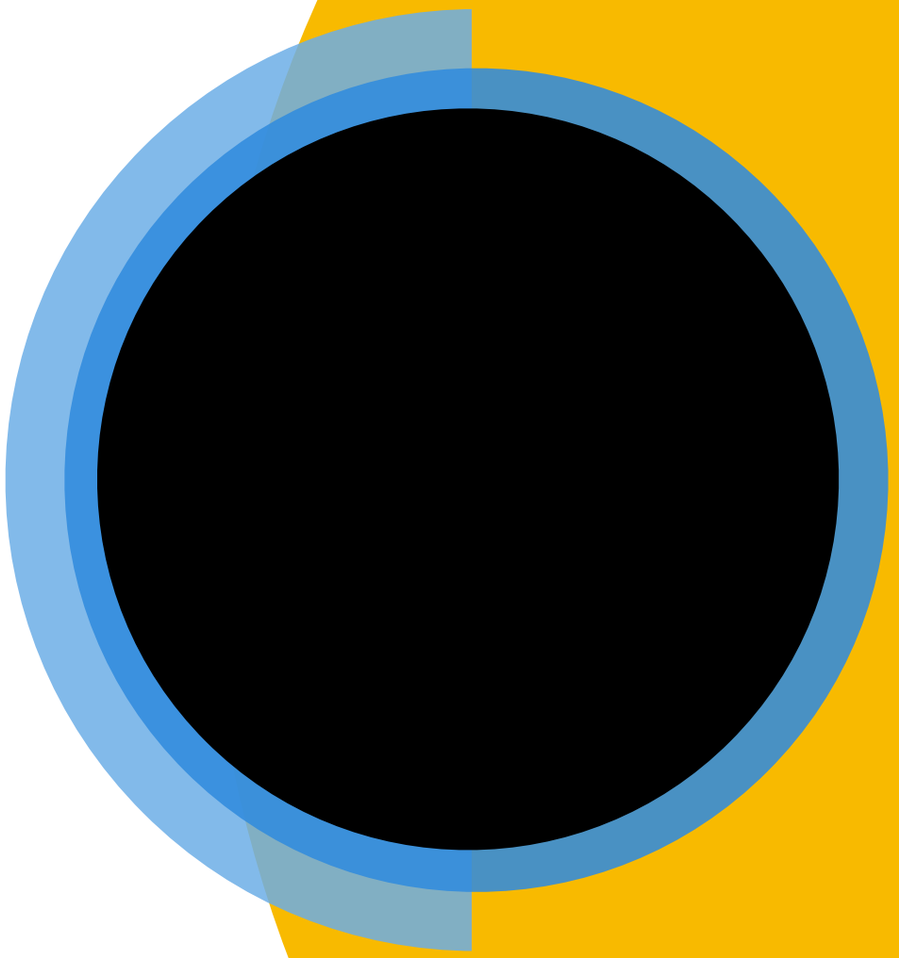
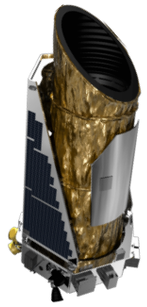


Constraining mornings and evenings of distant worlds:

state-of-the-art & future prospects

Néstor Espinoza | STScI | SPACE TELESCOPE SCIENCE INSTITUTE



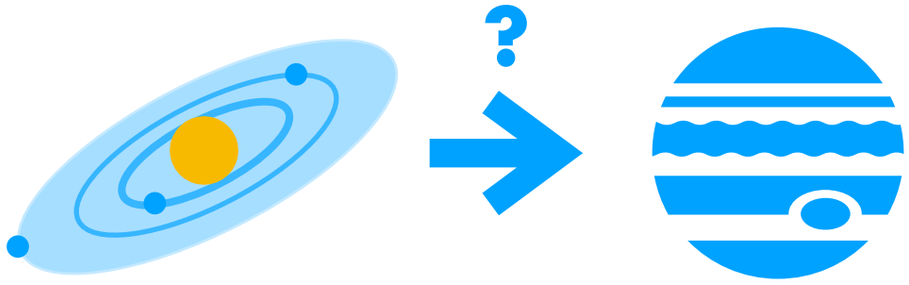
(most of which are Kepler discoveries)

4,461

confirmed exoplanets as of today

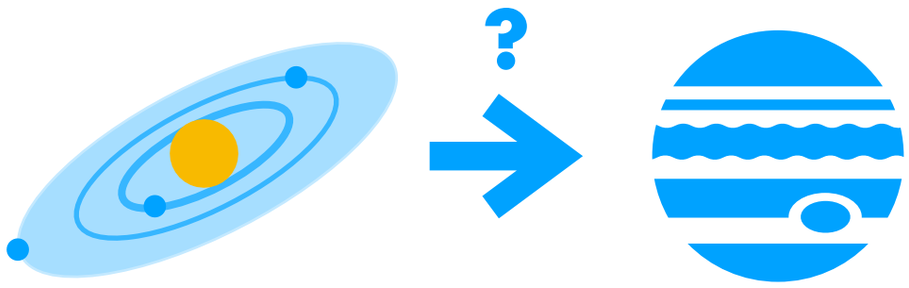
We can start to answer the Big Questions™

We can start to answer the **Big Questions**™

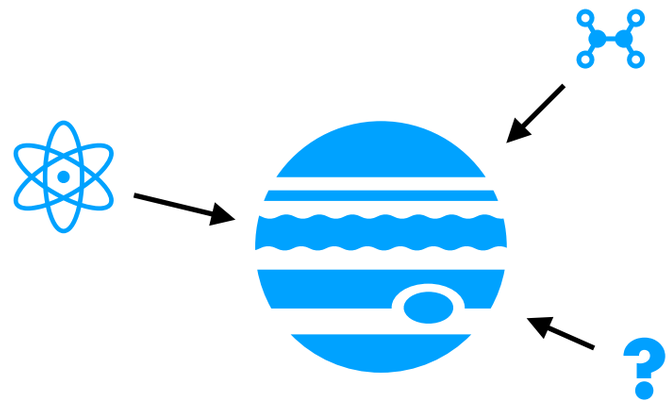


How are **planets formed**?

We can start to answer the **Big Questions**™

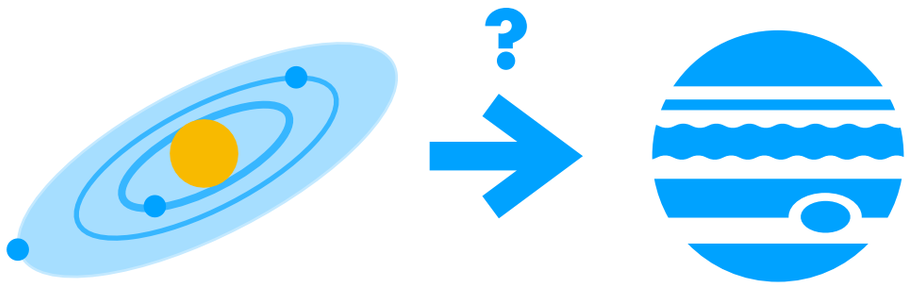


How are **planets formed**?

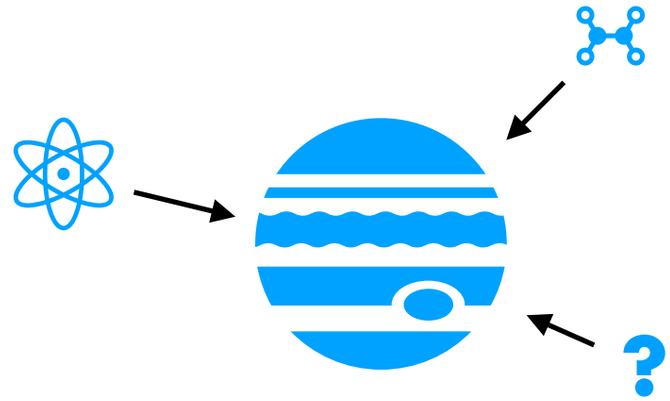


What are they **made of**?

We can start to answer the **Big Questions**™

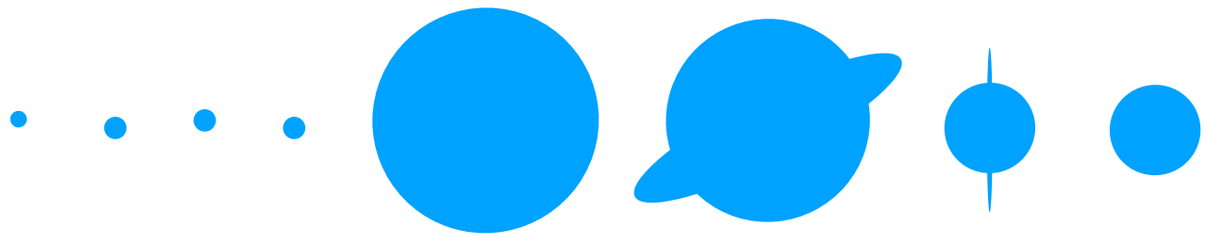


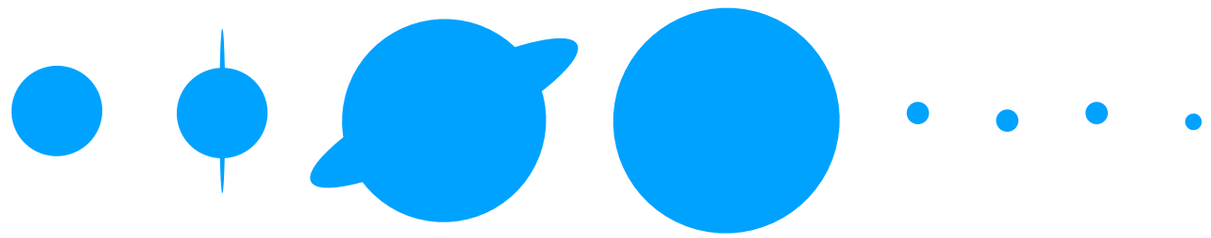
How are **planets formed**?



What are they **made of**?

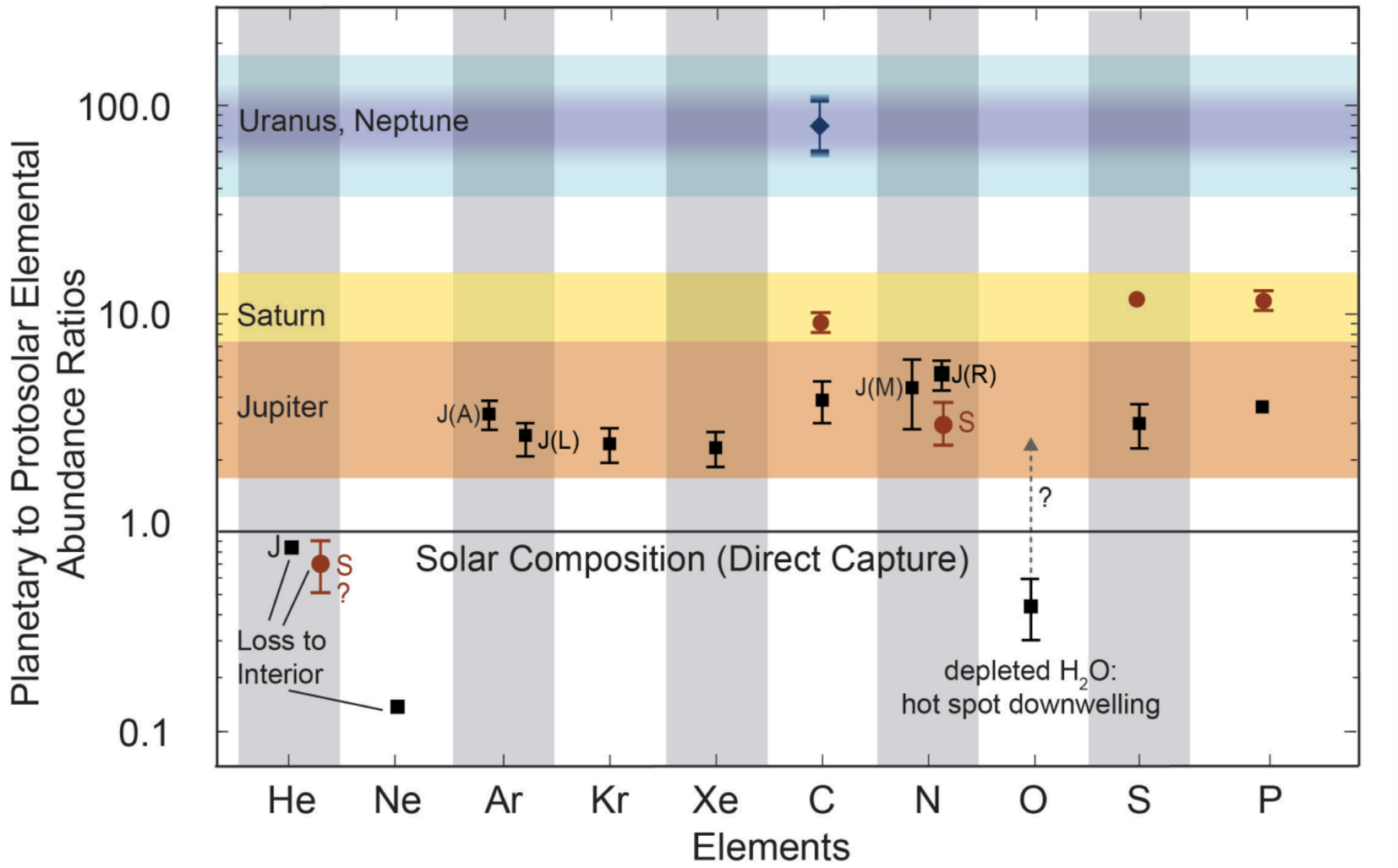
How do **we fit in this picture**?

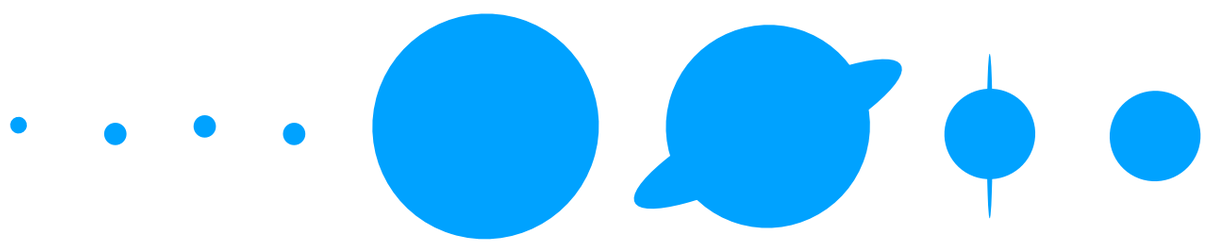




The Solar System is a diverse place to live in!

Figure Credit: Atreya et al. (2018 in "Saturn in the 21st Century", Cambridge University Press)





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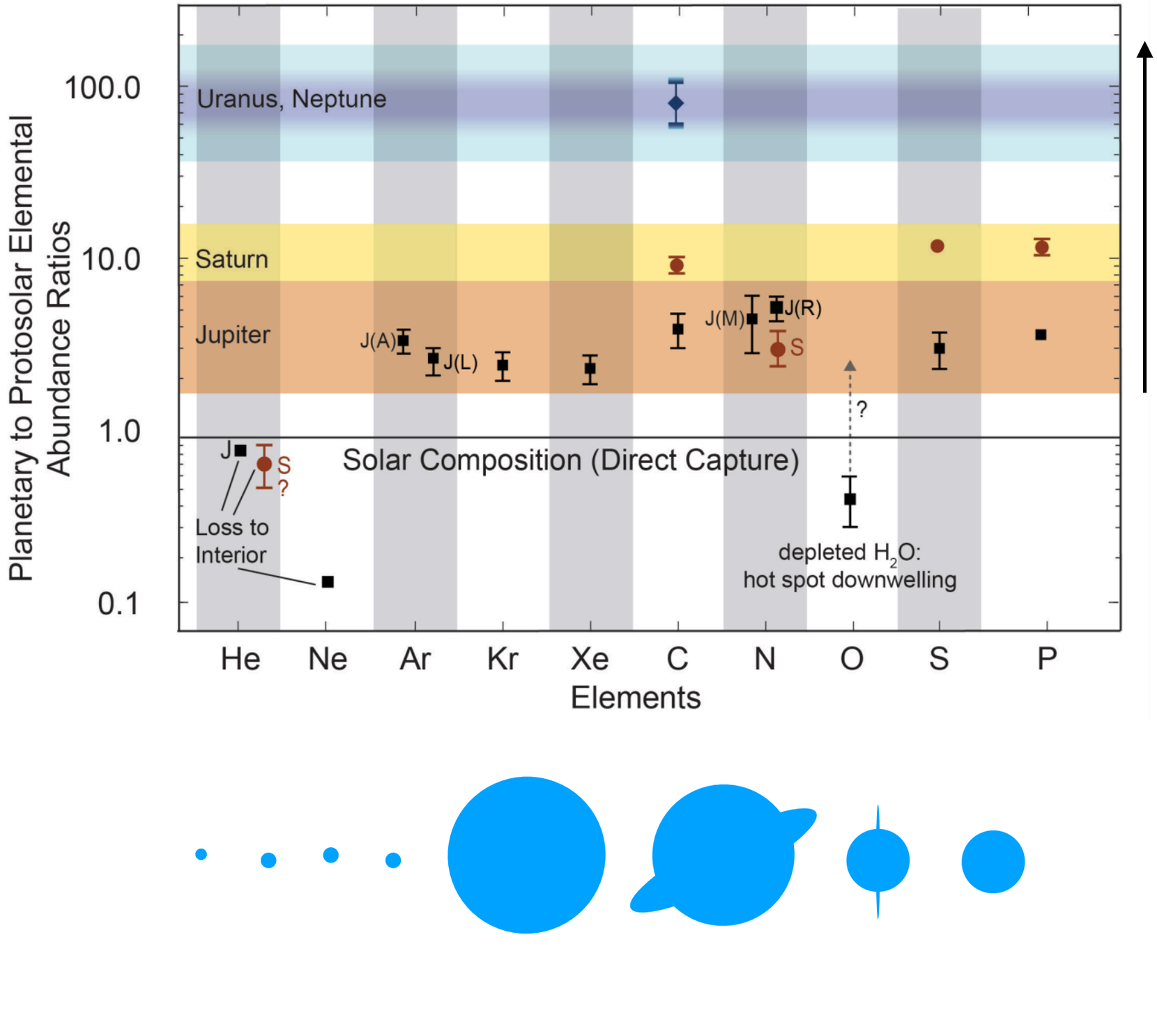
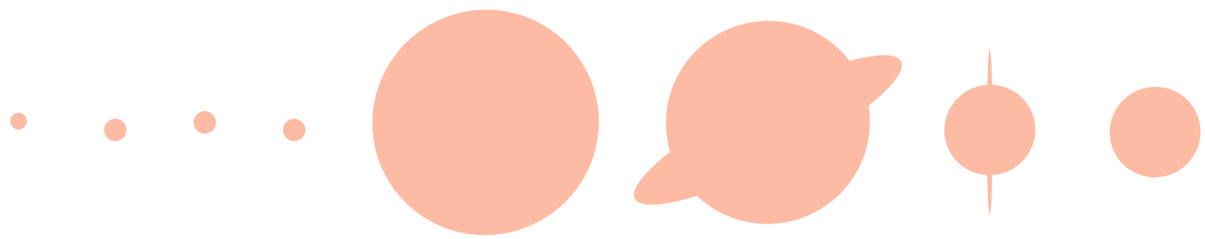


In line with core-accretion scenario:

$$\frac{Z_{planet}}{Z_{star}} \sim \frac{1}{M_{planet}}$$

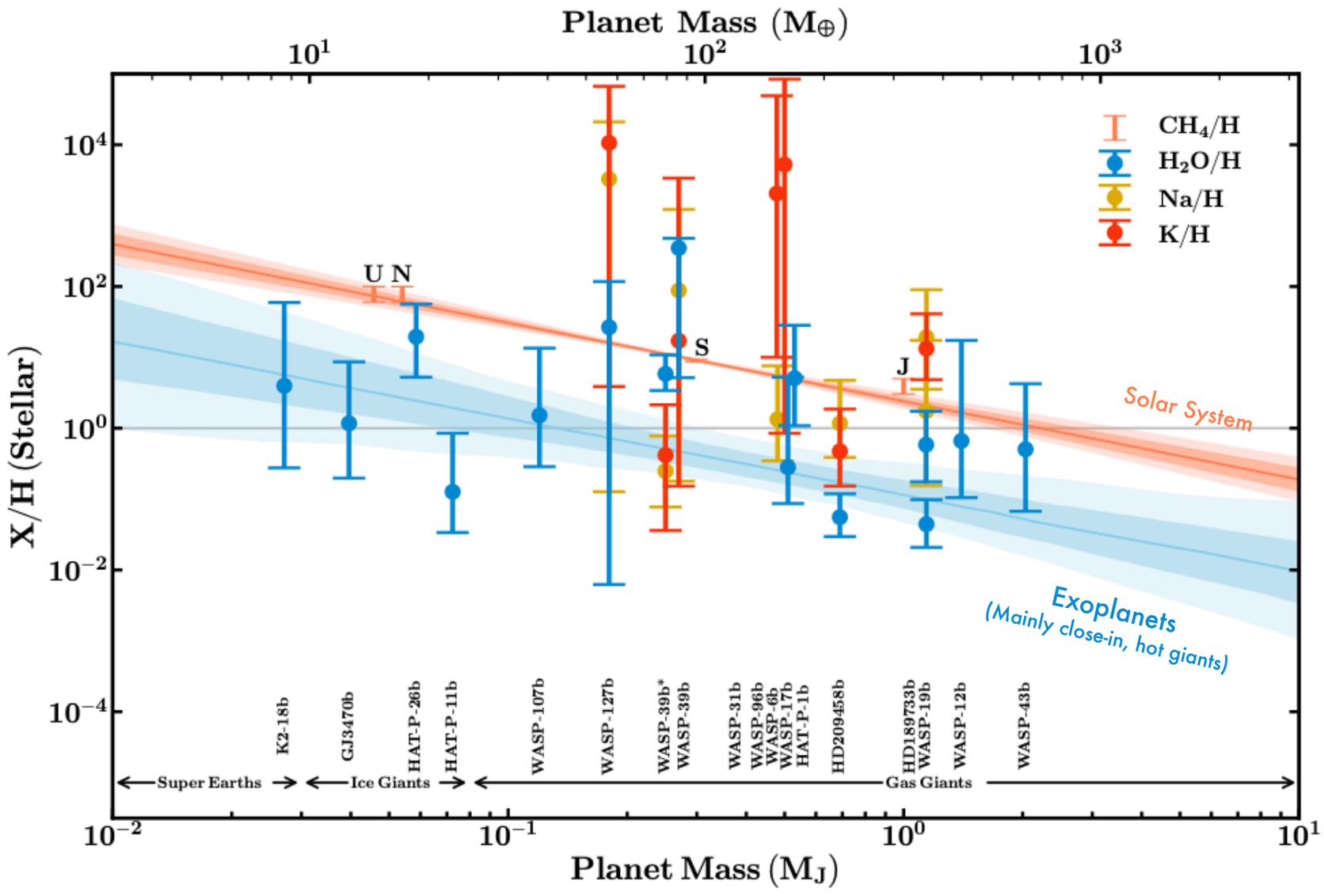
Galaxy

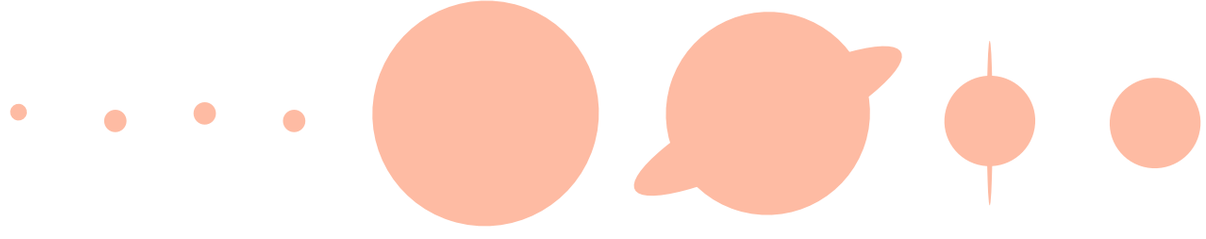
The [redacted] is a diverse place to live in!



The ~~Solar System~~ Galaxy is a diverse place to live in!

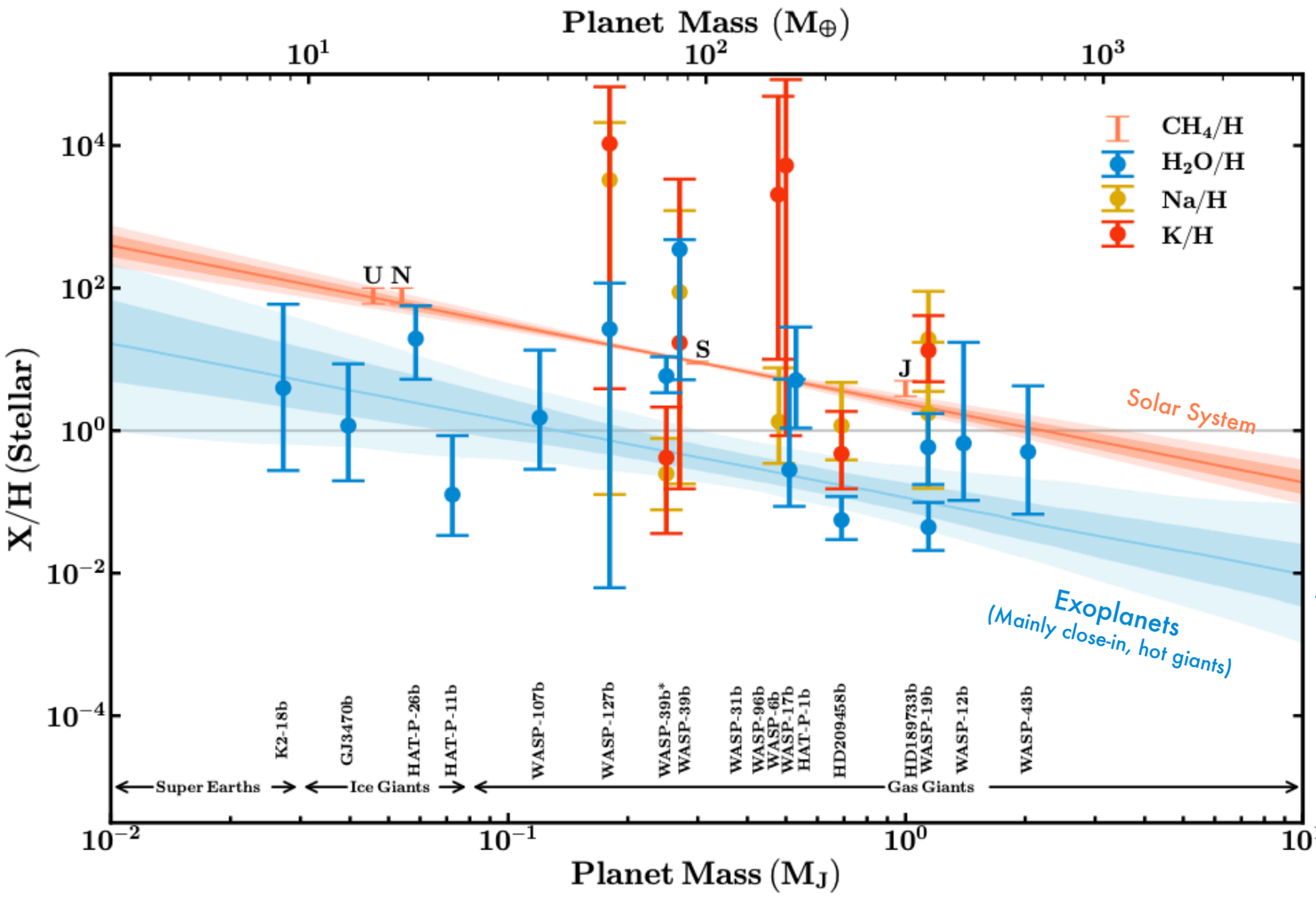
Figure Credit: Welbanks et al. (2019, ApJL, 887, 20)





The Galaxy is a diverse place to live in!

Figure Credit: Welbanks et al. (2019, ApJL, 887, 20)

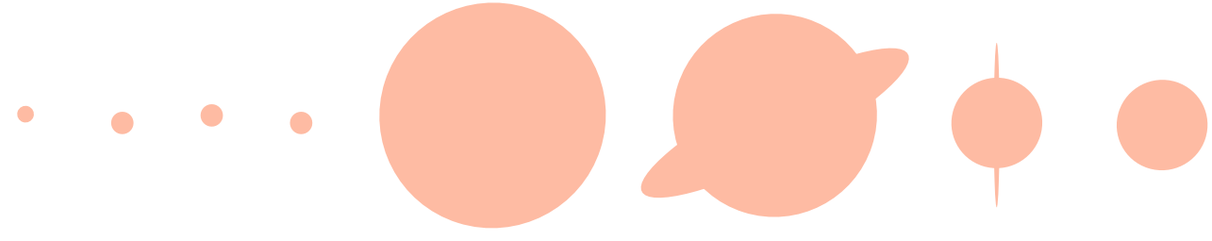


Formation?

Why?

Models? Clouds?

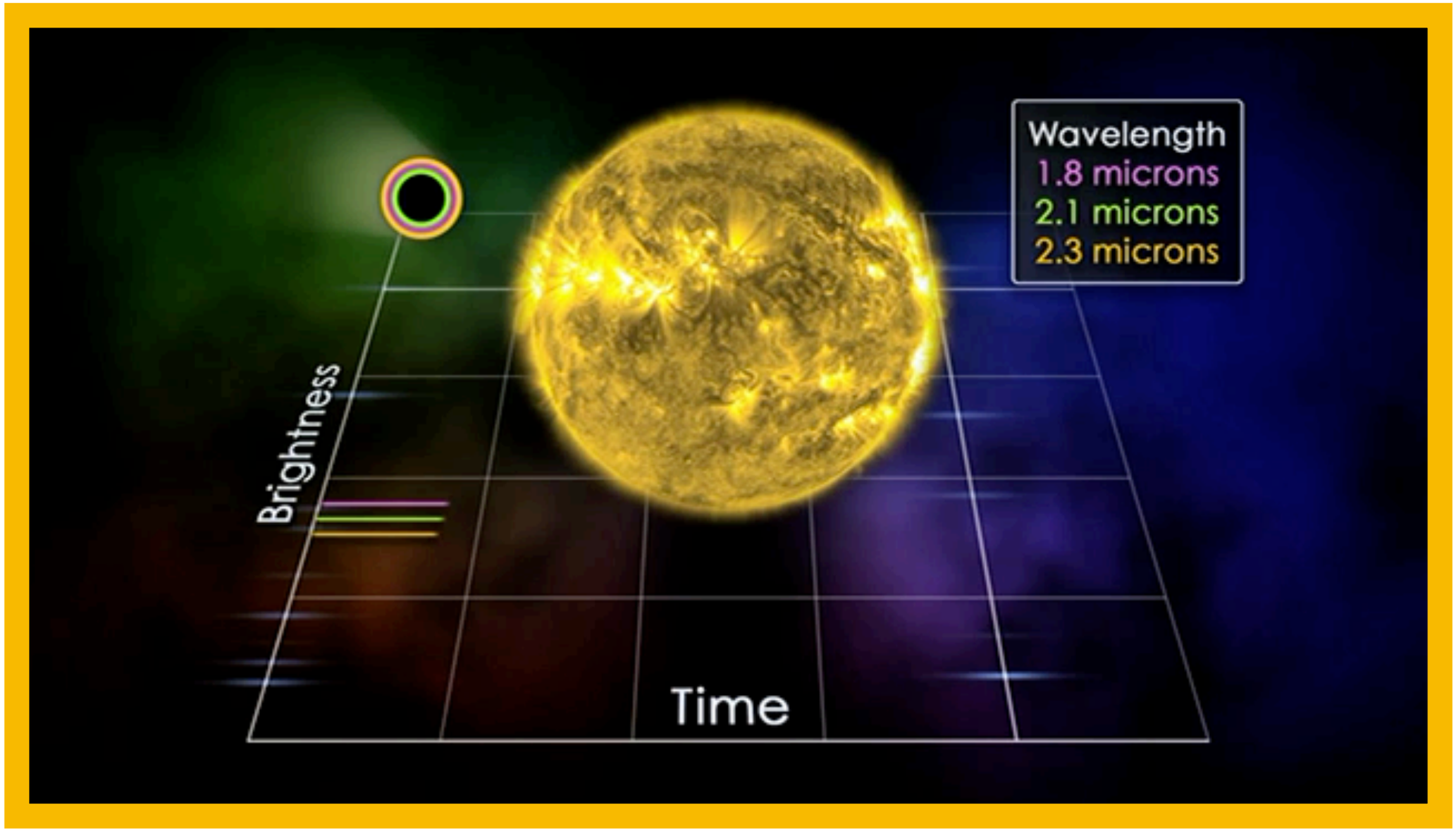
Elements?



"There is **no one abundance**
to extract from hot giant exoplanets"

- Christiane Helling (St. Andrews)

Exoplanet atmospheres with transit spectroscopy

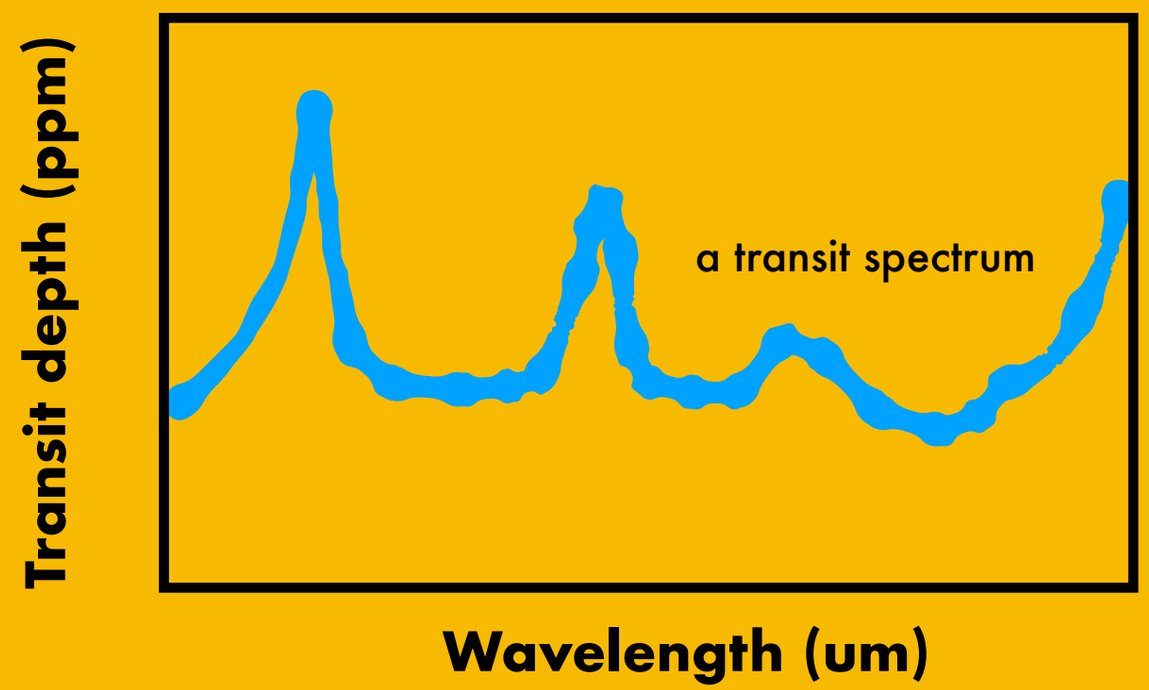


star

planet's atmosphere

star

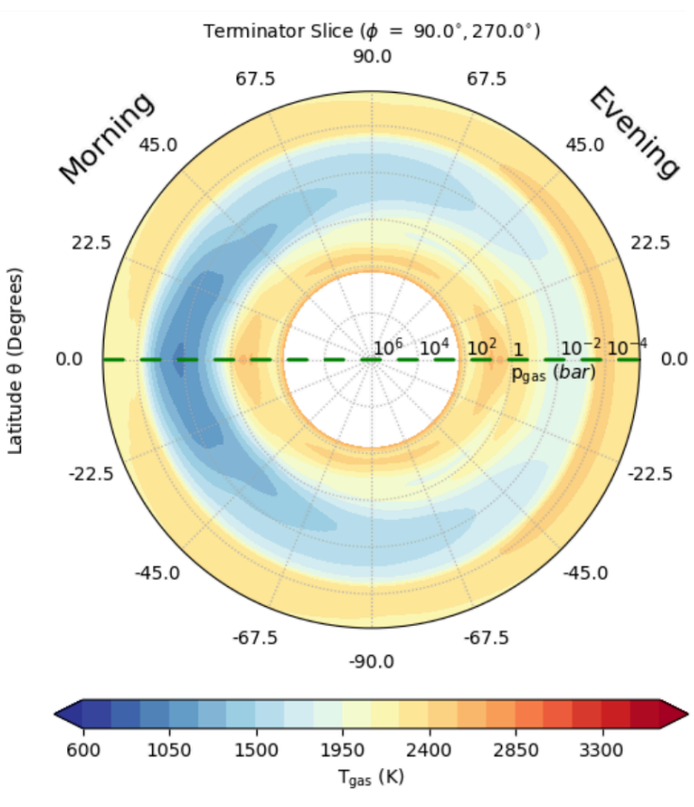
planet's atmosphere



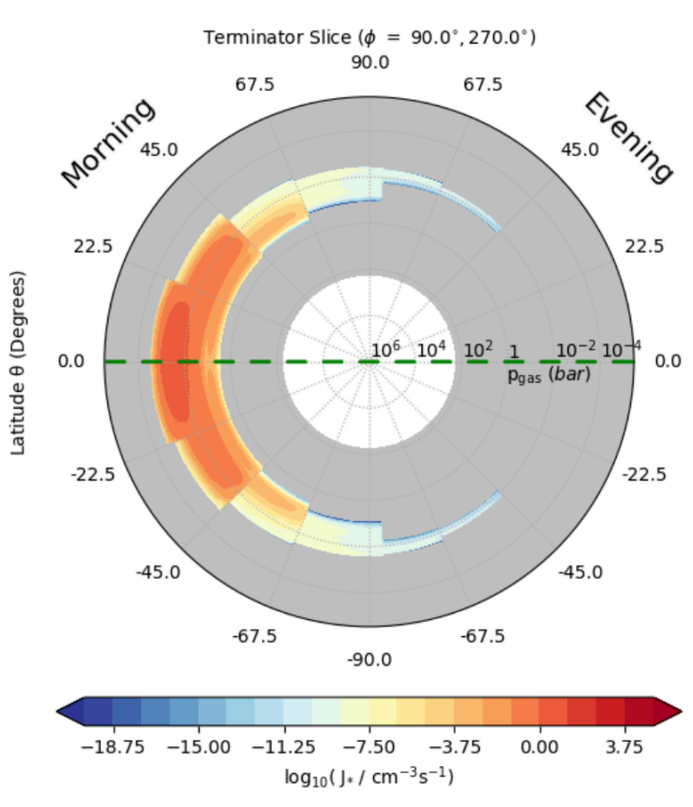
Inhomogeneus abundances: the case of HAT-P-7b

(Helling et al., 2020 — see also Fortney et al., 2010; Dobbs-Dixon et al., 2012; Line & Parmentier 2016; Kempton et al. 2017; Powell et al., 2019**)**

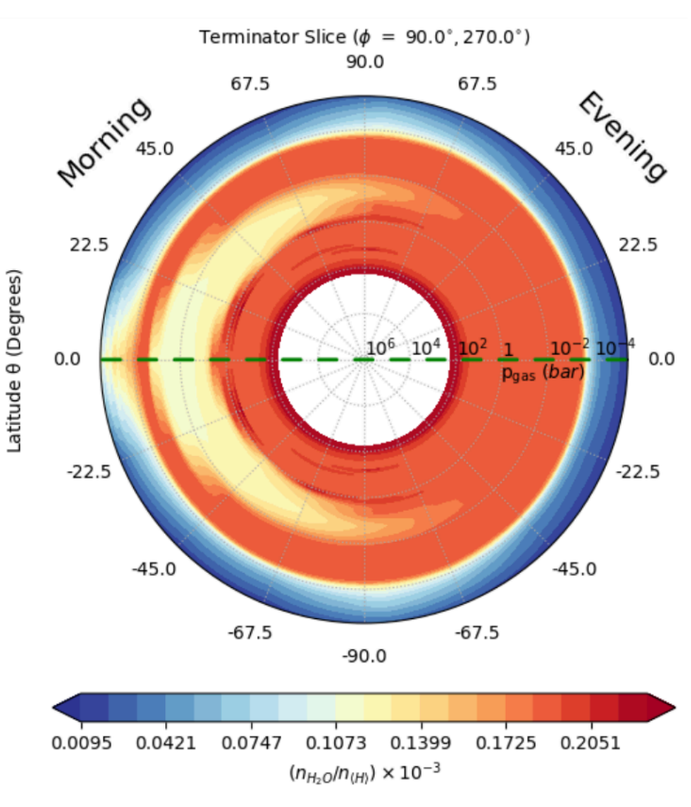
Gas temperature



Nucleation rate



Water abundance



We know this is real: condensation of Fe in an exoplanet

Figure Credit: Ehrenreich et al., 2020 (Nature, 580, 7805, 597)

Article

Nightside condensation of iron in an ultrahot giant exoplanet

https://doi.org/10.1038/s41586-020-2107-1

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Published online: 11 March 2020

Check for updates

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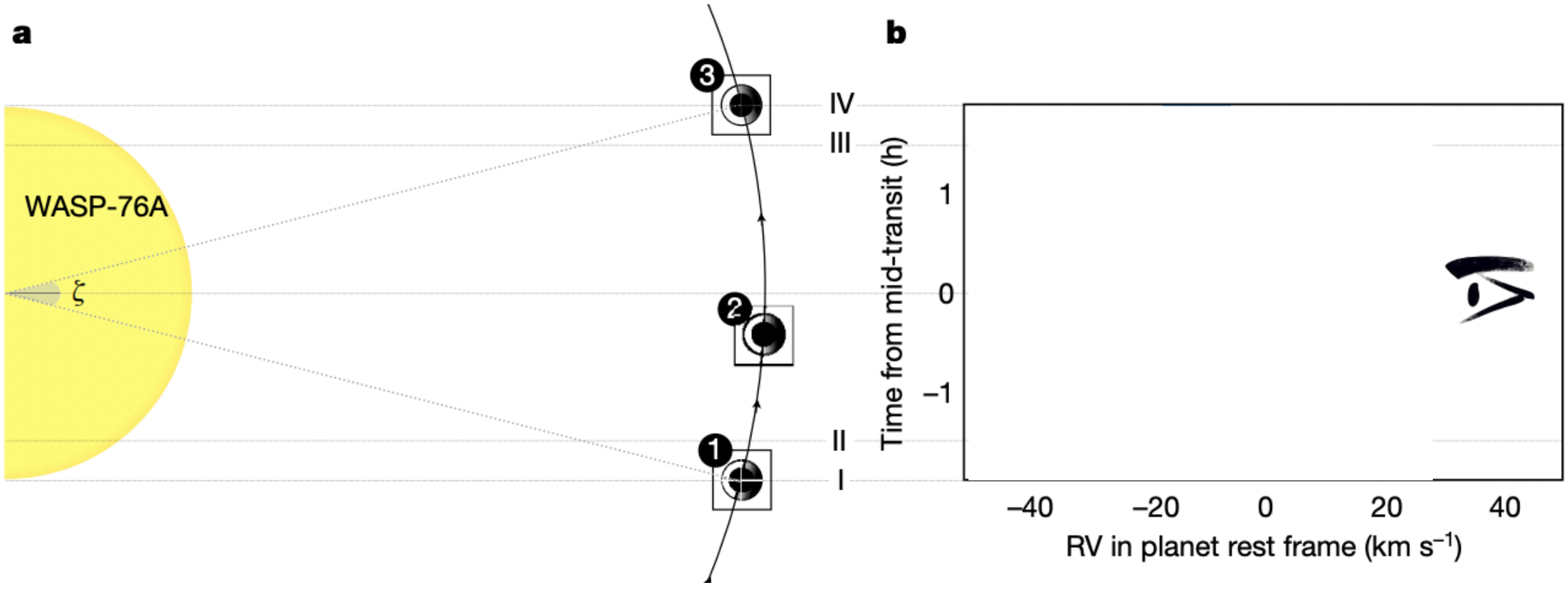
We know this is real: condensation of Fe in an exoplanet

Figure Credit: Ehrenreich et al., 2020 (Nature, 580, 7805, 597)



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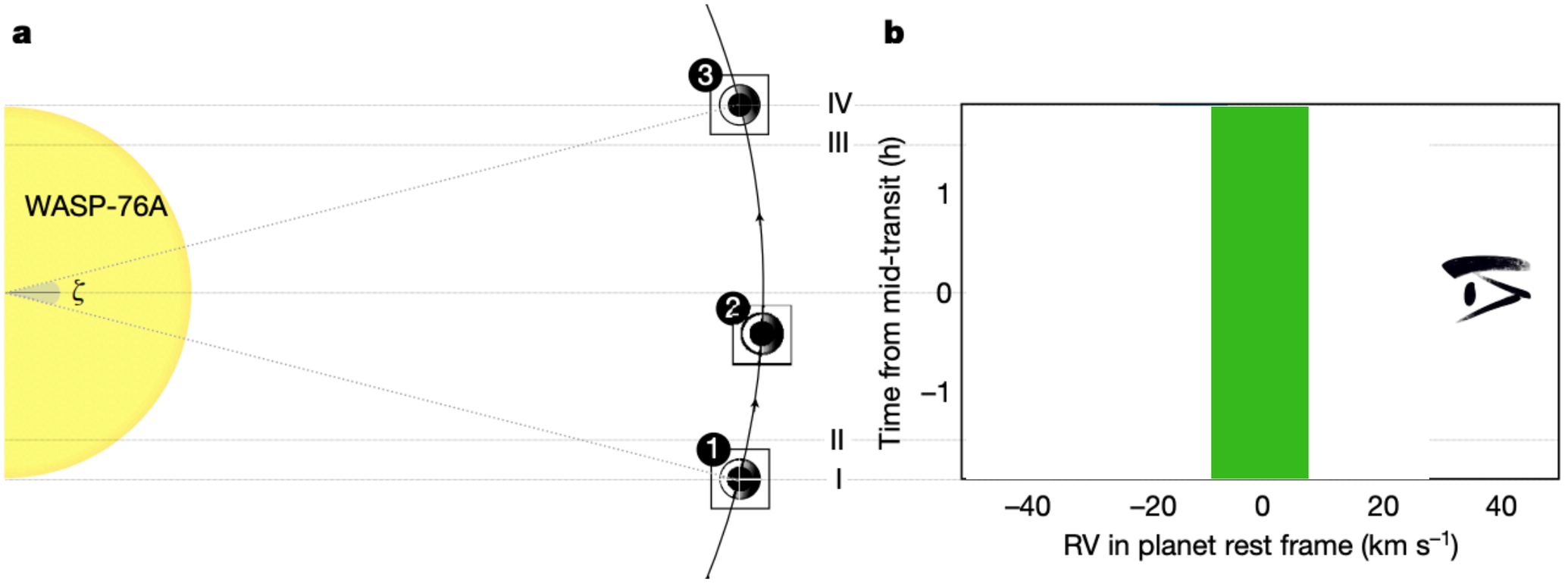
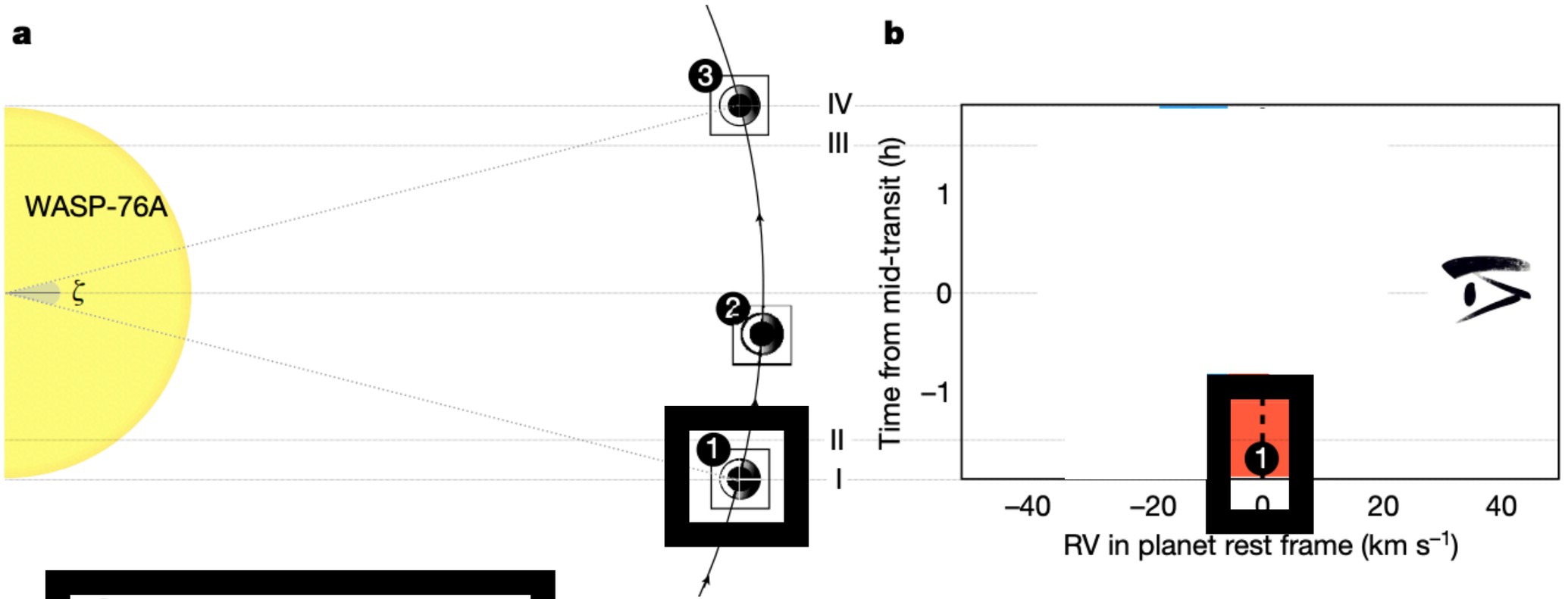


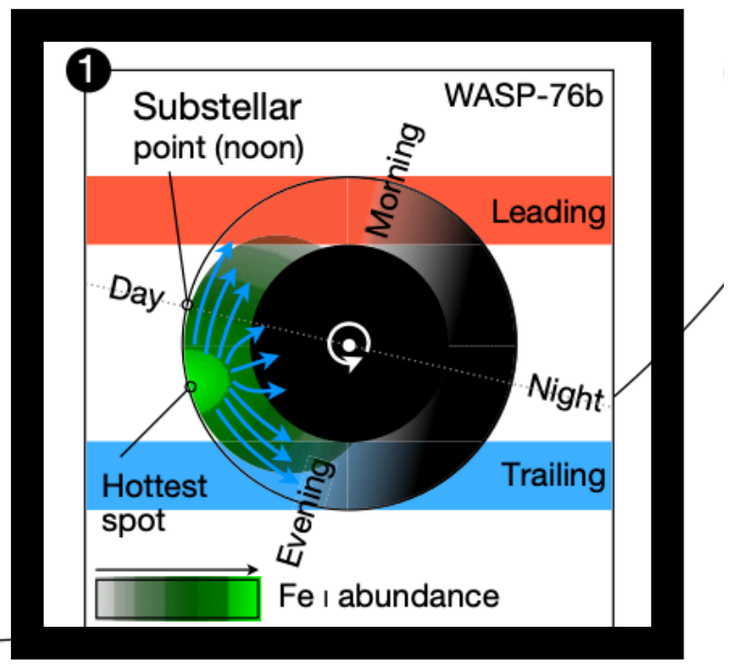
If no limb asymmetries, we should see a symmetric feature around 0.

(See Núria Casasayas-Barris & Julia Seidel's Monday lecture!)

We know this is real: condensation of Fe in an exoplanet

Figure Credit: Ehrenreich et al., 2020 (Nature, 580, 7805, 597)





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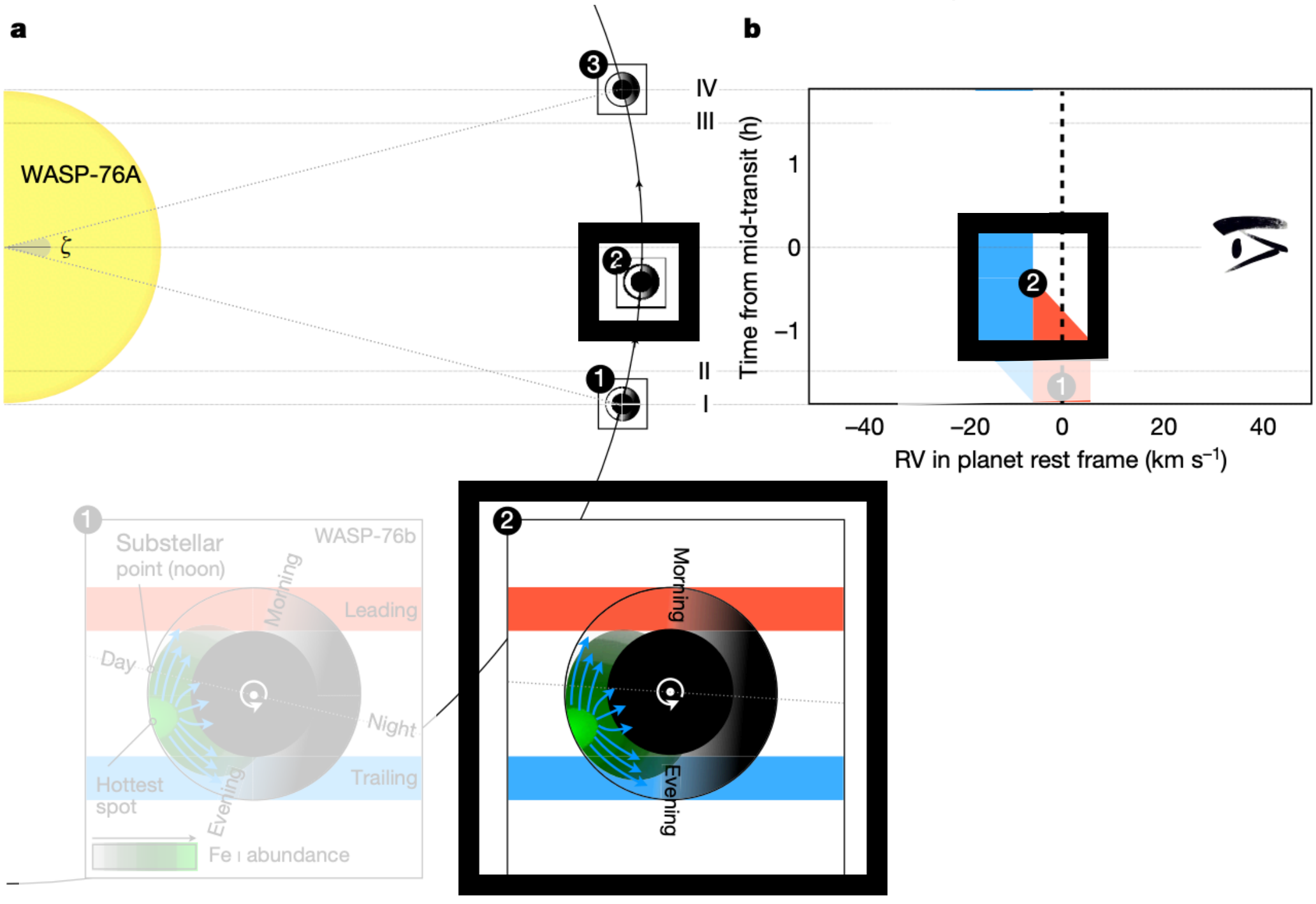

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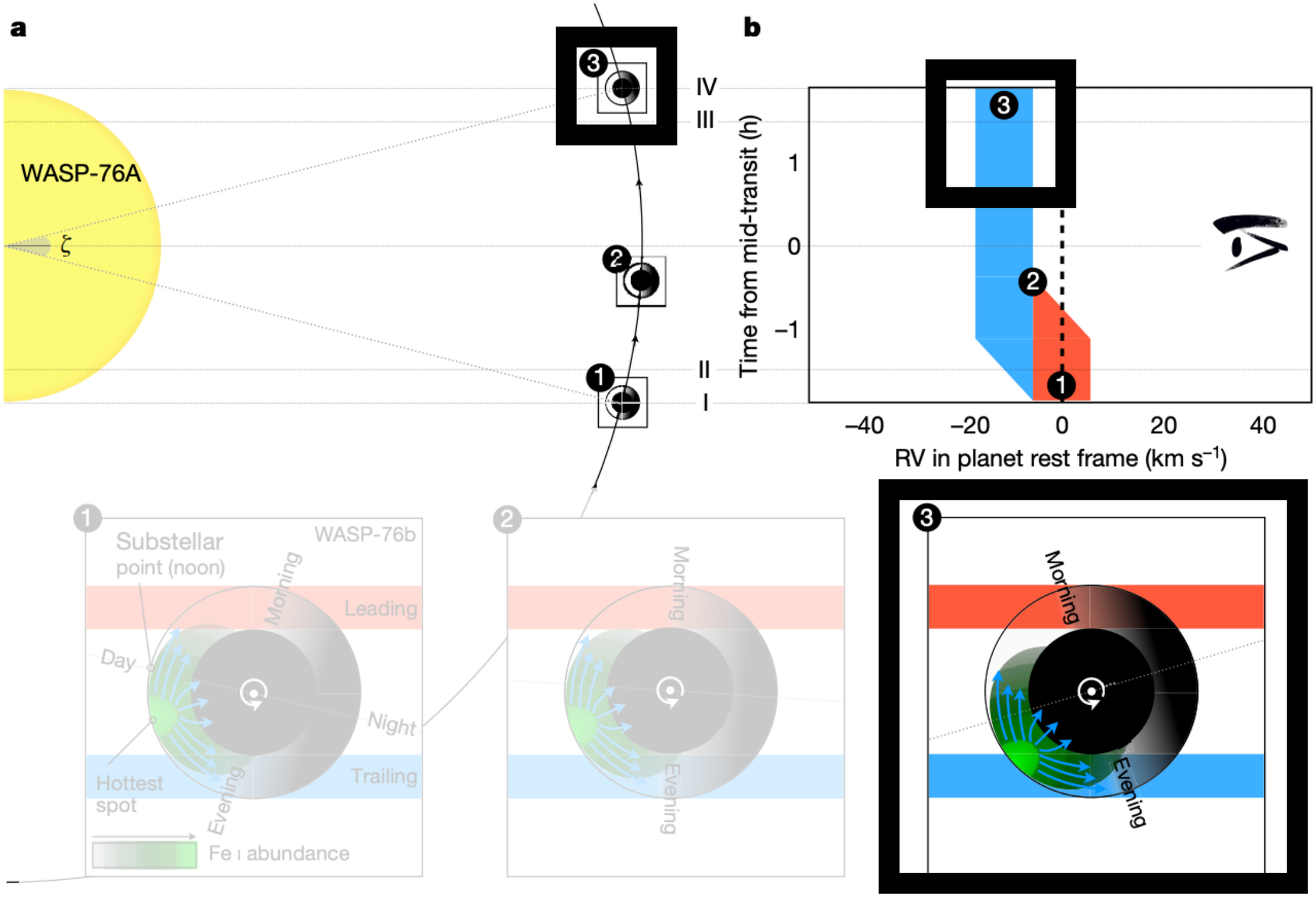

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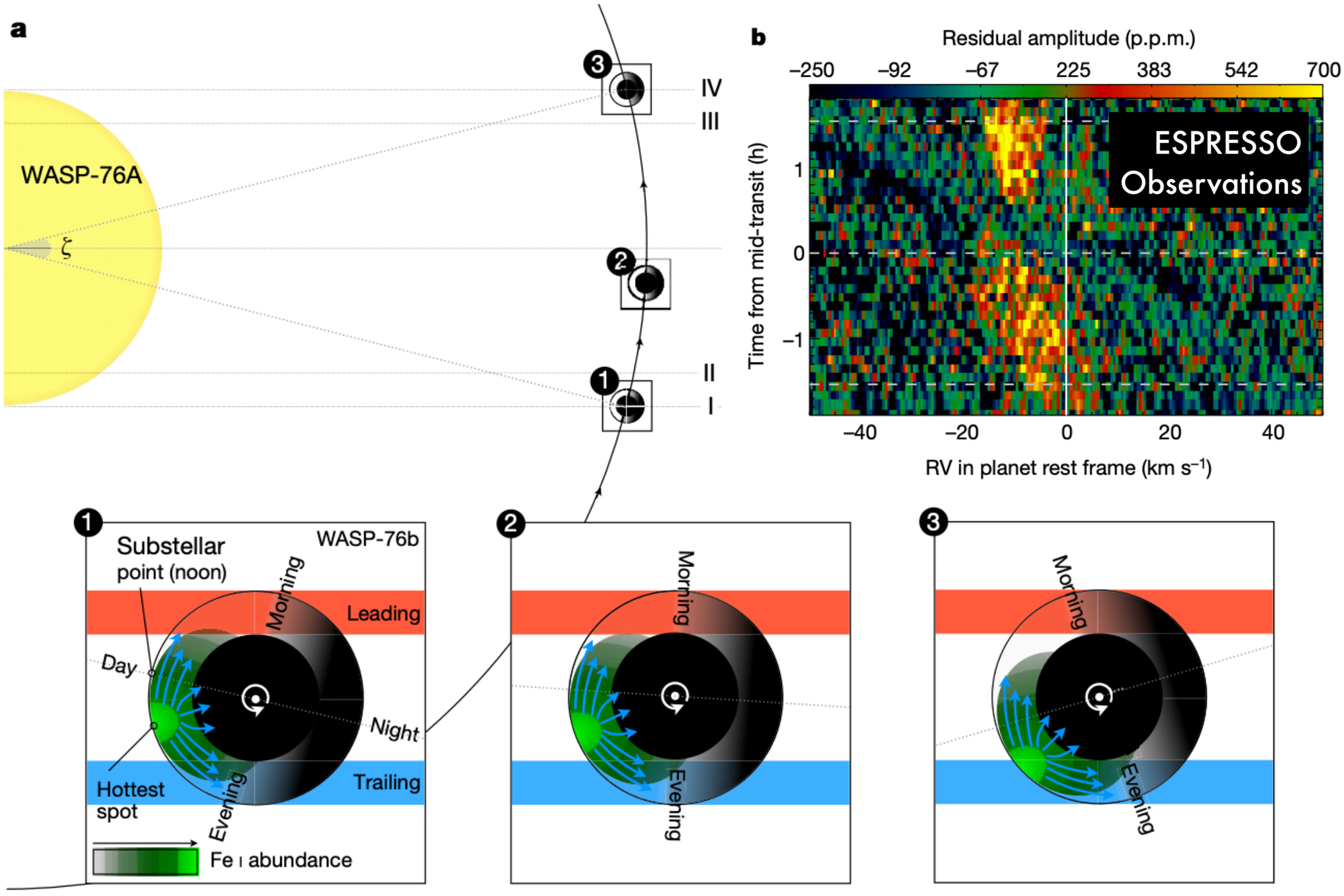

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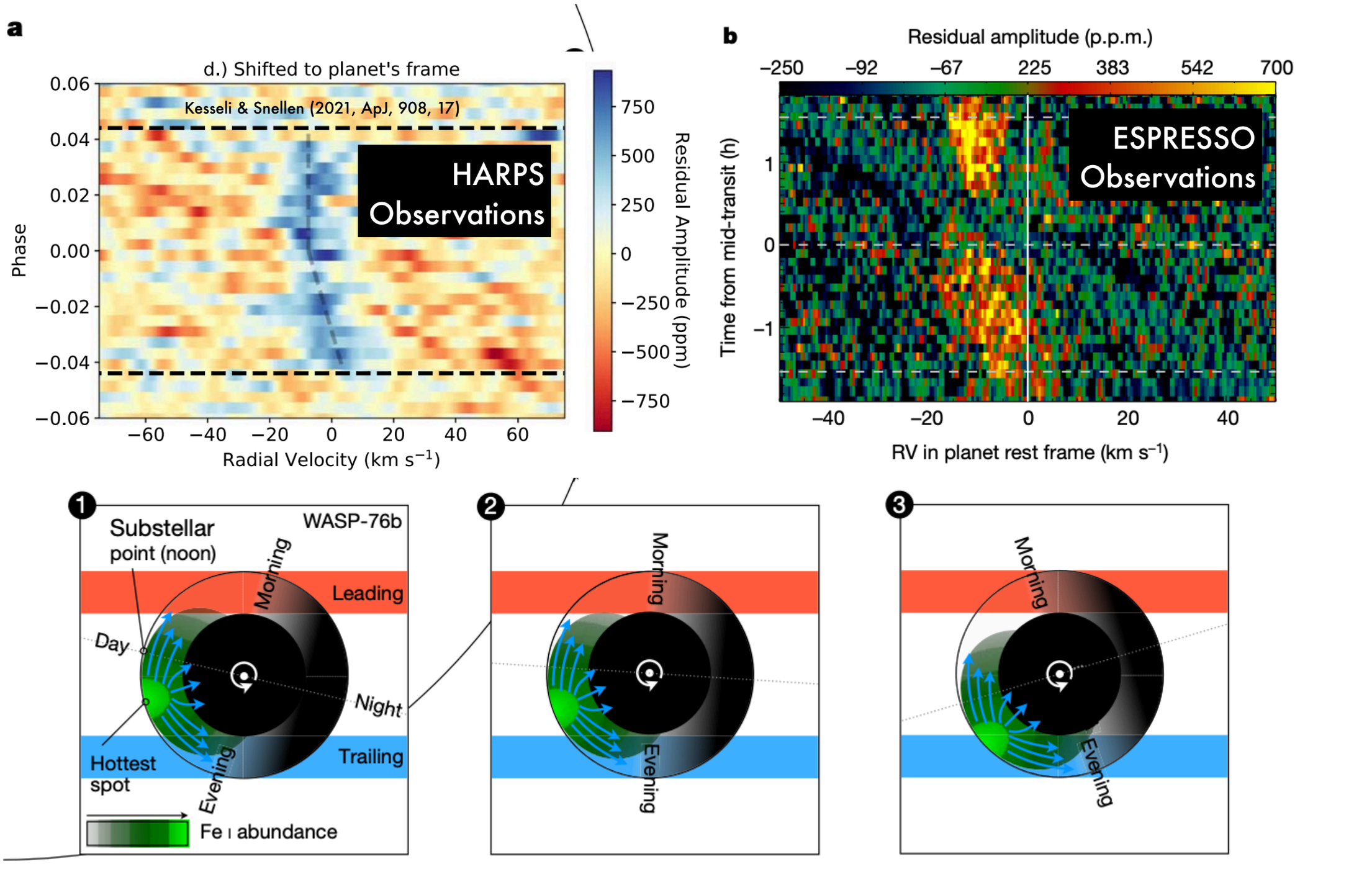


(See Chloe Fisher & Siddharth Gandhi's Tuesday hands-on lecture, Matteo Brogi's morning talk, Neale Gibsons' talk tomorrow + others)

Challenging to extract physical properties from CCF maps!

(See Chloe Fisher & Siddharth Gandhi's Tuesday hands-on lecture, Matteo Brogi's morning talk, Neale Gibsons' talk tomorrow + others)

Challenging to extract physical properties from CCF maps!

But what about abundances?

Actual cloud properties?

And temperatures in mornings & evenings?

star

planet's atmosphere

Evening
(day-to-night)
Terminator

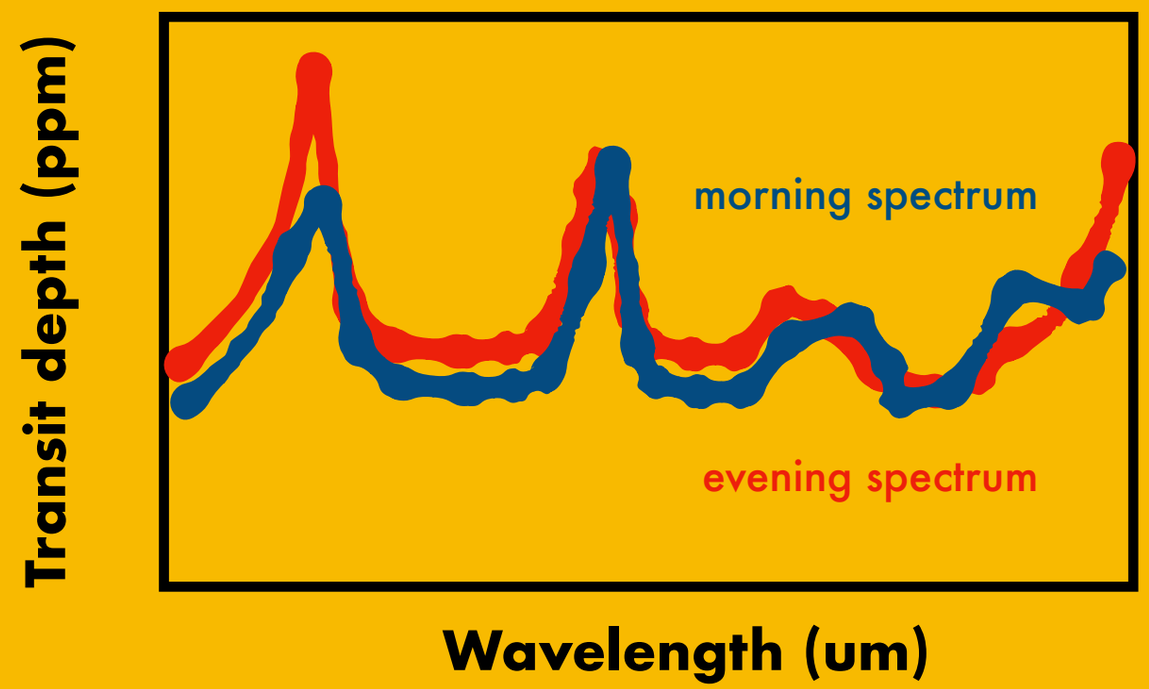
Morning (night-to-day)
Terminator

star

planet's atmosphere

Evening
(day-to-night)
Terminator

Morning (night-to-day)
Terminator



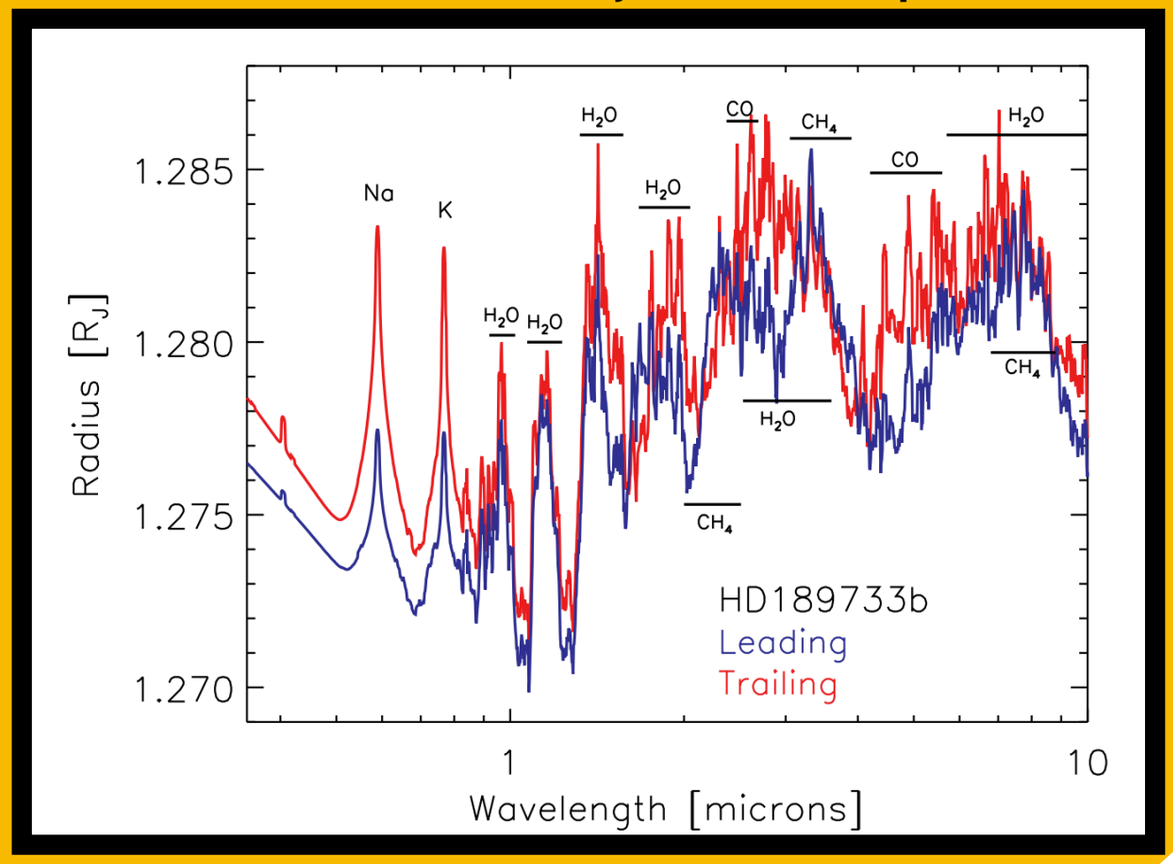
star

planet's atmosphere

Evening (day-to-night) Terminator

Morning (night-to-day) Terminator

Fortney et al. (2010, ApJ, 709, 1396)



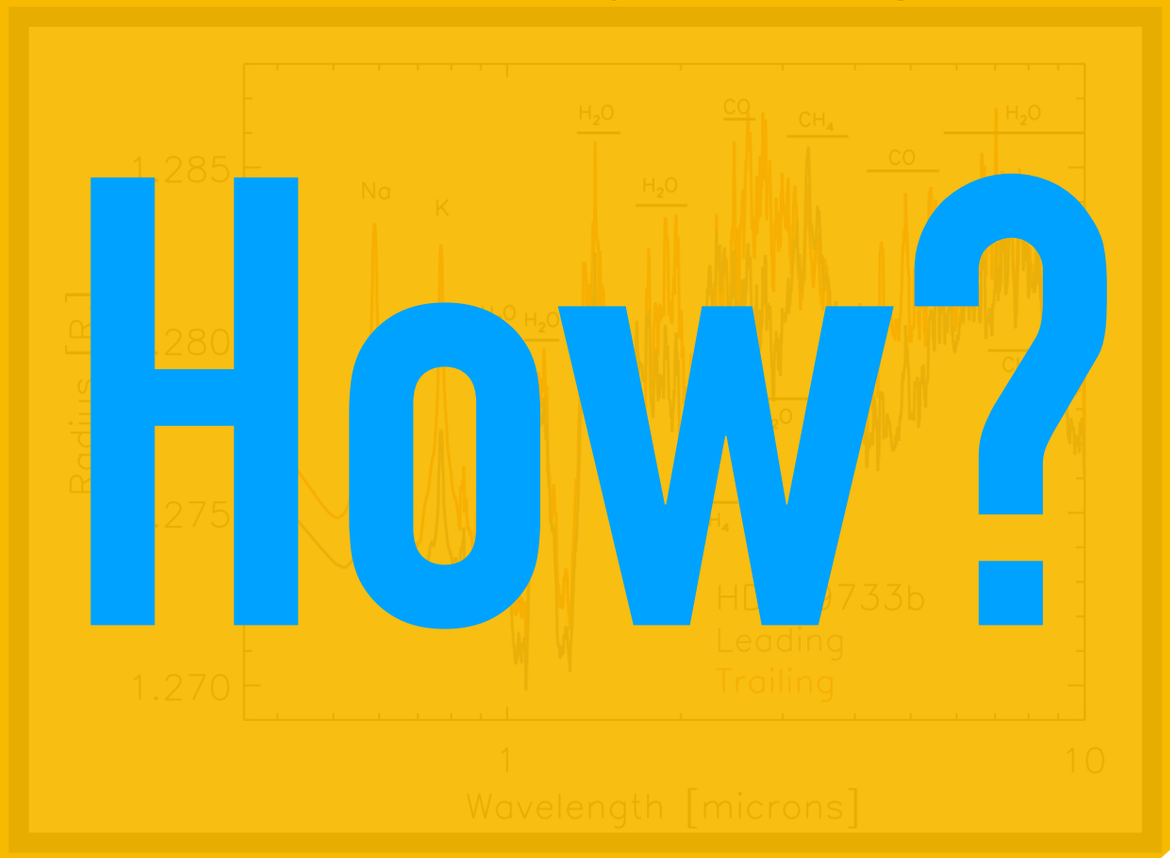
star

planet's atmosphere

Evening
(day-to-night)
Terminator

Morning (night-to-day)
Terminator

Fortney et al. (2010, ApJ, 709, 1396)



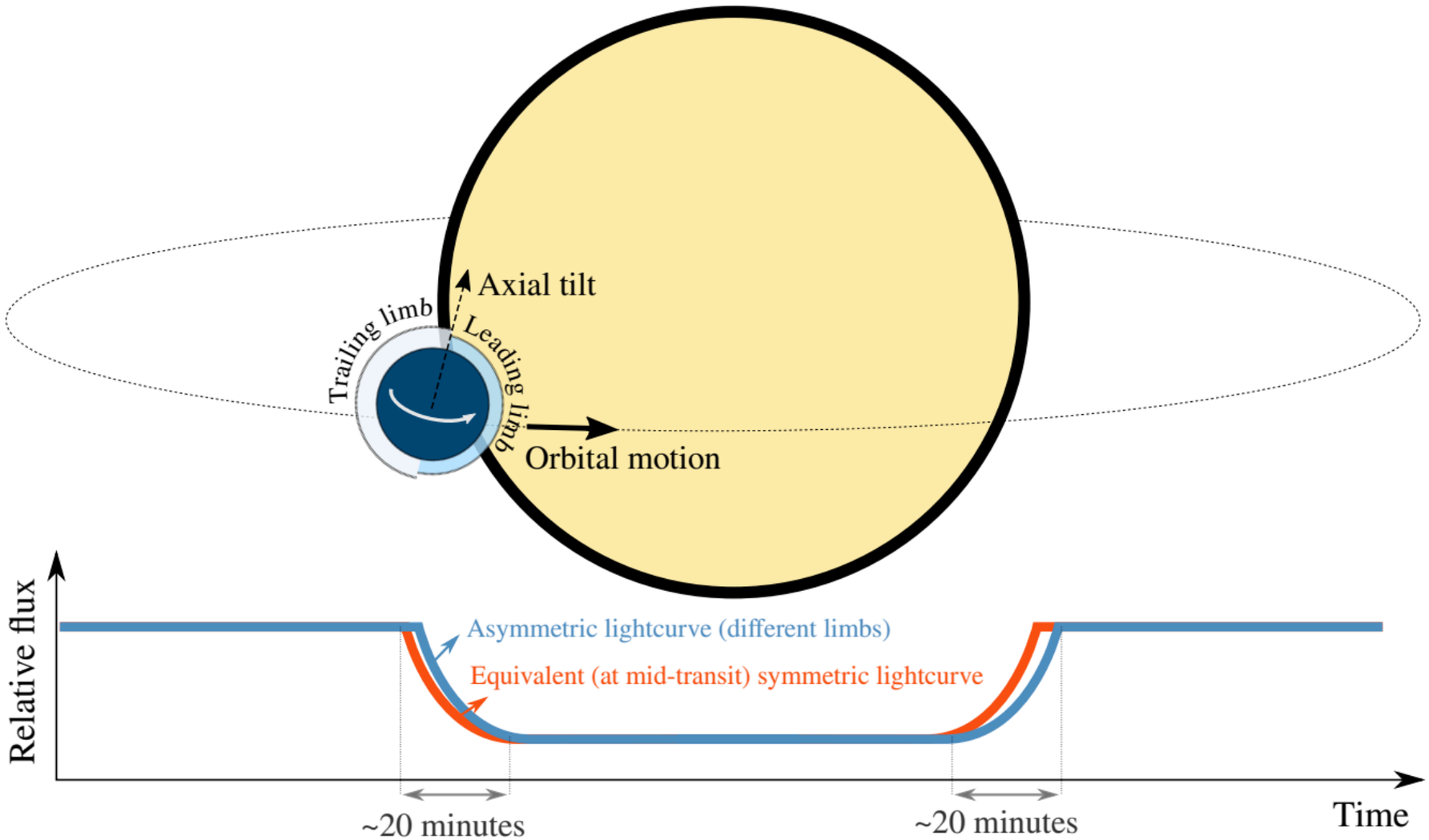
How?

Exoplanet limbs from transit light curves

(Jones & Espinoza, 2020, JOSS, 6, 2382)

See also von Paris et al (2016, A&A, 589, A52)

Kathryn Jones
PhD Student
University of Bern



Exoplanet limbs from transit light curves

(Jones & Espinoza, 2020, JOSS, 6, 2382)

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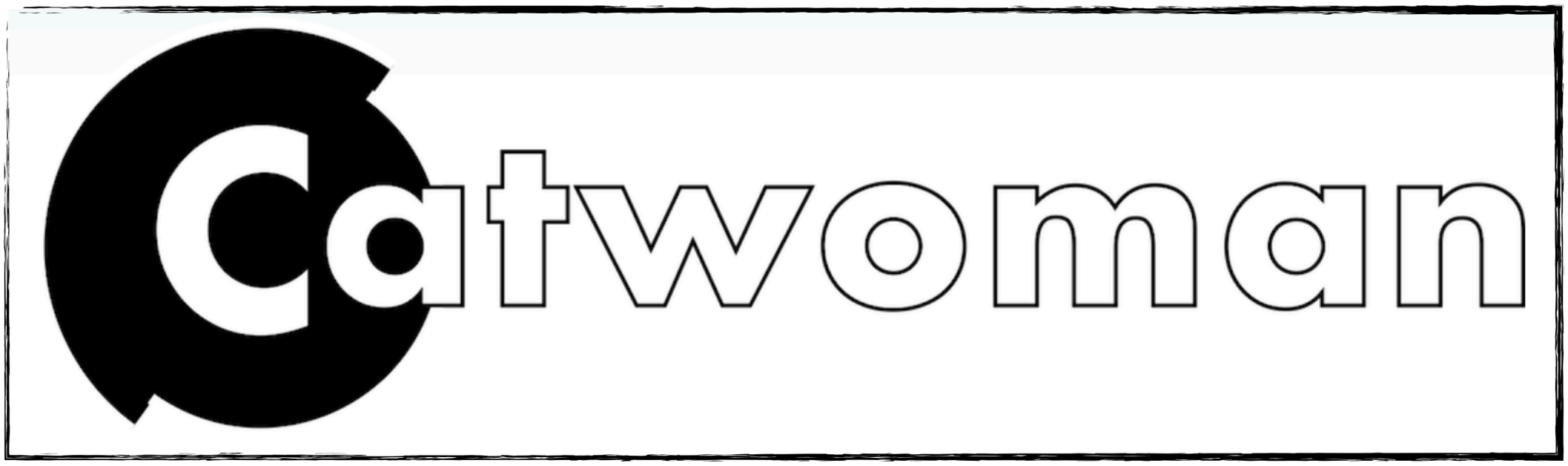
PhD Student
University of Bern

(because of batman; Kreidberg, 2015, PASP, 127, 1161)



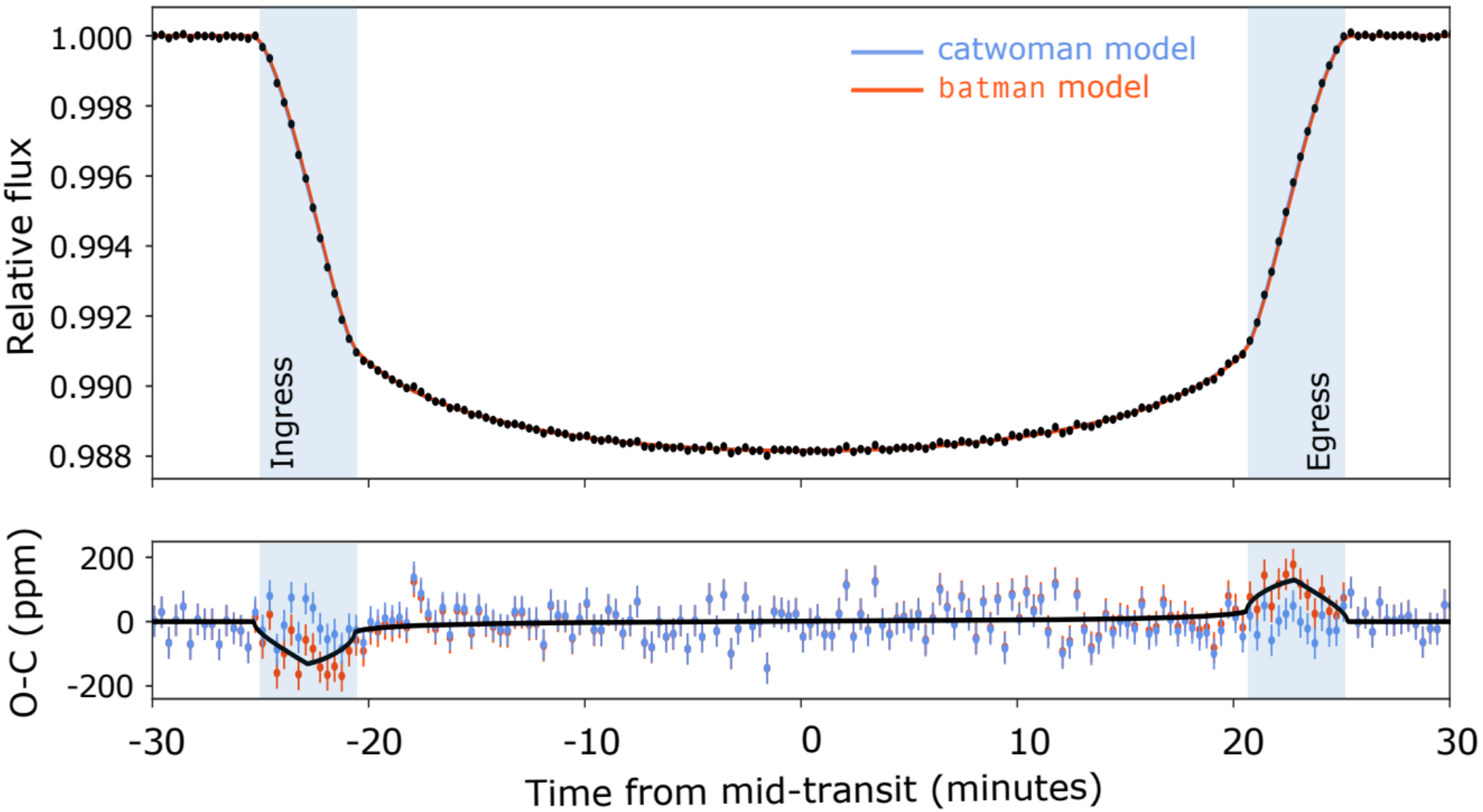
(catwoman.readthedocs.io)

Exoplanet limbs from transit light curves

(Espinoza & Jones, 2021, AJ accepted)

(arXiv e-print 2106.15687)

Kathryn Jones
PhD Student
University of Bern



Can we detect this? The case of JWST

(Espinoza & Jones, 2021, AJ accepted)

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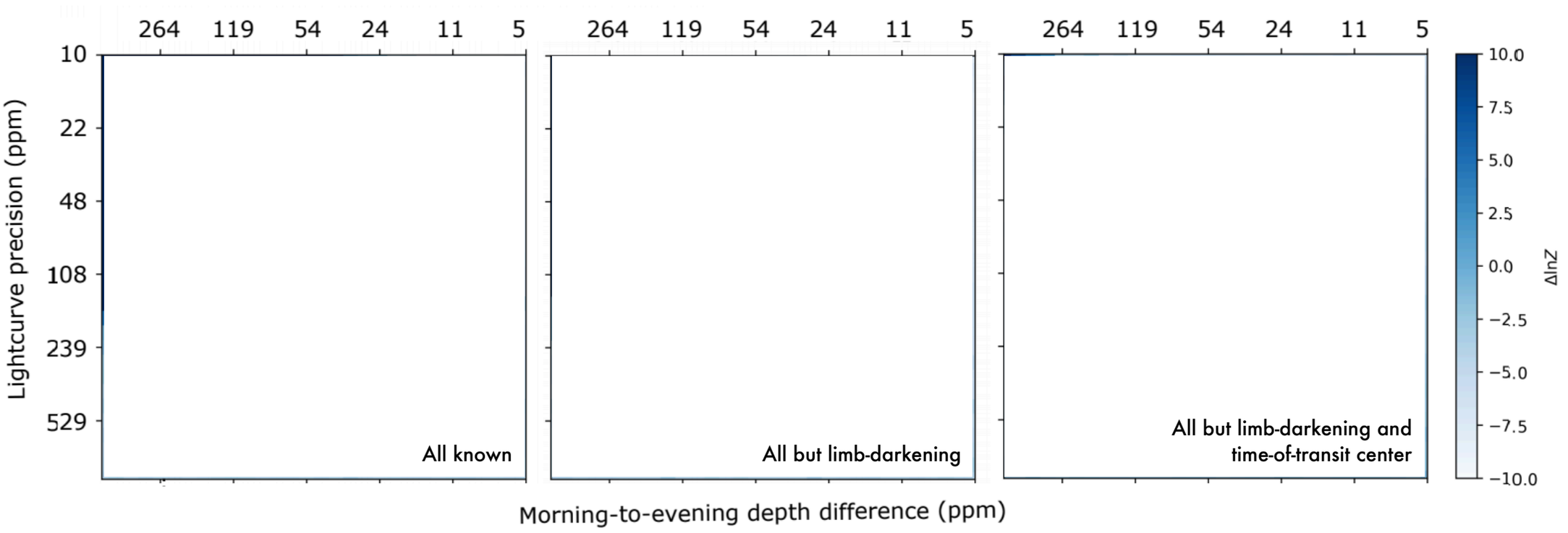

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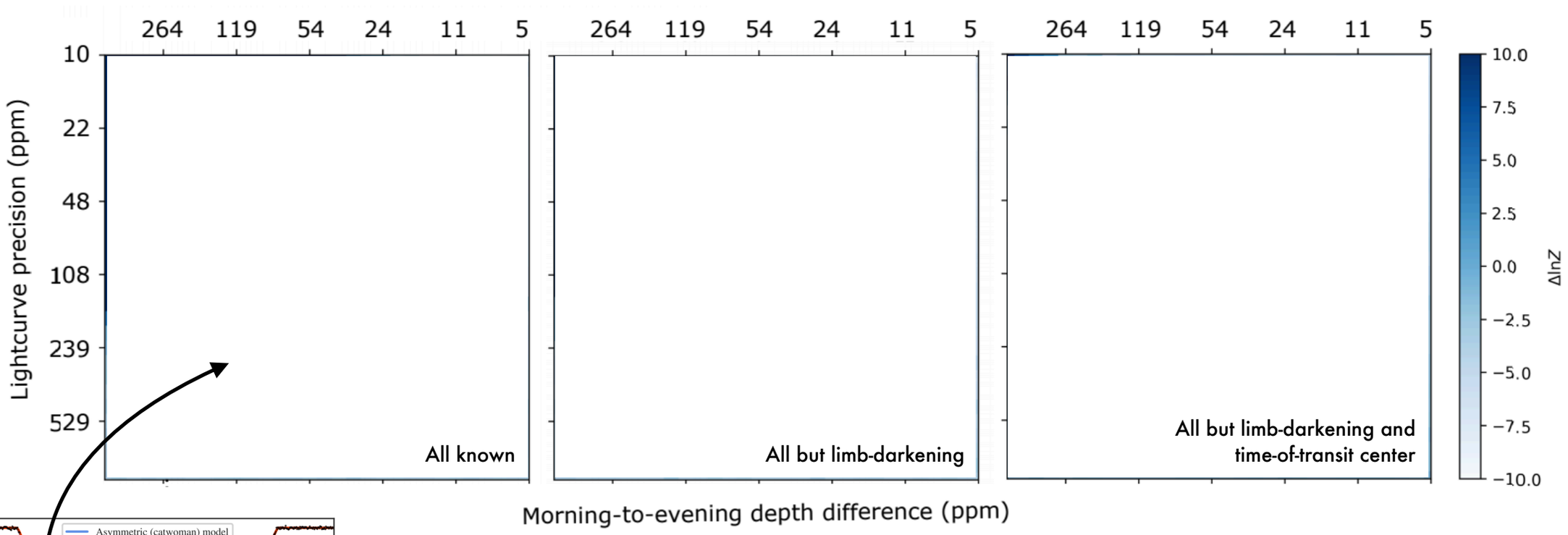

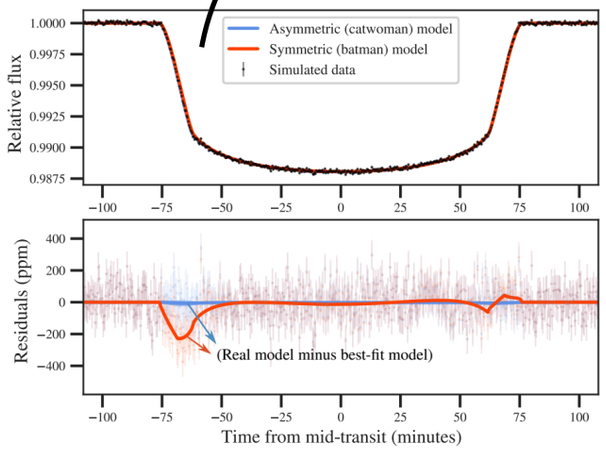

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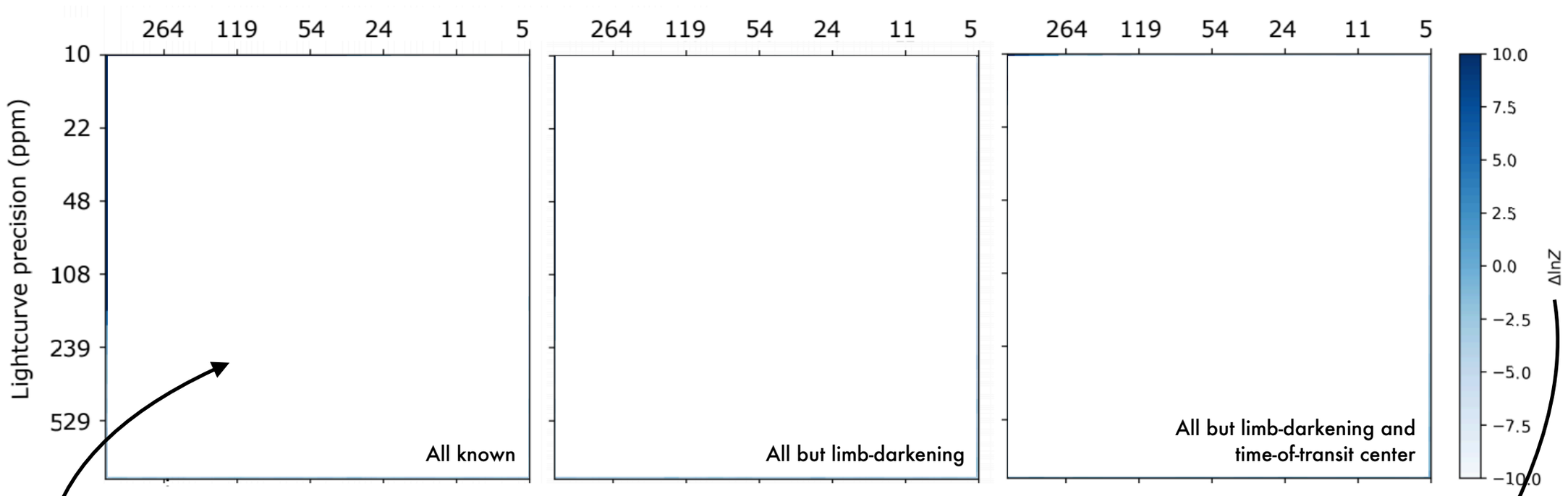

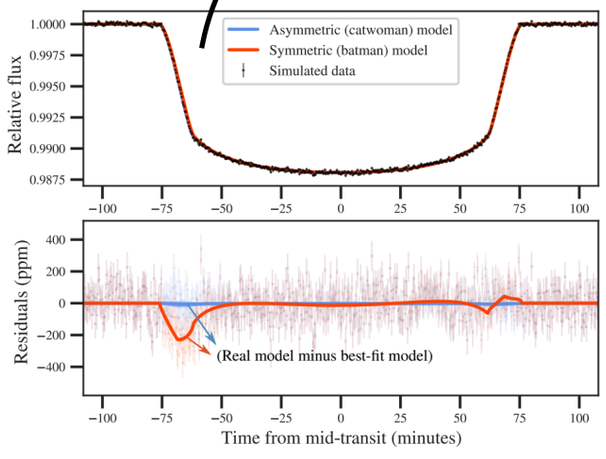

$$\ln \frac{P(\text{catwoman} \mid D)}{P(\text{batman} \mid D)}$$

Can we detect this? The case of JWST

(Espinoza & Jones, 2021, AJ accepted)

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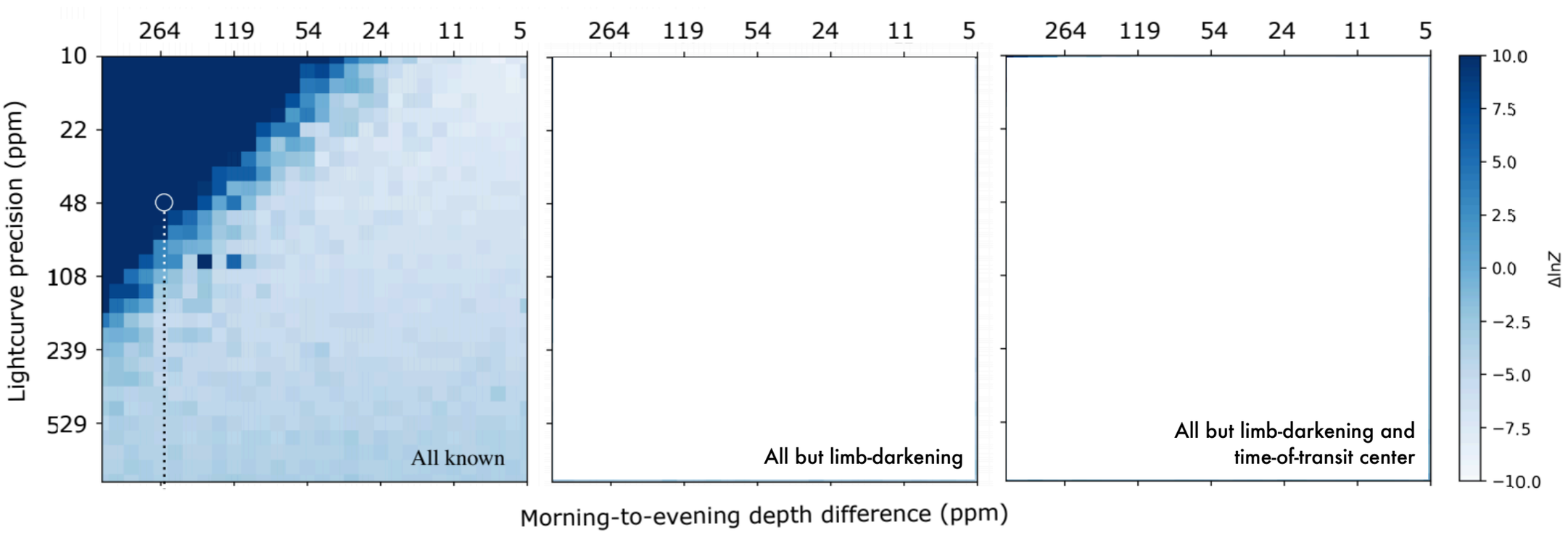

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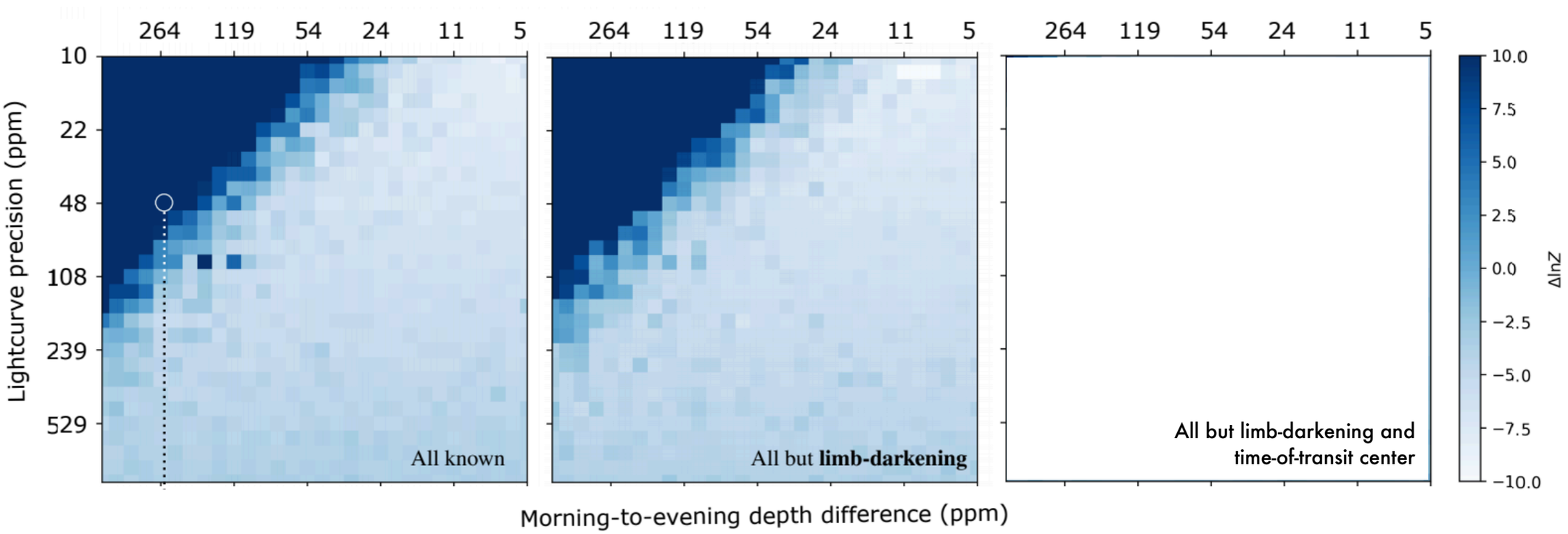

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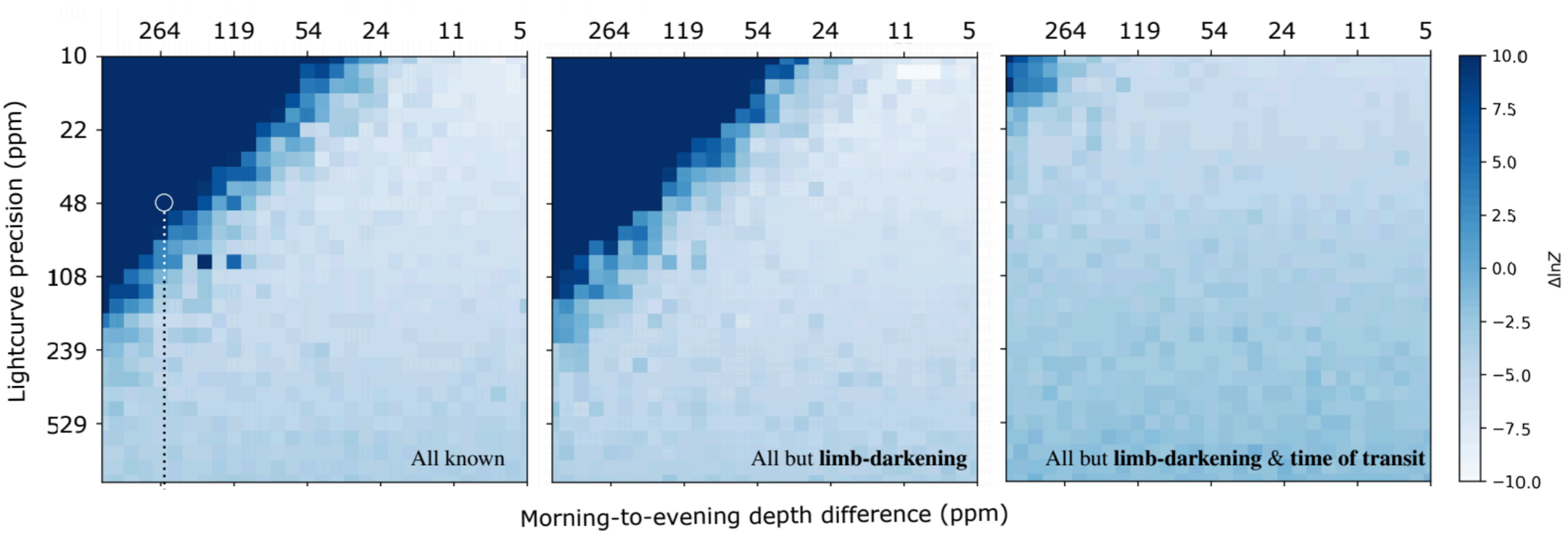


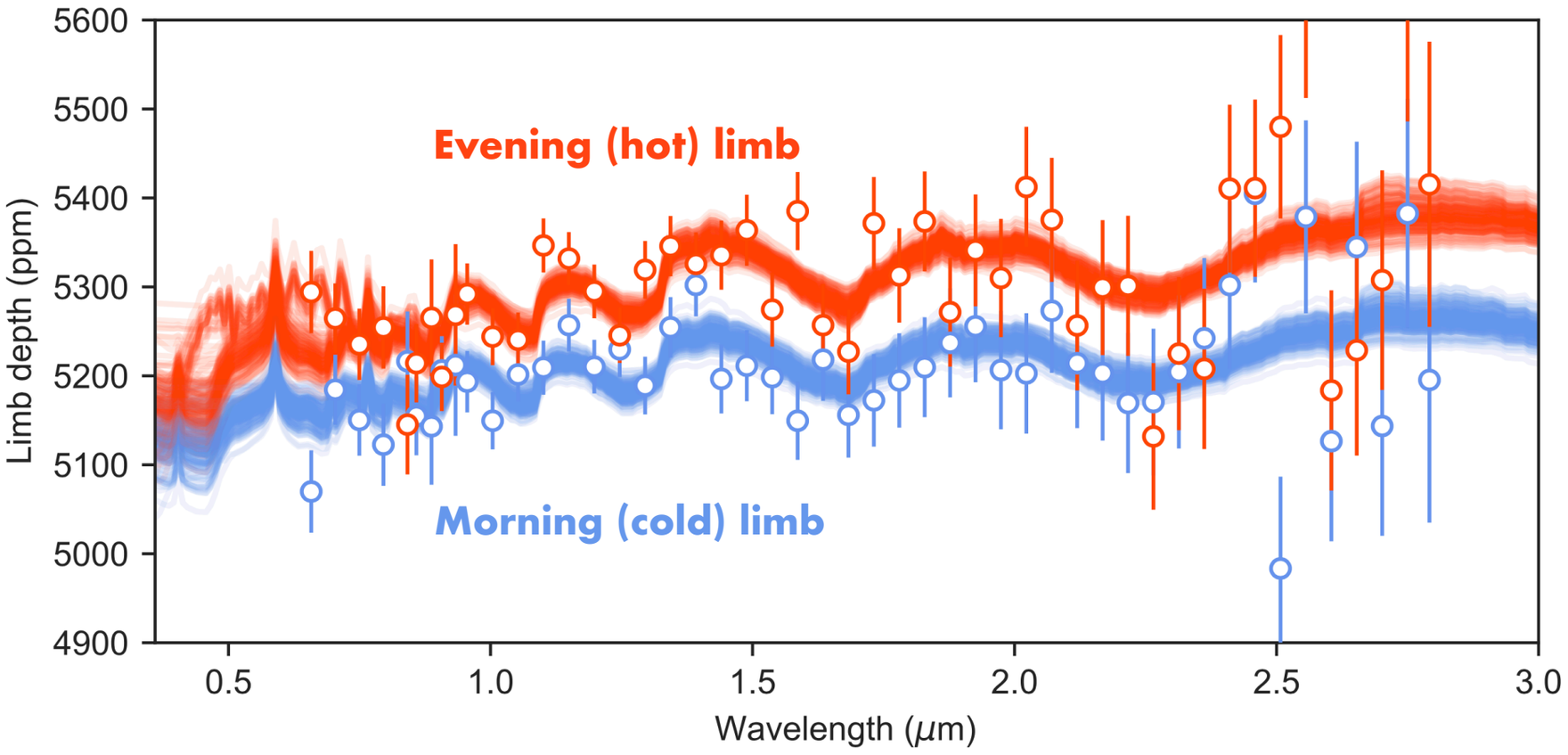
Can we detect this? The case of JWST

(Espinoza & Jones, 2021, AJ accepted)

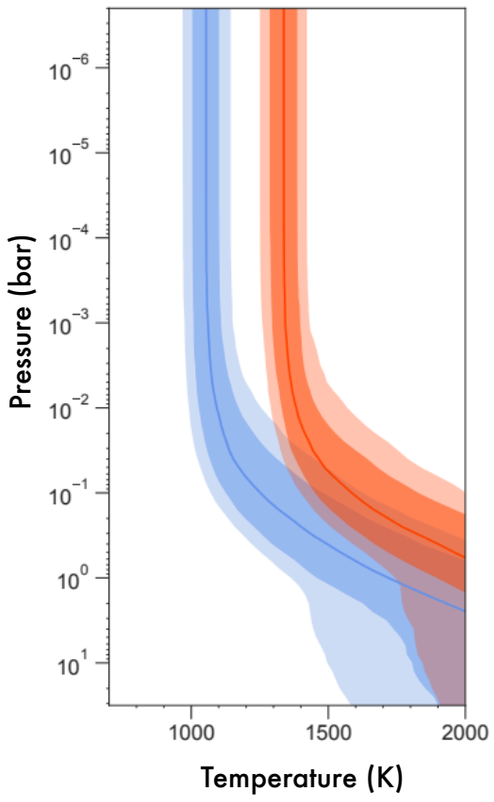
(arXiv e-print 2106.15687)

Kathryn Jones
PhD Student
University of Bern

Single JWST NIRISS/SOSS simulated observation (HAT-P-41b)



Retrieved T/P profile



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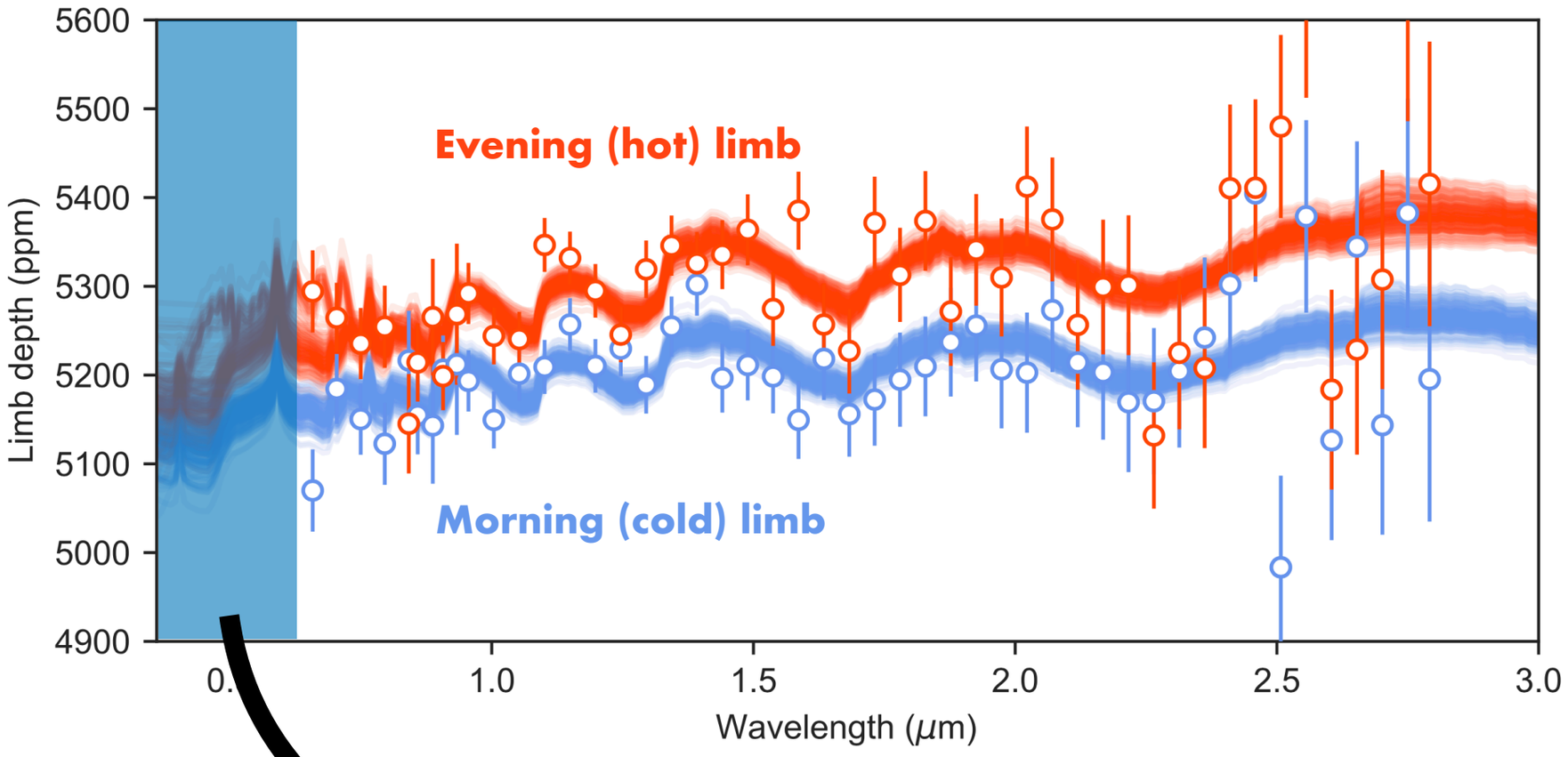

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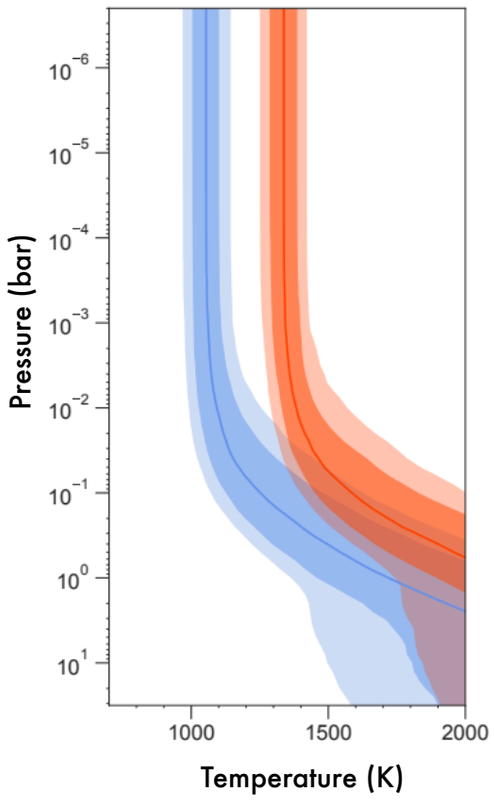

JWST will not give the full picture: optical constraints are needed!

Can we detect this? The case of HST (& the ground)

Can we detect this? The case of HST (& the ground)

An alternative approach: limb properties from transit spectra
(McDonald et al., 2020, ApJ, 893, 43)

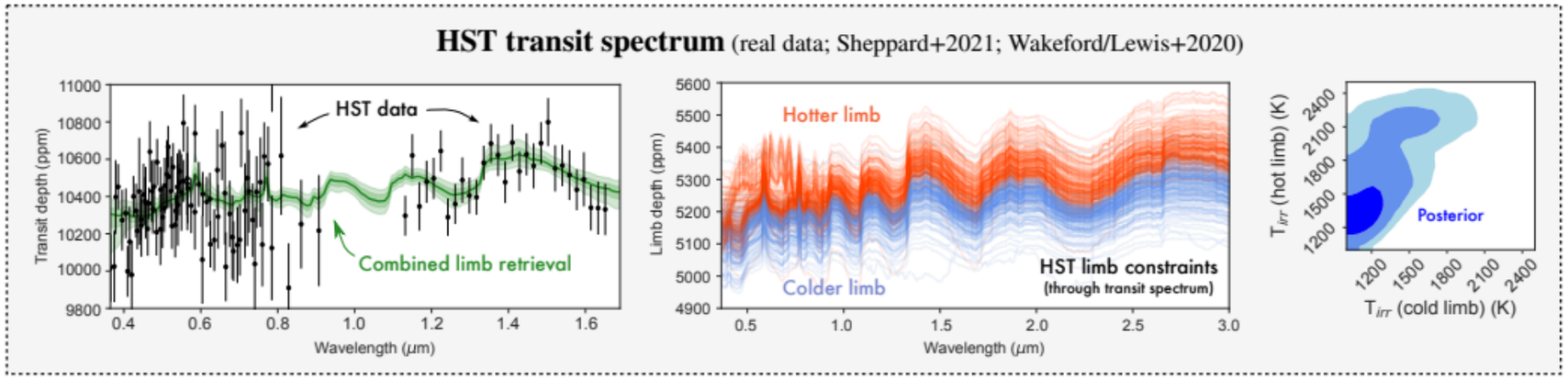

Figure credit: Espinoza & Jones (2021, AJ accepted)

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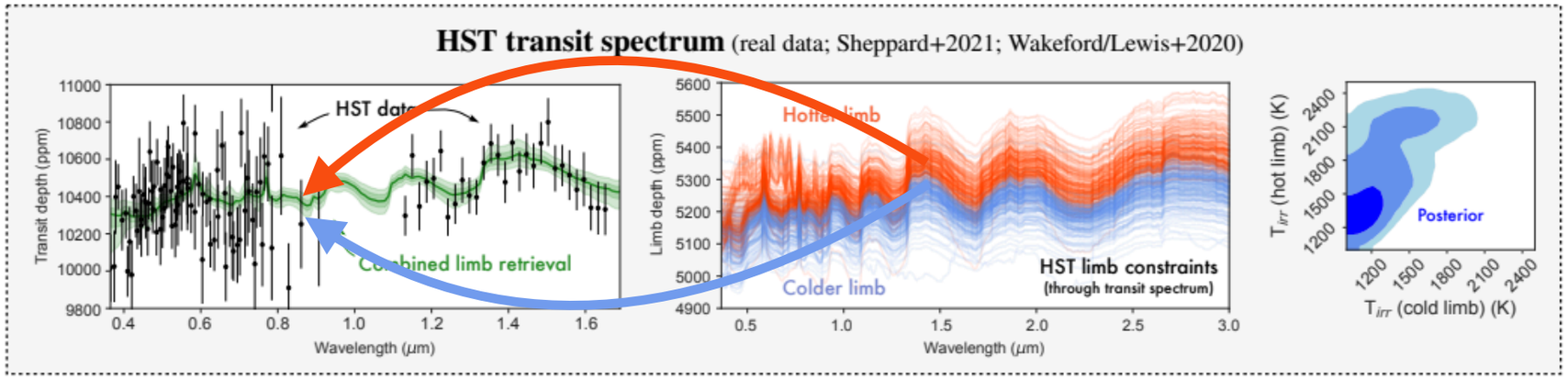

Figure credit: Espinoza & Jones (2021, AJ accepted)

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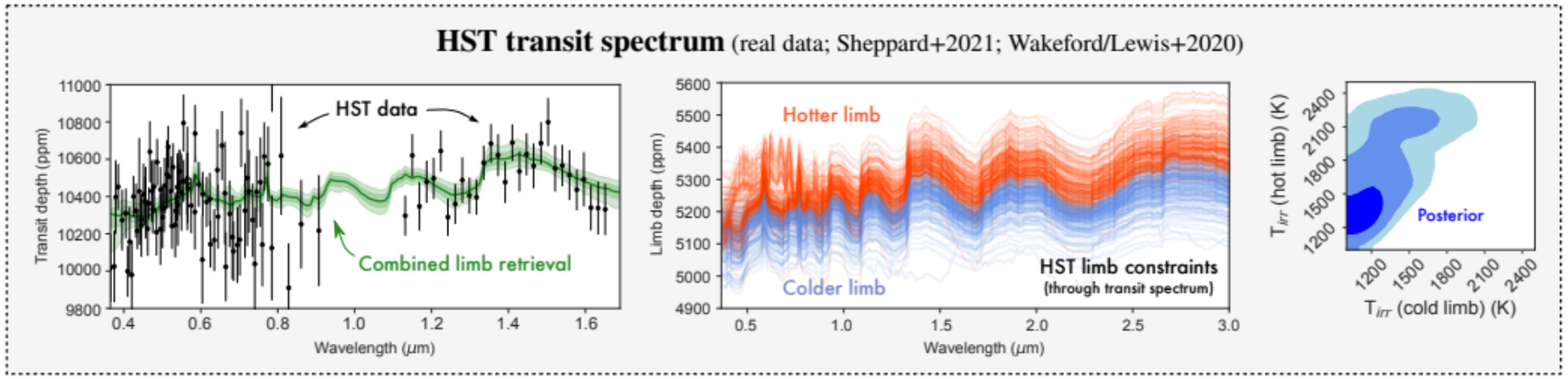
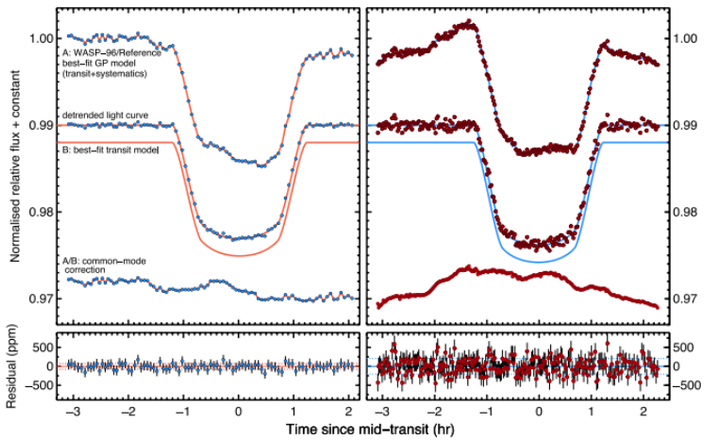


Figure credit: Espinoza & Jones (2021, AJ accepted)

Very Large Telescope/FORS2

Nikolov et al. (2018, Nature, 557, 526)

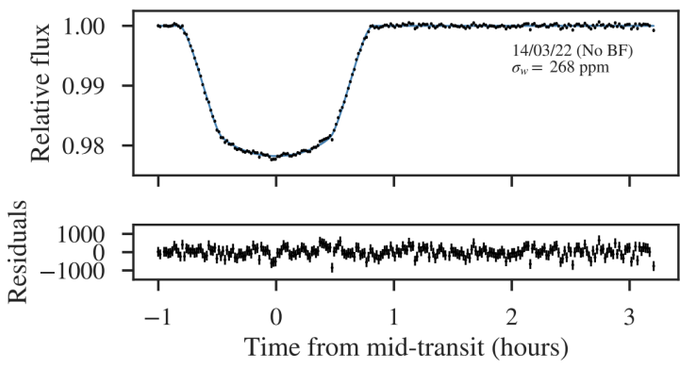
78 and 201 ppm precisions on WASP-69b



Magellan/IMACS

Espinoza et al. (2019, MNRAS, 482, 2065)

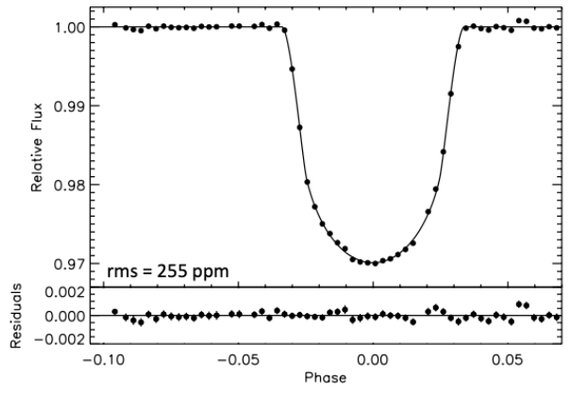
270 ppm precisions on WASP-19b



Gemini/GMOS

Huitson et al. (2017, AJ, 154, 95)

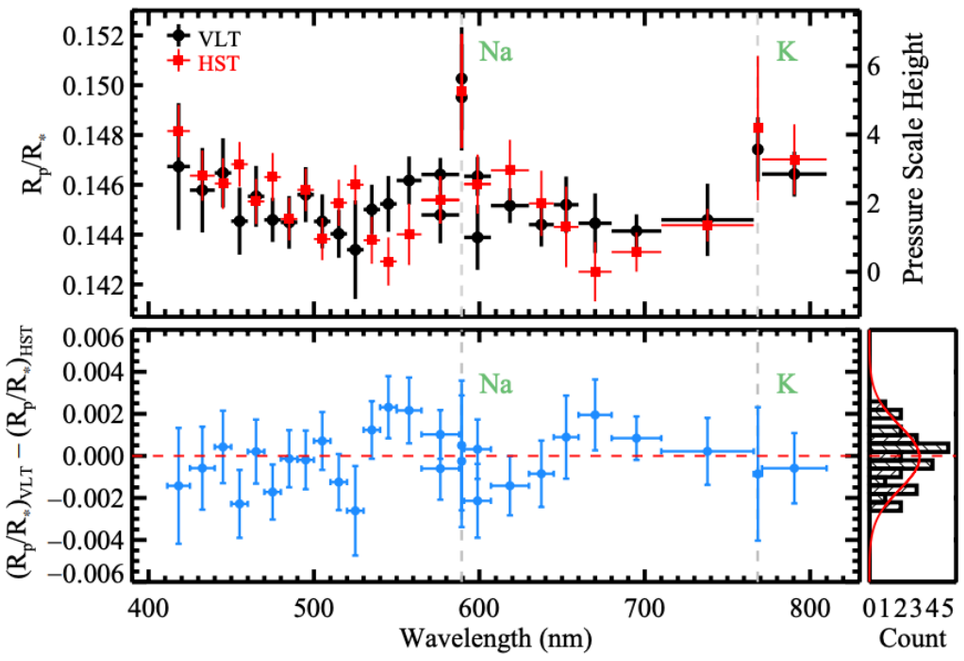
255 ppm precisions on WASP-4b



Can we detect this? The case of HST (& the ground)

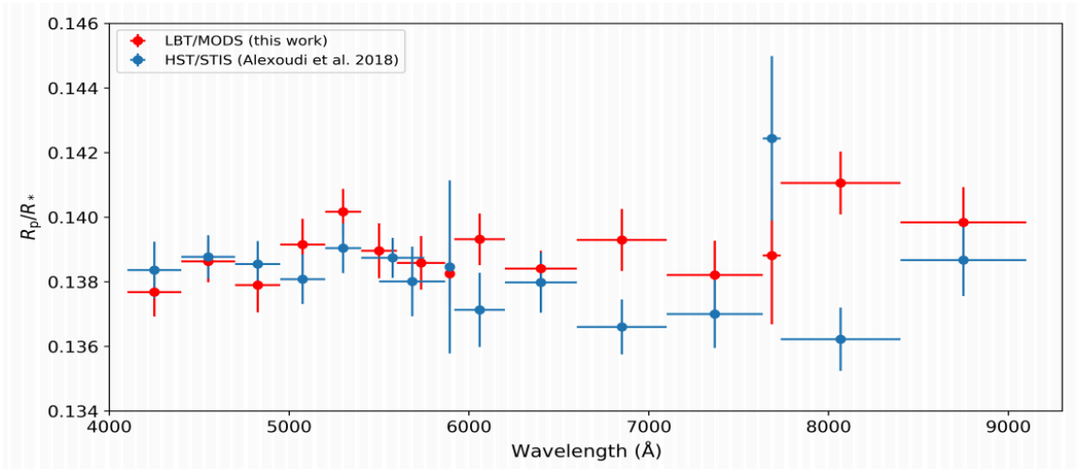
VLT/FORS2

Nikolov et al. (2016, ApJ, 832, 191)



LBT/MODS2

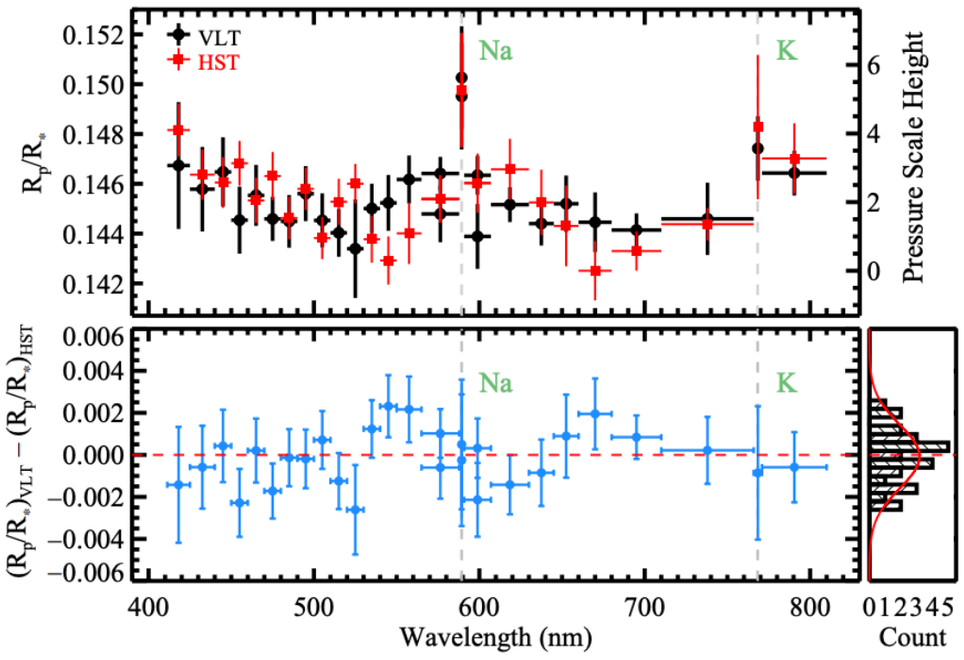
Yan et al. (2020, A&A, 642, 98)



Can we detect this? The case of HST (& the ground)

VLT/FORS2

Nikolov et al. (2016, ApJ, 832, 191)



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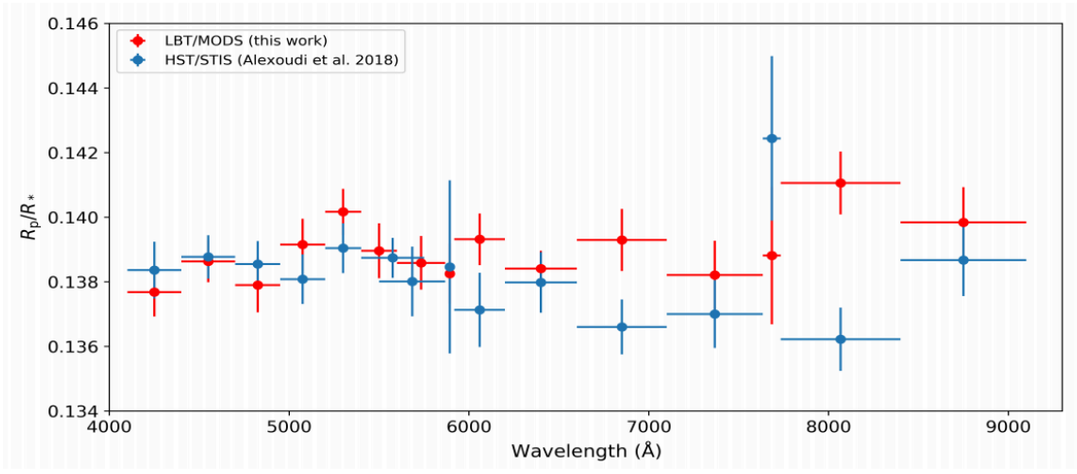


We can start constraining

mornings & evenings

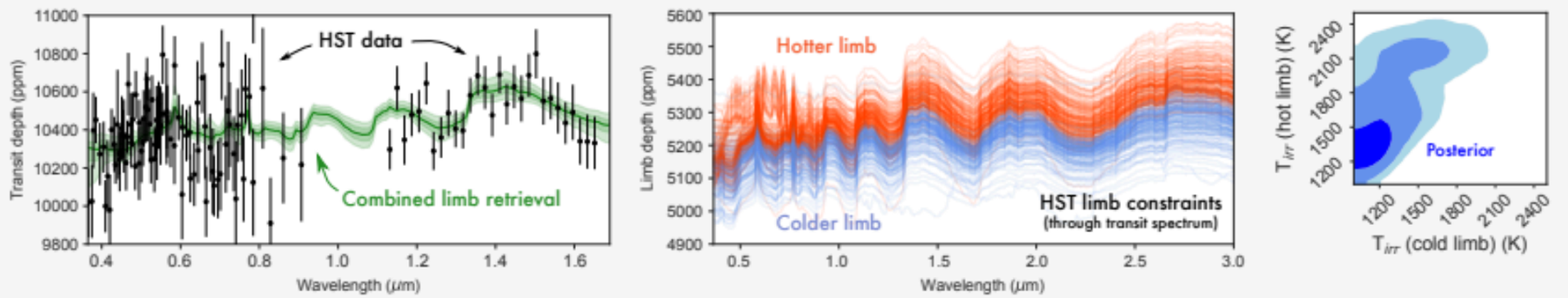
from the ground right now!

Can we detect this? The case of HST (& the ground)

But it could be much better with better instruments...

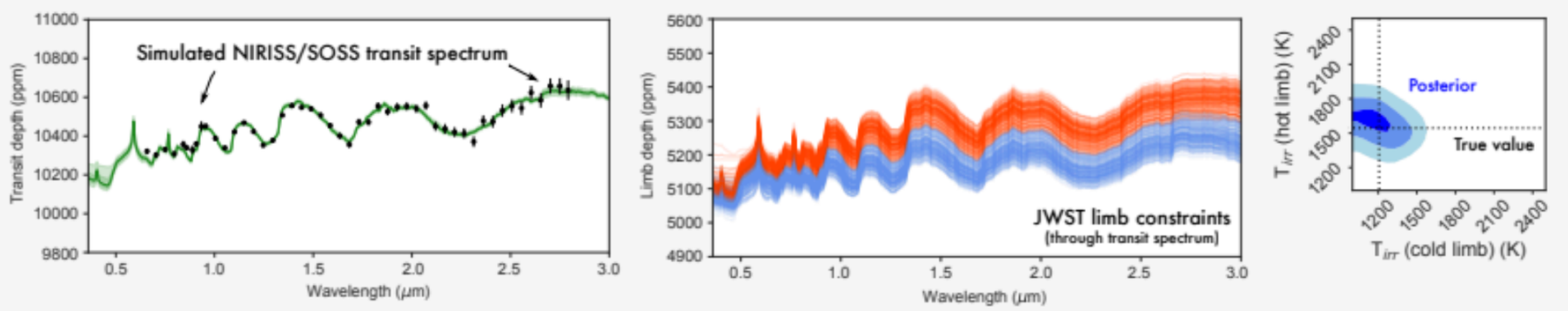
Current precision

HST transit spectrum (real data; Sheppard+2021; Wakeford/Lewis+2020)

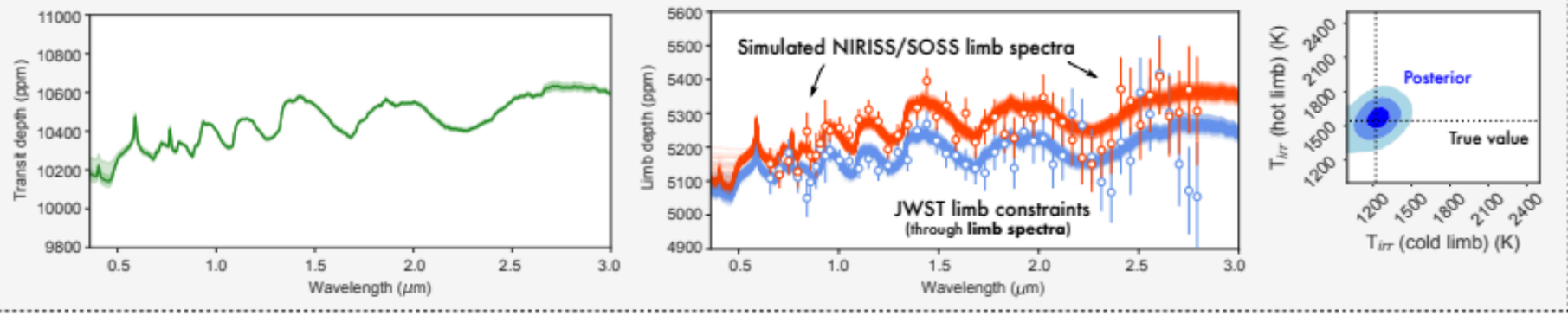


Future precision

JWST transit spectrum (simulated data)



JWST limb spectra (simulated data)



The **E-ELT** could do it even better!

E-ELT PROGRAMME

TOP LEVEL REQUIREMENTS FOR THE ELT-MOS

ESO-204696 Version 1

2014-1-23

Document Classification: Public

E-ELT Technical Archive
2014.02.17 12:25:19 +01'00'

Owner	P. Padovani	10/2/2014	
Programme Scientist	J. Spyromilio	14/2/14	
Programme Manager	R. Tamai	14 Feb 2014	
	Name	Date	Signature

	FoV (sub-apertures)	Spatial resolution	Spectral R	Wavelength range	Multiplex	Sensitivity	Other
Primordial galaxies and the reionisation of the Universe	0.9"x0.9"	not required	≥3,000	0.95 – 1.8 µm (goal 0.85 –2.45 µm)	400	Lyα flux ~ 10^{-19} erg/cm^2/s, S/N = 10, t_{exp}~ 20 h	
" "	2"x2"	40-90mas	5,000	0.95 – 1.8 µm (goal 0.85 – 2.45 µm)	40 (goal 80)	J_{AB} = 27, S/N ~ 3-5, t_{exp}~40h	
Chemodynamics of high redshift galaxies	2"x2"	50-75mas	4,000 – 5,000	1.0 – 2.45 µm	20 – 100	Emission line with equivalent continuum K_{AB} ~ 28, S/N~5, t_{exp}~24h	
IGM tomography	2"x2"	not required	5,000 (10,000 goal)	0.42 – 1.0 µm (0.37 – 1.0 µm goal)	10	R = 24.8, S/N = 8, t_{exp}~10h	
Characterization of exo-planetary atmospheres		not required	5,000 – 10,000	0.5 - 1.6 µm (0.5 - 2.45 µm goal)	≥2, possibly slitless spectroscopy or IFU to avoid flux losses		Photometric precision 10^{-5} (goal 10^{-6})

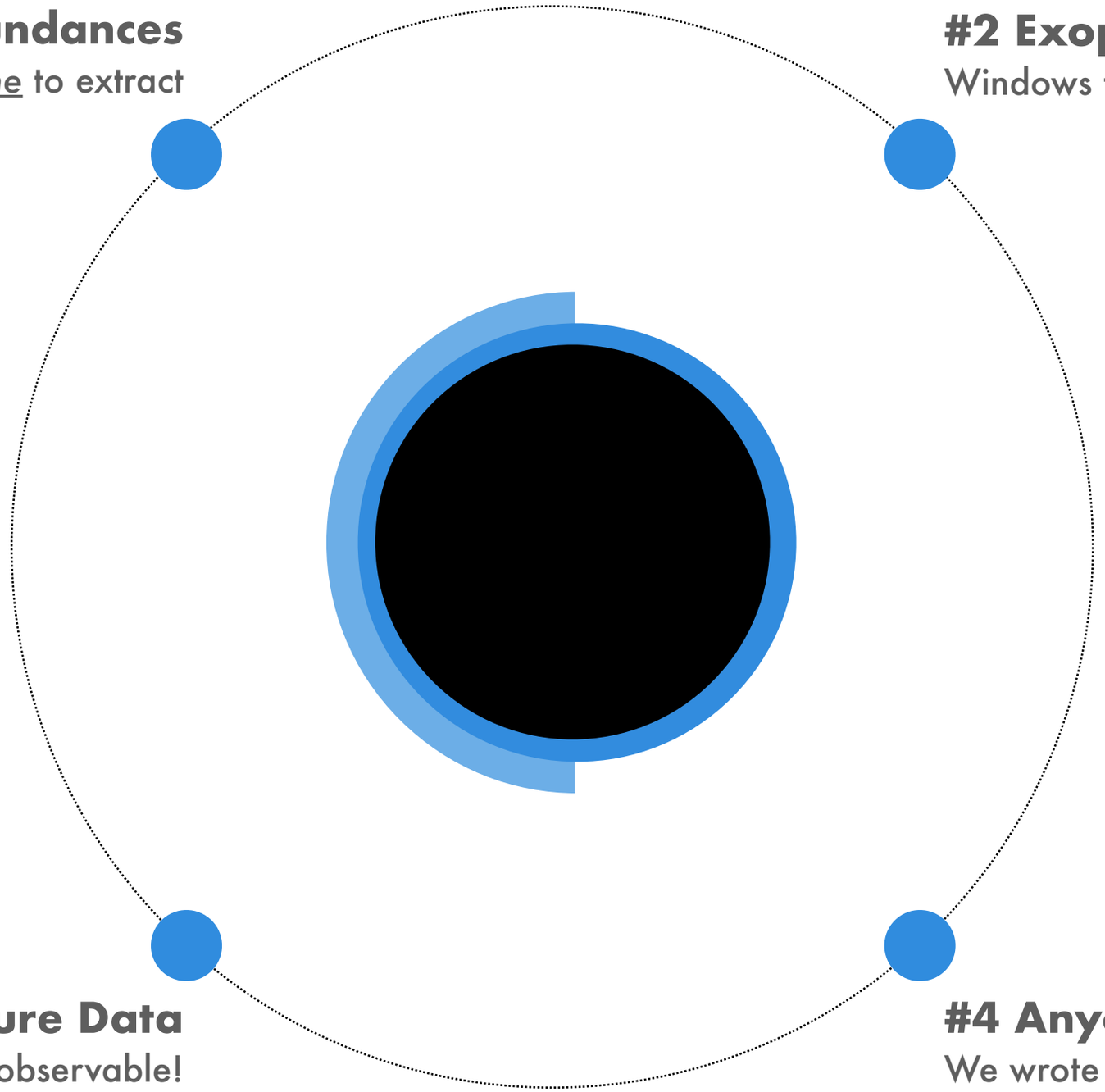
The **E-ELT** could do it even better!

#1 Gas abundances

There might not be *only one* to extract

#2 Exoplanet limbs are key

Windows for 3-D pictures of exoplanets



#3 Current & Future Data

Signatures might be observable!

Ground-based instruments can do this!

#4 Anyone can do it

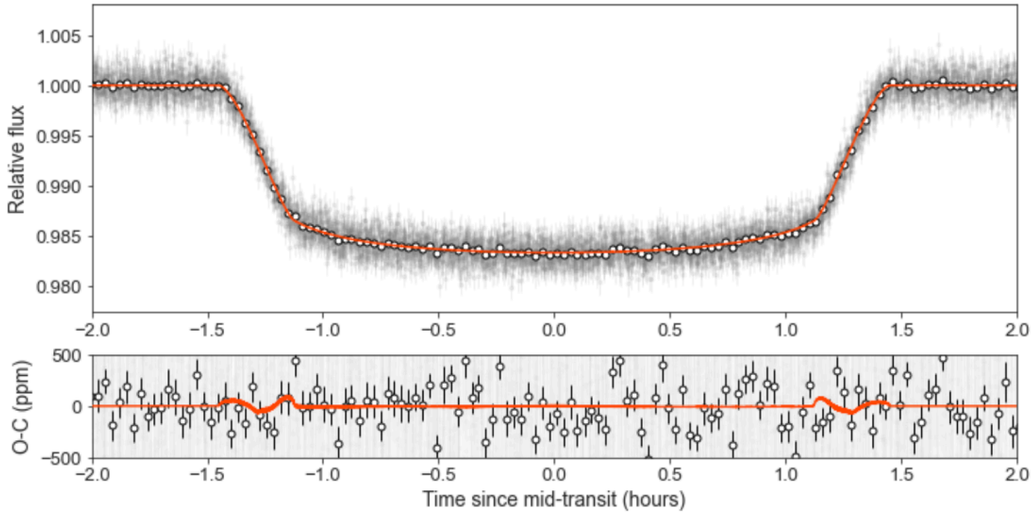
We wrote a library to do this

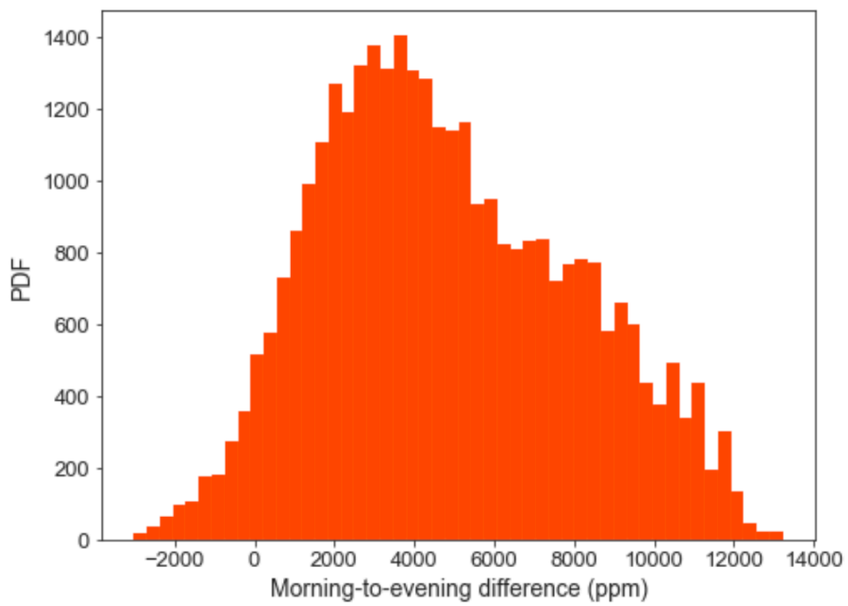
(Check out catwoman!)

Extra slides

There are many other systems we are working on, too!

WASP-121b (3 sectors)





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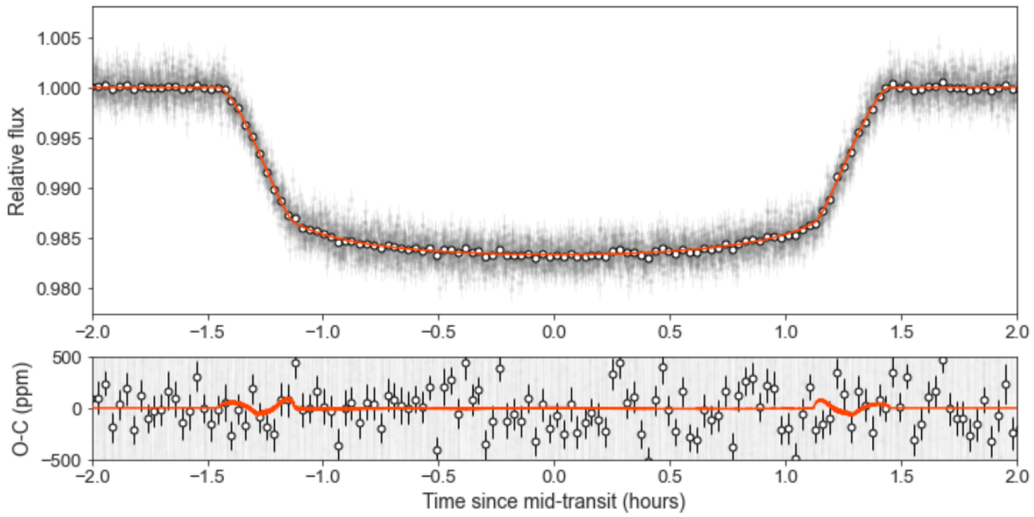
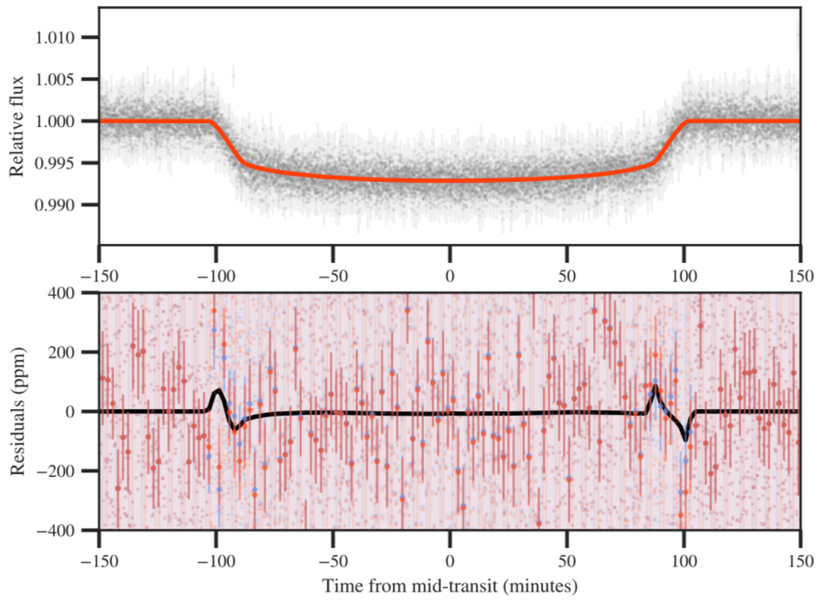
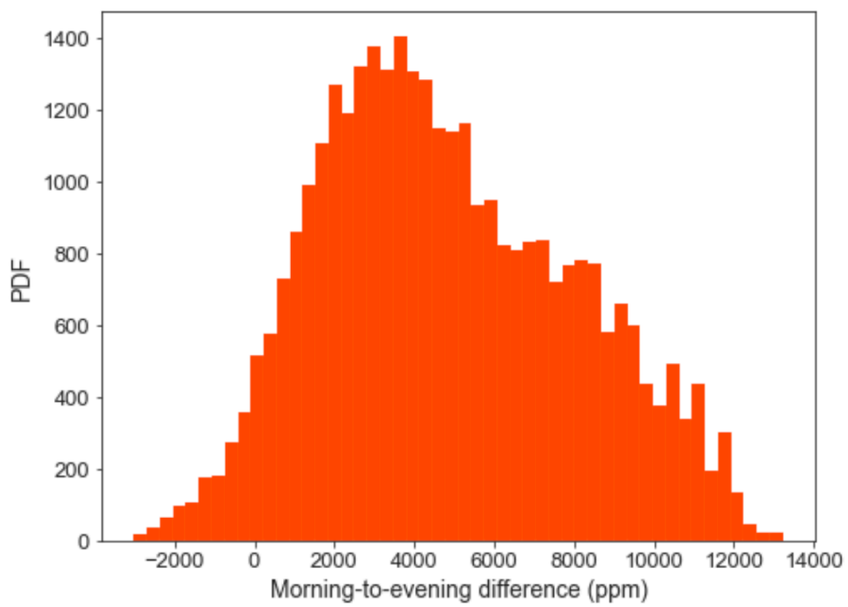
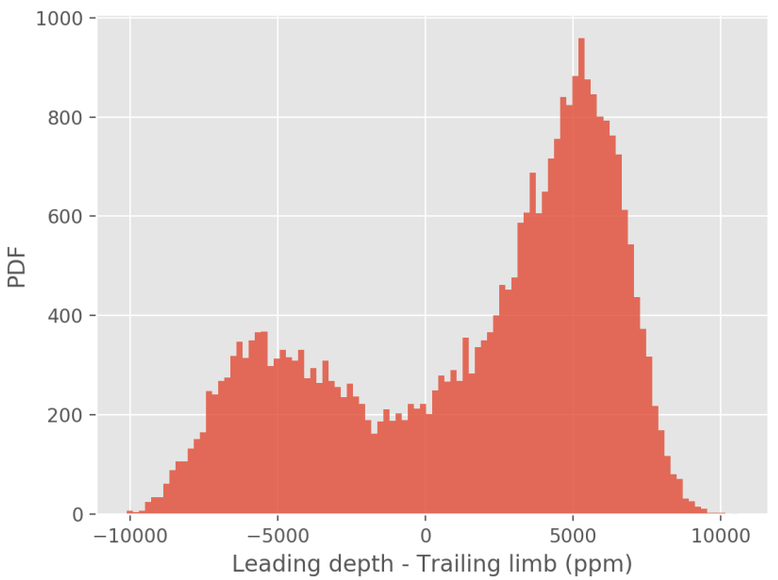


WASP-126b (13 sectors)







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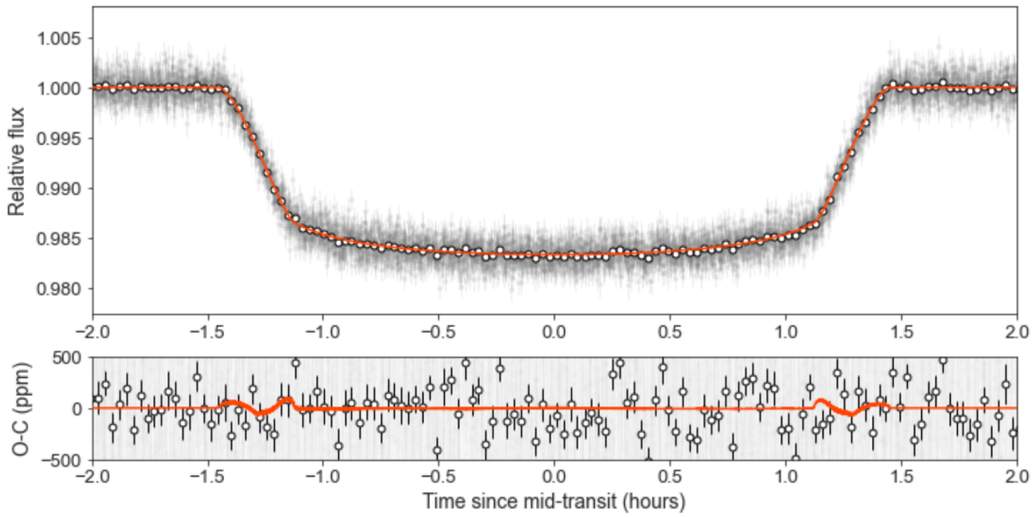
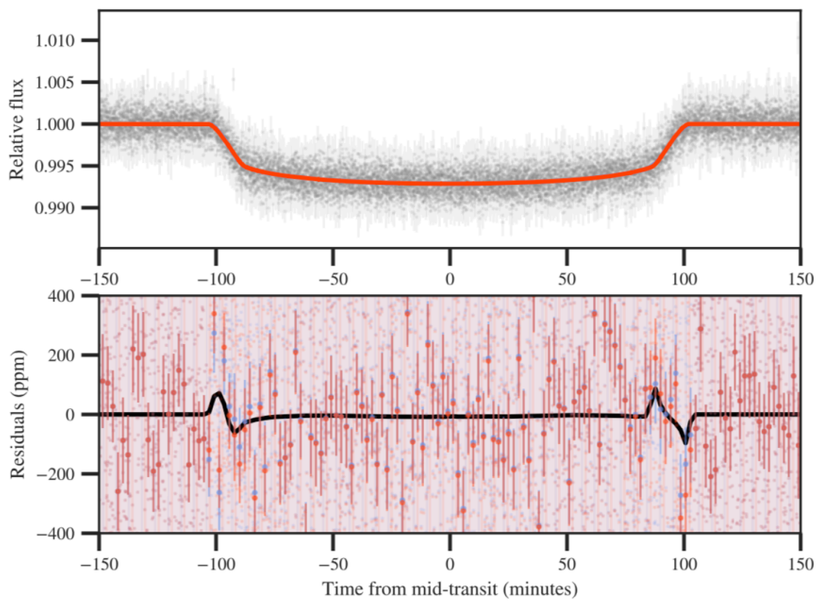
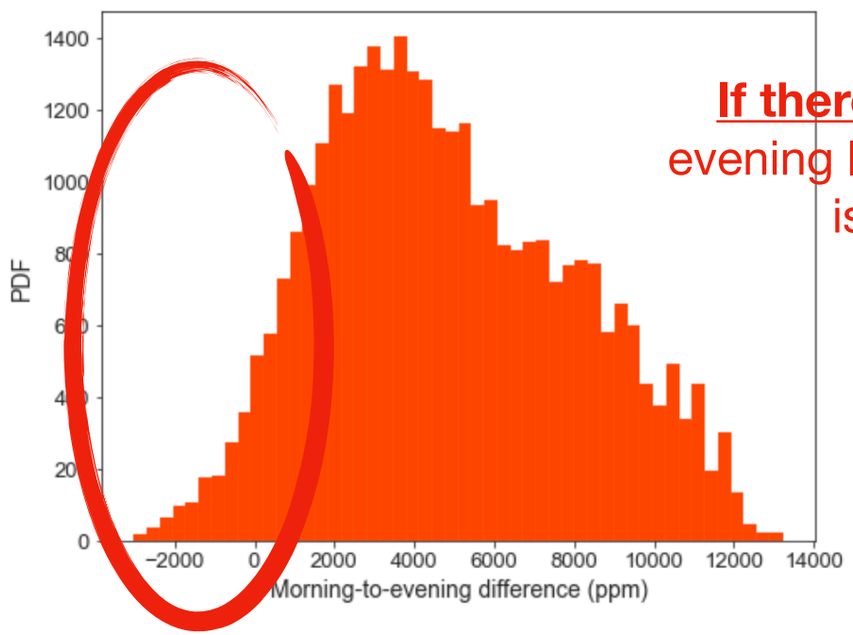
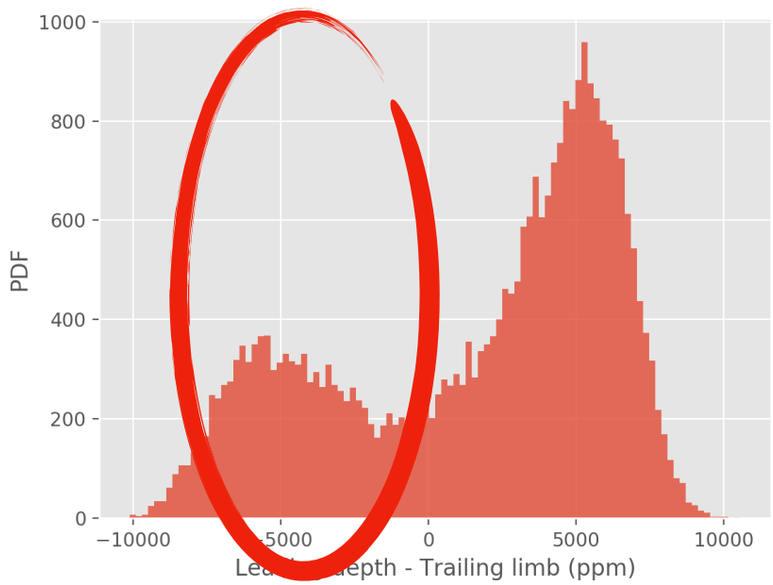


WASP-126b (13 sectors)





<u>If there is a difference</u>,
evening limb > morning limb
is more likely



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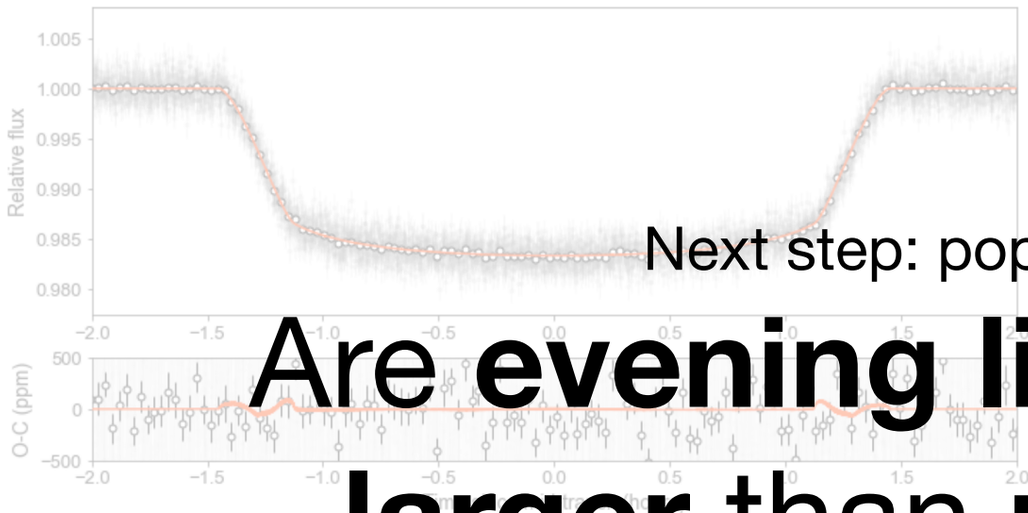
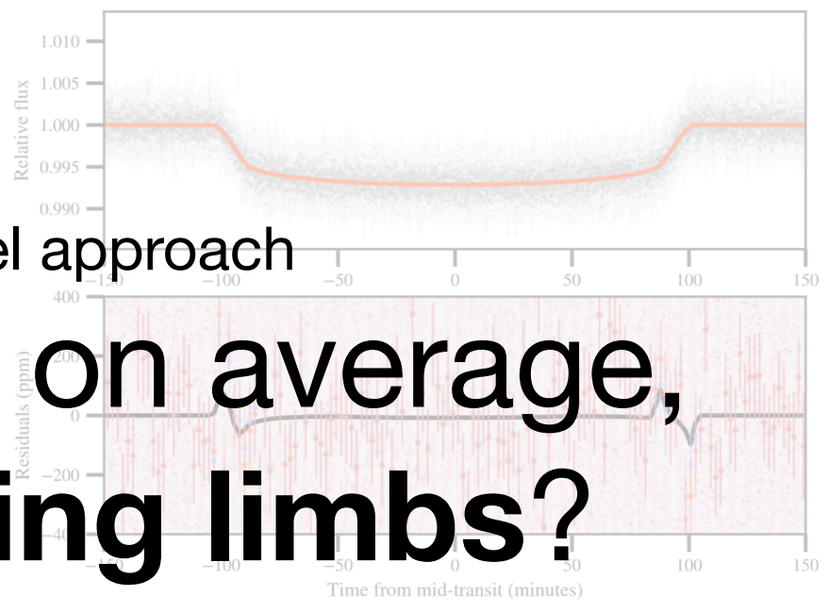


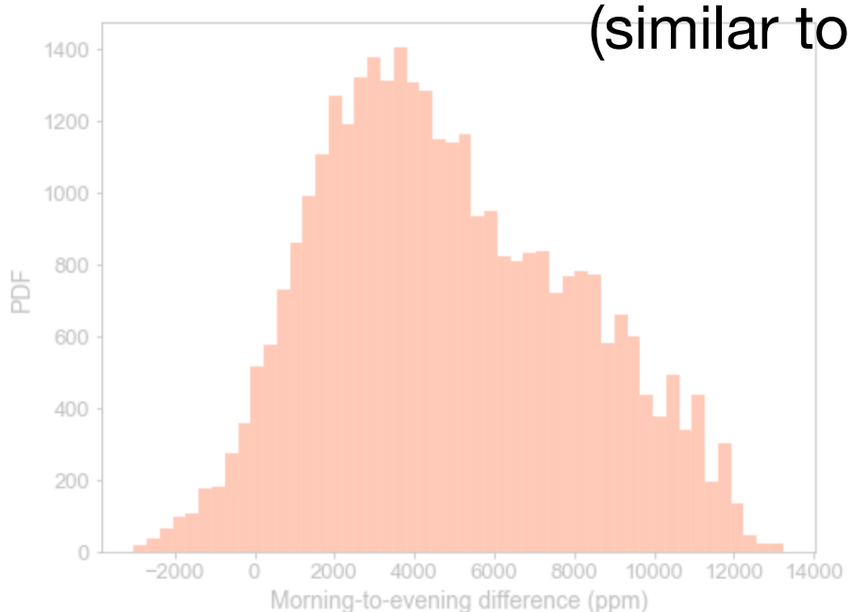
WASP-126b (13 sectors)

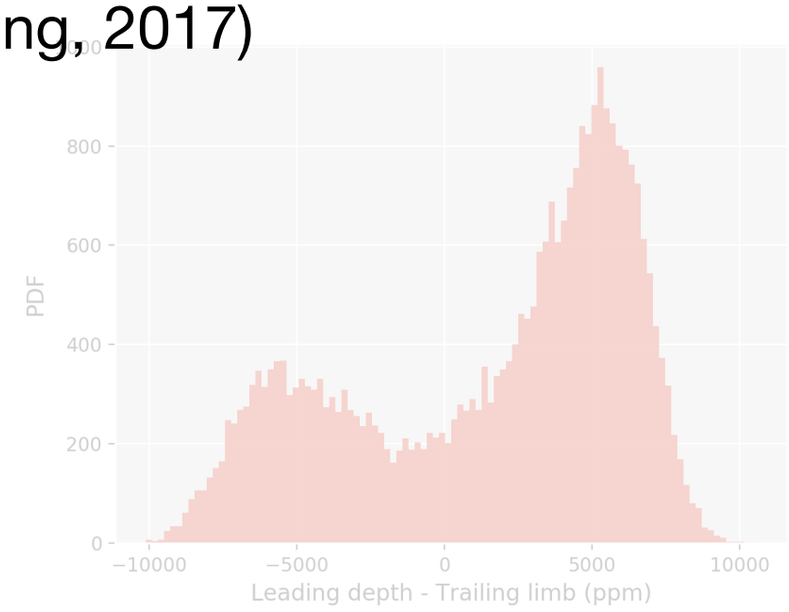


Next step: population level approach

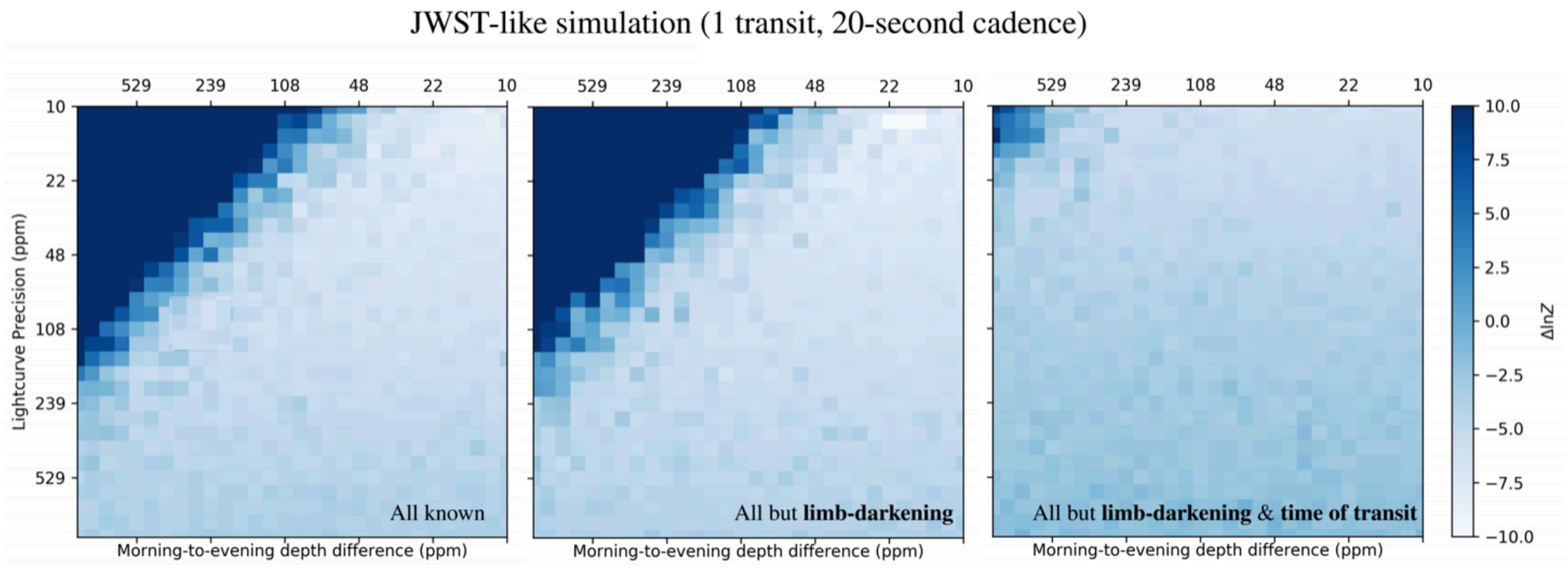
Are **evening limbs**, on average, **larger** than **morning limbs**?

(similar to Sheets & Deming, 2017)

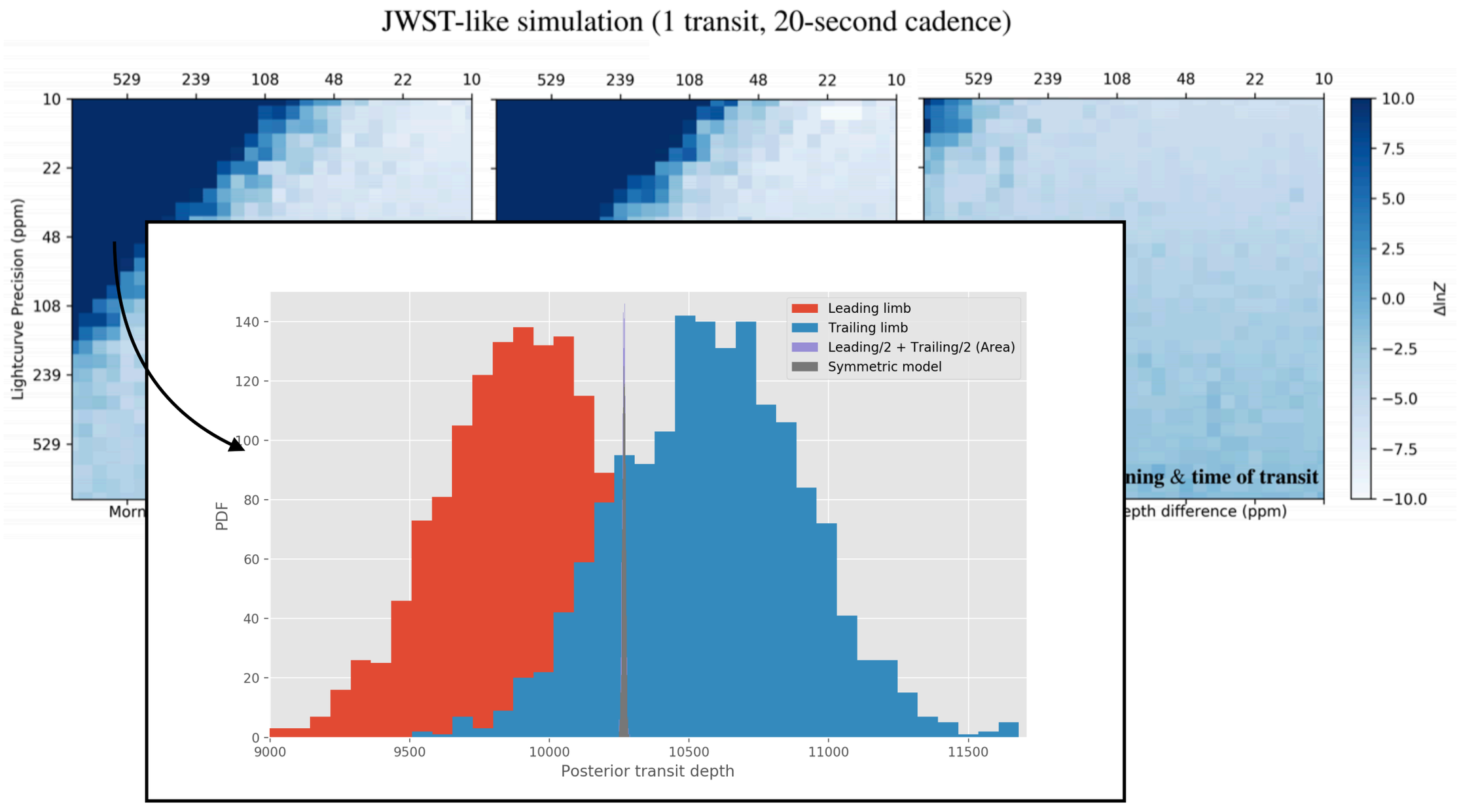




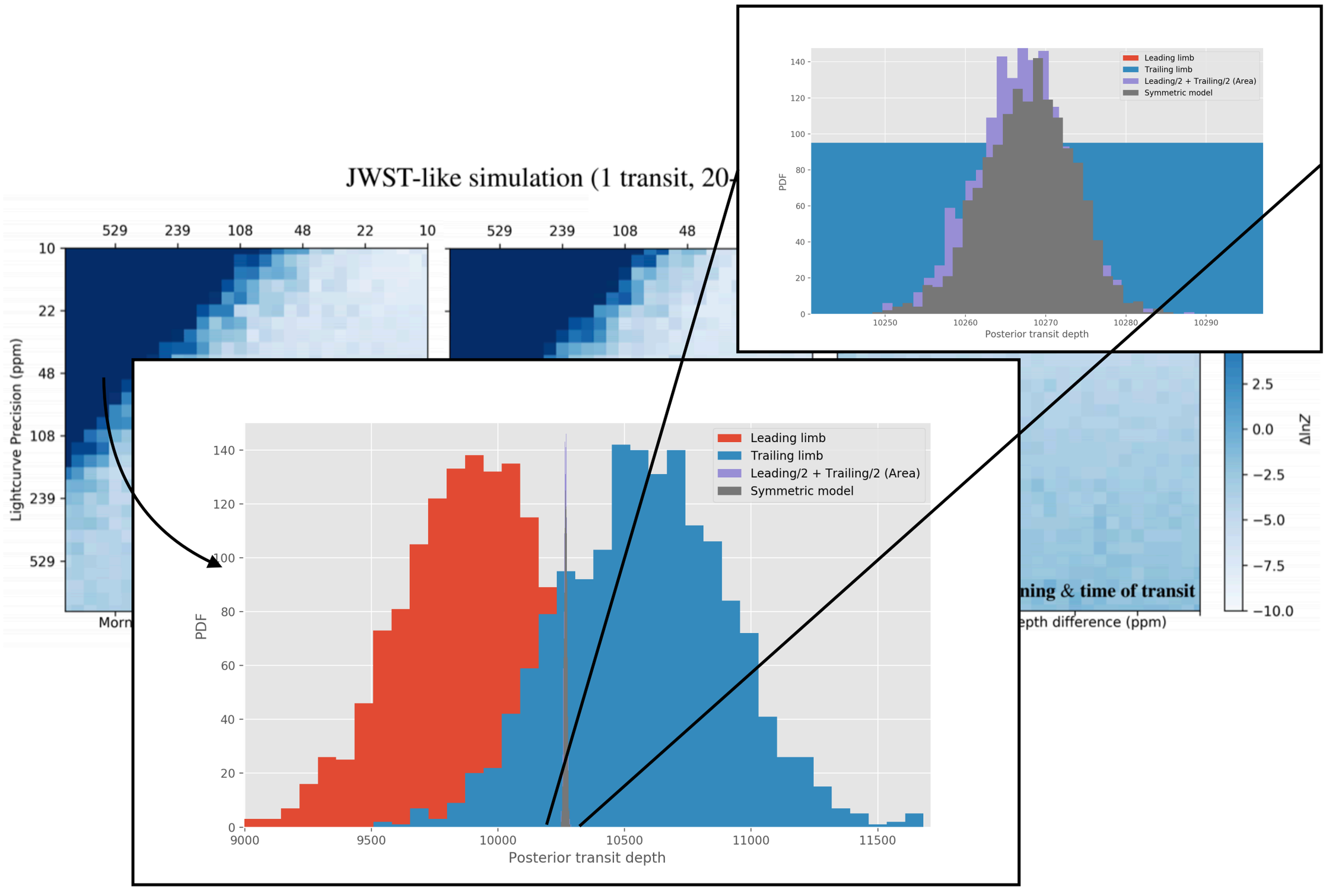
Errors on trailing and leading limb depths



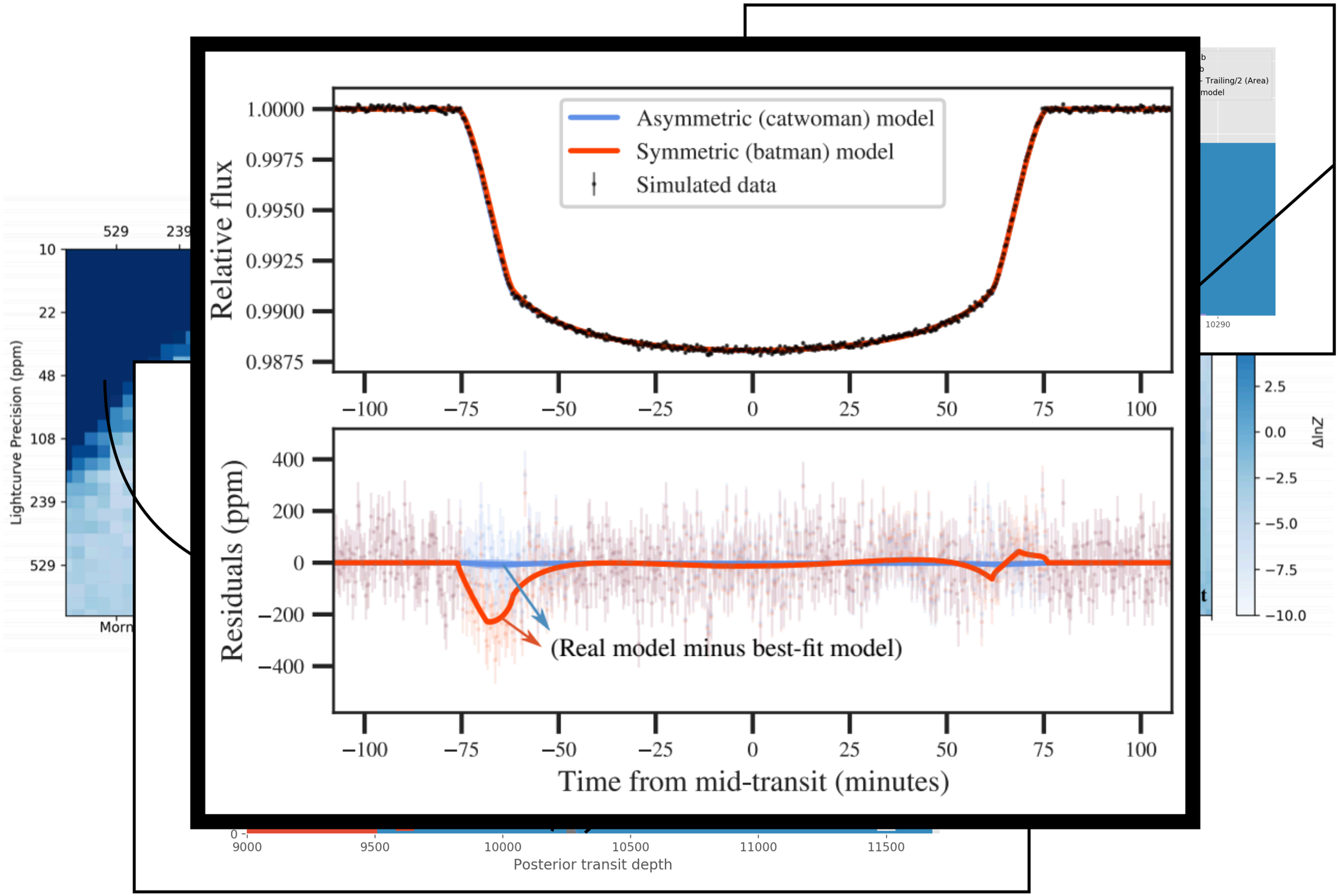
Errors on trailing and leading limb depths



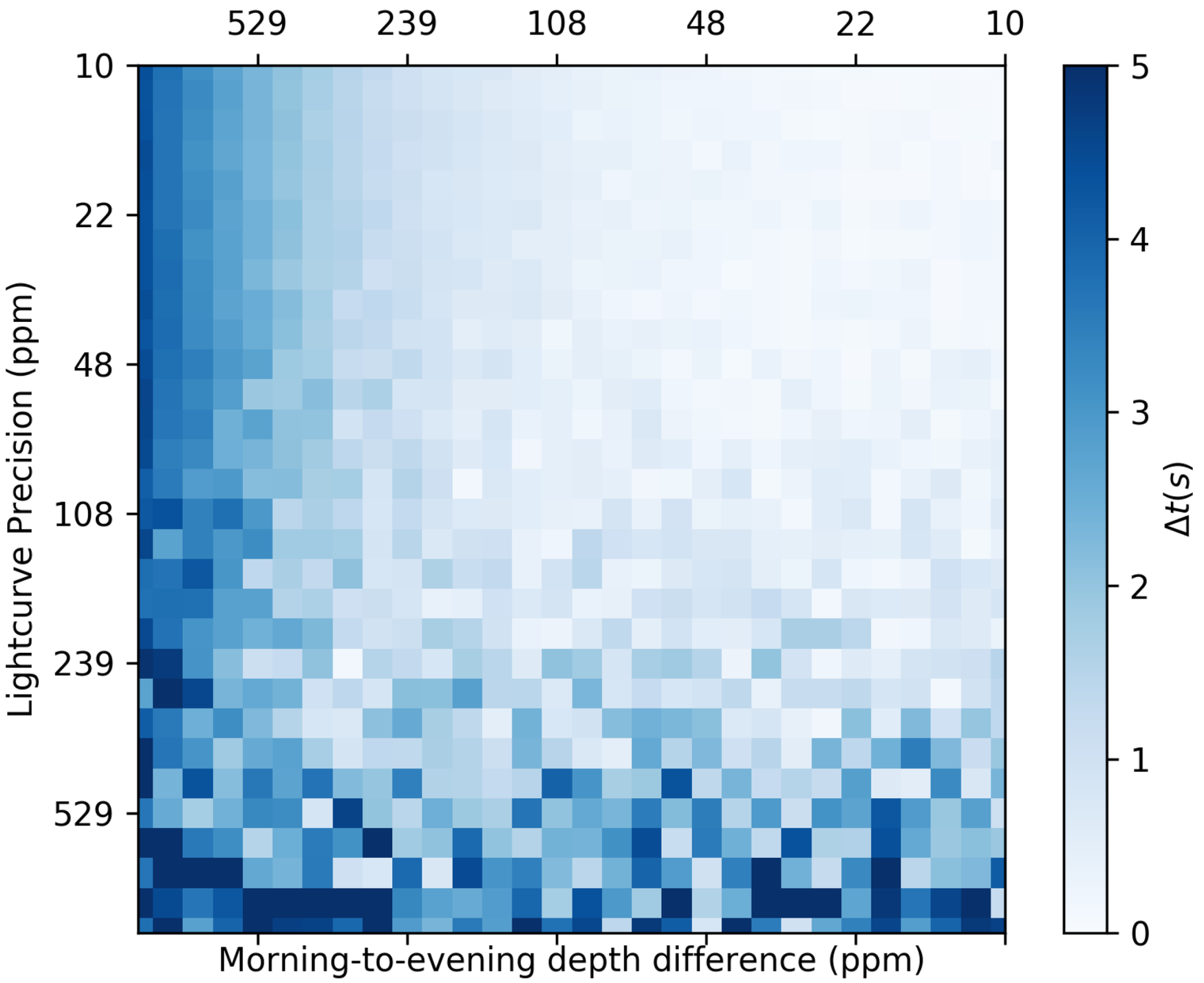
Errors on trailing and leading limb depths



Errors on trailing and leading limb depths



Errors on time-of-transit center



Errors on time-of-transit center