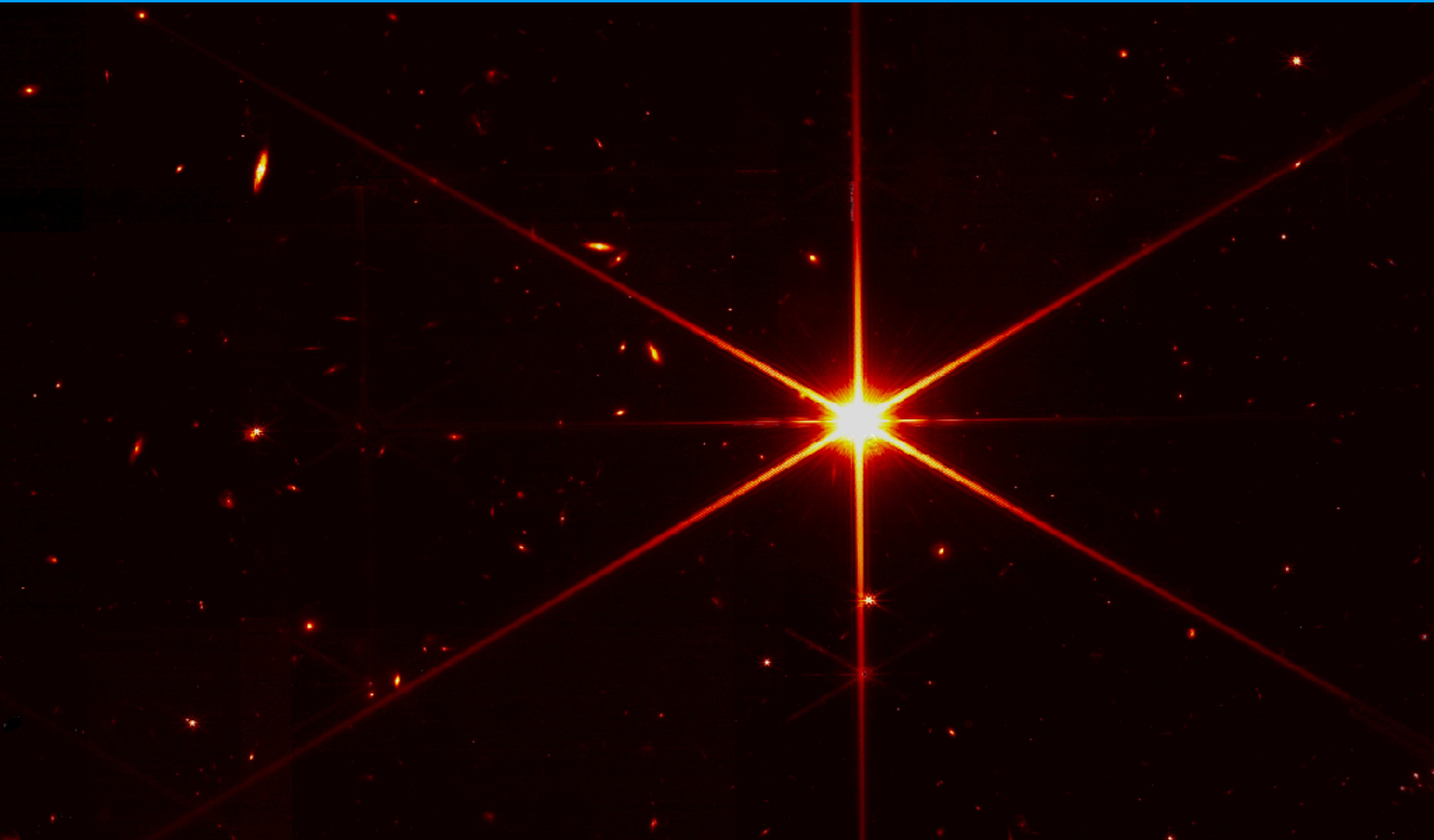
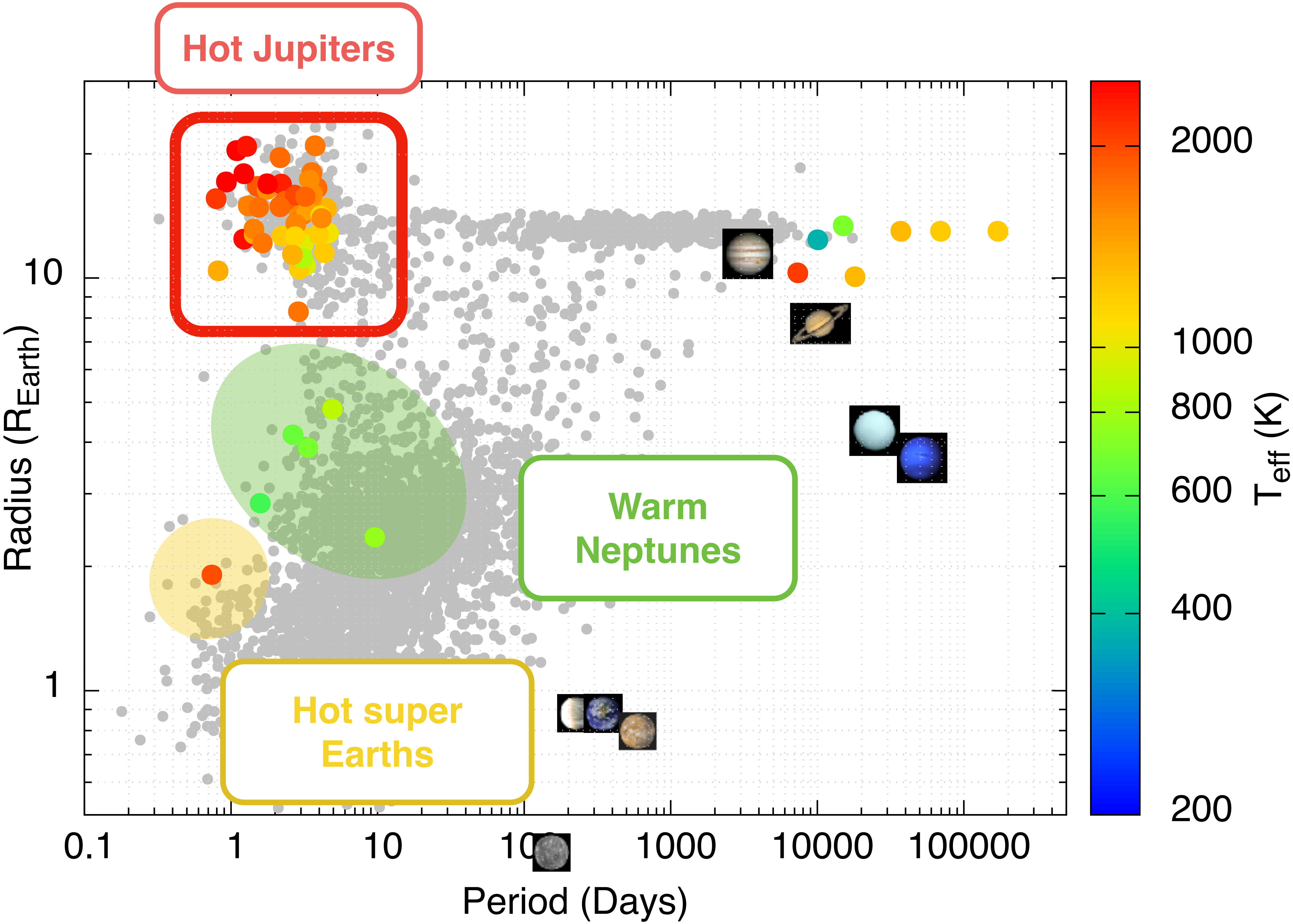
Exoplanets adventures in the 2020s

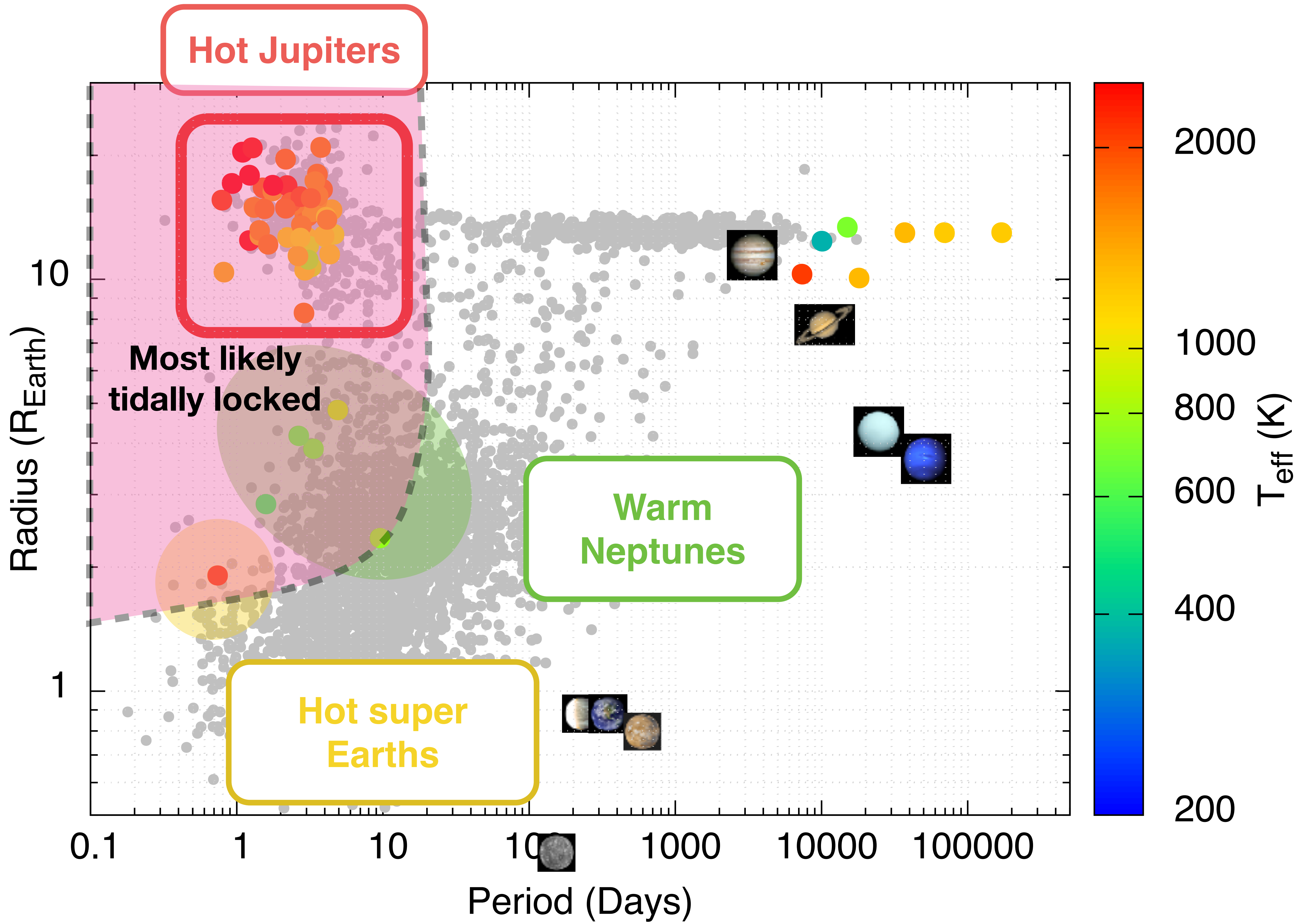
Vivien Parmentier — University of Oxford



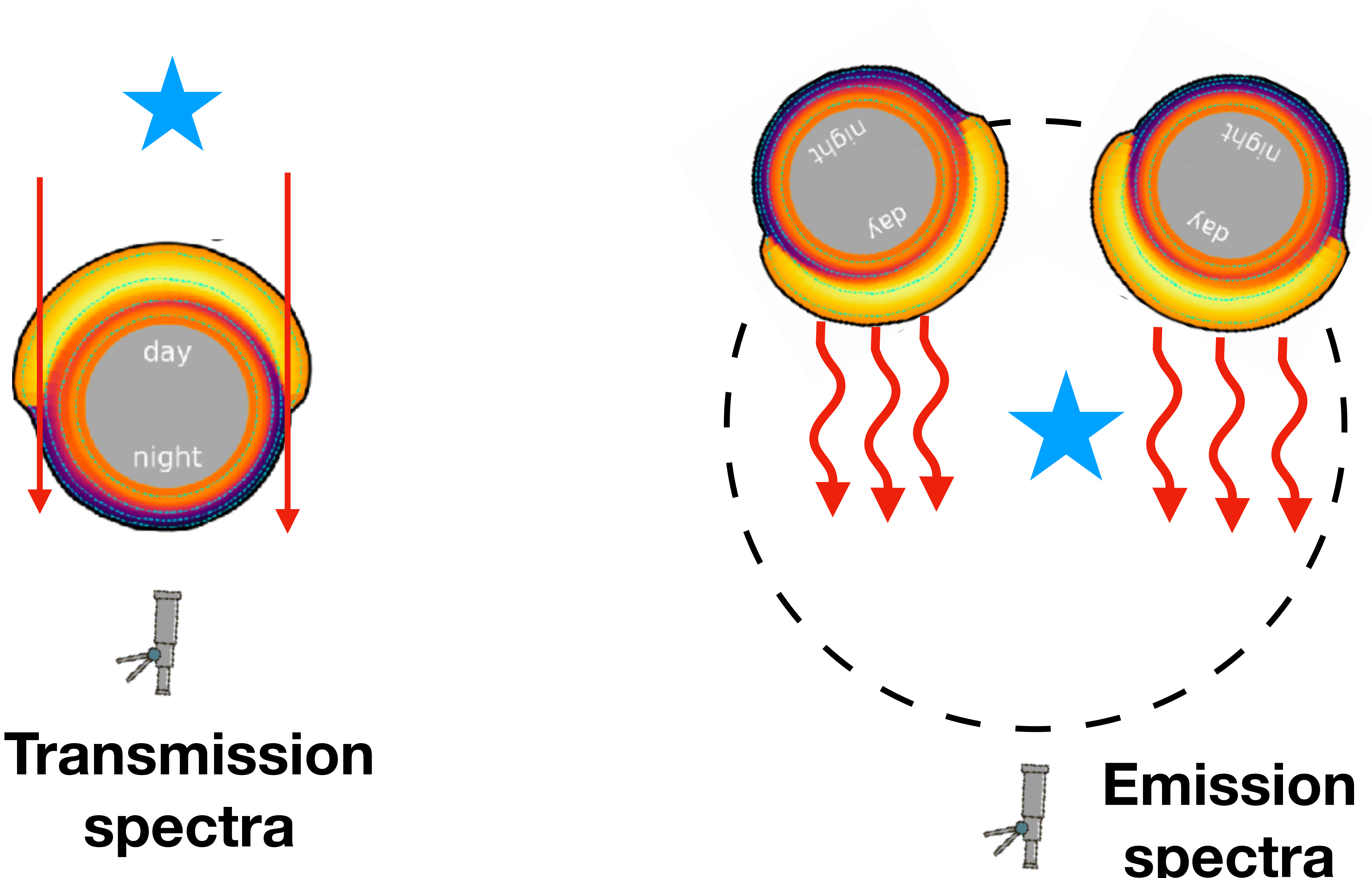
Linking hot Jupiters and Jupiter



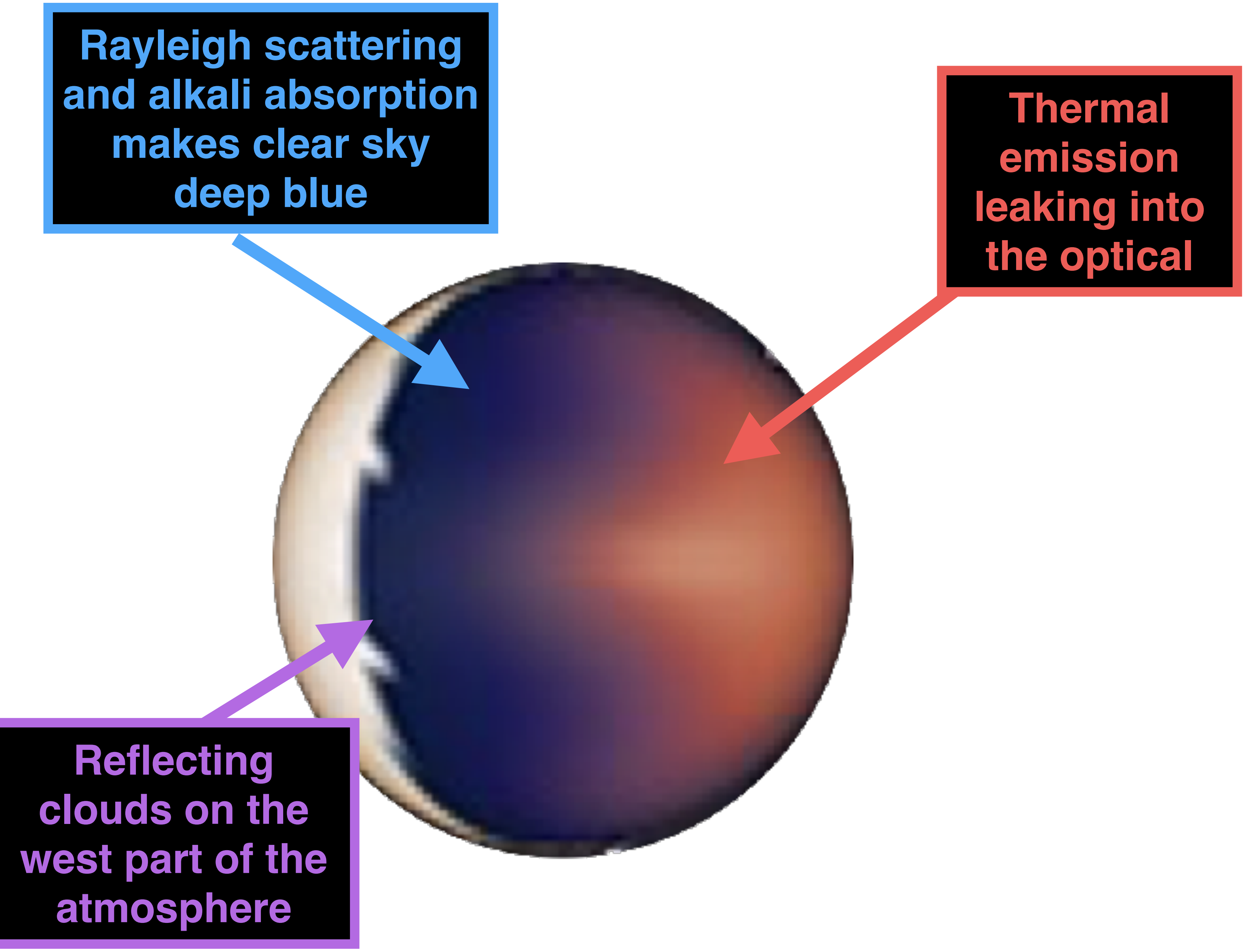
Linking hot Jupiters and Jupiter



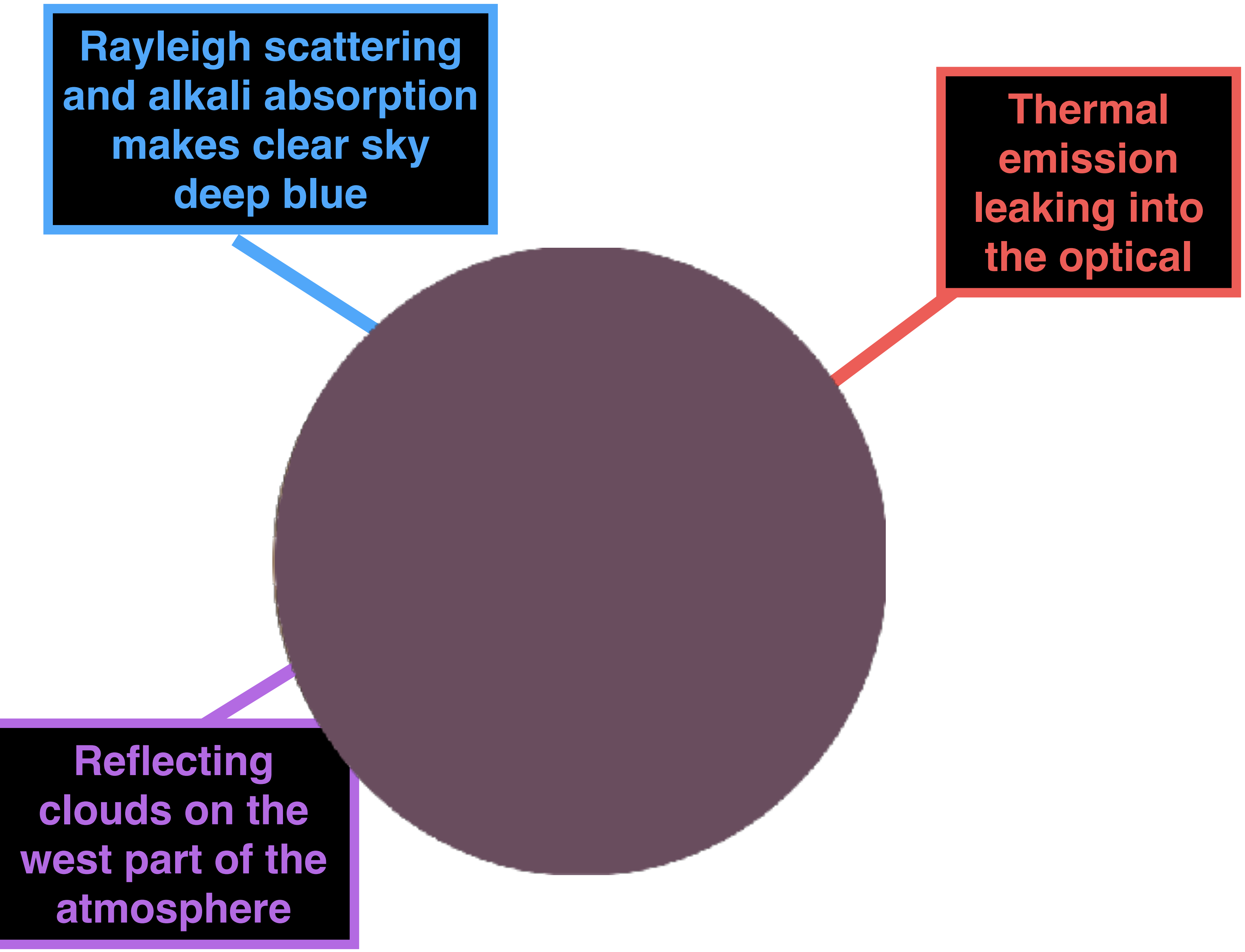
Exoplanet gas giant atmosphere



What a hot Jupiter really look like.



What a hot Jupiter really look like.



During eclipse and transit we see a mix of varied:

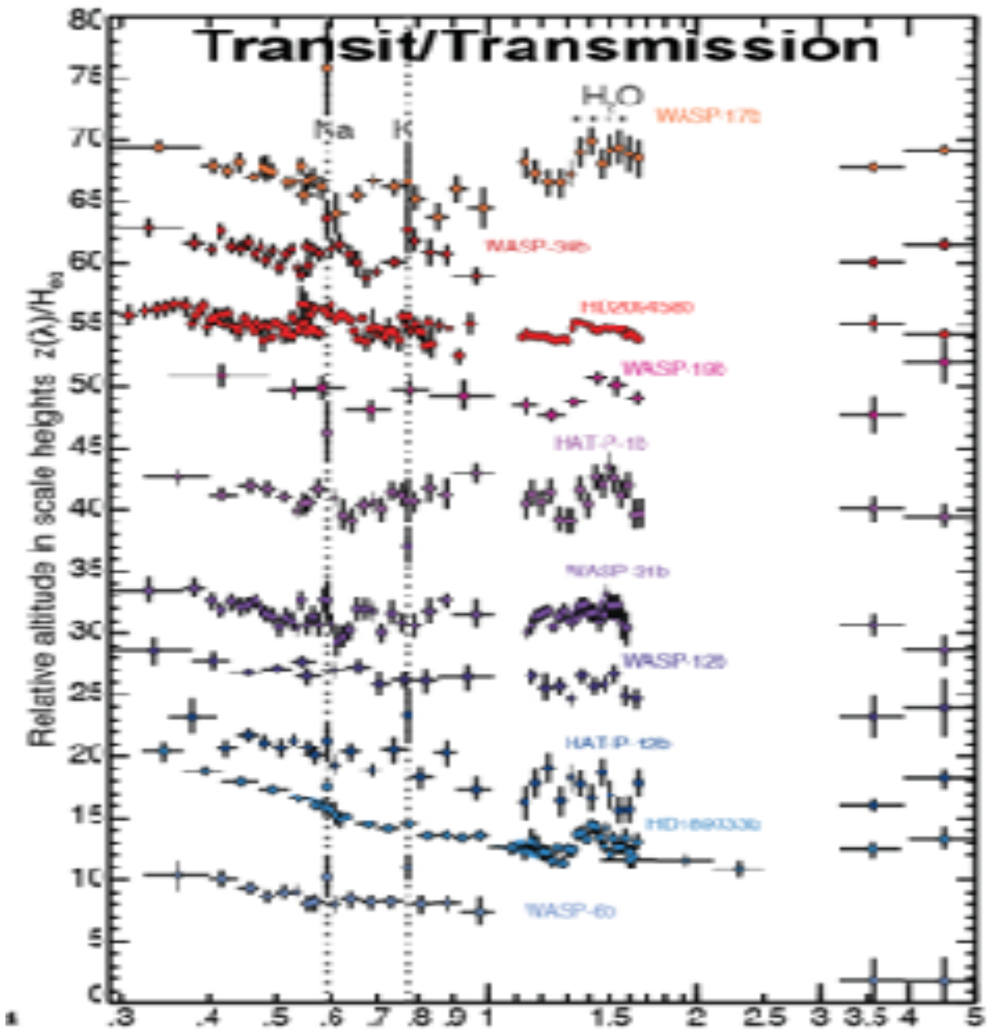
— cloudiness

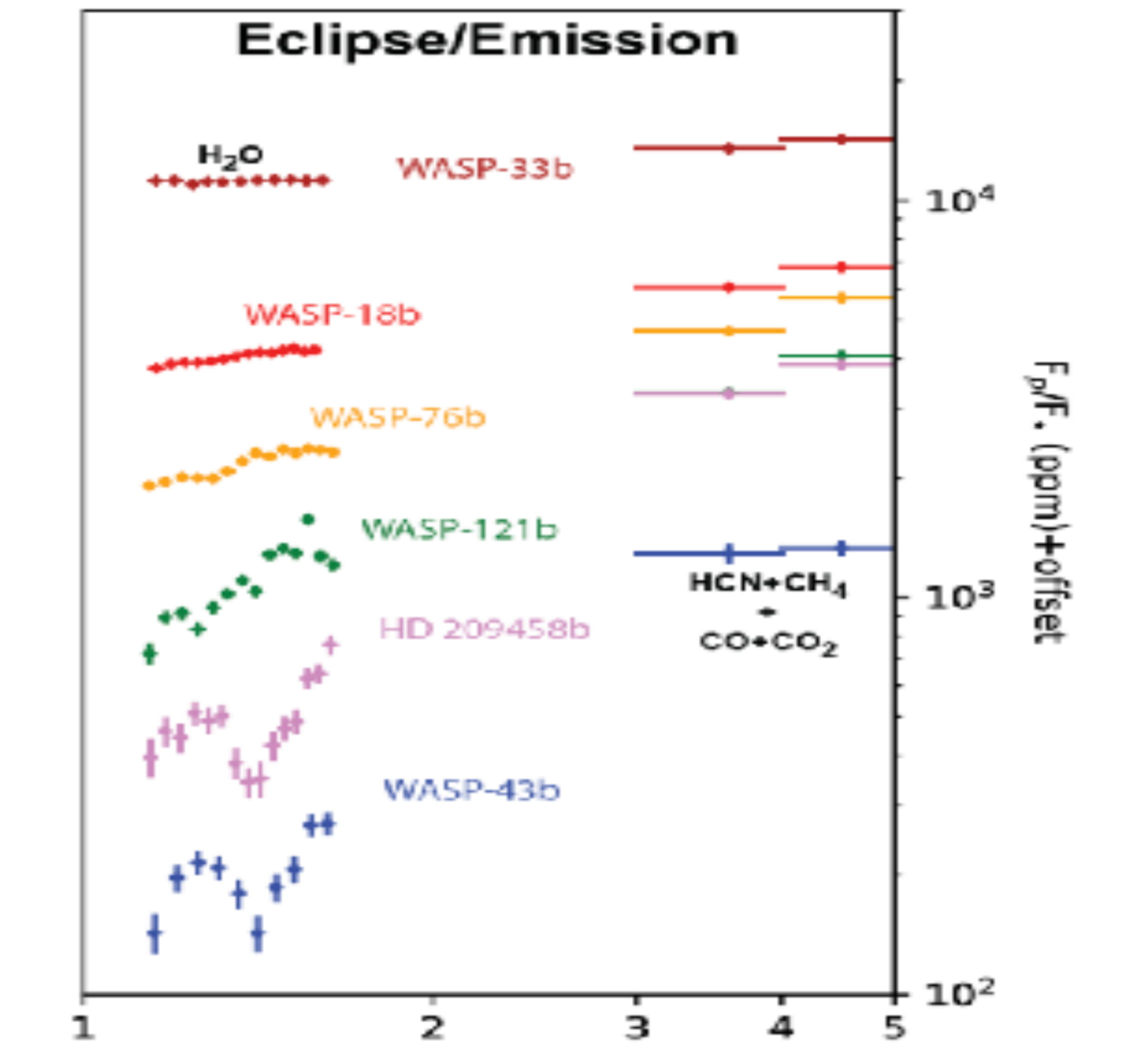
— temperature

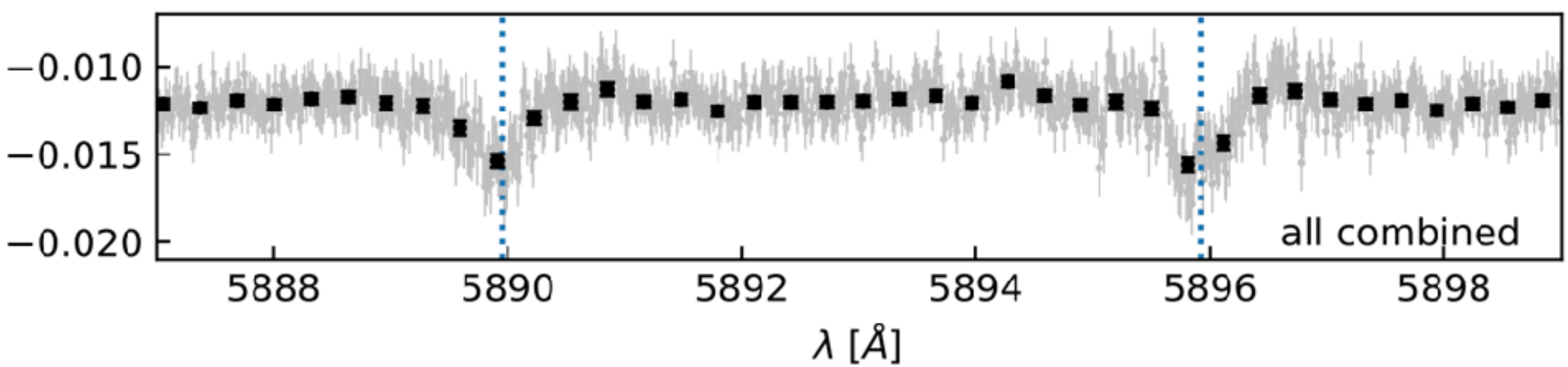
— chemistry

RGB (105,77,94)
best match : eggplant purple

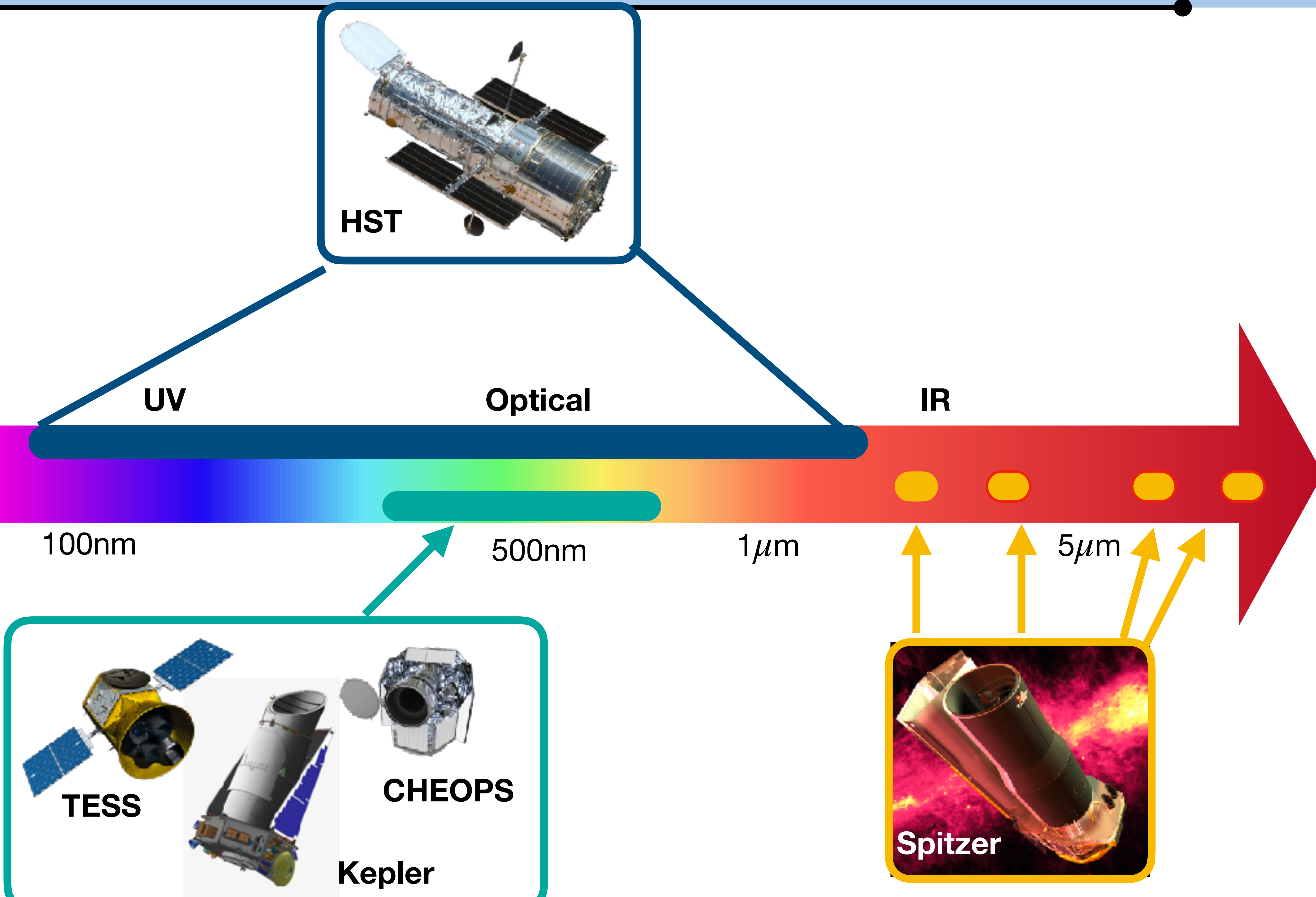
Current exoplanet atmospheres observations







Space telescopes



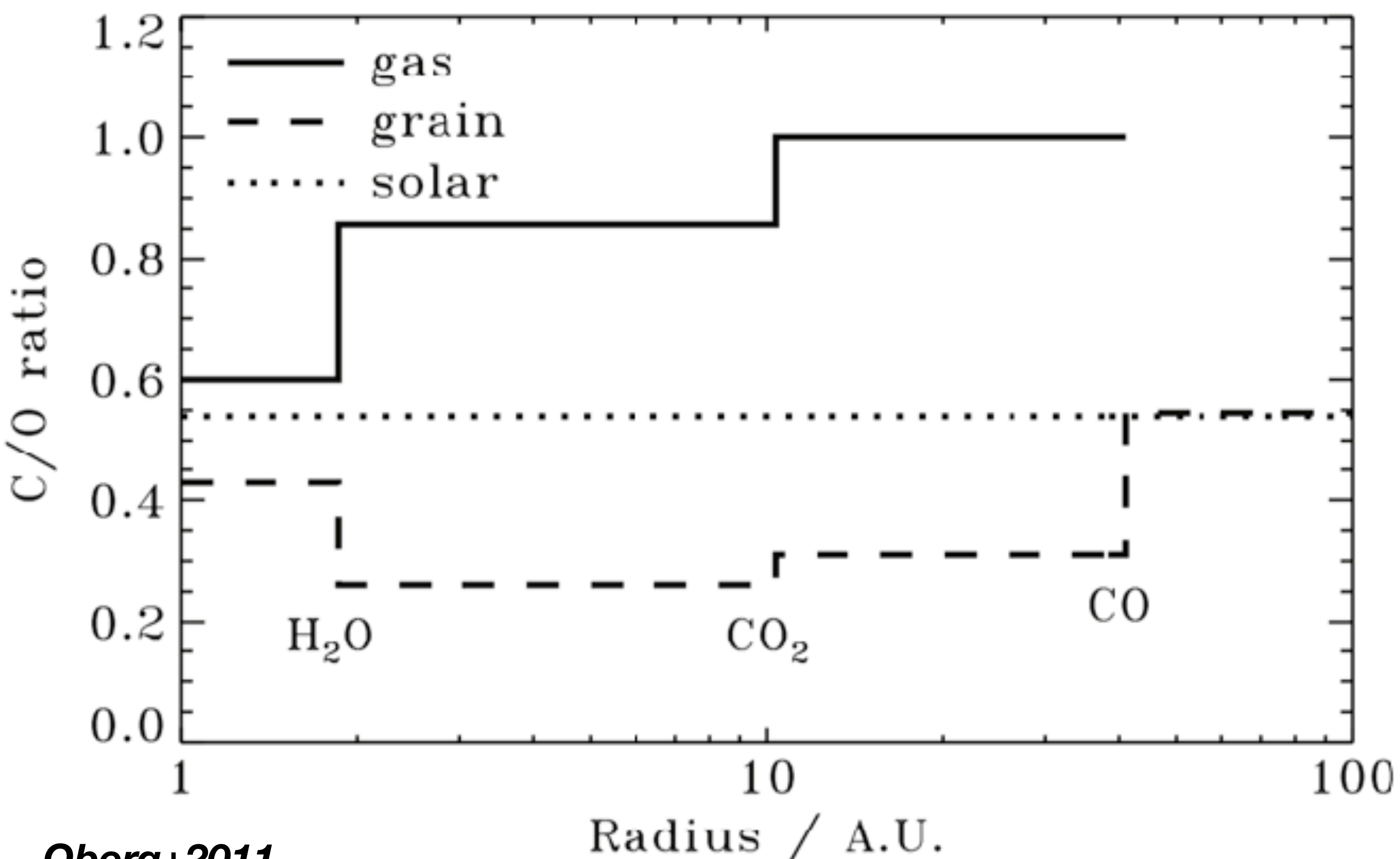
What have we found ? A chemical inventory !

		Properties		Bulk		Ices			Alkalis		Rocks							Isotope
	Planet name	Teq/ Teff (K)	M (M_{Jup})	H	He	H_2O	CO	CH_4	Na	K	Fe	Fe II	Mg	Ca II	Ca	Li	Sc II	^{13}CO
Transiting planets	KELT-9b	4048	2.88	H							H	H	M	H			L	
	WASP-33b	2781	2.1	L		L					H			H				
	WASP-12b	2594	1.5			L						L						
	WASP-121b	2359	1.18	H		M			H	H	H	L	H	H	H	L	L	
	KELT-20b	2255	3.38	H					H		H	H	L	H				
	WASP-76b	2182	0.92			L			H		L			L				
	WASP-77Ab	1741	2.29			H	L											L
	WASP-17b	1698	0.78			L			L									
	HD209458 b	1476	0.73	L	L	H	H	L	C			C	C		L			
	WASP-127b	1401	0.18			L			H	L						L		
	XO-2b	1327	0.566						L	L								
	HAT-P-1b	1322	0.525			L			L									
	WASP-52 b	1299	0.46			L			L									
	WASP-96b	1286	0.48			L			L									
	HD189733b	1192	1.13		H	H	H		H	L								
	WASP-39b	1120	0.28			L			L									
	WASP-6b	1093	0.37						L	L								
	WASP-69b	988	0.29		L	L			L	N								
	HAT-P-12b	957	0.21			L			L	L								
	HAT-P-18b	848	0.20		L	L												
	HAT-P-11b	829	0.084		M	L												
	WASP-107b	739	0.12		H	L												
Non Transiting	Tau Bootis b	1636	5.84			L	M											
	HD179949b	1552	0.92			M	L											
	HD 102195b	1053	0.46			L		L										
Directly imaged	CQ Lupi b	~2650	25			L	L											
	Beta Pictoris b	~1724	12.9			H	H											
	TYC 8998-760-1b	~1700	14			L	L											L
	HR8799c	~1100	8.1			H	H	C										
	HR8799b	~900	5.8			L	L	C										
	51 Eridiani b	~760	9.1			H		H										

Confidence level:
- High observed by at least 2 instruments
- Medium: observed by one instrument multiple times
- Low: observed once by one instrument
- Controversial

A lot of these are using ground-based high resolution spectrograph… we'll talk about it later.

Abundances as a tracer of planet formation ?



Oberg+2011

Elemental ratio vary in the protoplanetary disk

C/O ratio but also accessible:

Rock/ice ratio ? Fe/O, Na/O, Mg/C…

Rock/rock ratio ? Ti/Fe, Na/K, Fe/Mg…

Abundances as a tracer of planet formation ?

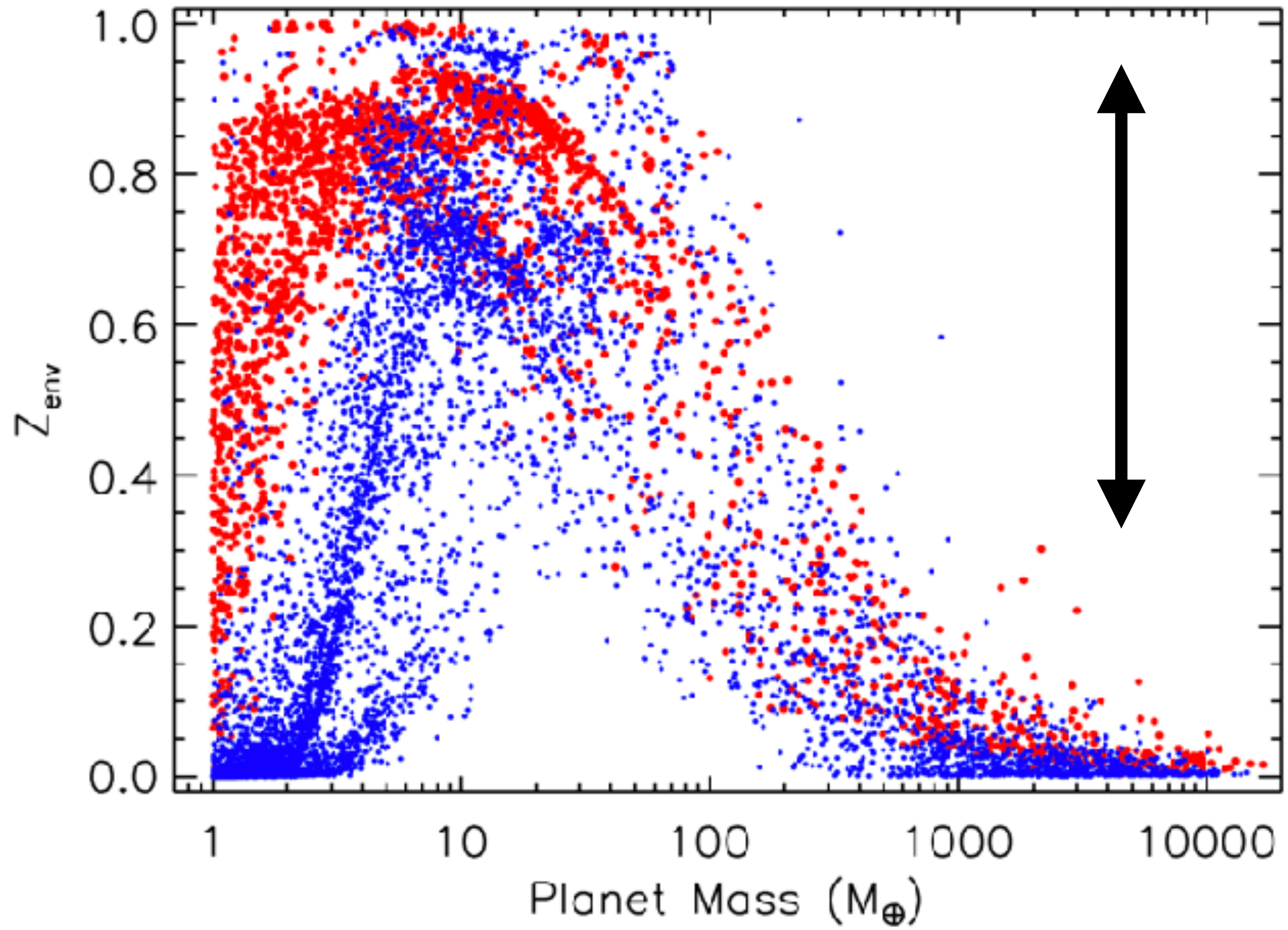


Figure 5. Heavy element mass in the H/He envelope (Z_{env}) as a function of planet mass for the output of the population synthesis models. Blue dots use 100 km planetesimals and red dots use 1 km planetesimals. We make a simple assumption of a uniform Z_{env} throughout the envelope.

(A color version of this figure is available in the online journal.)

Fortney+2013

Elemental ratio vary in the protoplanetary disk

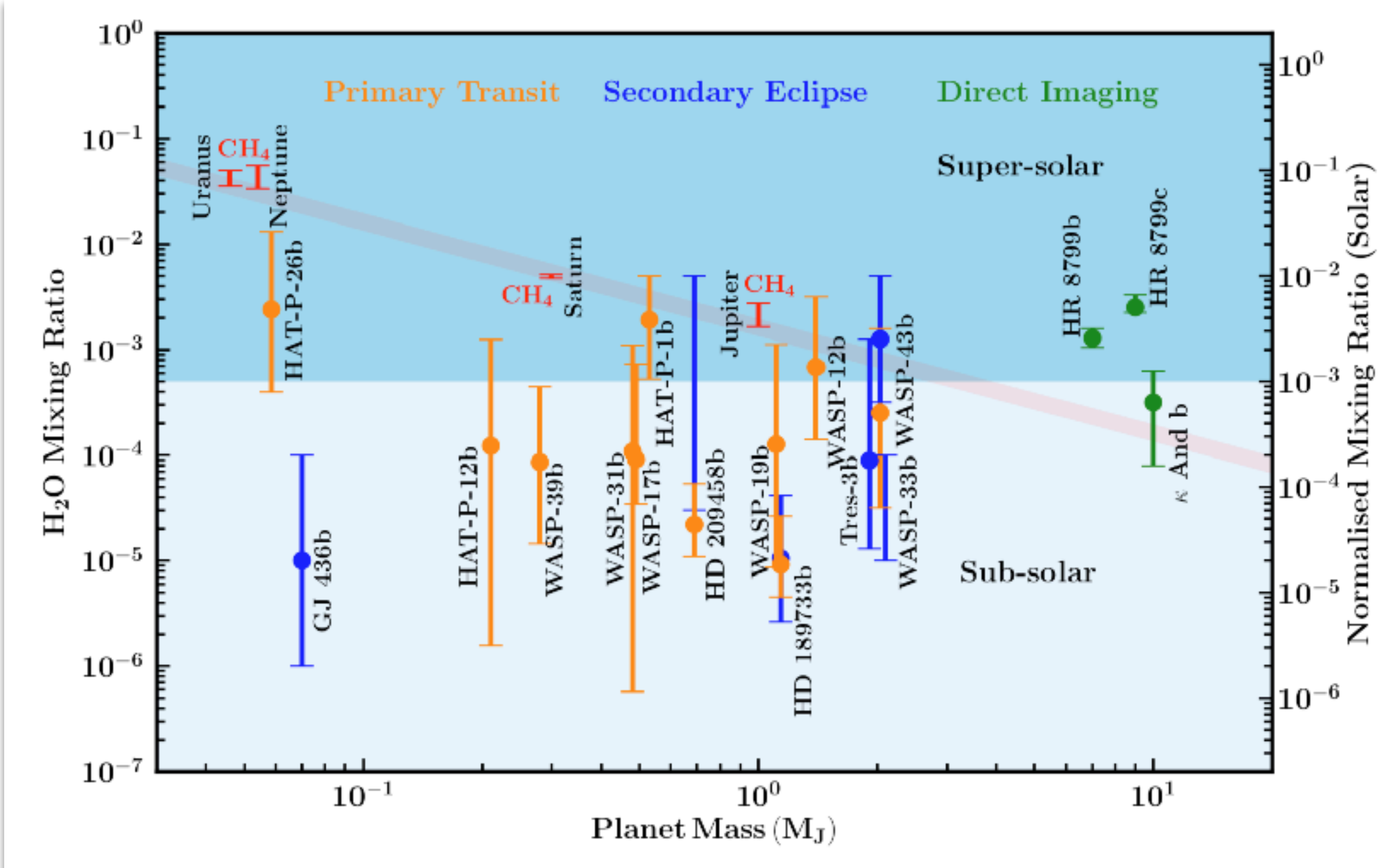
C/O ratio but also accessible:

Rock/ice ratio ?
Fe/O, Na/O, Mg/C…

Rock/rock ratio ?
Ti/Fe, Na/K, Fe/Mg…

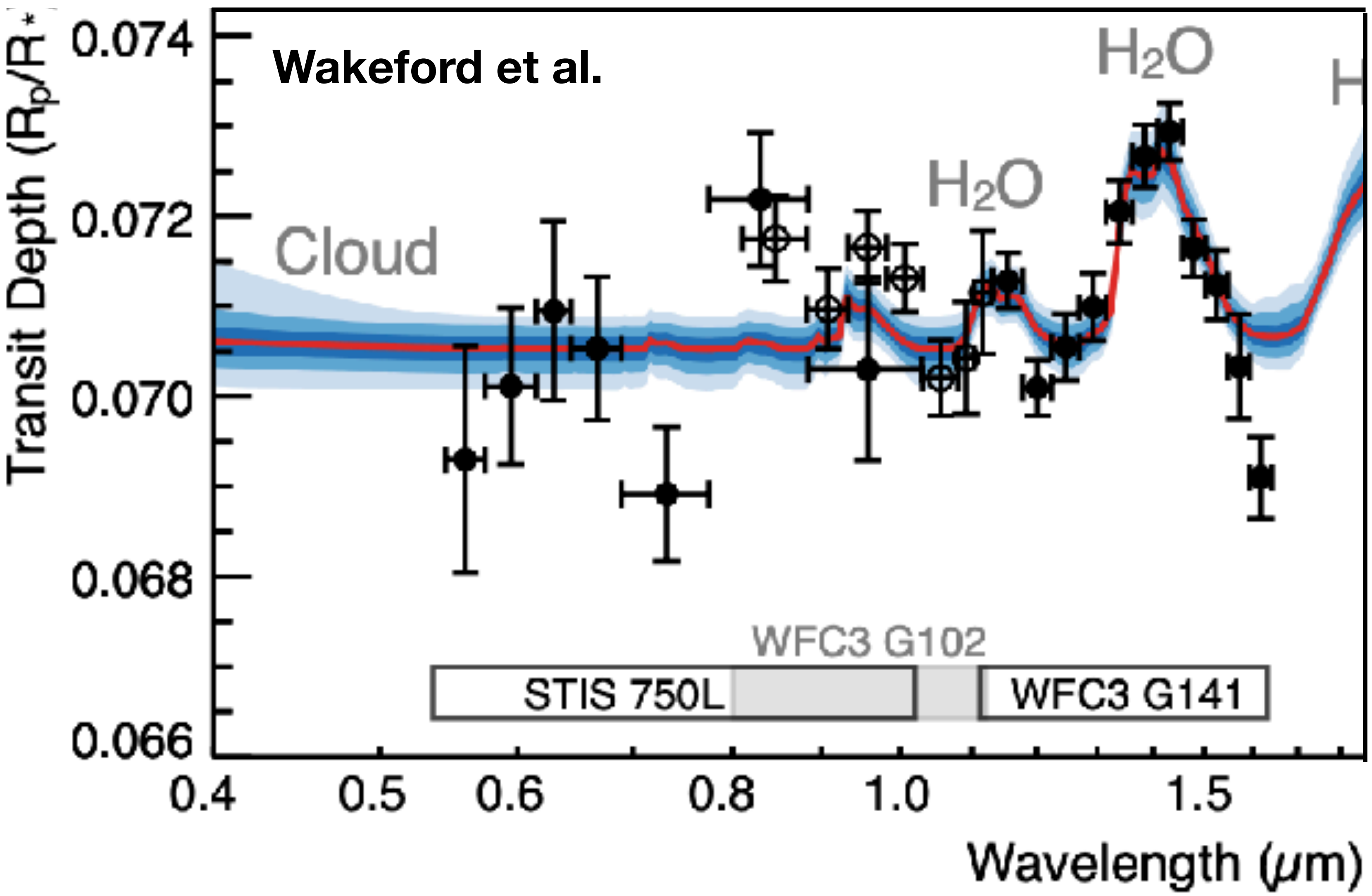
Planet formation can lead to a wide diversity of outcomes !

Abundances retrievals from spectra



Generally order-of-magnitude estimates !

Why is it so bad ?



ure 6. Transit spectrum of HAT-
17) using the Hubble Space Telesc
μm is due to water vapor.

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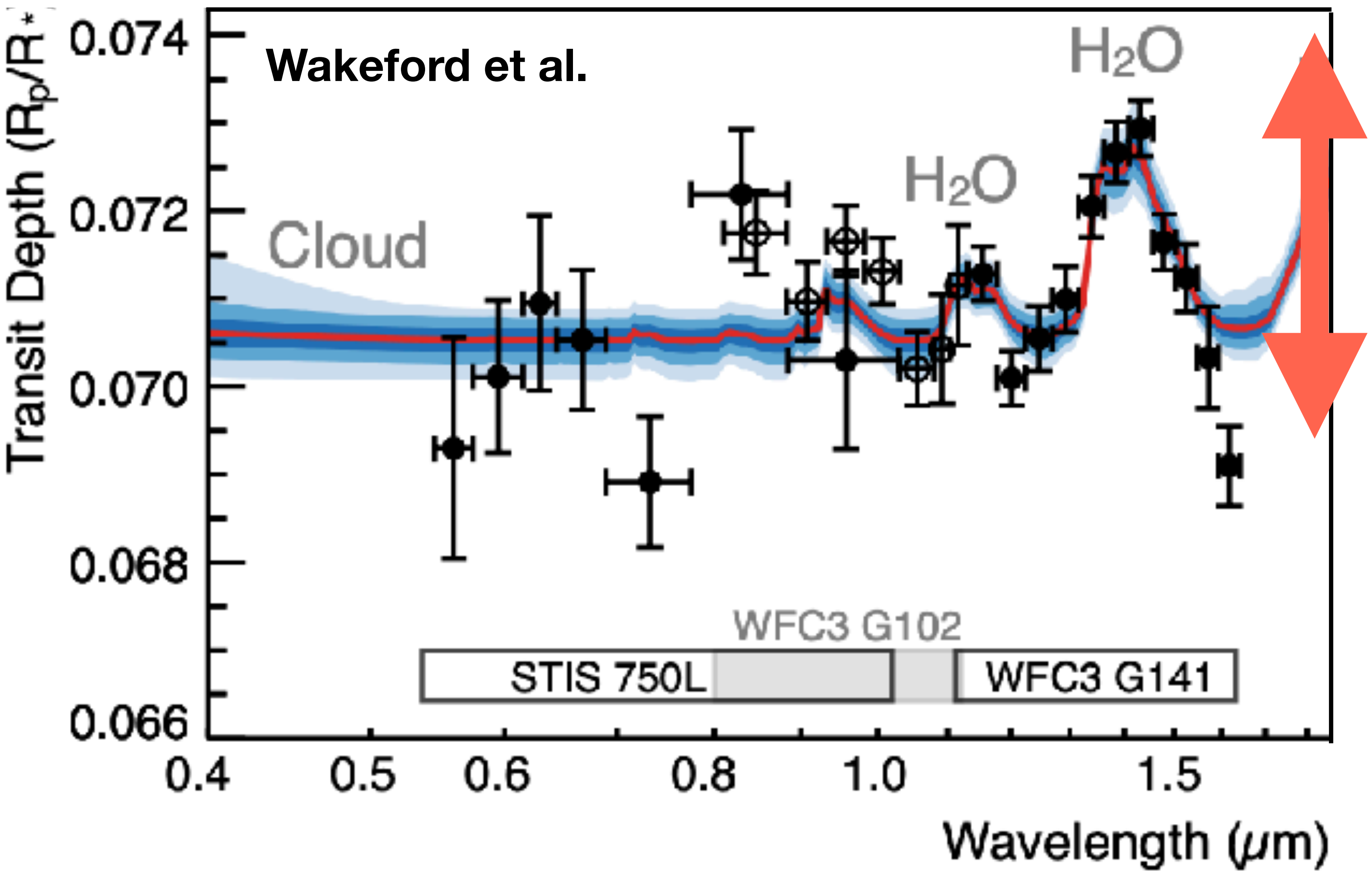

Detection driven by feature size

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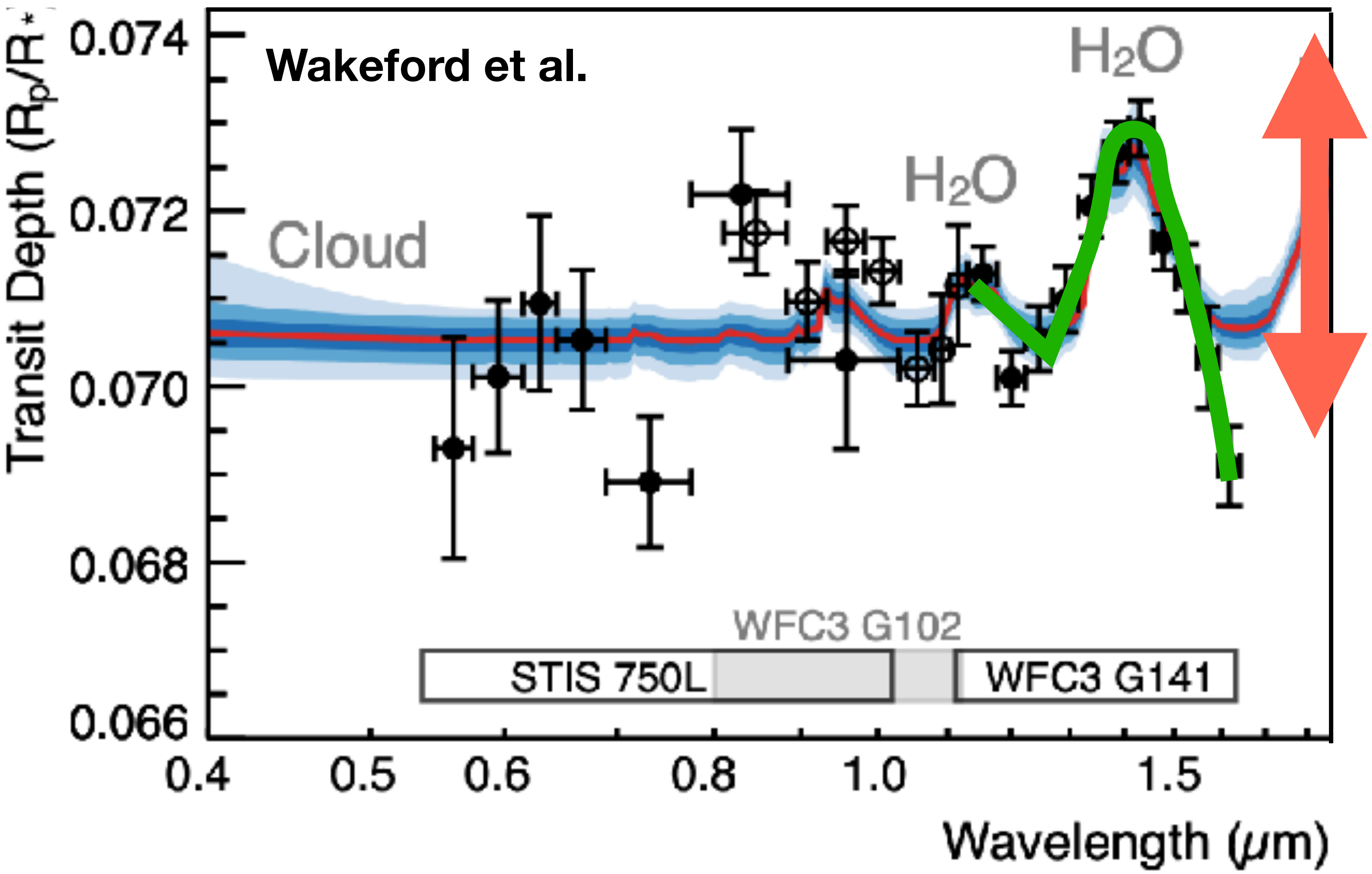

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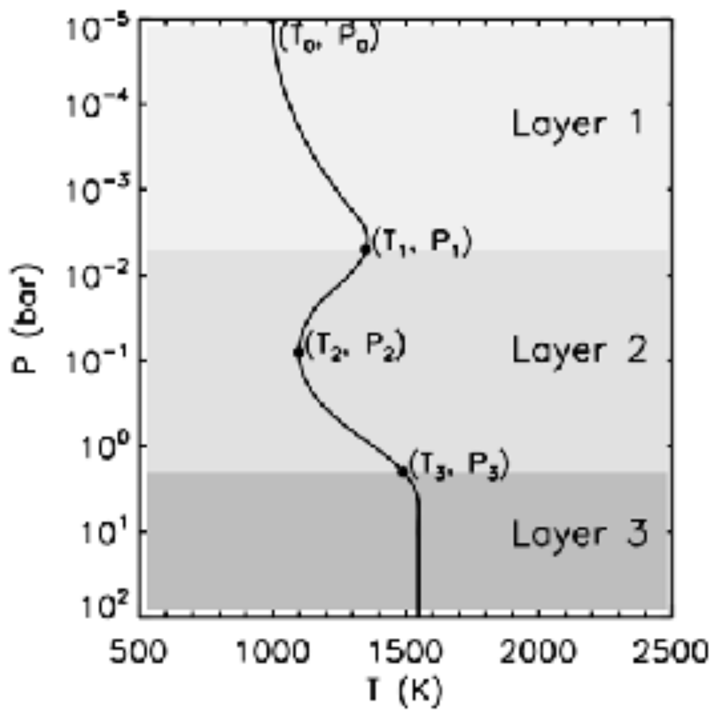
17) using the Hubble Space Telesc
μm is due to water vapor.

Detection driven by feature size

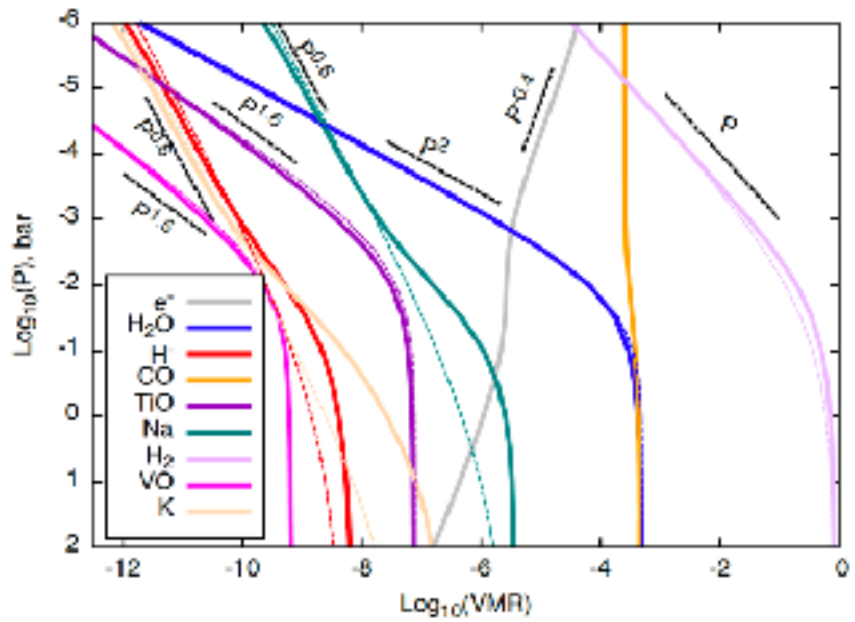
Abundance measurement driven by feature shape

Atmospheric modelling recipe

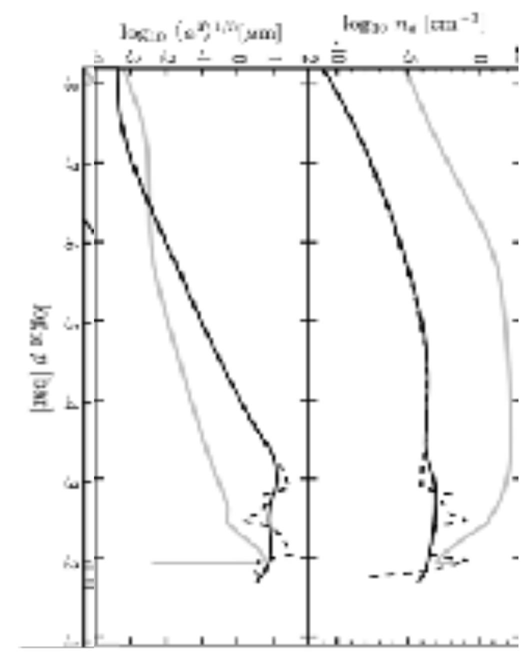
Temperature profile



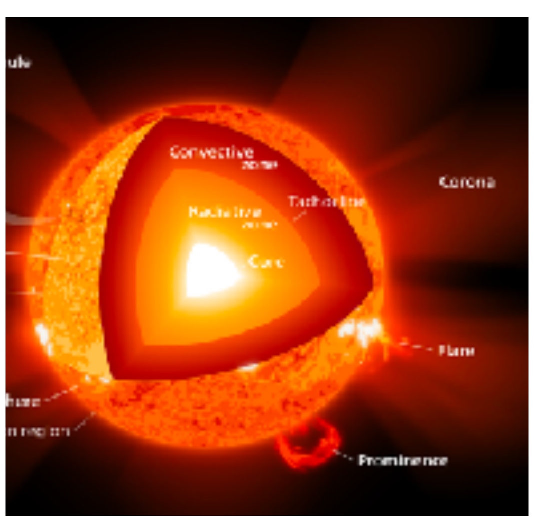
Chemical profile



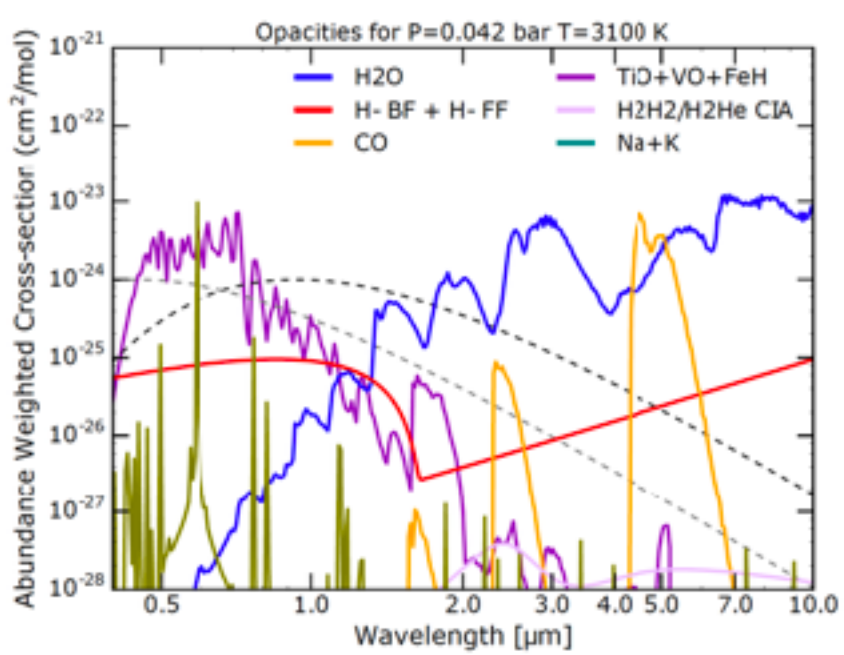
Cloud profile



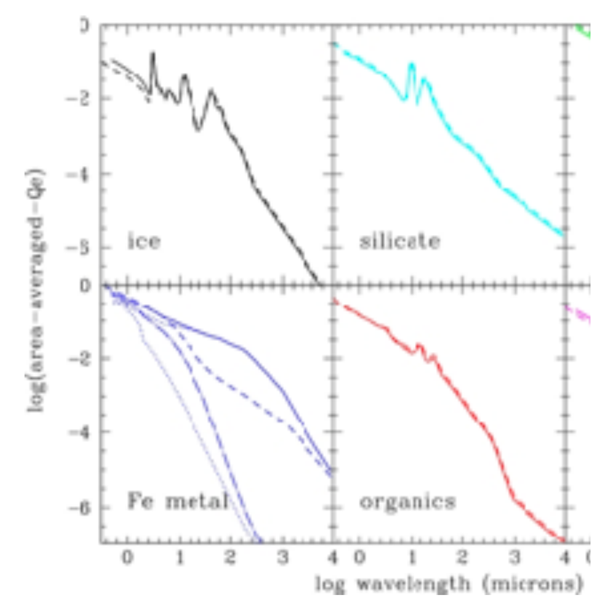
Stellar model



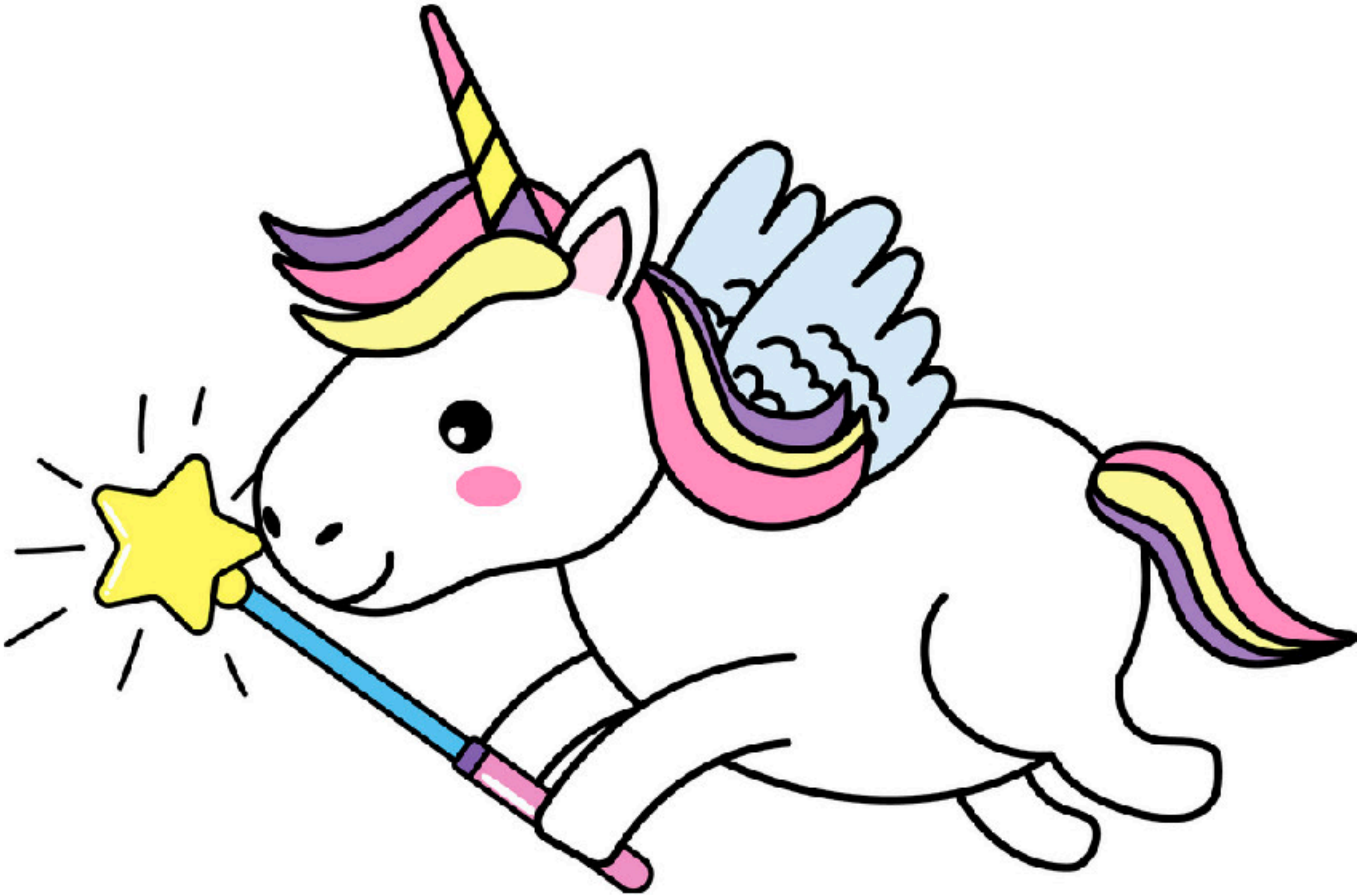
Molecular/atom/ions opacities



Cloud opacities



Atmospheric modelling recipe



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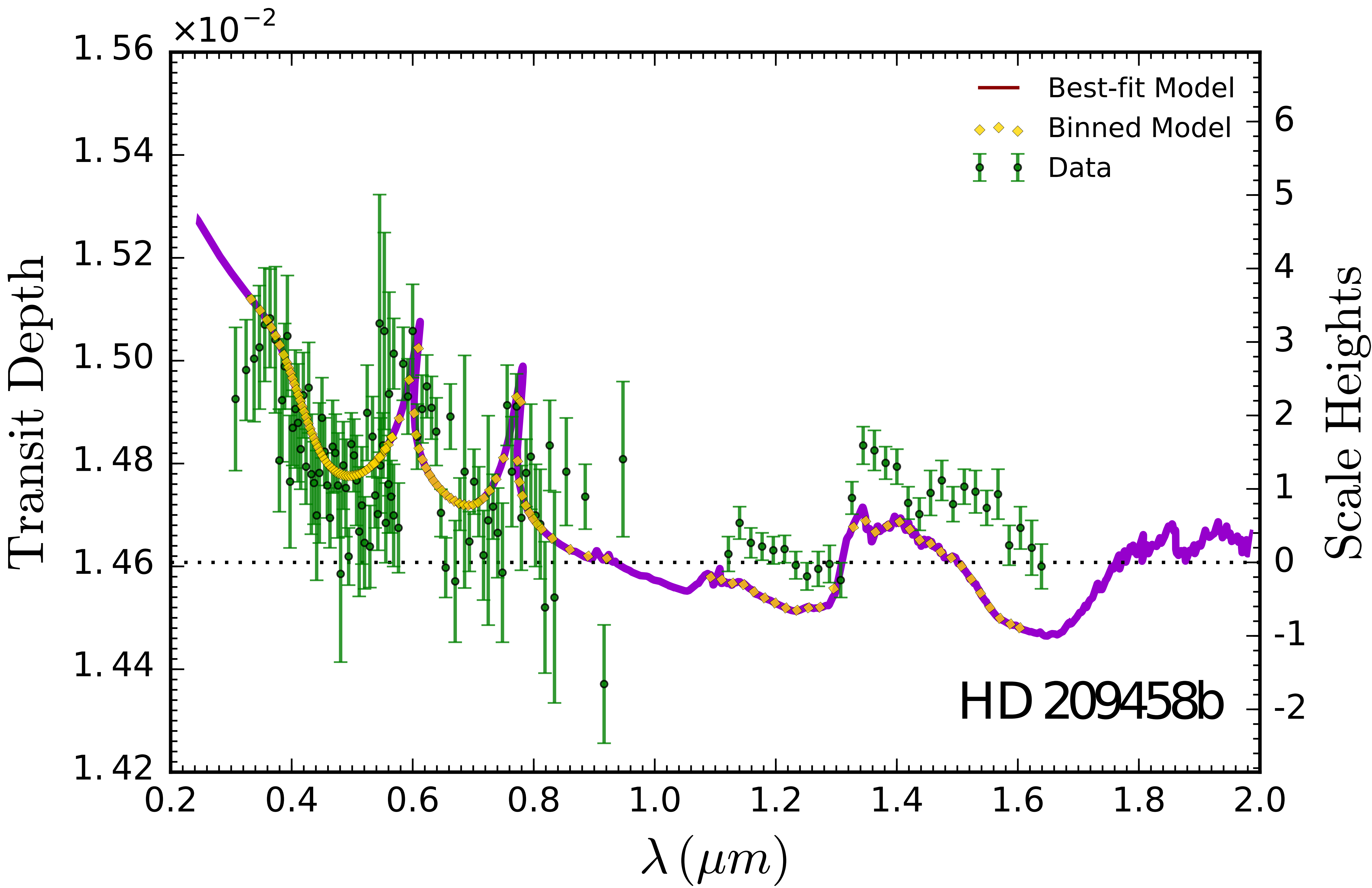

Atmospheric modelling recipe

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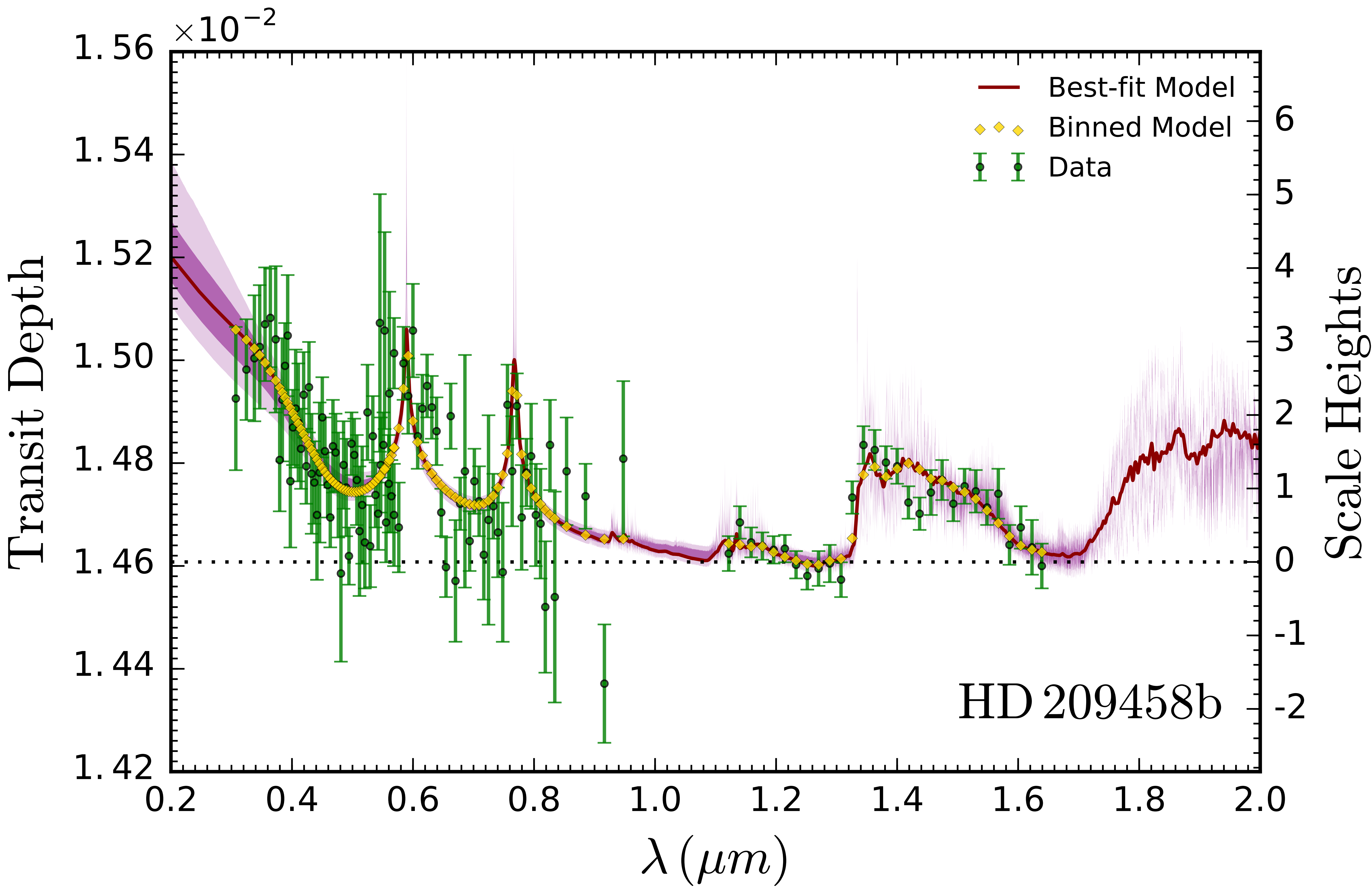
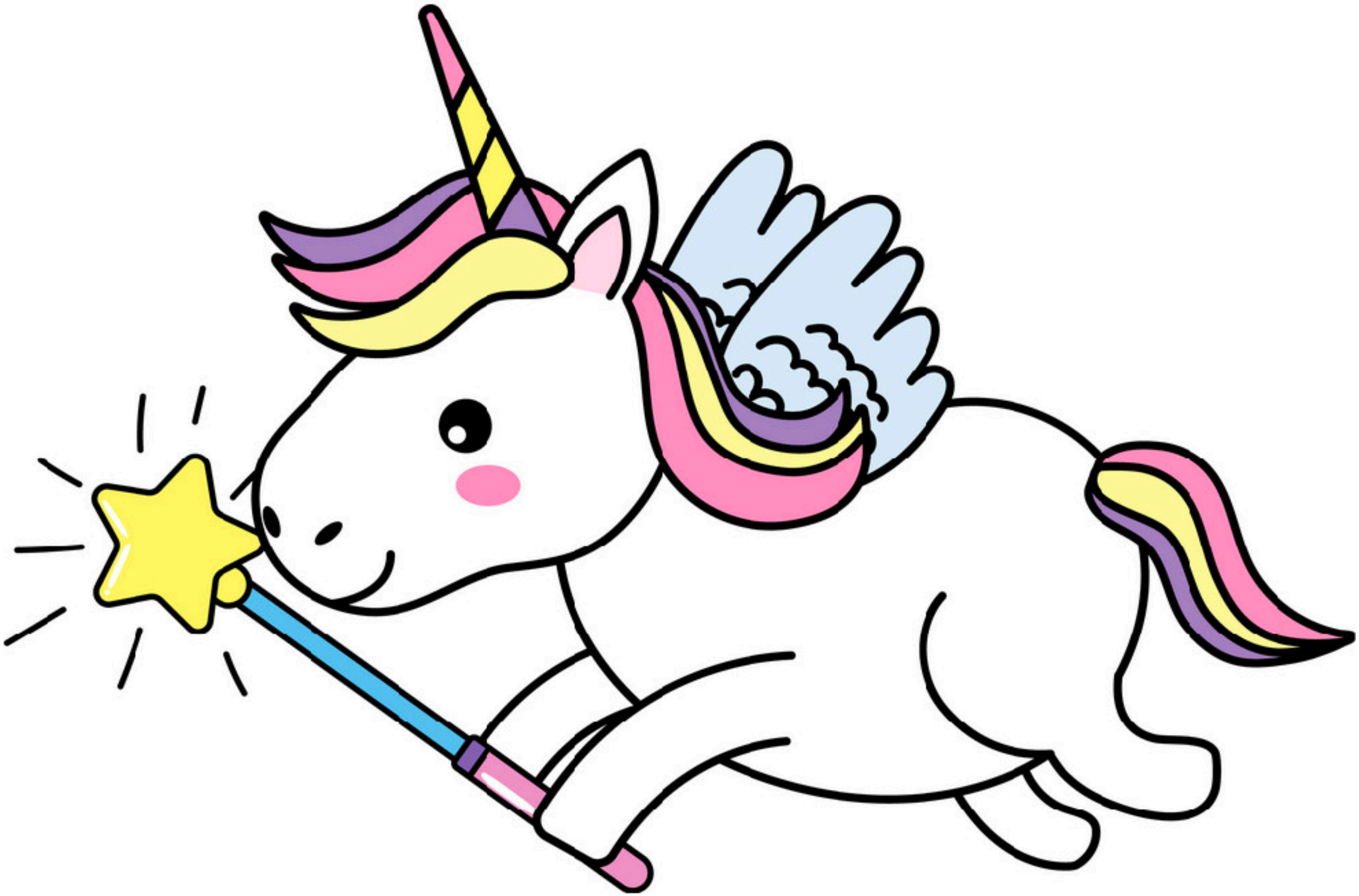


What is the magic unicorn doing ?



What is the magic unicorn doing ?

*Things** we want with observations we can get*

Nuisance physics we don't want to deal with but have to (star, noise)

$$A = \begin{pmatrix} \frac{\partial(Obs_1)}{\partial(physics_1)} & \frac{\partial(Obs_1)}{\partial(physics_2)} & \cdots & \frac{\partial(Obs_1)}{\partial(physics_n)} \\ \frac{\partial(Obs_2)}{\partial(physics_1)} & \frac{\partial(Obs_2)}{\partial(physics_2)} & \cdots & \frac{\partial(Obs_2)}{\partial(physics_n)} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{\partial(Obs_m)}{\partial(physics_1)} & \frac{\partial(Obs_m)}{\partial(physics_2)} & \cdots & \frac{\partial(Obs_m)}{\partial(physics_n)} \end{pmatrix}$$

Observations we want but can't yet get (but will with JWST ?

Things we don't know we want with observations we don't know we need

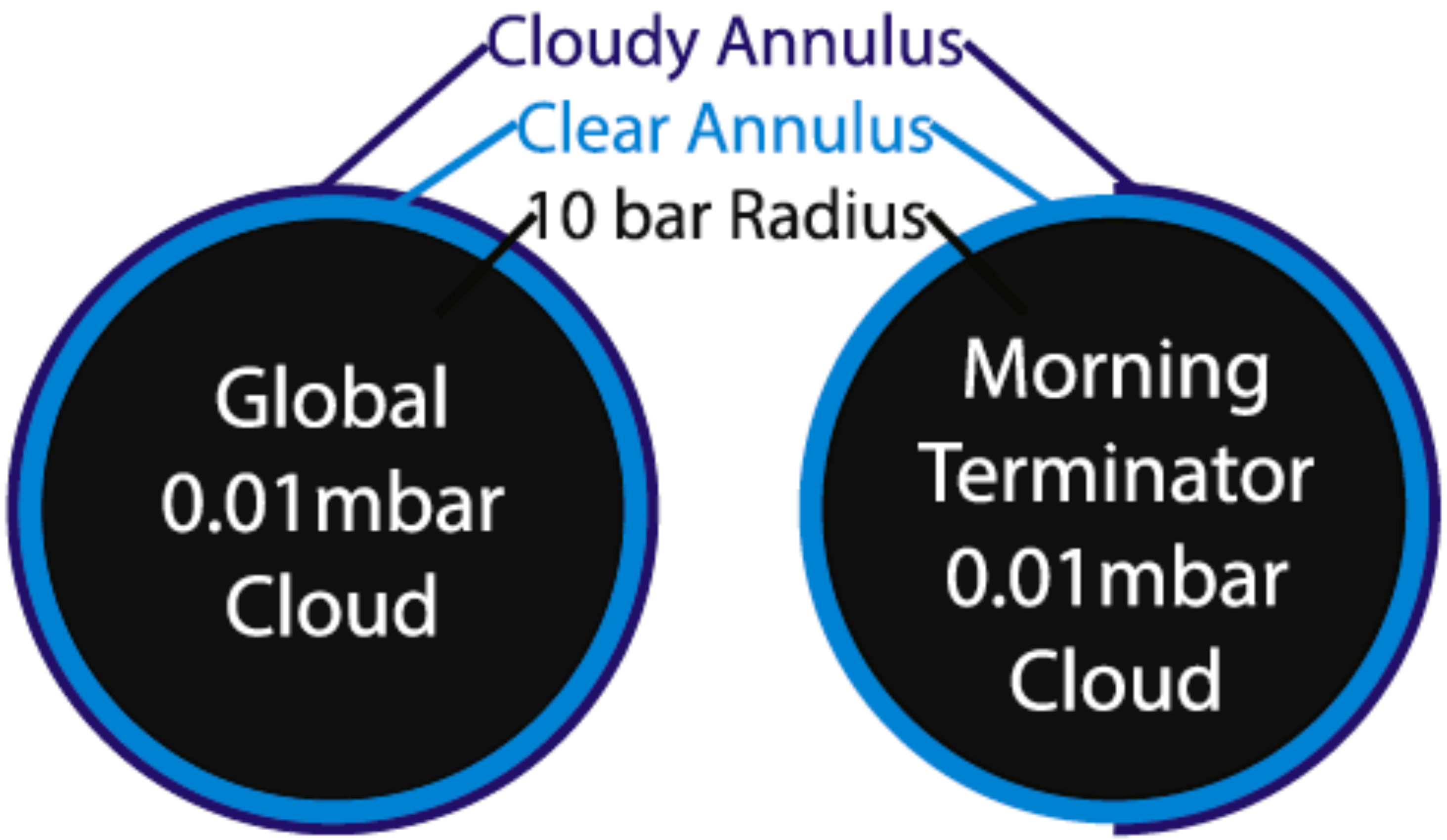
**We often debate what "Things" we want…

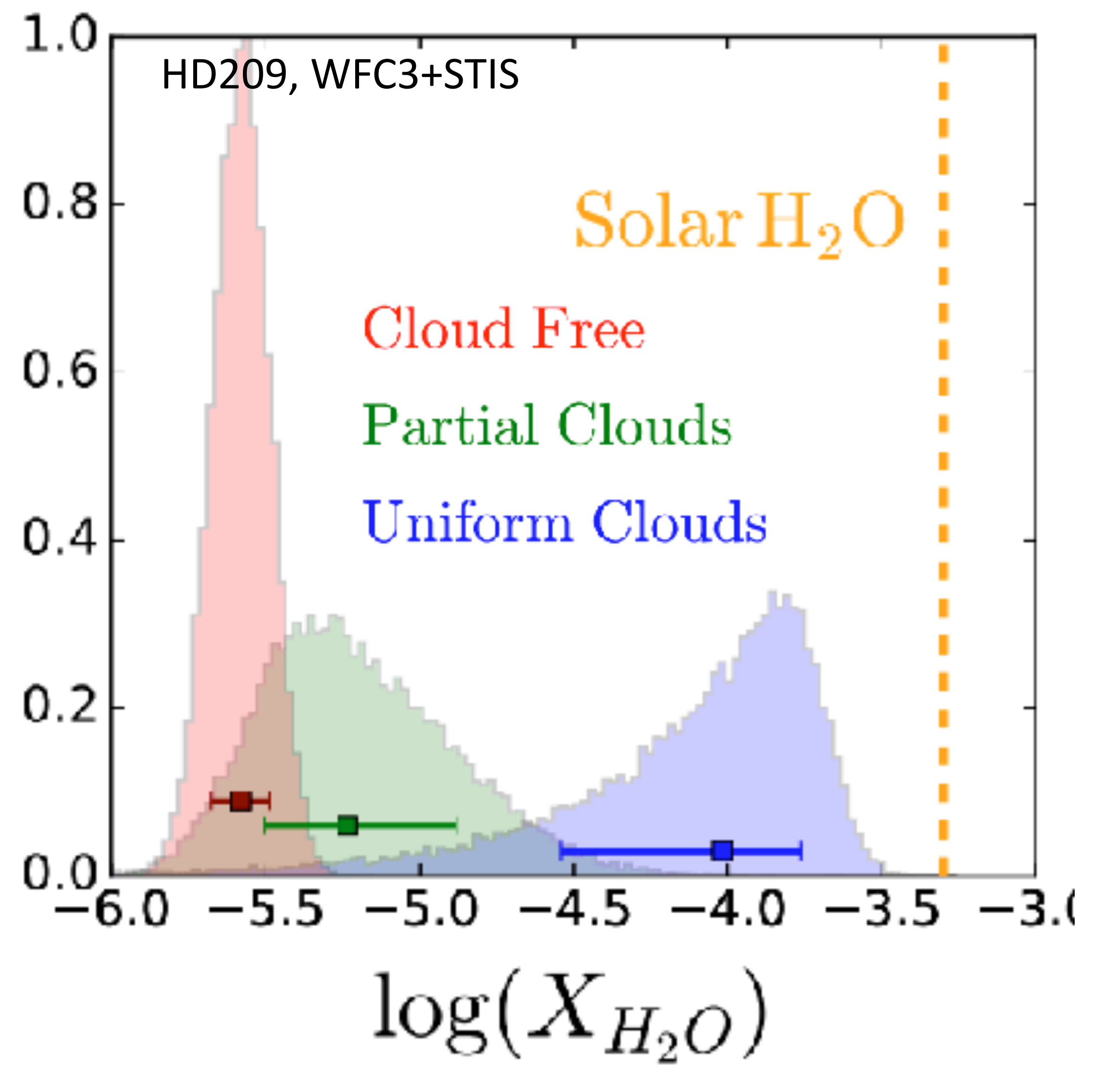
$$\vec{Physics} = A^{-1}\vec{Obs}$$

A range of model assumptions

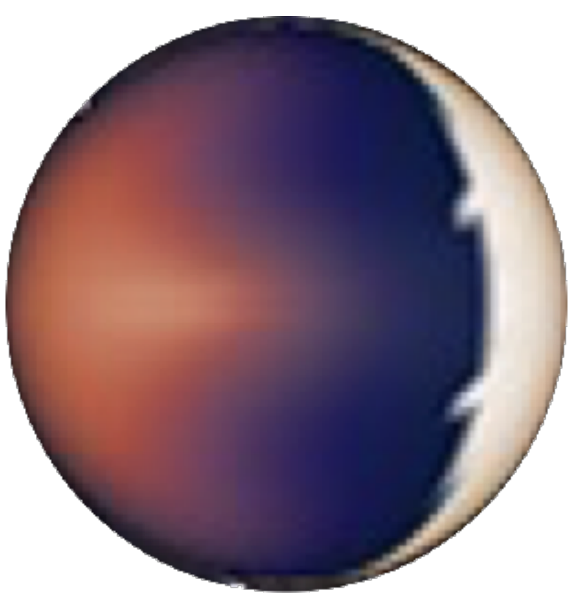
	Less assumptions More parameters		More assumptions Less parameters
Temperature profile	Free Semi-grey	1D Radiative/conv eq. Non-grey	2D/3D radiative/conv eq.
Chemistry	Free chemistry — Choice of species — Vertical profile	Equilibrium Choice of free parameters [M/H], [C/O] others ?	1/2/3D disequilibrium
Clouds	Parametrized Absorbing Grey	Simple equilibrium clouds Scattering, non-grey	Microphysics bin vs. moment ?
Geometry	1D	2D — Lat/long 2D — Limb depth	3D radiative transfer
Stars	Blackbody	1D stellar model	Inhomogeneous stellar model

3D effects : non-uniform clouds

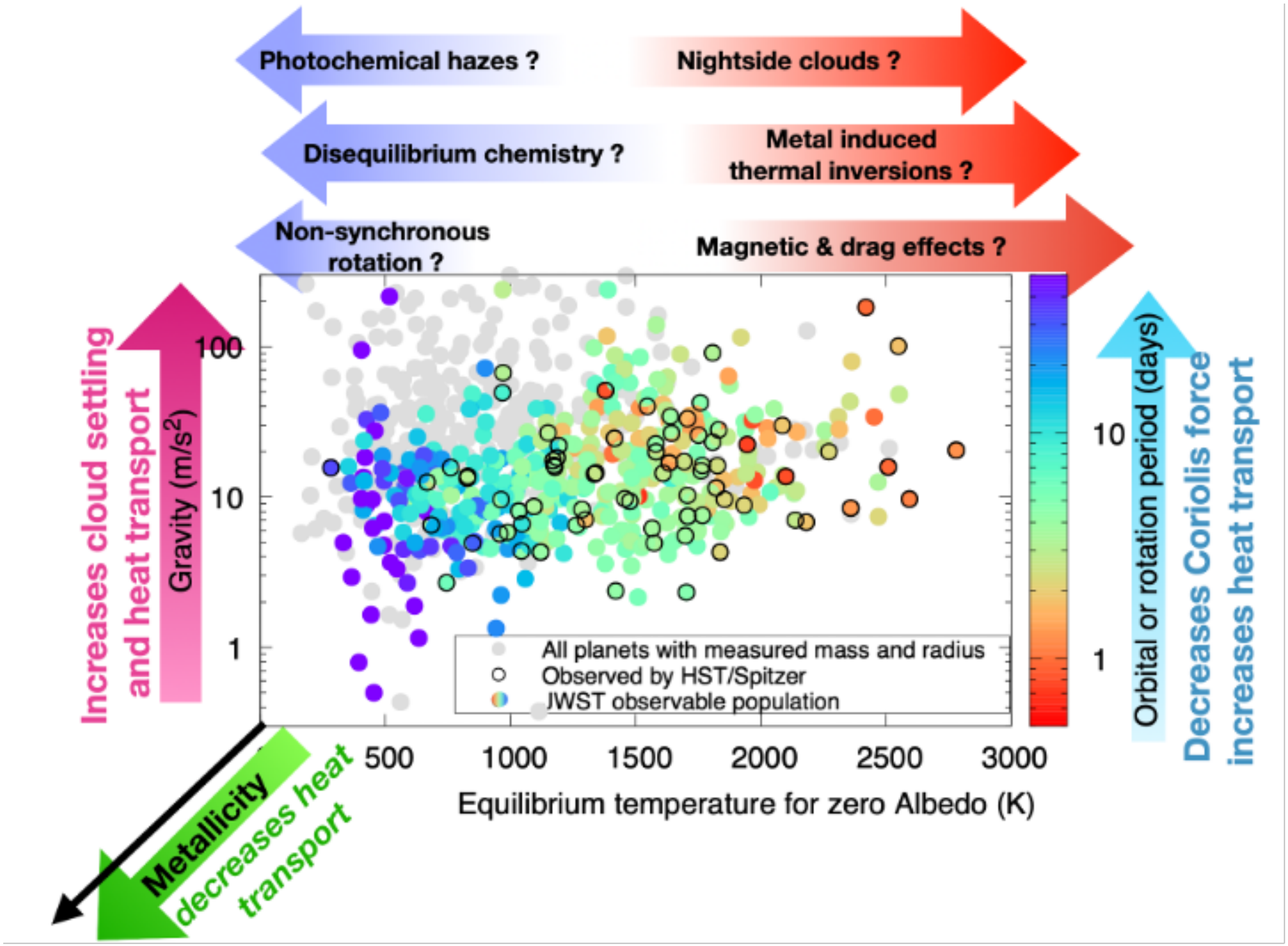




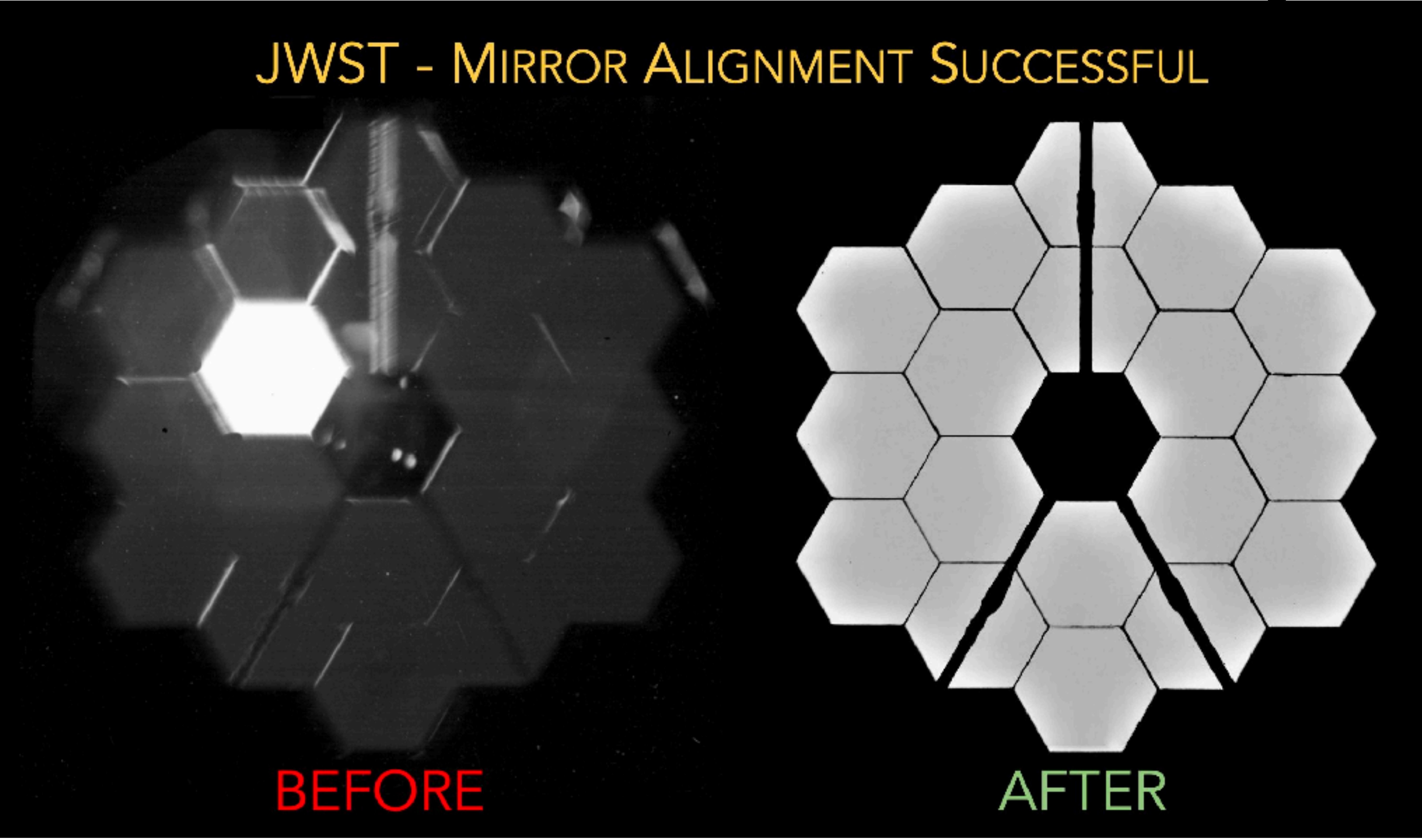
Line & Parmentier 2016; MacDonald & Madhusudhan 2017

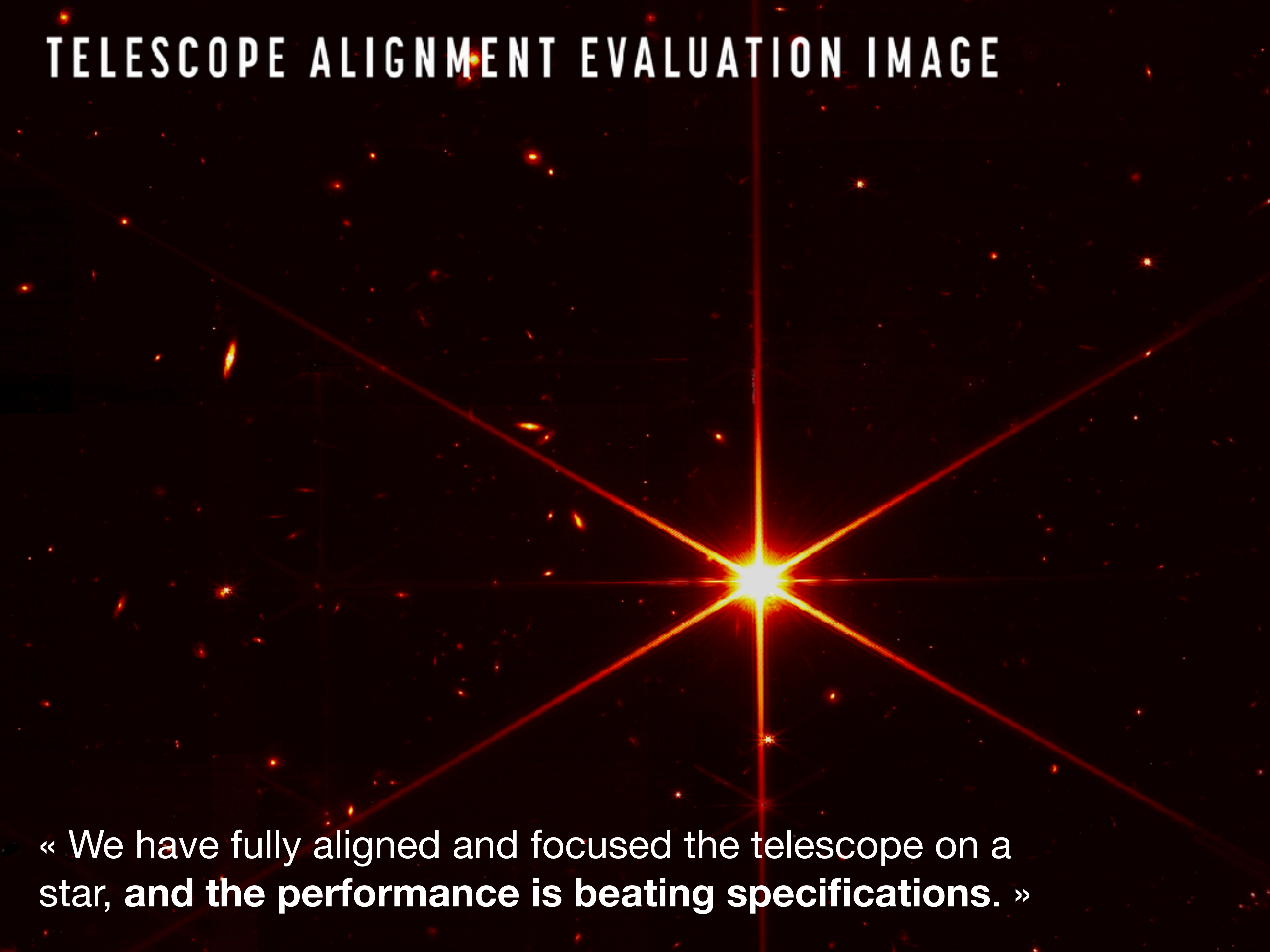


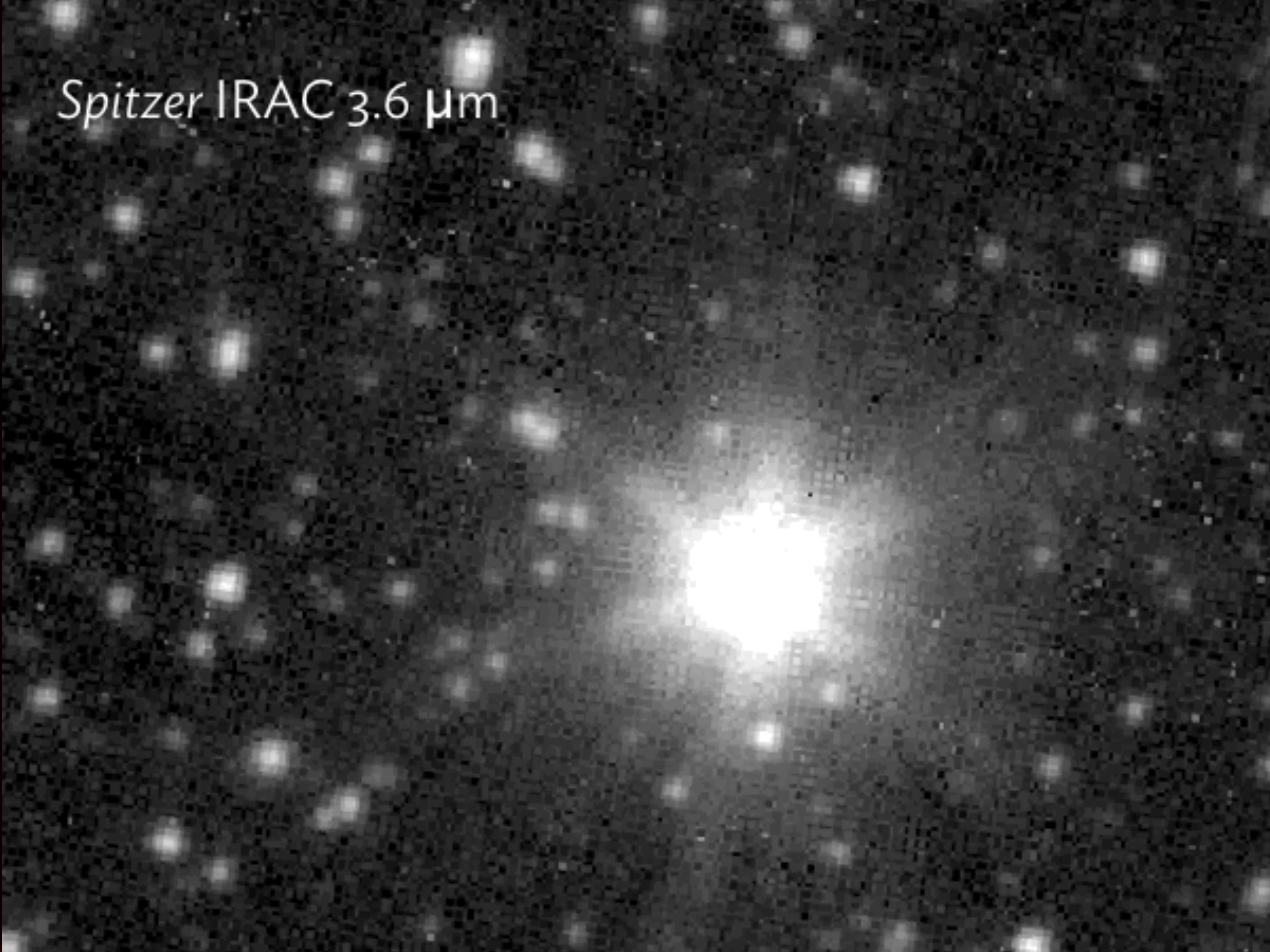
What part of the diversity is due to processes rather than formation ?



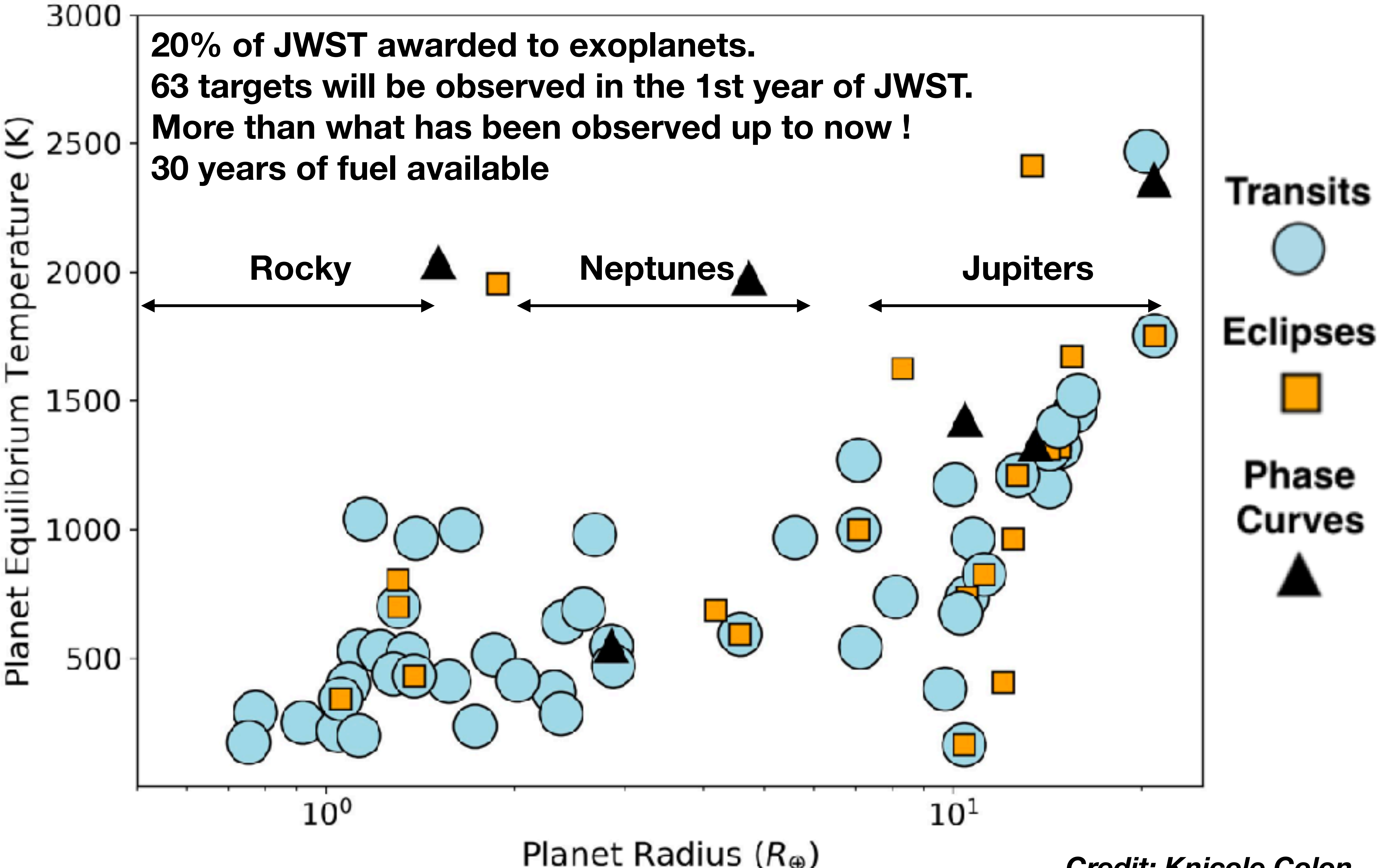

JWST launched on perfect trajectory
We have fuel for 30 years !


JWST - Mirror Alignment Successful
BEFORE
AFTER


TELESCOPE ALIGNMENT EVALUATION IMAGE
« We have fully aligned and focused the telescope on a star, **and the performance is beating specifications.** »

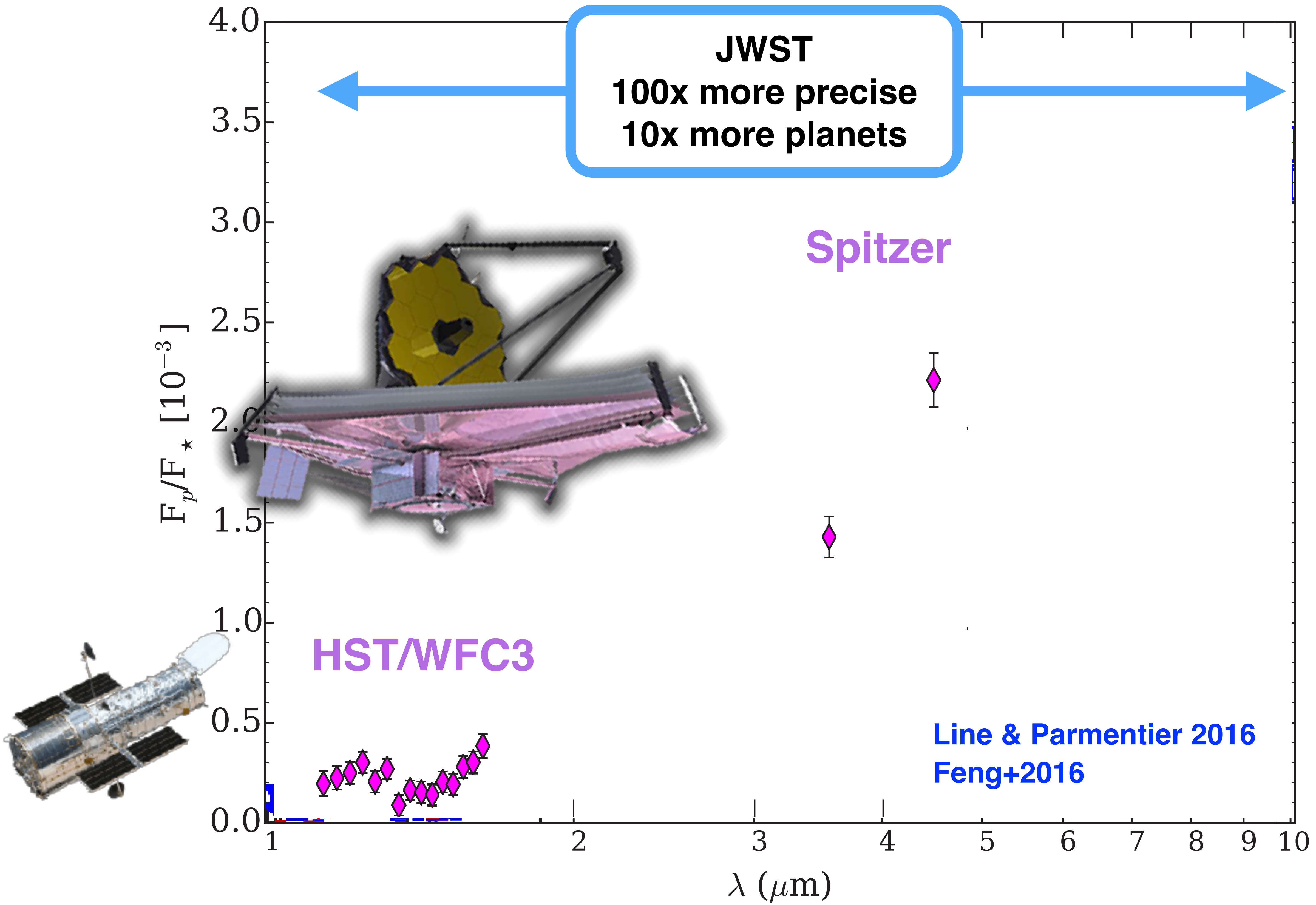

Spitzer IRAC 3.6 μm

The 1st year of JWST

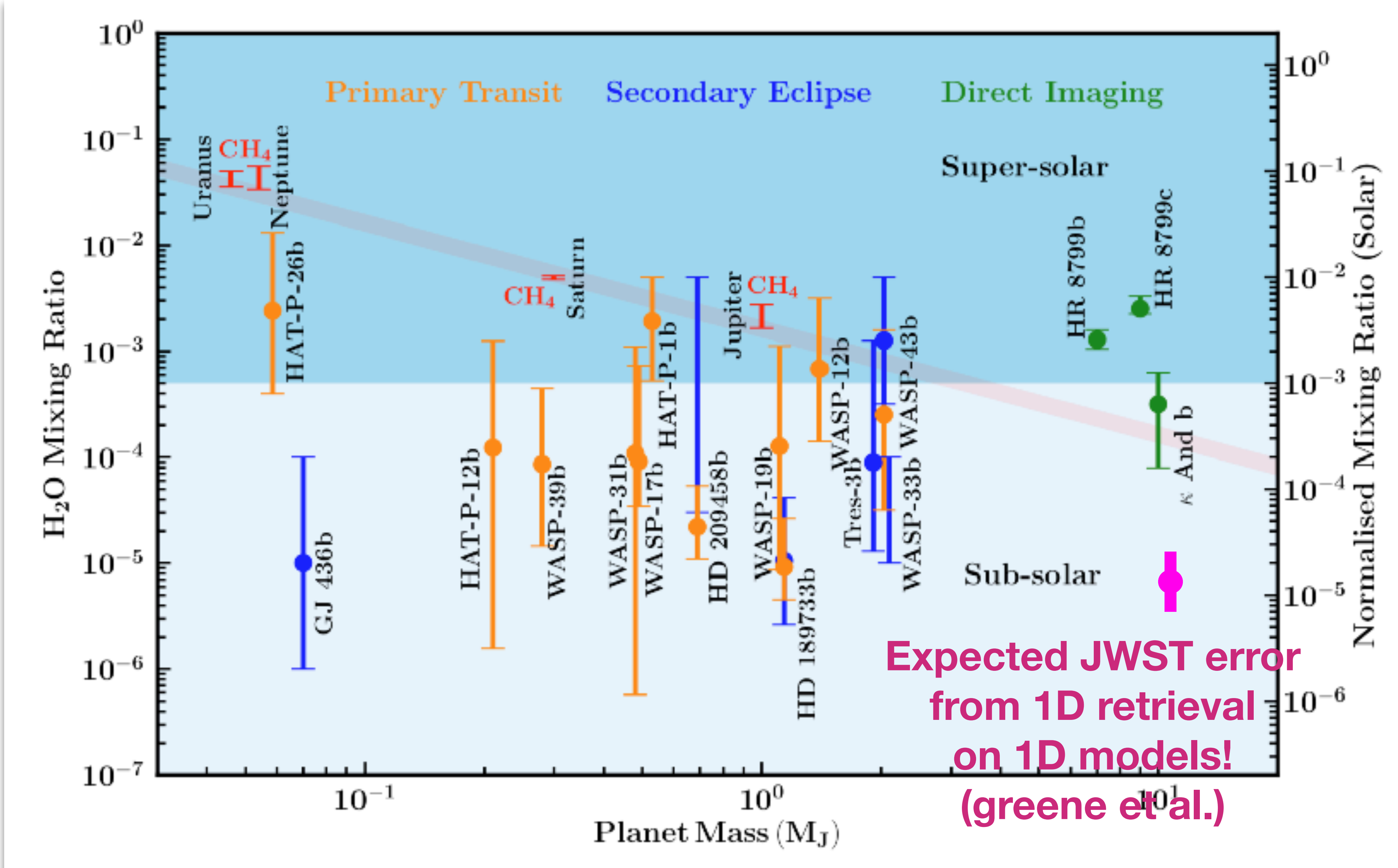


Credit: Knicole Colon

The future of exoplanets : JWST

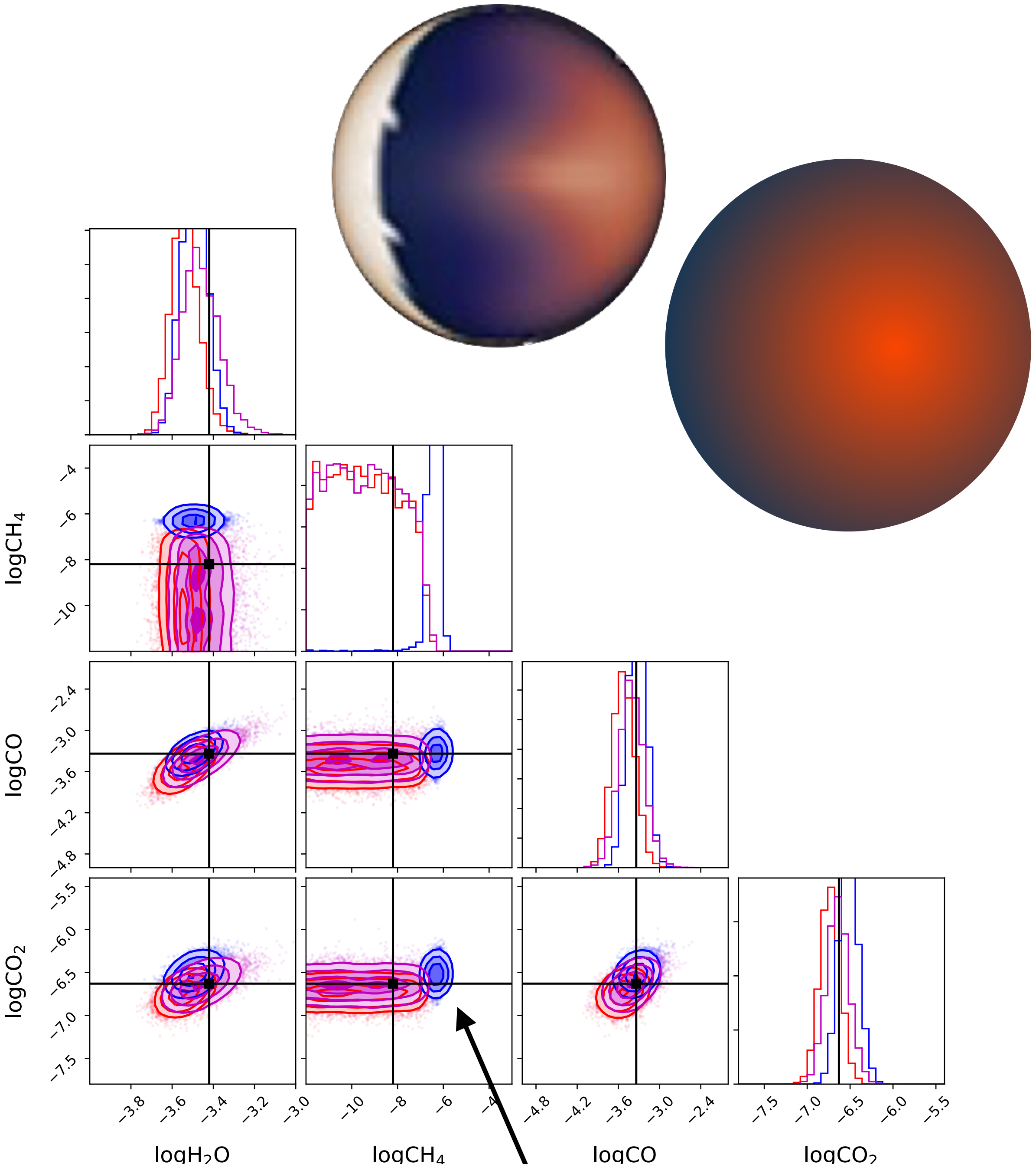


Abundances retrievals from spectra

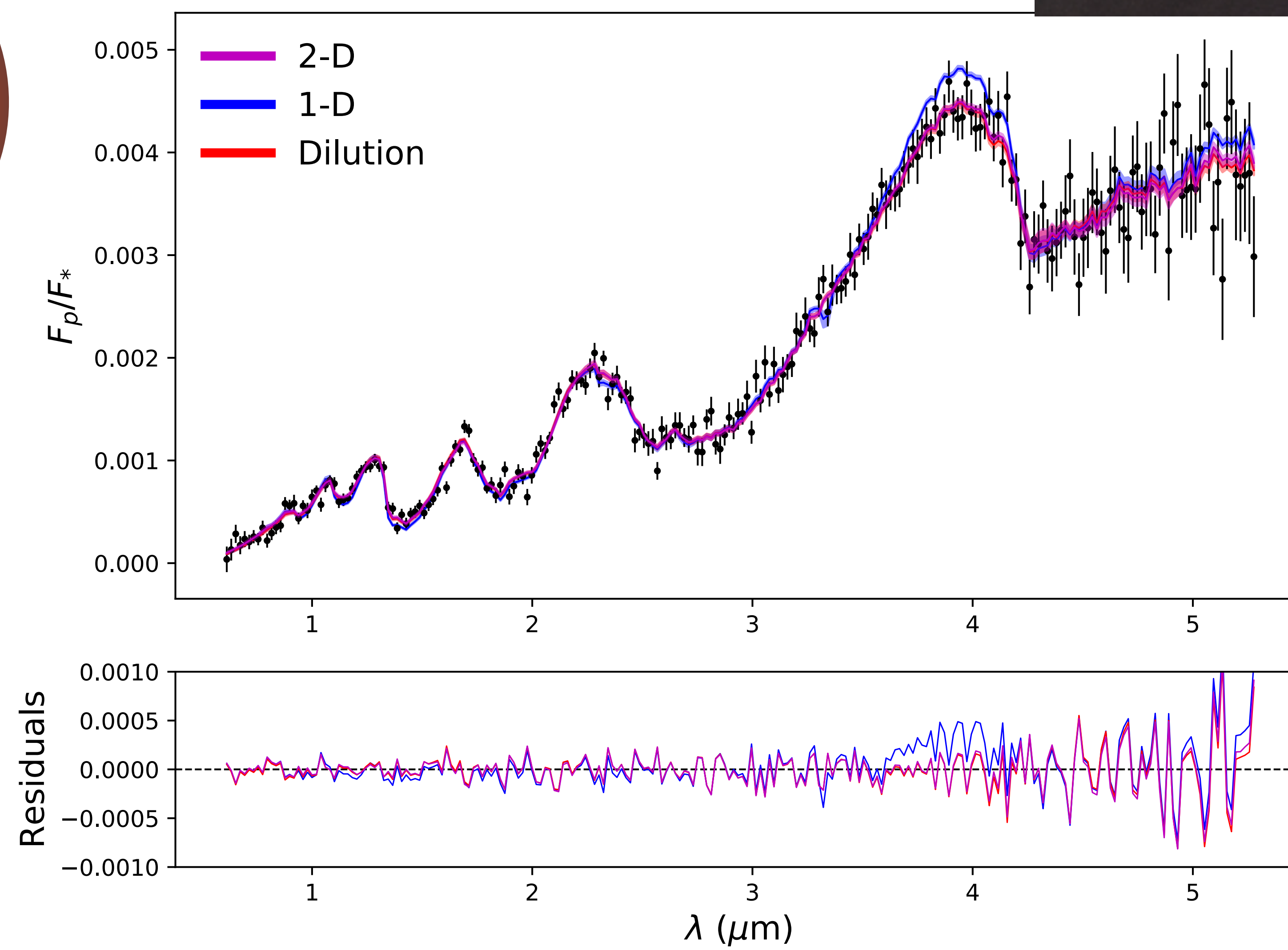


JWST should get us ~0.3 dex precision !

3D effects : non-uniform temperatures in emission



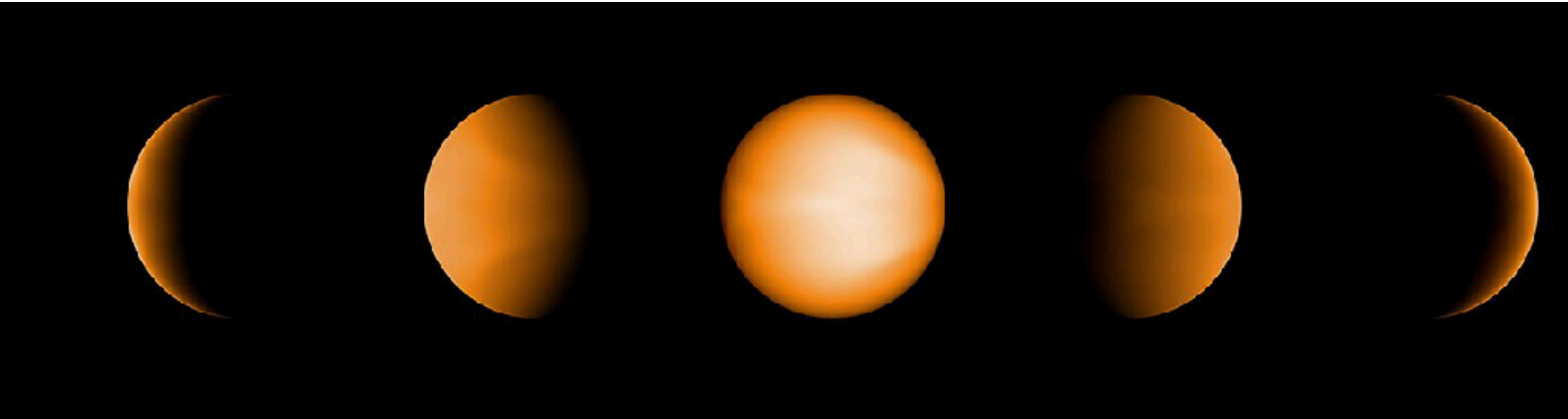
Work by Jake Taylor
now postdoc at McGill, canada



CH4 detection !

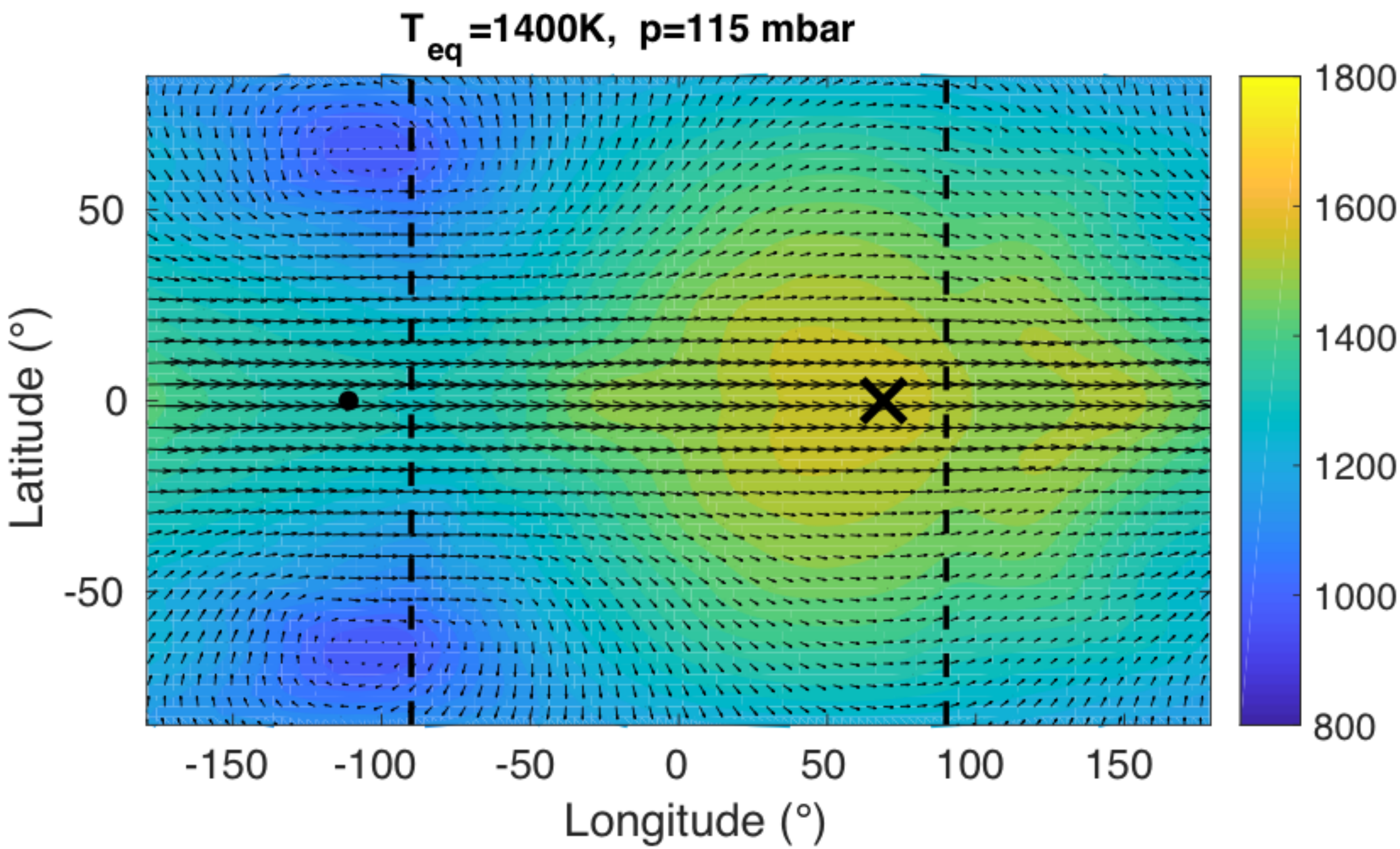
Taylor et al. 2020

We need to understand all aspects of planetary atmospheres before we can retrieve precise and accurate abundances from spectra and separate formation from evolution processes.



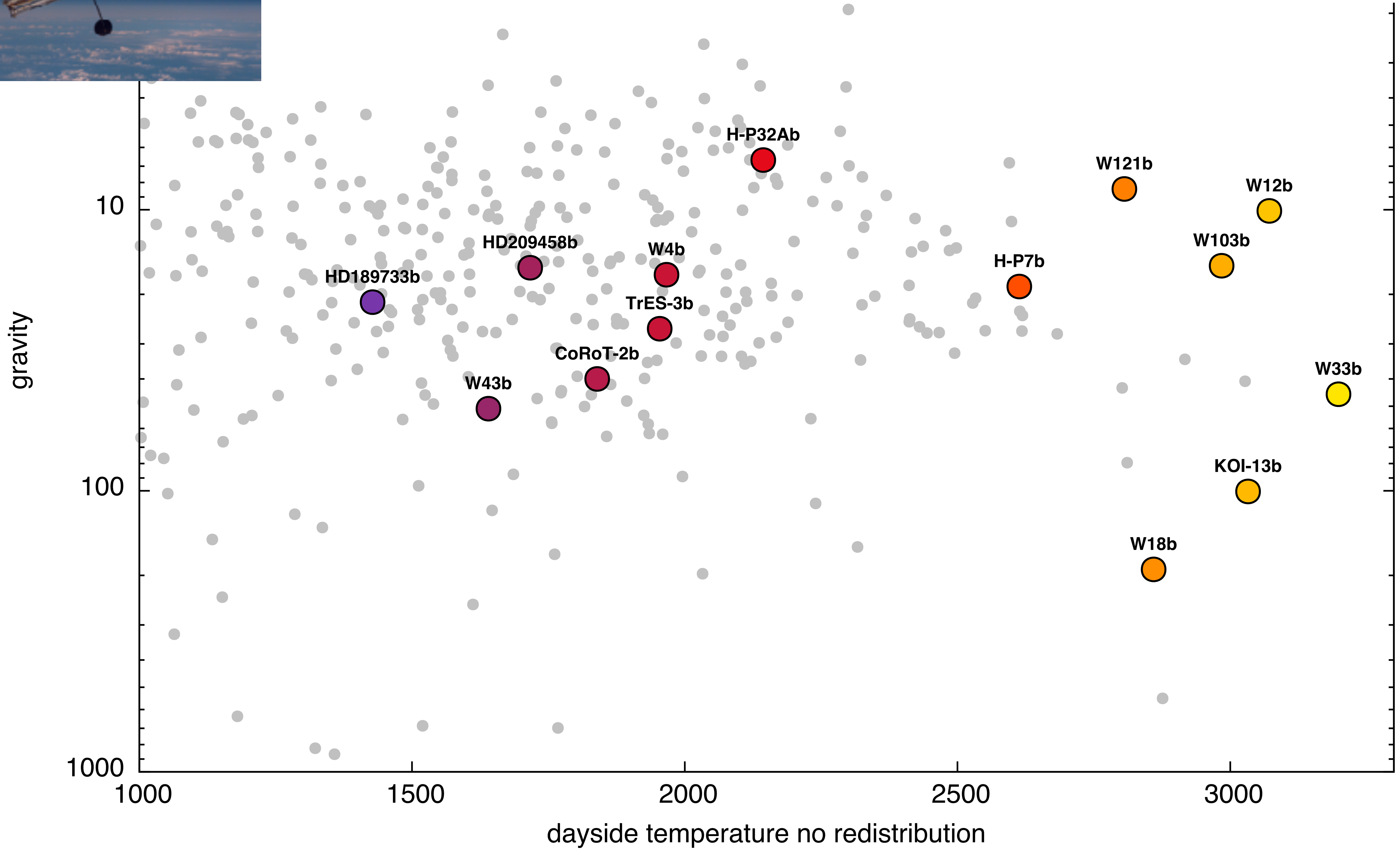
Temperature and clouds of a Hot Jupiter with SPARC/MITgcm

G*lobal* ***C****irculation* ***M****odel* : solves the primitive equation, Euler equation adapted to atmospheres
SPARC : solves the radiative energy balance with non-grey, molecular opacities



Parmentier+2020

HST/WFC3 observed 14 planets in secondary eclipse



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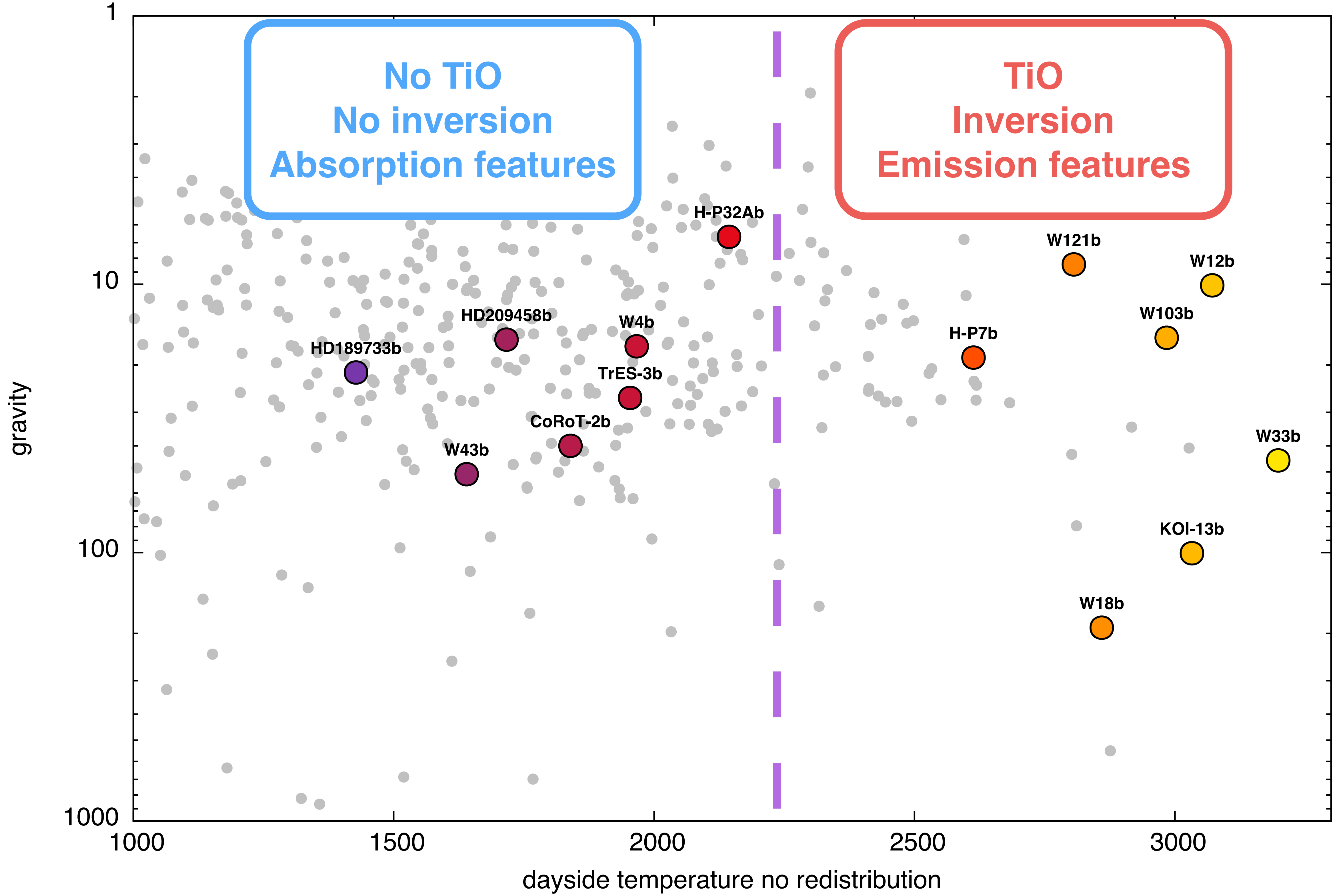
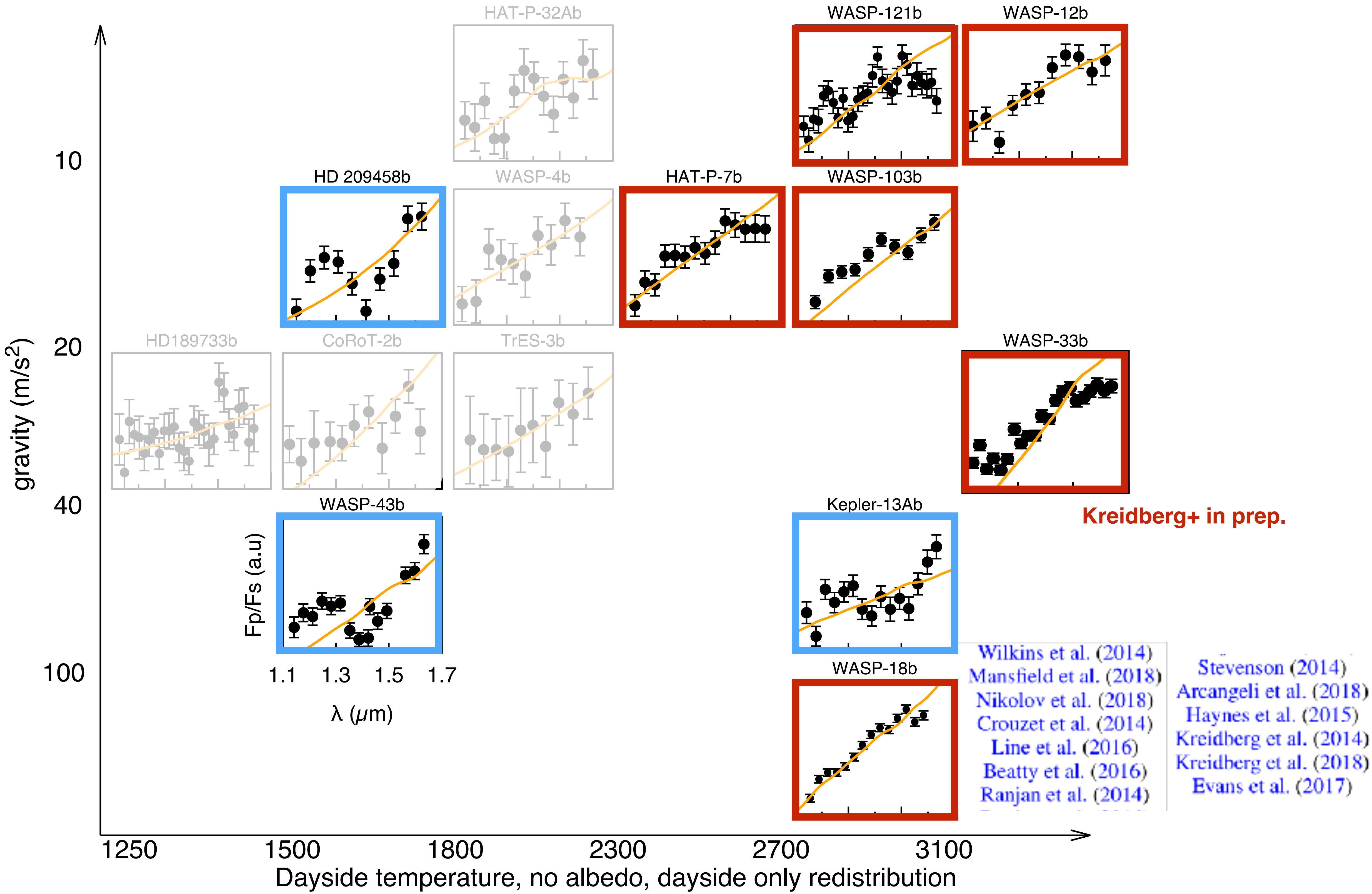
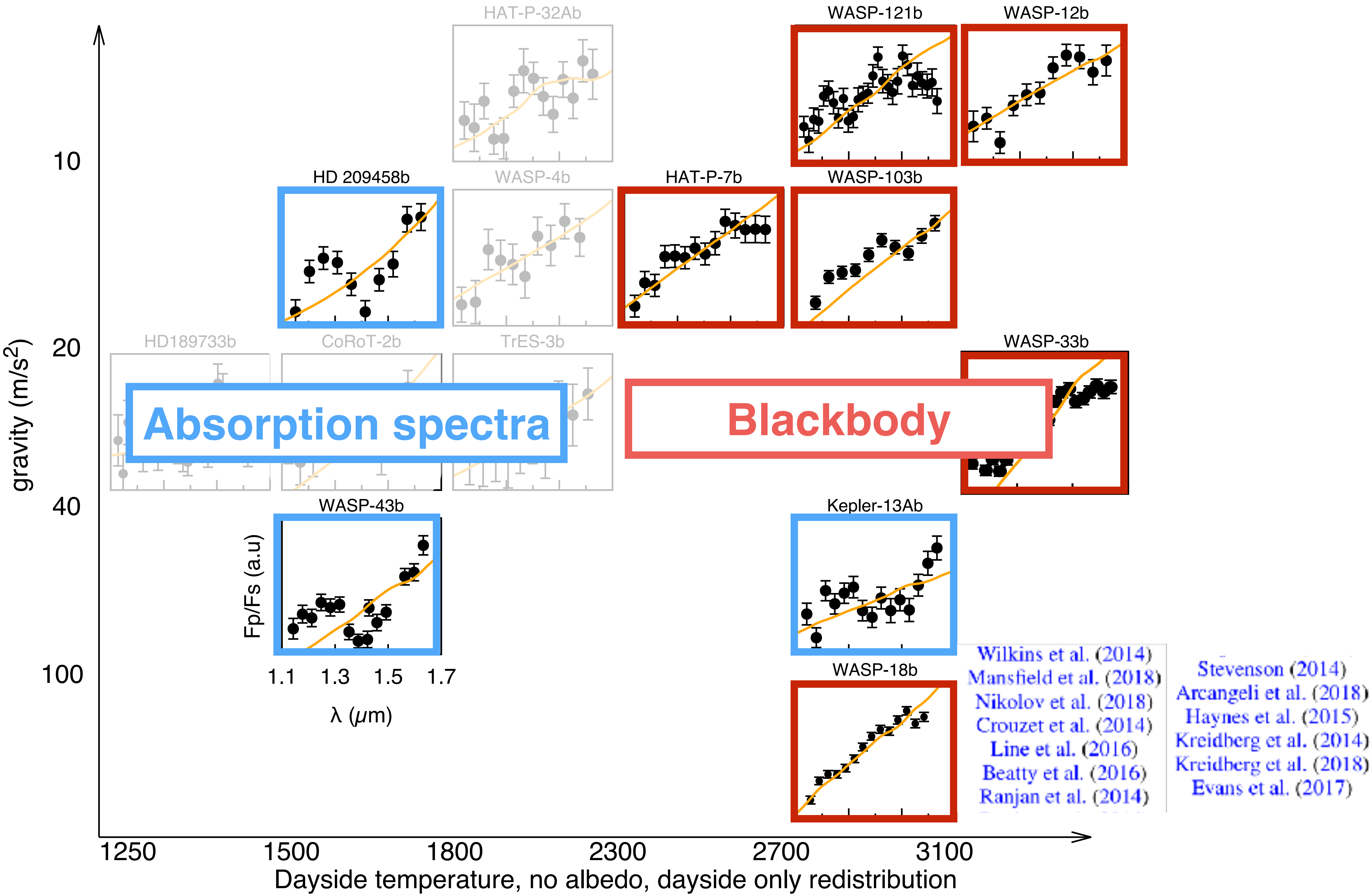


HST/WFC3 observed secondary eclipses



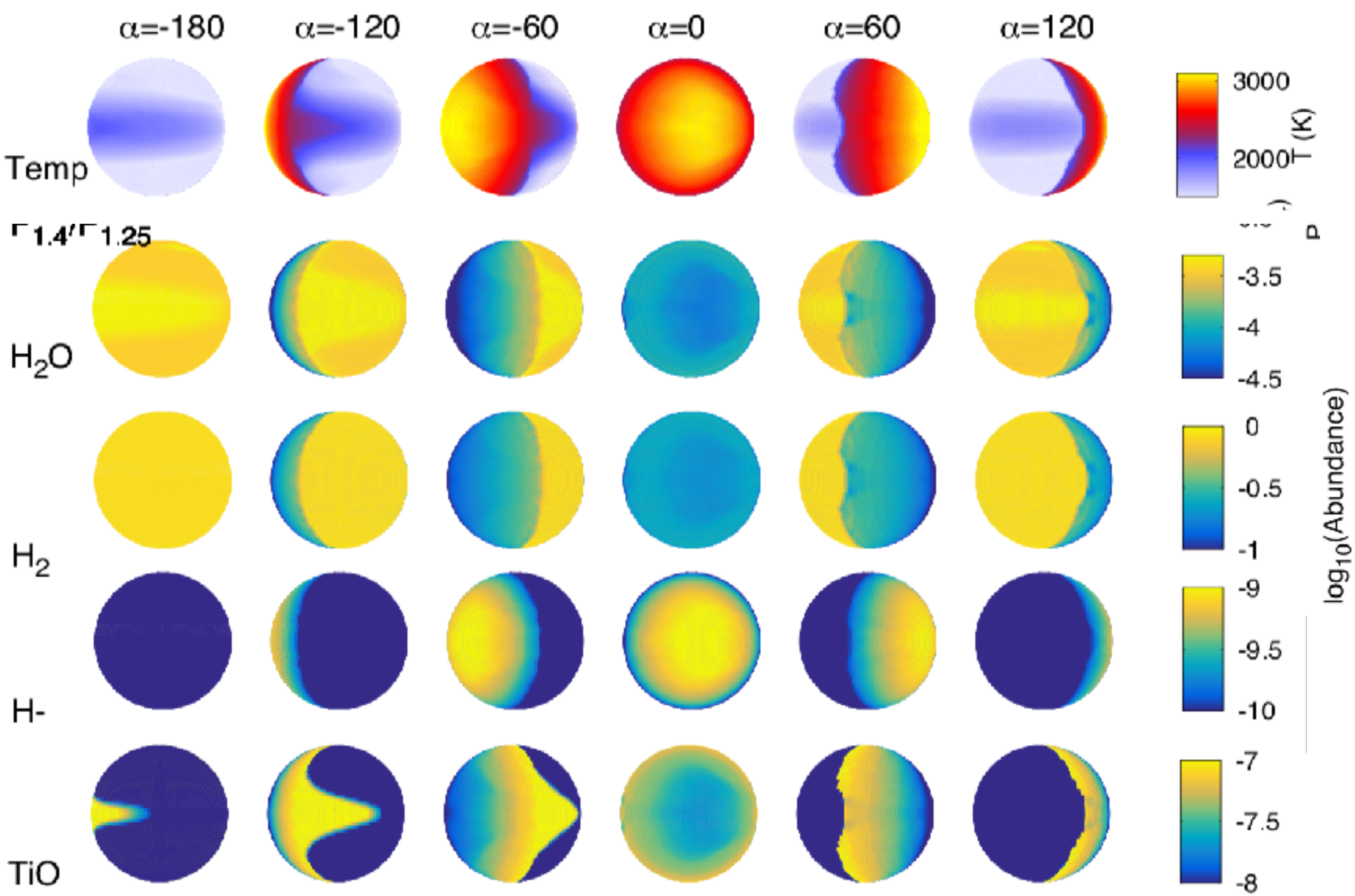
Parmentier+2018

HST/WFC3 observed secondary eclipses



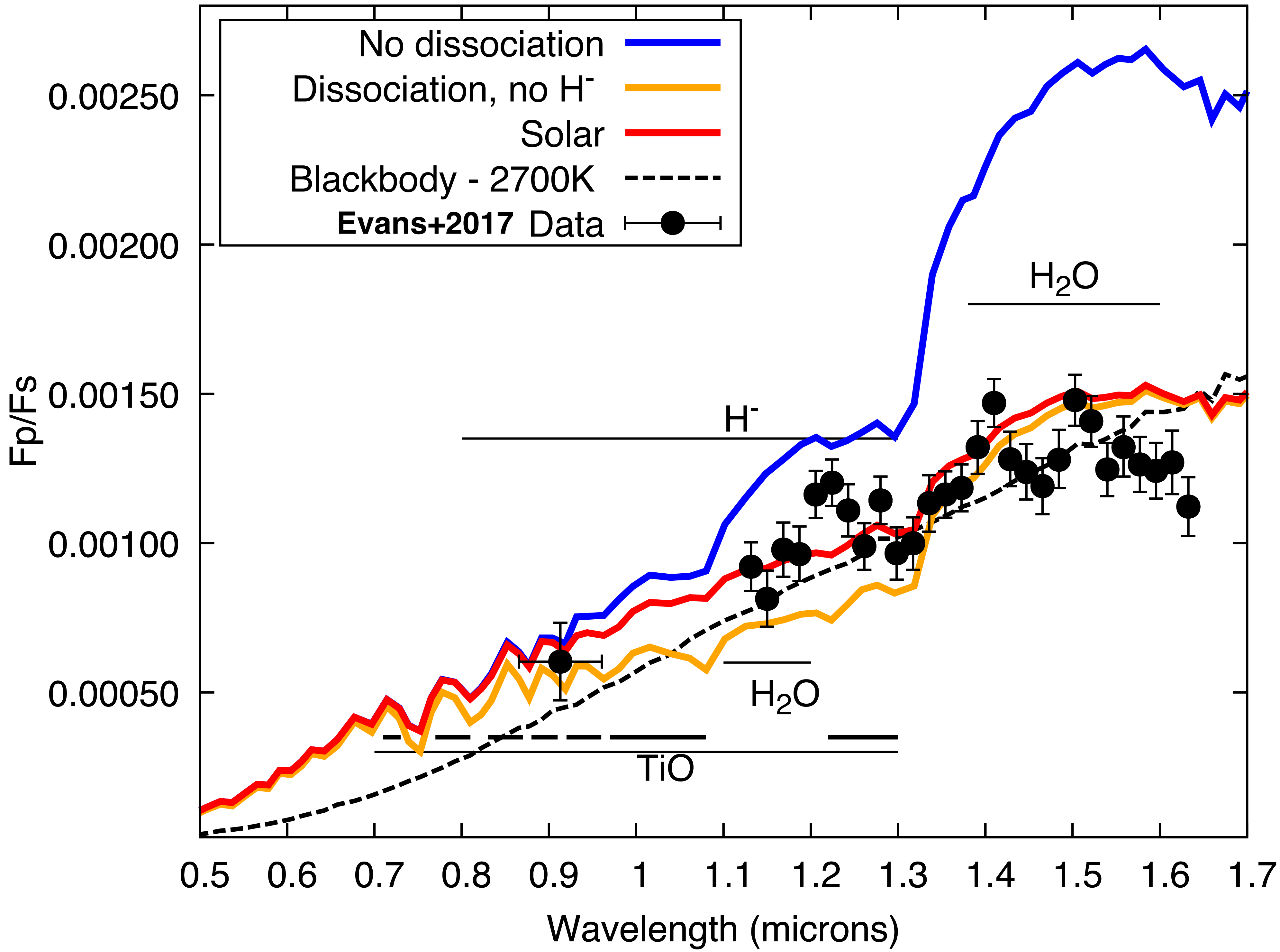
Parmentier+2018

SPARC/MITgcm: solving the dynamics and radiative transfer eq.



Parmentier+2018

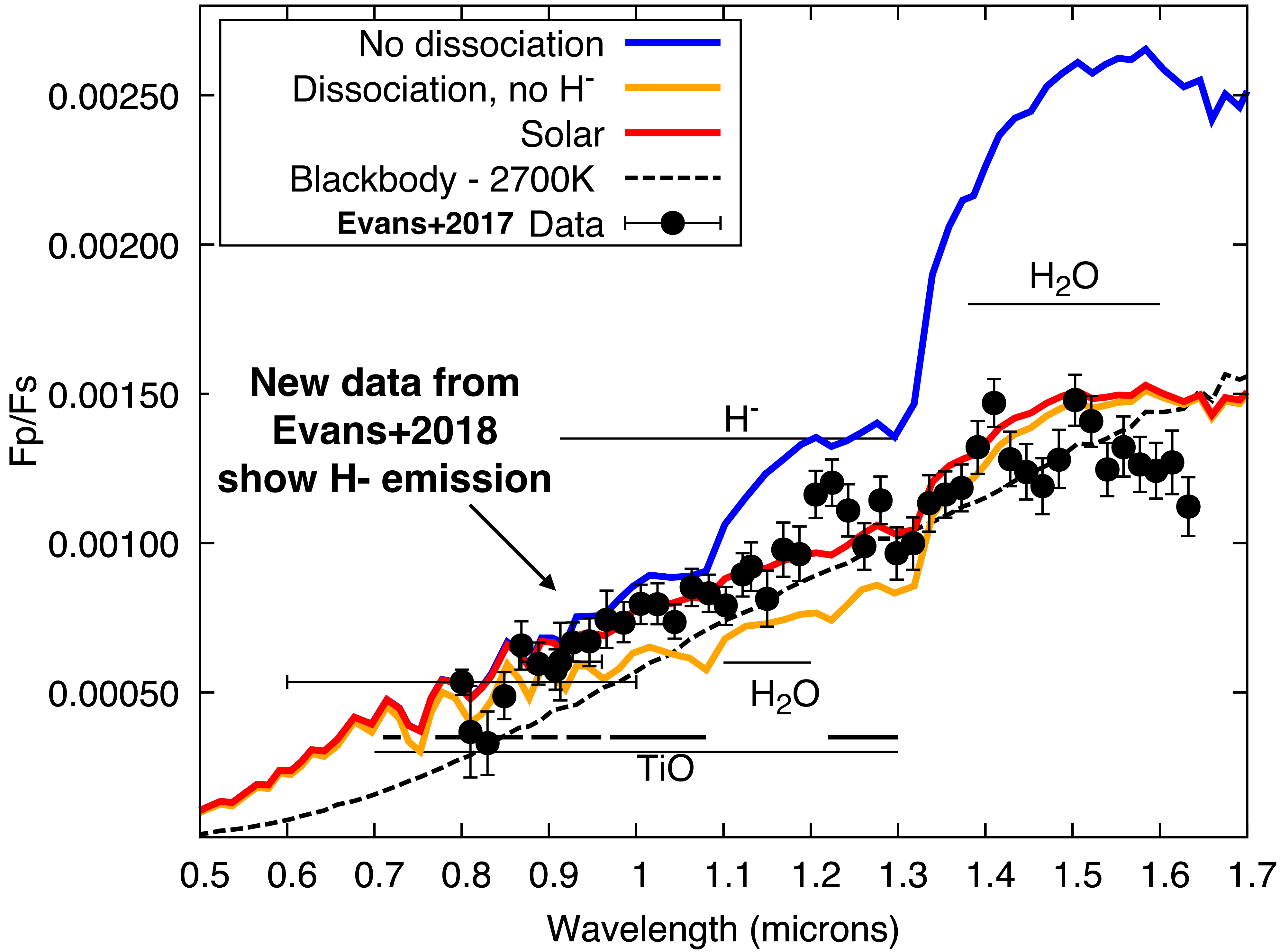
Molecular gradient and H- shape the spectrum



Parmentier+ 2018

Spectra from SPAC/MITgcm global circulation model including chemical eq. and non-grey rad. transfer

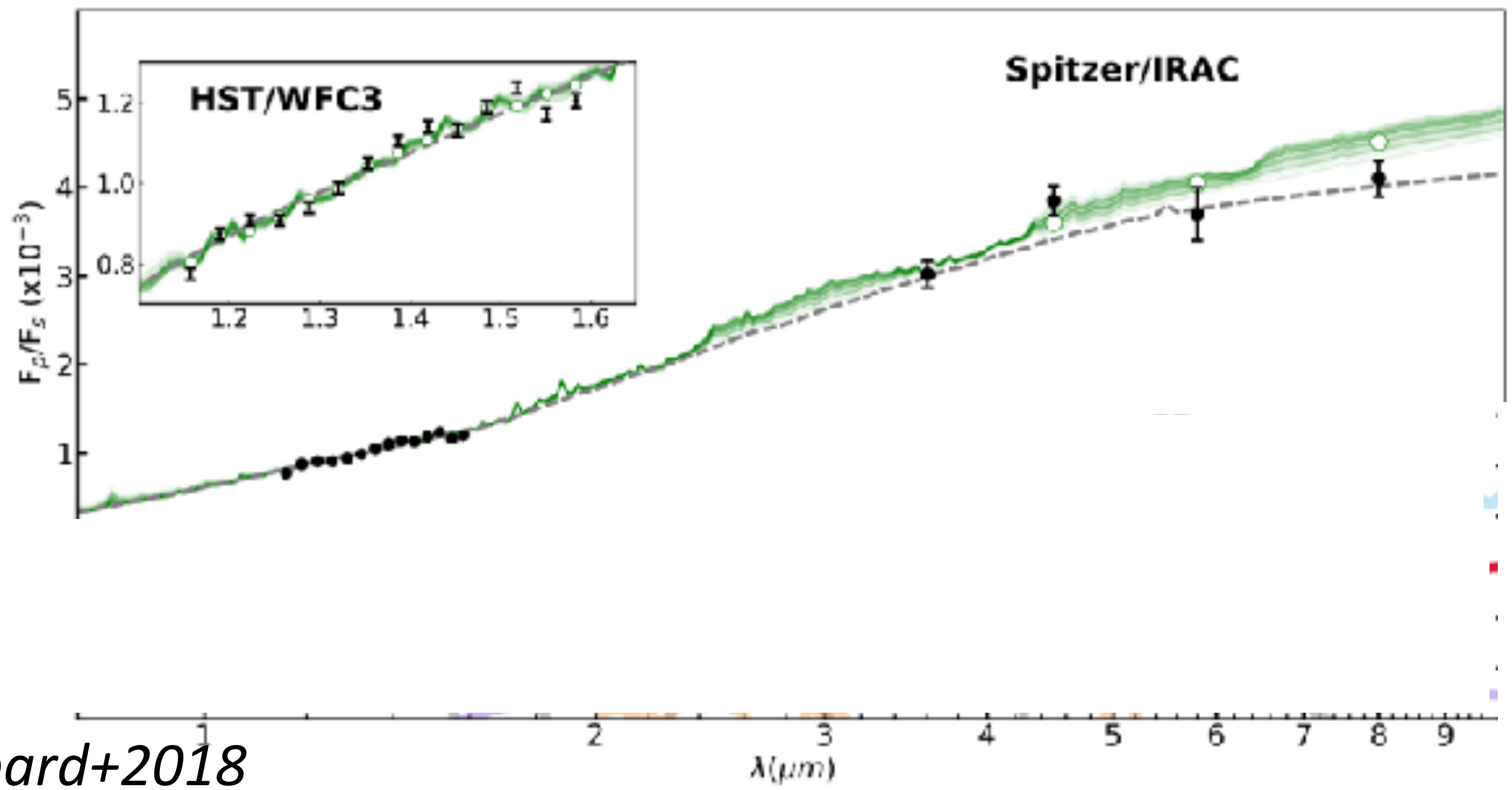
Molecular gradient and H- shape the spectrum



Spectra from SPAC/MITgcm global circulation model including chemical eq. and non-grey rad. transfer

Parmentier+ 2018

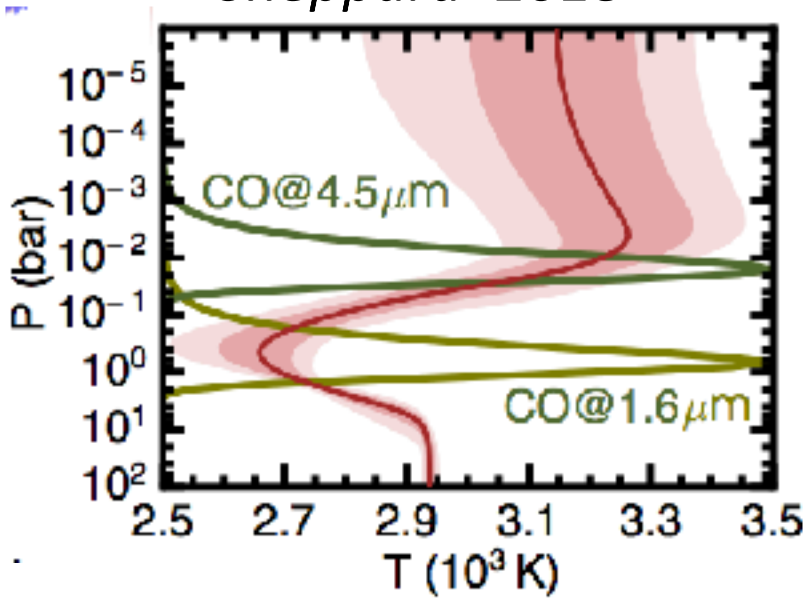
« Free » vs. « self-consistent » thermal and chemistry 1D retrievals



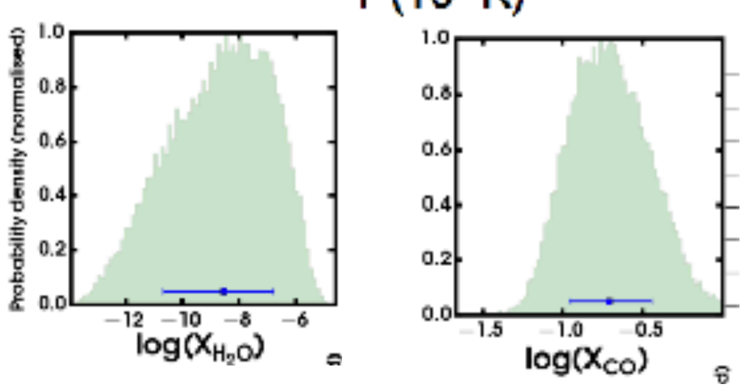
Hot Jupiter
WASP-18b
Teq~2500K

Self-Consistent 1D grid
MCMC interpolation

Sheppard+2018

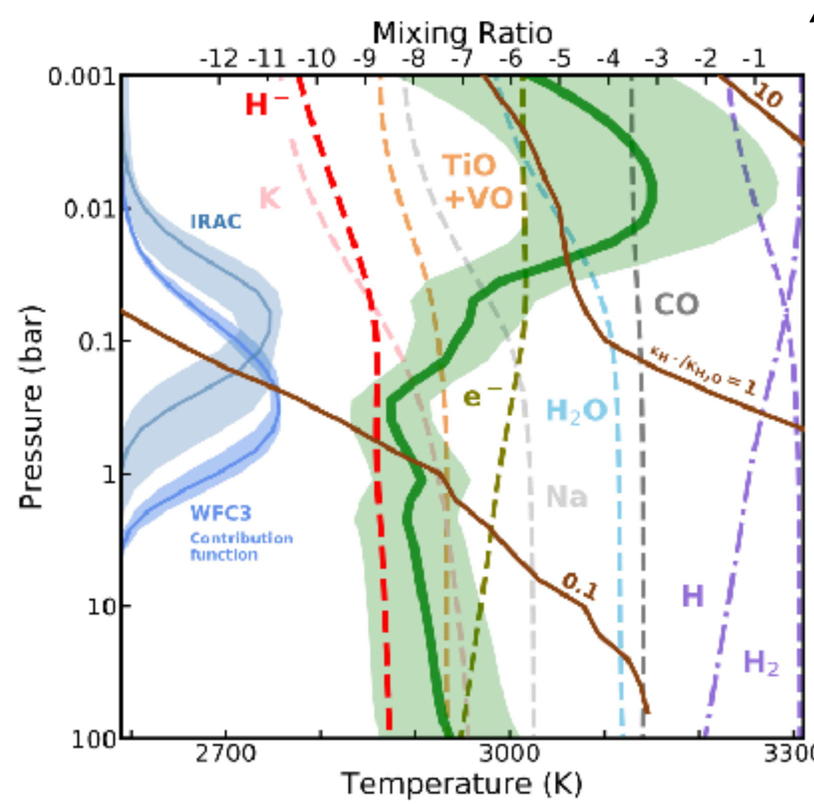


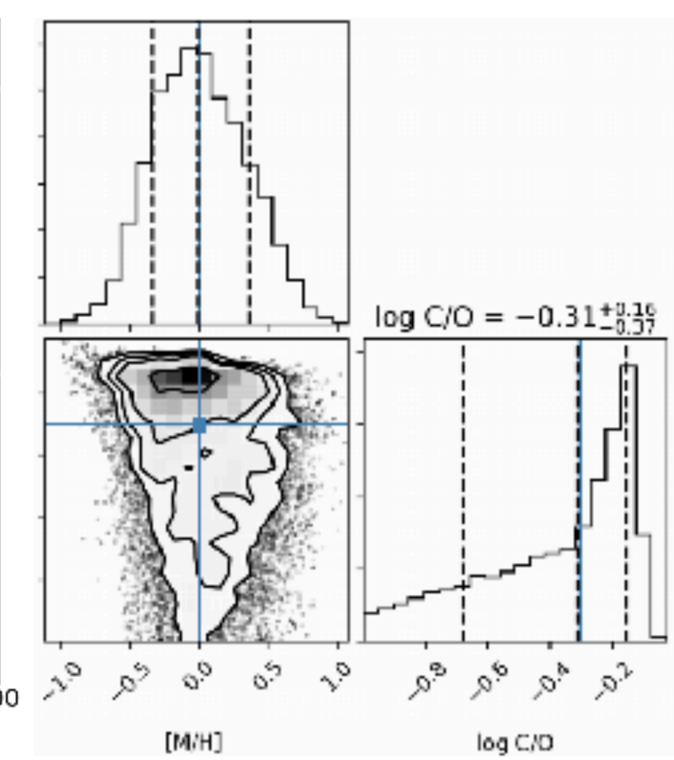
"Free
Retrieval"



~300x Solar
C/O~1
CO=20% of

Arcangeli+2018

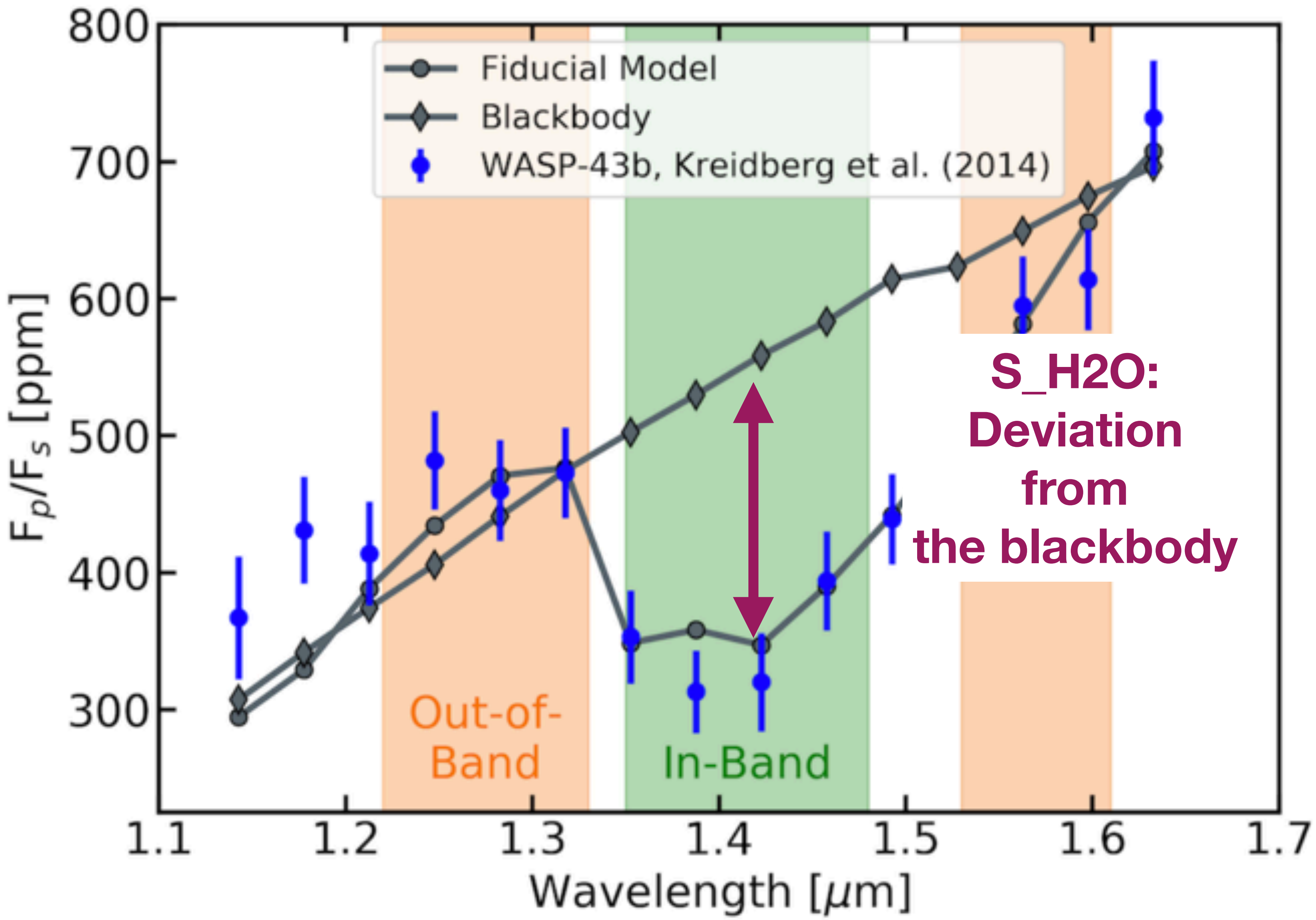




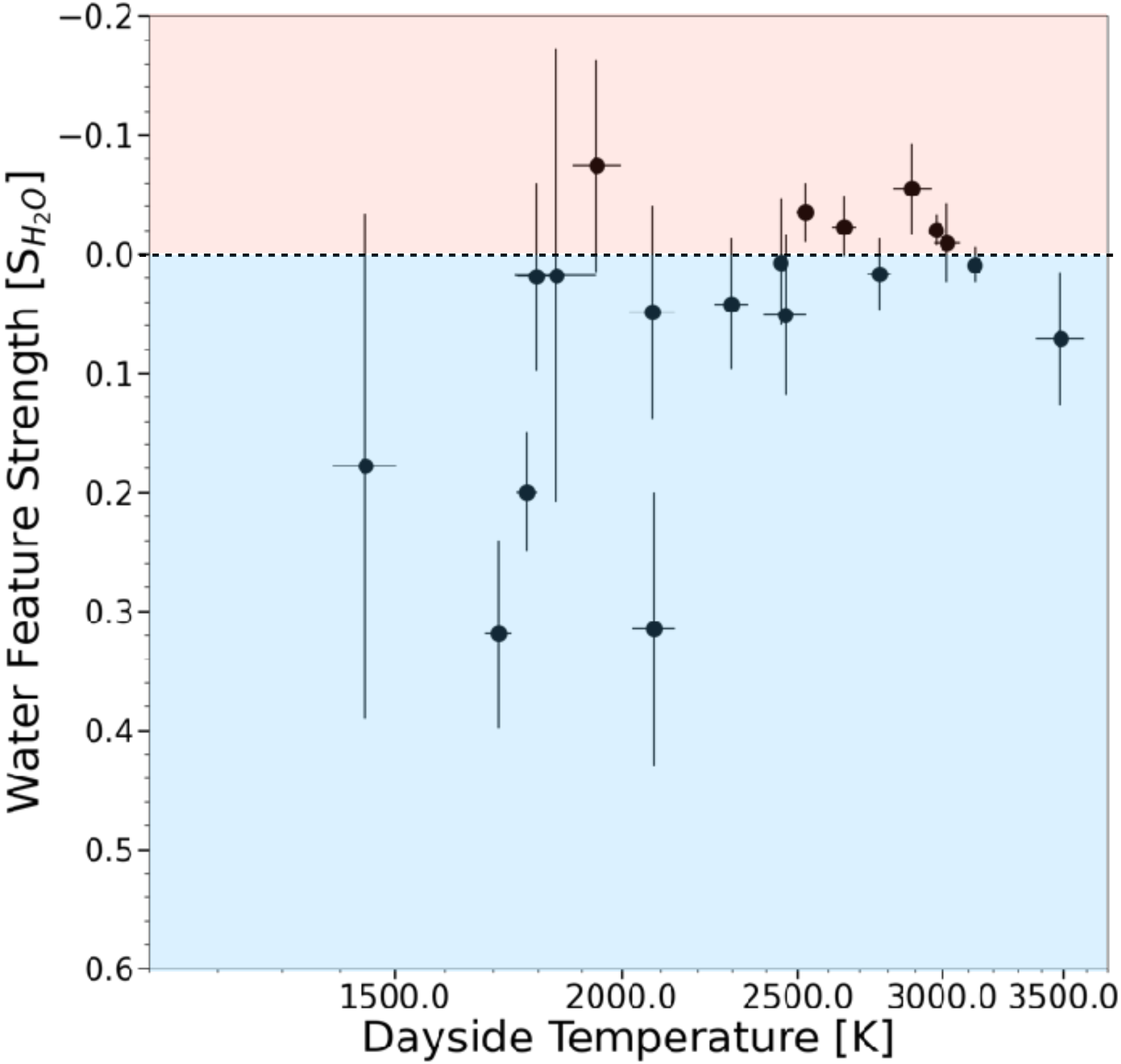
Solar Comp!

What about population trends ?

Supplementary Figures



SPARC/MITgcm: a population study



Emission feature

Blackbody

Absorption feature

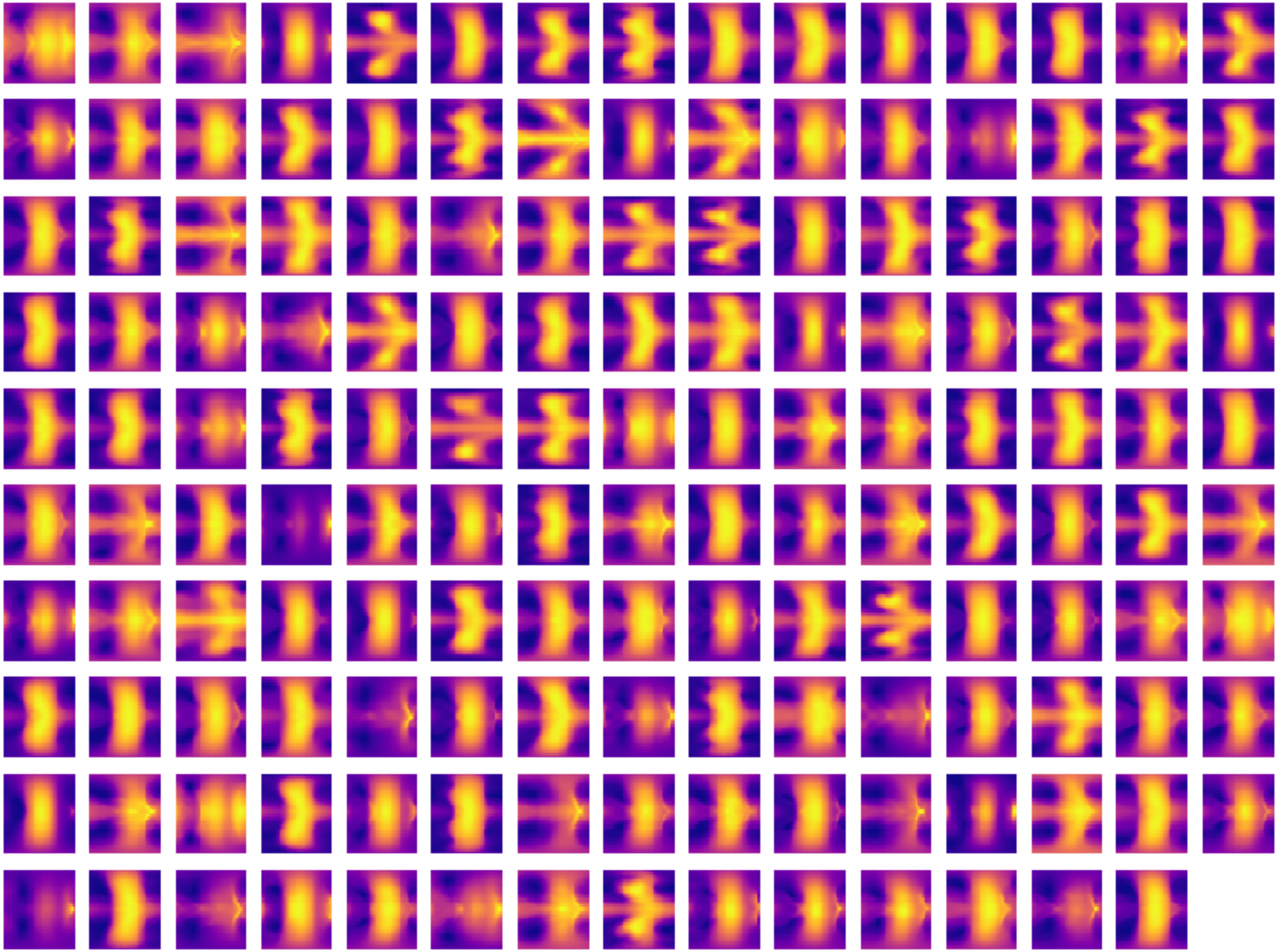
SPARC/MITgcm: a population study

A large grid of 149 models, including cross-terms

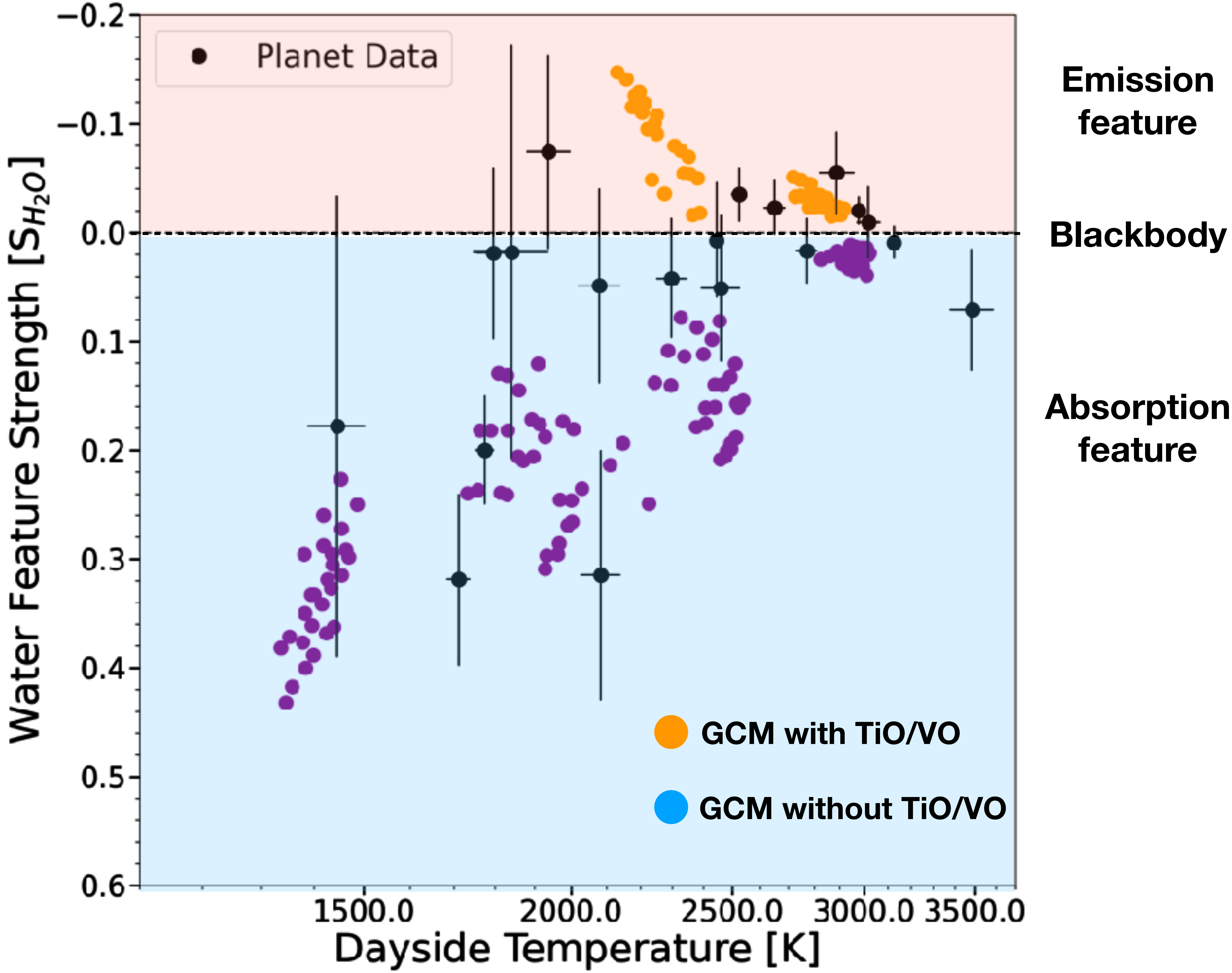
T_{eq} [K]	Log(M/H)	Stellar Mass [M_{sun}]	log(g)	TiO and VO	Number of Models
1200	0.0, 0.7, 1.5	0.8, 1.1, 1.5	0.8, 1.3, 1.8	No	27
1600	0.0, 0.7, 1.5	0.8, 1.1, 1.5	0.8, 1.3, 1.8	No	27
1800	0.0, 0.7, 1.5	0.8, 1.1, 1.5	0.8, 1.3, 1.8	No	4
2000	0.0, 0.7, 1.5	0.8, 1.1, 1.5	0.8, 1.3, 1.8	Yes & No	48
2400	0.0, 0.7, 1.5	0.8, 1.1, 1.5	0.8, 1.3, 1.8	Yes & No	43

Alexander Roth (2nd year)

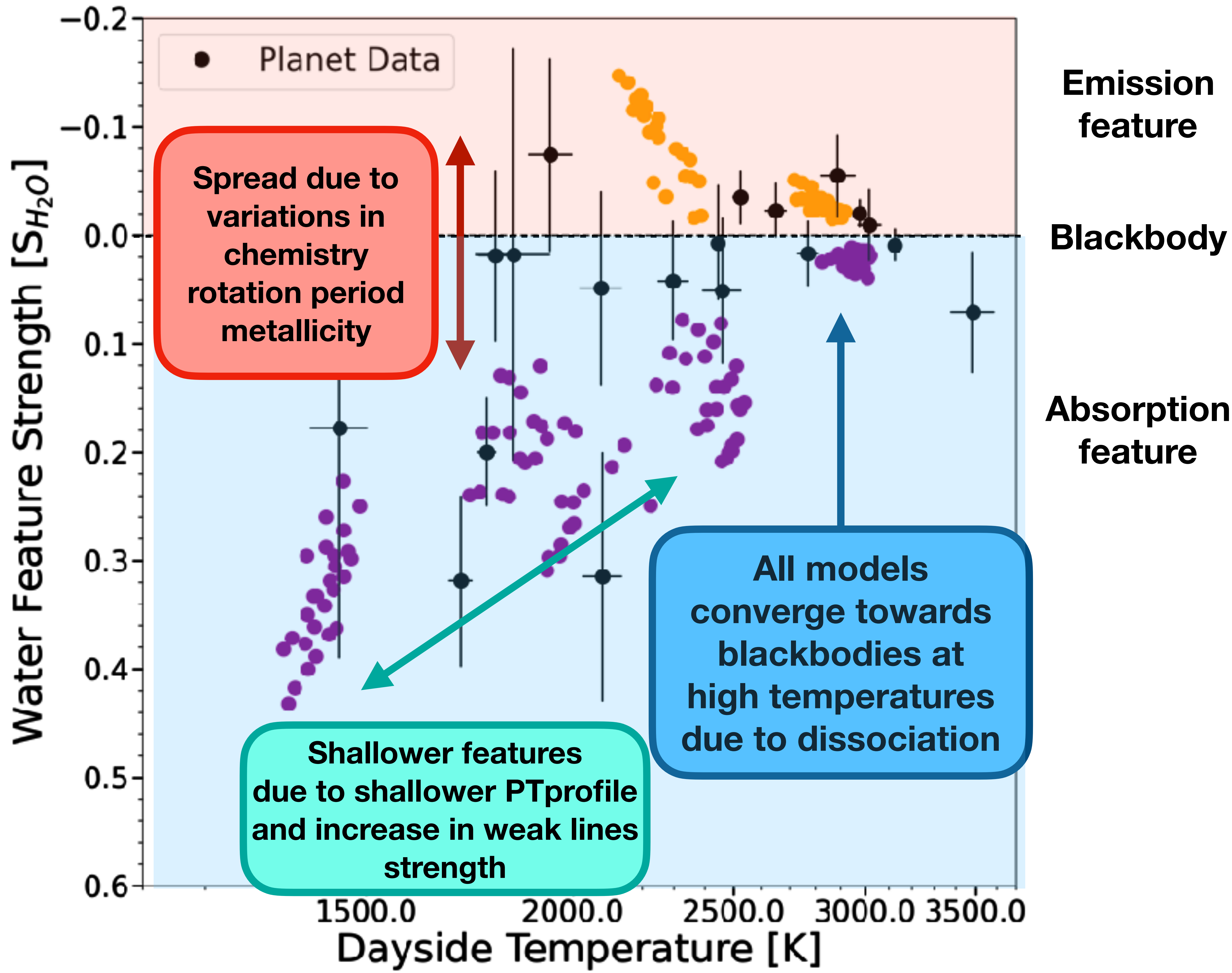
A diverse set of 149 models



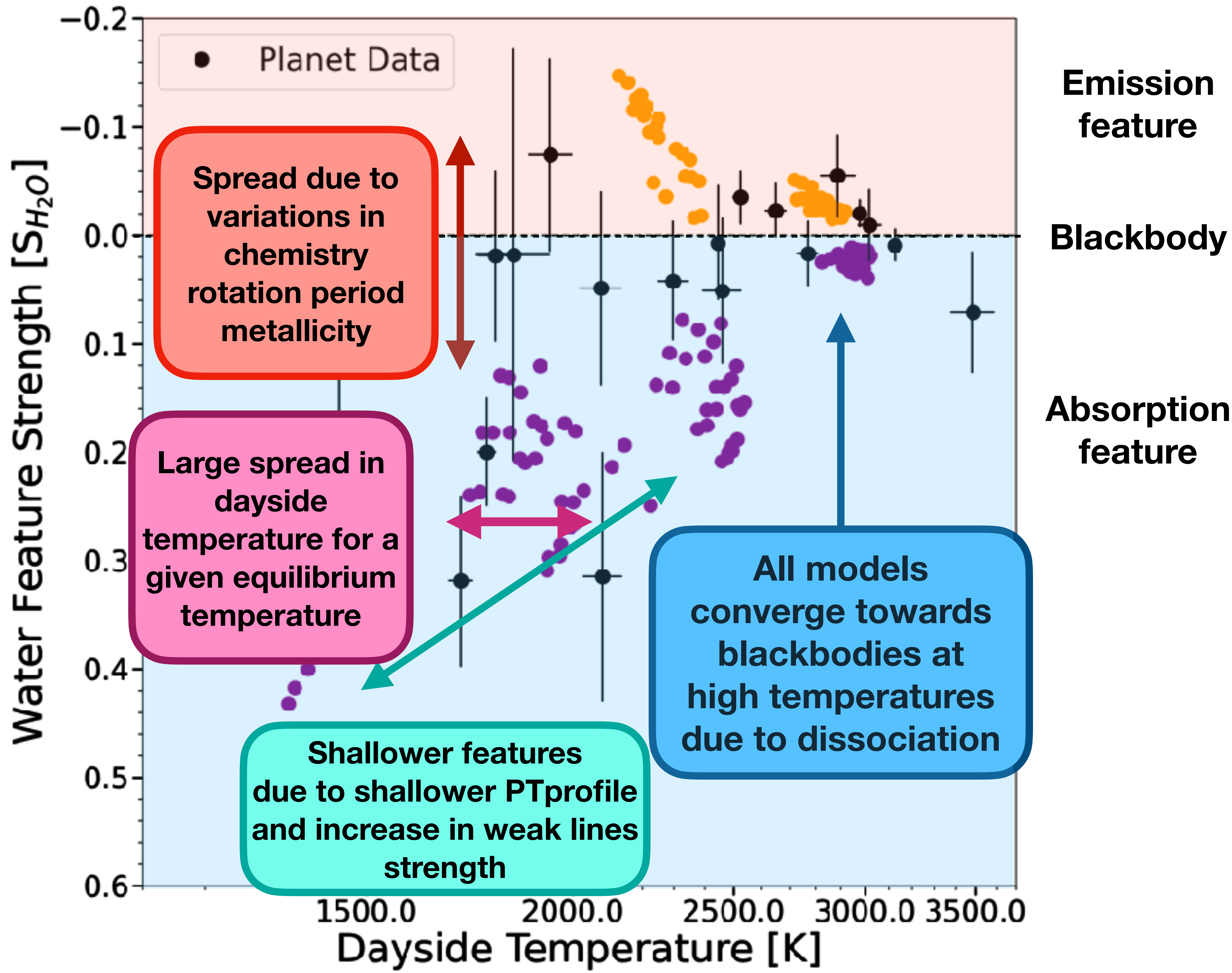
SPARC/MITgcm: a population study



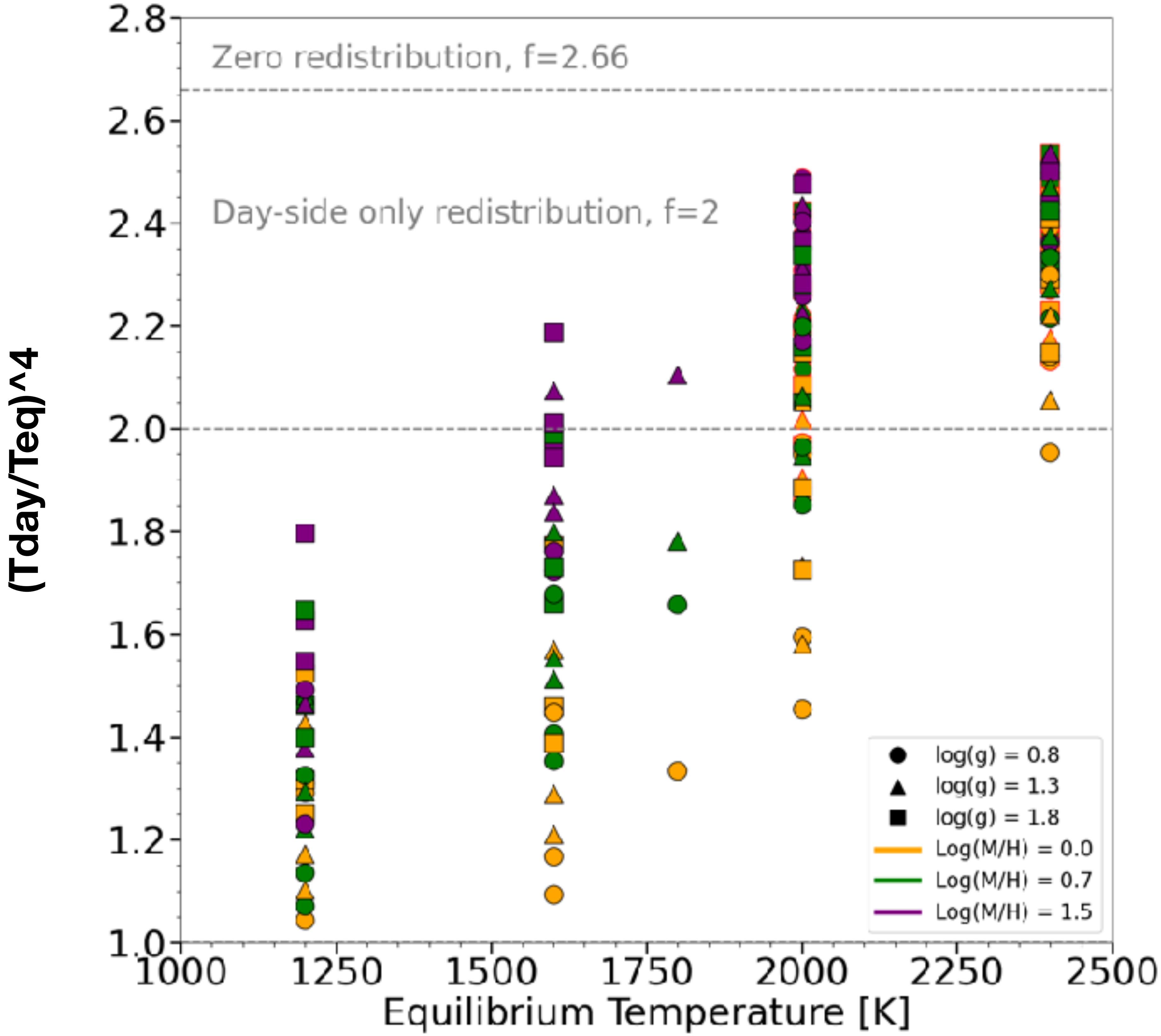
SPARC/MITgcm: a population study



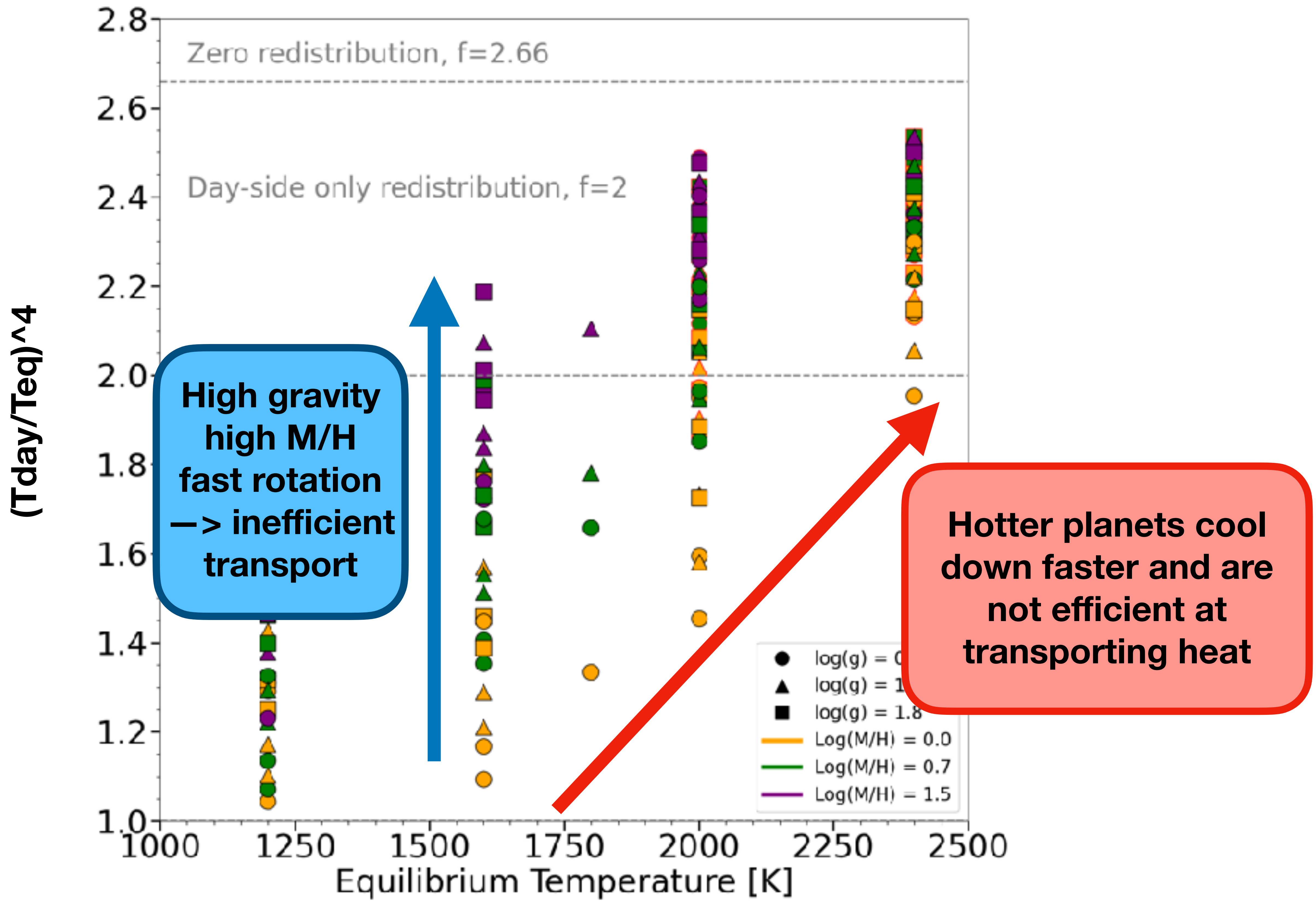
SPARC/MITgcm: a population study



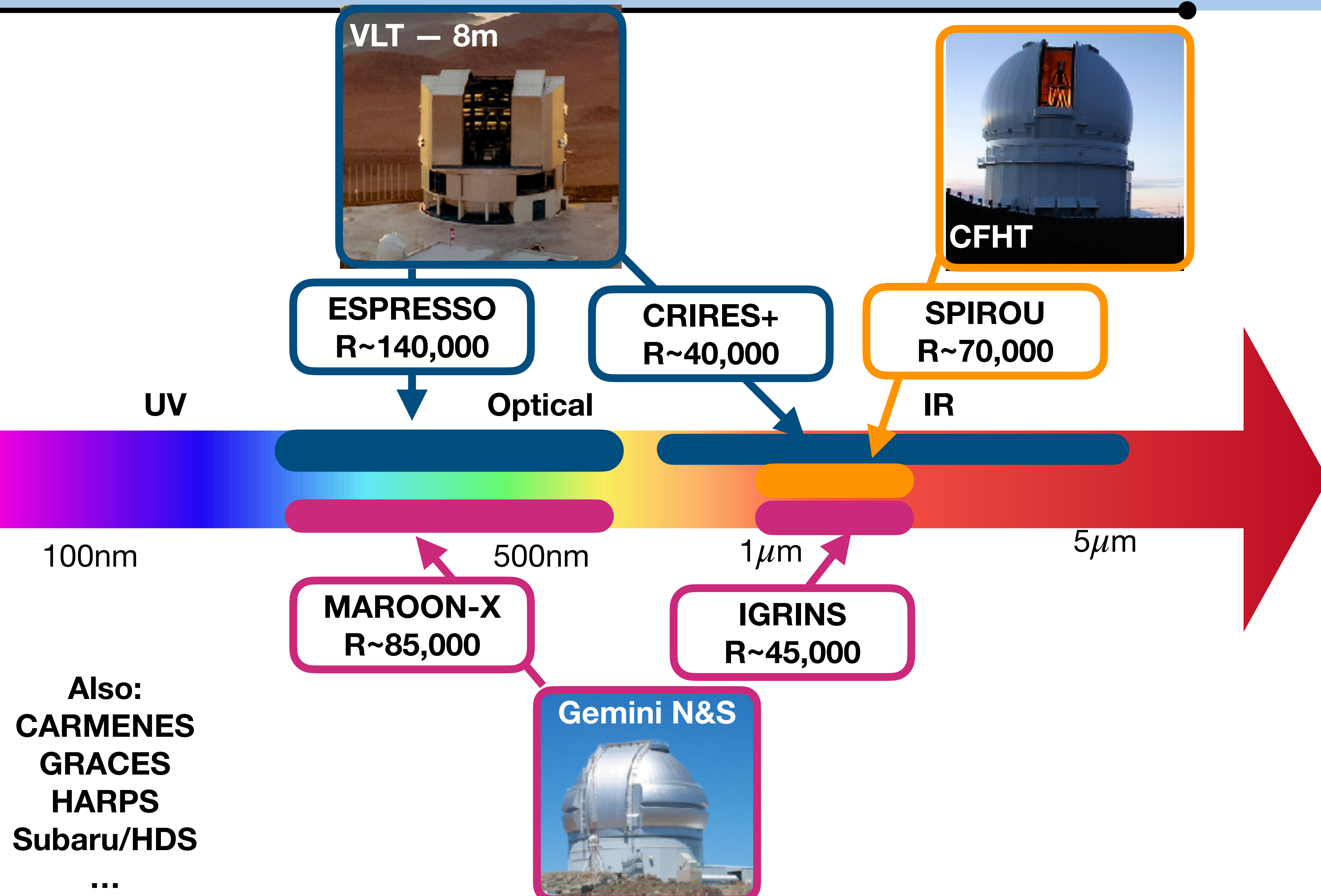
SPARC/MITgcm: a population study



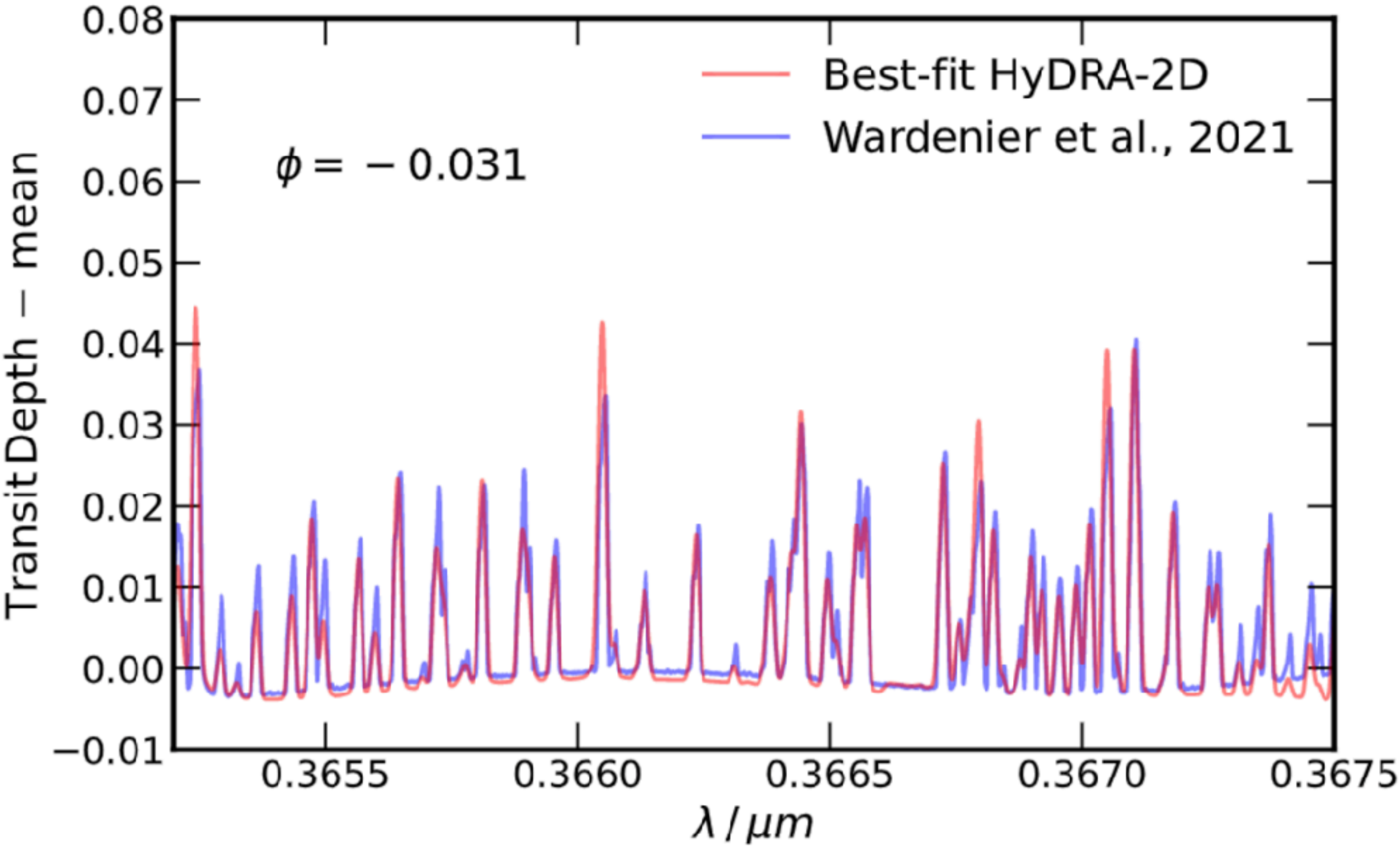
SPARC/MITgcm: a population study



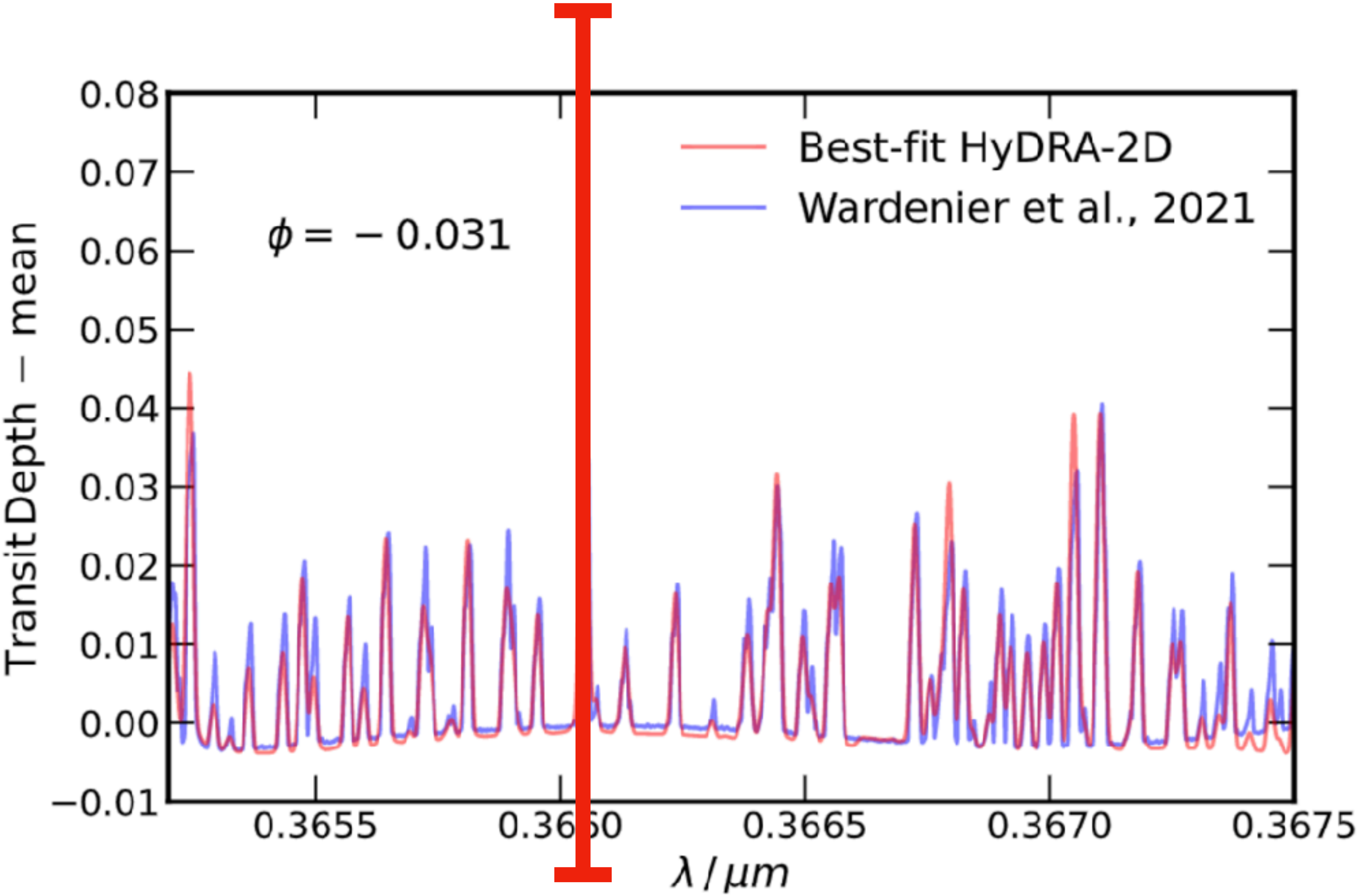
Ground based telescopes



Also:
CARMENES
GRACES
HARPS
Subaru/HDS
...



Best-fit HyDRA-2D
Wardenier et al., 2021
$\phi = -0.031$
Transit Depth − mean
$\lambda\,/\,\mu m$
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
−0.01
0.3655
0.3660
0.3665
0.3670
0.3675



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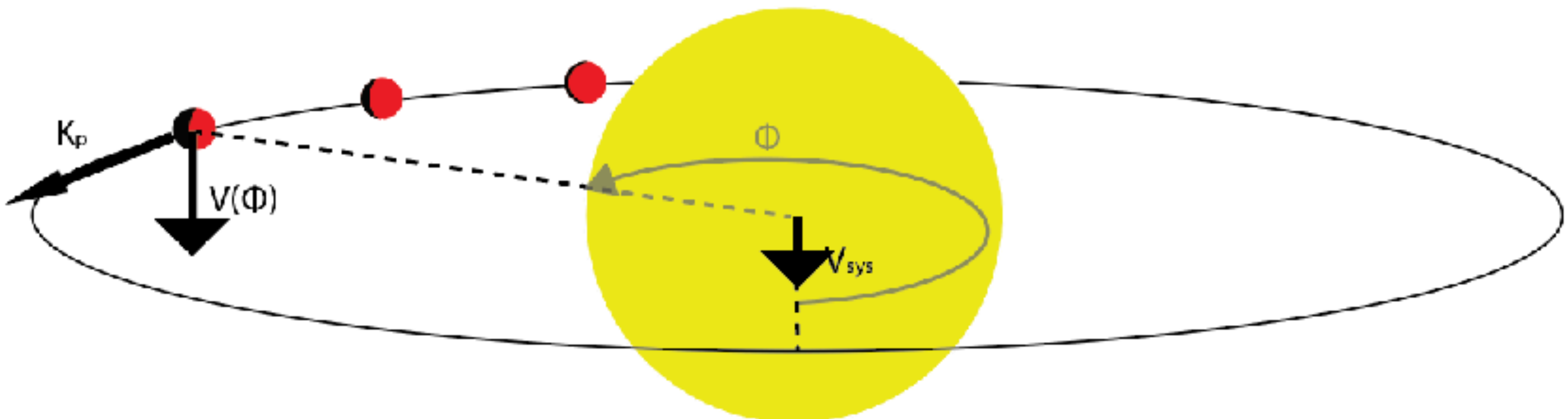
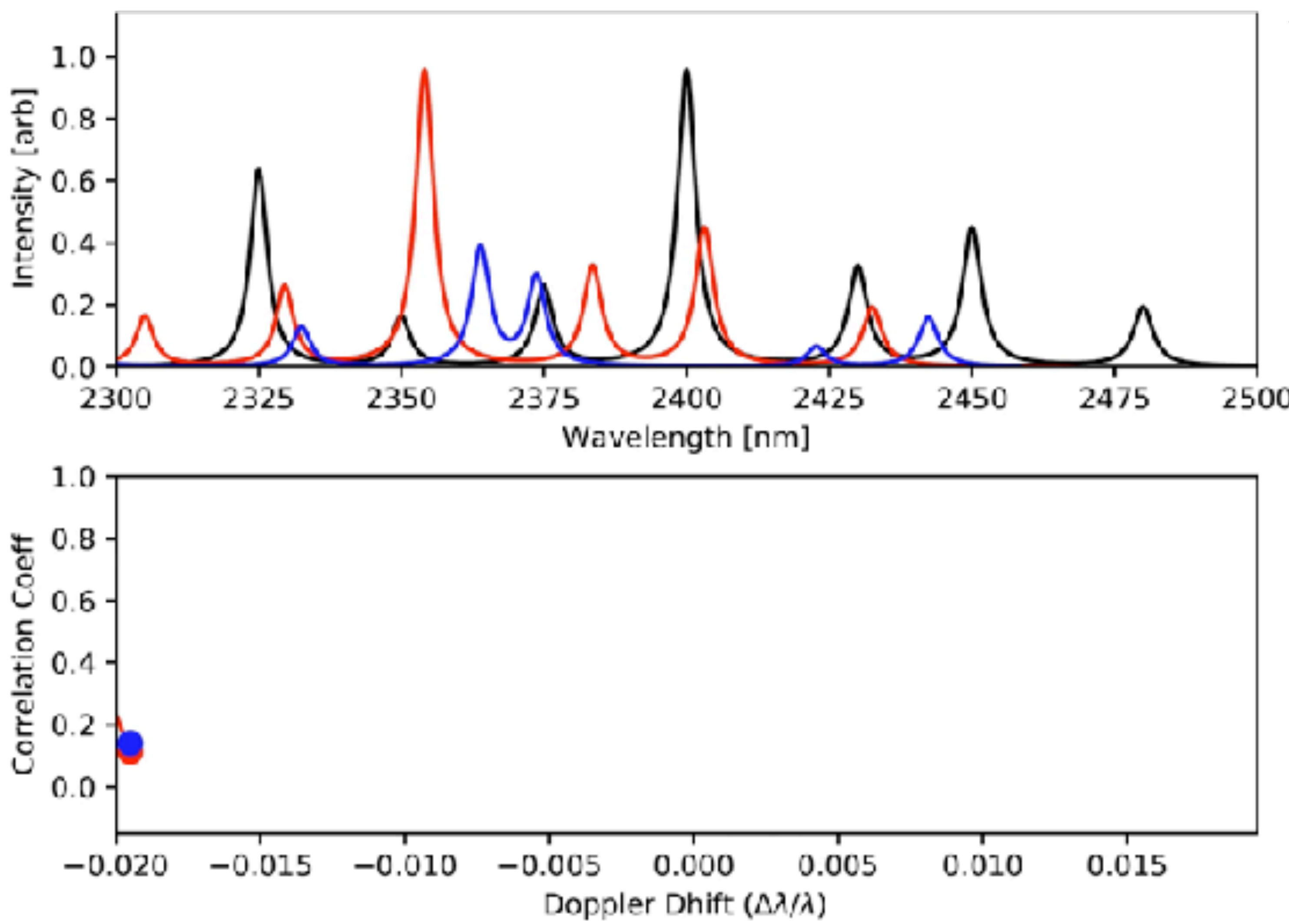
0.02
0.01
0.00
−0.01
0.3655
0.3660
0.3665
0.3670
0.3675
$\lambda\,/\,\mu m$

The Cross Correlation Function (CCF): How Atmospheric Information is Encoded





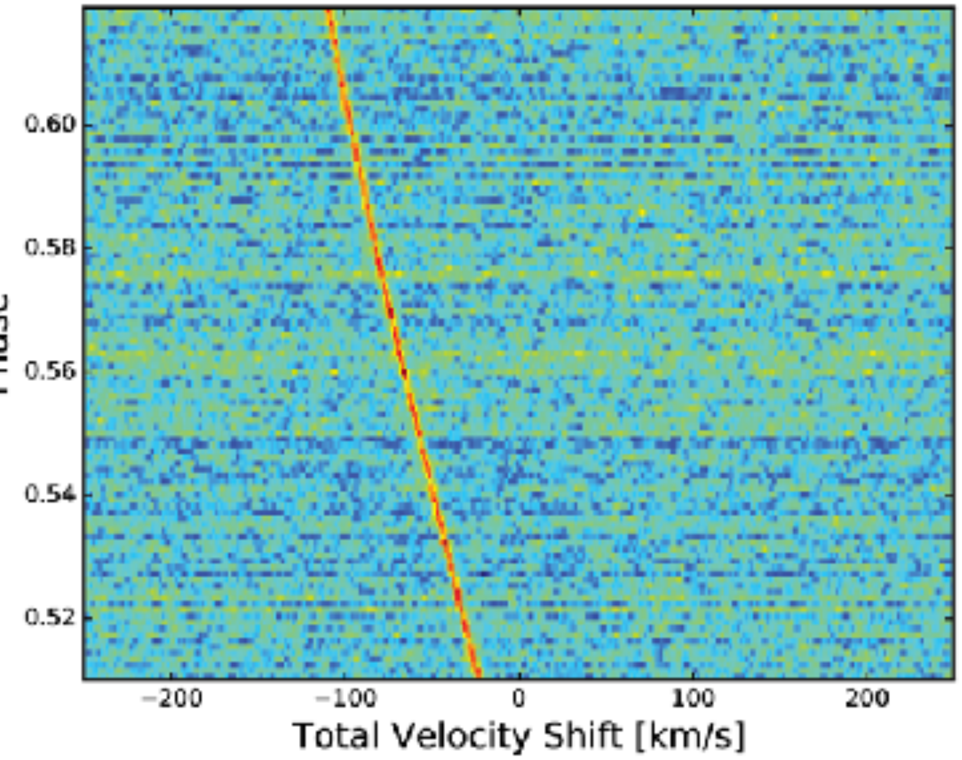
True Spectrum

Doppler Shifted Spectrum (correct atmosphere)

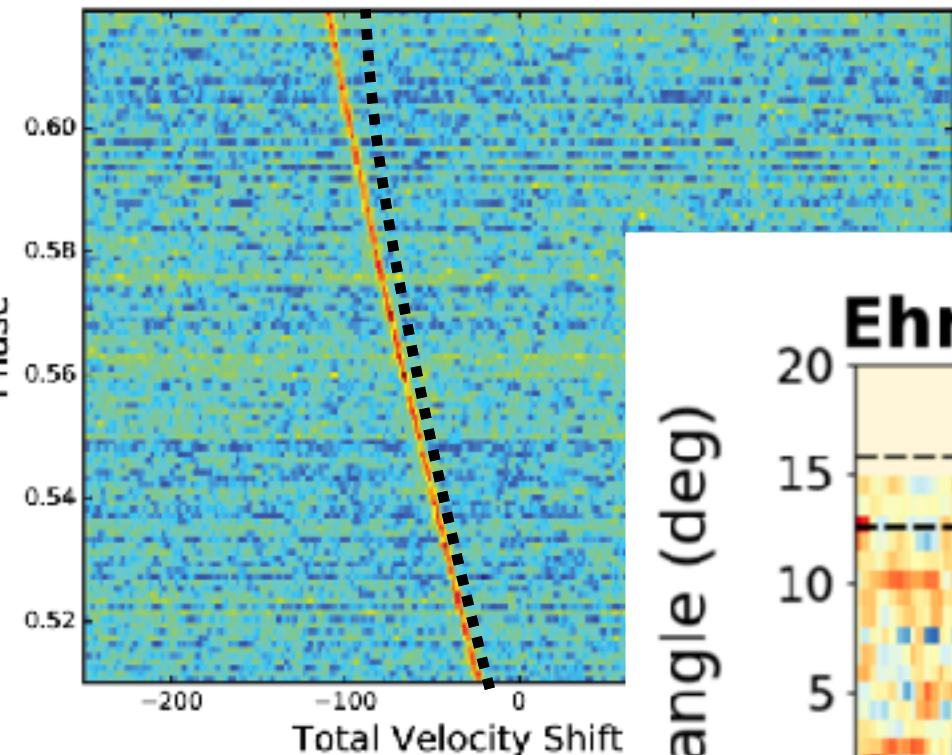
Doppler Shifted Spectrum (incorrect atmosphere)

$$\rho = \frac{\sigma_{dm}}{\sqrt{\sigma_m^2 \sigma_d^2}}$$

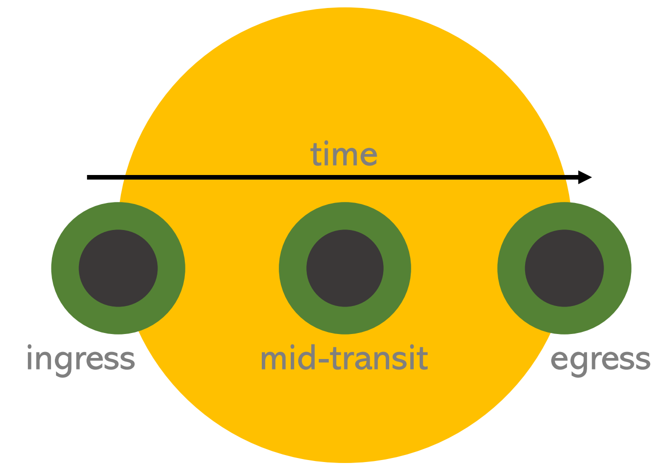
Cross-correlation trail as a function of time

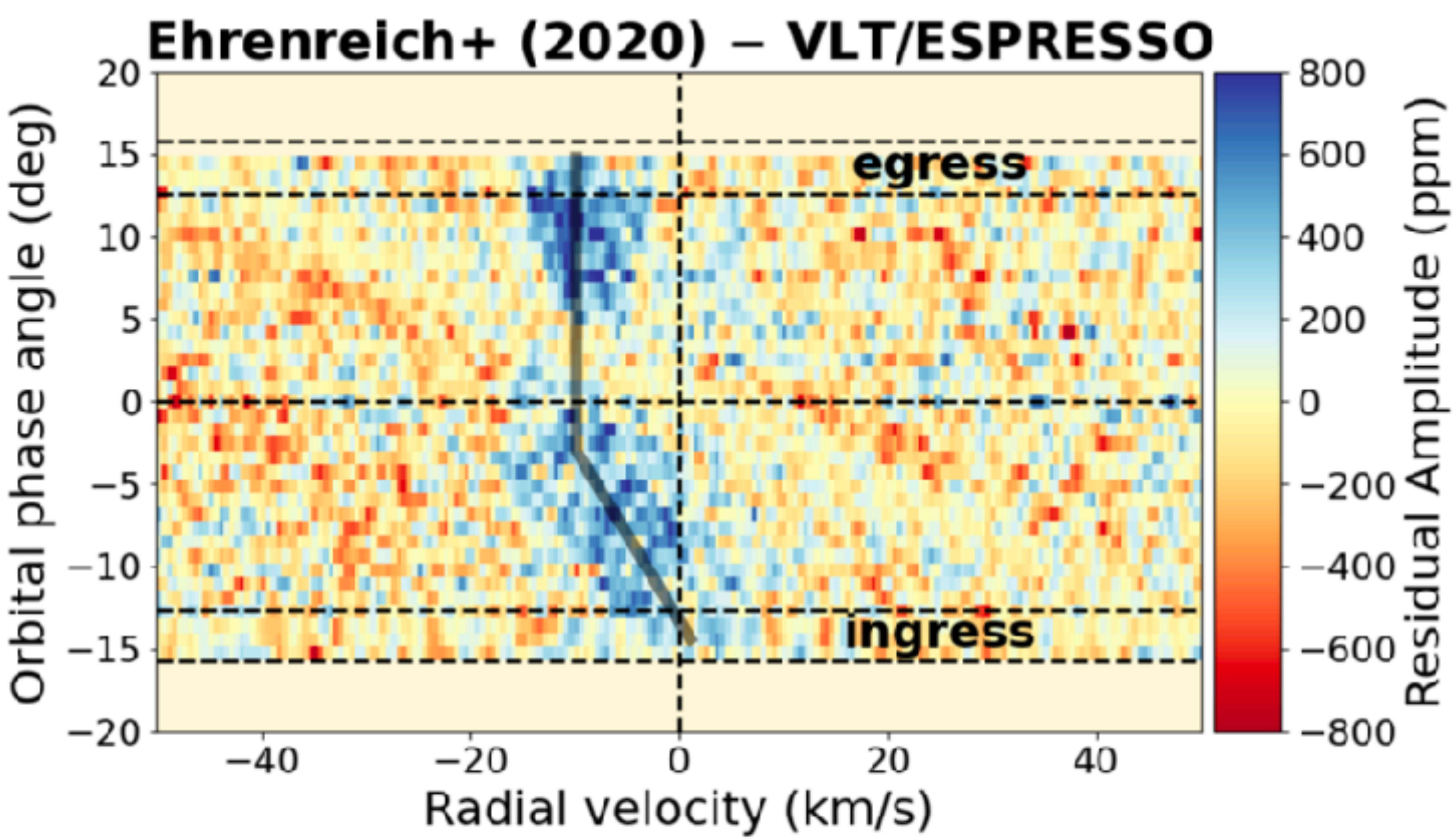


Cross-correlation trail as a function of time

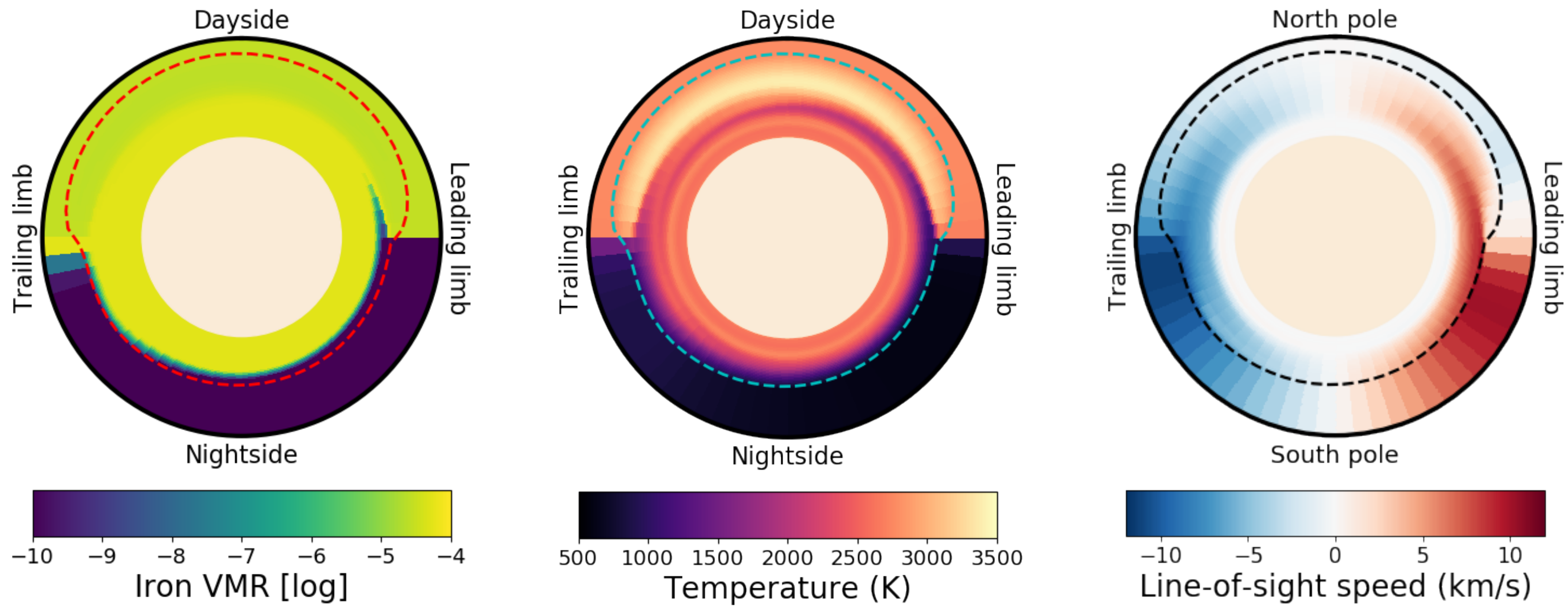


Remove the expected planet trail

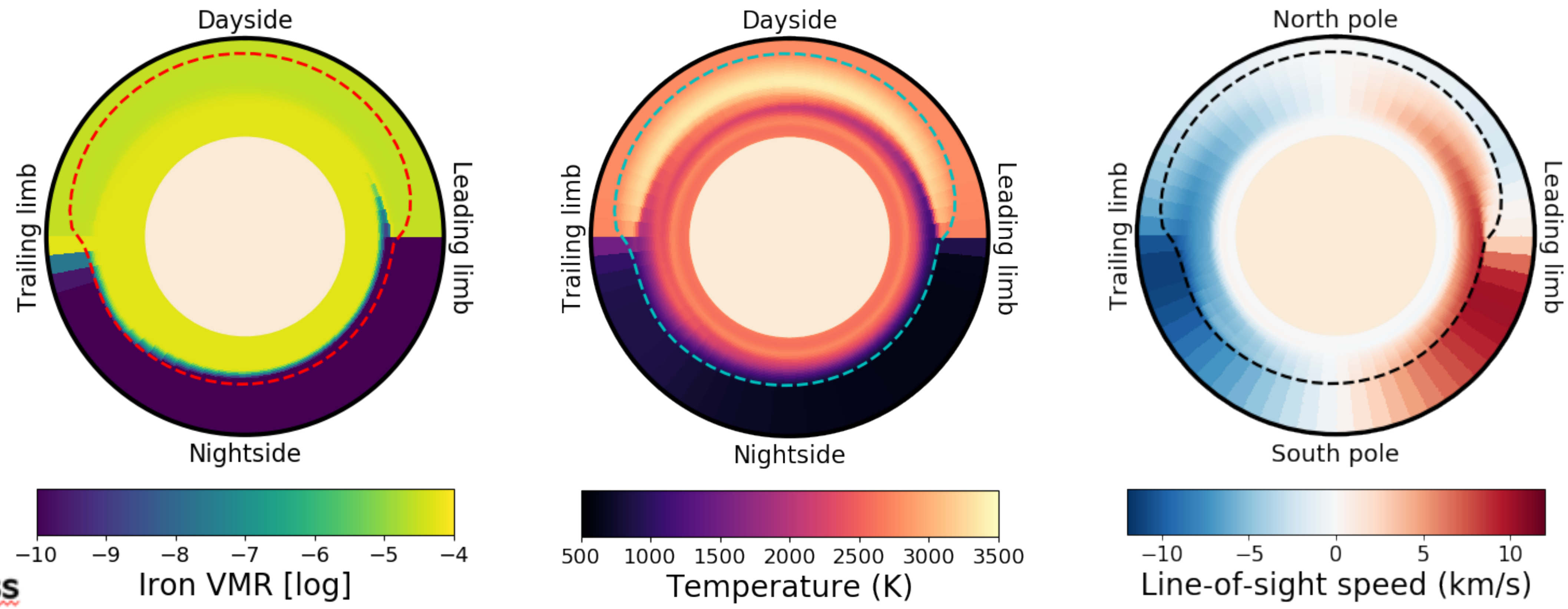


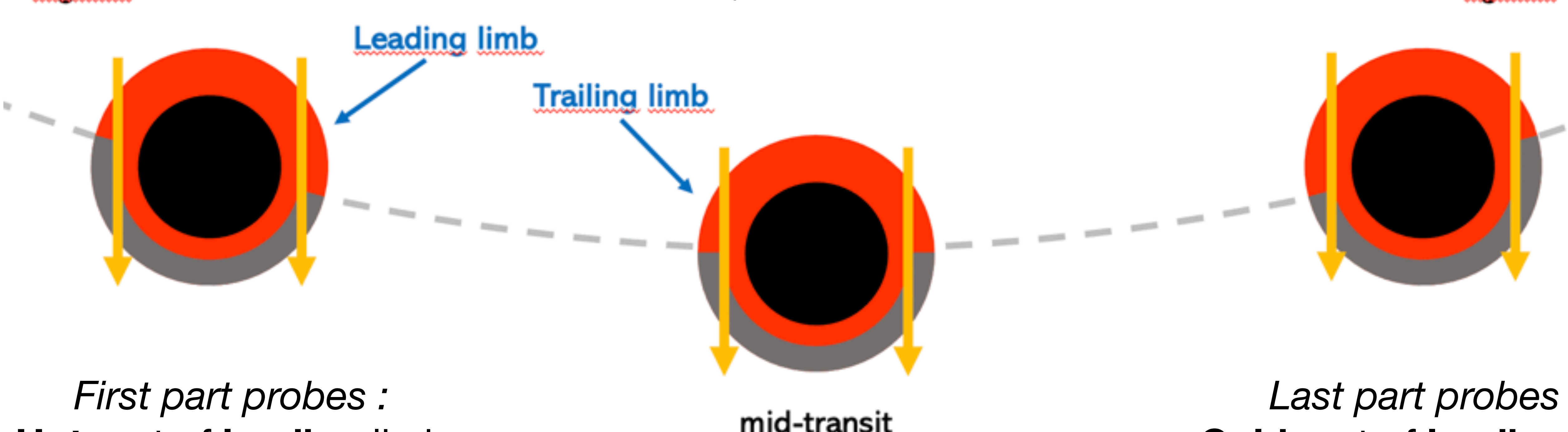


Modelling the high-resolution spectra of 3D exoplanets



Modelling the high-resolution spectra of 3D exoplanets

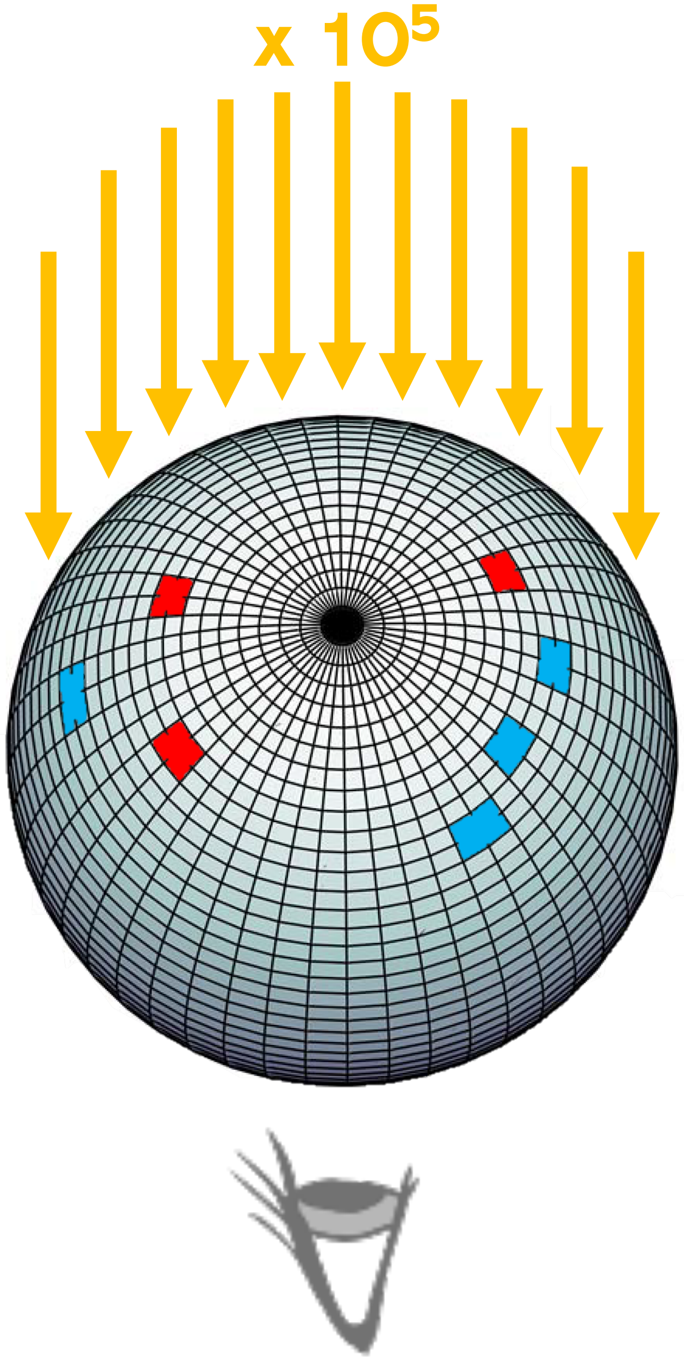


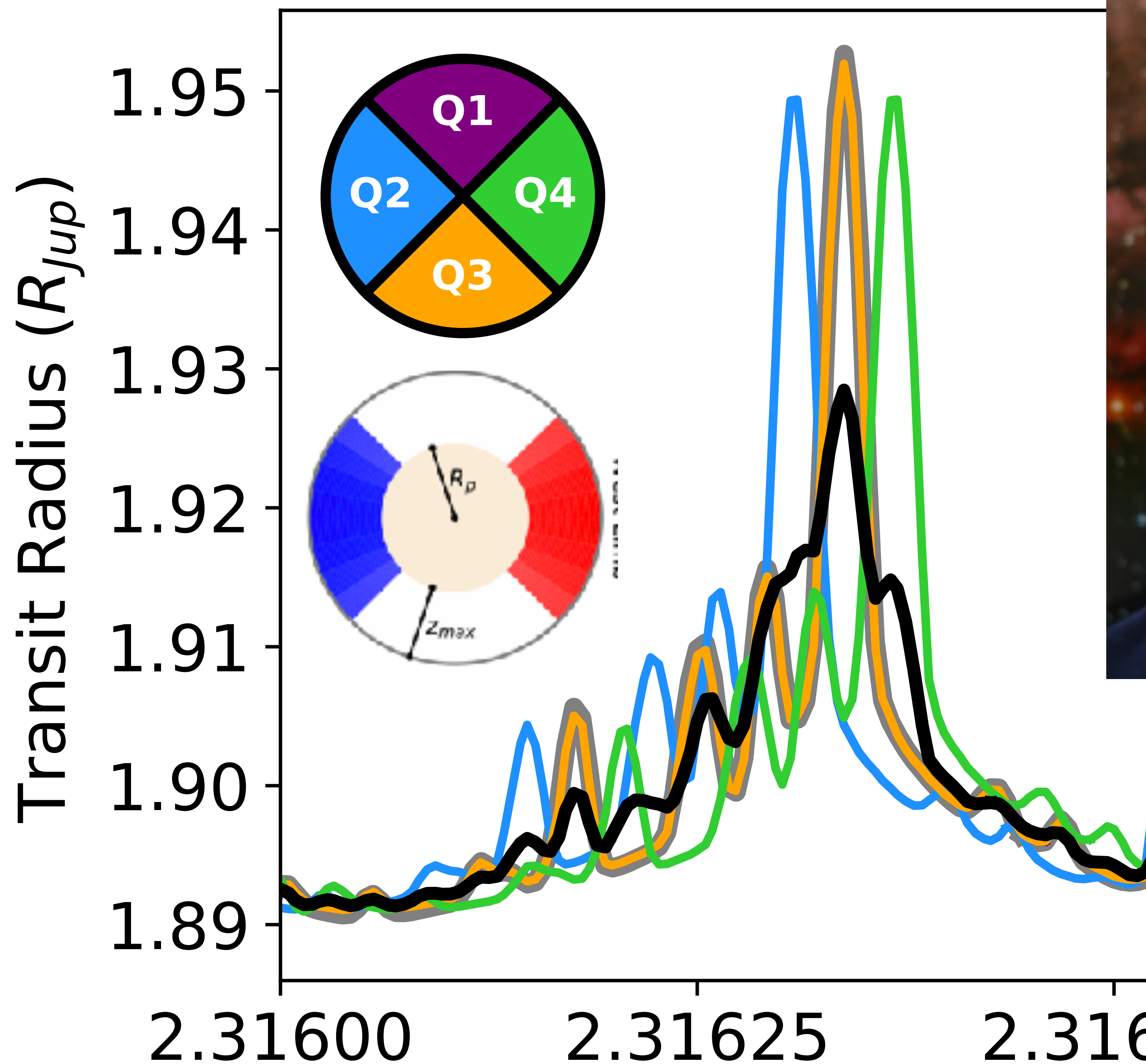


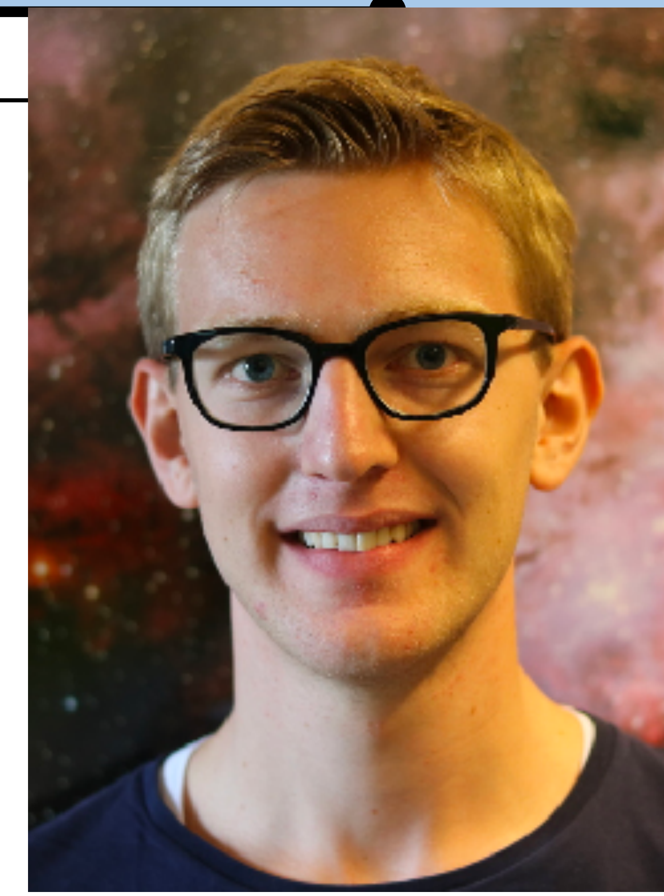
First part probes :
Hot part of **leading** limb
Cold part of **trailing** limb

Last part probes :
Cold part of **leading** limb
Hot part of **trailing** limb

Modelling the high-resolution spectra of 3D exoplanets





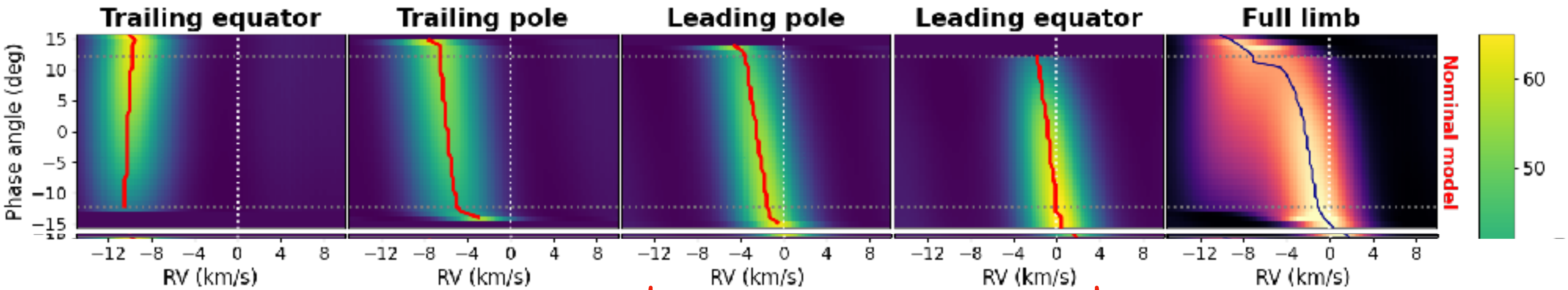


Joost Wardenier

Monte Carlo radiative transfer based on Lee et al. 2016

Wardenier et al. 2021

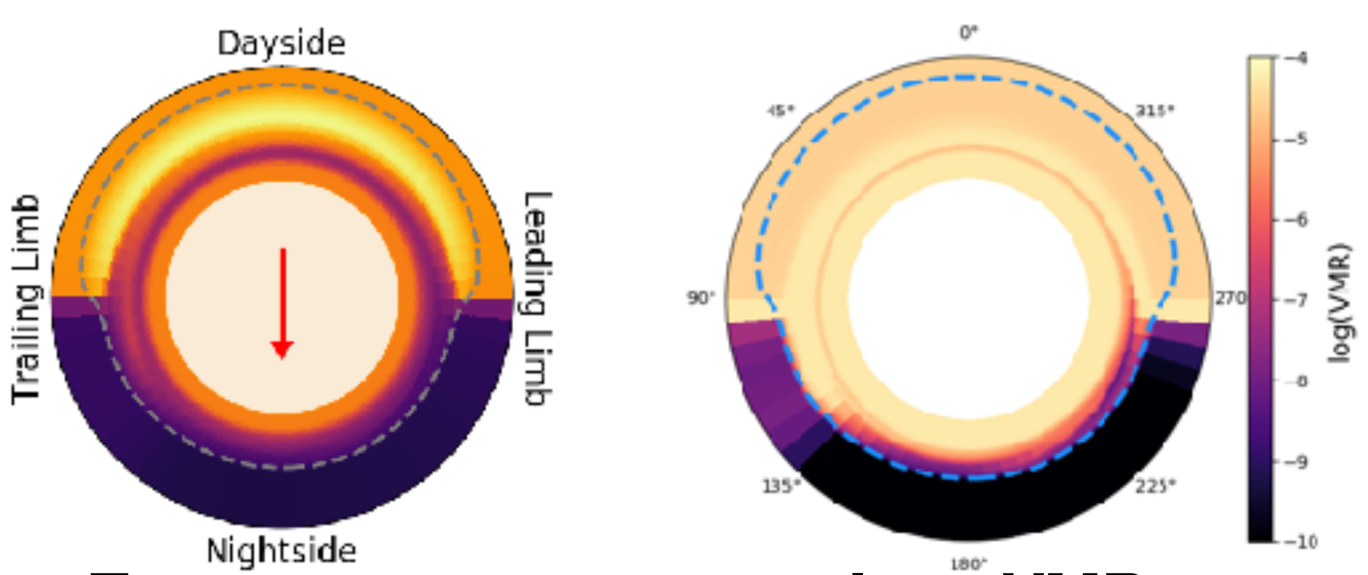
Understanding the CCF of a planet



Trailing part
comes towards us
Bulk blueshift
+ winds

Leading part
goes away from us
Bulk redshift
+ winds

Total cross-correlation function is the sum of all the parts.

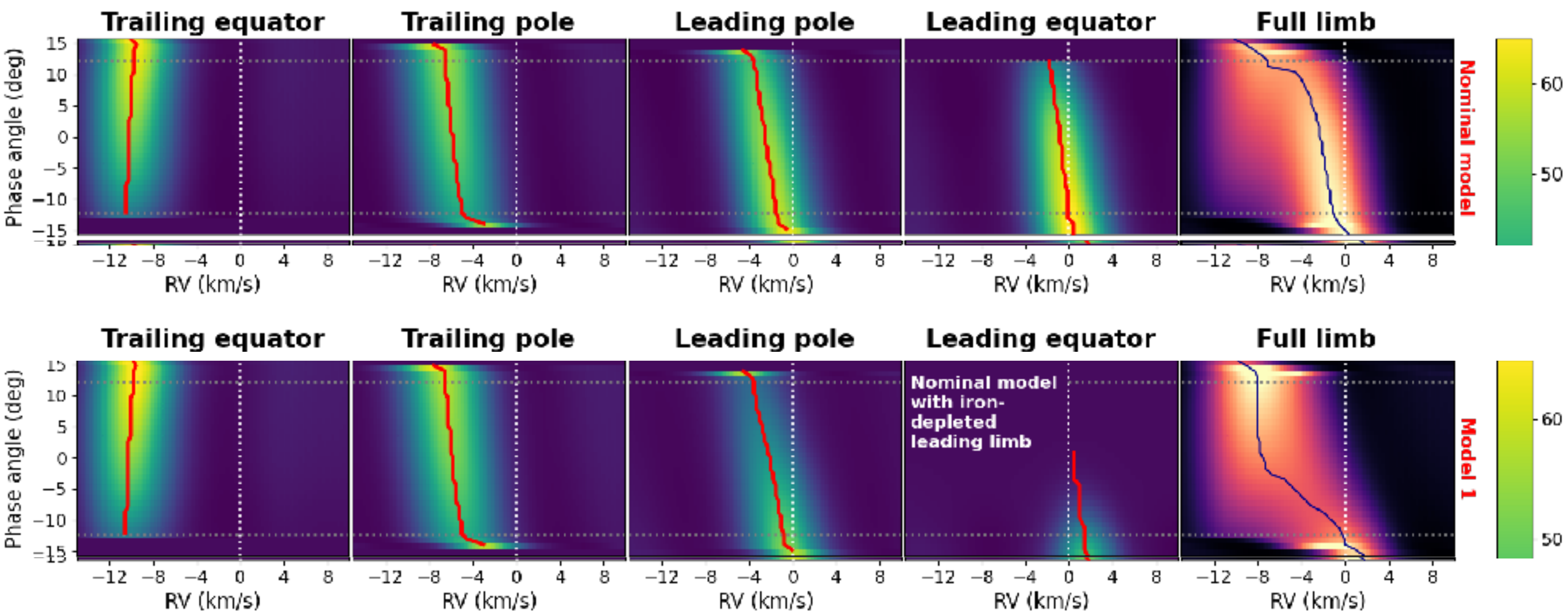


Temperature

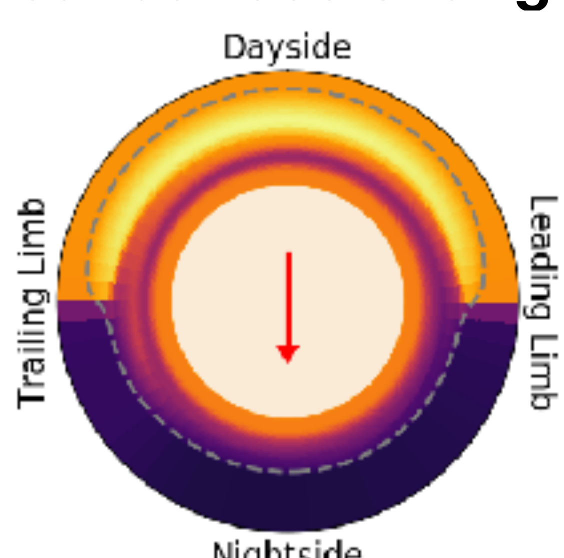
Iron VMR

Wardenier et al. 2021

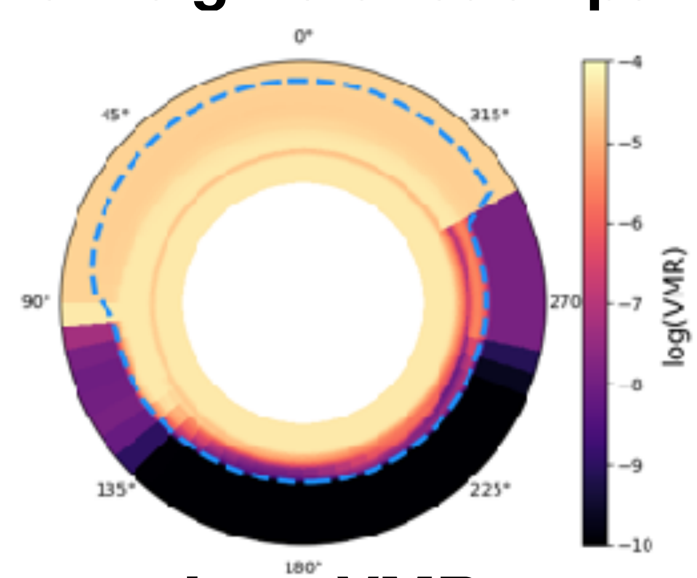
Understanding the CCF of a planet



Changing the abundances changes the weights of each parts of the atmosphere !



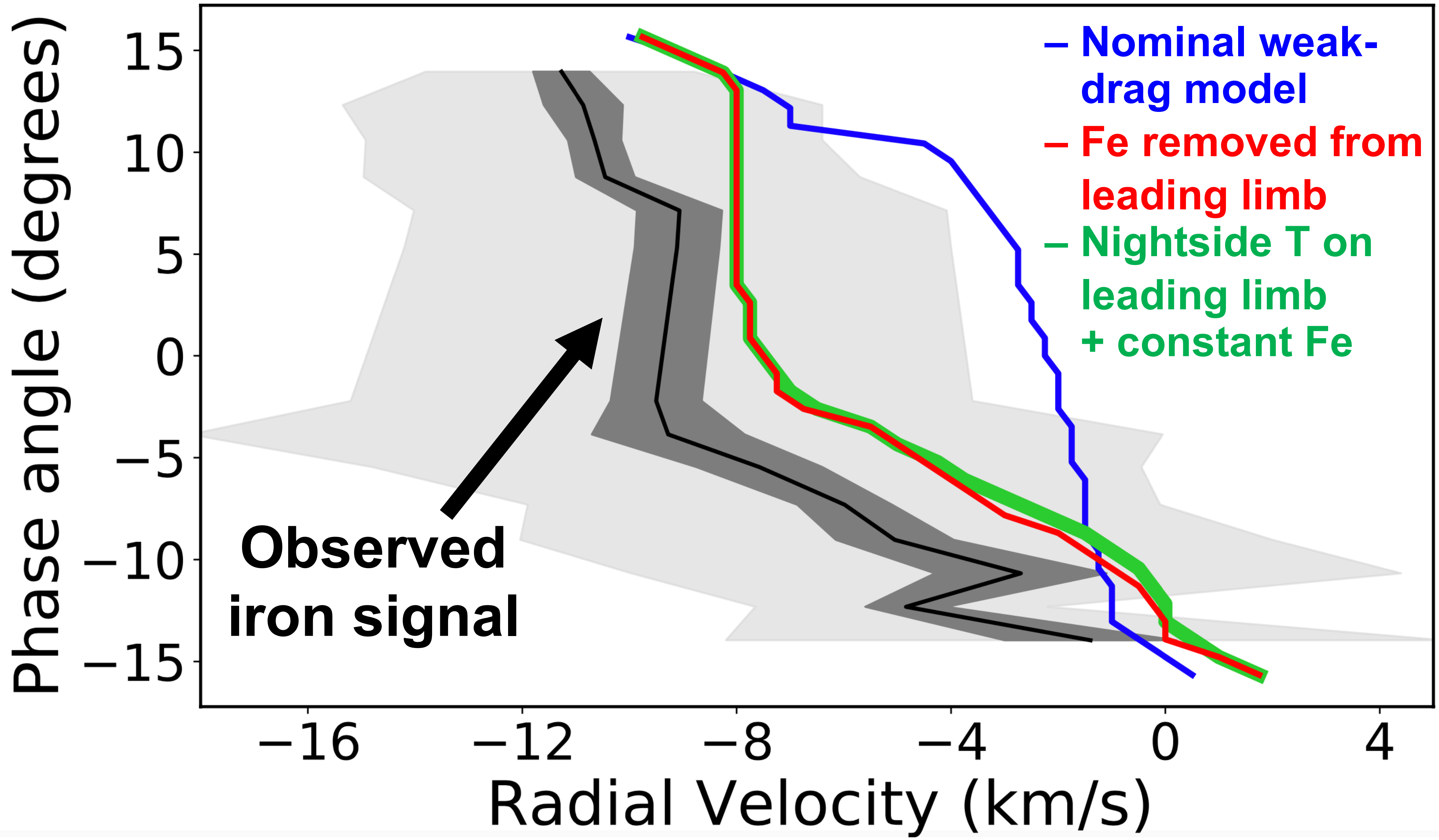
Temperature



Iron VMR

Wardenier et al. 2021

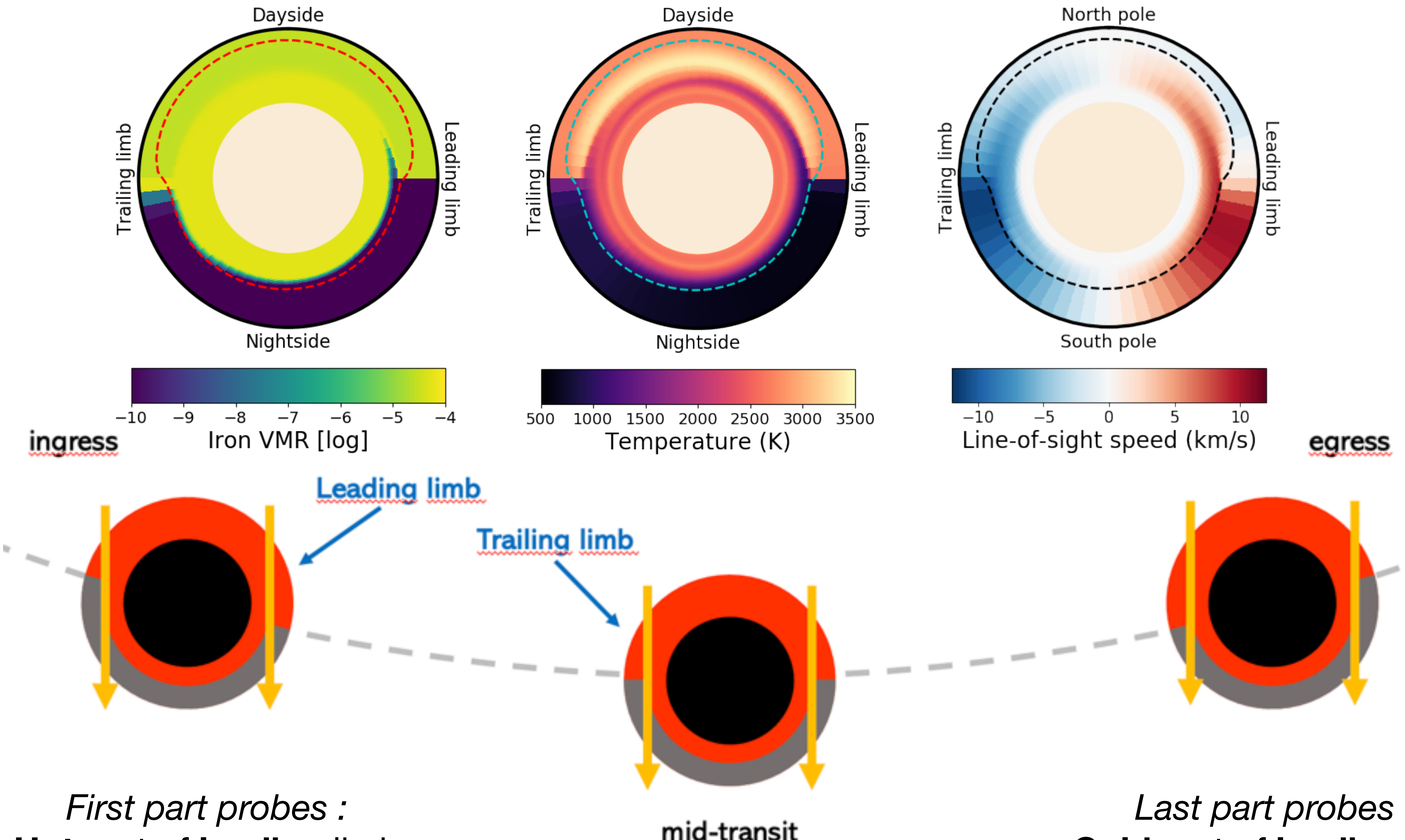
Understanding the CCF of a planet



WASP-76b signal can be due to either a depletion of iron or a colder than expected morning limb

Wardenier et al. 2021

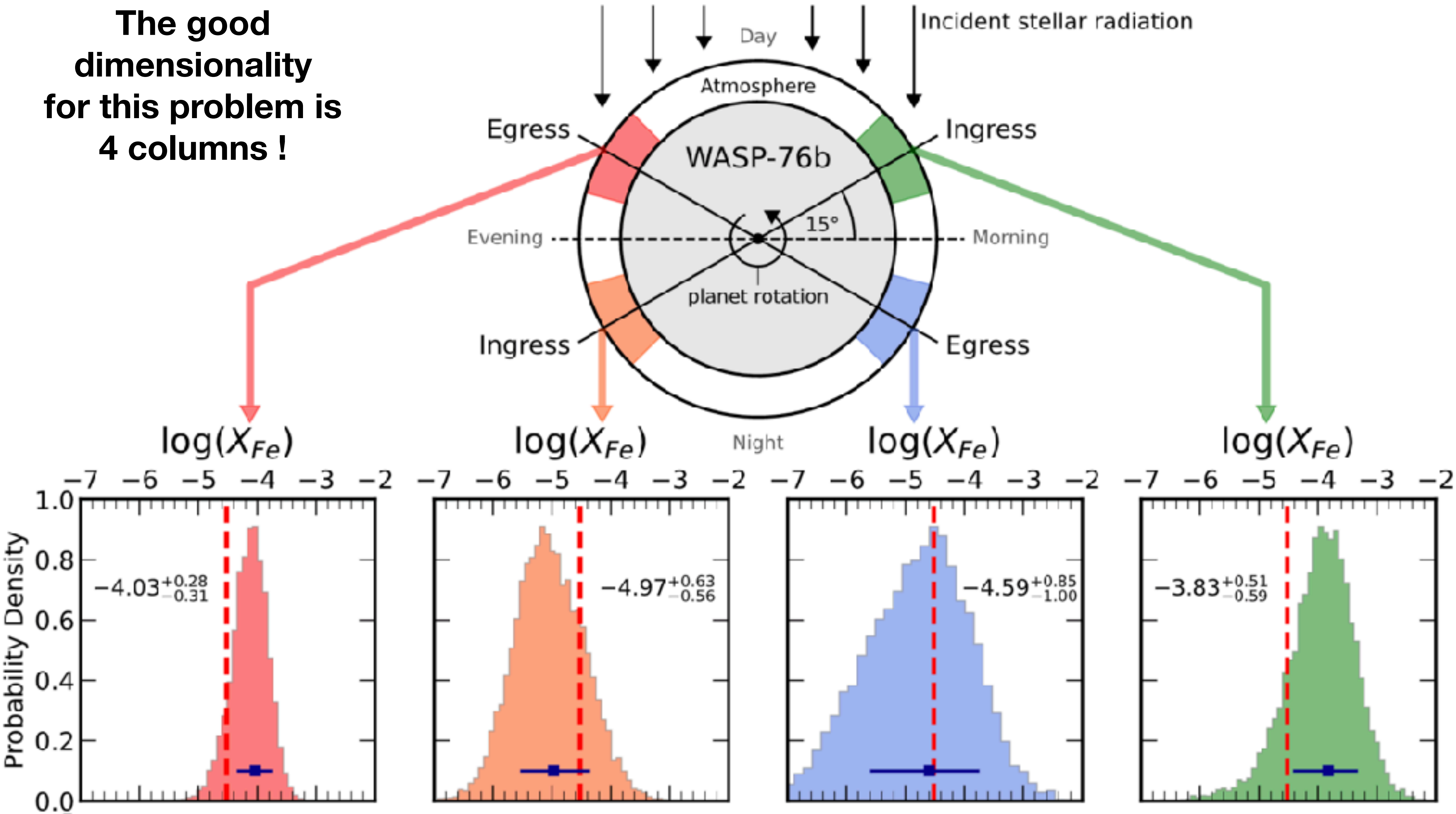
Modelling the high-resolution spectra of 3D exoplanets



First part probes :
Hot part of **leading** limb
Cold part of **trailing** limb

Last part probes :
Cold part of **leading** limb
Hot part of **trailing** limb

The good dimensionality for this problem is 4 columns !



First Iron abundance retrieval !

Gandhi et al. in prep.

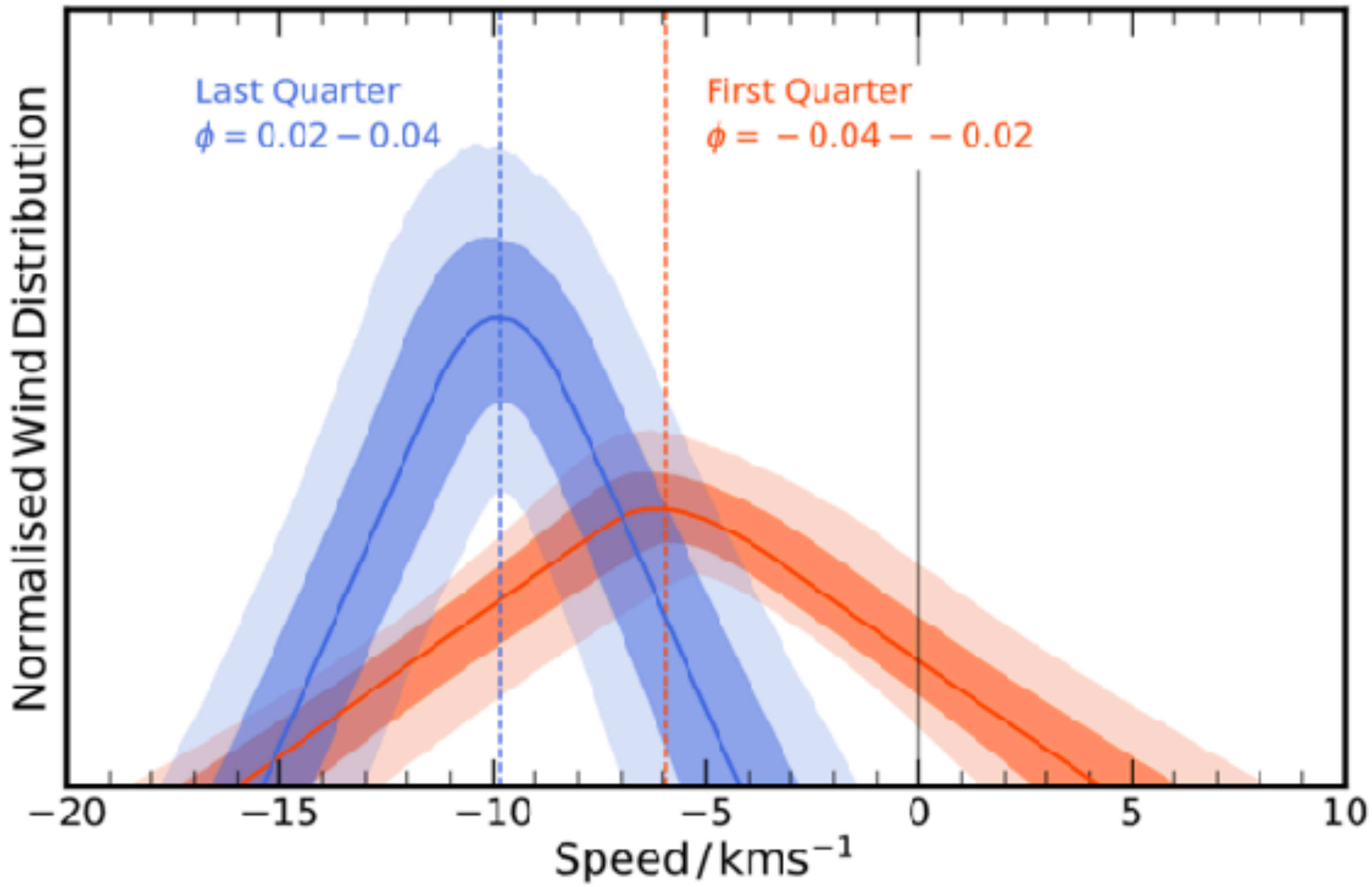


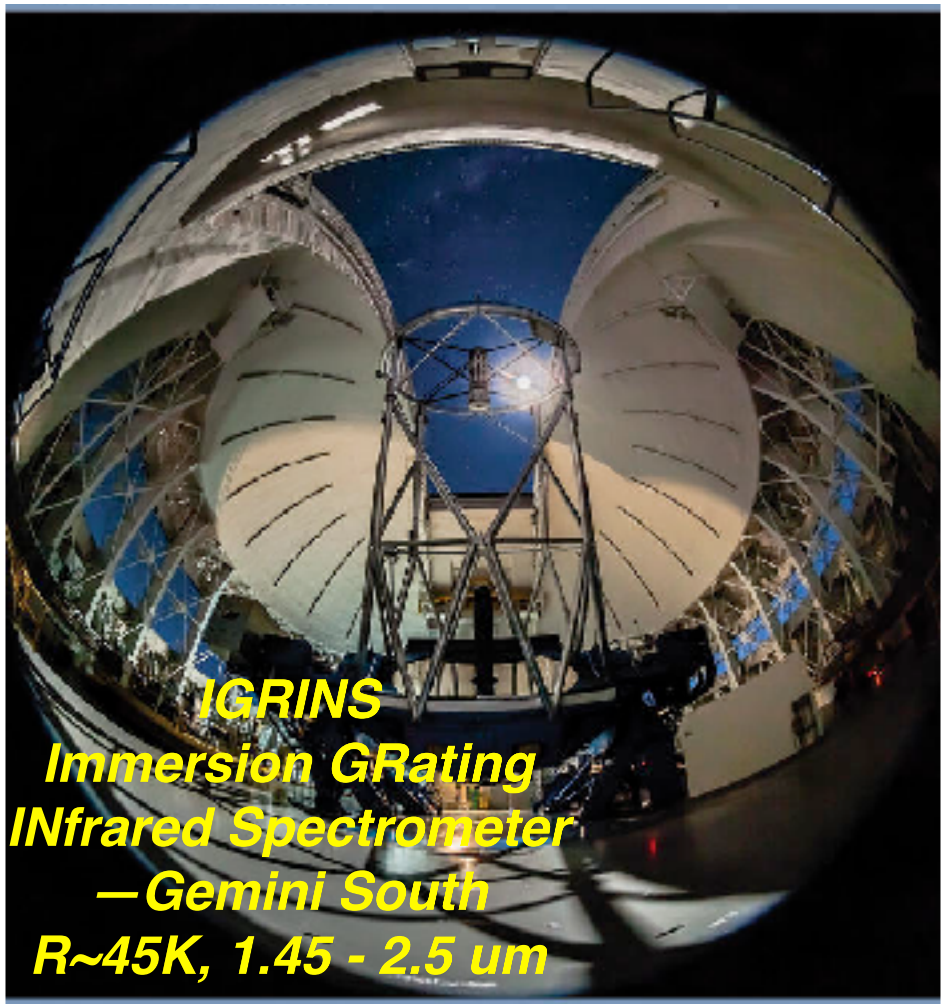
Figure 11. Wind speed distribution as derived from the ΔV_{sys} and δV_{wind} parameters given in Figure 10. The constraints on the $\phi = -0.04 - -0.02$ range are shown in red and the constraints on the $\phi = 0.02 - 0.04$ range in blue. The dashed lines indicate the median values of ΔV_{sys} from our retrieval.

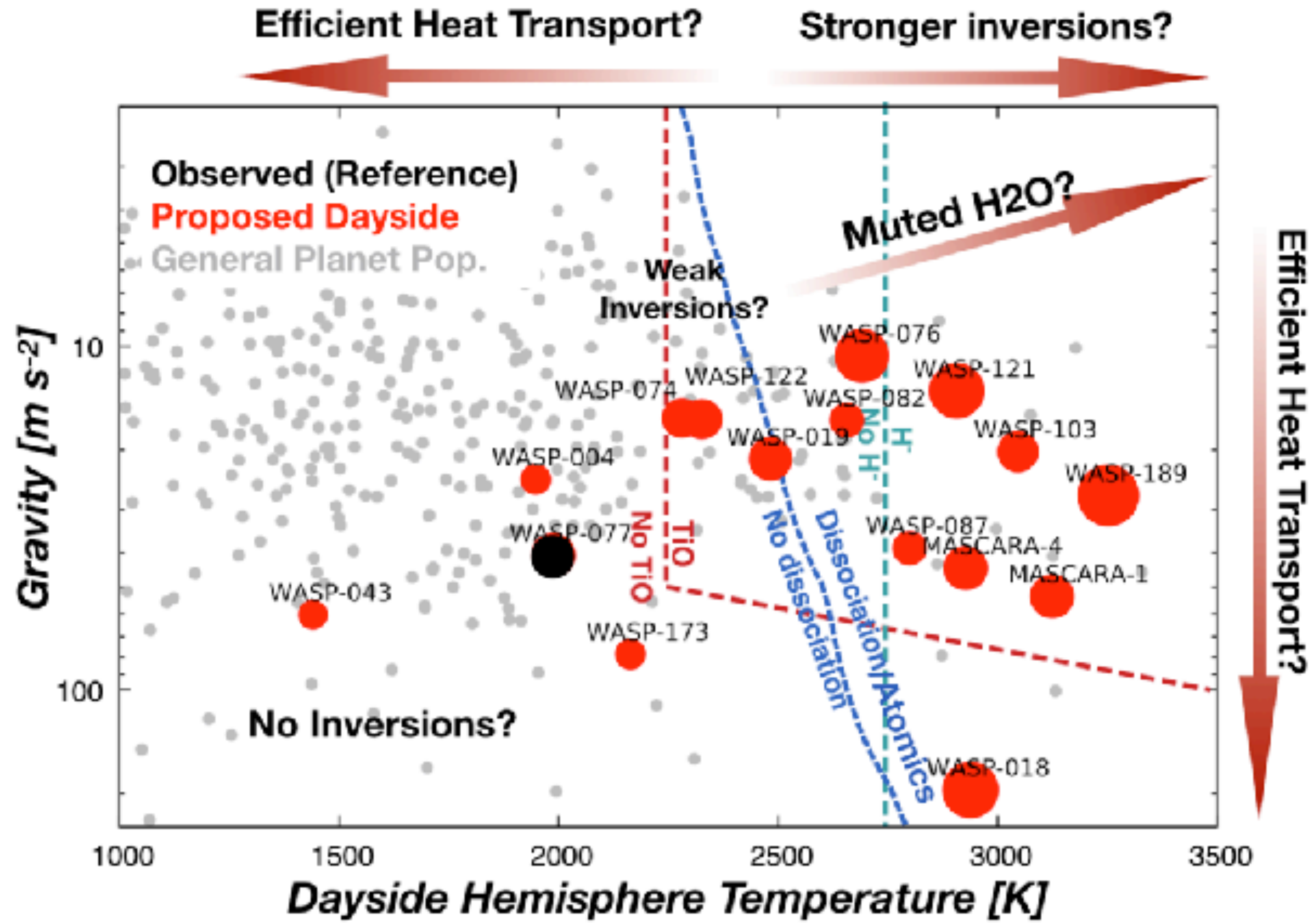
Wind speed retrievals too !

Gandhi et al. in prep.

What about high-resolution in emission ?

WASP-77Ab: A pretty bland hot Jupiter





Hot Jupiter WASP-77Ab

T_{eq}~1700

est. ~2000K dayside

T_{star} = 5605K

0.96 R_s

1.21 R_j

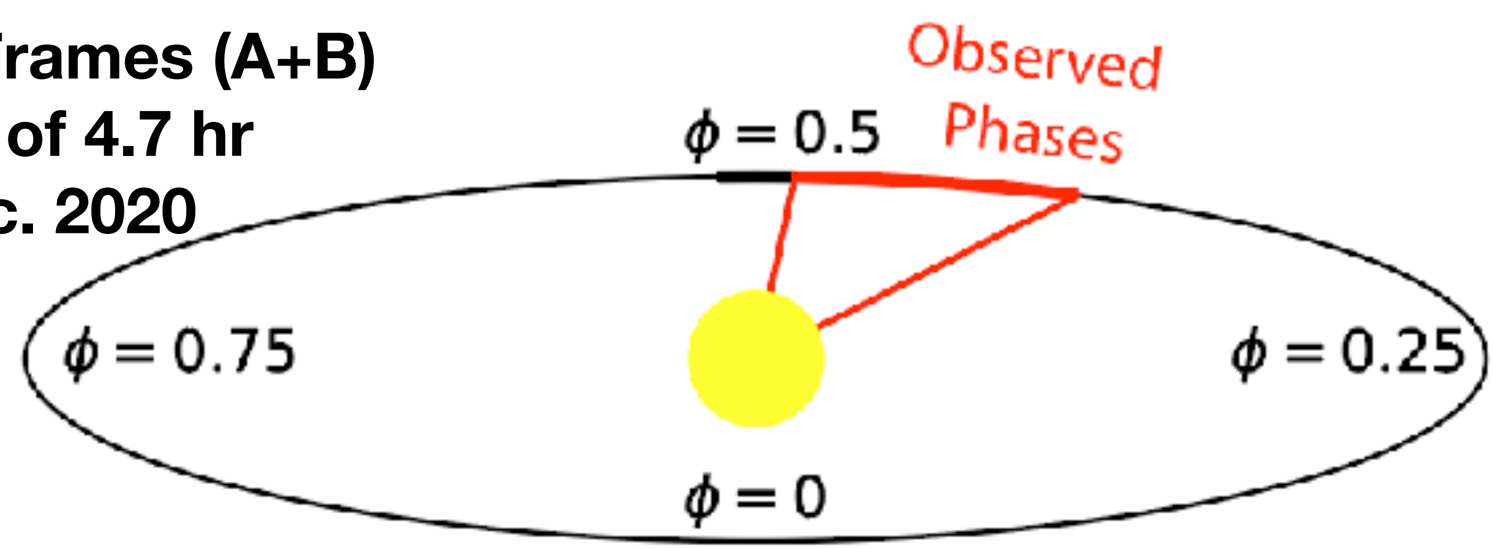
1.76 M_j ($g=31.1\ m/s^2$)

Kmag = 8.4

Kp~190 km/s

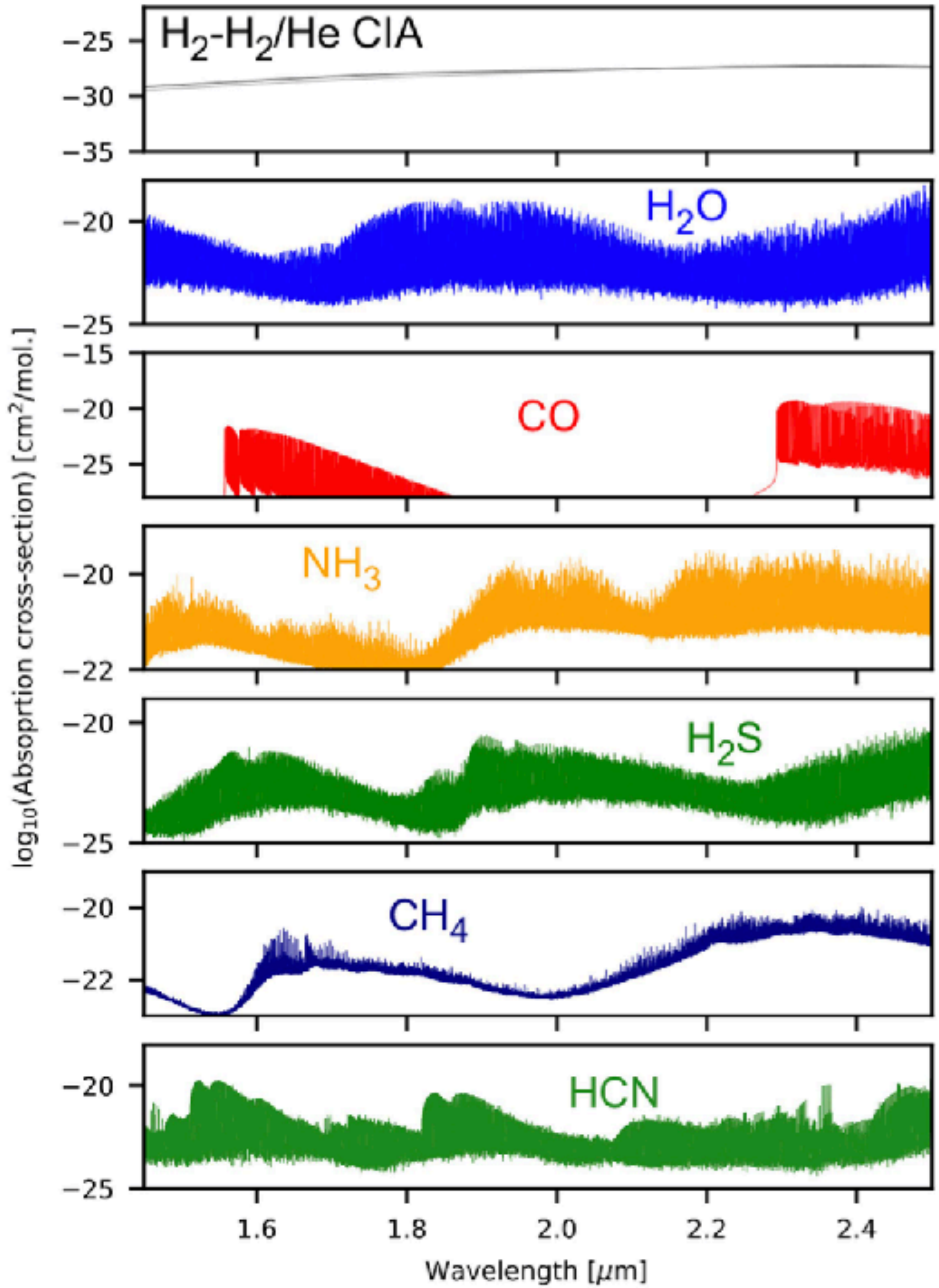
Vsys~1.7 km/s

79 140s Frames (A+B)
Total of 4.7 hr
Dec. 2020



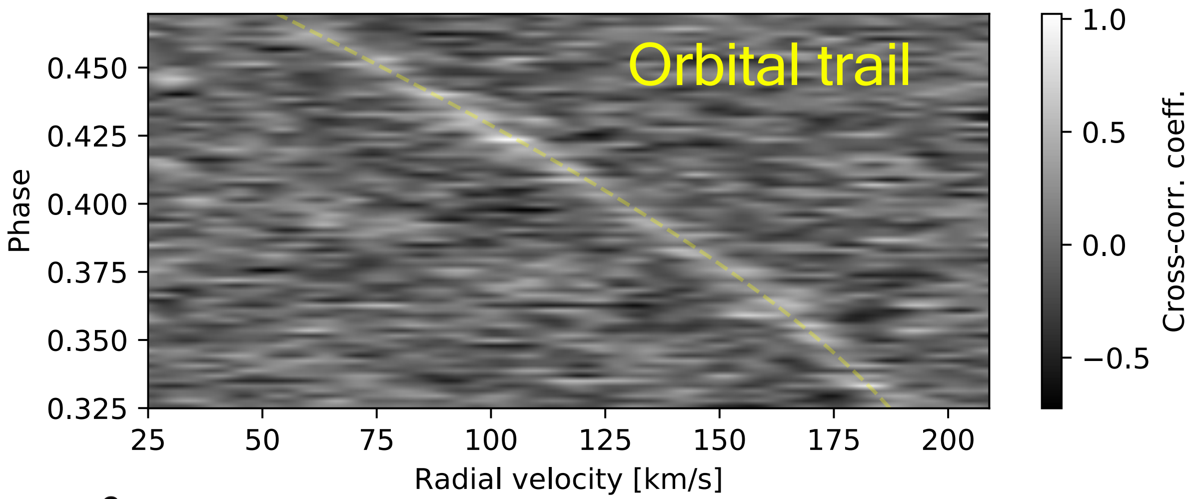
Line, Brogi incl. Parmentier et al., Nature, 2021

PI J. Zalesky

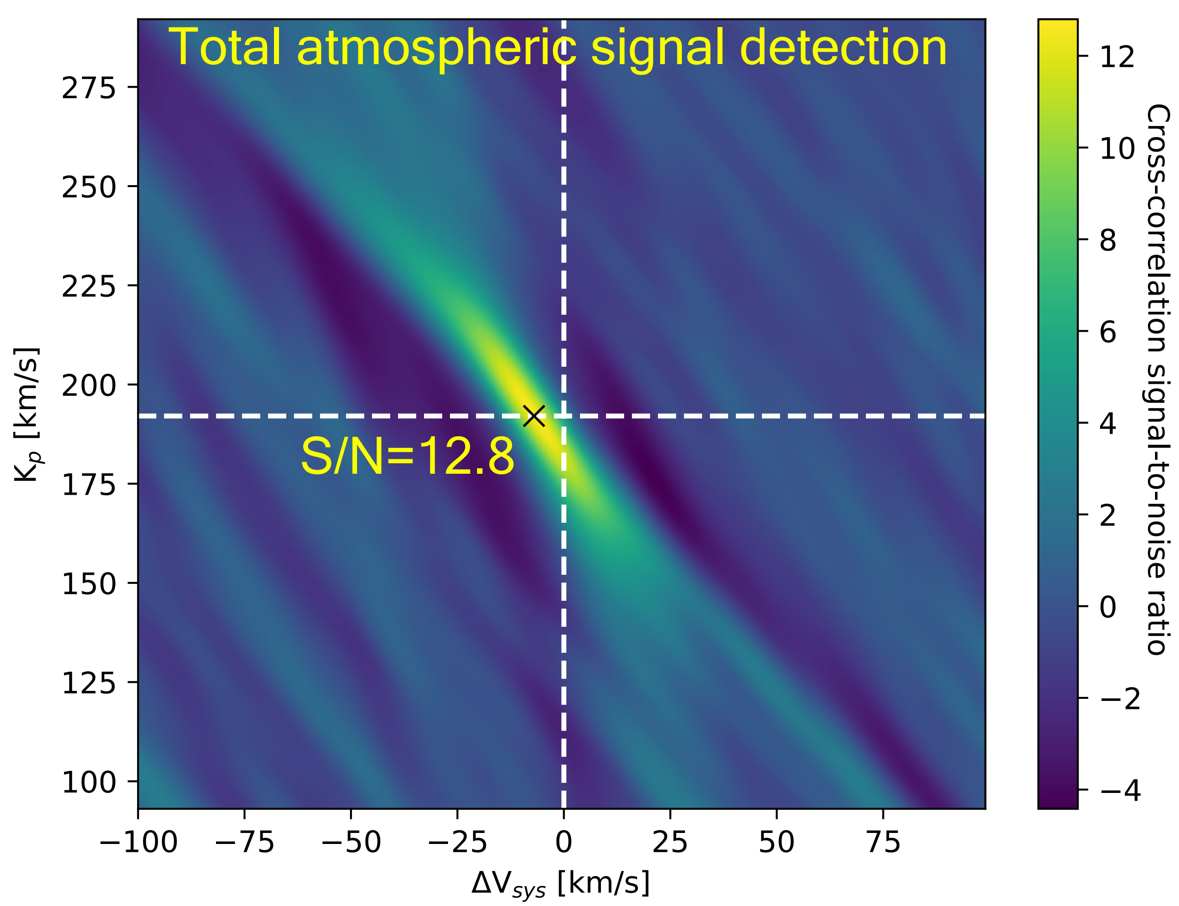


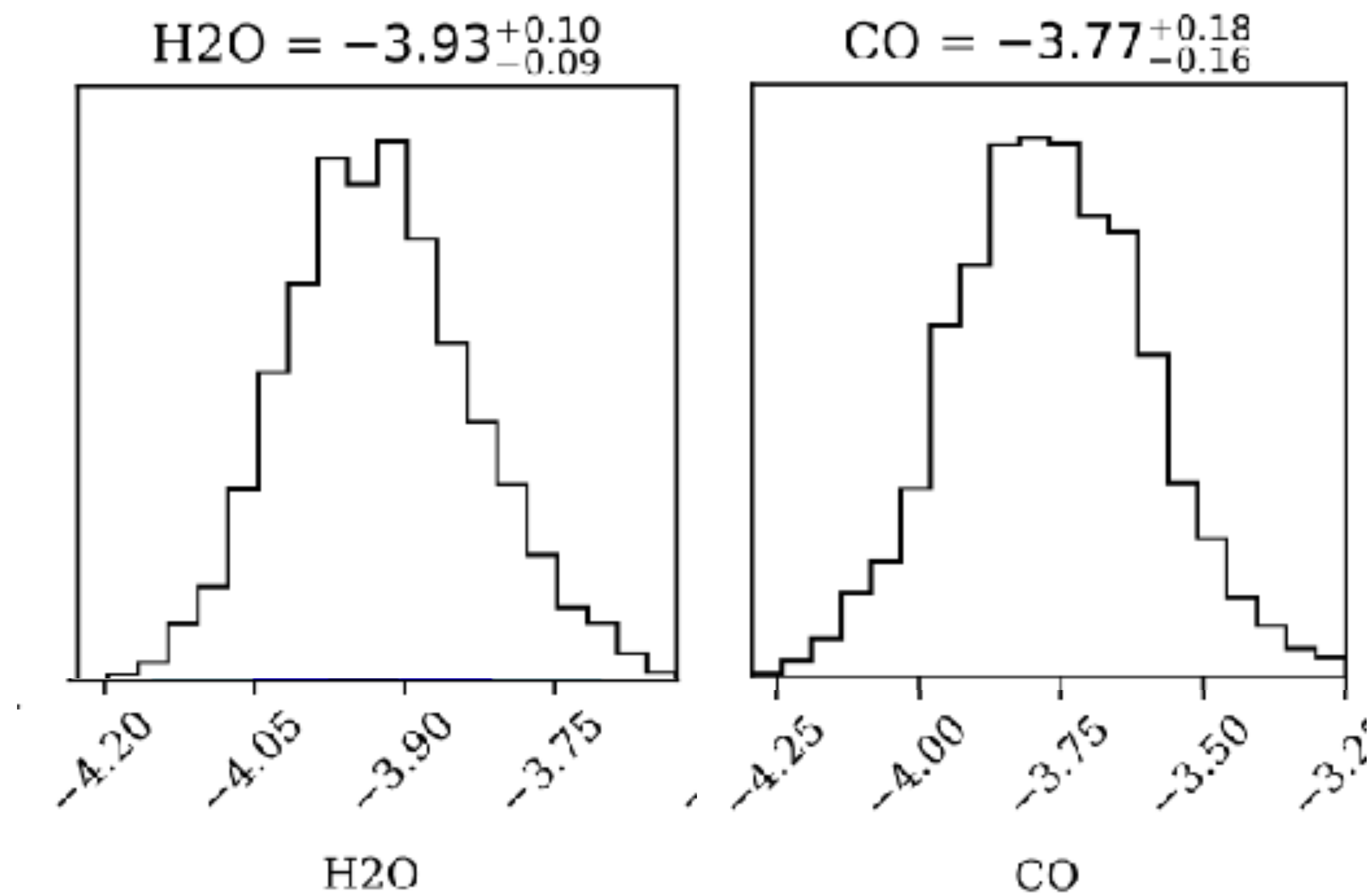
H2-H2/He CIA
H2O
CO
NH3
H2S
CH4
HCN
log10(Absoprtion cross-section) [cm2/mol.]
Wavelength [μm]

What do we find? "Standard" CC Analysis



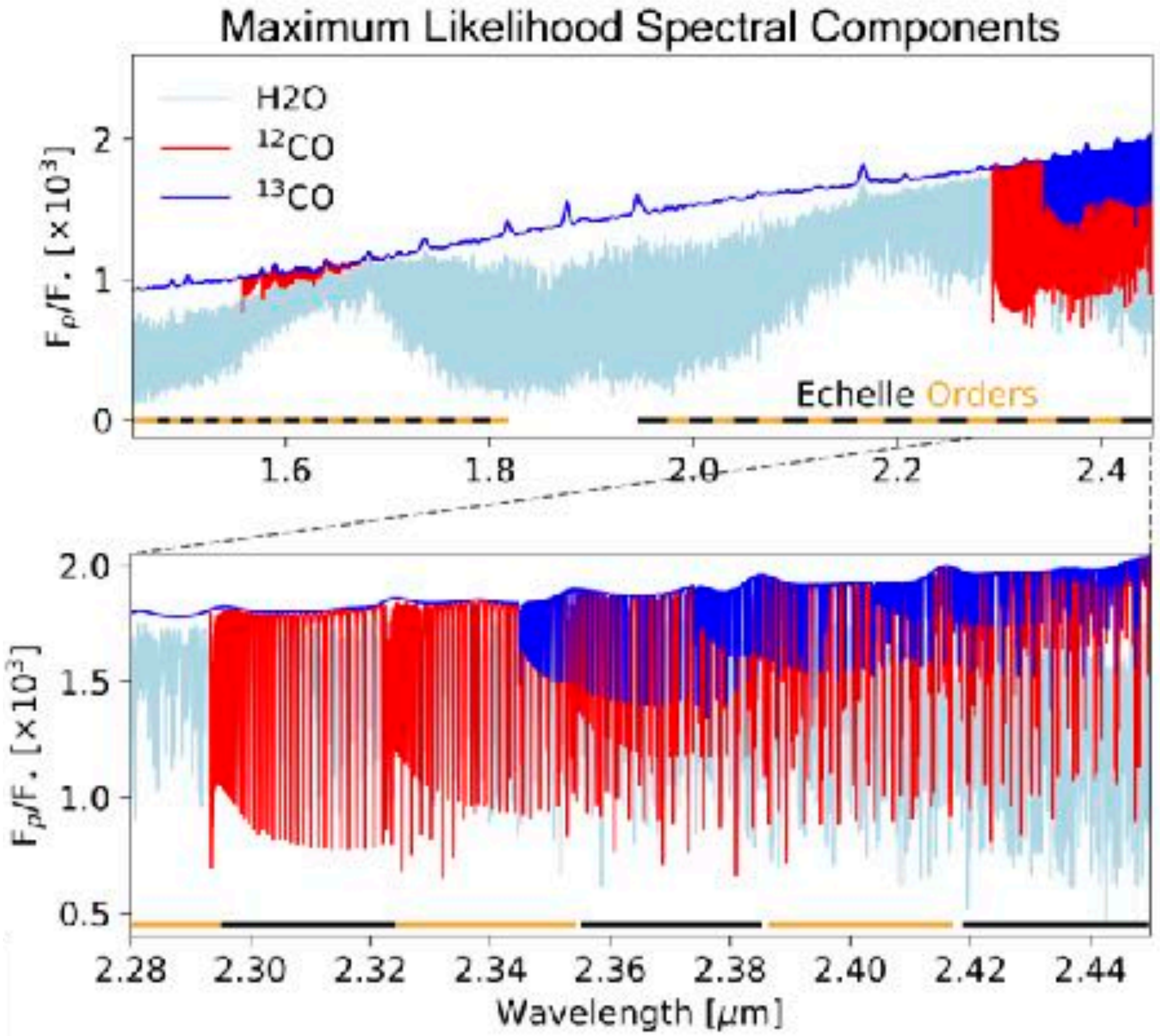
c

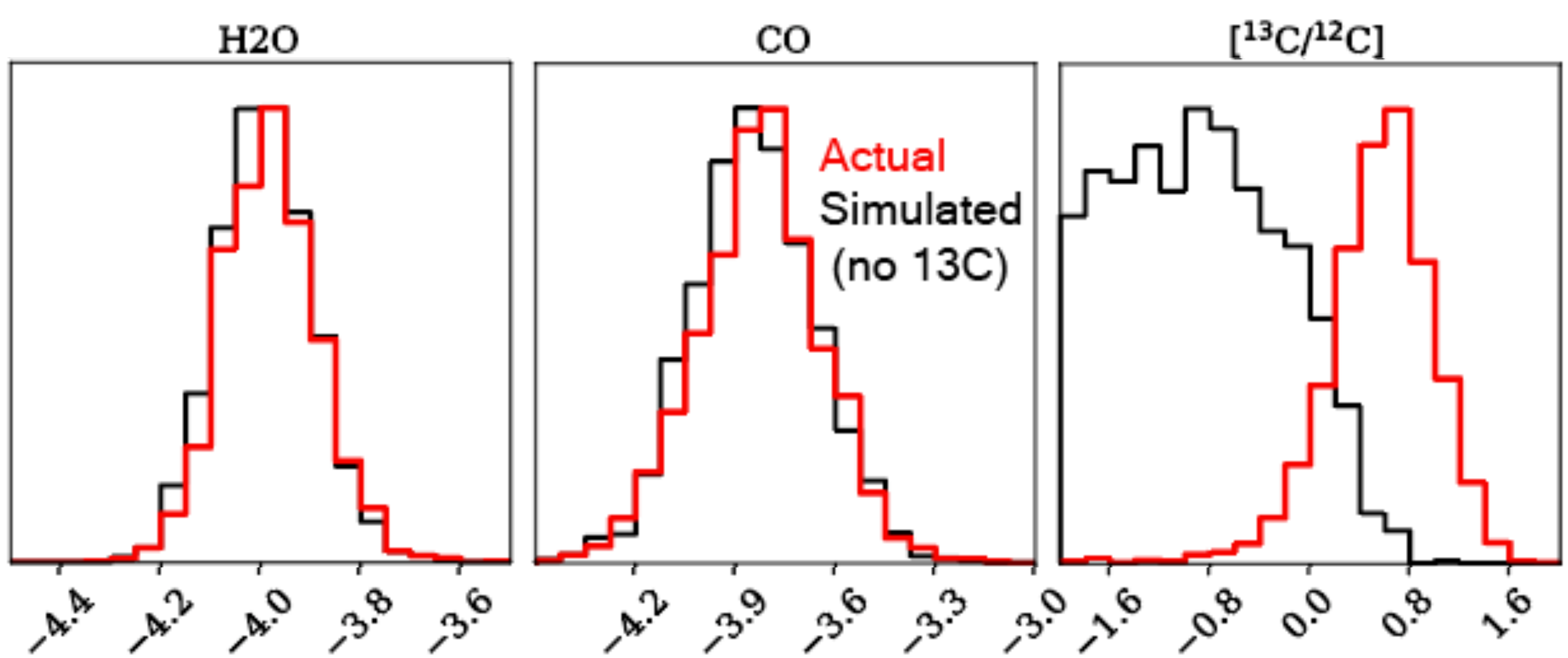




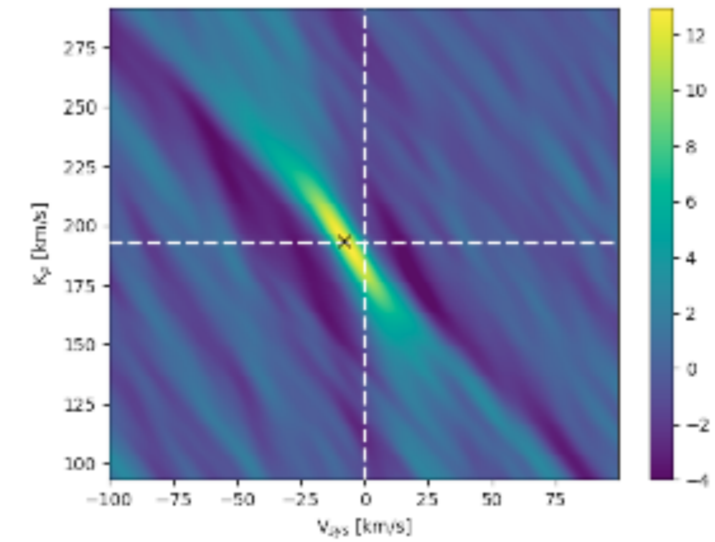
Similar than JWST expected precision !
Comparable to Solar-system precisions

ISOTOPE (maybe)!!!!

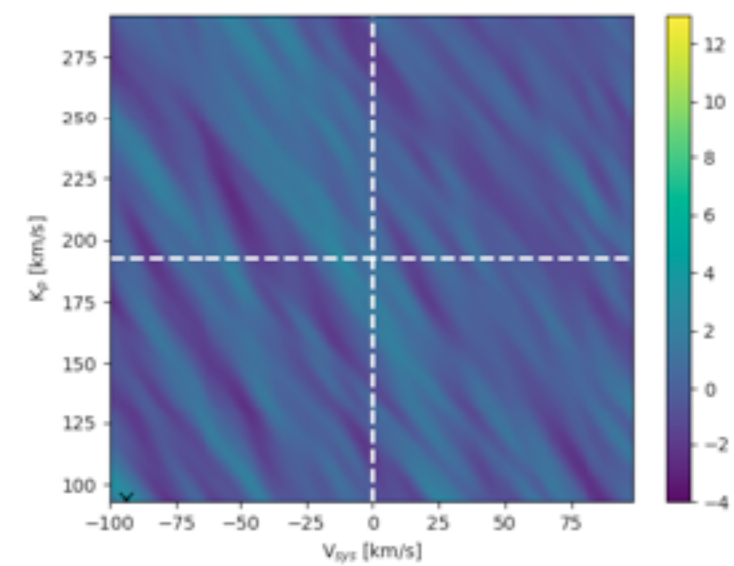




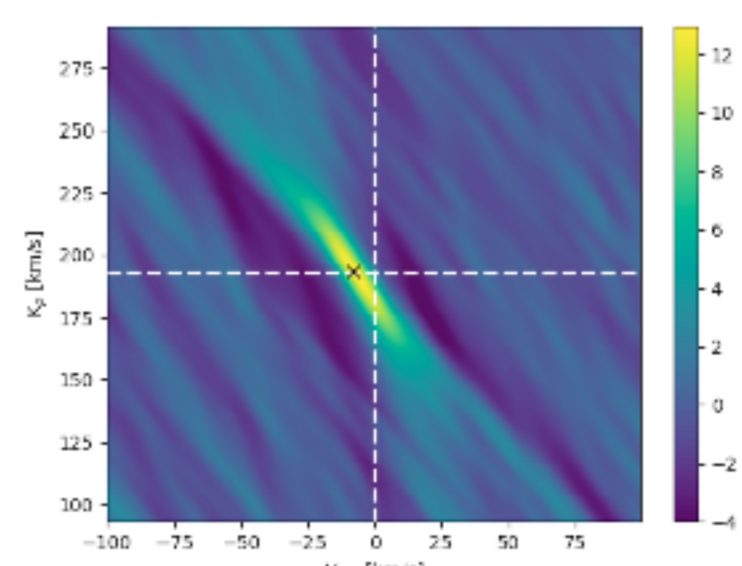
S/N Map From Best Fit



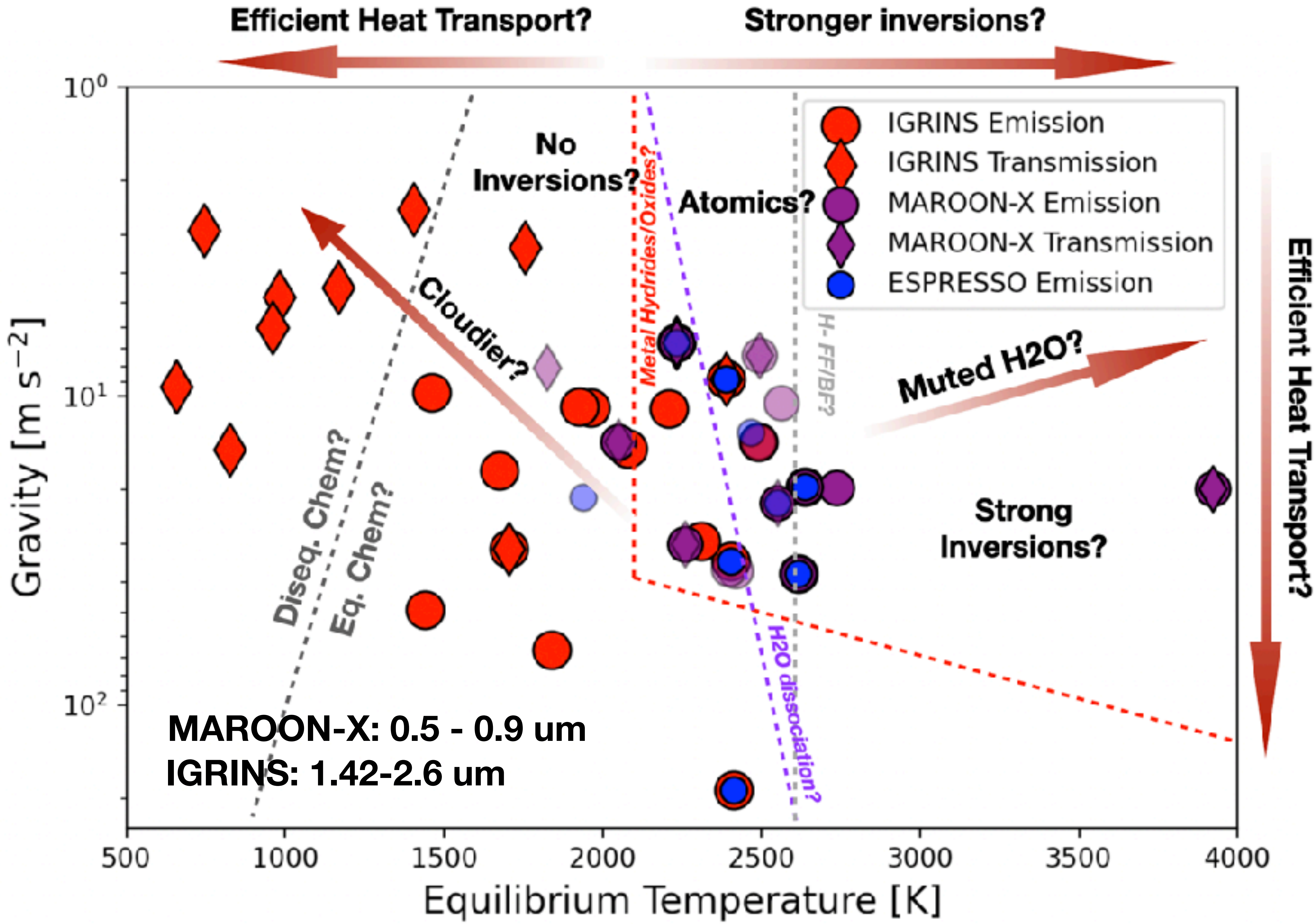
S/N Map Divide Best Fit



S/N Map From Best Fit - 13C

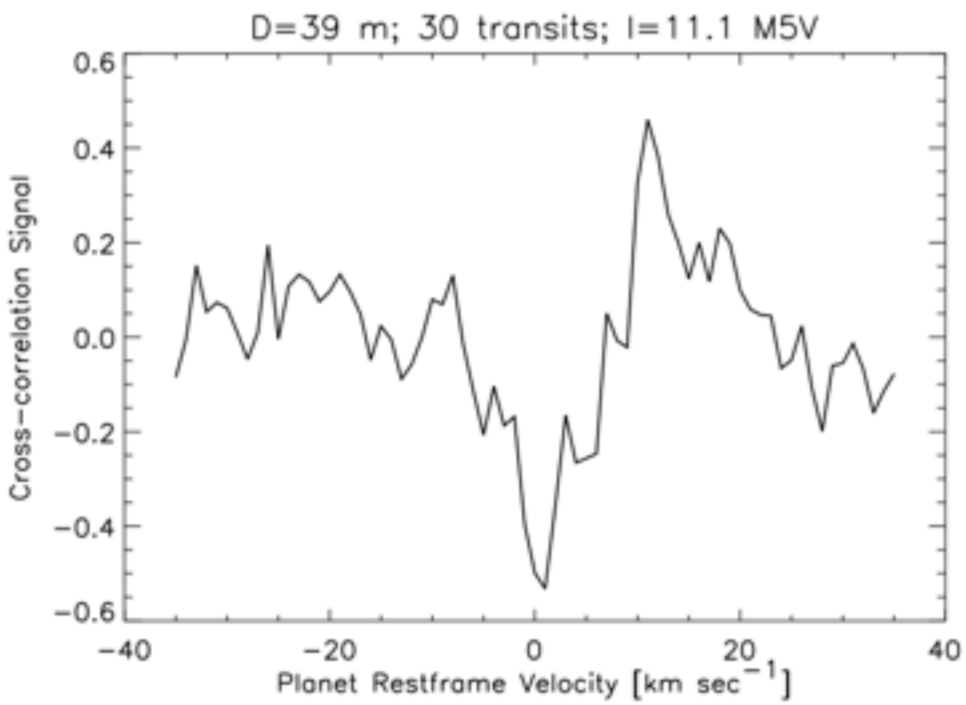


A lot more data coming!



Various PI's: Line, Mansfield, Wardenier Pino, Bean, Kasper ~30 planets awaiting

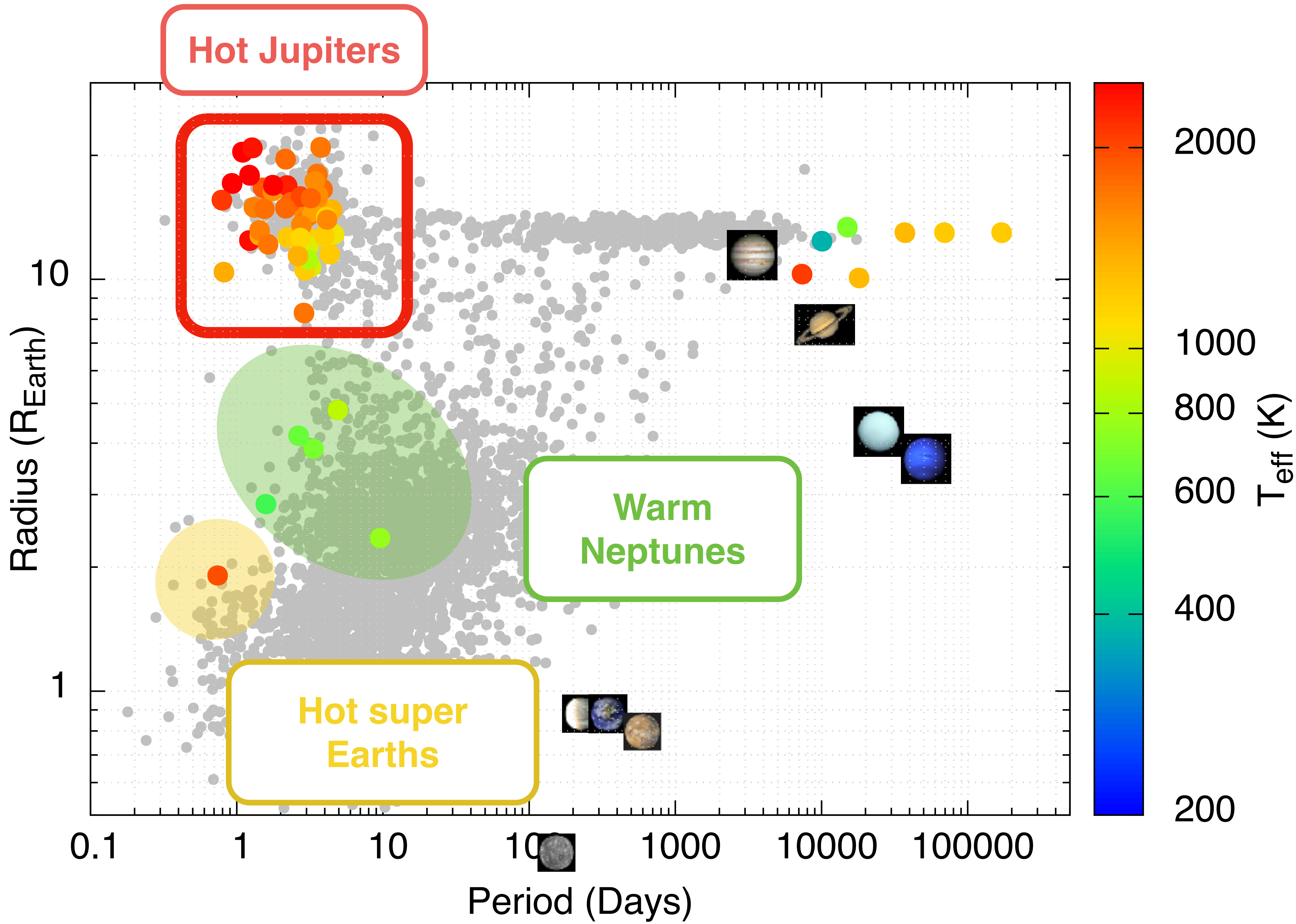
Towards Earth 2.0



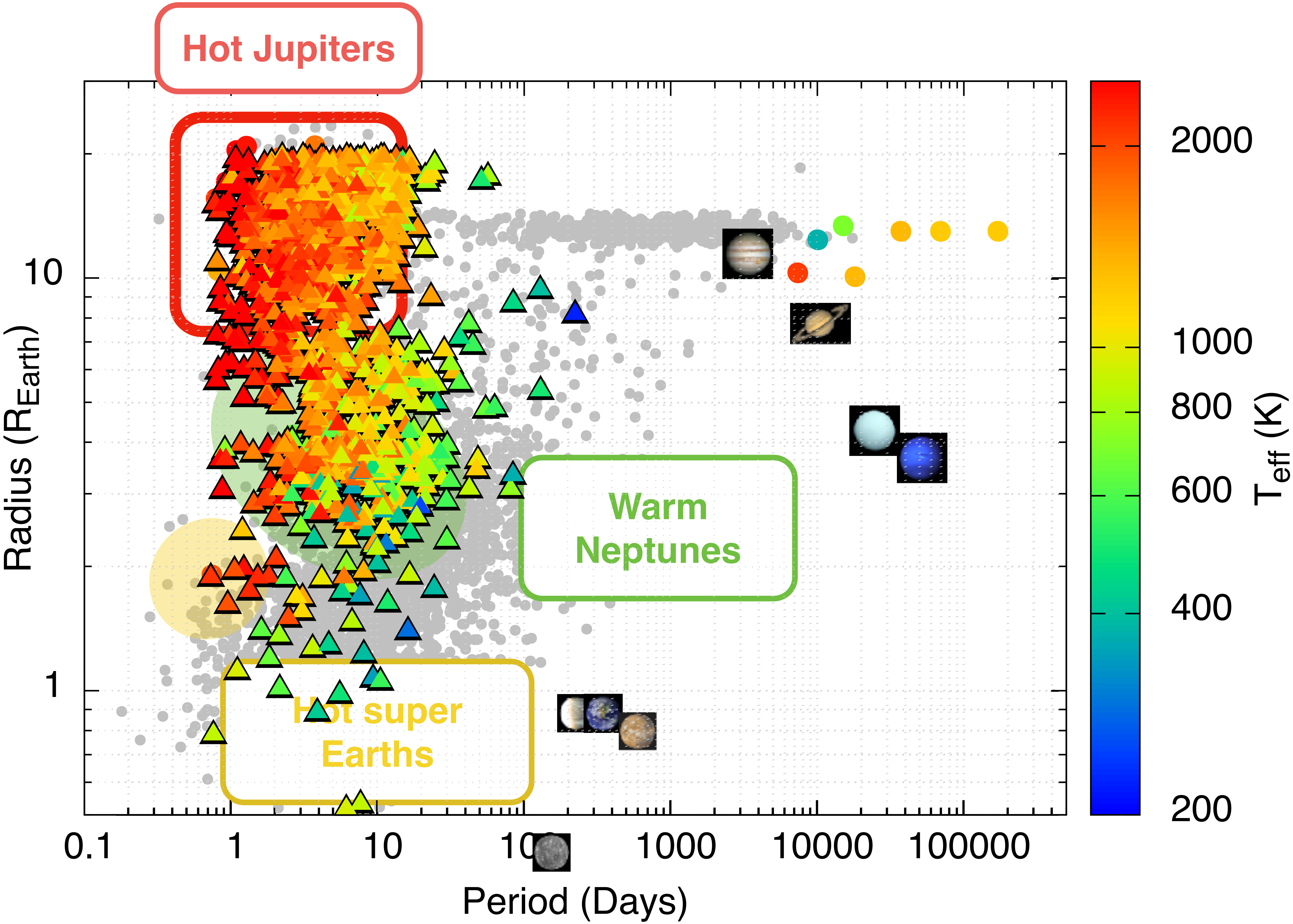
Snellen et al. 2013
Oxygen with E-ELT
on GJ1214 hypothetical Earth.

~2025

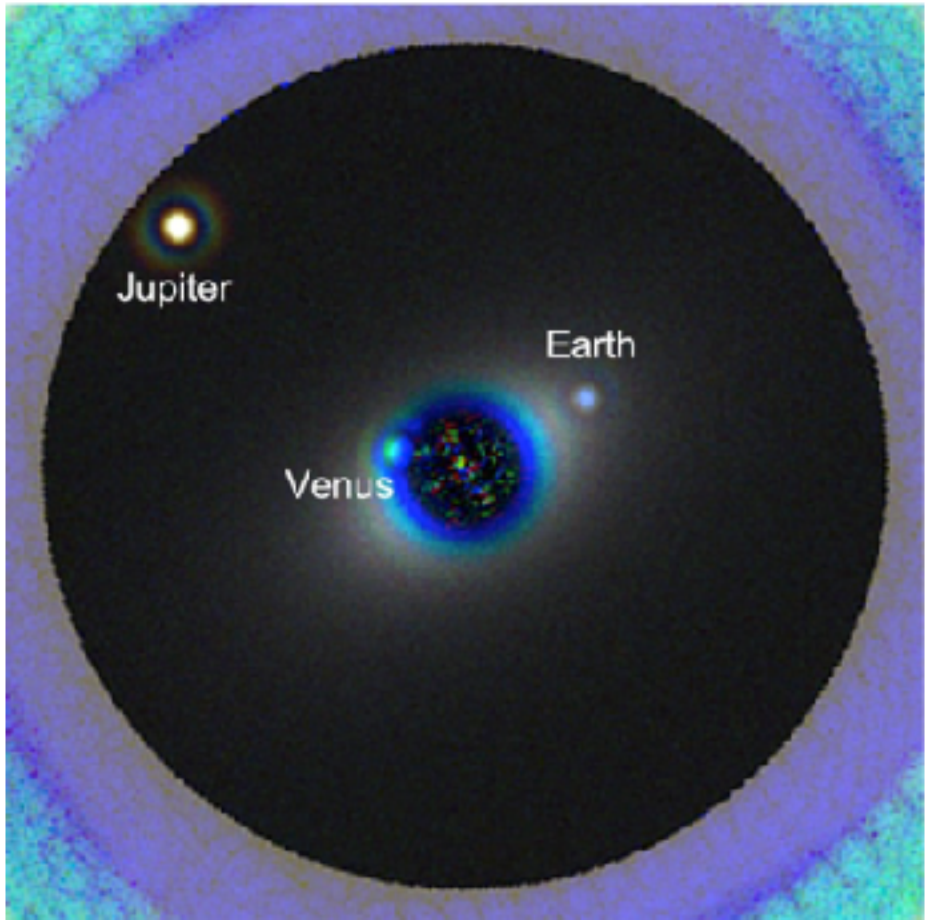
The future of exoplanets : Ariel (2030) & JWST (this year !)



The future of exoplanets : Ariel & JWST

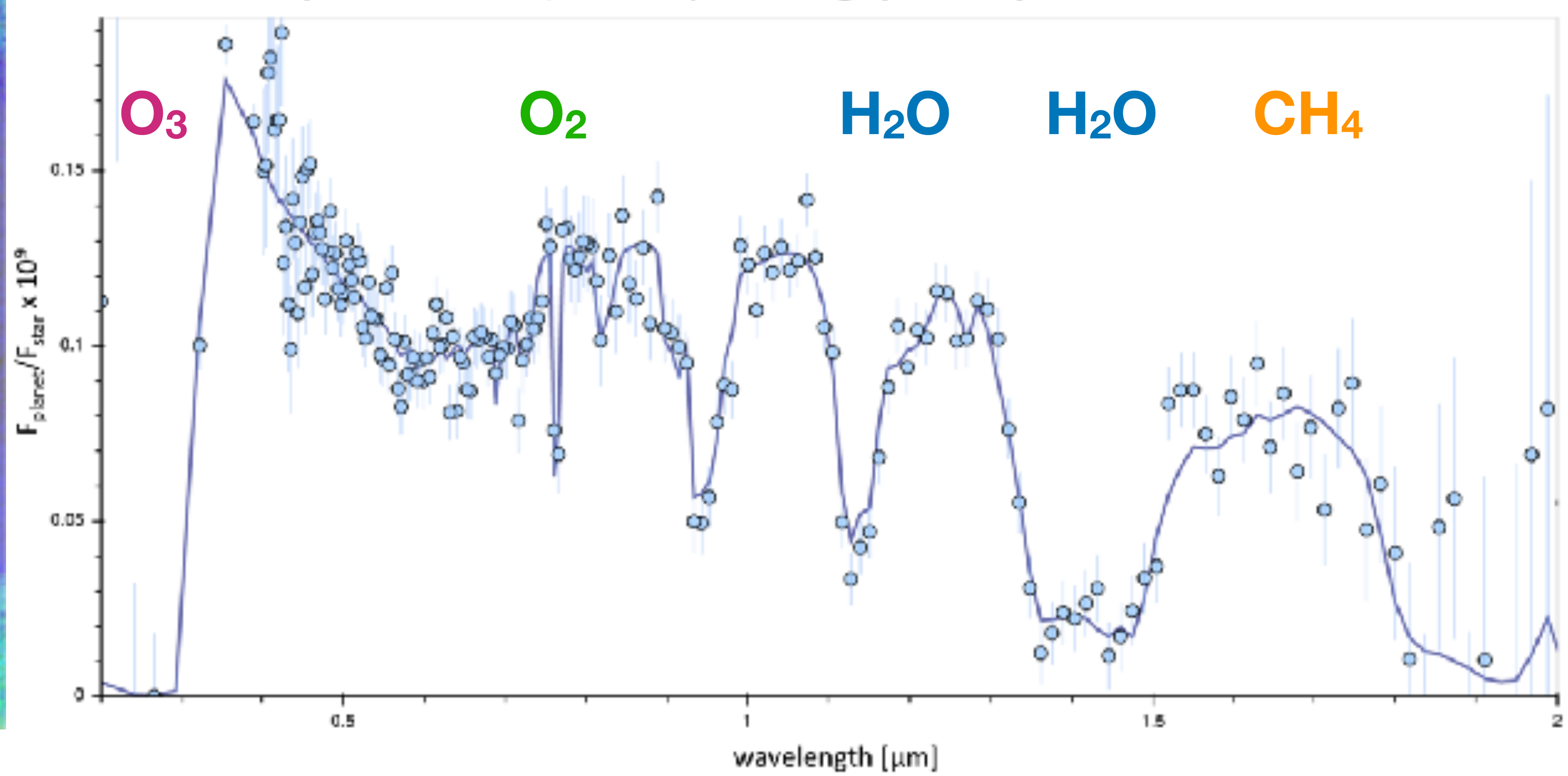


Towards Earth 2.0

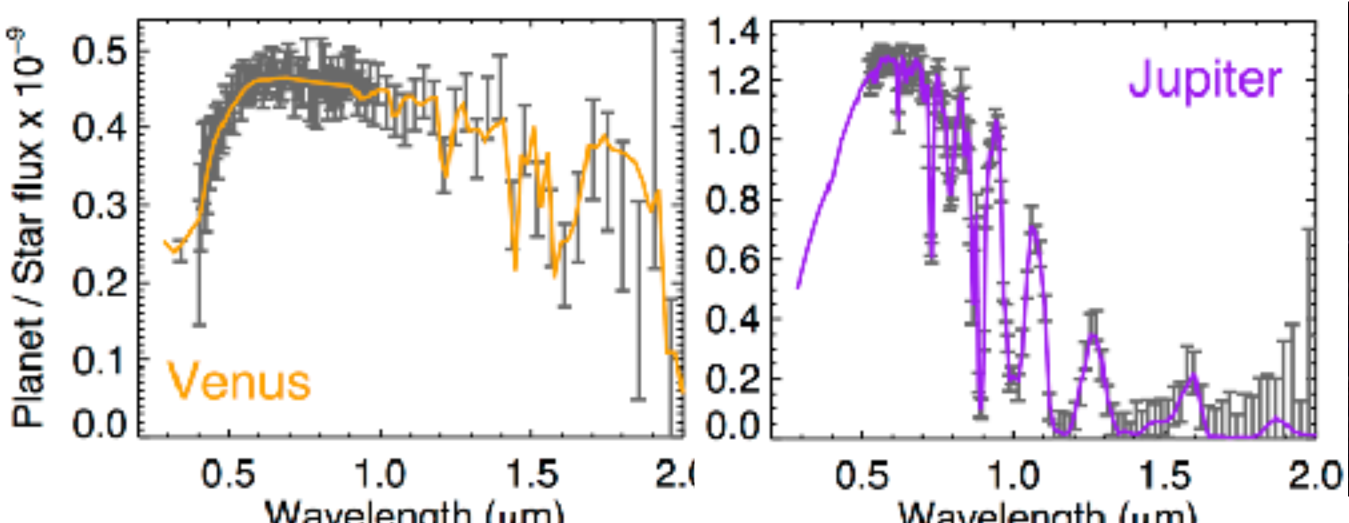


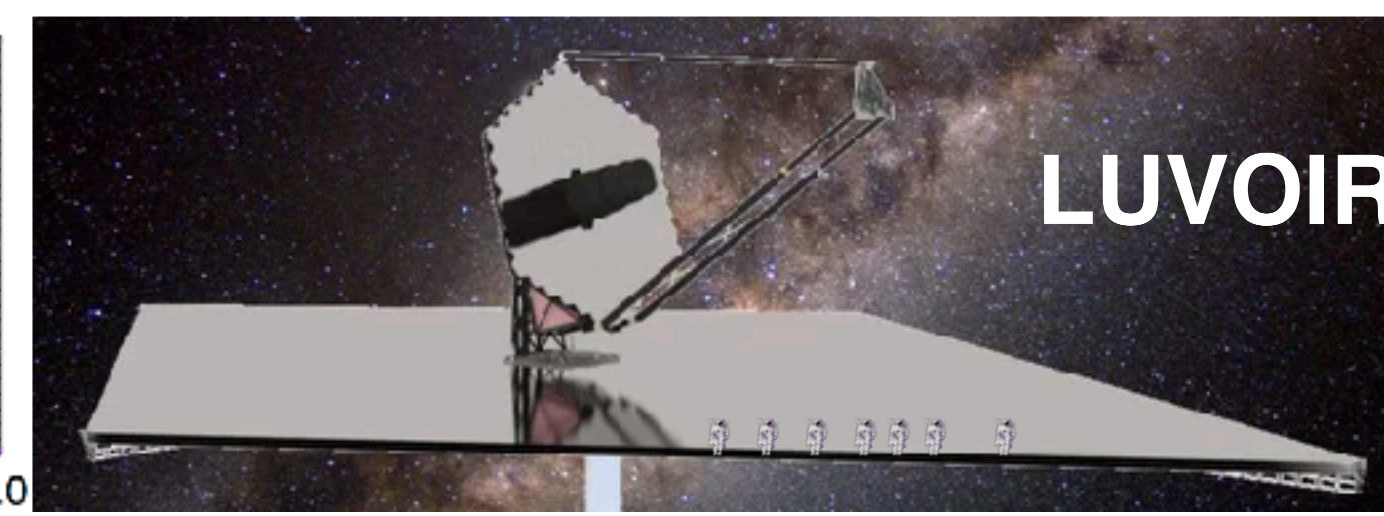
Solar system at 13pc with 12m LUVOIR
L. Pueyo / M. N'Diaye / A. Roberge

Earth twin at 5 pc with LUVOIR-A, 50 hours per coronagraphic bandpass ~ 1 month of total time



Credit: LUVOIR Tools / Roberge





~2045

Conclusions

Current observations have detected chemical species in exoplanet atmospheres but have had a hard time to quantify abundances.

JWST is observing and expected to get ~0.3dex precision but planets are complex and many effects can bias abundance measurements, including 3D effects ! 30 years of JWST means hundreds of planets observed !

We find that planetary spectra are primarily shaped by the temperature but that gravity, rotation period and metallicity can lead to a very large scatter in the population.

Current high-resolution spectra can retrieve abundances as precise as JWST but 3D effects are already apparent and it is not clear how they will affect the measured abundances.