Secondary eclipses and phase curves

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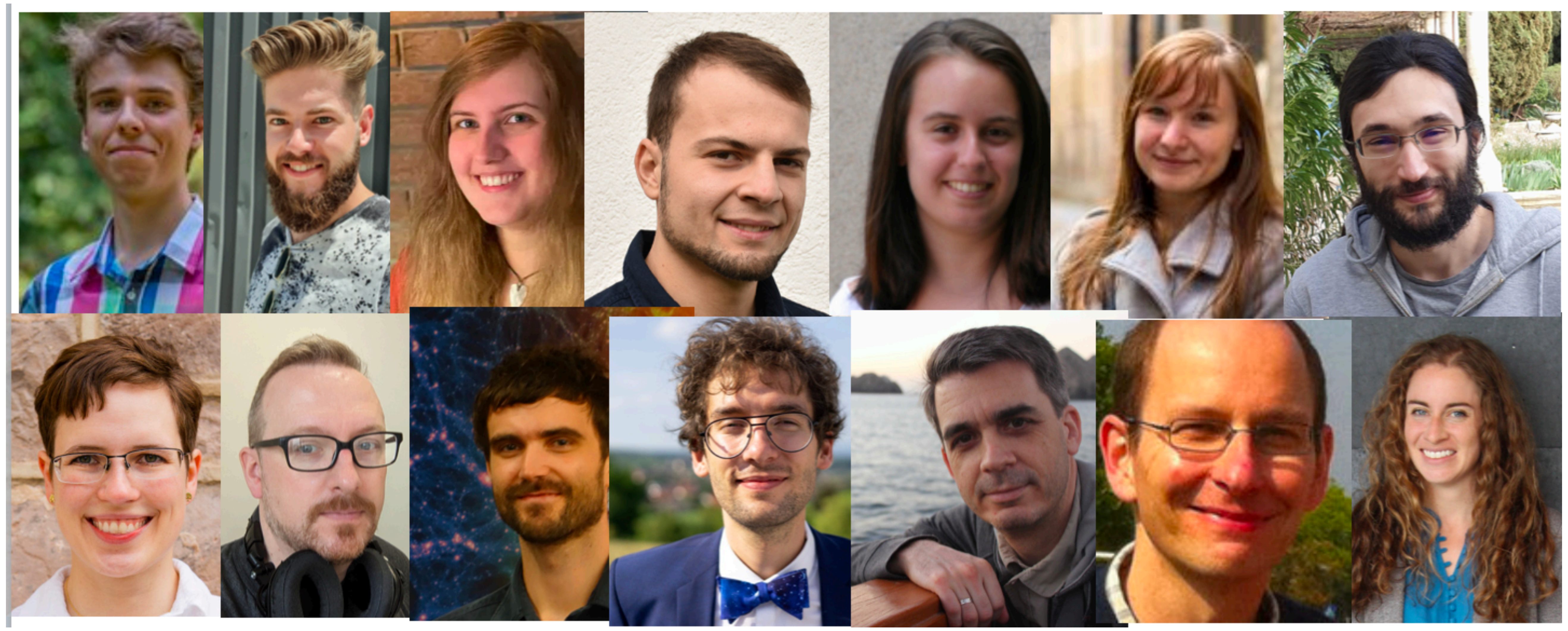
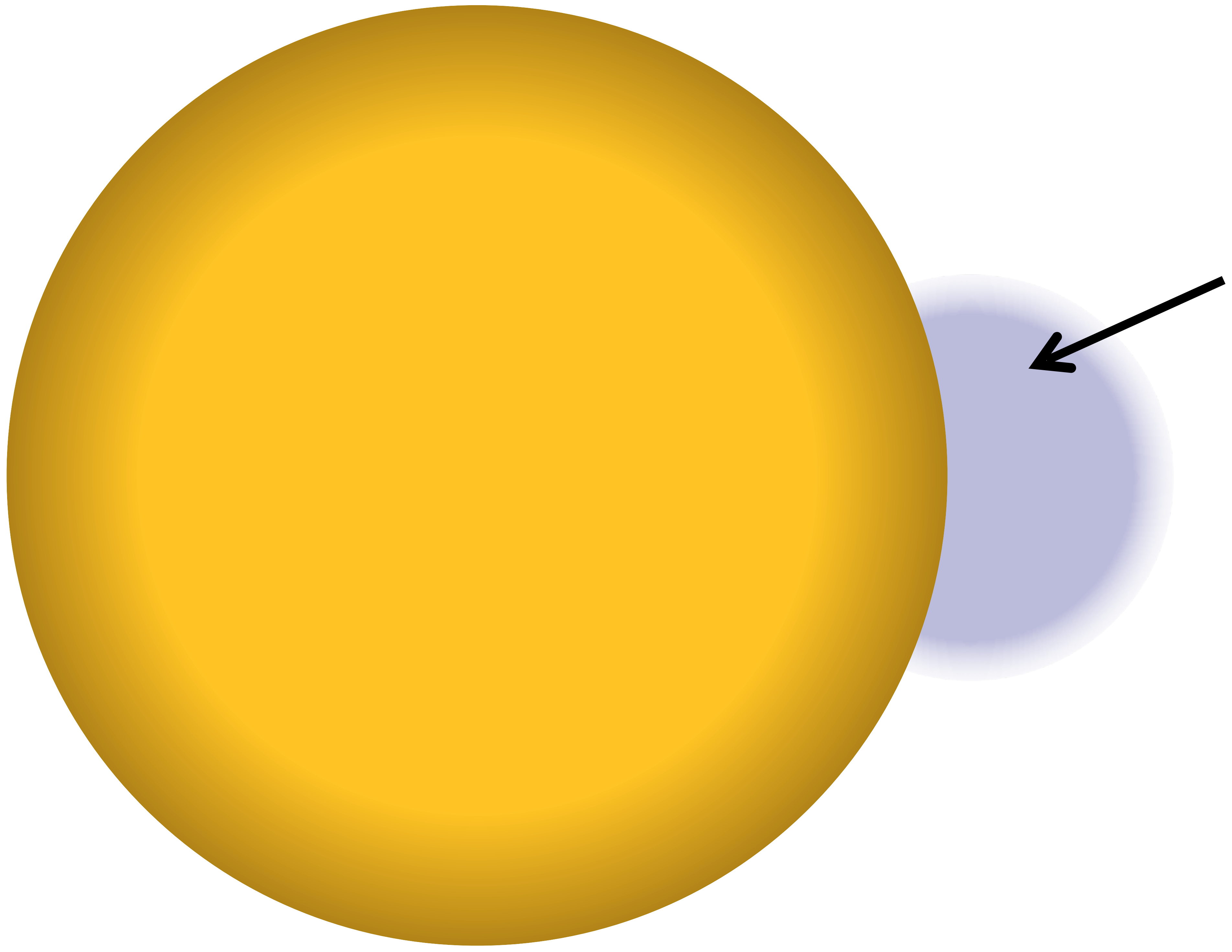
The APEx Department

Atmospheric Physics of Exoplanets

- New department at the Max Planck Institute of Astronomy in Heidelberg, Germany
- Focus is observations, theory, and instrumentation for exoplanet atmospheres!
- Advertisement: we are hiring at all levels! Jobs are advertised in the fall on the AAS job register



What is a secondary eclipse?

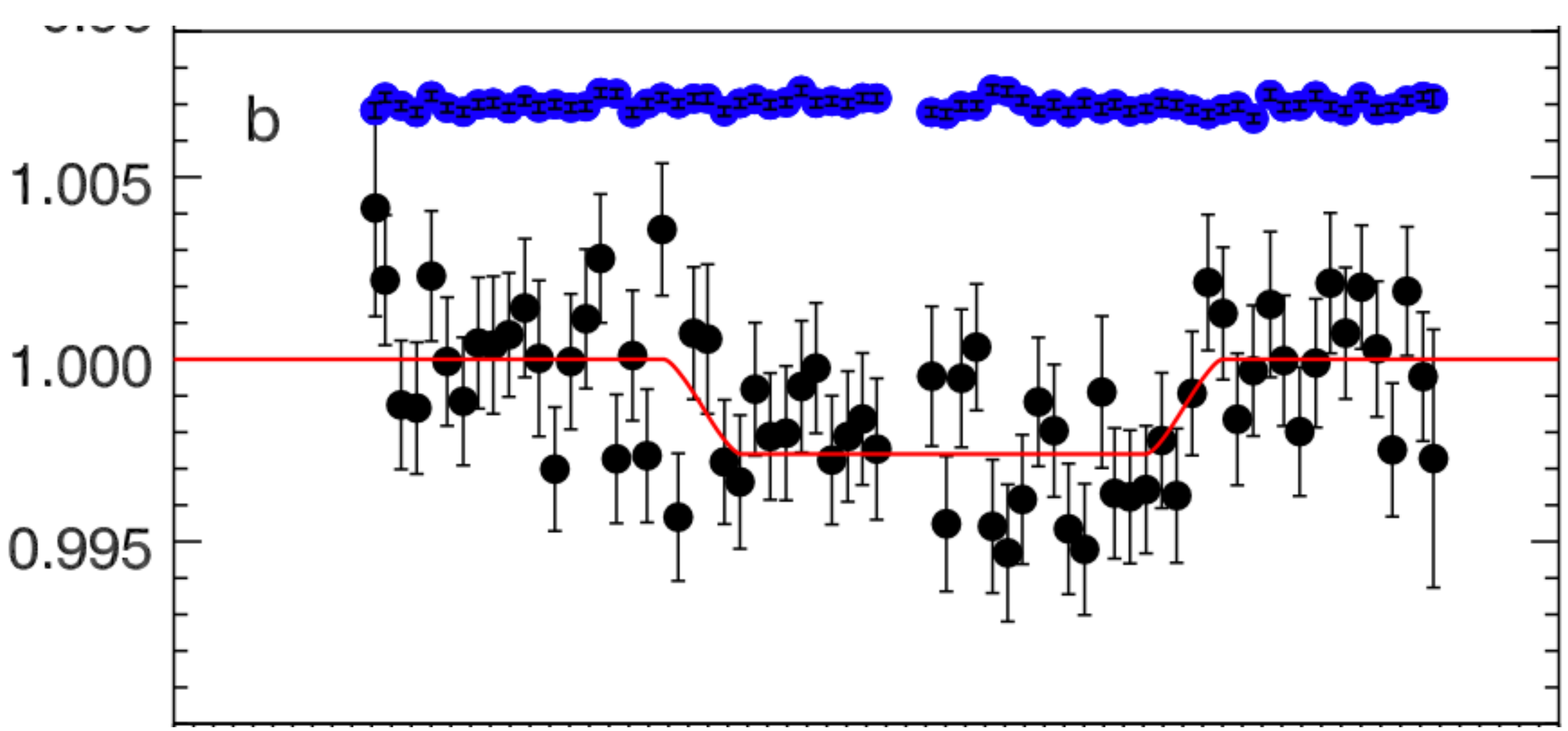


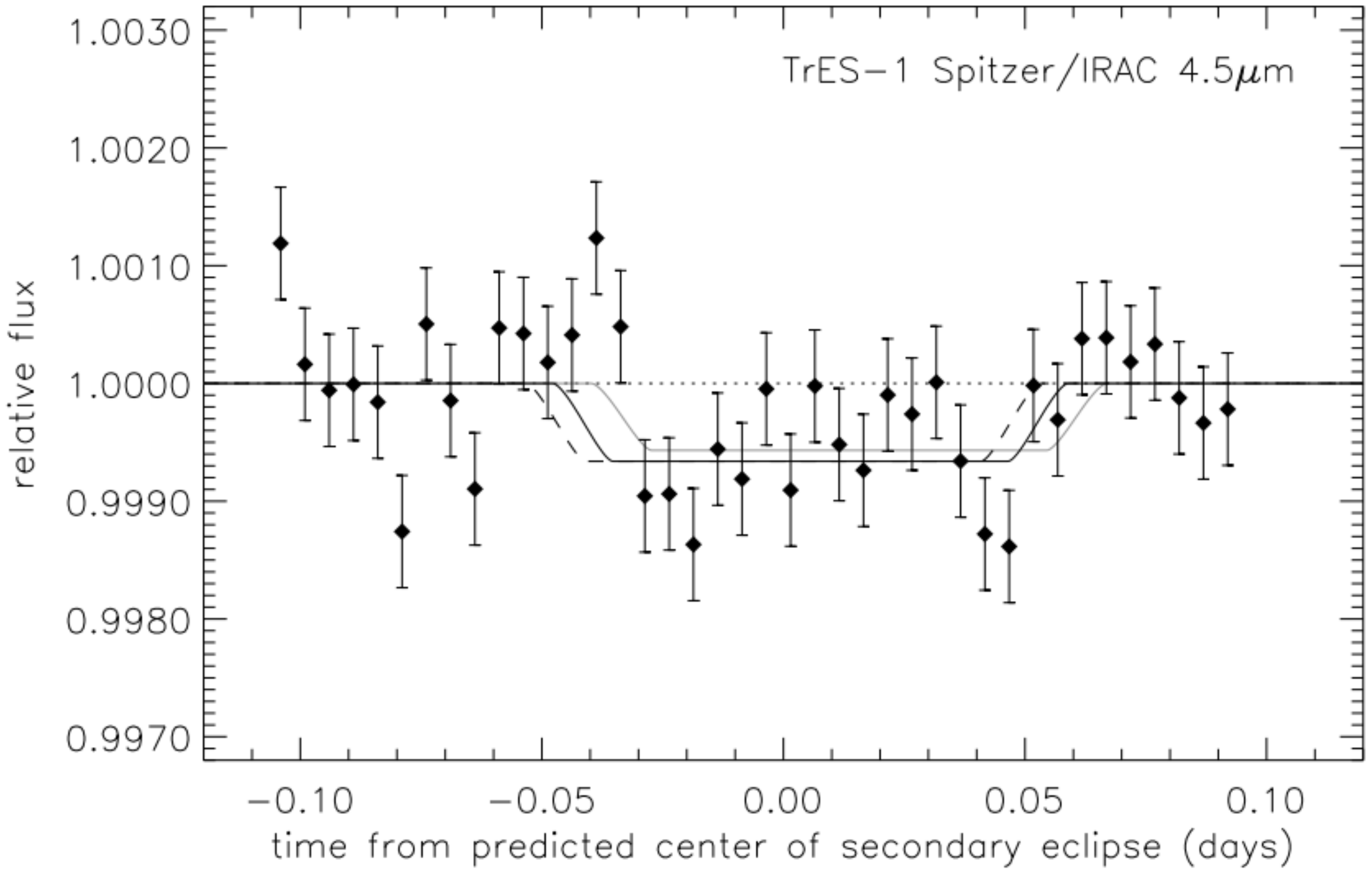
Thermal emission and reflected light from the planet are blocked during secondary eclipse

Reveals average spectrum of the dayside hemisphere

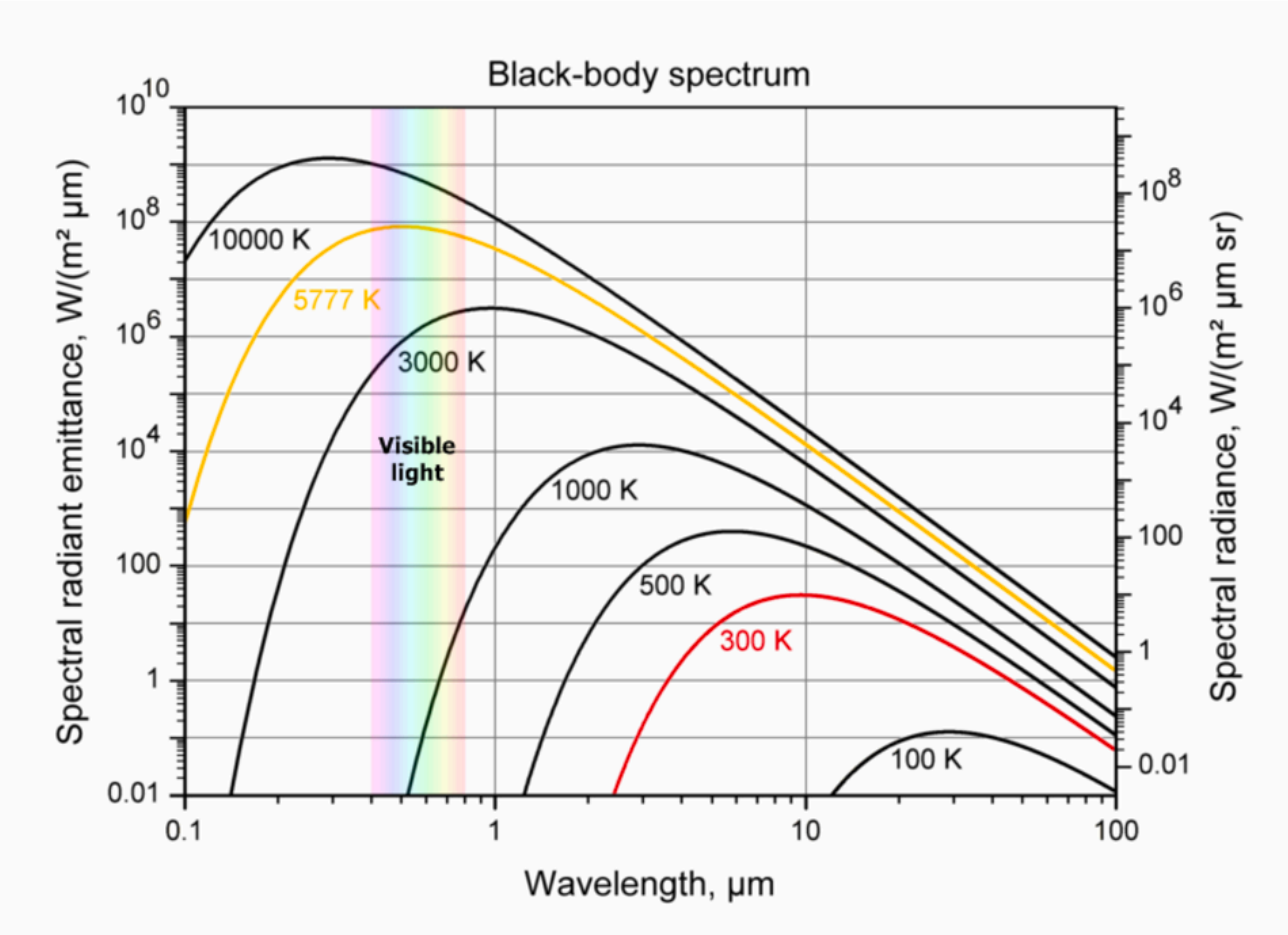
The first detections of thermal emission

Deming et al. 2005, Charbonneau et al. 2005





Intro to thermal emission — blackbody approximation



- Luminosity L ~ T^4
- Wavelength of peak emission is

$$\lambda_{\text{peak}} = \frac{b}{T}$$

where b = 3000 micron*Kelvin

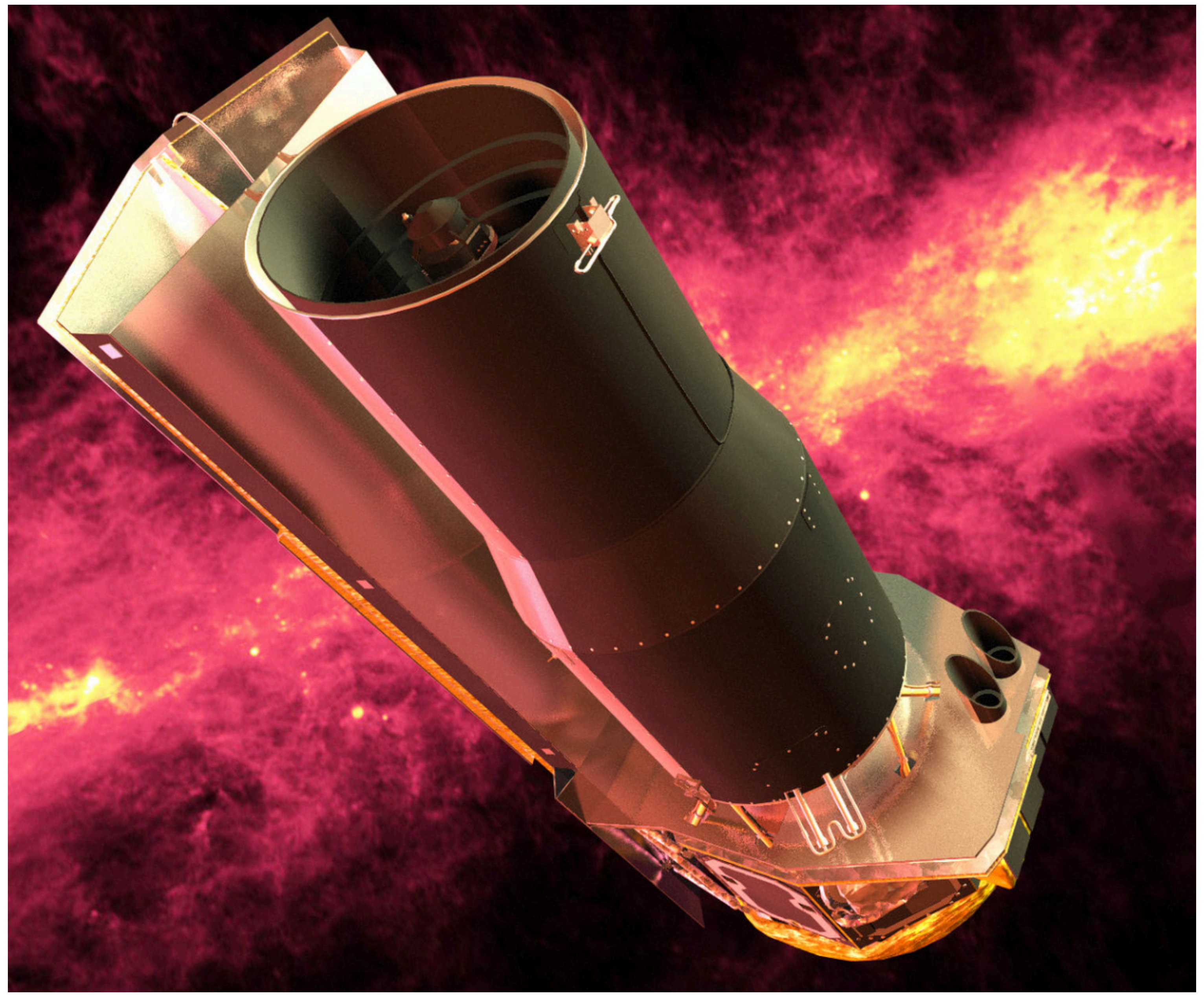
$$\frac{F_{\text{planet}}}{F_{\text{star}}} = \frac{\text{blackbody}(\lambda, T_{\text{planet}})}{\text{blackbody}(\lambda, T_{\text{star}})} \times (R_p/R_s)^2$$

credit: sun.org

Key facilities

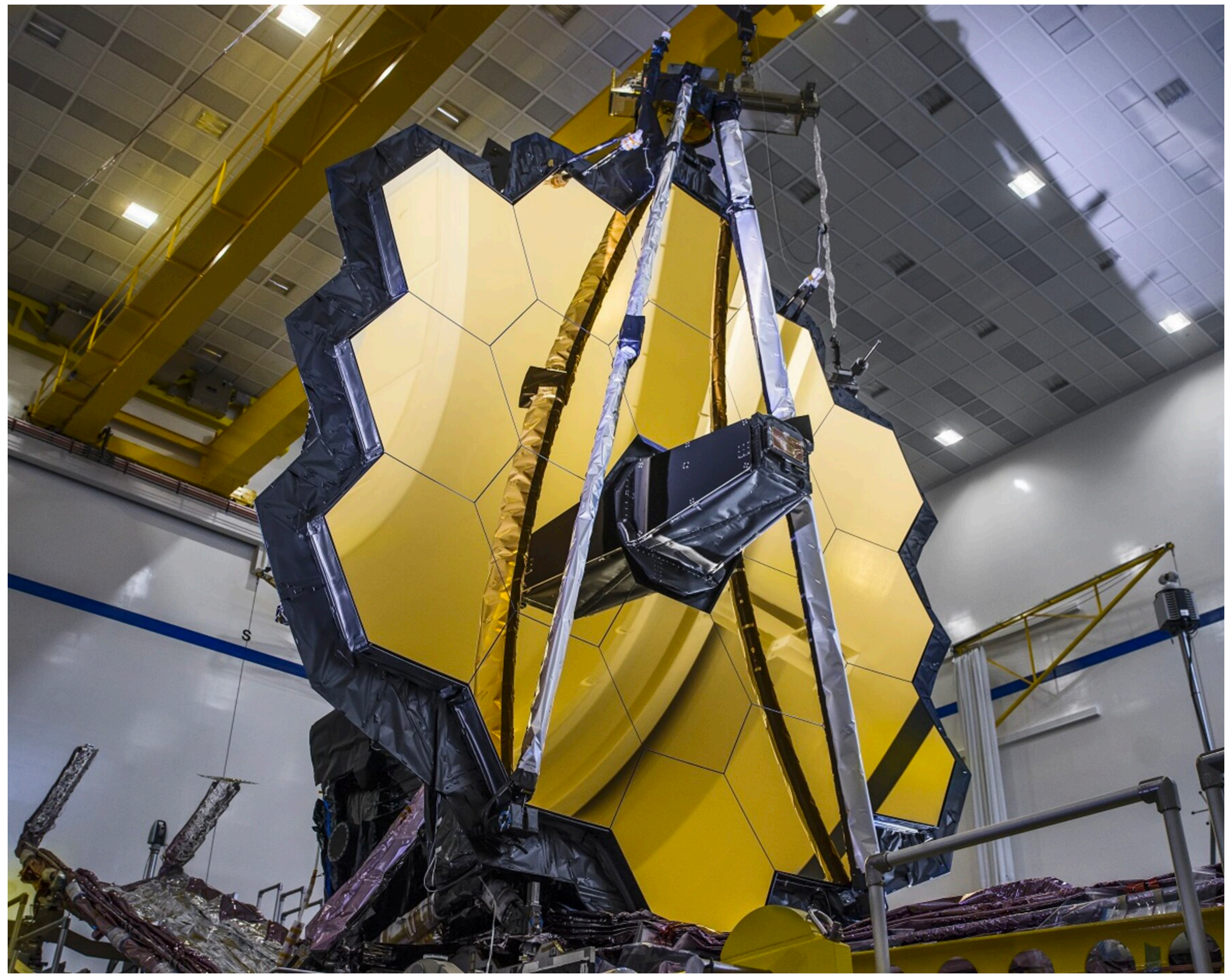
Atmosphere characterisation is easier when Earth's atmosphere is not in the way!

** note: ground-based observations are also important and complementary



Spitzer Space Telescope
Launch date: 2003
85 cm mirror
Infrared; 3.6 - 160 micron

Hubble Space Telescope
Launch date: 1990
2.4 m mirror
UV-near-IR: 0.1 - 1.7 micron



JWST
Launch date: 2021
6.5 m mirror
Optical - IR: 0.6 - 30 micron

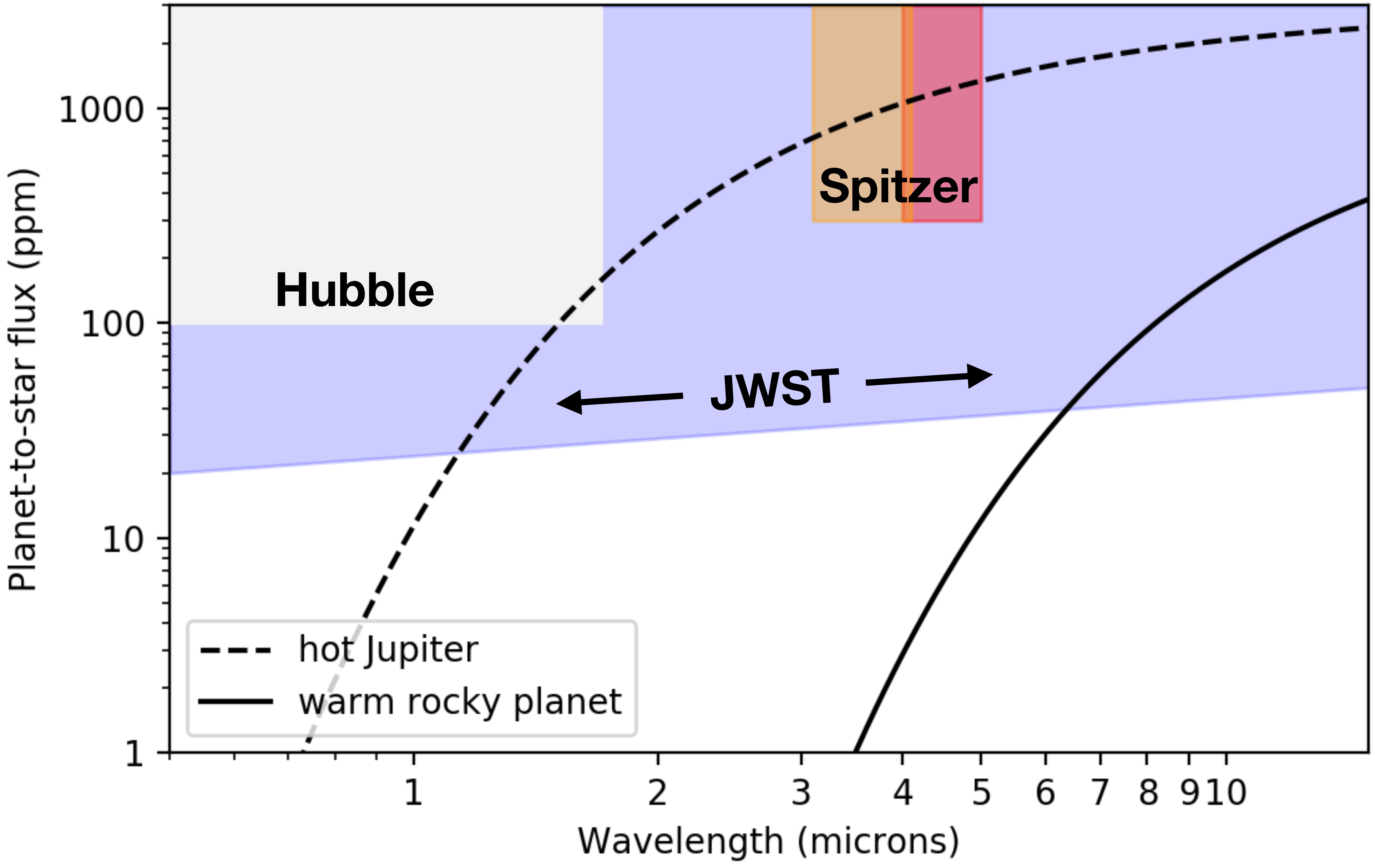
Typical thermal emission signal

Hot Jupiter orbiting a Sun-like star:

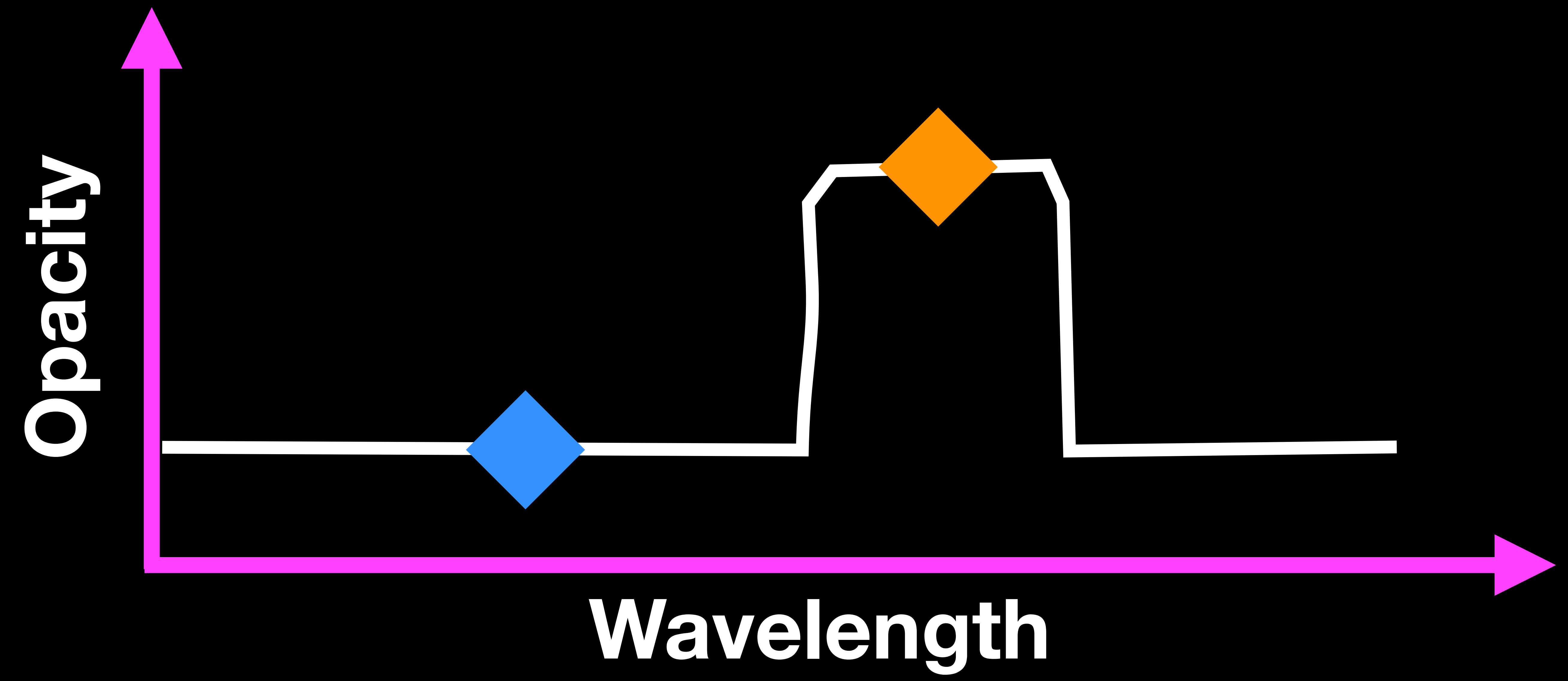
- Tp = 1500, Ts = 5000, Rp/Rs = 0.01

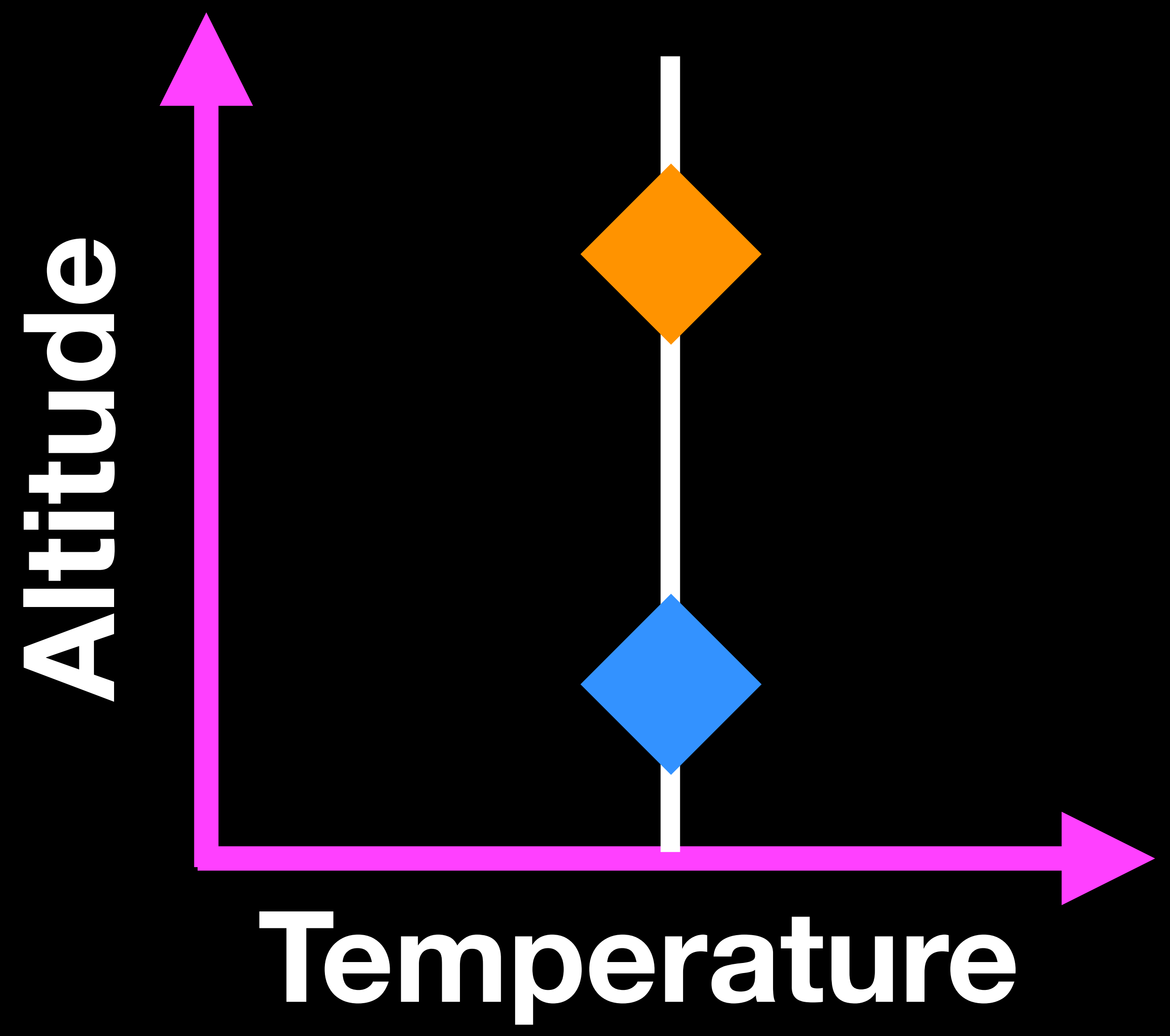
Warm rocky planet orbiting an M-dwarf:

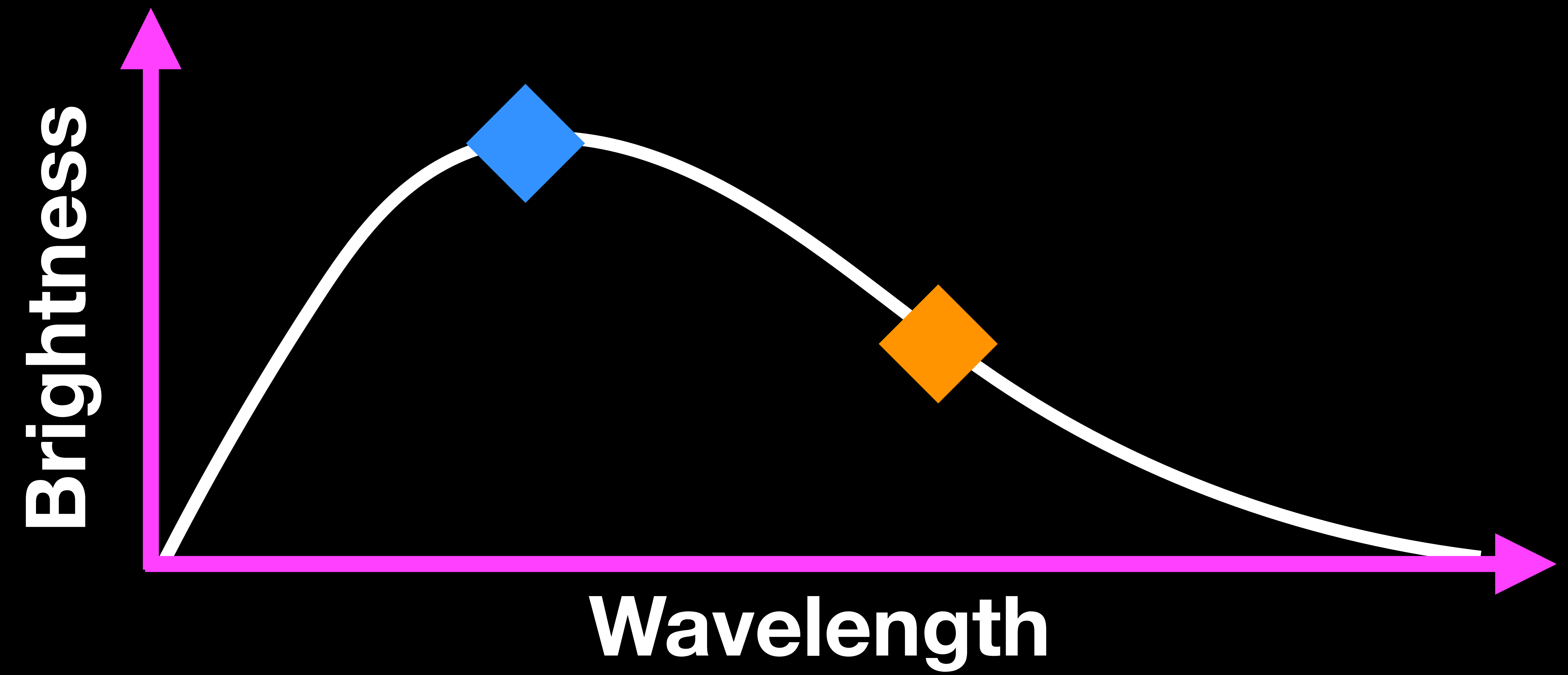
- Tp = 400, Ts = 3000, Rp/Rs = 0.01



Thermal emission *spectra* reveal chemical composition

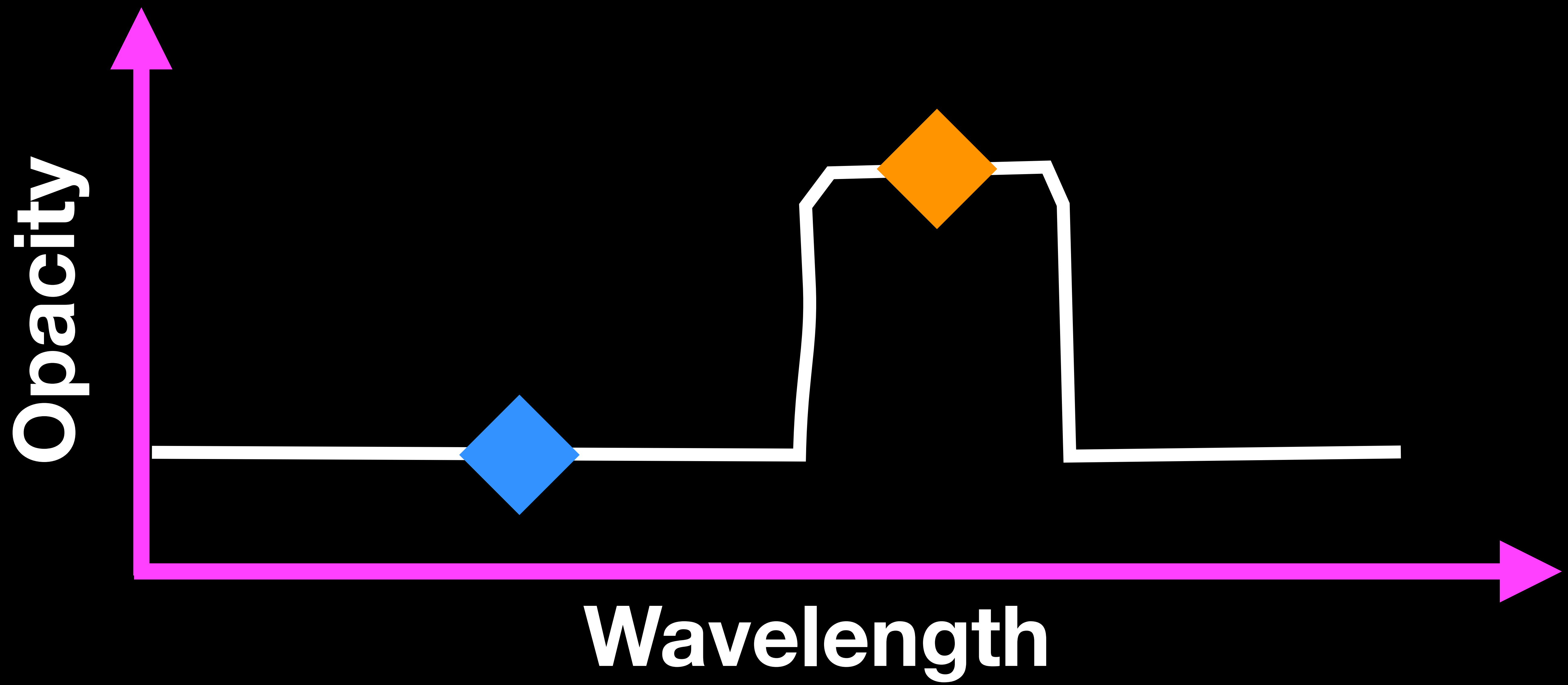


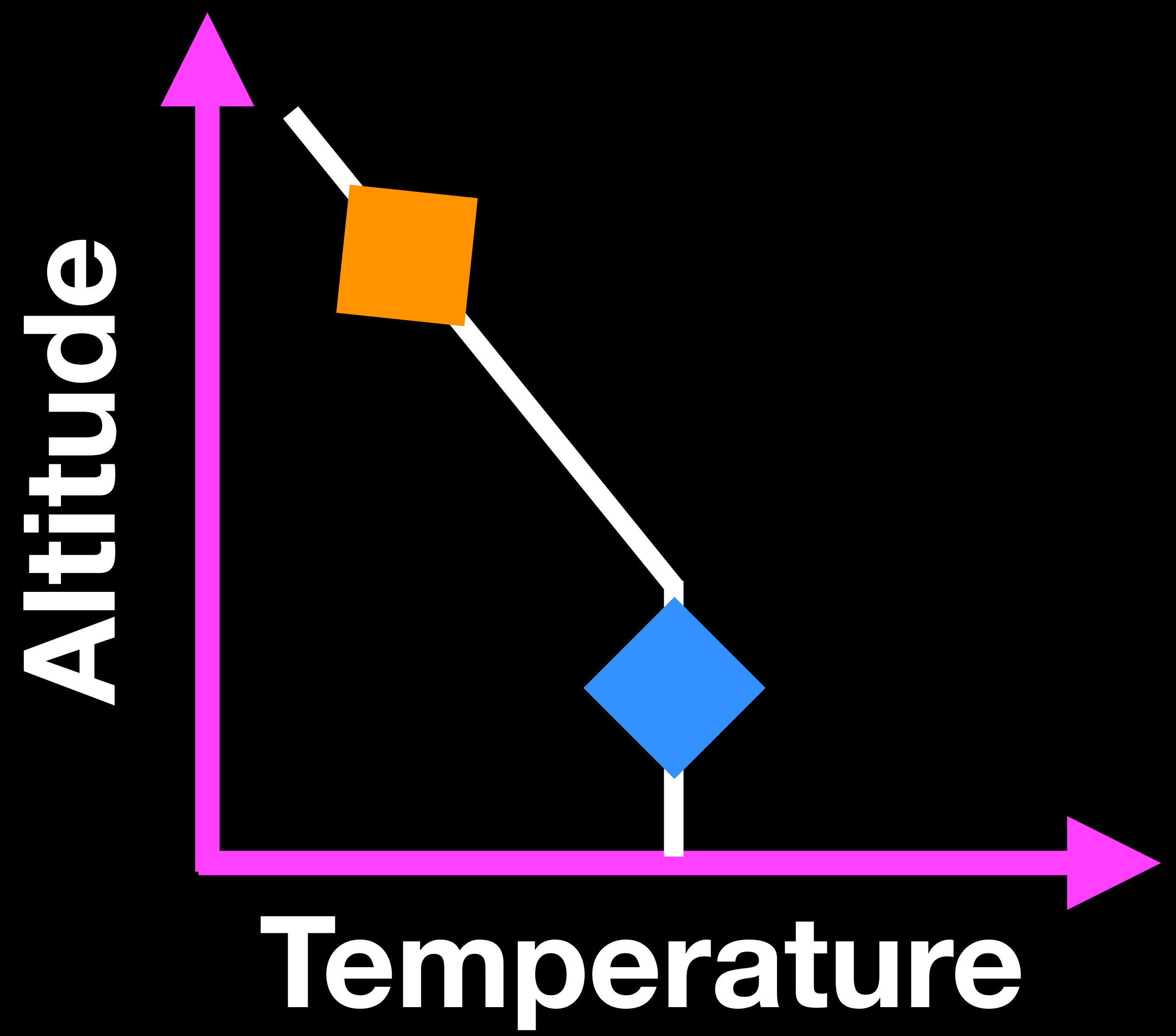


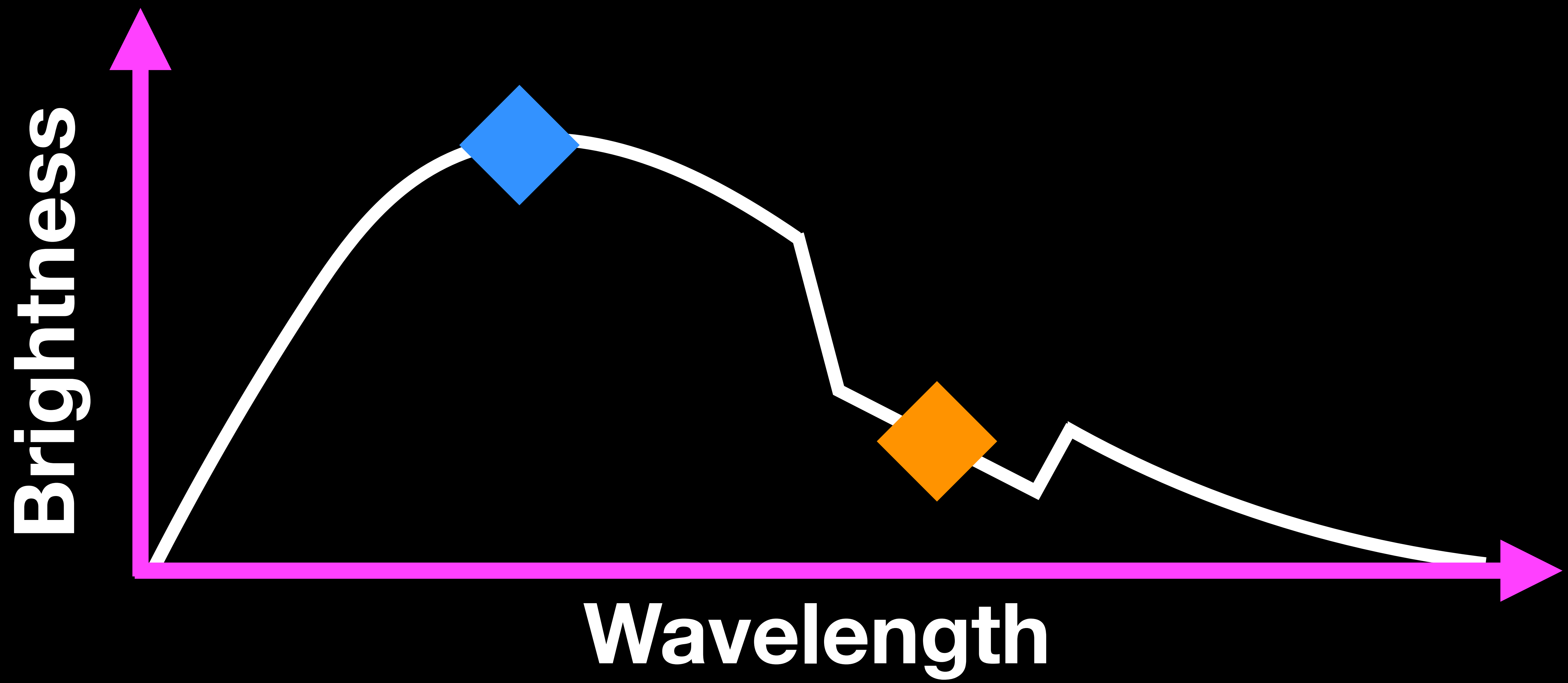


Credit: Tom Mikal-Evans

Thermal emission *spectra* reveal chemical composition

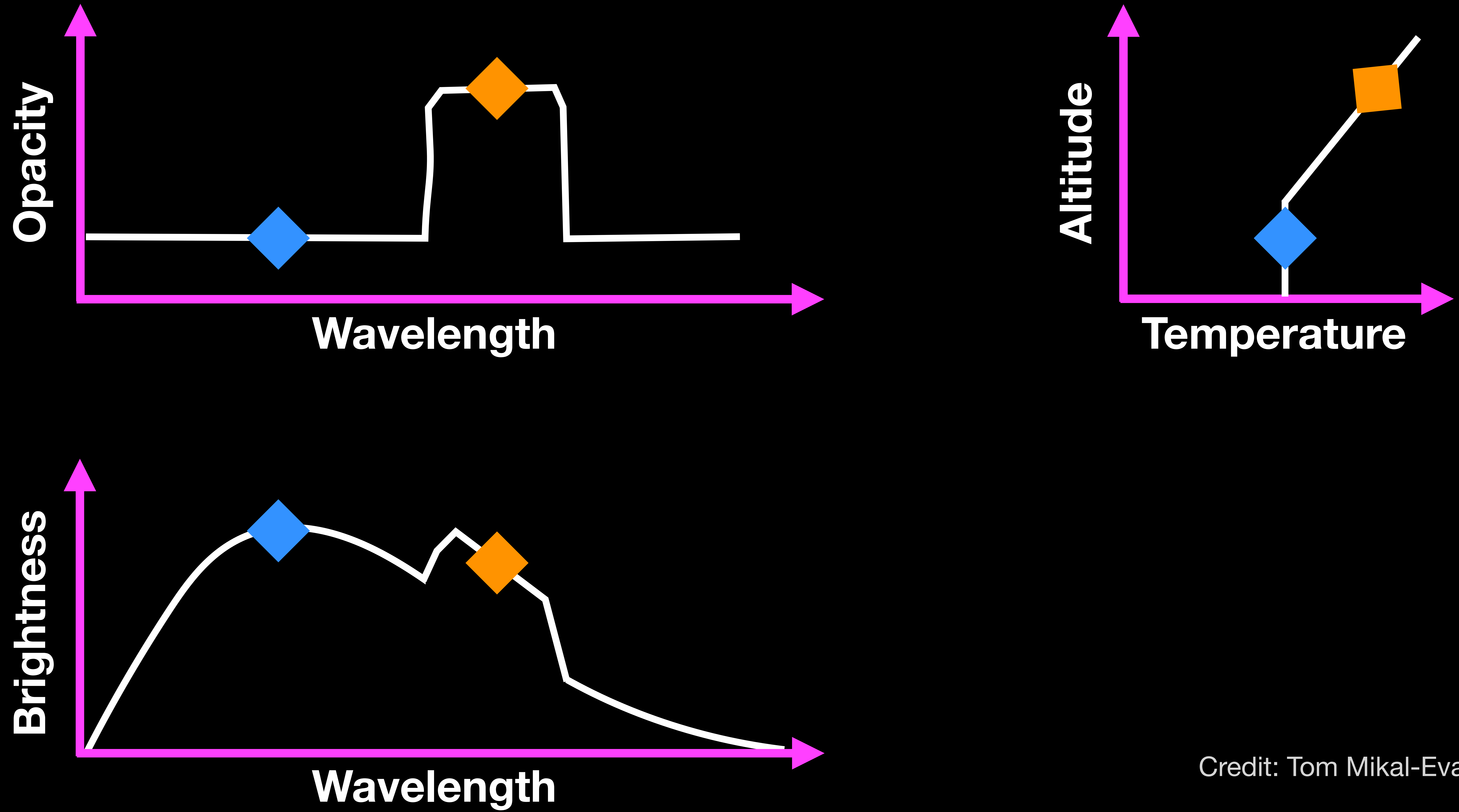






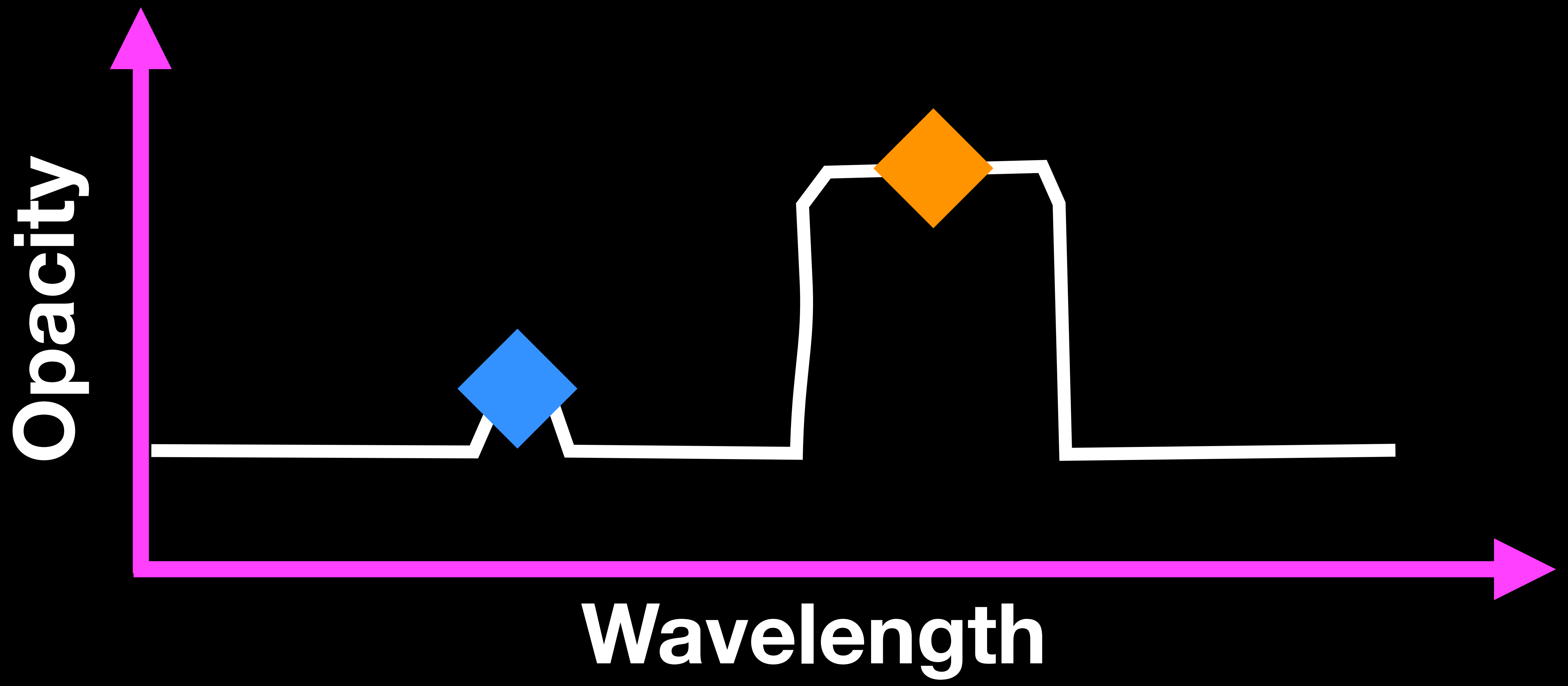
Credit: Tom Mikal-Evans

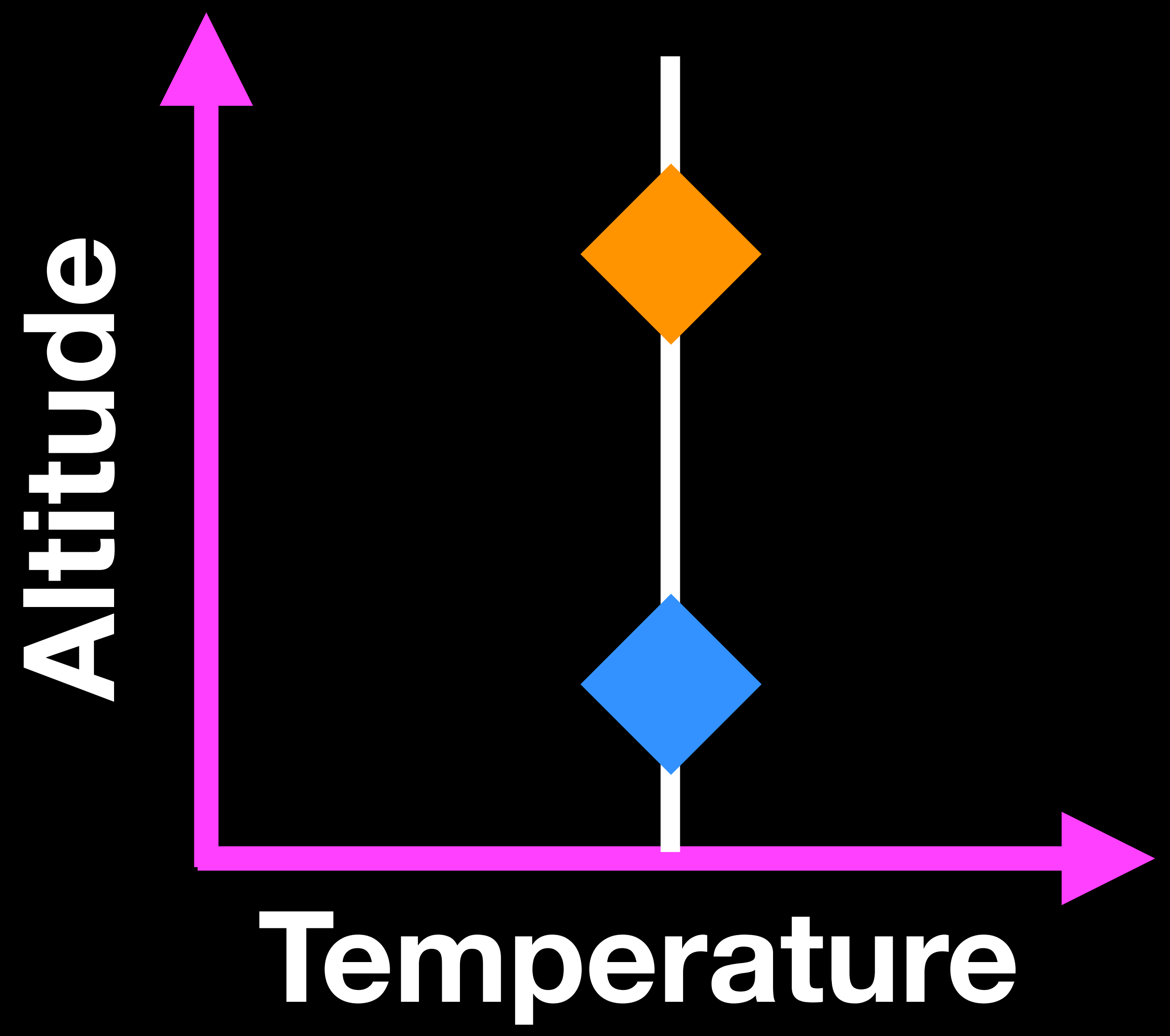
Thermal emission *spectra* reveal chemical composition

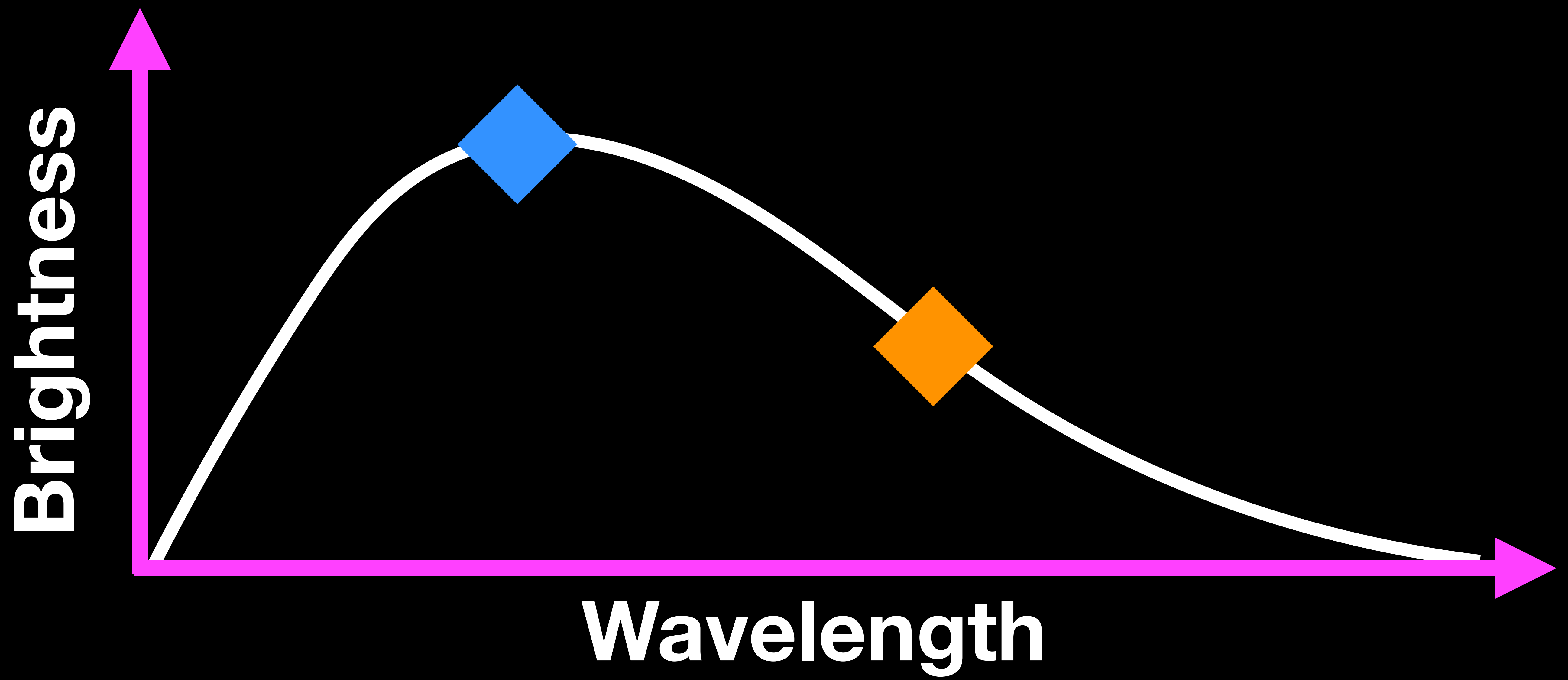


Credit: Tom Mikal-Evans

Thermal emission *spectra* reveal chemical composition

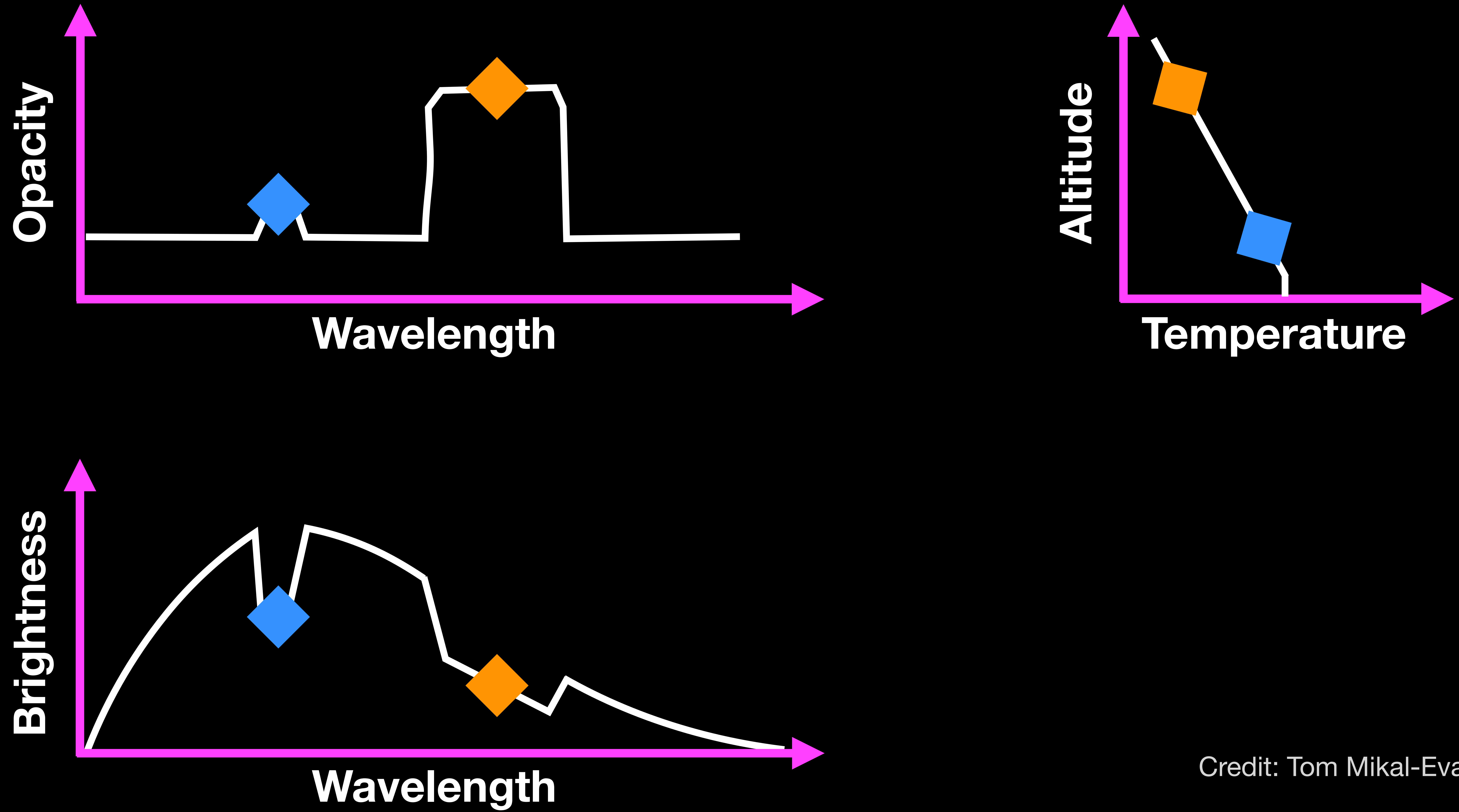






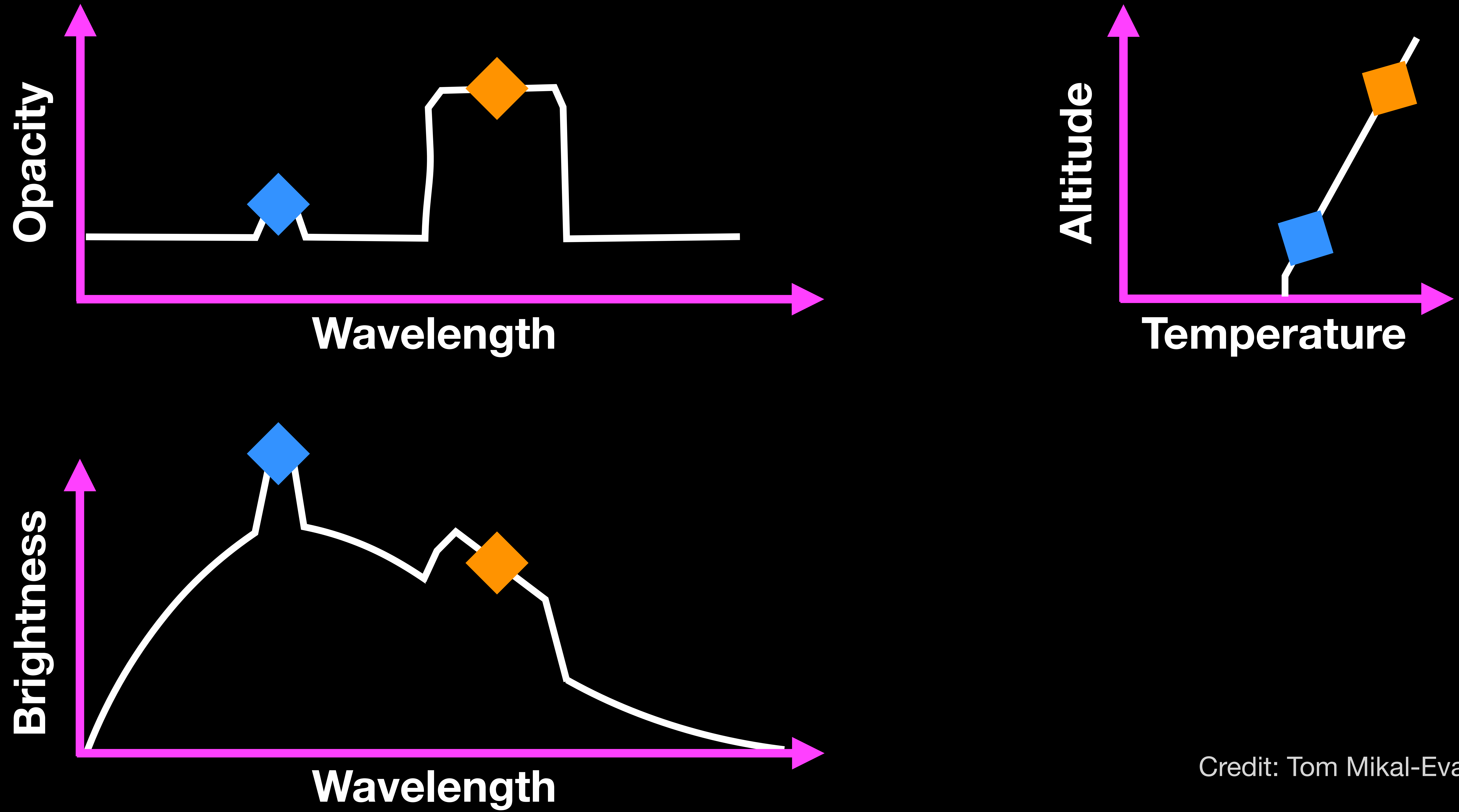
Credit: Tom Mikal-Evans

Thermal emission *spectra* reveal chemical composition



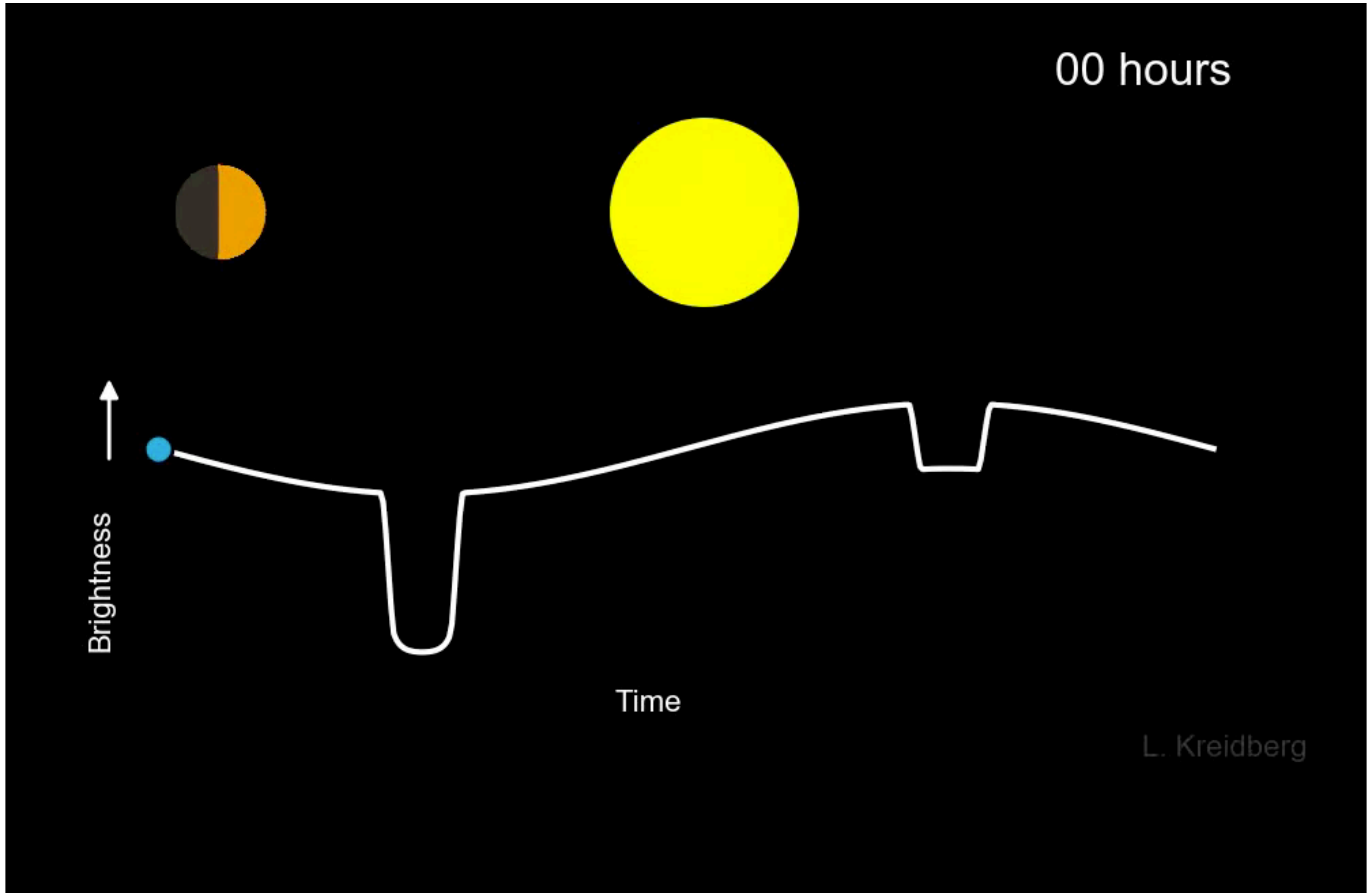
Credit: Tom Mikal-Evans

Thermal emission *spectra* reveal chemical composition



Credit: Tom Mikal-Evans

Intro to phase curves

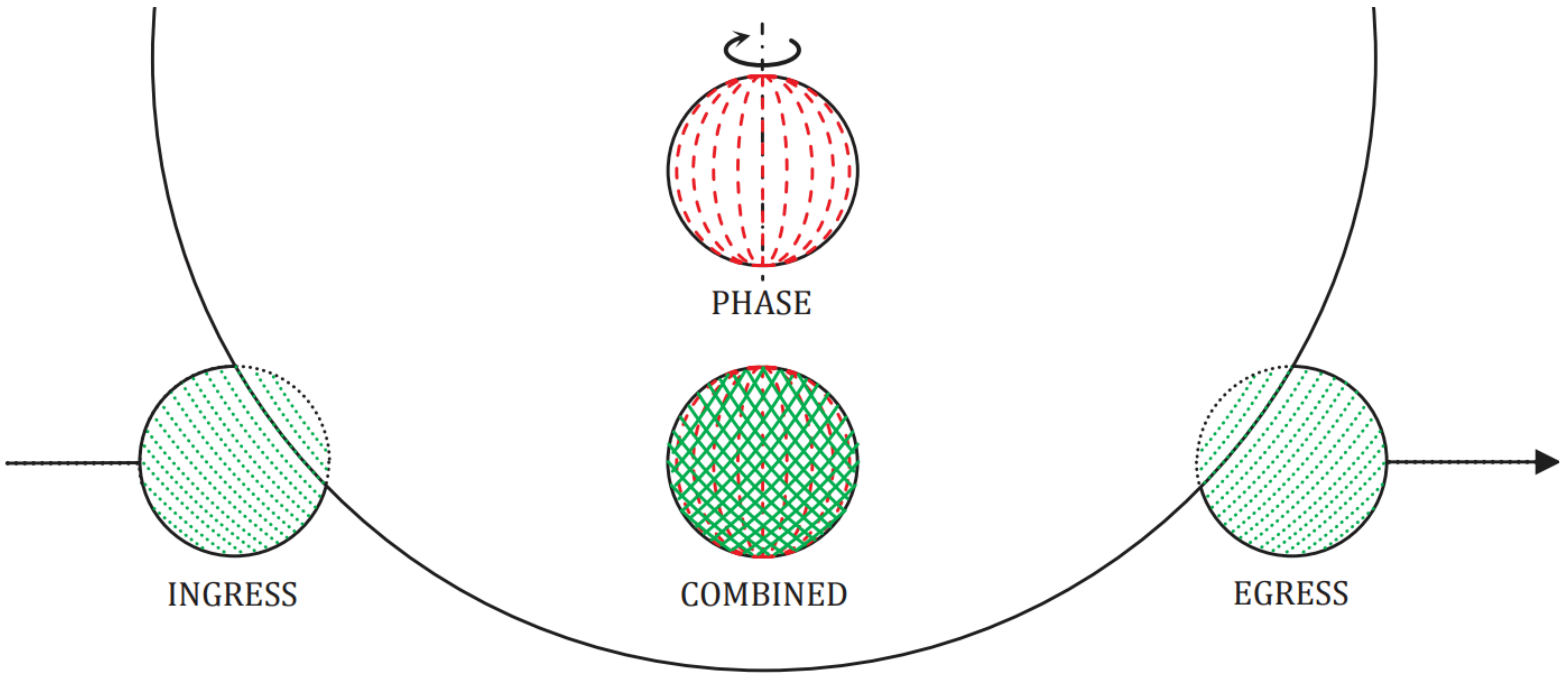


Animation available at github.com/lkreidberg

- Observe a complete orbital revolution
- Changing viewing angle reveals different regions of the atmosphere over time
- Can map the global climate and chemical composition!

A new frontier: eclipse mapping!

More on this from Emily Rauscher on Thursday!

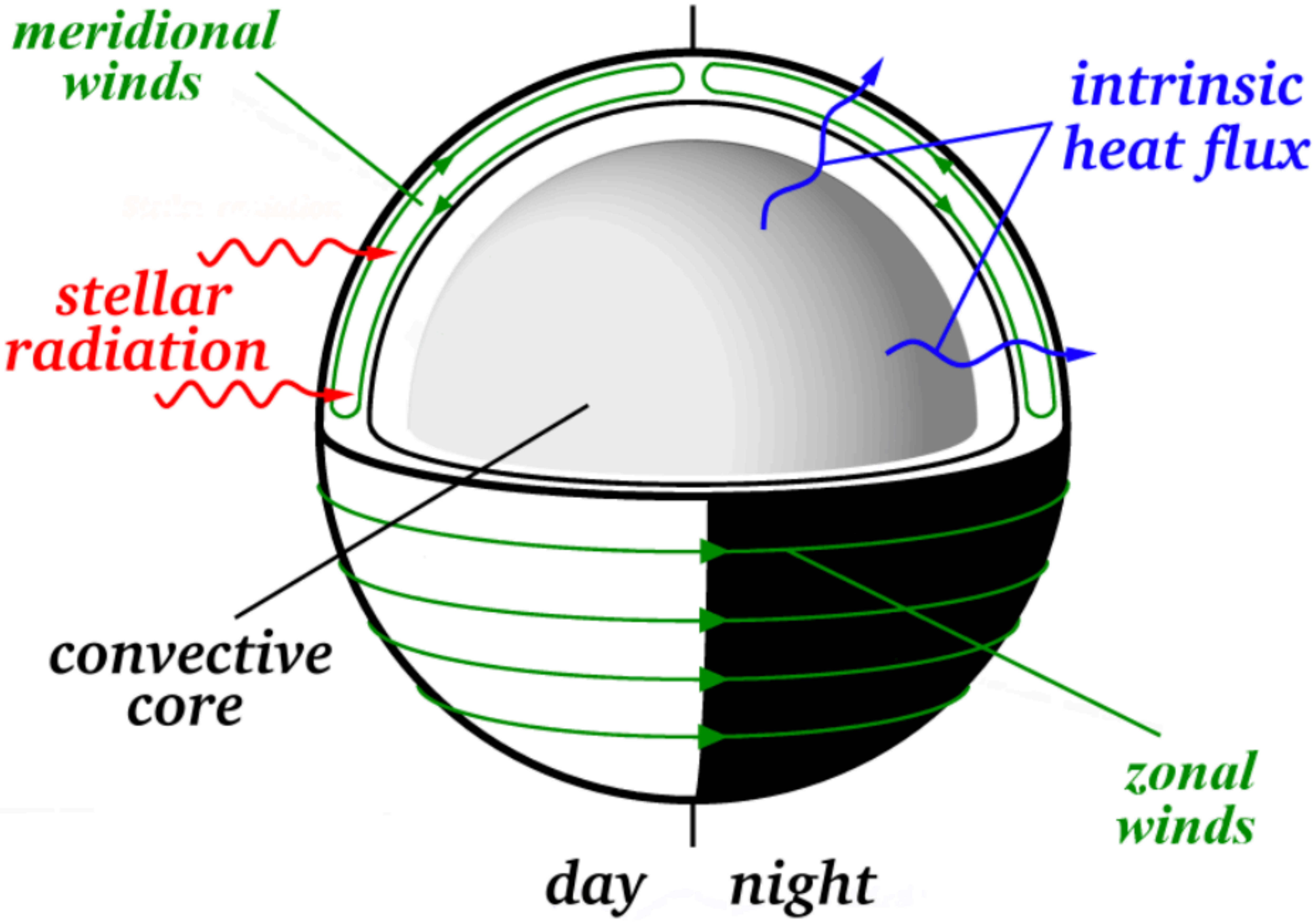


During ingress and egress, the visible disk of the planet changes incrementally

— De Wit et al. 2012

Science from eclipses and phase curves

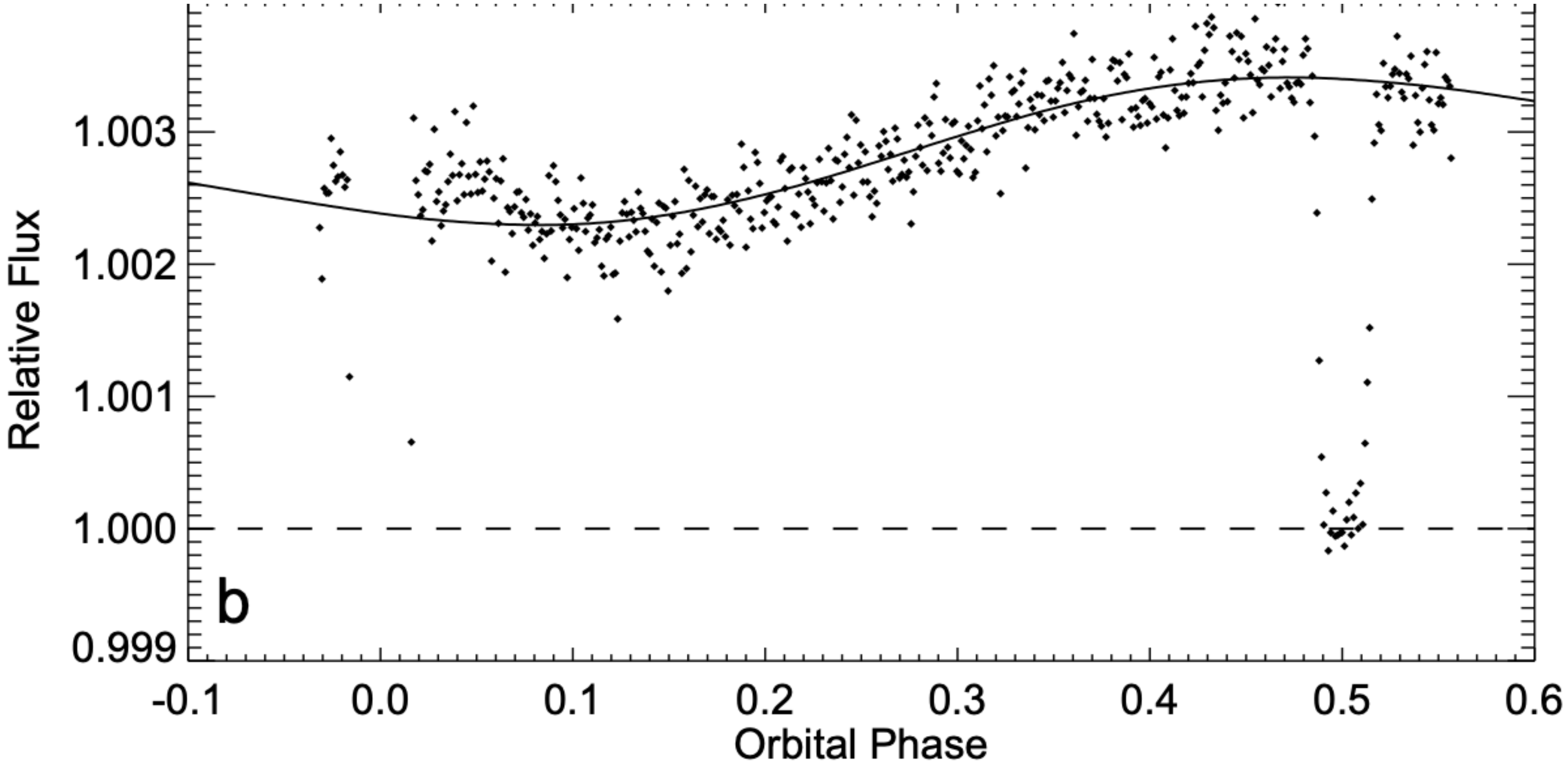
- How is heat recirculated in the atmosphere?
- What is the temperature structure? Are there thermal inversions?
- How do chemical composition and clouds vary as a function of longitude?
- What is the atmospheric metallicity?
- Is an atmosphere present?

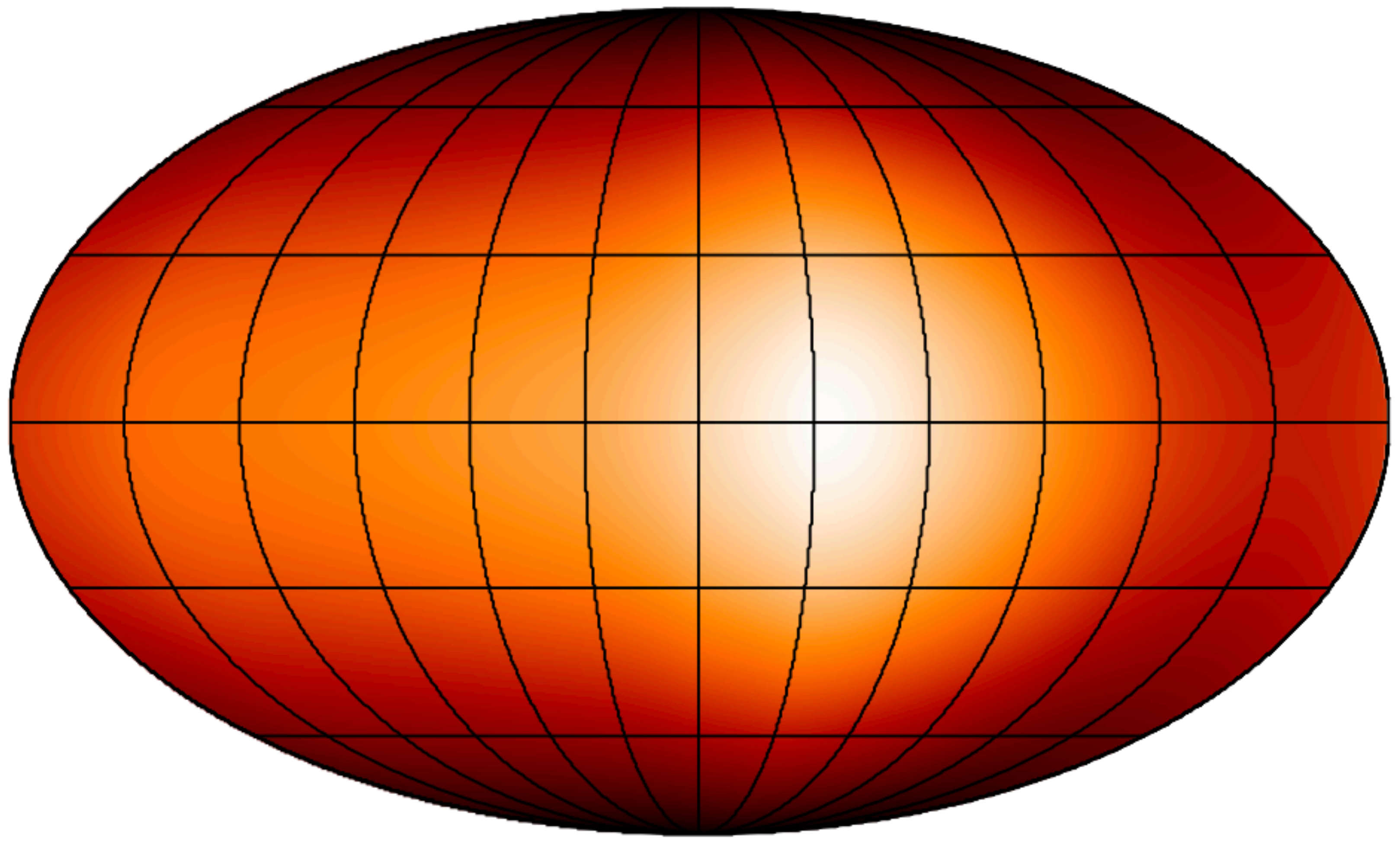


Showman & Guillot 2002

How is heat circulated in the atmosphere?

The first thermal phase curve, HD 189733b — Knutson et al. 2007

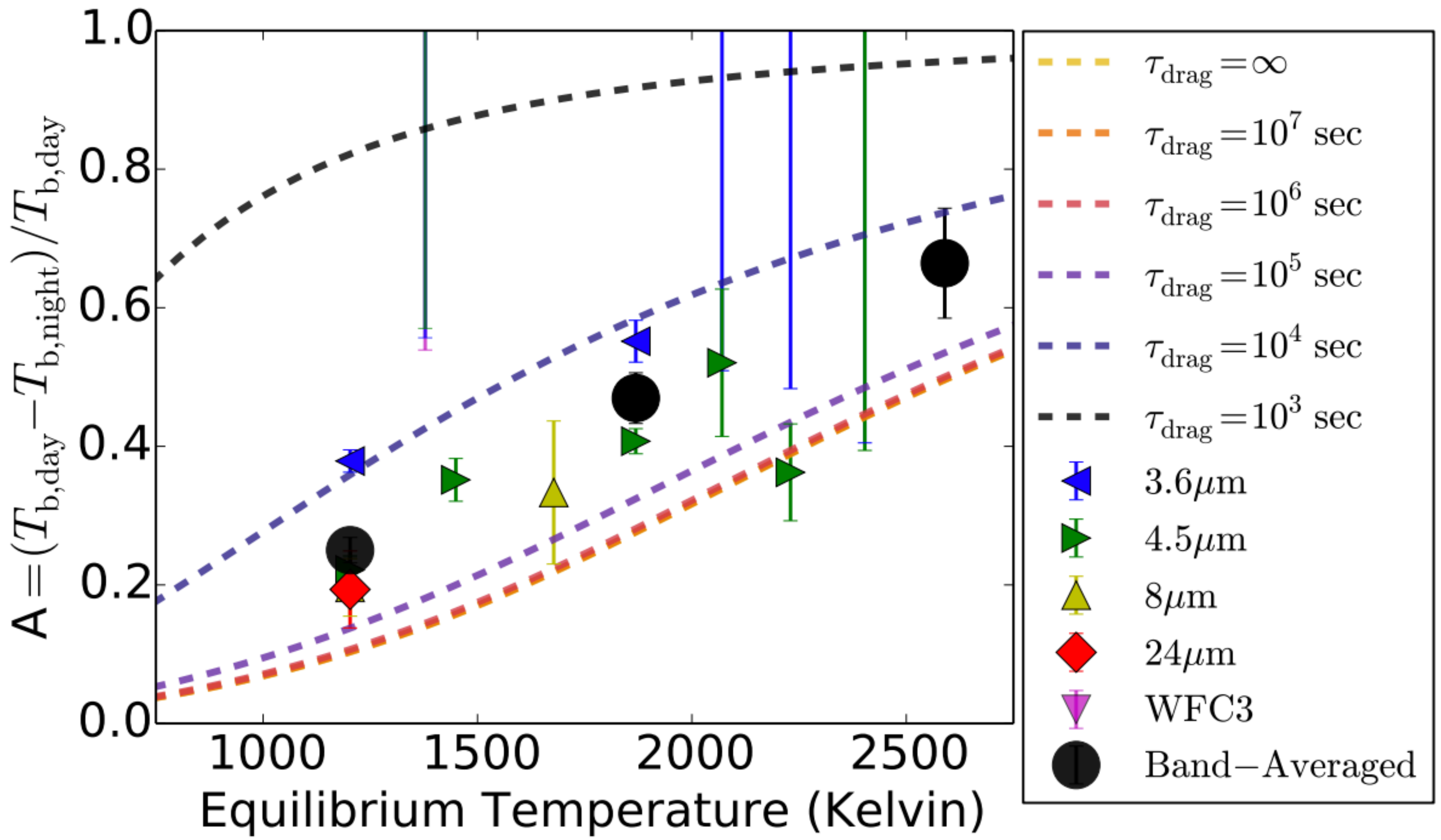




Peak brightness 16 +/- 6 degrees of the substellar point, day-night temp contrast ~ 240 K

How is heat circulated in the atmosphere?

Hotter planets have larger day-night temperature contrast

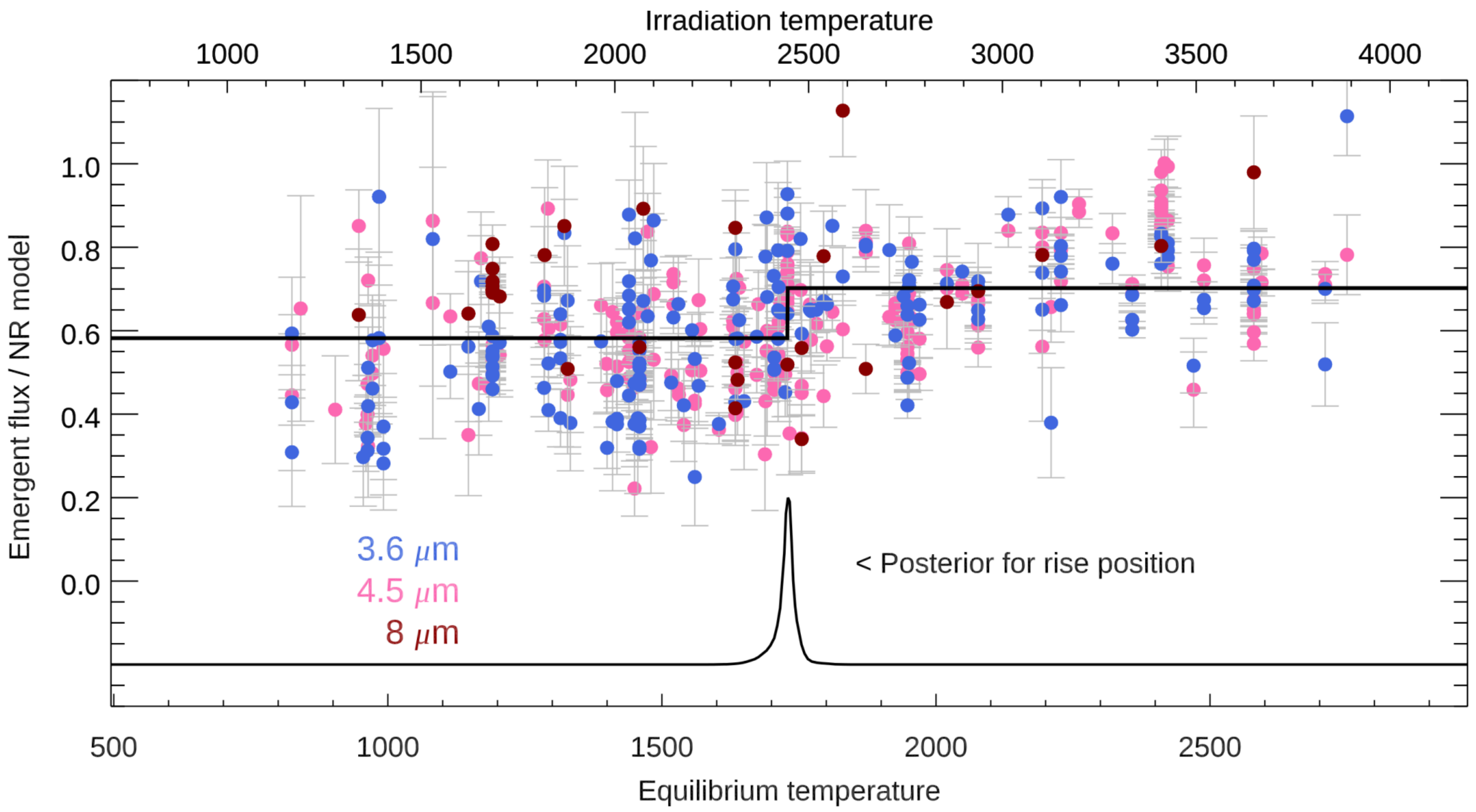


This trend is due to the decreasing ability with increasing incident stellar flux of waves to propagate from day to night and erase temperature differences.

Komacek et al. 2016

How is heat circulated in the atmosphere?

A sharp rise in brightness at 1730 K



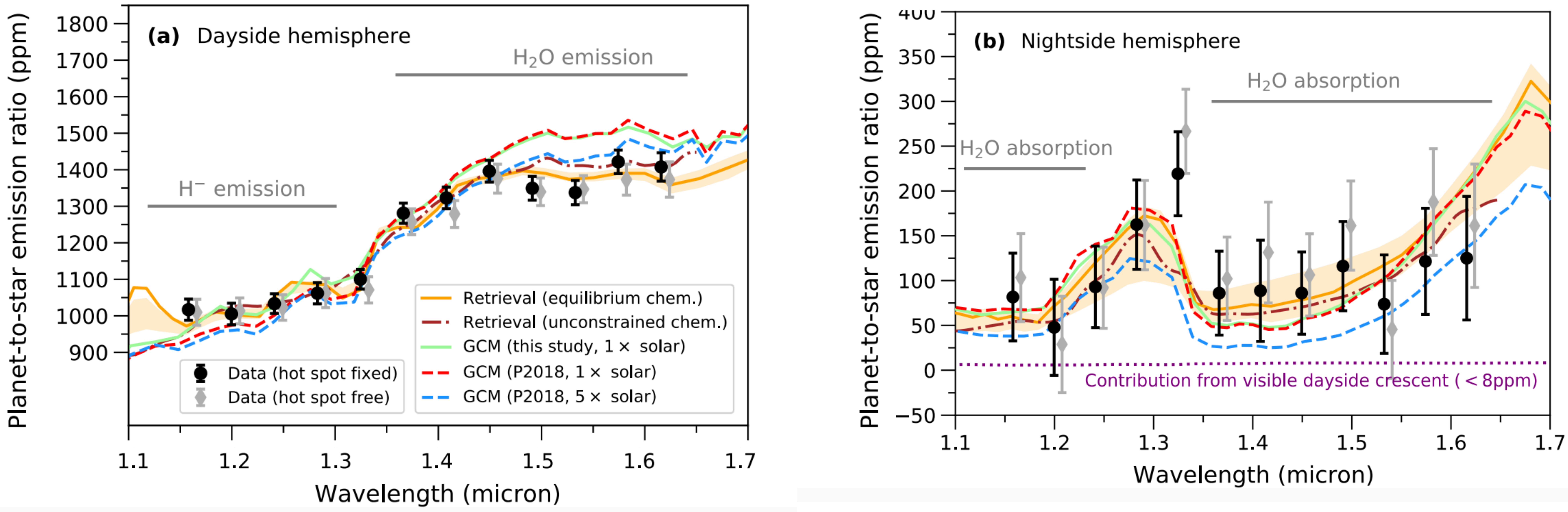
Deming et al. 2023

Onset of magnetic drag? and/or the rapid dissipation of day side clouds?

How does the temperature change with altitude?

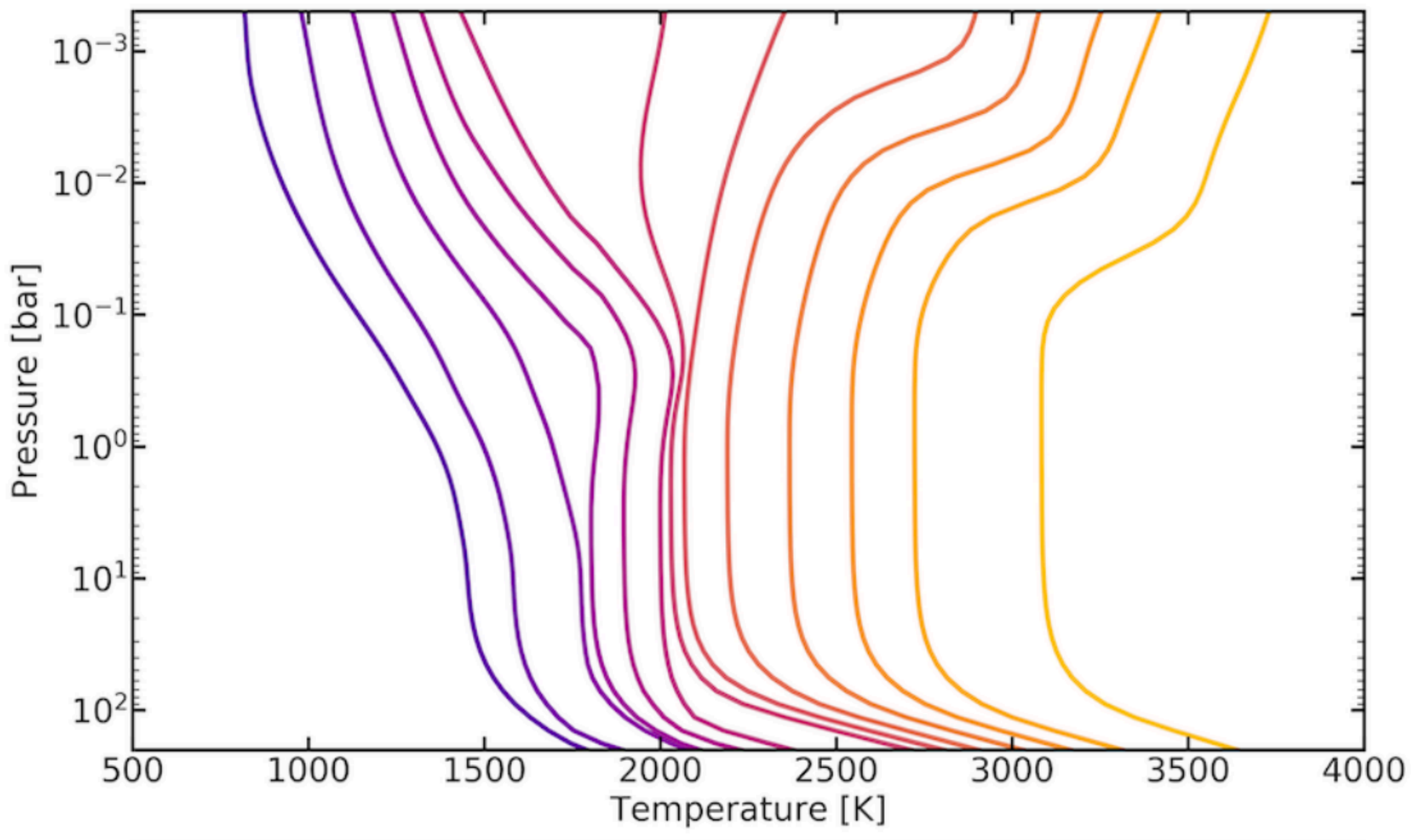
Thermal inversion on the dayside but not the nightside for an ultra-hot Jupiter

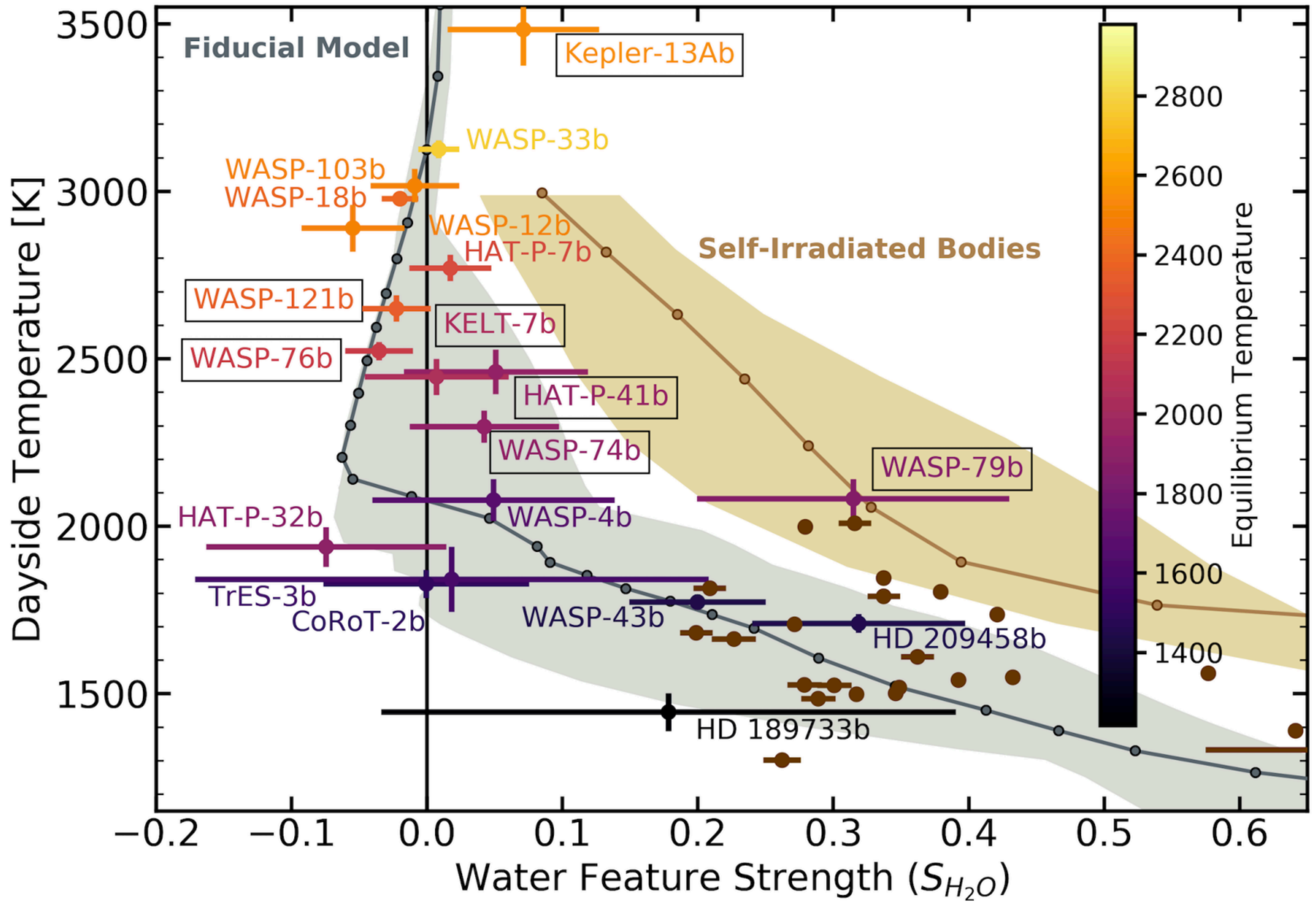
Mikal-Evans et al. 2022



How does the temperature change with altitude?

Inversions increase in strength with increasing irradiation

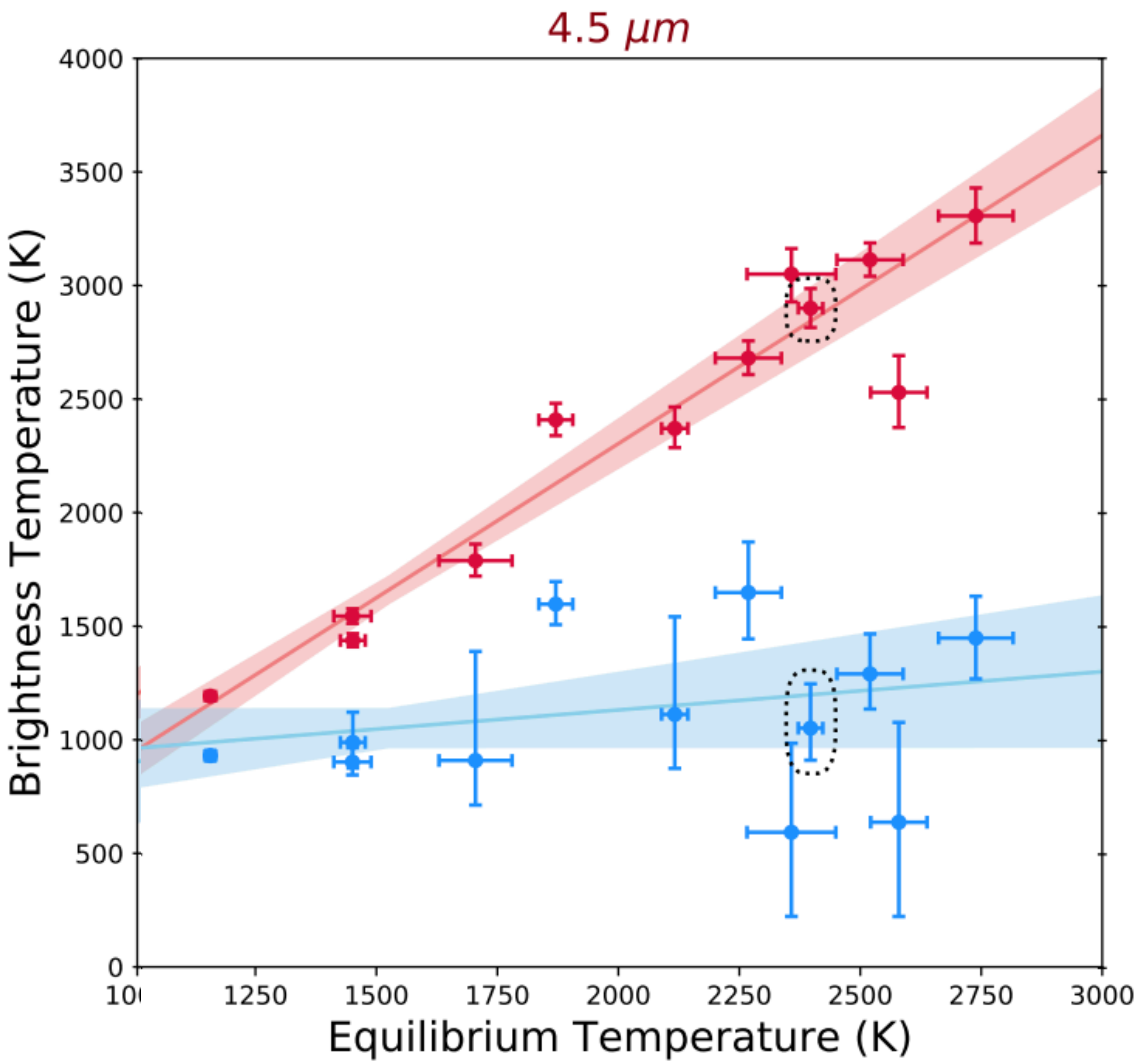




Mansfield et al. 2021

How does chemistry and cloud coverage change with longitude?

Evidence for nightside clouds



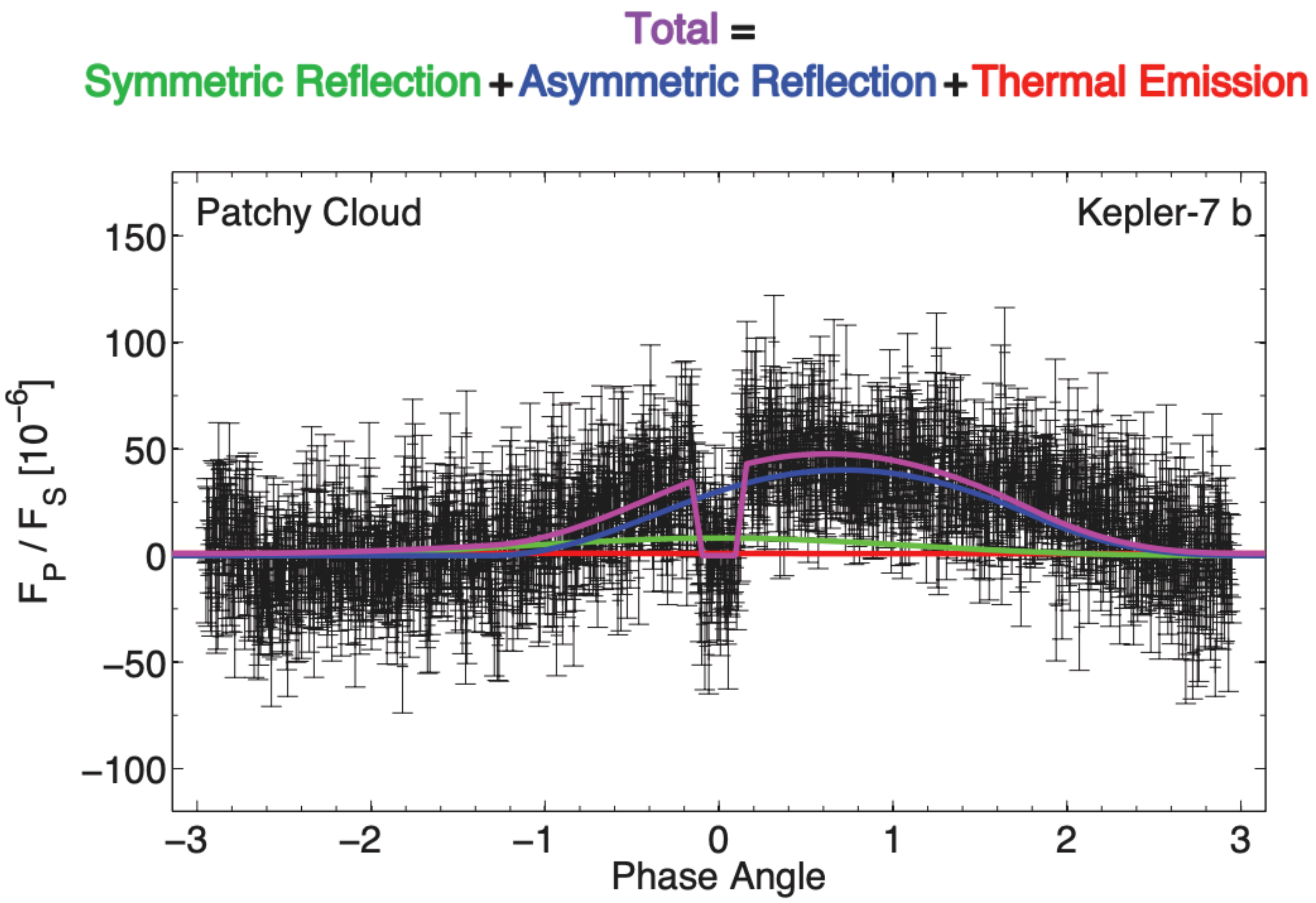
Ask me later about WASP-43b!

Uniform nightside temperature, possibly due to clouds (or the relatively long radiative timescale on the nightside)

Keating et al. 2019, Beatty et al. 2019, Parmentier et al. 2021

How does chemistry and cloud coverage change with longitude?

Sometimes we see clouds on the dayside!



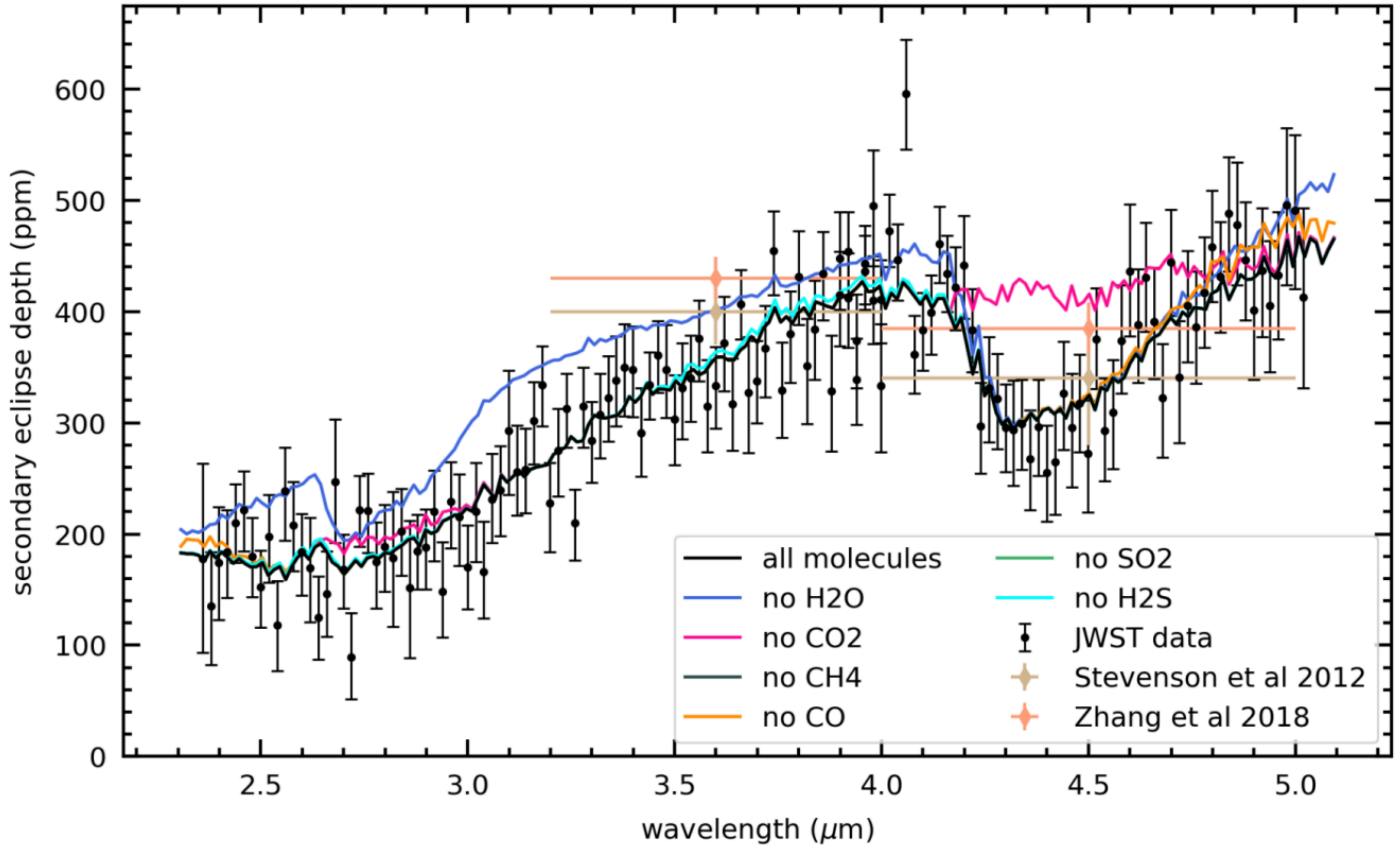
Evidence for reflective clouds west of the substellar point for Kepler-7b

Hu et al. 2015

(see also Demory et al. 2013, Parmentier et al. 2016)

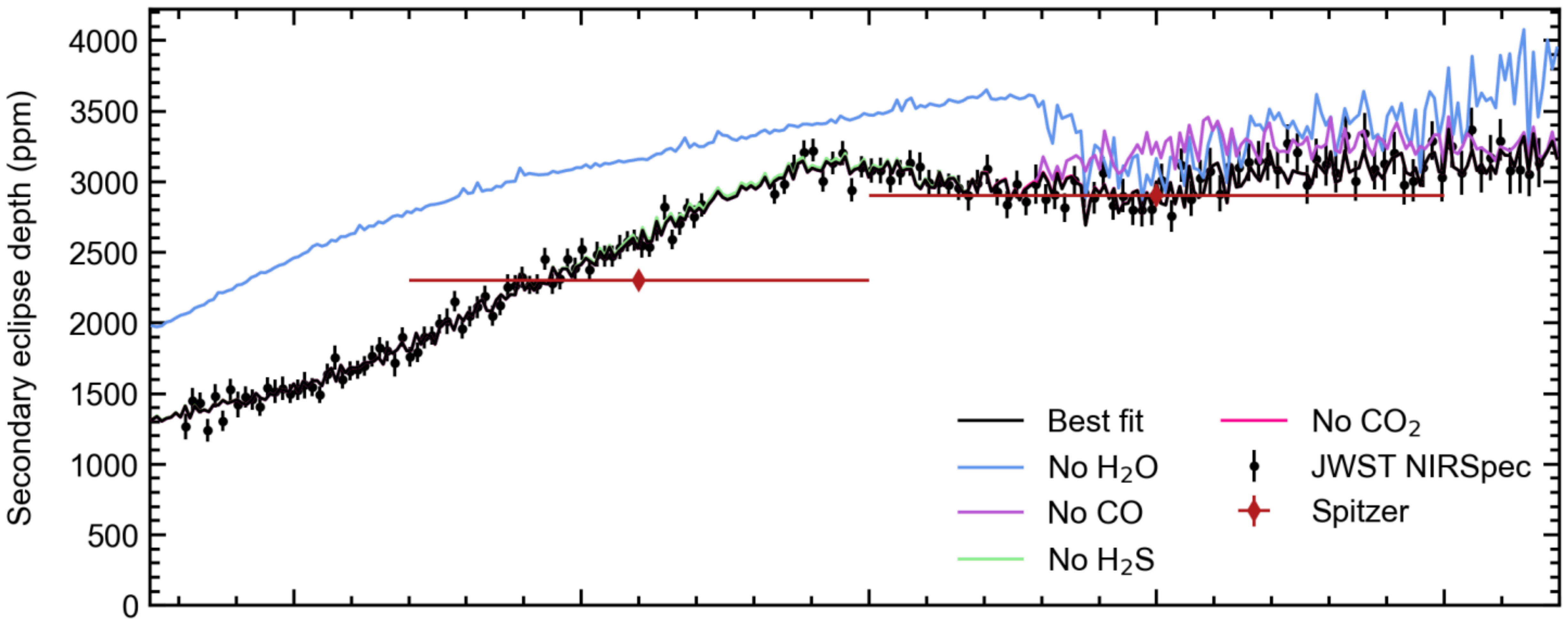
What is the atmospheric metallicity?

Gas giants show a diversity of compositions



Hot Saturn HD 149026b has approximately ~100x solar metallicity

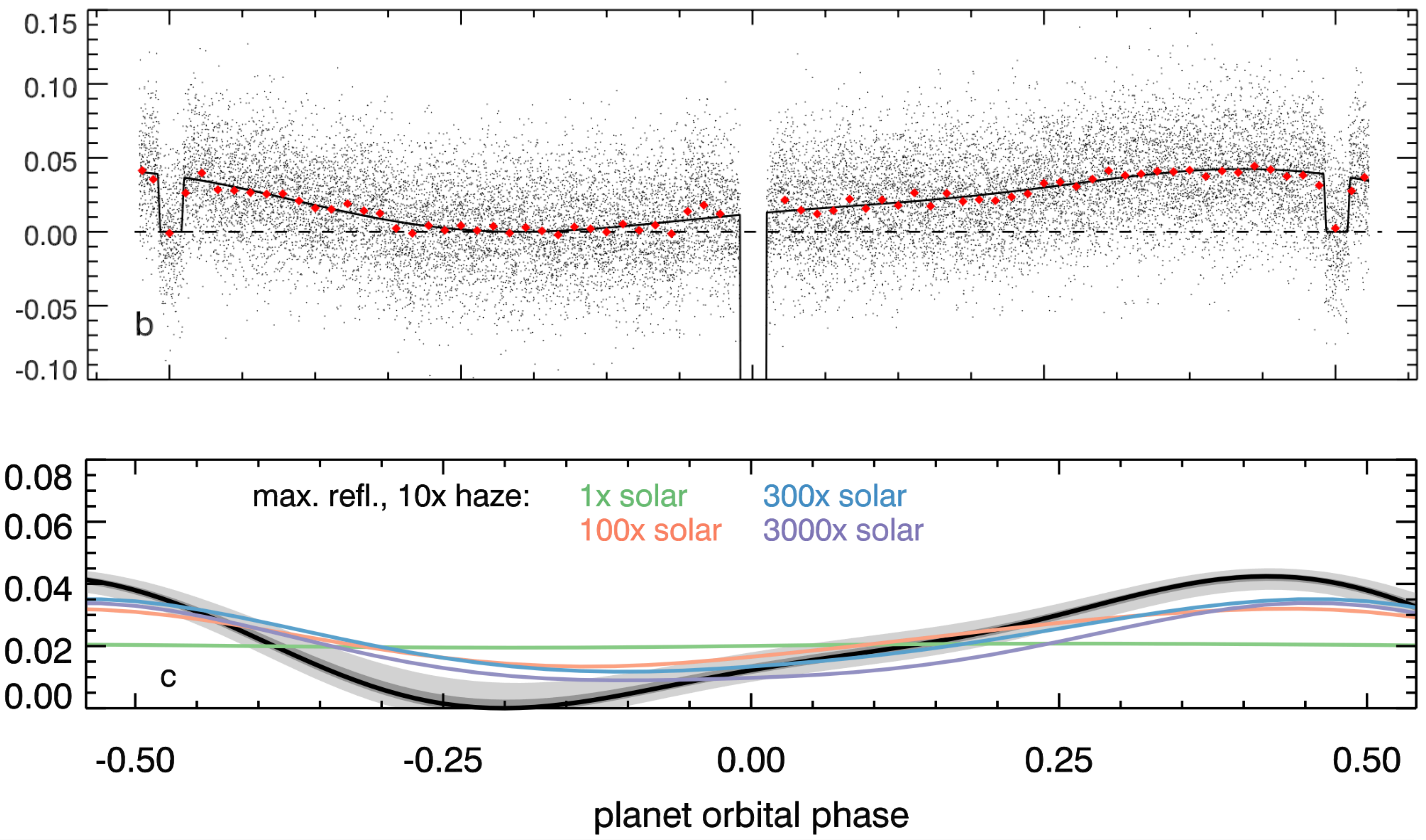
— Bean et al. 2023



Hot Jupiter WASP-77A b has a sub-solar metallicity

— August et al. 2023

Sub-Neptune GJ 1214b has a ~100 - 1000x solar metallicity atmosphere



Kempton et al. 2023

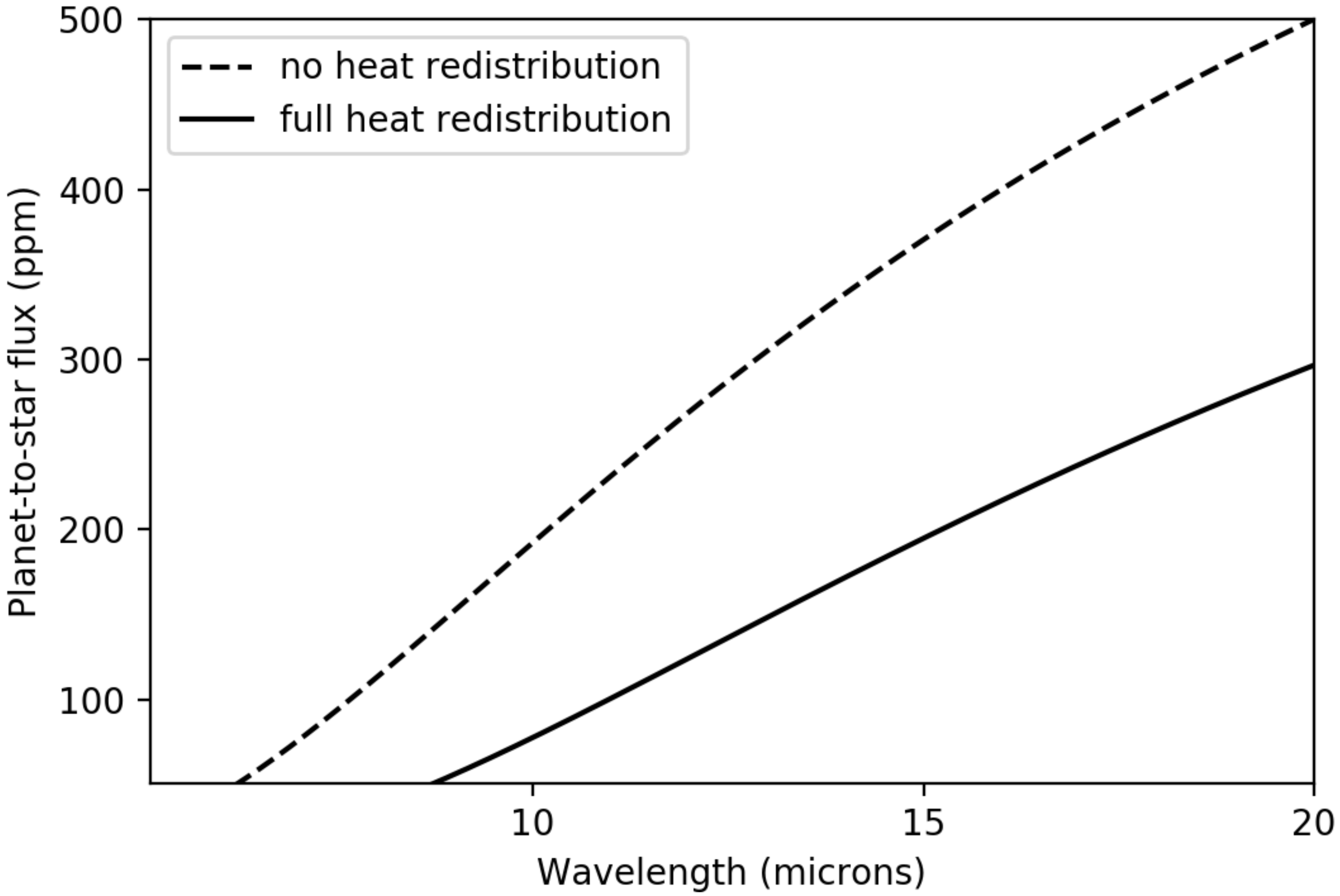
Do rocky planets have atmospheres?

Thick atmospheres transport heat to the nightside

TRAPPIST-1c

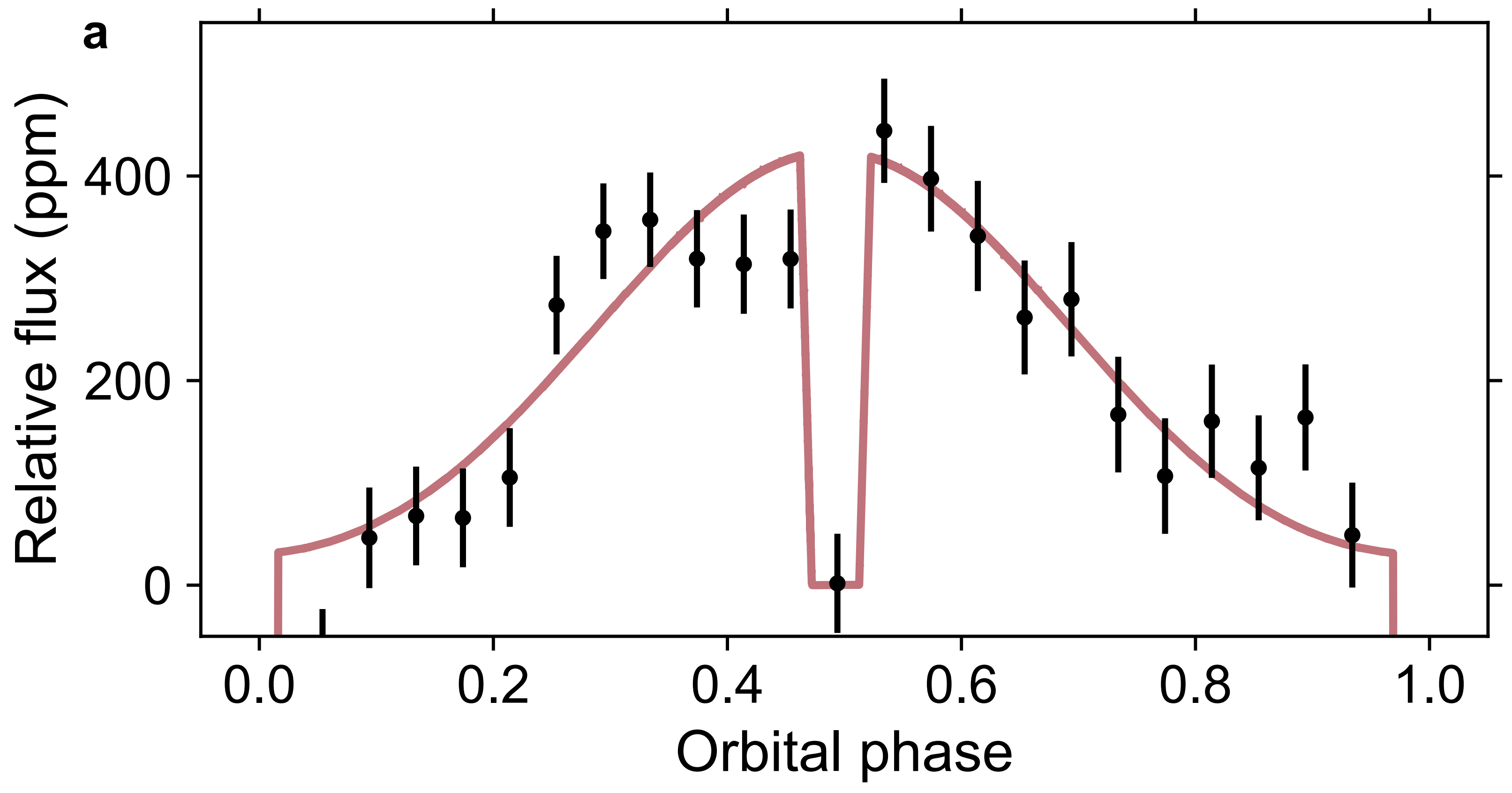
Thick atmosphere —>
full heat redistribution
—> 340 K

Bare rock —>
no heat redistribution
—> 430 K

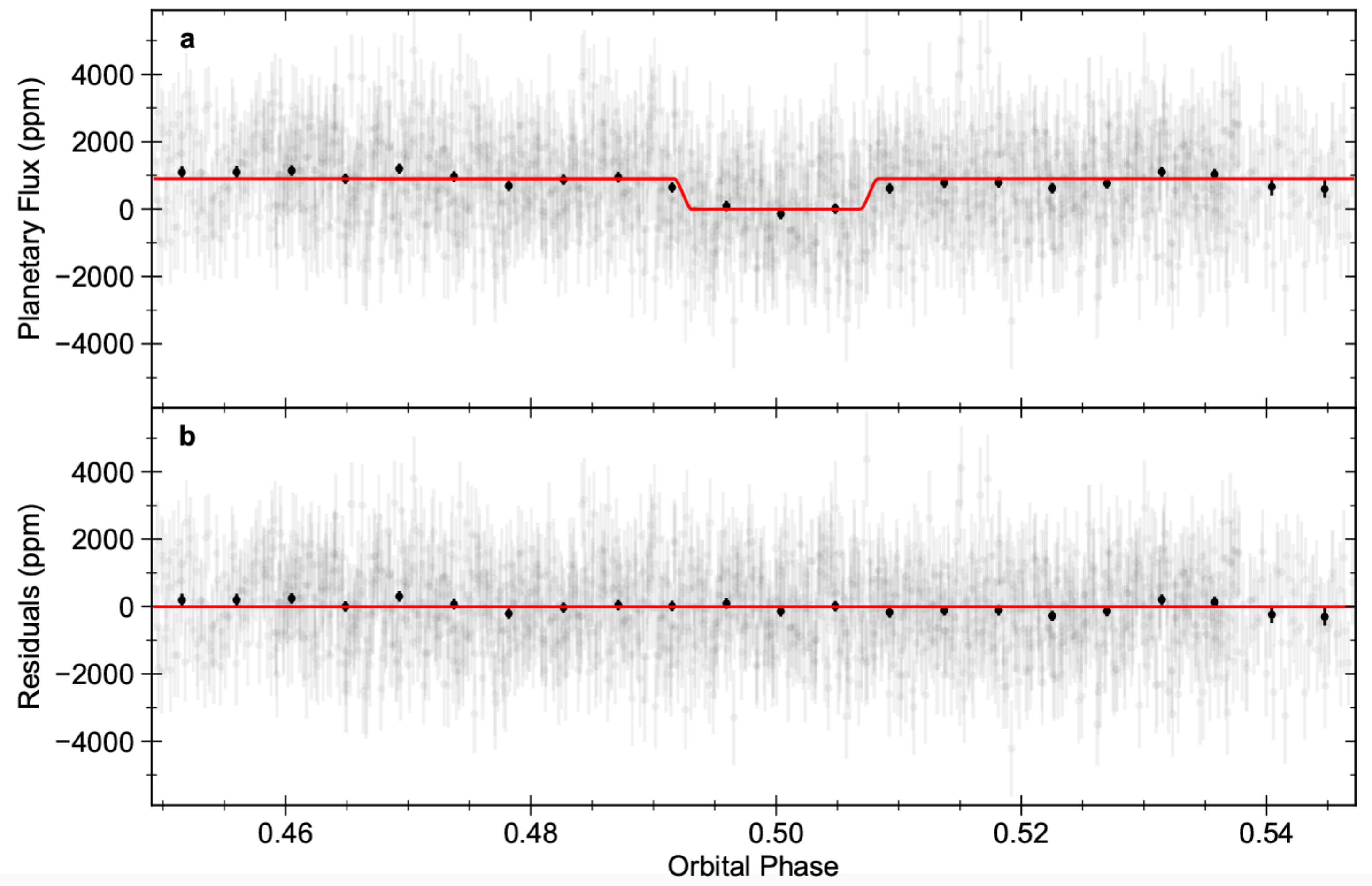


First results indicate that rocky planets do not have thick atmospheres

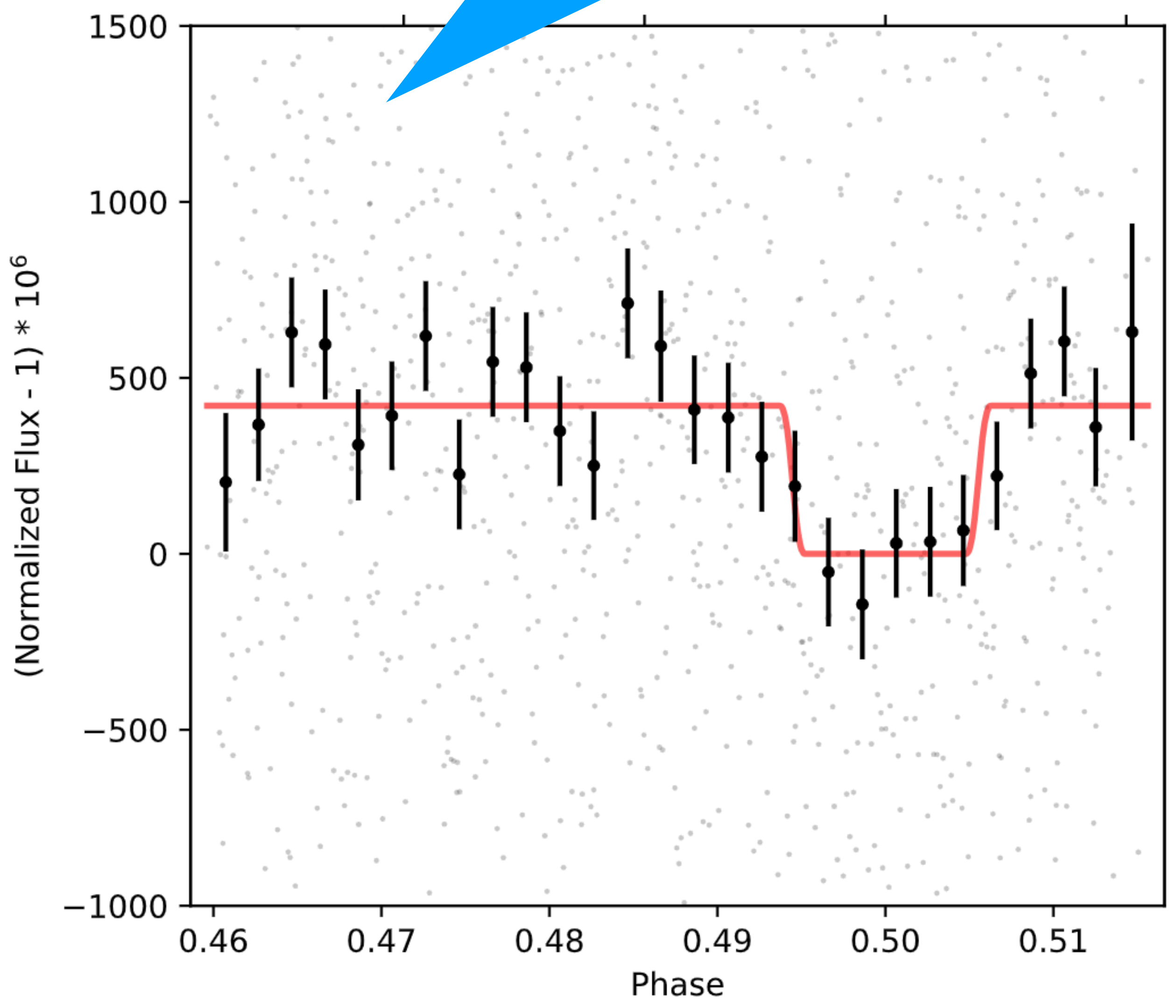
More on this from Natasha Batalha on Thursday!



LHS 3844b— Kreidberg et al. 2019



TRAPPIST-1c — Greene et al. 2023



TRAPPIST-1b — Zieba et al. 2023

Lots more to come!

23 phase curve, 90 eclipses in JWST Cycles 1 -2

1	L-231-32	Eclipse	MIRI.F1500W
1	L-231-32	Eclipse	MIRI.F1500W
1	L-231-32	Eclipse	MIRI.F1500W
1	L-231-32	Eclipse	MIRI.F1500W
1	TOI-824	Eclipse	NIRSPEC.BOTS+G395H
1	TOI-824	Eclipse	NIRSPEC.BOTS+G395H
1	HAT-P-11	Eclipse	NIRSPEC.BOTS+G395H
1	HAT-P-11	Eclipse	NIRSPEC.BOTS+G395H

1	WASP-80	Eclipse	MIRI.LRS
1	WASP-69	Eclipse	MIRI.LRS
1	GJ-436	Eclipse	MIRI.LRS
1	GJ-436	Eclipse	MIRI.LRS
1	TRAPPIST-1	Eclipse	MIRI.F1500W
1	TRAPPIST-1	Eclipse	MIRI.F1500W
1	TRAPPIST-1	Eclipse	MIRI.F1500W
1	TRAPPIST-1	Eclipse	MIRI.F1500W
1	TRAPPIST-1	Eclipse	MIRI.F1500W
1	HD-189733	Eclipse	NIRCAM.GRISMR+F444W
1	WASP-80	Eclipse	NIRCAM.GRISMR+F322W2
1	WASP-80	Eclipse	NIRCAM.GRISMR+F444W
1	WASP-69	Eclipse	NIRCAM.GRISMR+F322W2
1	WASP-69	Eclipse	NIRCAM.GRISMR+F444W
1	GJ-436	Eclipse	NIRCAM.GRISMR+F322W2
1	GJ-436	Eclipse	NIRCAM.GRISMR+F444W
1	GJ-436-offset	Eclipse	NIRCAM.GRISMR+F322W2
1	GJ-436	Eclipse	NIRCAM.GRISMR+F444W
1	GJ-436	Eclipse	NIRCAM.GRISMR+F322W2
1	GJ-436	Eclipse	NIRCAM.GRISMR+F444W
1	WASP-52	Eclipse	NIRSPEC.BOTS+PRISM
1	HD189733	Eclipse	NIRCAM.GRISMR+F322W2
1	WASP-19	Eclipse	NIRSPEC.BOTS+PRISM
1	WASP-77A	Eclipse	NIRSPEC.BOTS+G395H
1	GJ1132	Eclipse	MIRI.LRS

1	TRAPPIST-1	Eclipse	MIRI.F1280W
1	TRAPPIST-1	Eclipse	MIRI.F1280W
1	TRAPPIST-1	Eclipse	MIRI.F1280W
1	TRAPPIST-1	Eclipse	MIRI.F1280W
1	TRAPPIST-1	Eclipse	MIRI.F1280W
1	TRAPPIST-1	Eclipse	MIRI.F1280W
1	HAT-P-26	Eclipse	NIRSPEC.BOTS+G395H
1	HAT-P-26	Eclipse	NIRSPEC.BOTS+G395H
1	HAT-P-26	Eclipse	MIRI.LRS
1	WASP-17	Eclipse	NIRISS.SOSS
1	WASP-17	Eclipse	NIRSPEC.BOTS+G395H
1	WASP-17	Eclipse	MIRI.LRS
1	WASP-18	Eclipse	NIRISS.SOSS
1	GL486	Eclipse	MIRI.LRS
1	GL486	Eclipse	MIRI.LRS
1	LHS-3844	Eclipse	MIRI.LRS
1	LHS-3844	Eclipse	MIRI.LRS
1	LHS-3844	Eclipse	MIRI.LRS
1	RHO01-CNC	Eclipse	NIRCAM.GRISMR+F444W
1	RHO01-CNC	Eclipse	MIRI.LRS
1	HD-189733	Eclipse	MIRI.LRS
1	HD-189733	Eclipse	MIRI.LRS
1	HD-189733	Eclipse	MIRI.LRS
1	55CNC	Eclipse	NIRCAM.GRISMR+F444W
1	55CNC	Eclipse	NIRCAM.GRISMR+F444W
1	55CNC	Eclipse	NIRCAM.GRISMR+F444W
1	55CNC	Eclipse	NIRCAM.GRISMR+F444W
1	55CNC	Eclipse	NIRCAM.GRISMR+F444W

1	TRAPPIST-1	Eclipse
1	TRAPPIST-1	Eclipse
1	TRAPPIST-1	Eclipse
1	TRAPPIST-1	Eclipse
1	LTT1445A	Eclipse
1	LTT1445A	Eclipse
1	LTT1445A	Eclipse
1	WASP-121	Eclipse
1	WASP-47	Eclipse
1	WASP-47	Eclipse
1	GJ-3473	Eclipse
1	GJ-3473	Eclipse
1	GJ-3473	Eclipse
1	GJ-3473	Eclipse
1	GJ-357	Eclipse
1	HD-260655	Eclipse
1	HD-260655	Eclipse
1	L-98-59	Eclipse
1	LHS-1140	Eclipse
1	LHS-1140	Eclipse
1	LHS-1140	Eclipse
1	LHS-1478	Eclipse
1	LHS-1478	Eclipse
1	LTT-3780	Eclipse
1	LTT-3780	Eclipse
1	TOI-1468	Eclipse
1	TOI-1468	Eclipse
1	TOI-1468	Eclipse

1	TRAPPIST-1	Eclipse	MIRI.F1500W
1	TRAPPIST-1	Eclipse	MIRI.F1500W
1	TRAPPIST-1	Eclipse	MIRI.F1500W
1	TRAPPIST-1	Eclipse	MIRI.F1500W
1	LTT1445A	Eclipse	MIRI.LRS
1	LTT1445A	Eclipse	MIRI.LRS
1	LTT1445A	Eclipse	MIRI.LRS
1	WASP-121	Eclipse	MIRI.LRS
1	WASP-47	Eclipse	NIRSPEC.BOTS+G395H
1	WASP-47	Eclipse	NIRSPEC.BOTS+G395H
1	GJ-3473	Eclipse	MIRI.F1500W
1	GJ-3473	Eclipse	MIRI.F1500W
1	GJ-3473	Eclipse	MIRI.F1500W
1	GJ-3473	Eclipse	MIRI.F1500W
1	GJ-357	Eclipse	MIRI.F1500W
1	HD-260655	Eclipse	MIRI.F1500W
1	HD-260655	Eclipse	MIRI.F1500W
1	L-98-59	Eclipse	MIRI.F1500W
1	LHS-1140	Eclipse	MIRI.F1500W
1	LHS-1140	Eclipse	MIRI.F1500W
1	LHS-1140	Eclipse	MIRI.F1500W
1	LHS-1478	Eclipse	MIRI.F1500W
1	LHS-1478	Eclipse	MIRI.F1500W
1	LTT-3780	Eclipse	MIRI.F1500W
1	LTT-3780	Eclipse	MIRI.F1500W
1	TOI-1468	Eclipse	MIRI.F1500W
1	TOI-1468	Eclipse	MIRI.F1500W
1	TOI-1468	Eclipse	MIRI.F1500W

WASP-121	PhaseC	NIRISS.SOSS
LTT-9779	PhaseC	NIRISS.SOSS
WASP-43	PhaseC	NIRSPEC.BOTS+G395H
WASP-43	PhaseC	MIRI.LRS
WASP-121	PhaseC	NIRSPEC.BOTS+G395H
GJ1214	PhaseC	MIRI.LRS
HD-80606	PhaseC	MIRI.LRS
NGTS-10	PhaseC	NIRSPEC.BOTS+PRISM
K2-141	PhaseC	MIRI.LRS
HD-80606	PhaseC	NIRSPEC.BOTS+G395H
KEPLER-51	PhaseC	NIRSPEC.BOTS+PRISM
TOI-849	PhaseC	NIRSPEC.BOTS+PRISM
TOI-849	PhaseC	NIRSPEC.BOTS+PRISM
TOI-849	PhaseC	NIRSPEC.BOTS+PRISM
TOI-2109	PhaseC	NIRSPEC.BOTS+G395H
TOI-2109	PhaseC	NIRSPEC.BOTS+G395H
TOI-2109	PhaseC	NIRSPEC.BOTS+G395H
TRAPPIST-1	PhaseC	MIRI.F1500W
TRAPPIST-1	PhaseC	MIRI.F1500W
LTT9779	PhaseC	NIRSPEC.BOTS+G395H
KEPLER-86	PhaseC	NIRSPEC.BOTS+PRISM
TOI-1685	PhaseC	NIRSPEC.BOTS+G395H
TOI-561	PhaseC	NIRSPEC.BOTS+G395H
LHS3844	PhaseC	NIRSPEC.BOTS+G395H