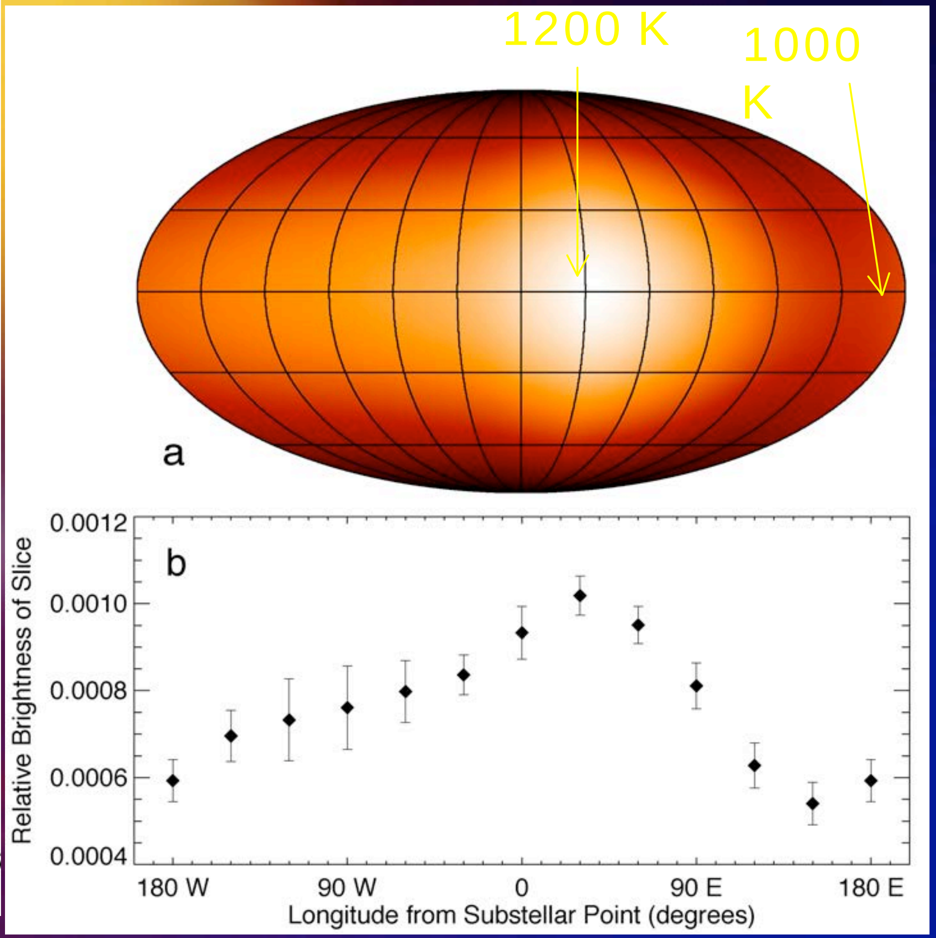



Future: Kepler, warm Spitzer, JWST

Harrington et al. 2010

# First Longitudinal Temperature Profile for an Exoplanet: HD 189733b's Warm Night Side

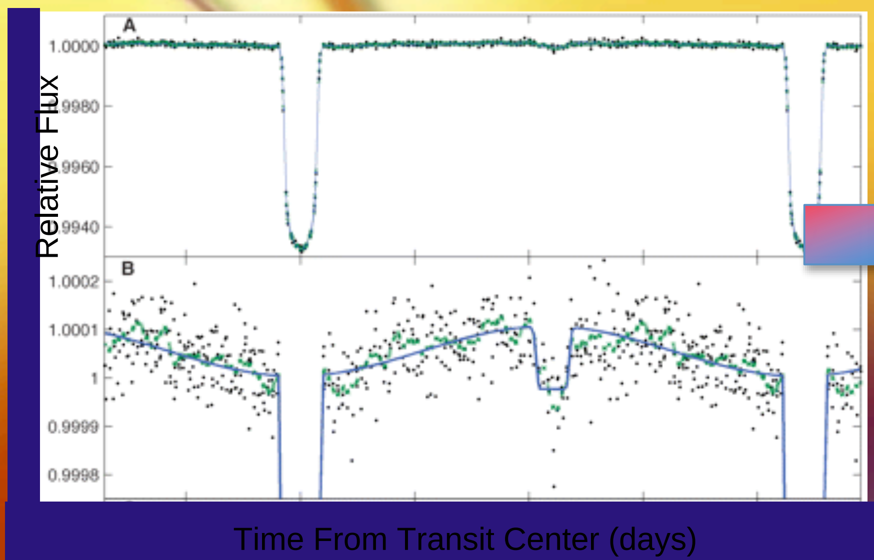


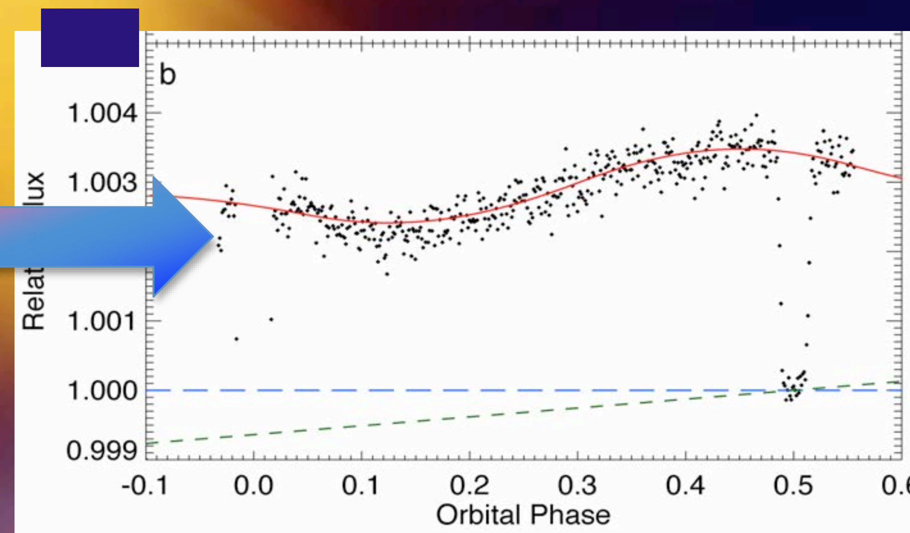

Spitzer 8 μm observations of HD 189733b (Knutson et al. 2007b, *Nature* 447, 183).

# Evidence for a Diversity of Day-Night Circulation Patterns

**Large day-night brightness gradient**
**HAT-P-7 / Kepler**




**Small day-night brightness gradient**
**HD 189733b / Spitzer**




**Large gradients:**

υ And b* (Harrington et al. 2007)

HD 179949* (Cowan et al. 2008)

HAT-P-7 (Borucki et al. 2009)

* non-transiting planet, brightness/temperature gradient degenerate with unknown orbital inclination and planet radius

**Intermediate gradients:**

HD 149026 (Knutson et al. 2009)

**Small gradients:**

HD 189733b (Knutson et al. 2007)

HD 209458 (Knutson et al., in prep.)

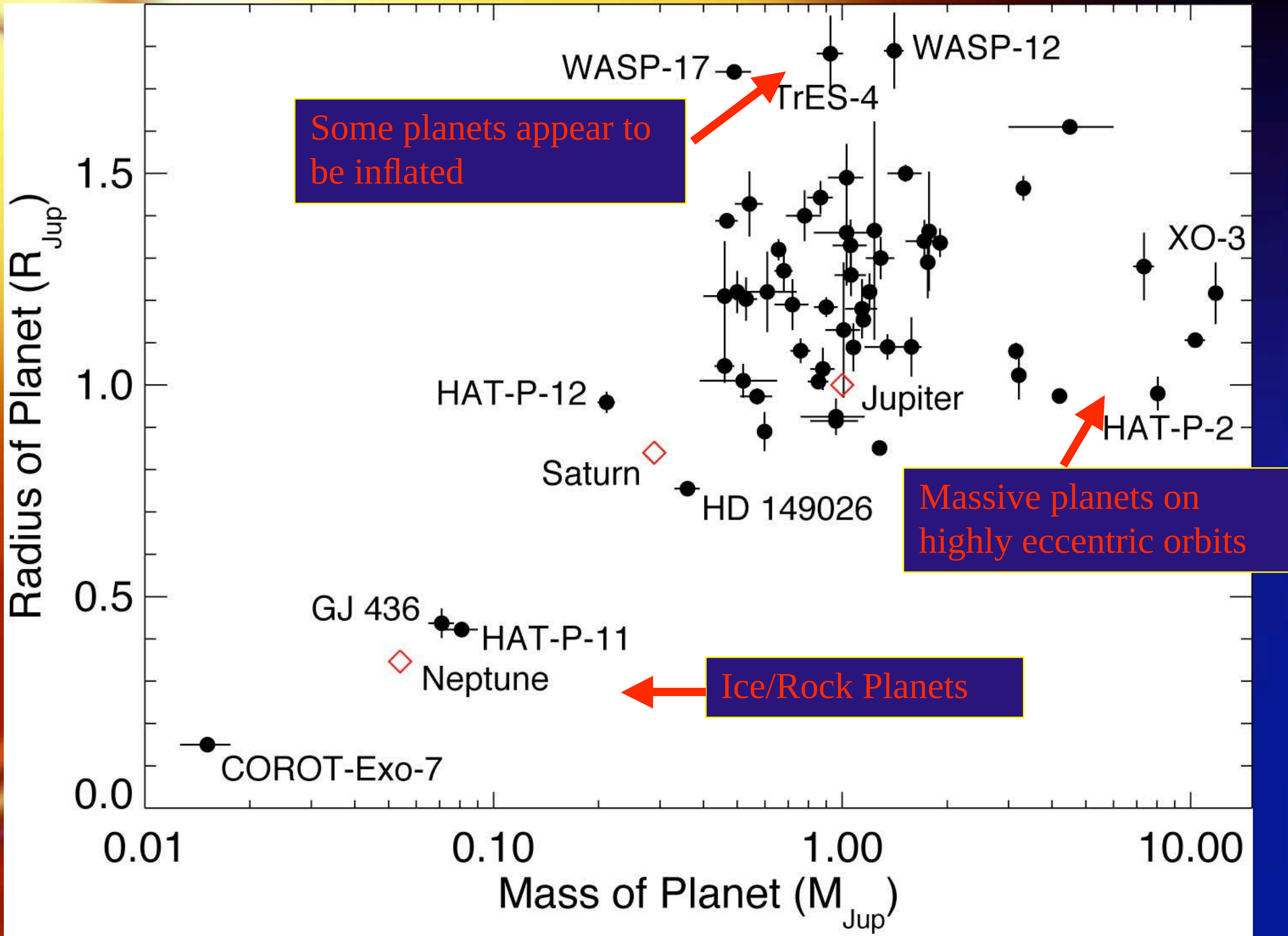
# Radius-Mass Relationship for Irradiated EGPs (“Hot Jupiters”)

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

# Giant Planet Radius Depends Upon Atmosphere

- Radius depends upon core entropy and mass
- Atmosphere regulates core heat loss
- Extra heating in atmosphere (e.g., Joule heating?) affects T/P profile and internal flux
- Day and Night sides cool differently
- Night side is colder, but may allow more core heat loss ($T_n^{eff}$ vs. $T_d^{eff}$)
- $T_n^{eff}(S,g)$ ; $T_d^{eff}(S,g)$ ---> $T_{eff}(S,g)$
- Opacities
- Metallicities
- Magnetic Torques and Joule Heating?
- Clouds
- 3D Effects (irradiation, rotation …)

# ...Hundreds of Planets Are Known to be Transiting.

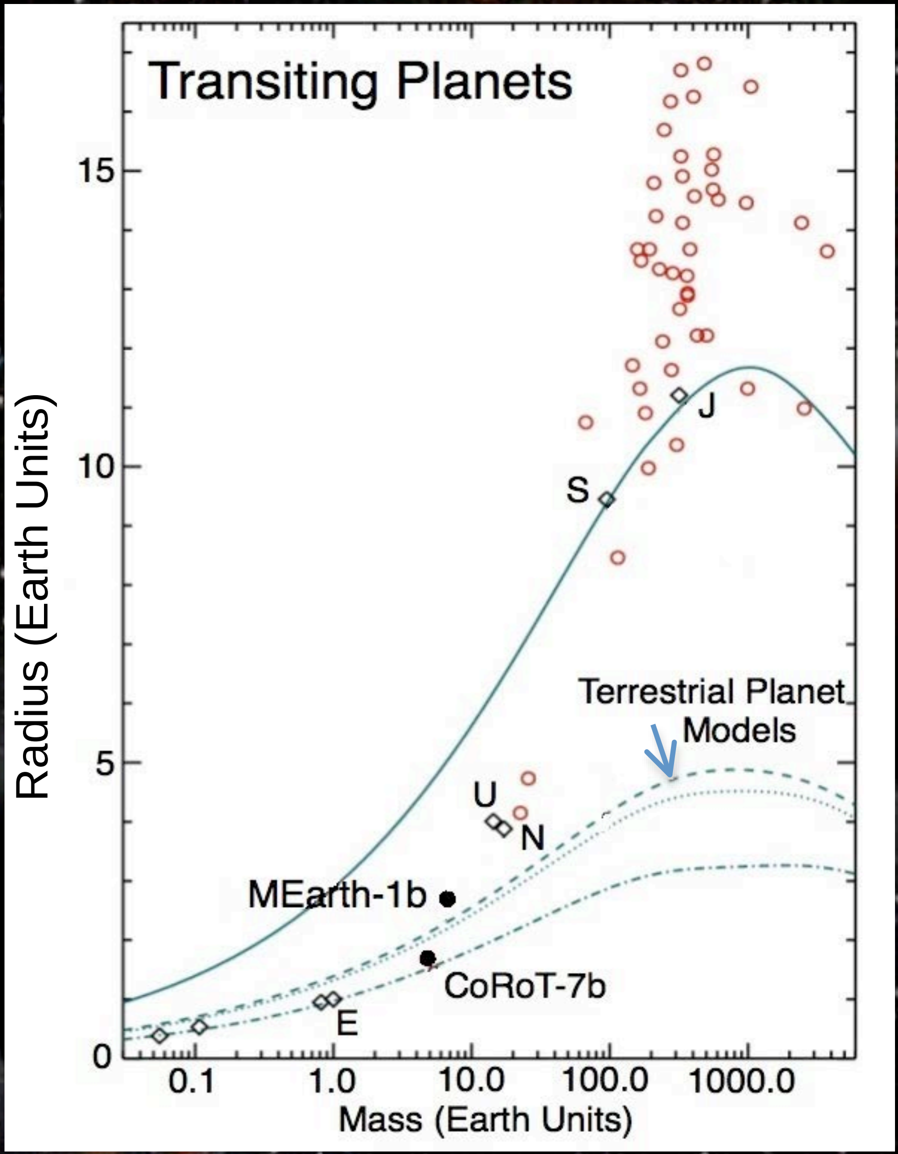


# Planet diversity

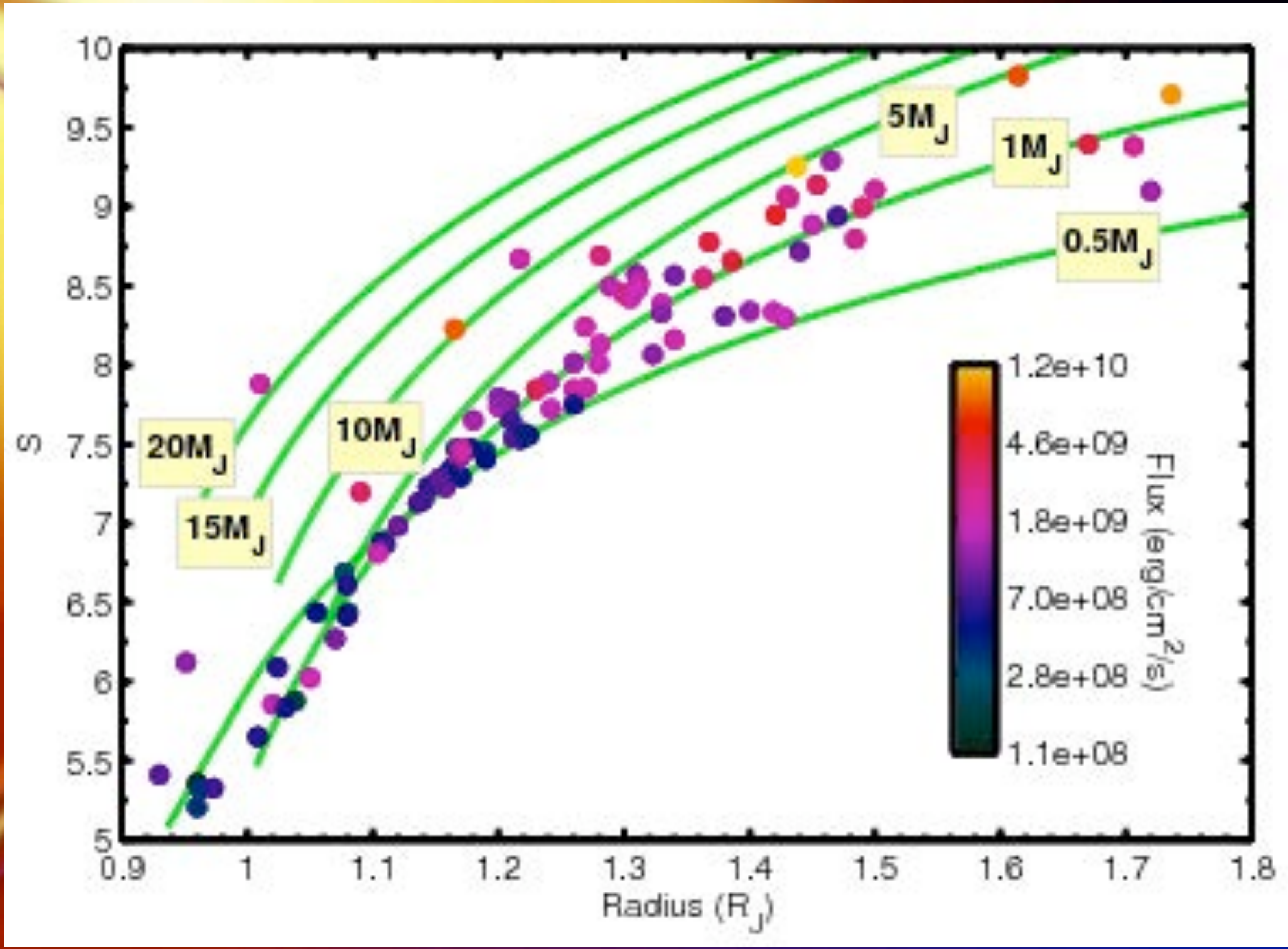
## CoRoT, M-Dwarf surveys

- Transit → fractional radius
  (relative to host star)
  → inclination.
- RV → planetary mass
- Solid planets:
  - CoRoT-7b : Period ~ 0.85 d
  - MEarth-1b: Period ~ 1.50 d

=> Diversity

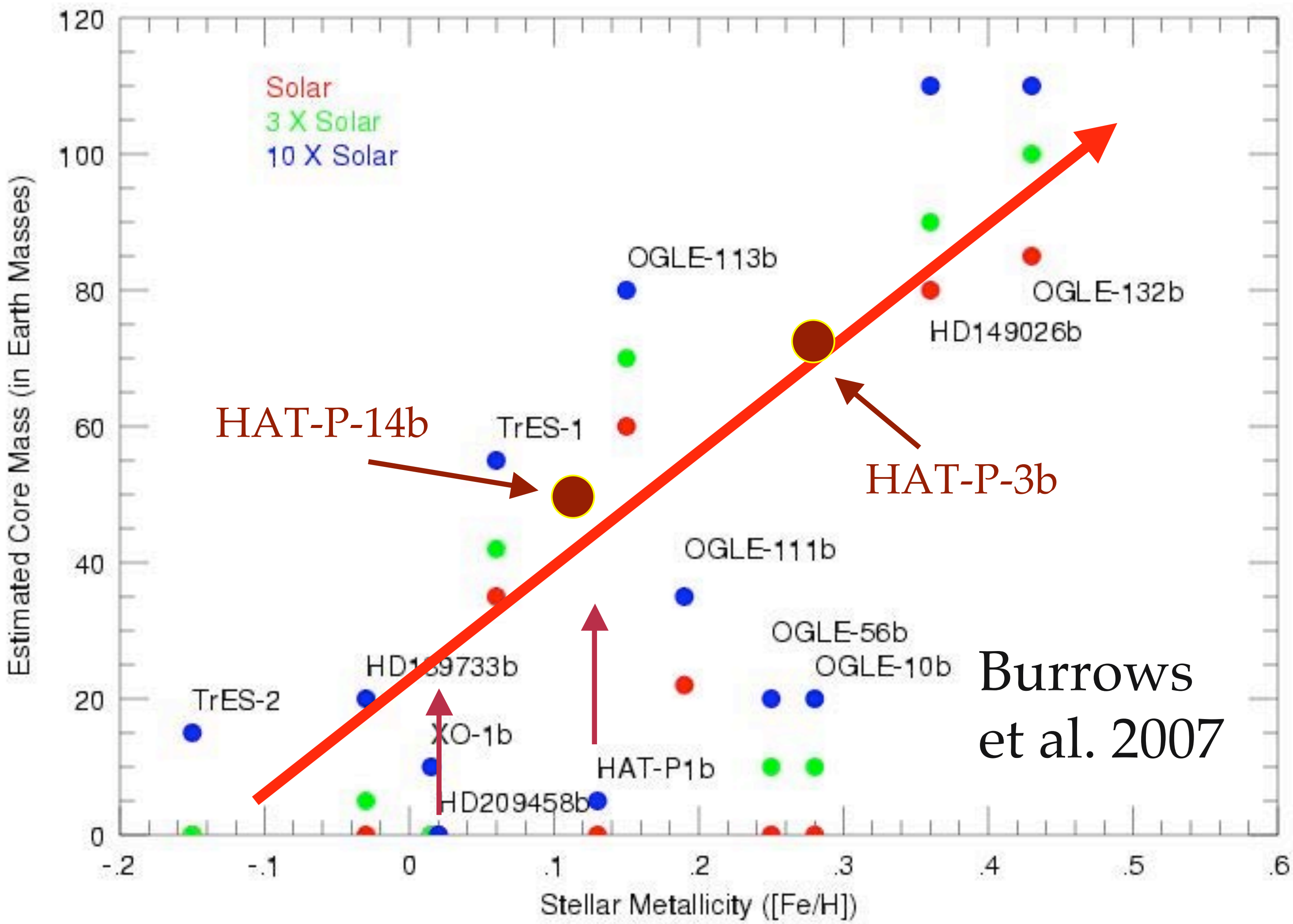


# Core Entropy vs. Radius for Transiting Giant Planets



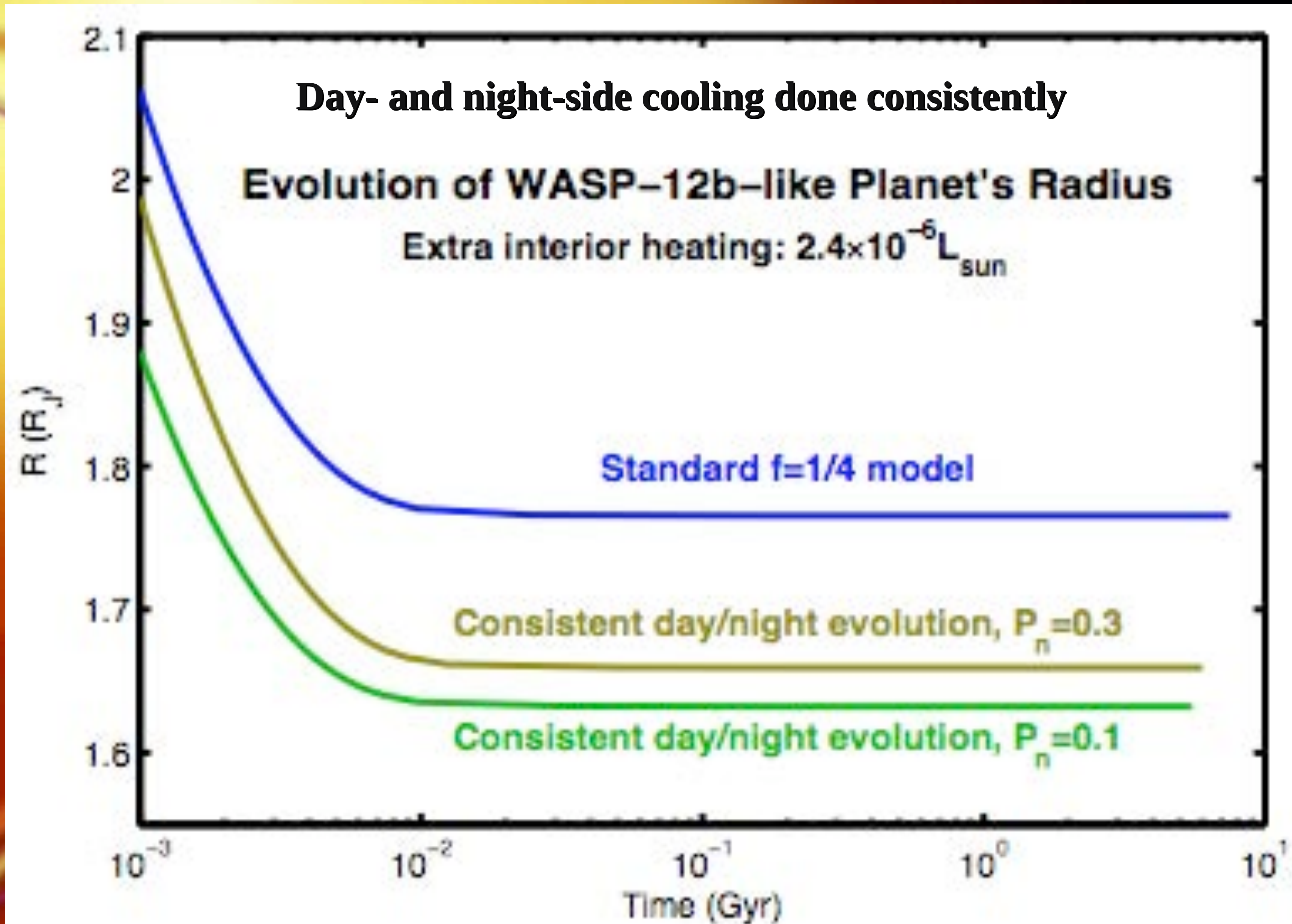

Spiegel & Burrows 2012

# Approximate "Core" Mass vs. Stellar Metallicity




Note measurement of HAT-P-1b

See also Guillot et al. 2006




Spiegel & Burrows 2012

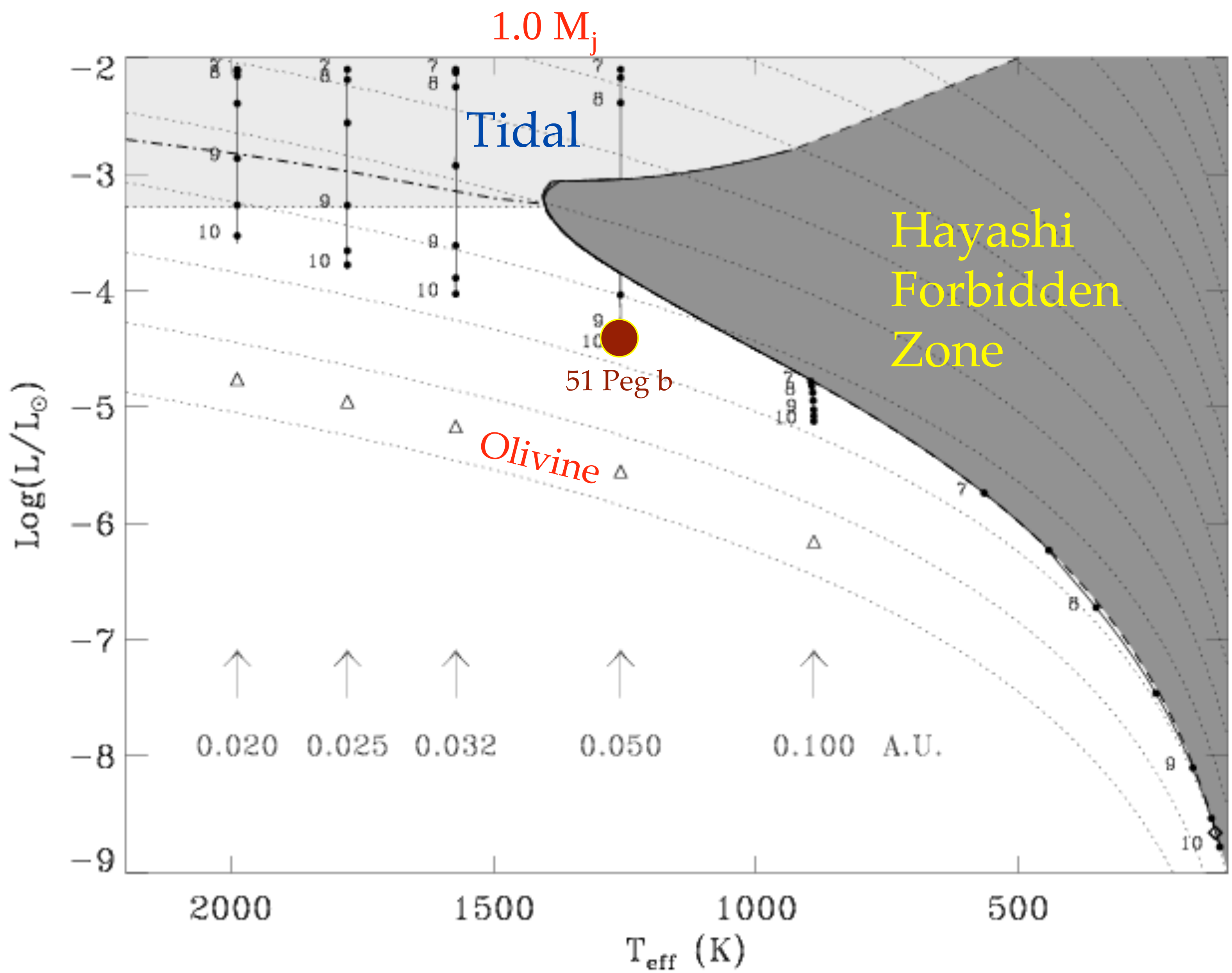
# Spectroscopic and Photometric Discriminants of Giant Planet Formation Scenarios

D. Spiegel and A. Burrows

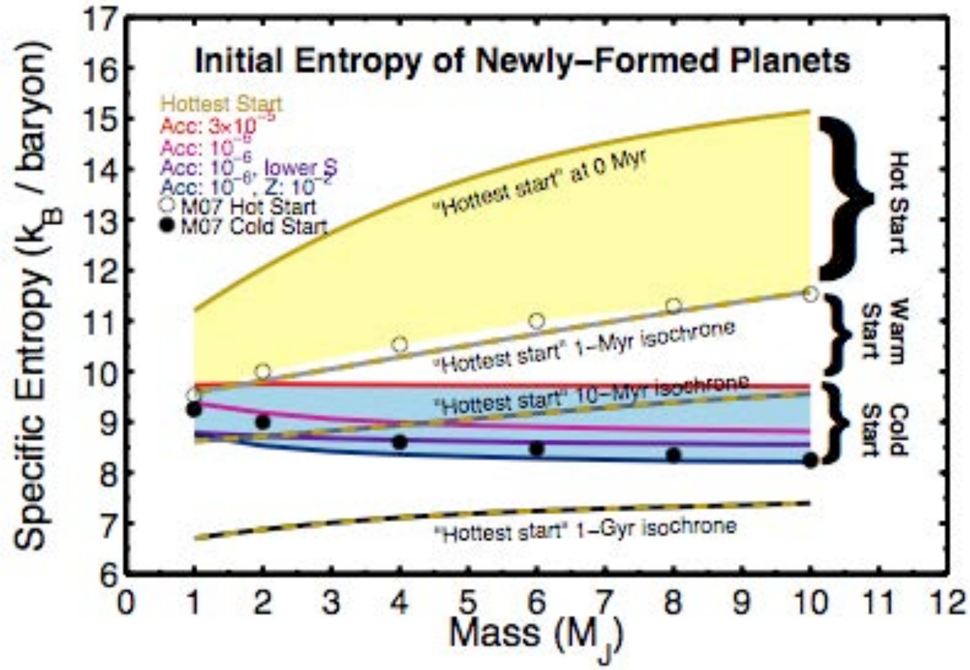
2011

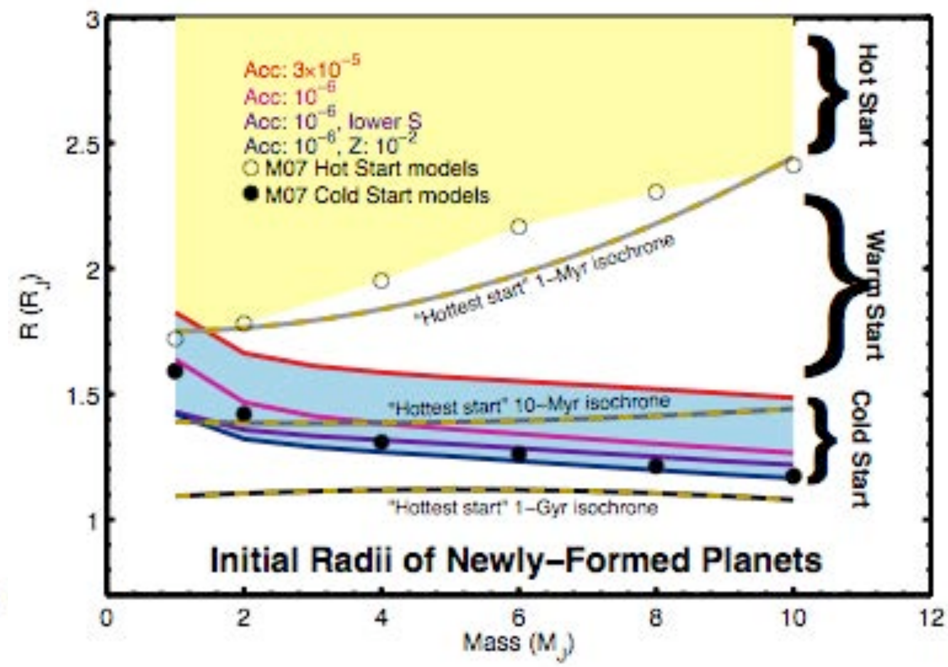
# Initial BD/EGP Models are Quite Uncertain

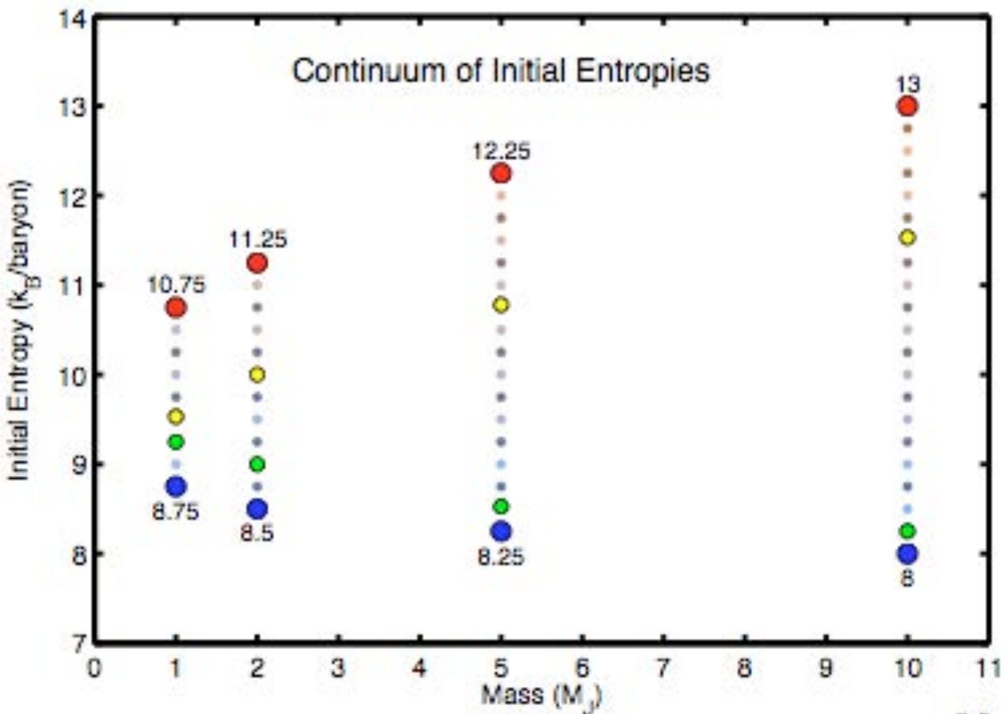
- Initial Radius, entropies determine flux evolution for quite some time
- Hot-start/cold-start/warm-start - Signatures of mode of formation

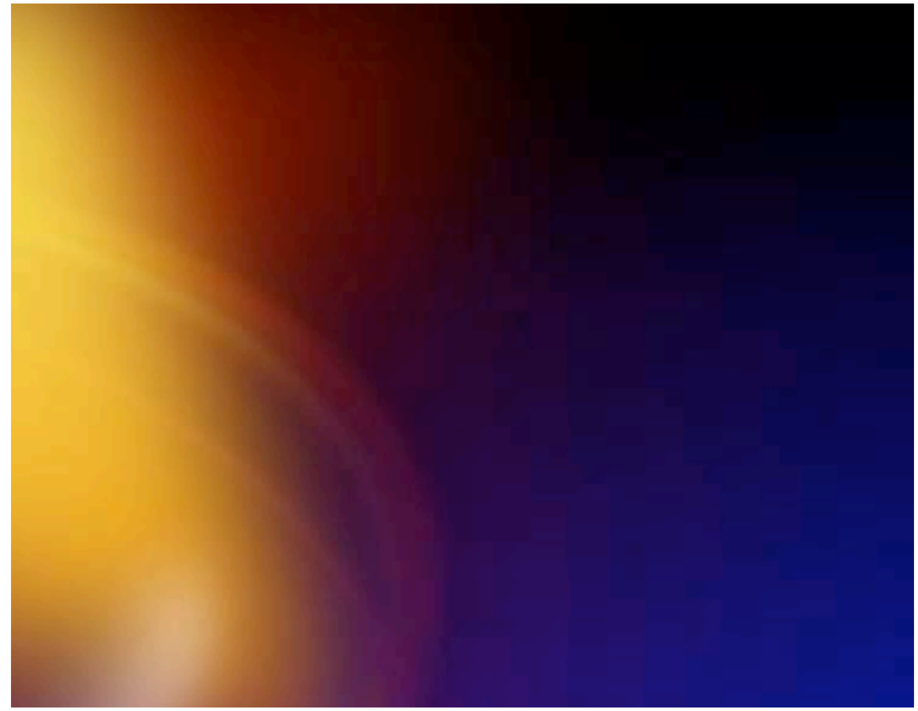


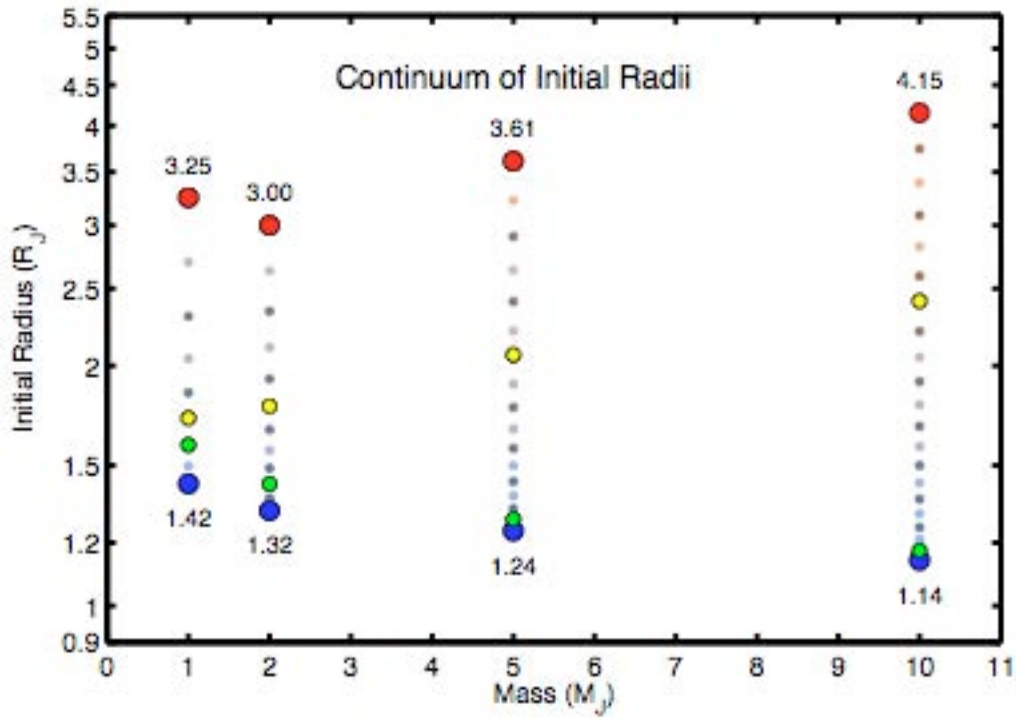
1.0 $M_j$
Tidal
Hayashi Forbidden Zone
51 Peg b
Olivine
0.020 0.025 0.032 0.050 0.100 A.U.
Log(L/L⊙)
$T_{eff}$ (K)
2000 1500 1000 500
−2 −3 −4 −5 −6 −7 −8 −9

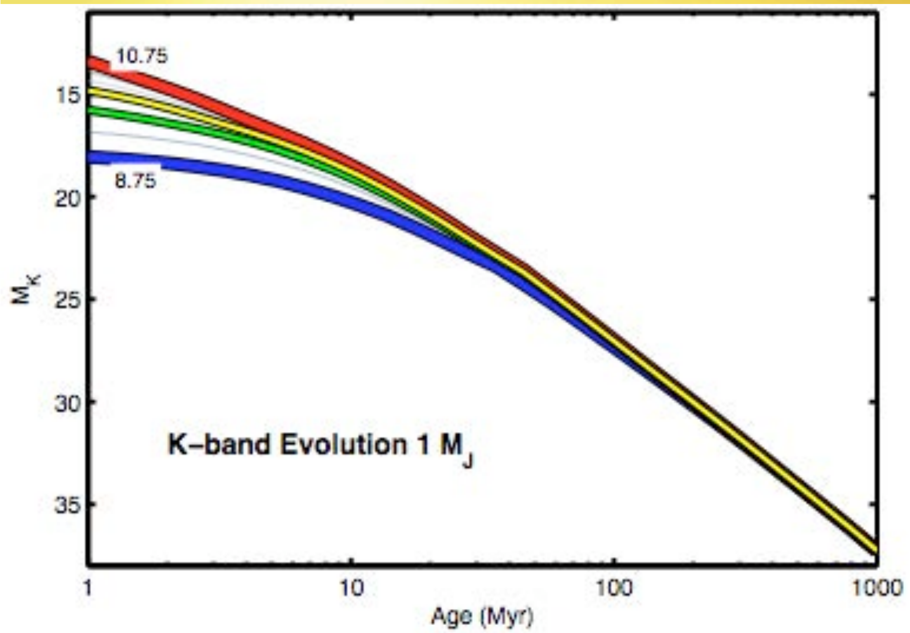

Initial Entropy of Newly–Formed Planets
Specific Entropy ($k_B$ / baryon)
Mass ($M_J$)
Hottest Start
Acc: $3\times10^{-5}$
Acc: $10^{-6}$
Acc: $10^{-6}$, lower S
Acc: $10^{-6}$, Z: $10^{-2}$
M07 Hot Start
M07 Cold Start
"Hottest start" at 0 Myr
"Hottest start" 1–Myr isochrone
"Hottest start" 10–Myr isochrone
"Hottest start" 1–Gyr isochrone
Hot Start
Warm Start
Cold Start

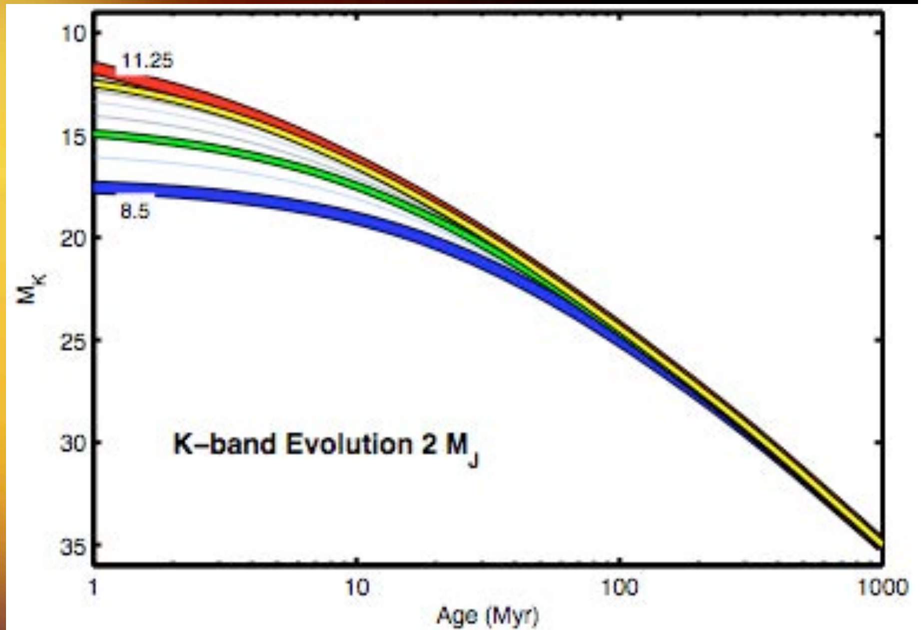

Initial Radii of Newly–Formed Planets
R ($R_J$)
Mass ($M_J$)
Acc: $3\times10^{-5}$
Acc: $10^{-6}$
Acc: $10^{-6}$, lower S
Acc: $10^{-6}$, Z: $10^{-2}$
M07 Hot Start models
M07 Cold Start models
"Hottest start" 1–Myr isochrone
"Hottest start" 10–Myr isochrone
"Hottest start" 1–Gyr isochrone
Hot Start
Warm Start
Cold Start

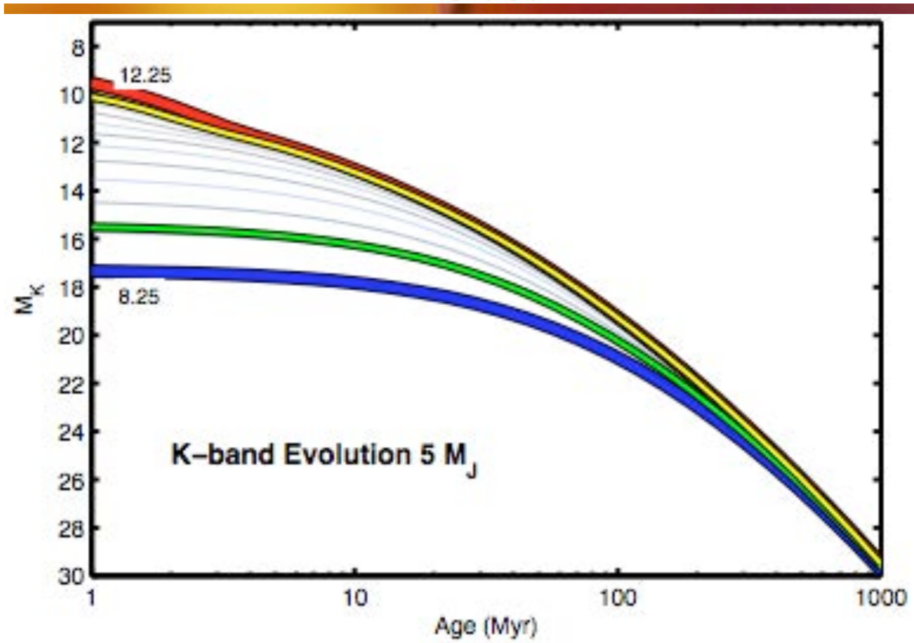

Continuum of Initial Entropies
Initial Entropy (k_B/baryon)
Mass (M_J)
10.75
8.75
11.25
8.5
12.25
8.25
13
8

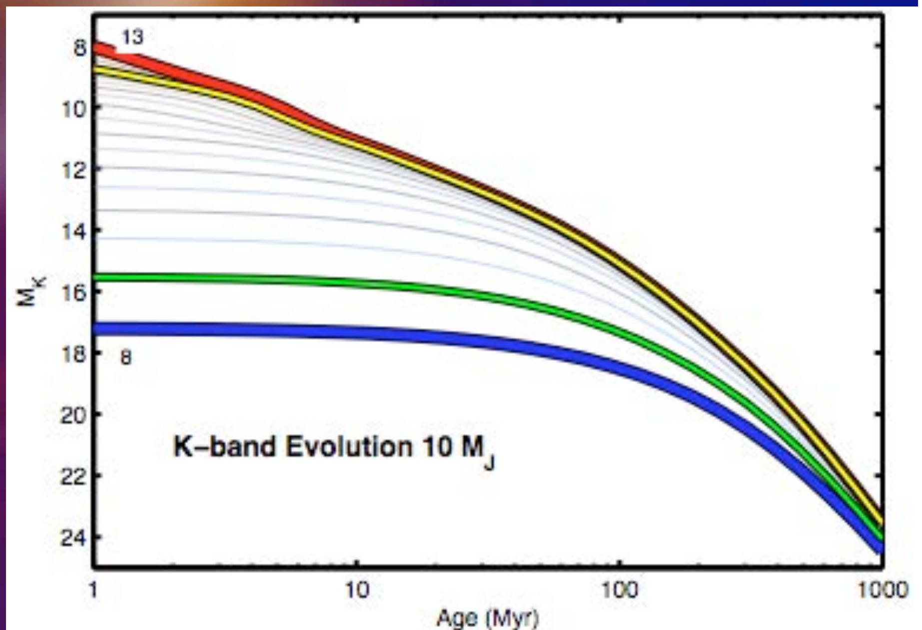



Continuum of Initial Radii
Initial Radius (R_J)
Mass (M_J)
3.25
1.42
3.00
1.32
3.61
1.24
4.15
1.14

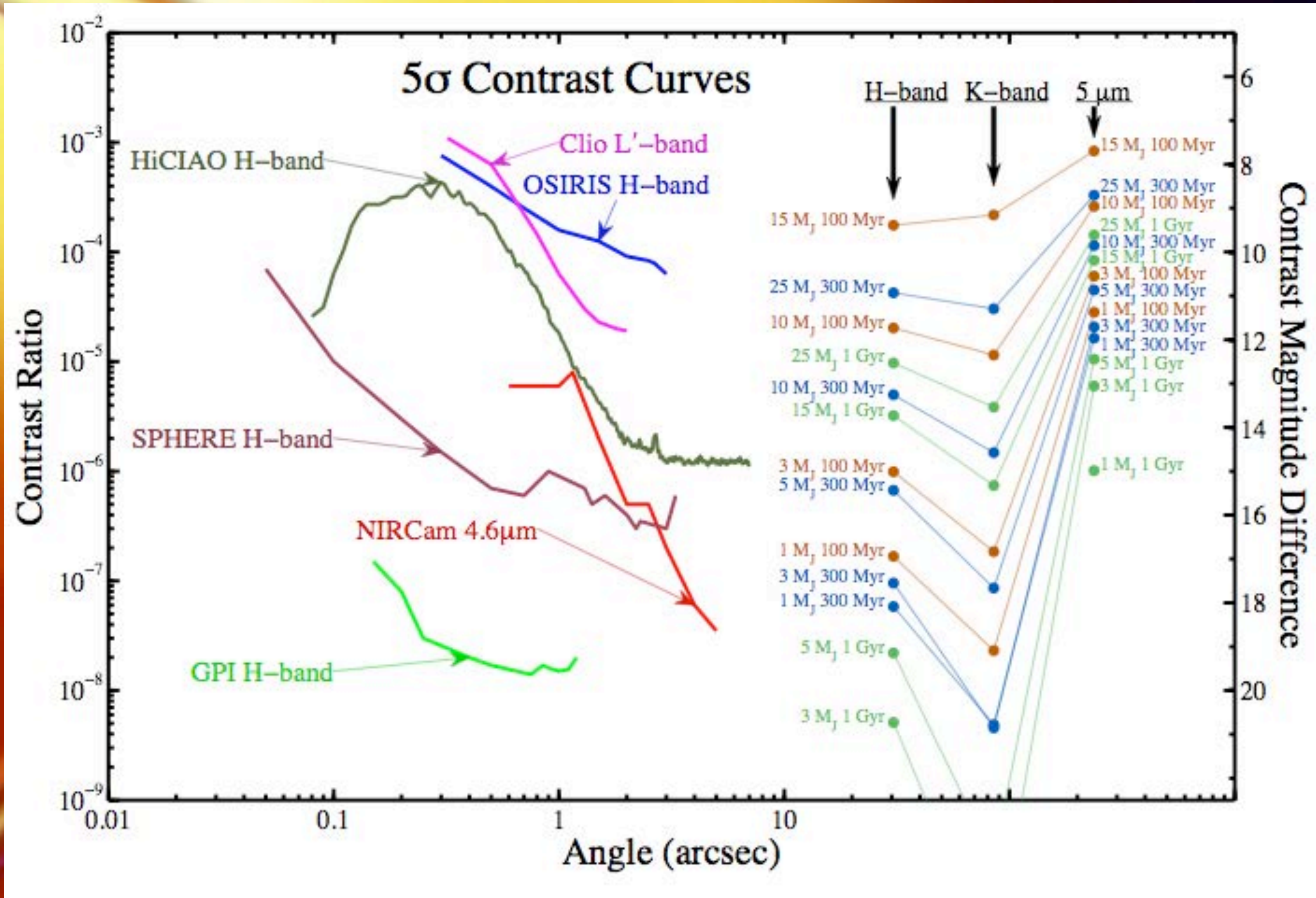

K–band Evolution 1 $M_J$
10.75
8.75
$M_K$
15
20
25
30
35
1
10
100
1000
Age (Myr)


K–band Evolution 2 $M_J$
11.25
8.5
$M_K$
10
15
20
25
30
35
1
10
100
1000
Age (Myr)

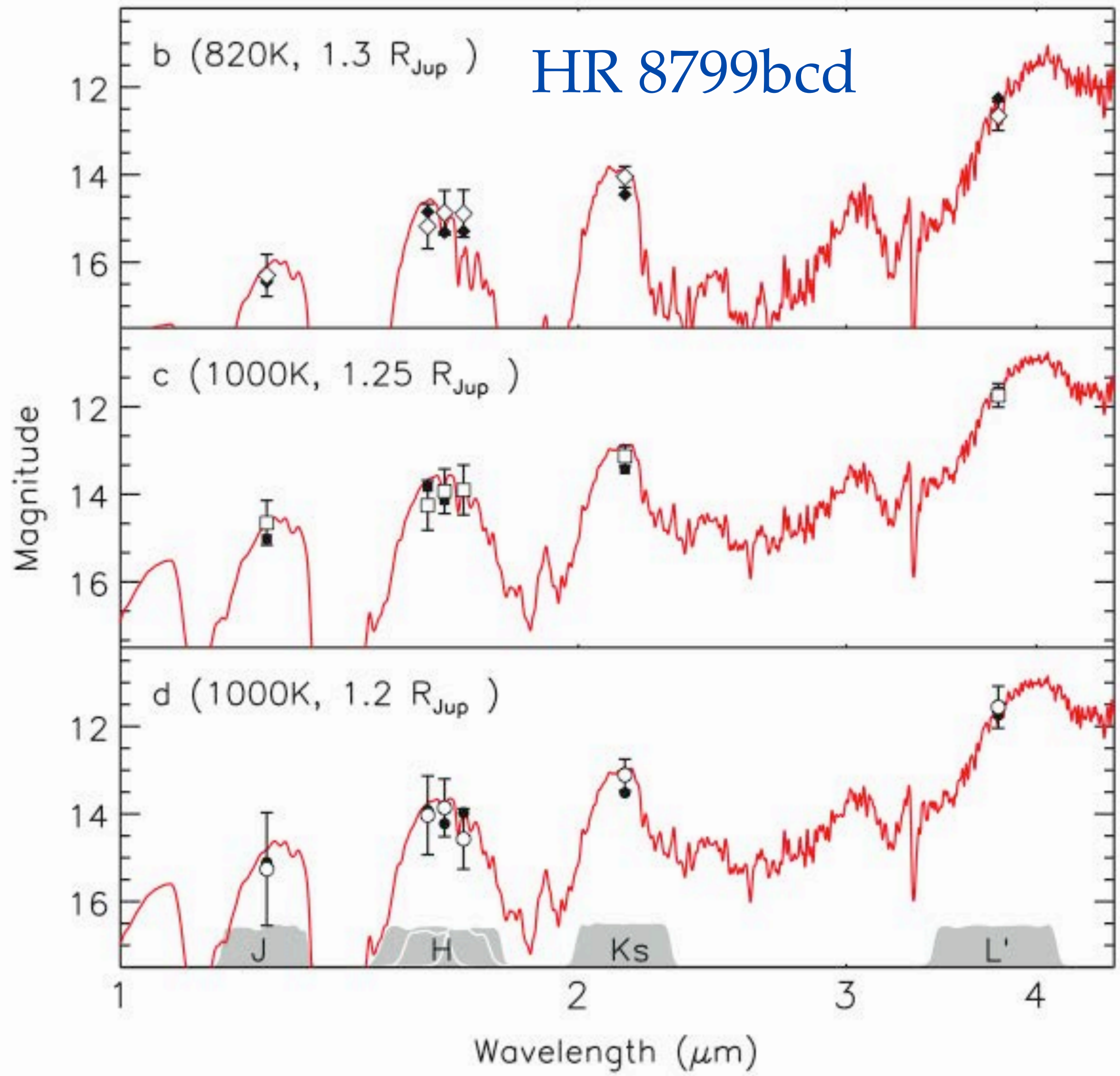

K–band Evolution 5 $M_J$
12.25
8.25
$M_K$
8
10
12
14
16
18
20
22
24
26
28
30
1
10
100
1000
Age (Myr)


K–band Evolution 10 $M_J$
13
8
$M_K$
8
10
12
14
16
18
20
22
24
1
10
100
1000
Age (Myr)

# High-Contrast Imaging



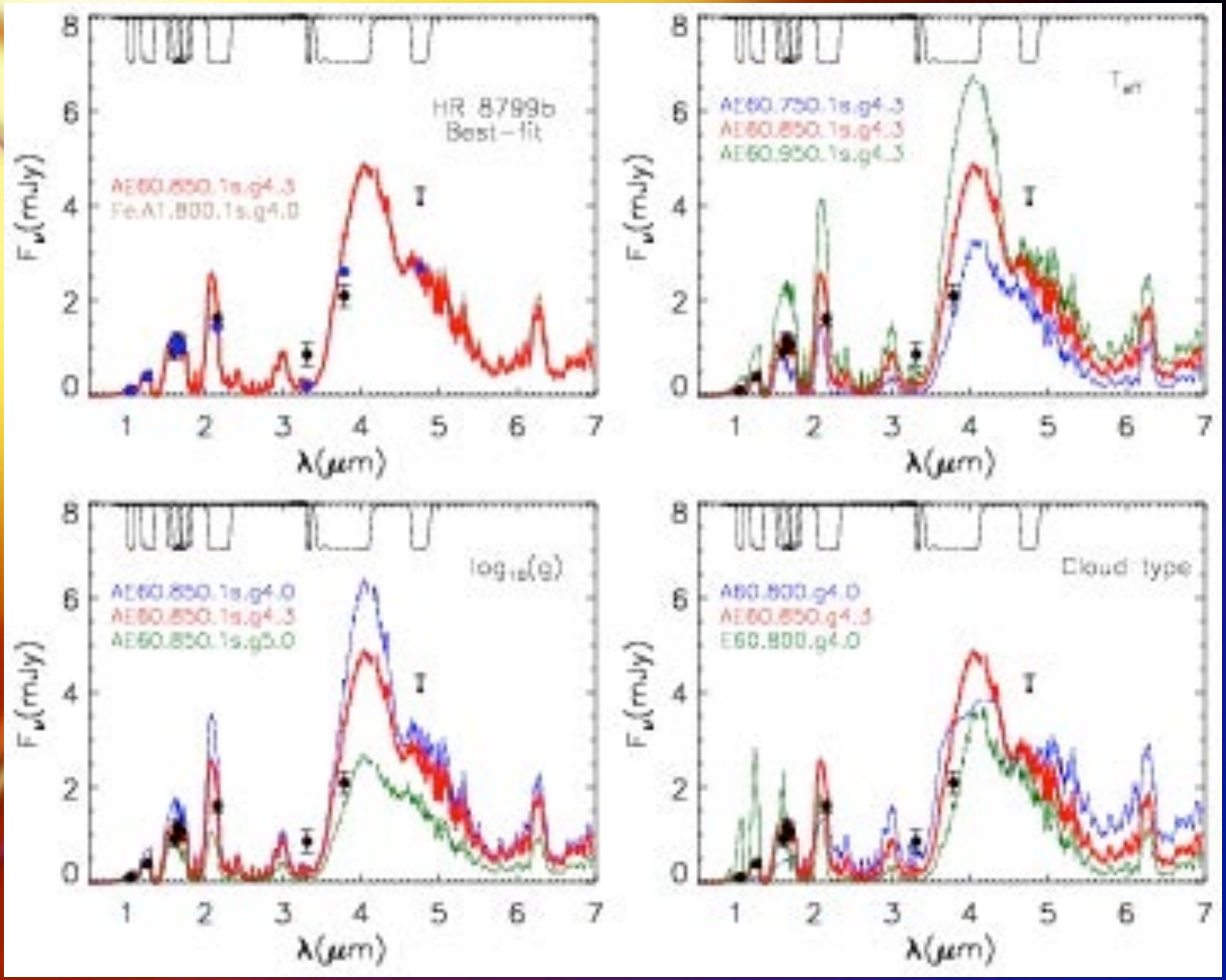
5σ Contrast Curves
Contrast Ratio
Angle (arcsec)
Contrast Magnitude Difference
HiCIAO H–band
Clio L′–band
OSIRIS H–band
SPHERE H–band
NIRCam 4.6μm
GPI H–band
H–band
K–band
5 μm
15 M_J 100 Myr
25 M_J 300 Myr
10 M_J 100 Myr
25 M_J 1 Gyr
10 M_J 300 Myr
15 M_J 1 Gyr
3 M_J 100 Myr
5 M_J 300 Myr
1 M_J 100 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



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)

## Very Dusty Atmospheres - low gravity?

HR 8799b




Madhusudhan, Burrows, & Currie 2011

**See also Barman et al.**

# WFIRST-2.4 Exoplanet Imaging Sensitivity

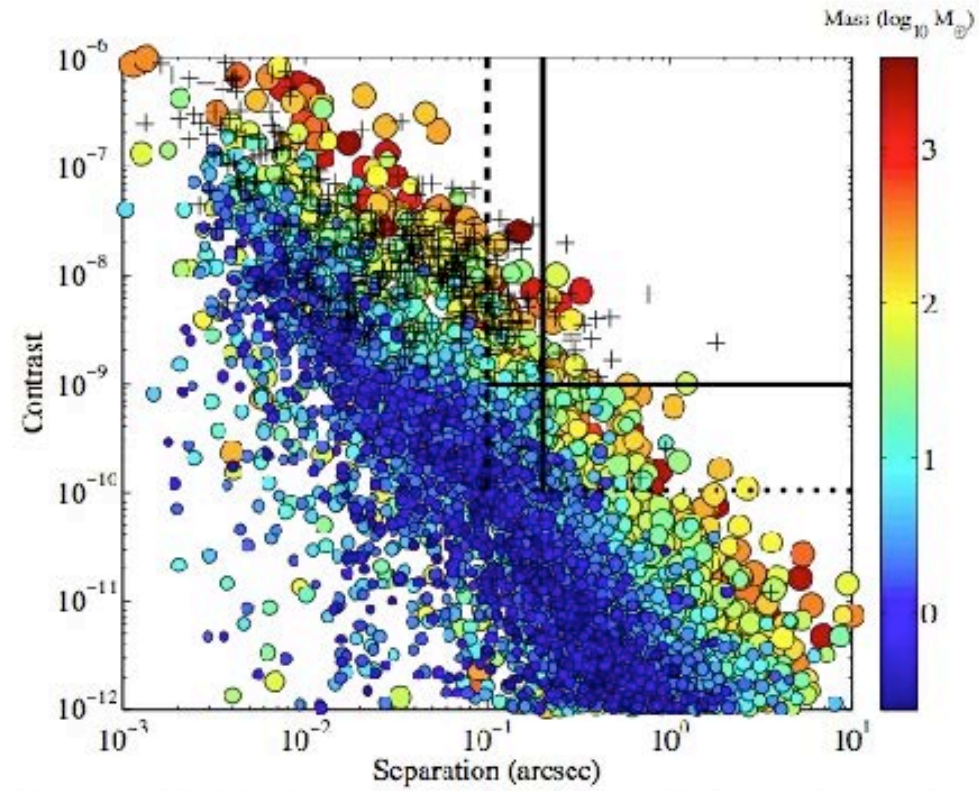



Figure 2-21: This figure is a snapshot in time of contrast and separation for model planets, ranging in size from Mars-like to several times the radius of Jupiter, for about 200 of the nearest stars within 30 pc. Color indicates planet mass while size indicates planet radius. Crosses represent known radial velocity planets. Solid black lines mark the baseline technical goal of 1 ppb contrast and 0.2 arcsec IWA, while the dotted lines show the more aggressive goals of 0.1 ppb and 0.1 arcsec IWA.

- Very sensitive to contrast limit (& IWA)

AFTA SDT report

# Exoplanet Science: Current Measurement and Interpretative Limitations

# Systematic Uncertainties/Ambiguities in Spectral Models

- Planets are not Stars - They have “character,” added complexity
- Opacities (line profiles …?)
- Abundances
- NLTE
- NCE
- Clouds
- Photochemistry
- 3D Effects (irradiation, rotation …)
- $\chi^2$ is of dubious real use when models systematics-dominated (models not merely a matter of physical parameters - but can have errors of unknown magnitude and kind)
- Retrieval (forward and inverse) techniques have been primitive - multiple degeneracies, systematic limitations
- Stellar Atmospheres took ~100 years to evolve as a discipline - molecular/exoplanetary atmospheres are more complicated

# Systematic Uncertainties in Data

- Limited SNR, bandwidths, resolution
- Star spots
- Absolute Calibration
- Earth's atmosphere ($H_2O$, OH, …)
- Spitzer "Ramps"
- Spitzer not designed for better than $10^{-2}$ - pushed to $\sim 10^{-3}$
- Planet/Star flux ratios have varied by factors of ~2 from epoch to epoch
- Measured Transit depths at the same wavelengths vary by factors of ~2

# Parameters > Number of Data Points

- Model fits are often under-constrained
- Frequently, just two points fit (e.g., $F_p / F_*$)!
- In the context of systematic data uncertainties, ….
- $CO_2$, abundances, thermal inversions, C/O ratios ?

# One-D models for 3D objects?

- Many adjustable parameters (f, $\varepsilon$, $\alpha$, $\kappa_a$, $P_n$ , ”A,” abundances, $T_{eff}$ , T/P profiles, “TiO”….)
- Advection of composition and heat?
- Latitudinal and longitudinal dependence of emissions/spectra - antenna gain?
- Solar ratios of elements?
- Metallicity dependence (weak for emission (secondary eclipse); strong for transit (primary eclipse)?)
- Mixing-length convection?
- Eddy mixing?
- Transit spectra are for terminator region - transition region, ingress/egress asymmetry

# Limitations of 3D GC Modeling

- 3D models have Mach ~ 1, but use “primitive” equations that assume M << 1
- Filter sound waves (one exception)
- Can’t handle shock waves
- Based on Earth GCMs and parametrizations
- Use Rayleigh drag, even for close-in EGPs (“hot Jupiters”)
- Super-rotational speeds depend on ad hoc parameters
- Non-ideal MHD?
- Don’t match to core convective regions consistently
- Don’t incorporate 3D multi-frequency radiative transfer

- Importantly, GCMs were configured to look at winds/pressure, not spectral emissions - there is a mismatch between the traditional goals of Planetary and Earth scientists and Exoplanet Astronomers

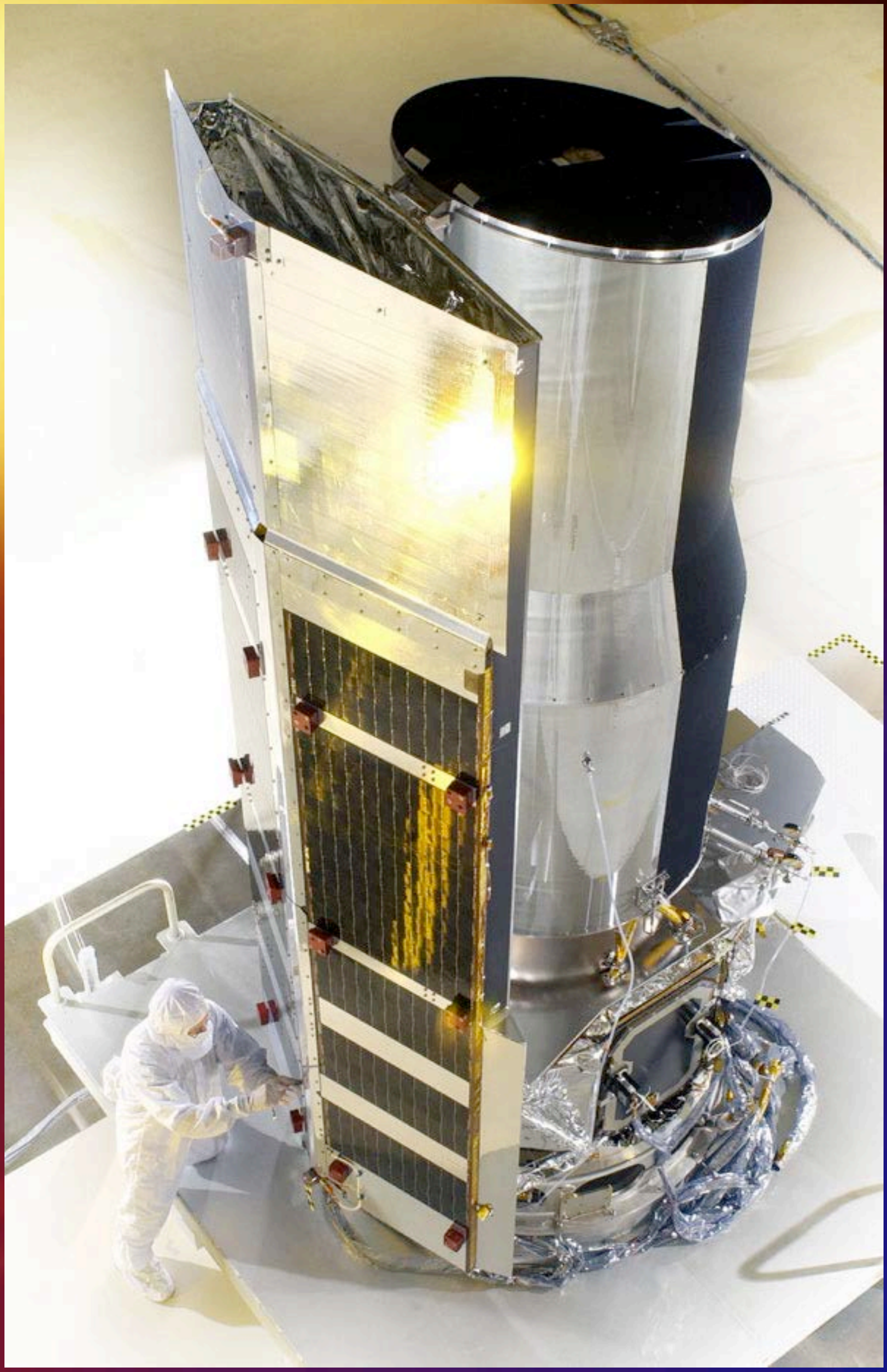
Need high-quality, uniform, calibrated data over a large spectral bandwidth

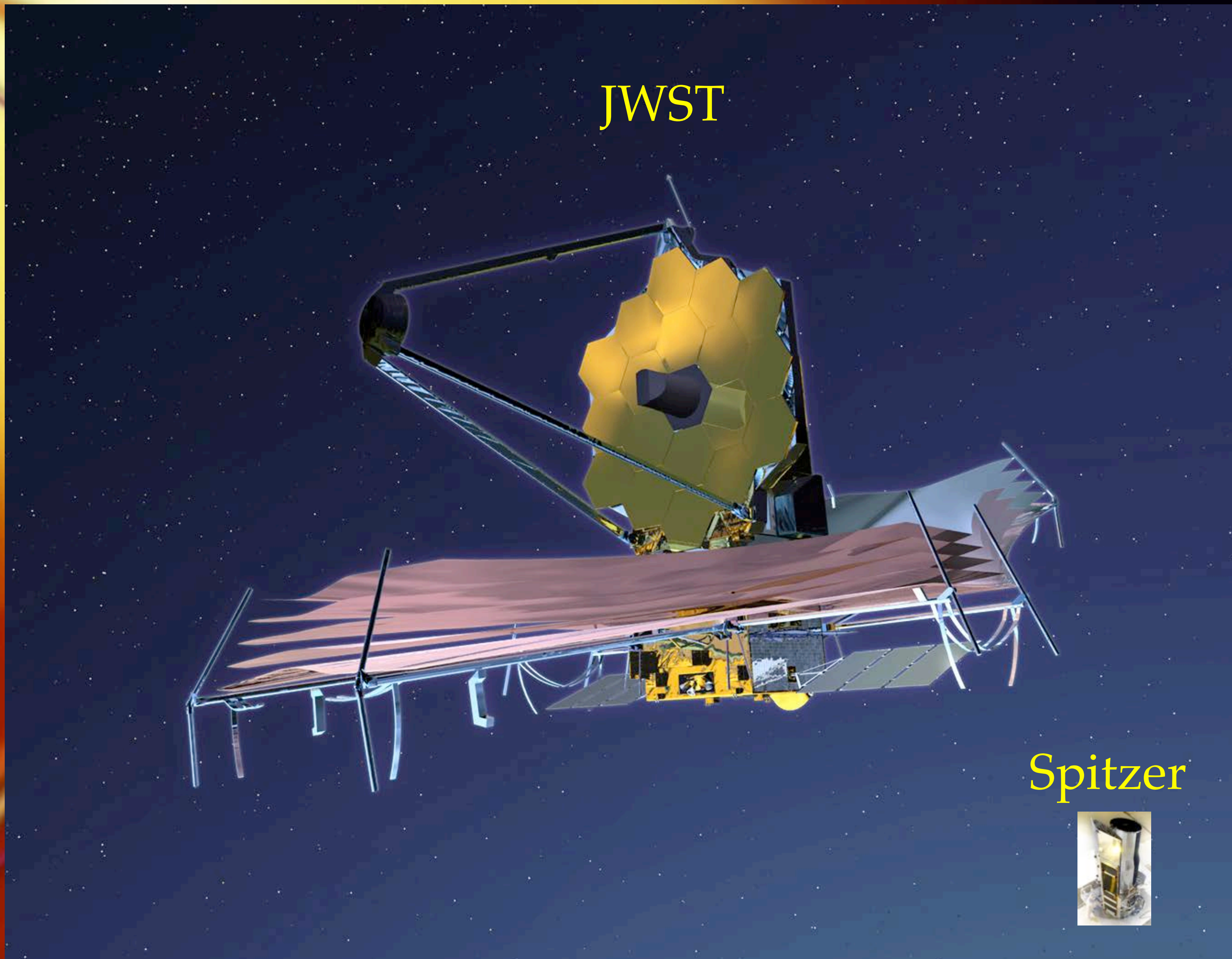
Need much more physical models, with realistic (multi-D) radiative transfer

# Training Set

- Many (most?) conclusions will be overturned
- The past 15 years has been but a training exercise - educating a community
- Community has been practicing for the future - winnowing of ideas, techniques ….
- With 2nd- and 3rd-generation data and much better and more comprehensive models, we may start truly to learn about exoplanet atmospheres and spectra
- Need mature ground-based and space-based initiatives and a credible, reliable international plan/Roadmap for exoplanet exploration in the next ~20 years
- Are we ready?

Spitzer ST:




JWST
Spitzer

# Theoretical Questions

- What limits super-rotational atmospheric flows?
- Day/Night Contrasts?
- What is the “extra absorber” in many hot-EGP atmospheres?
- Why are some “Hot Jupiters” so large ($R_p$ vs. $M_p$)?
- Is there a dynamical, structural, and/or thermal role for B-fields?
- What condensates reside in planetary atmospheres?
- Winds and Evaporation?
- Tidal Effects?
- Atmospheric, Envelope, and Core compositions?
- Mode(s) of Formation (and Signatures!)?