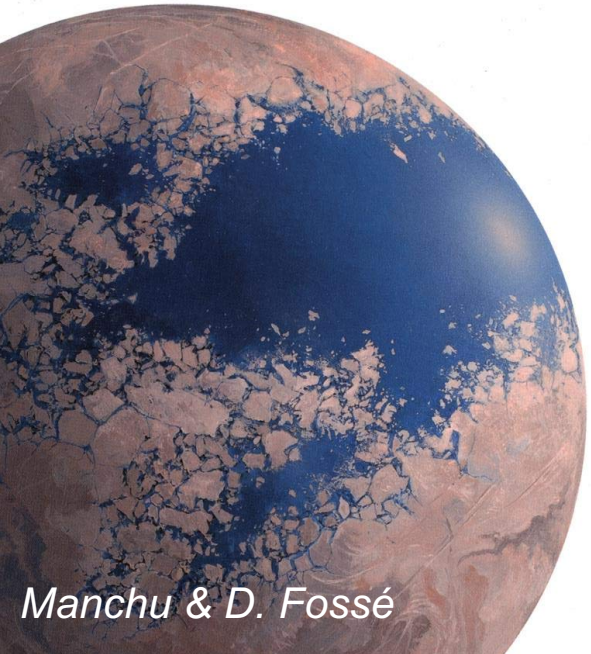
CHARACTERIZING THE ATMOSPHERES AND CLIMATES OF NEARBY EARTH-SIZED, TEMPERATE EXOPLANETS


Manchu & D. Fossé

Martin Turbet

And C. Lovis, E. Bolmont, D. Ehrenreich, G. Chaverot, T. Fauchez, M. Lefèvre, S. Quanz, J. Hagelberg, D. Mondelain, J-M Hartmann, H. Tran, A. Campargue, O. Pirali, D. Abbot, E. Kite, J. Leconte, F. Forget, F. Selsis, E. Millour, T. Kodama, E. Wolf

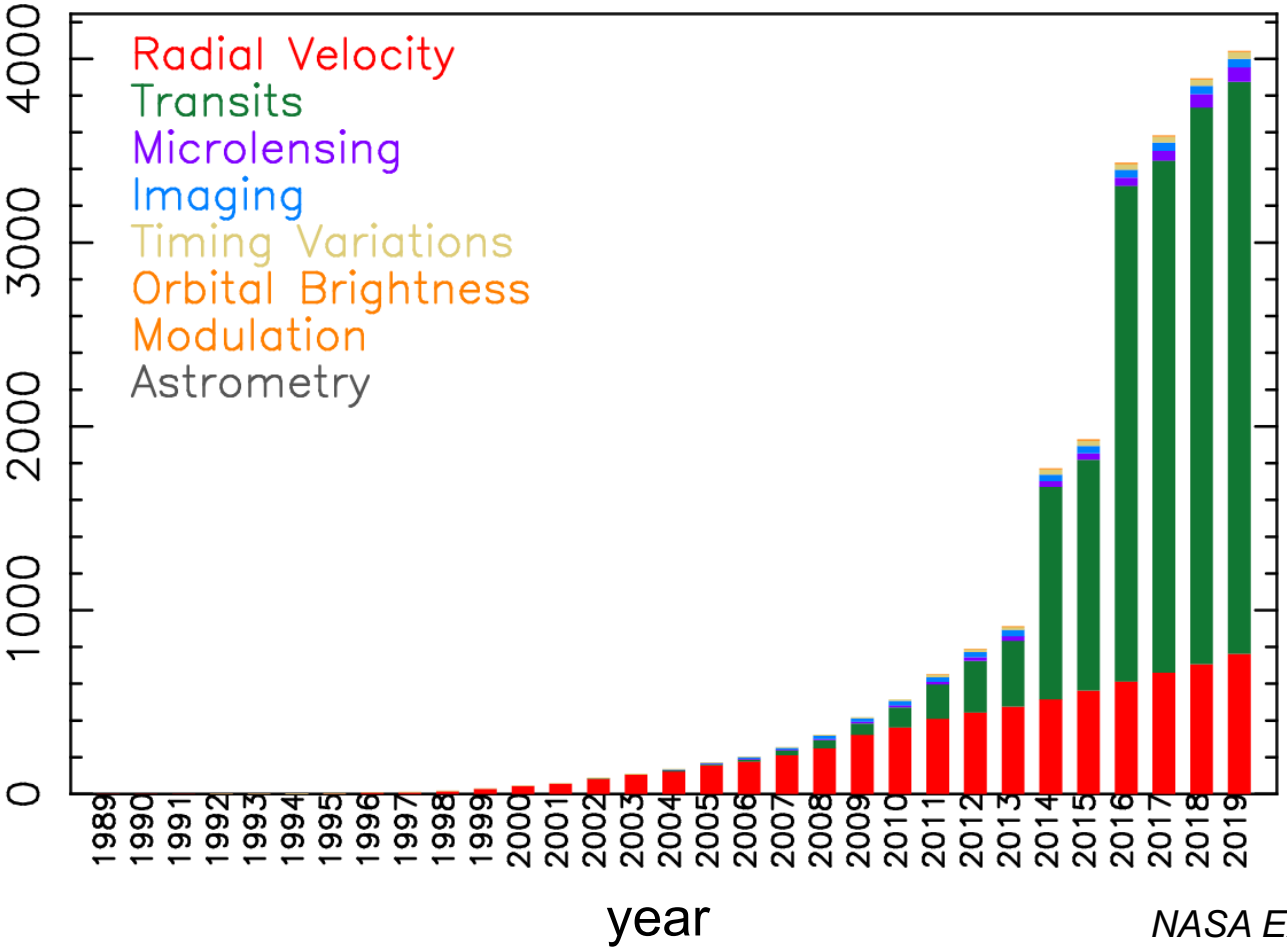
GRUBER FOUNDATION

MARIE CURIE ACTIONS

OBSERVATOIRE DE GENÈVE FONDÉ EN 1772

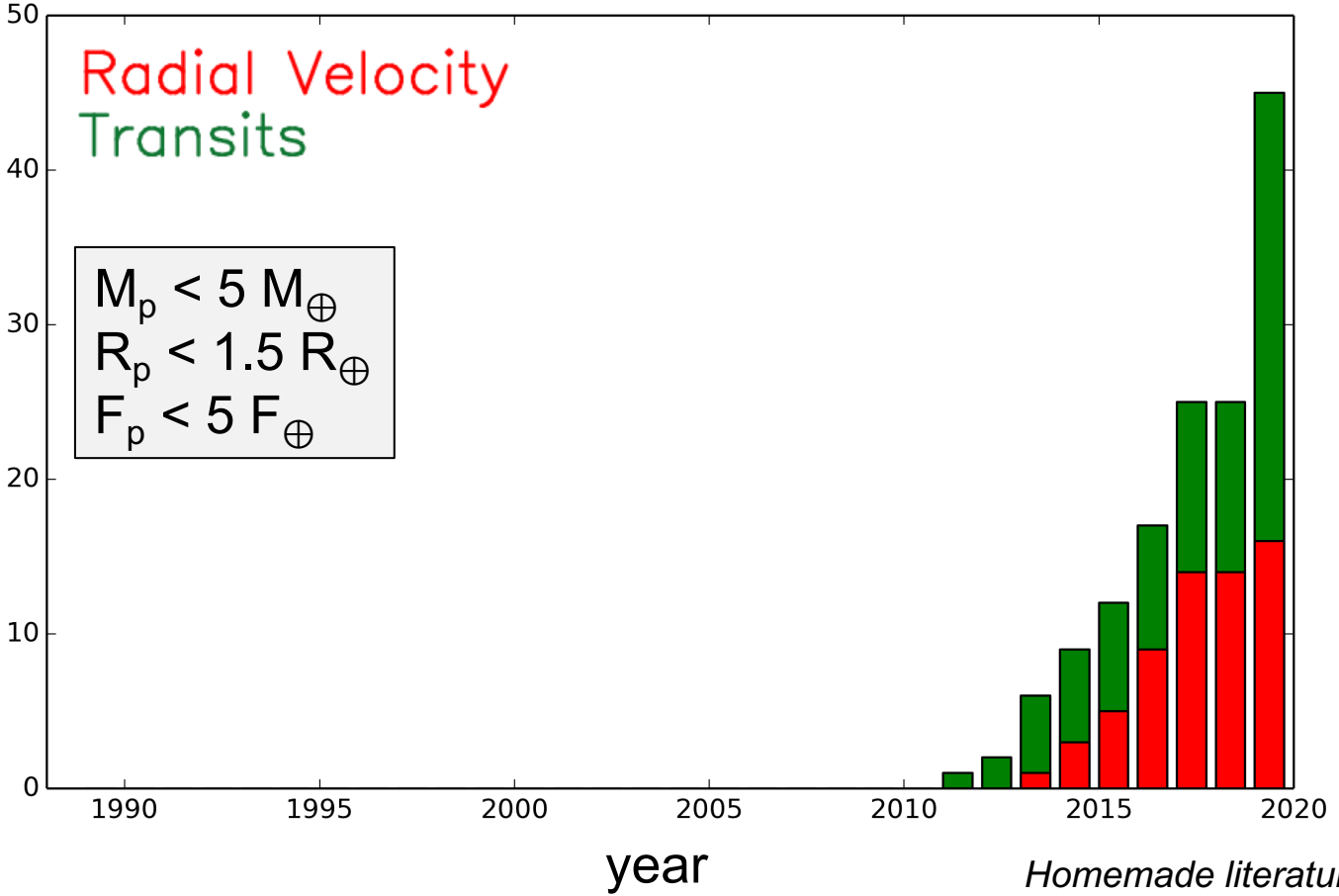
Marie Curie postdoctoral fellow and TGF fellow at the Geneva Observatory (CH)

CUMULATIVE DETECTION OF EXOPLANETS PER YEAR



NASA Exoplanet archive

CUMULATIVE DETECTION OF SMALL, TEMPERATE EXOPLANETS PER YEAR



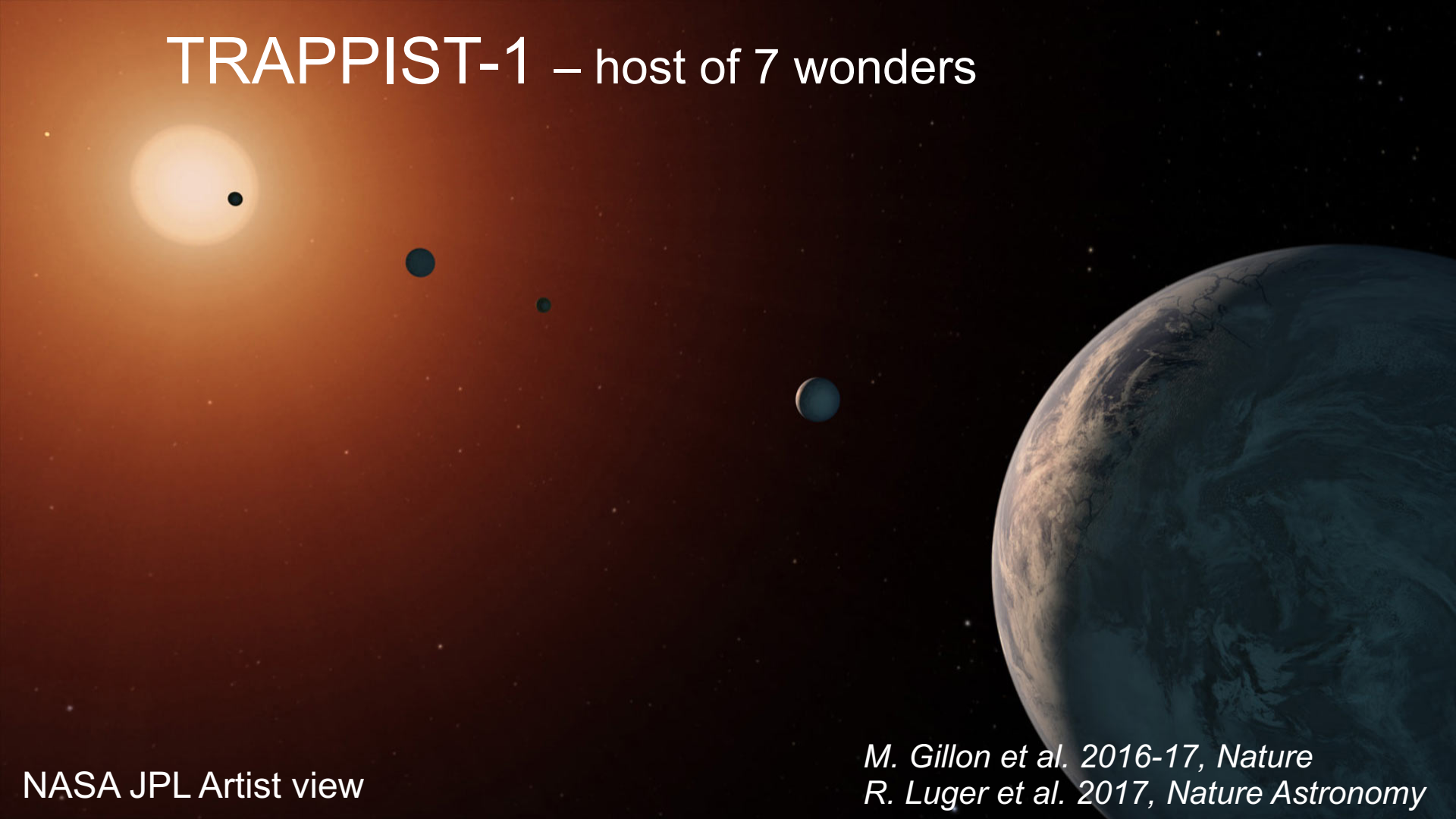
Homemade literature digging

PROXIMA CENTAURI b – our closest neighbour

ESO Artist view

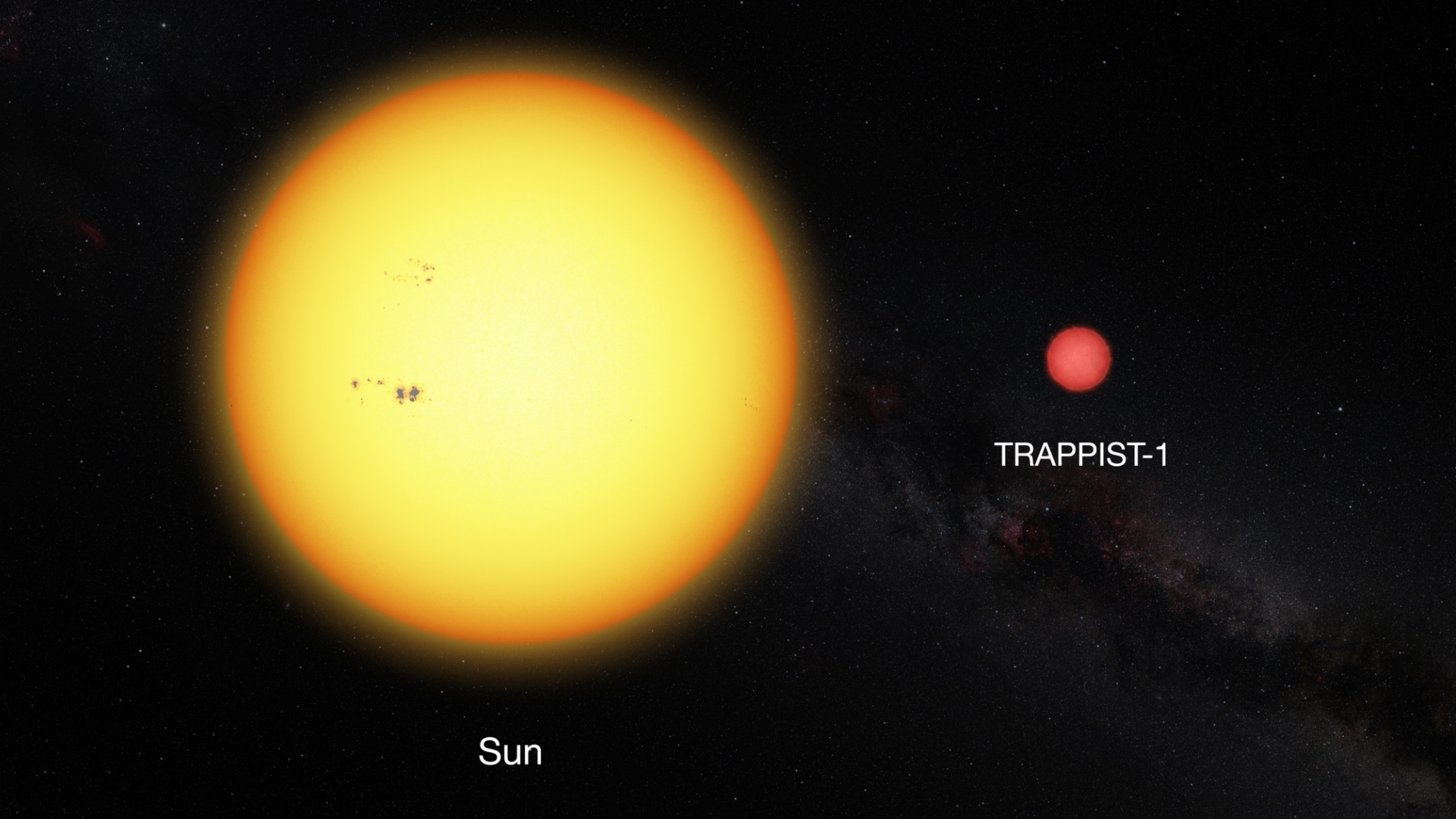
Anglada-Escudé et al. 2016, Nature

TRAPPIST-1 – host of 7 wonders



NASA JPL Artist view

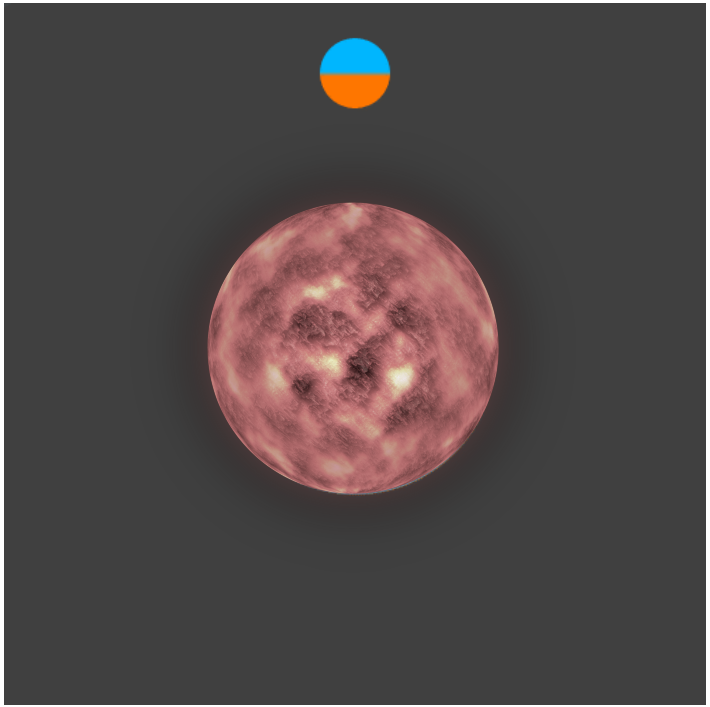
M. Gillon et al. 2016-17, Nature
R. Luger et al. 2017, Nature Astronomy


TRAPPIST-1
Sun

DIFFERENCES BETWEEN PLANETS ORBITING SUN-LIKE STARS VS LATE M-STARS

DIFFERENCES BETWEEN PLANETS ORBITING SUN-LIKE STARS VS LATE M-STARS

#1 Tidal locking / Synchronous rotation

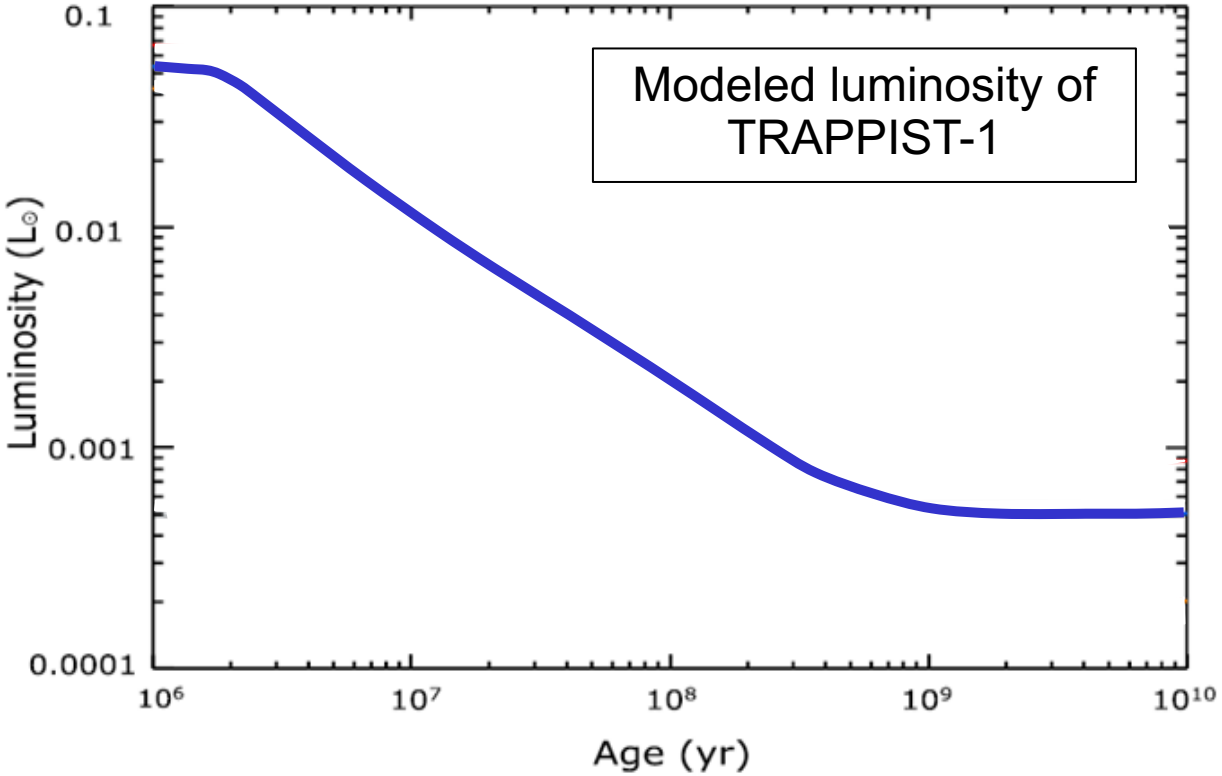


May not be accurate if:

- Strong atmospheric tides
(*Leconte et al. 2015, Science*)
- High eccentricity
(*Makarov 2012, Ribas et al. 2016, A&A*)
- Strong planet-planet interactions
(*Vinson et al. 2019*)

DIFFERENCES BETWEEN PLANETS ORBITING SUN-LIKE STARS VS LATE M-STARS

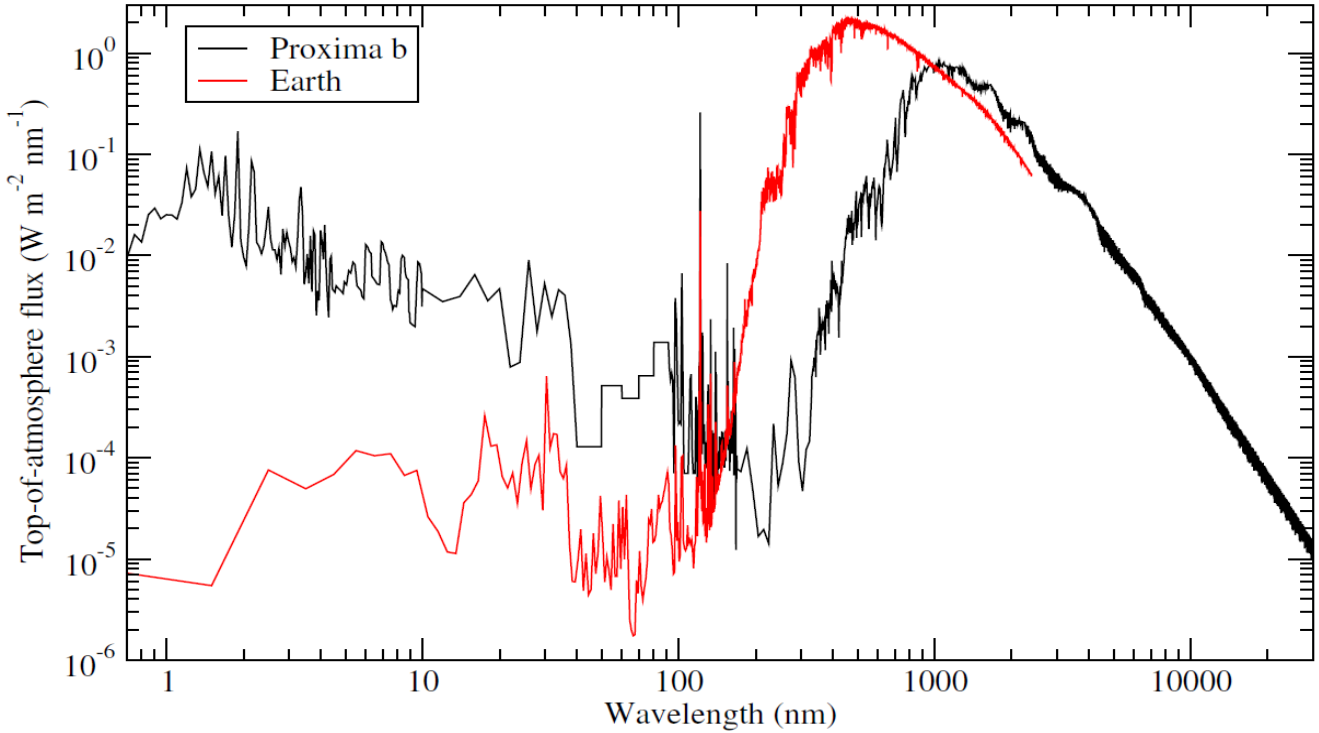
#2 Runaway greenhouse during the Pre Main Sequence phase of the host star



Adapted from Bolmont et al. 2017, MNRAS

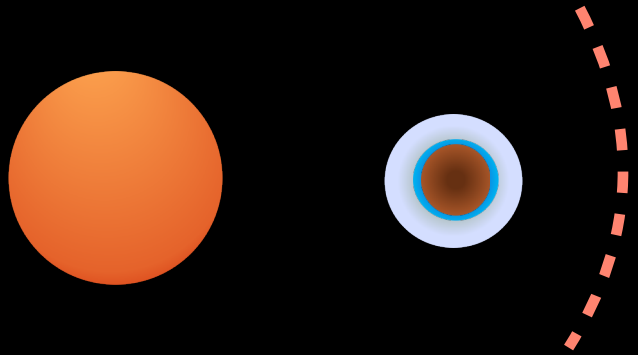
DIFFERENCES BETWEEN PLANETS ORBITING SUN-LIKE STARS VS LATE M-STARS

#3 Large X/EUV-driven atmospheric escape

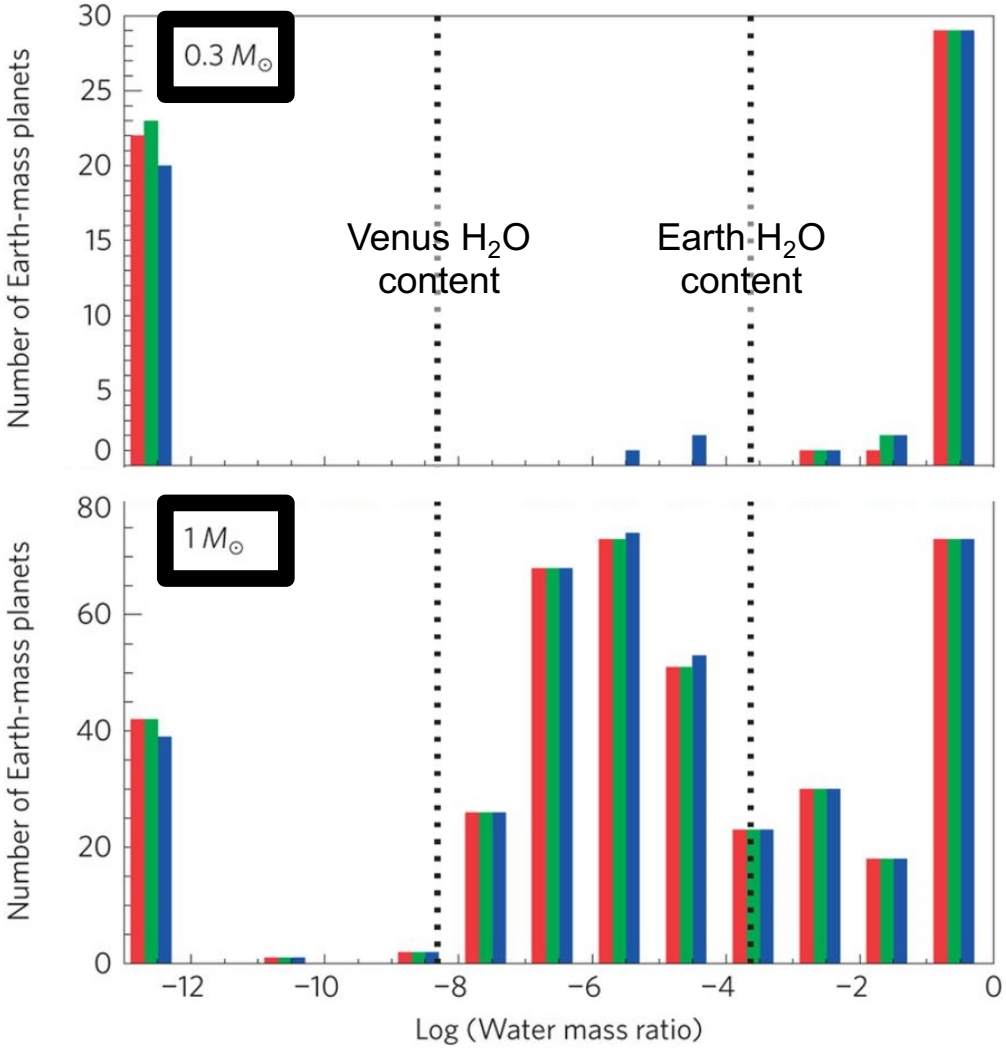


Proxima Centauri spectrum, based on multiple observations

Ribas et al. 2017, A&A



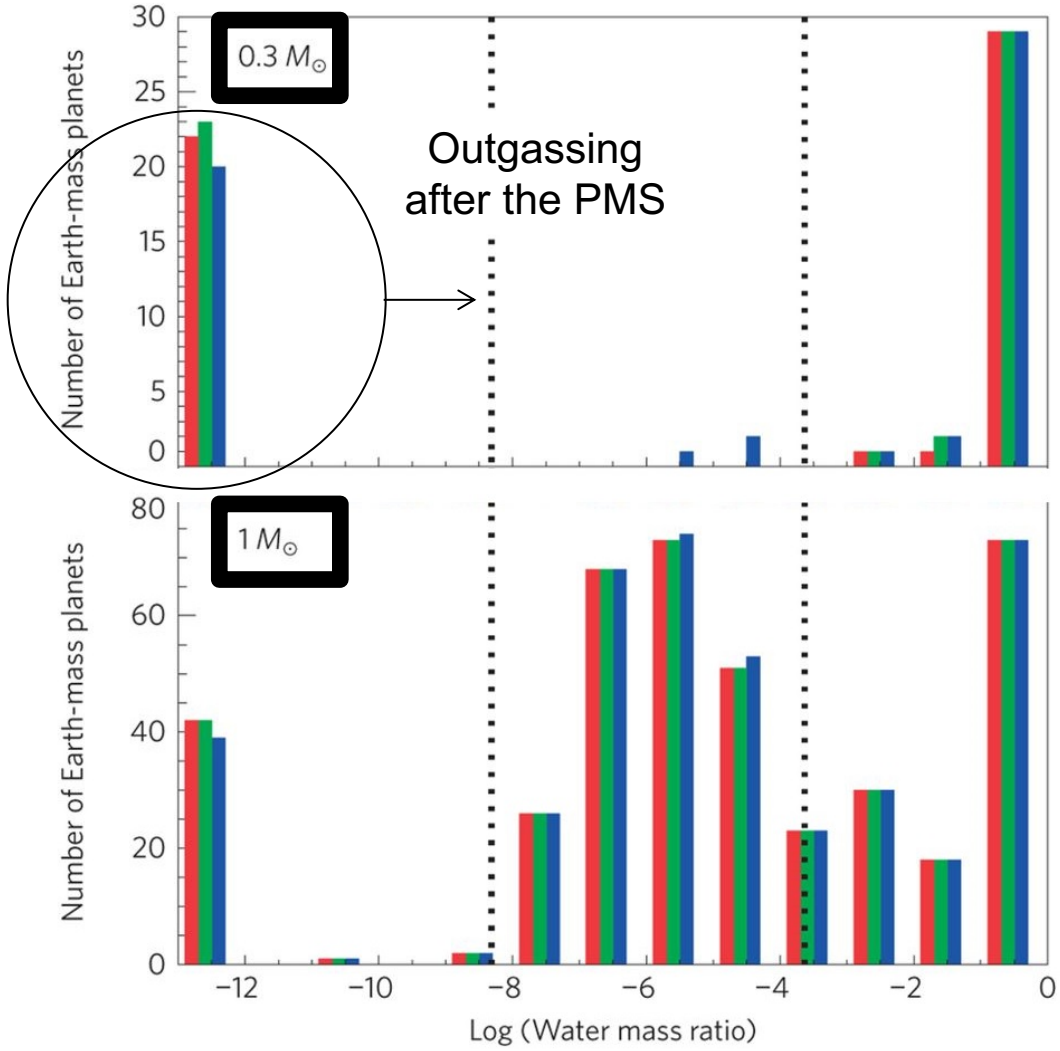
VOLATILE-POOR PLANET ENDS UP
COMPLETELY DRY AIRLESS PLANET



LOW MASS STAR

SUN-LIKE STAR

Tian & Ida 2015, Nature Geoscience



LOW MASS STAR

SUN-LIKE STAR

Tian & Ida 2015, Nature Geoscience

FOUR MAIN POSSIBLE SCENARIOS

Dry, airless planet

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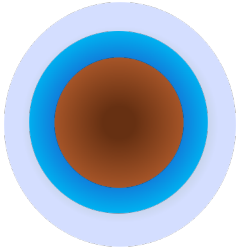
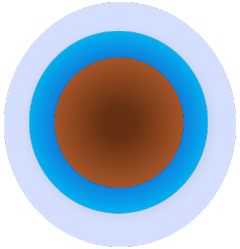
Dry, airless planet



Volatile-rich,
(e.g. water-rich) planet

FOUR MAIN POSSIBLE SCENARIOS

Dry, airless planet



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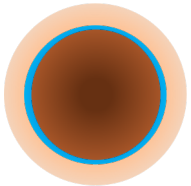
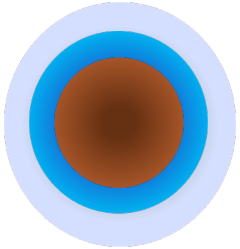


Dry, airless planet replenished with volatile delivery and volcanic outgassing after PMS

FOUR MAIN POSSIBLE SCENARIOS

Dry, airless planet



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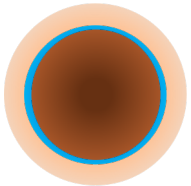

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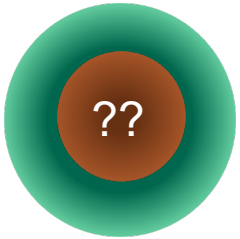
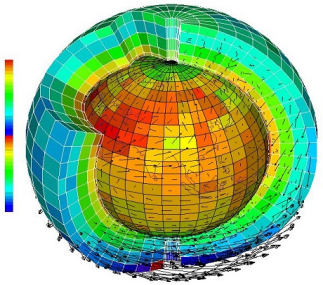


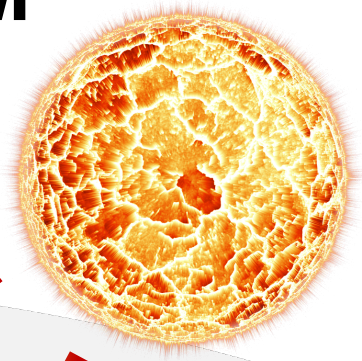
Known unknowns (H_2-rich planet? He-rich planet? Etc.) and unknown unknowns

THE LMD GENERIC GCM



1) Dynamical Core to compute large scale atmospheric motions and transport

6) Photochemical hazes and lifted aerosols



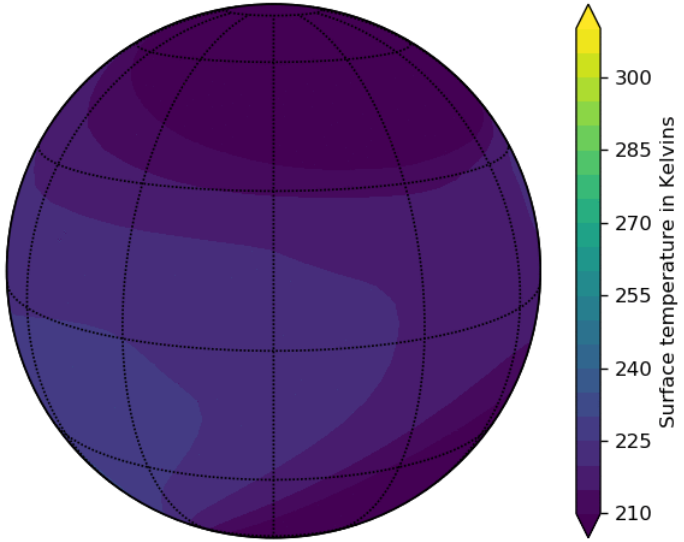
2) Radiative transfer through gas and aerosols

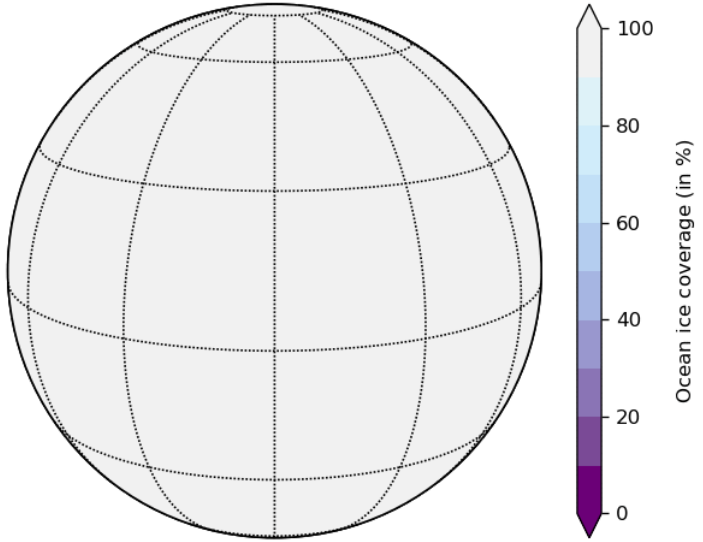
3) Subgrid-scale dynamics: Turbulence and convection in the boundary layer

5) Volatile condensation on the surface and in the atmosphere

4) Surface and subsurface thermal balance

Example of a 3D Global Climate Model simulation of a tidally-locked terrestrial **aquaplanet** orbiting around a low mass star

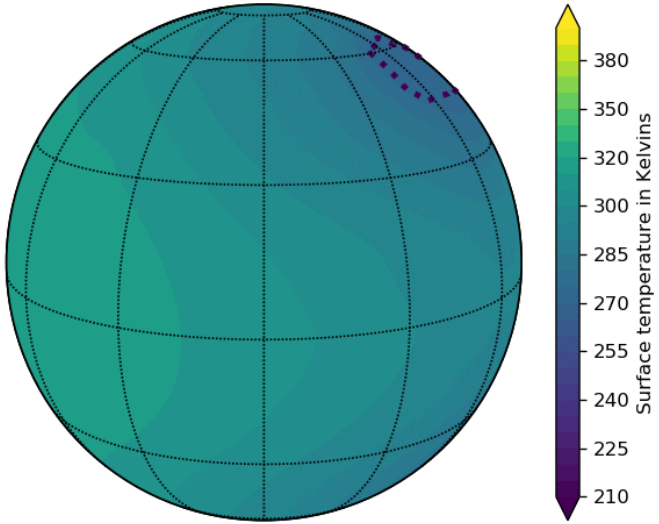


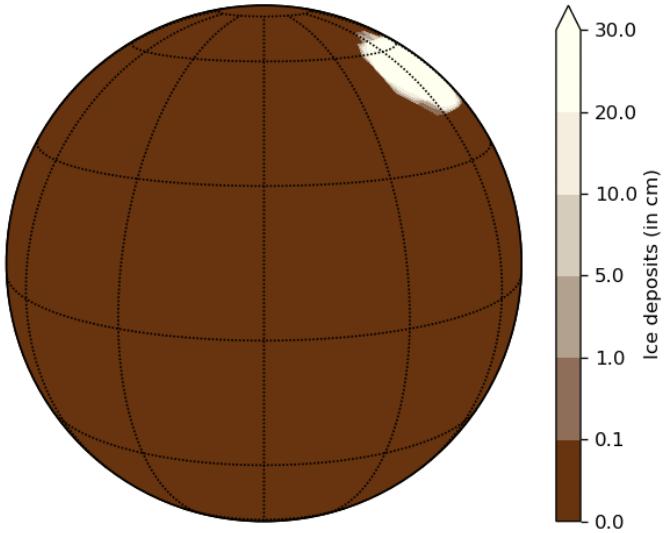


Made with the LMD Generic GCM

Turbet et al. 2016, 2018, A&A

Example of a 3D Global Climate Model simulation of a tidally-locked terrestrial **land planet** orbiting around a low mass star





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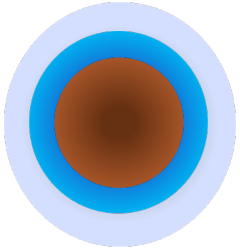

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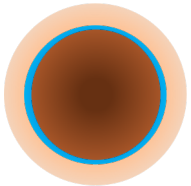

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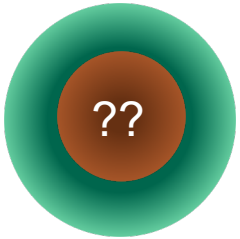

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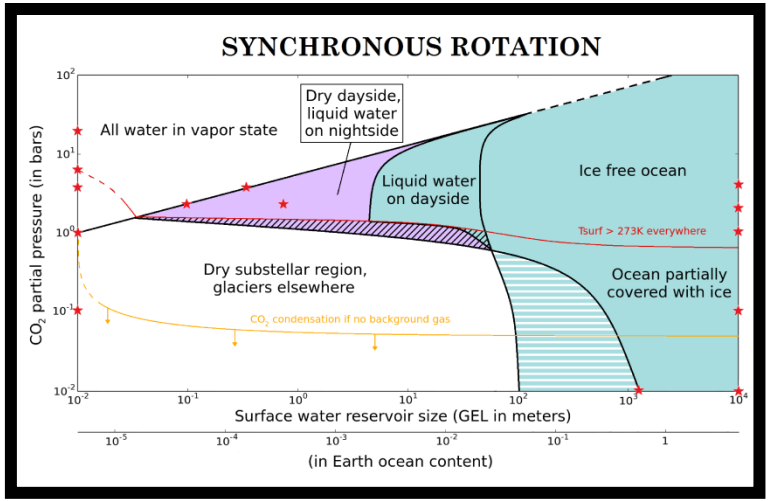
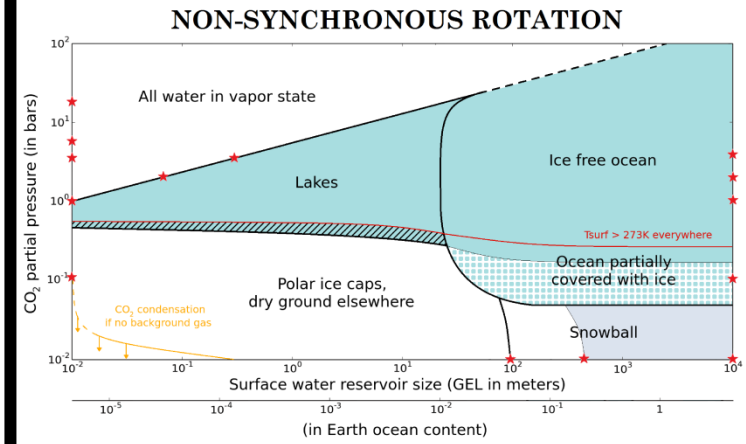
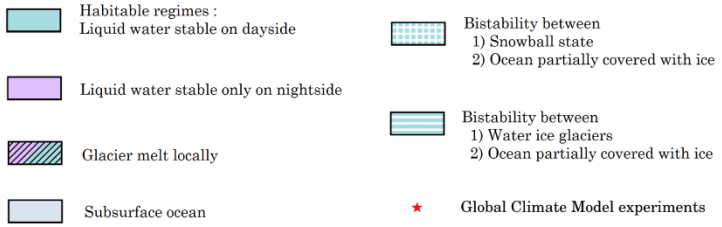
POSSIBLE CLIMATES OF A« TYPICAL » TEMPERATE PLANET AROUND M-STAR

(here diagrams are for Proxima b / TRAPPIST-1e)

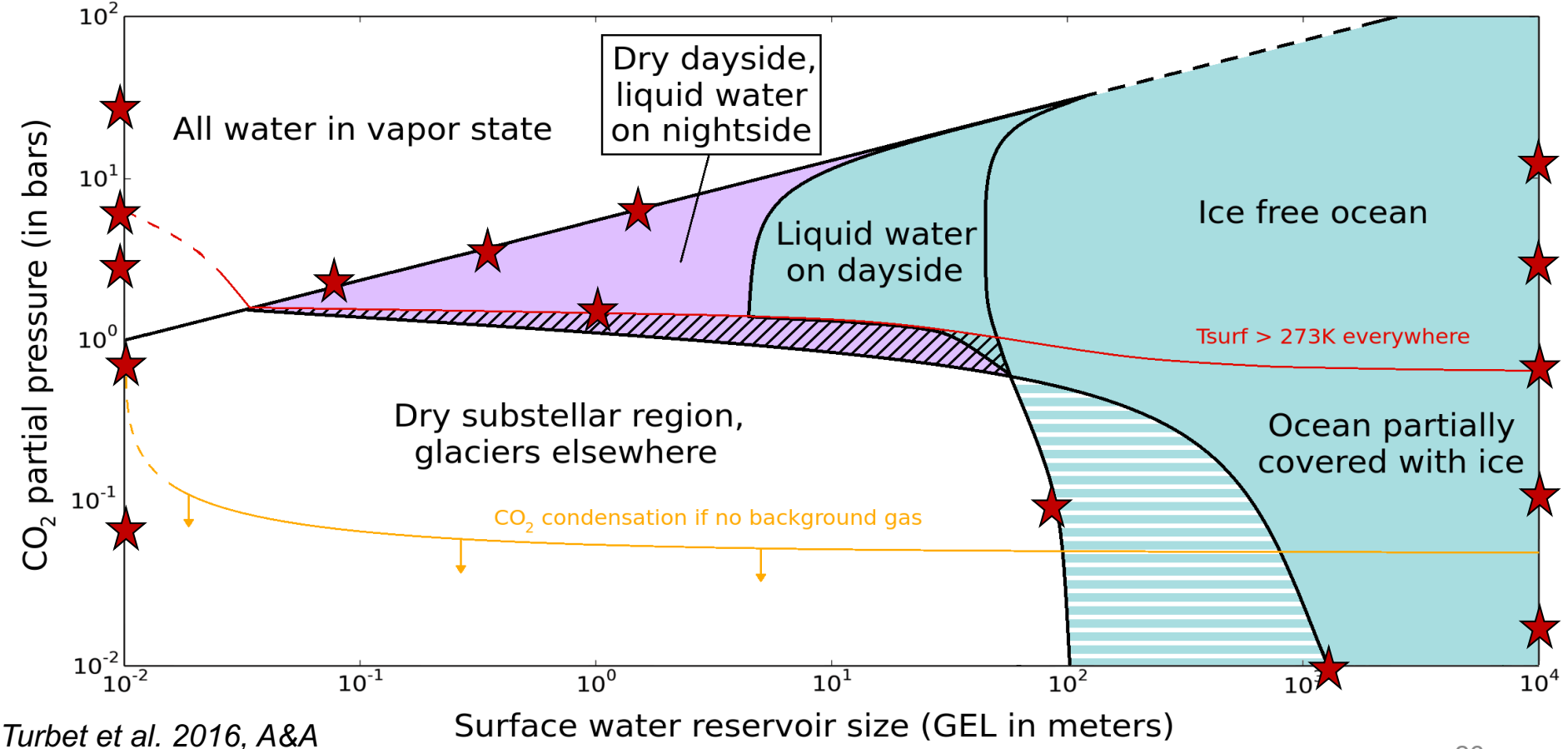




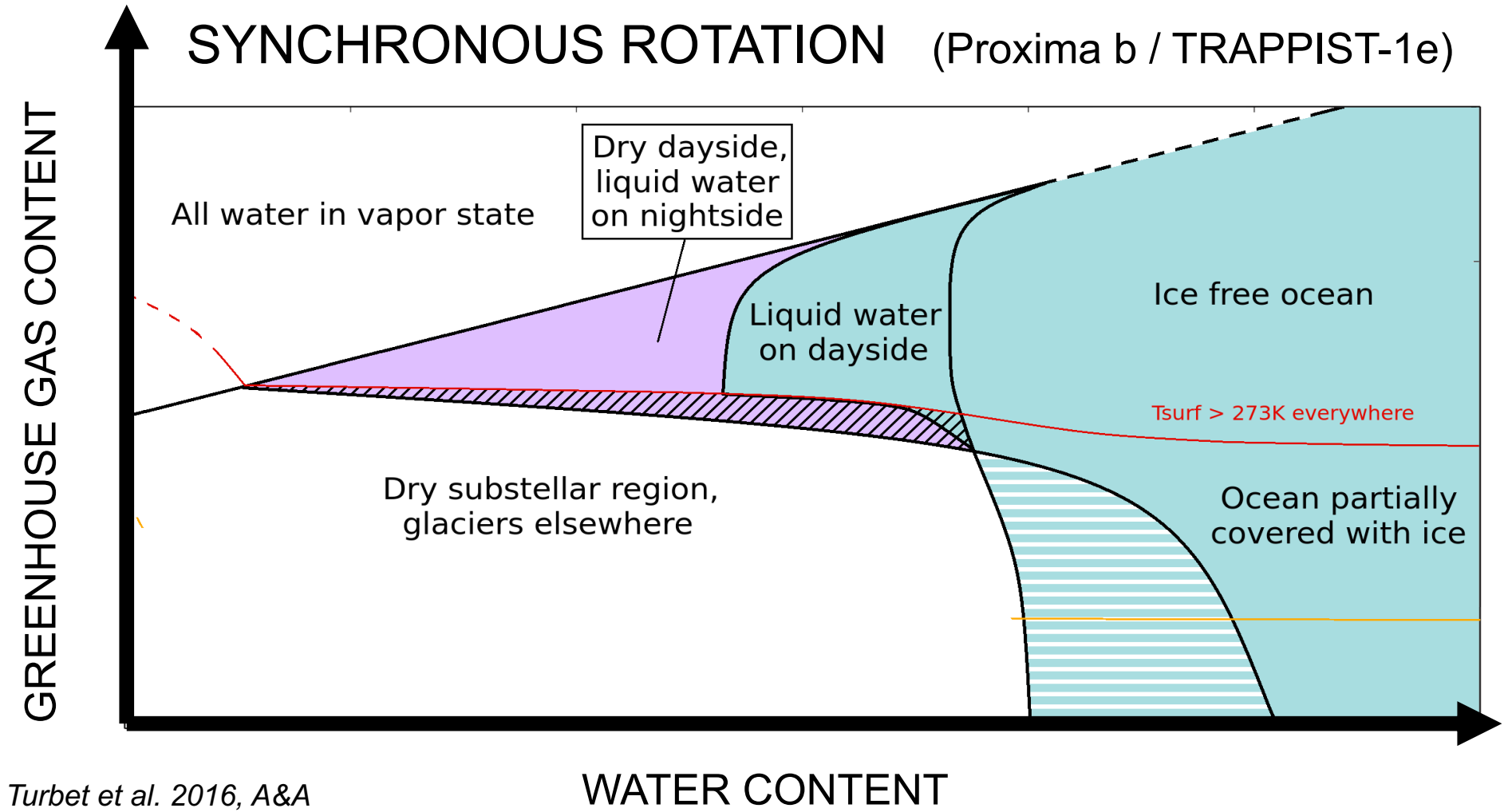


Turbet et al. 2016, A&A
Turbet et al. 2018, A&A

SYNCHRONOUS ROTATION (Proxima b / TRAPPIST-1e)



Turbet et al. 2016, A&A
Turbet et al. 2018, A&A



Turbet et al. 2016, A&A
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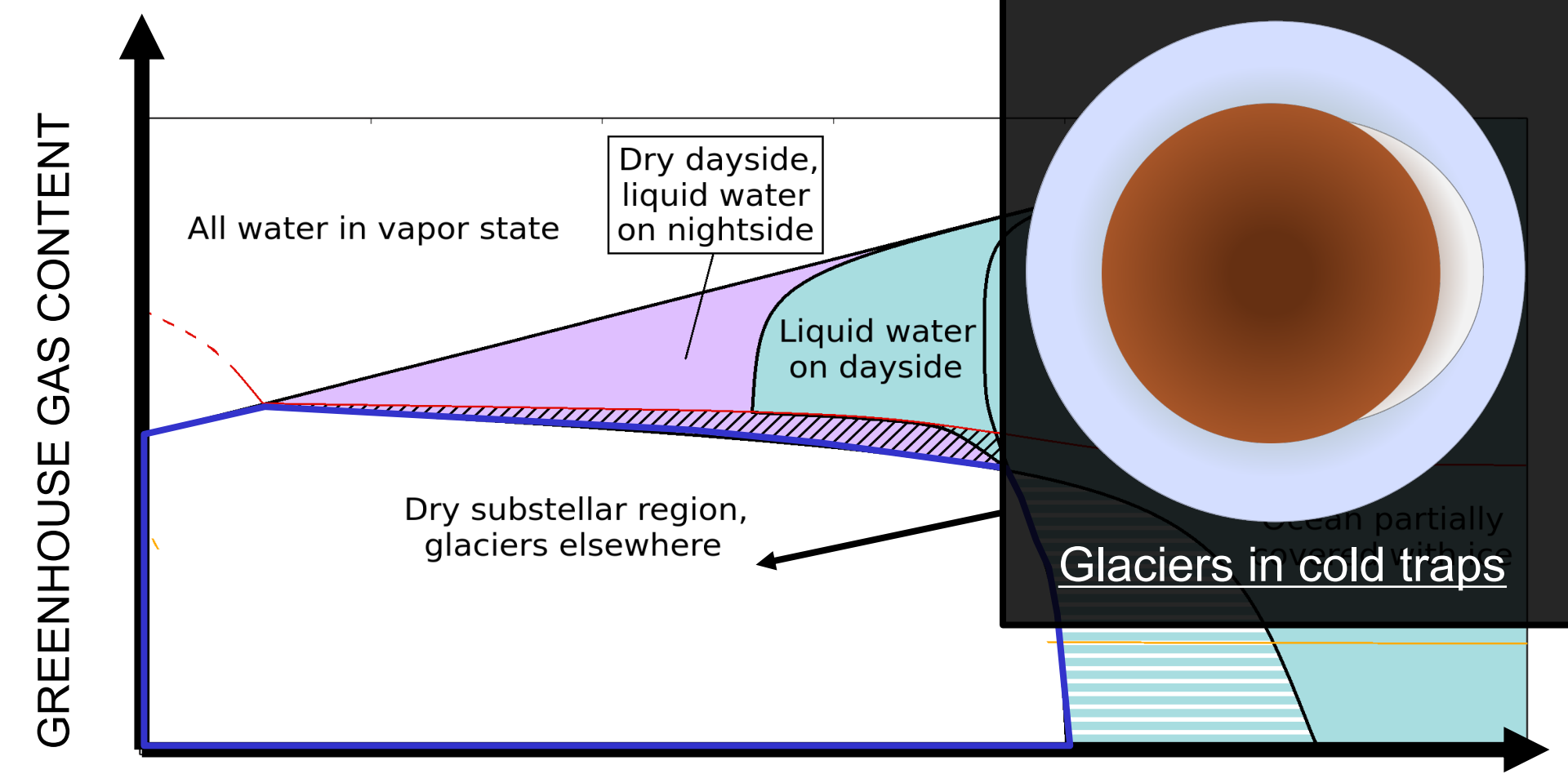
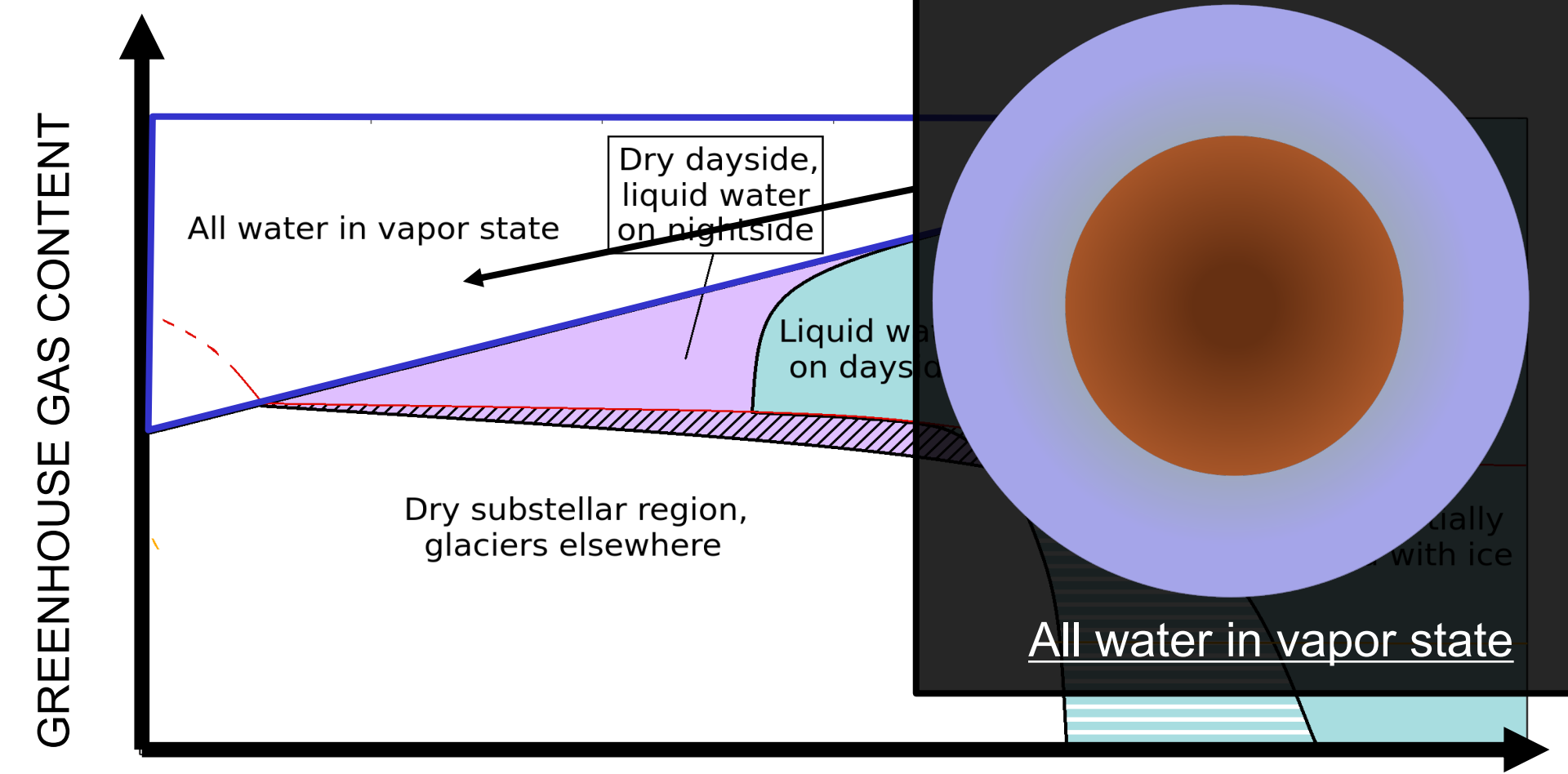
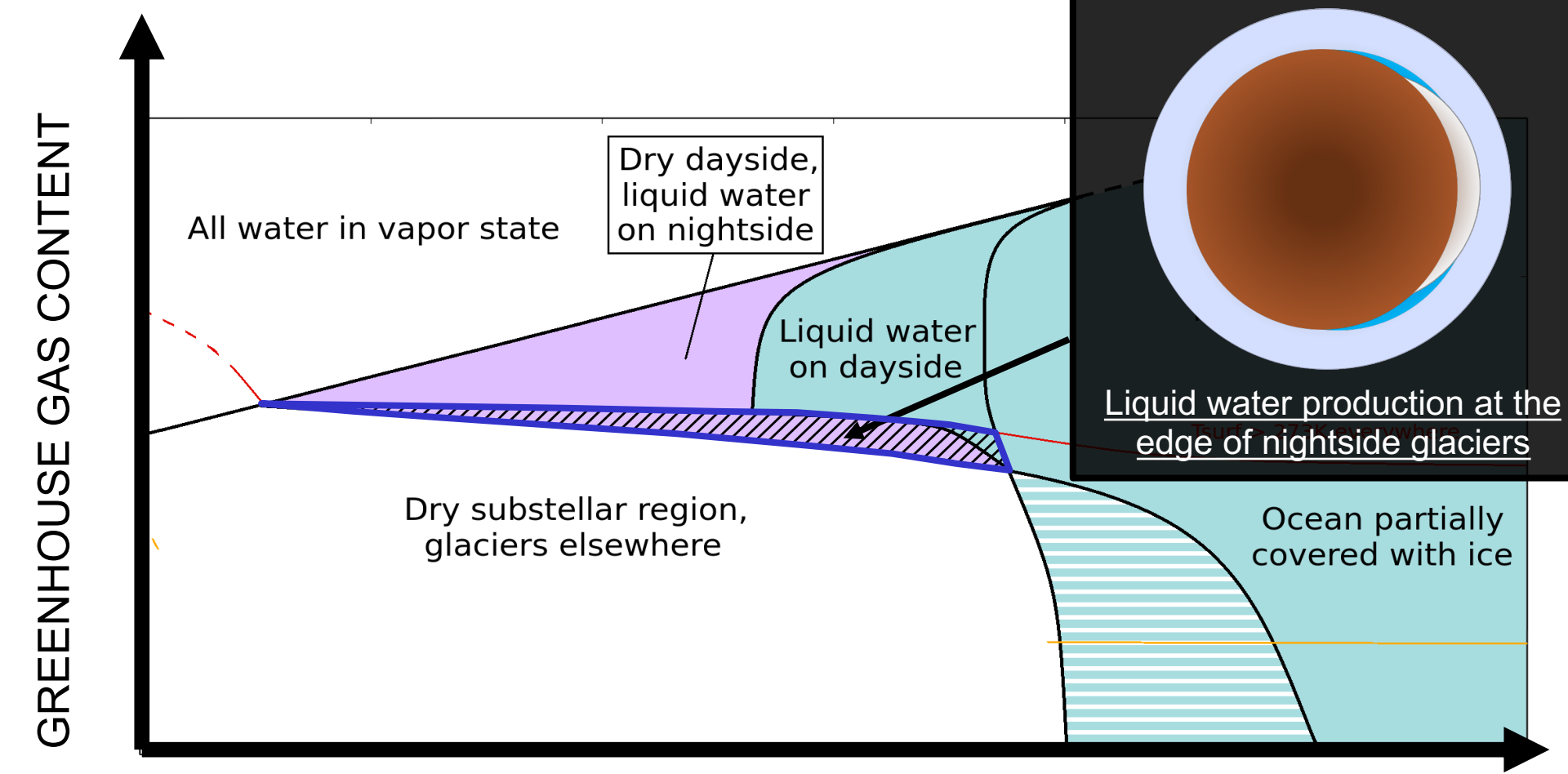


Turbet et al. 2016, A&A
Turbet et al. 2018, A&A

Recovering Leconte et al. 2013, A&A
Menou 2015, EPSL



Turbet et al. 2016, A&A
Turbet et al. 2018, A&A



Turbet et al. 2016, A&A
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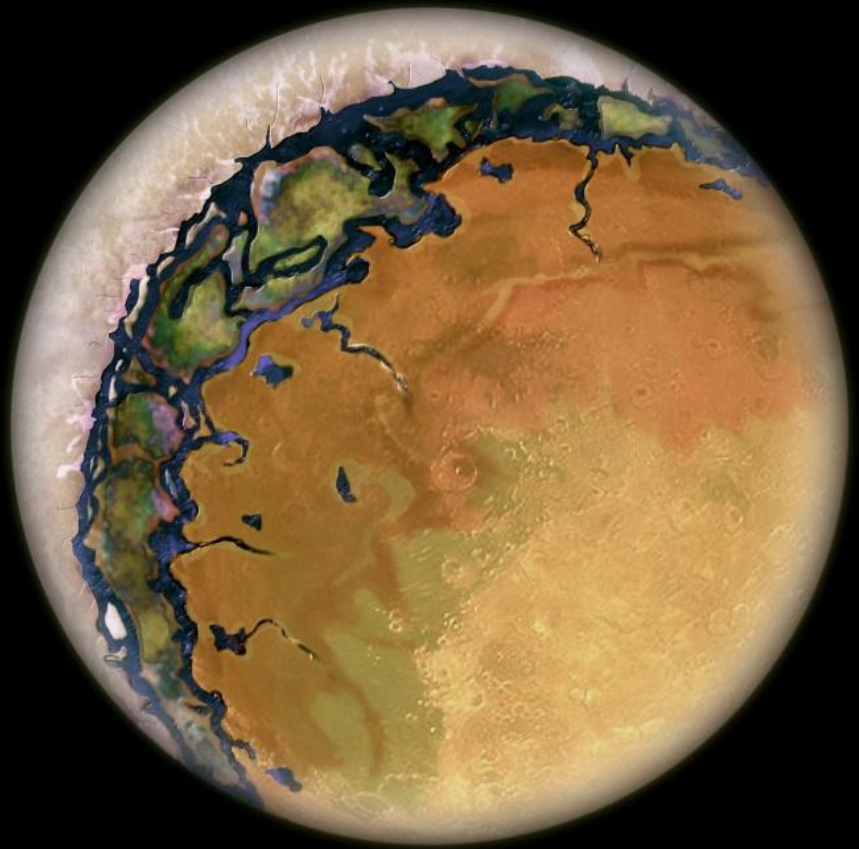
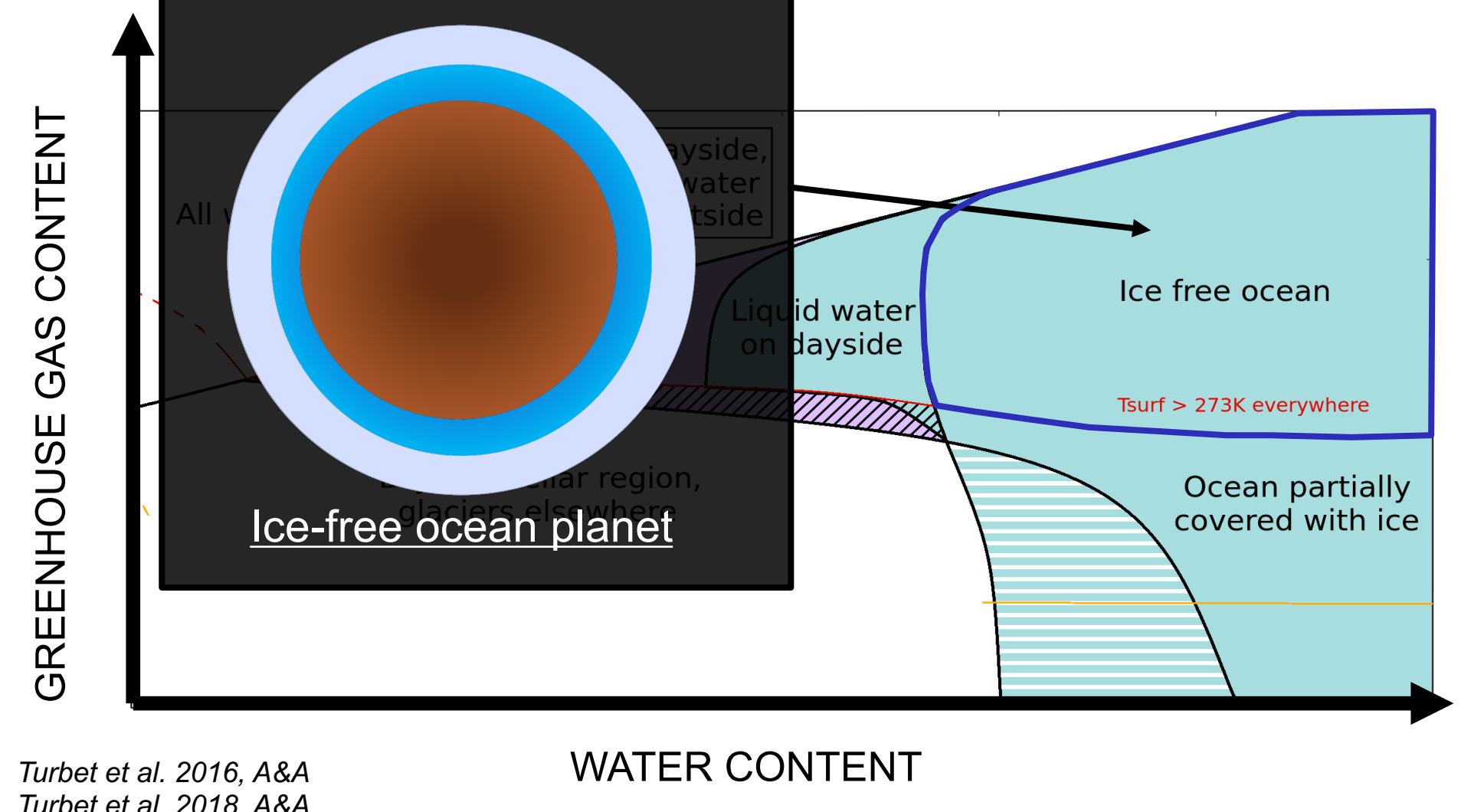
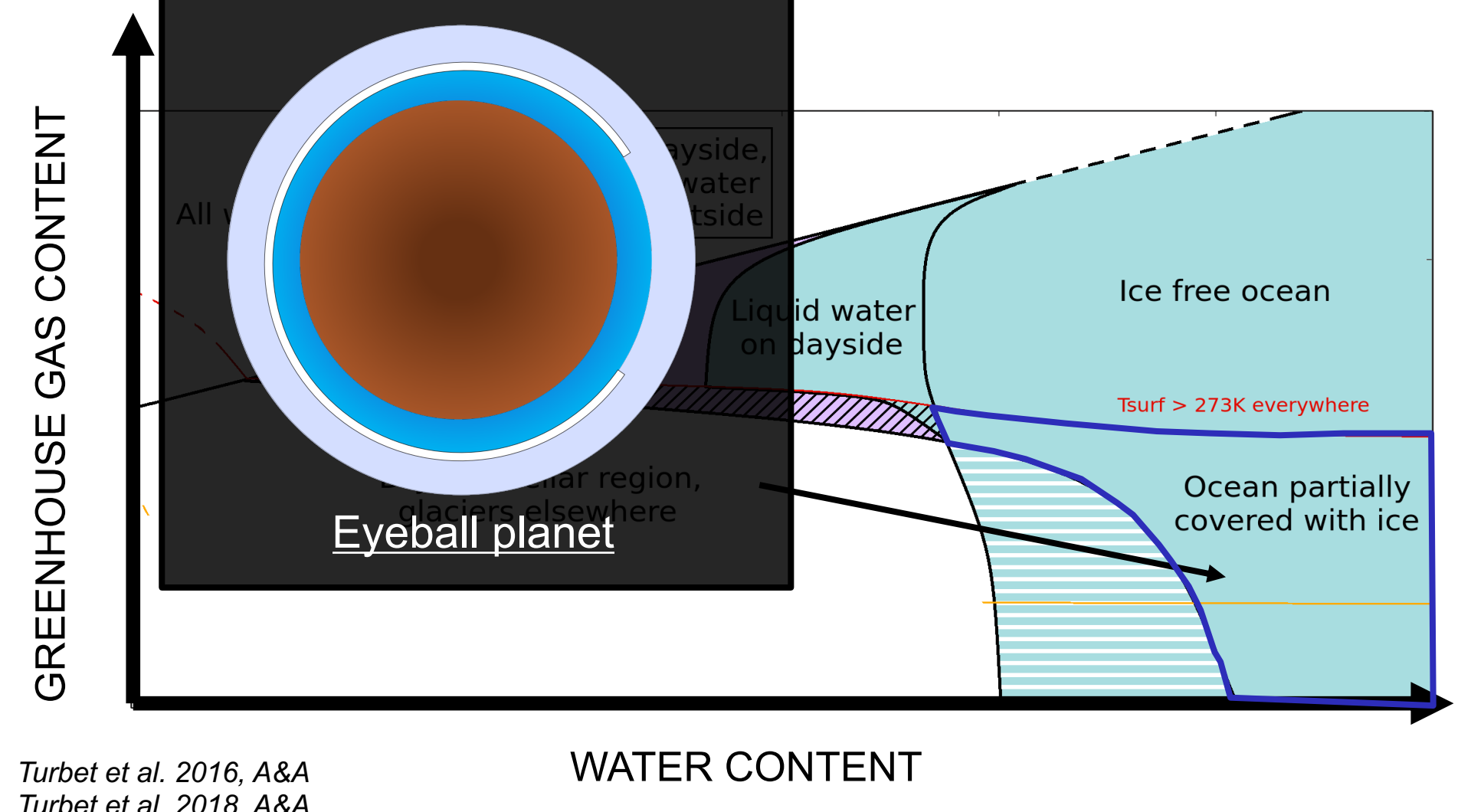


Artist’s view (Credit: *Beau.TheConsortium*)



Turbet et al. 2016, A&A
Turbet et al. 2018, A&A



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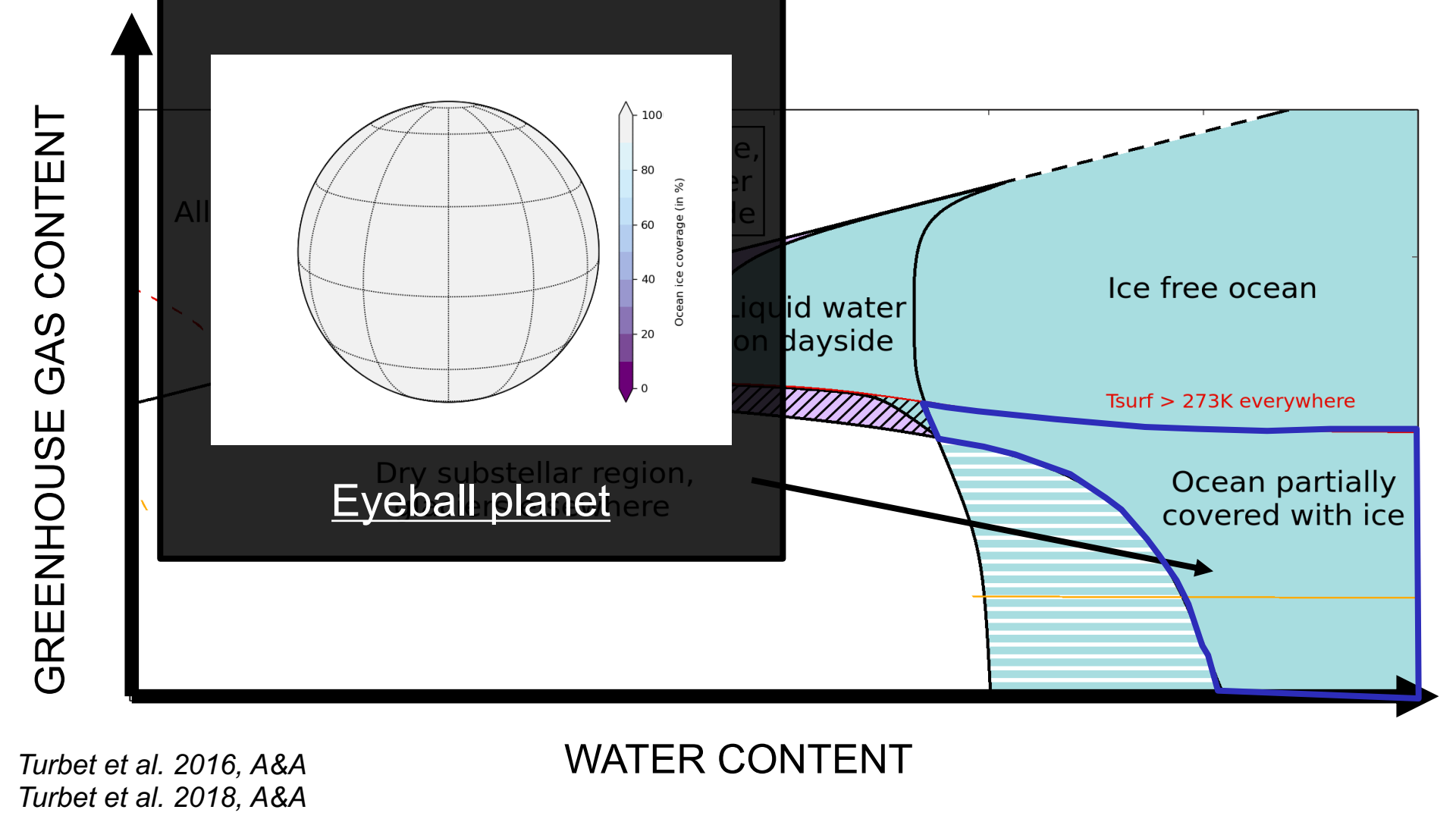

Turbet et al. 2016, A&A
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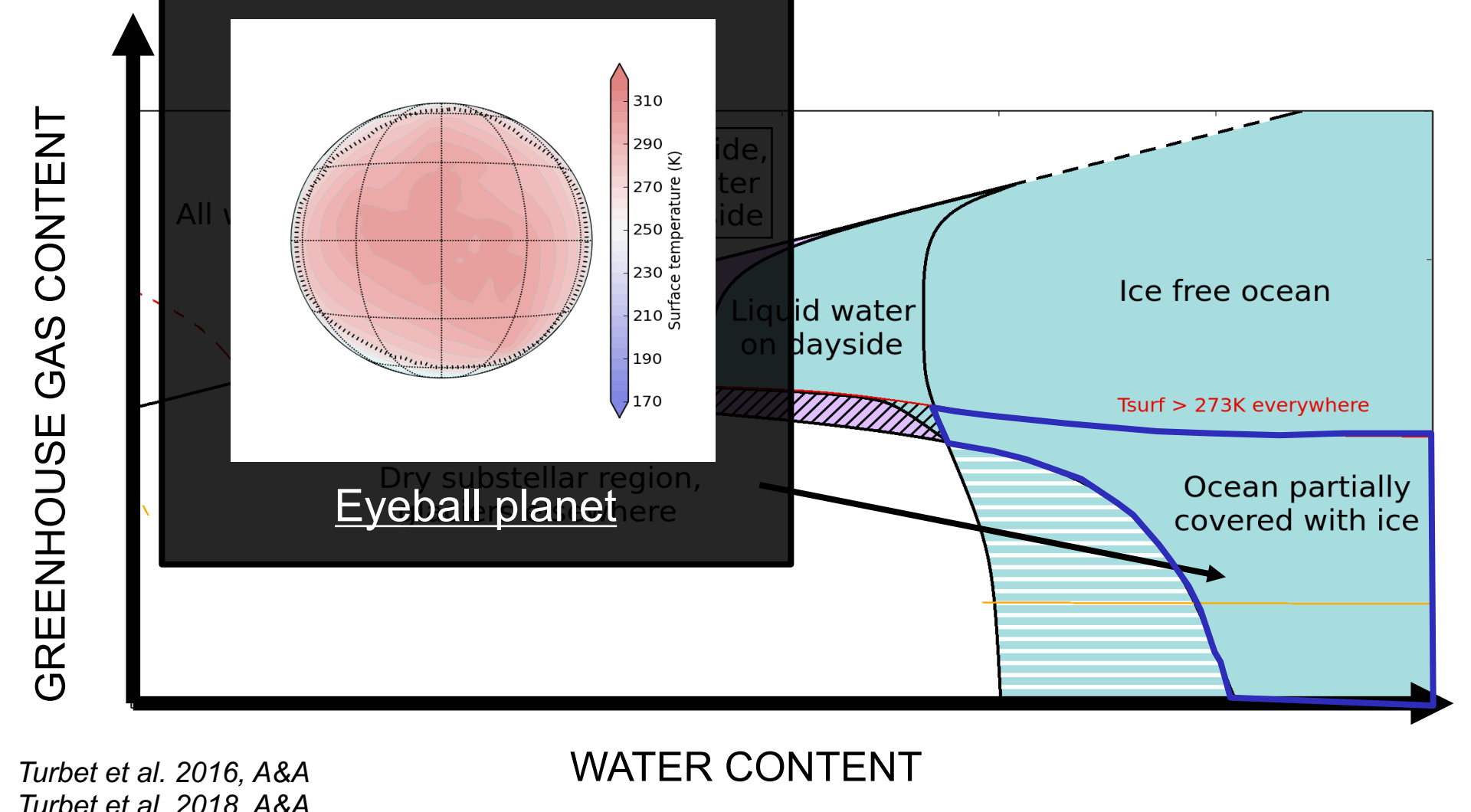
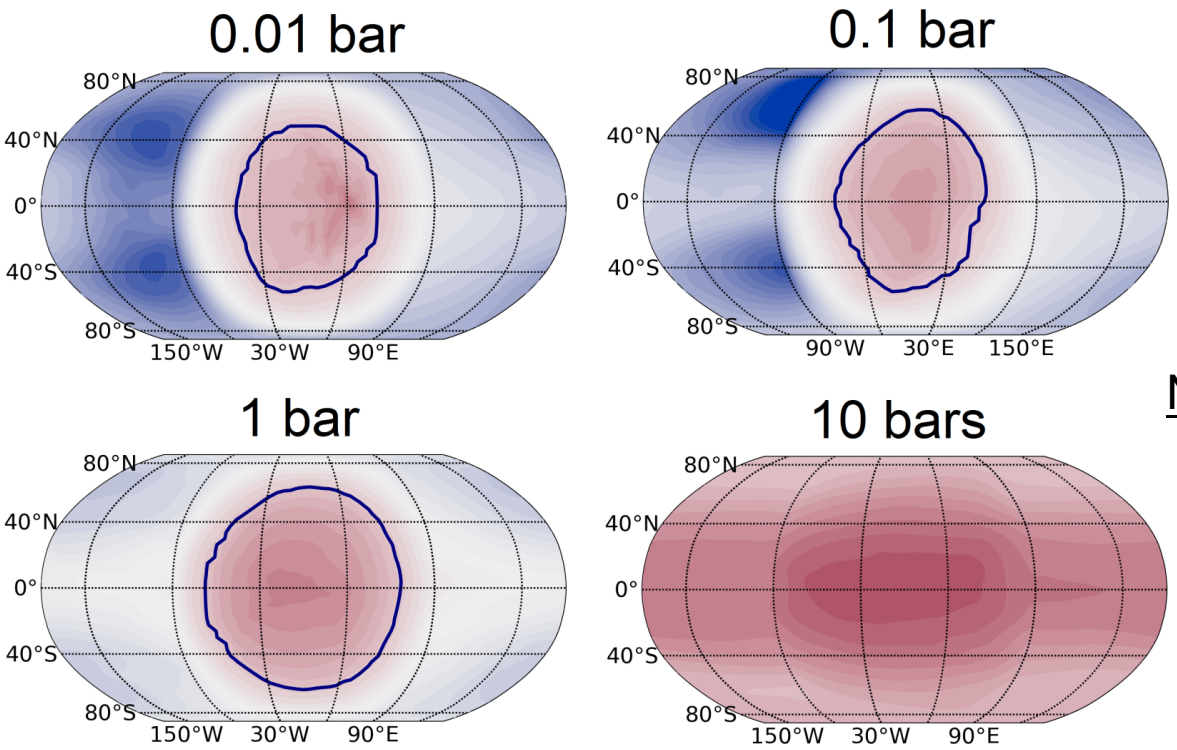


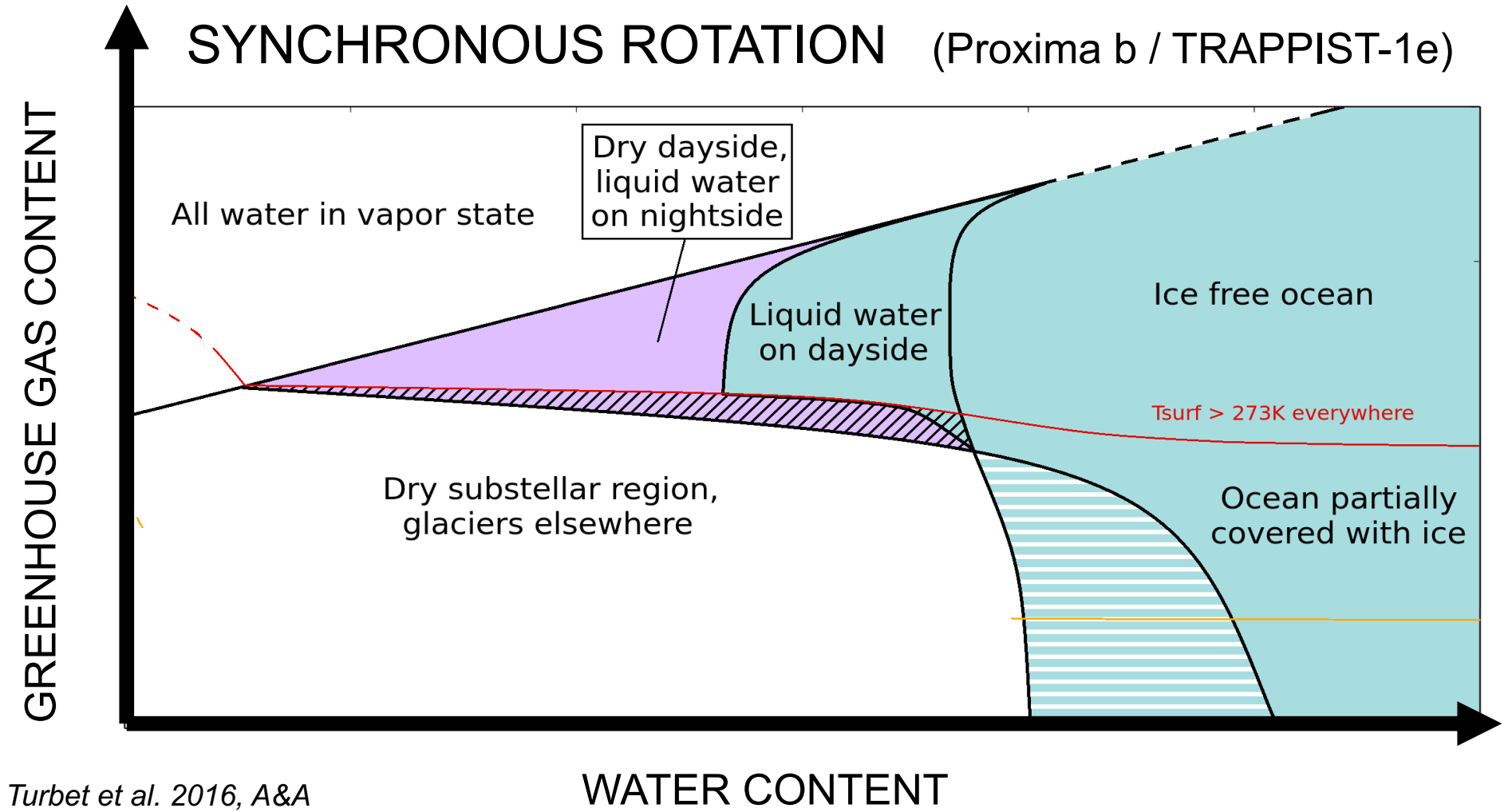
Turbet et al. 2016, A&A
Turbet et al. 2018, A&A

SURFACE TEMPERATURES OF PROXIMA B



N_2 total pressure

Turbet et al. 2016, A&A.
Turbet et al. 2018, A&A

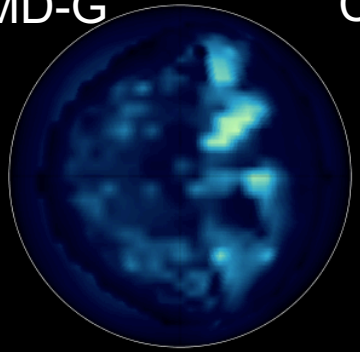


Turbet et al. 2016, A&A
Turbet et al. 2018, A&A

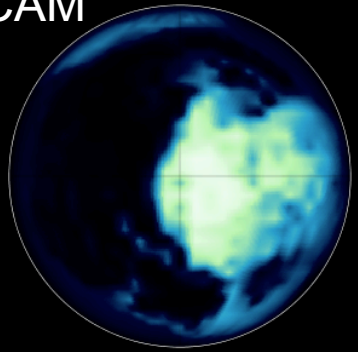
Trappist Habitable Atmospheres Intercomparison (THAI) project

Reflected stellar radiation

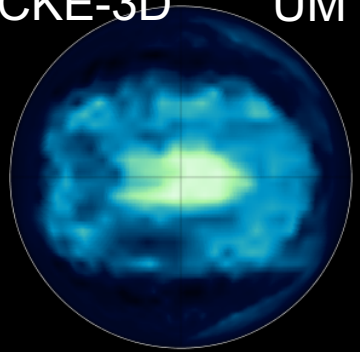
LMD-G



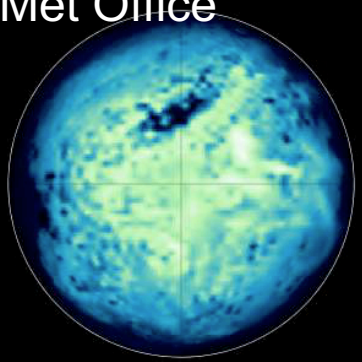
CAM



ROCKE-3D

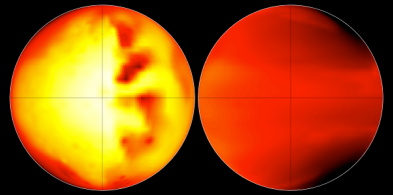


UM Met Office

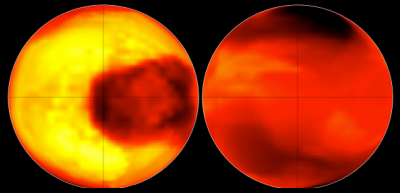


Outgoing thermal radiation

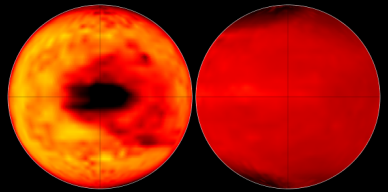
LMD-G



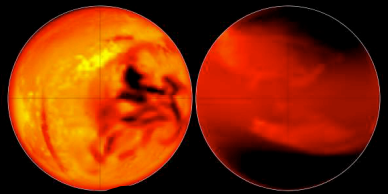
CAM



ROCKE-3D

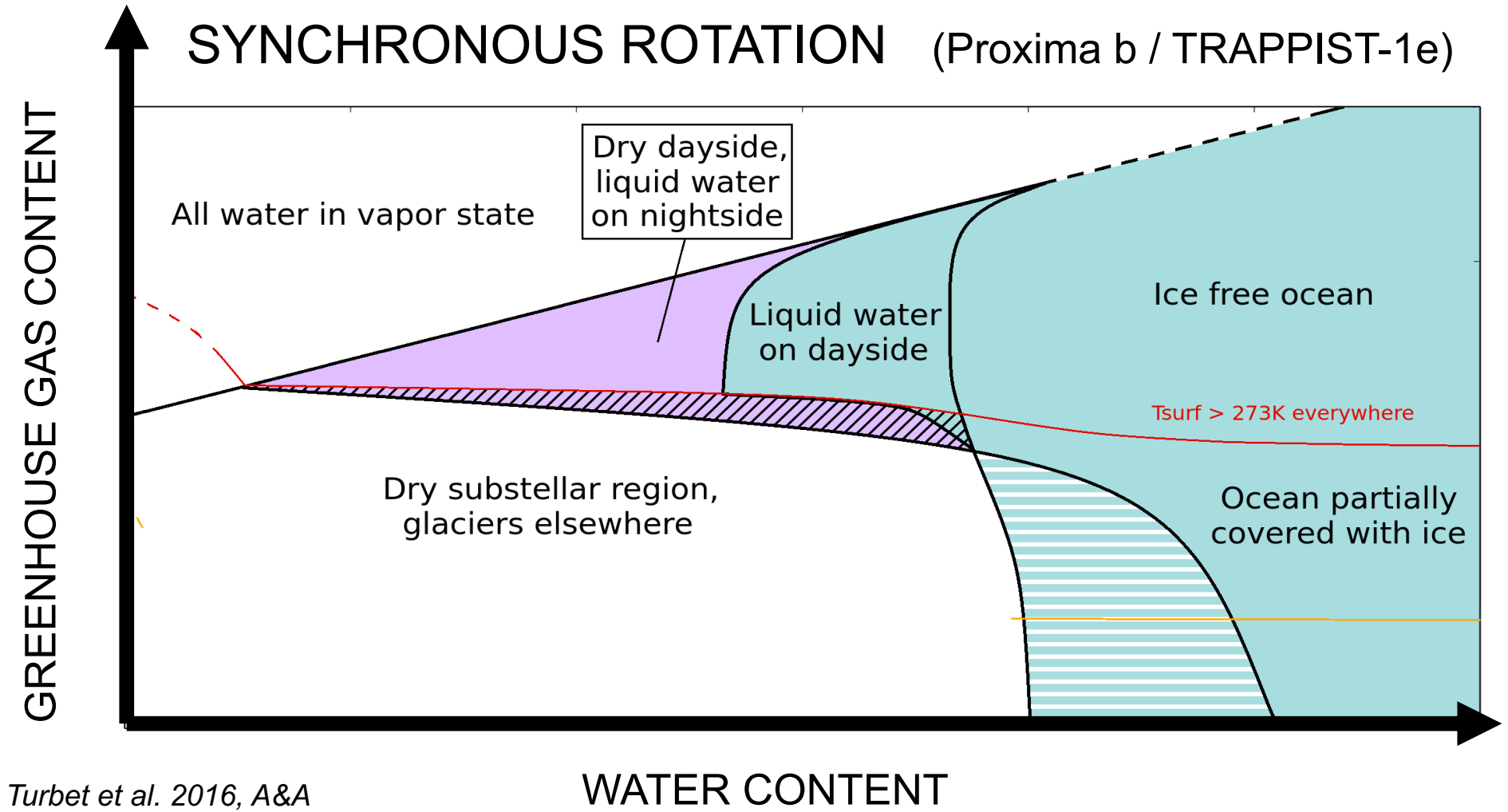


UM Met Office



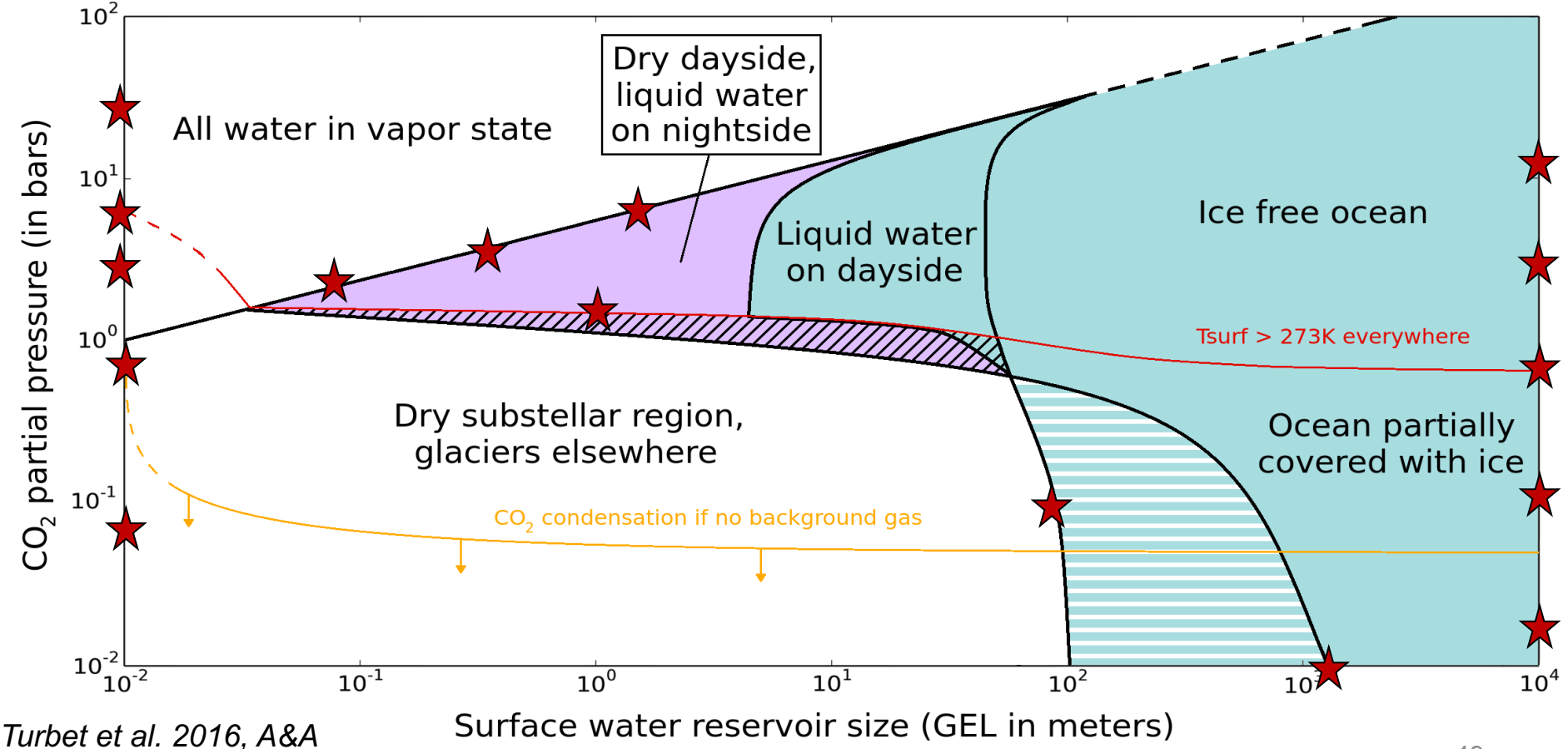
TRAPPIST-1e
Present day
Earth
atmosphere,
aquaplanet

Fauchez, Turbet et al. 2020, GMD

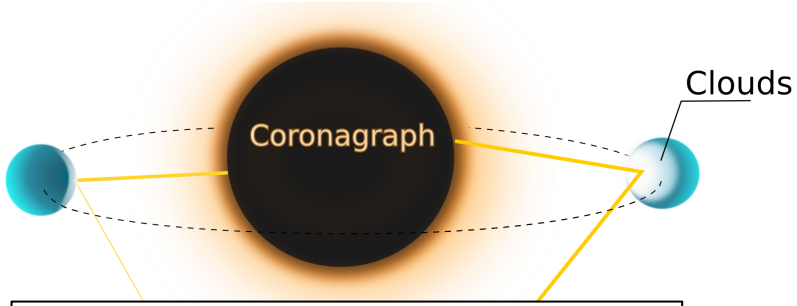


Turbet et al. 2016, A&A
Turbet et al. 2018, A&A

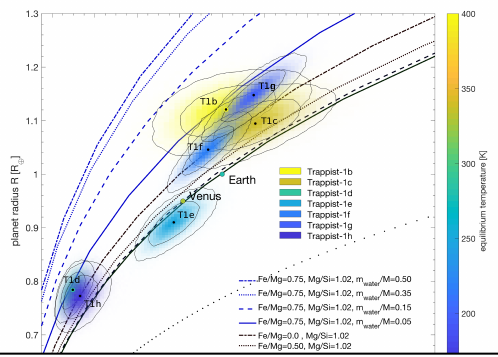
SYNCHRONOUS ROTATION (Proxima b / TRAPPIST-1e)



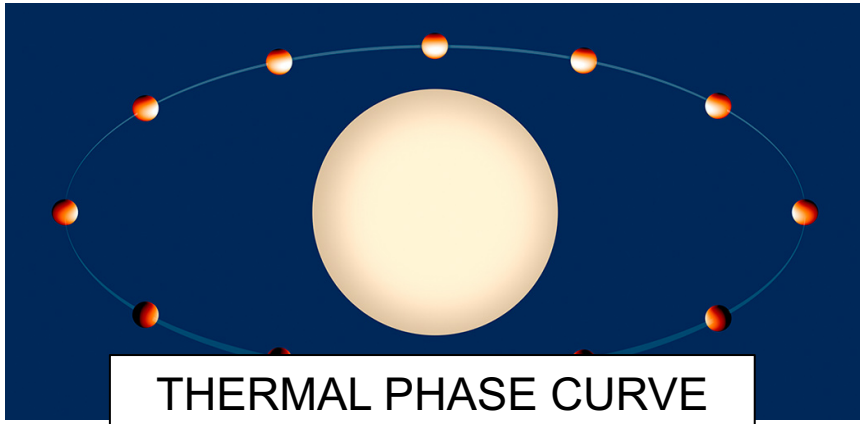
Turbet et al. 2016, A&A
Turbet et al. 2018, A&A



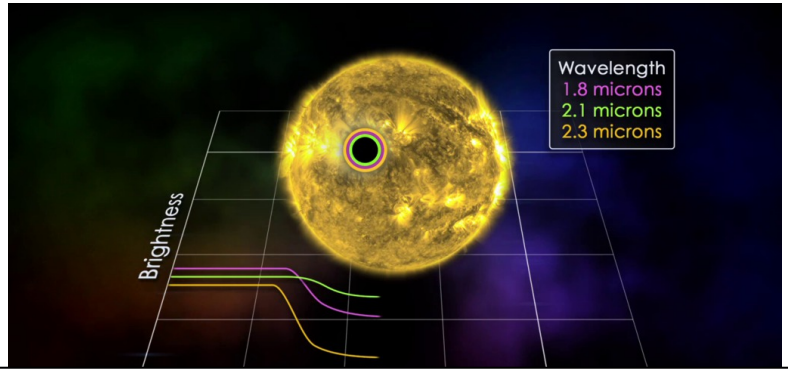
DIRECT IMAGING AND HRHC TECHNIQUE



DENSITY MEASUREMENTS

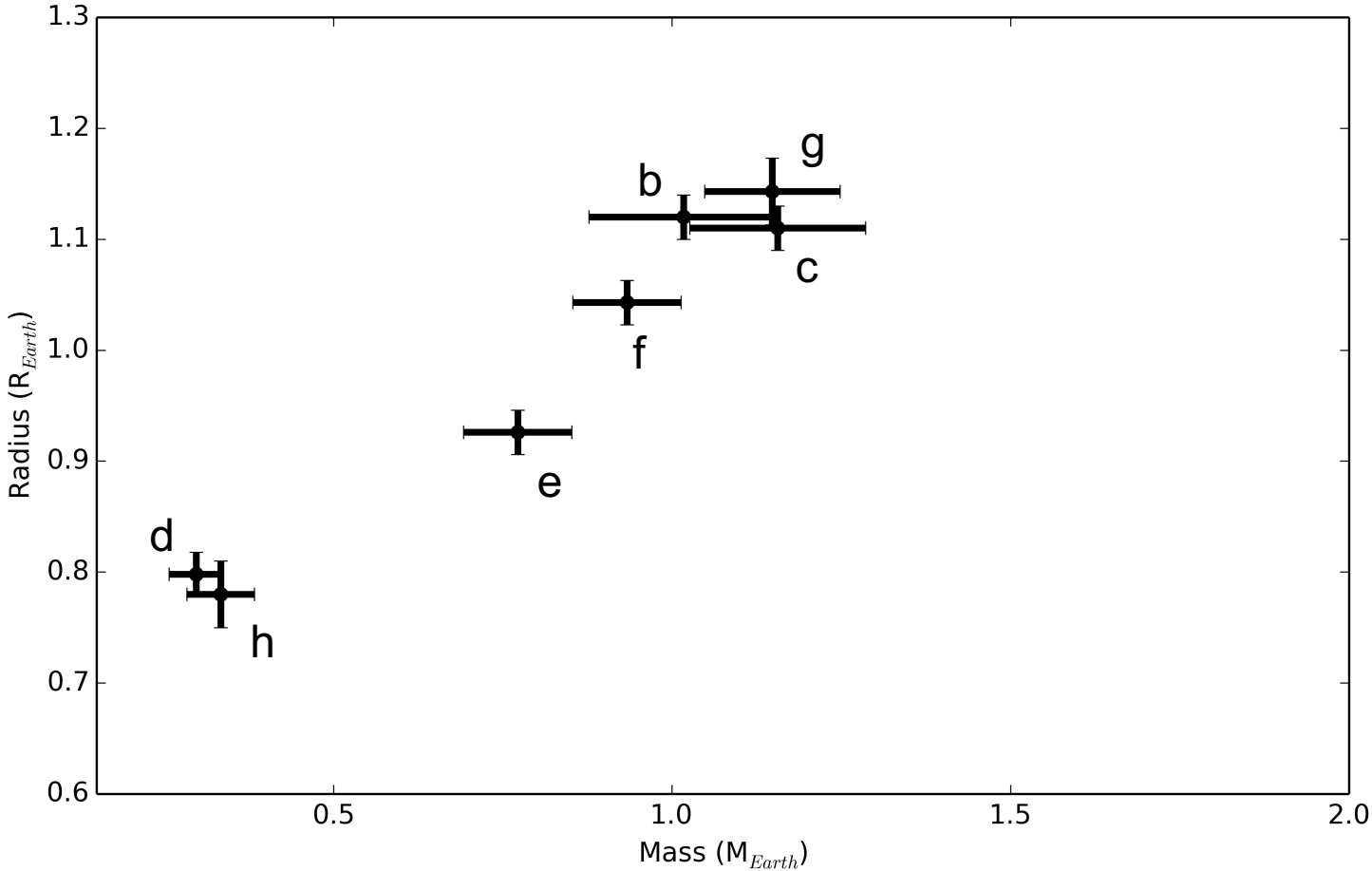


THERMAL PHASE CURVE AND SECONDARY ECLIPSE



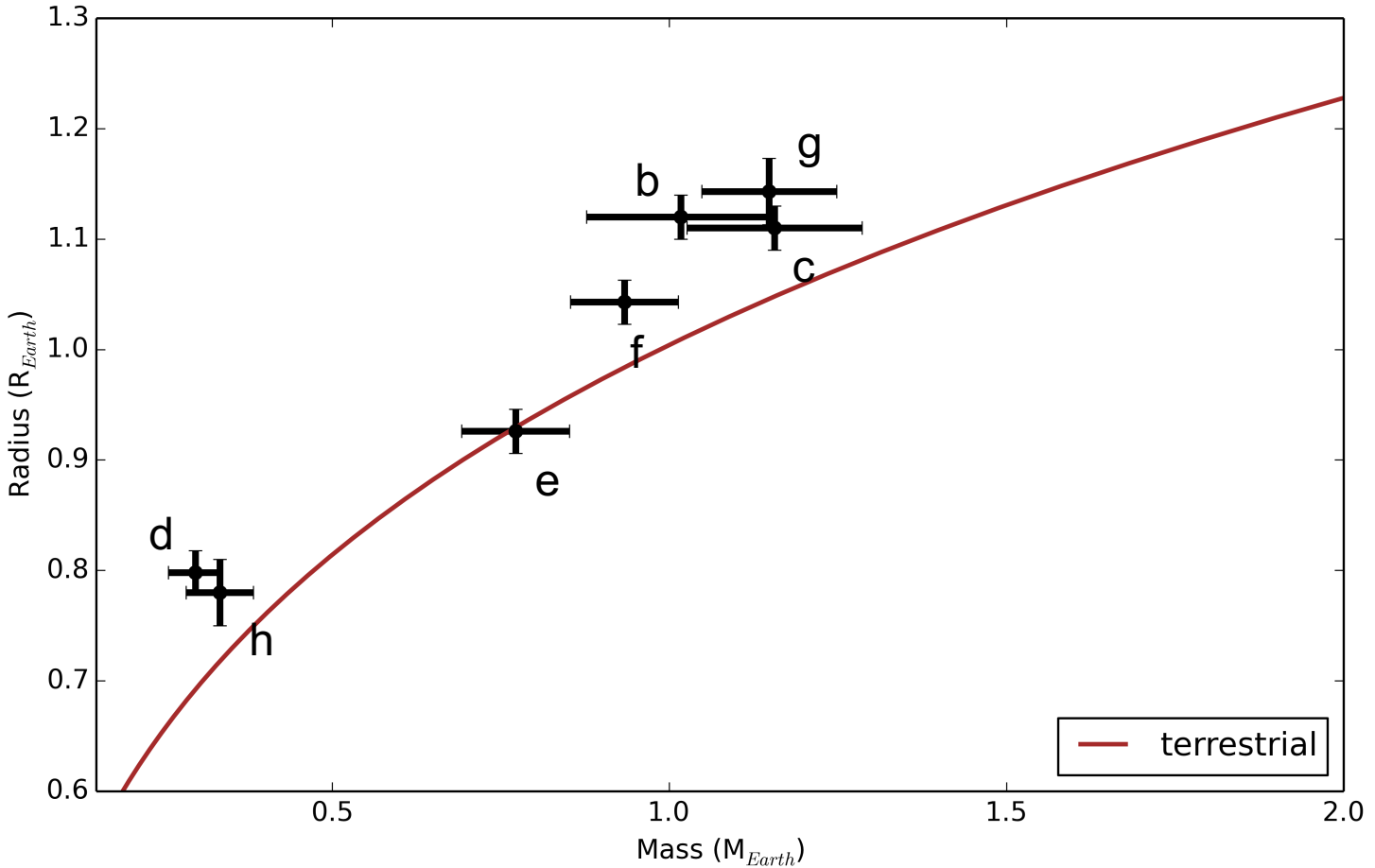
TRANSMISSION SPECTROSCOPY

MASS/RADIUS OF TRAPPIST-1 PLANETS



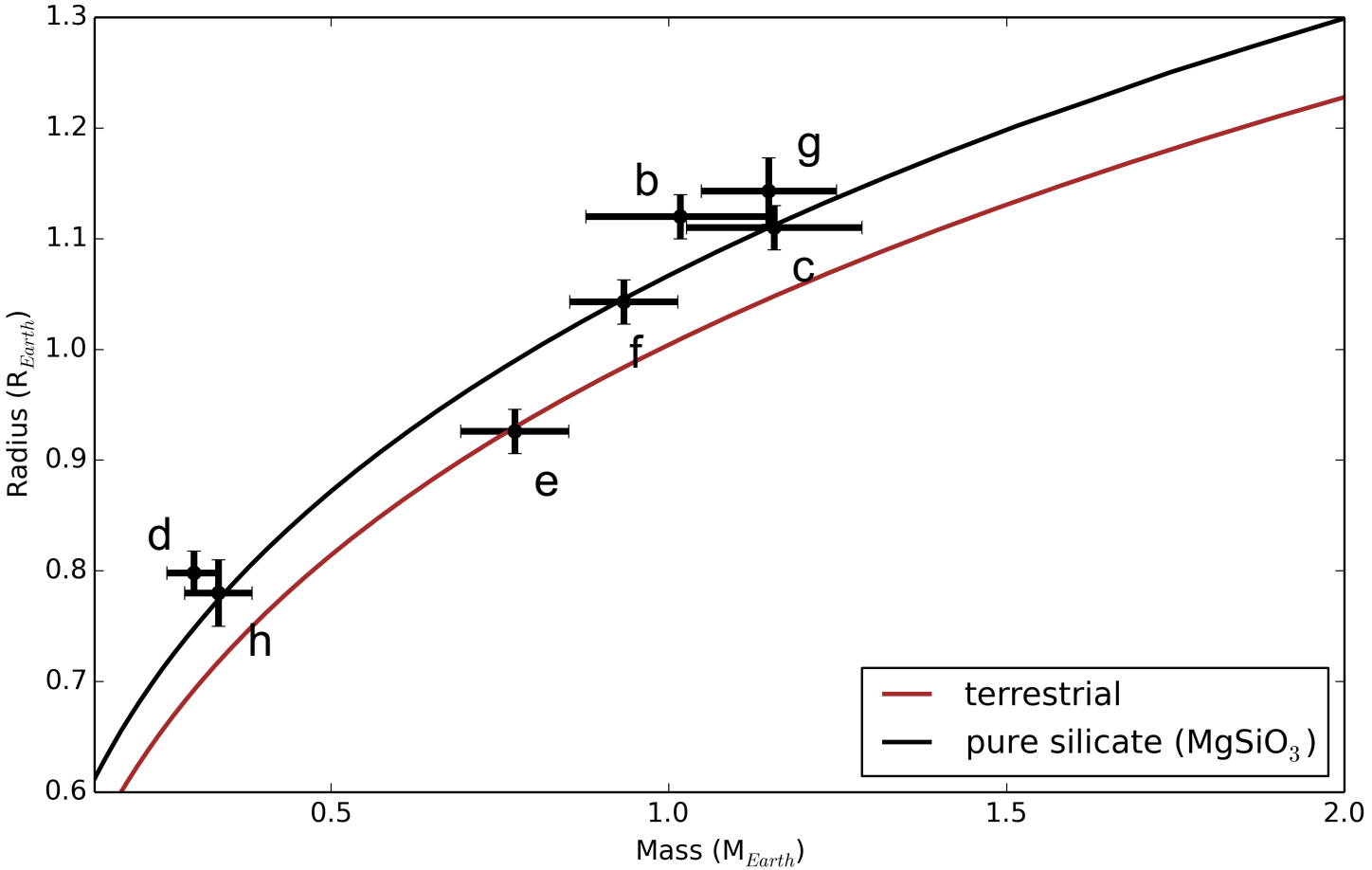
Grimm et al. 2018, A&A

MASS/RADIUS OF TRAPPIST-1 PLANETS



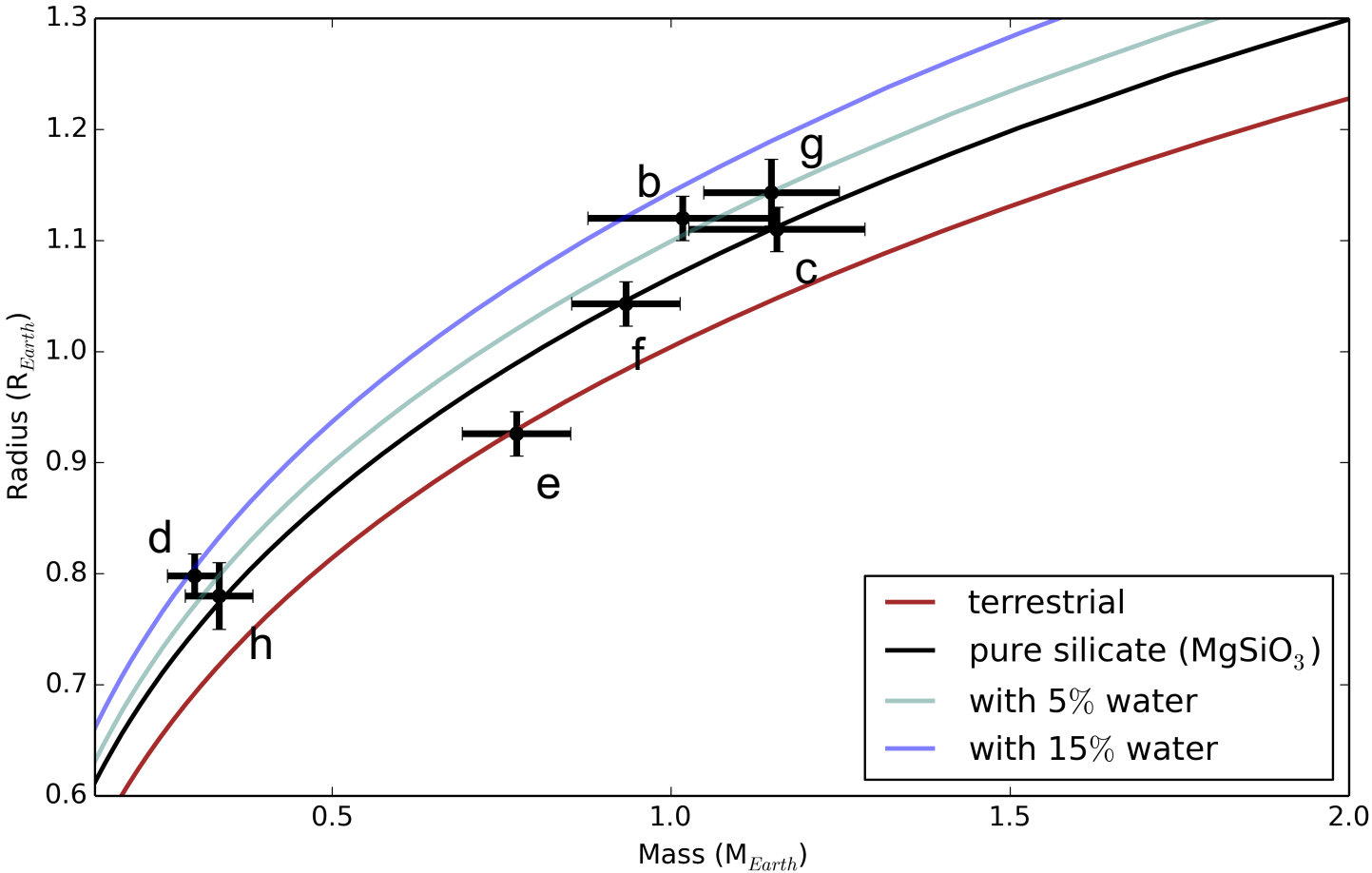
Grimm et al. 2018, A&A

MASS/RADIUS OF TRAPPIST-1 PLANETS



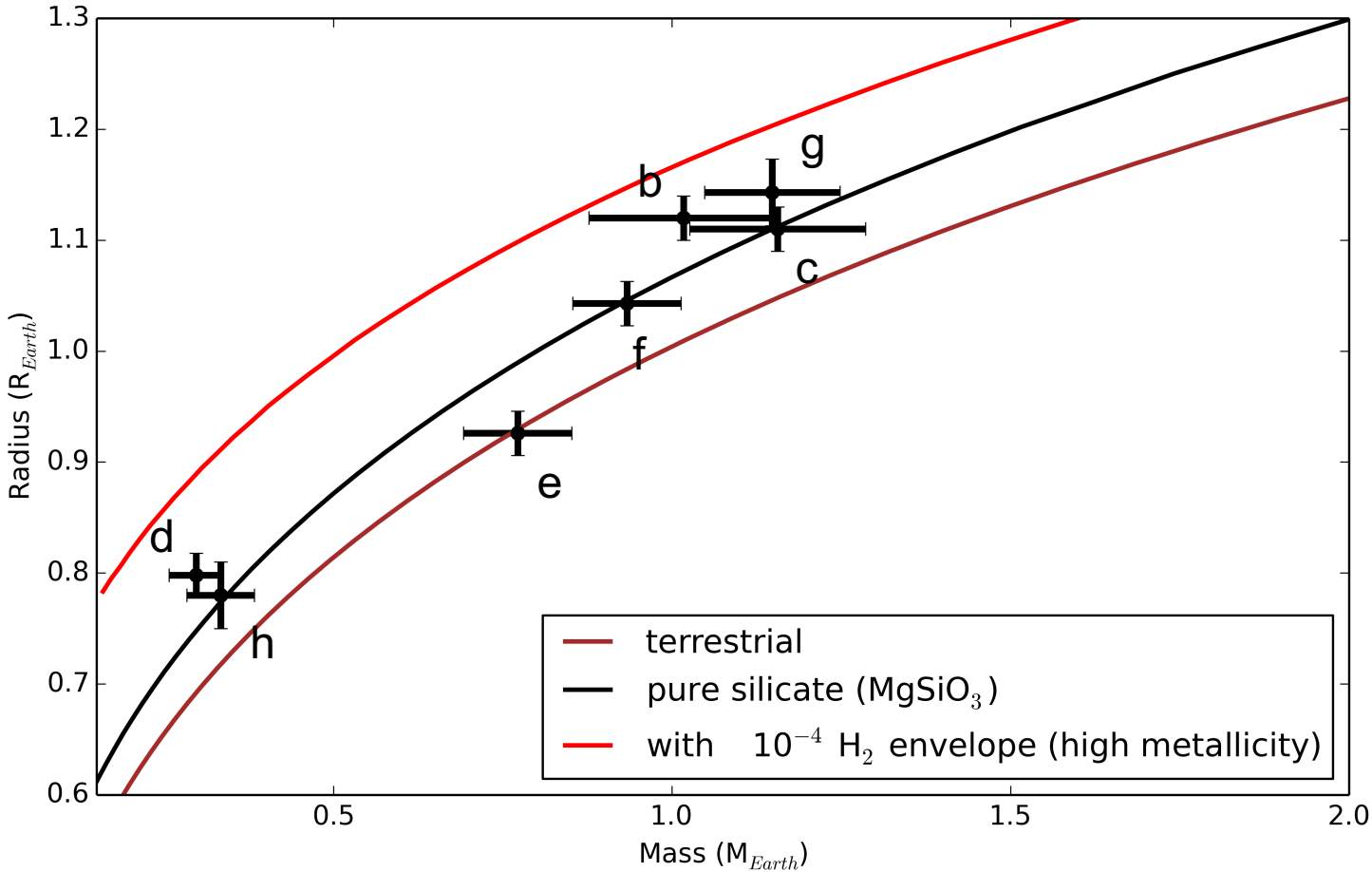
Grimm et al. 2018, A&A

MASS/RADIUS OF TRAPPIST-1 PLANETS



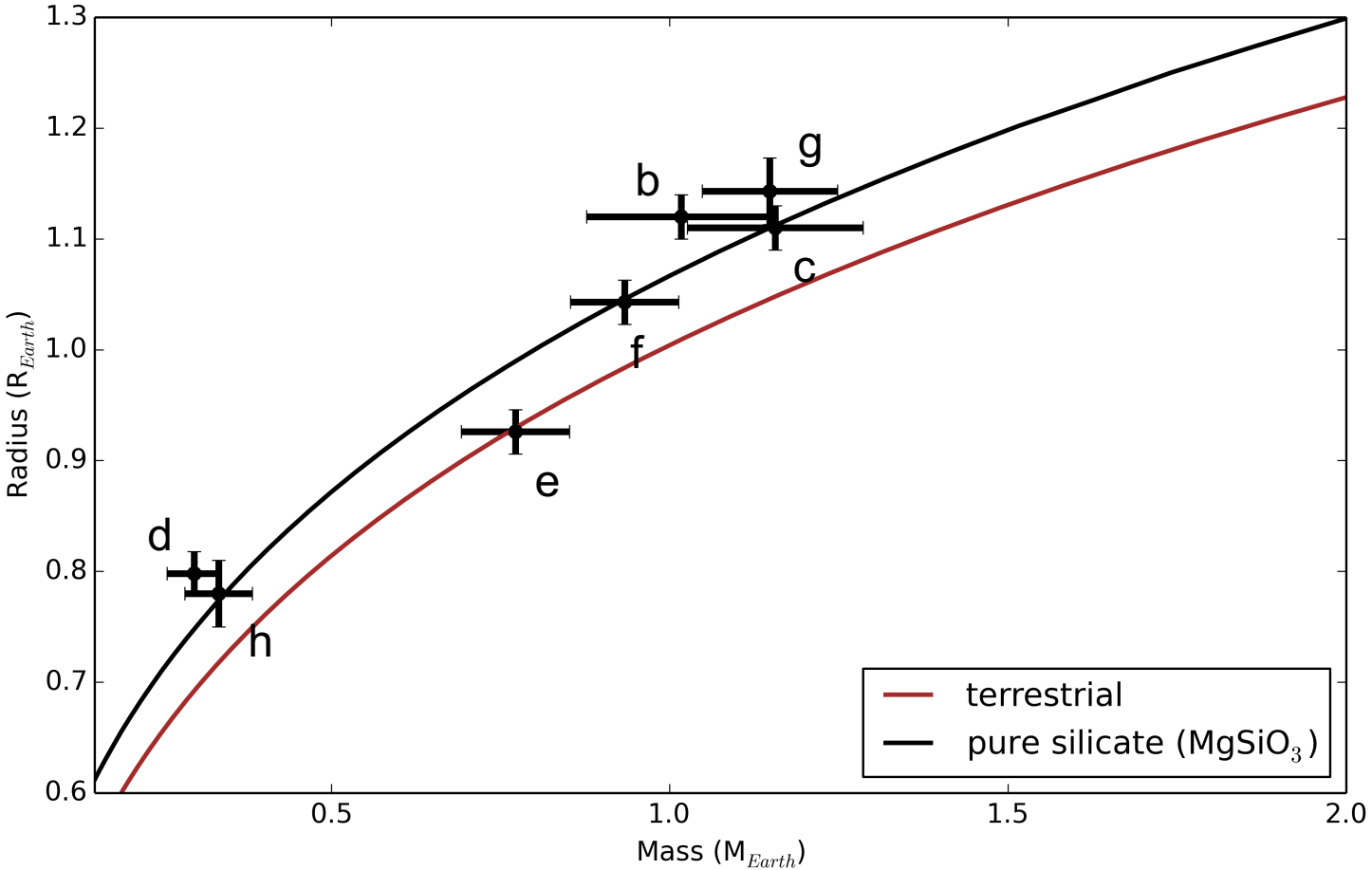
Grimm et al. 2018, A&A

MASS/RADIUS OF TRAPPIST-1 PLANETS

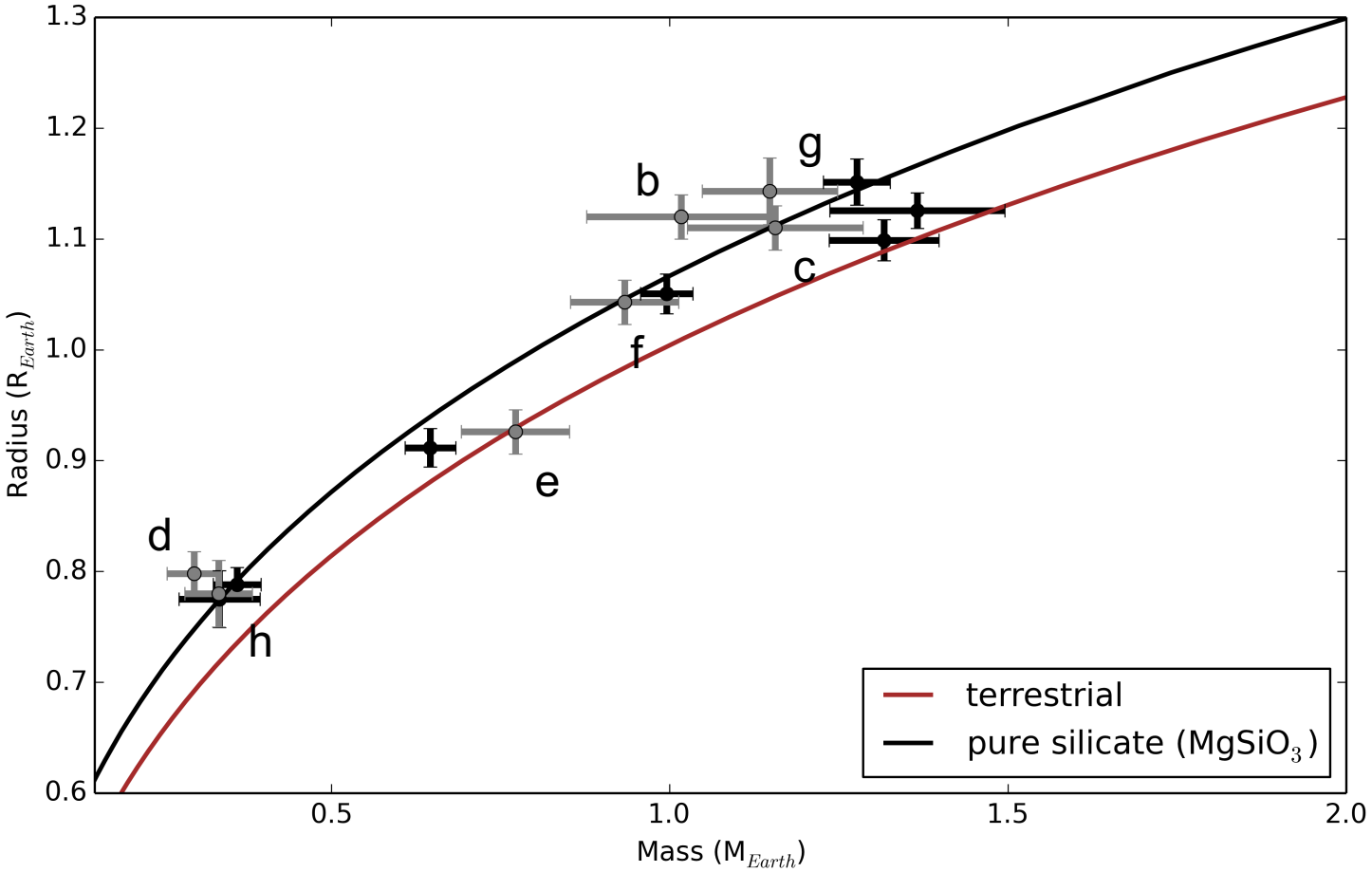


Turbet et al. 2020a, Submitted to Space Science Reviews

MASS/RADIUS OF TRAPPIST-1 PLANETS

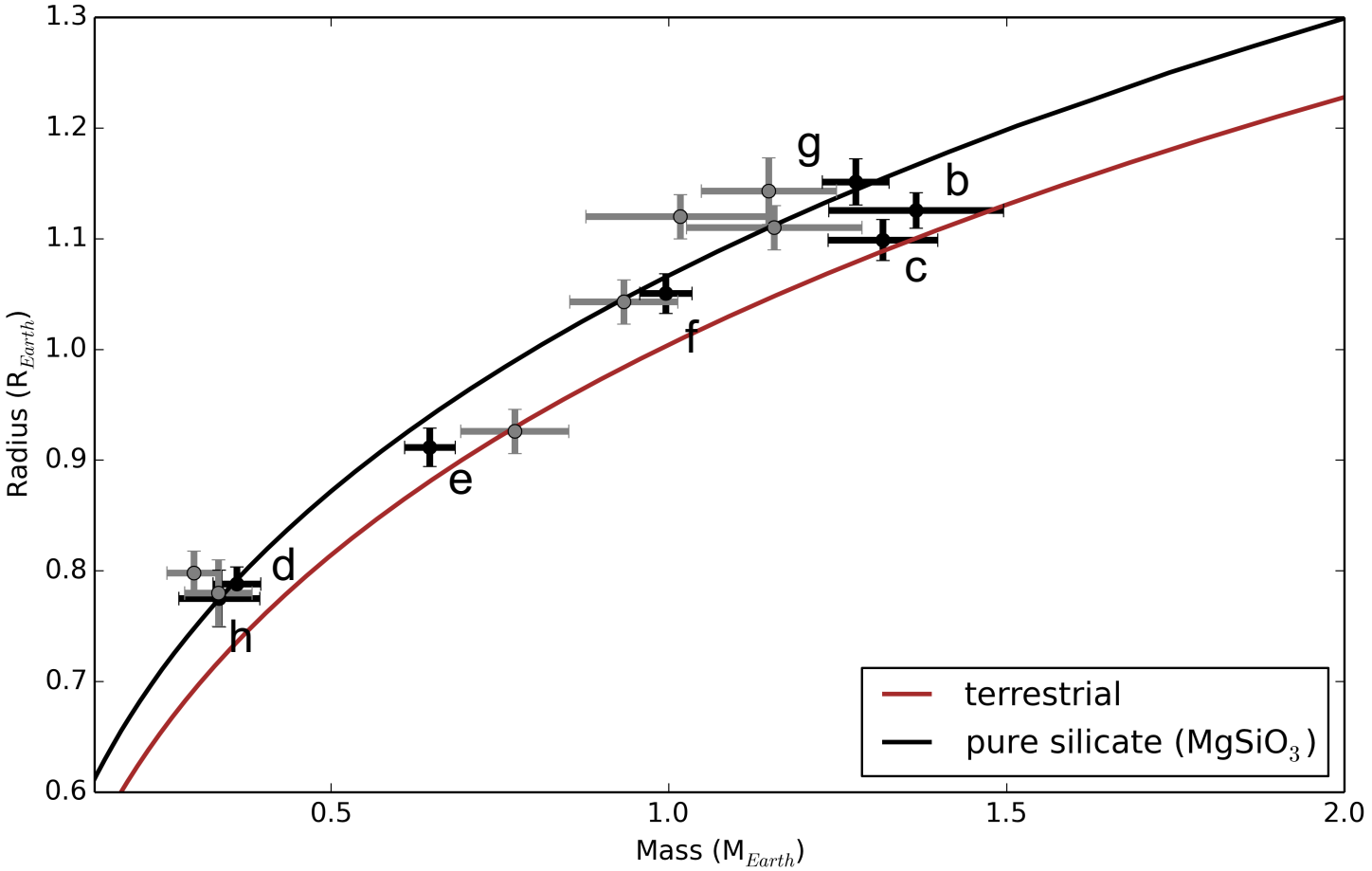


MASS/RADIUS OF TRAPPIST-1 PLANETS



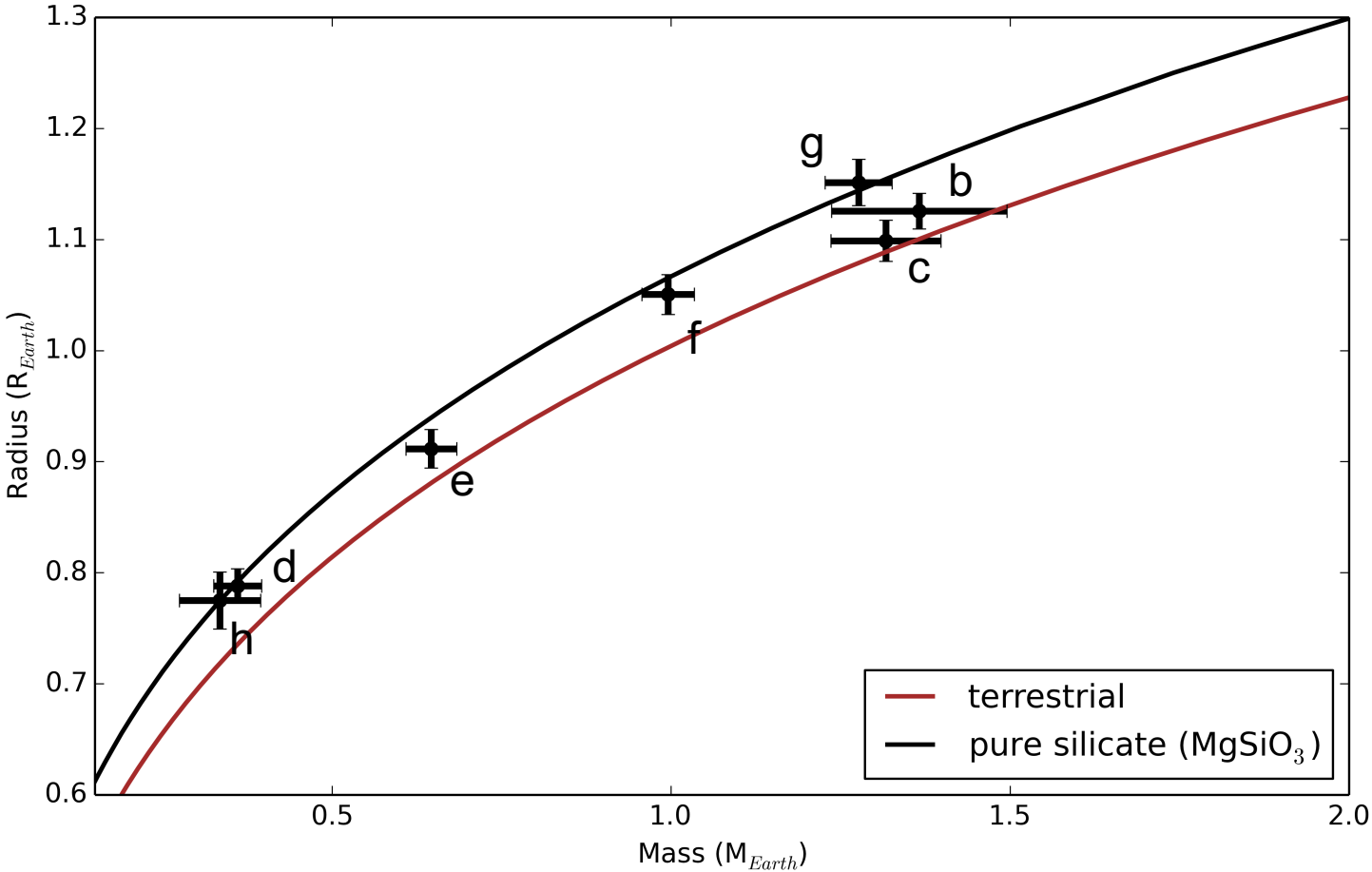
Grimm et al. 2018, A&A
Agol et al., in prep

MASS/RADIUS OF TRAPPIST-1 PLANETS



Grimm et al. 2018, A&A
Agol et al., in prep

MASS/RADIUS OF TRAPPIST-1 PLANETS



Agol et al., in prep

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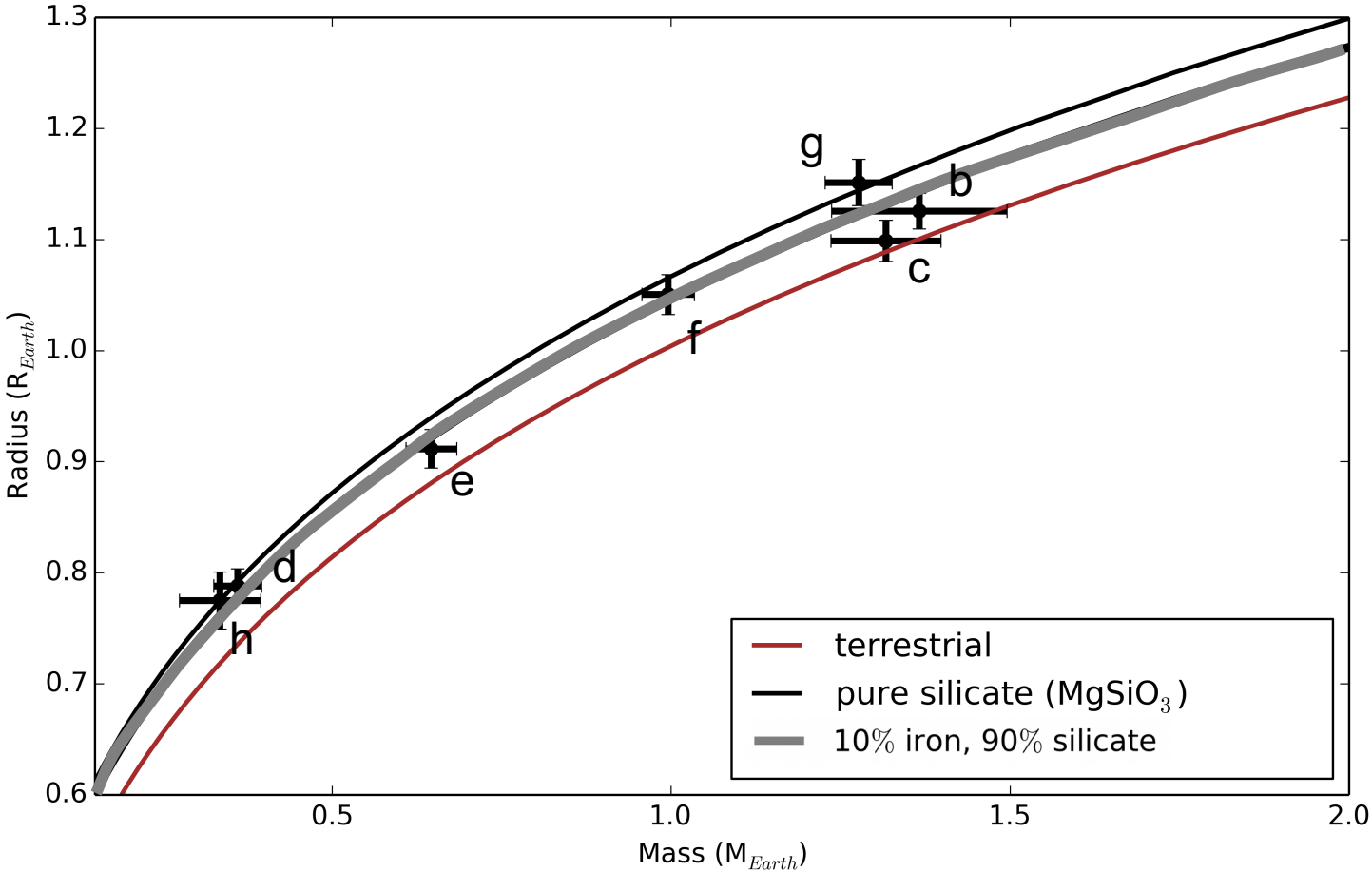

Agol et al., in prep

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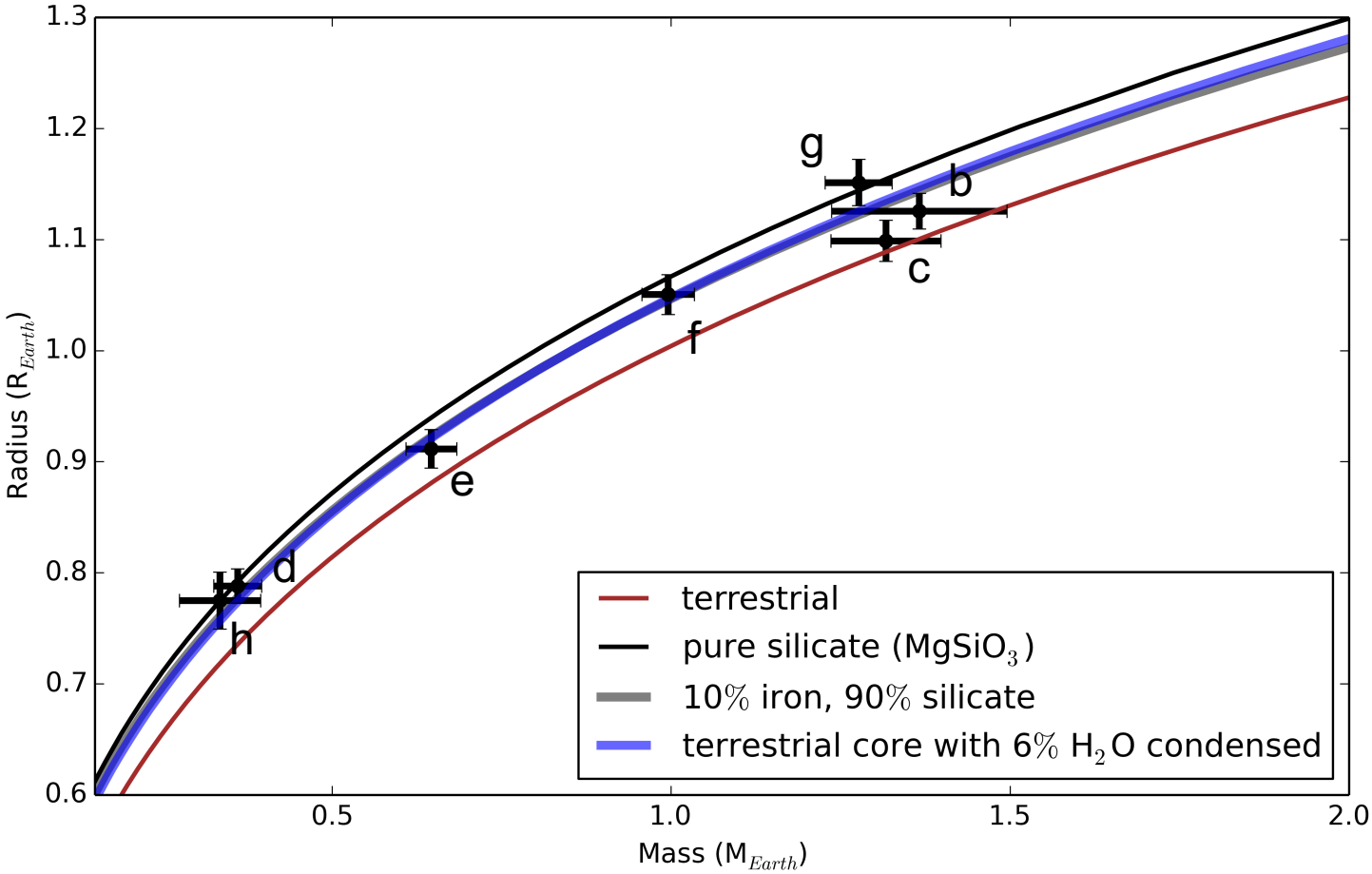
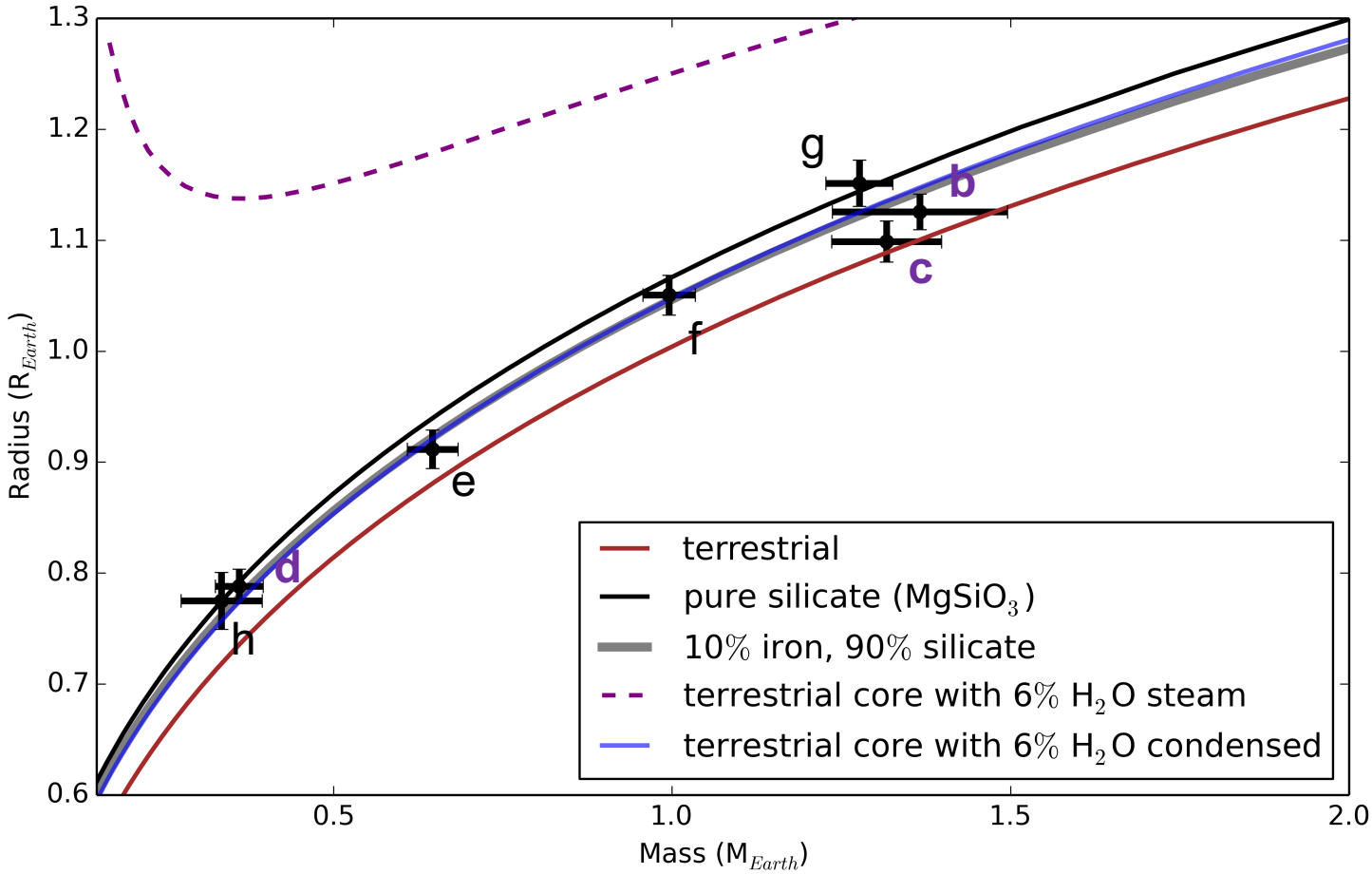


Agol et al., in prep

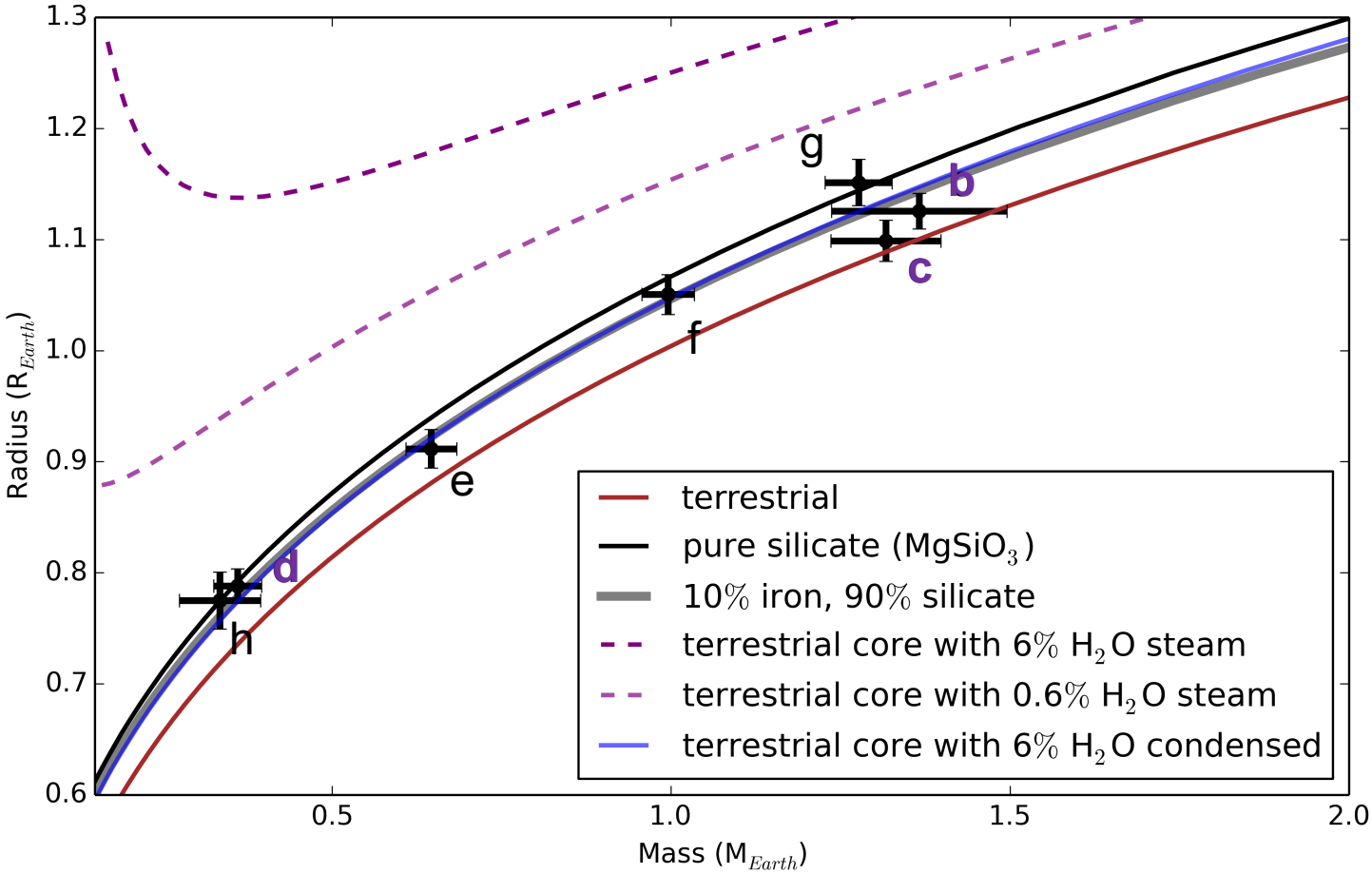
Turbet et al. 2020b, In revision for A&A (available on arXiv)

MASS/RADIUS OF TRAPPIST-1 PLANETS



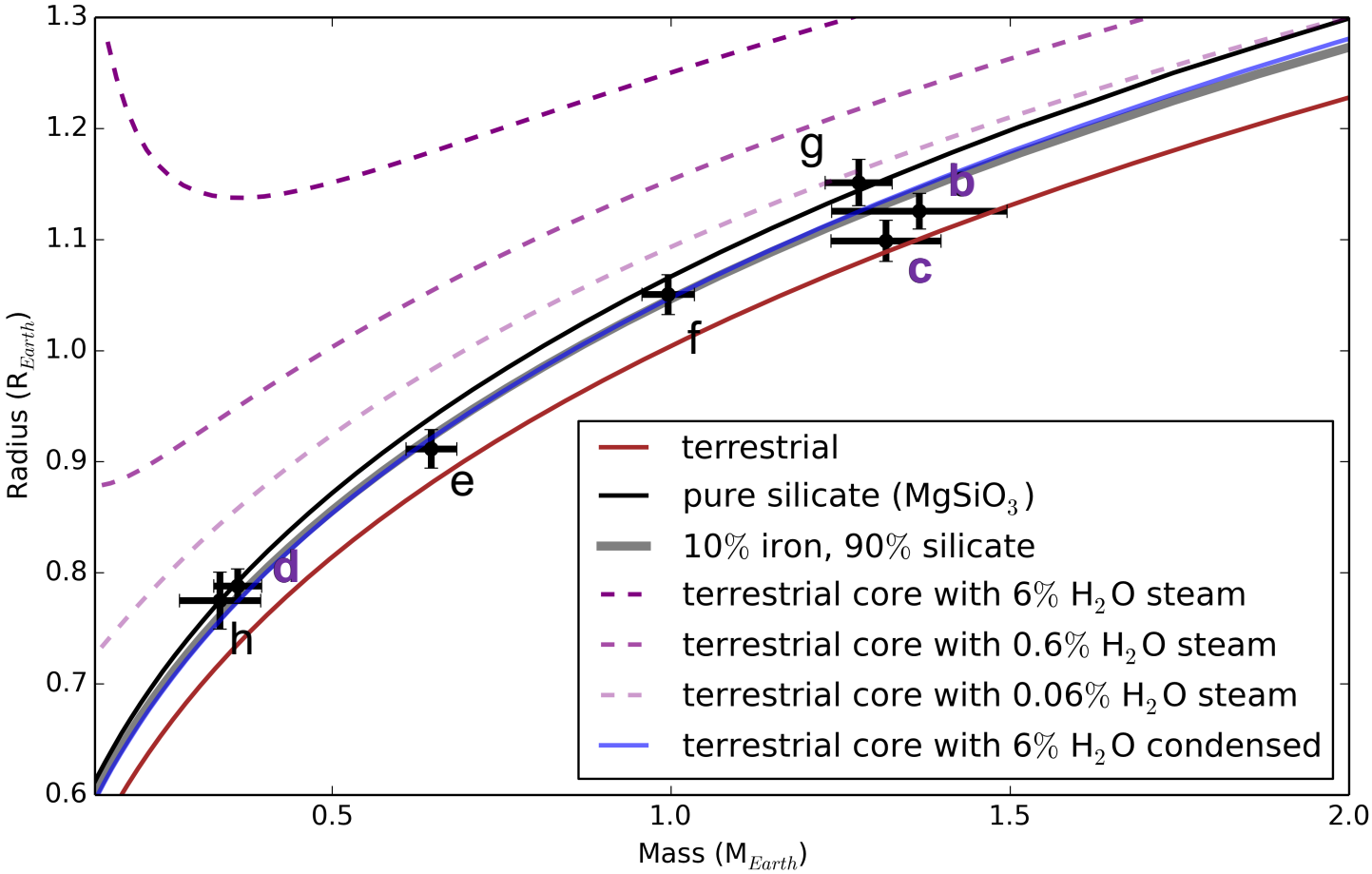
Turbet et al. 2020b, In revision for A&A (available on arXiv)

MASS/RADIUS OF TRAPPIST-1 PLANETS



Turbet et al. 2020b, In revision for A&A (available on arXiv)

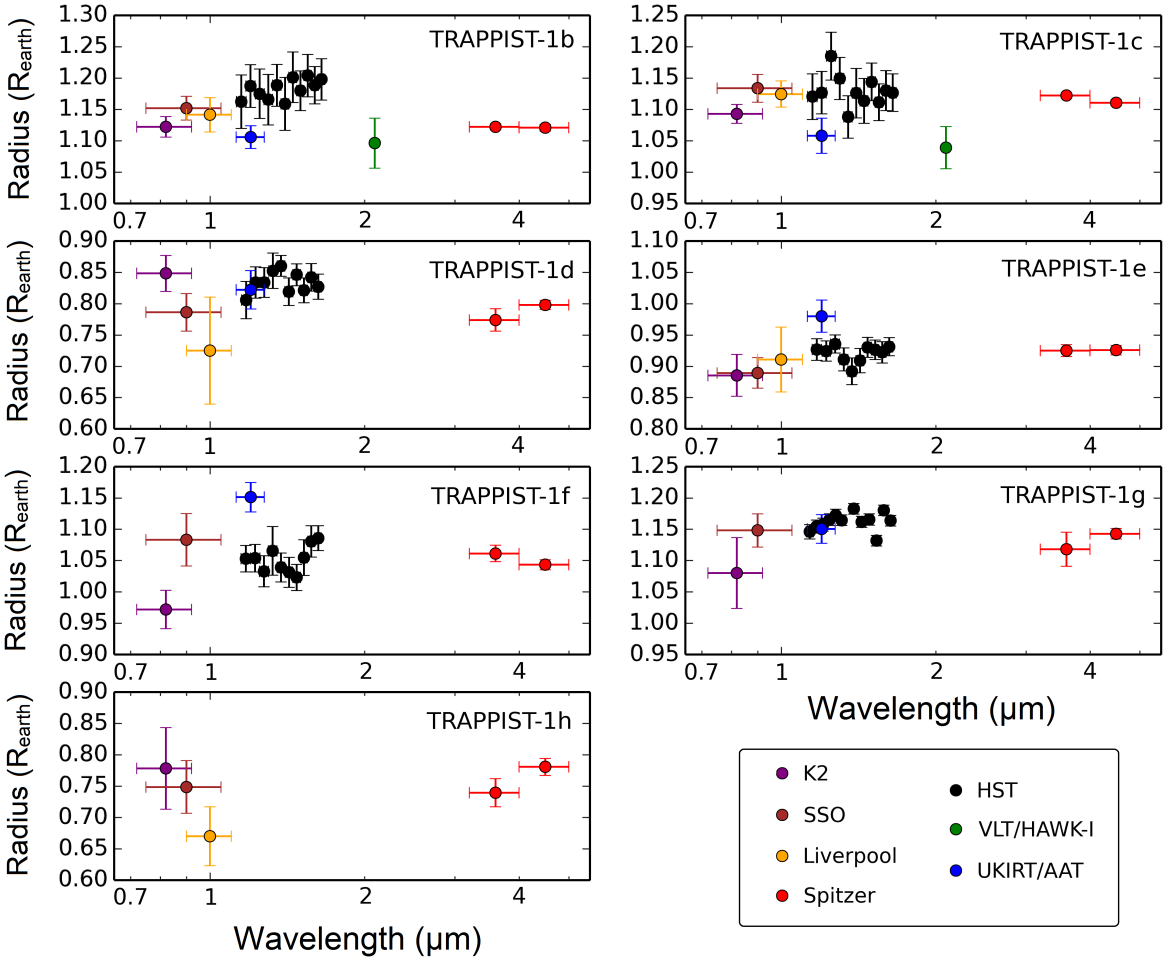
MASS/RADIUS OF TRAPPIST-1 PLANETS



Turbet et al. 2020b, In revision for A&A (available on arXiv)

TRANSIT SPECTROSCOPY

NASA GSFC



TRANSMISSION SPECTRA OF TRAPPIST-1 PLANETS

Turbet et al. 2020b,
submitted to Space Science Reviews

Based on the work of
De Wit et al. 2016, 2018
Gillon et al. 2017
Delrez et al. 2018
Ducrot et al. 2018, 2020

TRAPPIST-1 planets

James Webb Space Telescope

1331 - Transit Spectroscopy of TRAPPIST-1e

Cycle: 1, Proposal Category: GTO

INVESTIGATORS

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Dr. Kevin B. Stevenson (CoI)	Space Telescope Science Institute	kbs@stsci.edu

OBSERVATIONS

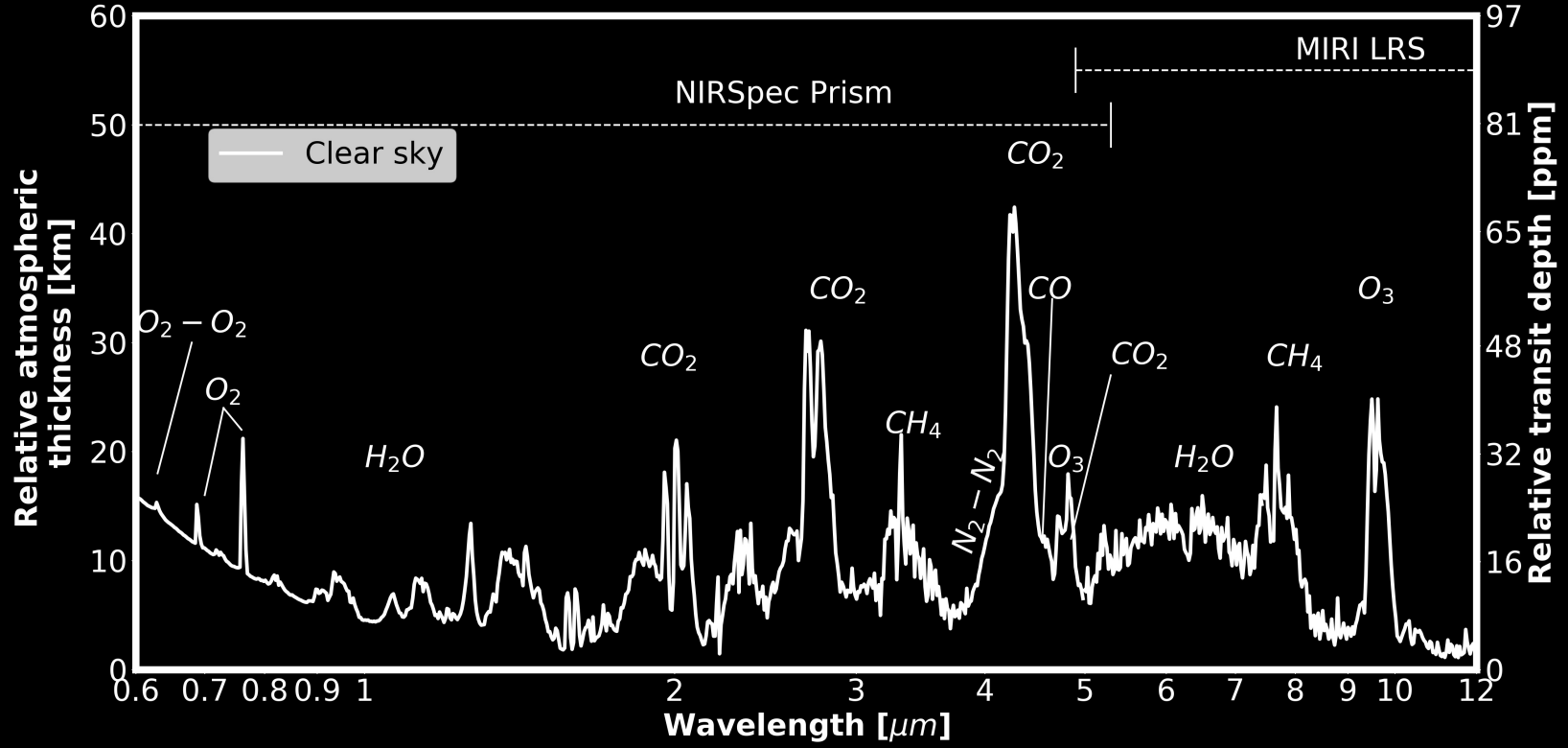
Folder	*Observation*	*Label*	*Observing Template*	*Science Target*
TRAPPIST-1e				
	1	Prism Transit 1	NIRSpec Bright Object Time Series	(1) TRAPPIST-1
	2	Prism Transit 1	NIRSpec Bright Object Time Series	(1) TRAPPIST-1
	3	Prism Transit 1	NIRSpec Bright Object Time Series	(1) TRAPPIST-1
	4	Prism Transit 1	NIRSpec Bright Object Time Series	(1) TRAPPIST-1

ABSTRACT

We will construct the transmission spectra of this planet. Transmission studies will be conducted from 0.6-5 microns using four transit observations (when the planet passes in front of the host star). The transmission for this planets atmosphere will be obtained using NIRSpec SLIT1600 Prism.

Modern Earth-like atmosphere

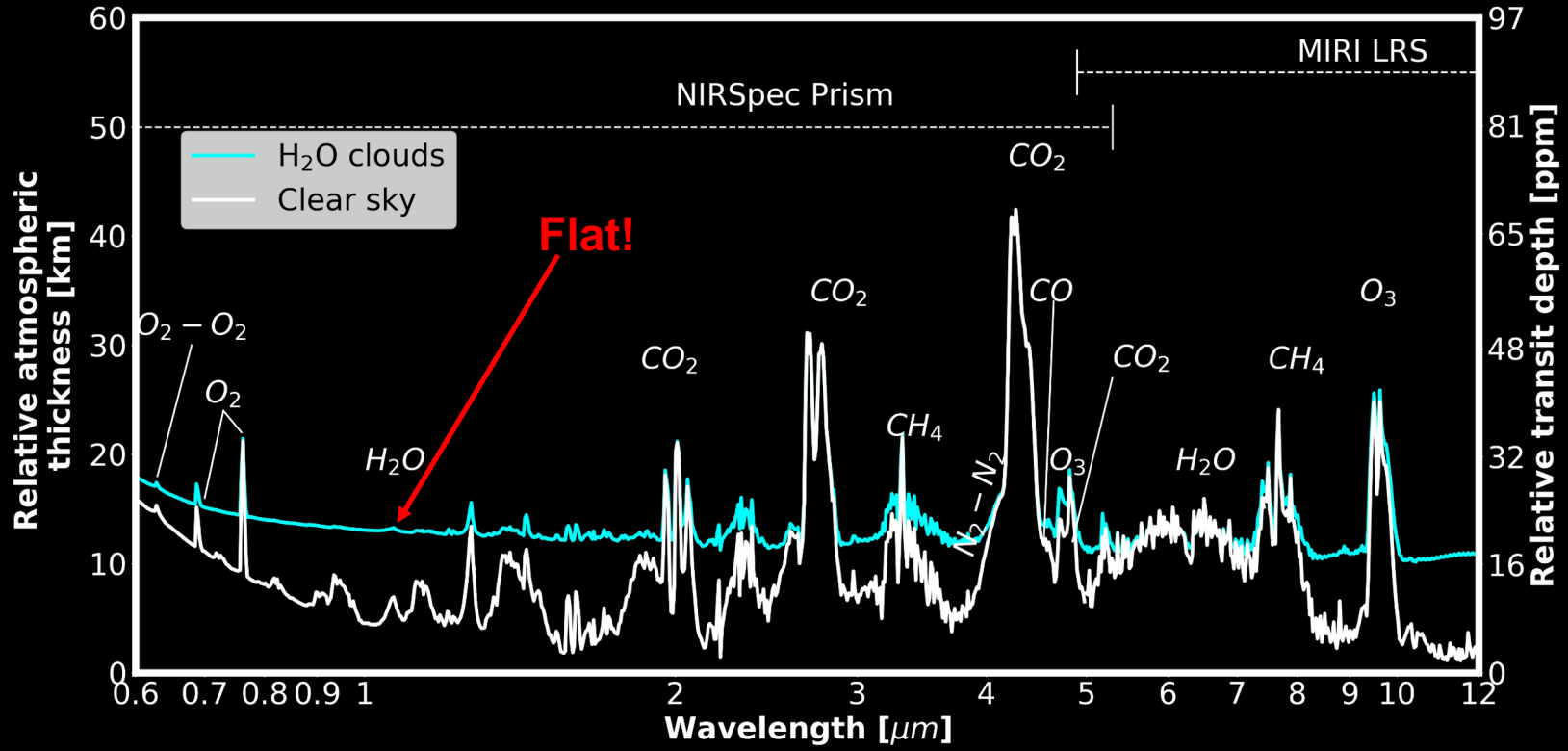
TRAPPIST-1e



Fauchez, Turbet et al. 2019, ApJ

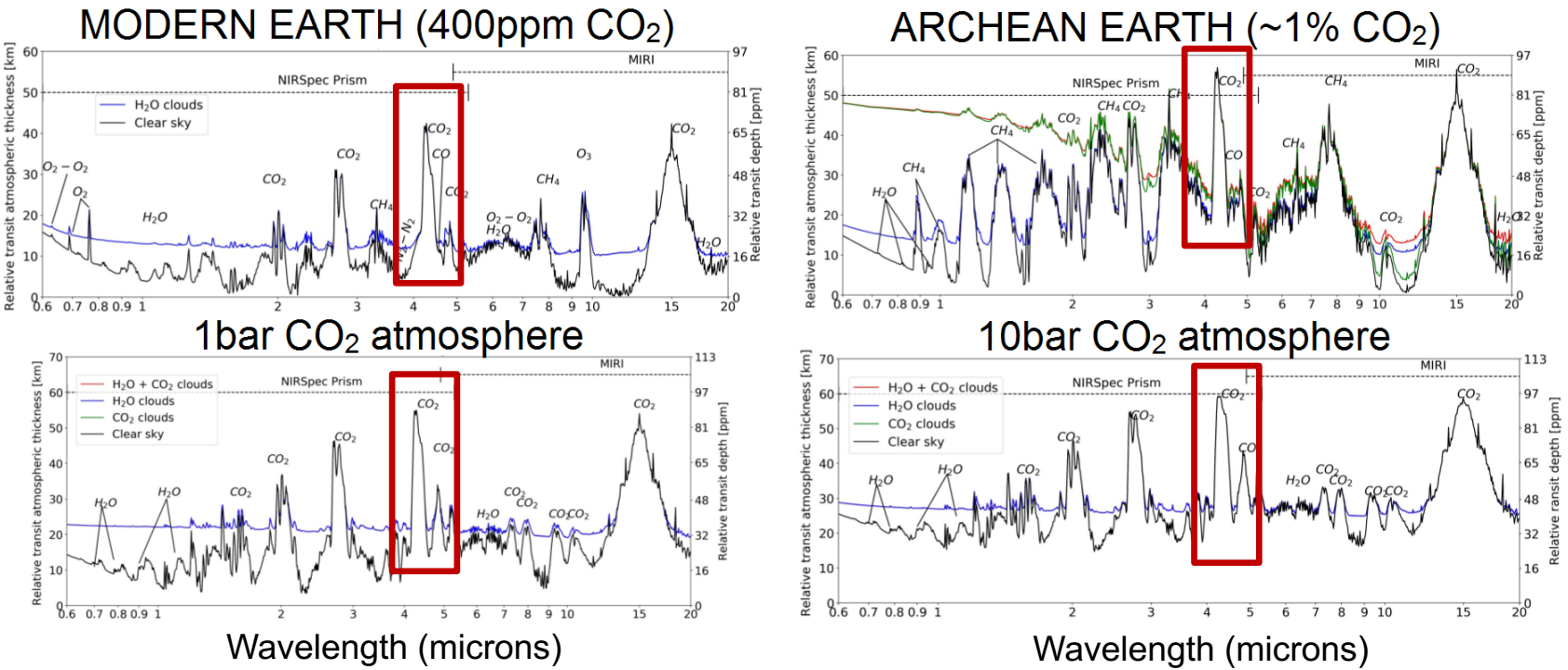
Modern Earth-like atmosphere

TRAPPIST-1e



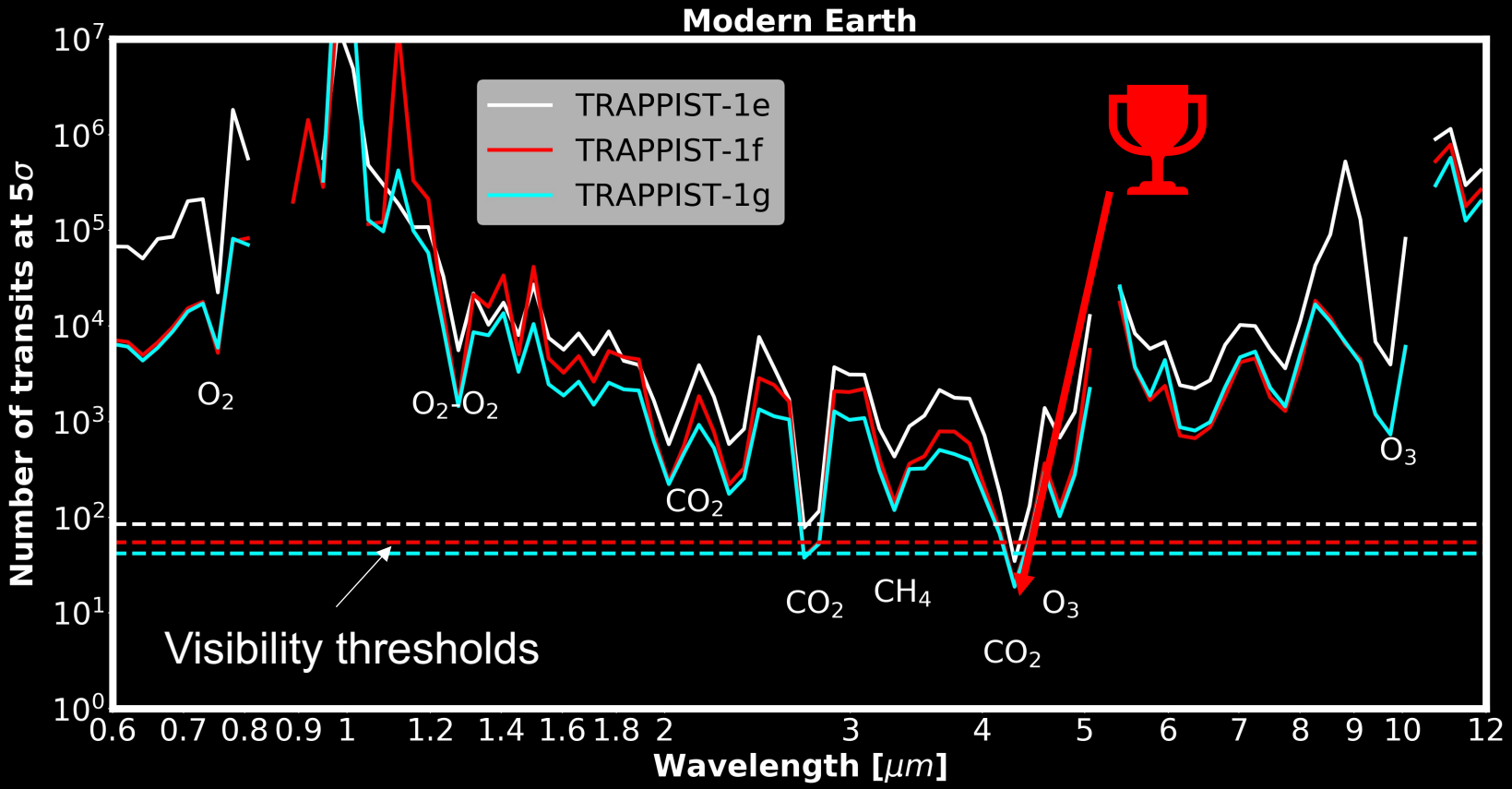
Fauchez, Turbet et al. 2019, ApJ

TRANSMISSION SPECTROSCOPY FOR TRAPPIST-1 PLANETS WITH JWST



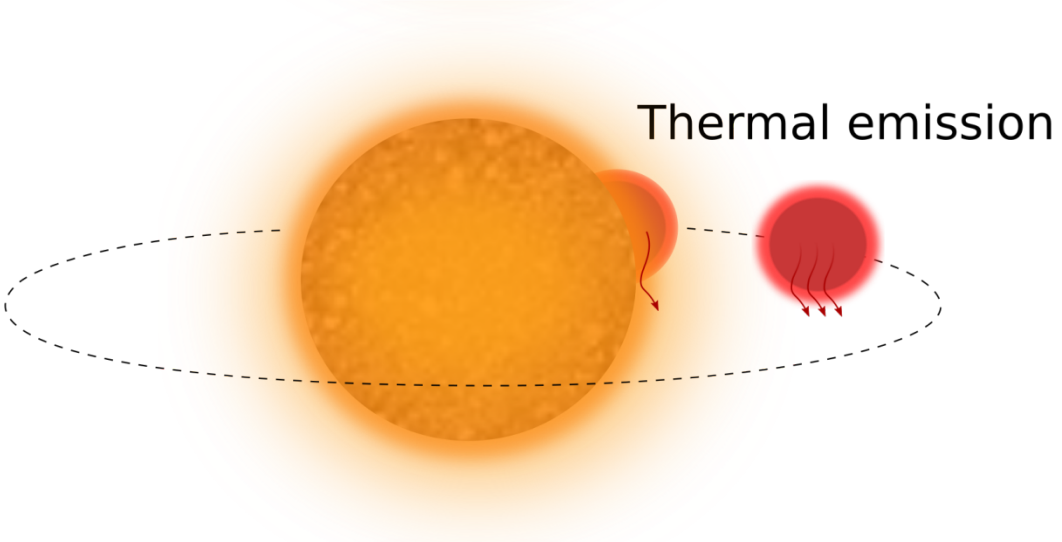
Fauchez, Turbet et al. 2019, ApJ

Detectability (SNR > 5)



Fauchez, Turbet et al. 2019, ApJ

SECONDARY ECLIPSES WITH JWST IN 2021+



Secondary eclipse

Morley et al. 2017
Lincowski et al. 2018
Lustig-Yaeger et al. 2019
Fauchez et al. 2019

1279 - Thermal emission from Trappist1-b

Cycle: 1, Proposal Category: GTO

INVESTIGATORS

Name	*Institution*	*E-Mail*
Dr. Pierre-Olivier Lagage (PI) (ESA Member)	**Commissariat a l'Energie Atomique (CEA)**	**pierre-olivier.lagage@cea.fr**
Dr. Jeroen Bouwman (CoI) (ESA Member) (Contact)	Max-Planck-Institut fur Astronomie, Heidelberg	bouwman@mpia.de

OBSERVATIONS

Folder	*Observation*	*Label*	*Observing Template*	*Science Target*
MIRIM TRAPPIST-1b				
	1	TRAPPIST-1 b Eclipse 1	MIRI Imaging	(1) TRAPPIST-1B
	2	TRAPPIST-1 b Eclipse 1	MIRI Imaging	(1) TRAPPIST-1B
	3	TRAPPIST-1 b Eclipse 1	MIRI Imaging	(1) TRAPPIST-1B
	4	TRAPPIST-1 b Eclipse 1	MIRI Imaging	(1) TRAPPIST-1B
	5	TRAPPIST-1 b Eclipse 1	MIRI Imaging	(1) TRAPPIST-1B

ABSTRACT

The aim is to detect the thermal emission from the TRAPPIST1 b exoplanet, an Earth mass like transiting exoplanet.

The emission will be obtained from photometric observations of eclipses of the exoplanet.

Given the temperature of the exoplanet, around 400 K, we will use the MIRI instrument.

1177 - MIRI observations of transiting exoplanets

Cycle: 1, Proposal Category: GTO

INVESTIGATORS

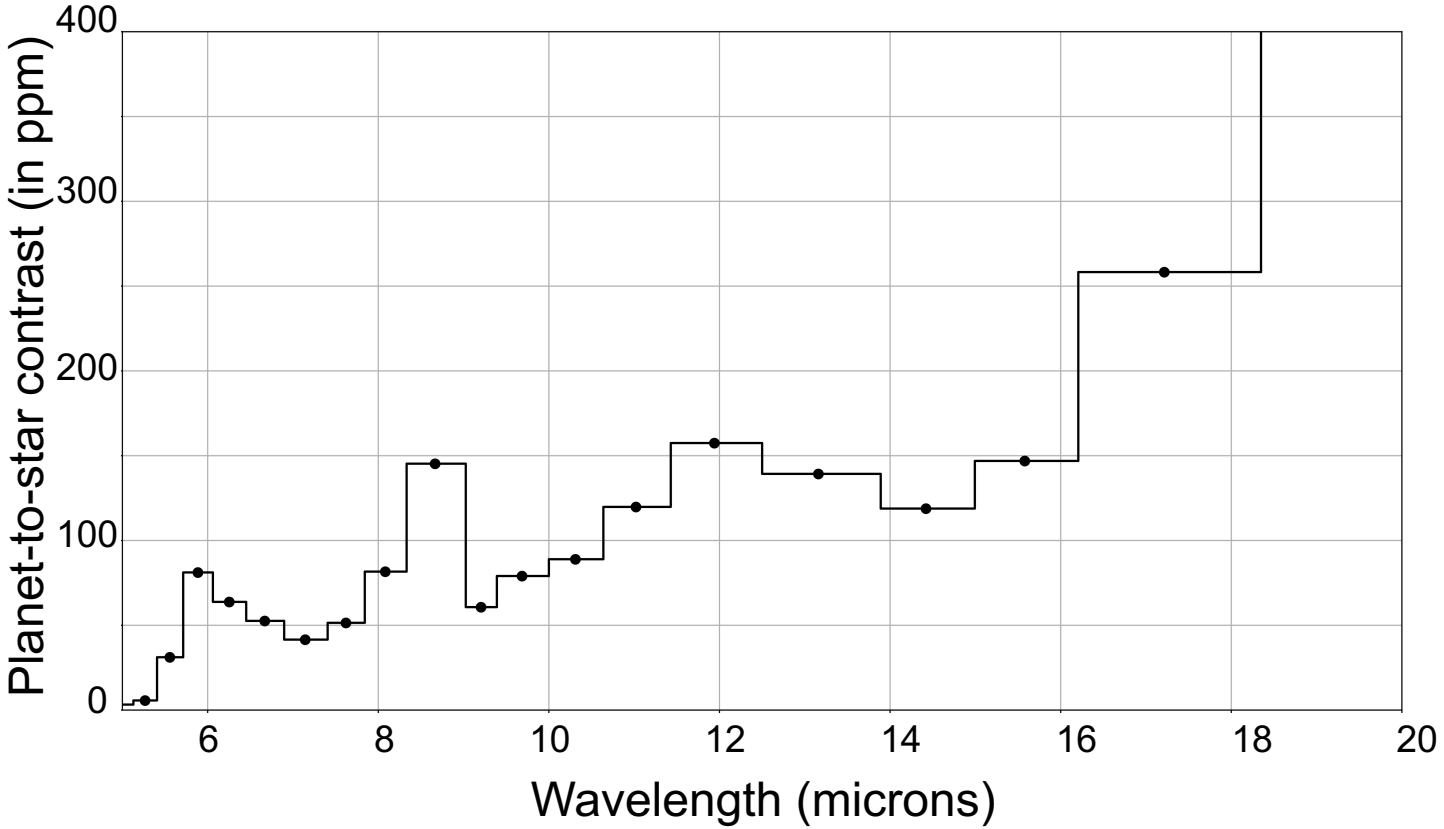
Name	*Institution*	*E-Mail*
Dr. Thomas P. Greene (PI)	**NASA Ames Research Center**	**tom.greene@nasa.gov**
Everett Schlawin (CoI) (Contact)	University of Arizona	eas342@email.arizona.edu
Dr. Pierre-Olivier Lagage (CoI) (ESA Member)	Commissariat a l'Energie Atomique (CEA)	pierre-olivier.lagage@cea.fr
Dr. Marcia J. Rieke (CoI)	University of Arizona	mrieke@as.arizona.edu

OBSERVATIONS

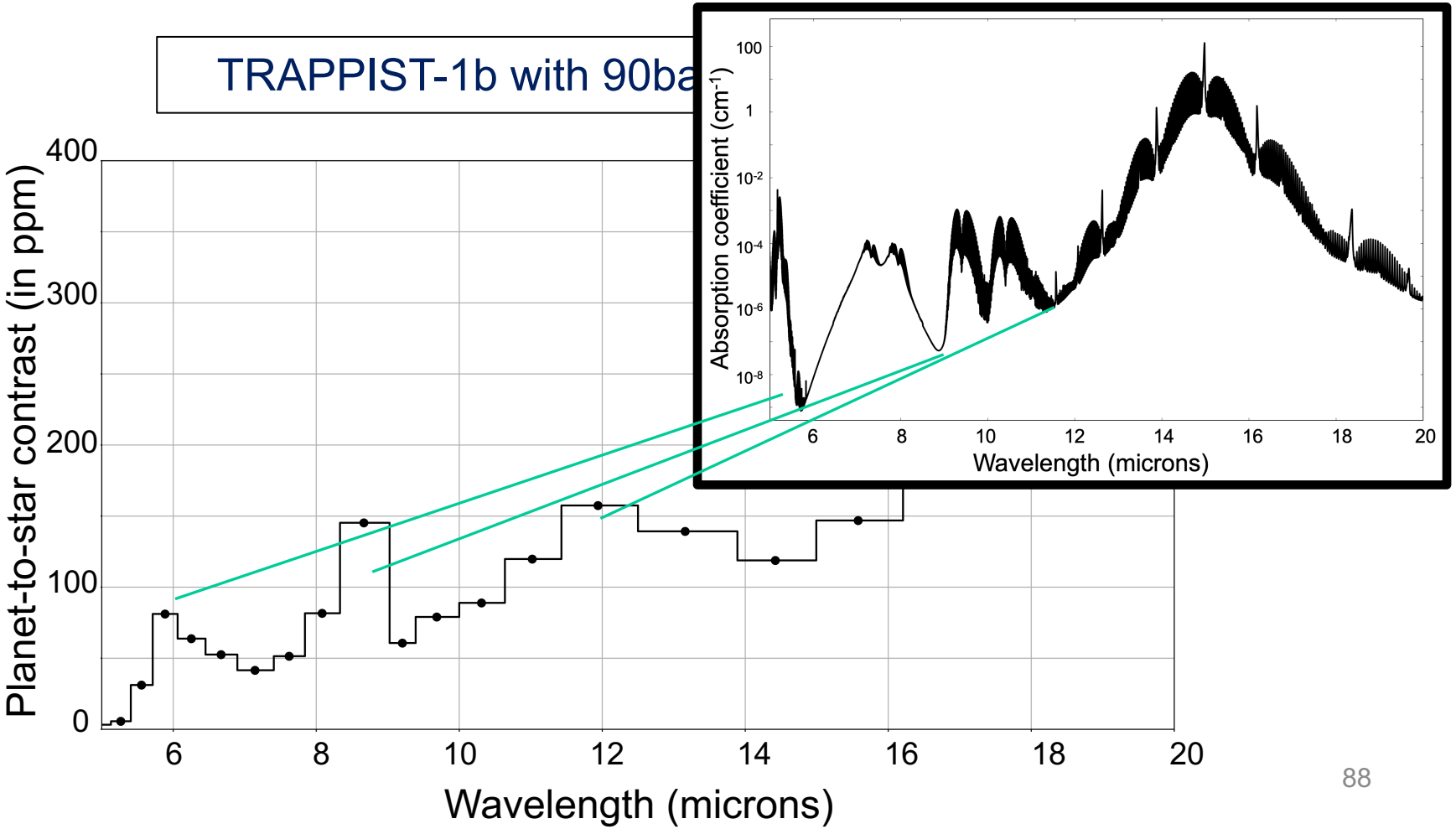
Folder	*Observation*	*Label*	*Observing Template*	*Science Target*
MIRIM Transiting Planets				
	7	TRAPPIST-1 b Sec Eclipse	MIRI Imaging	(5) TRAPPIST-1B
	8	TRAPPIST-1 b Sec Eclipse	MIRI Imaging	(5) TRAPPIST-1B
	9	TRAPPIST-1 b Sec Eclipse	MIRI Imaging	(5) TRAPPIST-1B
	10	TRAPPIST-1 b Sec Eclipse	MIRI Imaging	(5) TRAPPIST-1B

THERMAL EMISSION SPECTRUM DURING SECONDARY ECLIPSE

TRAPPIST-1b with 90bar CO_2 atmosphere

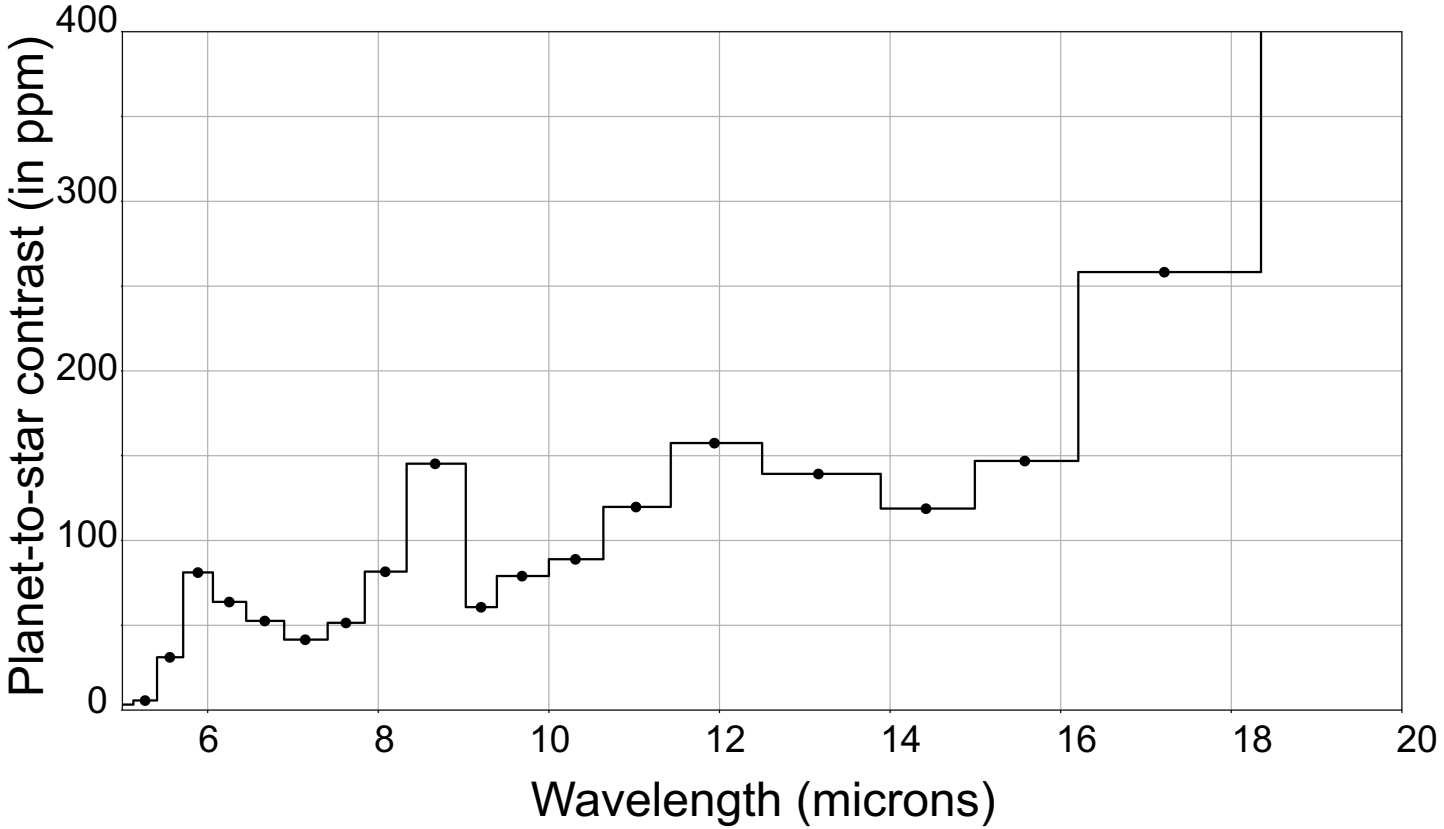


THERMAL EMISSION SPECTRUM DURING SECONDARY ECLIPSE



THERMAL EMISSION SPECTRUM DURING SECONDARY ECLIPSE

TRAPPIST-1b with 90bar CO_2 atmosphere



THERMAL EMISSION SPECTRUM DURING SECONDARY ECLIPSE

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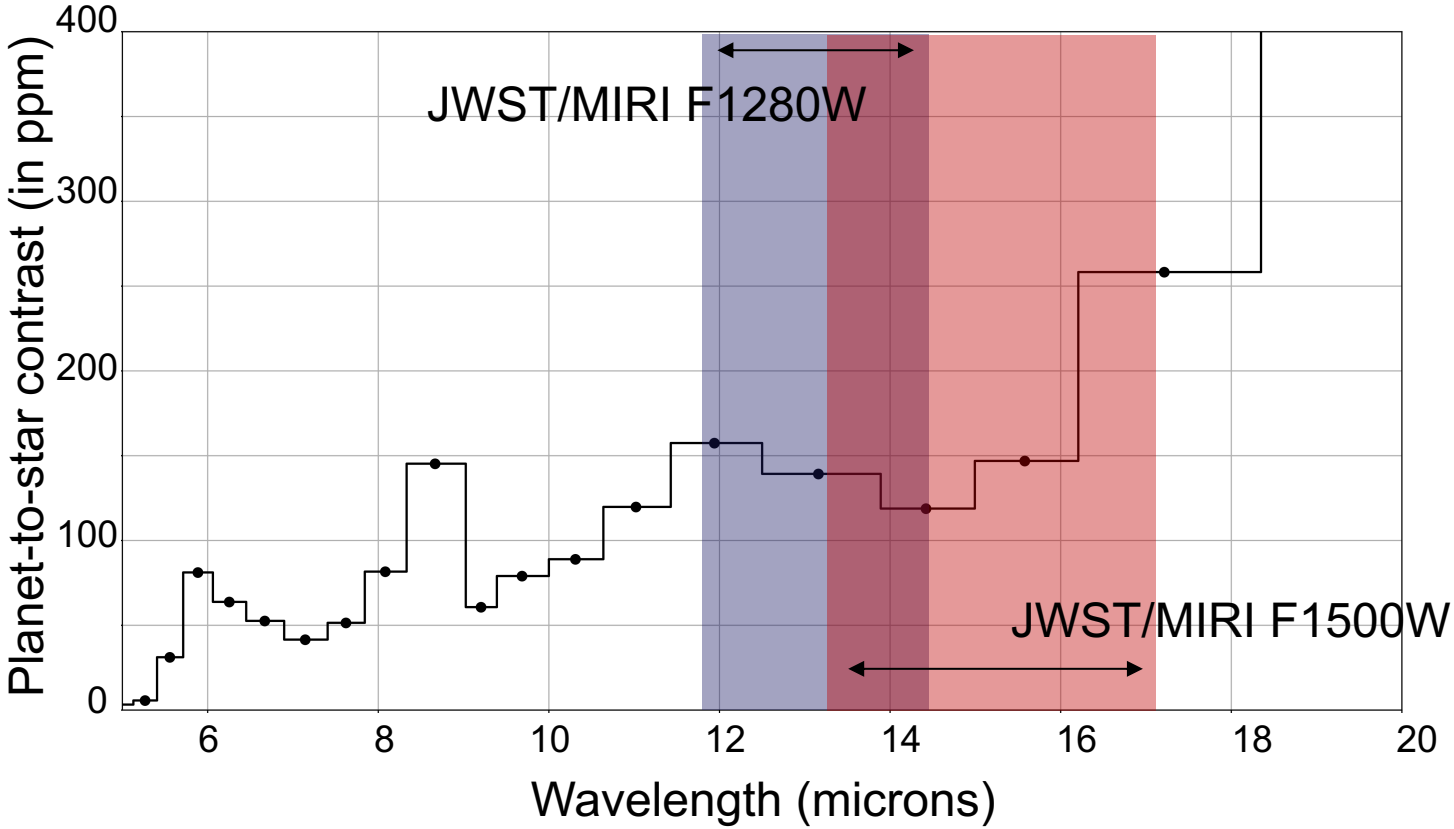
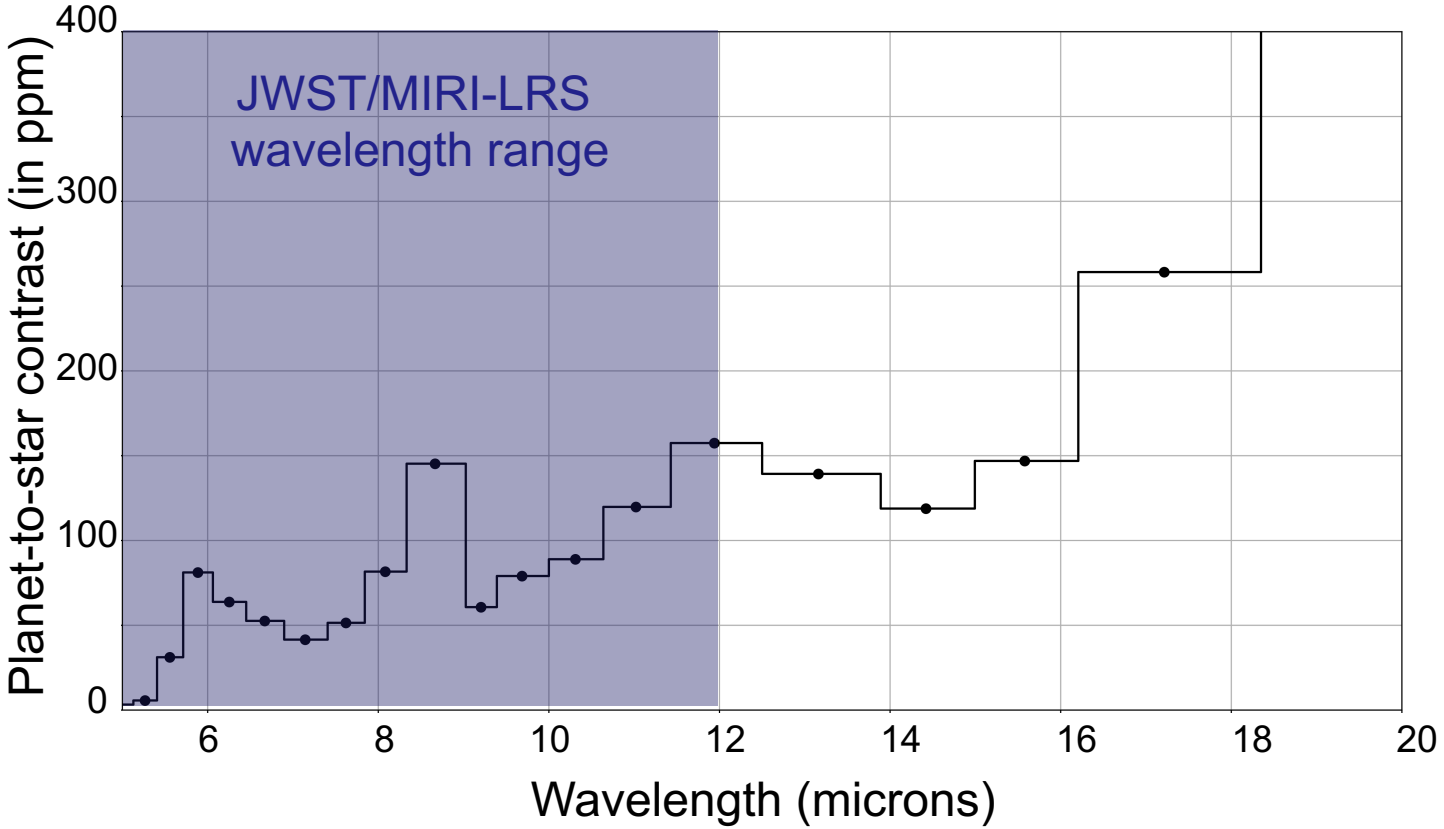


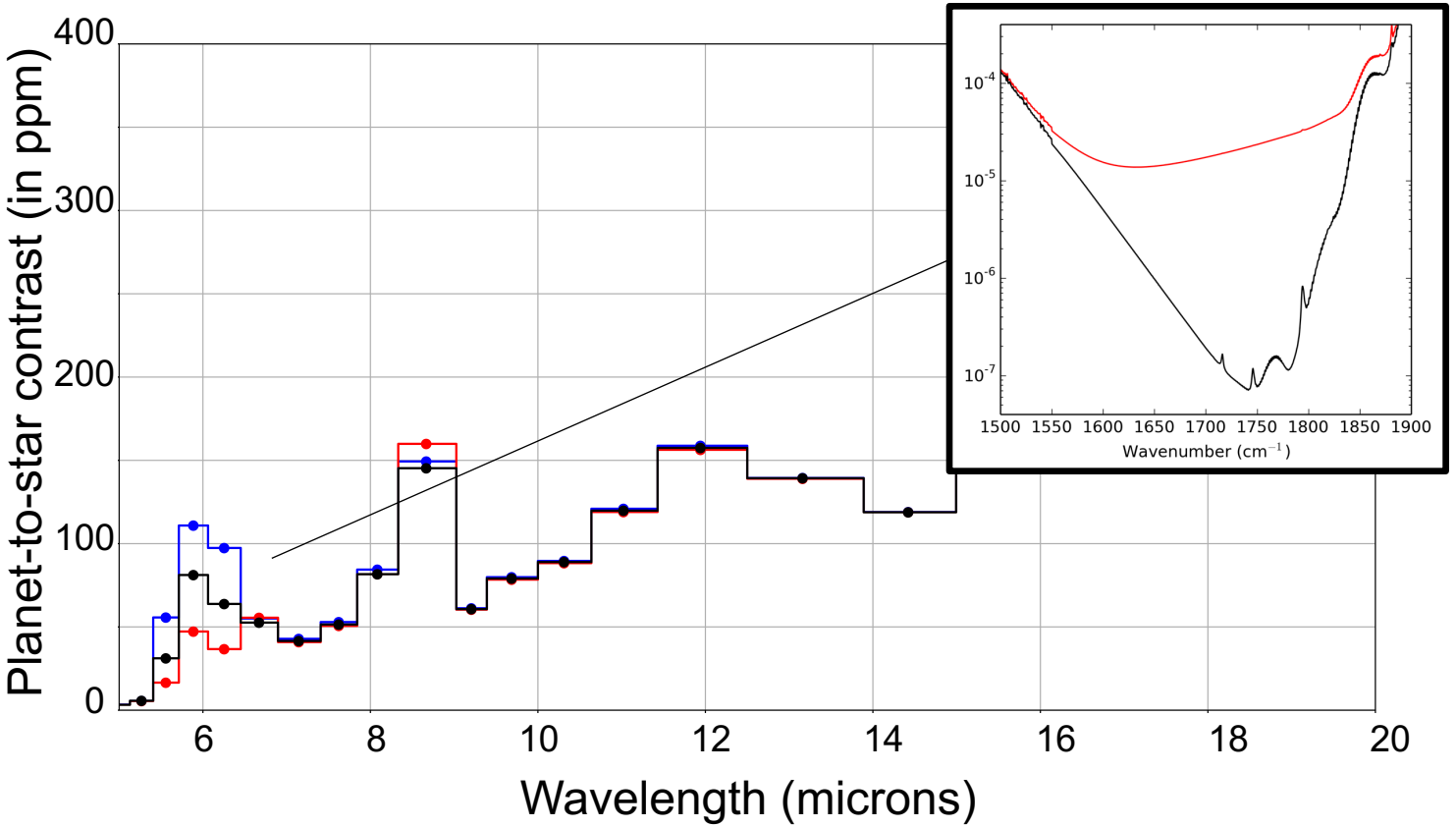
THERMAL EMISSION SPECTRUM DURING SECONDARY ECLIPSE

TRAPPIST-1b with 90bar CO_2 atmosphere



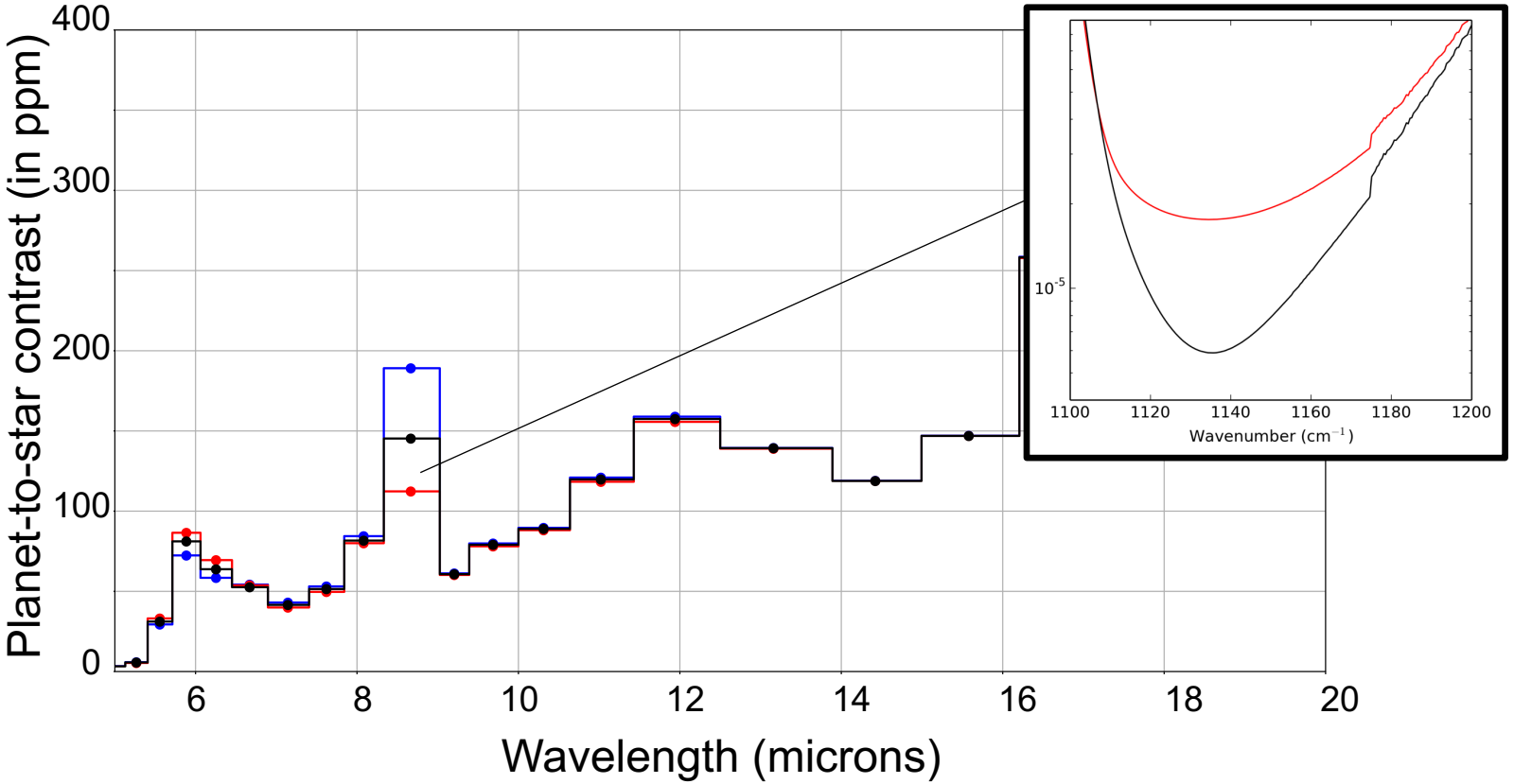
THERMAL EMISSION SPECTRUM DURING SECONDARY ECLIPSE

TRAPPIST-1b with 90bar CO_2 atmosphere



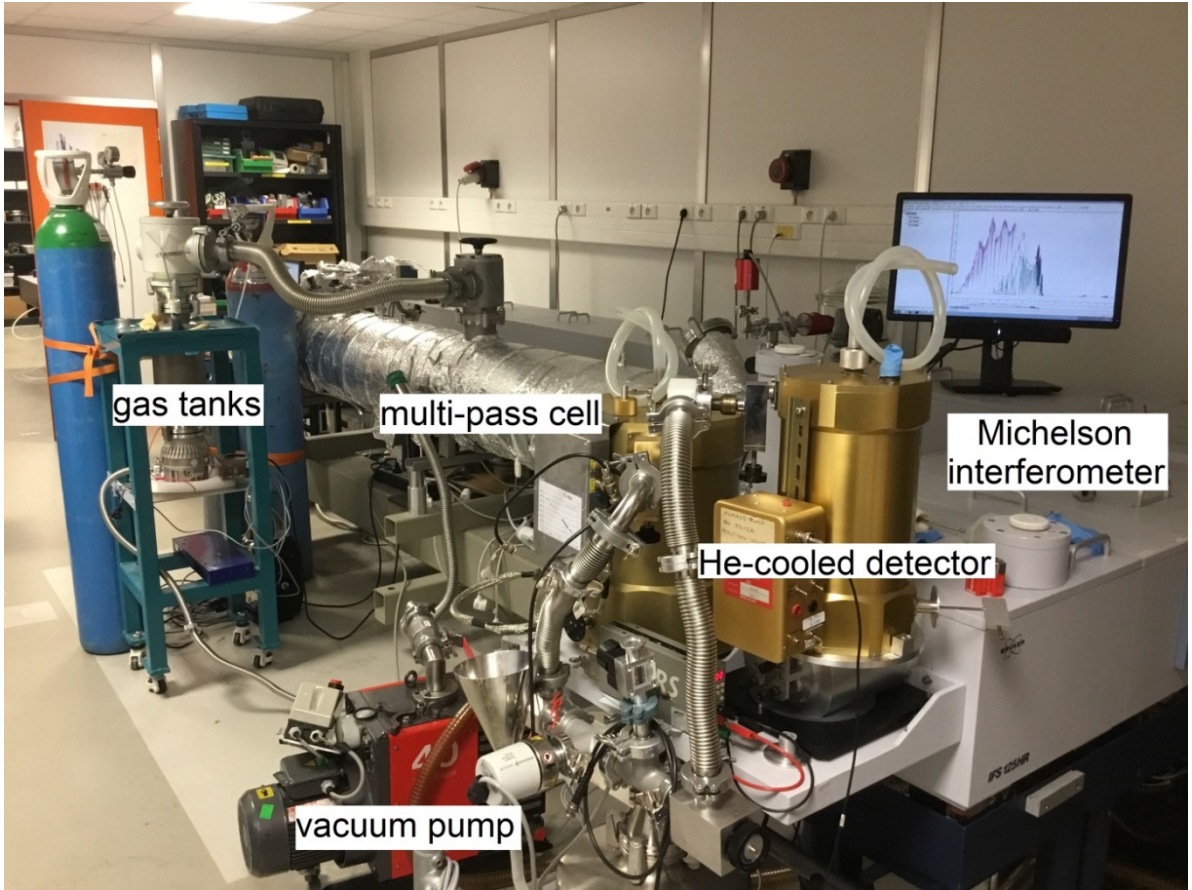
THERMAL EMISSION SPECTRUM DURING SECONDARY ECLIPSE

TRAPPIST-1b with 90bar CO_2 atmosphere



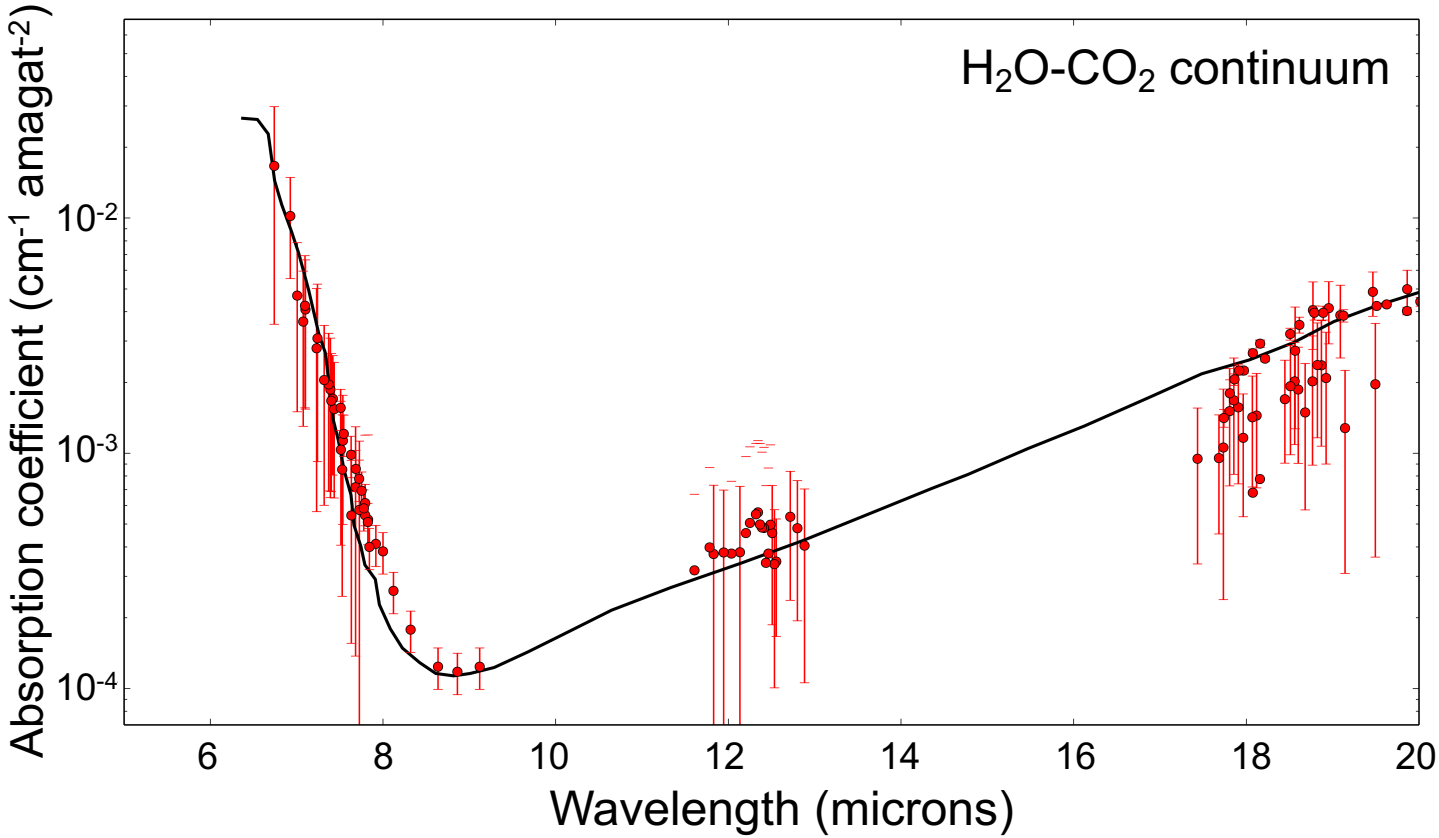
THE AILES FOURIER TRANSFORM SPECTROSCOPY EXPERIMENTAL SETUP

Turbet et al. 2019b, 2020c
Tran, Turbet et al. 2018, 2019

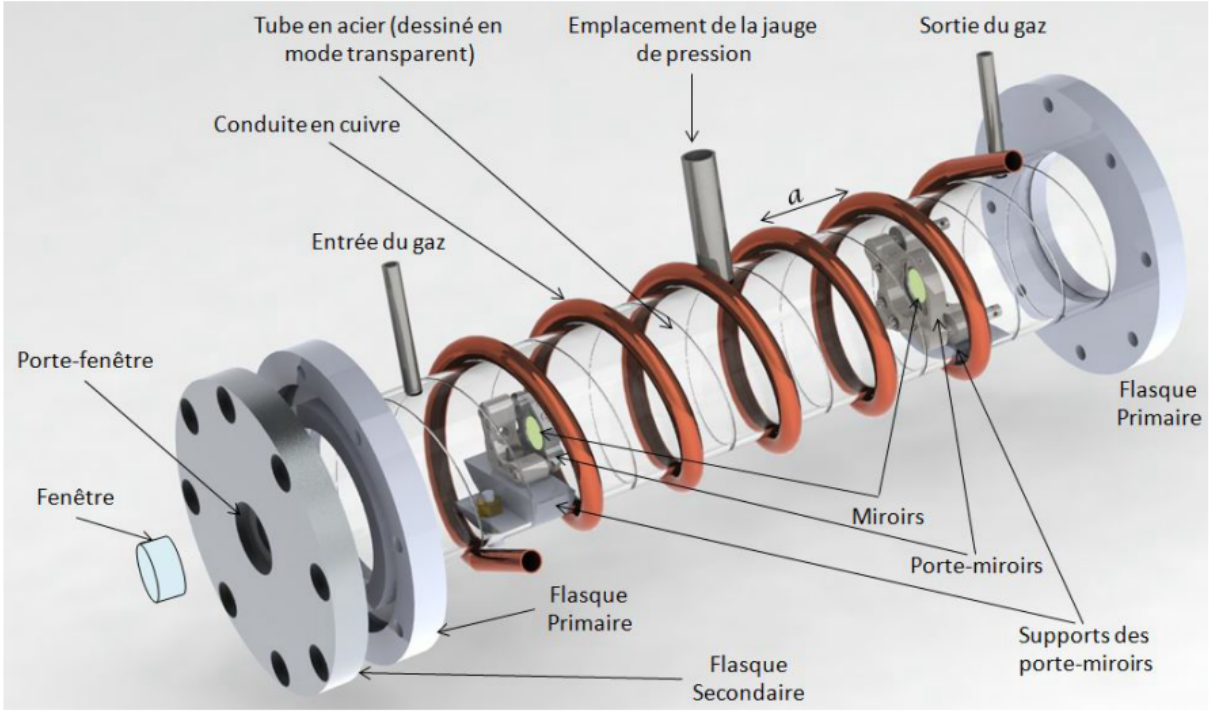


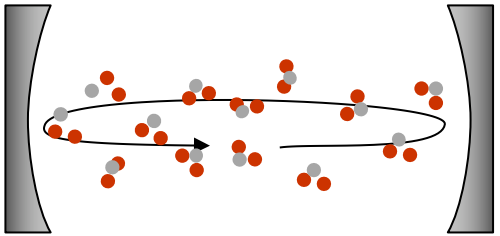
FTS MEASUREMENTS OF CONTINUUM ABSORPTION IN CO_2-RICH ATMOSPHERES

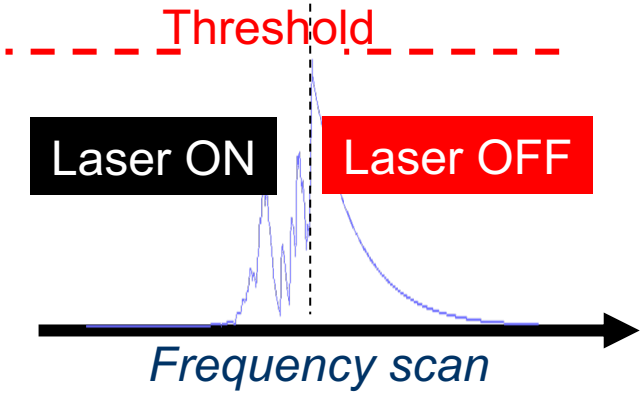
Tran, Turbet et al. 2019



THE CAVITY RING DOWN SPECTROSCOPY (CRDS)
GRENOBLE EXPERIMENTAL SETUP



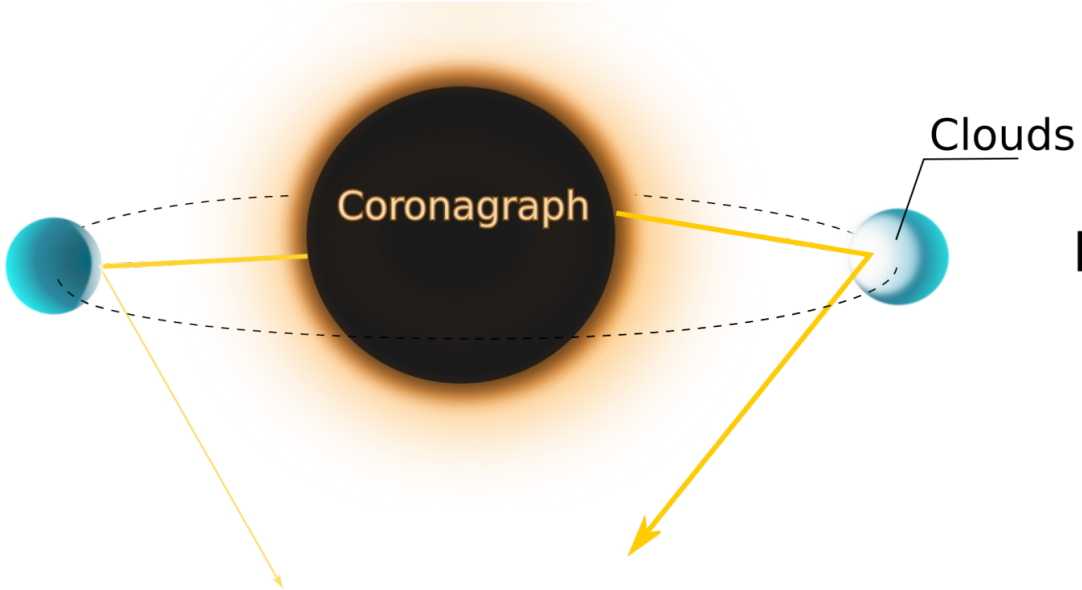




COMPLEAT Project – Credit: D. Mondelain and A. Campargue

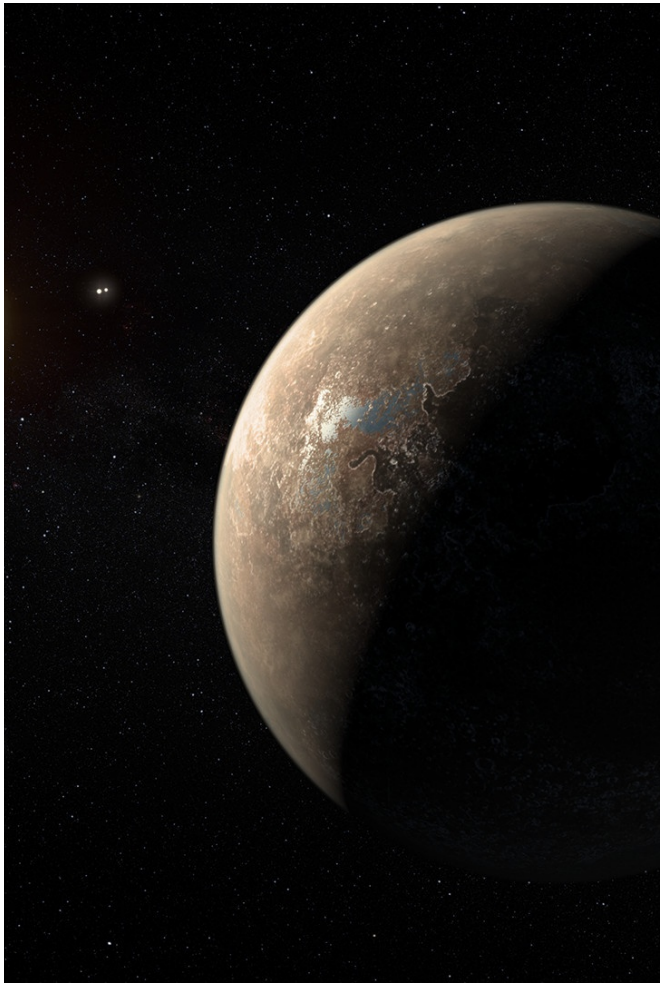
DIRECT IMAGING WITH E-ELT IN 2030+

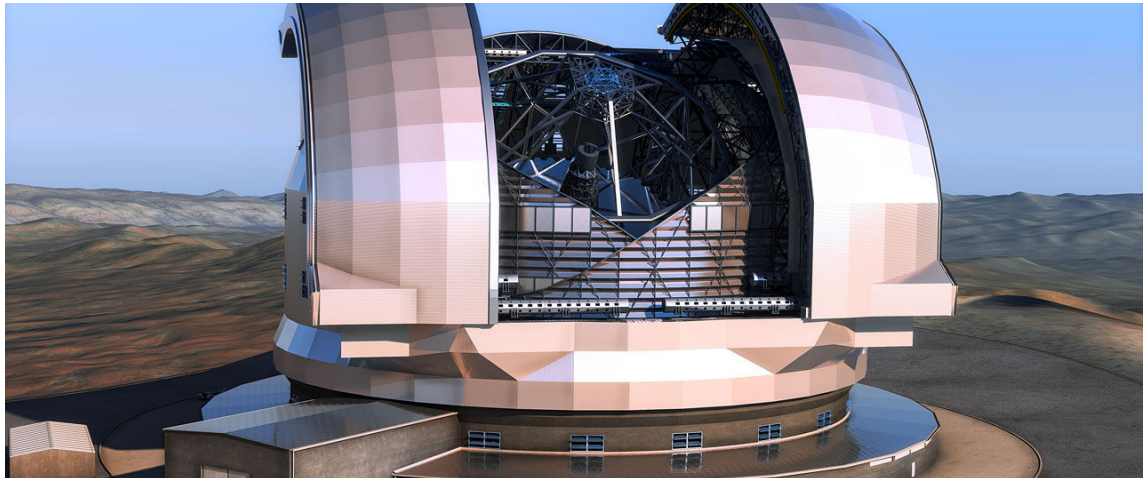
(or maybe - and hopefully ! – before using the HCHR technique)



Reflexion phase curves
with direct imaging

Turbet et al. 2016
Meadows et al. 2016
Lovis et al. 2017
Boutle et al. 2017

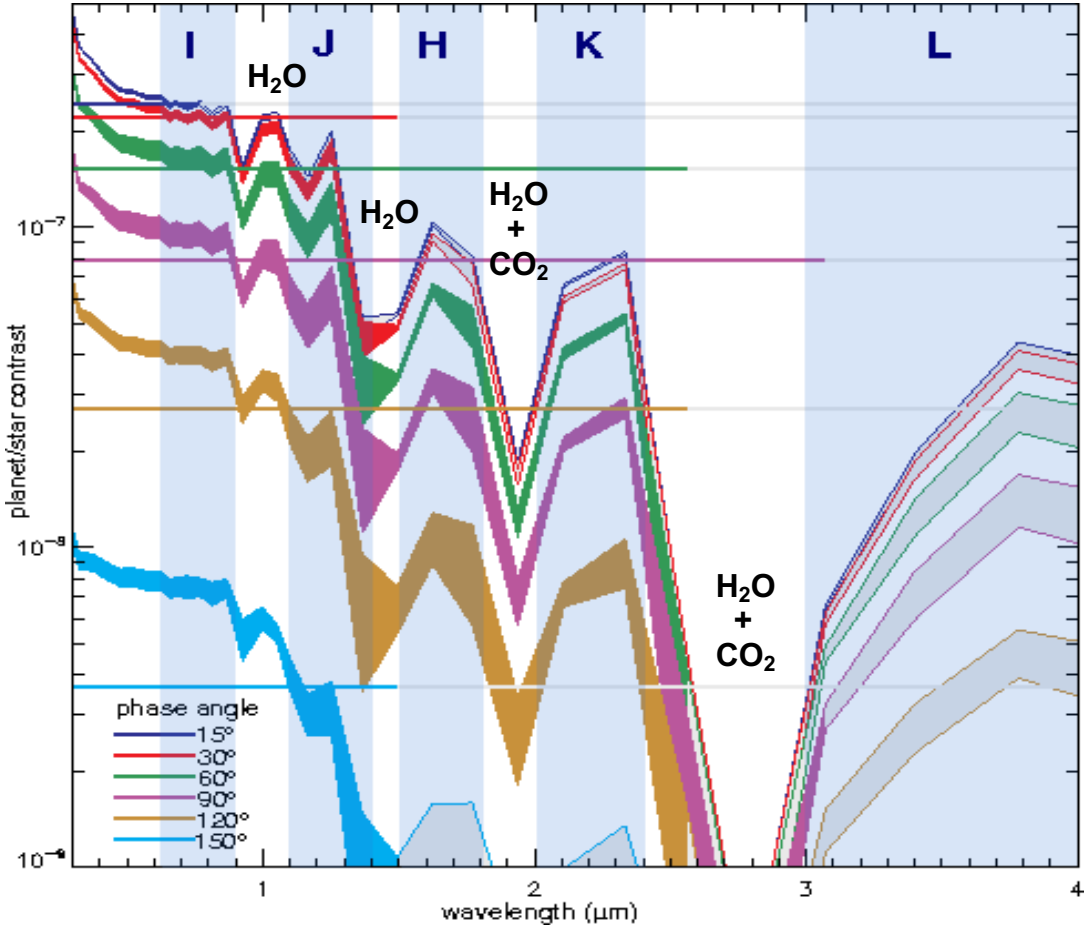




Direct imaging of **Proxima b** using the European “Extremely large telescope” (E-ELT)

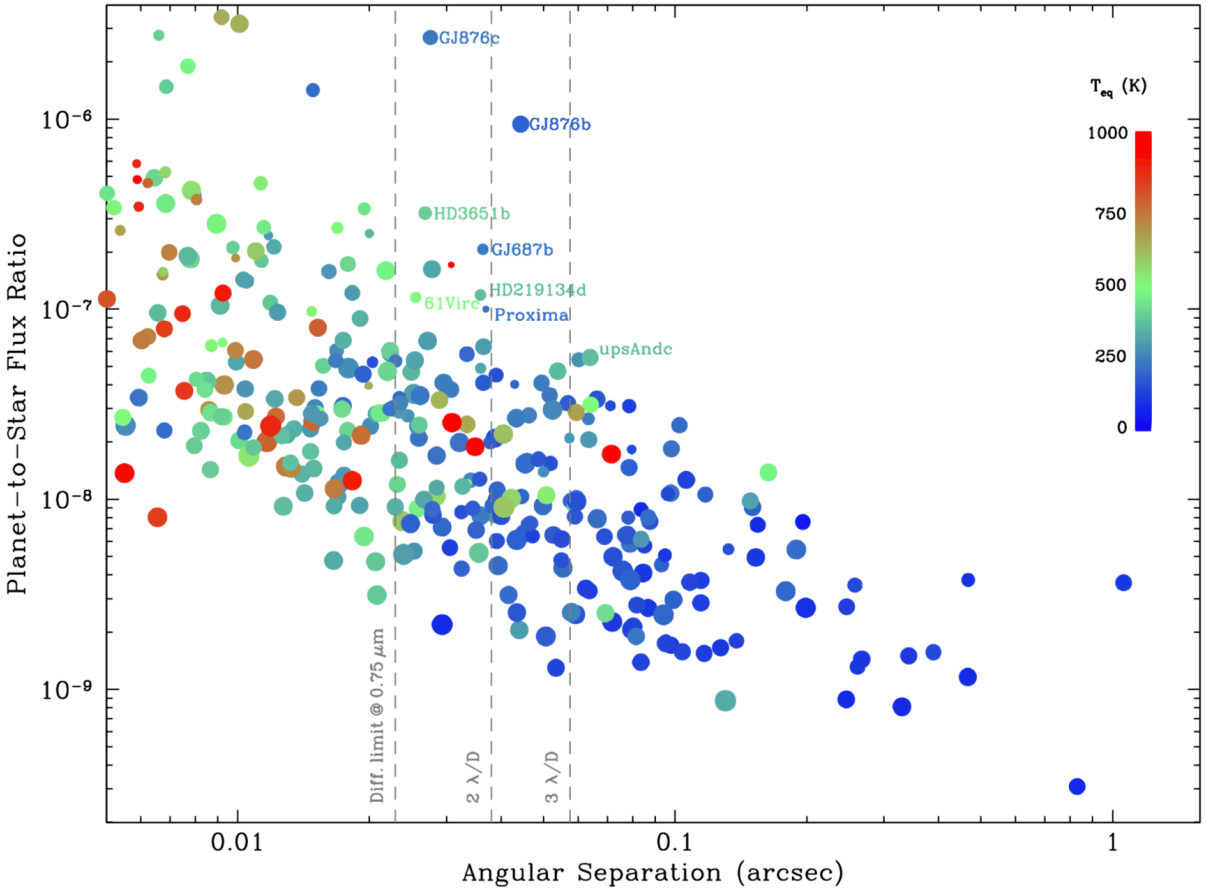
(diameter 39 m ; 2024+)

SYNTHETIC SPECTRA FOR DIRECT IMAGING OF PROXIMA B



Synchronous rotation mode and Earth-like oceans/atmosphere

Turbet et al. 2016, A&A



Combining ***high-contrast coronagraphy*** to ***high-resolution spectroscopy*** in the visible/near-IR directly detects the planet ***reflected light*** and measures:

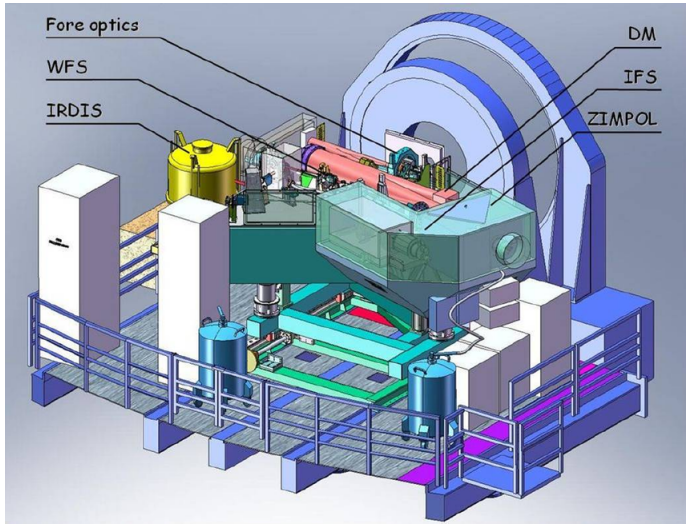
- True mass
- Albedo estimate
- Atmospheric composition
- Cloud properties
- Planet rotation
- Surface properties
- Atmospheric circulation
- Weather patterns
- Biosignatures

Lovis et al. 2017

DIRECT IMAGING OF PROXIMA B ON THE VLT?!

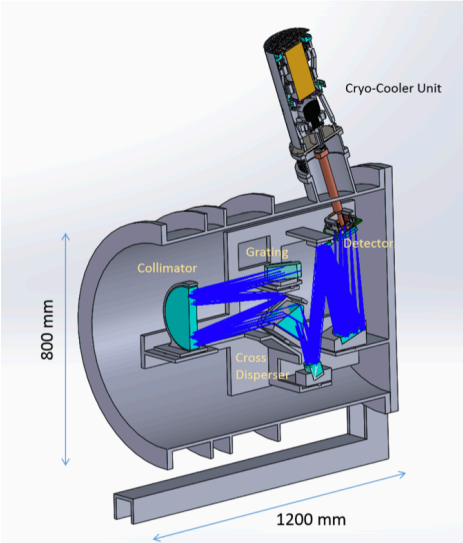
Lovis et al. 2017, A&A

SPHERE or other imager



and

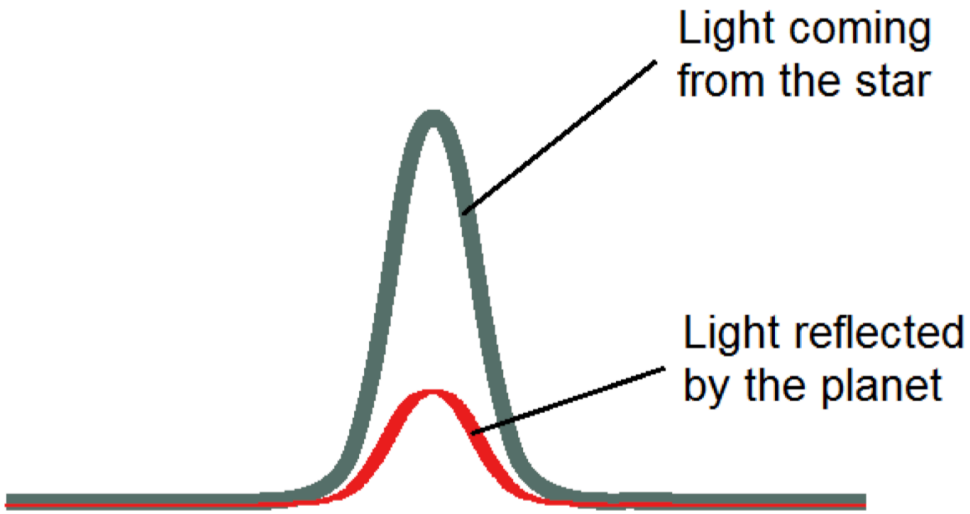
RISTRETTO
(high-resolution spectrograph)



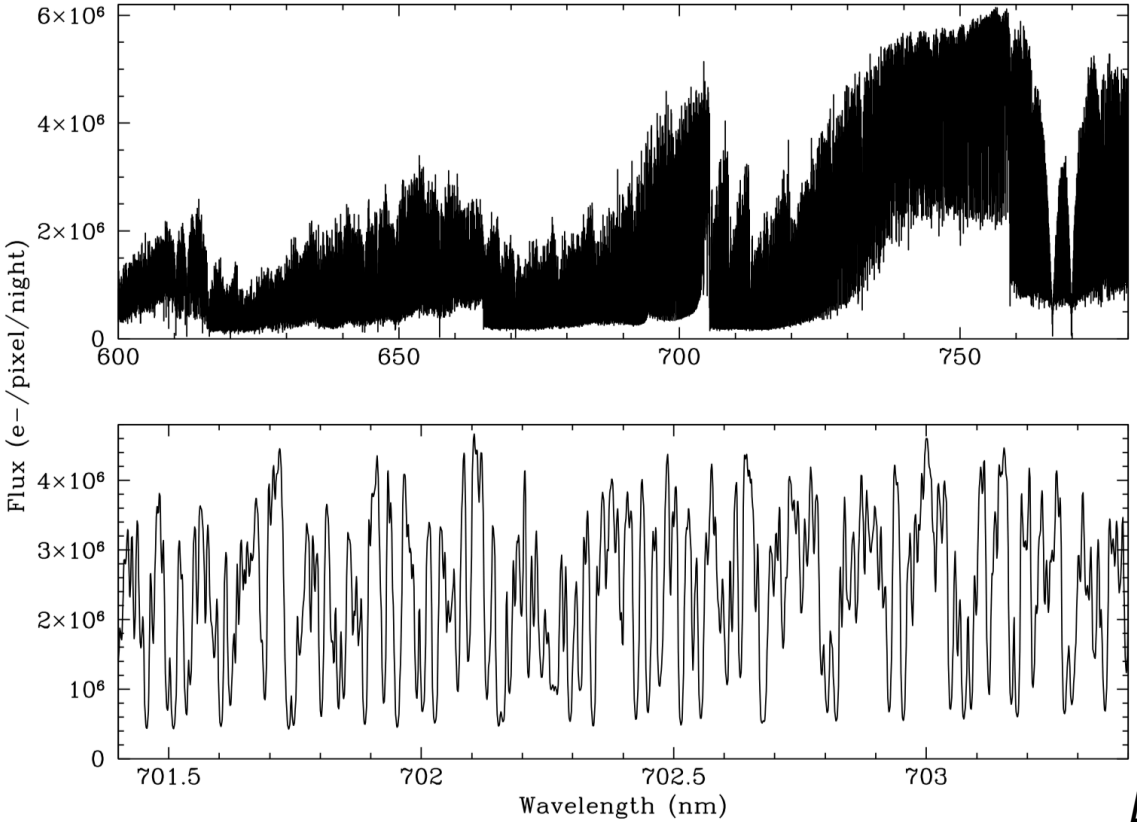
High-contrast High-resolution technique

Snellen et al. 2015

USING HIGH-RESOLUTION TO FURTHER REDUCE THE PLANET/STAR CONTRAST

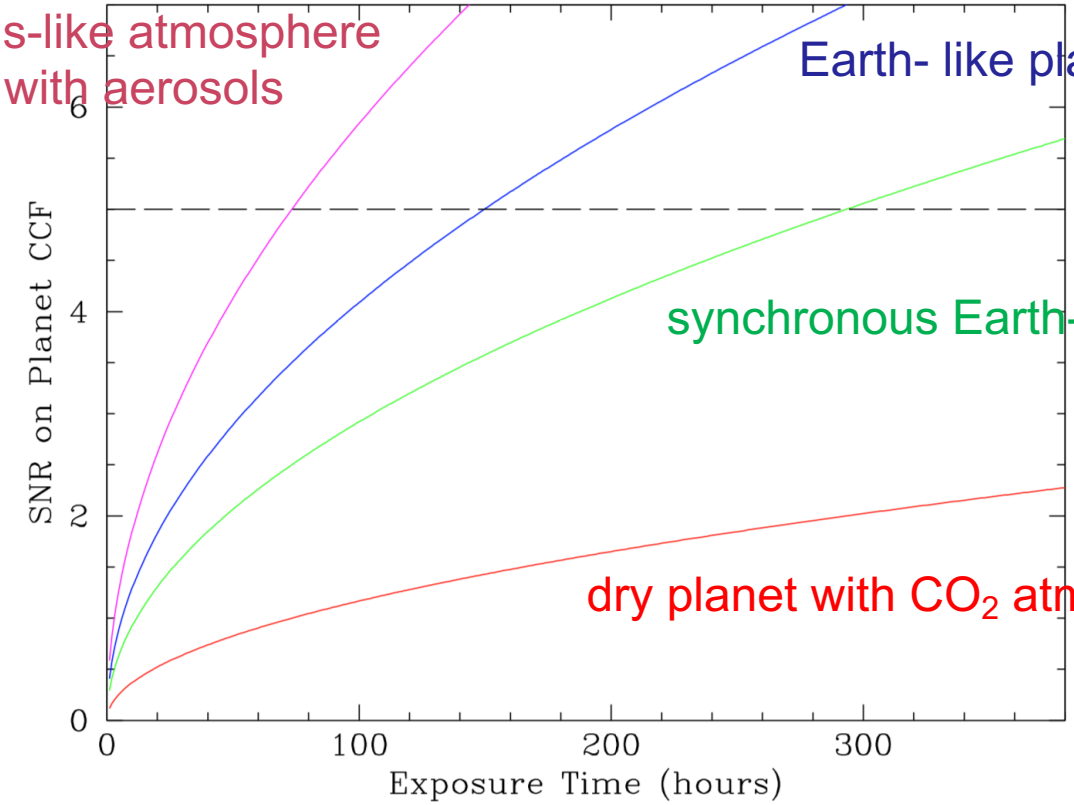


HIGH-RESOLUTION SPECTRA OF PROXIMA (the star) AND PROXIMA B



Lovis et al. 2017, A&A

DETECTABILITY OF PROXIMA B IN REFLECTED LIGHT



Lovis et al. 2017, A&A
Based on
Turbet et al. 2016, A&A