

Inferring Atmospheric Characteristics From Transiting Exoplanets

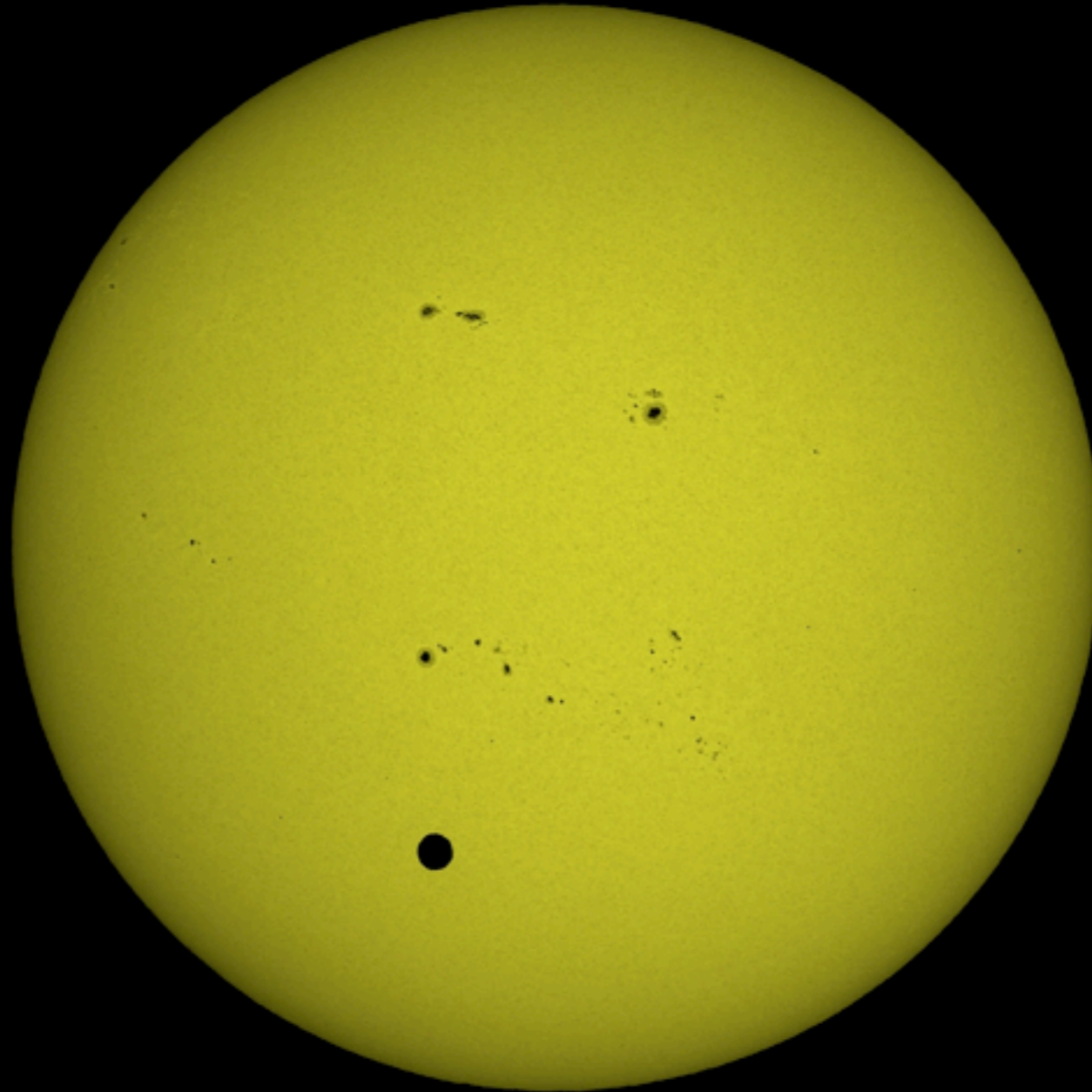


Jean-Michel Désert

Caltech - Sagan Fellow

Sagan Summer School, July 26th 2012

Inferring Atmospheric Characteristics From Transiting Exoplanets



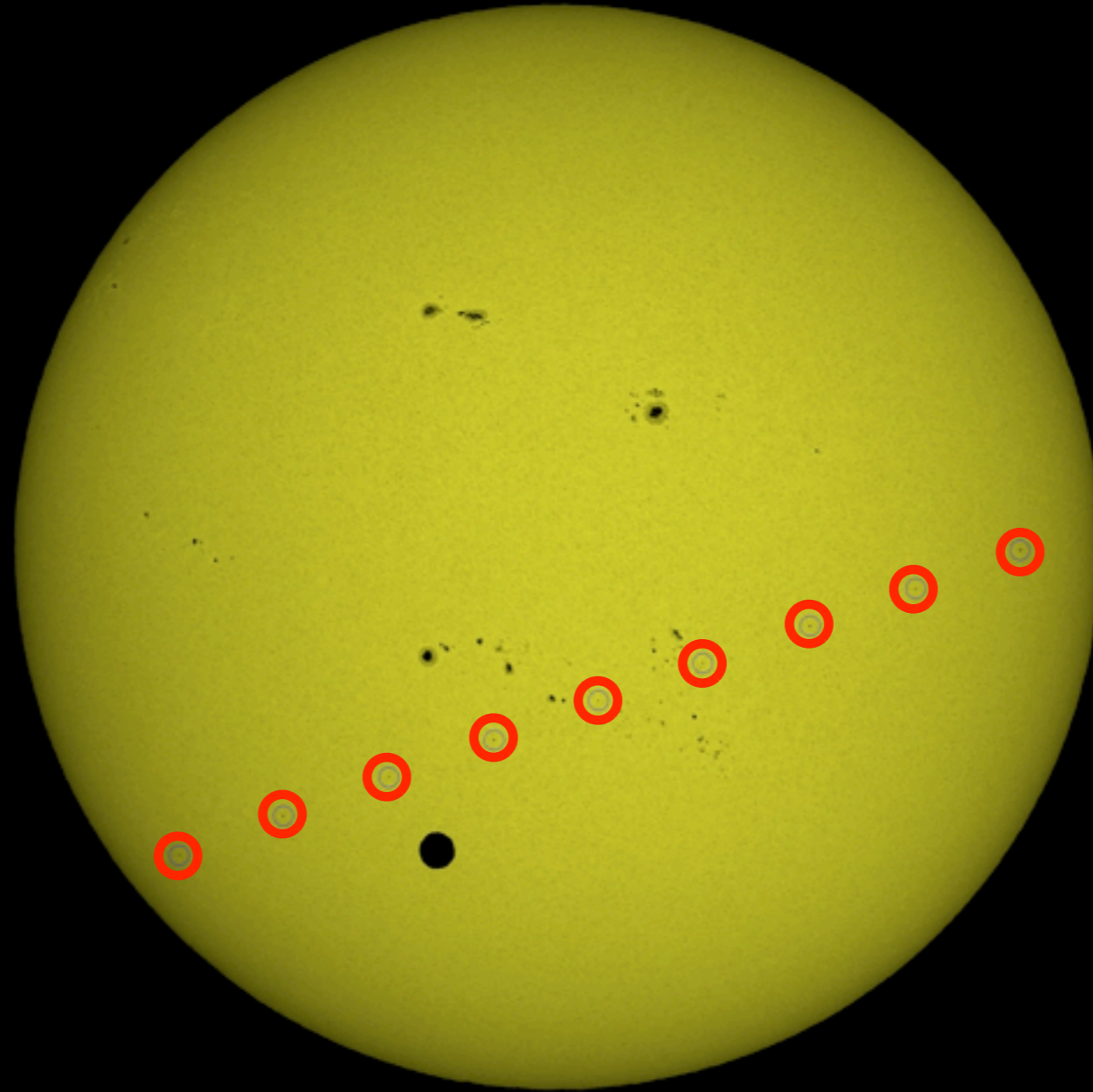
*Image credit:
THIERRY LEGAULT*

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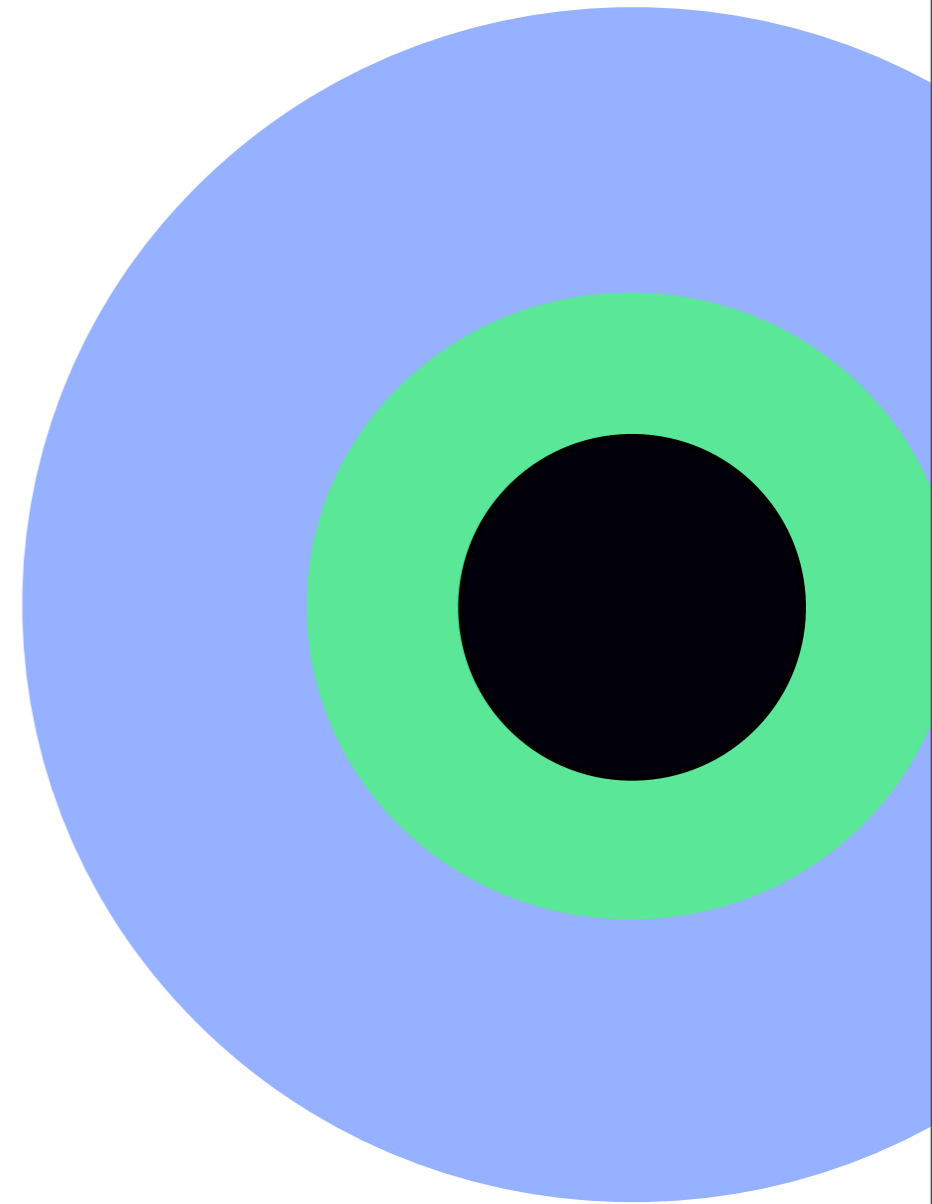
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I) From Transits (Eclipses) Depths to Atmospheric Signals

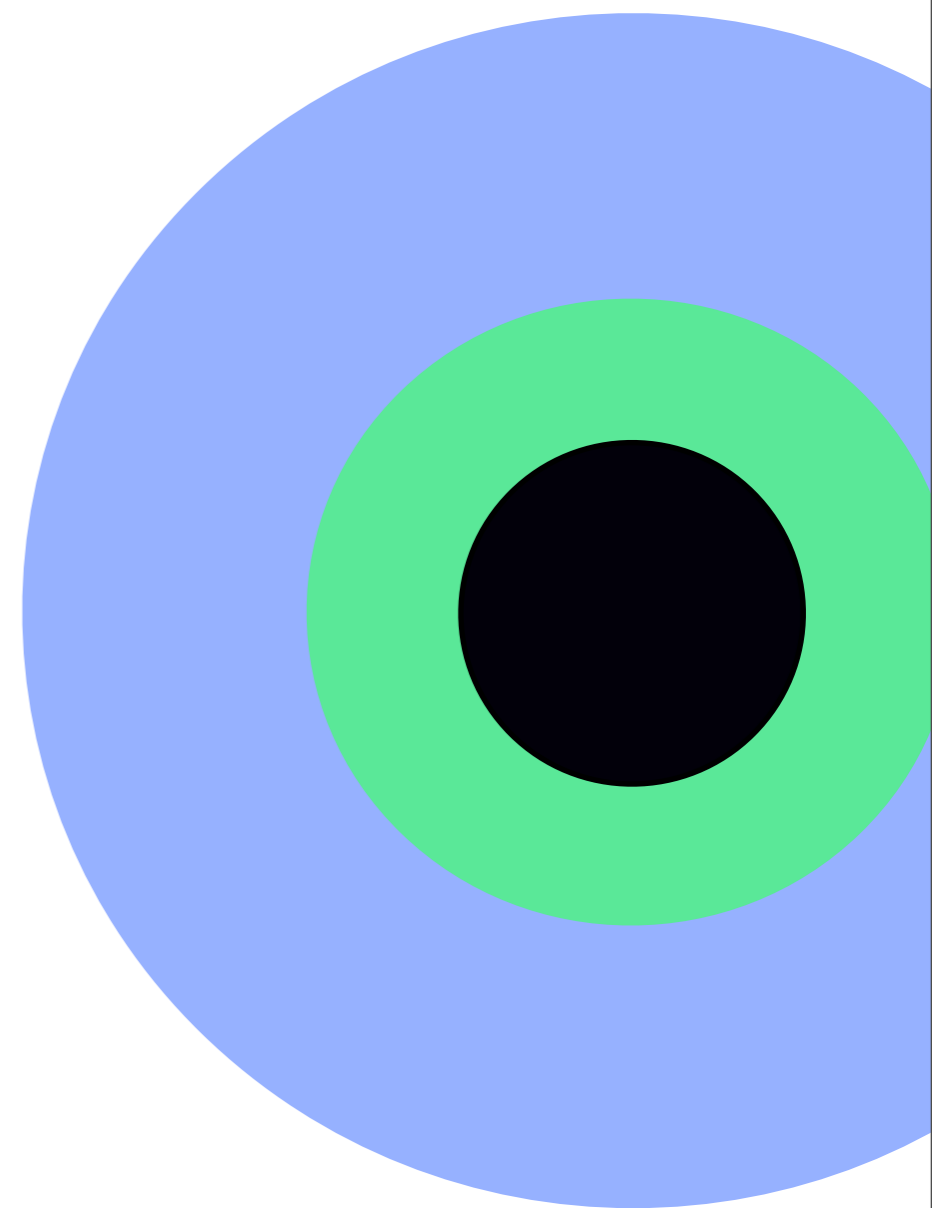
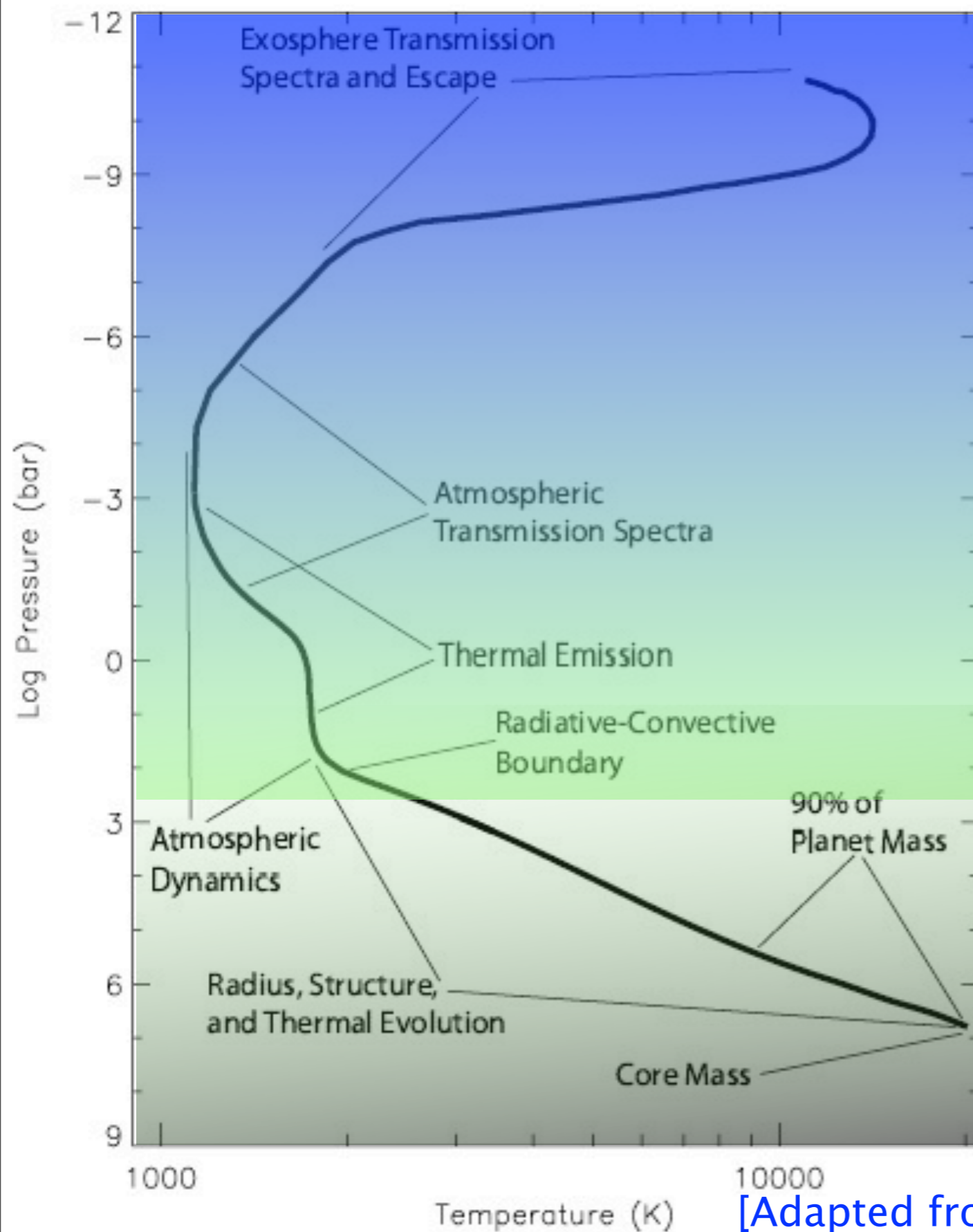
II) Pushing Observational Limits

III) New Frontiers for Atmospheric Studies

Atmospheric Structure



Atmospheric Structure



[Adapted from Fortney 2008]

HD209458b: 12 years of transits

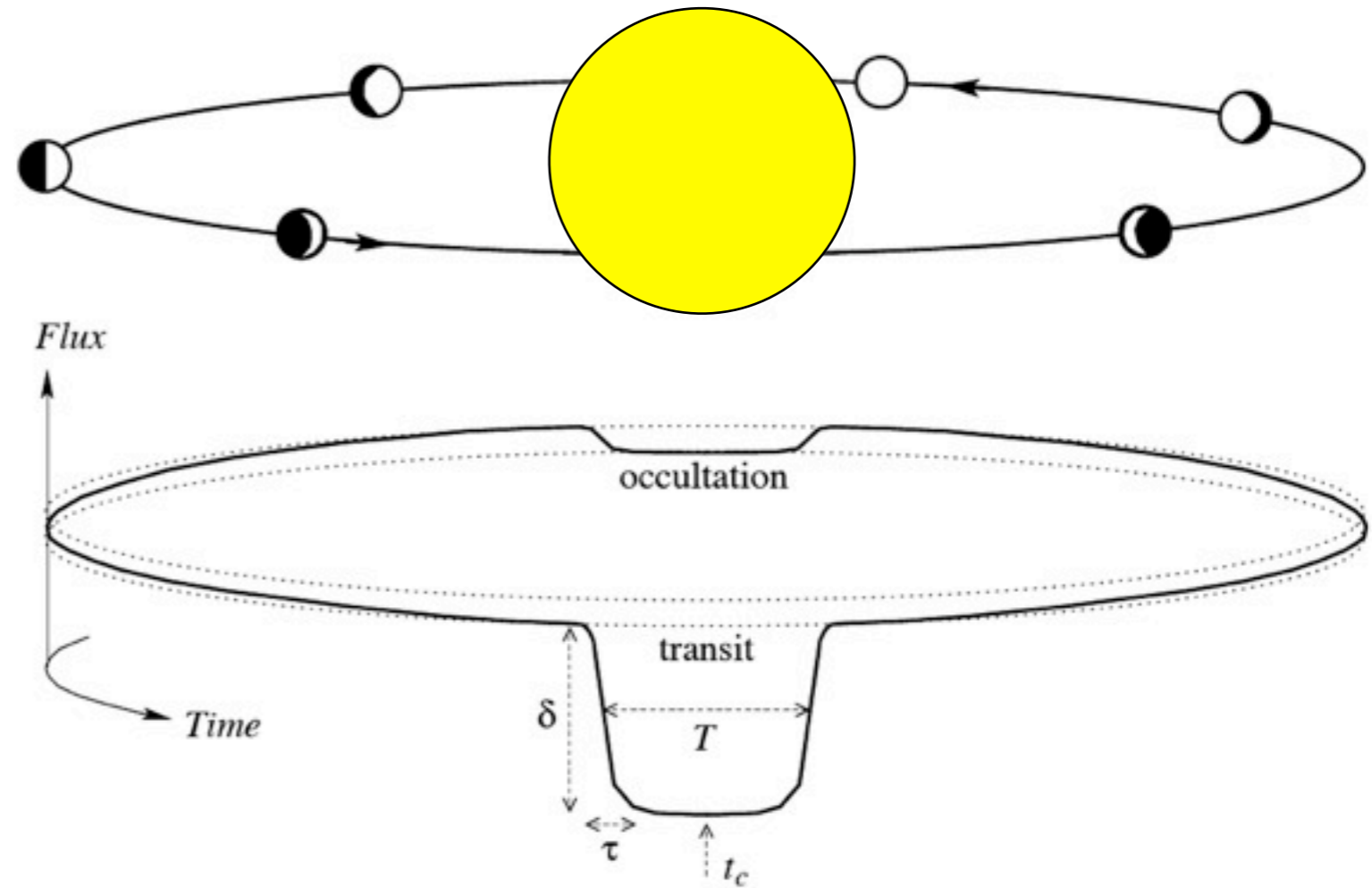
★ First transit: $(R_p / R_*)^2 \sim 10^{-2}$

$\sim 1.6\%$

[[Charbonneau et al. 2000](#)]

[[Henry et al. 2000](#)]

$1.27 \pm 0.02 R_{jup}$



Updated from Winn et al. (2008)

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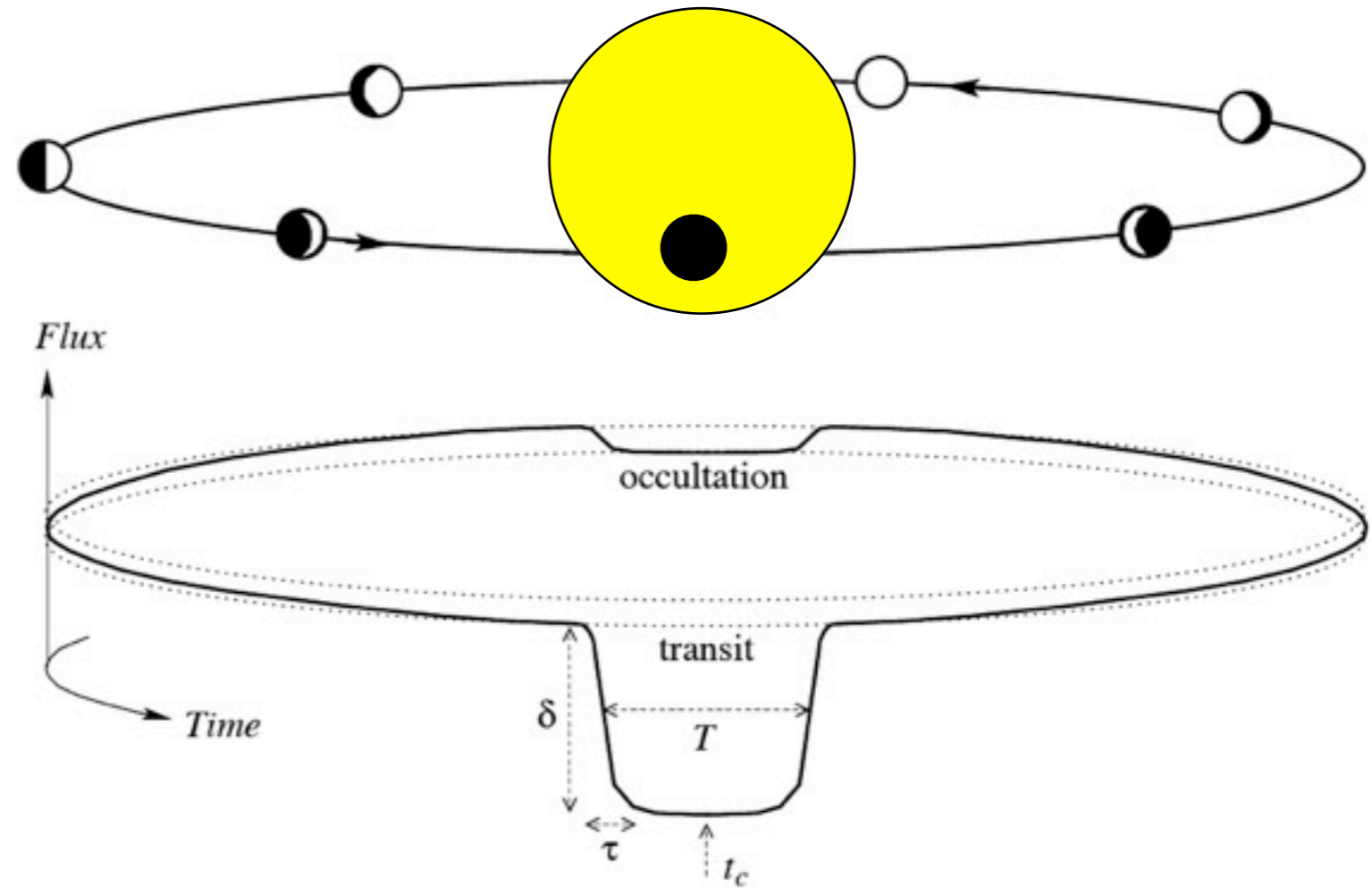
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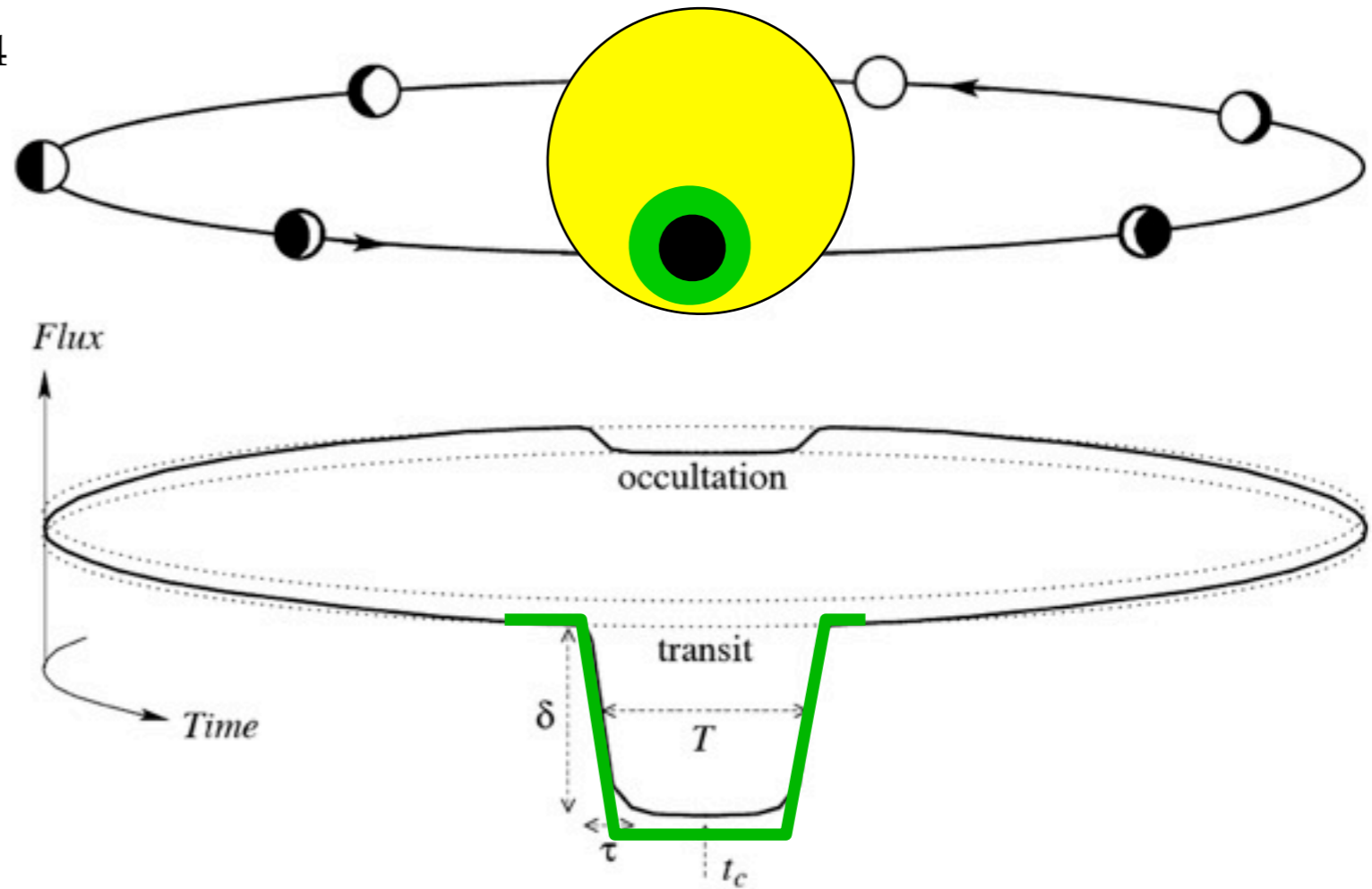
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★ First atmosphere: $(atm / R_*)^2 \sim 10^{-4}$

$\text{NaI } 0.0232 \pm 0.0057 \%$

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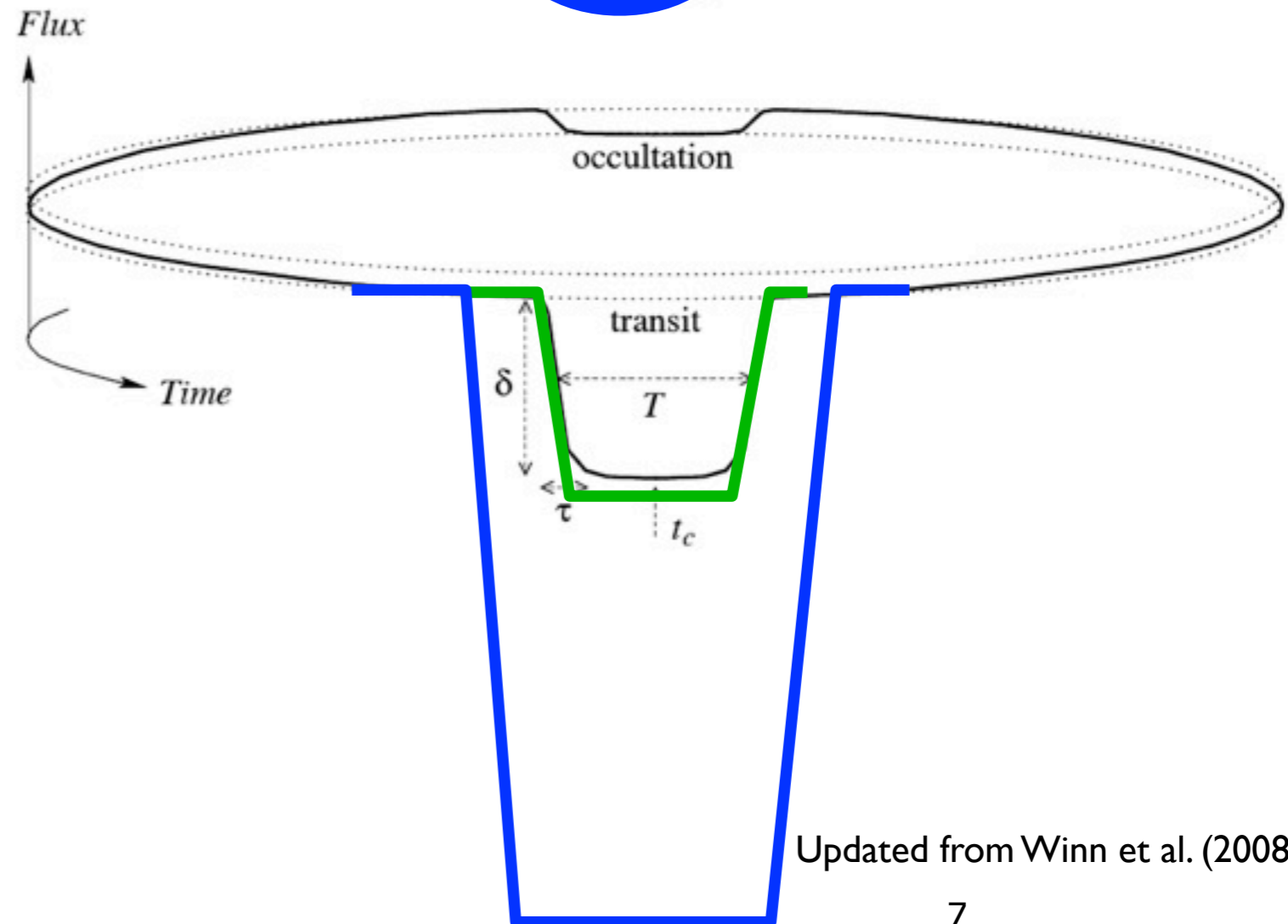
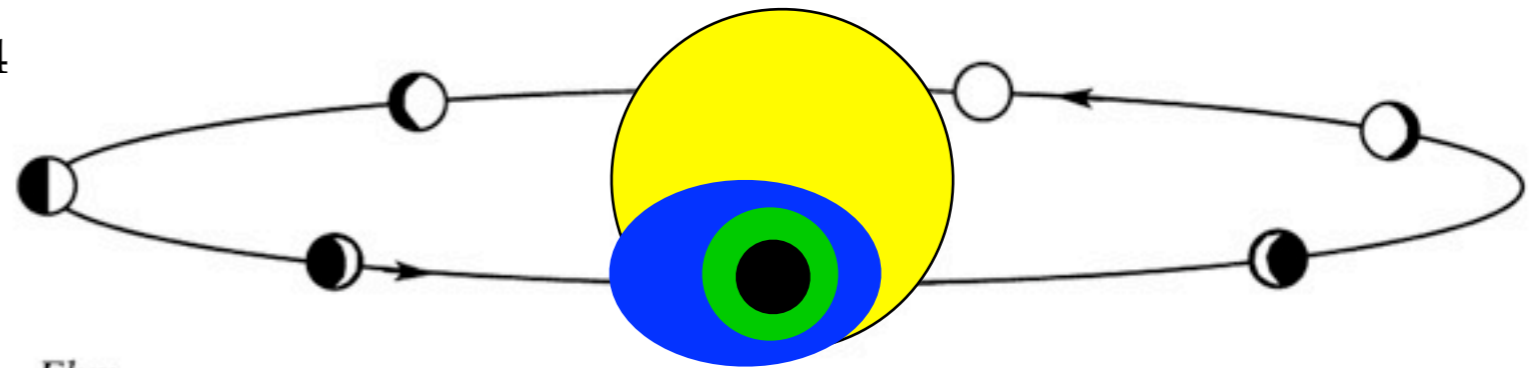
NaI $0.0232 \pm 0.0057 \%$

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★ Exosphere

H $\sim 15 \pm 4\%$

[Vidal-Madjar *et al.* 2003]



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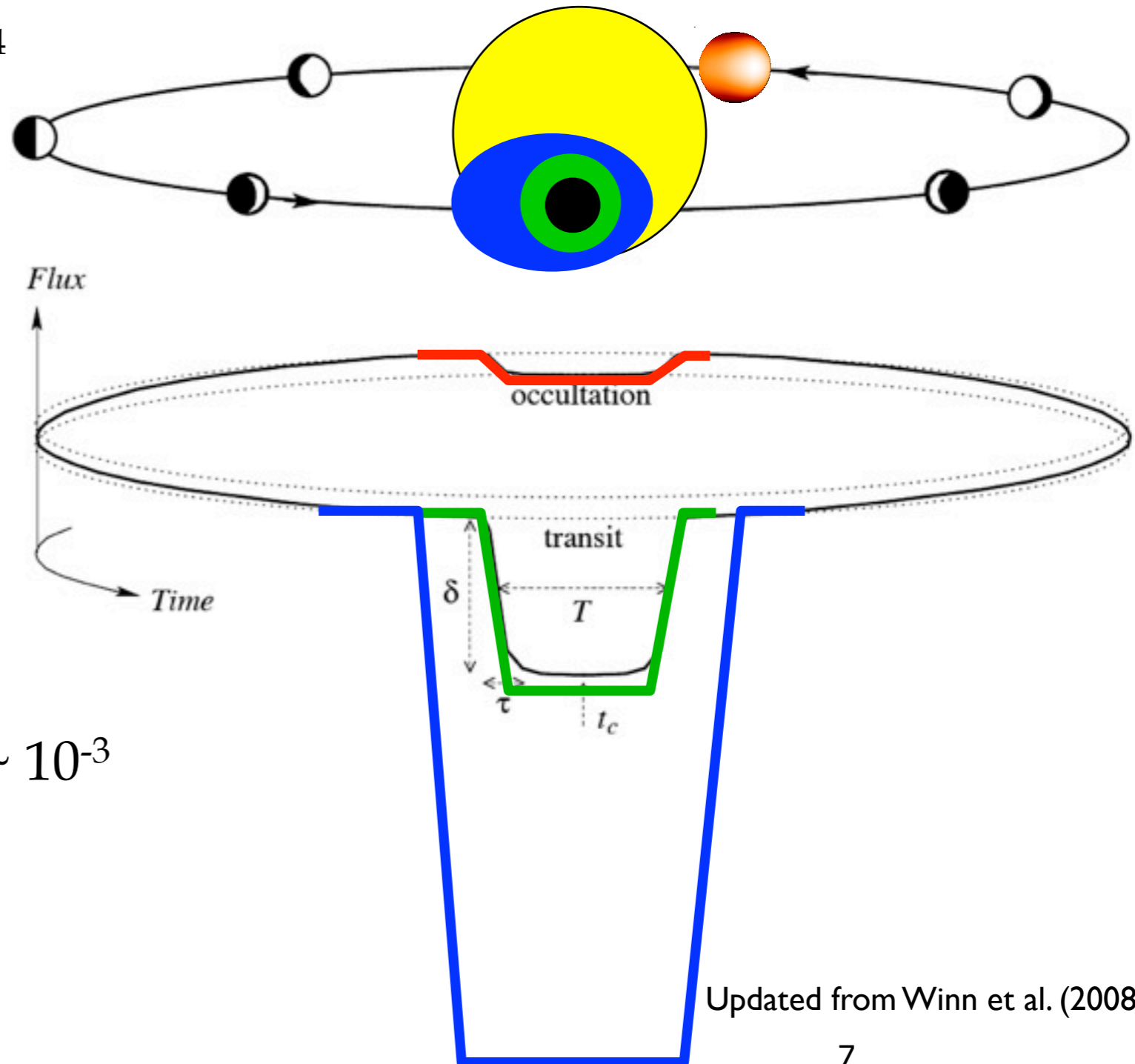
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[Vidal-Madjar *et al.* 2003]

★ First direct lights: $T_p / T_* (R_p / R_*)^2 \sim 10^{-3}$

$T_B (24 \mu m) \sim 1130 \pm 150 K$

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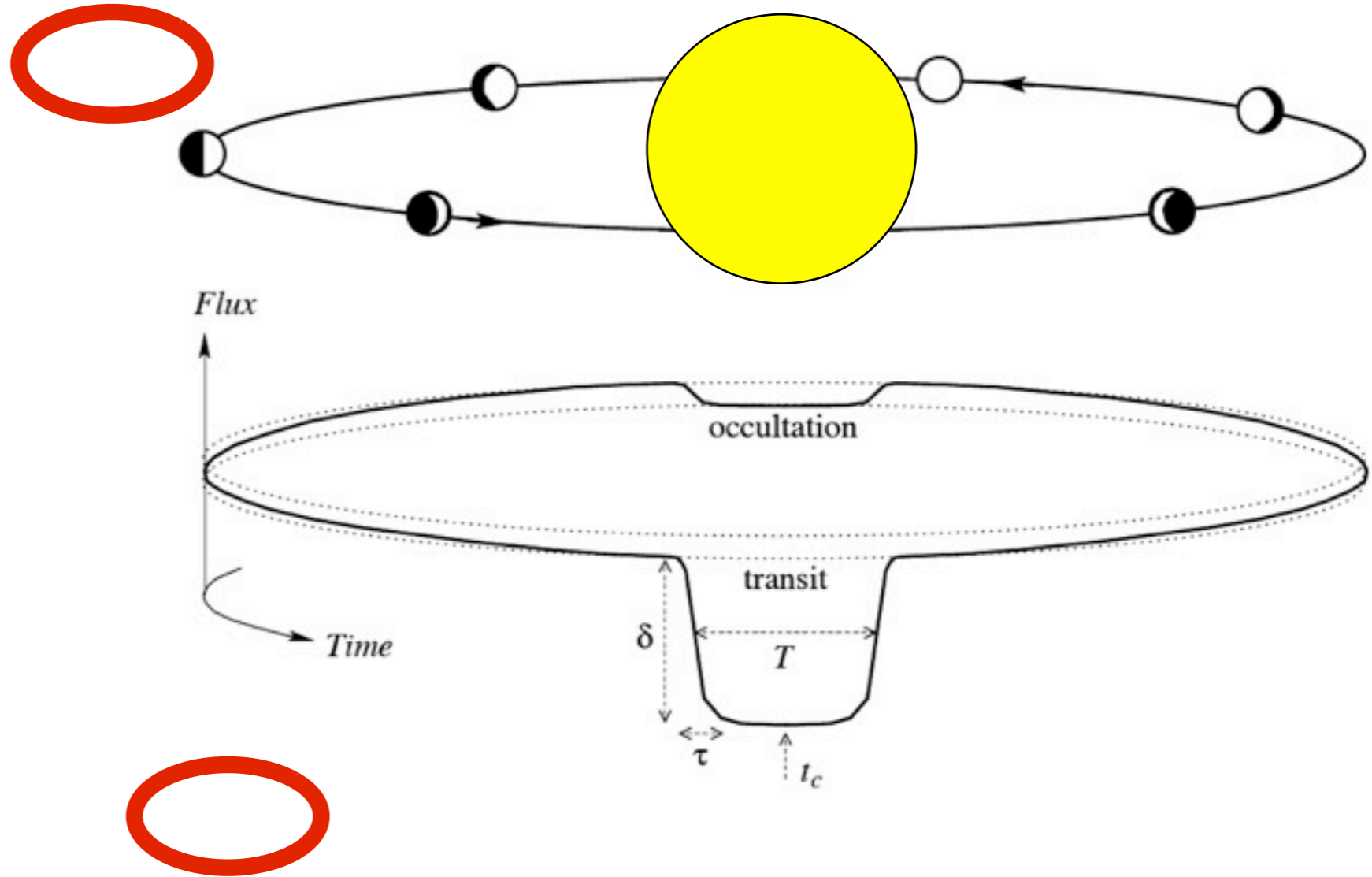
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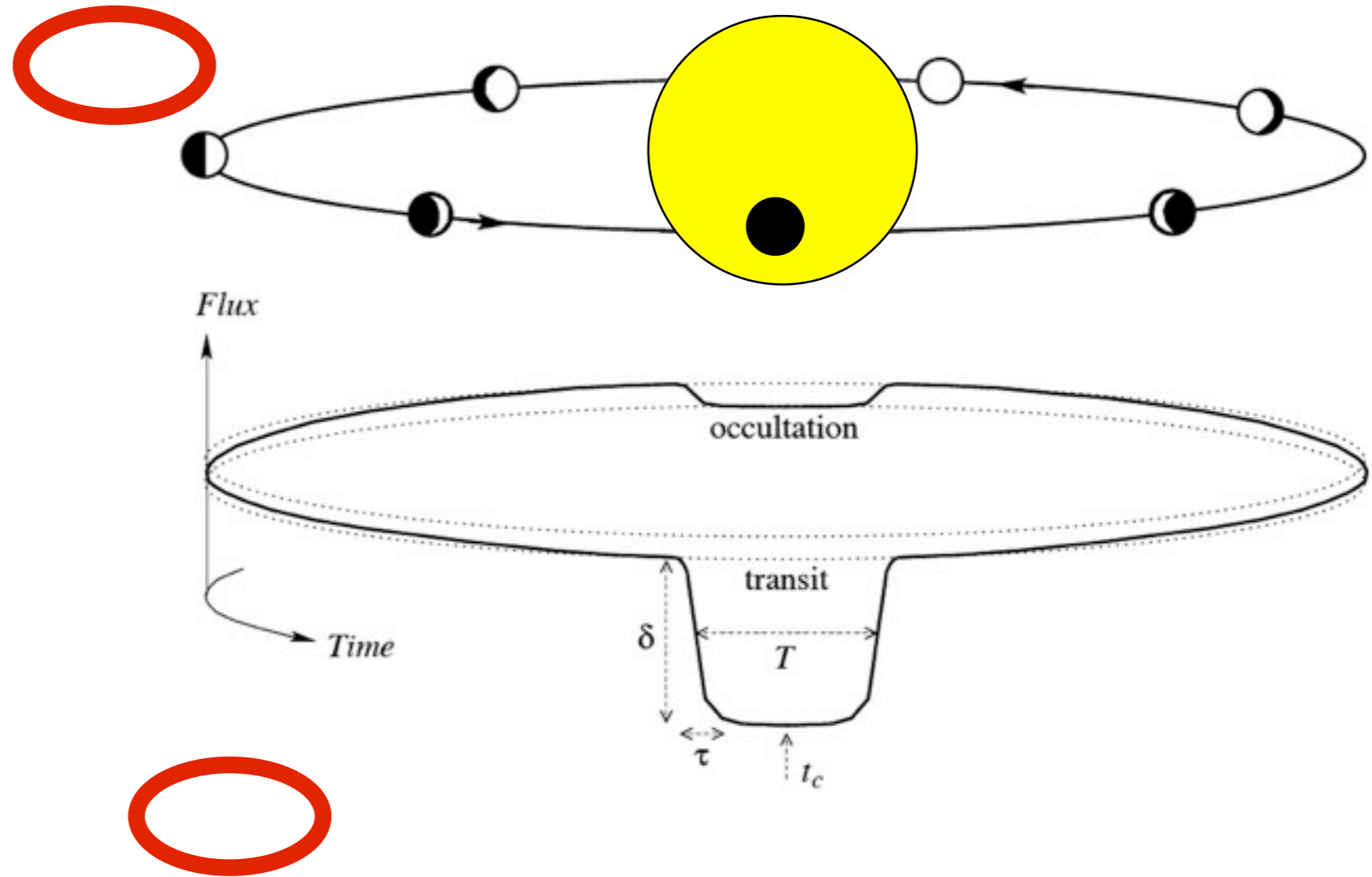
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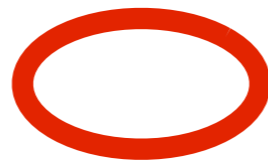
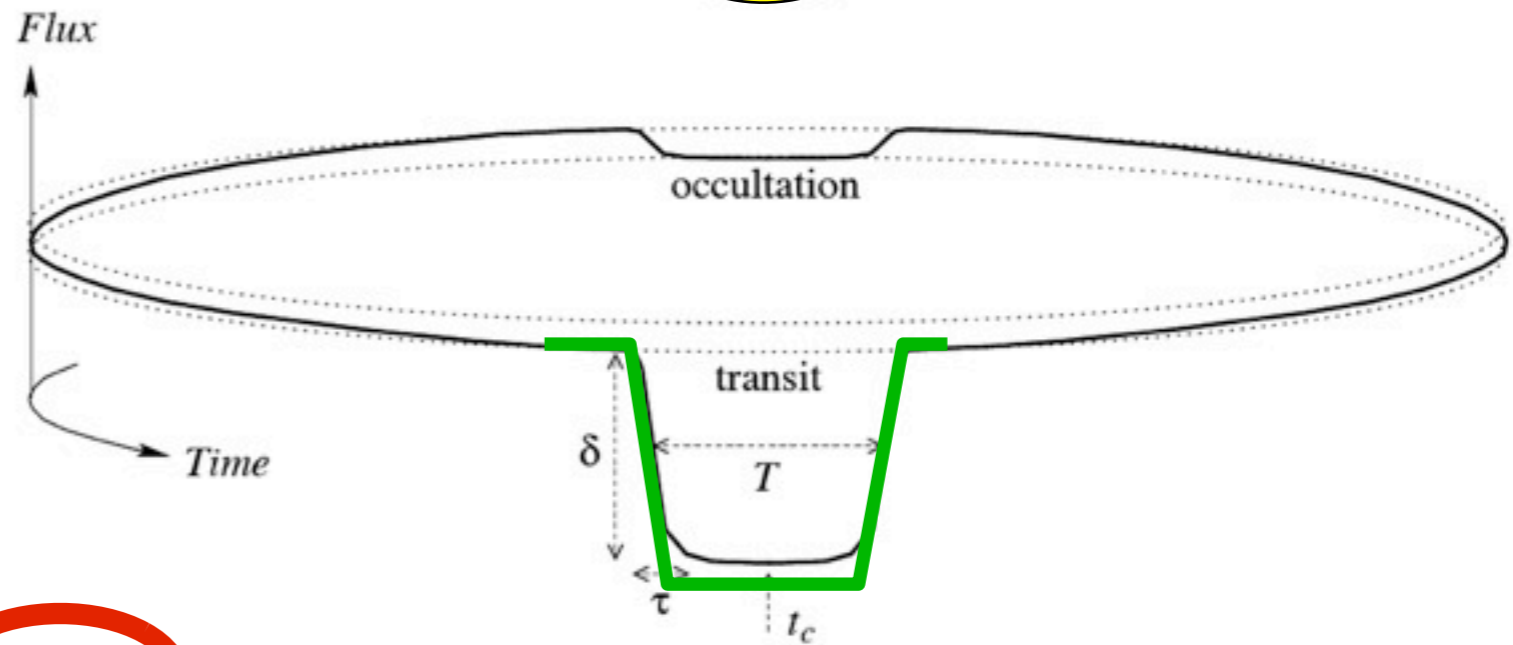
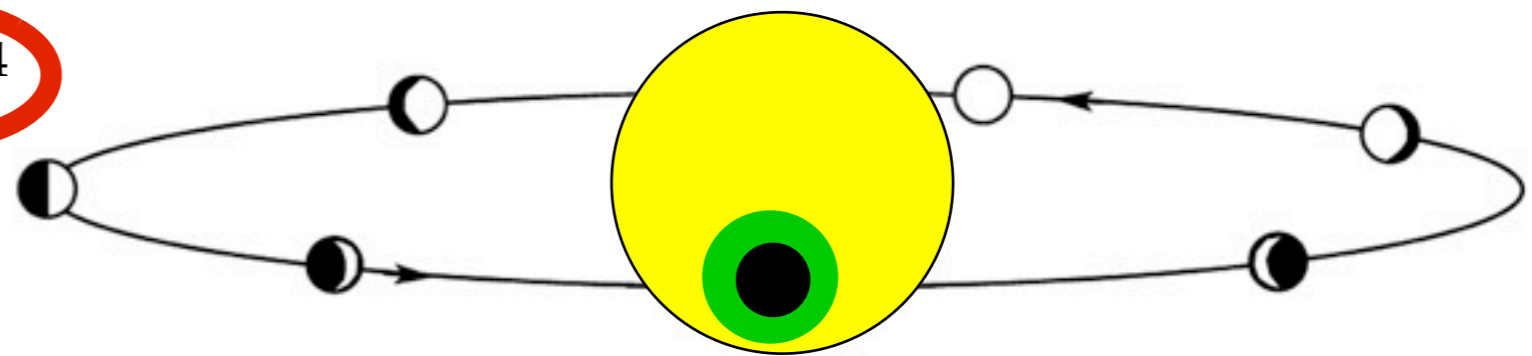
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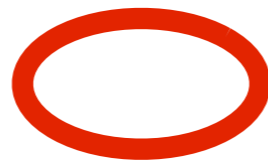
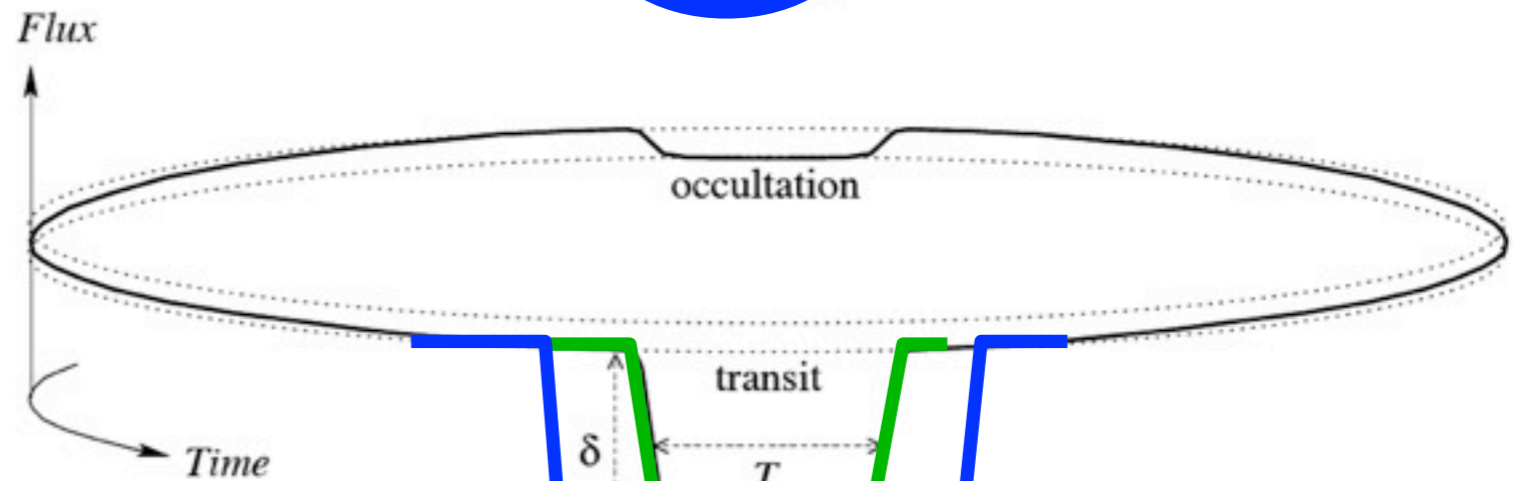
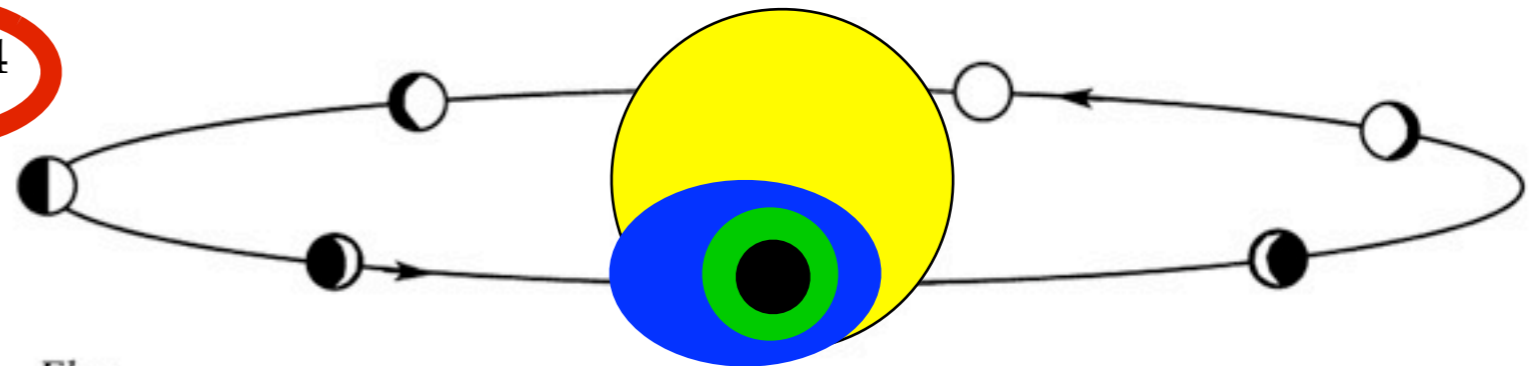
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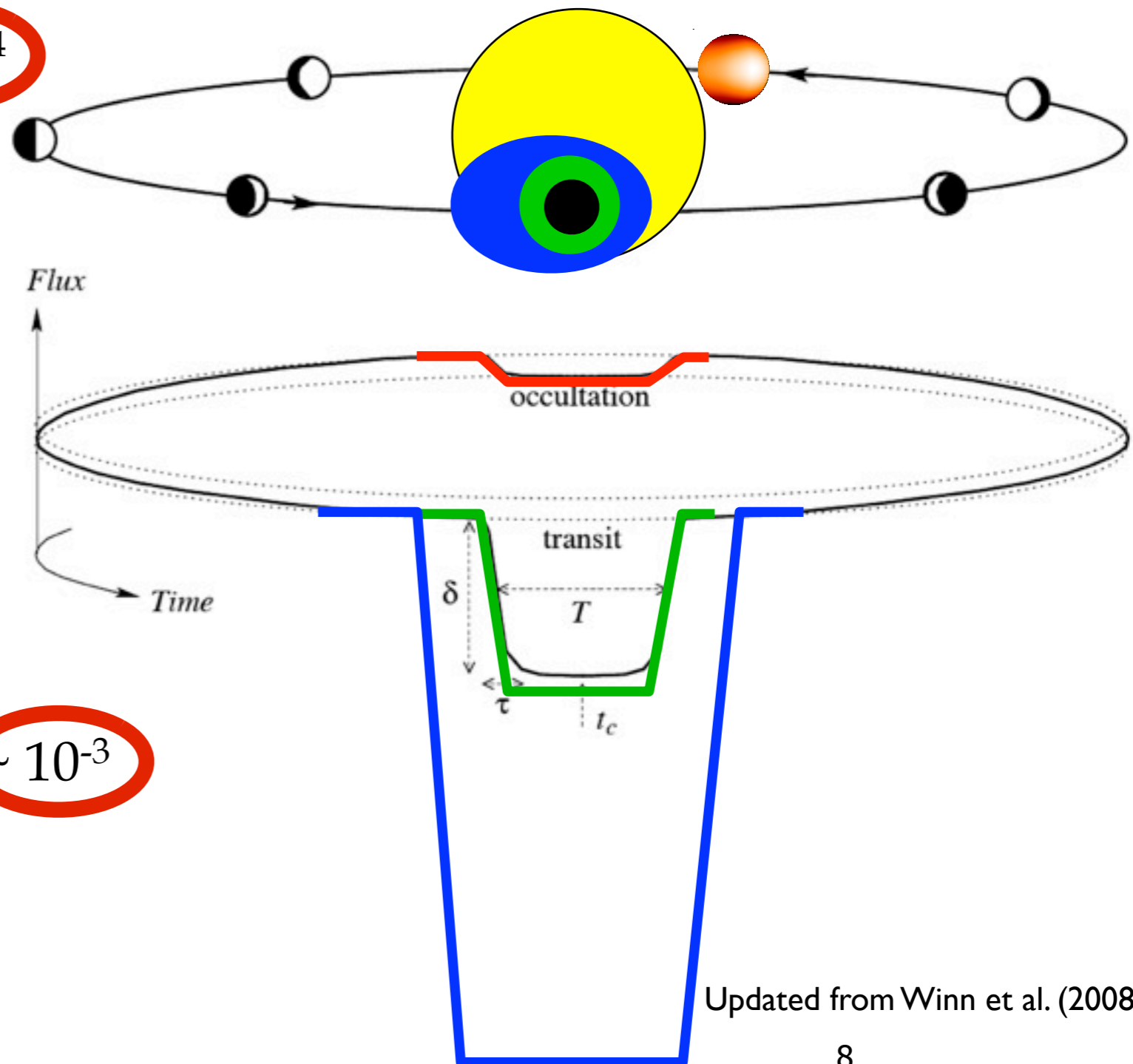
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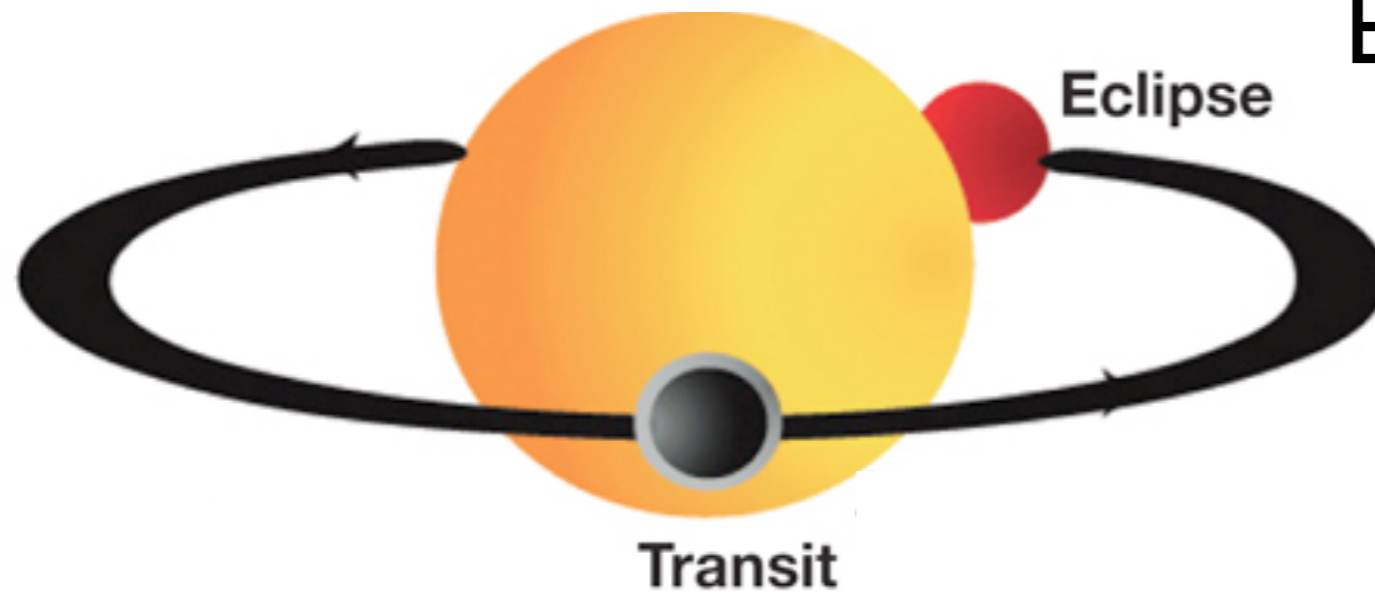


Updated from Winn *et al.* (2008)

Probing Transiting Exoplanet Atmospheres

$$\text{Reflected: } \frac{F_p}{F_\star} = A_g \left(\frac{R_p}{a} \right)^2$$

$$\text{Emitted: } \frac{\Delta f}{f} \simeq \frac{T_p}{T_\star} \left(\frac{R_p}{R_\star} \right)^2$$



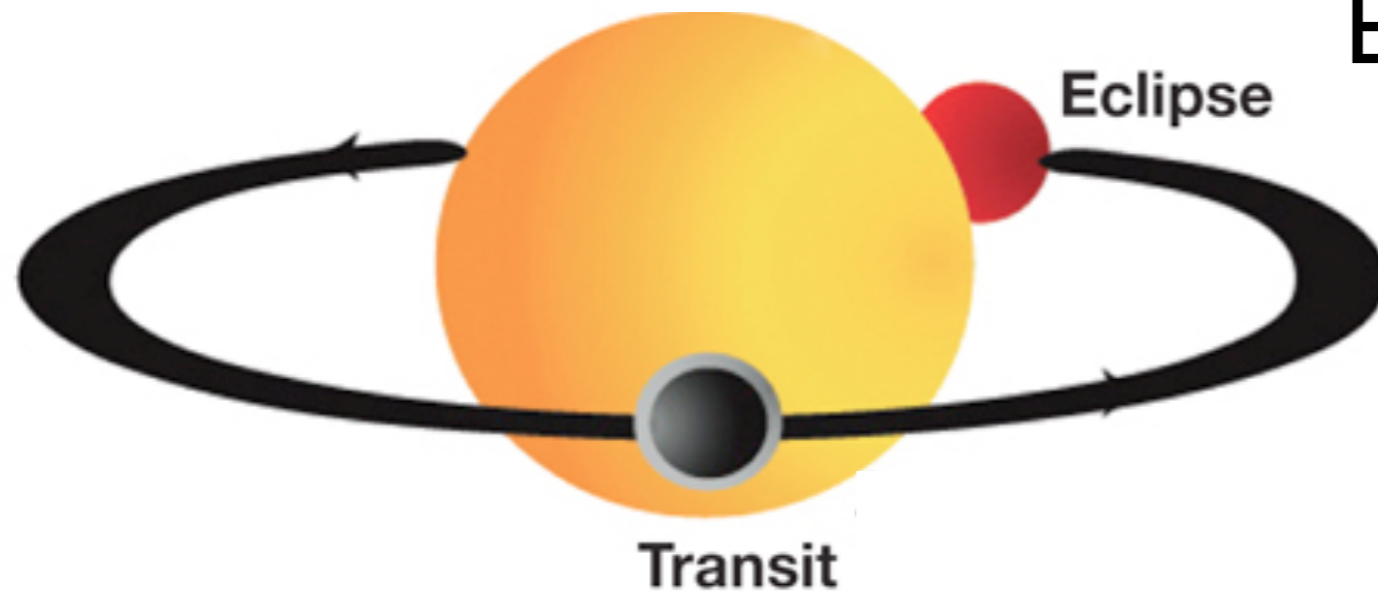
$$\text{Transmitted: } \Delta D \sim \frac{2H R_{pl}}{R_\star^2}$$

$$H = \frac{kT}{\mu_m g}$$

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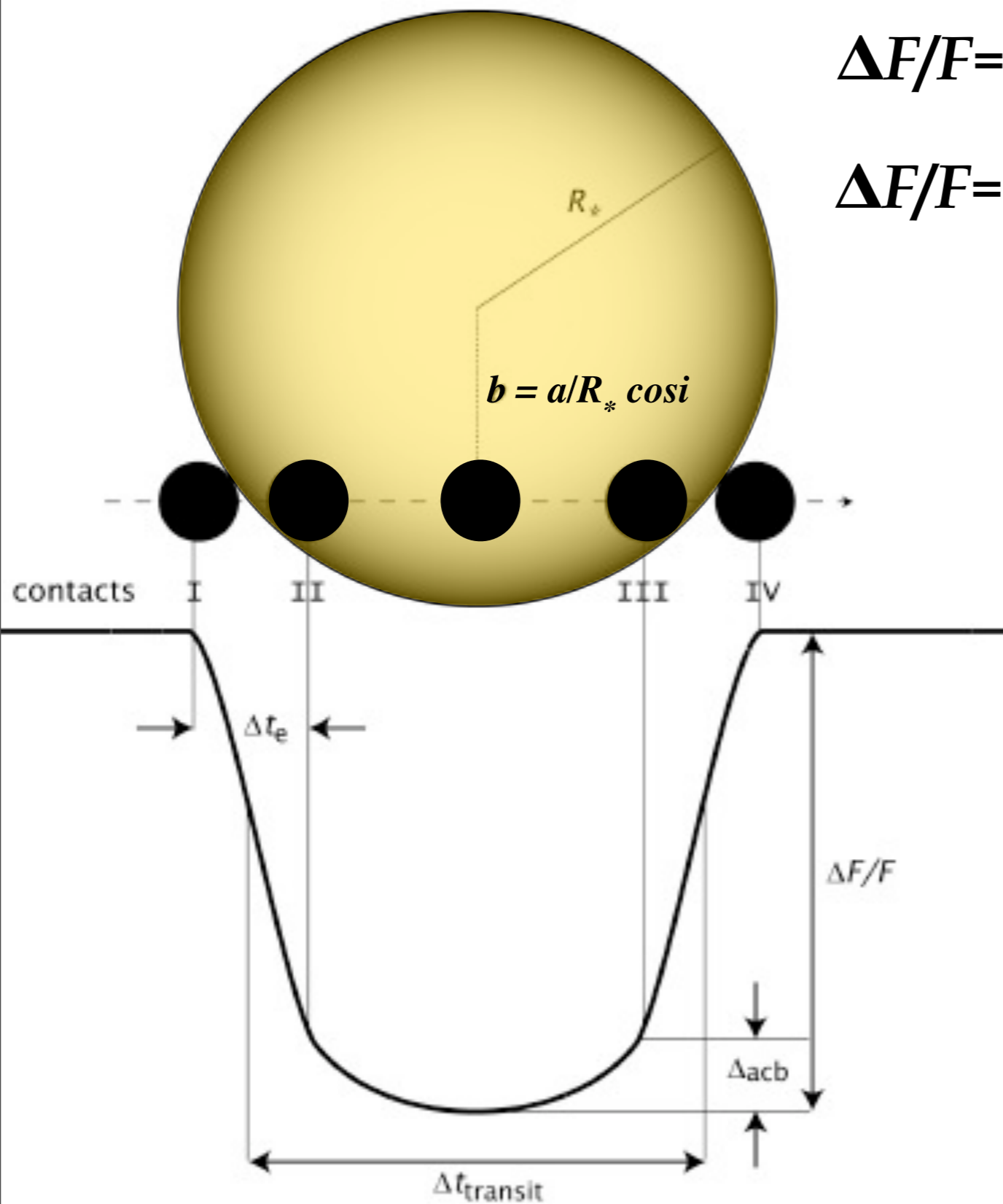
Hot-Jupiters

- Albedo, Temperature
- Thermal profile
- Composition
- Dynamics

Transmission Spectroscopy

$$\Delta F/F = (F_{\text{out}} - F_{\text{in}}) / F_{\text{out}} \quad \text{Transit depth}$$

$$\Delta F/F = (R_p / R_*)^2$$

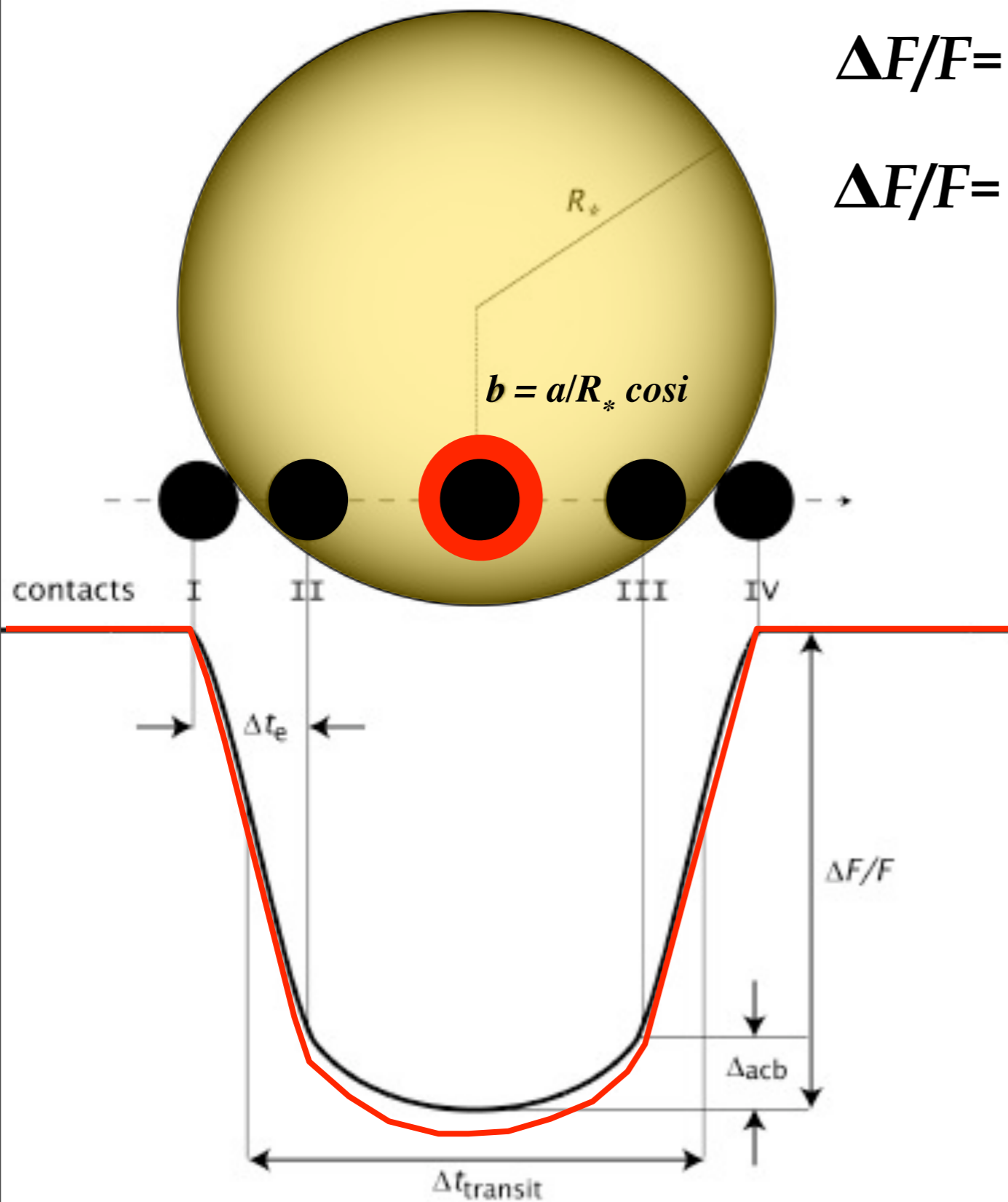


Transmission Spectroscopy

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$$R_p = R_c + z_{\text{atm}}$$



Transmission Spectroscopy

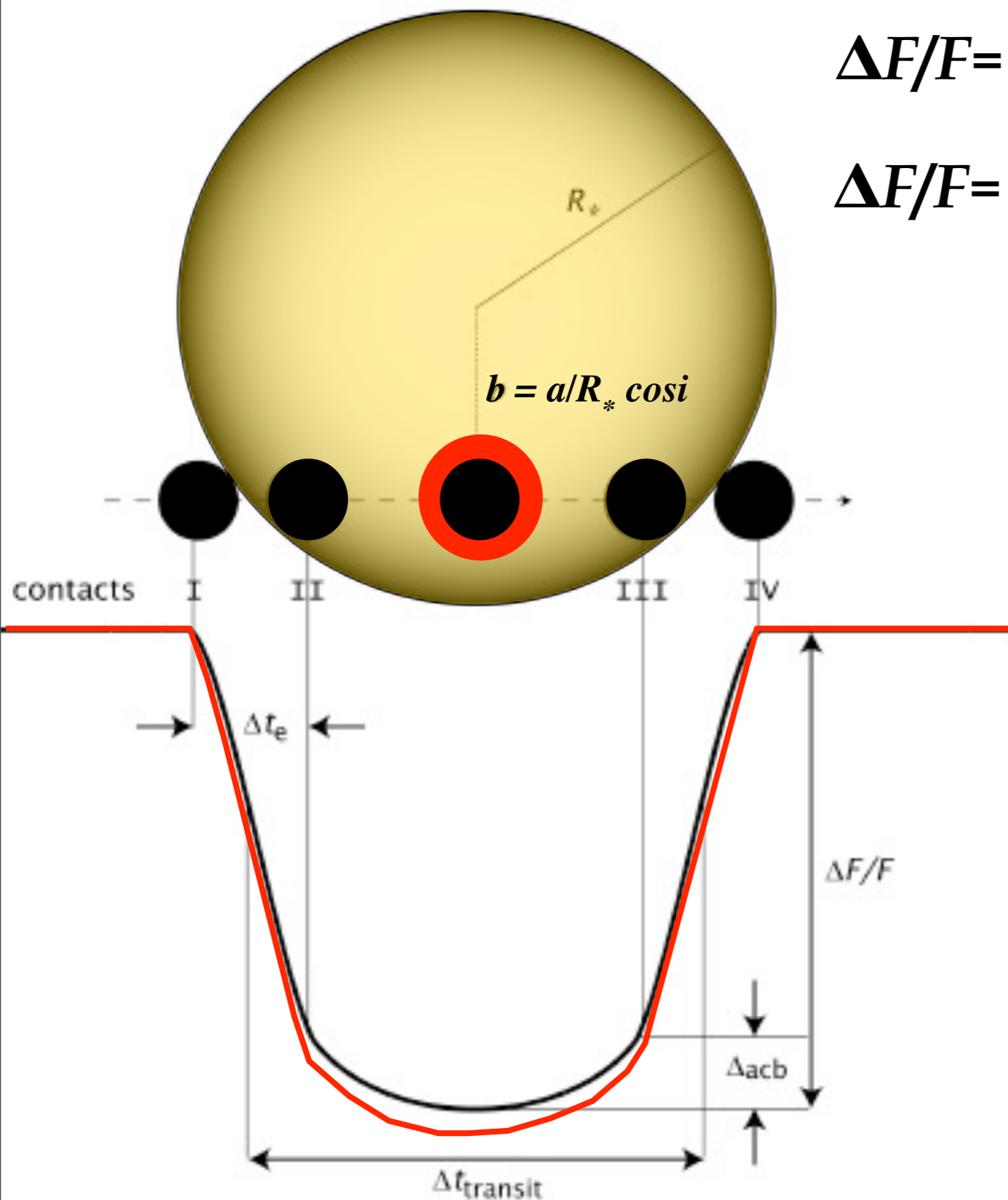
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$$R_{\text{Jup}} \sim 1\% \quad \sim 0.01\%$$

$$R_{\oplus} \sim 0.01\% \quad \sim 10^{-5}$$



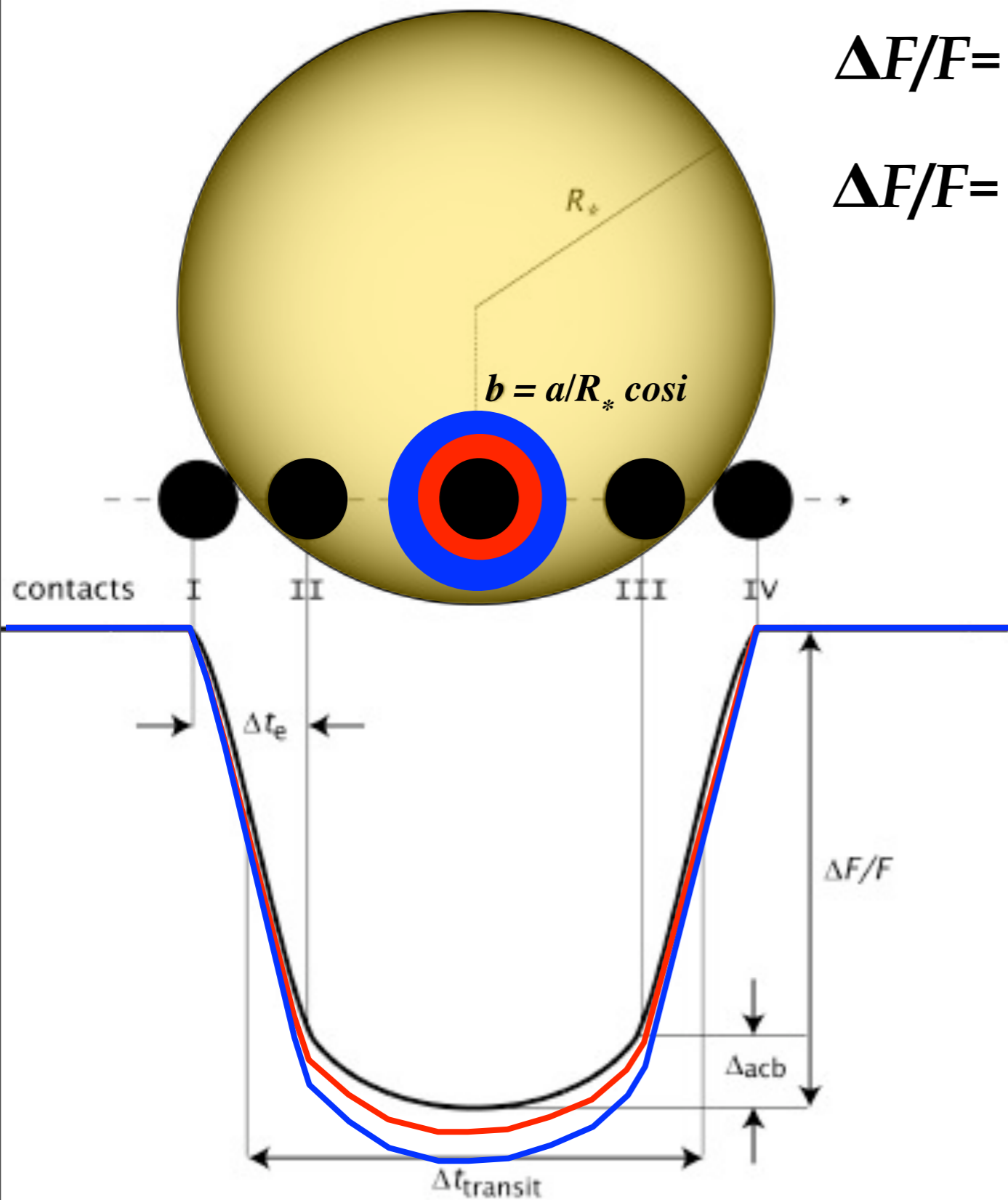
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Transmission Spectroscopy

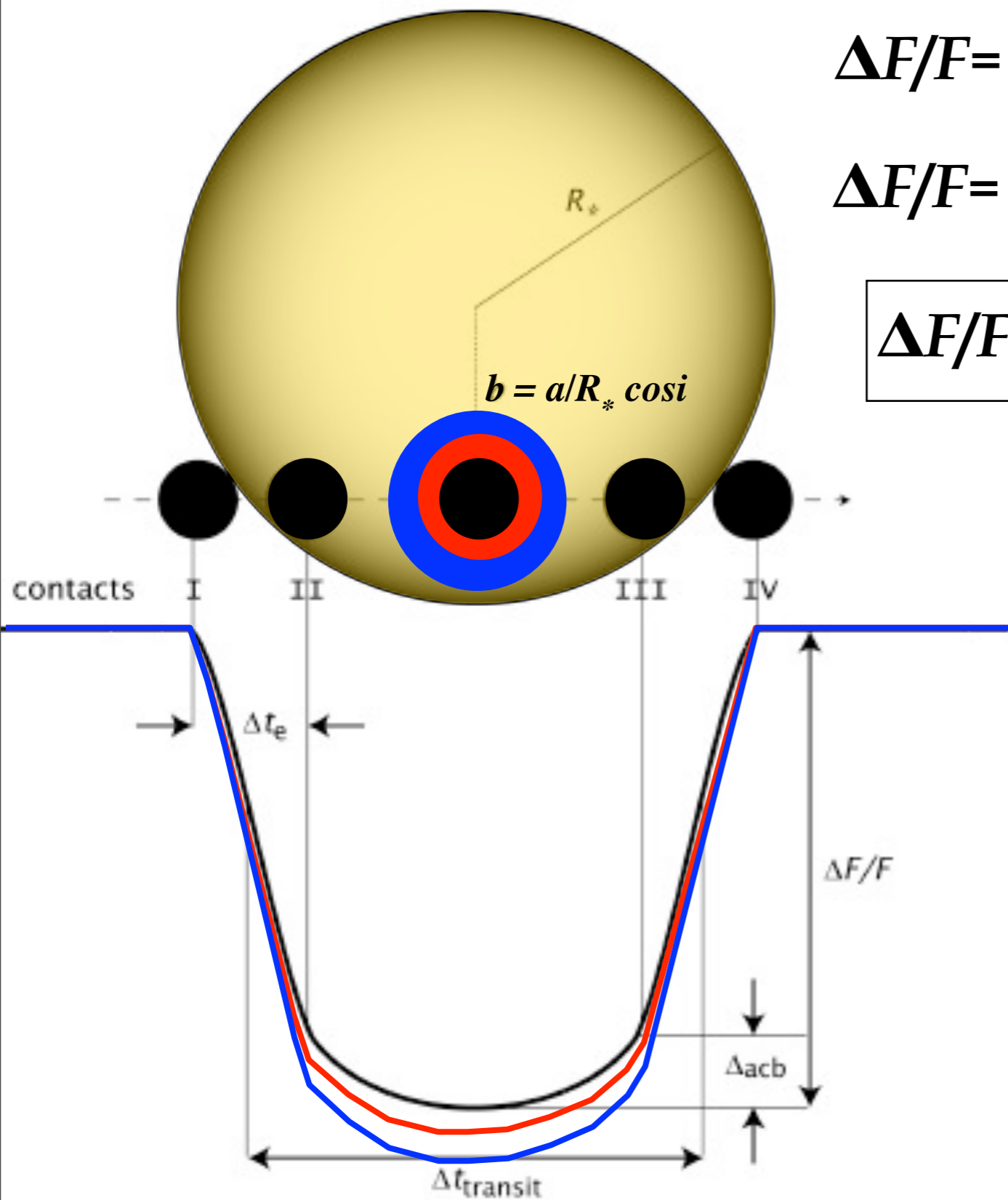
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$$\Delta F/F(\lambda) \Rightarrow R_p(\lambda)$$

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Transmission Spectroscopy

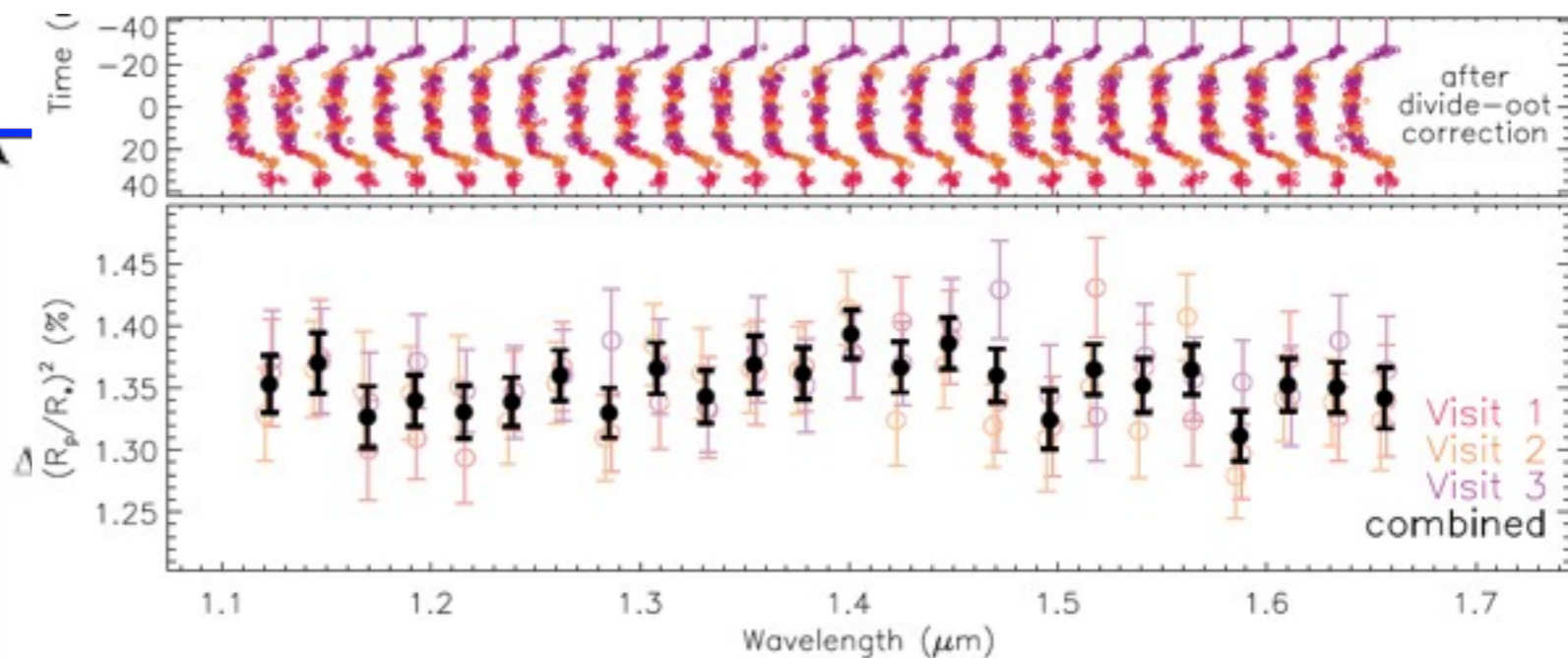
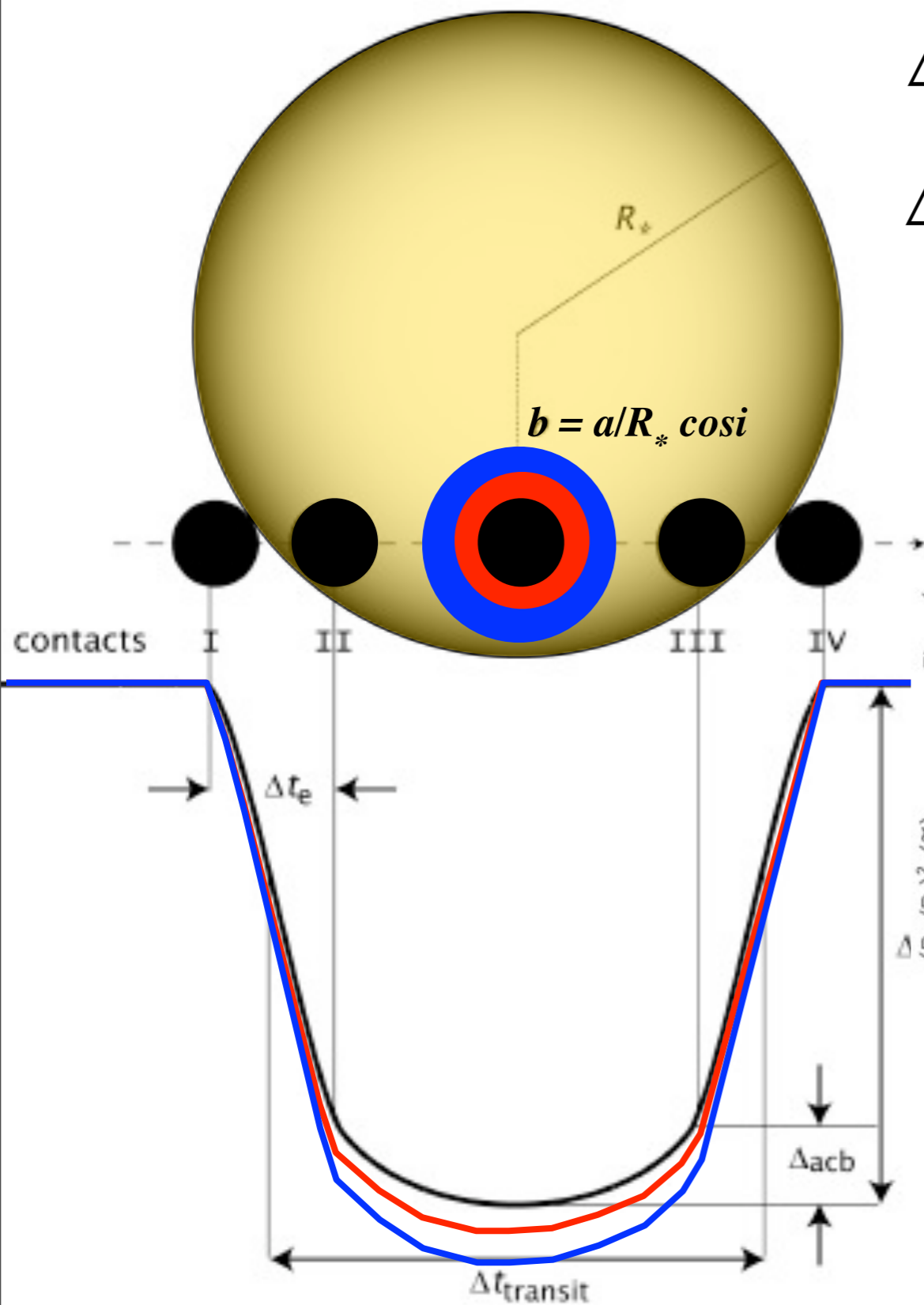
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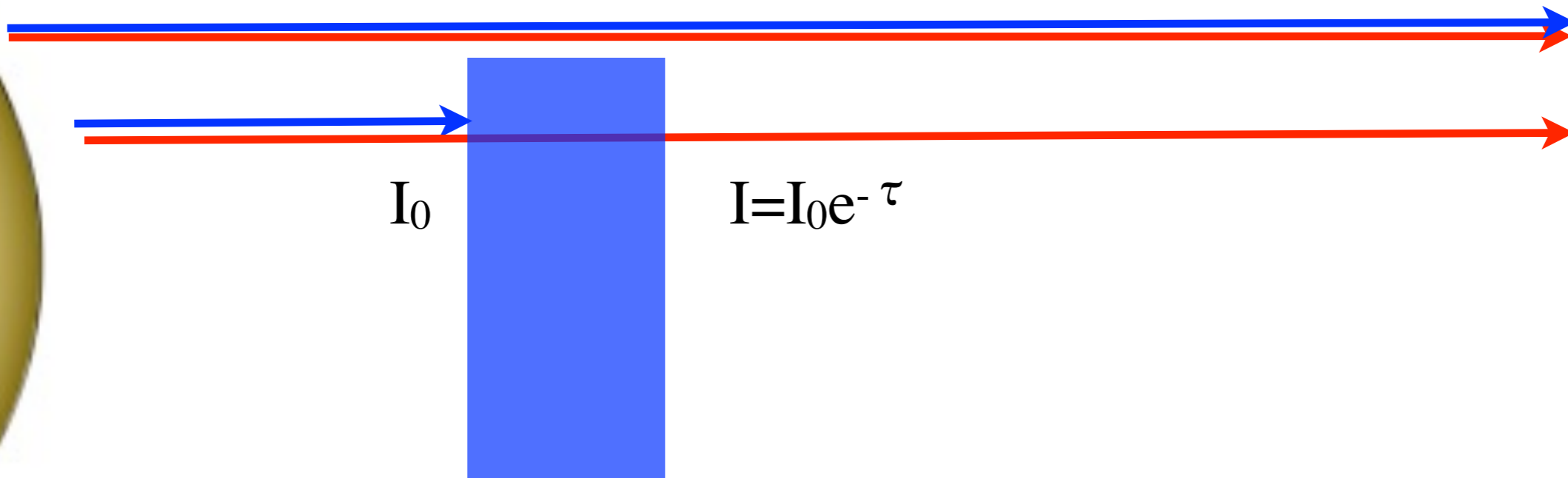
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Berta et al. (2011)

Transmission Spectroscopy



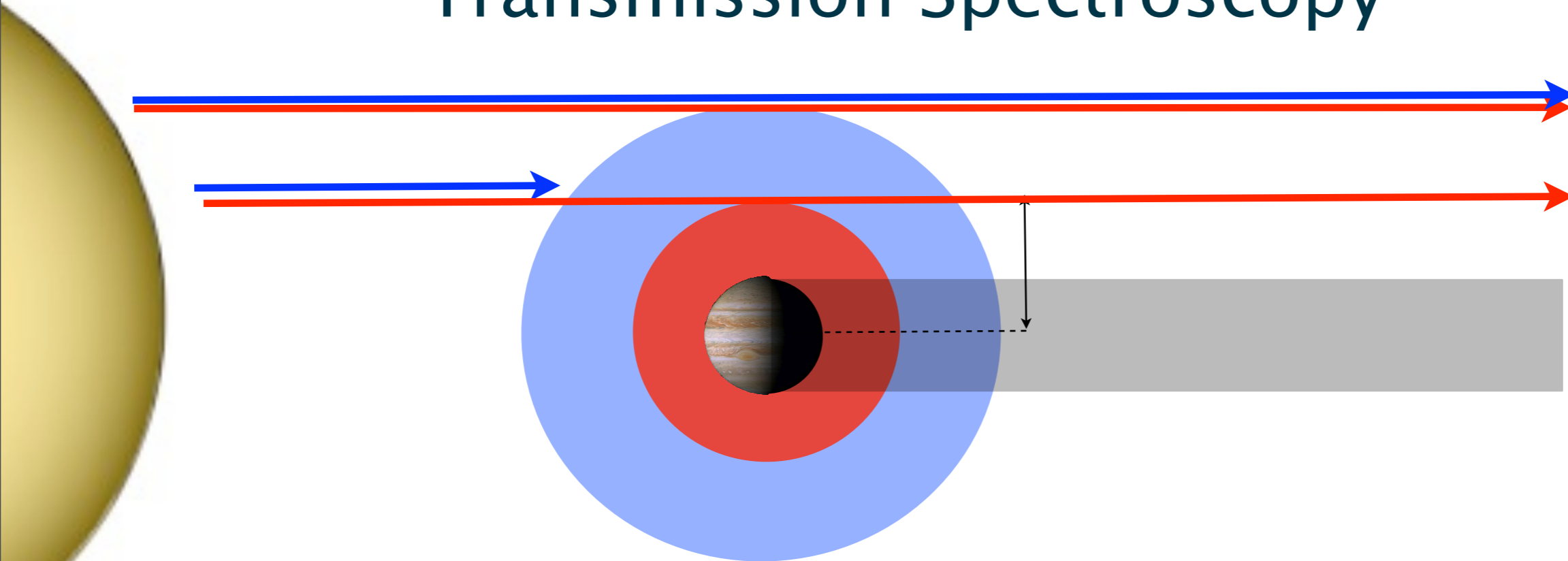
I_0

$I = I_0 e^{-\tau}$

$$\tau(\lambda) \approx \sigma(\lambda)n$$

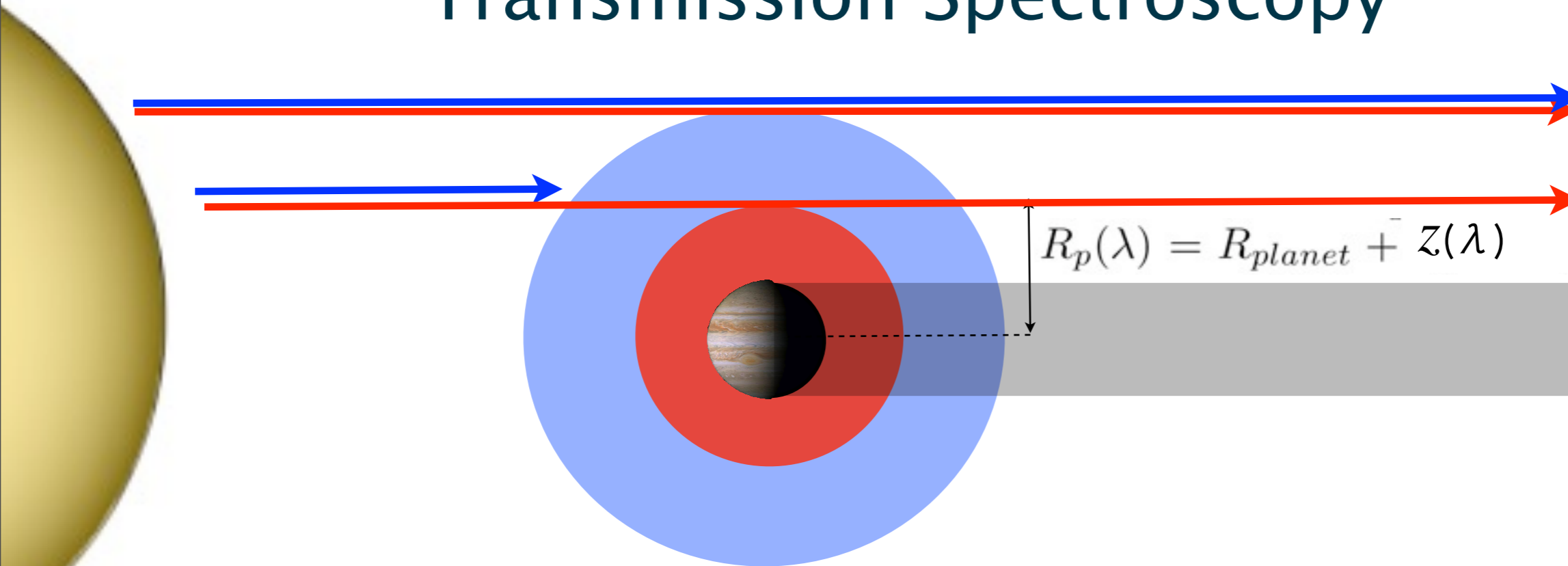


Transmission Spectroscopy



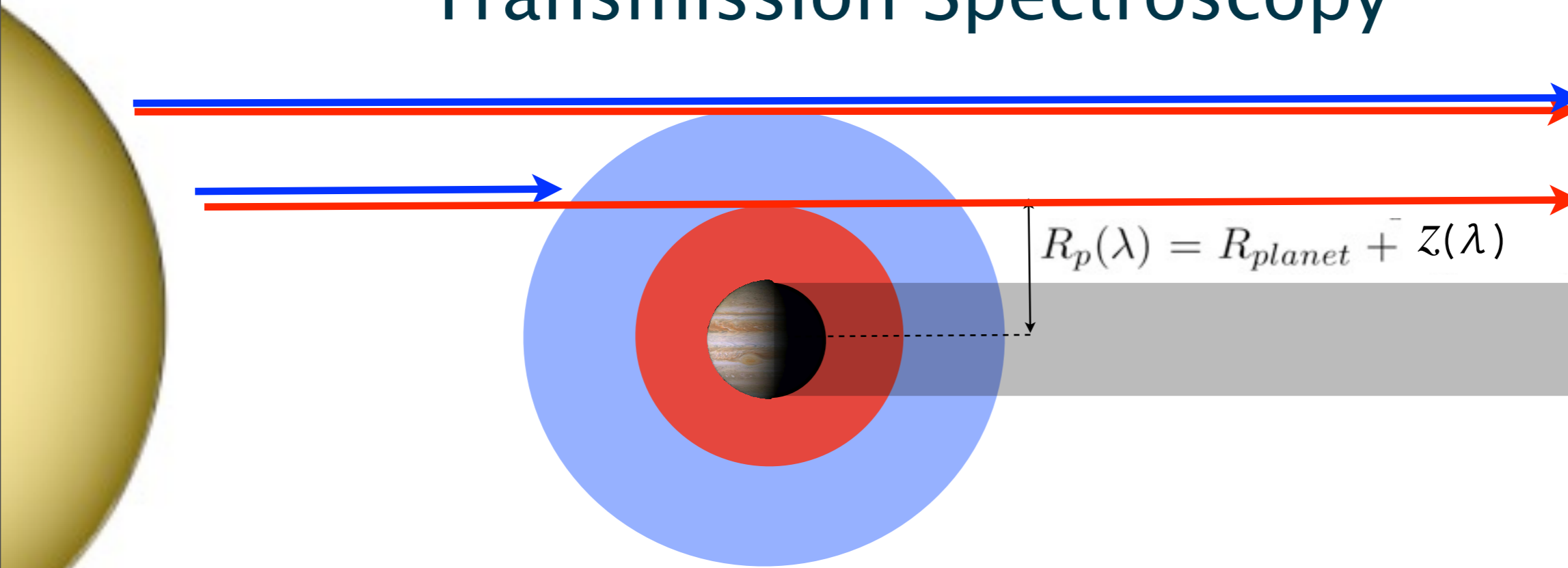
Lecavelier et al. (2008)

Transmission Spectroscopy



Lecavelier et al. (2008)

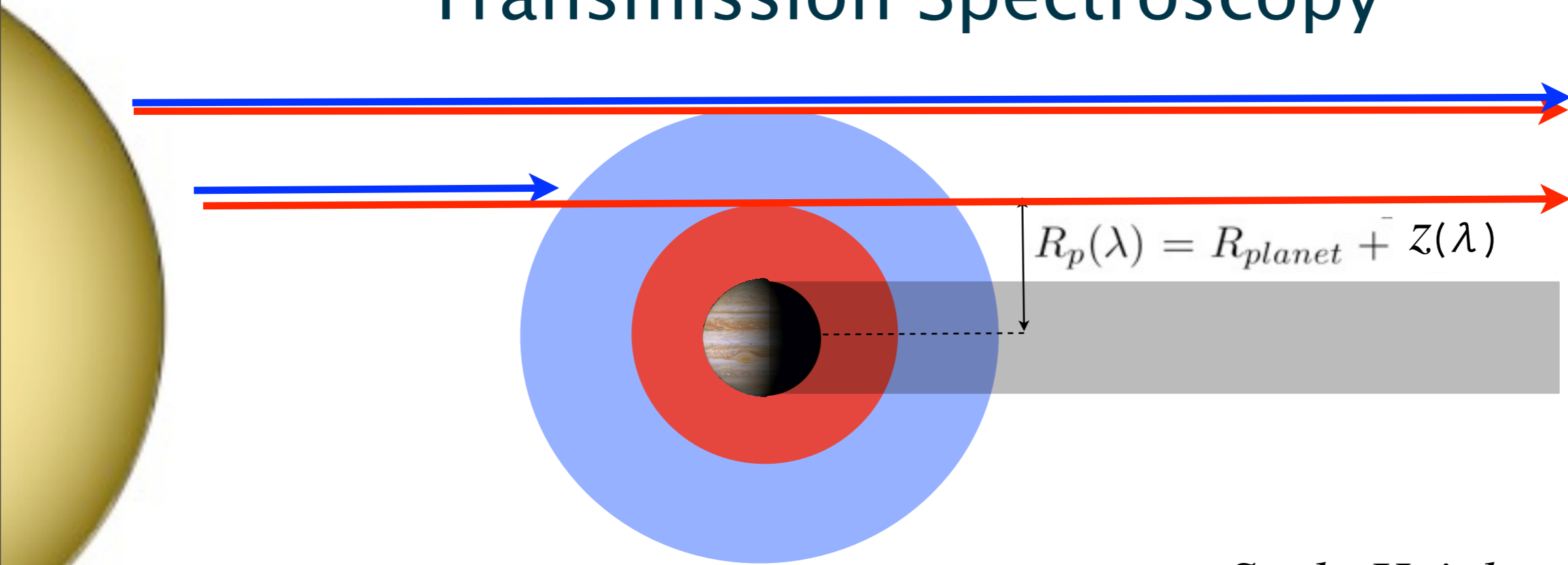
Transmission Spectroscopy



$$\tau(\lambda, z) \approx \sigma(\lambda)n(z)\sqrt{2\pi R_{planet}H}$$

Lecavelier et al. (2008)

Transmission Spectroscopy

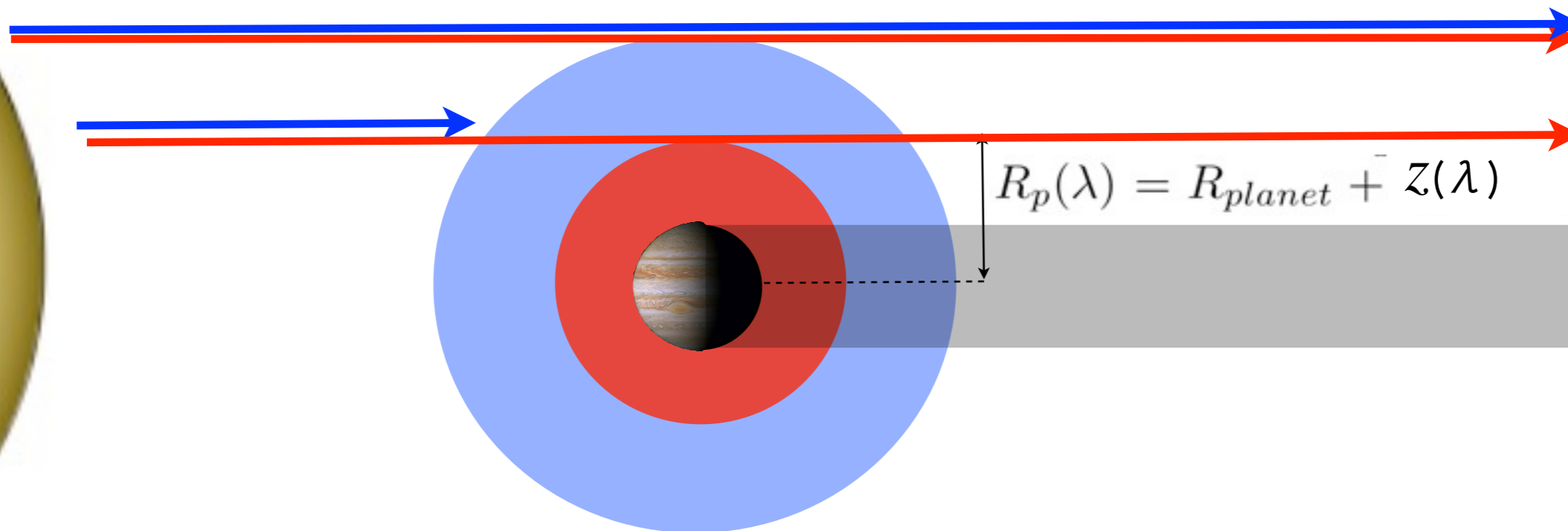


$$\tau(\lambda, z) \approx \sigma(\lambda)n(z)\sqrt{2\pi R_{planet}H}$$

Scale Height
 $H(z) = kT(z)/\mu g$

Lecavelier et al. (2008)

Transmission Spectroscopy



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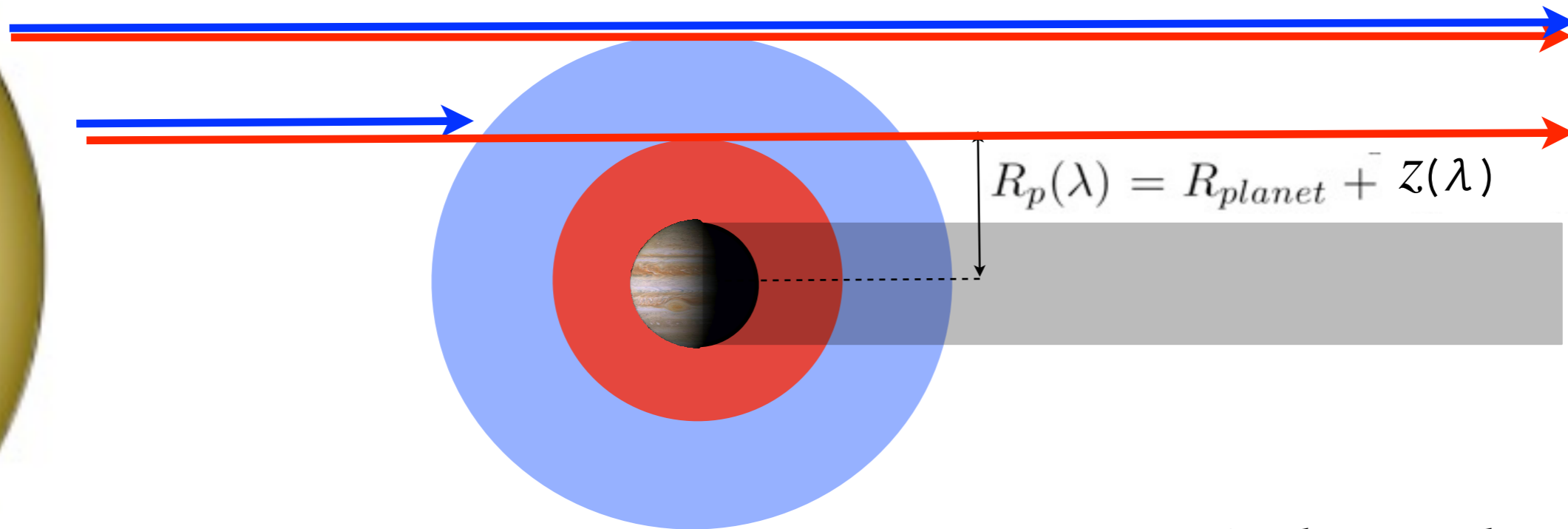
$$H(z) = kT(z)/\mu g$$

Hydrostatic equilibrium:

$$n(z) = n_{(z=0)}\exp(-z/H)$$

Lecavelier et al. (2008)

Transmission Spectroscopy



$$R_p(\lambda) = R_{\text{planet}} + z(\lambda)$$

$$\tau(\lambda, z) \approx \sigma(\lambda)n(z)\sqrt{2\pi R_{\text{planet}}H}$$

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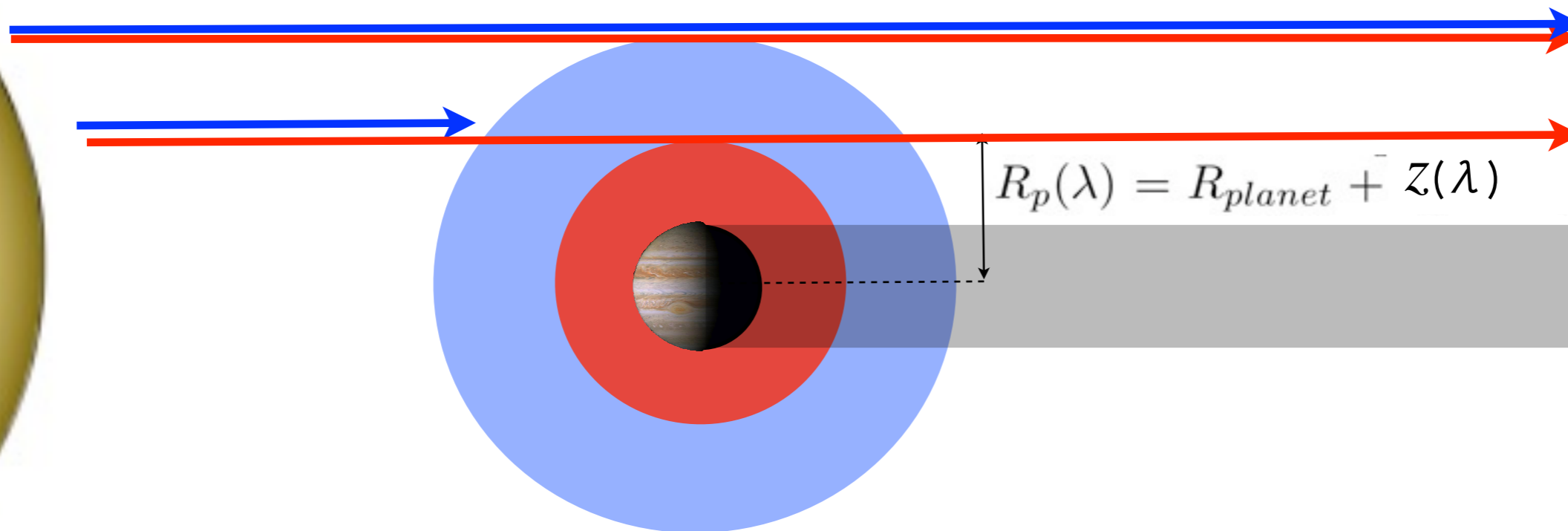
Hydrostatic equilibrium:

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What do we measure?

Lecavelier et al. (2008)

Transmission Spectroscopy



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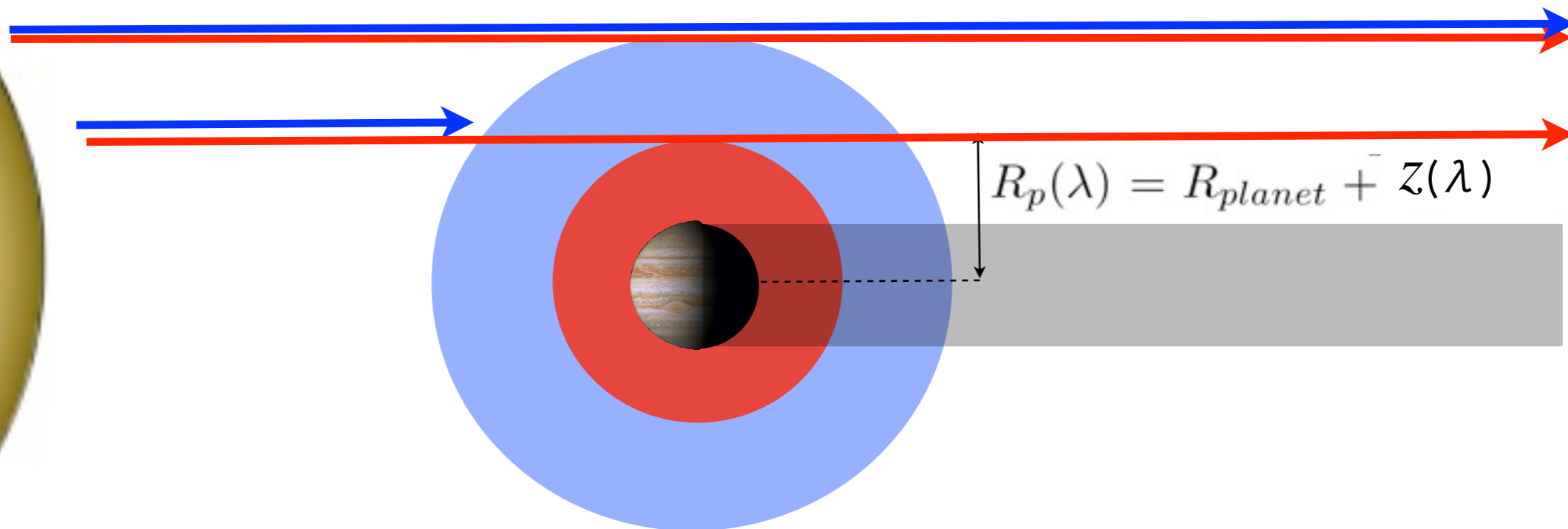
Hydrostatic equilibrium:
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What do we measure?

$$z(\lambda) = H \ln \left(\frac{\xi_{abs} P_{z=0} \sigma(\lambda)}{\tau_{eq} \mu g} \sqrt{\frac{2\pi R_p}{H}} \right)$$

Lecavelier et al. (2008)

Transmission Spectroscopy



$$\tau(\lambda, z) \approx \sigma(\lambda) n(z) \sqrt{2\pi R_{planet} H}$$

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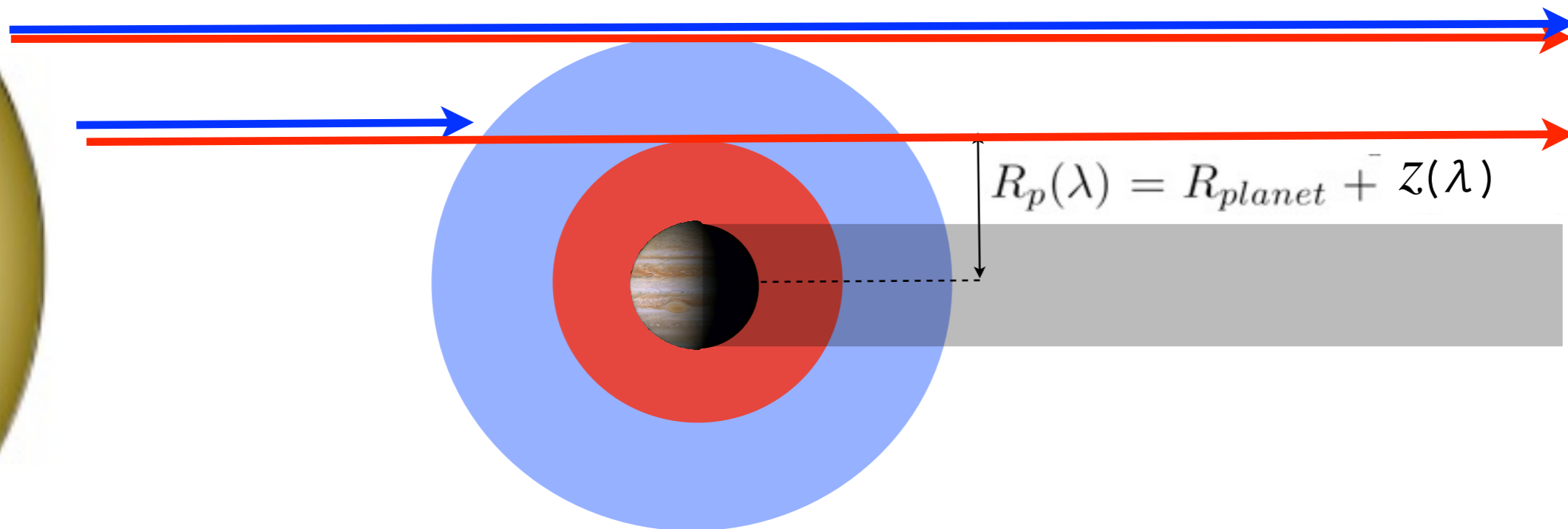
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$$z(\lambda) = H \ln \left(\frac{\xi_{abs} P_{z=0} \sigma(\lambda)}{\tau_{eq} \mu g} \sqrt{\frac{2\pi R_p}{H}} \right) \Rightarrow \Delta_{Rp} = H \Delta \ln(\sigma)$$

Lecavelier et al. (2008)

Transmission Spectroscopy



$$\tau(\lambda, z) \approx \sigma(\lambda) n(z) \sqrt{2\pi R_{\text{planet}} H}$$

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What do we measure?

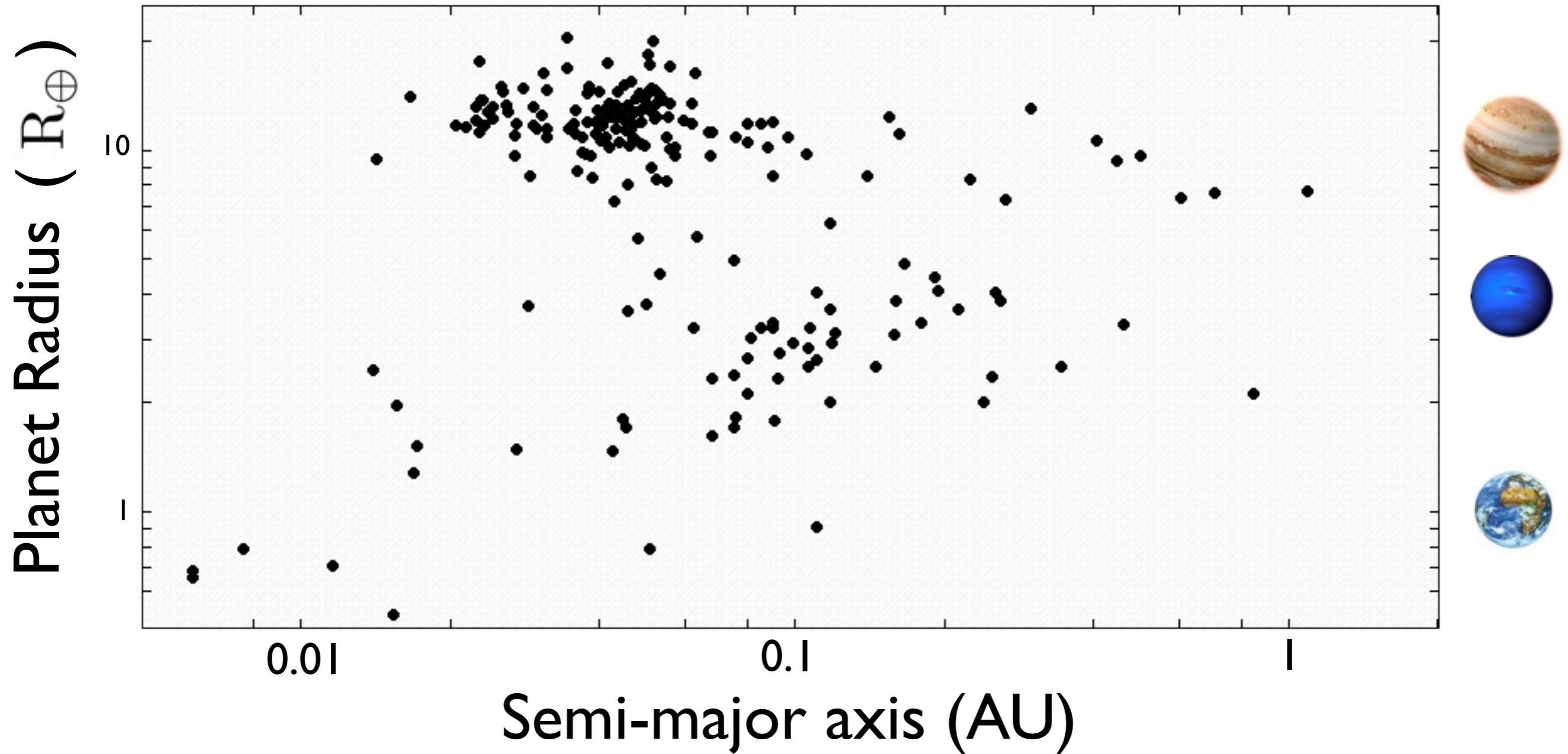
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$$\Rightarrow \Delta R_p = H \Delta \ln(\sigma)$$

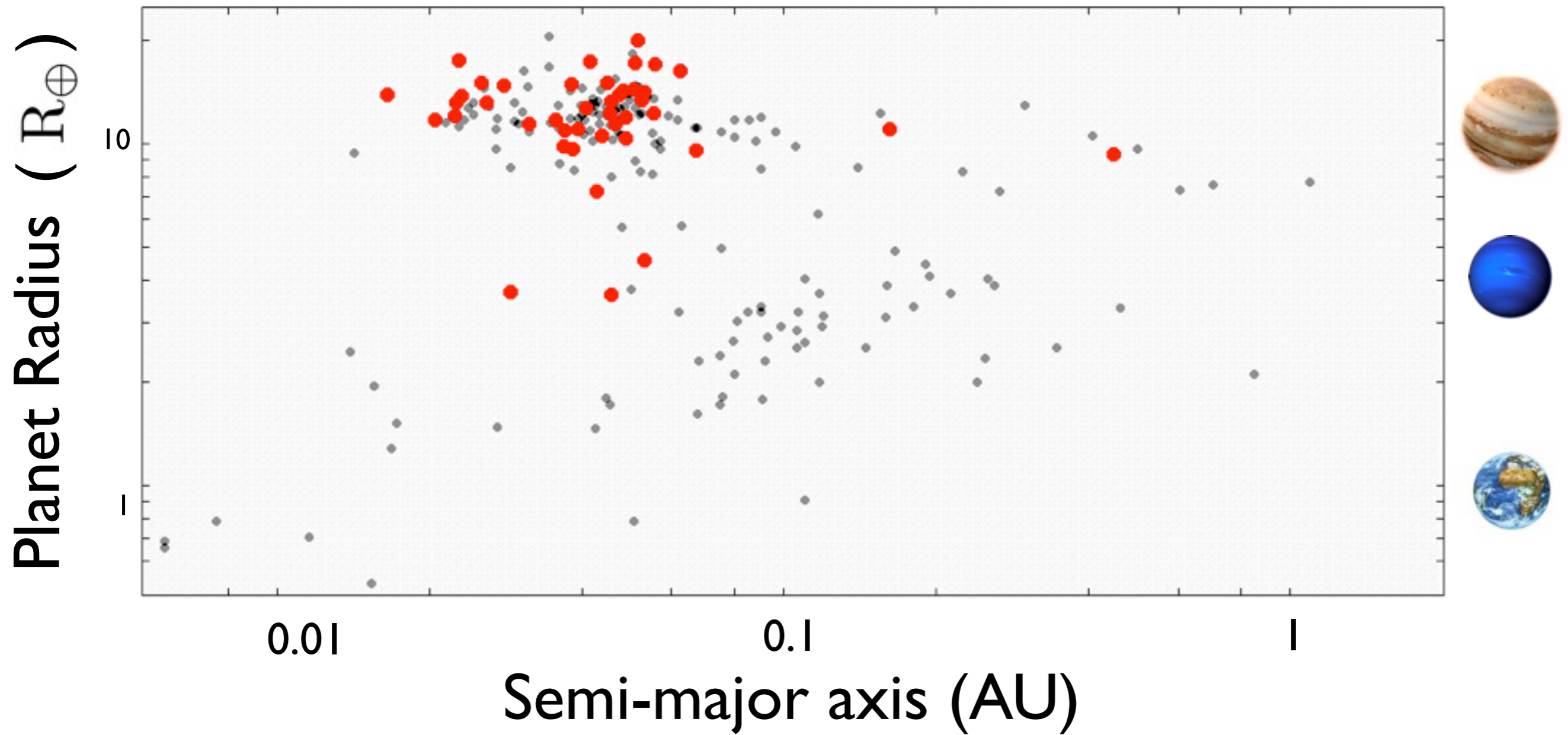
Lecavelier et al. (2008)

To remember:
 $R_{pl}(\lambda) \Rightarrow f(P, T, n)$
 $\Delta R_{pl}(\lambda) \Rightarrow T$

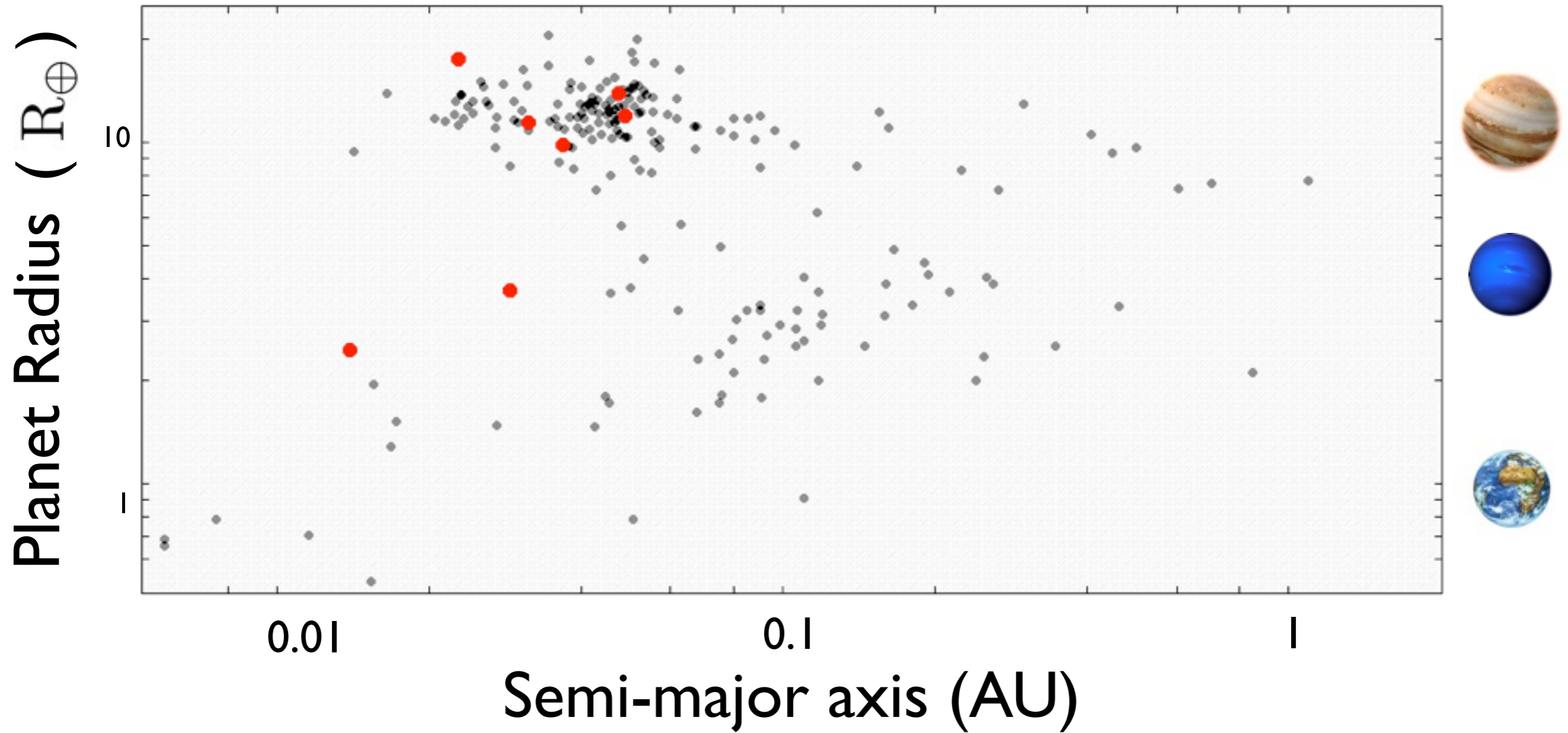
Transiting Exoplanets



● Emission Measurements (IR)



● Transmission Measurements (XEUV -> IR)



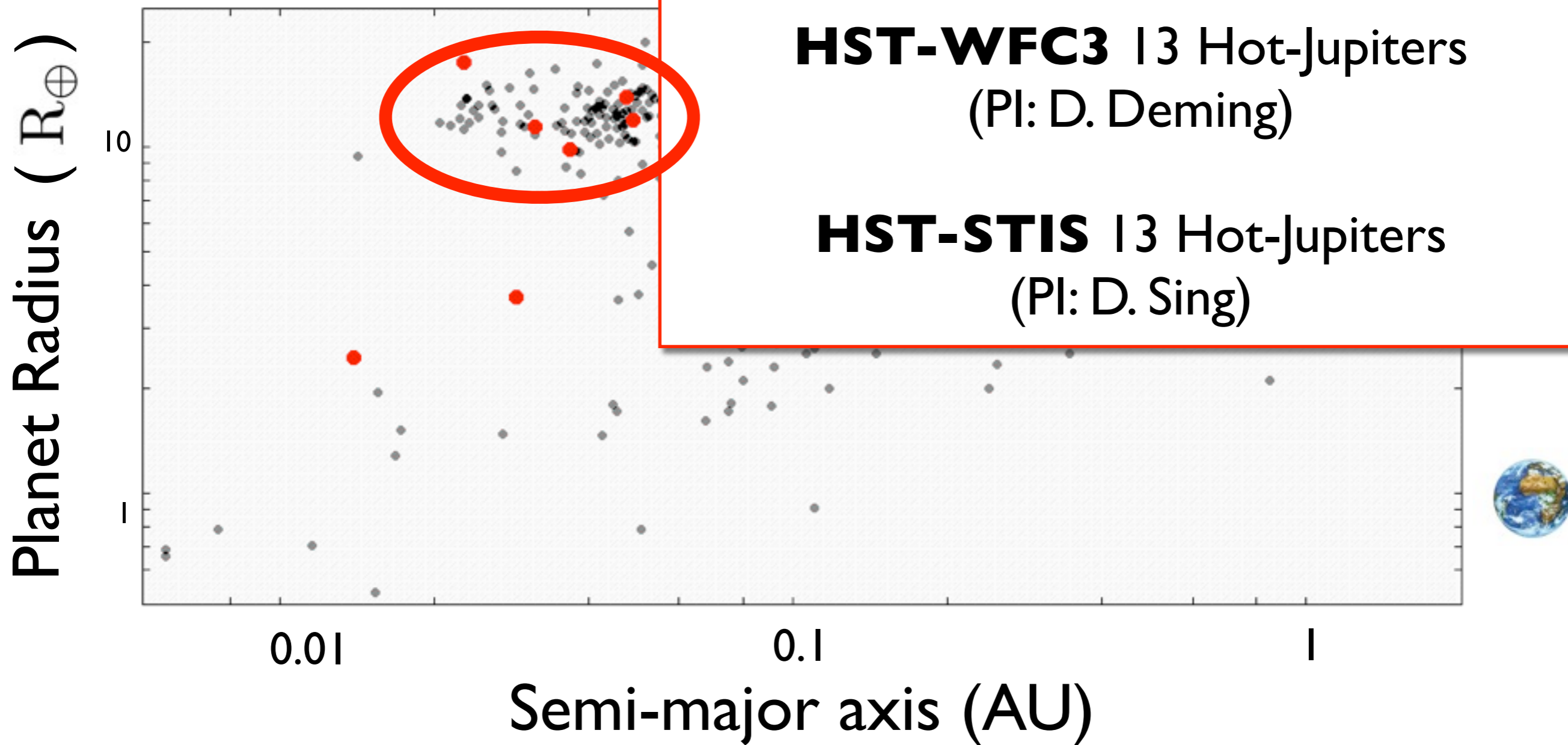
Hot-Jupiters Survey

Transmission Spectroscopy

Space-based Surveys:

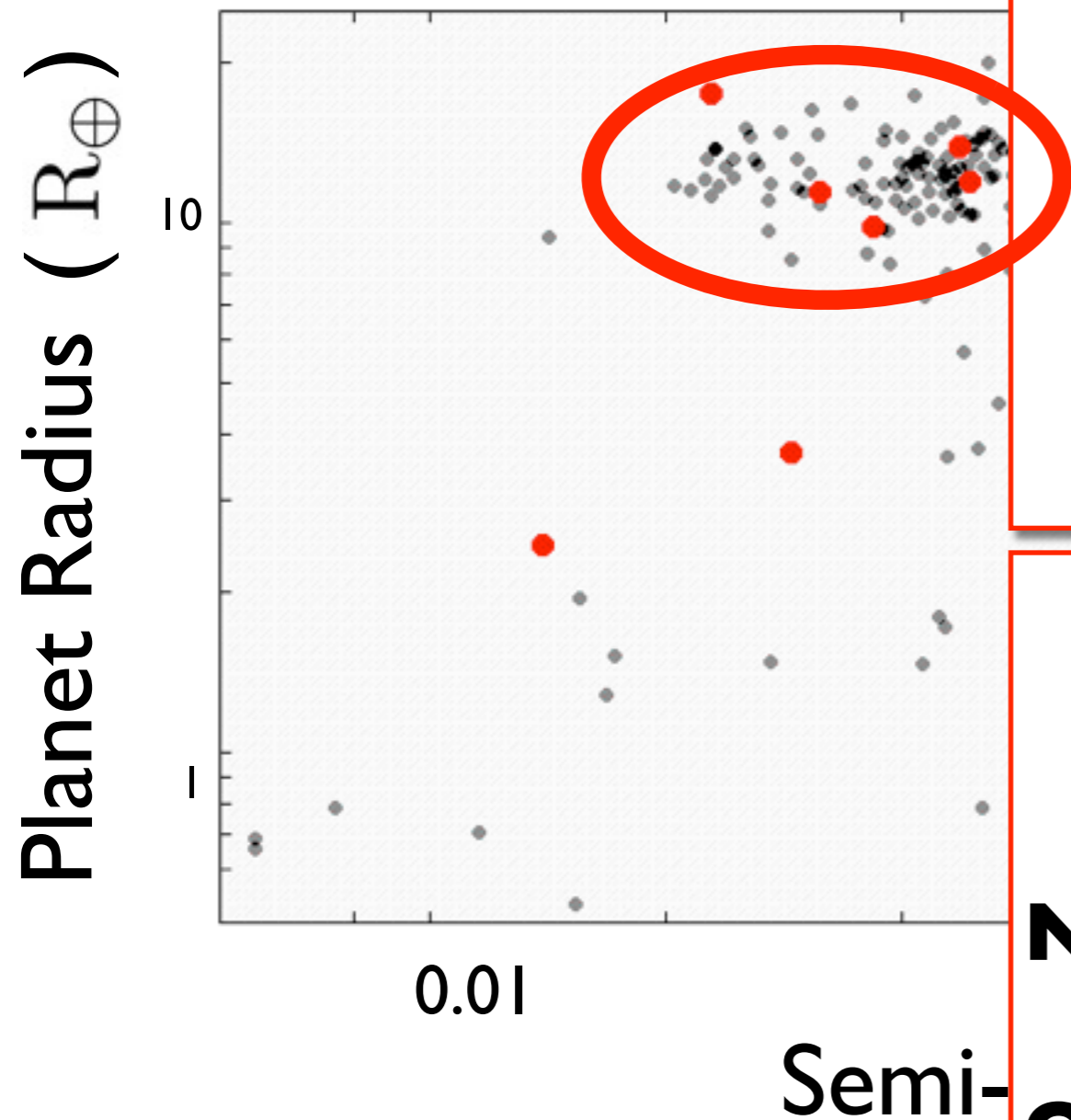
HST-WFC3 13 Hot-Jupiters
(PI: D. Deming)

HST-STIS 13 Hot-Jupiters
(PI: D. Sing)



Hot-Jupiters Survey

Transmission Spectroscopy



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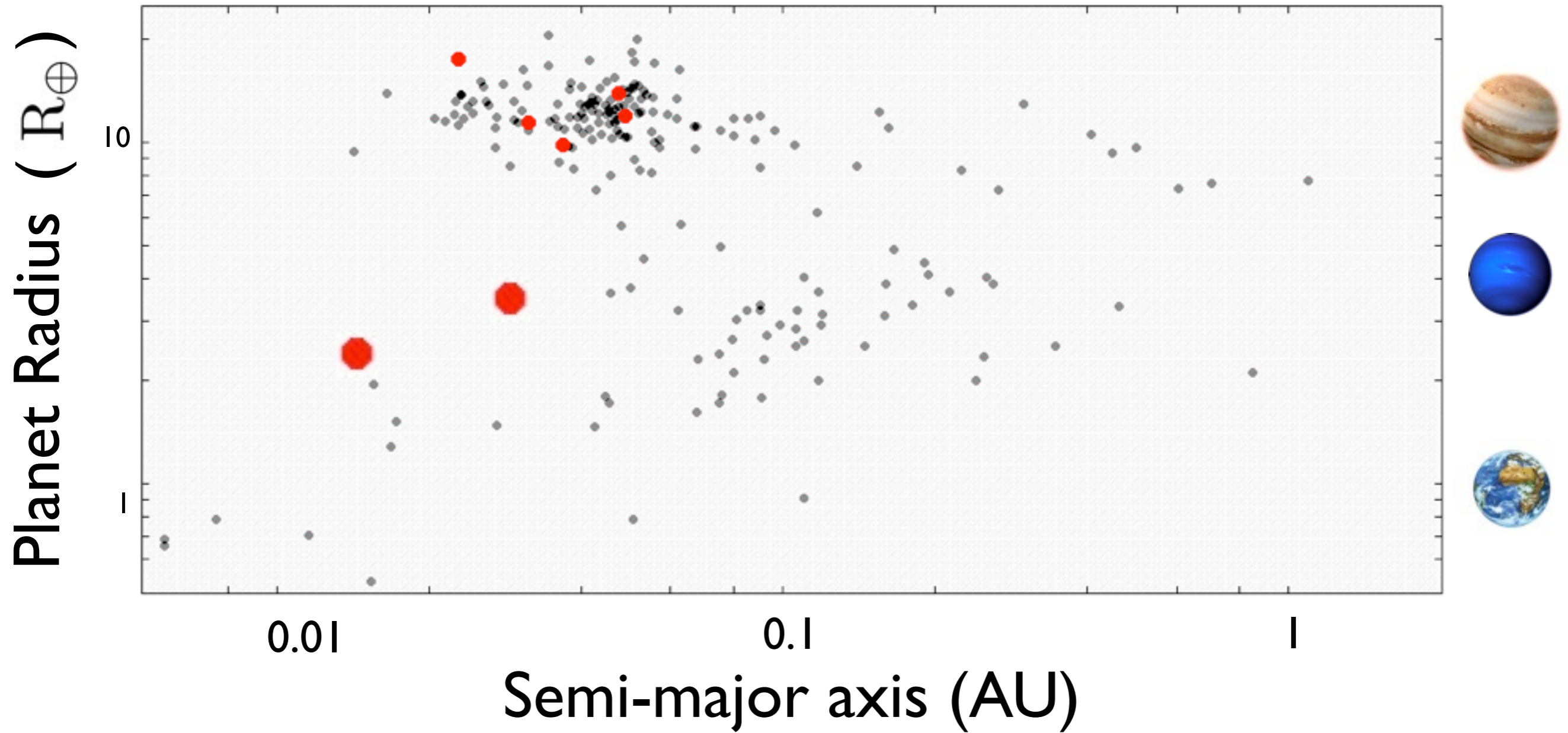
HST-STIS 13 Hot-Jupiters
(PI: D. Sing)

Ground-based Surveys:

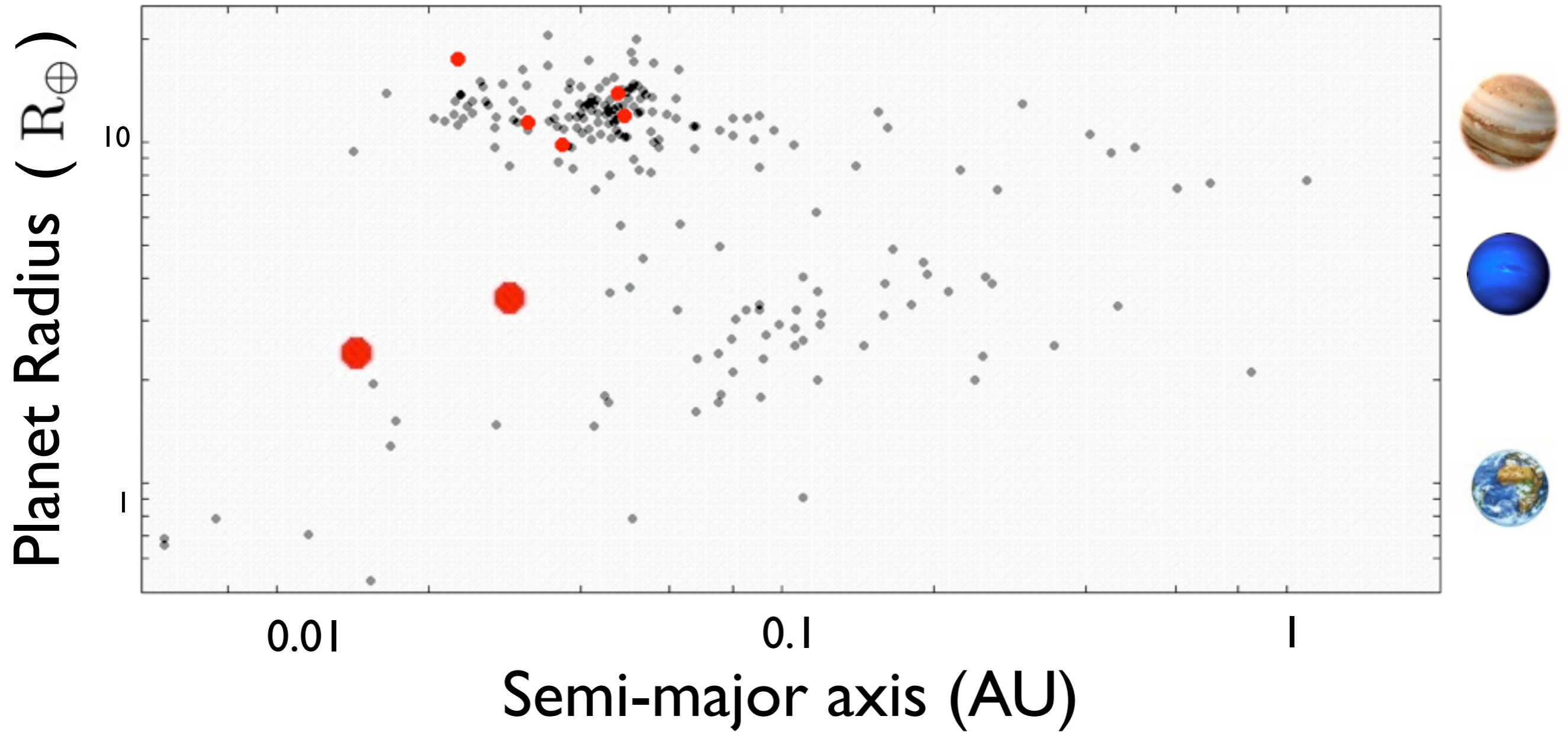
NIR: Magellan (PI: JM Désert / J. Bean)

Optical: Gemini (PI: JM Désert)

● Transmission Measurements (XEUV -> IR)



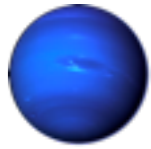
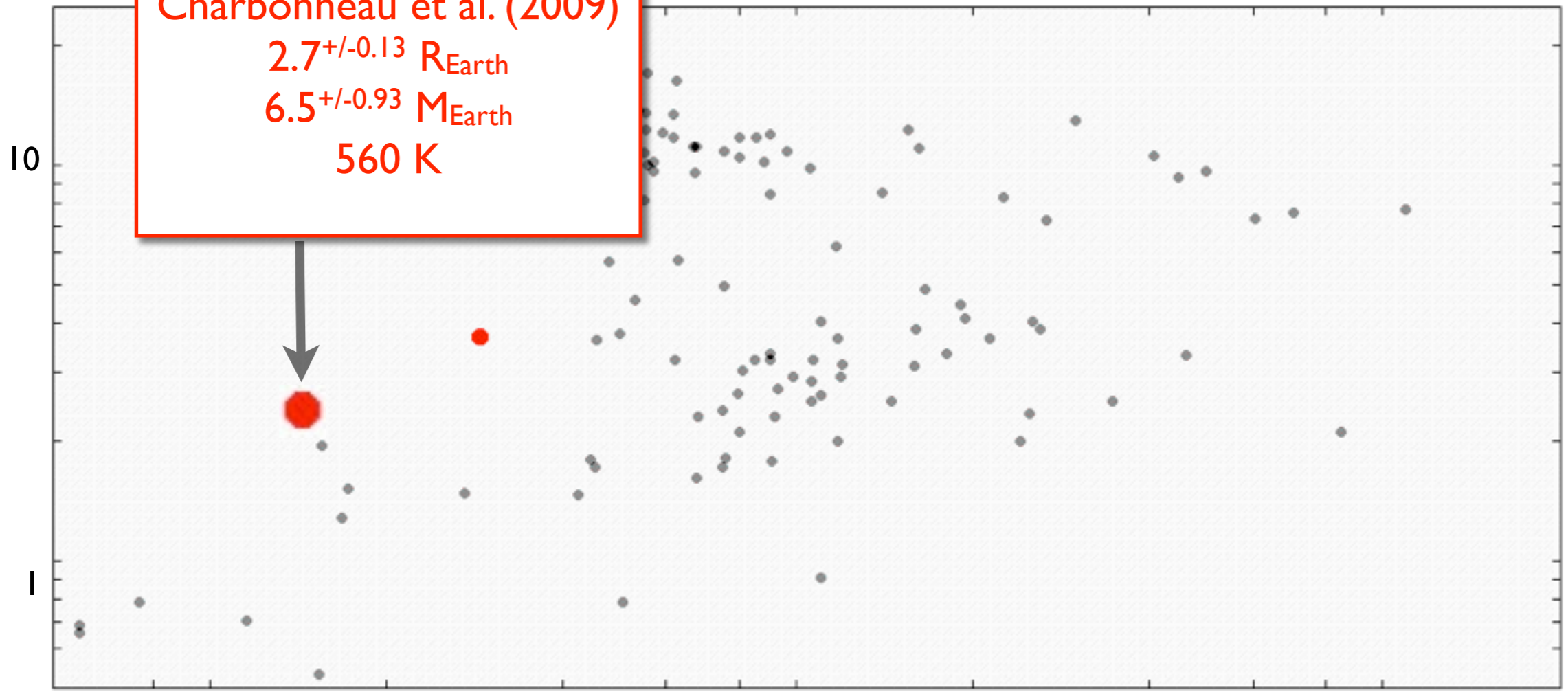
M-dwarfs Opportunity



GJ-1214b

Planet Radius (R_{\oplus})

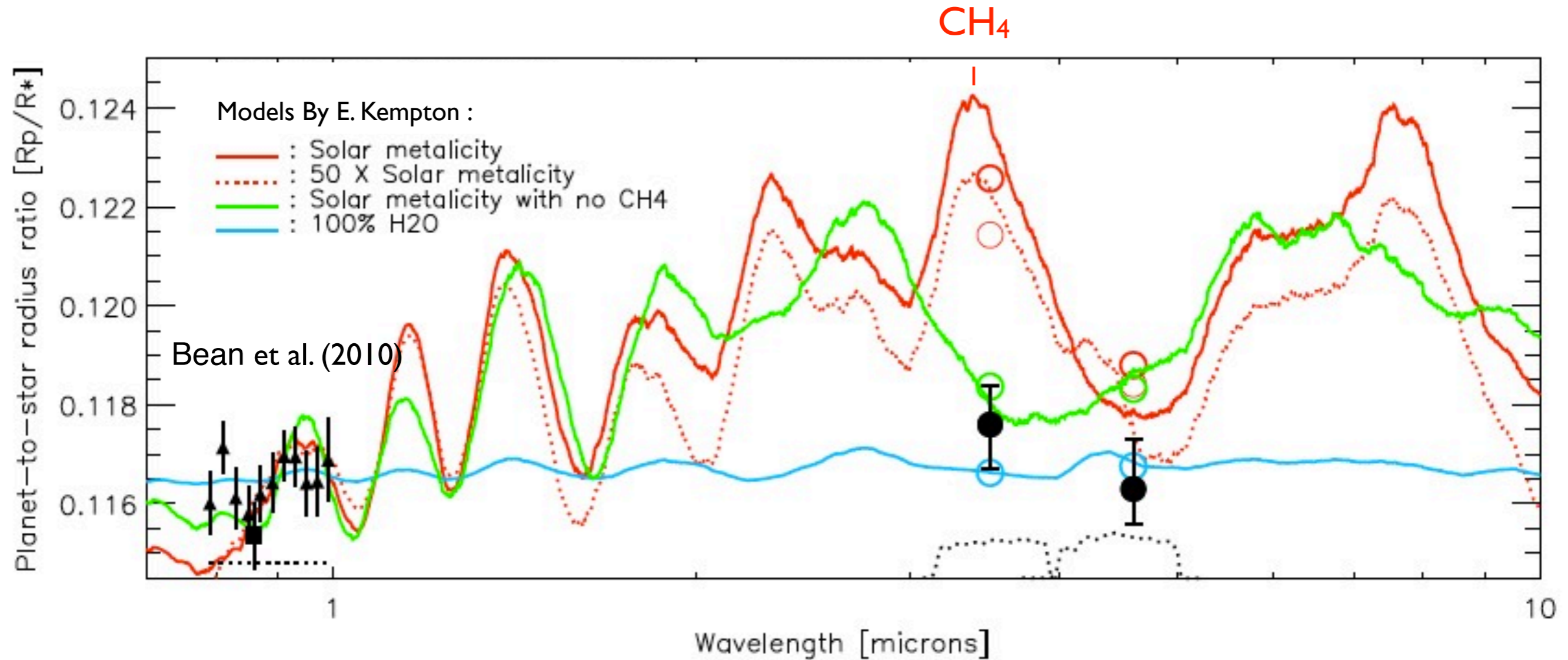
GJ-1214b
Charbonneau et al. (2009)
 $2.7^{+/-0.13} R_{\text{Earth}}$
 $6.5^{+/-0.93} M_{\text{Earth}}$
560 K



Semi-major axis (AU)

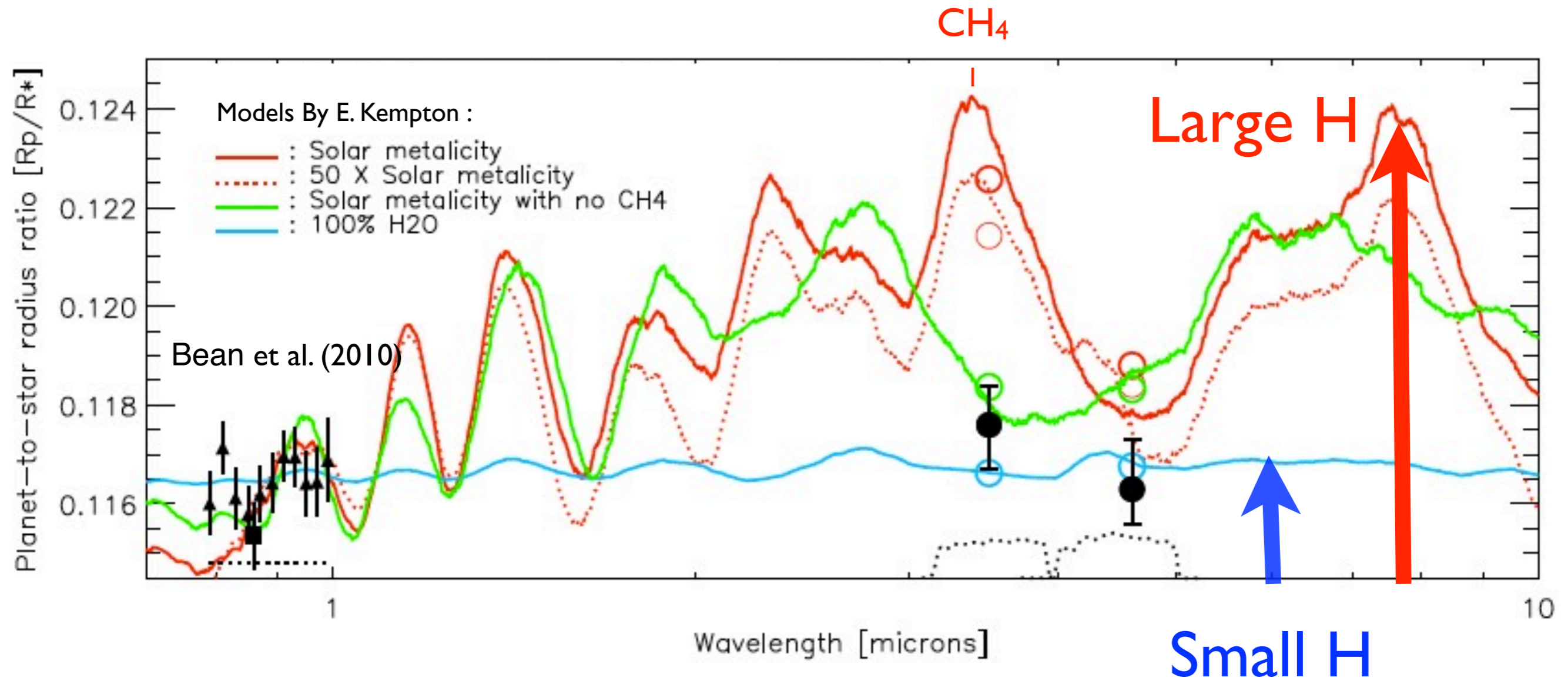
Transmission Spectroscopy of GJ1214b

Désert et al. (2011)



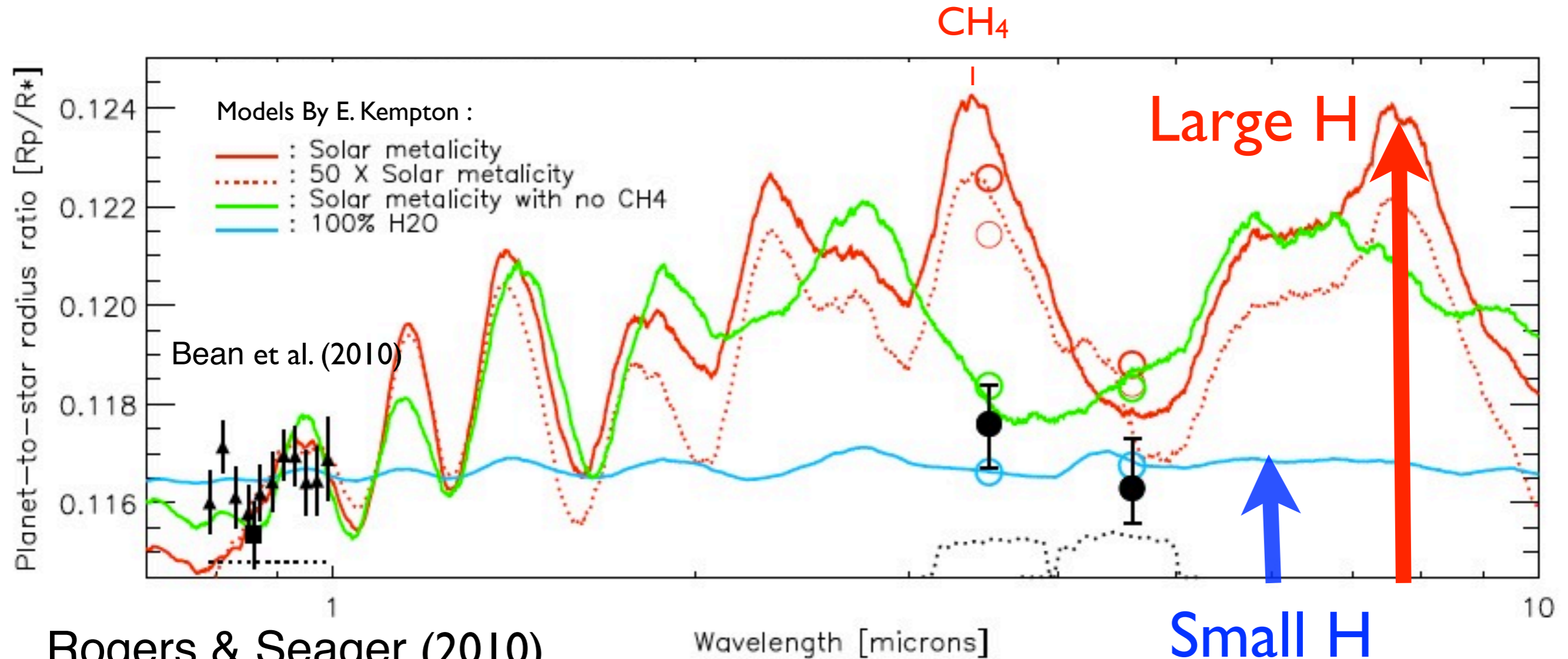
GJ1214b: Distinguishing H-rich/H-poor atmospheres

Désert et al. (2011)

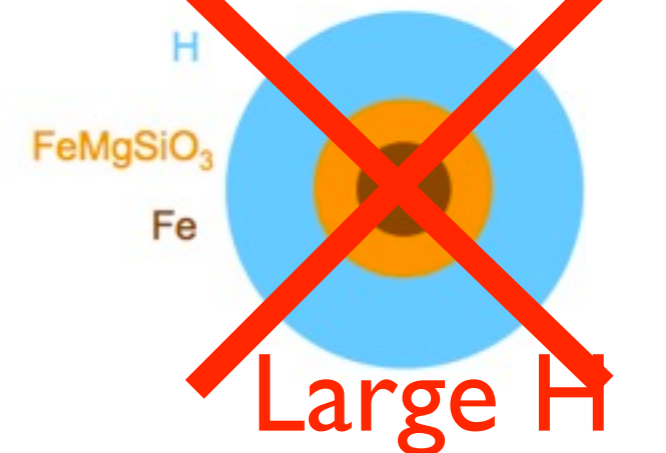
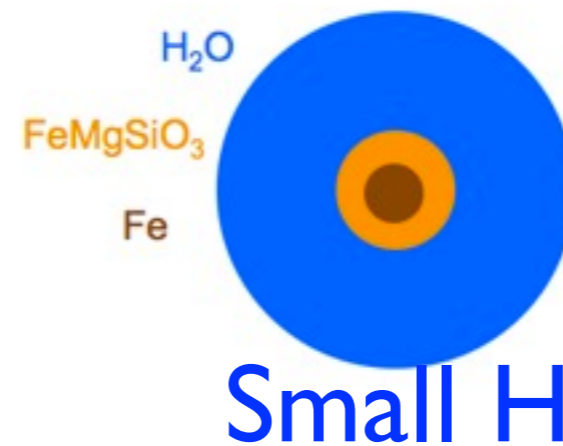
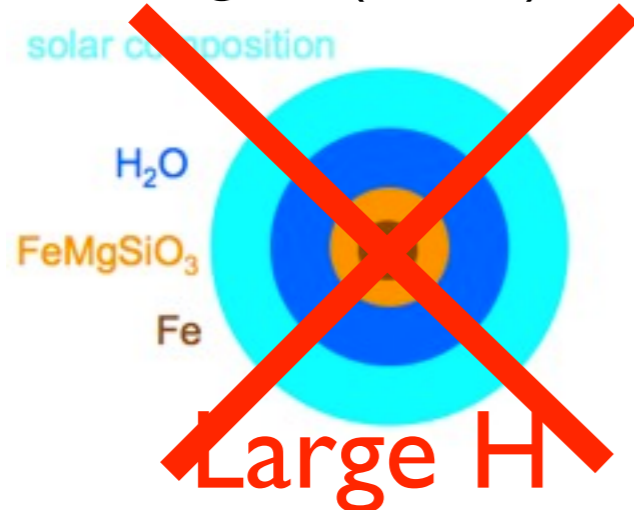


GJ1214b: Distinguishing H-rich/H-poor atmospheres

Désert et al. (2011)

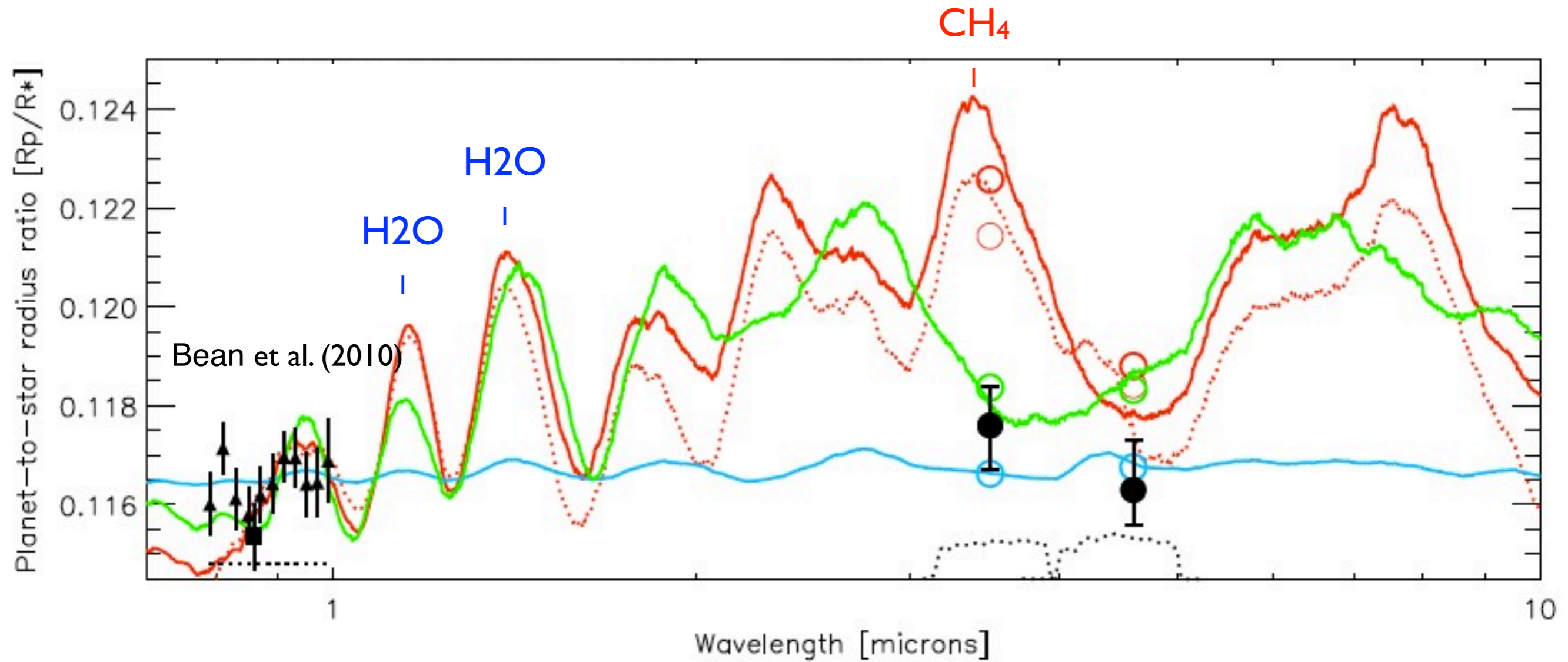


Rogers & Seager (2010)



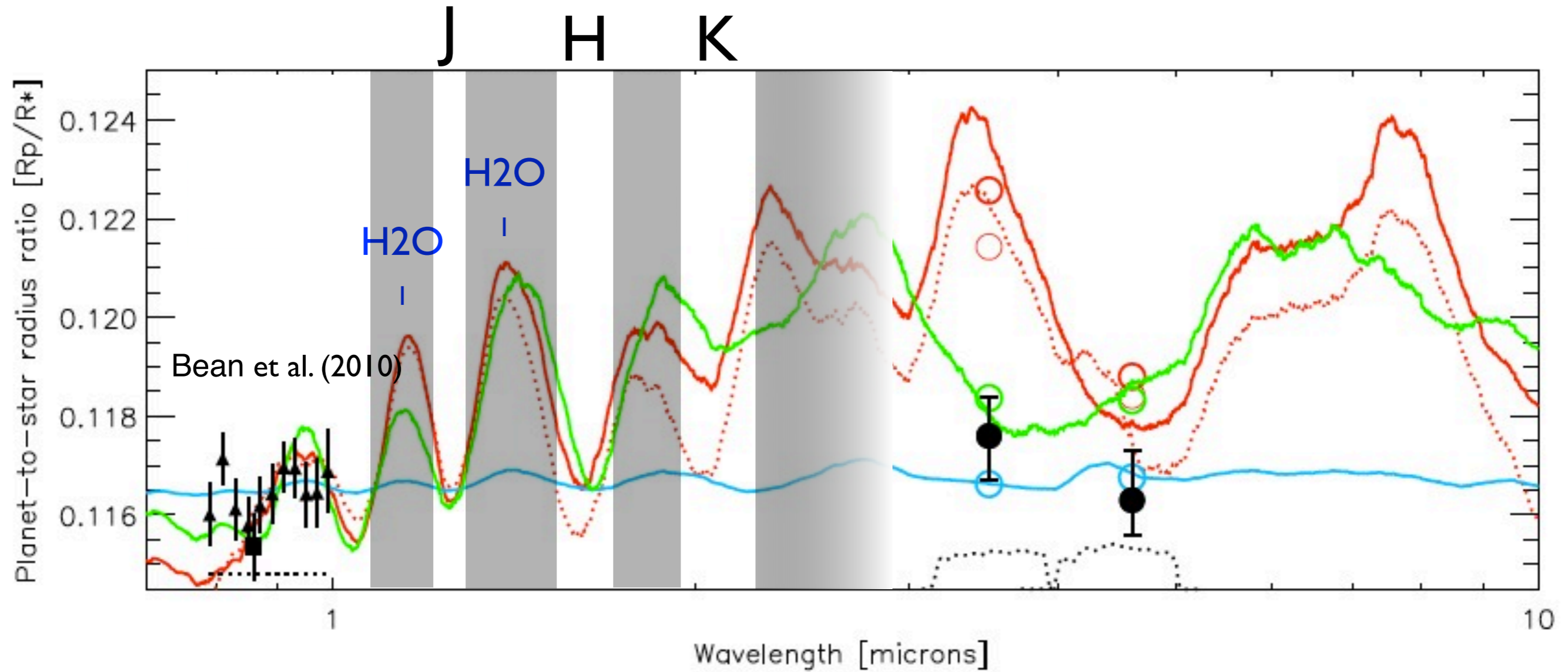
Transmission Spectroscopy of GJ1214b

Désert et al. (2011)



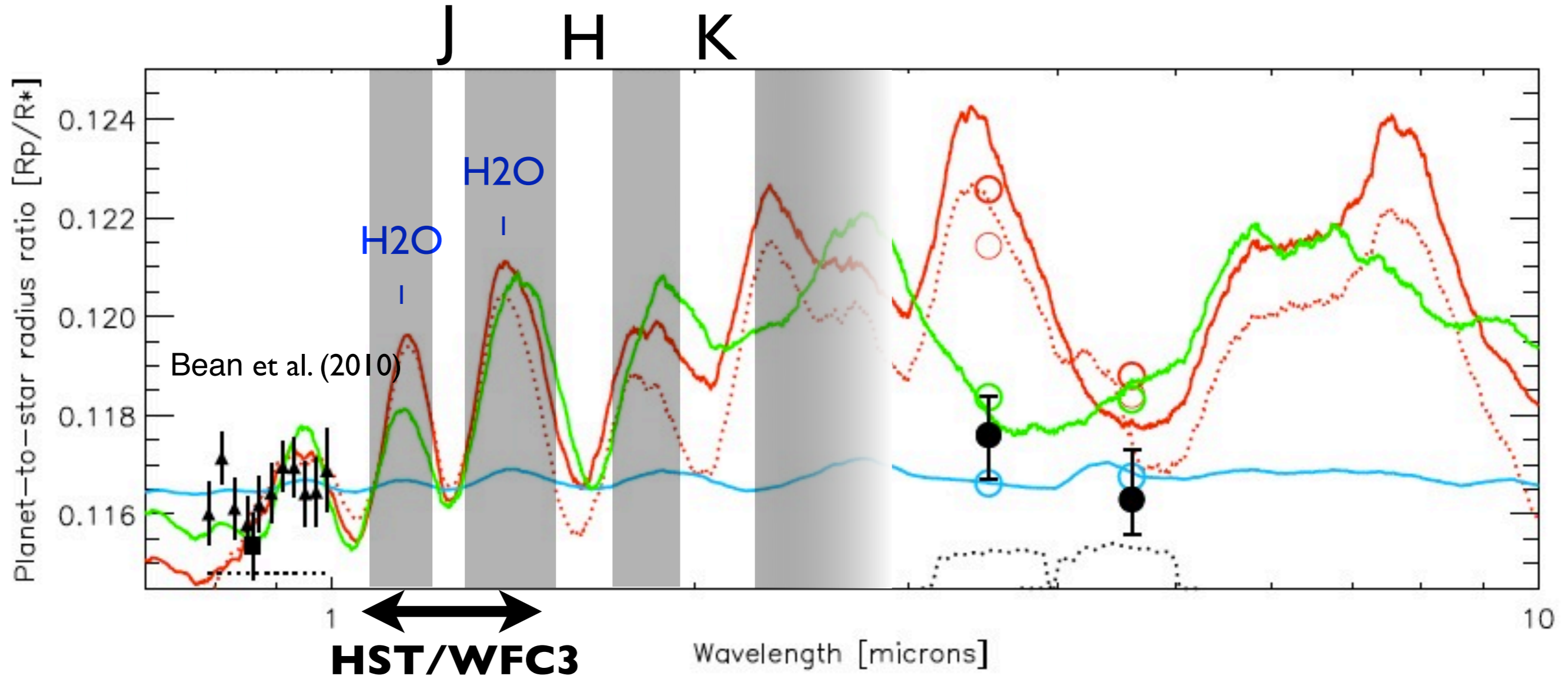
Transmission Spectroscopy of GJ1214b

Désert et al. (2011)



Transmission Spectroscopy of GJ1214b

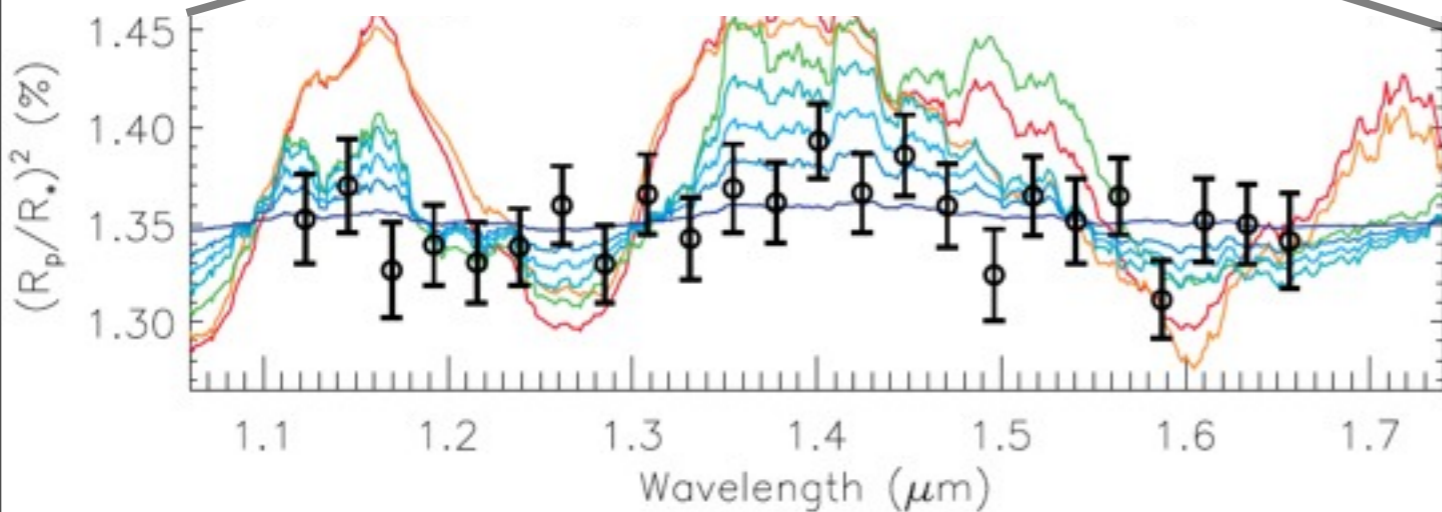
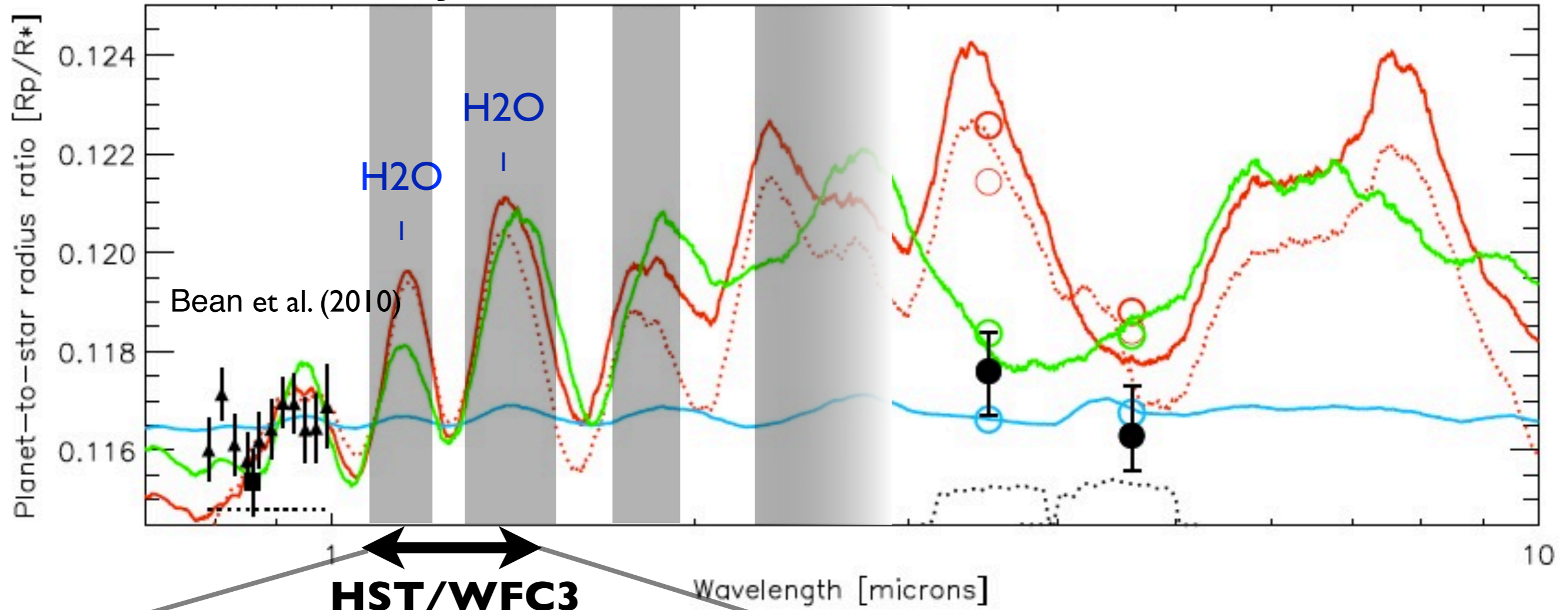
Désert et al. (2011)



Transmission Spectroscopy of GJ1214b

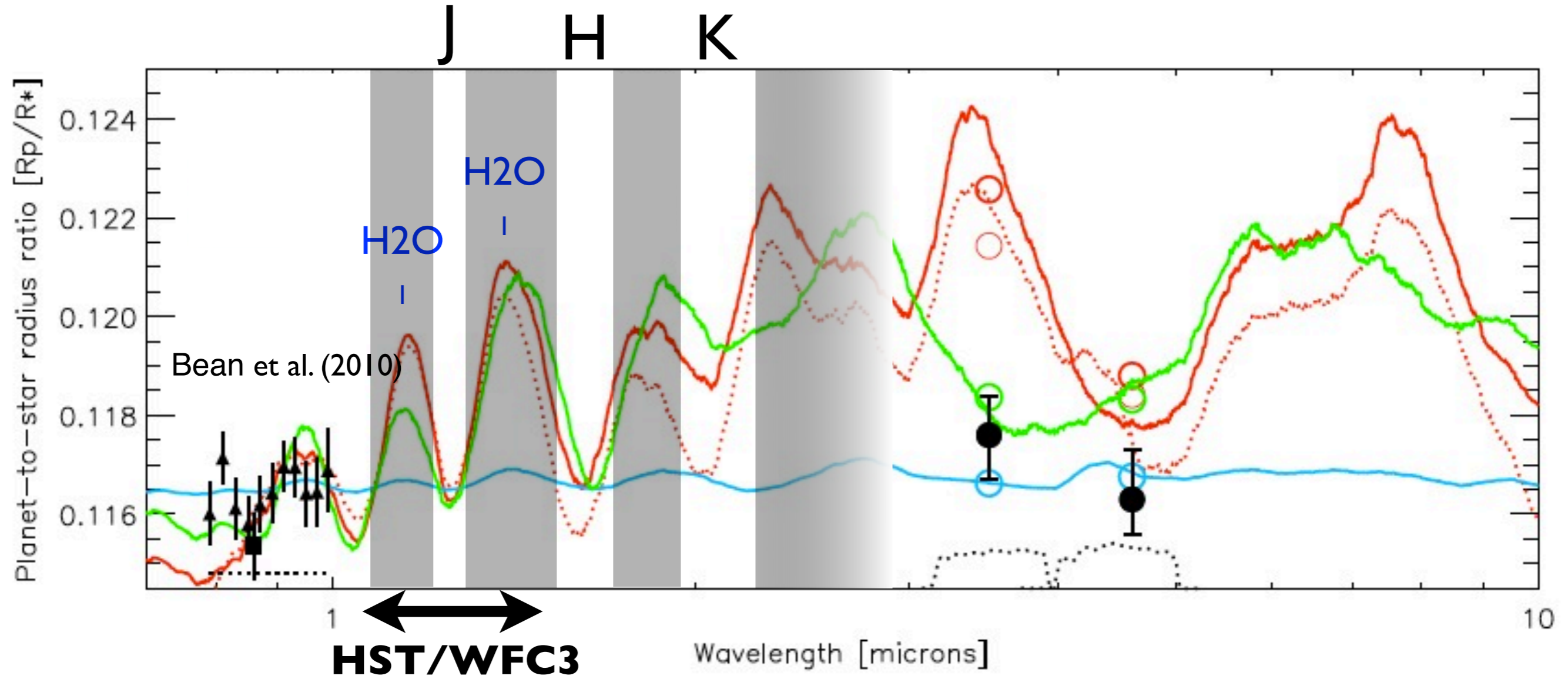
Désert et al. (2011)

J H K



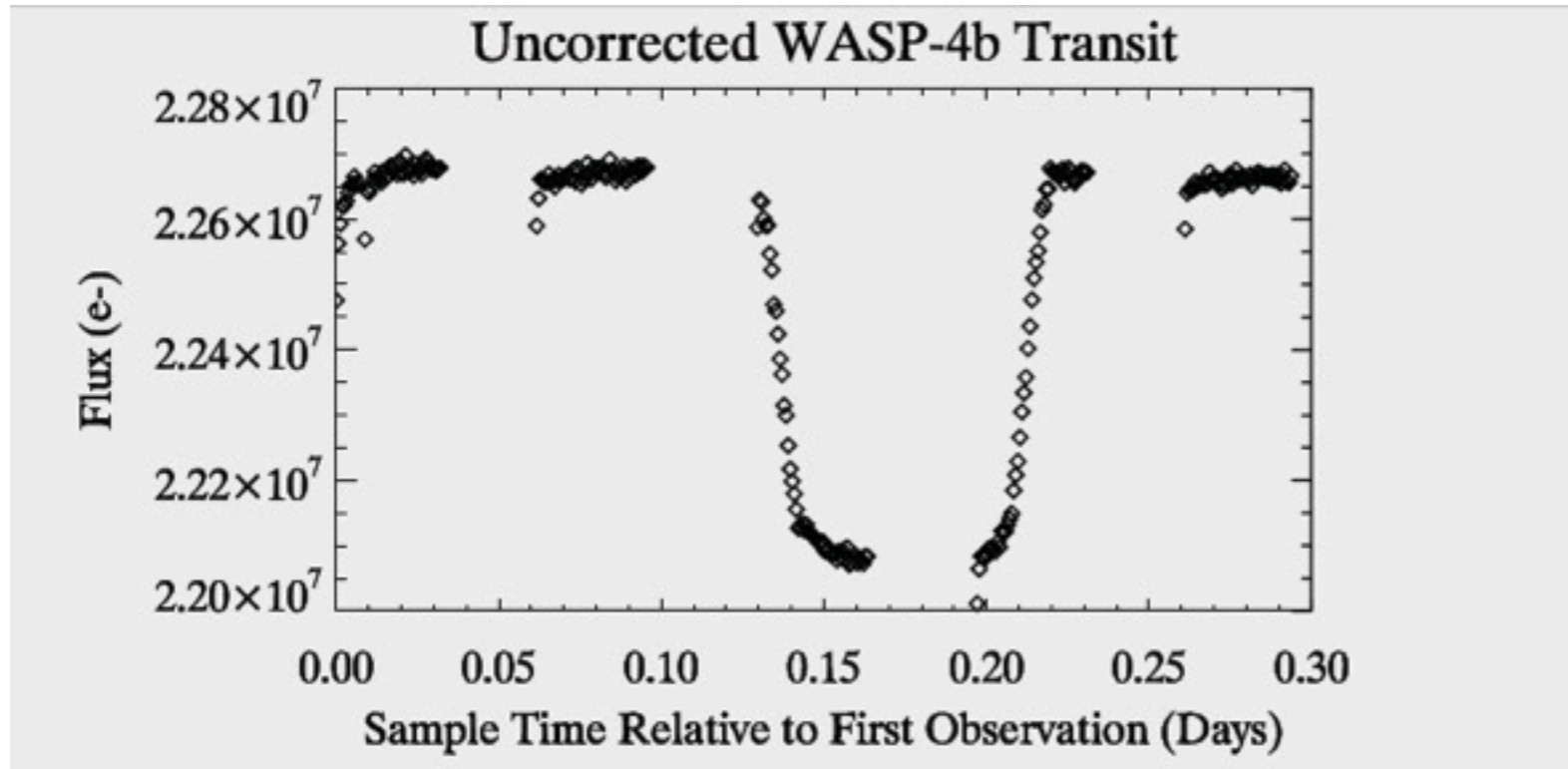
Transmission Spectroscopy of GJ1214b

Désert et al. (2011)



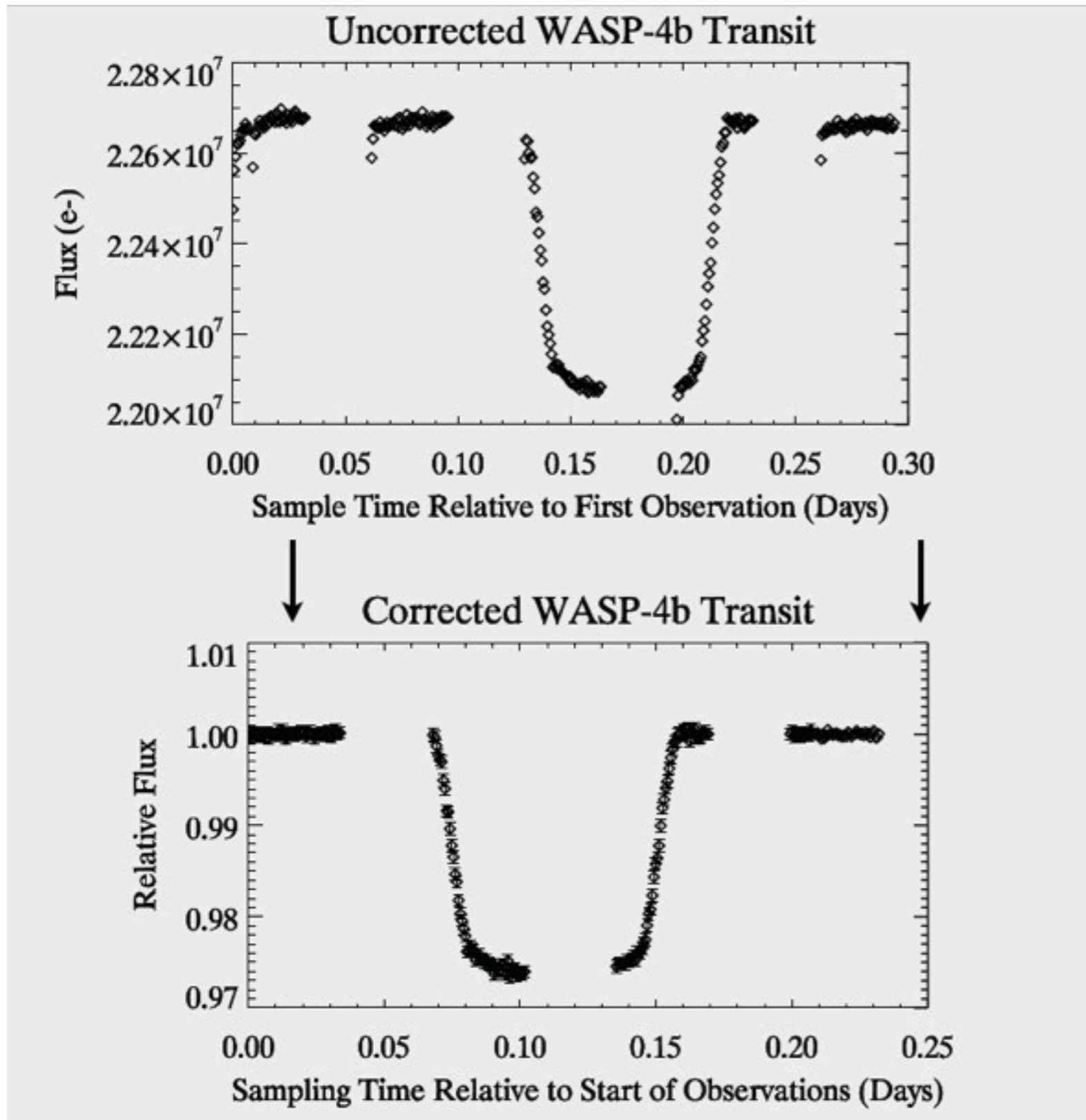
Hot-Jupiters Survey with HST/WFC3

Sukrit Ranjan (CfA)



Hot-Jupiters Survey with HST/WFC3

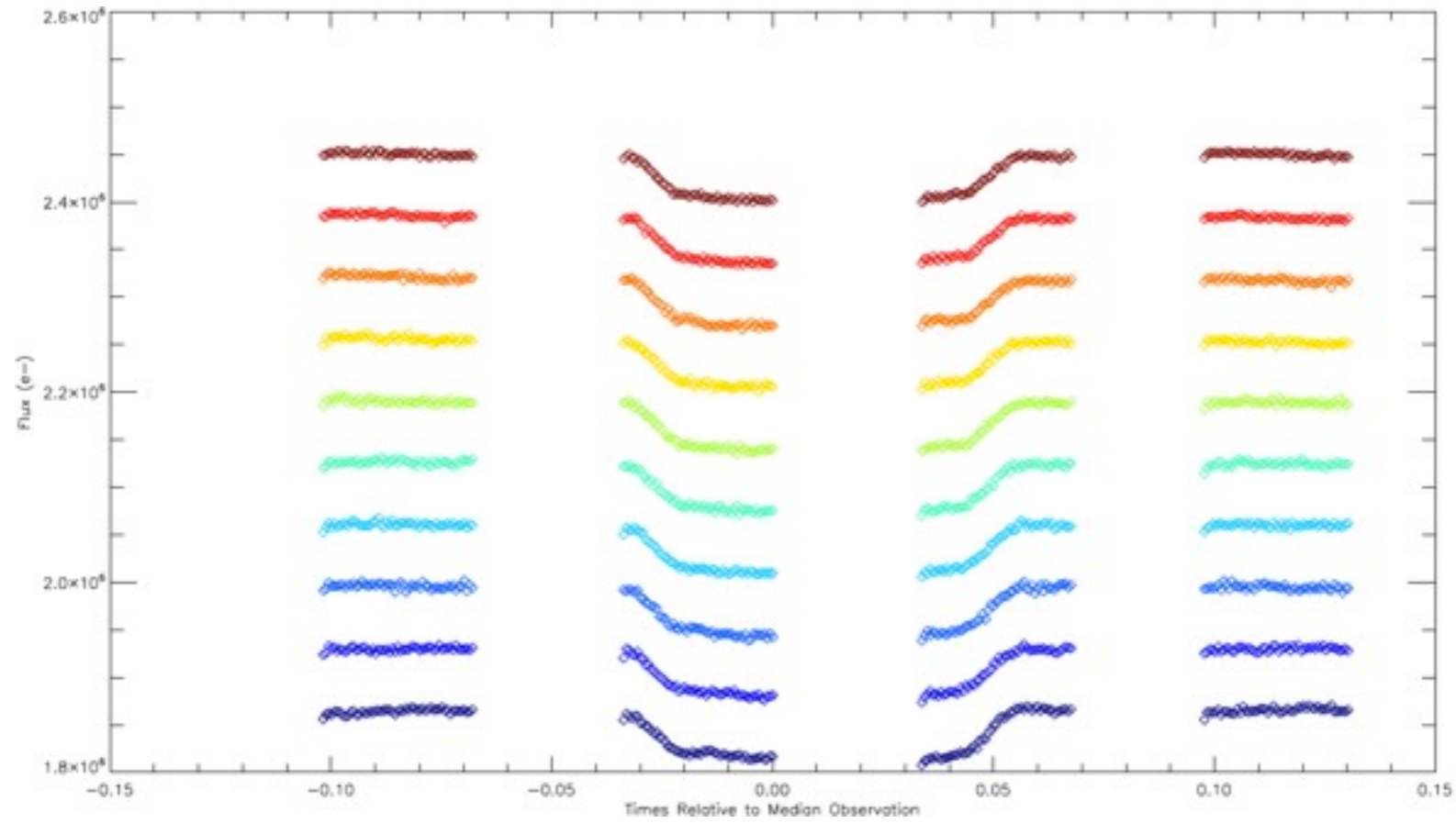
Sukrit Ranjan (CfA)



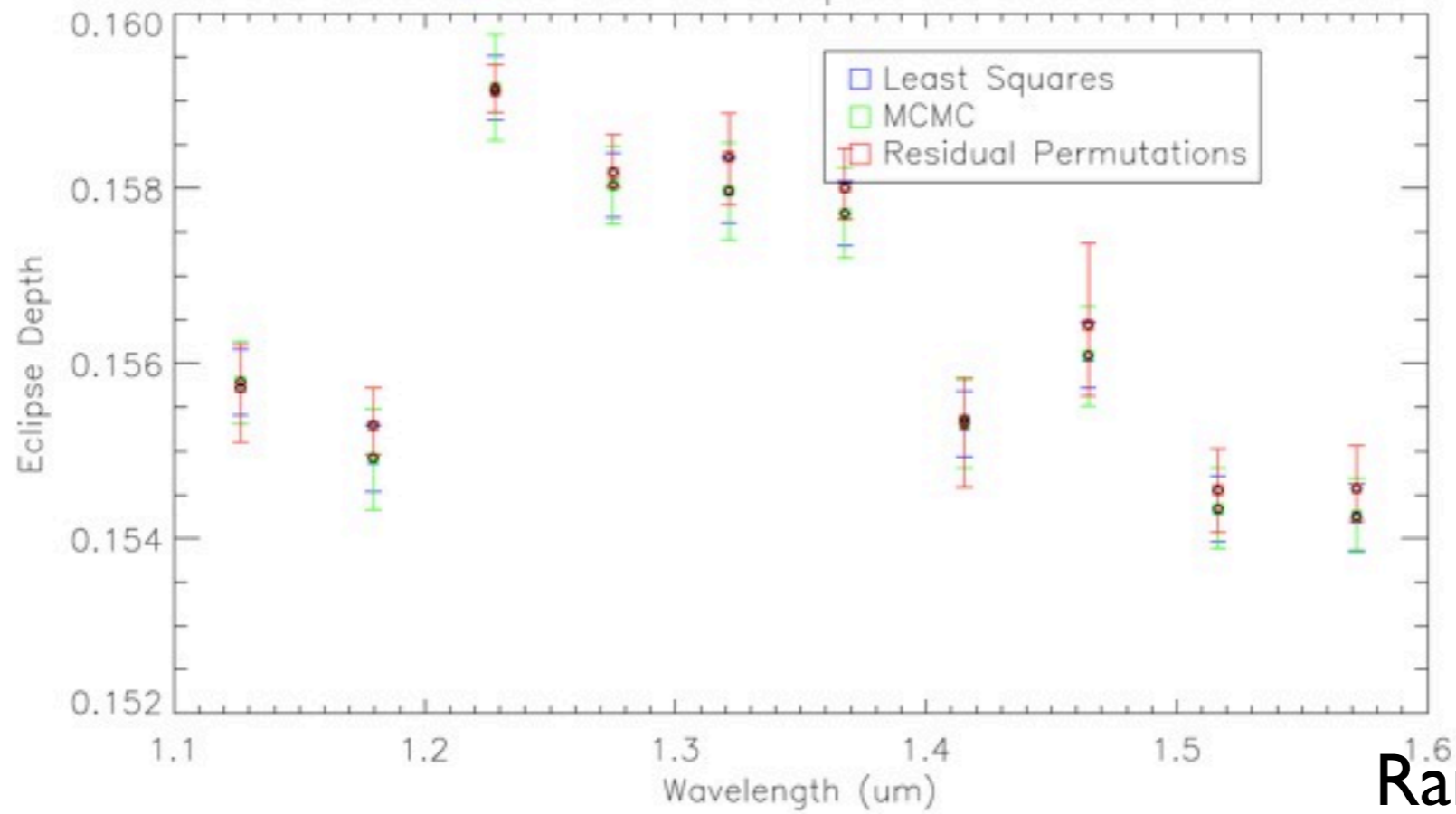
Ranjan et al. (in prep)

WASP-4b

HST/WFC3



WASP-4 Spectrum



Ranjan et al. (in prep)

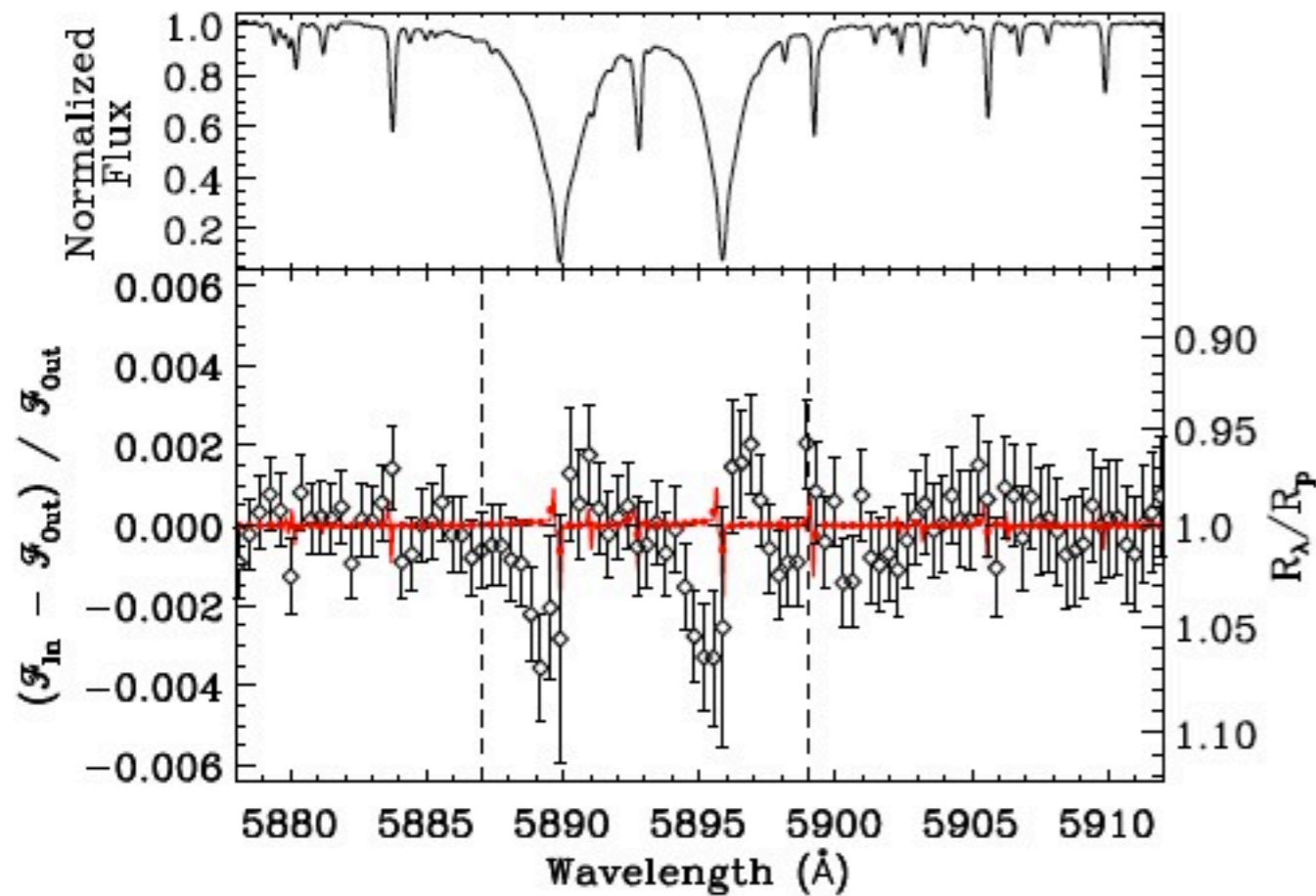
Ground-Based Observations of Exoplanet Atmospheres with the MOS Technique

- **Optical:** Gemini (PI: JM Désert)
- **NIR:** Magellan (PI: JM Désert / J. Bean)

Ground-Based Observations

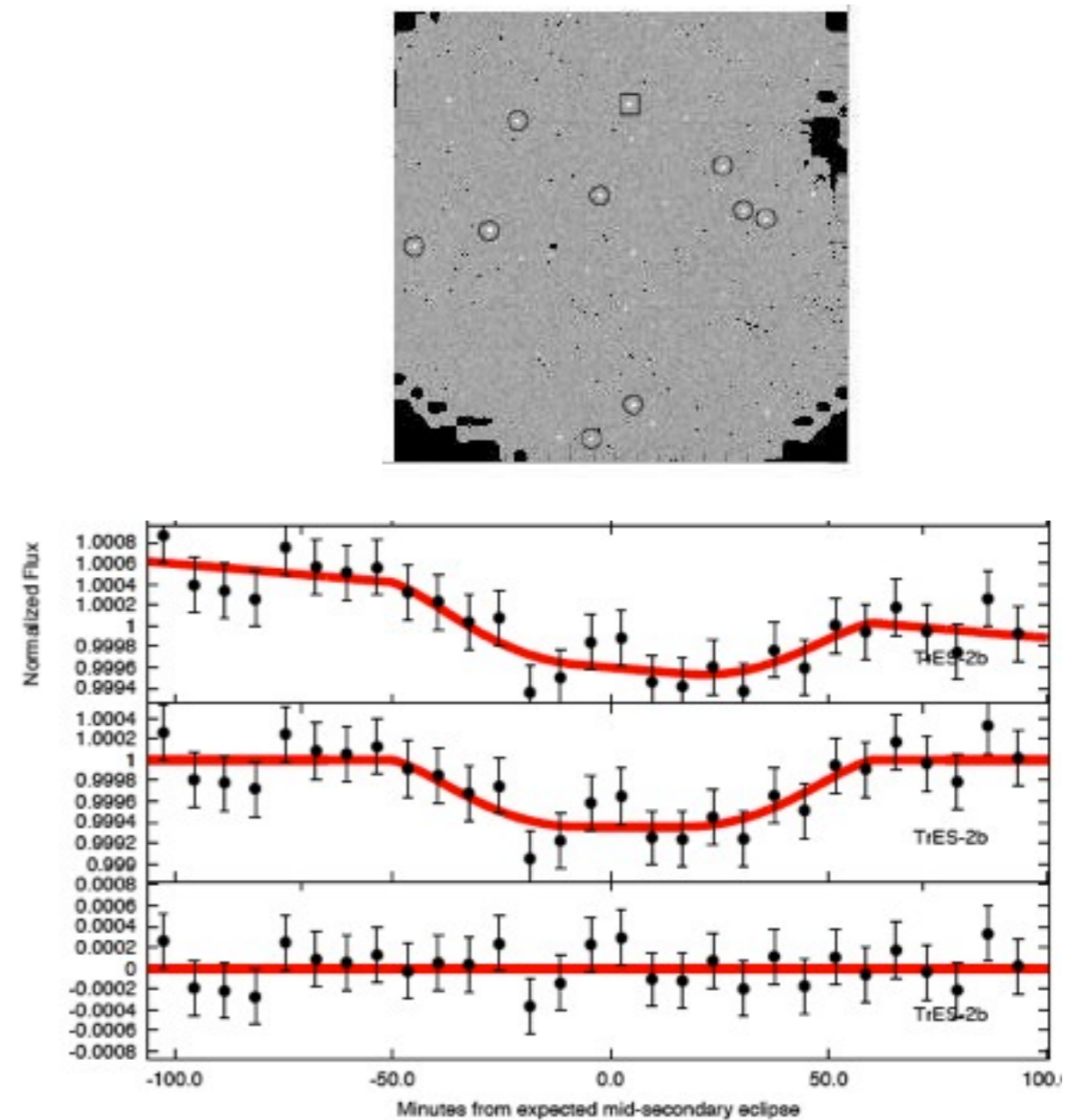
Redfield et al. (2008)

Transit HD189733b



Croll et al. (2010)

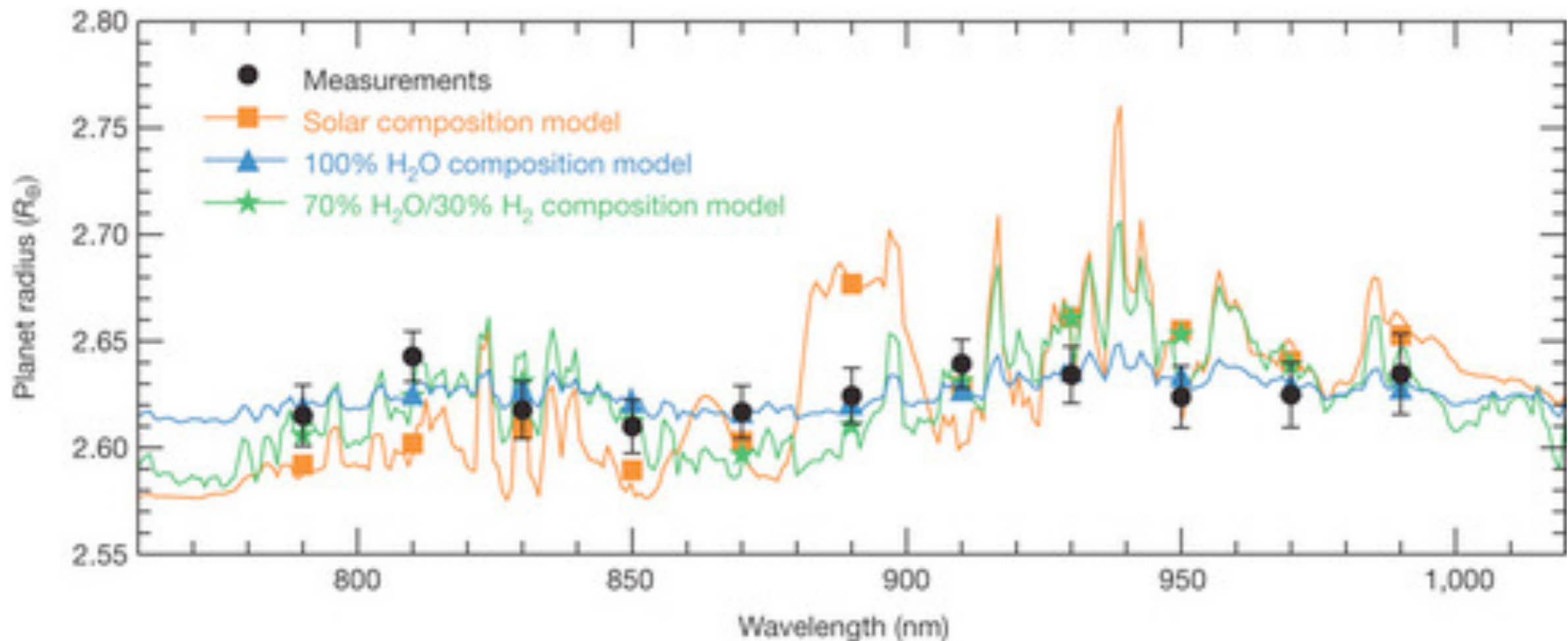
Eclipse TrES-2b



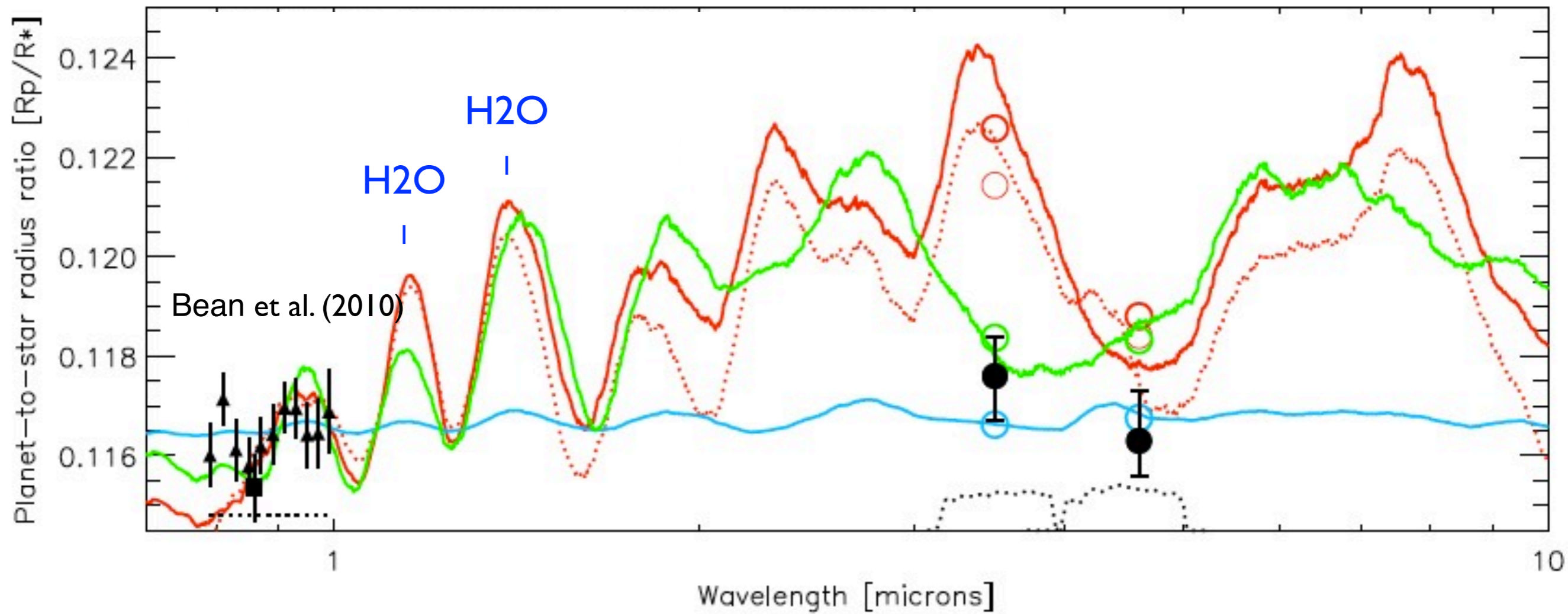
The Multi-Object Spectroscopy Technique

Bean et al. (2010)

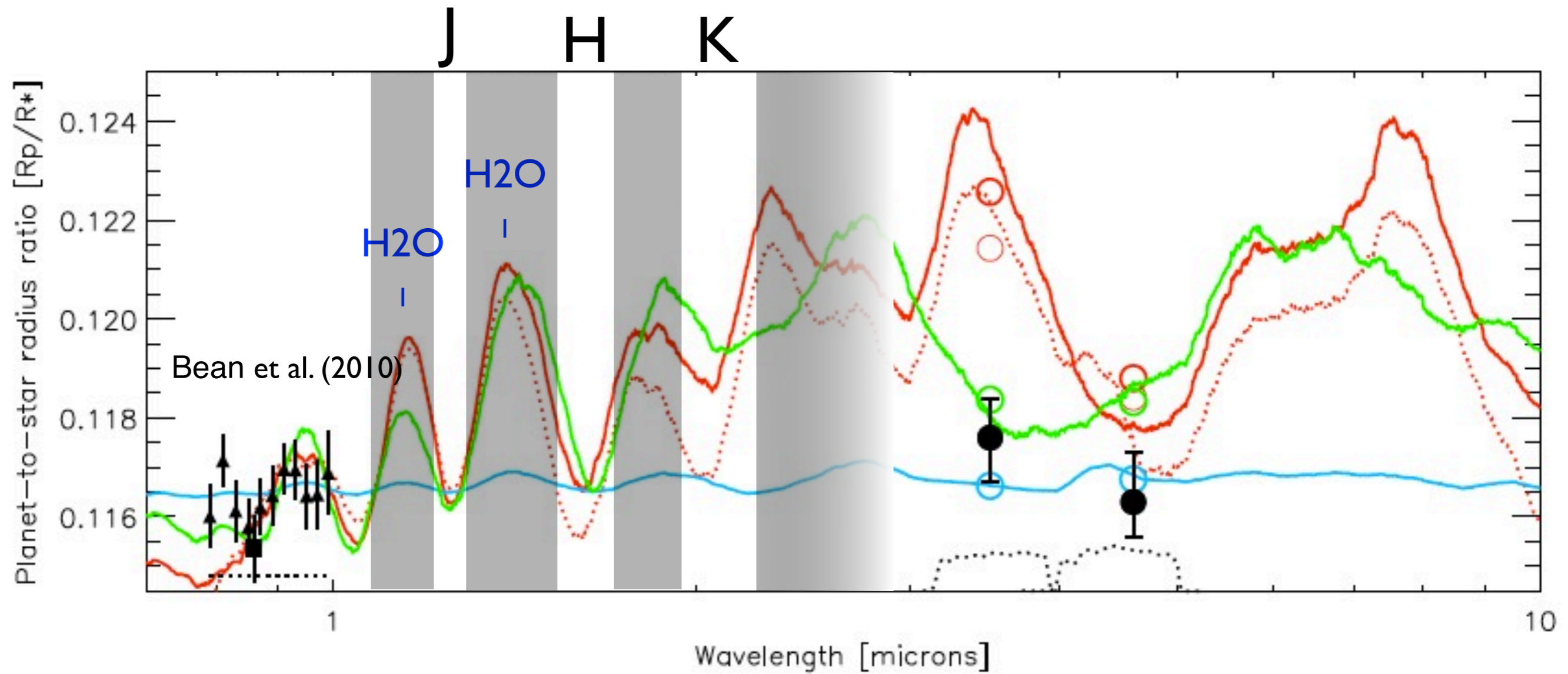
Transits GJ1214b



Transmission Spectroscopy of GJ1214b



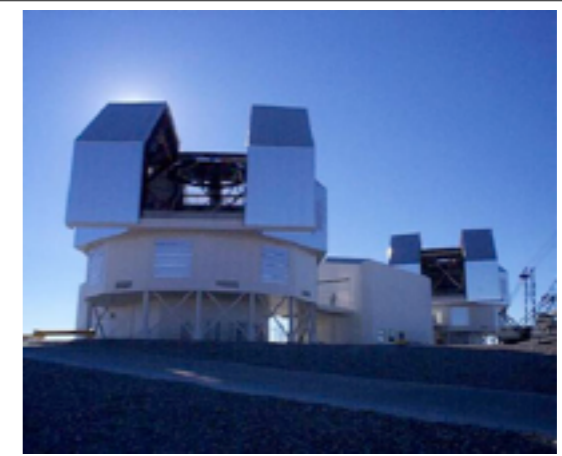
Transmission Spectroscopy of GJ1214b



←————→
Magellan/MMIRS

Multi-Object Spectroscopy (GJ 1214b, Magellan/MMIRS)

Bean, Désert et al. (2011)

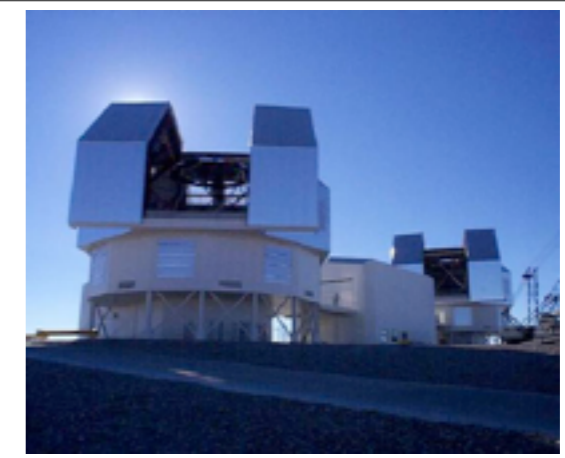


6.9 Arcmin



Slit-mask

Multi-Object Spectroscopy (GJ 1214b, Magellan/MMIRS)

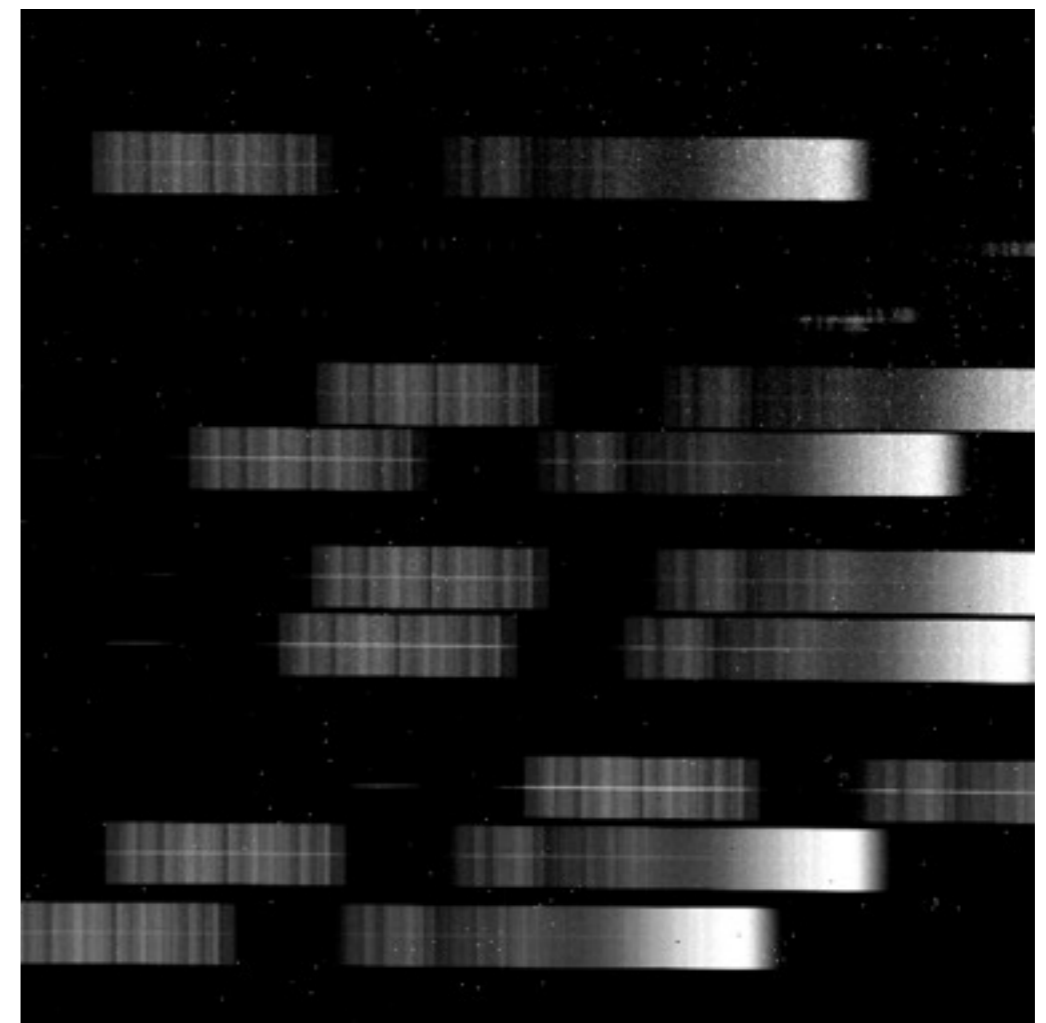


Bean, Désert et al. (2011)

6.9 Arcmin

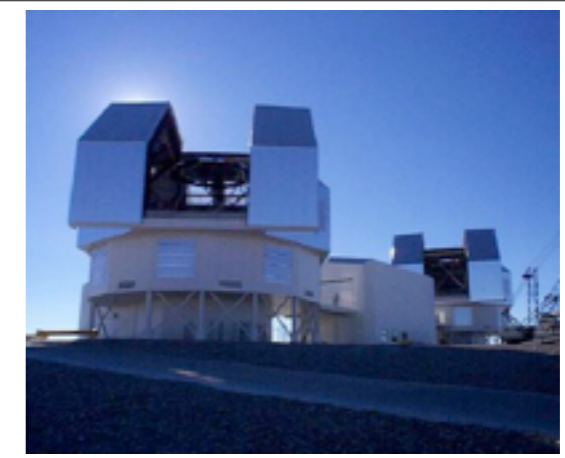


Slit-mask

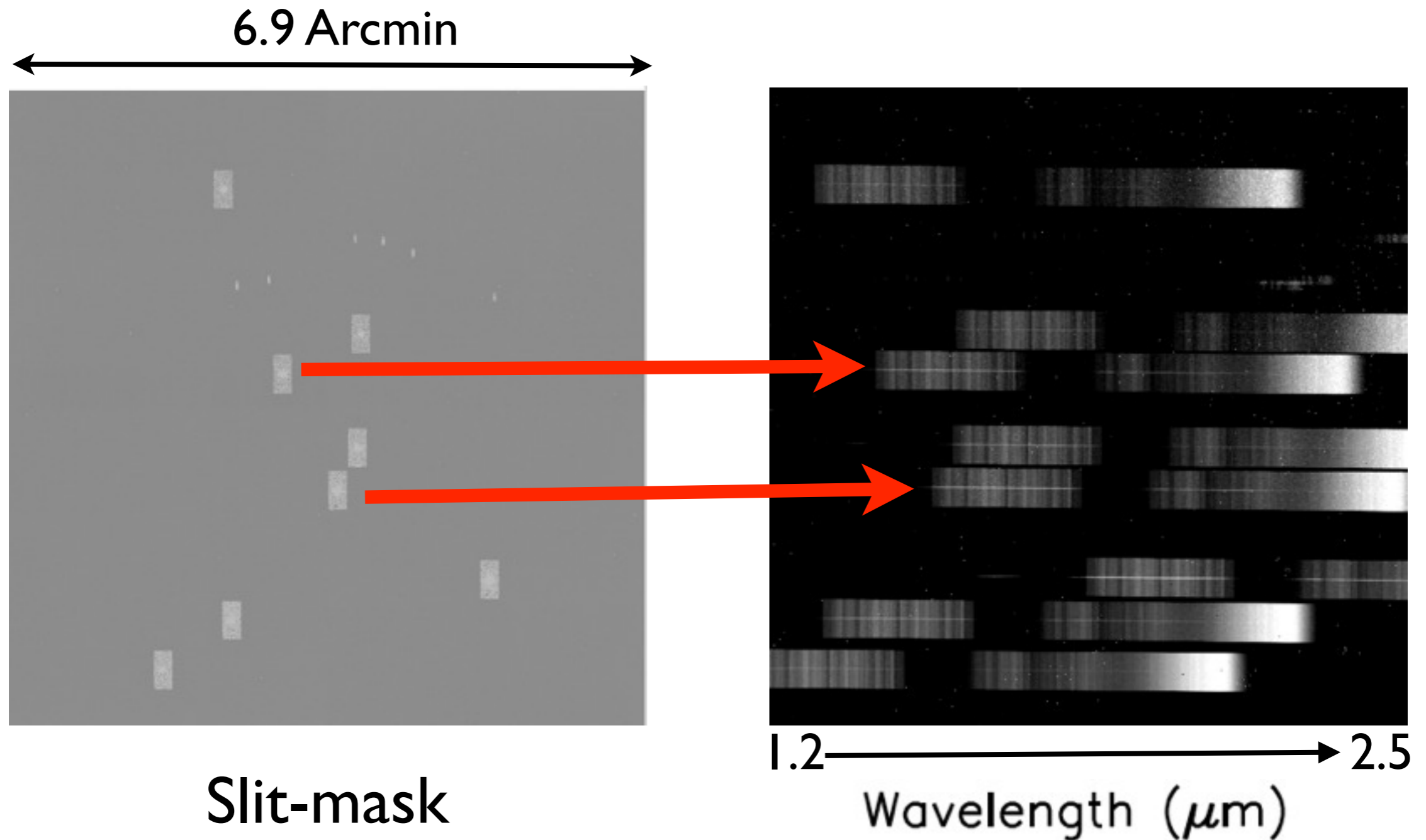


1.2 \rightarrow 2.5
Wavelength (μm)

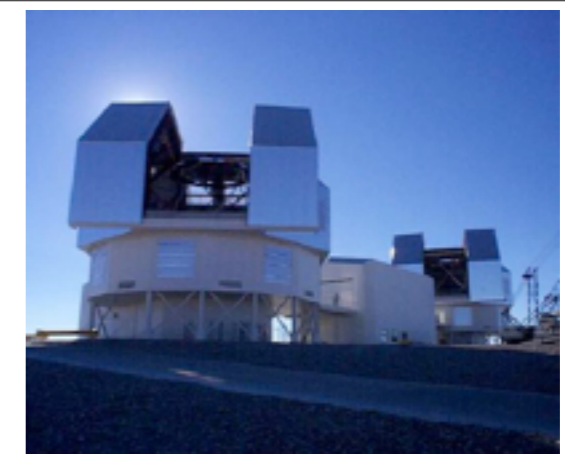
Multi-Object Spectroscopy (GJ1214b, Magellan/MMIRS)



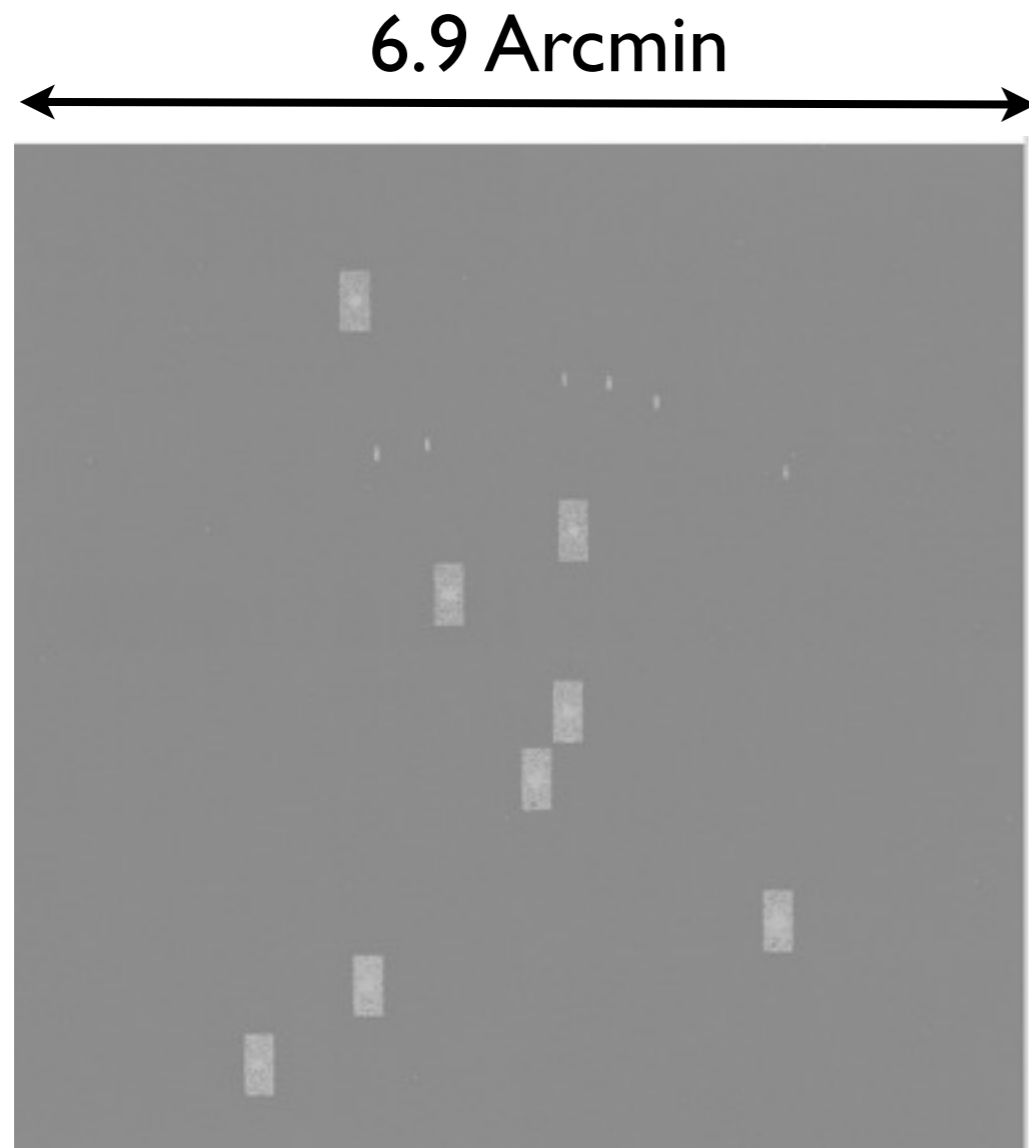
Bean, Désert et al. (2011)



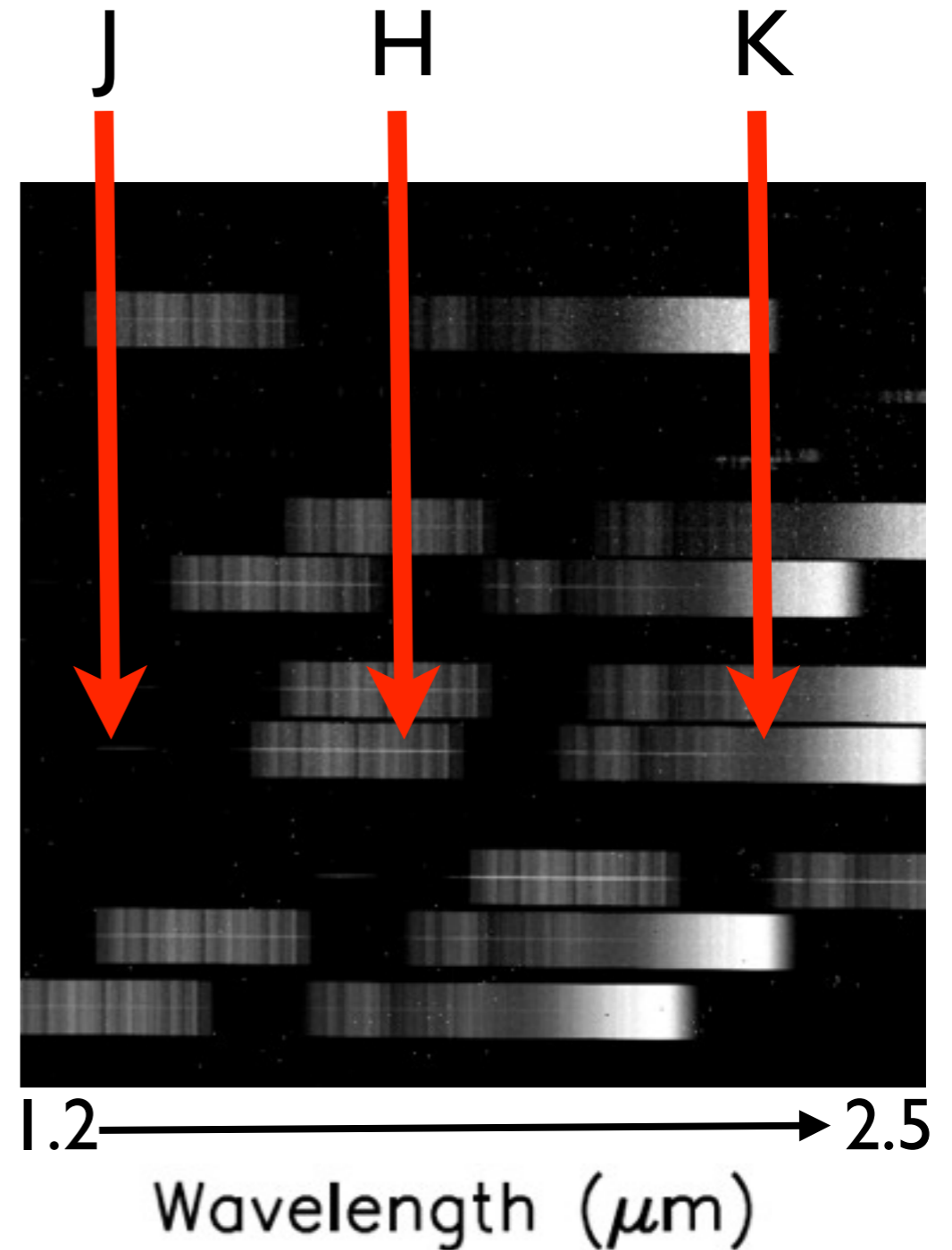
Multi-Object Spectroscopy (GJ 1214b, Magellan/MMIRS)



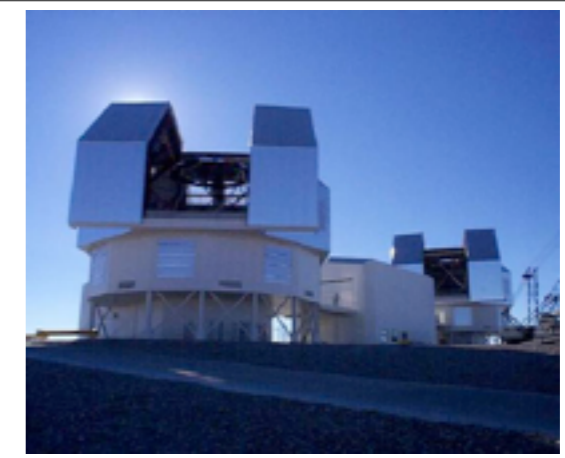
Bean, Désert et al. (2011)



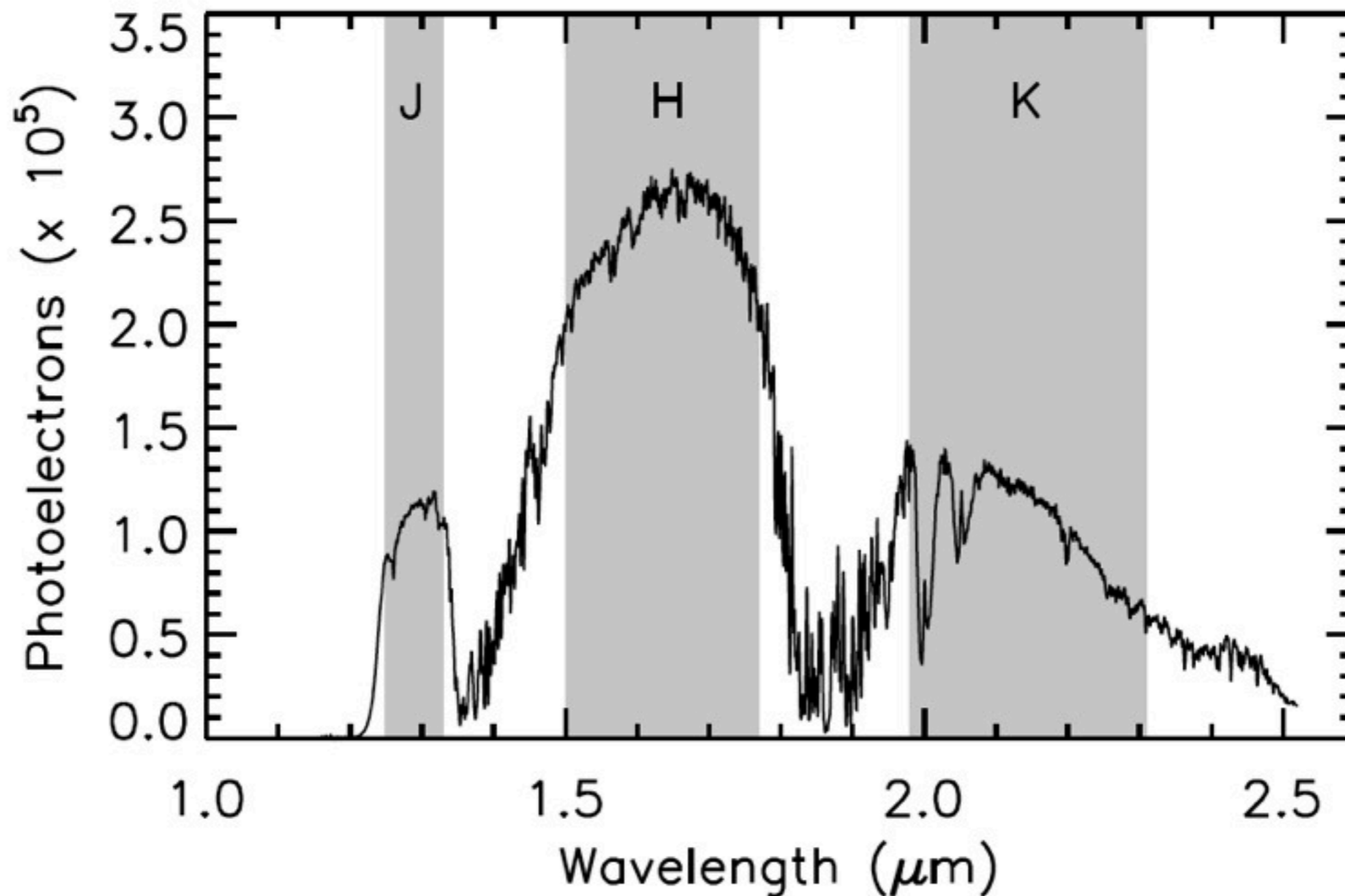
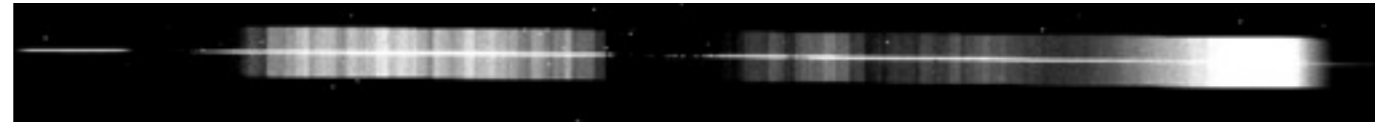
Slit-mask



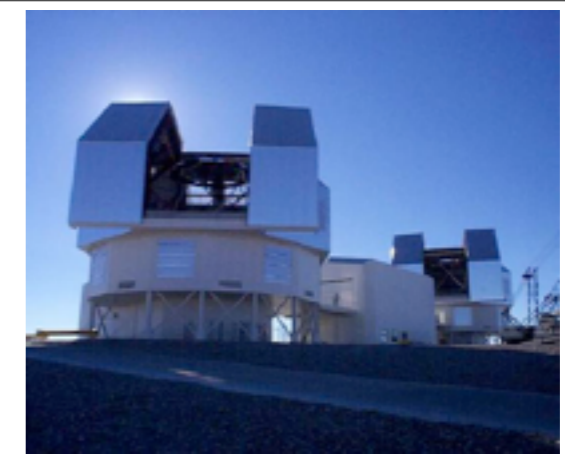
Multi-Object Spectroscopy (GJ 1214b, Magellan/MMIRS)



Bean, Désert et al. (2011)

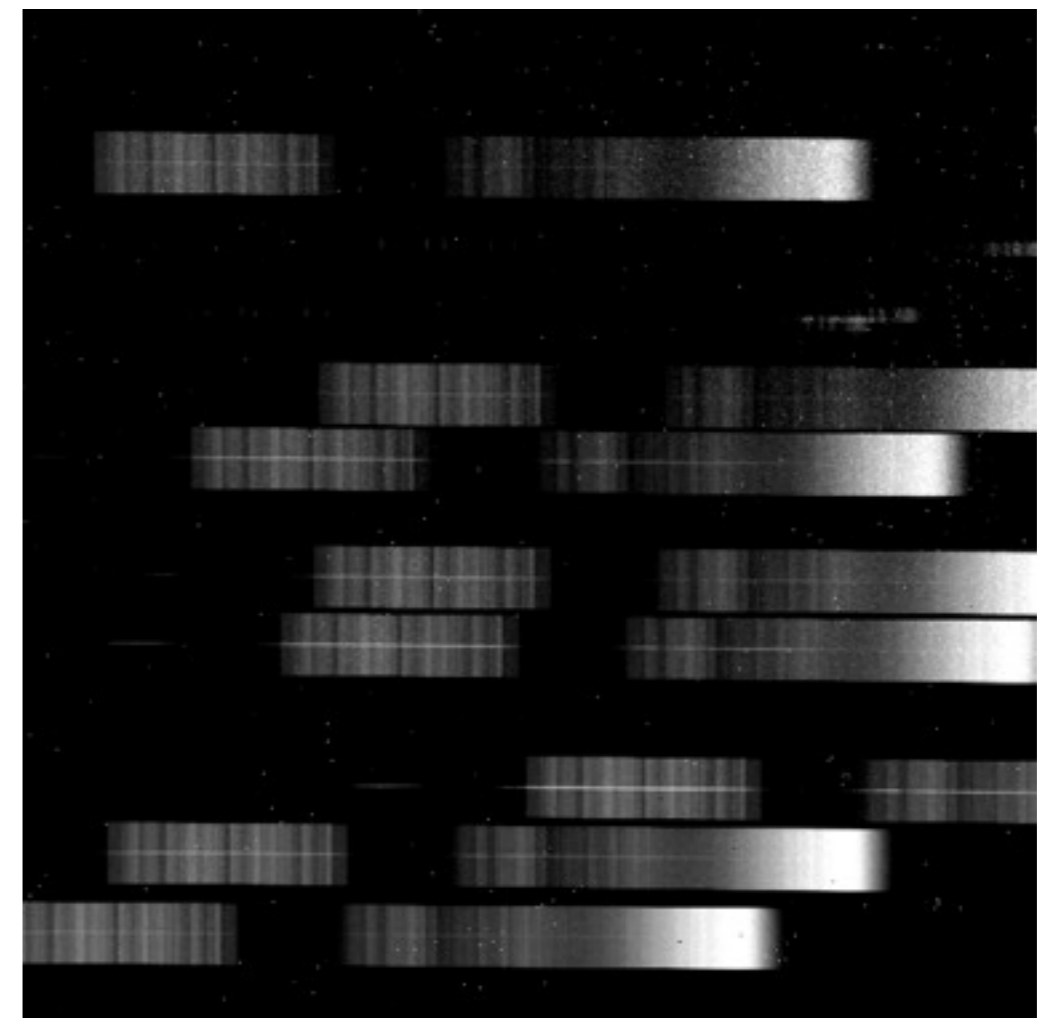


Multi-Object Spectroscopy (GJ1214b, Magellan/MMIRS)



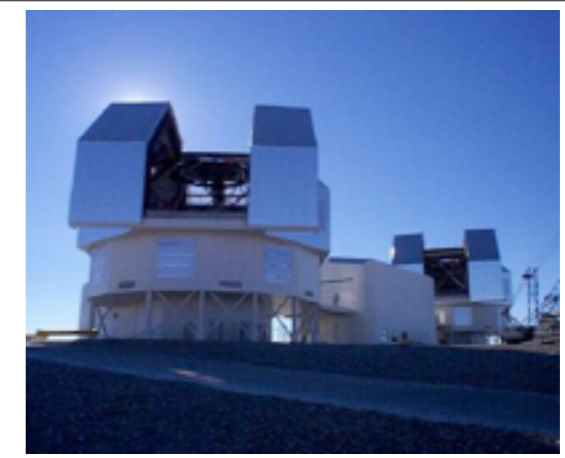
Bean, Désert et al. (2011)

Control systematics



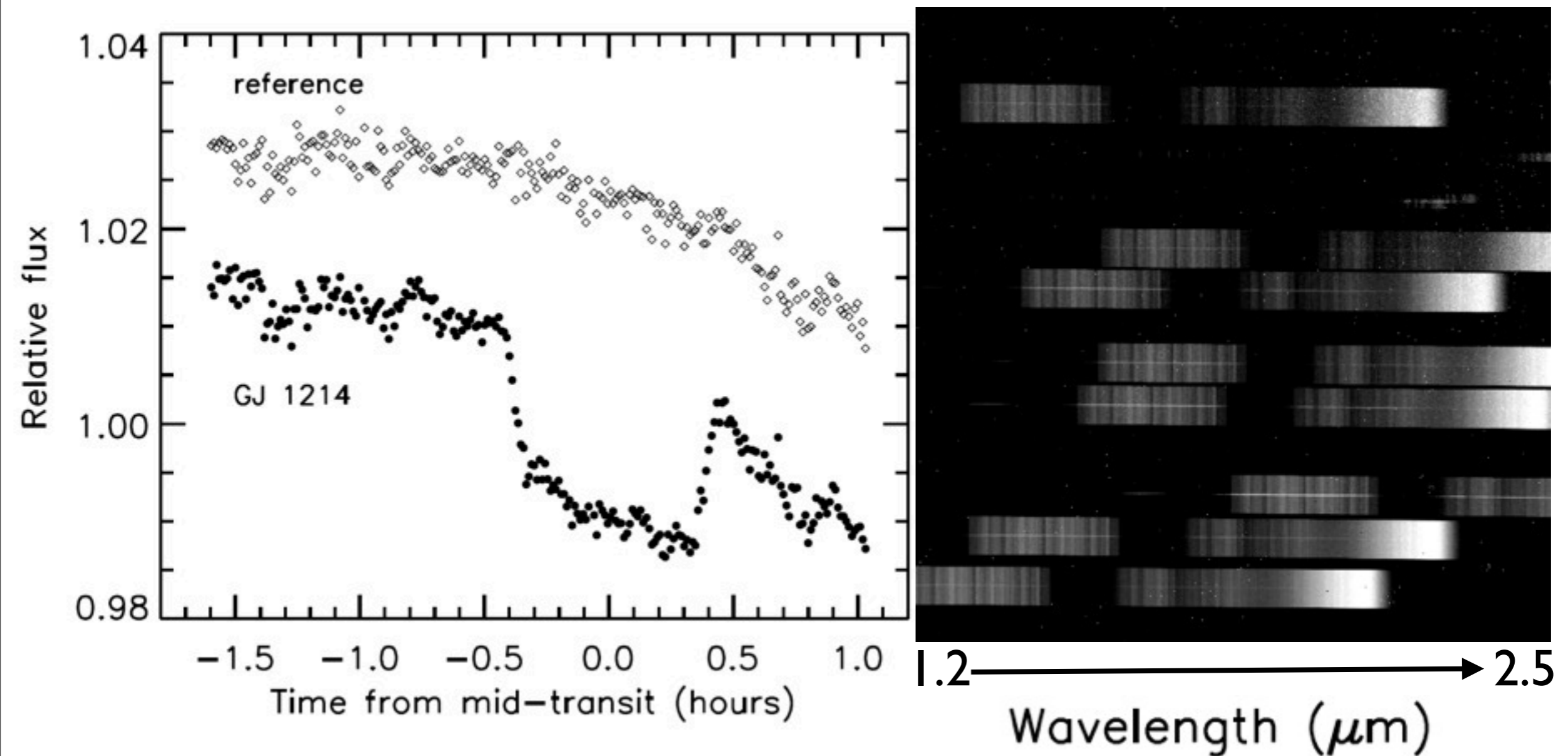
1.2 → 2.5
Wavelength (μm)

Multi-Object Spectroscopy (GJ 1214b, Magellan/MMIRS)

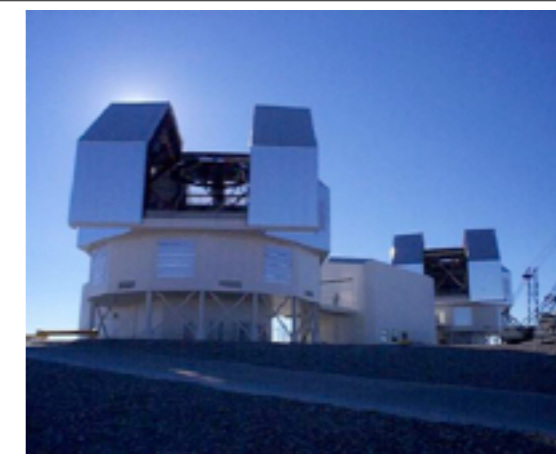


Bean, Désert et al. (2011)

Control systematics

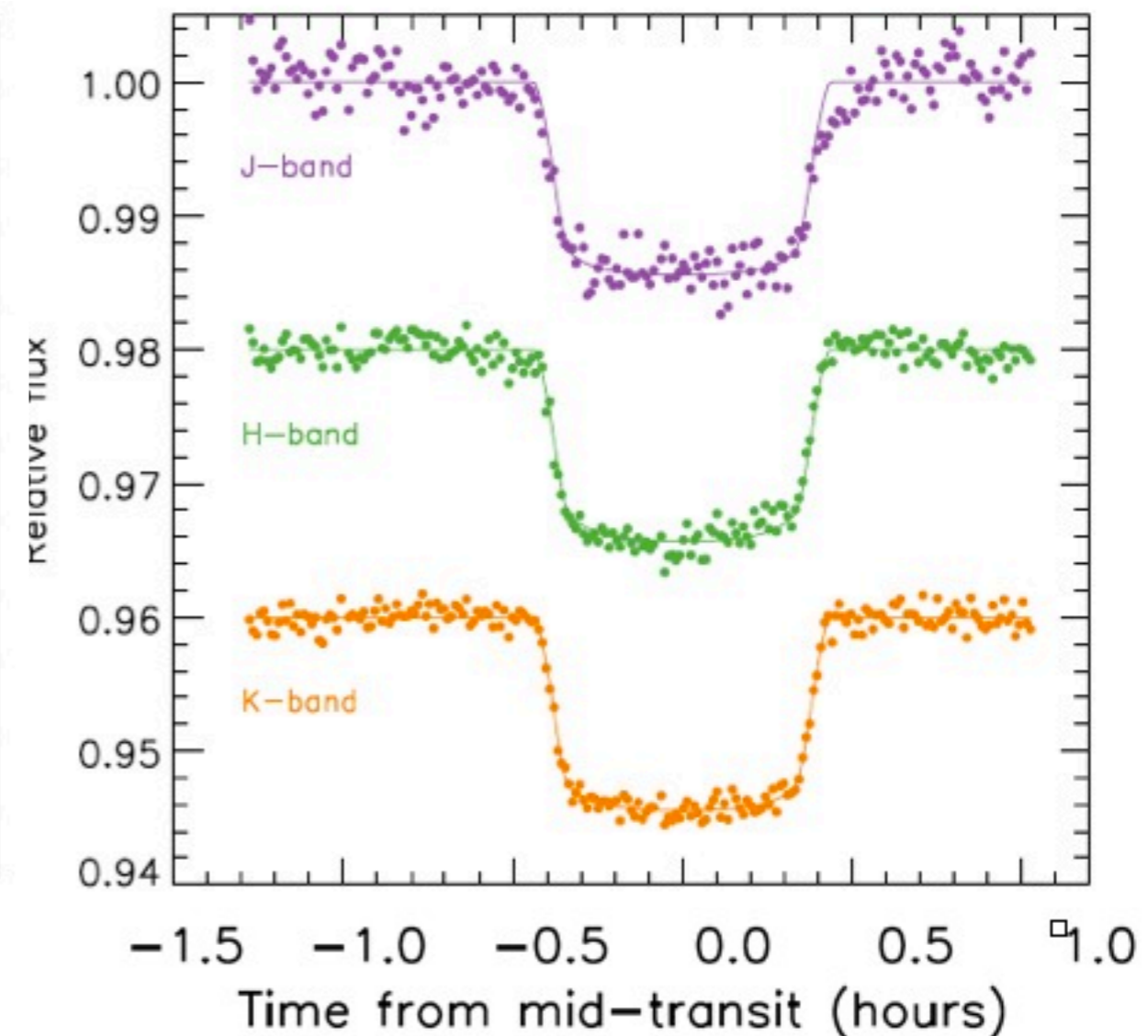
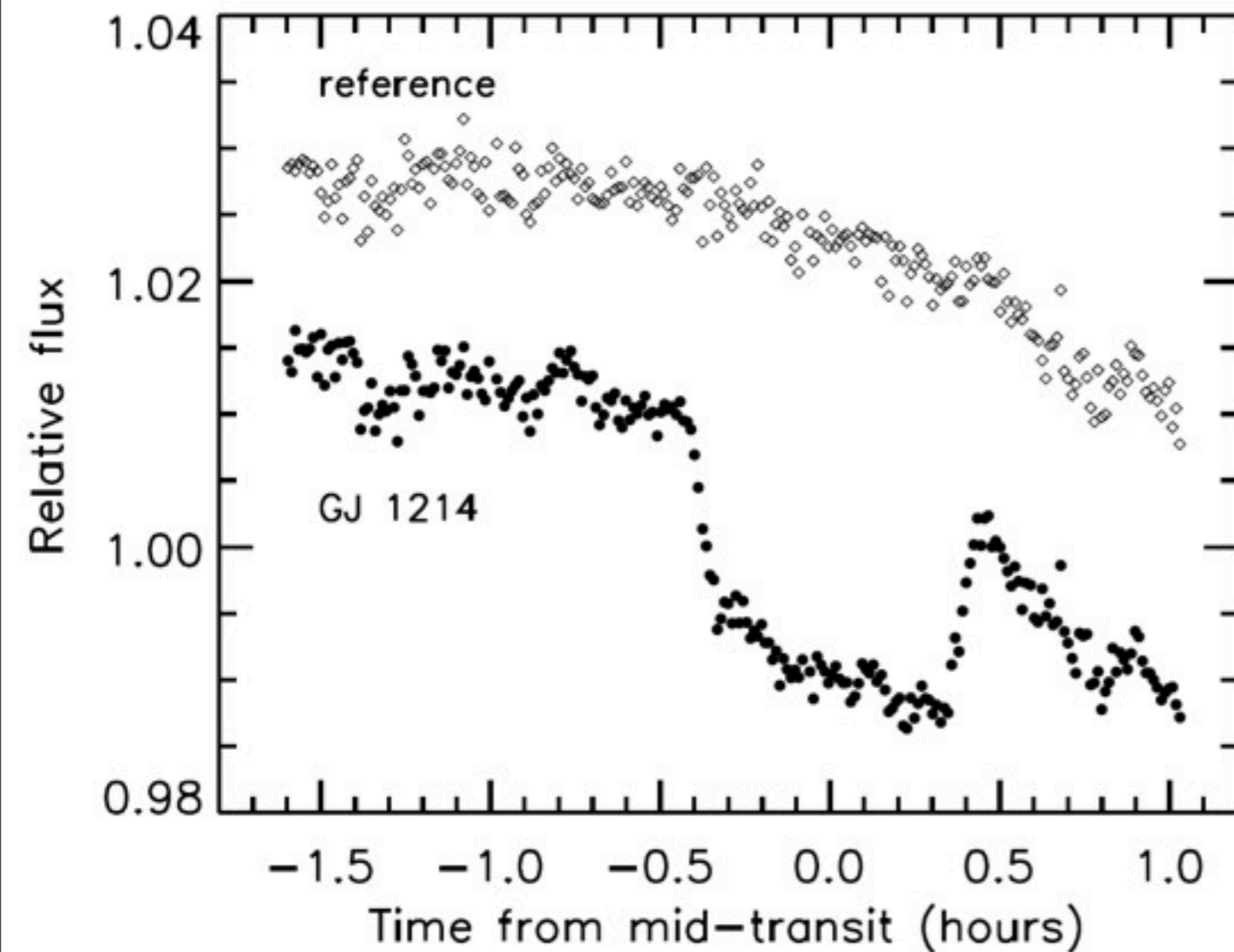


Multi-Object Spectroscopy (GJ 1214b, Magellan/MMIRS)



Bean, Désert et al. (2011)

Control systematics

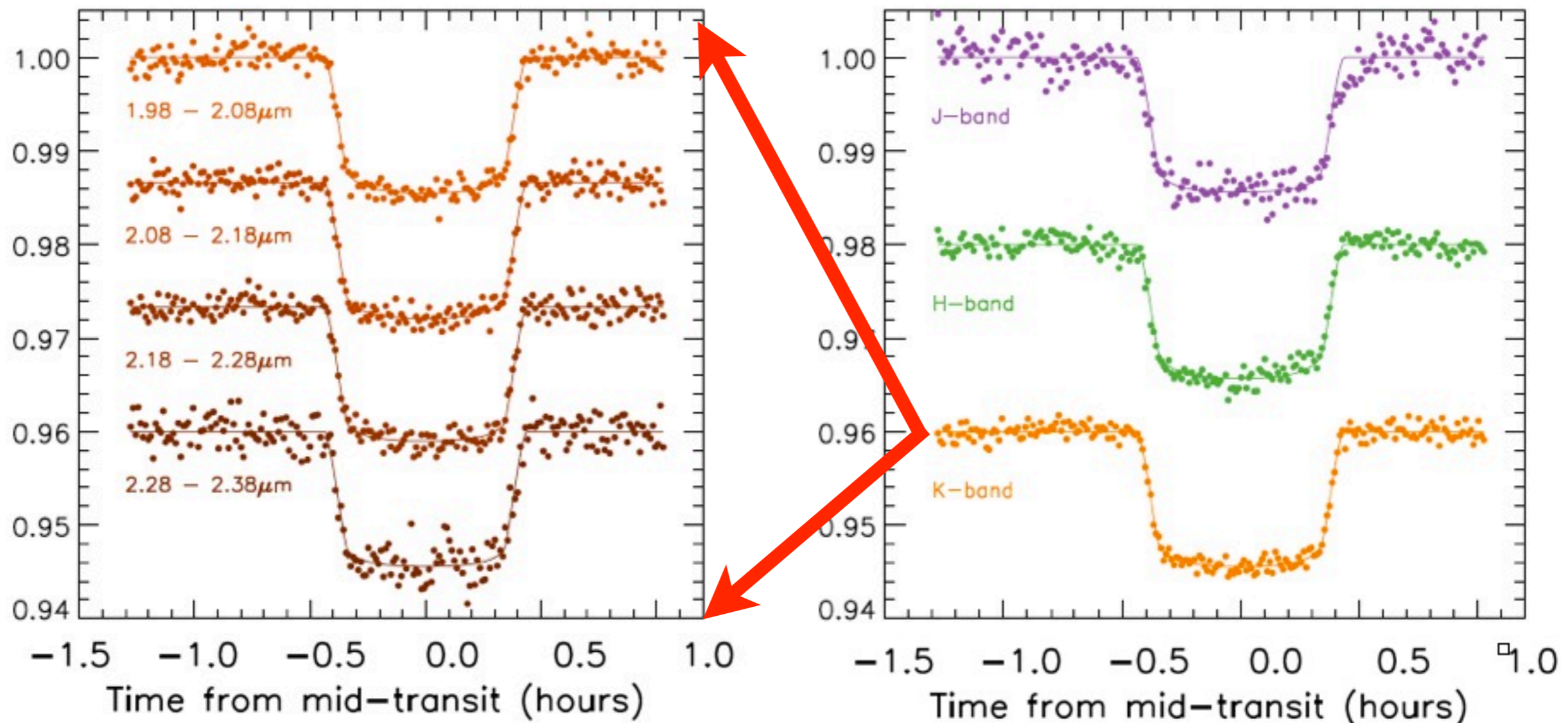


Multi-Object Spectroscopy (GJ 1214b, Magellan/MMIRS)

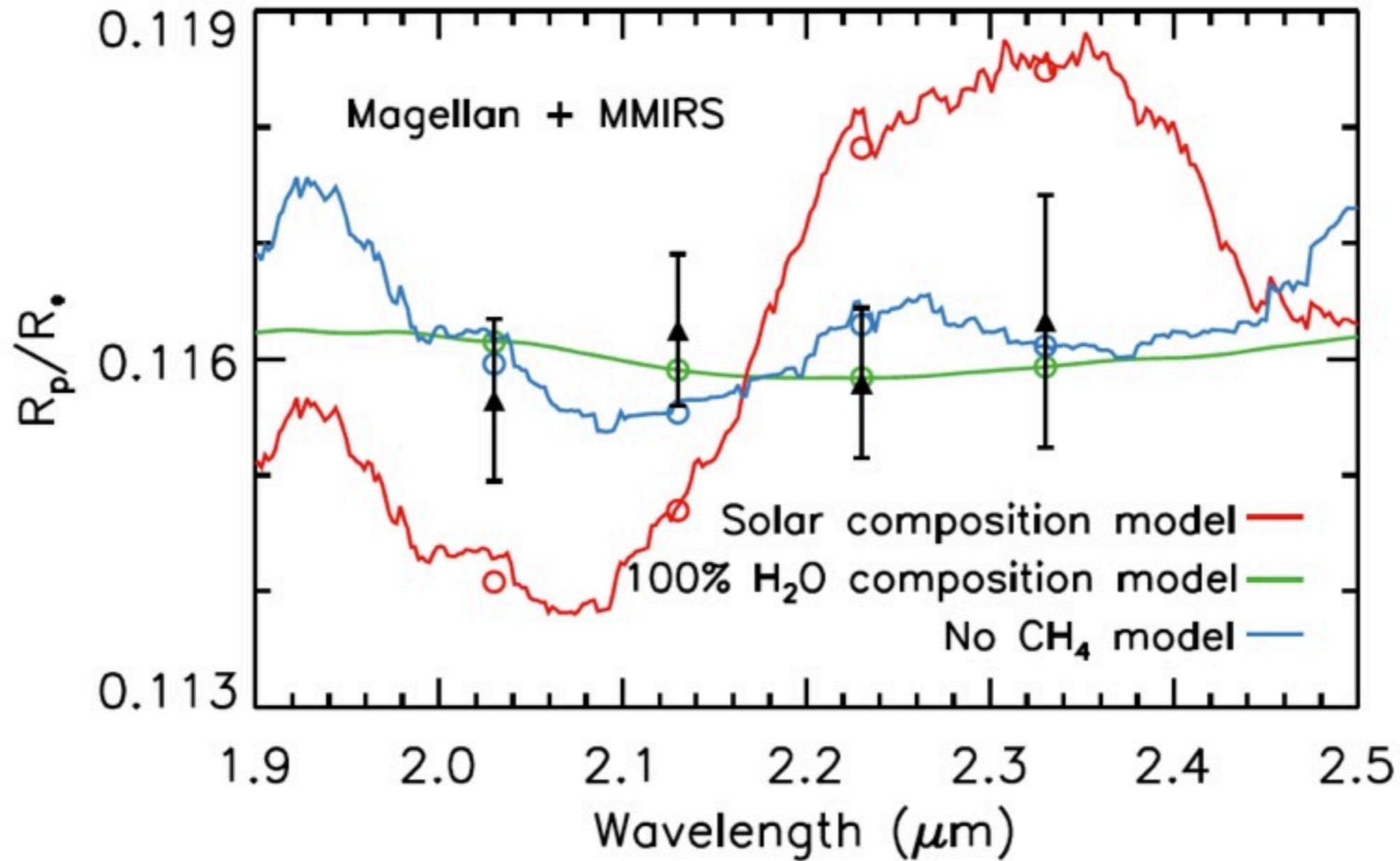
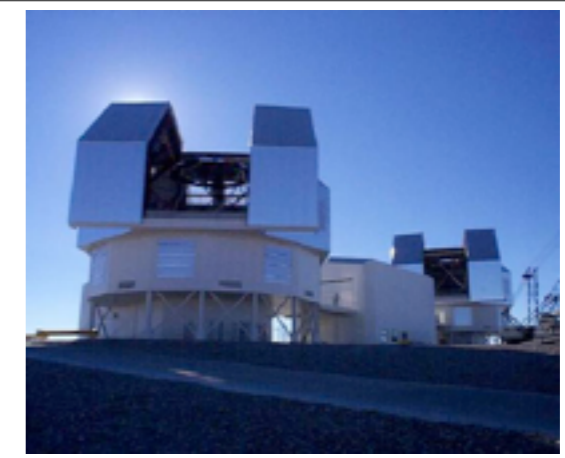


Bean, Désert et al. (2011)

K-band

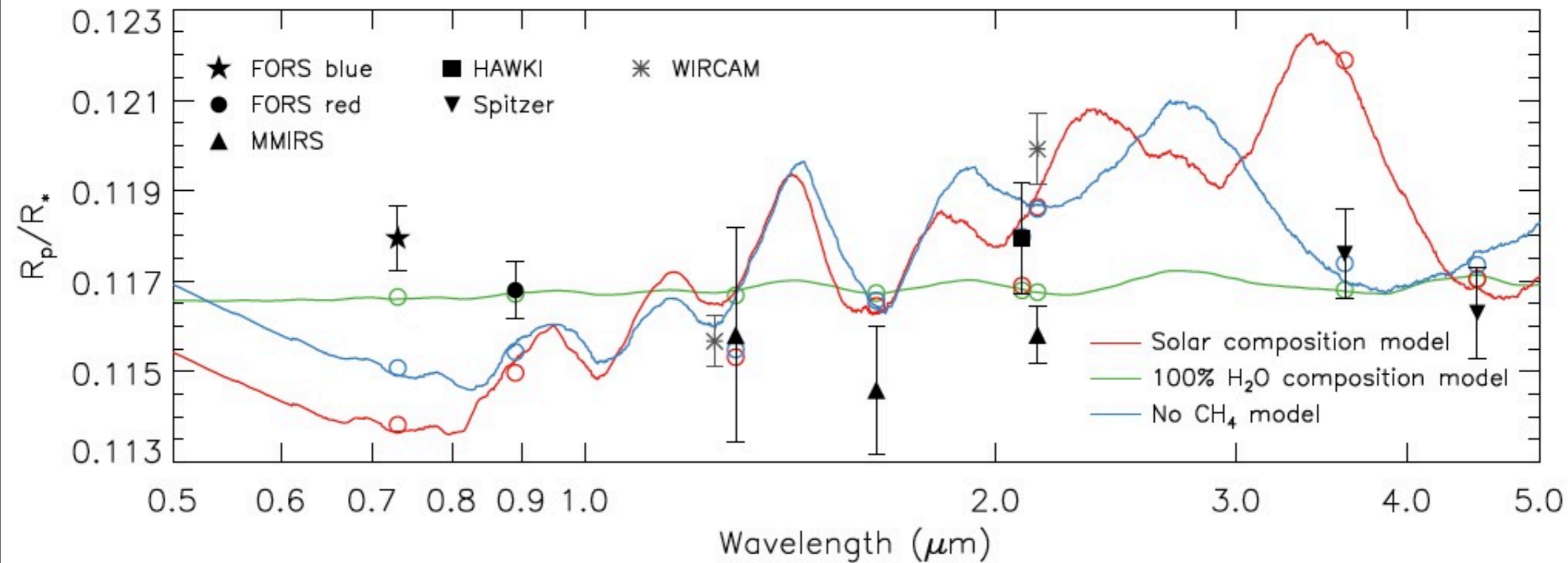
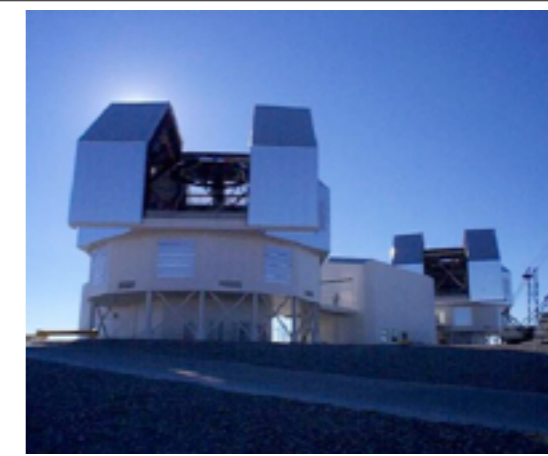


Multi-Object Spectroscopy (GJ 1214b, Magellan/MMIRS)



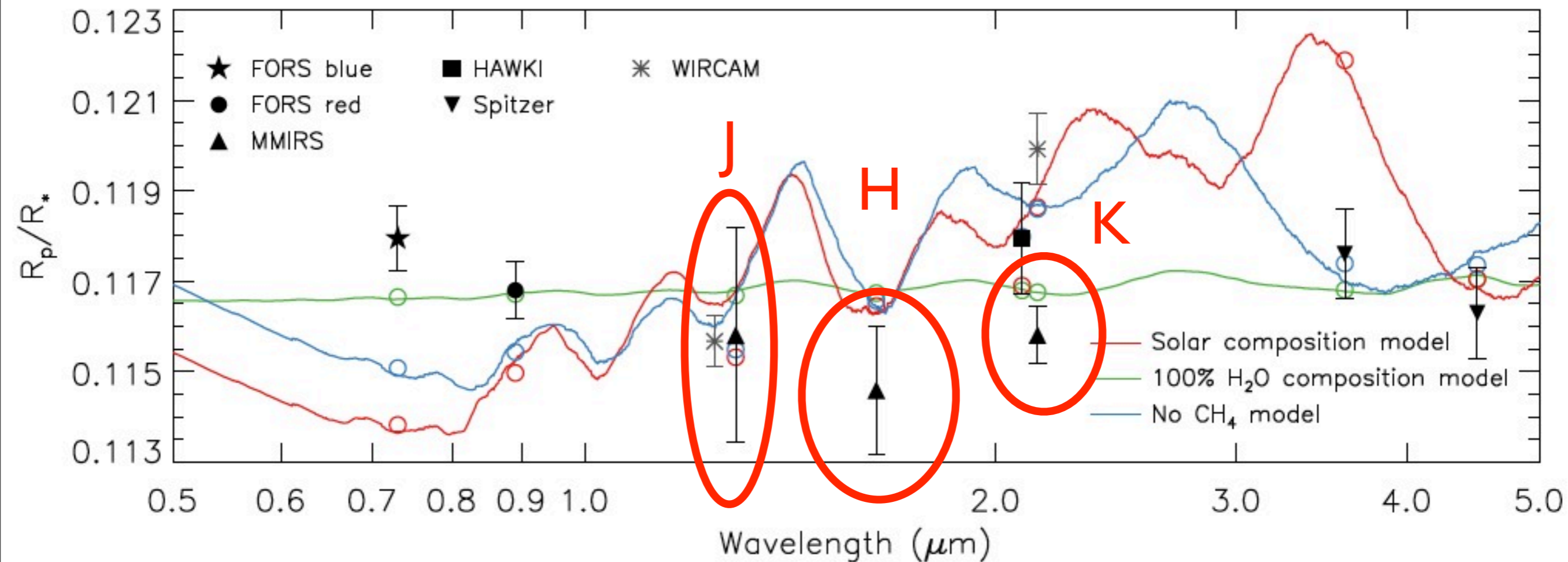
Bean, Désert et al. (2011)

Multi-Object Spectroscopy (GJ 1214b, Magellan/MMIRS)



Bean, Désert et al. (2011)

Multi-Object Spectroscopy (GJ 1214b, Magellan/MMIRS)



- 50% times photon noise , or >
- Uncontrolled systematics

Bean, Désert et al. (2011)

Immediate Goals:

Comparative exoplanetology of Hot-Giants:

Surveys of HJs on Magellan (NIR) and Gemini (Visible)
with MOS technique

Ultimate Goals:

Low-Mass Planets Around Low-Mass-Stars

Main Challenges:

**Understanding and Controlling Instrumental and
Astrophysical Systematics.**

III) New Frontiers in Observations of Exoplanet Atmospheres



New Frontiers



New Frontiers

Comparative exoplanetology of hot-Jupiters



New Frontiers

**Comparative
exoplanetology
of hot-Jupiters**

**Super-Earths
around low
mass stars**



New Frontiers

**Comparative
exoplanetology
of hot-Jupiters**

**Super-Earths
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mass stars**



**Kepler
Transiting
planets**

New Frontiers

**Comparative
exoplanetology
of hot-Jupiters**

**Super-Earths
around low
mass stars**



**Kepler
Transiting
planets**

**Transiting
planets in front
of bright stars**

Atmospheric Studies in the Era of Kepler

Atmospheric Studies in the Era of Kepler

- **Hot Jupiters** (Reflected light, Phase-curves, etc...)
- **Combining IR+Vis.** (Désert et al. 2011c,d, Fortney et al. 2011)
- **Hot Super-Earth** (e.g. Batalha et al. 2010: Kepler-10b)
- **Gas giants at larger orbital distances than HJs**

Finding transiting planets around bright stars

- MEarth
- KELT (KELT 2Ab :Beatty et al. 2012)
- e.g. TERMS, MASCARA
- MOST
- ExoplanetSat (S. Seager)
- TESS / PLATO

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- e.g. TERMS, MASCARA
- MOST
- ExoplanetSat (S. Seager)
- TESS / PLATO

Difficult to apply the MOS technique!

The End