EVAPORATING EXOPLANETS FOR EVERYONE

AN OPEN-SOURCE FRAMEWORK TO PLAN AND INTERPRET OBSERVATIONS OF ATMOSPHERIC ESCAPE IN EXOPLANETS

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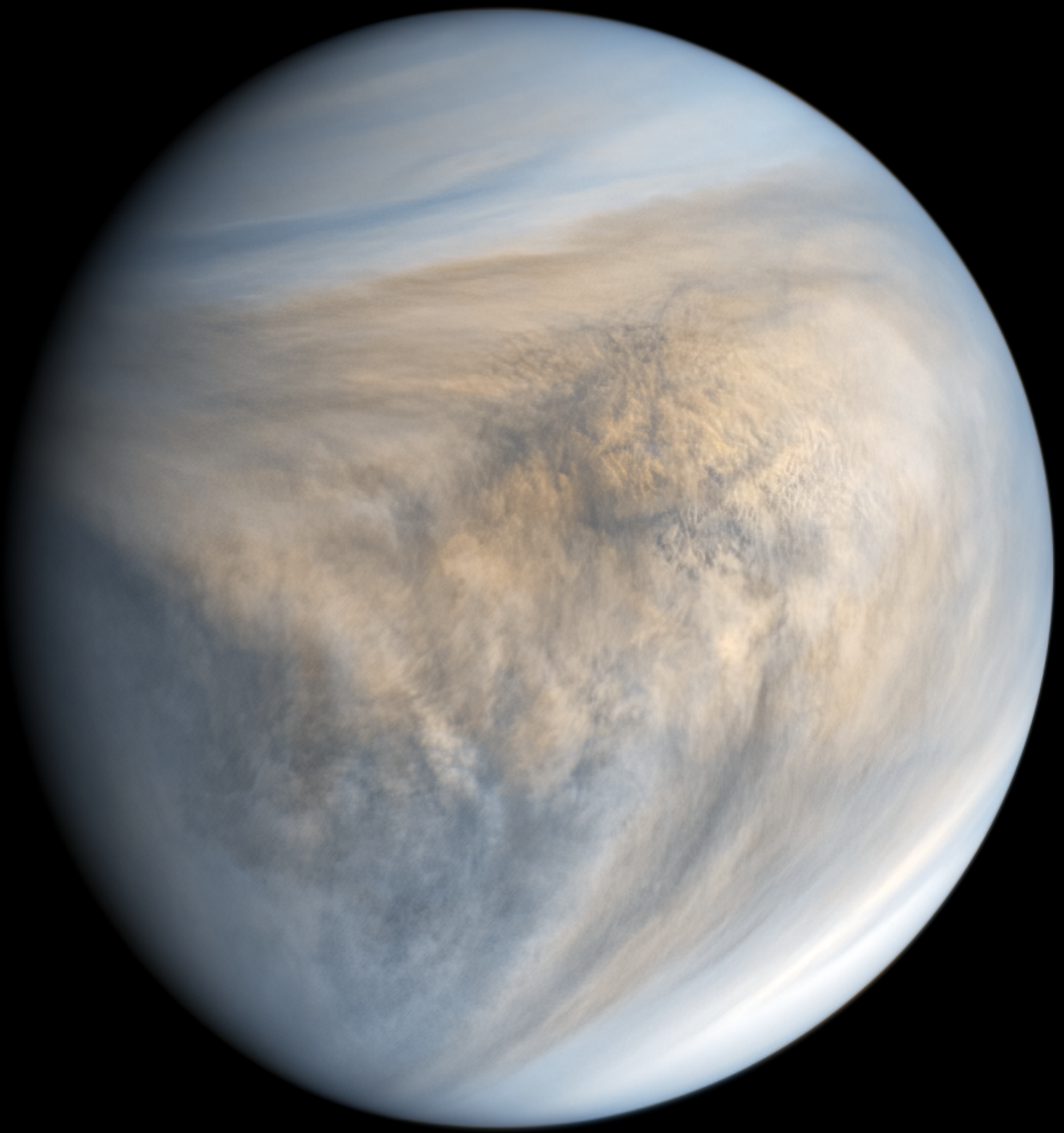
STScI | SPACE TELESCOPE SCIENCE INSTITUTE



Cloud structure in the atmosphere of Venus. Credit: JAXA/ISAS/DARTS/Kevin M. Gill

Artist's impression of iron rain in WASP-76b. Credit: ESO/M. Kornmesser (see Ehrenreich et al. 2020, Nature 580)

PLANET HUNTING

'Hot Jupiters' Leave Theorists in the Cold

CAPRI, ITALY—It has been just 10 months since a pair of Swiss astronomers first identified a planet orbiting a sunlike star other than our own, but the tally of so-called "exoplanets" has now passed the total of nine familiar planets of our solar system. That mark came earlier this month at the Fifth International Conference on Bioastronomy on this island off the southern Italian coast, where astronomers reported several new sightings, including the first evidence of another multiplanet system around a sunlike star. And with the total steadily growing, researchers are beginning to identify tentative groupings of planet types, one of which, says Geoff Marcy of San Francisco State University, is "a class of planets that is completely unlike the planets in our solar system."

Within the group of less massive companions in circular orbits, astronomers have been surprised to find a completely new class of planets, which they dubbed "hot Jupiters." These giant planets are termed hot because their orbits are between 10 and 20 times closer to their parent stars than the Earth is to the sun, and their orbital periods—or "years"—are only a few days long. The original exoplanet, around 51 Pegasi, belongs to this class, and three more have since been discovered orbiting 55 Cancri, Tau Bootis, and Upsilon Andromedae, Marcy and Butler's most recent find. "55 Cancri and Tau Bootis are close cousins of 51 Pegasi, while Upsilon Andromedae is a real twin," says Marcy. Within a couple of months Mayor expects to announce four new members of this class, based on observations

Schilling (1996, Science 273)

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PLANETS DISCOVERED AROUND OTHER SUNLIKE STARS

Star	Distance to star (Earth-Sun = 1)	Orbital period	Lower limit on mass (Jupiter = 1)	Notes
51 Pegasi	0.05	4.3 days	0.5	First exoplanet, "hot Jupiter"
47 Ursae Majoris	2.1	1103 days	2.4	
70 Virginis	ecc. orbit	116.7 days	6.6	Possible brown dwarf
55 Cancri	0.11	14.76 days	0.8	"Hot Jupiter"
55 Cancri	>5	unknown	>5	
HD 114762	ecc. orbit	84.01 days	10	Possible brown dwarf
Tau Bootis	0.0047	3.31 days	3.7	"Hot Jupiter"
Upsilon Andromedae	0.054	4.61 days	0.6	"Hot Jupiter"
Lalande 21185	2.2	5.8 years	0.9	Astrometric detection
Lalande 21185	11	30 years	1.1	Astrometric detection (uncertain)

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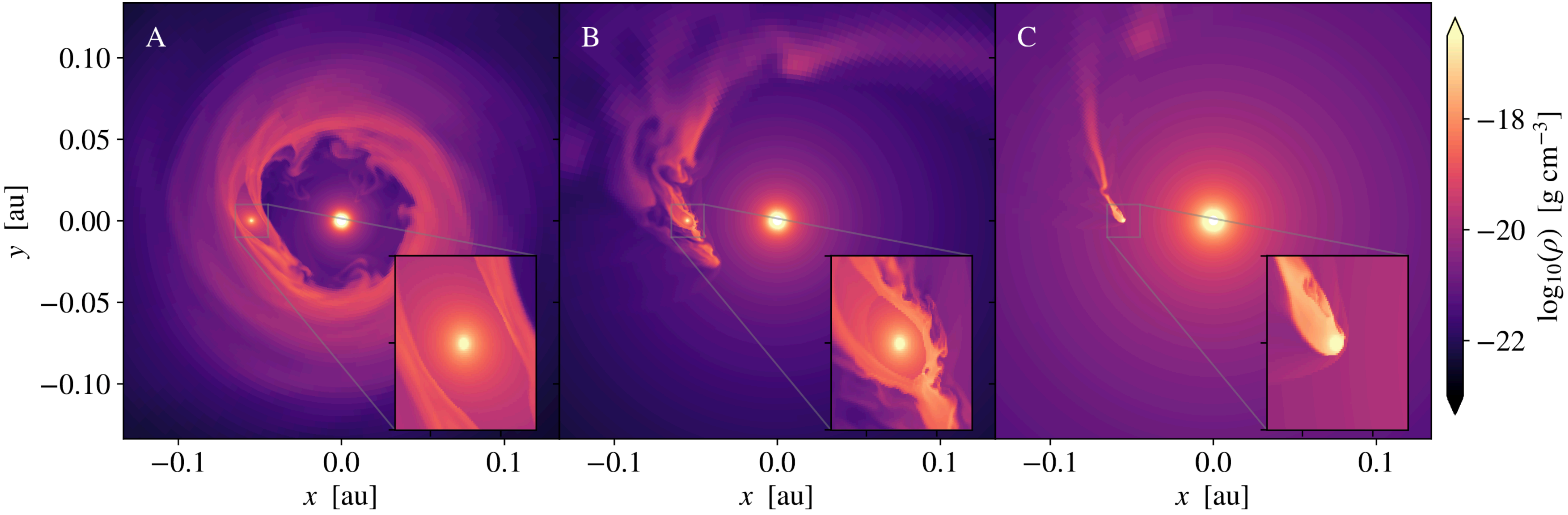
Schilling (1996, Science 273)

Hydrogen escapes thermally

Credit: D. Brain, M. Chaffin, H. Egan, R. Ramstad, B. Jakosky, S. Curry, J. Luhmann, C. Dong, R. Yelle

Simulations of an escaping atmosphere in the hot Jupiter WASP-107b

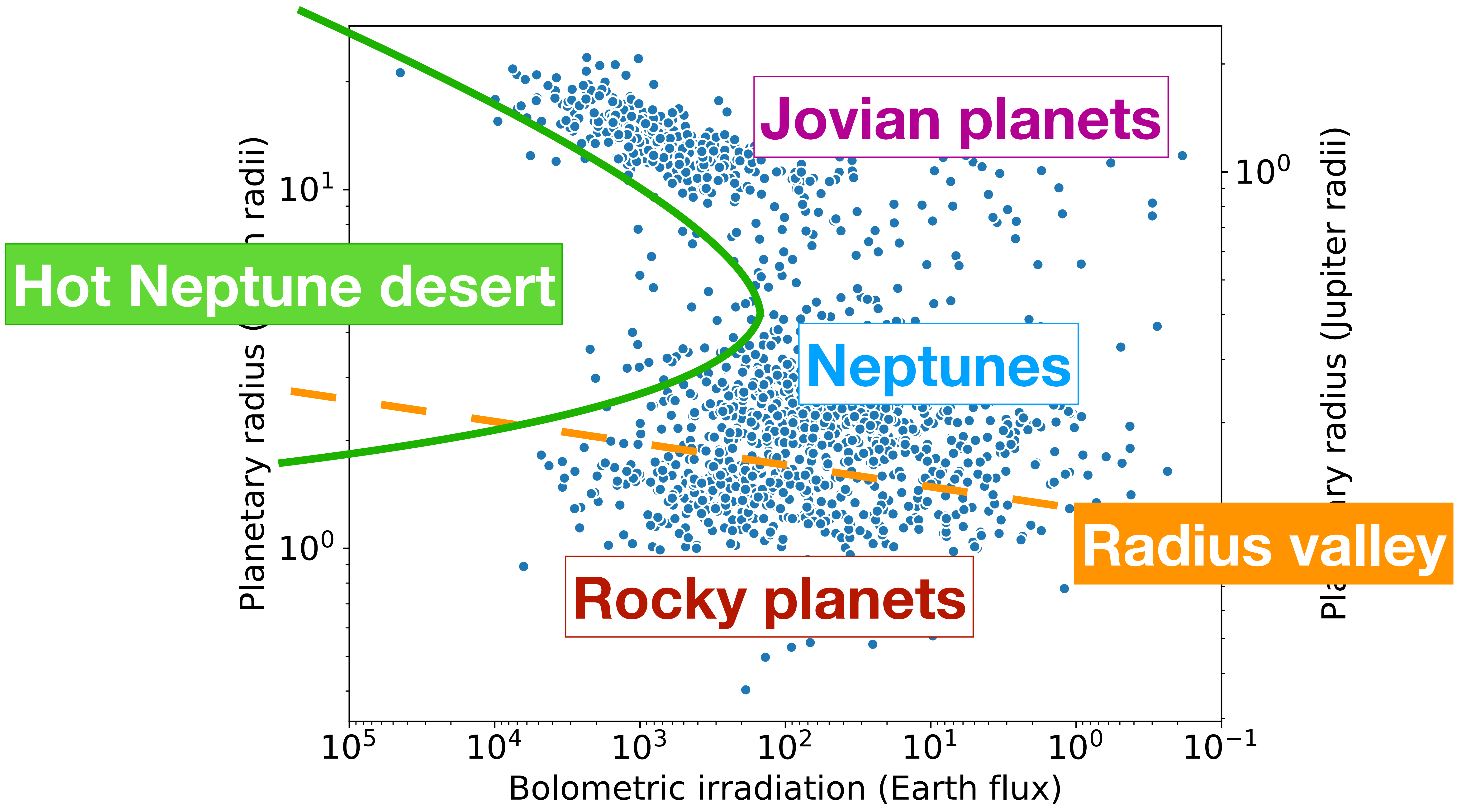


MacLeod & Oklopčić (2022, AAS Journals in press, arXiv:2107.07534)

HOT (SUB-)NEPTUNES, BEWARE

YOU WILL LOSE YOUR MAJESTIC FLUFF

Direction of radius evolution



More irradiated

Less irradiated

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- What are the timescales of mass loss and radius change?
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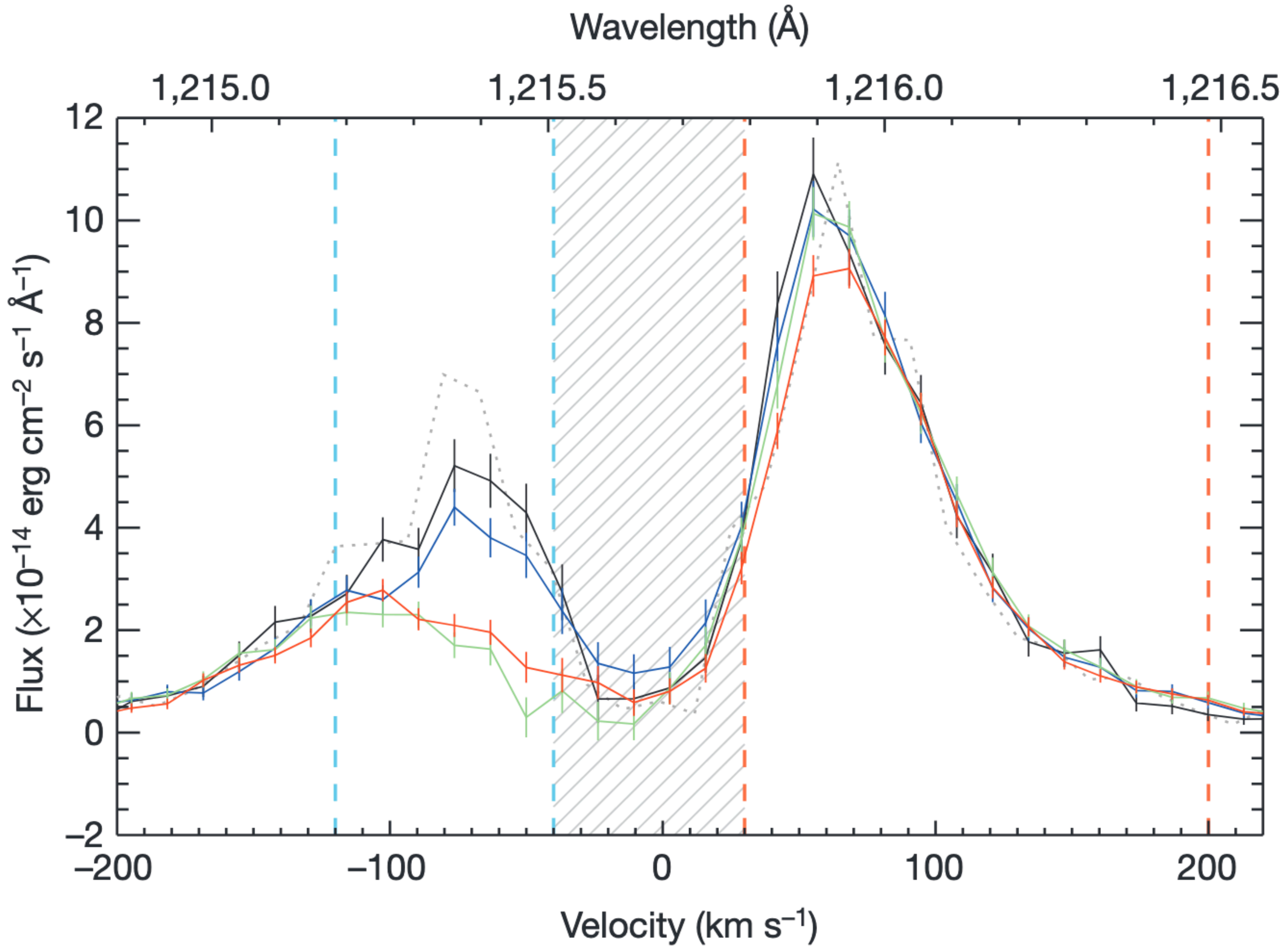
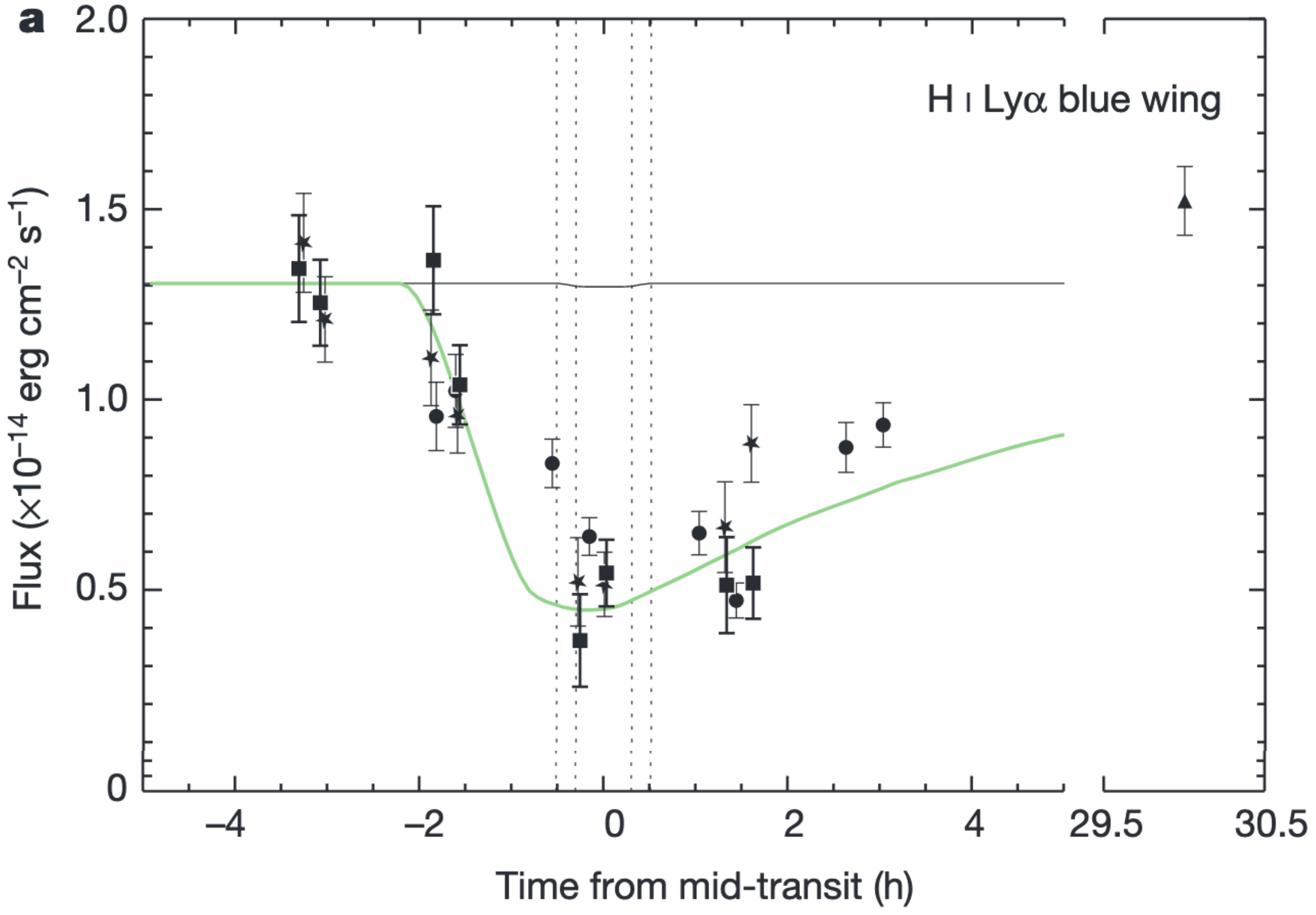
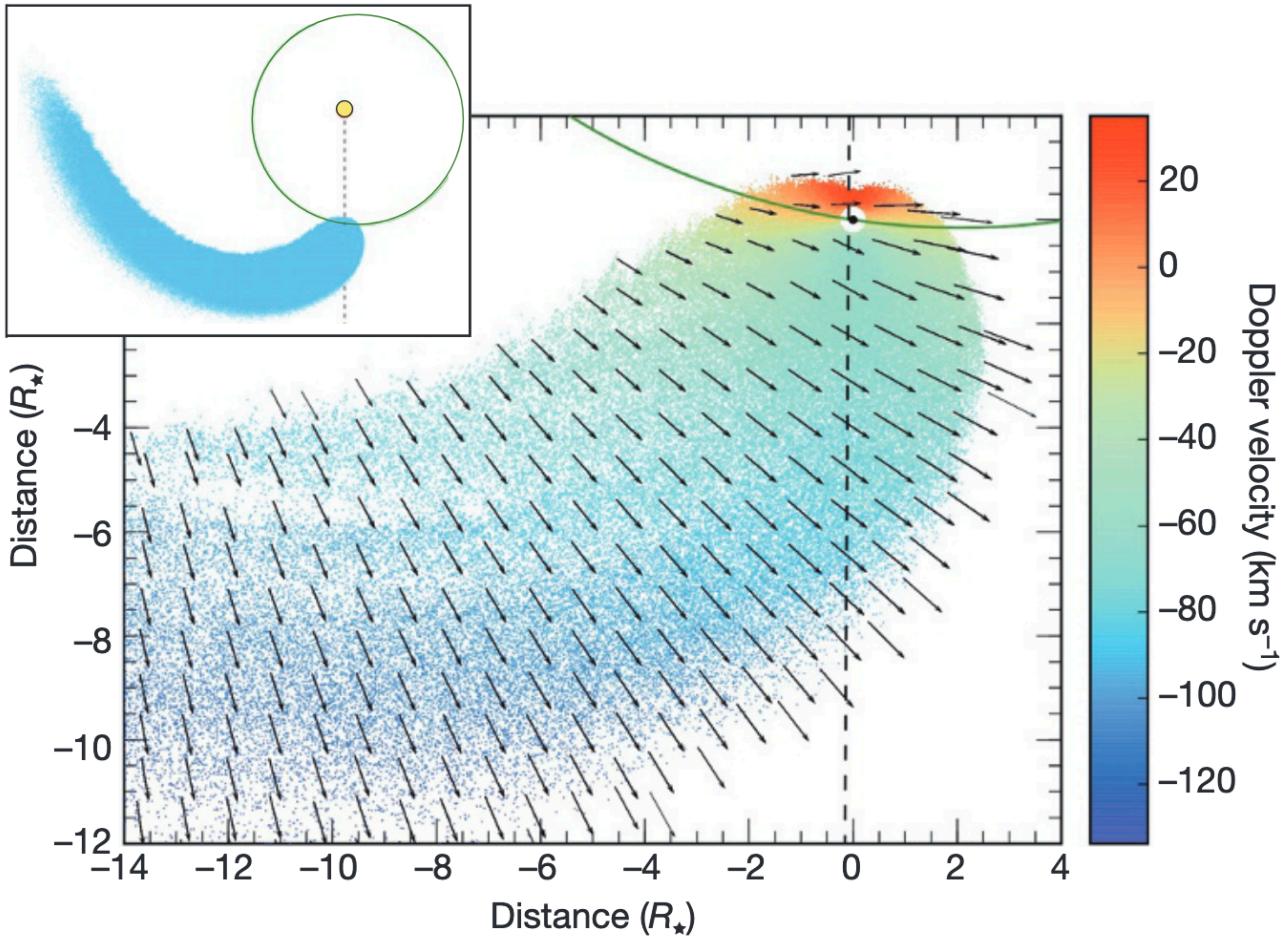
- And what about magnetic fields?!*

* ASK YOUR NEAREST THEORETICIAN



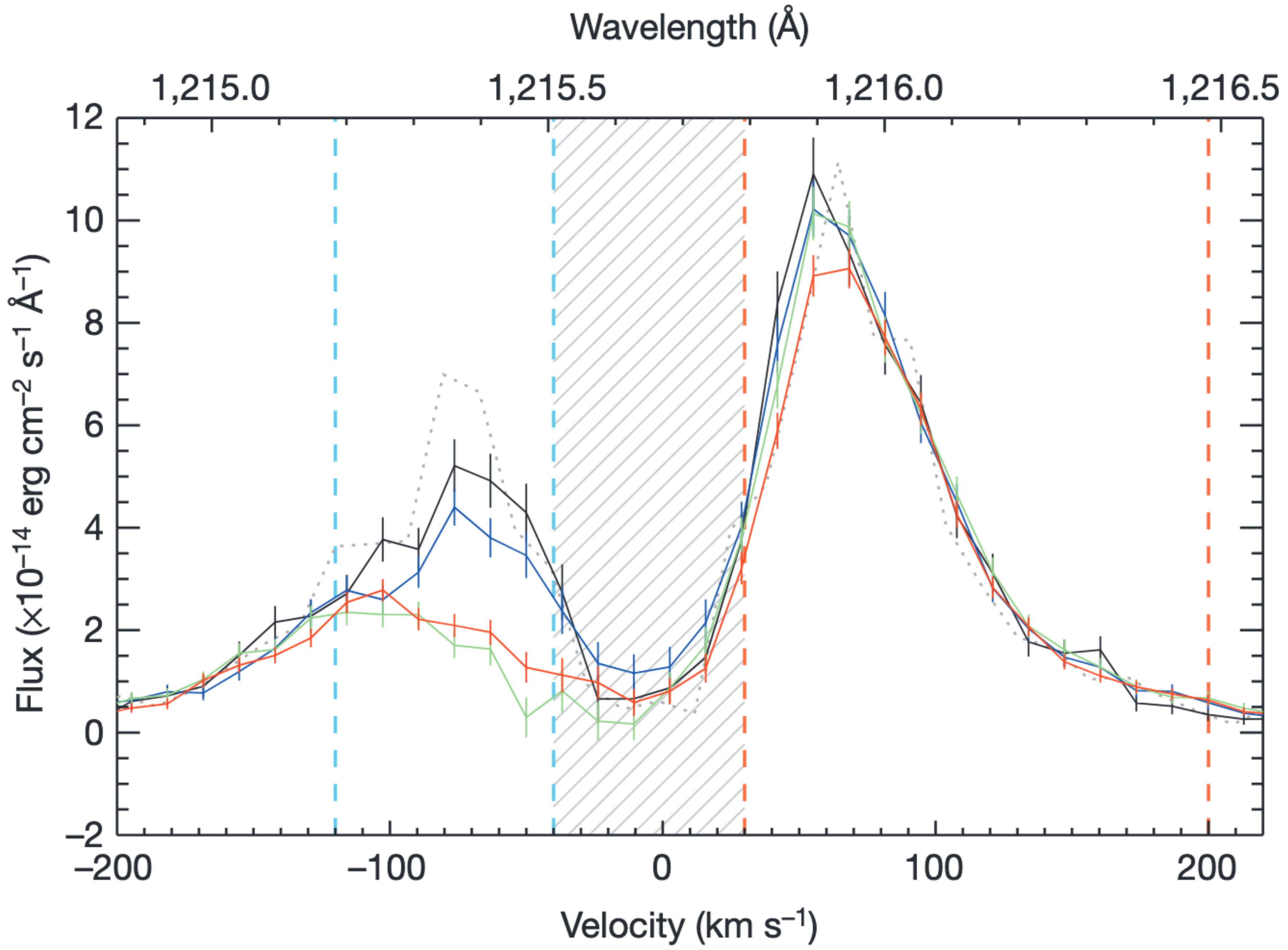
Lyman-α transit spectroscopy of GJ 436 b

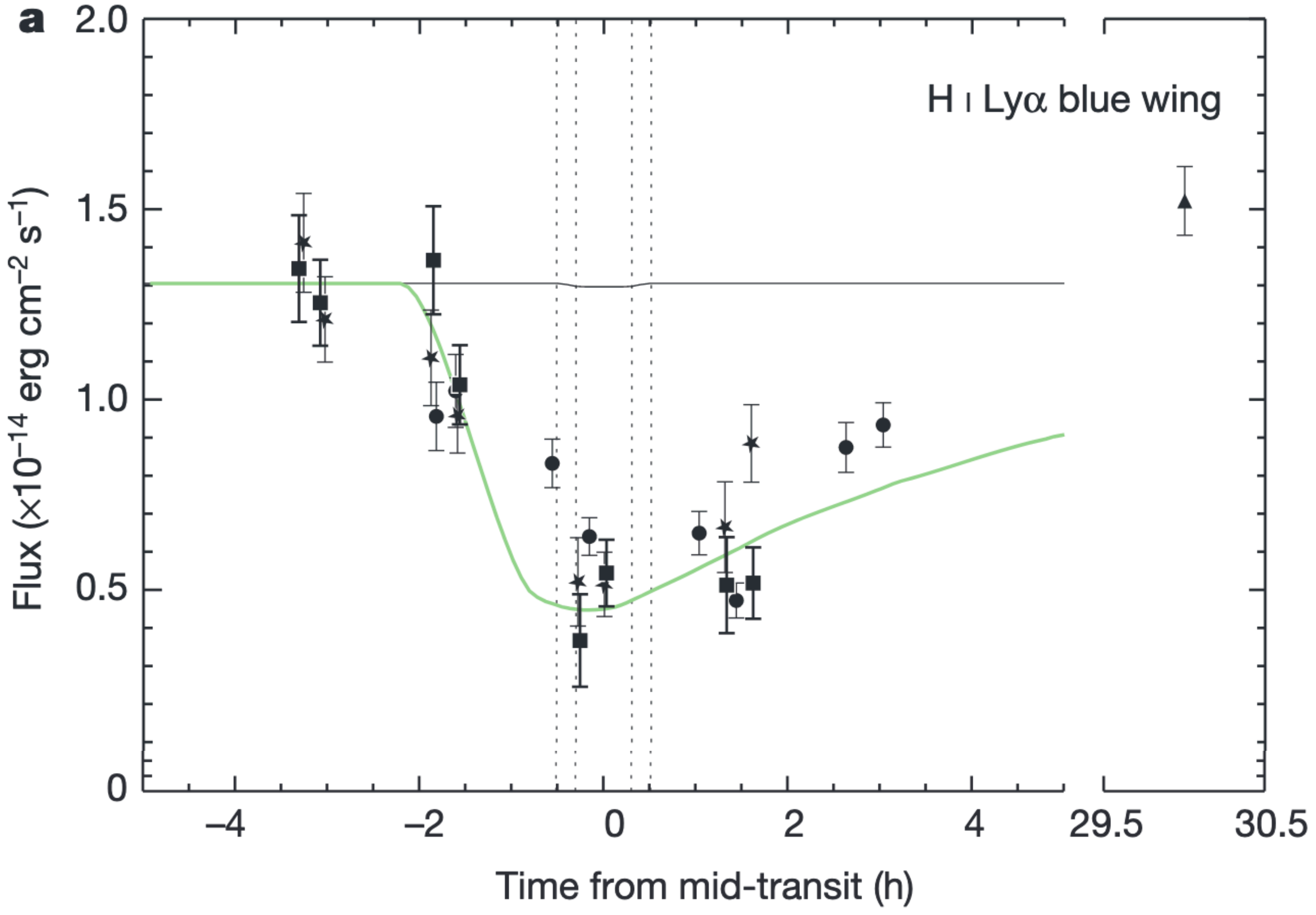




Ehrenreich et al. (2015, Nature 522)

Lyman-α transit spectroscopy of GJ 436 b



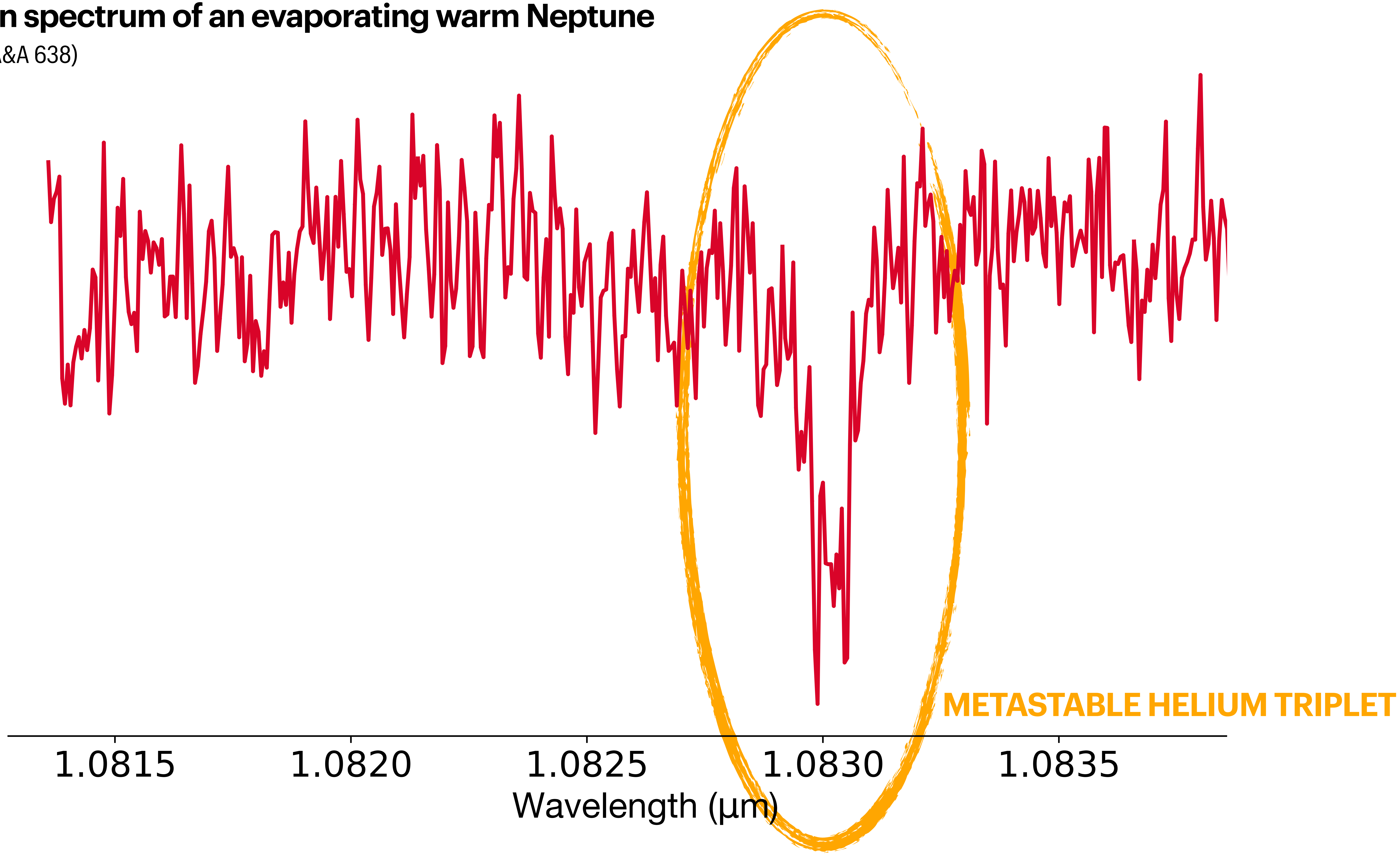


- **Only the *Hubble* can observe**
- **Low-mass stars are faint in UV**
- **Interstellar medium attenuation**

Ehrenreich et al. (2015, Nature 522)

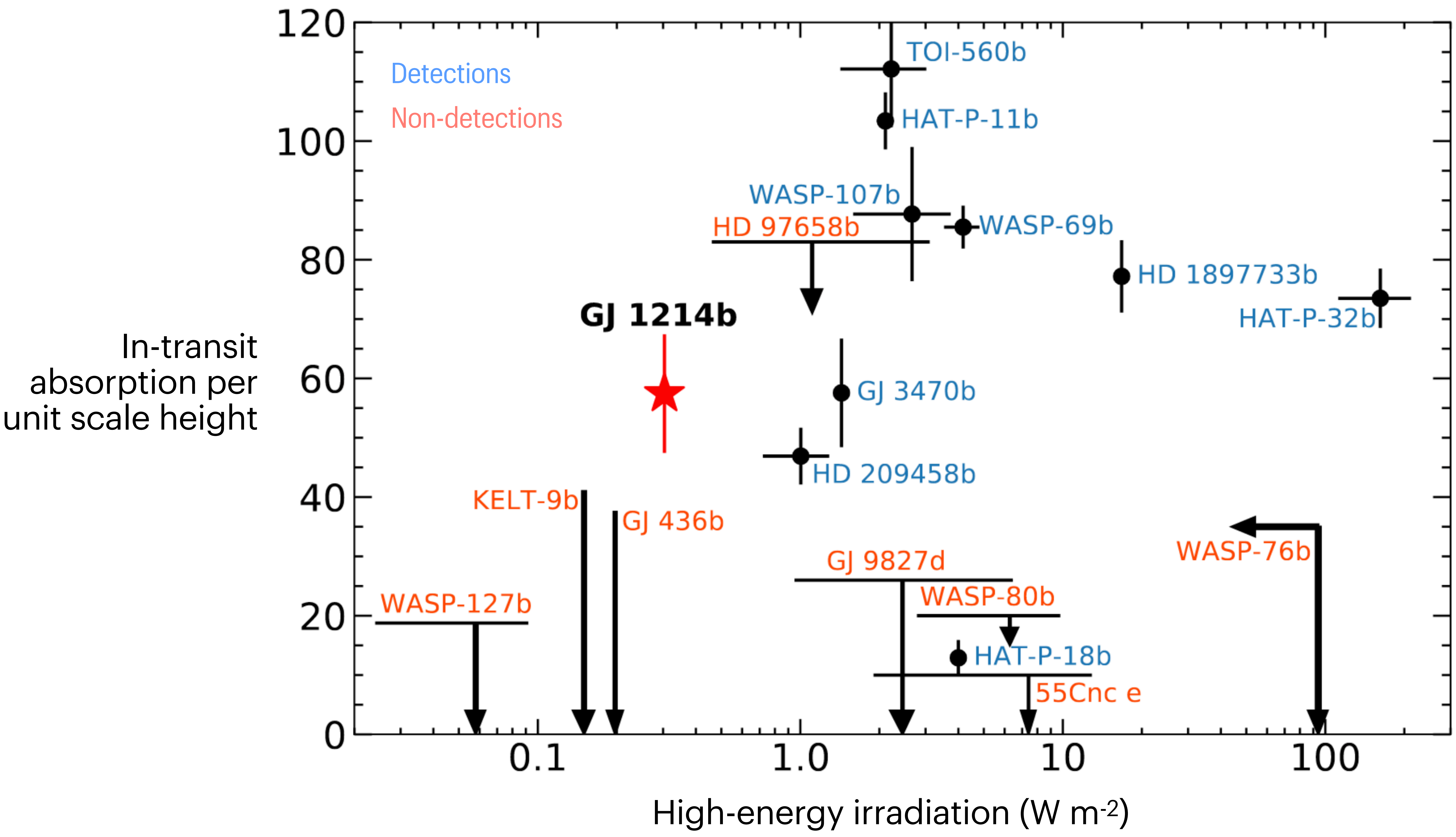
Transmission spectrum of an evaporating warm Neptune

Pallé et al. (2020, A&A 638)



Metastable He spectroscopy has become very productive and popular!

Orell-Miquel et al. (2022, A&A in press)



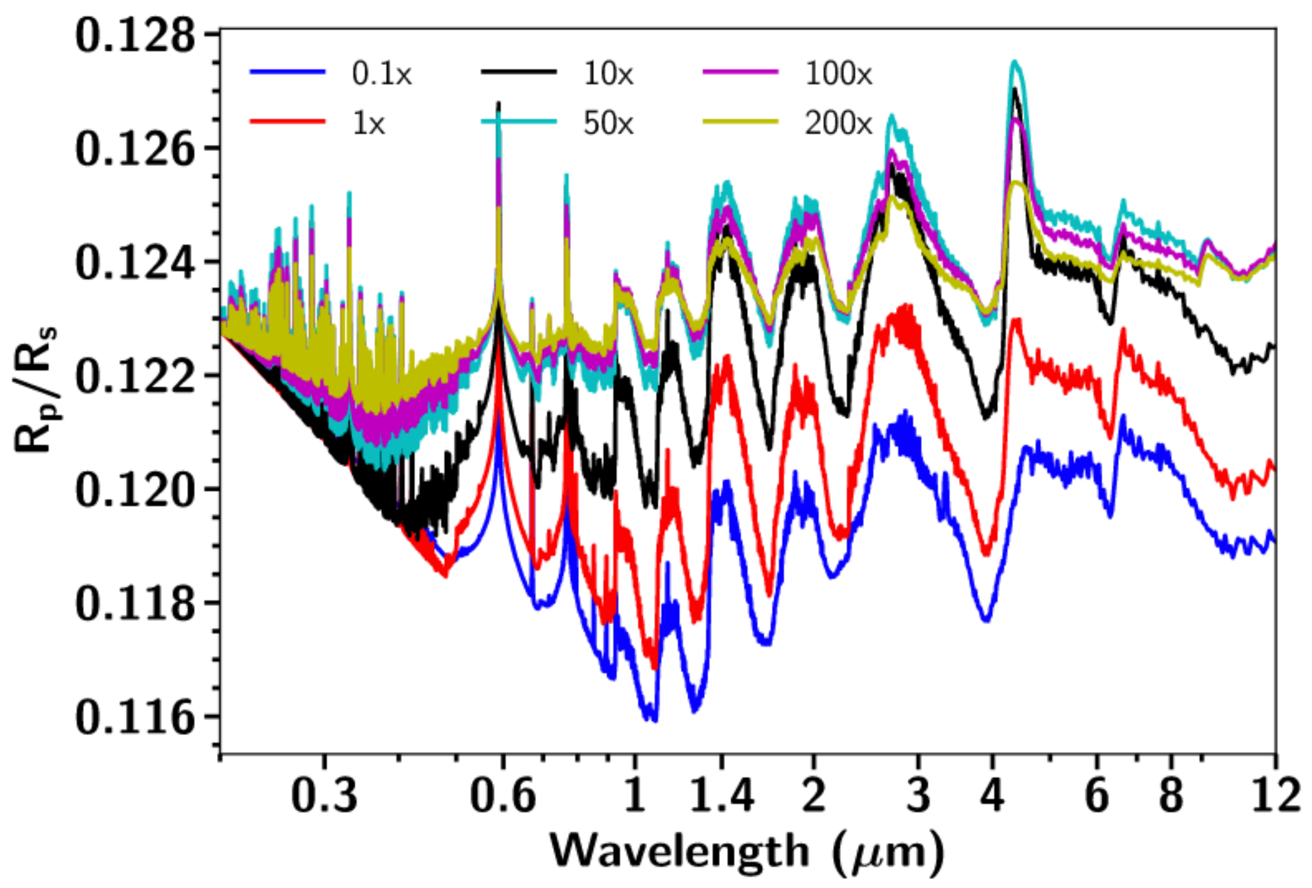
OPEN-POLICY TOOLS

(OPEN-SOURCE, OPEN-DATA, ETC.)

And many others!

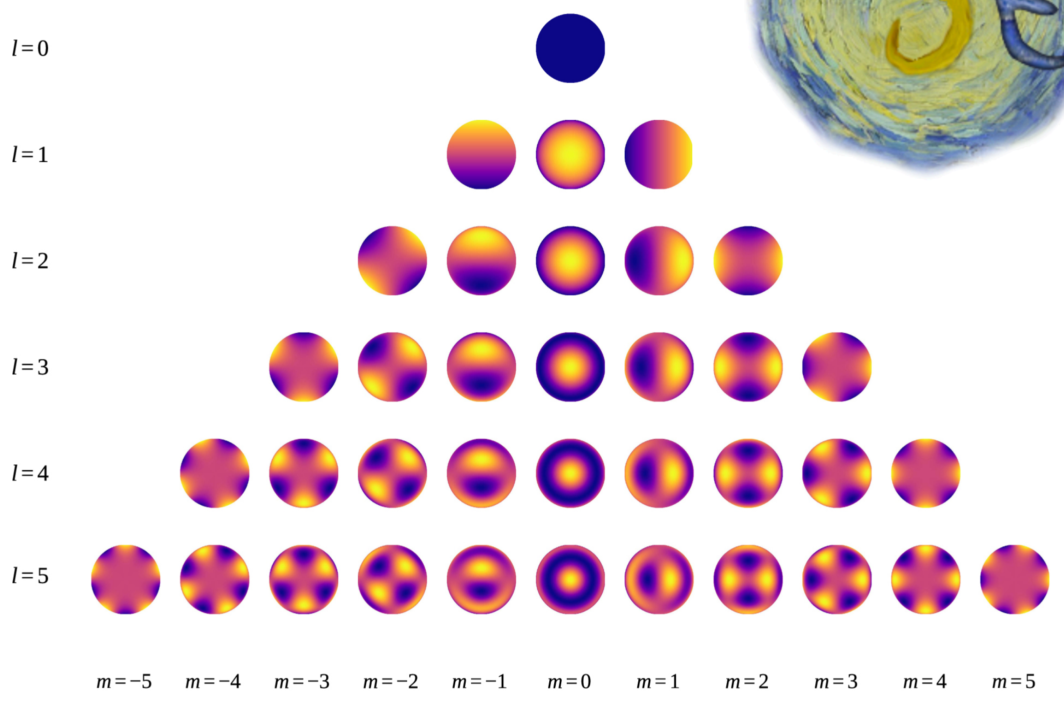
batman:
Bad-Ass Transit Model cAlculatioN

Welcome to the documentation for `batman`, a Python pack…
exoplanet transit light curves. The package supports calcu…



PLATON

starry



petit RADTRANS

OPEN-POLICY TOOLS

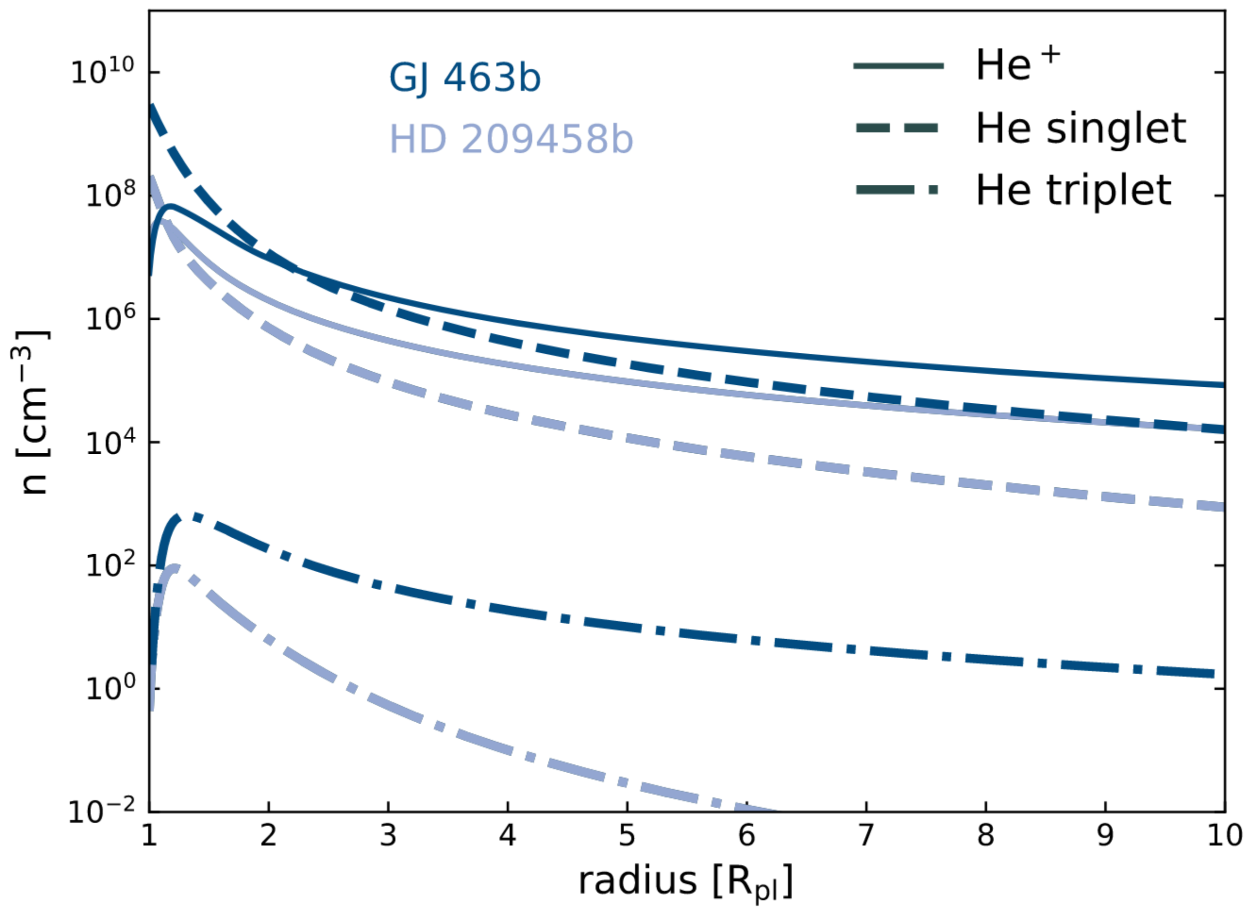
FOR ATMOSPHERIC ESCAPE

p-winds

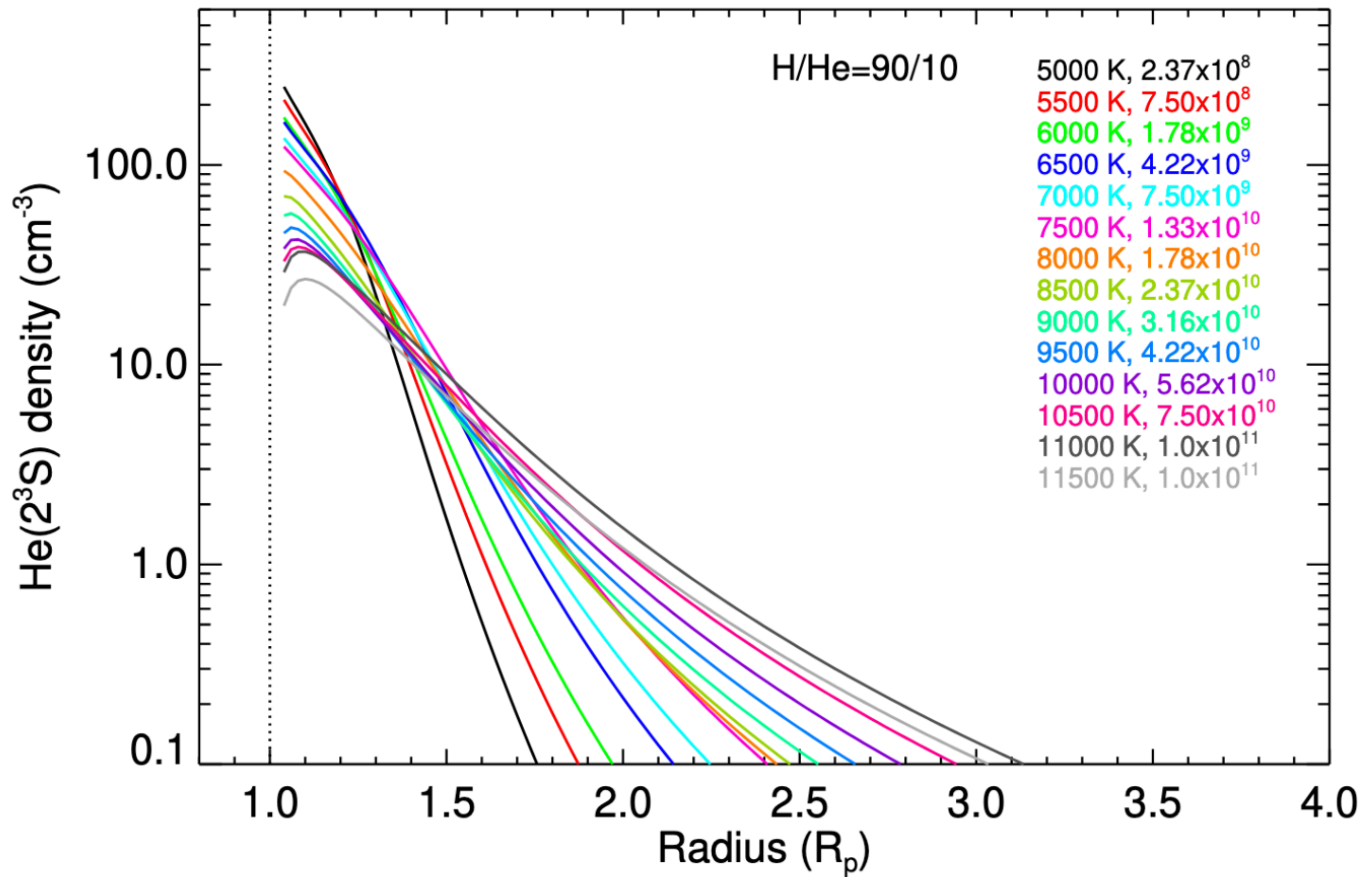
docs passing | build passing | coverage 72% | arXiv 2111.11370 | DOI 10.5281/zenodo.4551621

Python implementation of Parker wind models for planetary atmospheres. **So many p's!** (Hence the name for the code.)

The main objective of this code is to produce simplified, 1-D models of the upper atmosphere of a planet, and perform radiative transfer to calculate observable spectral signatures.



Oklopčić & Hirata (2018, ApJL 855)



Lampón et al. (2020, A&A 636)

A&A 640, A29 (2020)
https://doi.org/10.1051/0004-6361/202038802

Astronomy & Astrophysics

Search for helium in the upper atmosphere of the hot Jupiter WASP-127 b using Gemini/Phoenix

Leonardo A. dos Santos[1], David Ehrenreich[1], Vincent Bourrier[1], Romain Allart[1], George King[2,3], Monika Lendl[1], Christophe Lovis[1], Steve Margheim[4], Jorge Meléndez[5], Julia V. Seidel[1], and Sérgio G. Sousa[6]

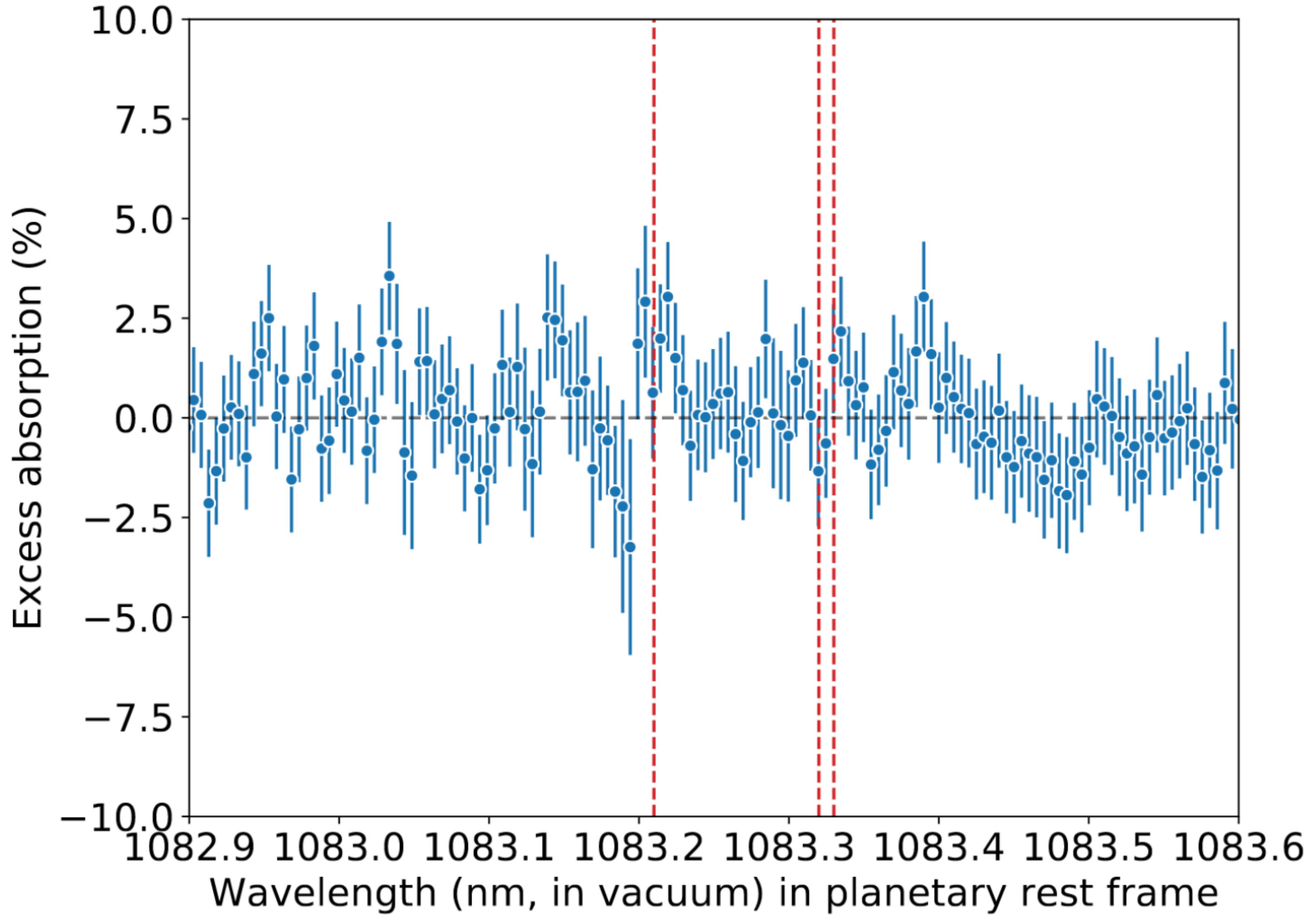


Fig. 4. Transmission spectrum of WASP-127 b around the He triplet. Absorption is positive.

$$\frac{\partial f_{\rm ion}}{\partial r} = \frac{1-f_{\rm ion}}{v}\Phi e^{-\tau_0} - \frac{0.9\rho}{1.3 m_{\rm H} v} f_{\rm ion}^2 \alpha_{\rm rec}$$

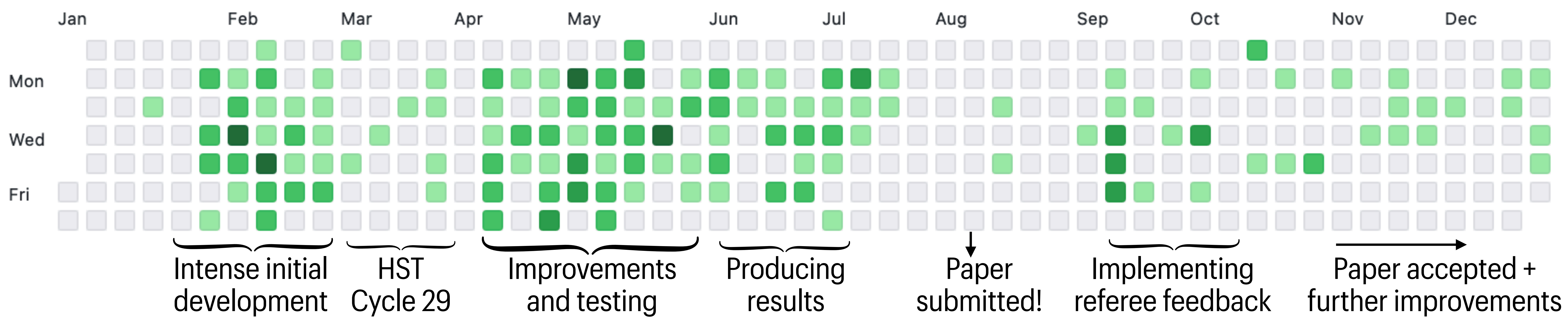
$$v\frac{\partial f_1}{\partial r} = (1 - f_1 - f_3) n_e \alpha_1 + f_3 A_{31} - f_1 \Phi_1 e^{-\tau_1} - f_1 n_e q_{13a} + f_3 n_e q_{31a} + f_3 n_e q_{31b} + f_3 n_{\rm H^0} Q_{31},$$

$$v\frac{\partial f_3}{\partial r} = (1 - f_1 - f_3) n_e \alpha_3 - f_3 A_{31} - f_3 \Phi_3 e^{-\tau_3} + f_1 n_e q_{13a} - f_3 n_e q_{31a} - f_3 n_e q_{31b} - f_3 n_{\rm H^0} Q_{31}.$$

Oklopčić & Hirata (2018, ApJL 855)

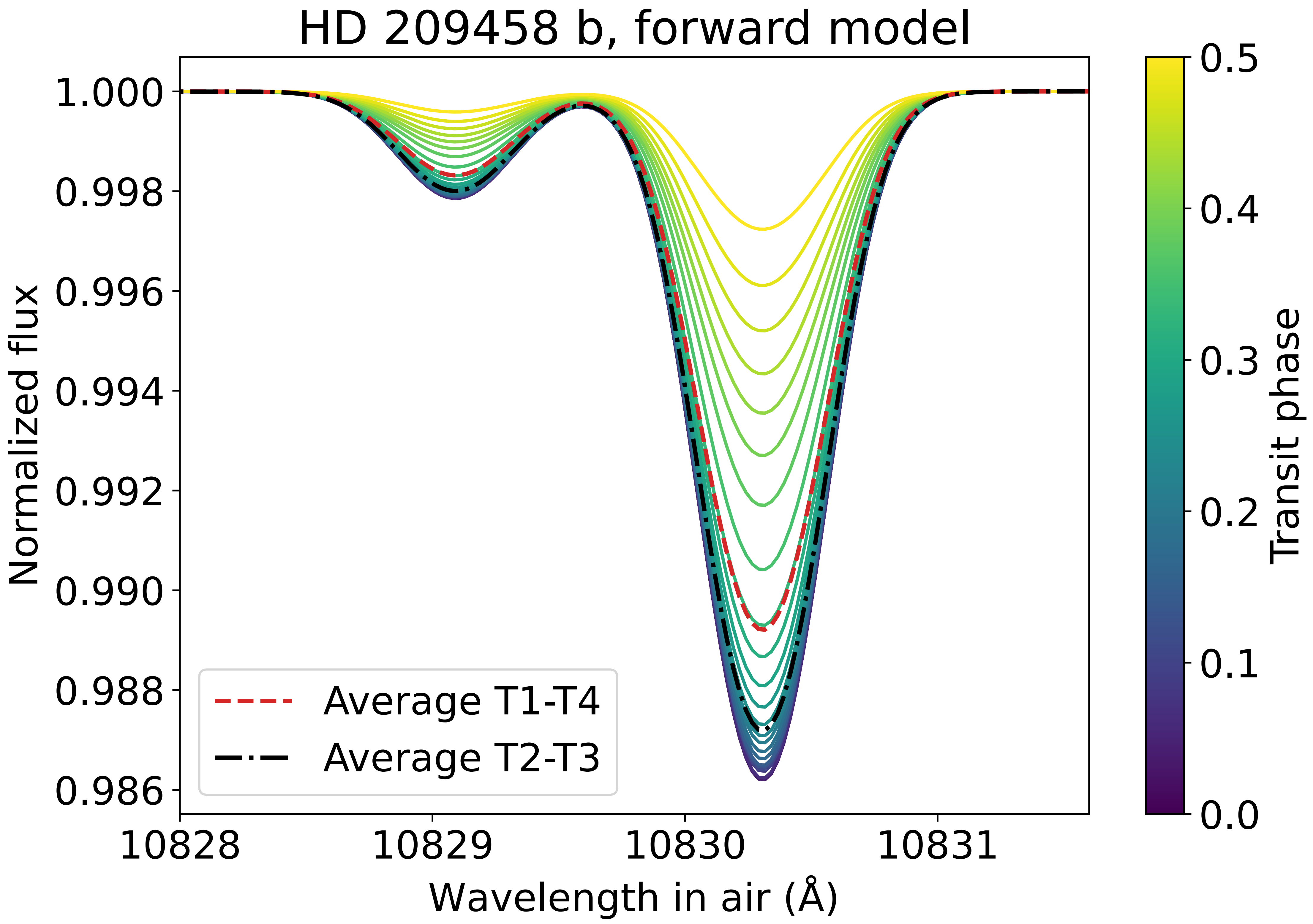
p-winds

AN OPEN-SOURCE CODE TO MODEL 1D EXOPLANET OUTFLOWS



p-winds

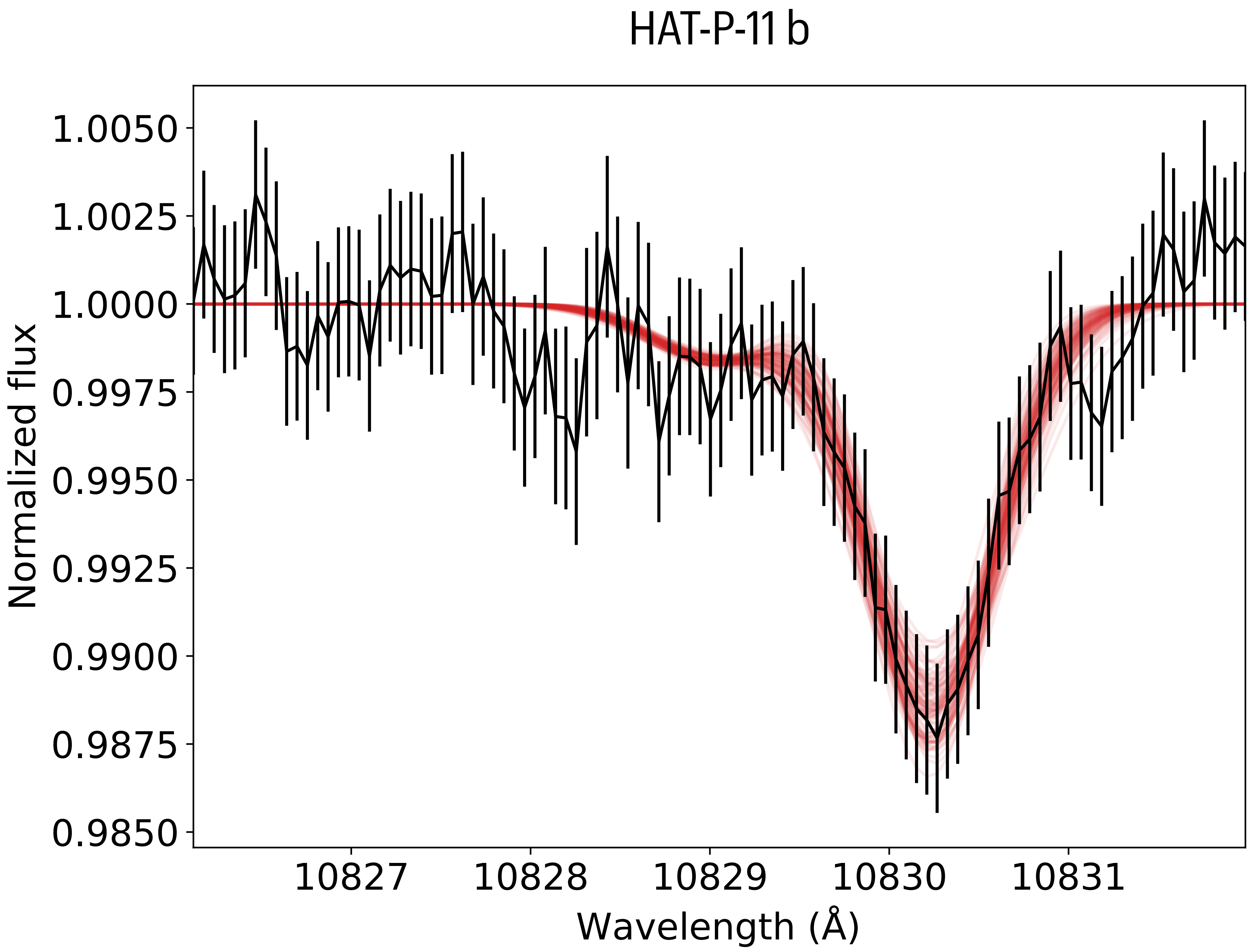
FORWARD MODELLING: ABSORPTION IN FUNCTION OF TRANSIT PHASE

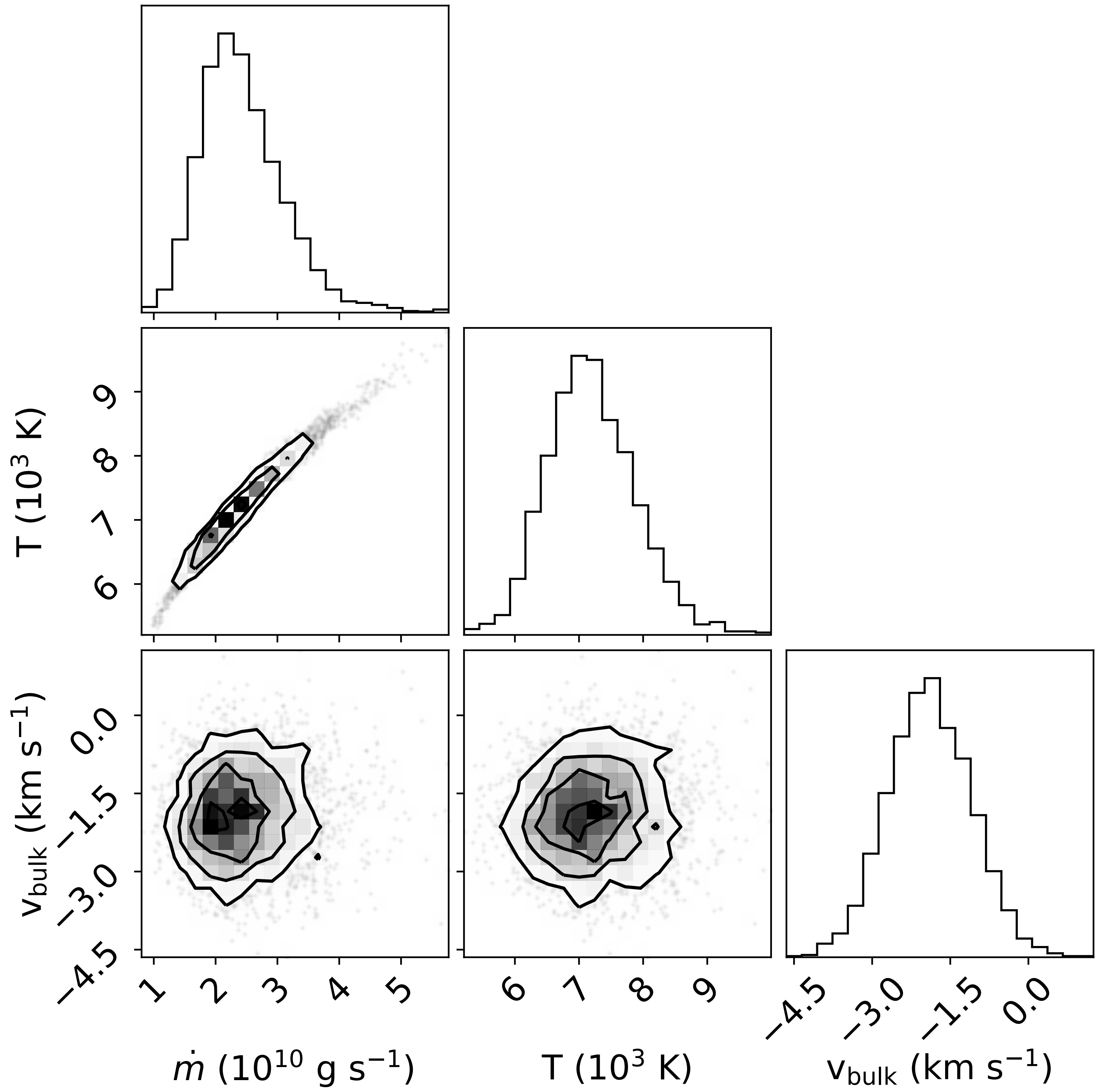


Dos Santos et al. (2022, A&A in press, arXiv:2111.11370)

p-winds

RETRIEVALS: ATMOSPHERIC ESCAPE RATE AND OUTFLOW TEMPERATURE





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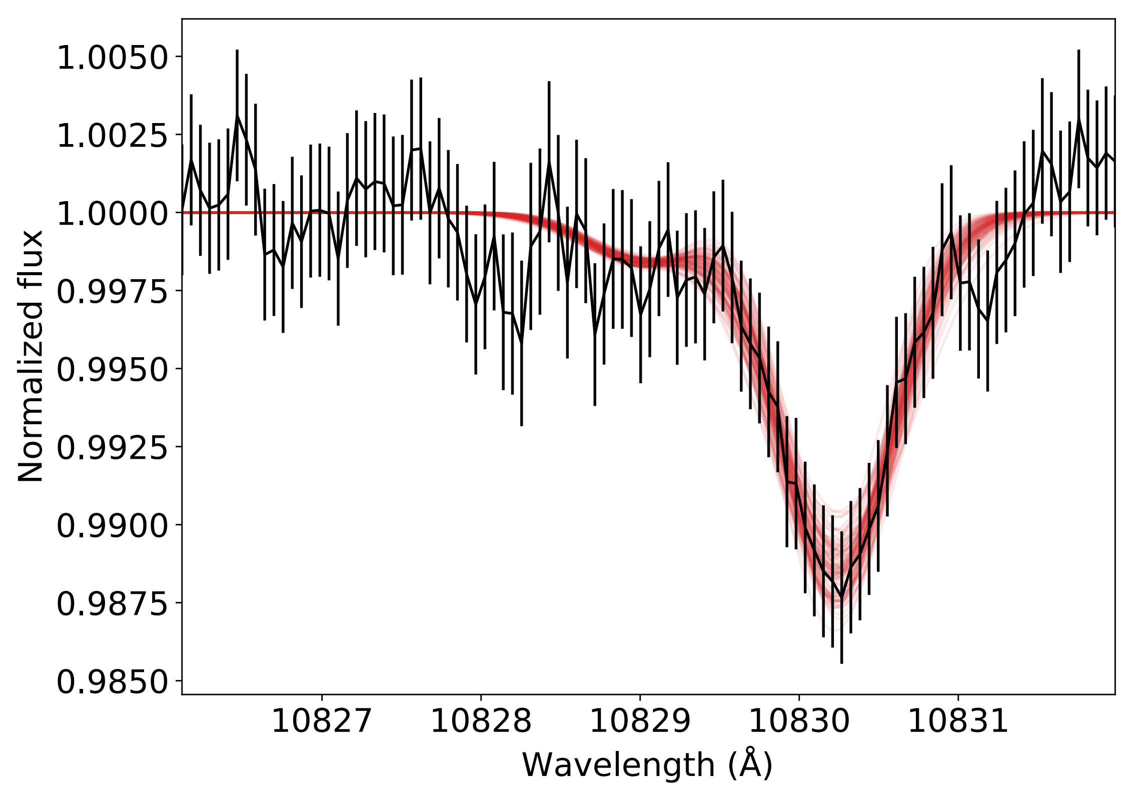

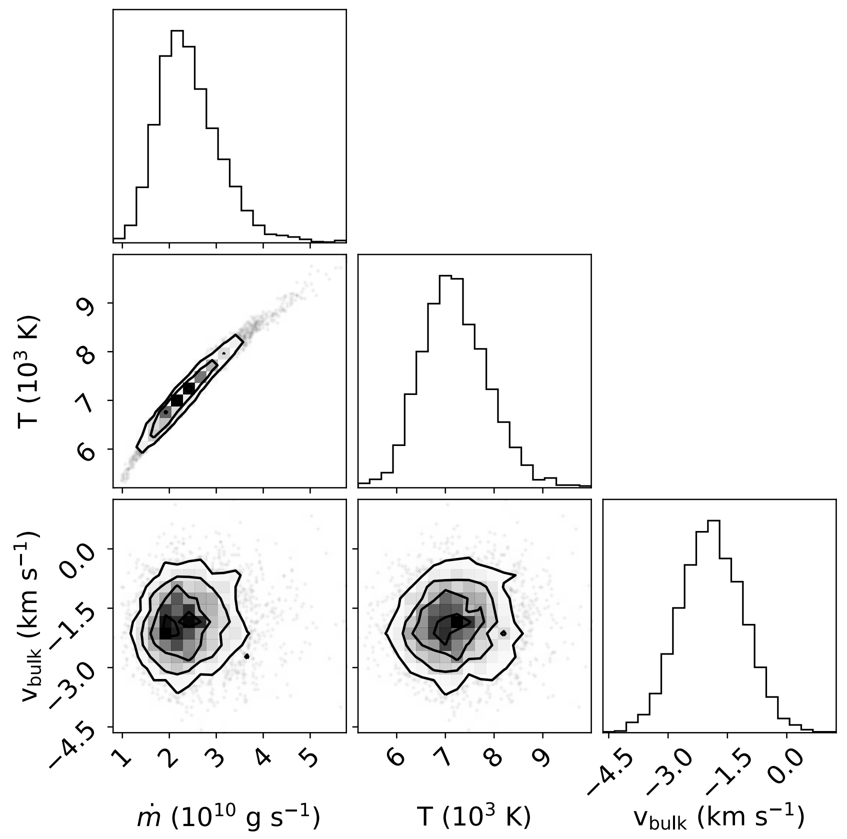

$$\dot{m} = 0.14^{+0.08}_{-0.04}\,\mathrm{M_\oplus\,Gyr^{-1}} \approx 0.5\,\%^{+0.3\%}_{-0.1\%}\,\mathrm{Gyr^{-1}}$$

HAT-P-11 b is, likely, stable against evaporation

Dos Santos et al. (2022, A&A in press, arXiv:2111.11370)

p-winds

WARNING: PRELIMINARY RESULTS!

CARMENES data is a kind courtesy of M. López-Puertas and M. Lampón
Keck/NIRSPEC result is under review (Kirk, Dos Santos et al. 2022)

p-winds

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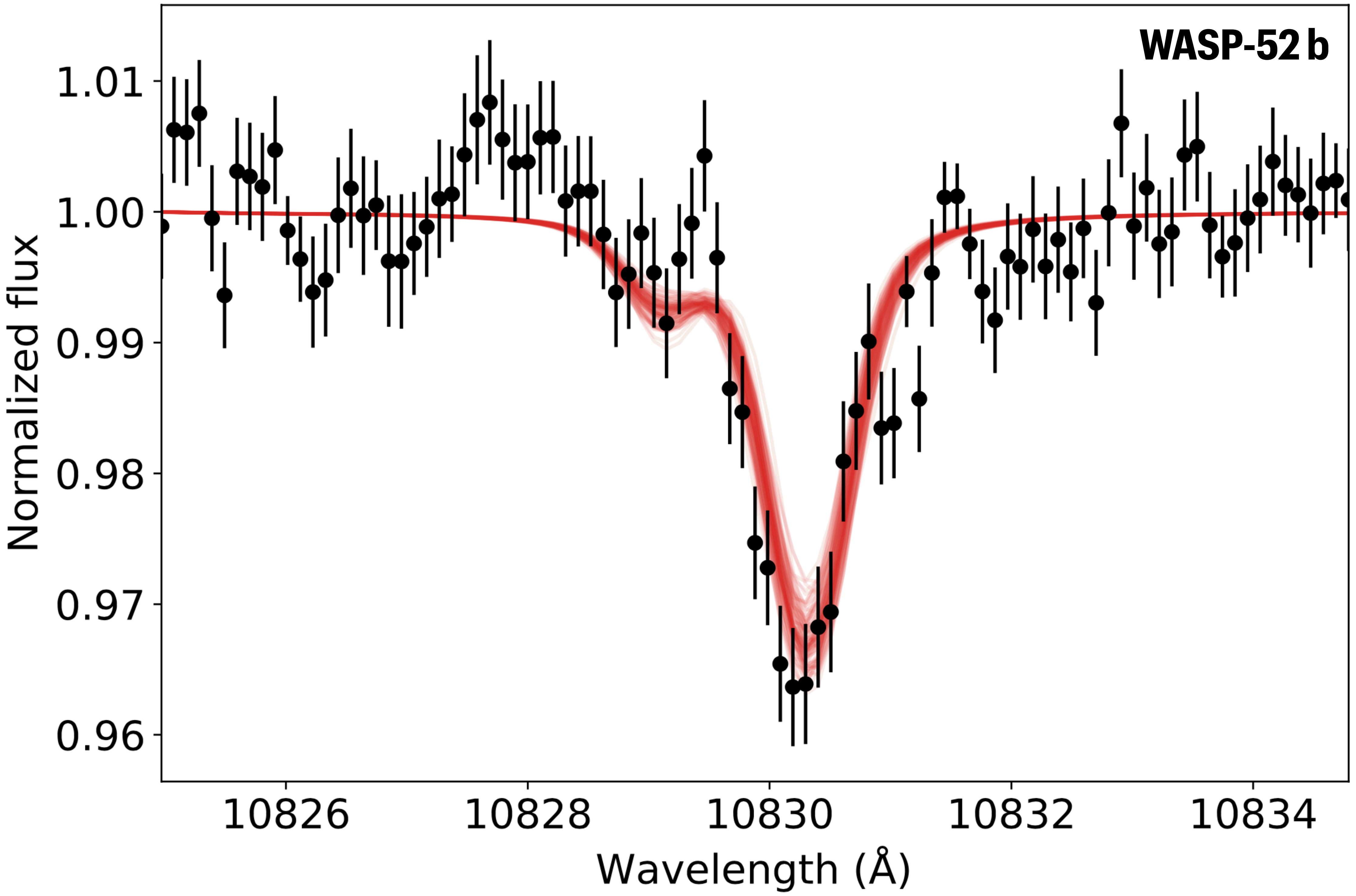


Kirk, Dos Santos et al. (2022, AAS Journals under review)

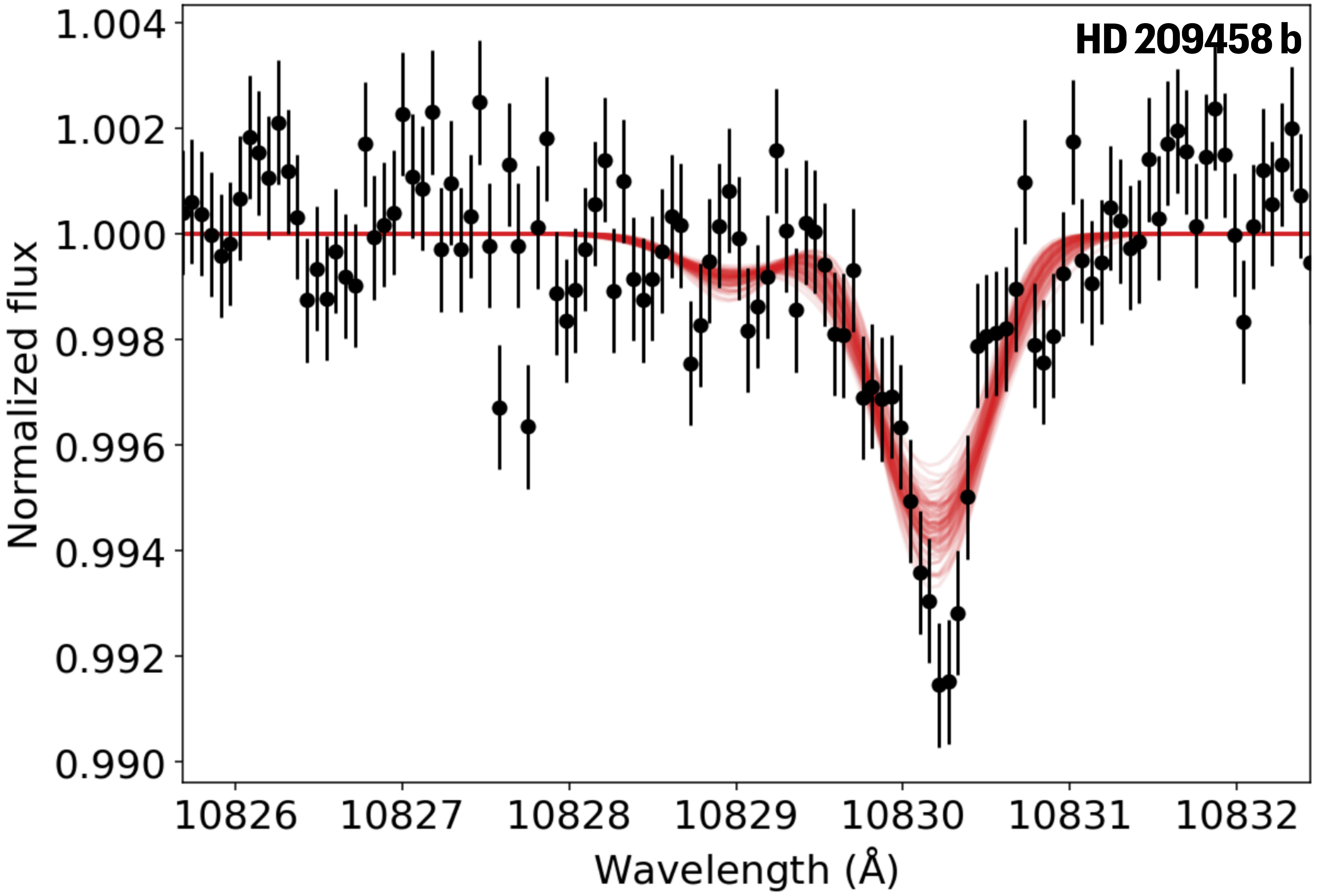
WASP-52 b, observed with Keck/NIRSPEC
Hot Jupiter

$$\dot{m} = 0.63^{+0.26}_{-0.21}\,\mathrm{M}_{\oplus}\,\mathrm{Gyr}^{-1}$$

or $\dot{m} \approx 1.2 \times 10^{11}\,\mathrm{g\,s}^{-1}$

p-winds

WARNING: PRELIMINARY RESULTS!



Data is courtesy of the M. López-Puertas and M. Lampón

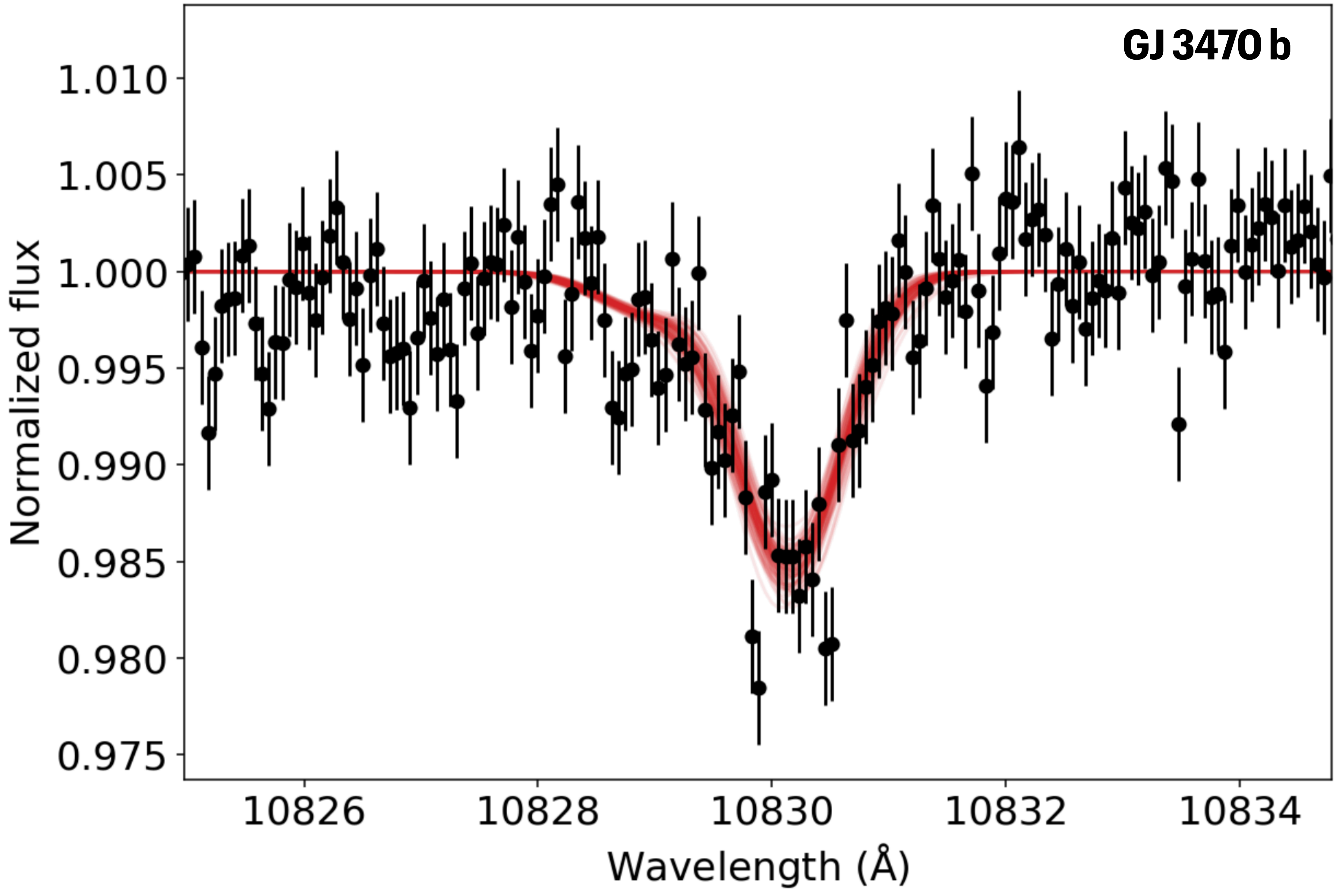
HD 209458 b, observed with CARMENES
Hot Jupiter

$$\dot{m} = 0.08^{+0.12}_{-0.06}\,\mathrm{M}_\oplus\,\mathrm{Gyr}^{-1}$$

or $\dot{m} \approx 1.5 \times 10^{10}\,\mathrm{g\,s^{-1}}$

p-winds

WARNING: PRELIMINARY RESULTS!



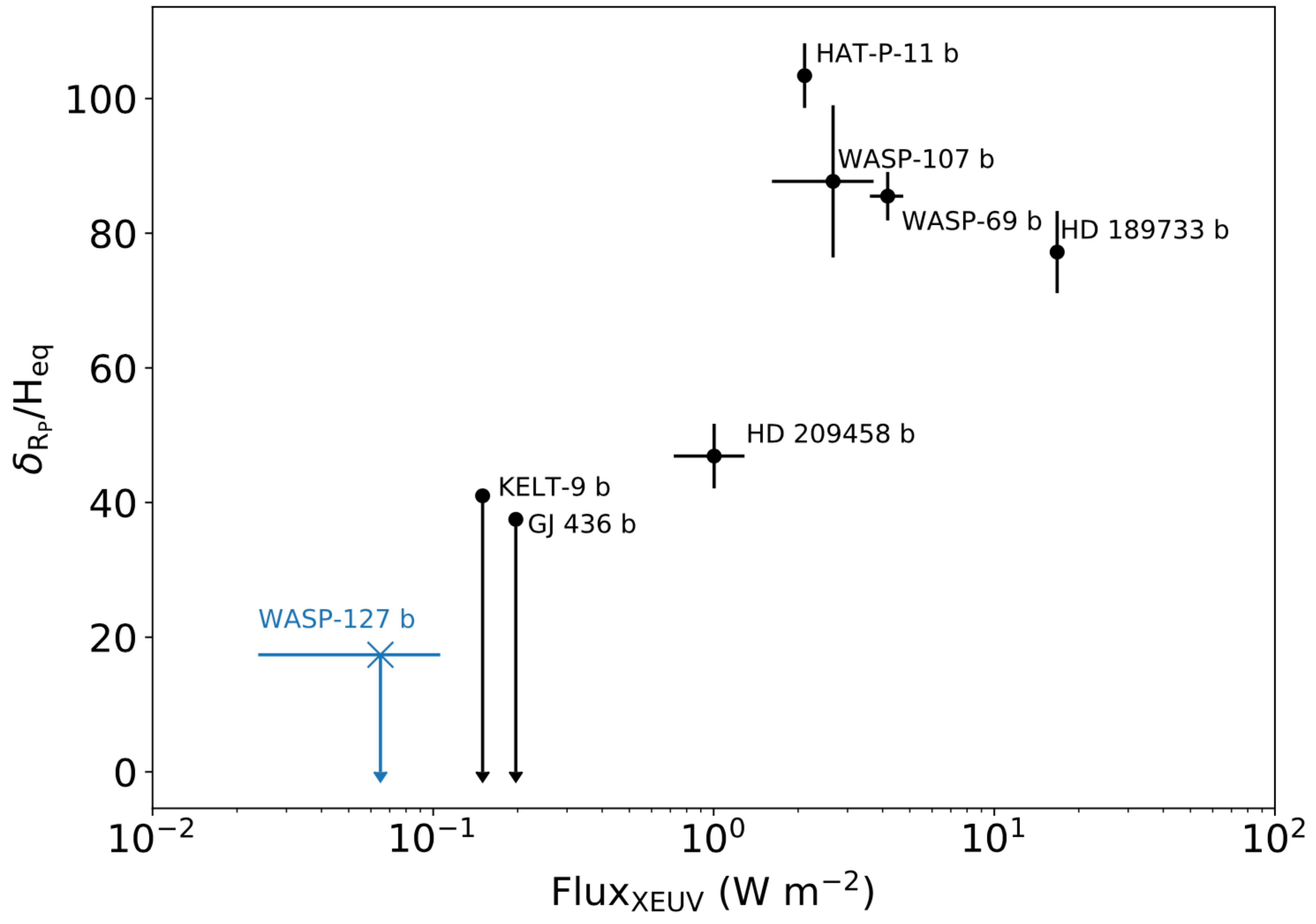
Data is courtesy of the M. López-Puertas and M. Lampón

GJ 3470 b, observed with CARMENES
Warm Neptune

$$\dot{m} = 0.30^{+0.08}_{-0.06}\,\mathrm{M}_{\oplus}\,\mathrm{Gyr}^{-1}$$

or
$$\dot{m} \approx 5.7 \times 10^{10}\,\mathrm{g\,s^{-1}}$$
$$\dot{m} \approx 2\,\%\,\mathrm{Gyr}^{-1}$$

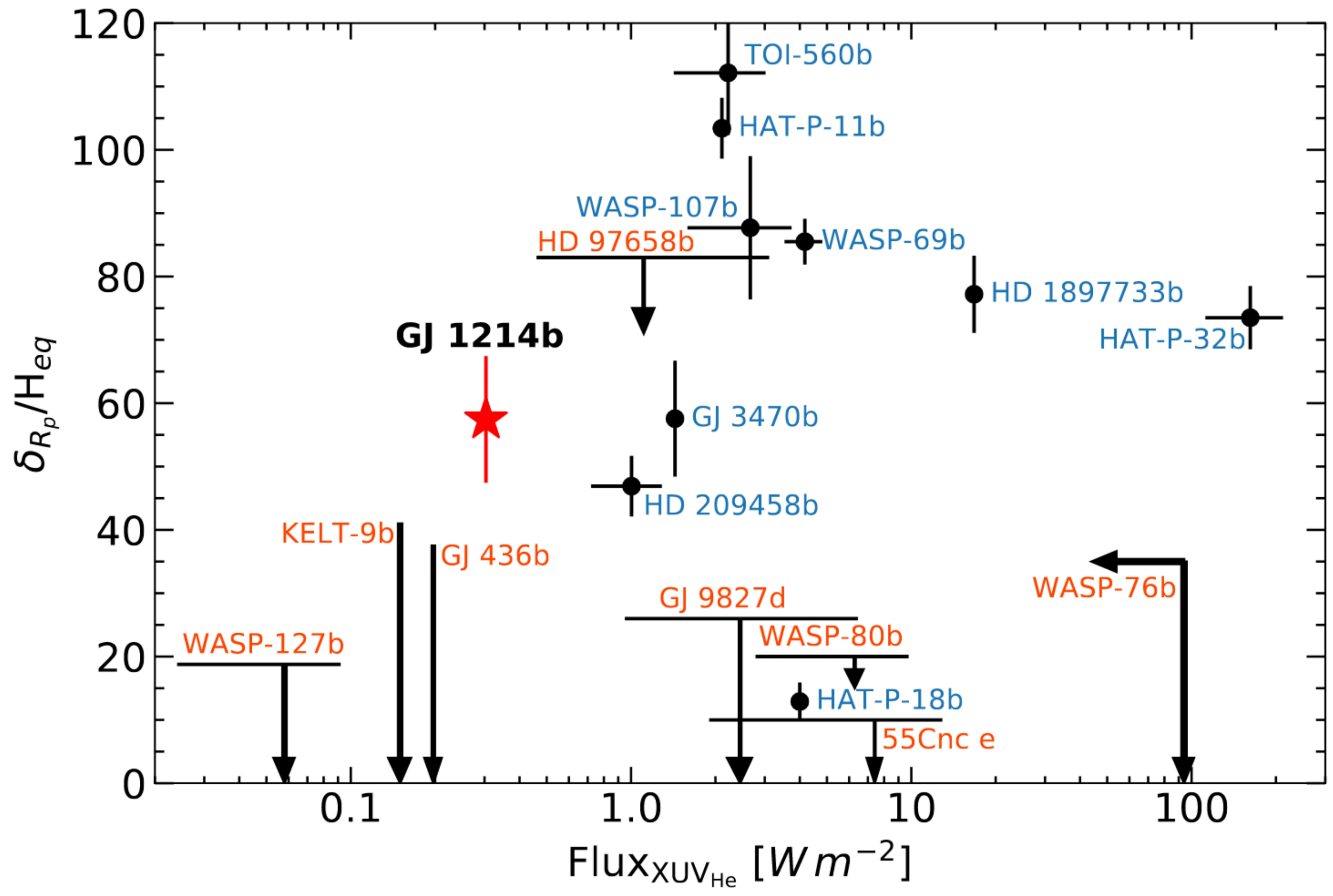
SAMPLE-LEVEL TRENDS



Dos Santos et al. (**2019**, A&A 640)

- F_{XUV} vs. He absorption

SAMPLE-LEVEL TRENDS



Orell-Miquel et al. (**2022**, A&A in press)

- F_{XUV} vs. He absorption

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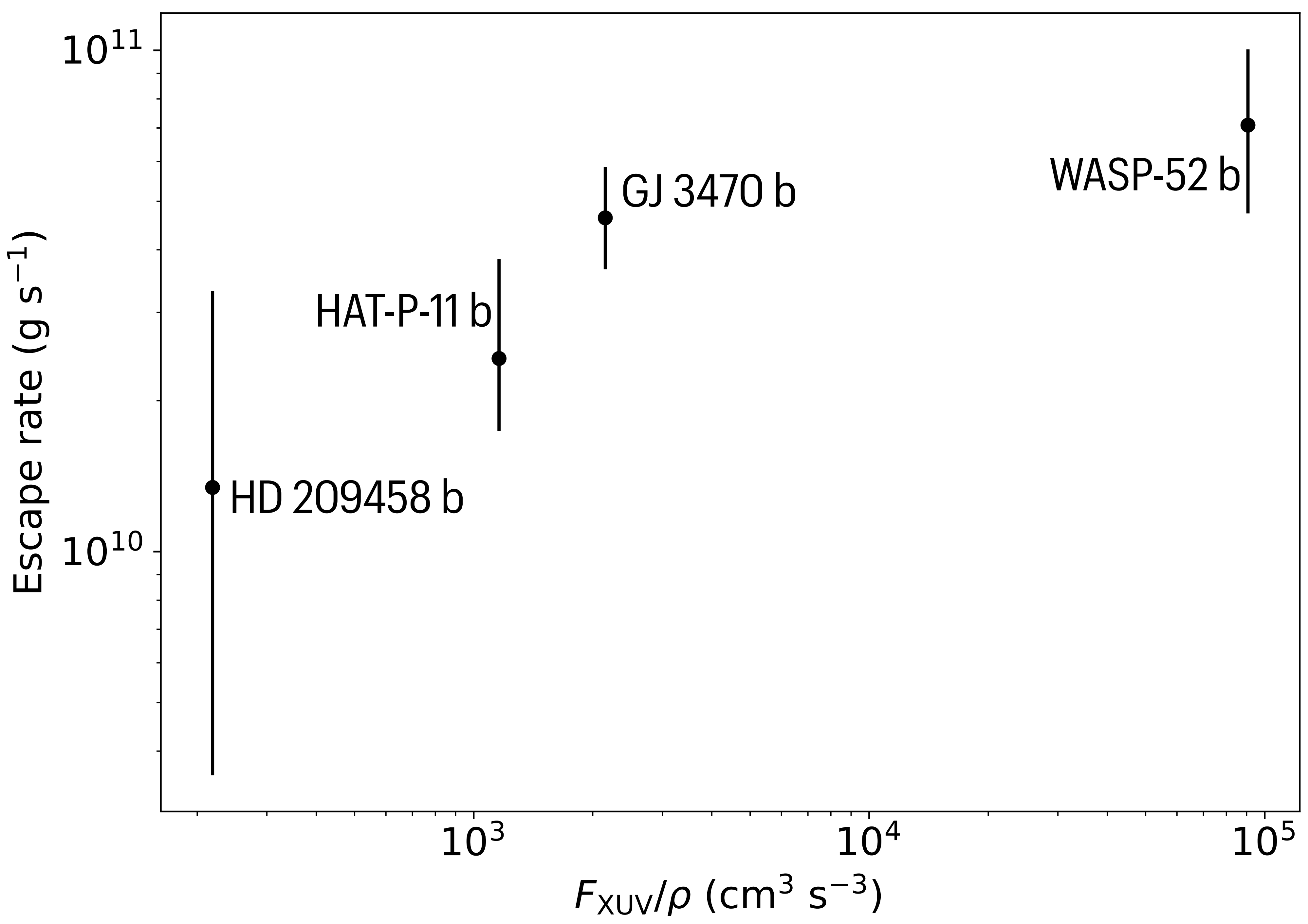

Sample-level trends:

- F_{XUV} vs. He absorption
- F_{XUV}/ρ vs. mass loss rate

$$\dot{m} \propto \eta \frac{F_{XUV}}{\rho_{bulk}}$$

Energy-limited mass loss formulation

pesky heating efficiency factor

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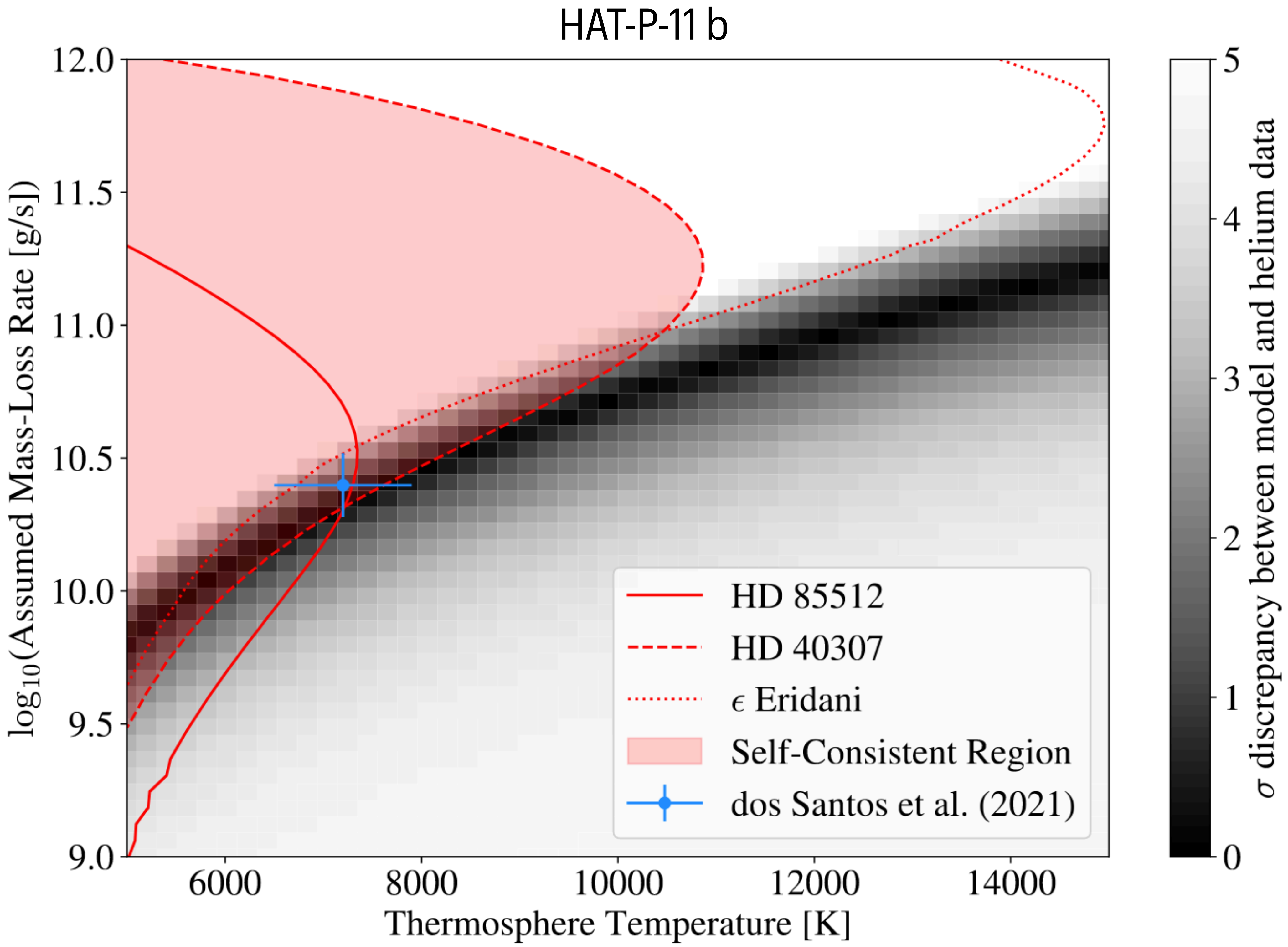
PUBLISHED RESULT!



He narrow-band photometry yield a subset of self-consistent models (Vissapragada et al. 2022, ApJ in press)

p-winds

MORE RESULTS AND PROJECTS ARE IN THE PIPELINE!

MORE OPEN-SOURCE CODES

FOR ATMOSPHERIC ESCAPE STUDIES

PLATYPOS - PLAneTarY PhOtoevaporation Simulator

Tool to estimate the atmospheric mass loss of planets induced by stellar X-ray and extreme UV irradiation.

Ketzer & Poppenhaeger (2022, proceedings of the XMM-Newton Workshop 2021)

The ATES code

The ATES code has been created to perform hydrodynamical simulations of the atmospheric mass loss from irradiated exoplanets. For a detailed description of the code, we refer to [1] In the following we describe the code organization and how to run.

Requirements

The code can be compiled with both `gfortran` (tested successfully in version 9.3.0) and `ifort` (tested on the 2021.2.0 20210228 version). For the compiler choice, see below. A basic installation of `python3` is required. The following libraries are used: `numpy,tkinter,os,shutil,matplotlib,sys,time`.

Installation

The code doesn't require any special installation, and can be directly downloaded from the Github page or, in alternative, the repository can be cloned via

```
git clone https://github.com/AndreaCaldiroli/ATES-Code
```

Caldiroli et al. (2021, A&A 655)

TAKE-HOME POINTS

- **Hot Jupiters and (sub-)Neptunes are a laboratory to study atmospheric escape in exoplanets**
- **The whole community benefits from open-policy initiatives**
- **We need to analyze the sample of evaporating exoplanets <u>with a common framework</u>**

AN OPEN-SOURCE FRAMEWORK TO PLAN AND INTERPRET OBSERVATIONS OF ATMOSPHERIC ESCAPE IN EXOPLANETS
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