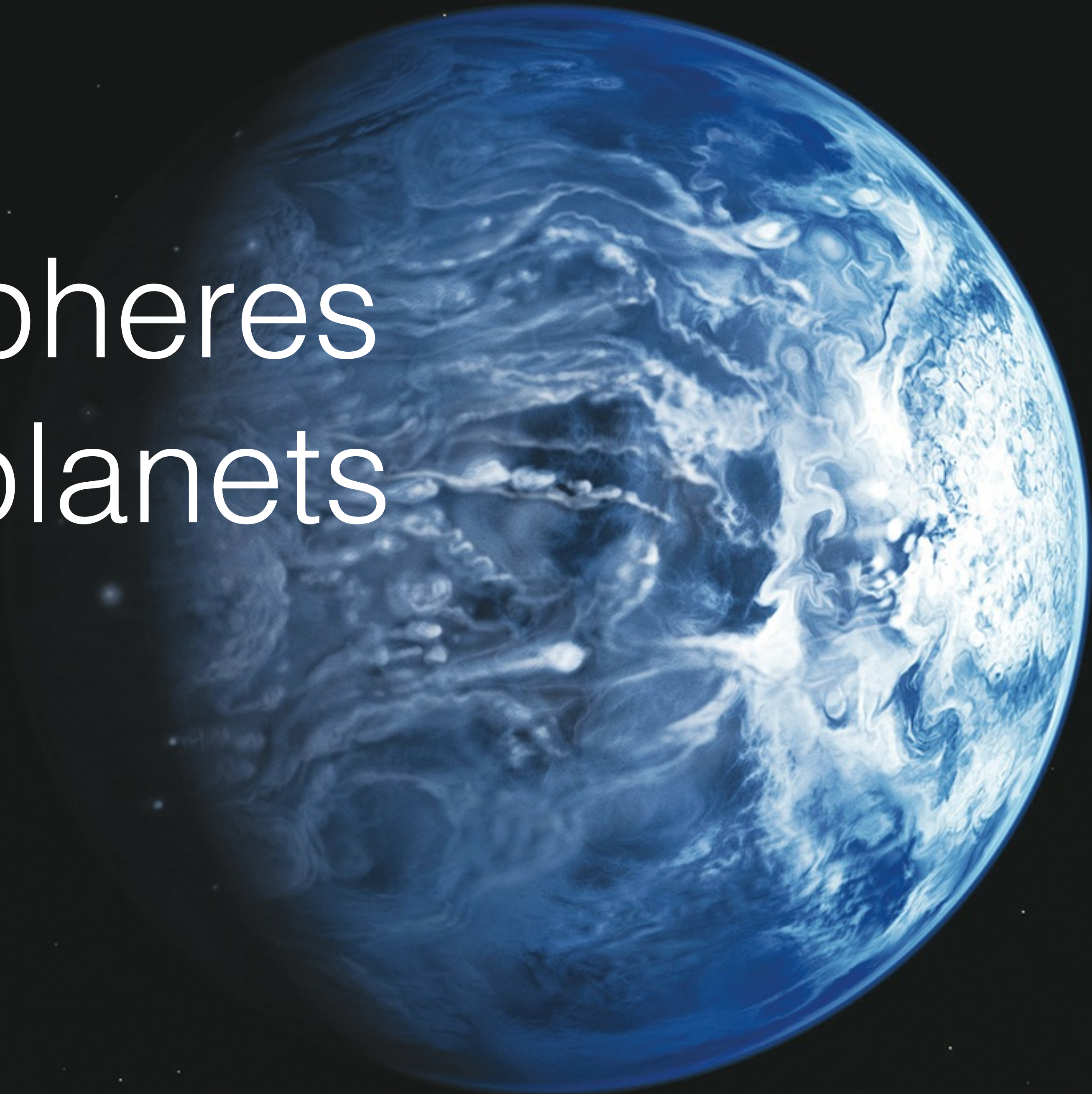
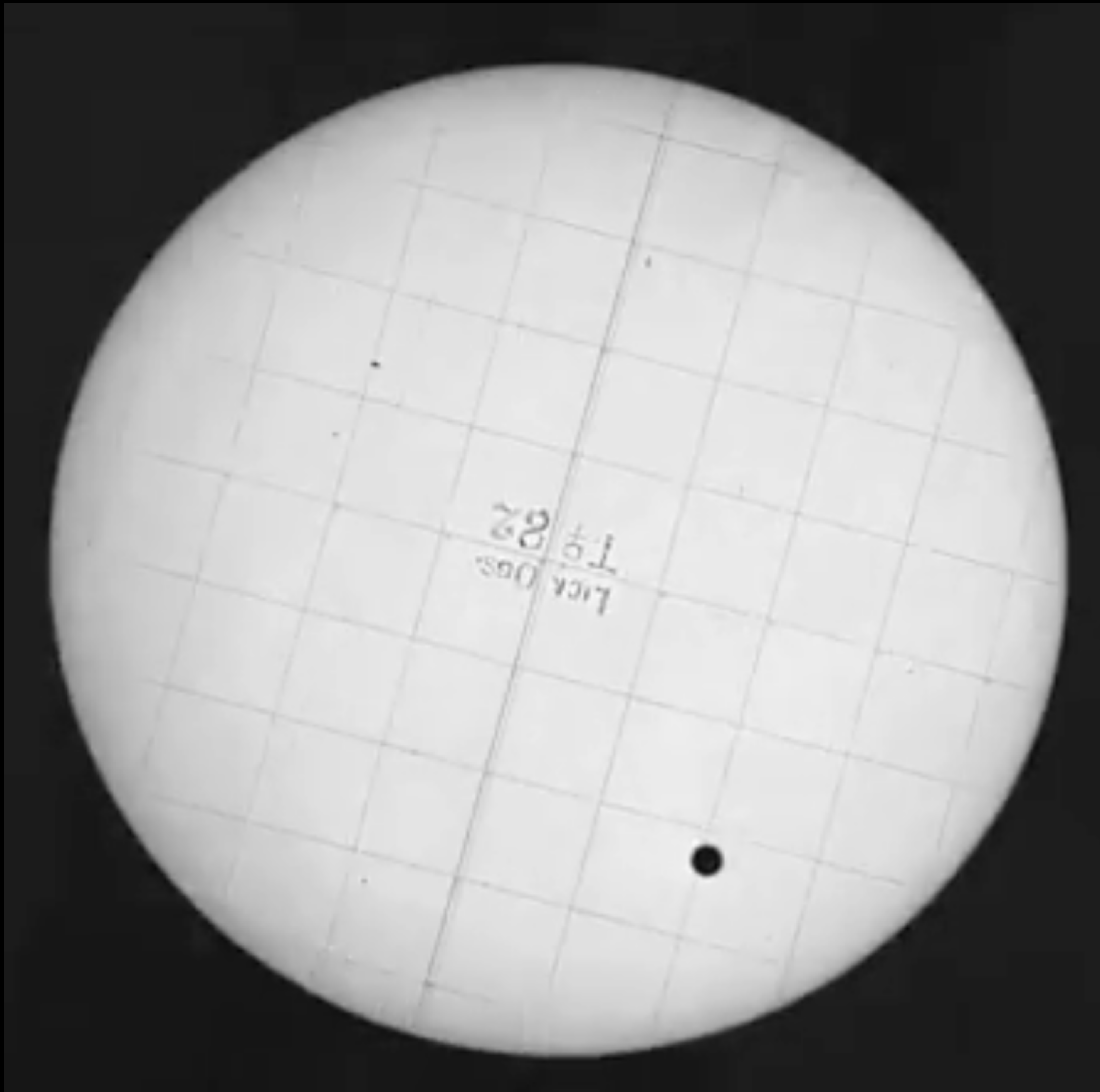
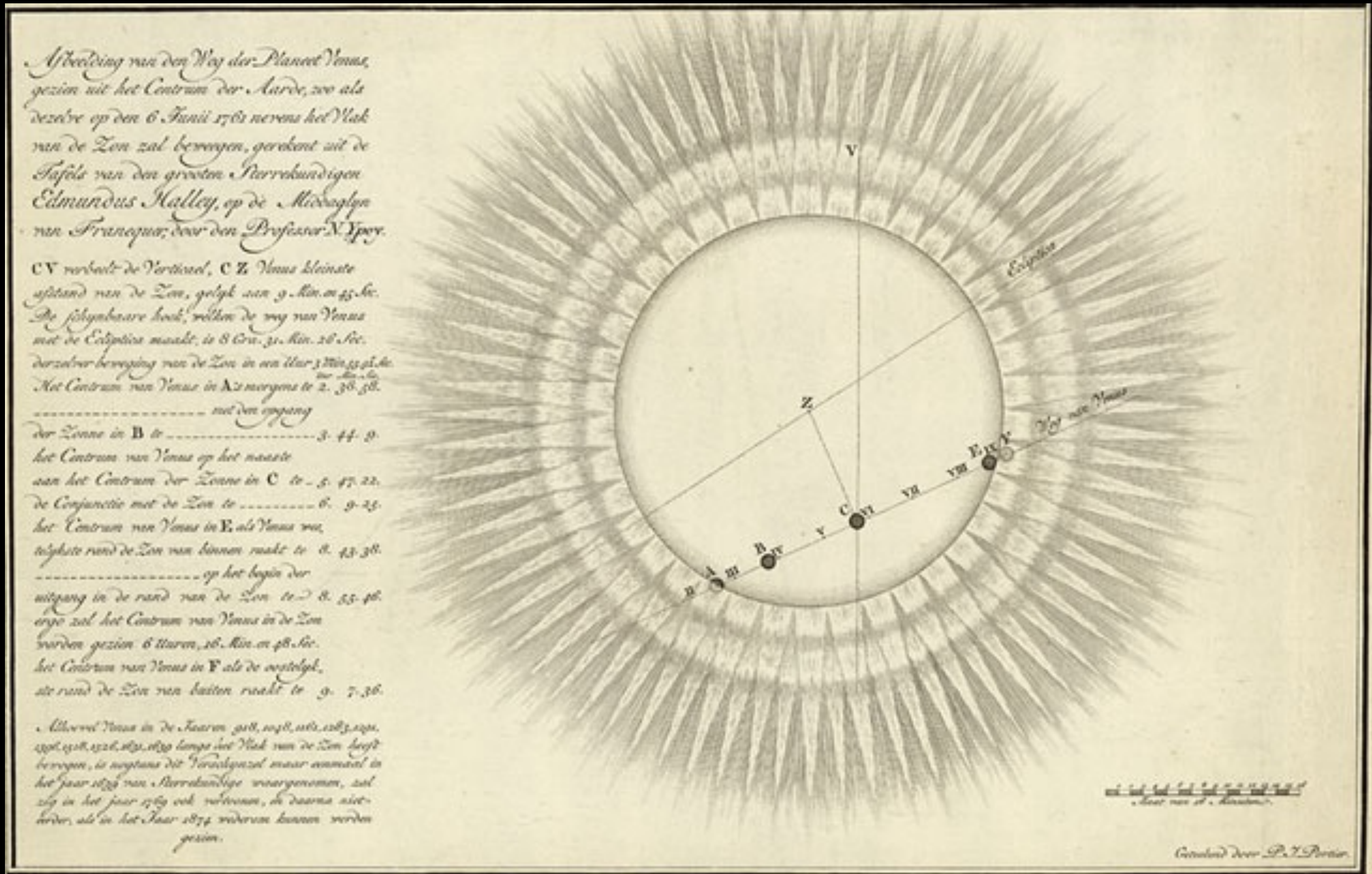


Atmospheres of exoplanets

David Ehrenreich

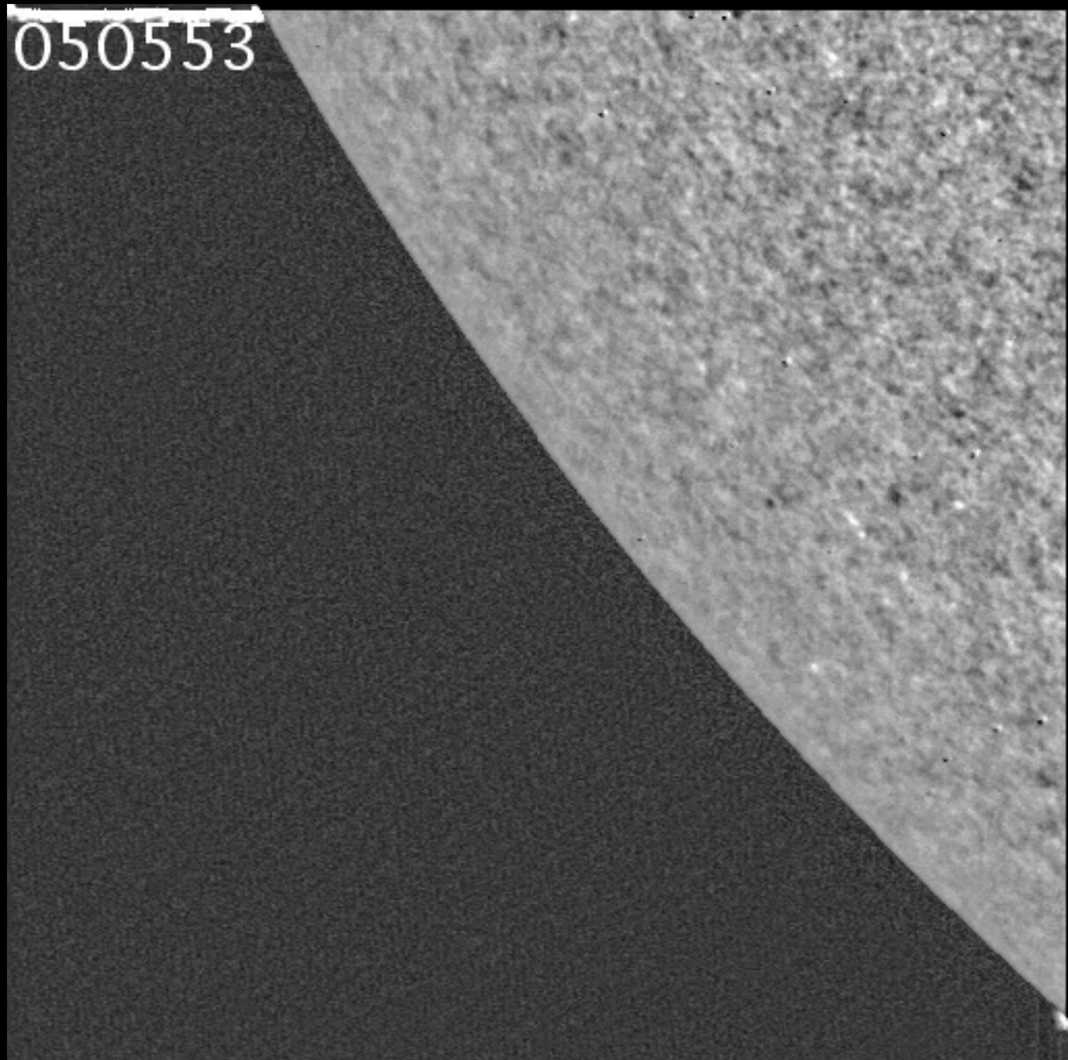




1761 transit of Venus (N. Ypey)

Mikhaïl Lomonosov
(1711–1765)

observed the 1761 transit of Venus
& proved that Venus has an atmosphere



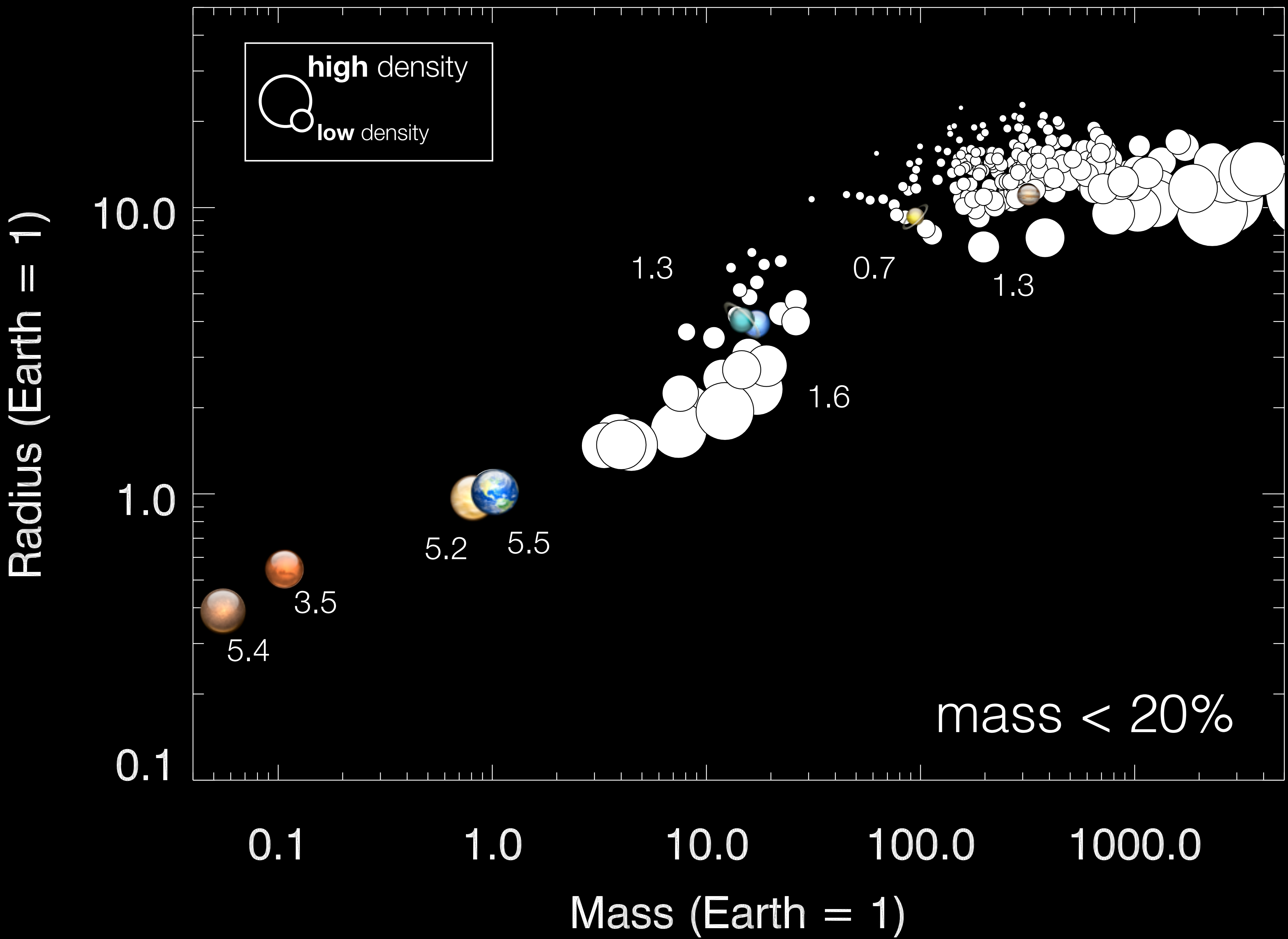
8 June 2004 transit of Venus
w/ *TRACE* satellite
Courtesy: G. Schneider
http://nicmosis.as.arizona.edu:8000/ECLIPSE_WEB/TRANSIT_04/TRACE/TOV_TRACE.html

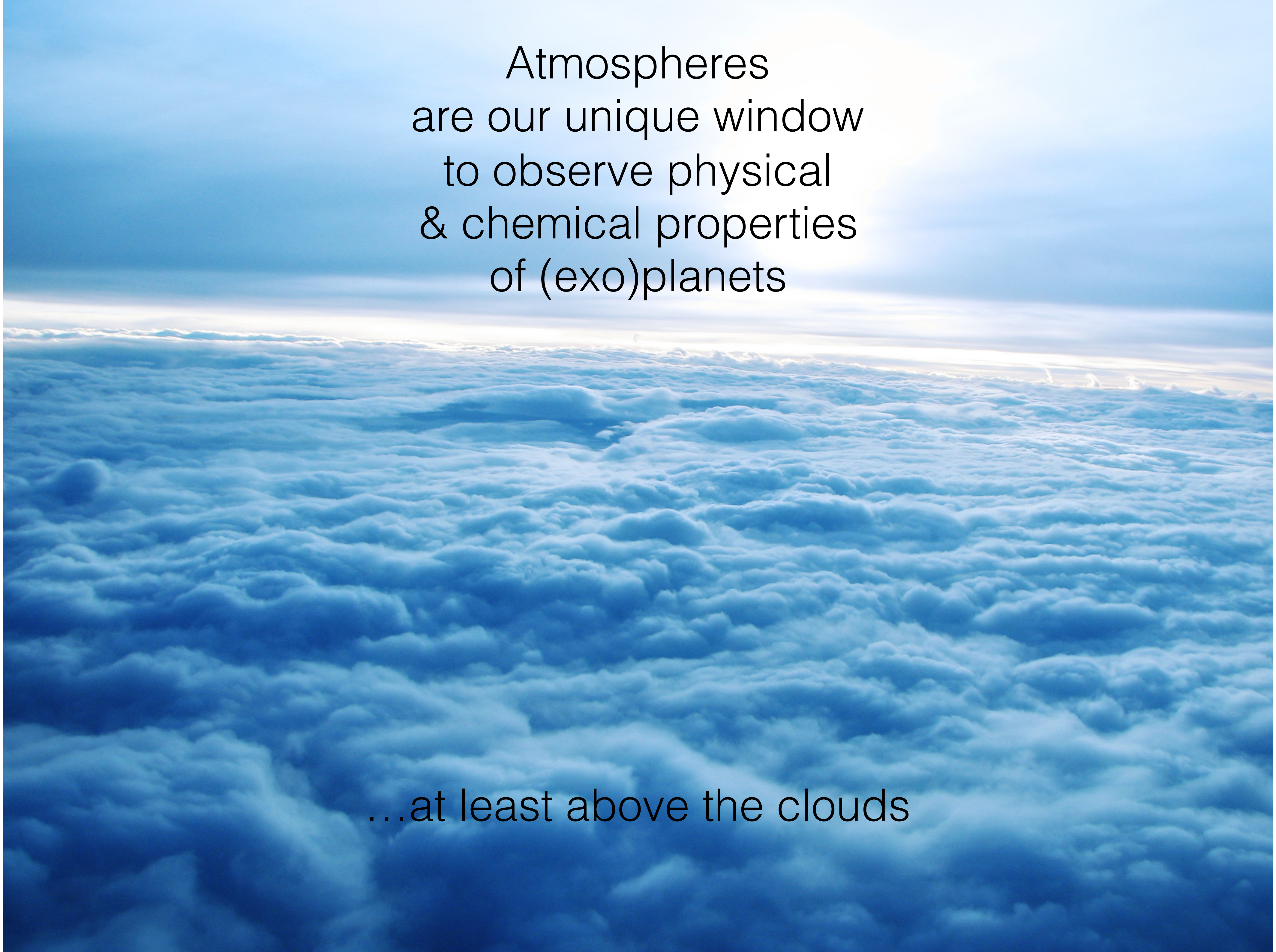
Earth & Venus have
similar **masses** & **sizes**,
hence **densities**

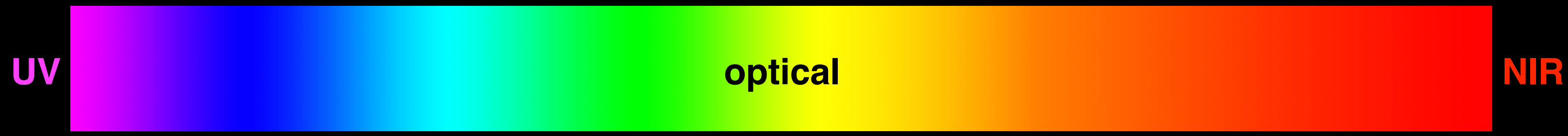
If Venus has an **atmosphere**,
surely it must be even more Earth-like?
(albeit a tad warmer)

Planet Comics #51 (1947)

Planets with measured density

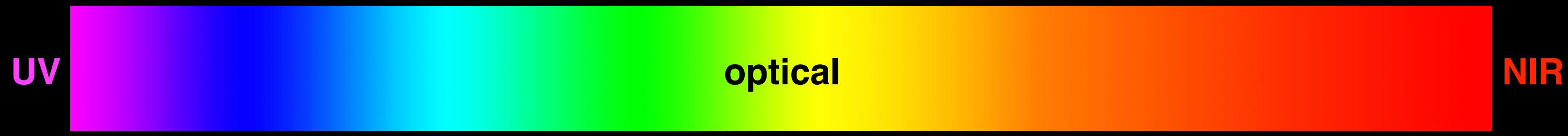



Atmospheres
are our unique window
to observe physical
& chemical properties
of (exo)planets
…at least above the clouds

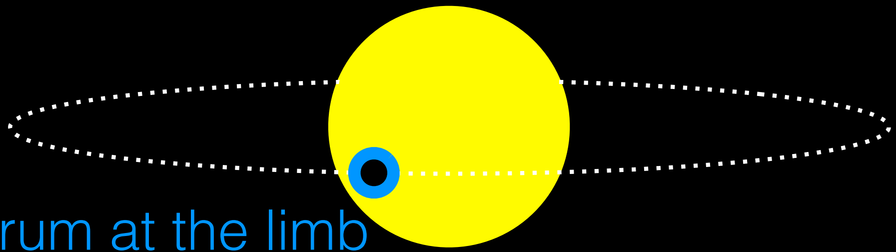


Spatially unresolved techniques

Spatially resolved techniques



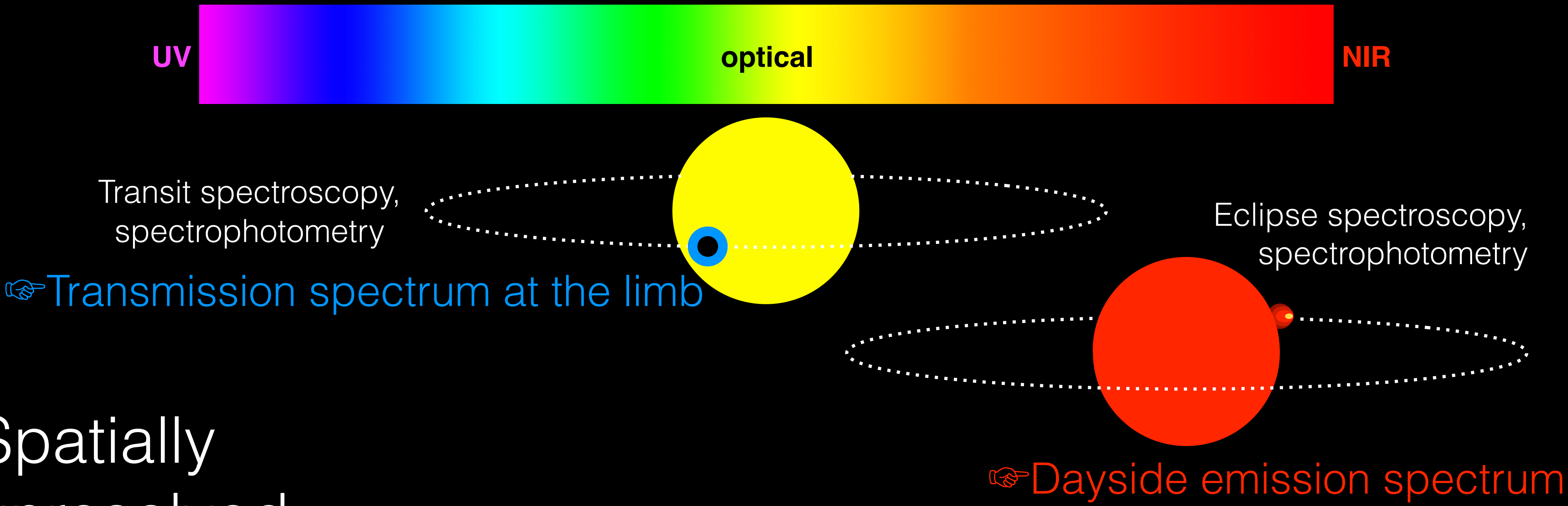
Transit spectroscopy,
spectrophotometry



☞Transmission spectrum at the limb

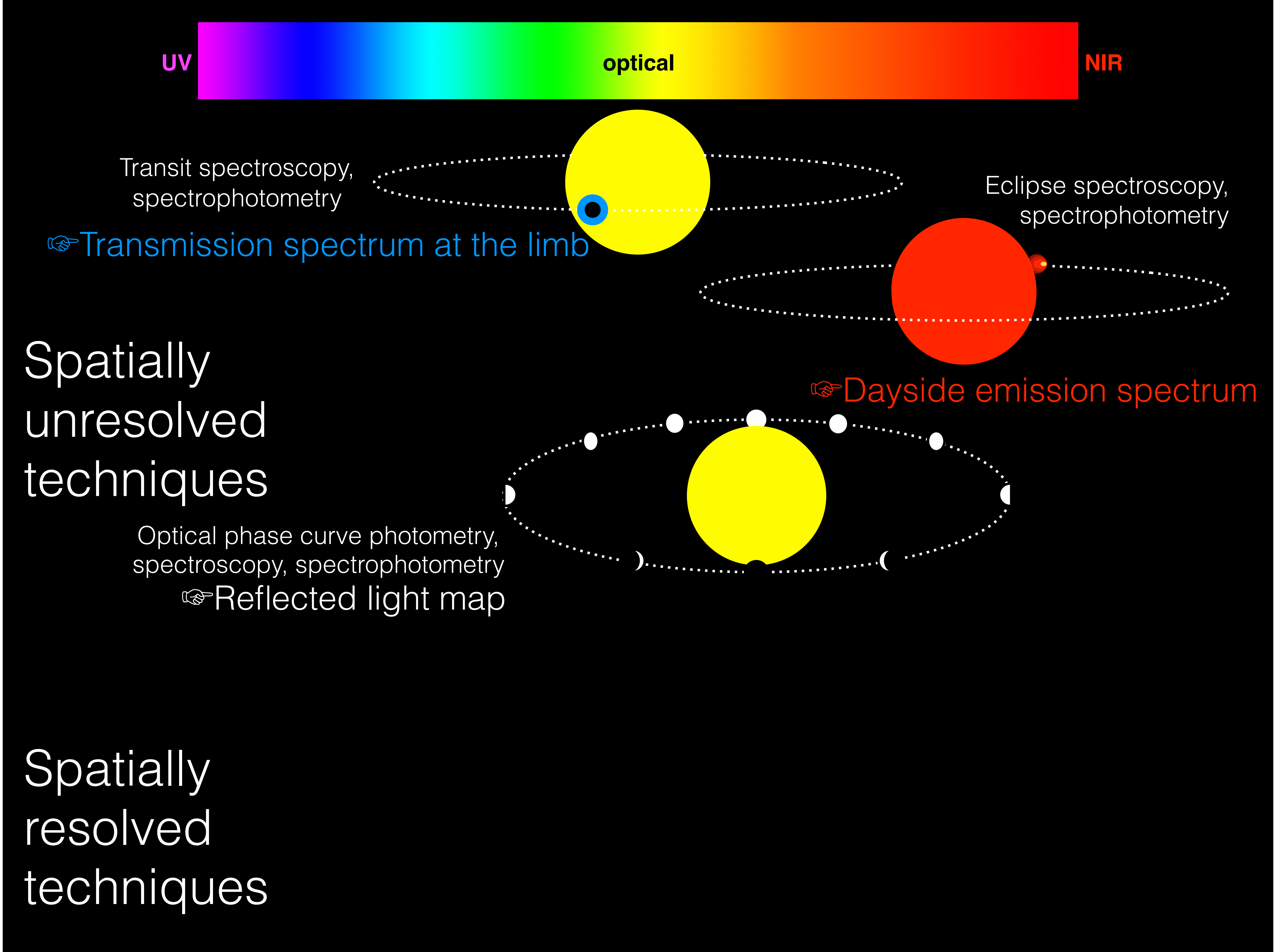
Spatially unresolved techniques

Spatially resolved techniques

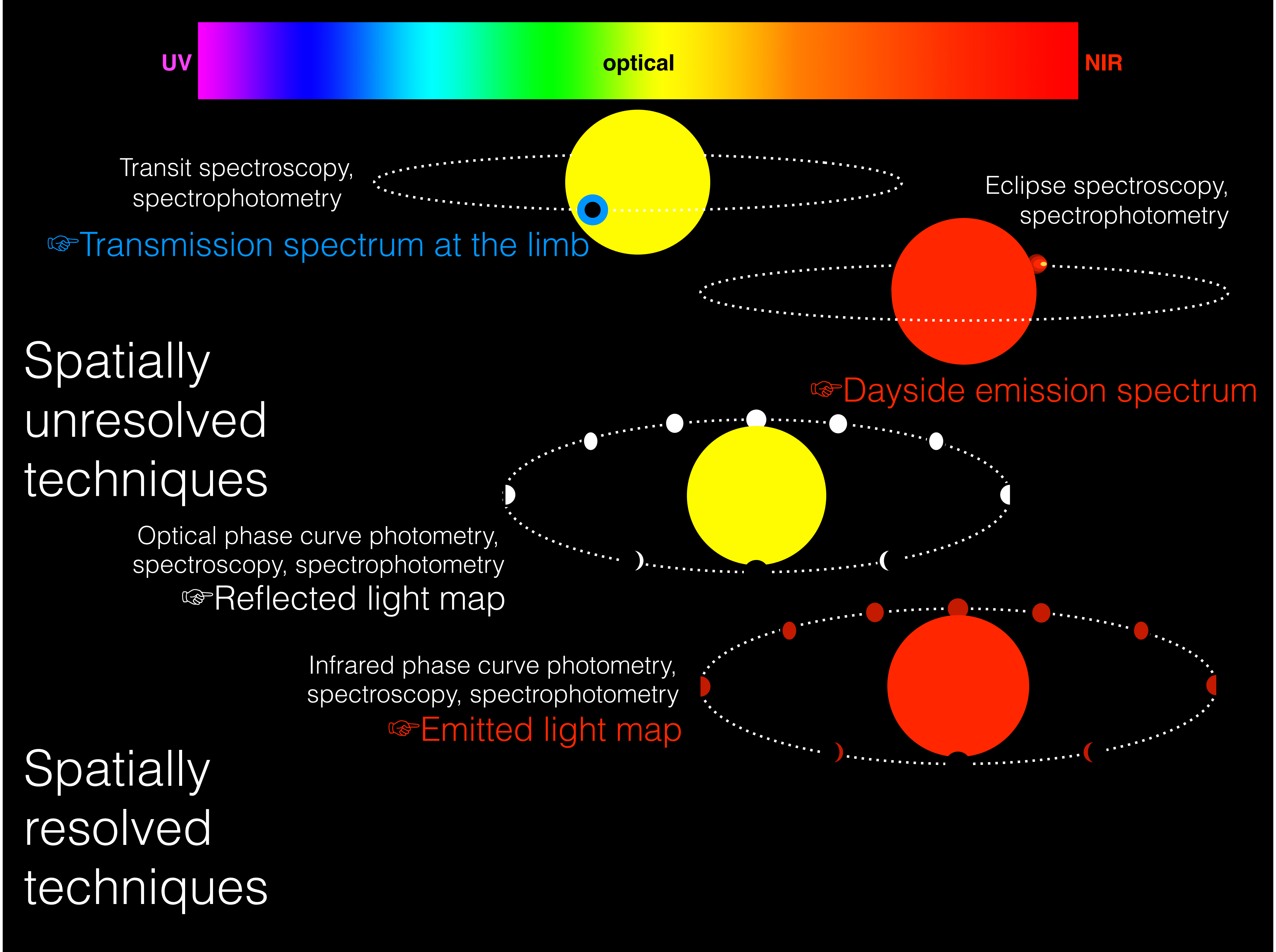


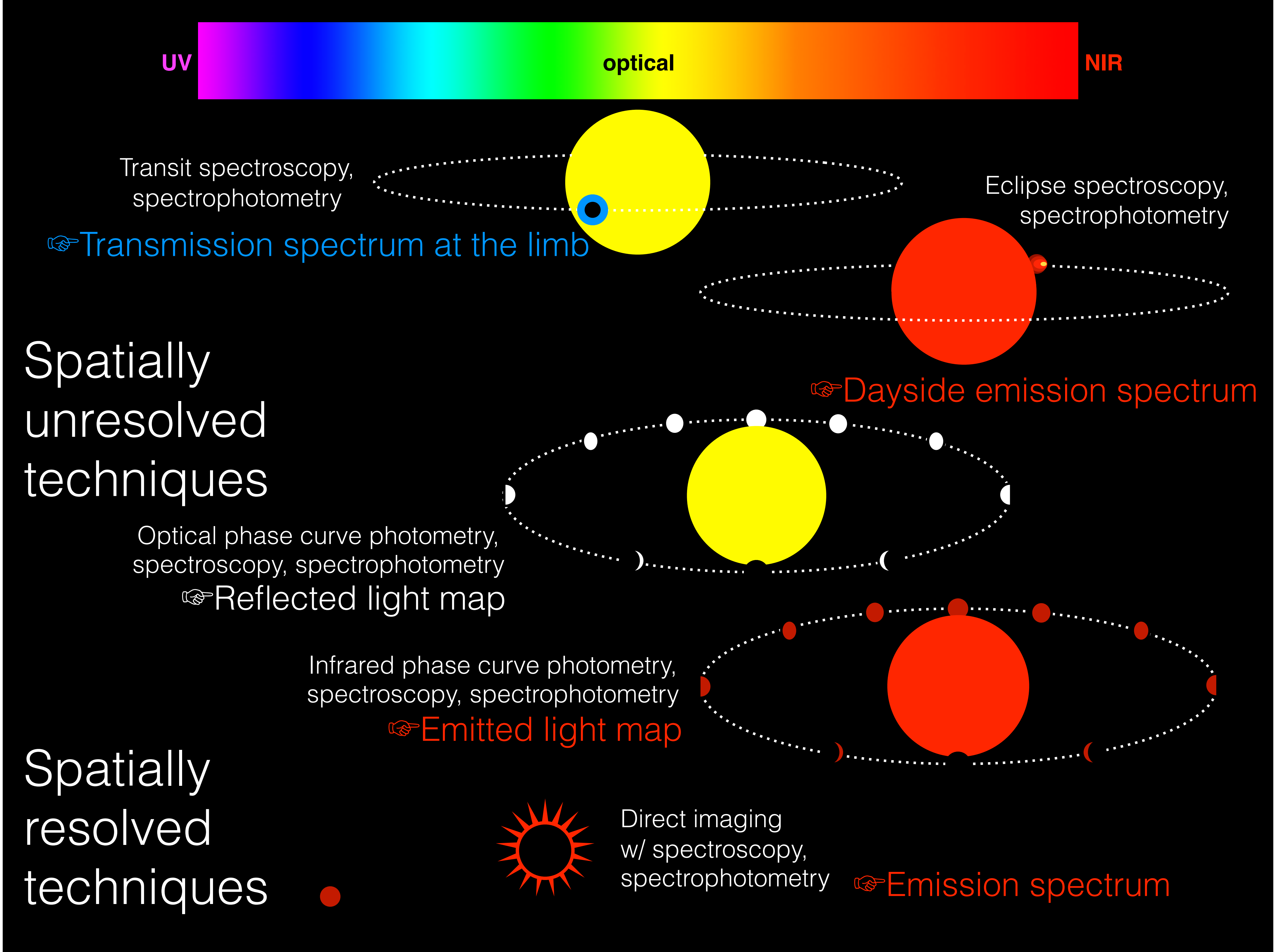
Spatially unresolved techniques

Spatially resolved techniques



UV
optical
NIR
Transit spectroscopy,
spectrophotometry
☞Transmission spectrum at the limb
Eclipse spectroscopy,
spectrophotometry
☞Dayside emission spectrum
Spatially unresolved techniques
Optical phase curve photometry,
spectroscopy, spectrophotometry
☞Reflected light map
Spatially resolved techniques


UV
optical
NIR
Transit spectroscopy,
spectrophotometry
☞Transmission spectrum at the limb
Eclipse spectroscopy,
spectrophotometry
☞Dayside emission spectrum
Spatially
unresolved
techniques
Optical phase curve photometry,
spectroscopy, spectrophotometry
☞Reflected light map
Infrared phase curve photometry,
spectroscopy, spectrophotometry
☞Emitted light map
Spatially
resolved
techniques



UV
optical
NIR
Transit spectroscopy,
spectrophotometry
☞Transmission spectrum at the limb
Eclipse spectroscopy,
spectrophotometry
☞Dayside emission spectrum
Spatially
unresolved
techniques
Optical phase curve photometry,
spectroscopy, spectrophotometry
☞Reflected light map
Infrared phase curve photometry,
spectroscopy, spectrophotometry
☞Emitted light map
Spatially
resolved
techniques
Direct imaging
w/ spectroscopy,
spectrophotometry
☞Emission spectrum

Course outline

1. Transit spectroscopy

    1.1 Basics: method, radiative transfer, atmospheric structure

    1.2 Amplitude of the expected signal

    1.3 Best targets

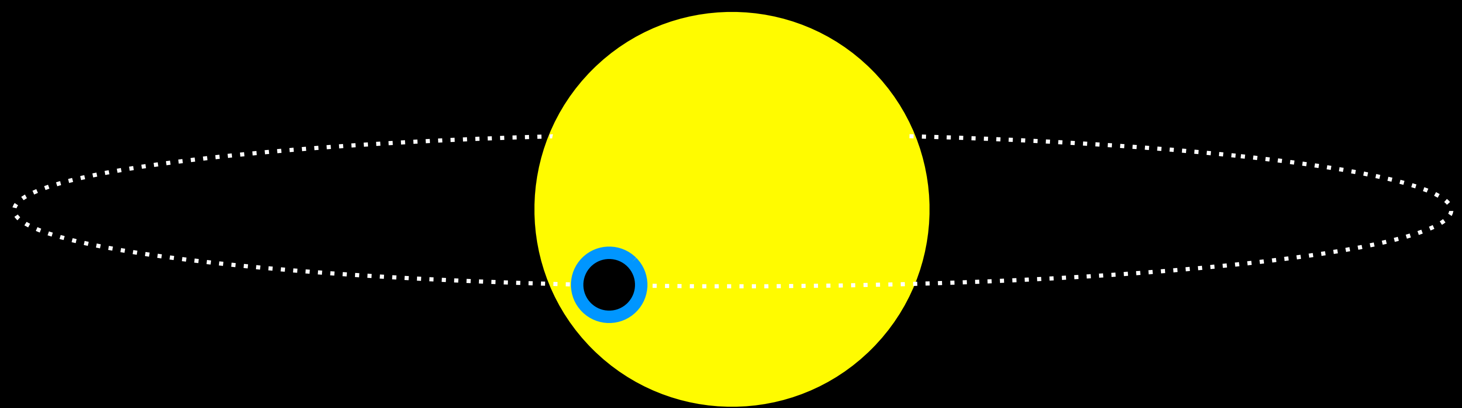
2. Cases of study

    2.1 Sodium sky of a hot Jupiter

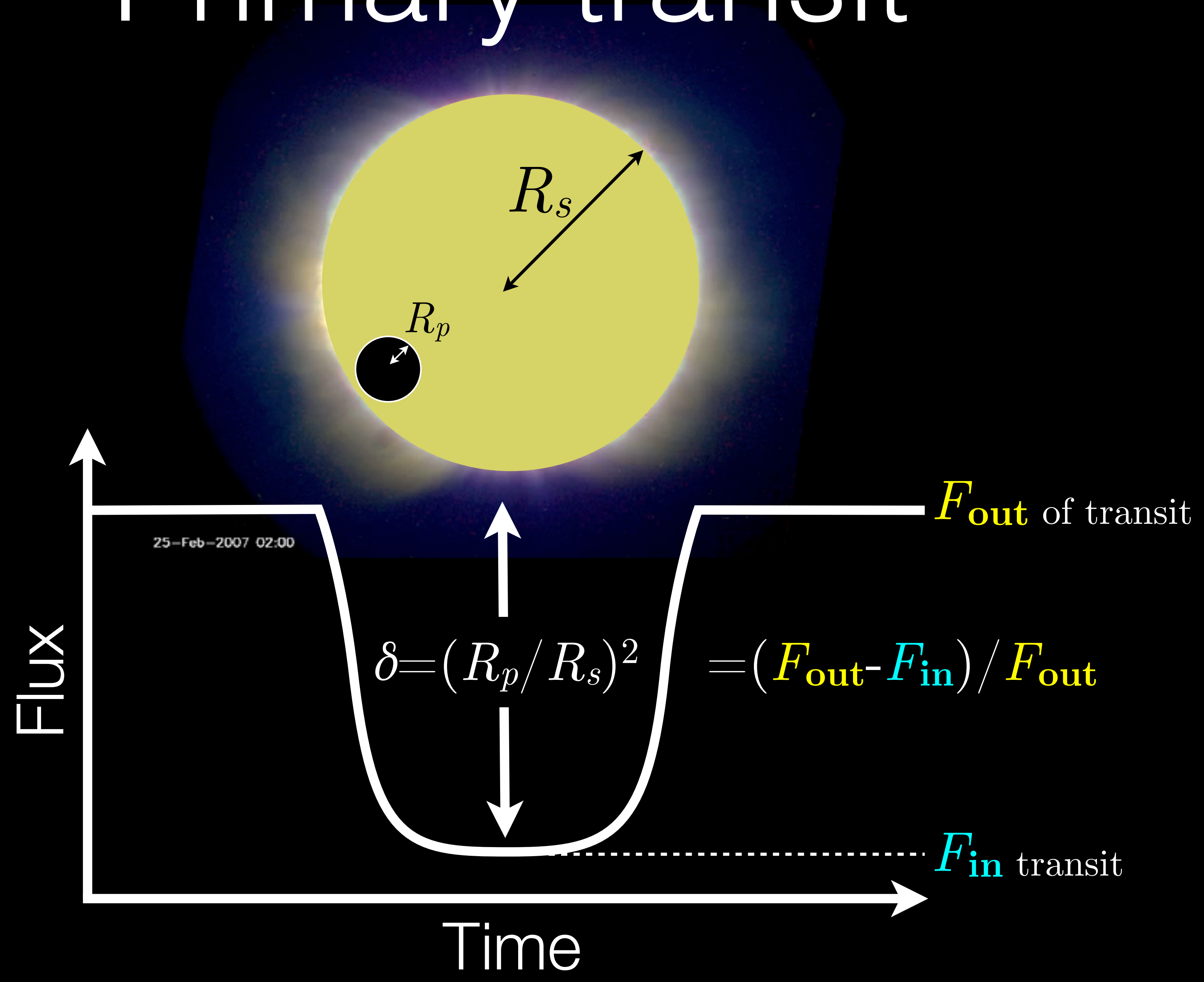
    2.2 Hydrogen evaporating from a warm Neptune

    2.3 Water vapour in some cloudy planets

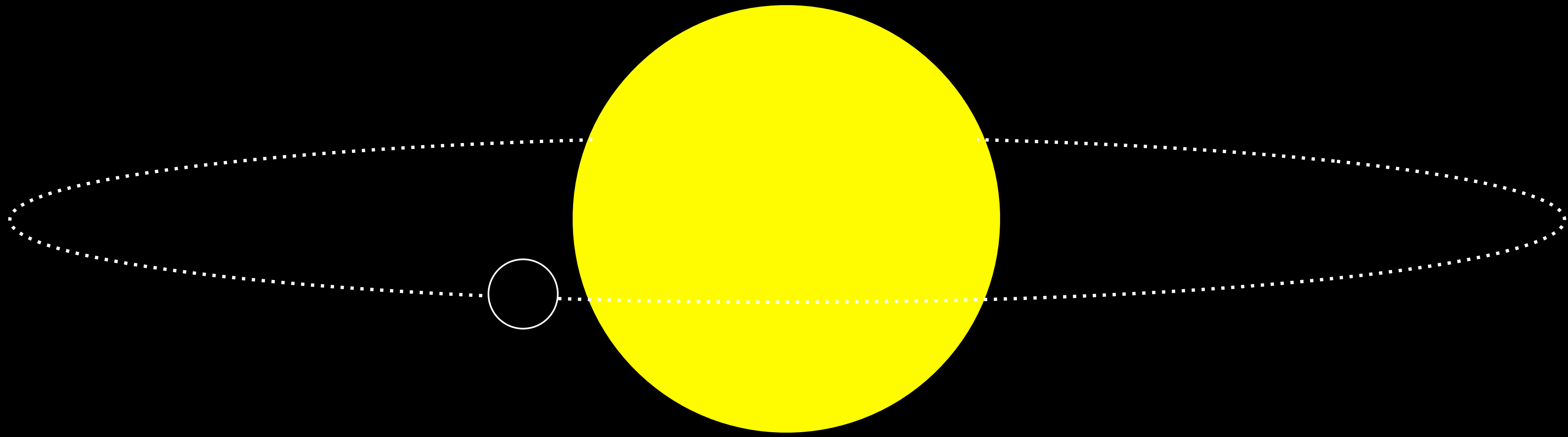
1. Transit spectroscopy



Primary transit

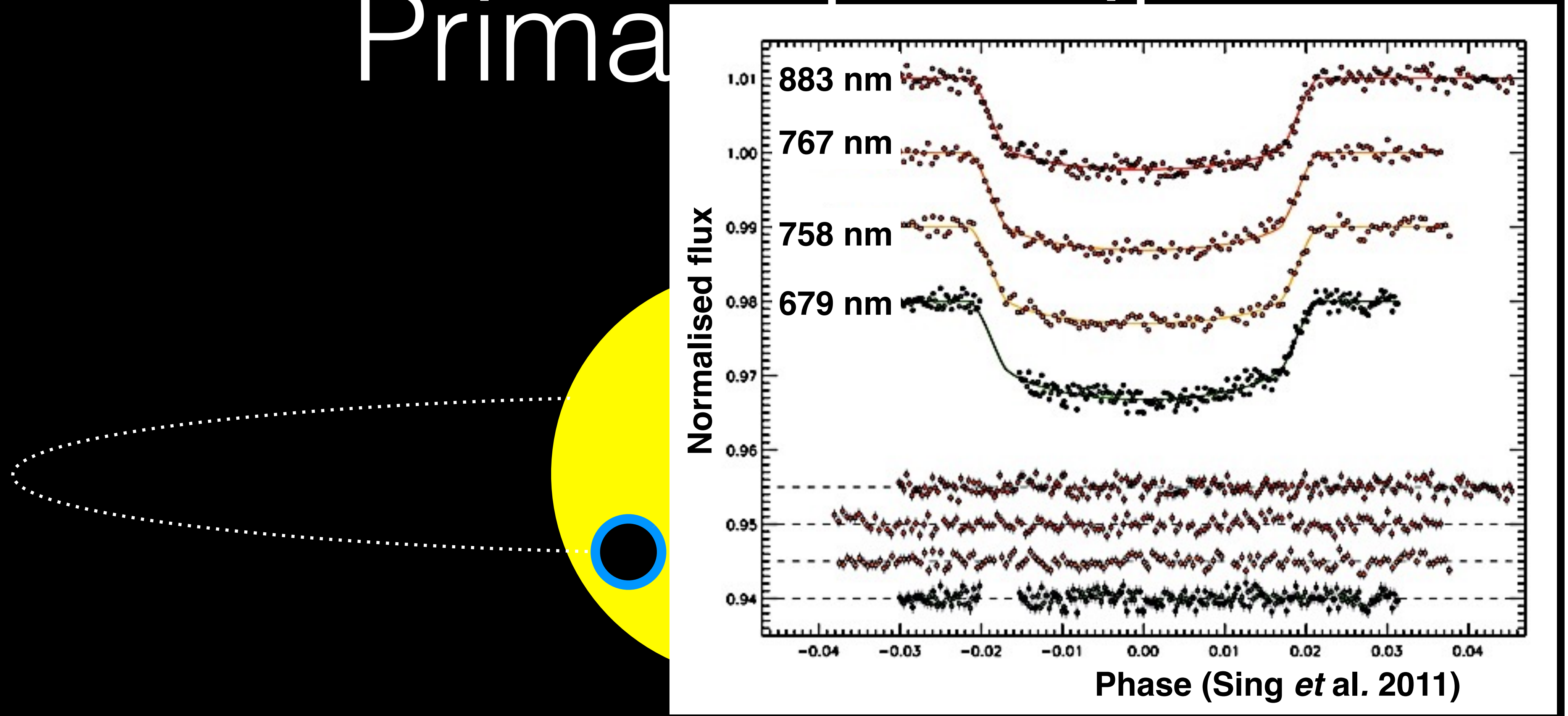


Primary transit



$$\delta = (R_p/R_s)^2$$

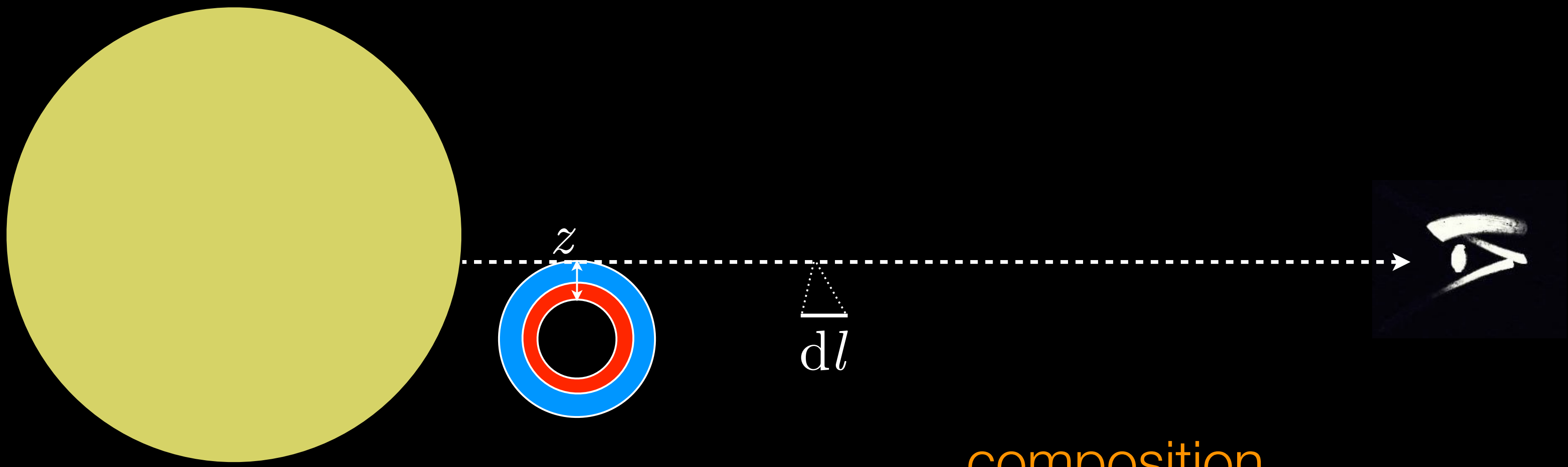
Prima



$$\delta(\lambda) = [R(\lambda)/R_s]^2$$

➡ Transmission spectroscopy through the limb

Transit spectroscopy



composition

$$\tau(z,\lambda) = \int n(z)\sigma(\lambda)\,\mathrm{d}l$$

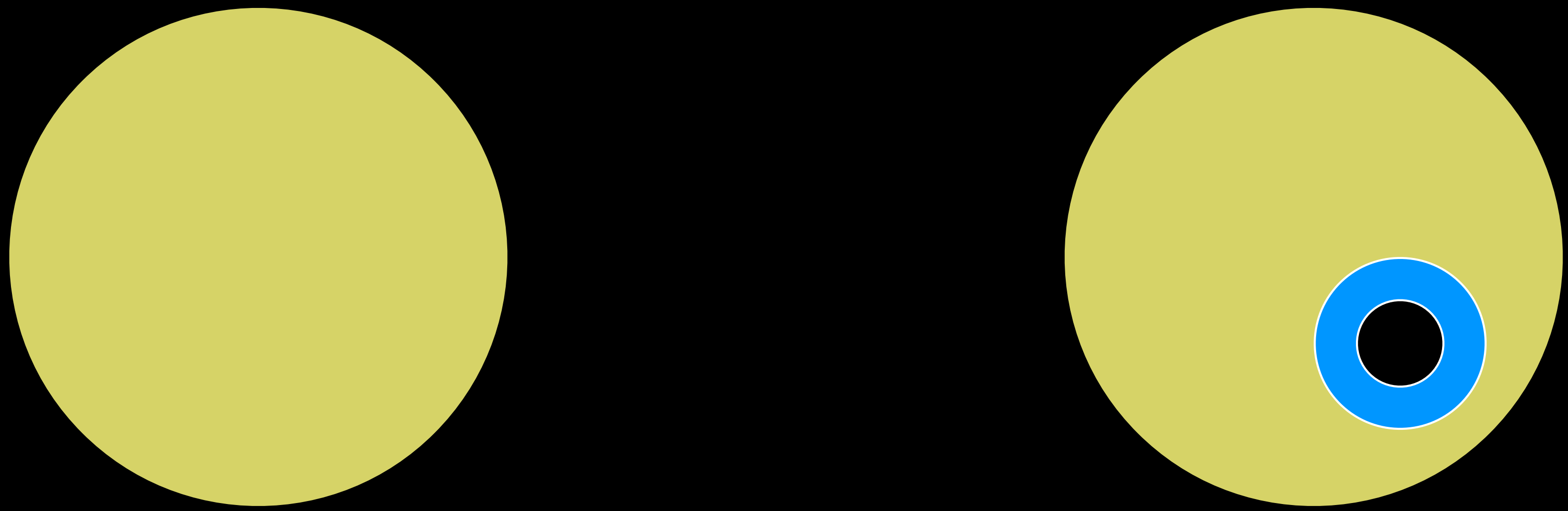
atmospheric
structure

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

See Fortney (2005)

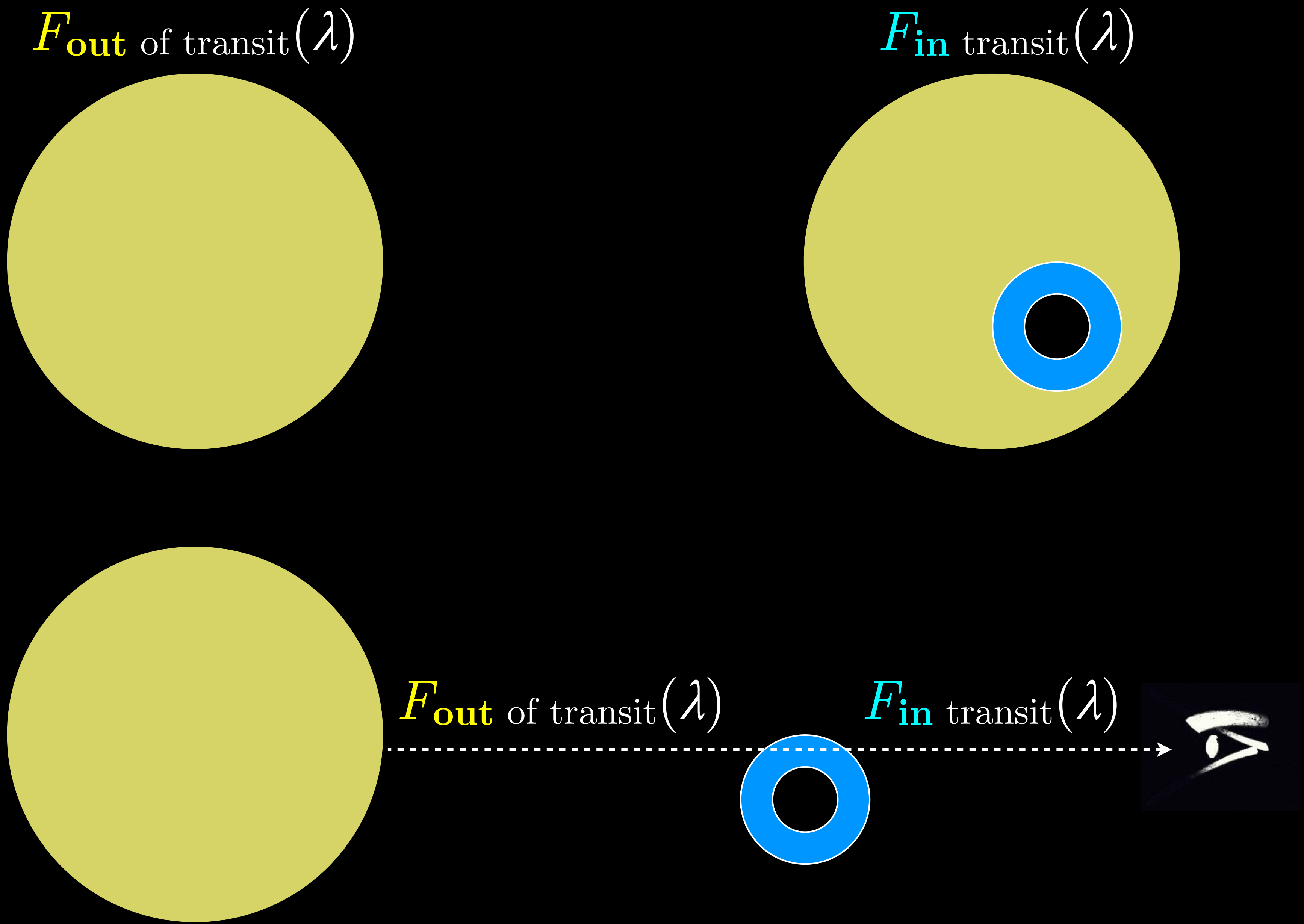
$$\tau(z,\lambda) \approx n(z)\sigma(\lambda)\sqrt{(2\pi R_p H)}$$

$F_{\mathbf{out}}$ of transit(λ) $F_{\mathbf{in}}$ transit(λ)



1.1 Basics: radiative transfer

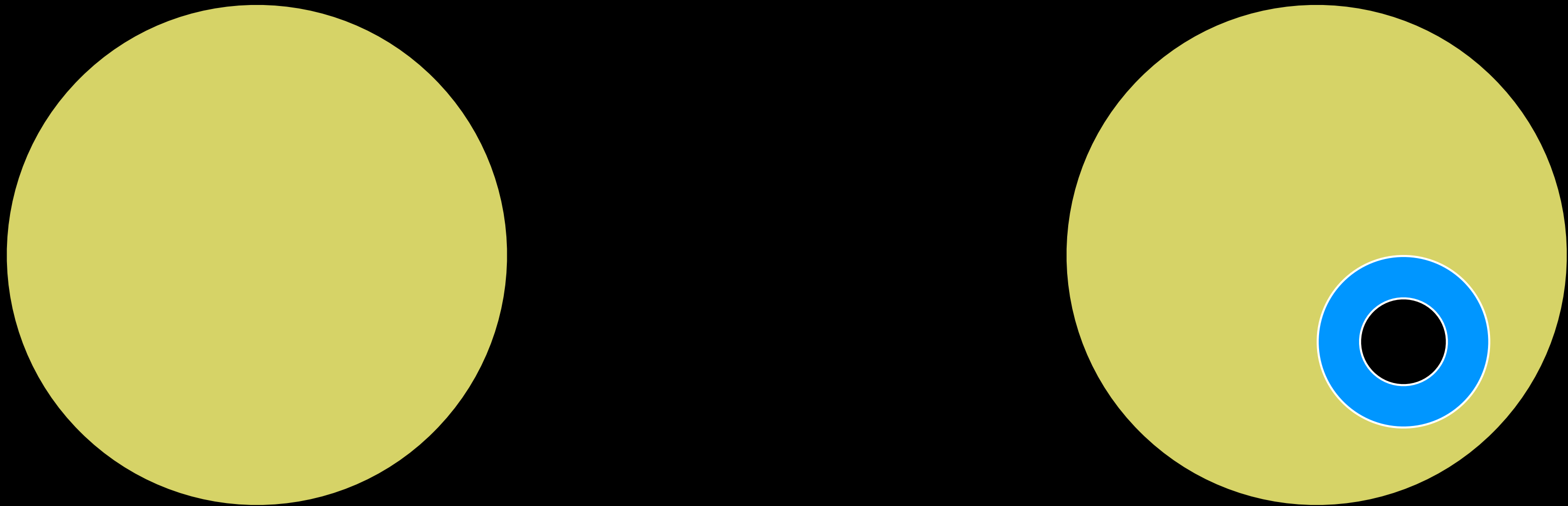
$$\tau(z,\lambda) \approx n(z)\sigma(\lambda)\sqrt{(2\pi R_p H)}$$



1.1 Basics: radiative transfer

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

$F_{\mathbf{out}}$ of transit(λ) $F_{\mathbf{in}}$ transit(λ)



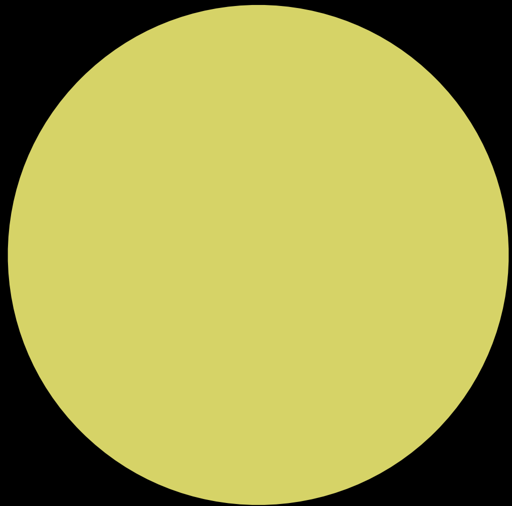
Solution of radiative transfert equation

$$F_{\mathrm{in}}(\lambda) = F_{\mathrm{out}}(\lambda)\mathrm{e}^{-\tau}$$

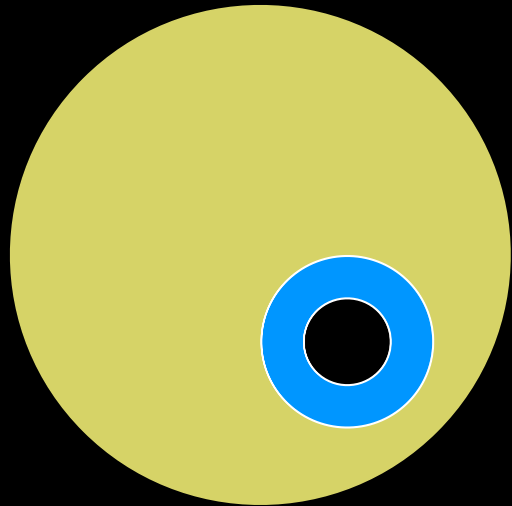
$$F_{\mathrm{in}}(\lambda)/F_{\mathrm{out}}(\lambda)-1 = \mathrm{e}^{-\tau}-1$$

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

$F_{\textbf{out}}$ of transit(λ)



$F_{\textbf{in}}$ transit(λ)



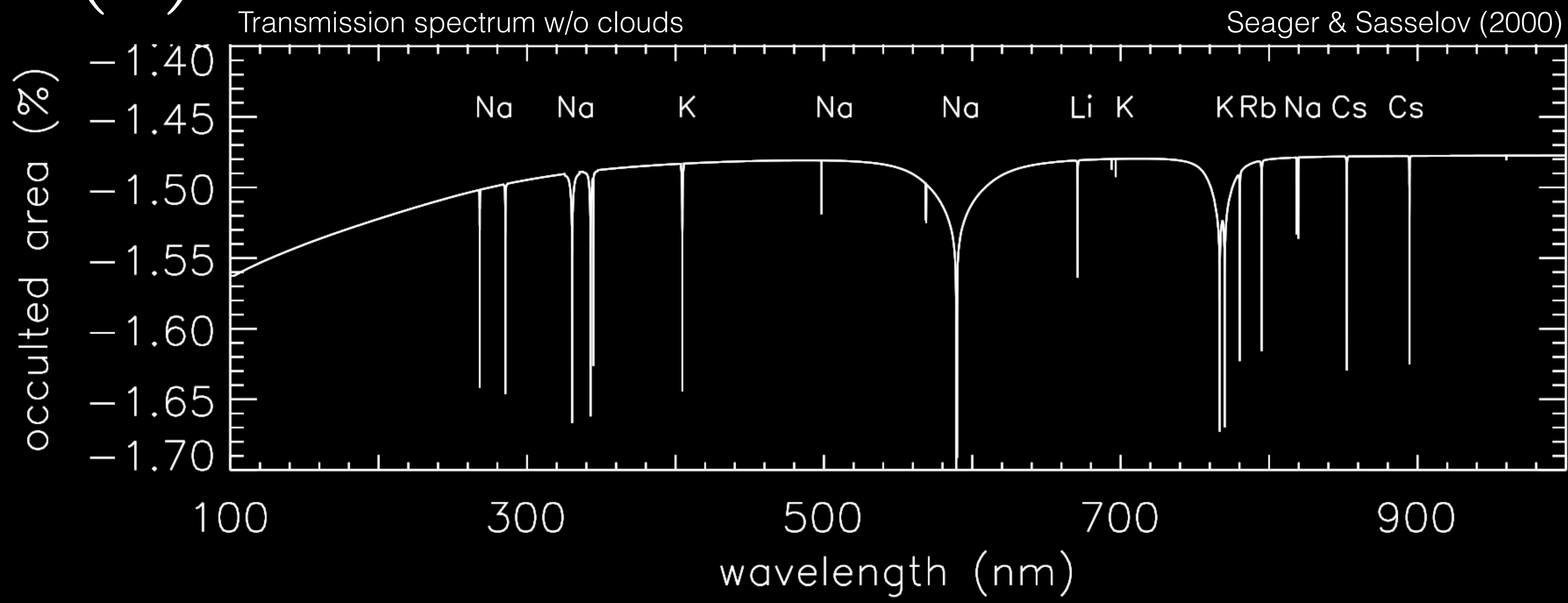
Solution of radiative transfert equation

$$F_{\text{in}}(\lambda) = F_{\text{out}}(\lambda)\mathrm{e}^{-\tau}$$

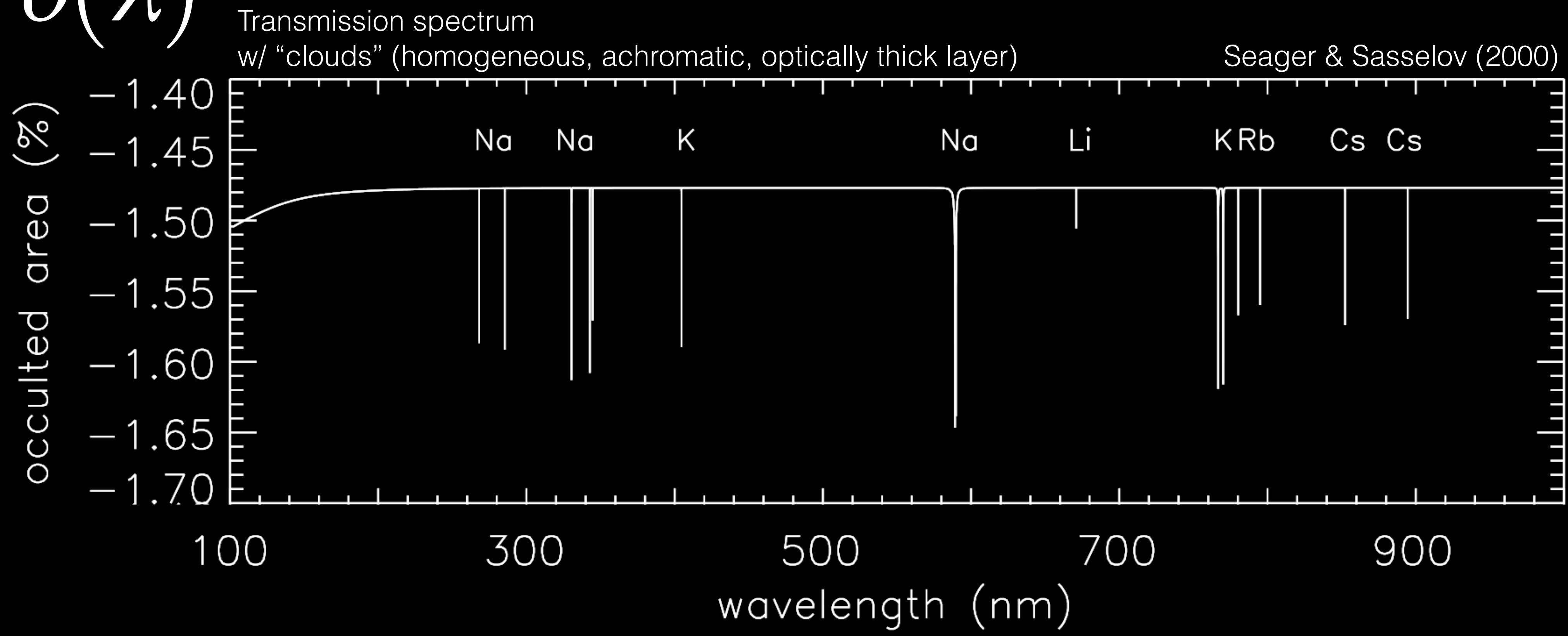
$$\delta(\lambda) = -[R(\lambda)/R_s]^2 = \mathrm{e}^{-\tau}-1$$

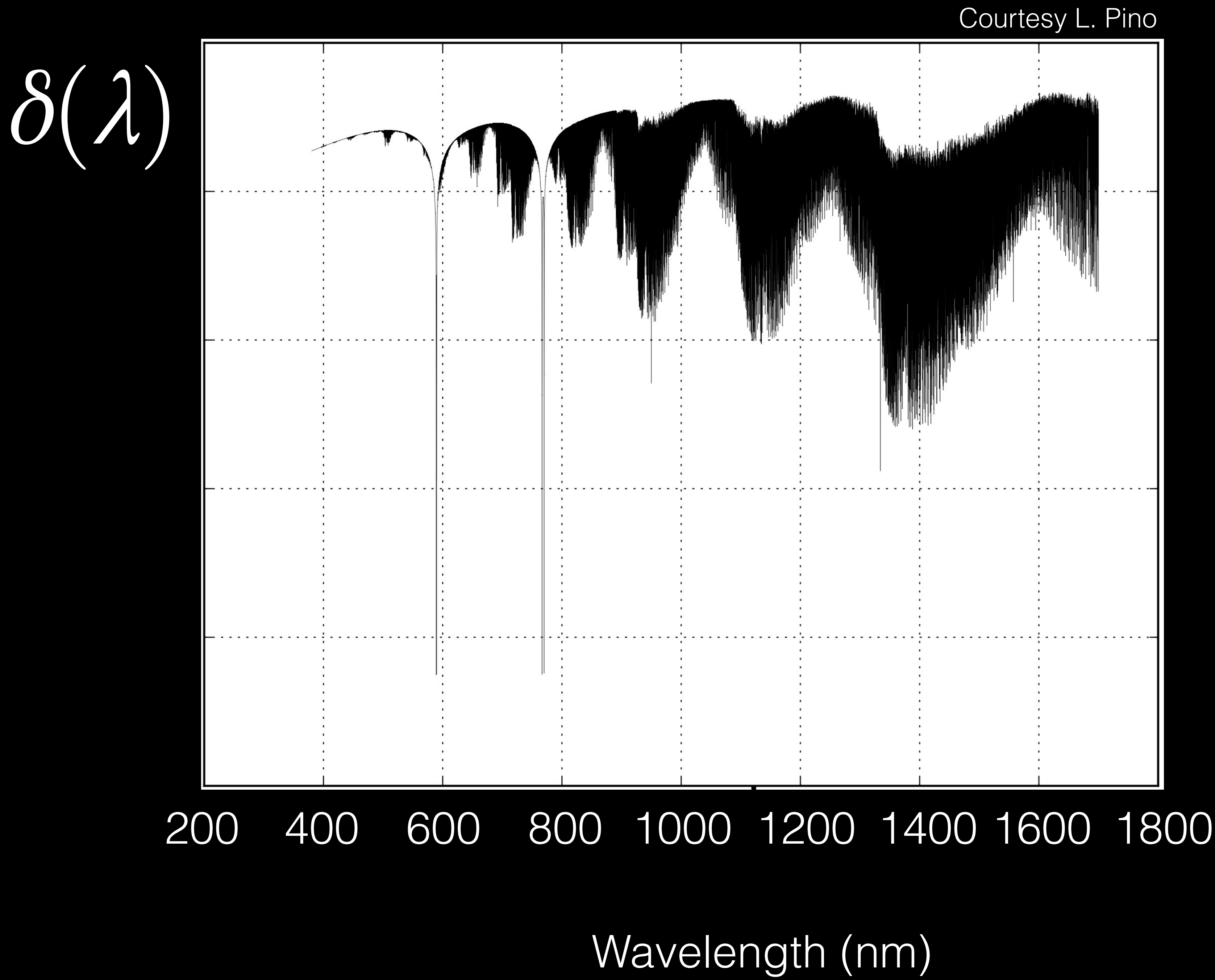
$$\delta(\lambda) = \exp[-n\sigma\sqrt{(2\pi R_p H)}]-1$$

$$\delta(\lambda)$$



$\delta(\lambda)$




Courtesy L. Pino
$\delta(\lambda)$
200
400
600
800
1000
1200
1400
1600
1800
Wavelength (nm)

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

- Composition: What does extinguish light?
- Atmospheric structure: In what quantity?
- Order of magnitude of transit spectroscopy signal

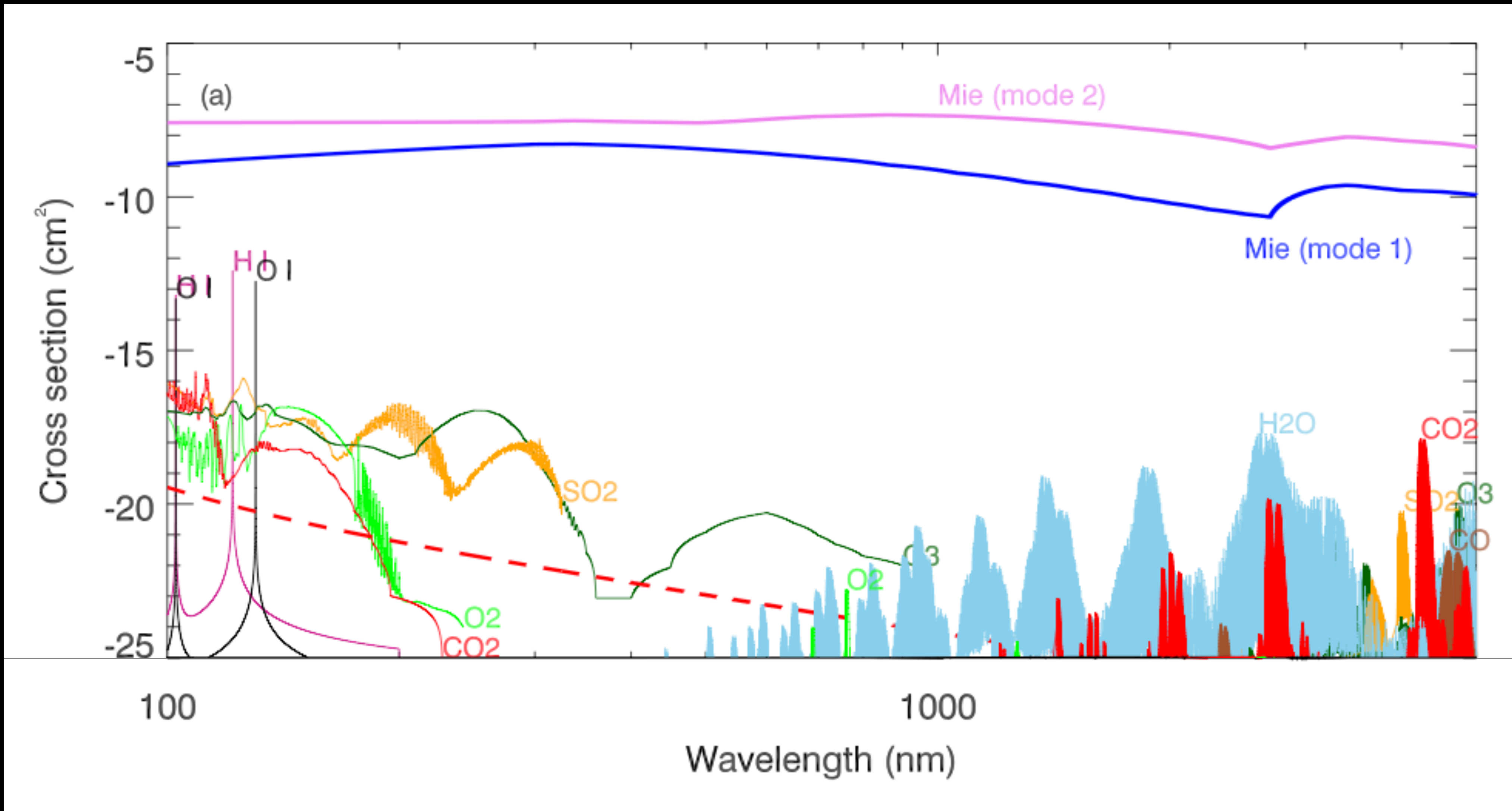
Extinction cross sections

- Photo-absorption by atoms & molecules
- Scattering of light by atoms & molecules
- Scattering of light by larger particles (dust, droplets in hazes or clouds)

Extinction cross sections

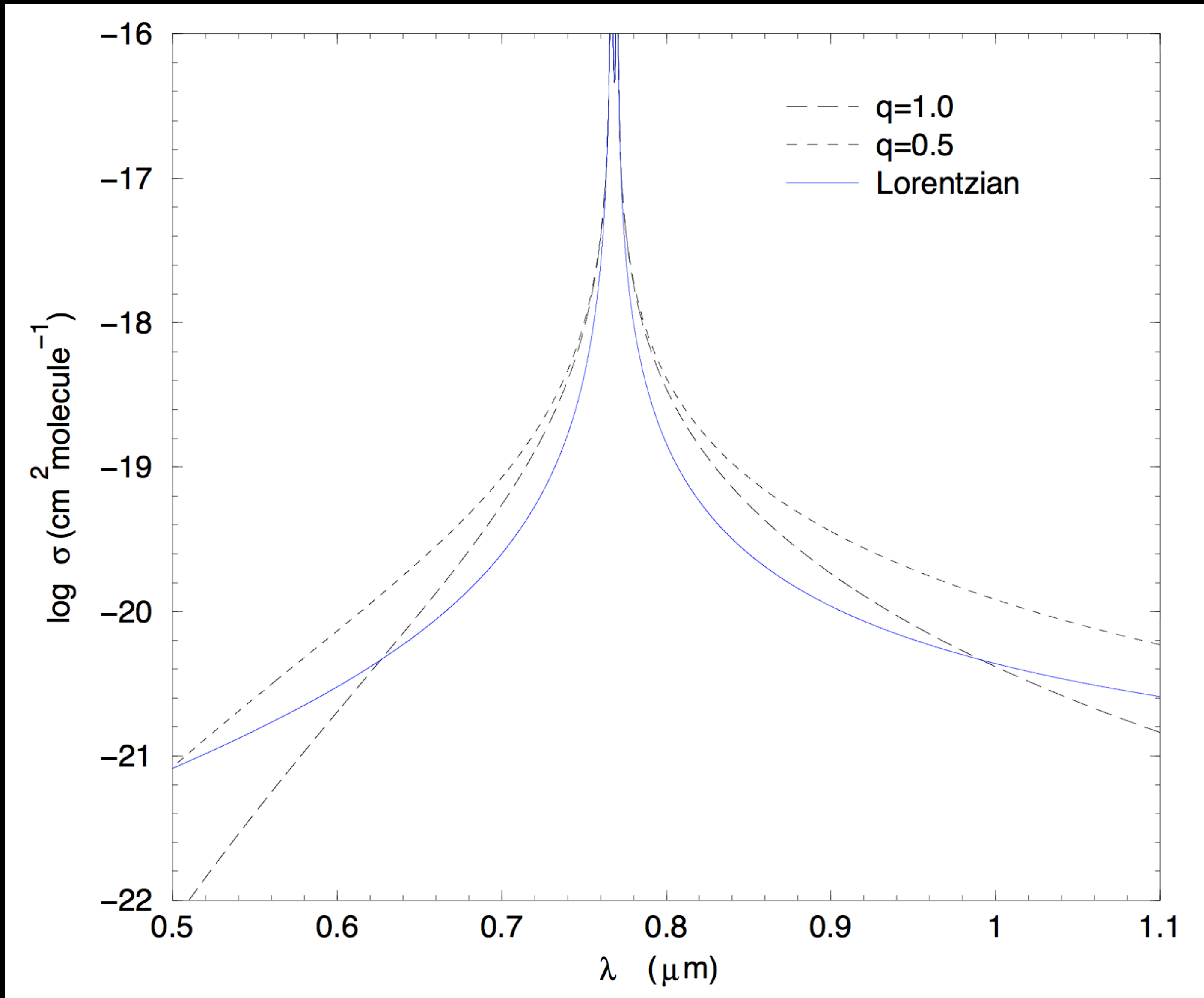
Relevant for the atmosphere of Venus

Ehrenreich et al. (2012)

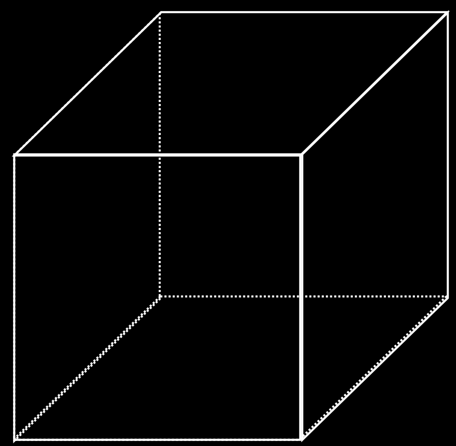


Extinction cross sections

Pressure-broadened profile of the sodium doublet (589 nm) Iro (2005)



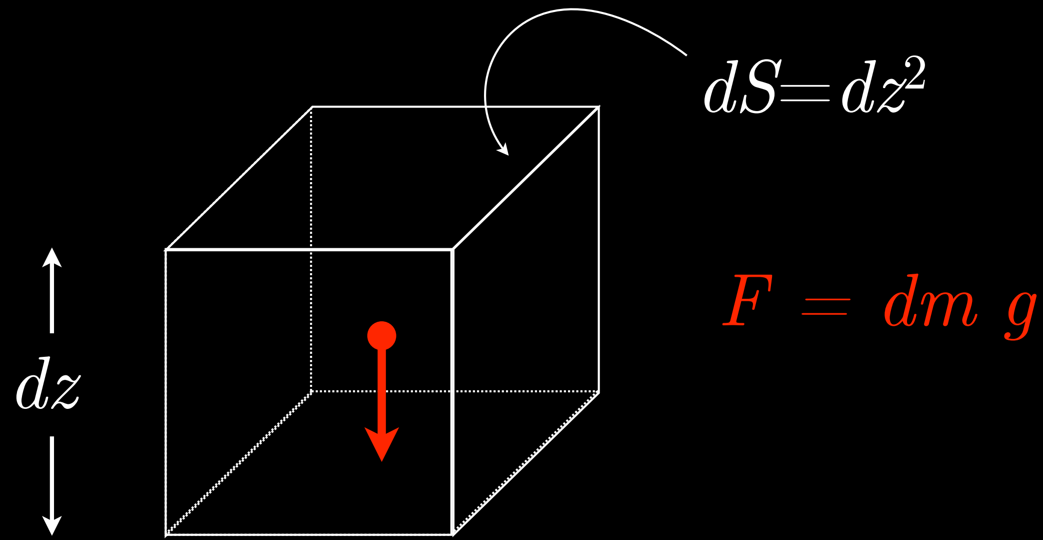
Atmospheric structure



cube of gas

mass dm, volume $dV = dz^3$

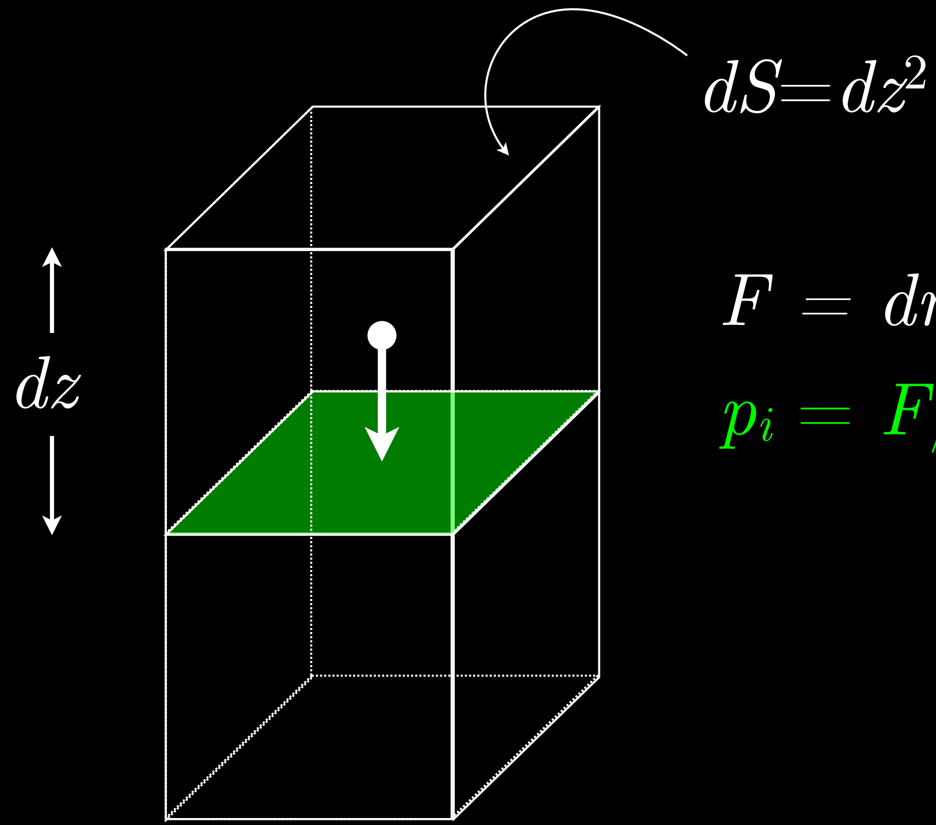
density $\varrho = dm/dV$



cube of gas

$$dm,\ dV = dz^3$$

$$\varrho = dm/dV$$



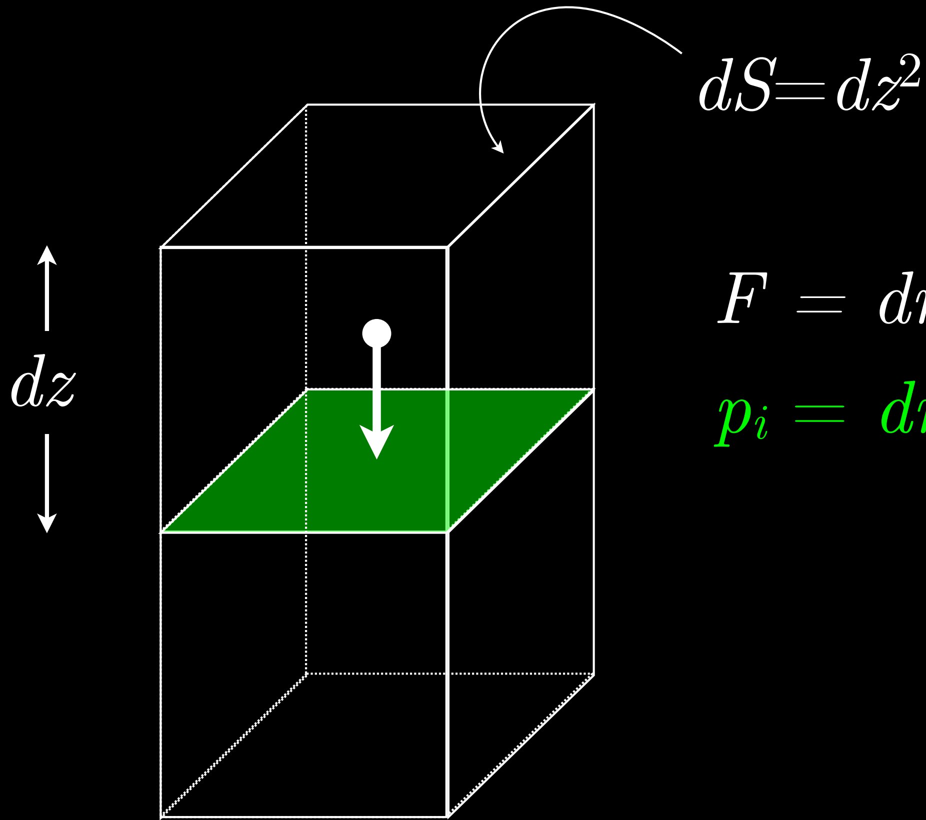
$$F = dm\ g$$

$$p_i = F/dS$$

cube of gas

$dm,\ dV = dz^3$

$\varrho = dm/dV$



$F = dm\ g$

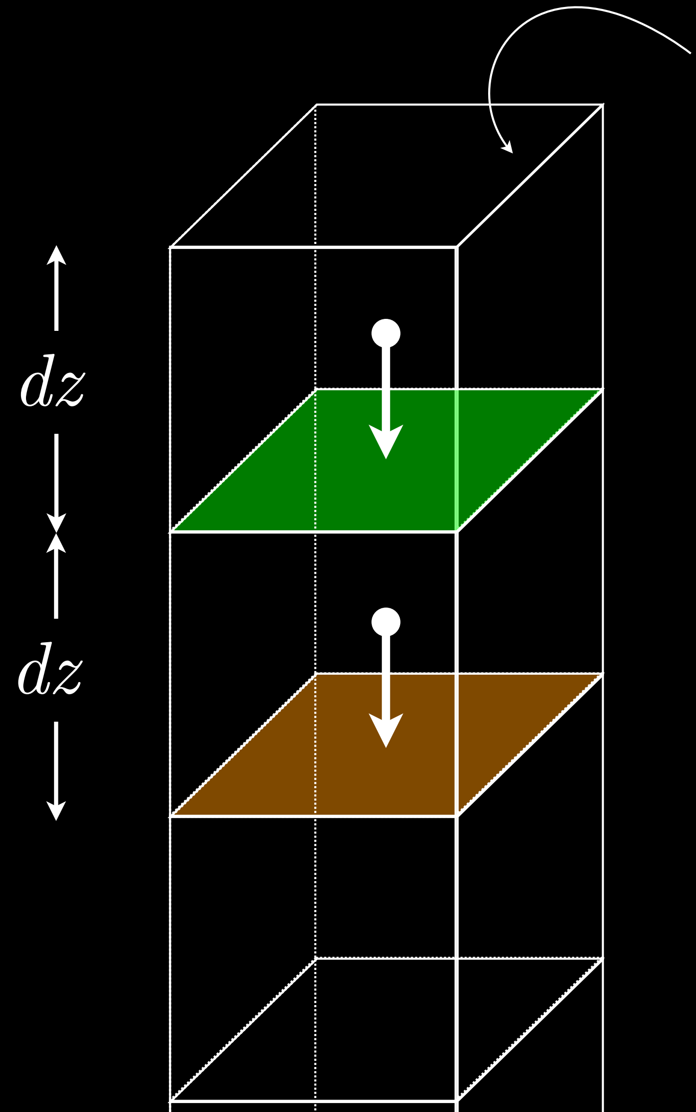
$p_i = dm\ g/dS$

cube of gas

$dm,\ dV = dz^3$

$\varrho = dm/dV$

$dS = dz^2$



$F = dm\ g$

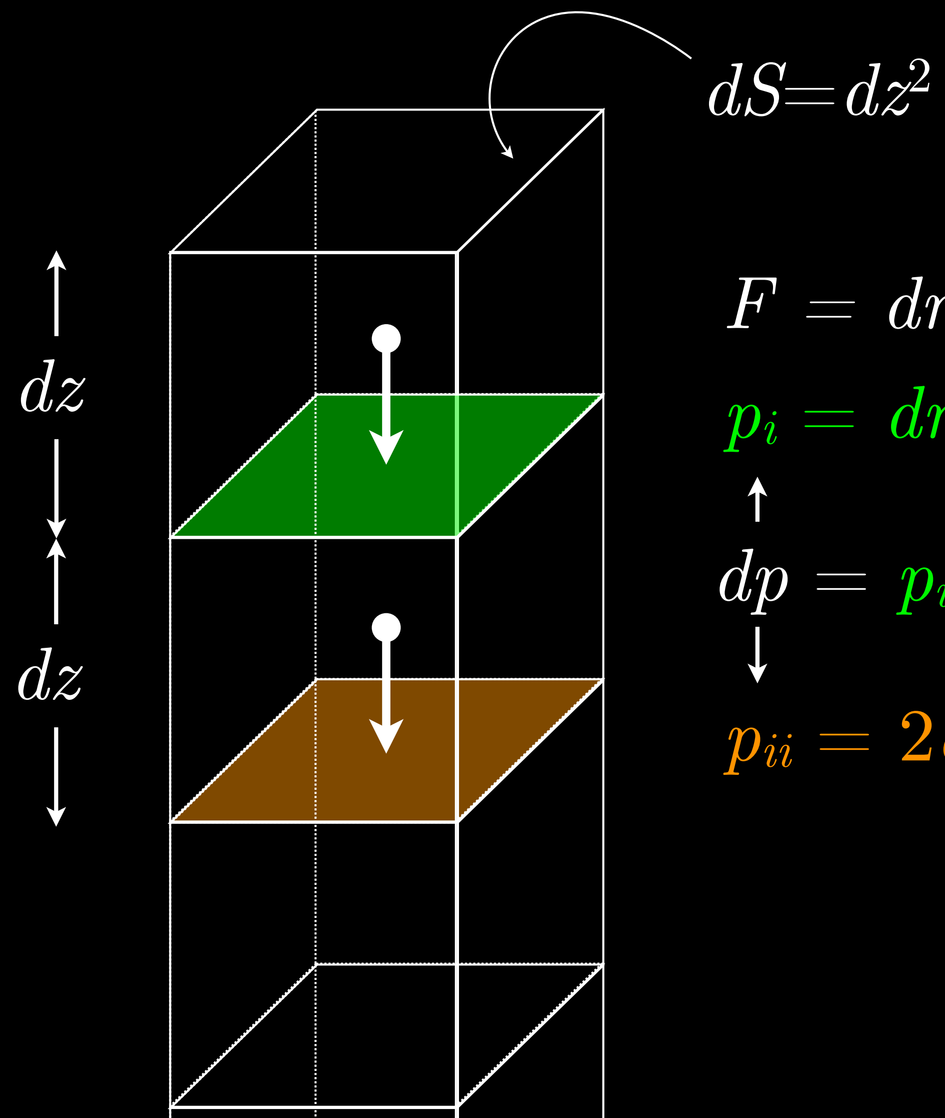
$p_i = dm\ g/dS$

$p_{ii} = 2dm\ g/dS$

cube of gas

$dm,\ dV = dz^3$

$\varrho = dm/dV$



$F = dm\ g$

$p_i = dm\ g/dS$

$dp = p_i - p_{ii}$

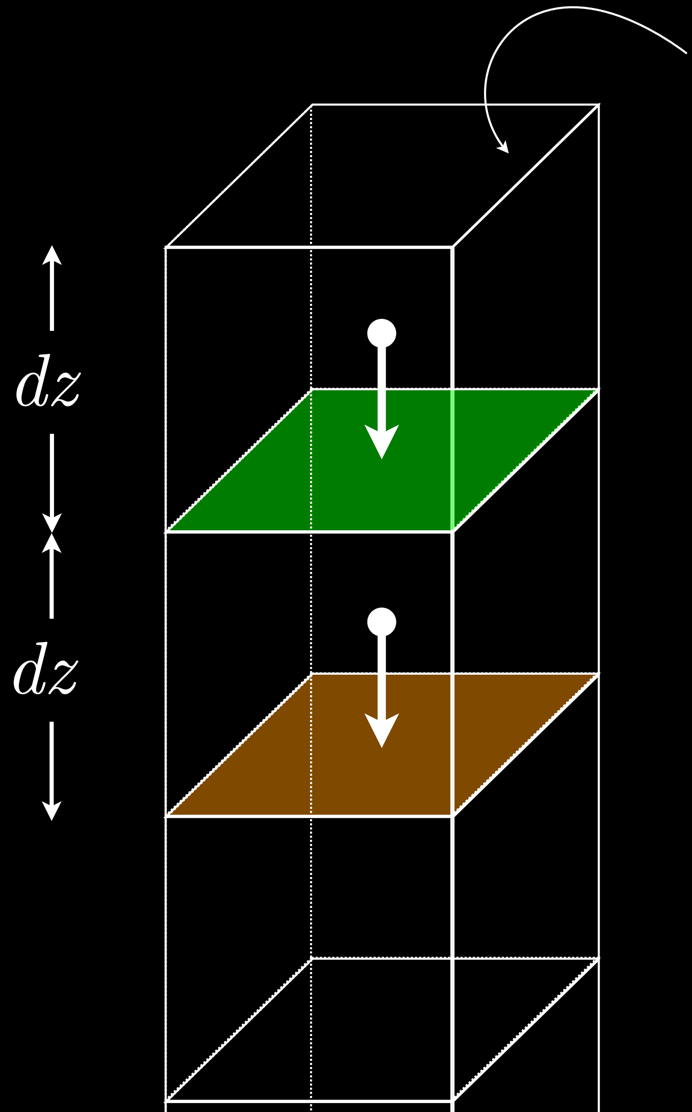
$p_{ii} = 2dm\ g/dS$

cube of gas

$$dm,\ dV = dz^3$$

$$\varrho = dm/dV$$

$$dS = dz^2$$



$$F = dm\ g$$

$$p_i = dm\ g/dS$$

$$dp = -dm\ g/dS$$

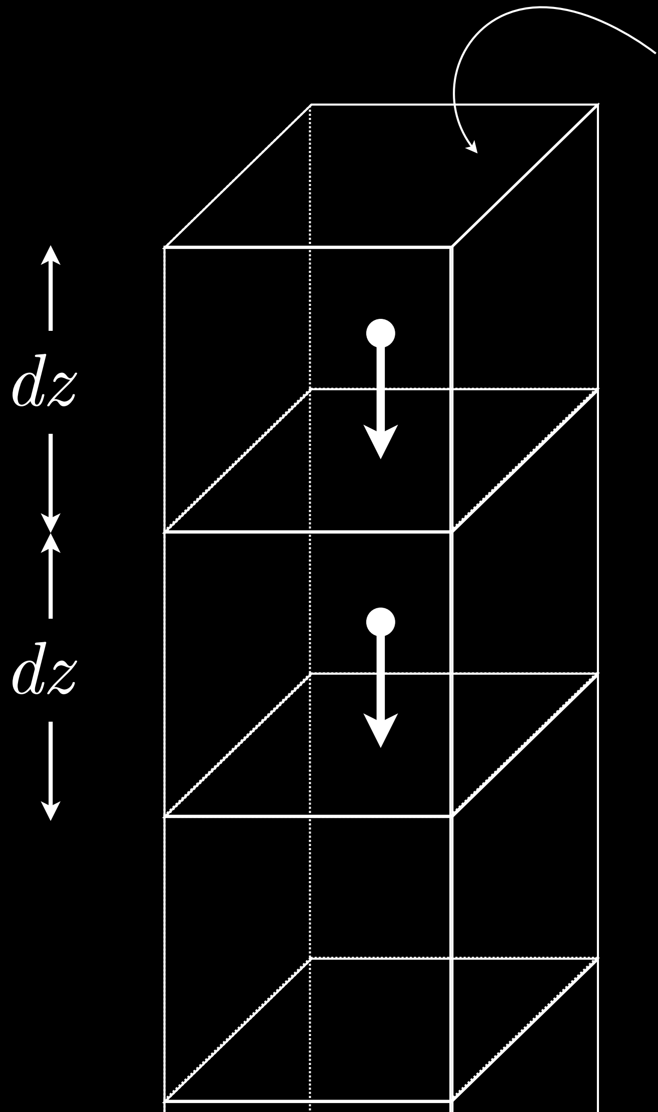
$$p_{ii} = 2dm\ g/dS$$

cube of gas

$$dm,\ dV = dz^3$$

$$\varrho = dm/dV$$

$$dS = dz^2$$

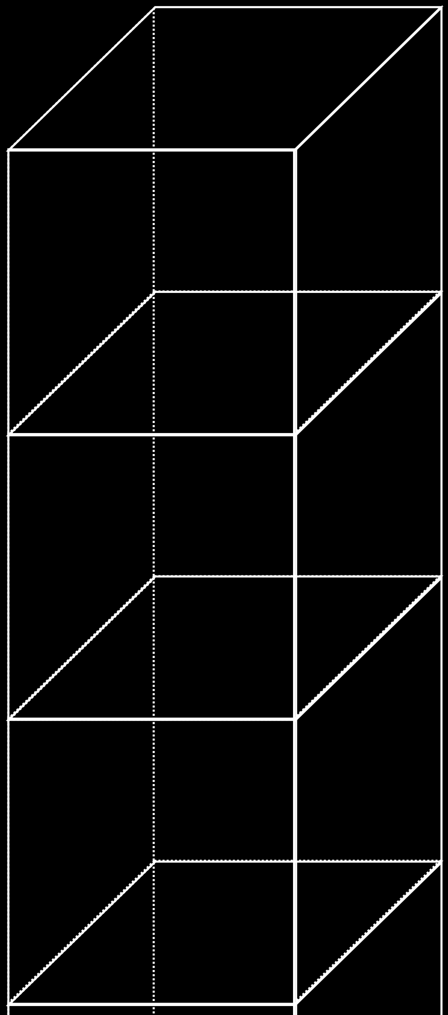


$$dp = -dm\ g/dS = -\underbrace{dm/dV}_{\varrho}\ g\ \overbrace{dV/dS}^{dz}$$

cube of gas

$$dm,\ dV = dz^3$$

$$\varrho = dm/dV$$



$$dp = -\varrho\ g\ dz$$

$$\frac{dp}{dz} = -\varrho \; g$$

Hydrostatic equilibrium

mass density
[g cm^{-3}]

$$\frac{dp}{dz} = -\rho g$$

gravity acceleration
[cm s^{-2}]

Hydrostatic equilibrium

$$\frac{dp}{dz} = -\rho g$$

of what?

Equation of state

number density
[cm^{-3}]

$$p = n \mathrm{k_B} T$$

temperature
[K]

pressure
[dyn cm^{-2}],
also “barye” [ba]
1 ba = 0.1 Pa

$$\frac{dp}{dz} = -\rho g$$

mass vs. number density

number density
[cm^{-3}]

$$\rho = n\mu$$

mass density
[g cm^{-3}]

mean molecular mass
[g $molecule^{-1}$]
not [g mol^{-1}]

$$\frac{dp}{dz} = -\rho g$$

$$p = n\,\mathrm{k_B}T$$

$$\rho = n\mu \qquad \frac{dp}{dz} = -\rho g$$

$$p = \varrho/\mu \, \mathrm{k_B} T$$

$$\frac{dp}{dz} = -\rho g$$

$$p = -dp/dz \, \boxed{k_B T/\mu g}$$

$$H$$

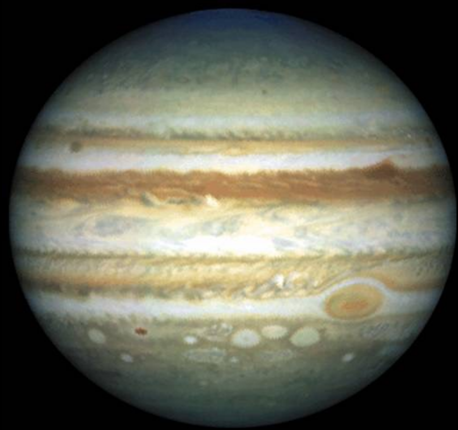
Atmospheric scale height [cm]

$$p = -dp/dz \, \boxed{k_B T/\mu g}$$

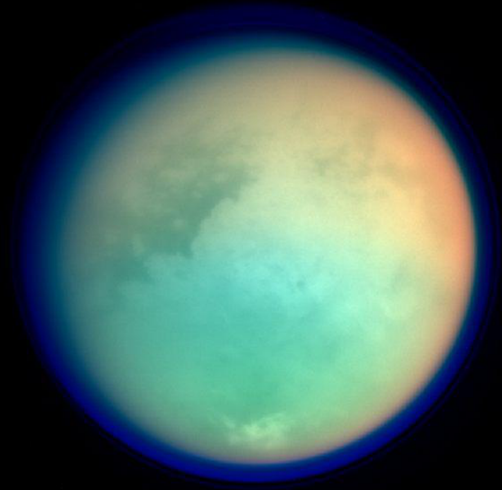
Who has the largest H?

a

b



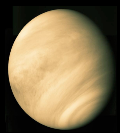
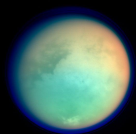
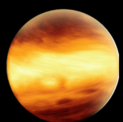
c



d

1.1 Basics: scale height

$$p = -dp/dz\ \boxed{\mathrm{k_B}\, T/\mu g}$$

	T (K)	g (m s^{-2})	μ (g mol^{-1})	H (km)
	300	10	29	**8–9**
	740	9	44	**16**
	110	25	2.2	**16!**
	90	1.4	29	**20**
	1,100	25	2.2	**160**

$$p = -dp/dz\ H$$

$$\frac{dp}{p} = -\frac{dz}{H}$$

$$\int_{p_0}^{p} \frac{dp'}{p'} = -\int_{z_0}^{z} \frac{dz'}{H}$$

$$\int_{p_0}^{p} \frac{dp'}{p'} = - \int_{z_0}^{z} \frac{dz'}{H}$$

$$\ln \frac{p}{p_0} = - \frac{z - z_0}{H}$$

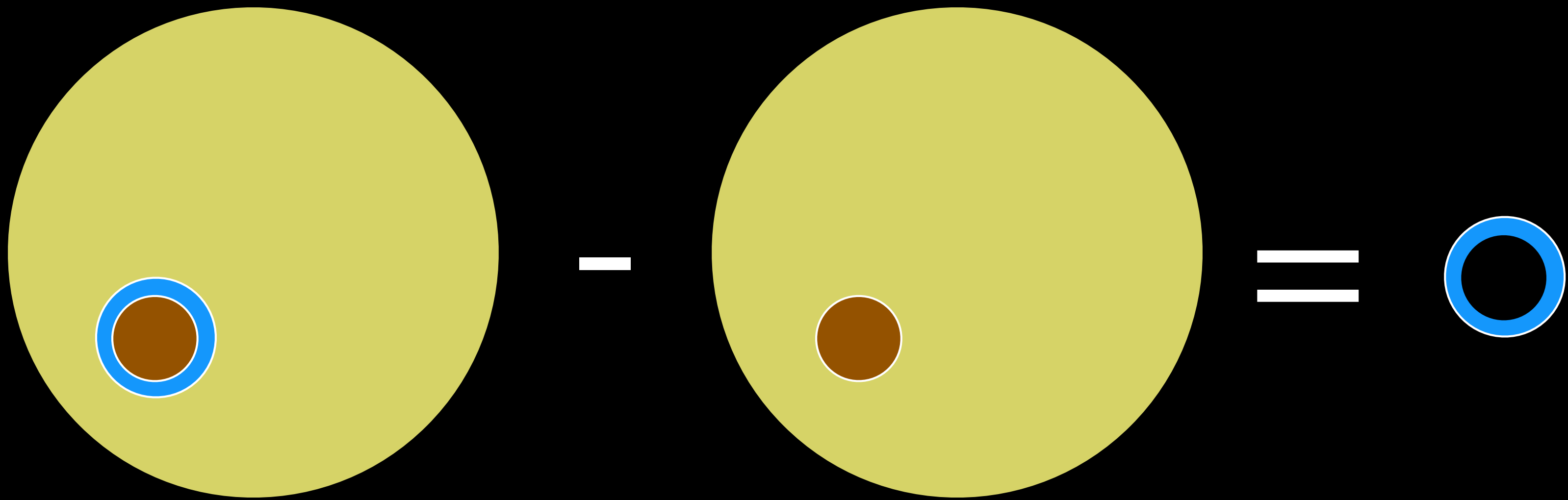
$$\ln \frac{p}{p_0} = -\frac{z - z_0}{H}$$

$$p = p_0 \exp\left(-\frac{z - z_0}{H}\right)$$

only **true** if H is constant with z,
(=isothermal profile), otherwise:

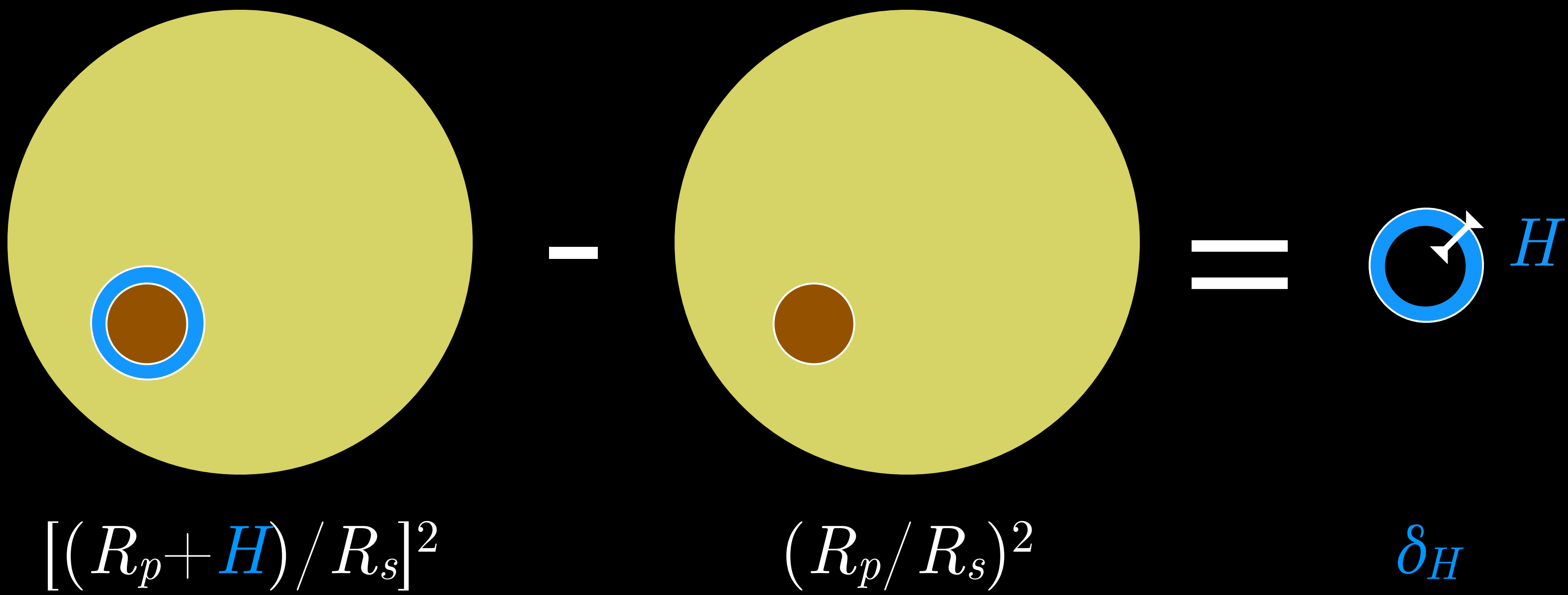
$$p(z) = p_0 \exp\left(-\int_{z_0}^{z} \frac{dz'}{H(z)}\right)$$

Signal amplitude



$(R(\lambda)/R_s)^2$ $\quad$ $(R_p/R_s)^2$ $\quad$ δ_{atm}

Signal amplitude



1.2 Atmospheric signal

$$\delta_H = [(R_p + H)/R_s]^2 - (R_p/R_s)^2$$

$$\delta_H = [(R_p + H)/R_s]^2 - (R_p/R_s)^2$$

$$\delta_H = [(R_p + H)^2 - R_p^2]/R_s^2$$

$$\delta_H = [R_p^2 + H^2 + 2R_pH - R_p^2]/R_s^2$$

$$\delta_H = [H^2 + 2R_pH]/R_s^2$$

$$\delta_H = [(H/R_p)^2 + 2H/R_p]R_p^2/R_s^2$$

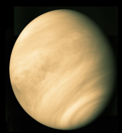
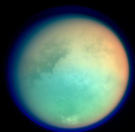
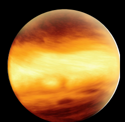
$$H \ll R_p,\ (H/R_p)^2 \approx 0$$

$$\delta_H = (2H/R_p)R_p^2/R_s^2$$

$$\delta_H = (2H/R_p)\delta$$

$$\delta_H \approx 2 \left(\frac{R_p}{R_s} \right)^2 \frac{H}{R_p}$$

$$\delta_H \approx 2 \left(\frac{R_p}{R_s} \right)^2 \frac{H}{R_p}$$

	R_p ($R_\oplus$)	H (km)	δ	δ_H
	1	8–9	80 ppm	0.2 ppm
	1	16	80 ppm	0.4 ppm
	11	16	1%	5 ppm
	0.4	20	14 ppm	0.2 ppm
	17	160	2.5%	70 ppm

$$\delta_H \approx 2\left(\frac{R_p}{R_s}\right)^2 \frac{H}{R_p}$$

$$\delta_H \approx 2\left(\frac{R_p}{R_s}\right)^2 \frac{1}{R_p}\frac{\mathrm{k_B}T}{\mu g}$$

$$\delta_H \approx 2\left(\frac{R_p}{R_s}\right)^2 \frac{1}{R_p}\frac{\mathrm{k_B}T}{\mu G}\frac{R_p^2}{M_p}$$

$$\delta_H \approx 2\left(\frac{R_p}{R_s}\right)^2 \frac{1}{R_p}\frac{k_B T}{\mu G}\frac{{R_p}^2}{M_p}$$

$$\rho = \frac{M_p}{\frac{4}{3}\pi {R_p}^3}$$

$$\delta_H \approx 2\left(\frac{R_p}{R_s}\right)^2 \frac{k_B}{\frac{4}{3}\pi G}\frac{T}{\mu\rho R_p^2}$$

Signal amplitude

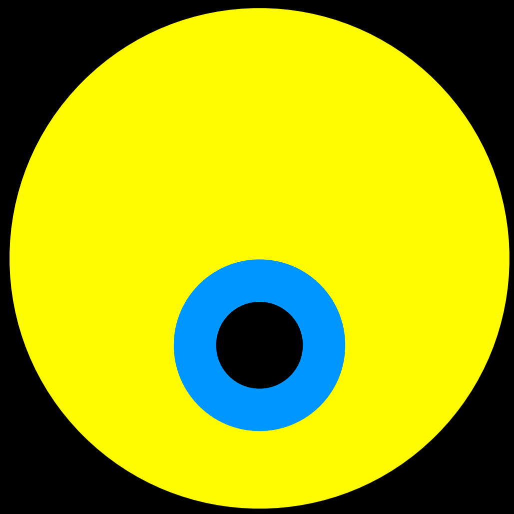
$$\delta_H \propto (R_s)^{-2} (\rho)^{-1} (\mu)^{-1} (T)^{+1}$$

small stars hosting
low-density planets
with **light** & **hot** atmospheres

= great targets for atmospheric characterisation!

Signal-to-noise

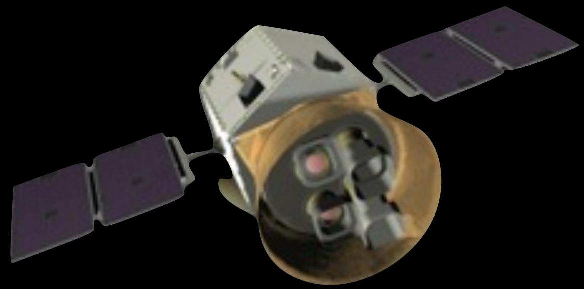
$$S/N \propto \sqrt{F_\star}$$



To study exoplanetary atmospheres
☞ more planets around **bright stars**

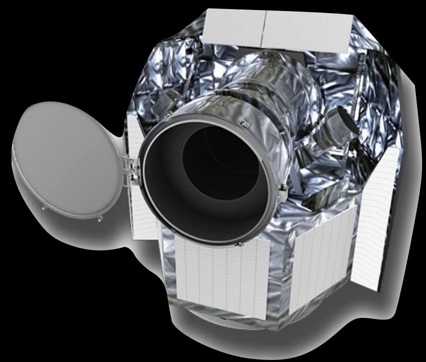
K2

NASA (➠)



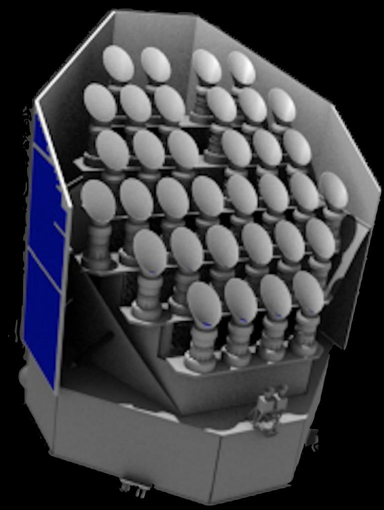
TESS

NASA (2017)



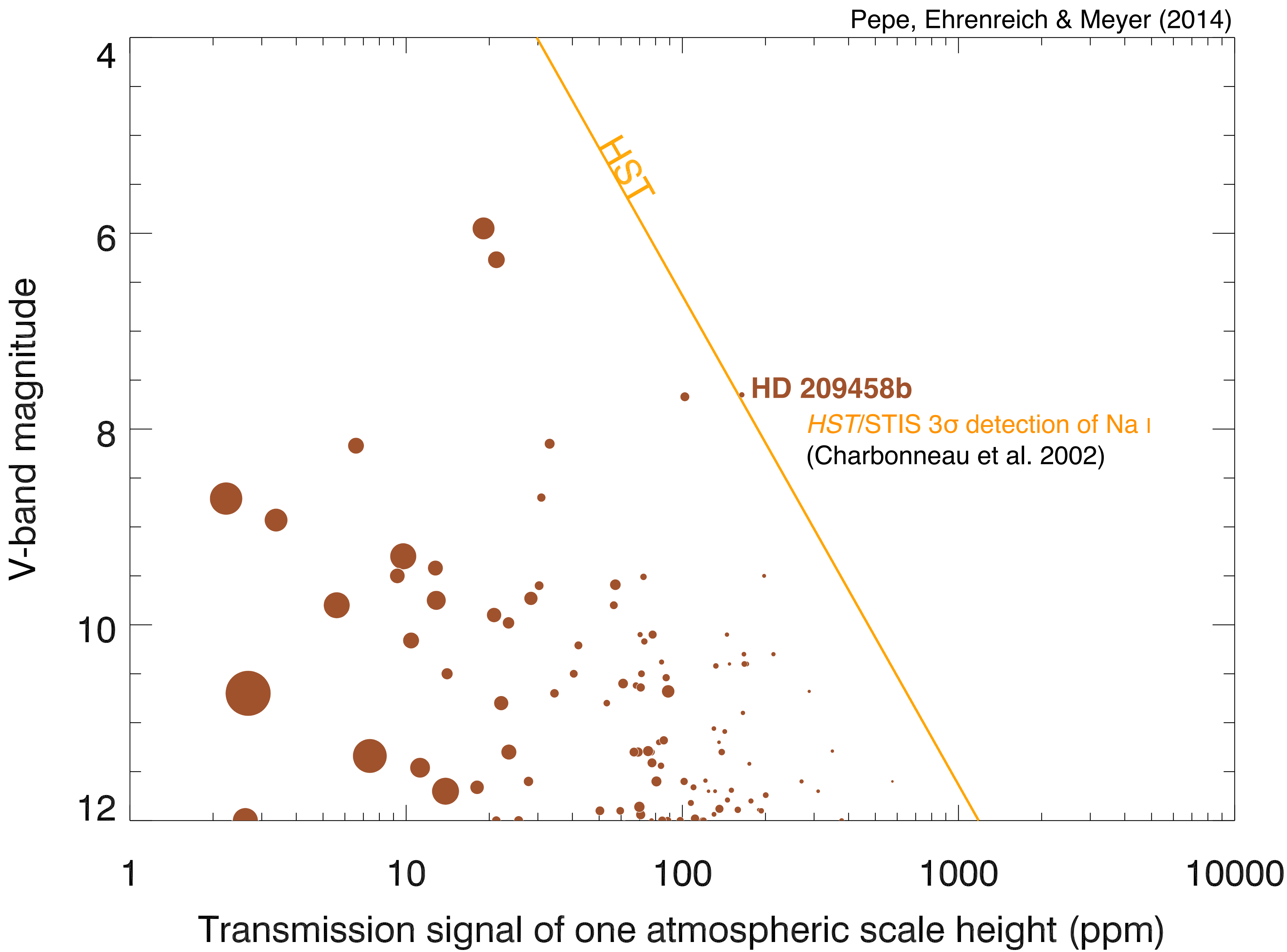
CHEOPS

ESA (2018)

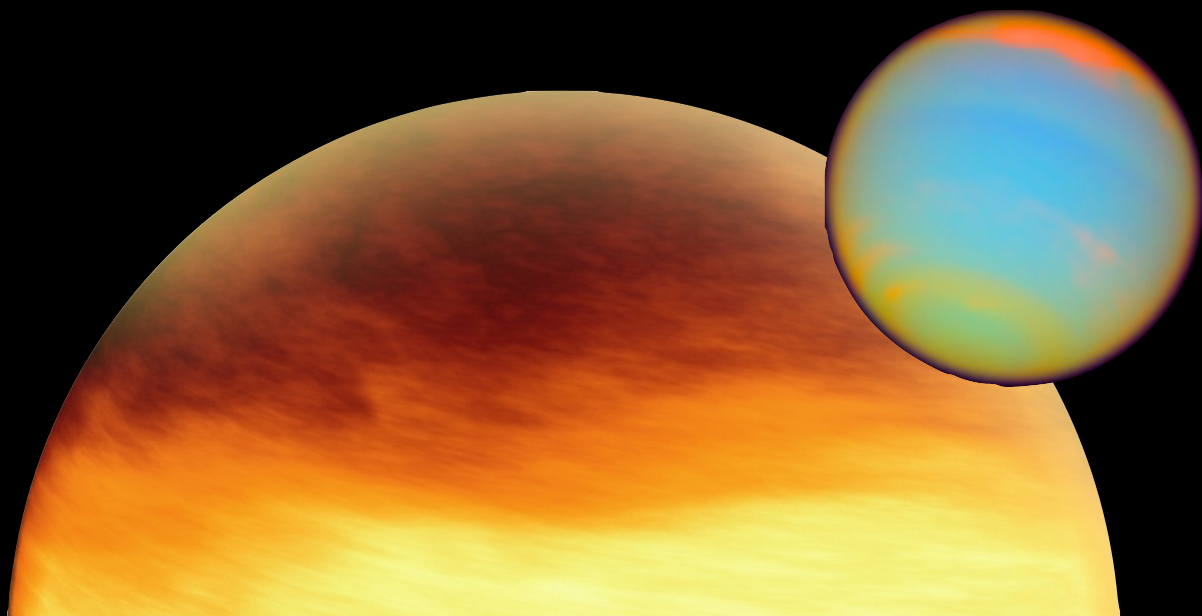


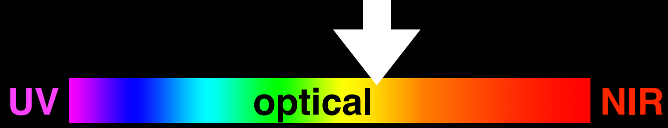
PLATO

ESA (2025)


Pepe, Ehrenreich & Meyer (2014)
HST
HD 209458b
HST/STIS 3σ detection of Na I
(Charbonneau et al. 2002)
V-band magnitude
4
6
8
10
12
1
10
100
1000
10000
Transmission signal of one atmospheric scale height (ppm)

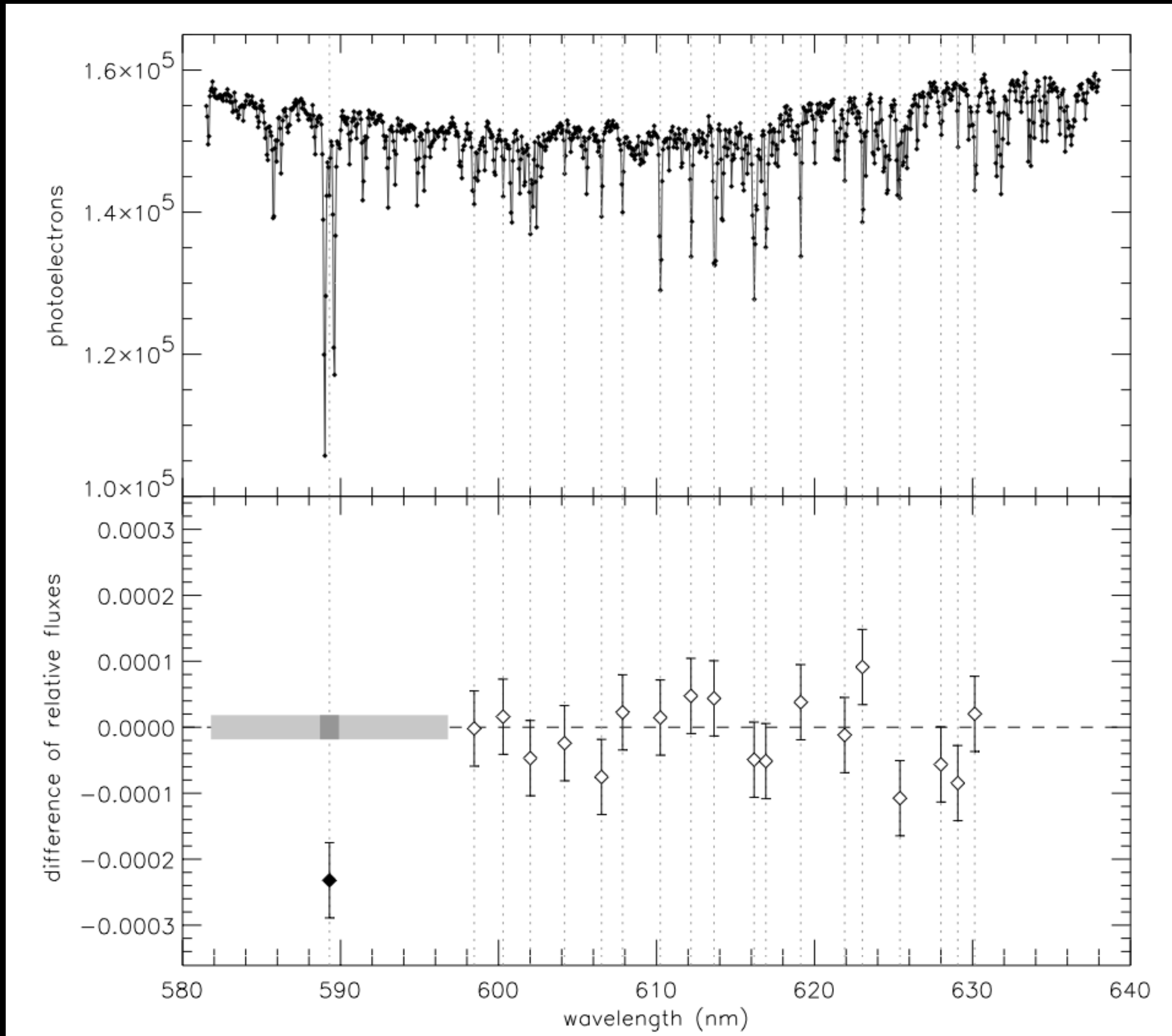
2. Case studies

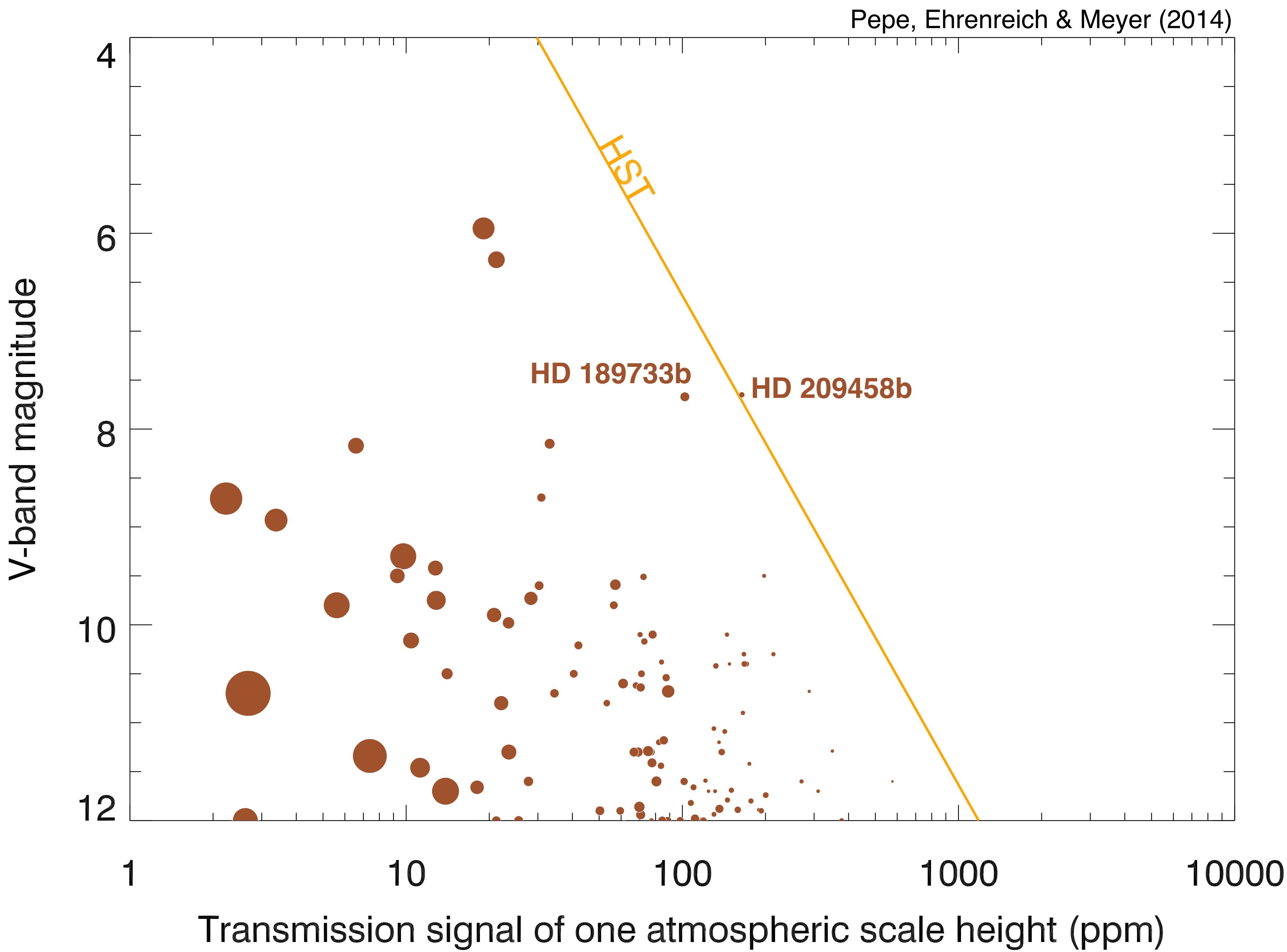




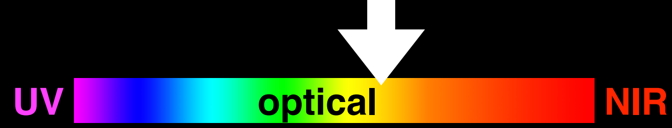
Optical sodium

Sodium detection in HD 209458b — Charbonneau et al. (2002)





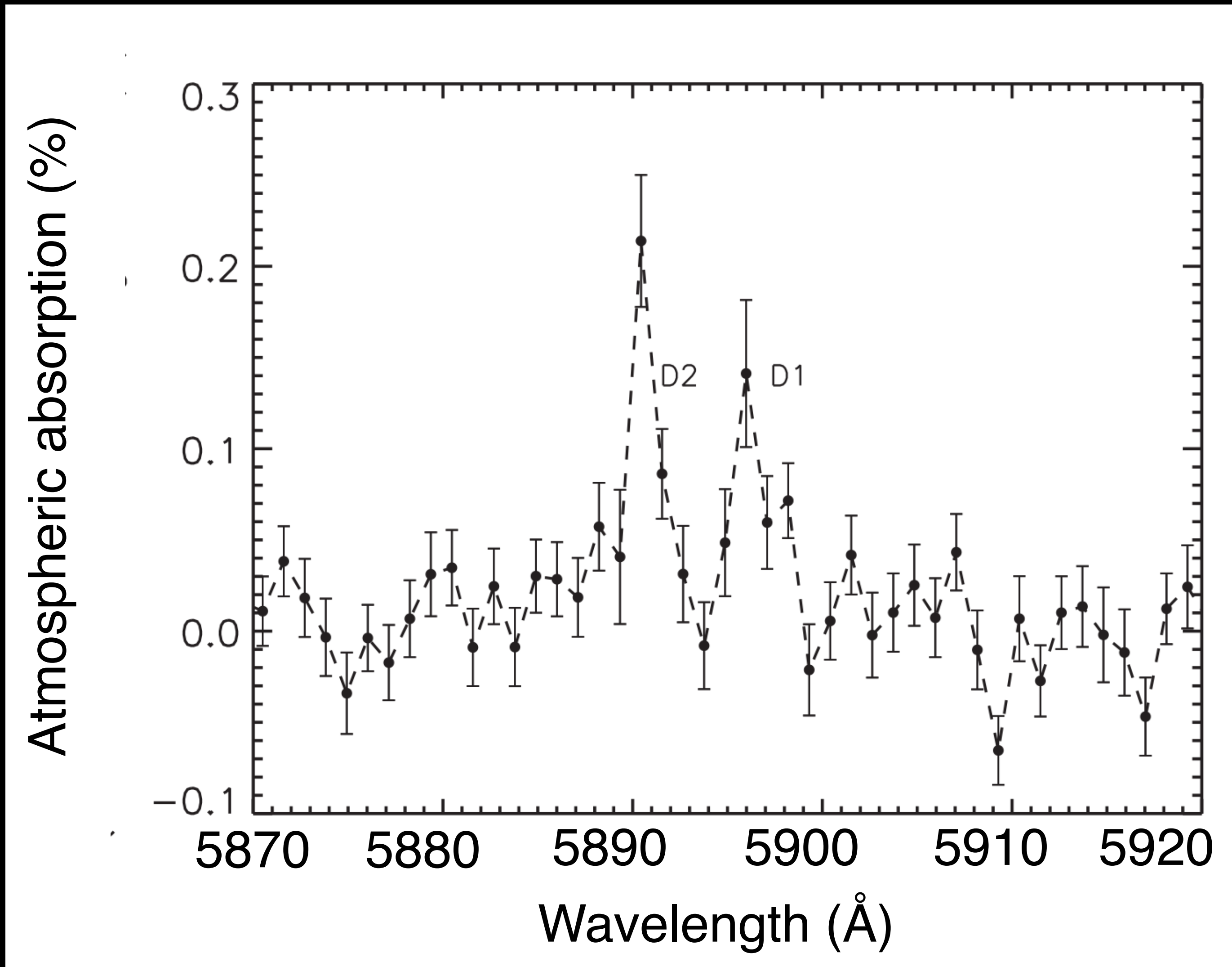
Pepe, Ehrenreich & Meyer (2014)
V-band magnitude
4
6
8
10
12
HST
HD 189733b
HD 209458b
1
10
100
1000
10000
Transmission signal of one atmospheric scale height (ppm)



Optical sodium

Sodium detection in HD 189733b

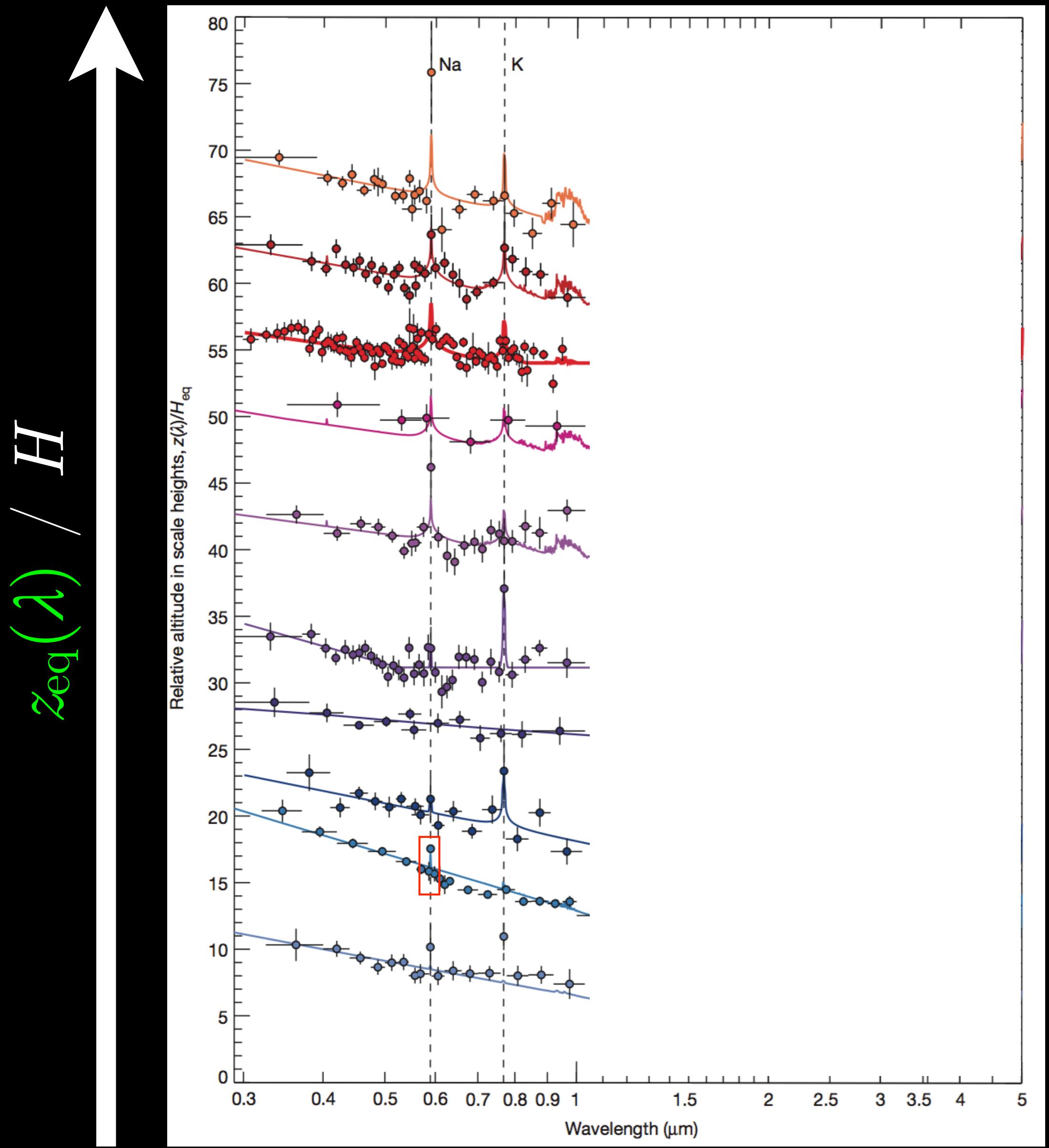
Huitson et al. (2012)



UV optical NIR

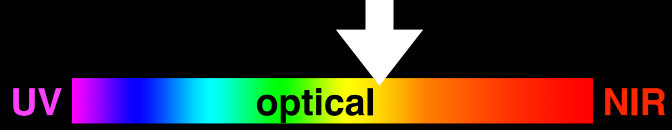
Optical transit spectra

Sample of ~10 exoplanets Sing et al. (2016)



$$T = \frac{\mu g}{k_B} \frac{\partial z(\lambda)}{\partial \lambda} \left(\frac{\partial \ln \sigma(\lambda)}{\partial \lambda} \right)^{-1}$$

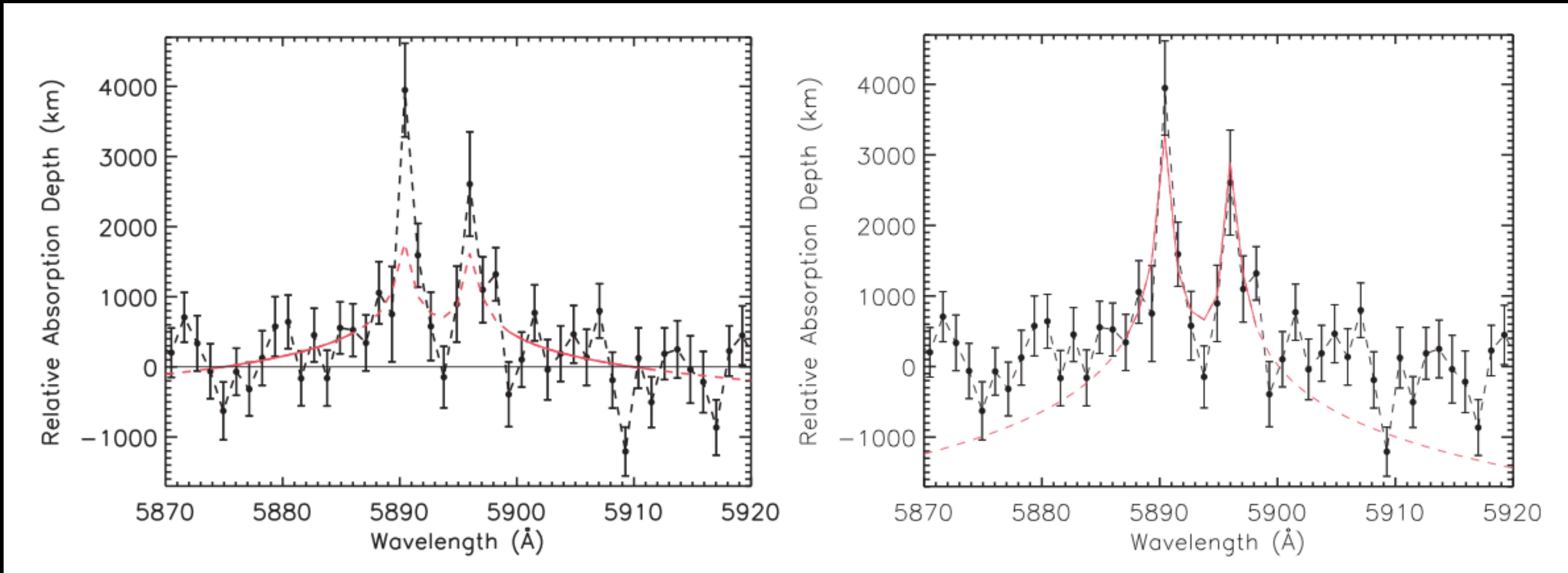
Lecavelier des Etangs et al. (2008)



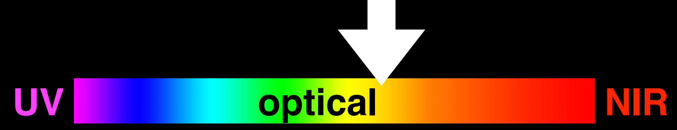
Optical sodium

Sodium detection in HD 189733b w/ *HST*

Huitson et al. (2012)



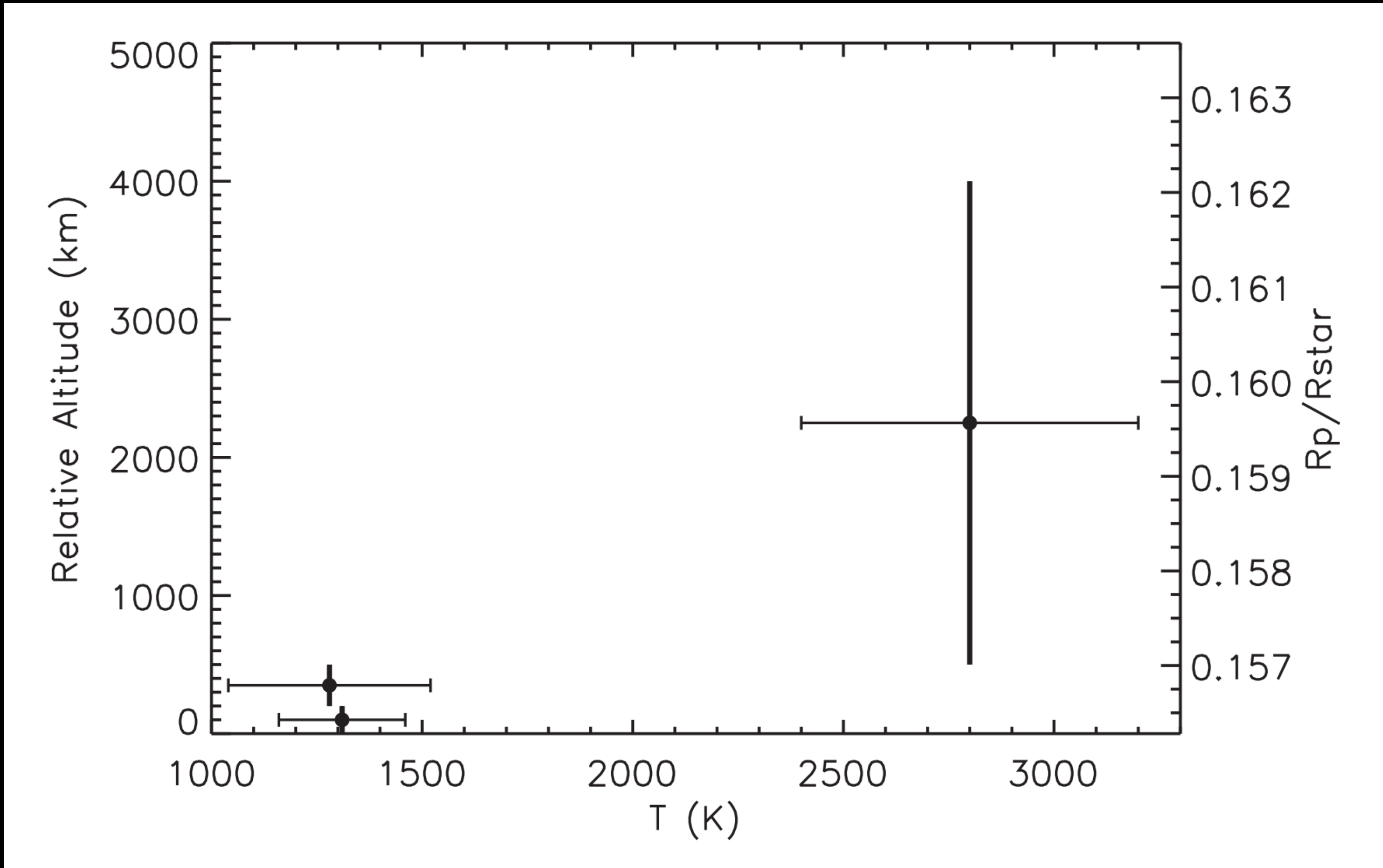
$$T = \frac{\mu g}{\mathrm{k_B}} \frac{\partial z(\lambda)}{\partial \lambda} \left(\frac{\partial \ln \sigma(\lambda)}{\partial \lambda} \right)^{-1}$$



Optical sodium

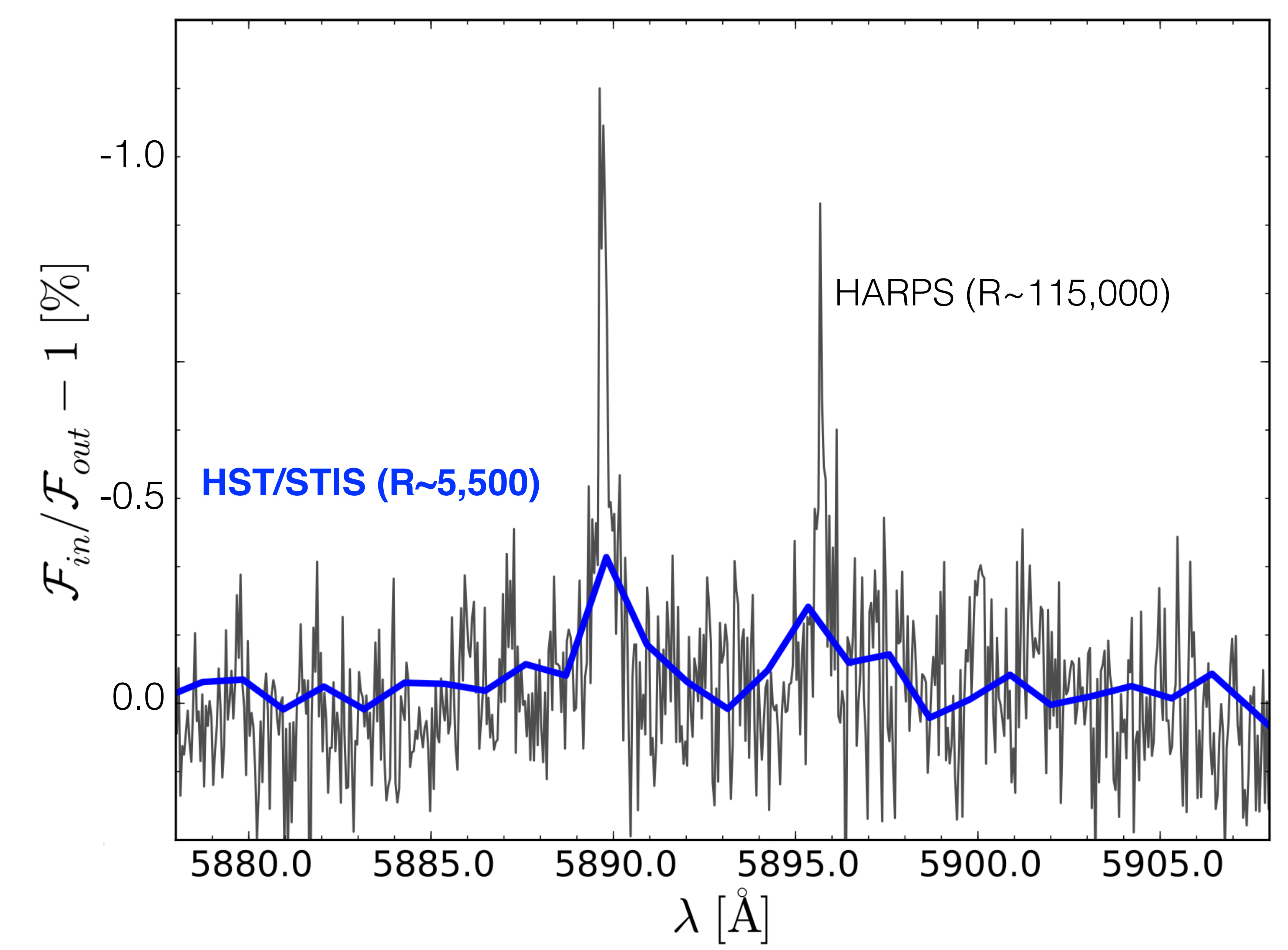
Sodium detection in HD 189733b w/ *HST*

Huitson et al. (2012)



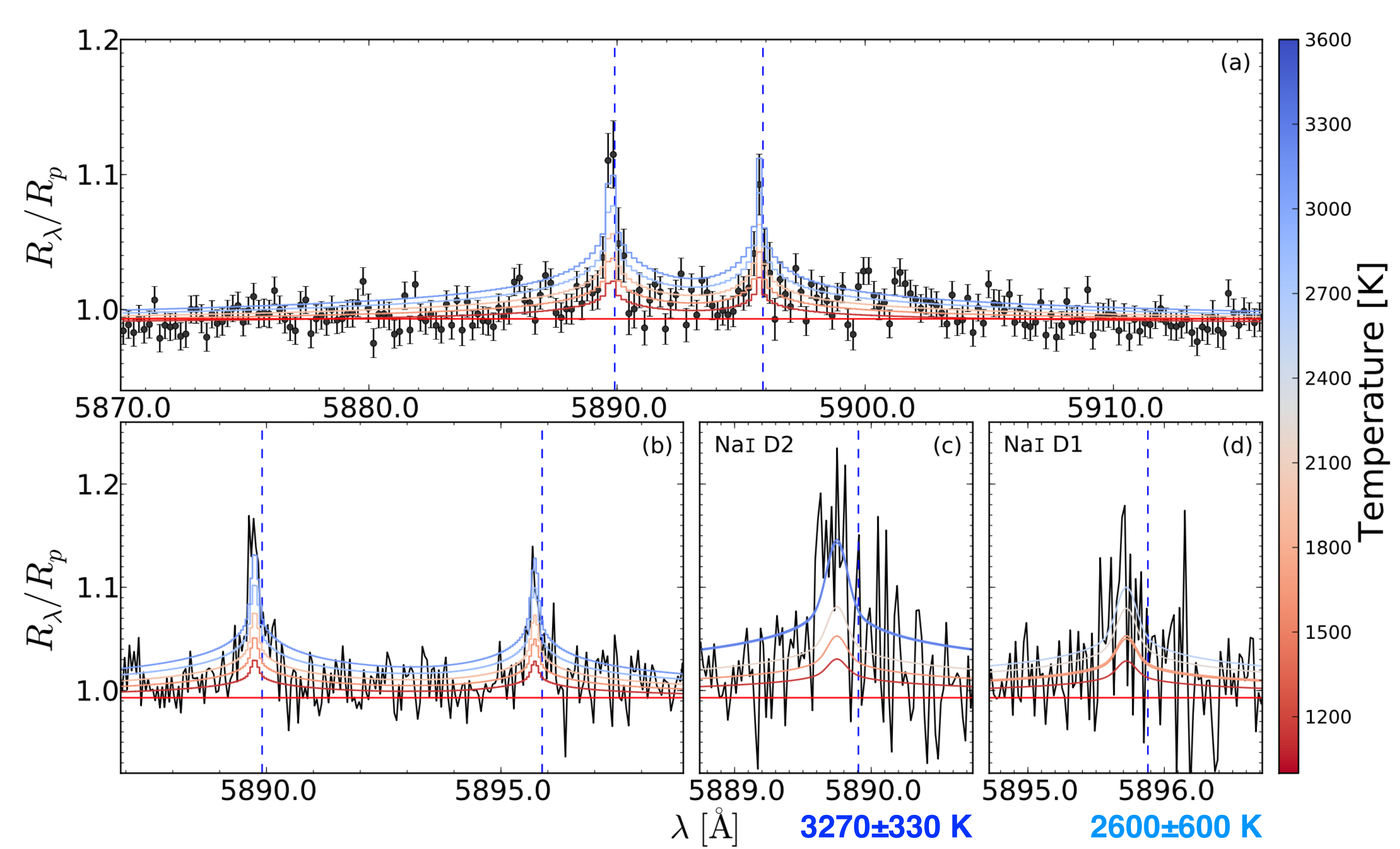
Sodium detection in HD 189733b w/ HARPS

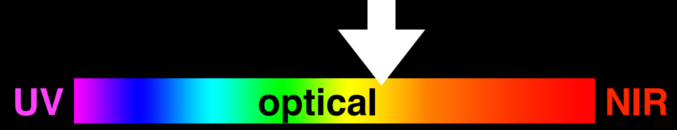
Wyttenbach et al. (2015)



Sodium detection in HD 189733b w/ HARPS

Wyttenbach et al. (2015)

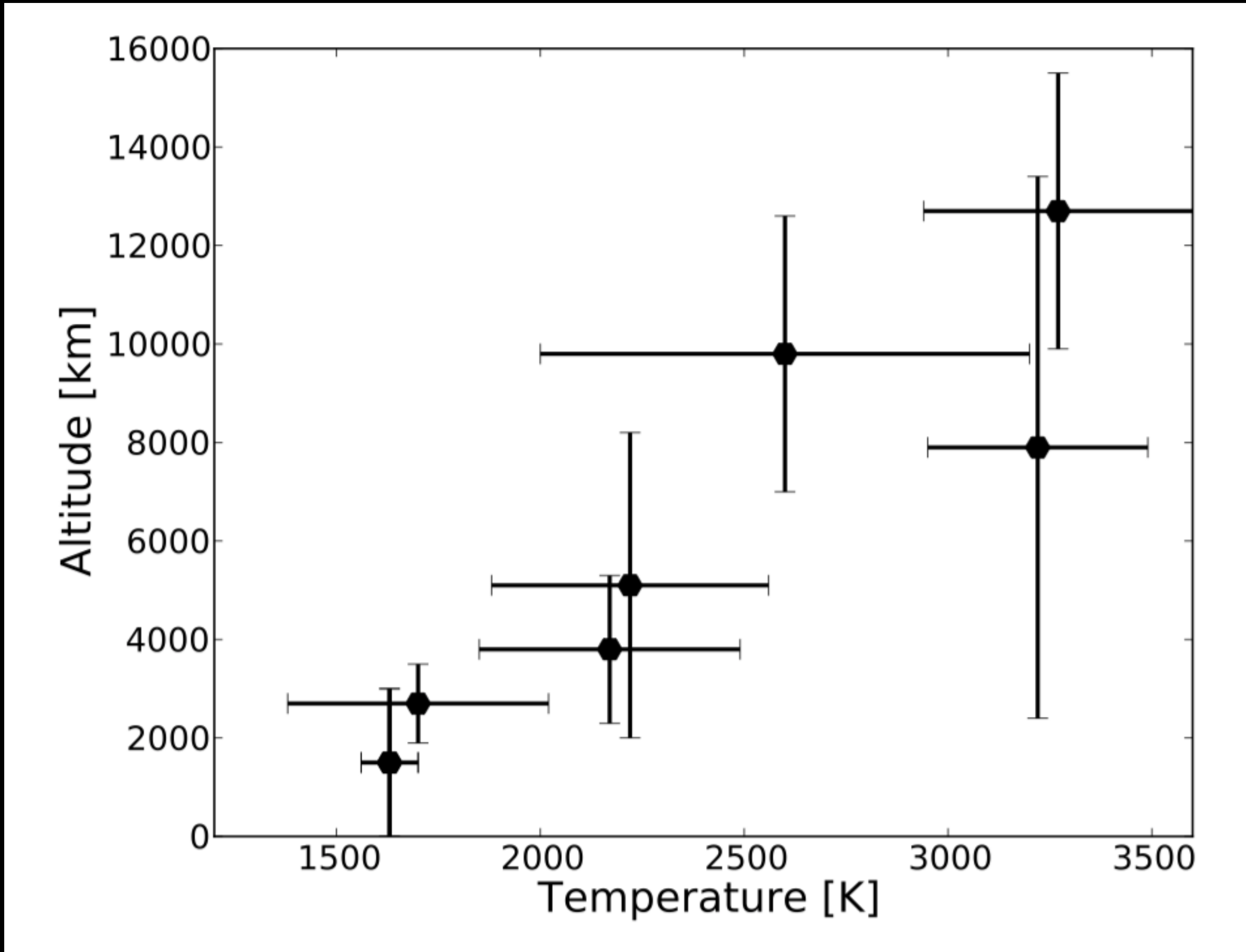


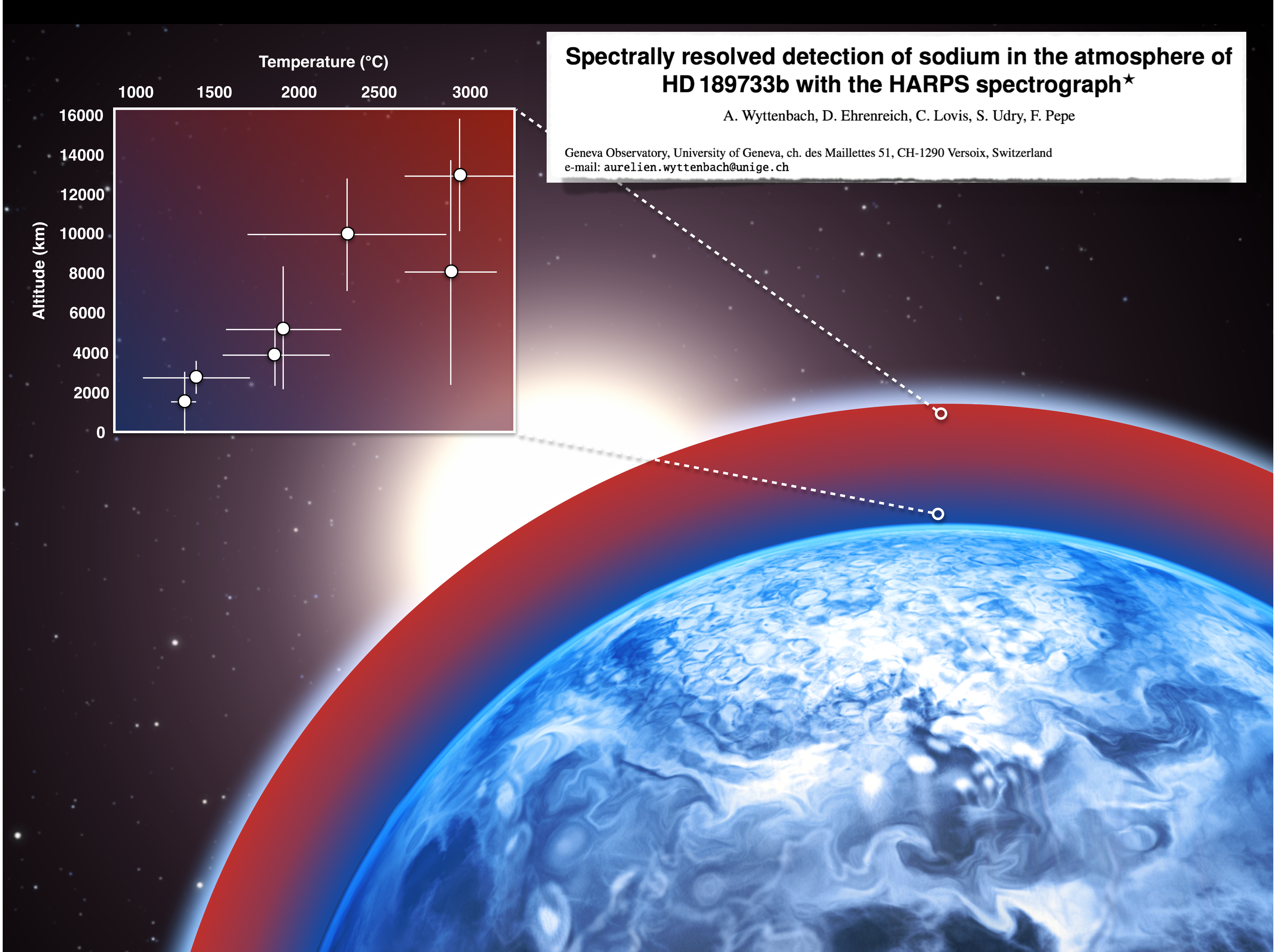


Optical sodium

Sodium detection in HD 189733b w/ HARPS

Wyttenbach et al. (2015)





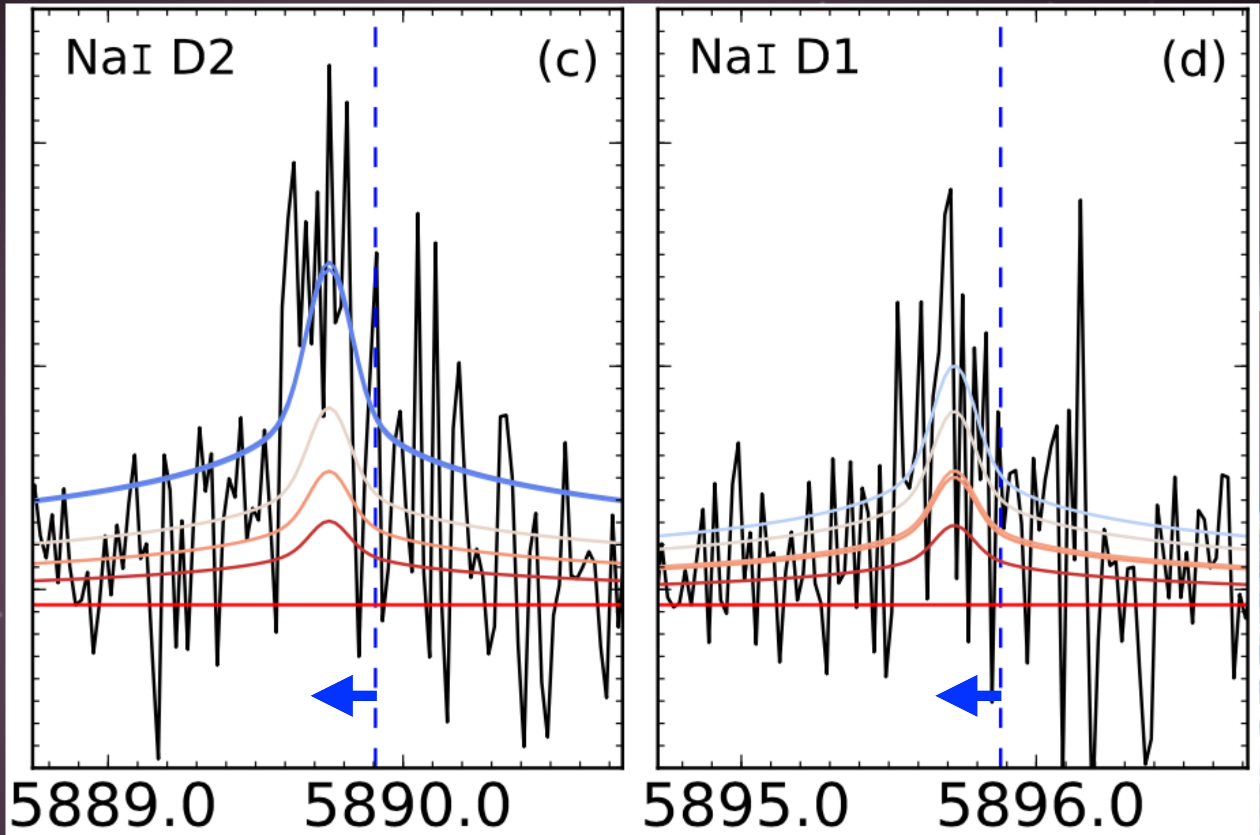
Spectrally resolved detection of sodium in the atmosphere of HD 189733b with the HARPS spectrograph★

A. Wyttenbach, D. Ehrenreich, C. Lovis, S. Udry, F. Pepe

Geneva Observatory, University of Geneva, ch. des Maillettes 51, CH-1290 Versoix, Switzerland
e-mail: aurelien.wyttenbach@unige.ch

net blue shifts of ~1–10 km/s

Wyttenbach et al. (2015)



New atmospheric surveys
at high spectral resolution

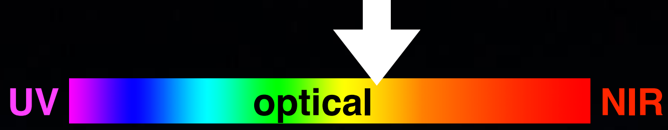
$\lambda/\Delta\lambda \approx 115{,}000$

HARPS@ESO 3.6, La Silla (Chile)

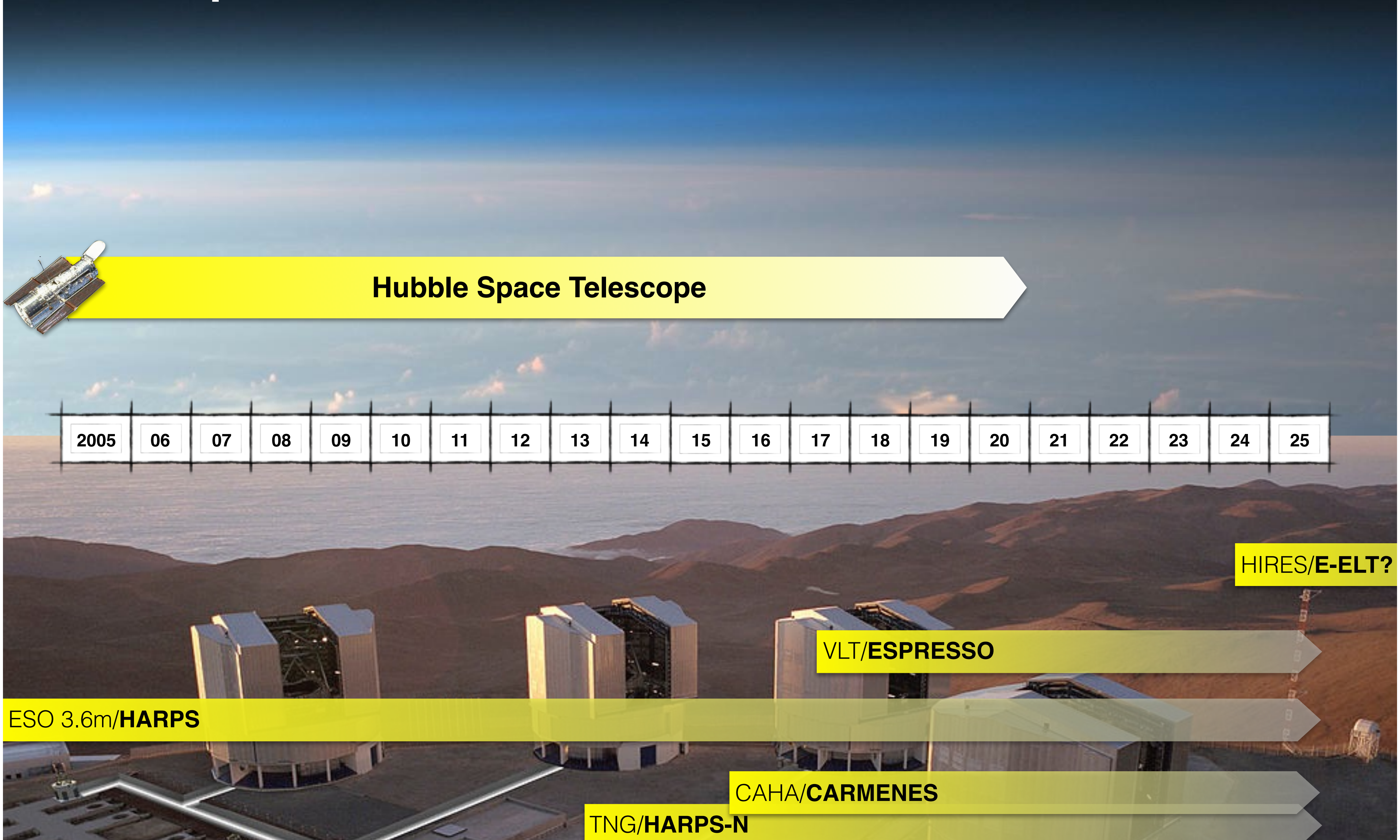
HARPS-N@TNG, La Palma (Canary Is.)

ESPRESSO@VLT

HIRES@E-ELT



Optical characterisation



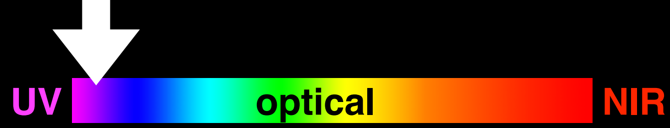
What happens at high altitude

if T↗

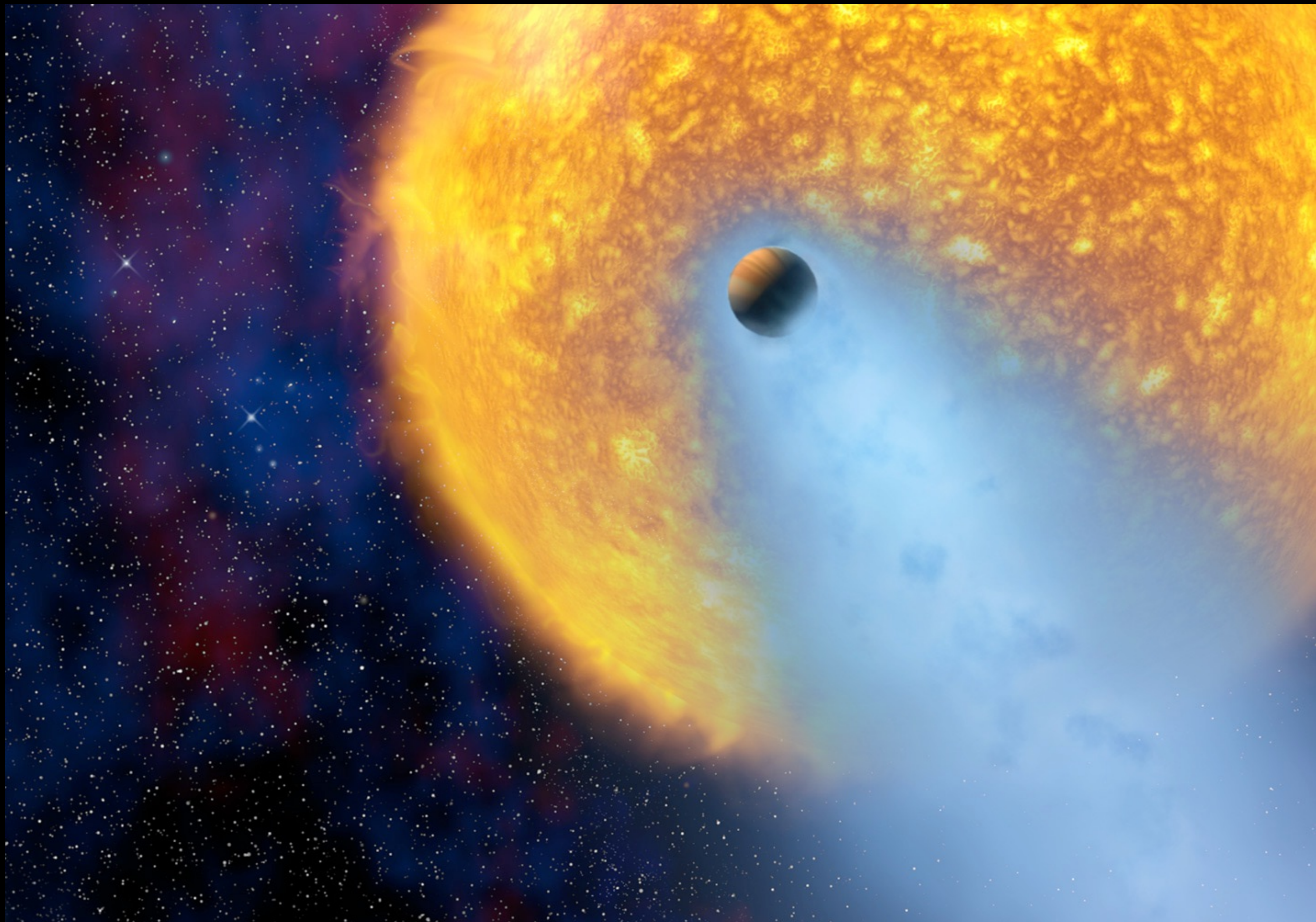
& wind↗

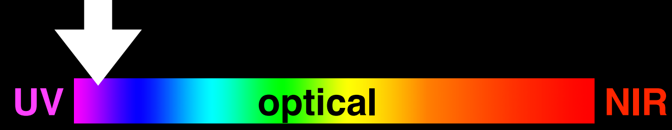
???

Courtesy A. Lecavelier des Etangs



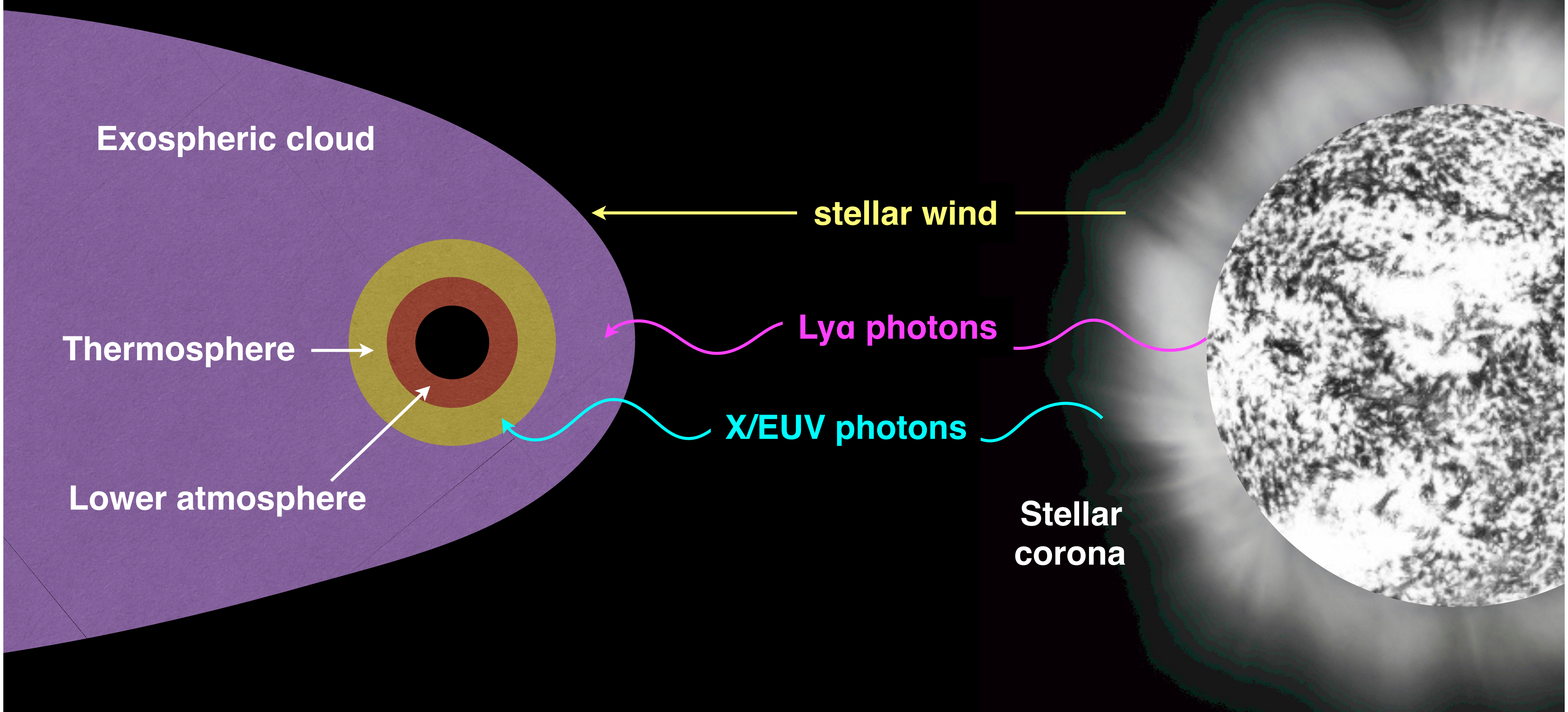
Ultraviolet hydrogen





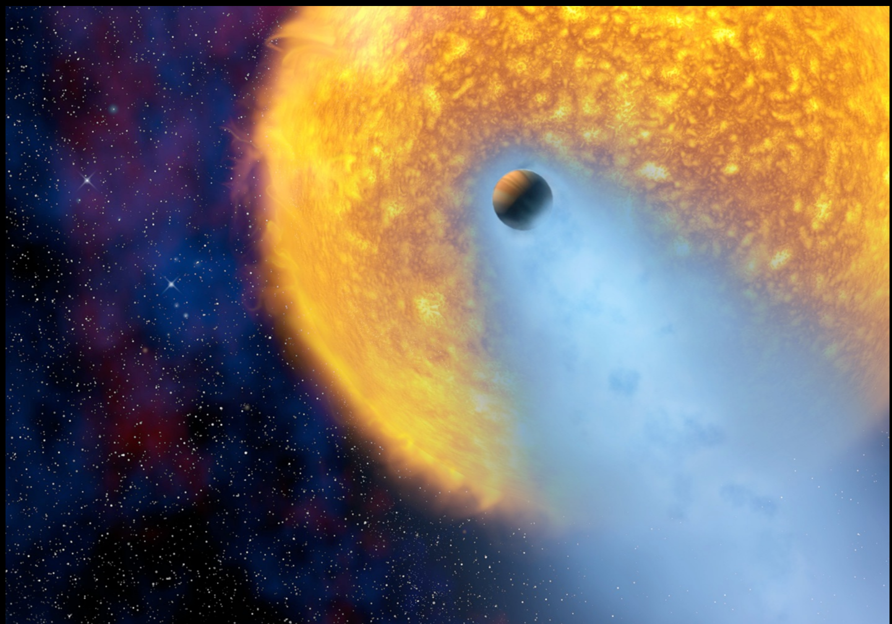
Evaporation?

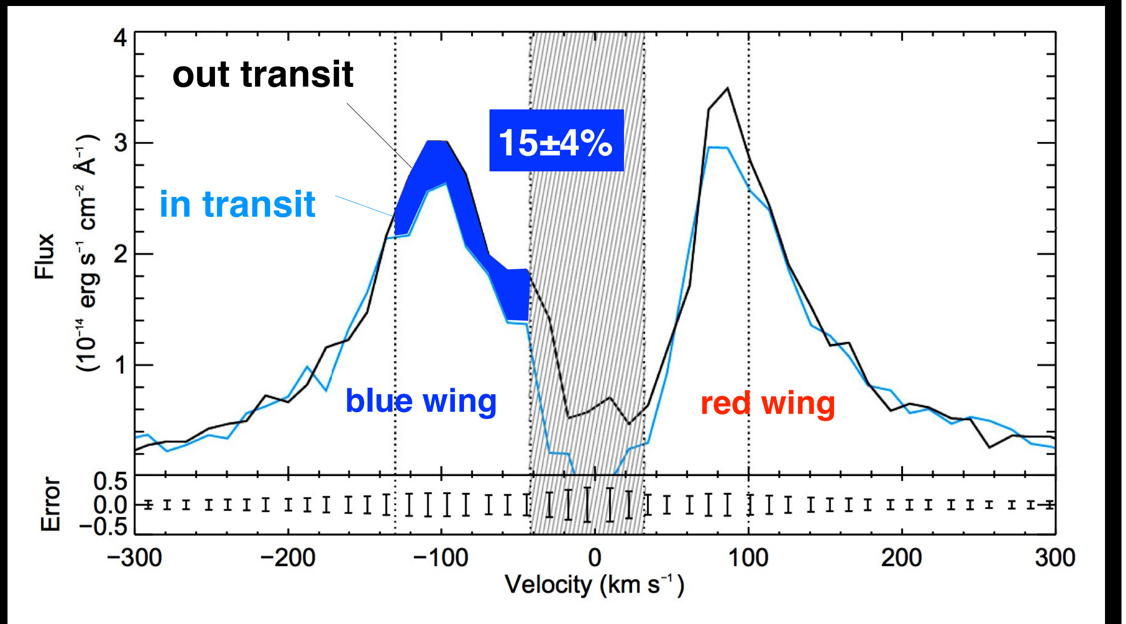
- Tremendous amounts of **XUV** energy deposited in atmospheres of close-in planets
- Leads to expansion & hydrodynamical thermal escape of **exospheres**
- Escaping atoms (hydrogen) repelled & ionised, sculpting large envelopes



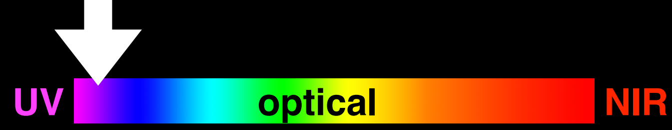
Previously...

- Hydrogen envelopes detected for several hot gas giants
- Transit observation in the stellar Lyα line (1215 Å)
- Only reachable with the Hubble Space Telescope (HST)

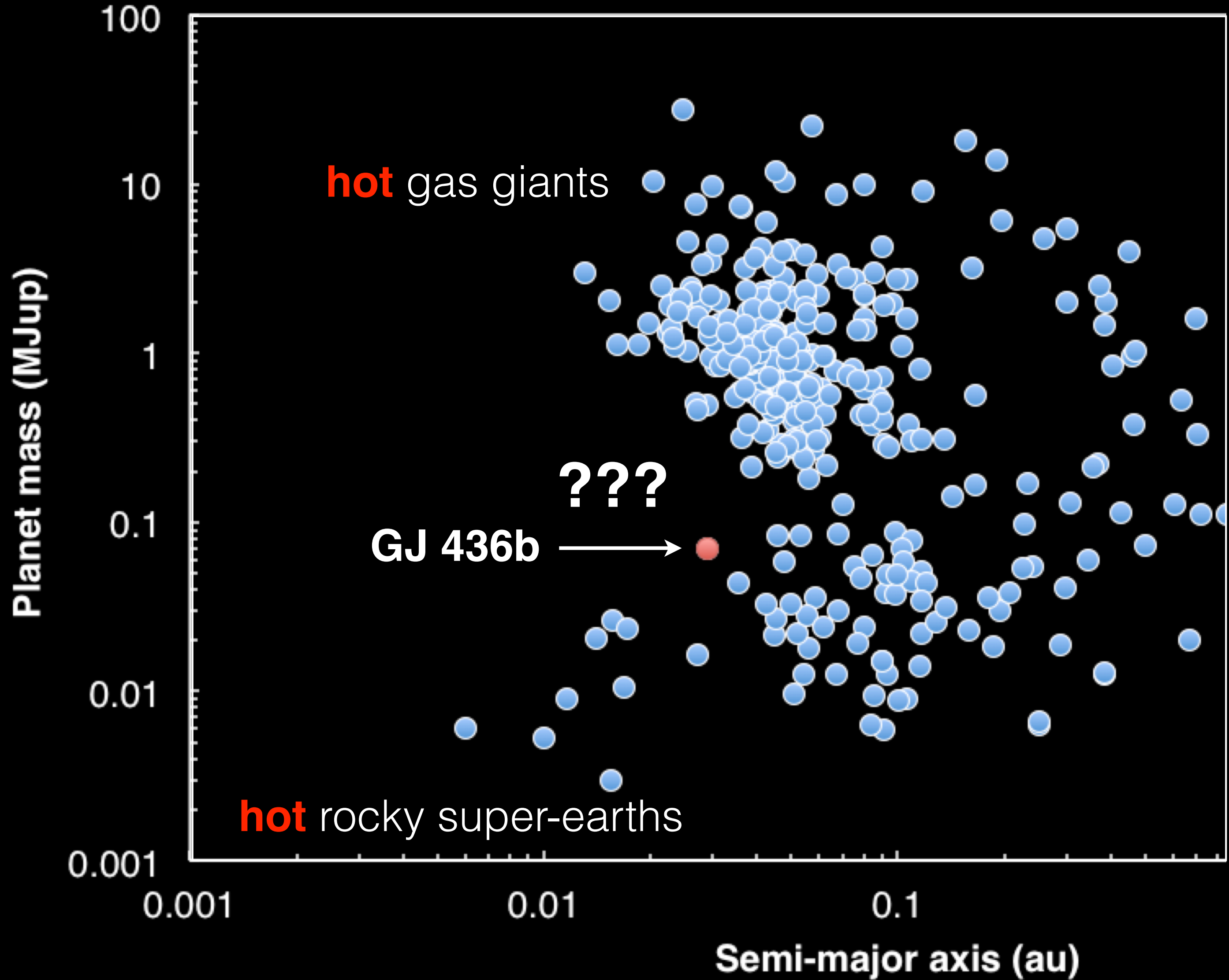




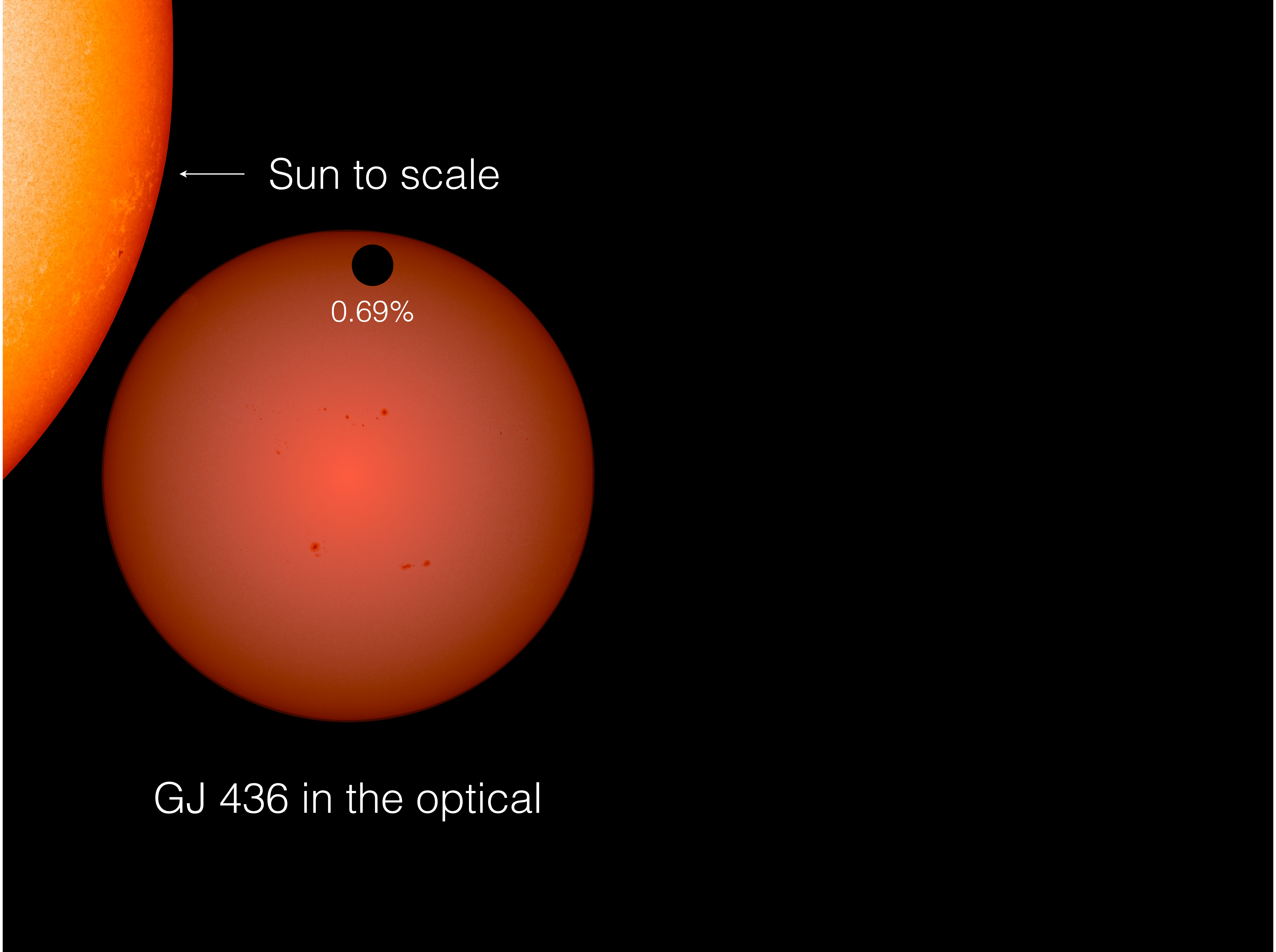
Vidal-Madjar et al. (2003, 2004)
Ehrenreich et al. (2008, 2012)
Lecavelier des Etangs et al. (2010, 2012)
Bourrier et al. (2013, 2014)



Lost population of planets?

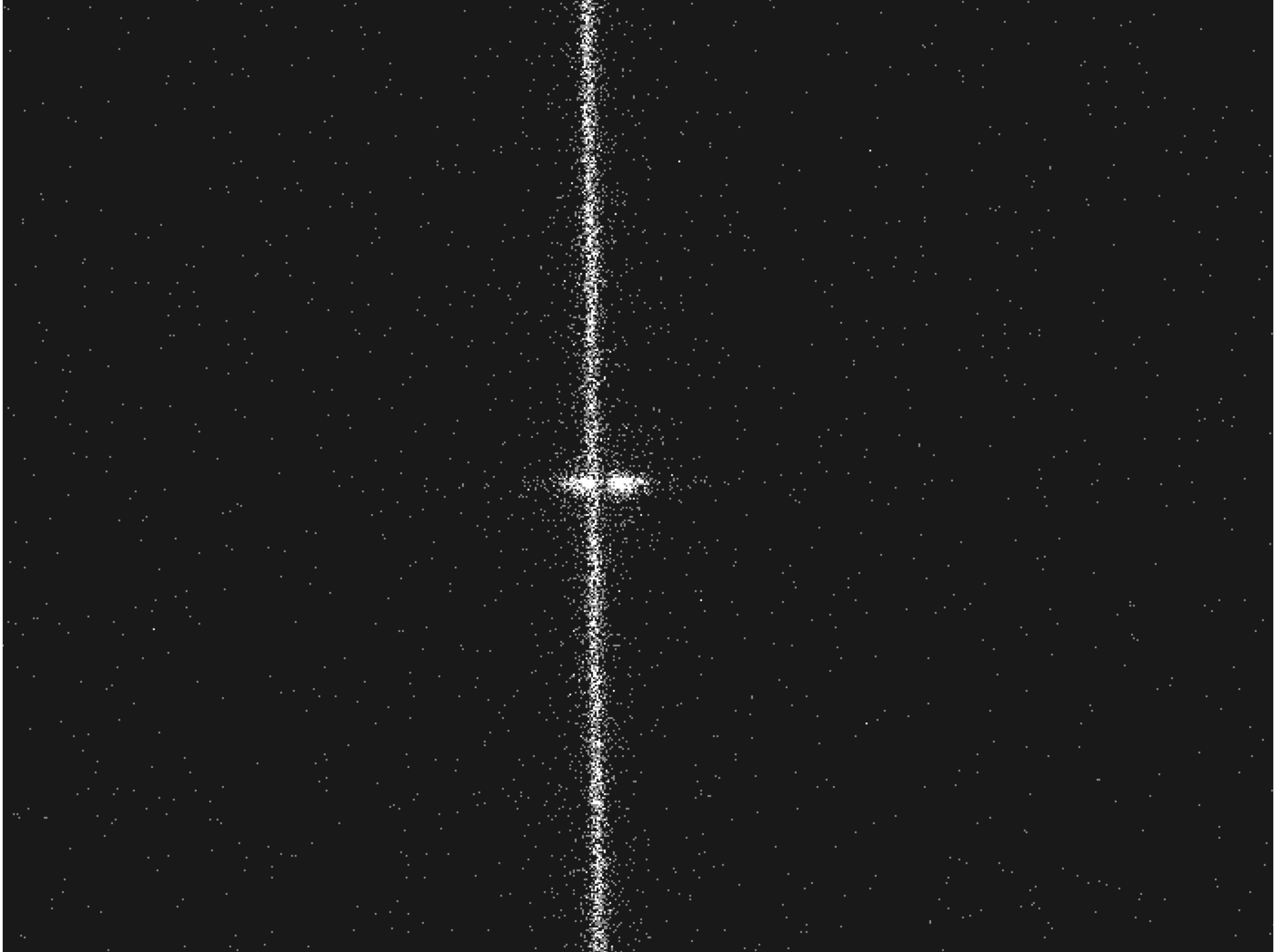


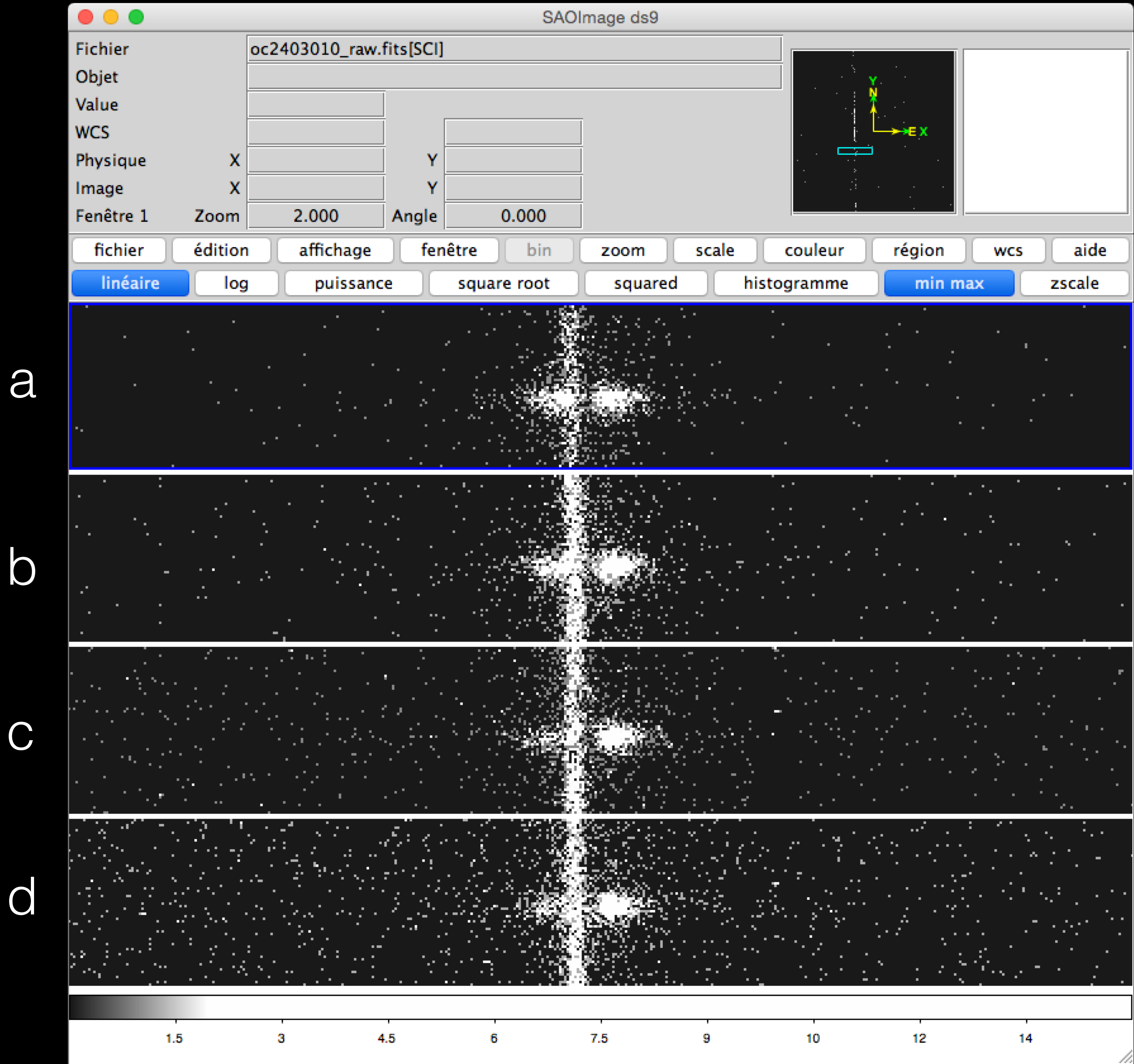
Lecavelier des Etangs et al. (2004)
Lecavelier des Etangs (2007)
Davis & Wheatley (2009)
Ehrenreich & Désert (2011)
Hansen & Murray (2012)
Owen & Jackson (2012)
Lopez & Fortney (2013)

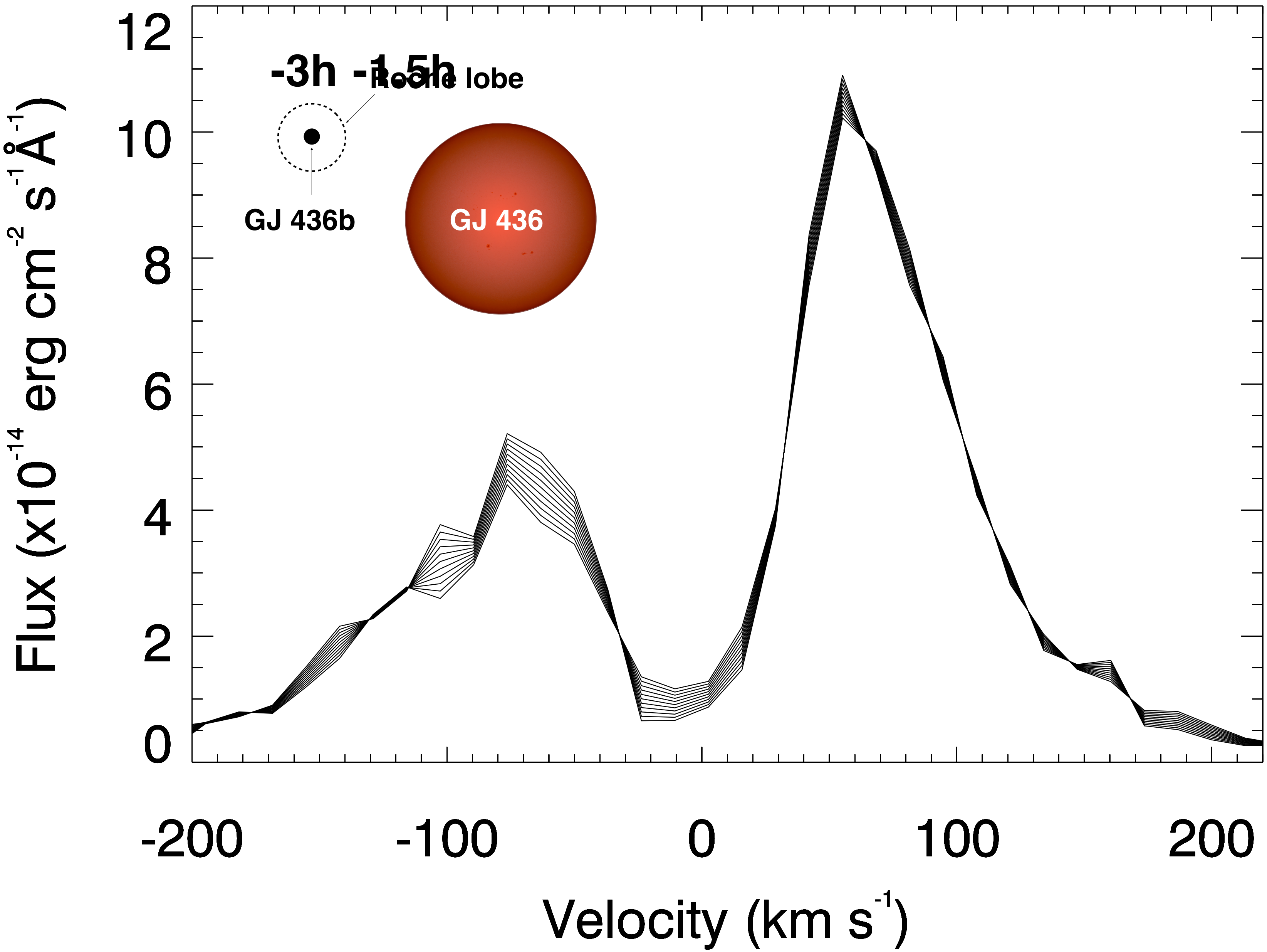

Sun to scale
0.69%
GJ 436 in the optical

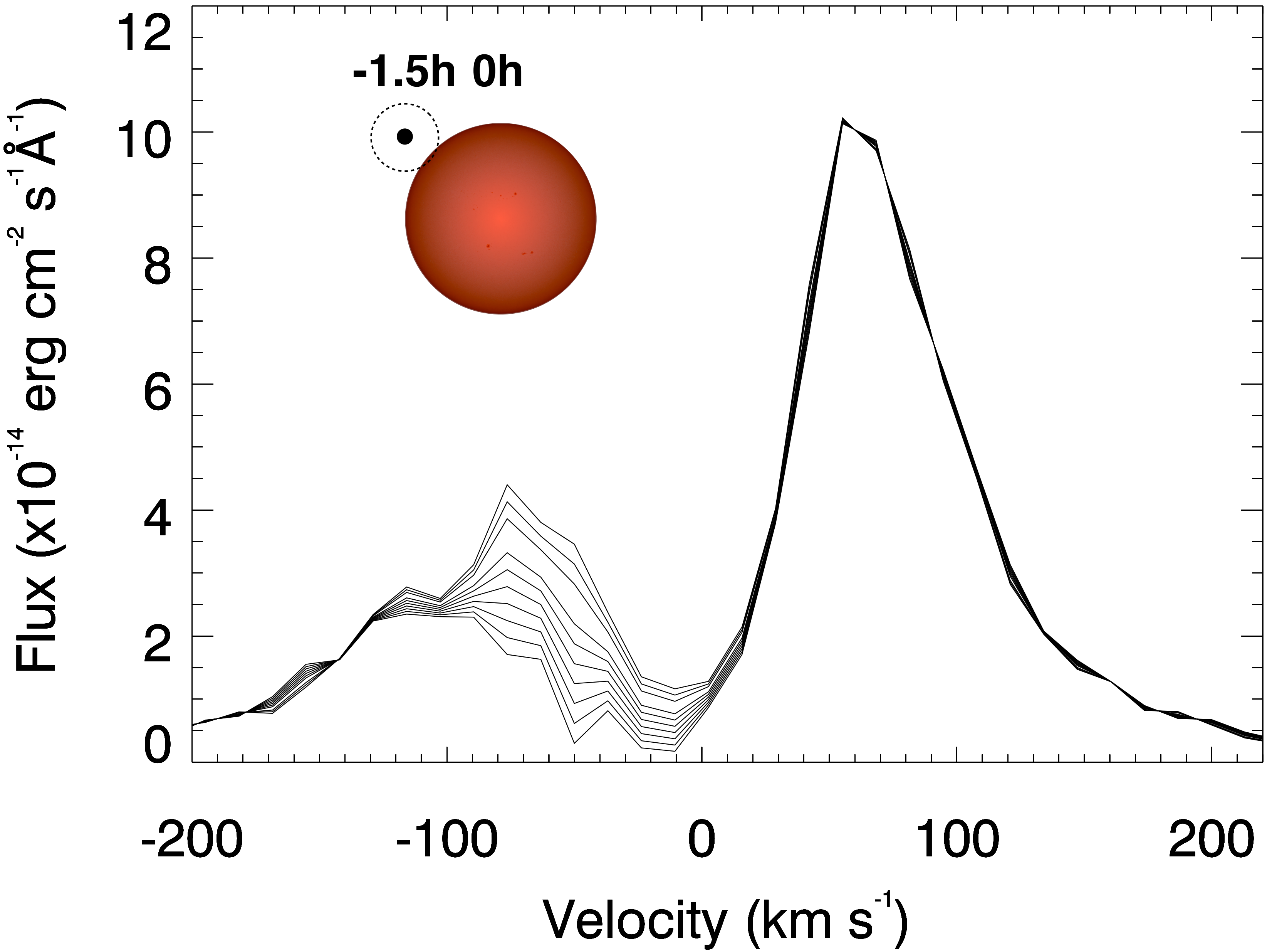
In the next slides,
we will attempt to reduce
transit spectroscopy data

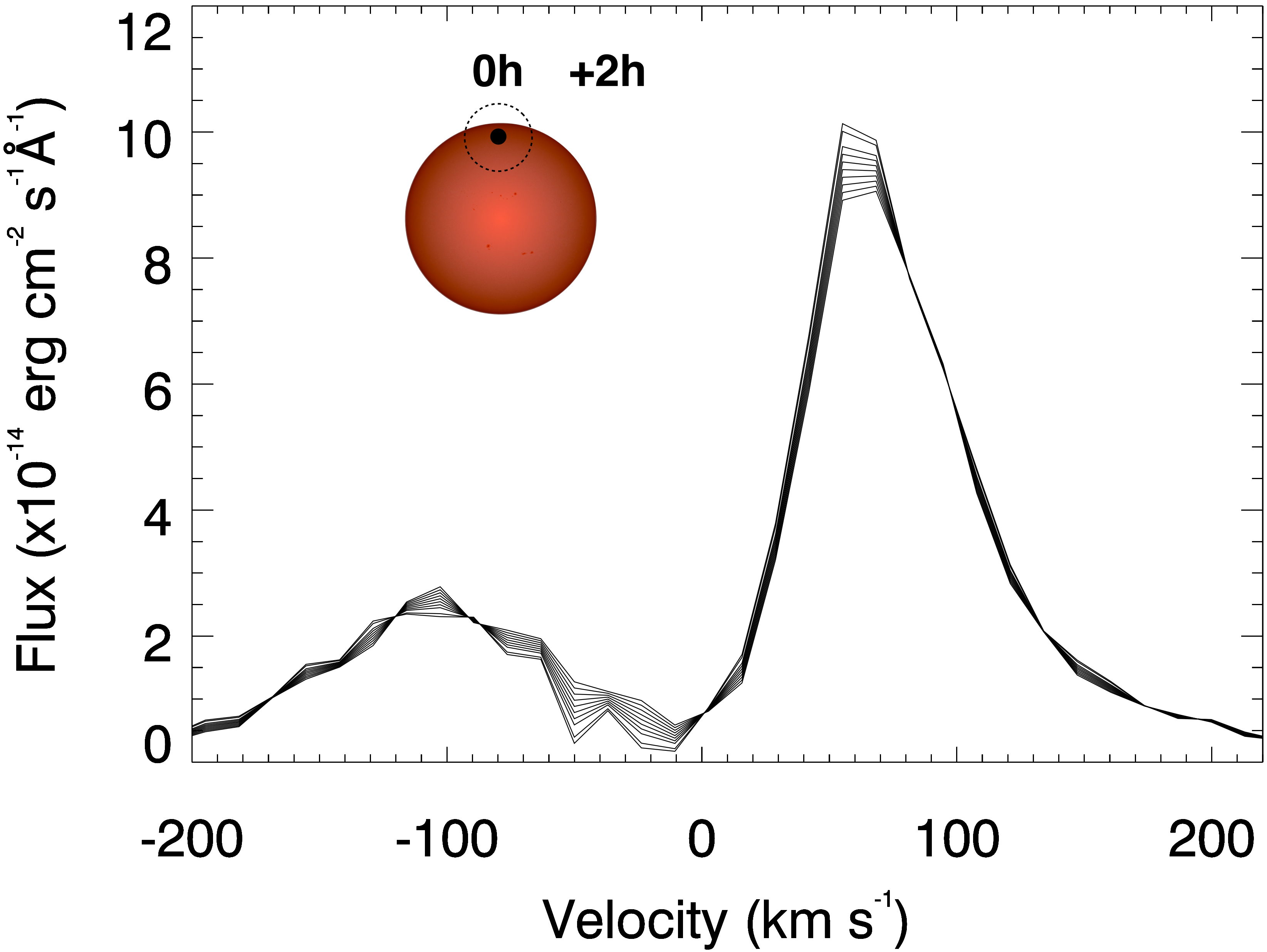
with your naked eyes

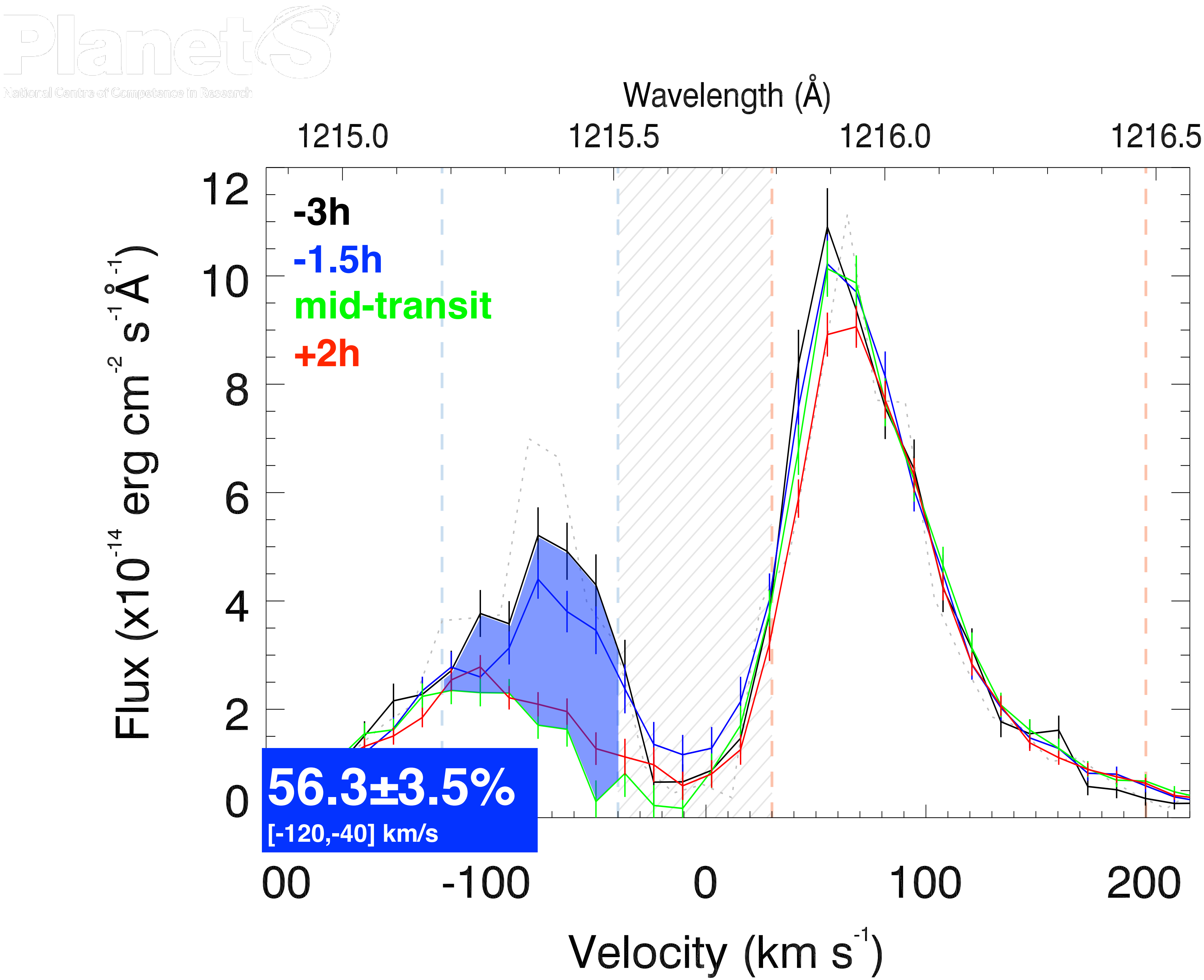



SAOImage ds9
Fichier
oc2403010_raw.fits[SCI]
Objet
Value
WCS
Physique X Y
Image X Y
Fenêtre 1 Zoom 2.000 Angle 0.000
fichier édition affichage fenêtre bin zoom scale couleur région wcs aide
linéaire log puissance square root squared histogramme min max zscale
a
b
c
d
1.5 3 4.5 6 7.5 9 10 12 14

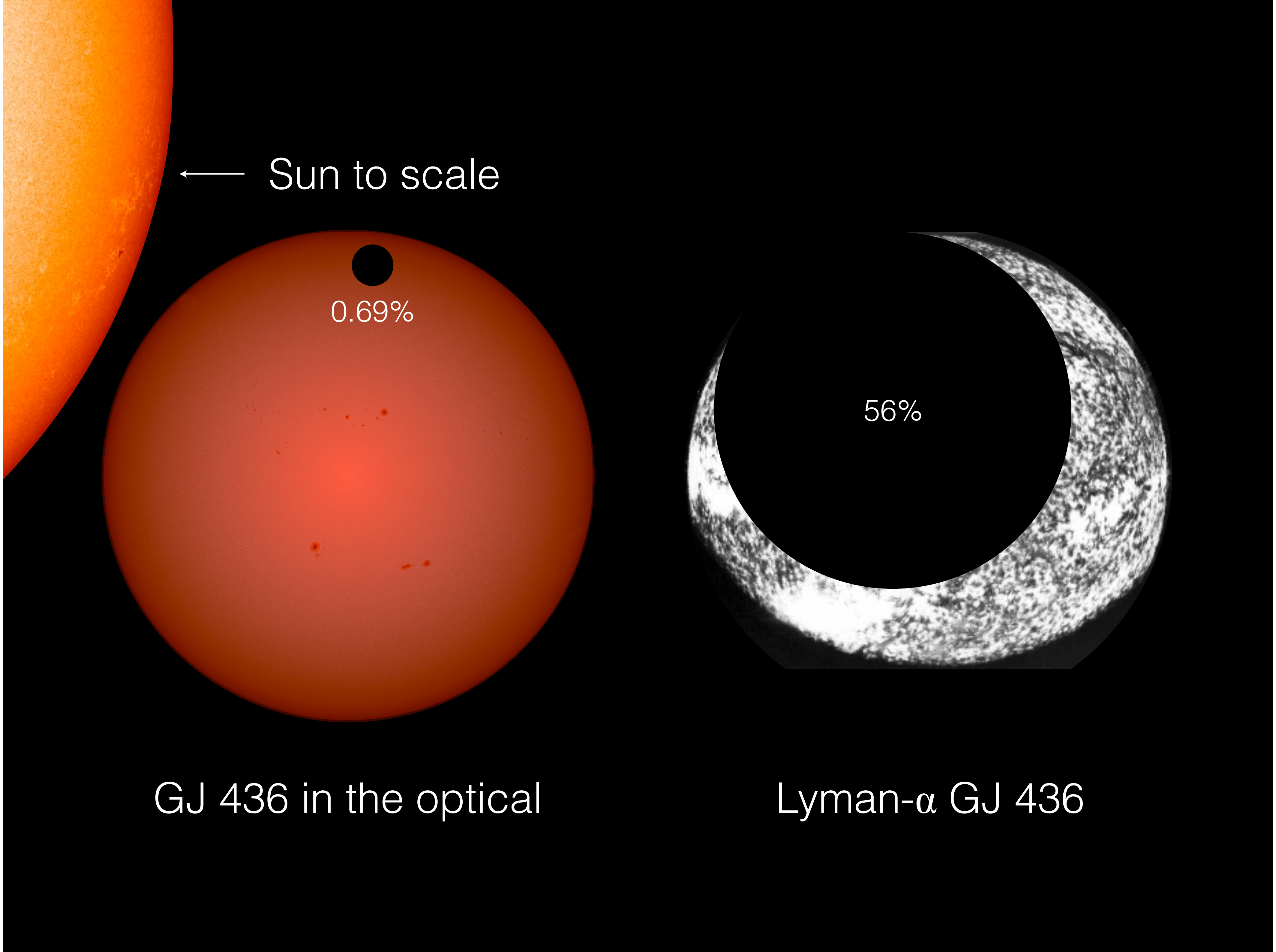

-3h
-1.5h
Roche lobe
GJ 436b
GJ 436
Flux (x10^-14 erg cm^-2 s^-1 Å^-1)
Velocity (km s^-1)
0
2
4
6
8
10
12
-200
-100
0
100
200

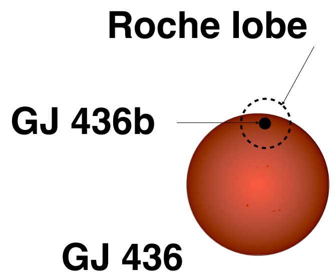

-1.5h 0h
Flux (x10^{-14} erg cm^{-2} s^{-1} Å^{-1})
12
10
8
6
4
2
0
-200
-100
0
100
200
Velocity (km s^{-1})

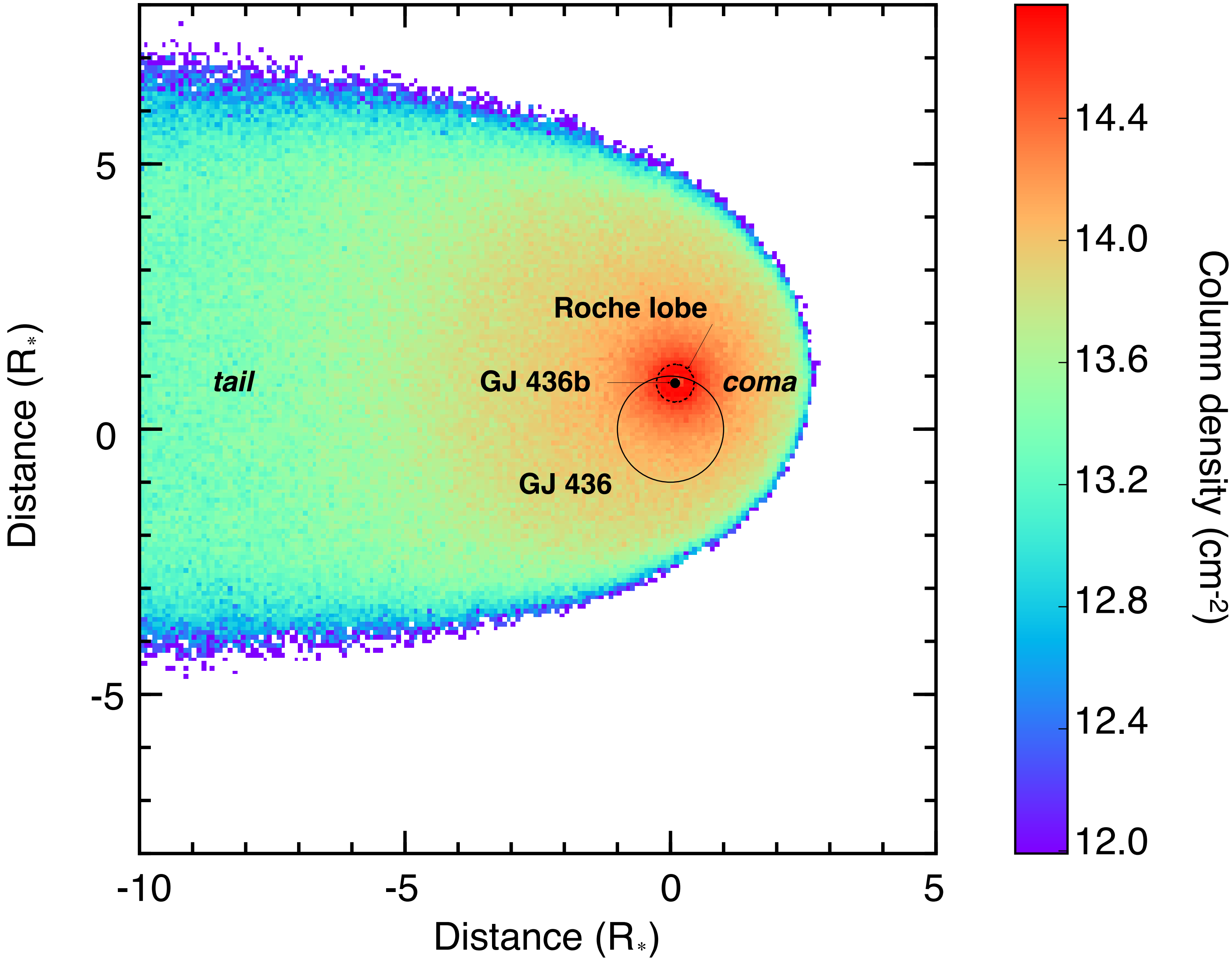

0h
+2h
Flux (x10^{-14} erg cm^{-2} s^{-1} Å^{-1})
0
2
4
6
8
10
12
-200
-100
0
100
200
Velocity (km s^{-1})



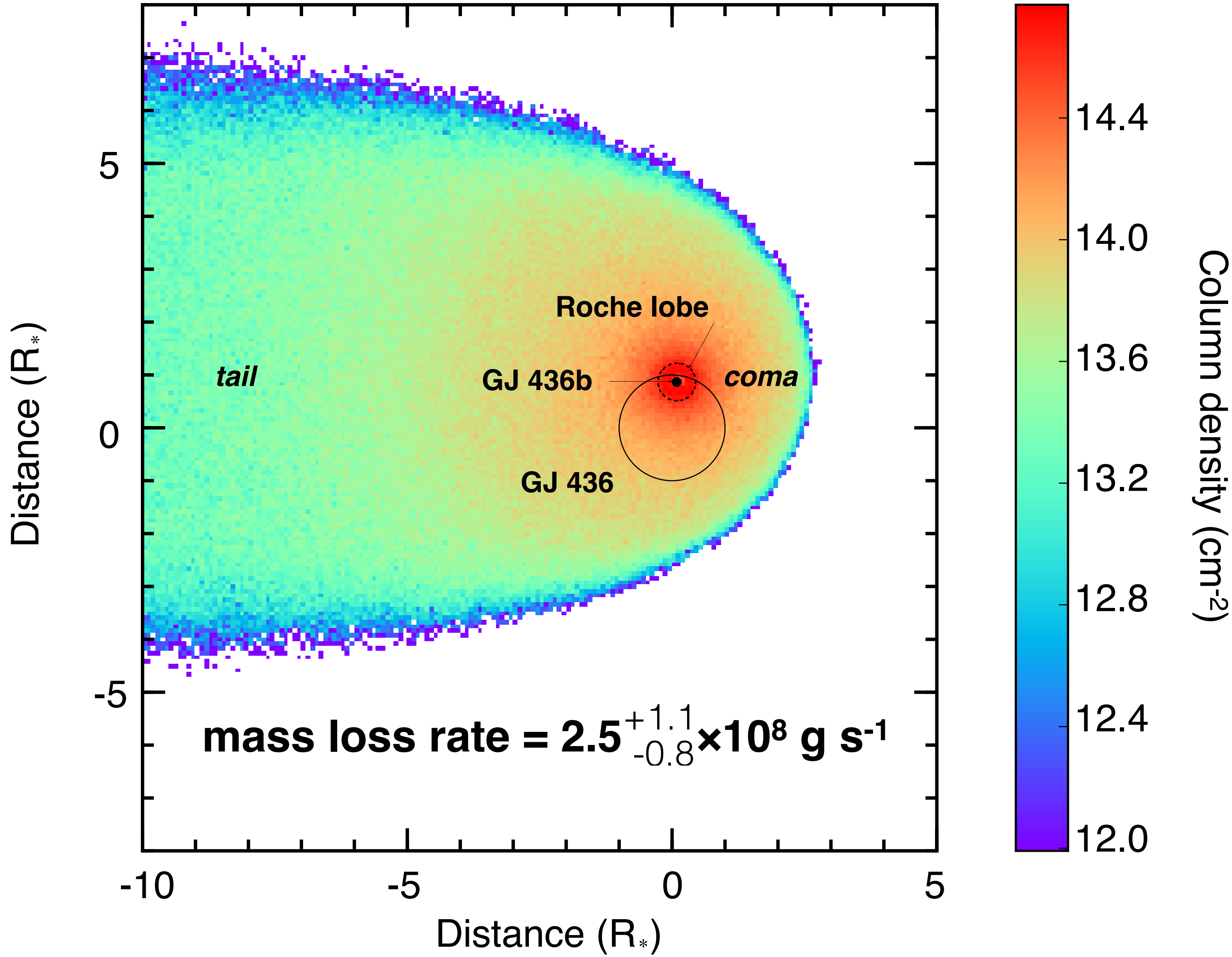
Ehrenreich et al. (2015)


Sun to scale
0.69%
56%
GJ 436 in the optical
Lyman-α GJ 436


Roche lobe
GJ 436b
GJ 436

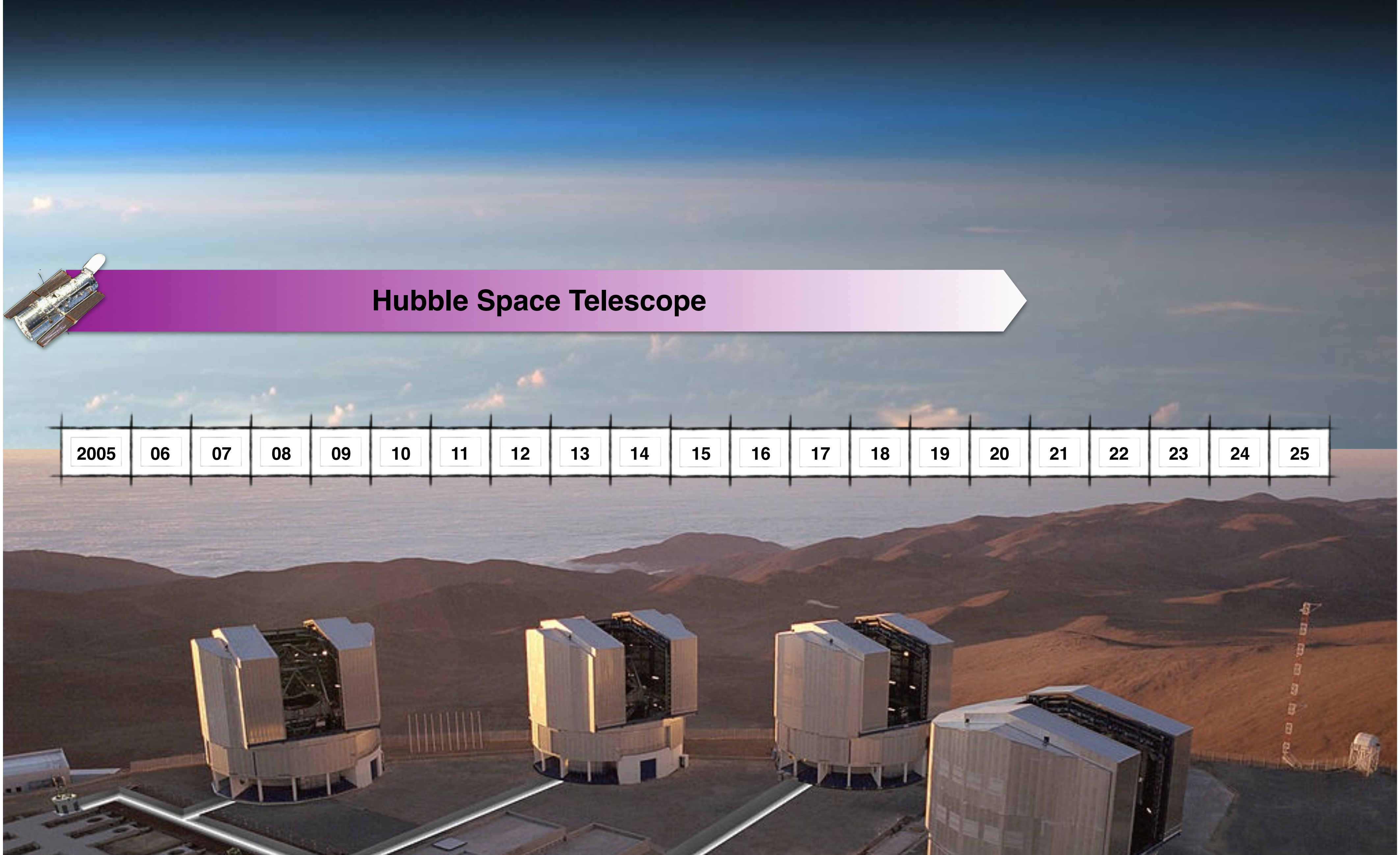


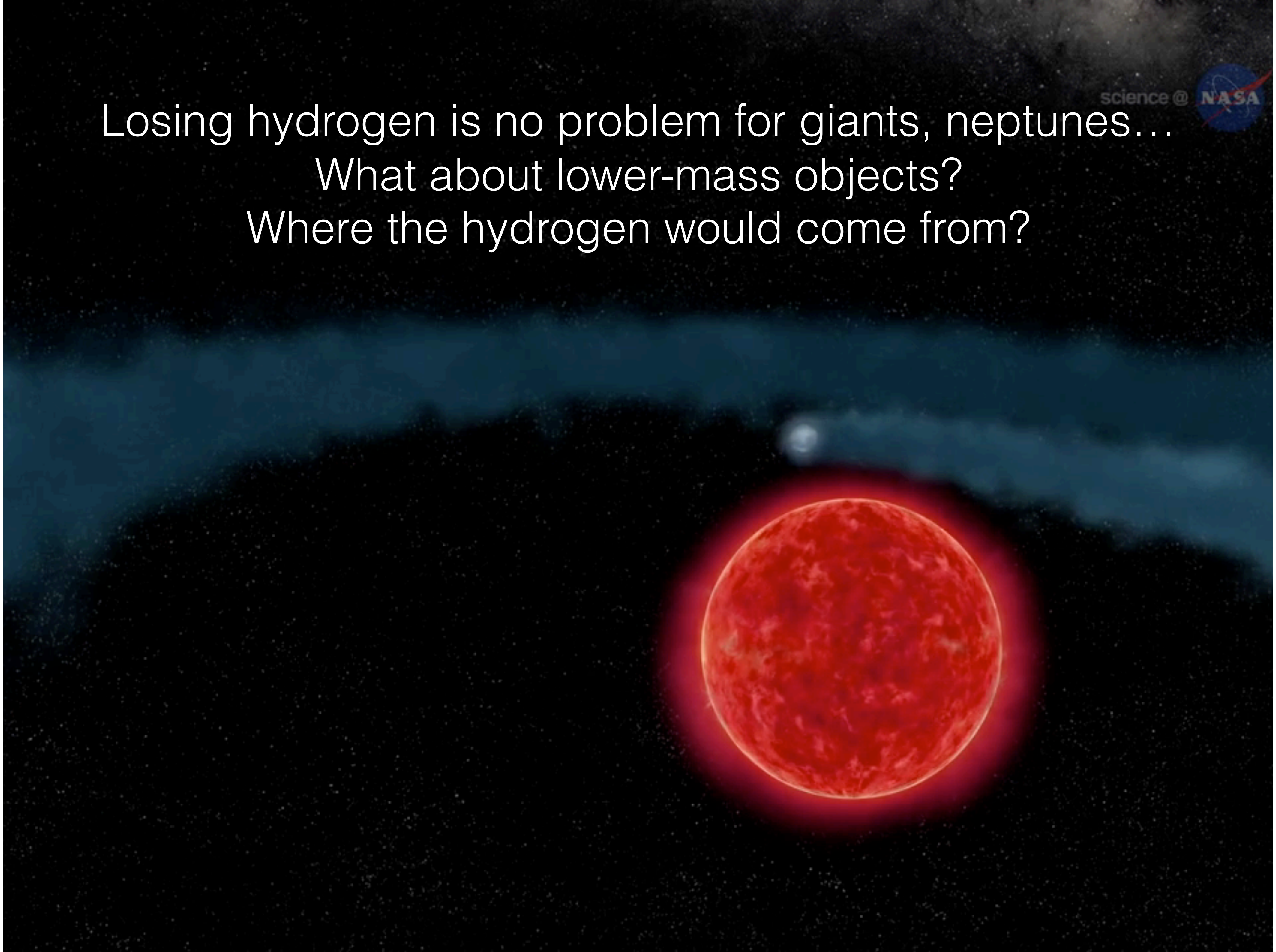
Ehrenreich et al. (2015)
Bourrier et al. (2016)



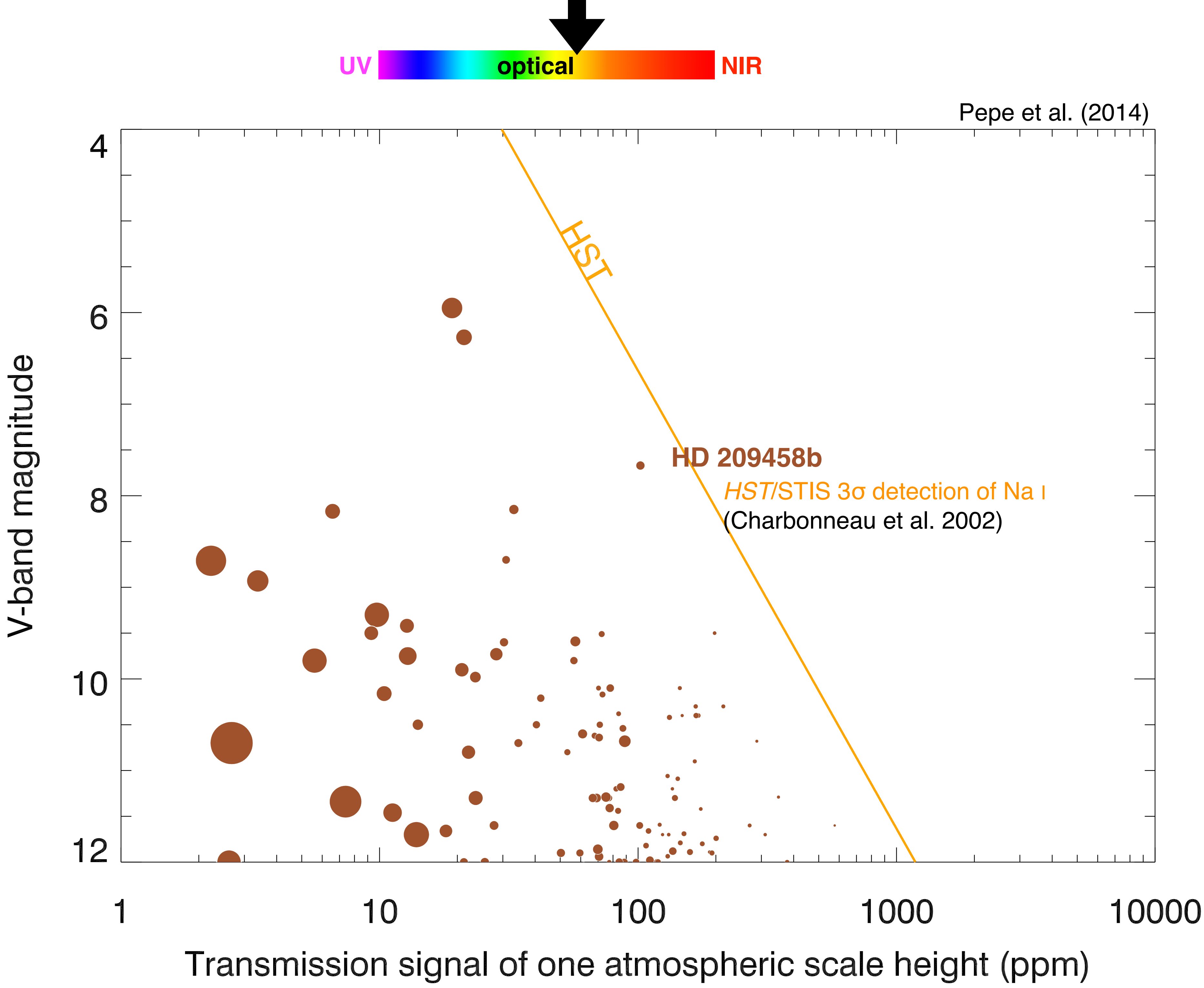
Ehrenreich et al. (2015)
Bourrier et al. (2016)

Ultraviolet characterisation




Losing hydrogen is no problem for giants, neptunes…
What about lower-mass objects?
Where the hydrogen would come from?
science @ NASA

Infrared water



UV
optical
NIR
Pepe et al. (2014)
HST
HD 209458b
HST/STIS 3σ detection of Na I
(Charbonneau et al. 2002)
V-band magnitude
4
6
8
10
12
1
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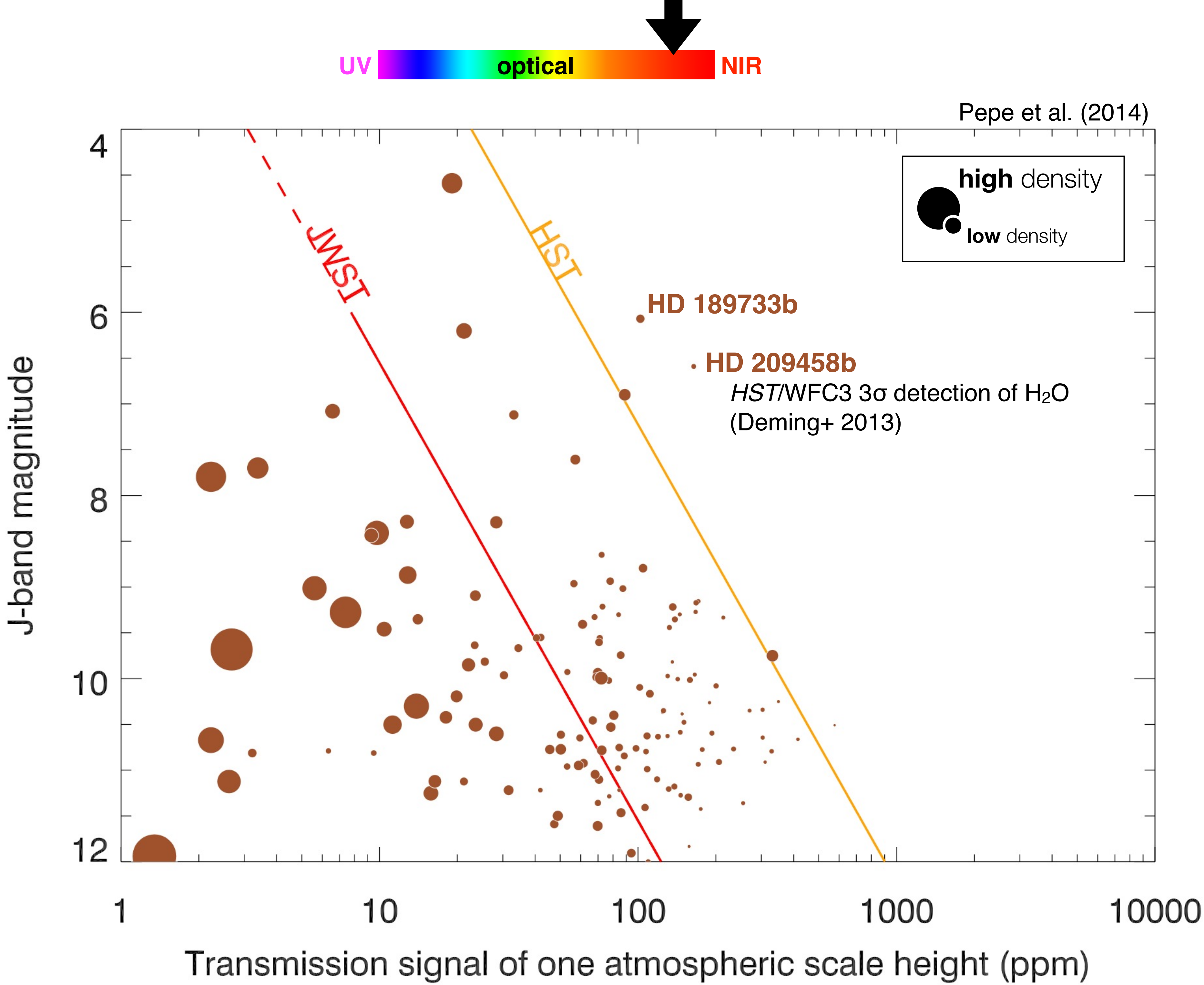
100
1000
10000
Transmission signal of one atmospheric scale height (ppm)

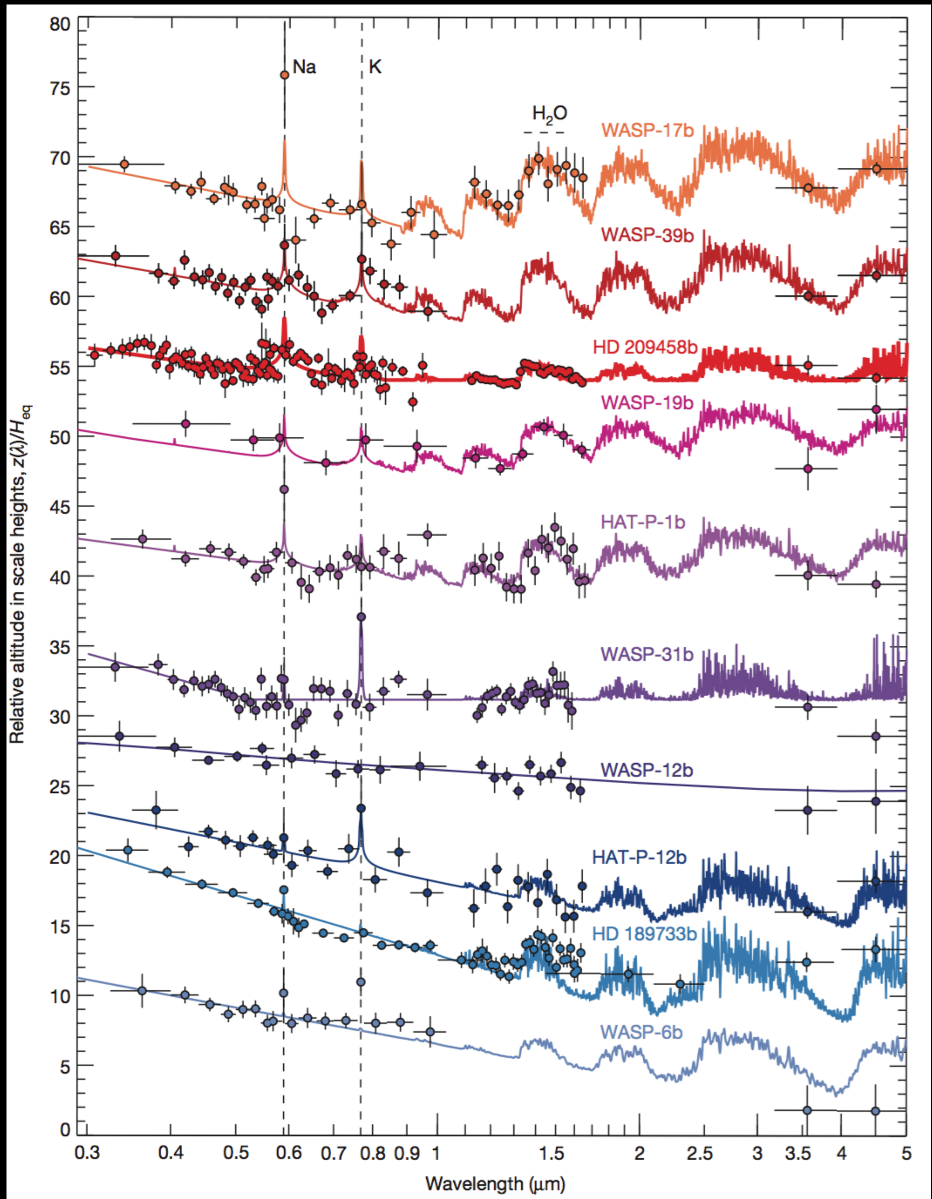


UV
optical
NIR
Pepe et al. (2014)
high density
low density
JWST
HST
HD 189733b
HD 209458b
HST/WFC3 3σ detection of H_2O
(Deming+ 2013)
J-band magnitude
4
6
8
10
12
1
10
100
1000
10000
Transmission signal of one atmospheric scale height (ppm)

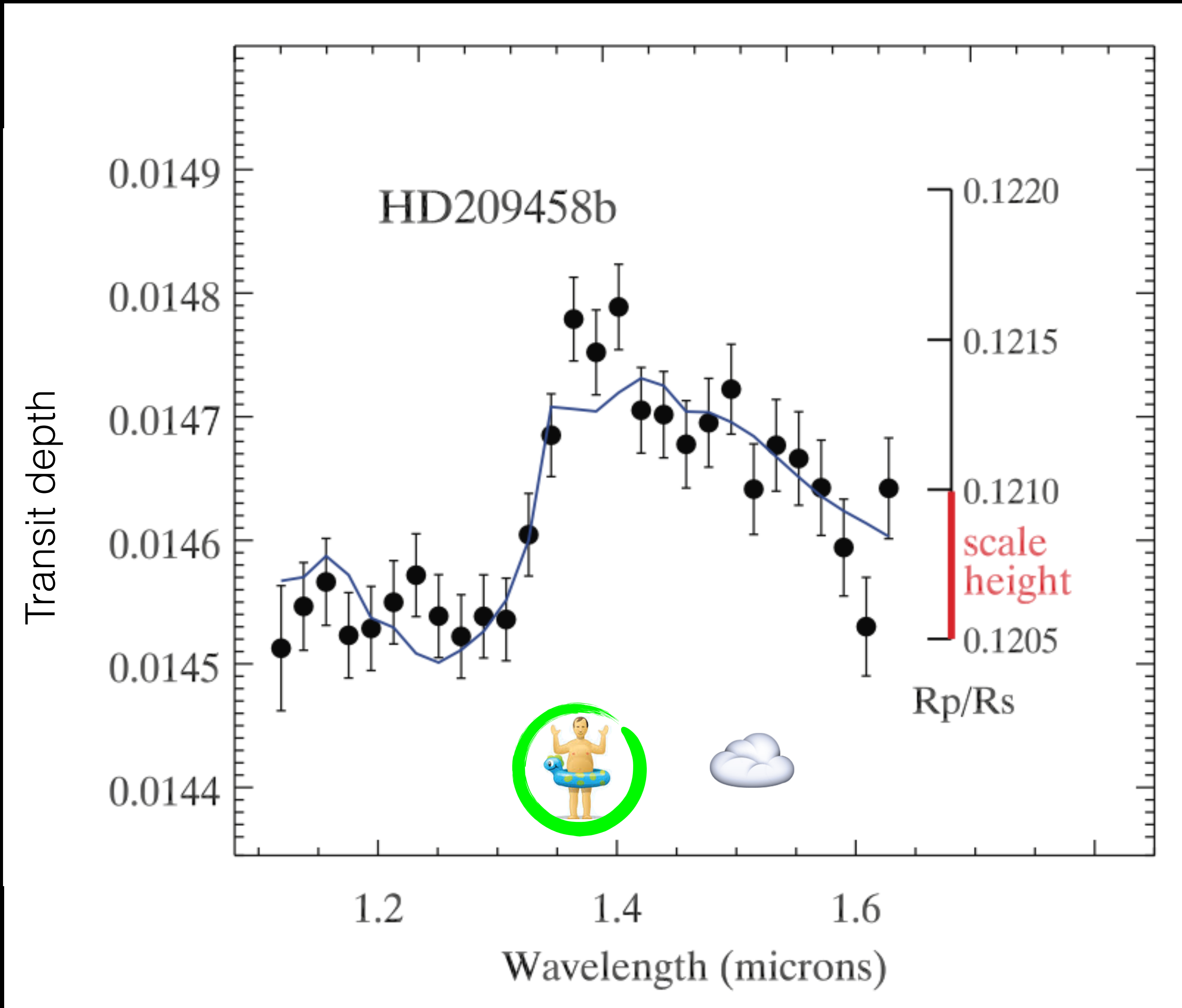
UV optical NIR

Near IR transit spectra

Sample of ~10 exoplanets Sing et al. (2016)



Deming et al. (2013)

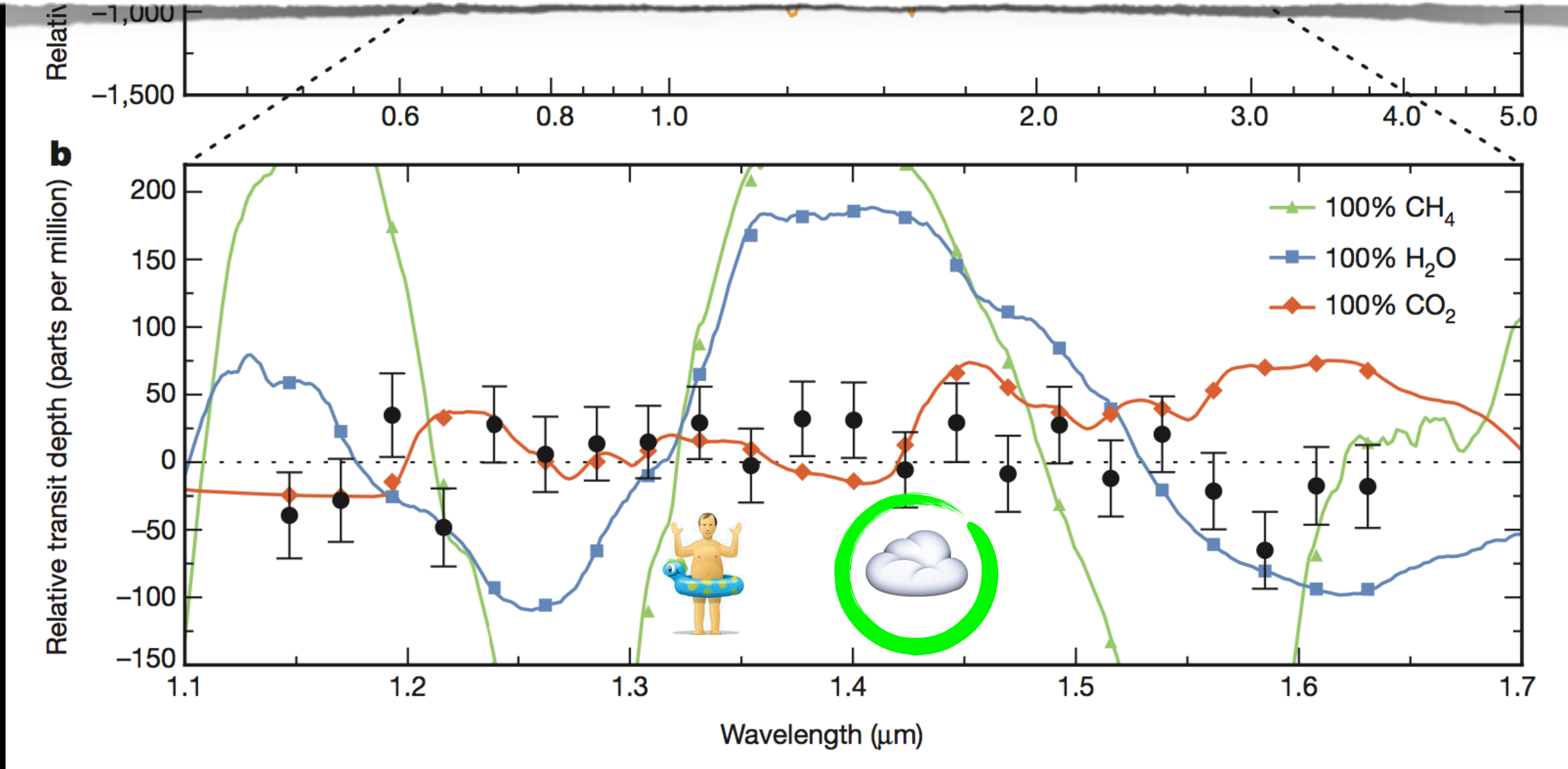


LETTER

doi:10.1038/nature12888

Clouds in the atmosphere of the super-Earth exoplanet GJ 1214b

Laura Kreidberg[1], Jacob L. Bean[1], Jean-Michel Désert[2,3], Björn Benneke[4], Drake Deming[5], Kevin B. Stevenson[1], Sara Seager[4], Zachory Berta-Thompson[6,7], Andreas Seifahrt[1] & Derek Homeier[8]

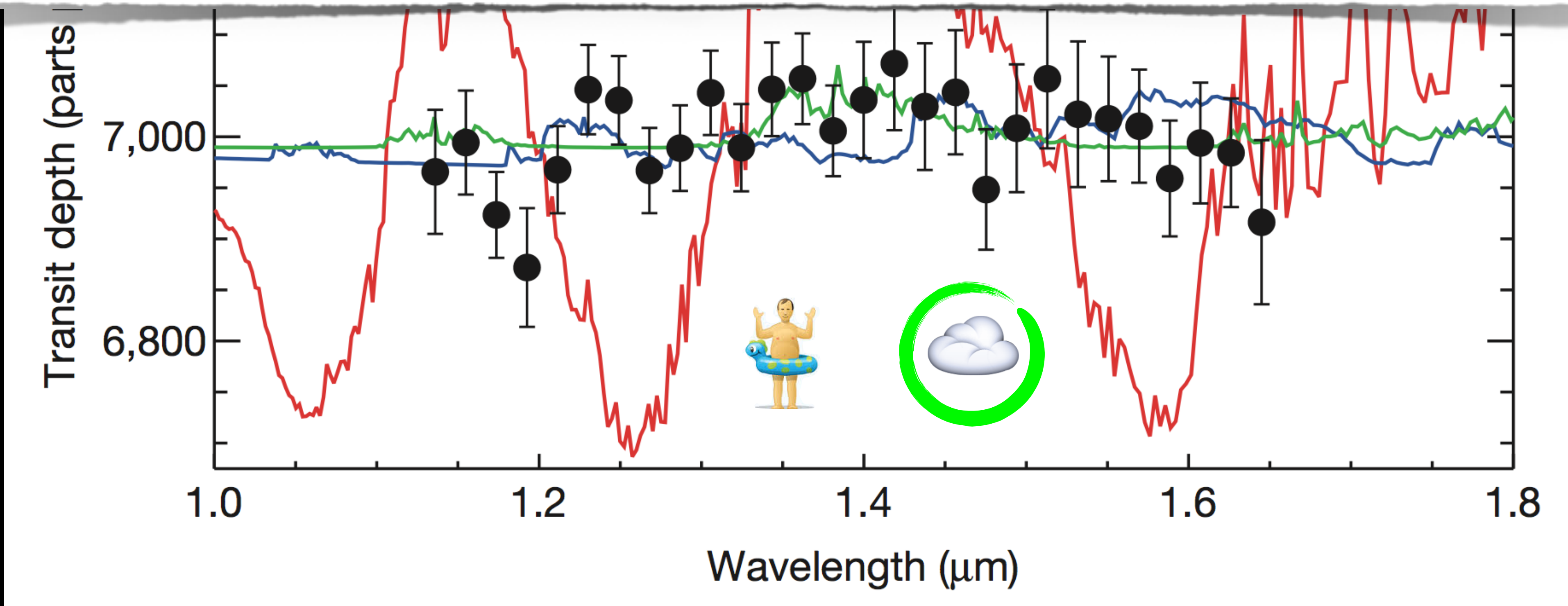


LETTER

doi:10.1038/nature12887

A featureless transmission spectrum for the Neptune-mass exoplanet GJ 436b

Heather A. Knutson[1], Björn Benneke[1,2], Drake Deming[3] & Derek Homeier[4]

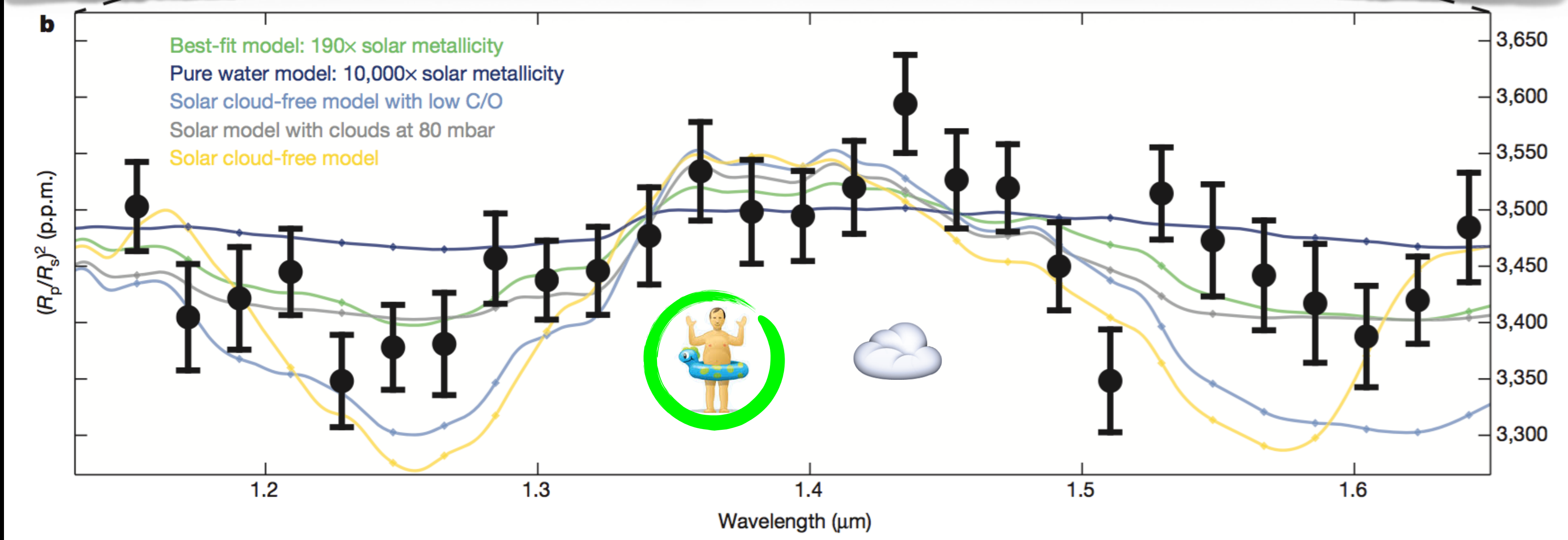


LETTER

doi:10.1038/nature13785

Water vapour absorption in the clear atmosphere of a Neptune-sized exoplanet

Jonathan Fraine[1,2,3], Drake Deming[1,4], Bjorn Benneke[3], Heather Knutson[3], Andrés Jordán[2], Néstor Espinoza[2], Nikku Madhusudhan[5], Ashlee Wilkins[1] & Kamen Todorov[6]



The Astrophysical Journal, 794:155 (10pp), 2014 October 20 doi:10.1088/0004-637X/794/2/155

HUBBLE SPACE TELESCOPE NEAR-IR TRANSMISSION SPECTROSCOPY OF THE SUPER-EARTH HD 97658B

Heather A. Knutson[1], Diana Dragomir[2,3], Laura Kreidberg[4], Eliza M.-R. Kempton[5], P. R. McCullough[6], Jonathan J. Fortney[7], Jacob L. Bean[4], Michael Gillon[8], Derek Homeier[9], and Andrew W. Howard[10]
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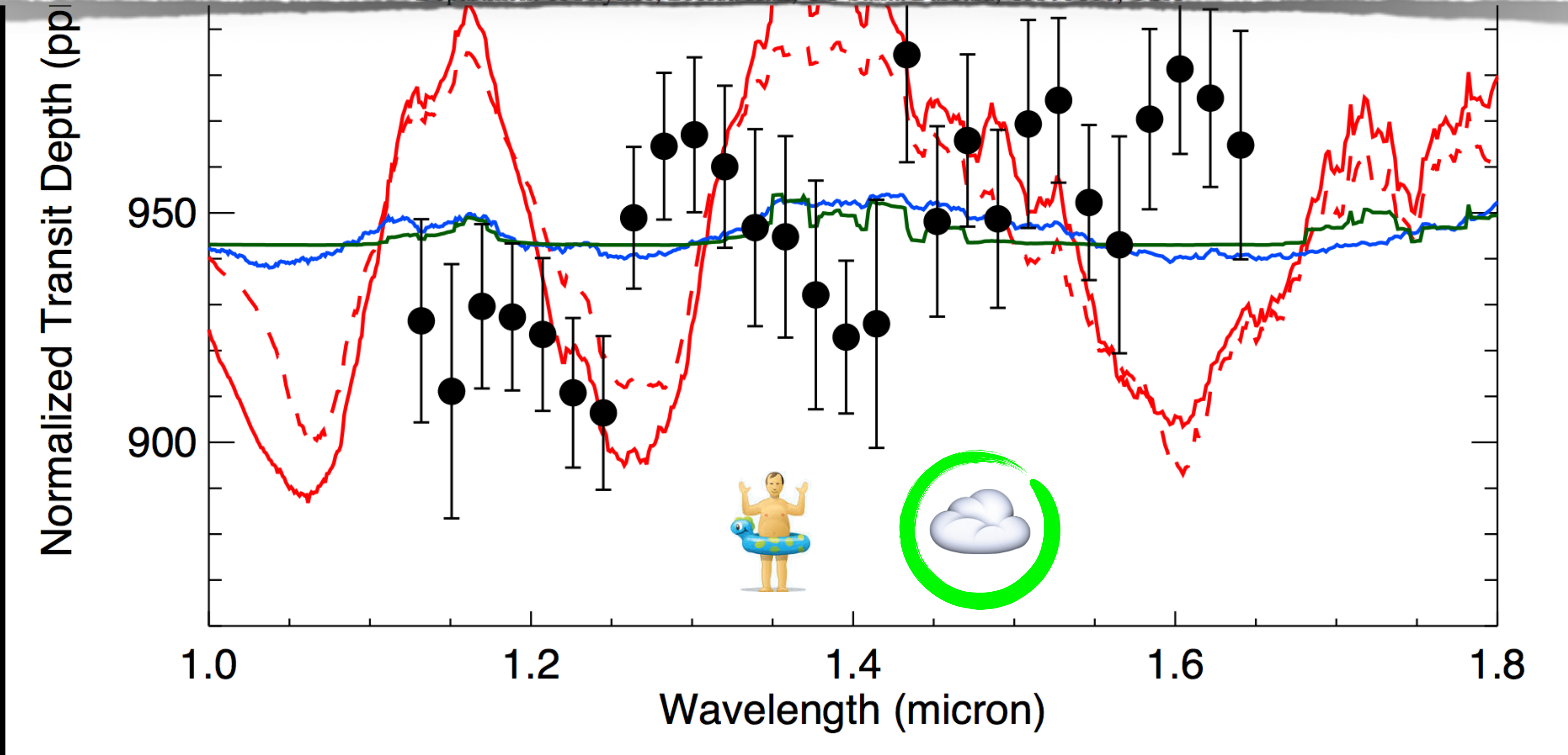
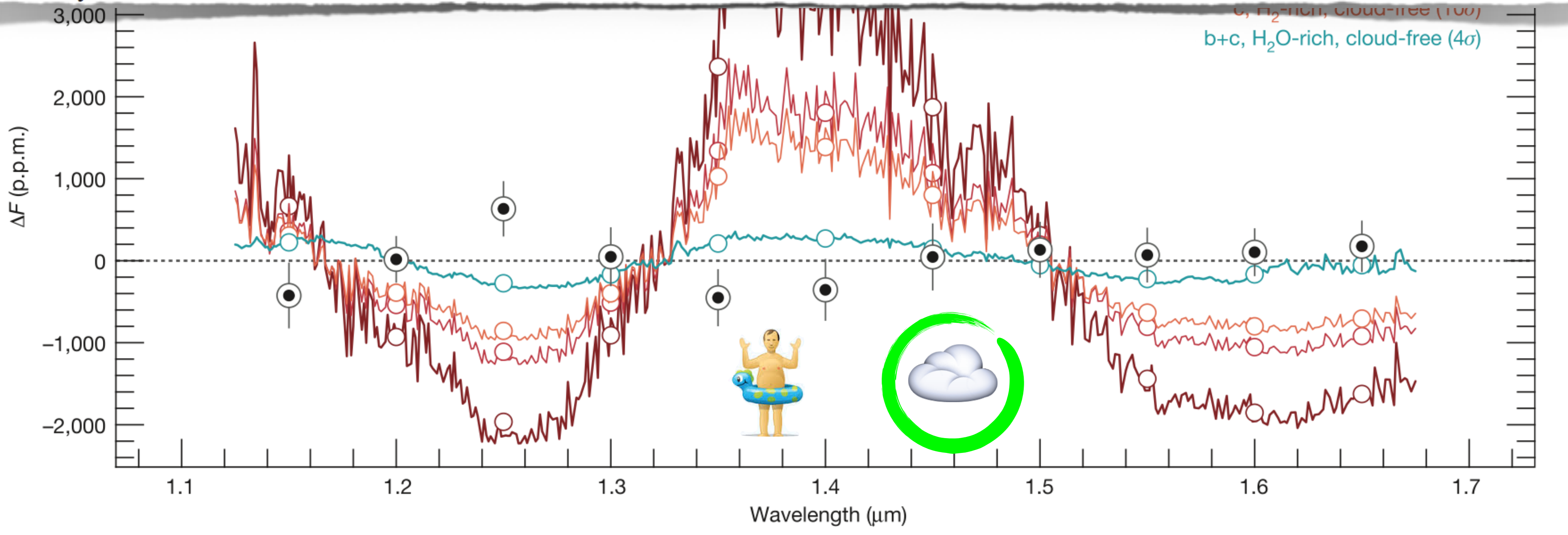


LETTER

doi:10.1038/nature18641

A combined transmission spectrum of the Earth-sized exoplanets TRAPPIST-1 b and c

Julien de Wit[1], Hannah R. Wakeford[2], Michaël Gillon[3], Nikole K. Lewis[4], Jeff A. Valenti[4], Brice-Olivier Demory[5], Adam J. Burgasser[6], Artem Burdanov[3], Laetitia Delrez[3], Emmanuël Jehin[3], Susan M. Lederer[7], Didier Queloz[5], Amaury H. M. J. Triaud[8] & Valérie Van Grootel[3]

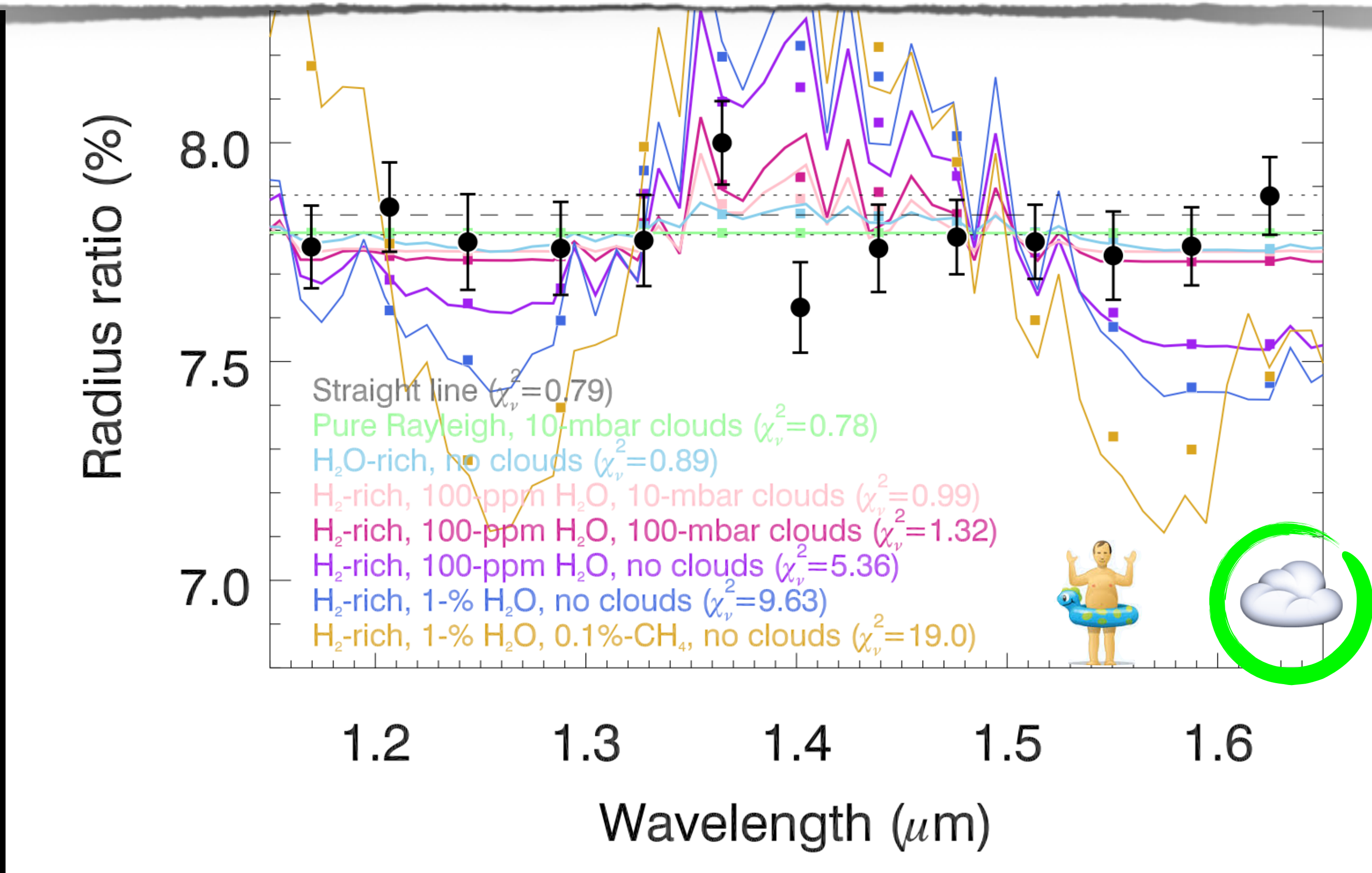


A&A 570, A89 (2014)
DOI: 10.1051/0004-6361/201423809

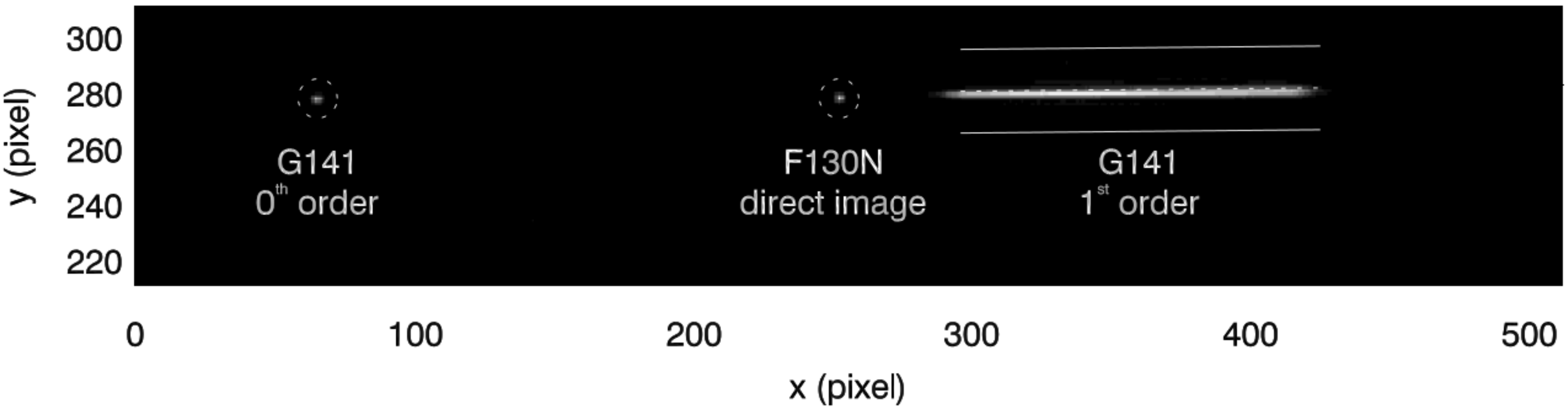
Astronomy & Astrophysics

Near-infrared transmission spectrum of the warm-Uranus GJ 3470b with the Wide Field Camera-3 on the *Hubble* Space Telescope*

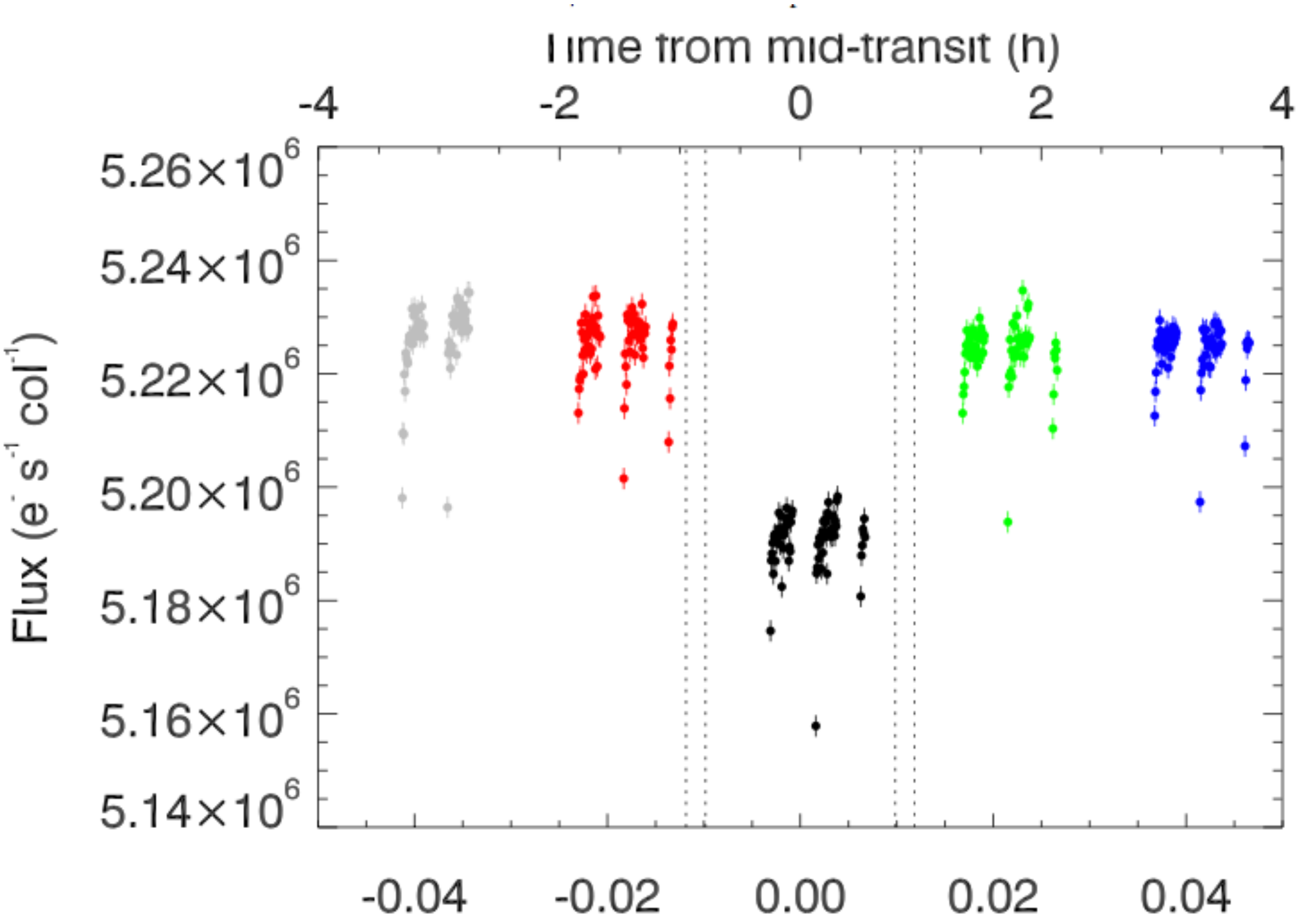
D. Ehrenreich[1], X. Bonfils[2], C. Lovis[1], X. Delfosse[2], T. Forveille[2], M. Mayor[1], V. Neves[2,3,4], N. C. Santos[3,4], S. Udry[1], and D. Ségransan[1]



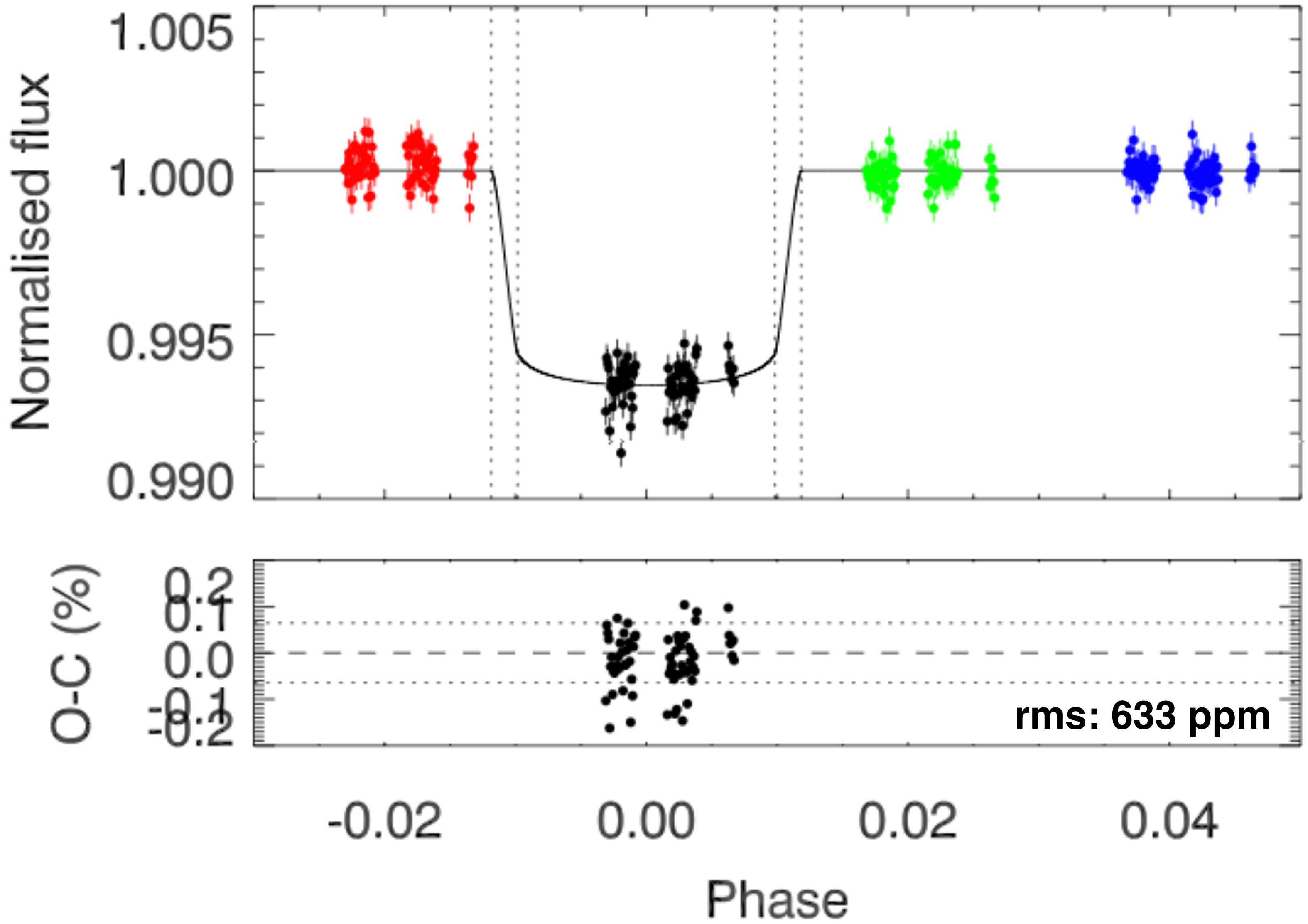
HST/WFC3 data
("stare mode")

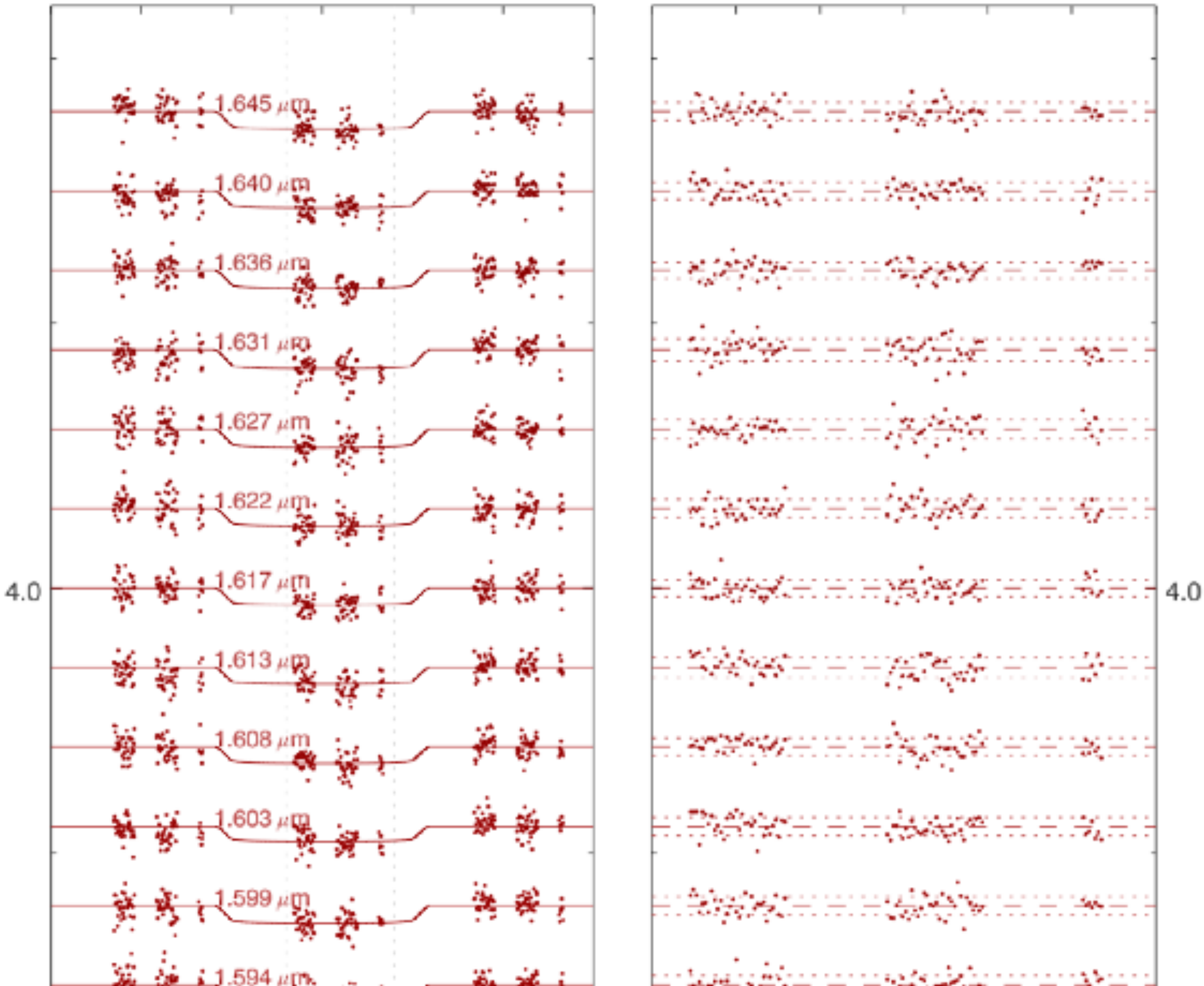


HST/WFC3 “white” light curve

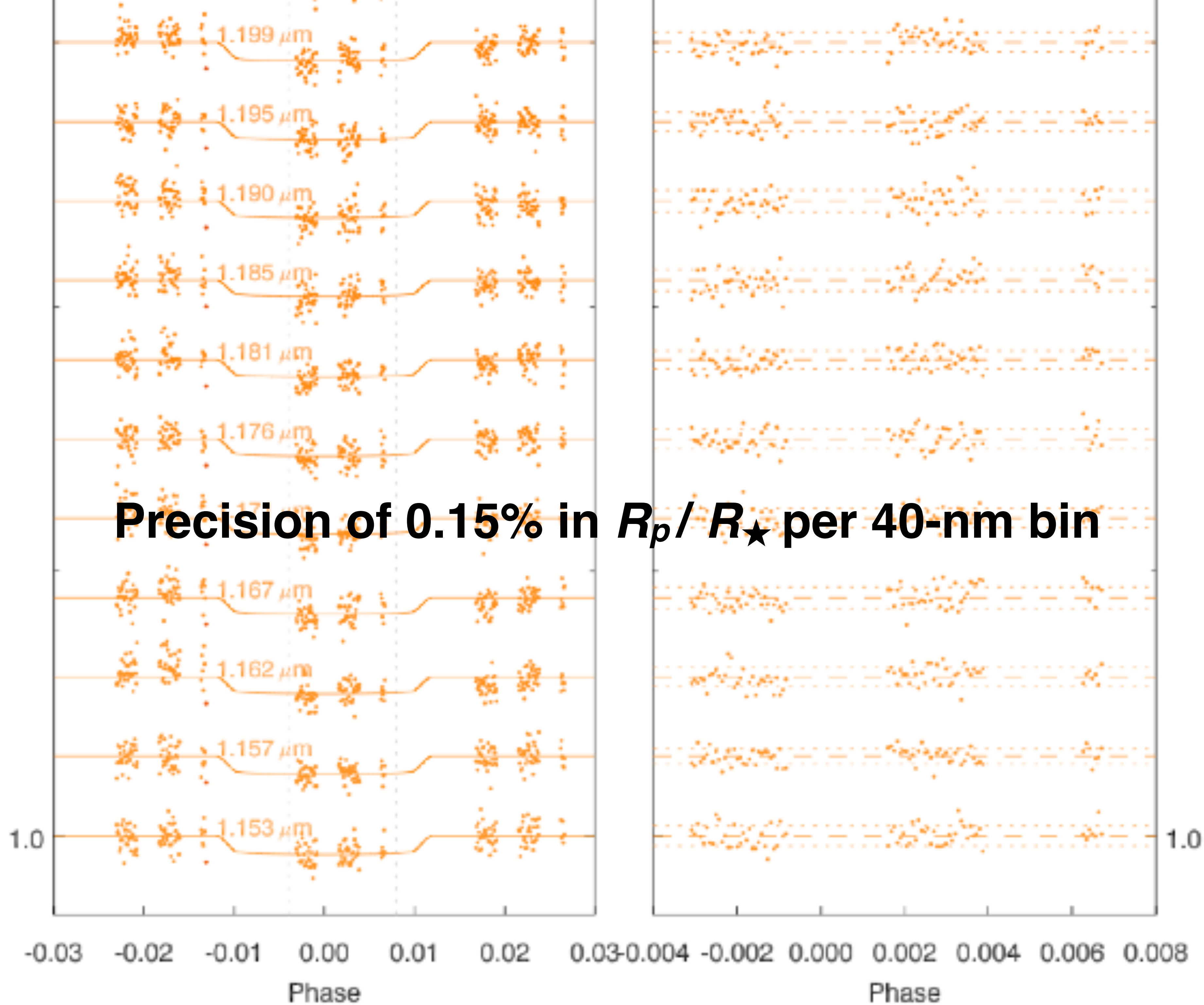


HST/WFC3 “white” light curve

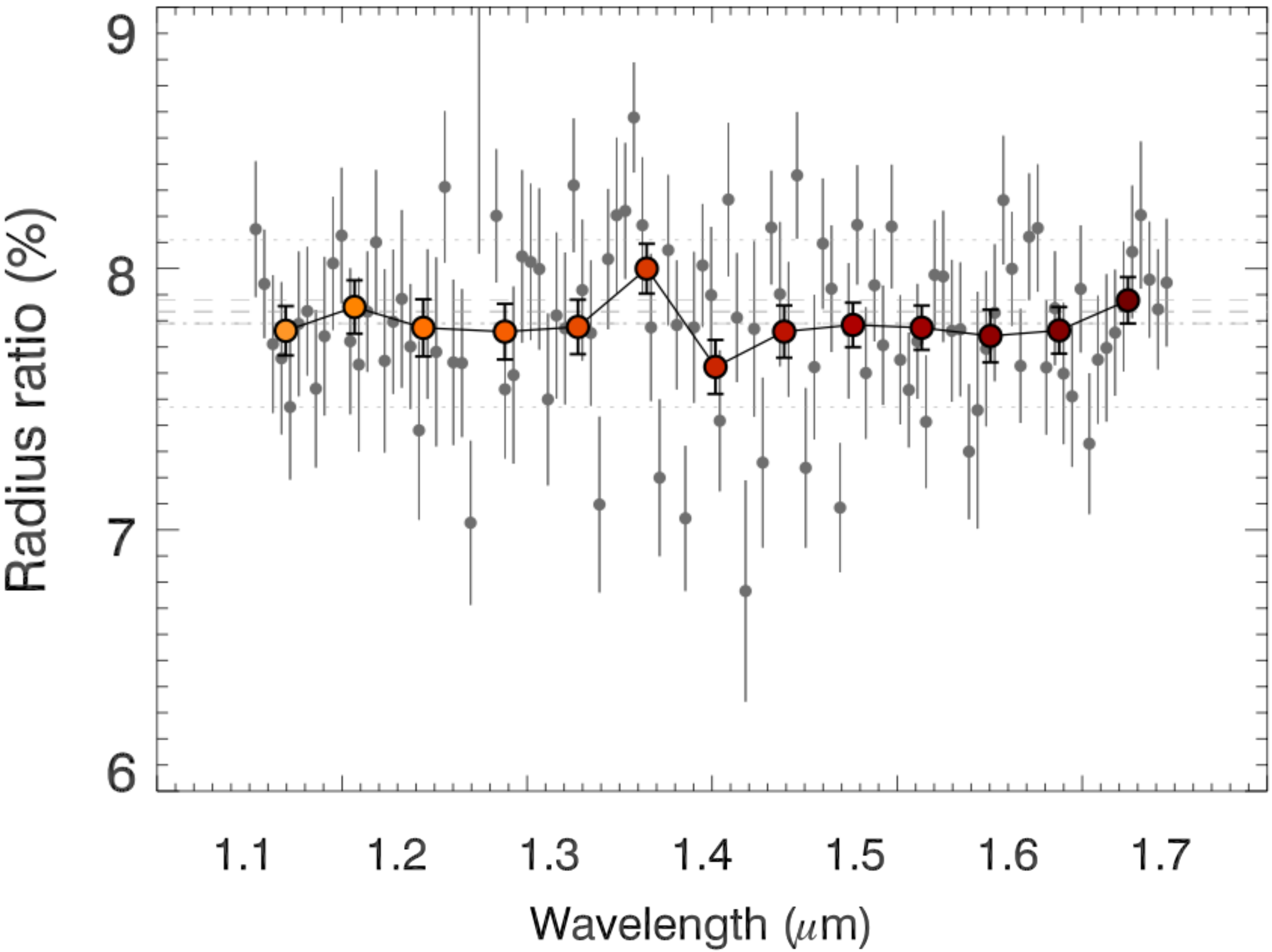




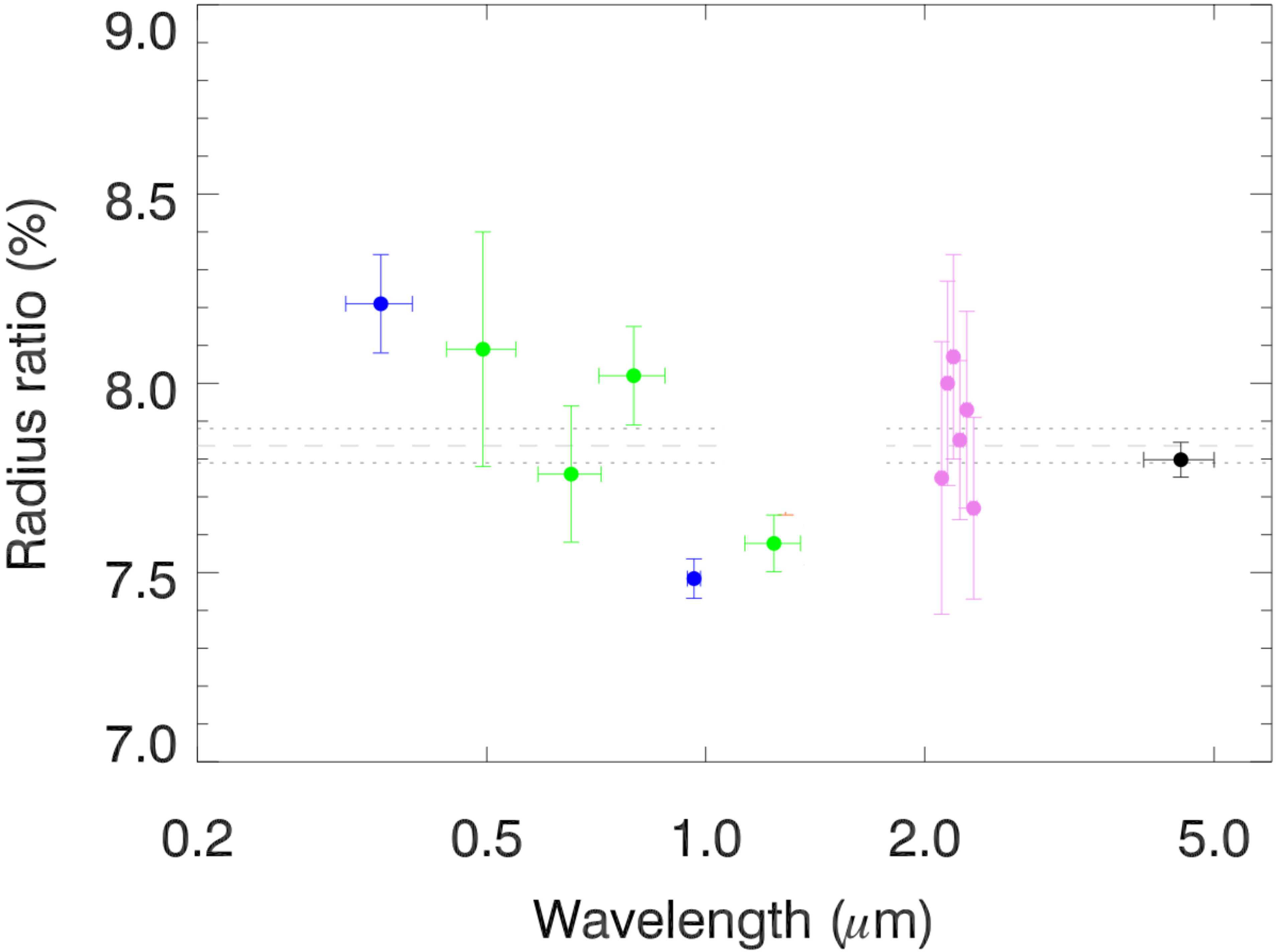
1.645 μm
1.640 μm
1.636 μm
1.631 μm
1.627 μm
1.622 μm
1.617 μm
1.613 μm
1.608 μm
1.603 μm
1.599 μm
1.594 μm
4.0
4.0



1.199 μm
1.195 μm
1.190 μm
1.185 μm
1.181 μm
1.176 μm
1.167 μm
1.162 μm
1.157 μm
1.153 μm
1.0
1.0
-0.03
-0.02
-0.01
0.00
0.01
0.02
0.03
-0.004
-0.002
0.000
0.002
0.004
0.006
0.008
Phase
Phase
Precision of 0.15% in $R_p / R_\star$ per 40-nm bin

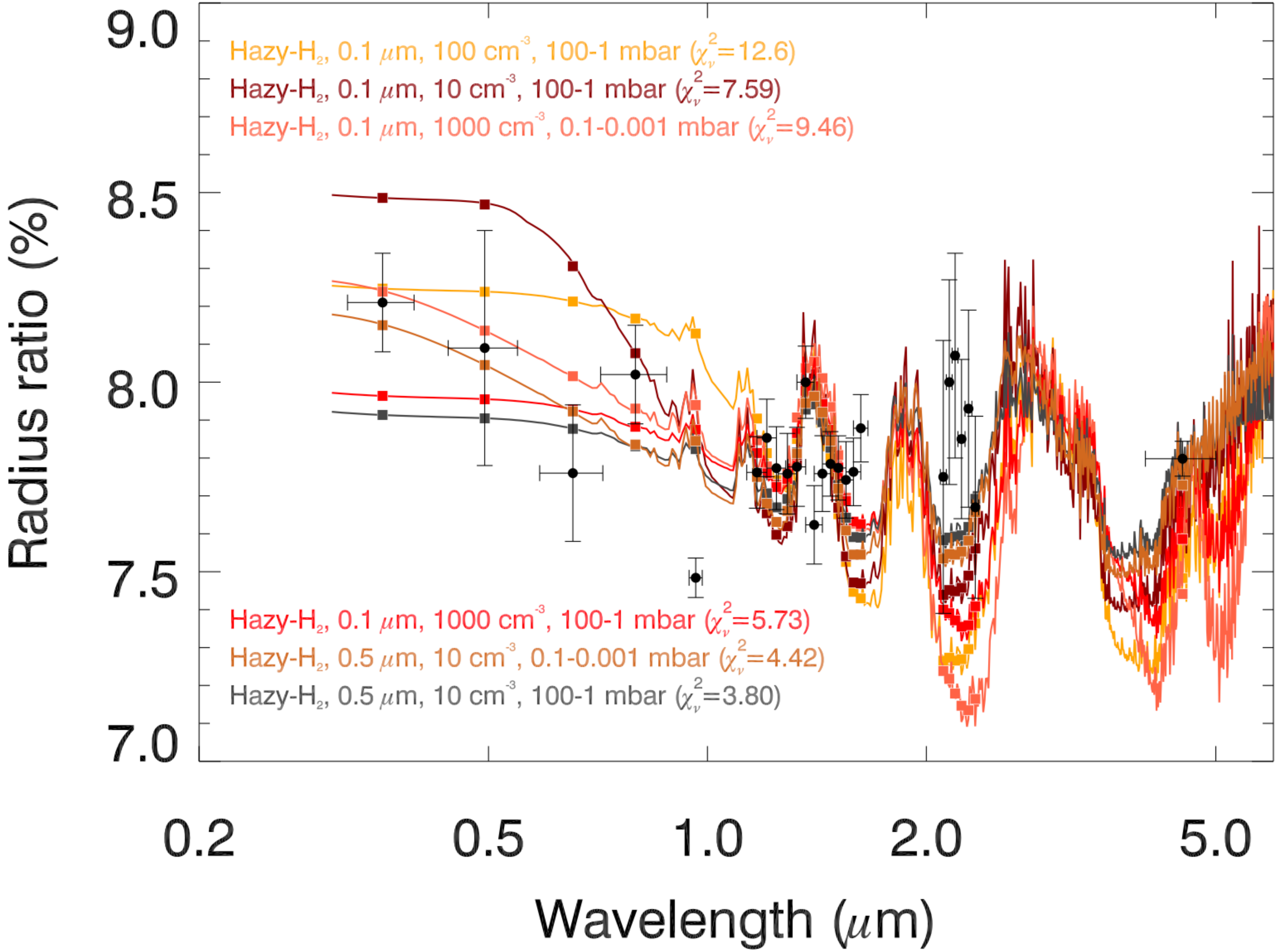


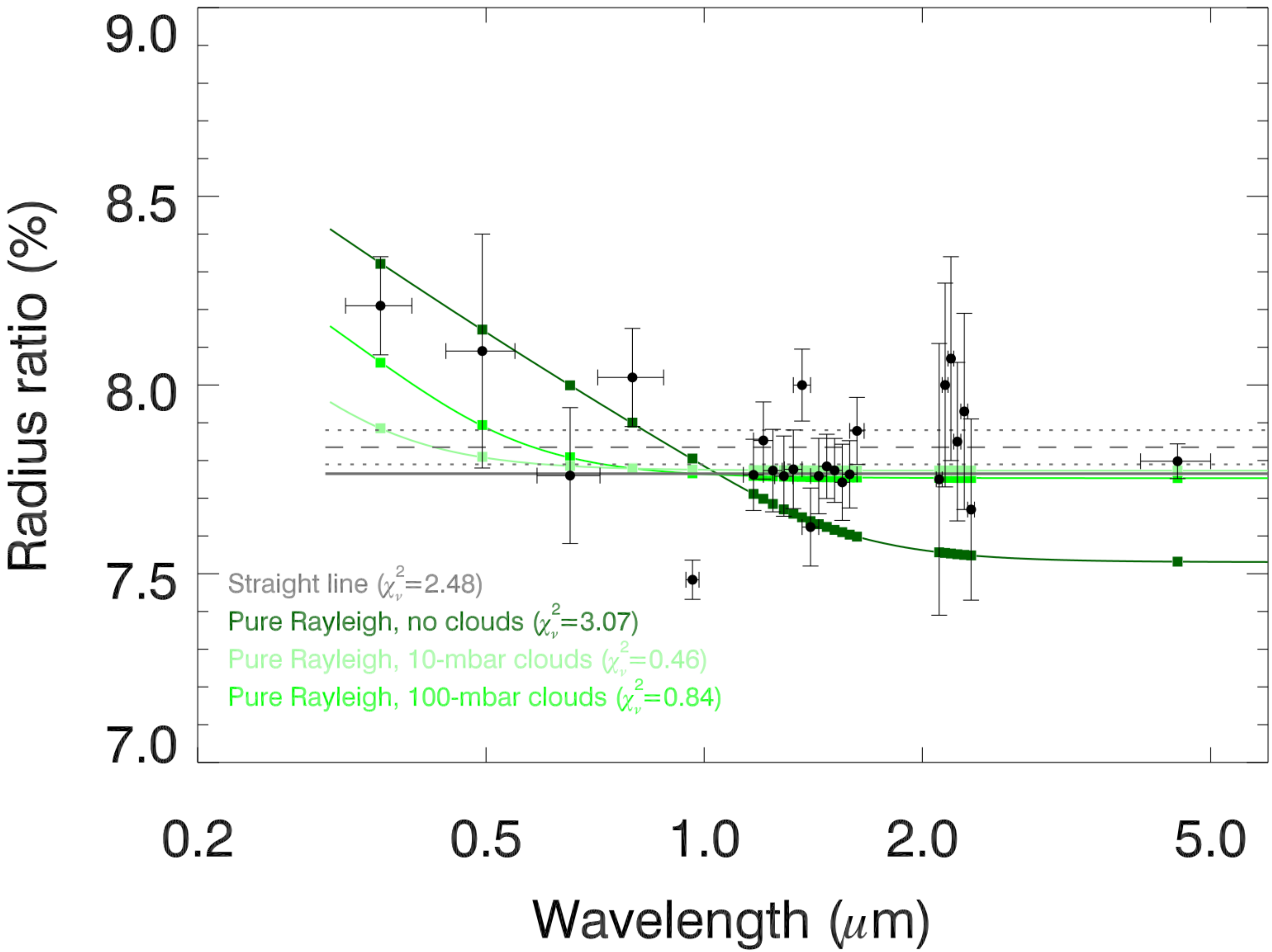
Radius ratio (%)
9
8
7
6
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength (μm)



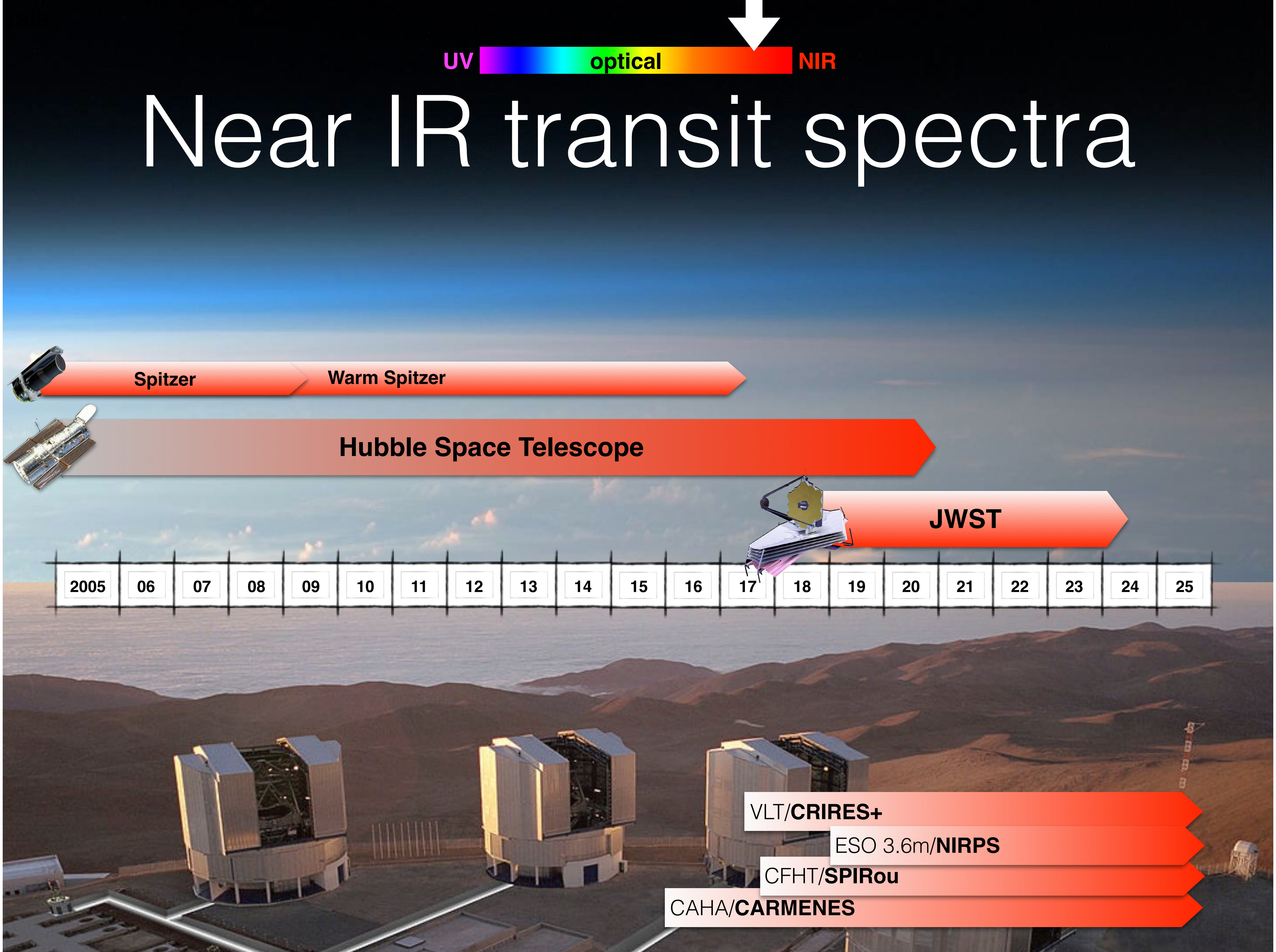
9.0
8.5
8.0
7.5
7.0
Radius ratio (%)
0.2
0.5
1.0
2.0
5.0
Wavelength (μm)

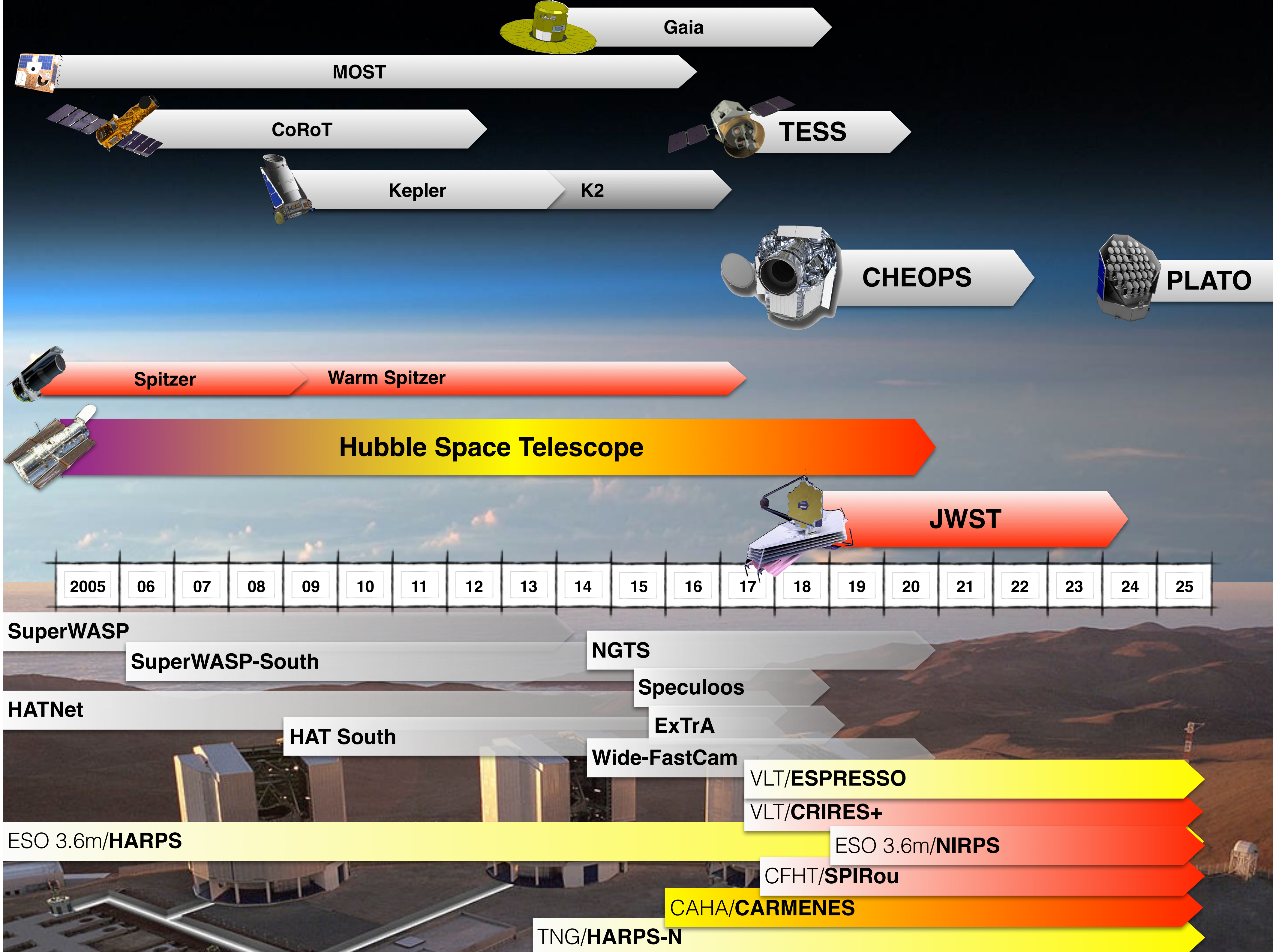
Howe & Burrows (2012) ➡ tholin refraction indices from Khare (1984)

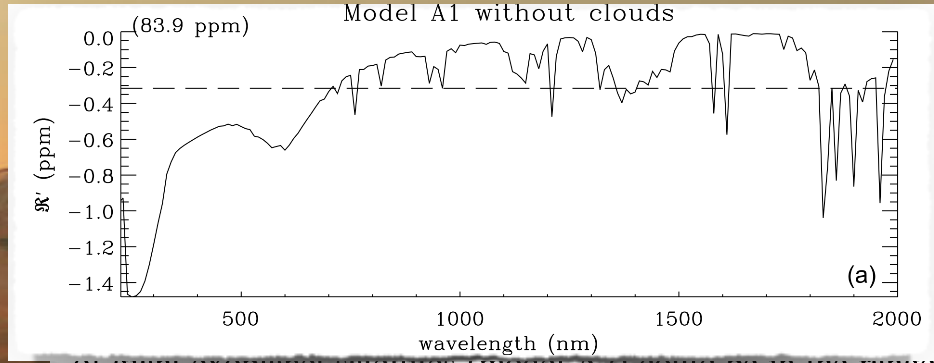




9.0
8.5
8.0
7.5
7.0
Radius ratio (%)
0.2
0.5
1.0
2.0
5.0
Wavelength (μm)
Straight line (χ^2_ν=2.48)
Pure Rayleigh, no clouds (χ^2_ν=3.07)
Pure Rayleigh, 10-mbar clouds (χ^2_ν=0.46)
Pure Rayleigh, 100-mbar clouds (χ^2_ν=0.84)


UV
optical
NIR
Near IR transit spectra
Spitzer
Warm Spitzer
Hubble Space Telescope
JWST
2005
06
07
08
09
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
VLT/CRIRES+
ESO 3.6m/NIRPS
CFHT/SPIRou
CAHA/CARMENES


Gaia
MOST
CoRoT
TESS
Kepler
K2
CHEOPS
PLATO
Spitzer
Warm Spitzer
Hubble Space Telescope
JWST
2005
06
07
08
09
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
SuperWASP
SuperWASP-South
NGTS
Speculoos
HATNet
HAT South
ExTrA
Wide-FastCam
VLT/ESPRESSO
VLT/CRIRES+
ESO 3.6m/HARPS
ESO 3.6m/NIRPS
CFHT/SPIRou
CAHA/CARMENES
TNG/HARPS-N

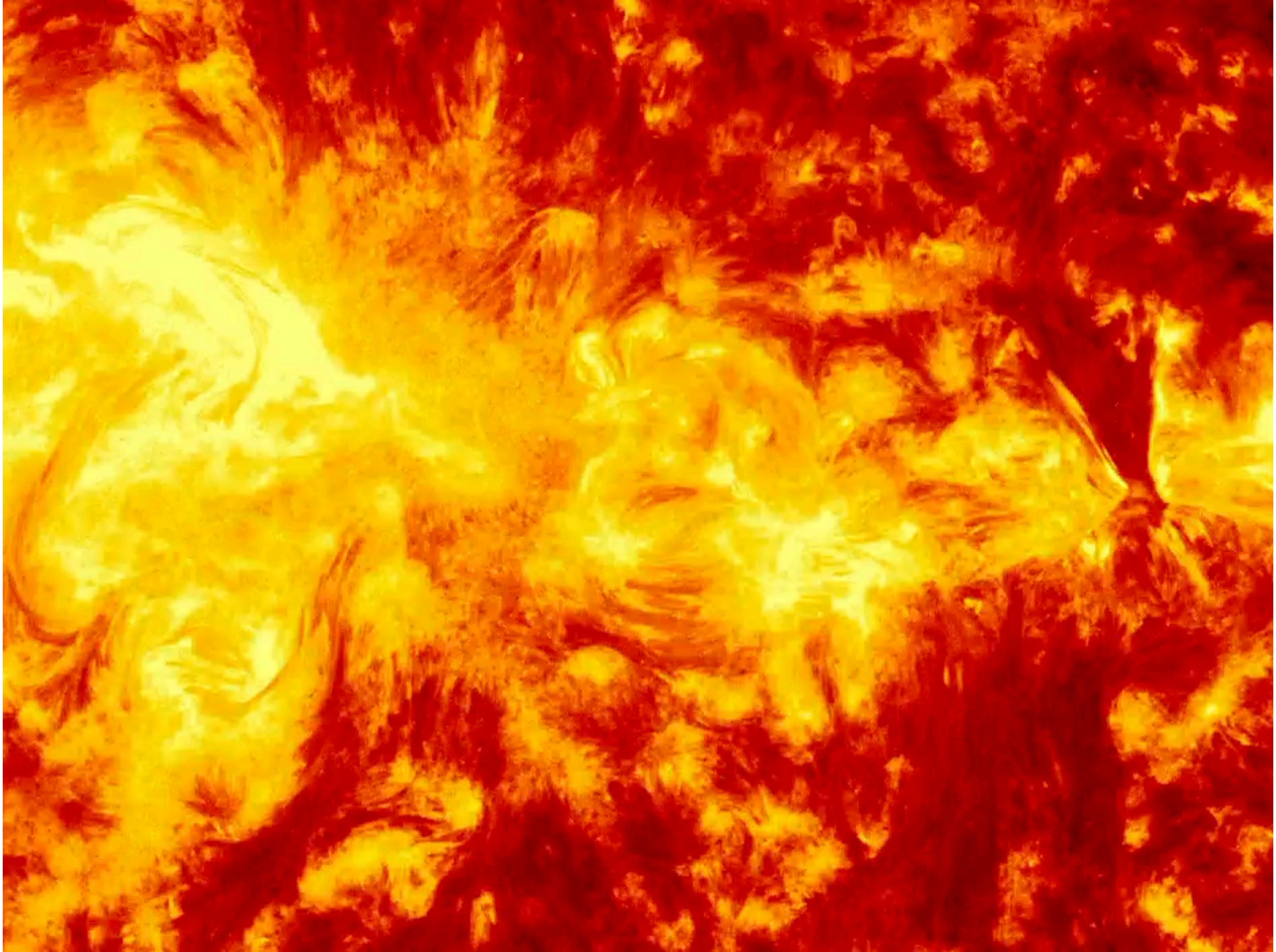


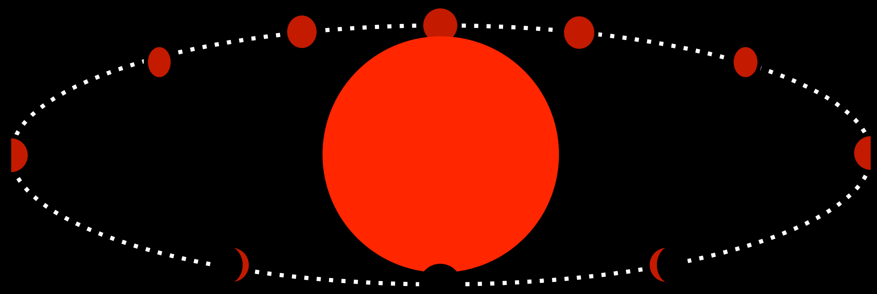
of giant exoplanet satellites (model A2) could be in the range of a 20−30 m instrument. A 30−40 m telescope would be required to probe Earth-like atmospheres around Earth-like planets (model A1). These numbers suppose that Earth-size planets are frequent and are efficiently detected by surveys.

Finally, planets with an extended upper atmosphere like the

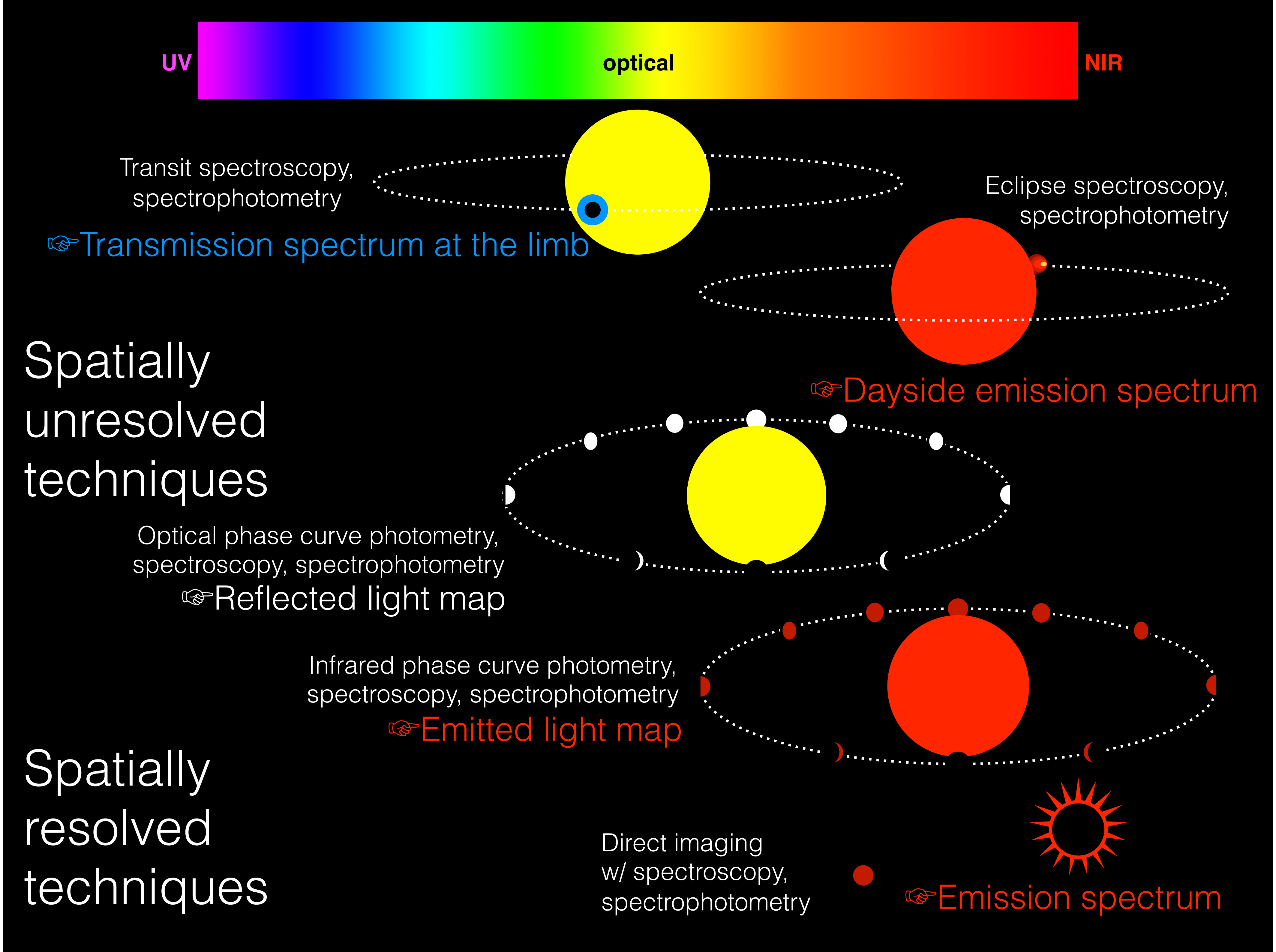
Ehrenreich et al. (2006)

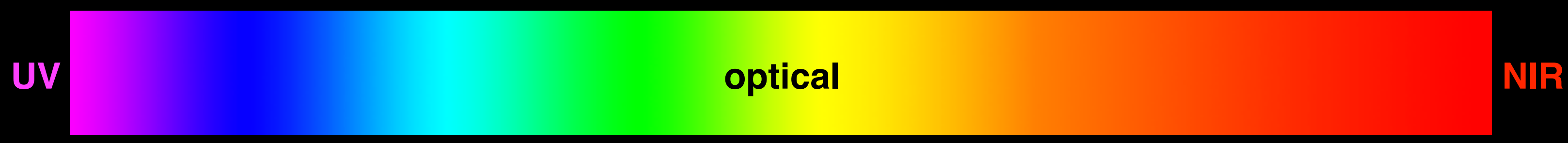
A hyper-HARPS on the E-ELT?
"HiRES" ~ 2028



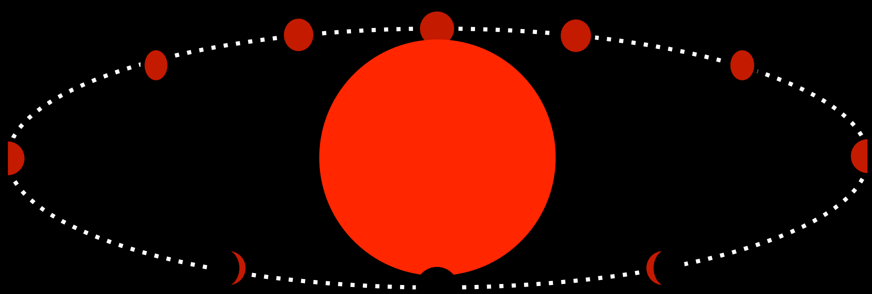


Supplementary material on thermal emission


UV
optical
NIR
Transit spectroscopy,
spectrophotometry
☞Transmission spectrum at the limb
Eclipse spectroscopy,
spectrophotometry
☞Dayside emission spectrum
Spatially unresolved techniques
Optical phase curve photometry,
spectroscopy, spectrophotometry
☞Reflected light map
Infrared phase curve photometry,
spectroscopy, spectrophotometry
☞Emitted light map
Spatially resolved techniques
Direct imaging
w/ spectroscopy,
spectrophotometry
☞Emission spectrum

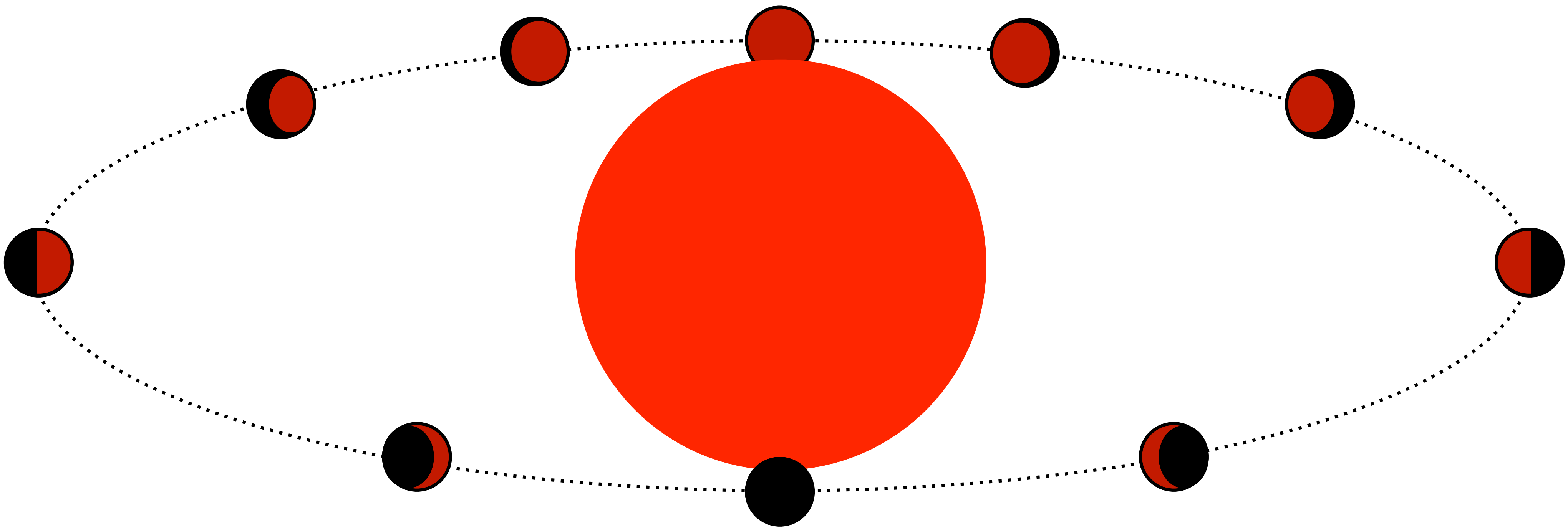


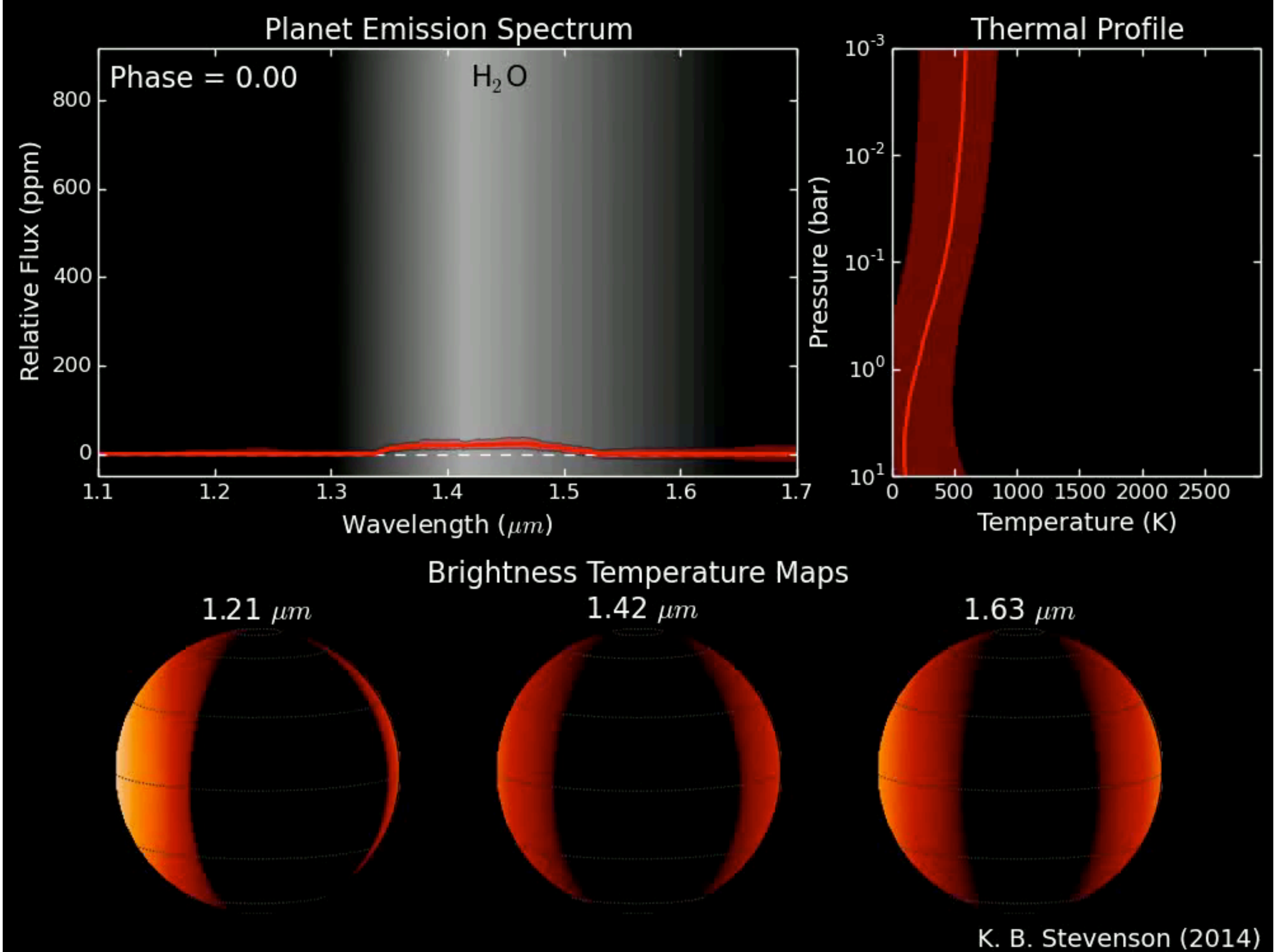
Spatially unresolved techniques

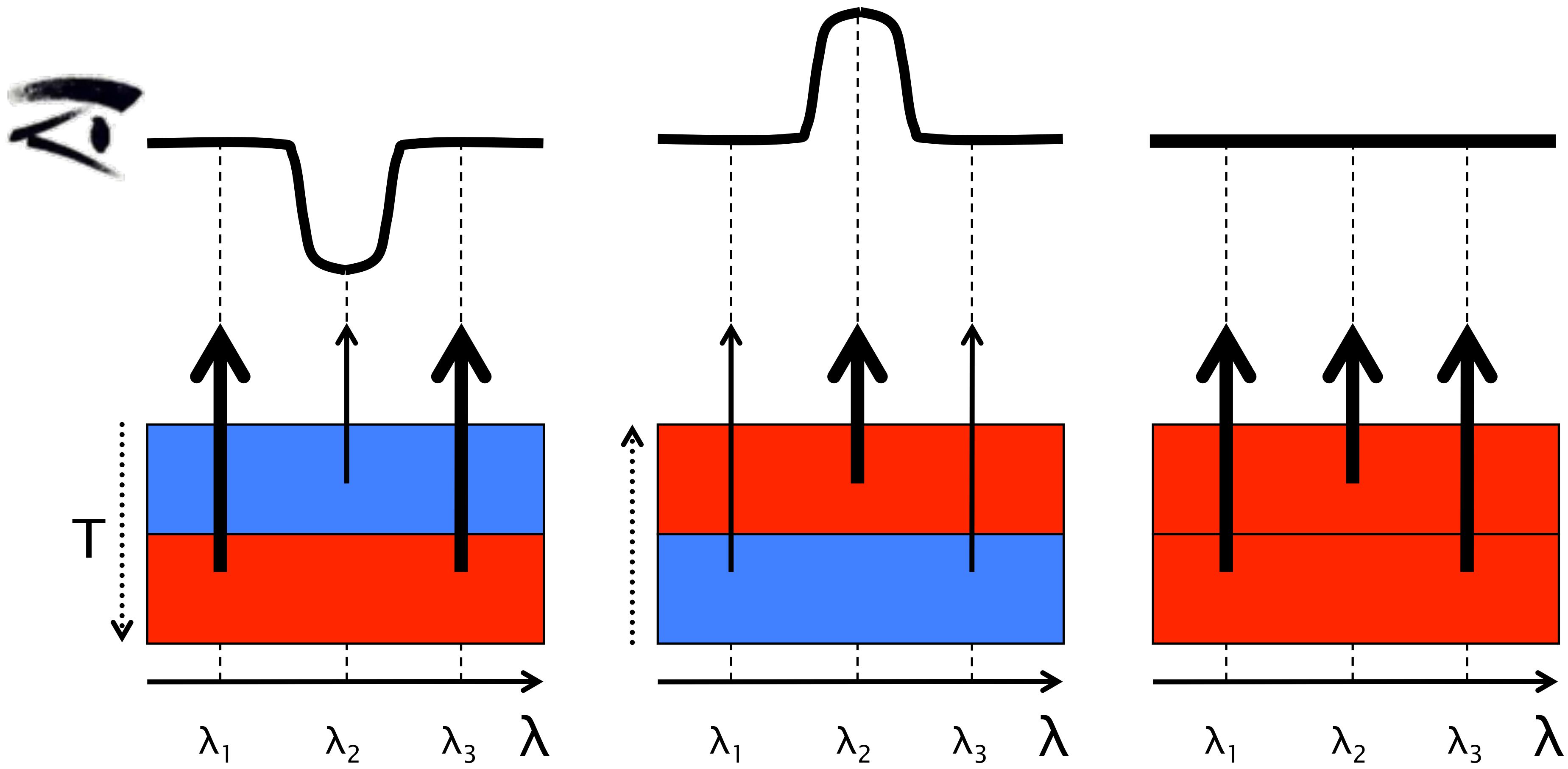


Infrared phase curve photometry,
spectroscopy, spectrophotometry
☞Emitted light map

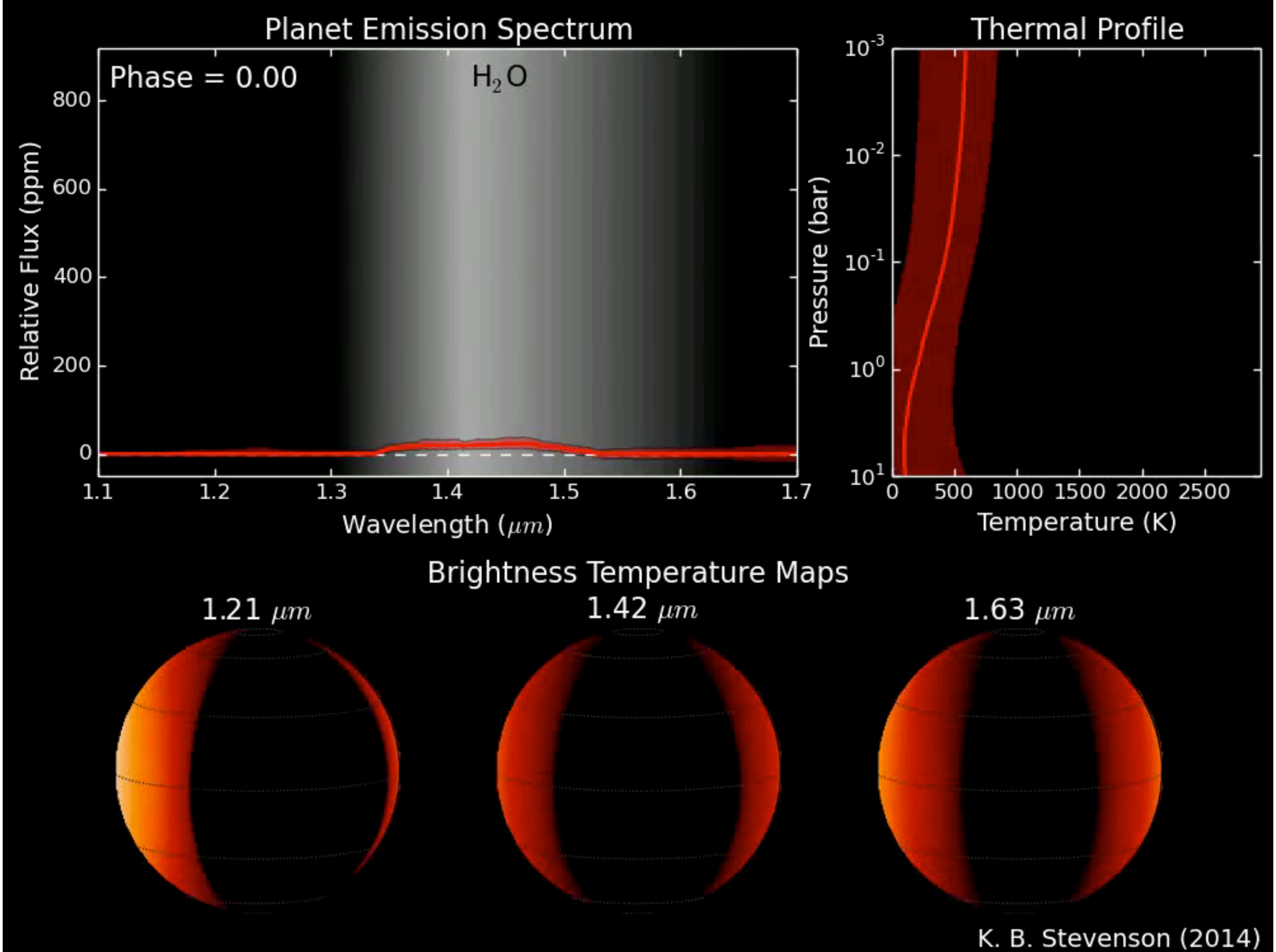
Thermal emission




Planet Emission Spectrum
Phase = 0.00
H2O
Relative Flux (ppm)
800
600
400
200
0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength (μm)
Thermal Profile
Pressure (bar)
10-3
10-2
10-1
100
101
0
500
1000
1500
2000
2500
Temperature (K)
Brightness Temperature Maps
1.21 μm
1.42 μm
1.63 μm
K. B. Stevenson (2014)

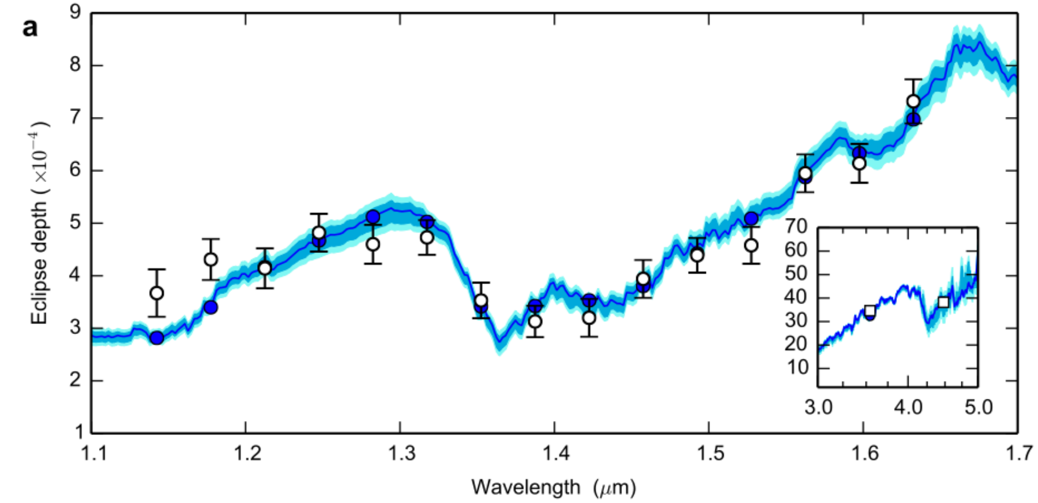


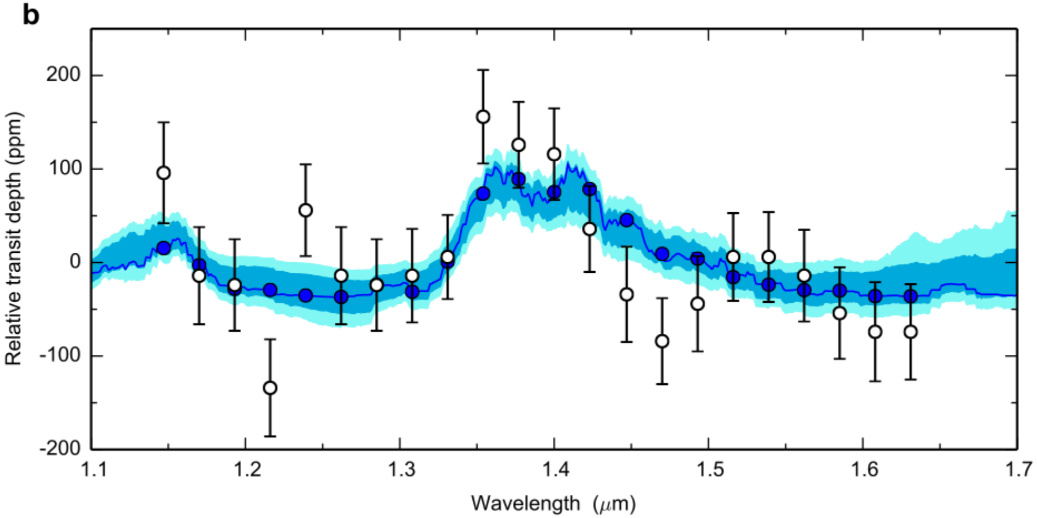
T
λ1
λ2
λ3
λ
λ1
λ2
λ3
λ
λ1
λ2
λ3
λ

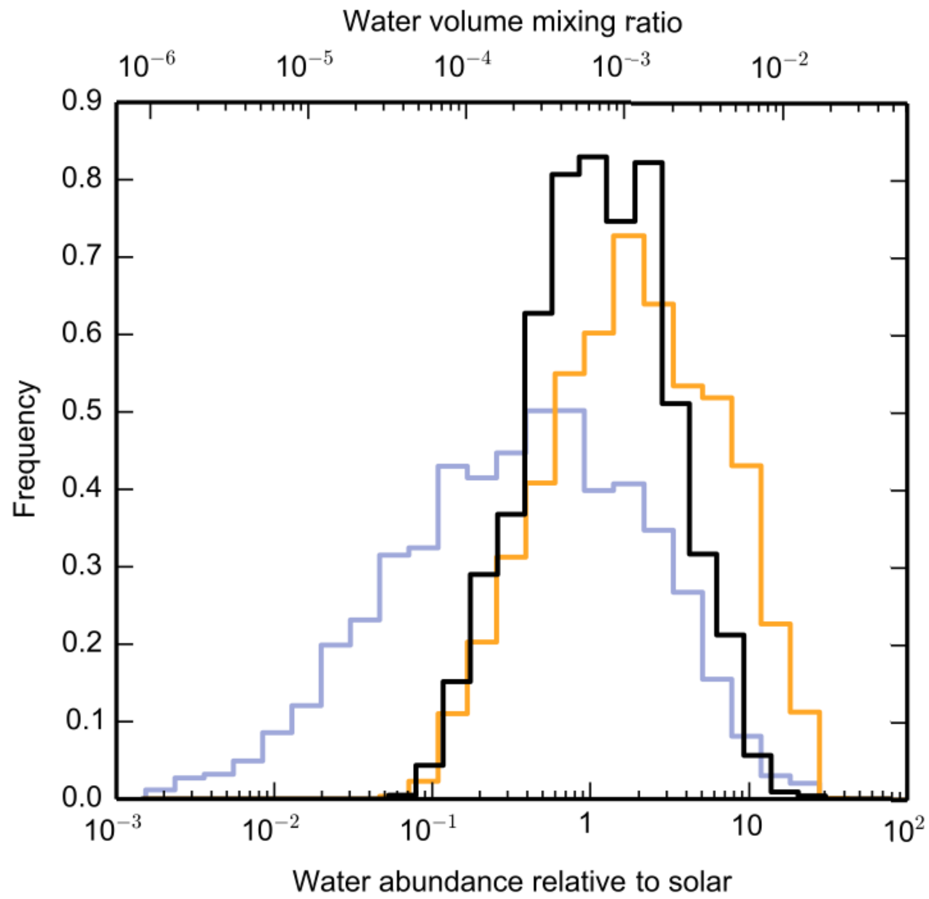

Planet Emission Spectrum
Phase = 0.00
H_2O
Relative Flux (ppm)
800
600
400
200
0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Wavelength (μm)
Thermal Profile
Pressure (bar)
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
0
500
1000
1500
2000
2500
Temperature (K)
Brightness Temperature Maps
1.21 μm
1.42 μm
1.63 μm
K. B. Stevenson (2014)

Emission+transmission spectroscopy

HST/WFC3 emitted spectrum of Wasp-43b (Kreidberg+2014)



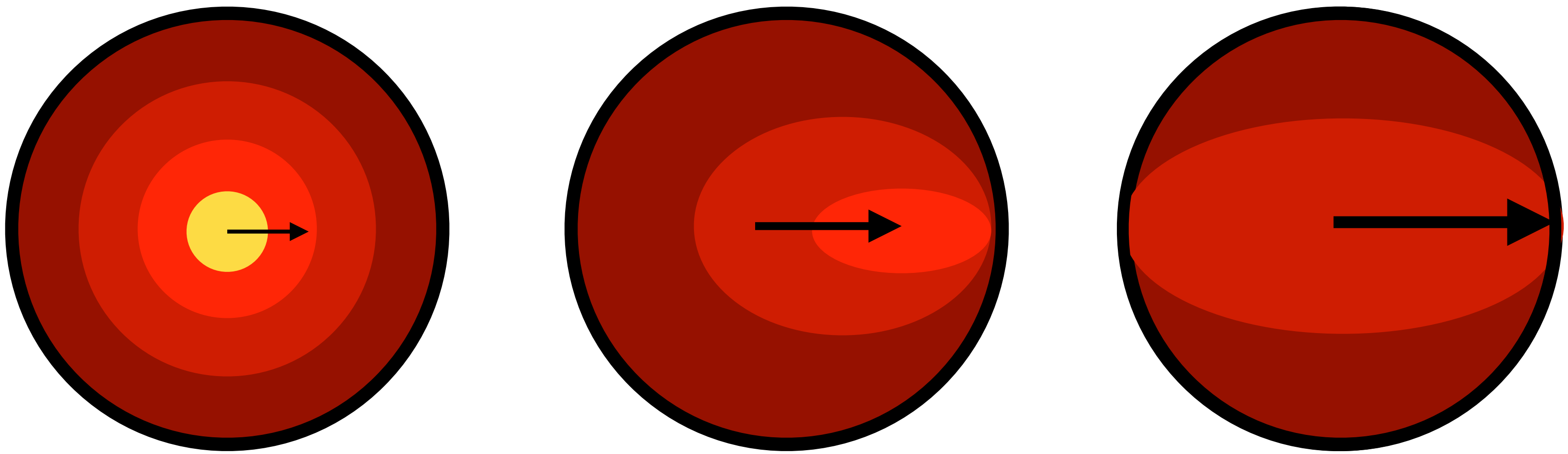




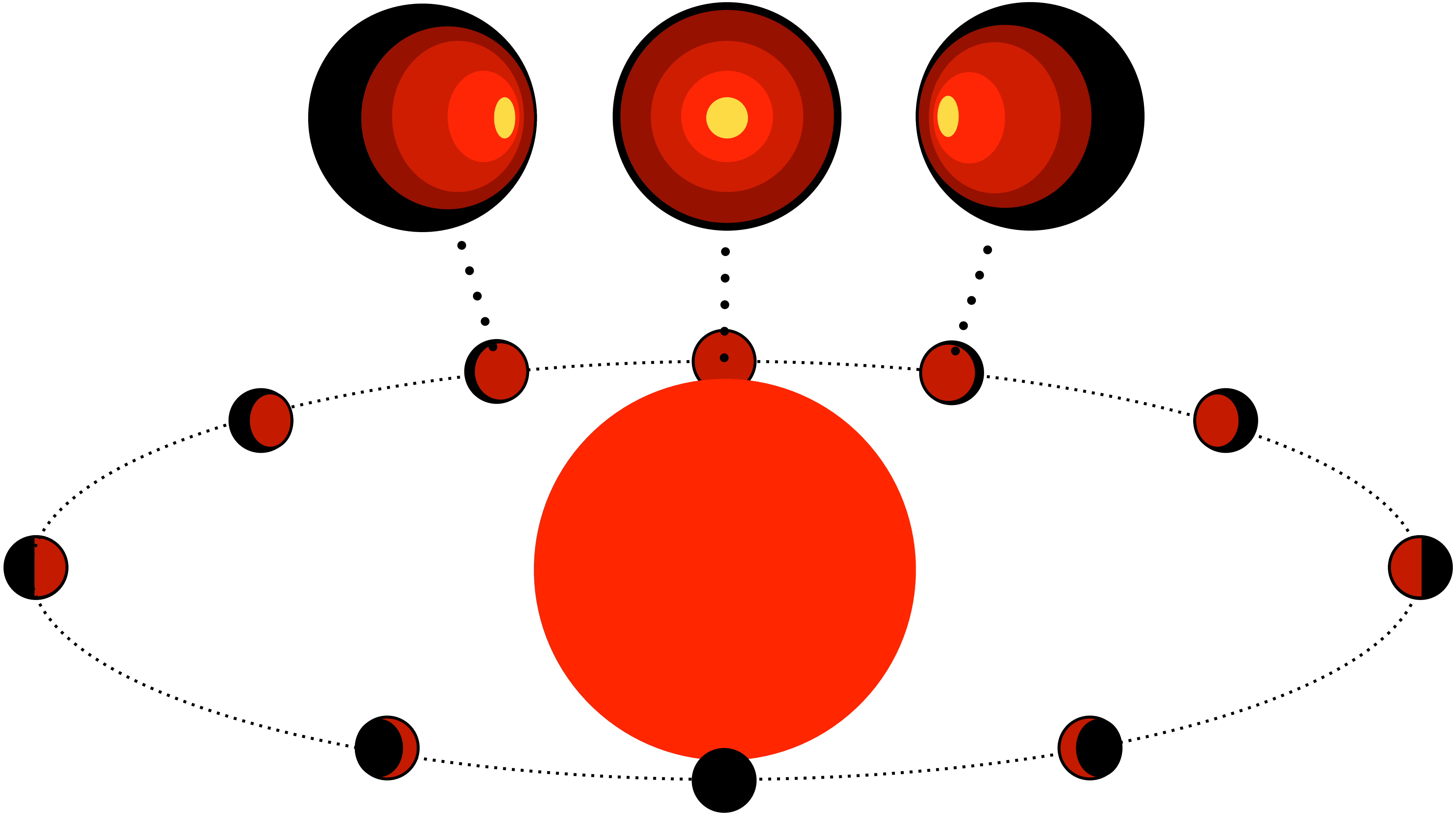
HST/WFC3 transmission spectrum of Wasp-43b (Kreidberg+2014)

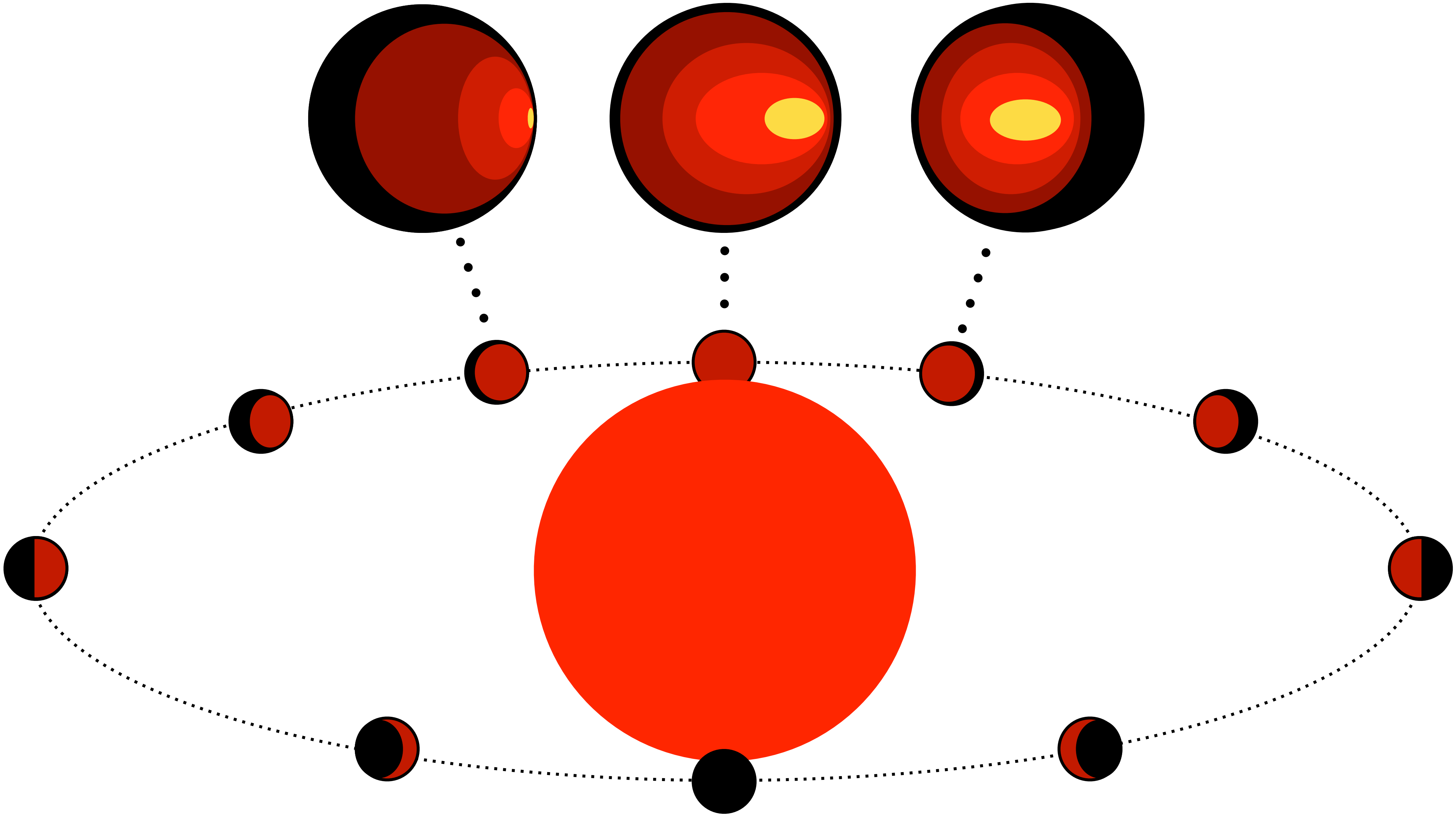
Inhomogeneities

$\tau_{rad}/\tau_{adv} << 1$ $\tau_{rad}/\tau_{adv} \sim 1$ $\tau_{rad}/\tau_{adv} >> 1$



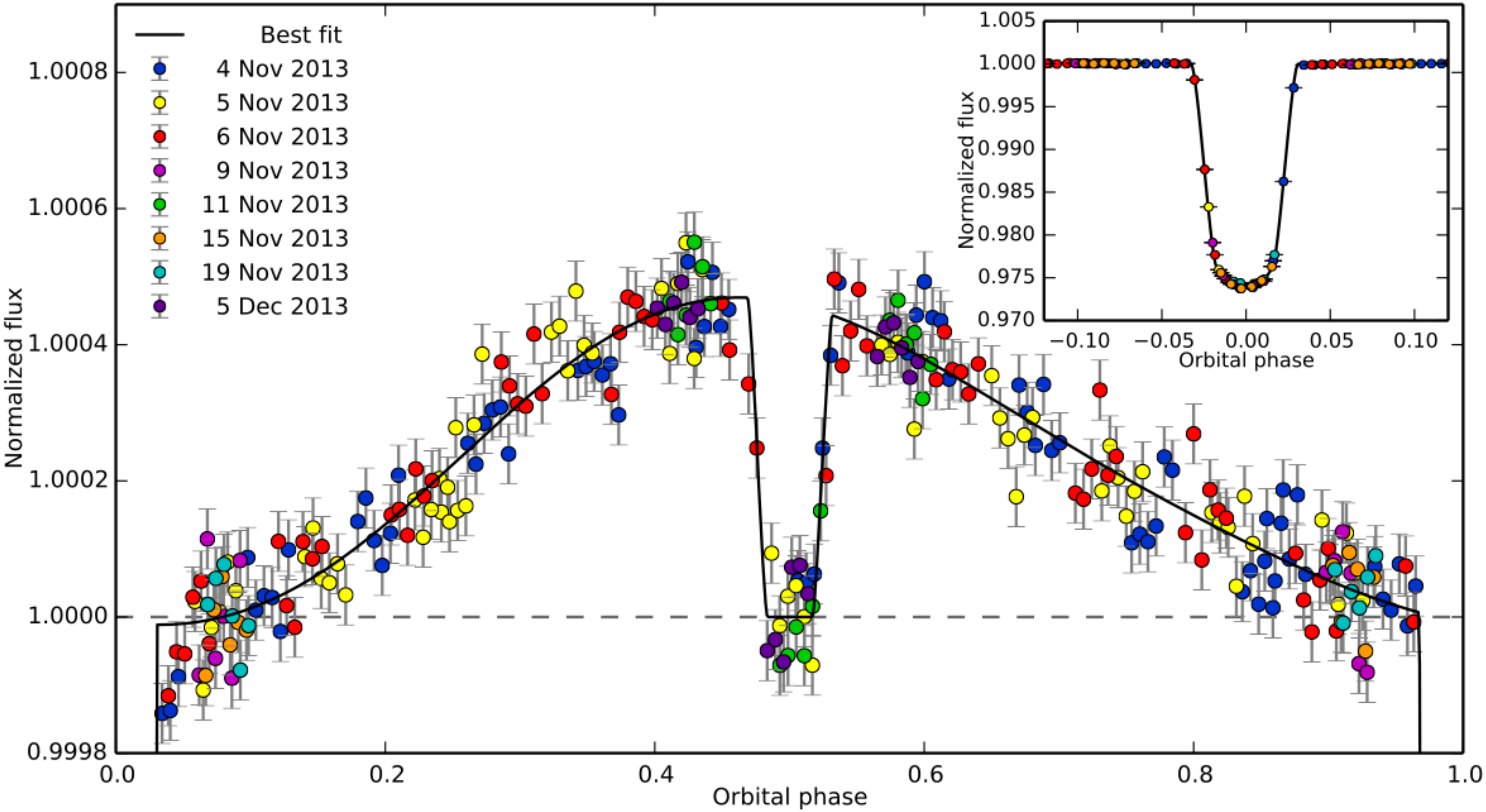
☞ **Temperature maps**
☞ **Geometrical albedos**

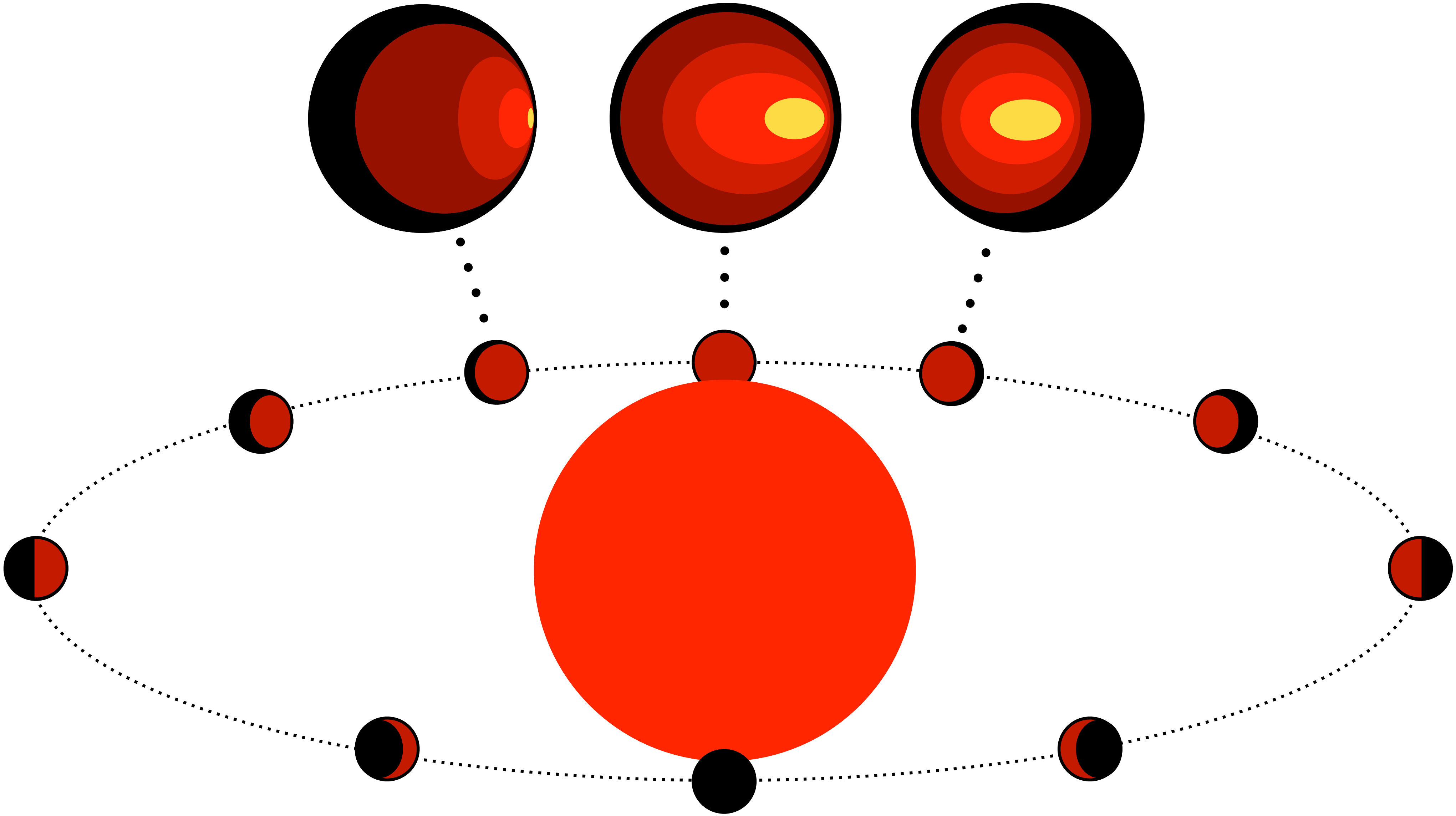


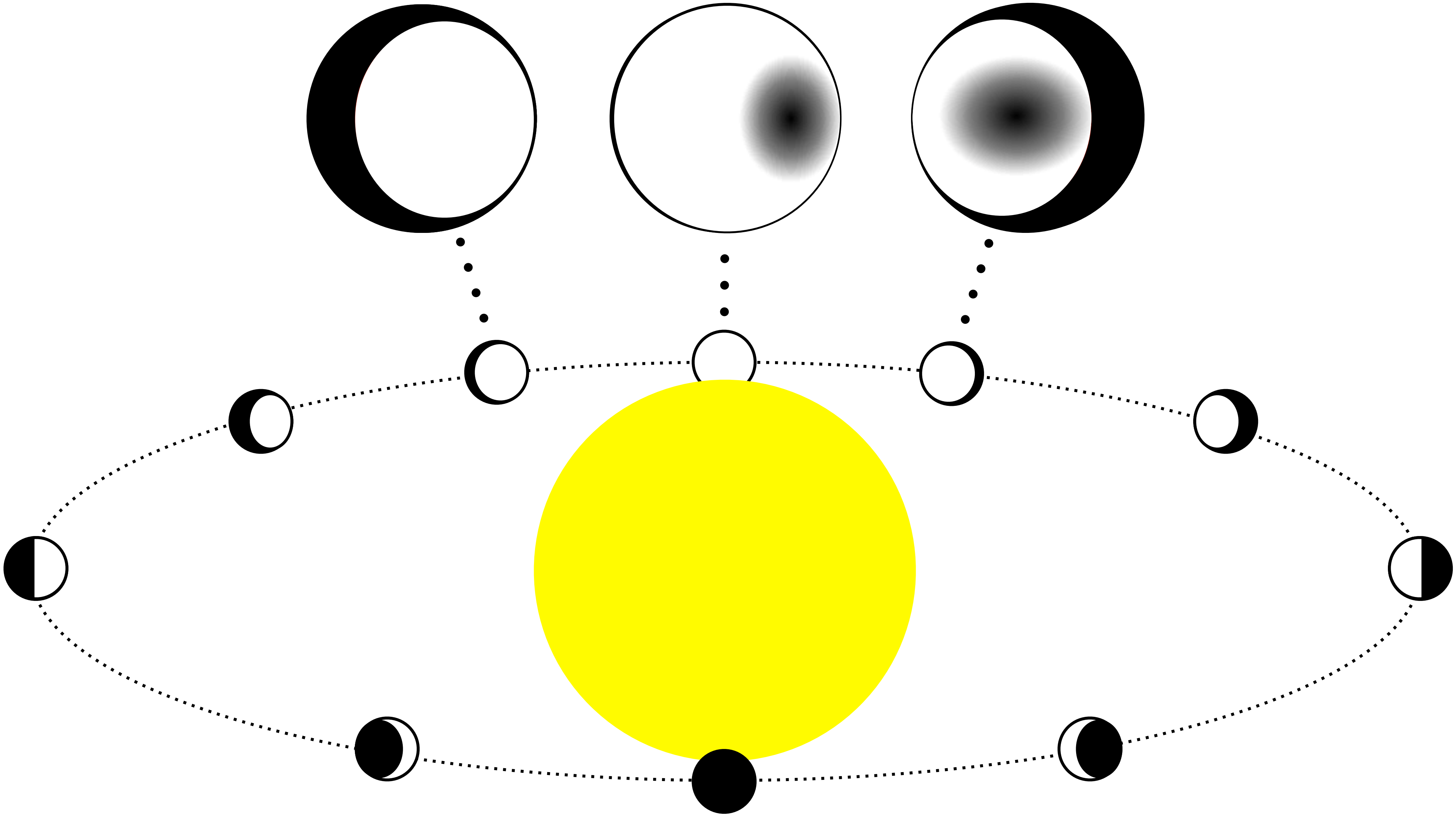


Emergent light photometry

HST/WFC3 NIR phase curve of Wasp-43b (Stevenson+2014)







Reflected light photometry

Kepler visible light curve of Kepler-7b (Demory+2013)