ハビタブル惑星はどこまで理解されてきたか？

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目次

1. Exoplanets

いっぱいexoplanetsは検出されている.

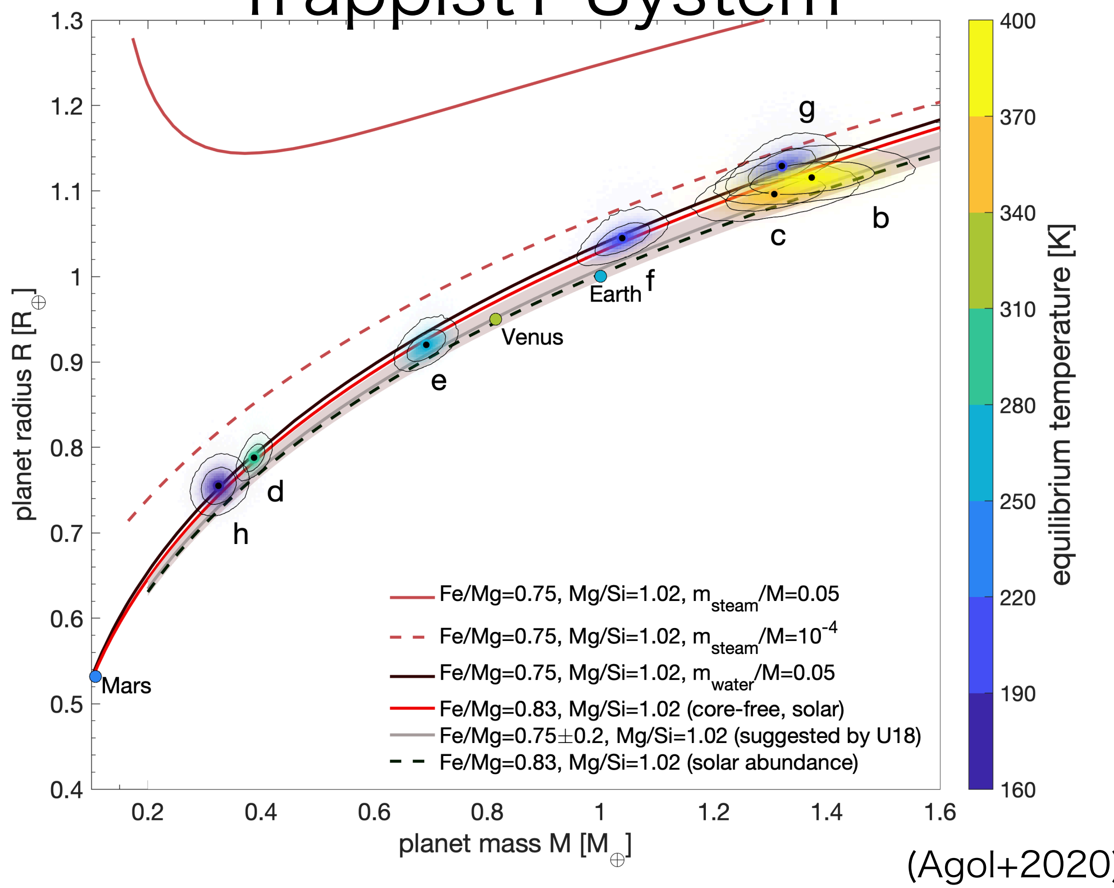
地球型と思われる
系外惑星も検出されている.

長期TTV観測より,
かなりいい精度で
Mass-Radius関係
がわかっている.

しかし、
大気&海は制約できない…

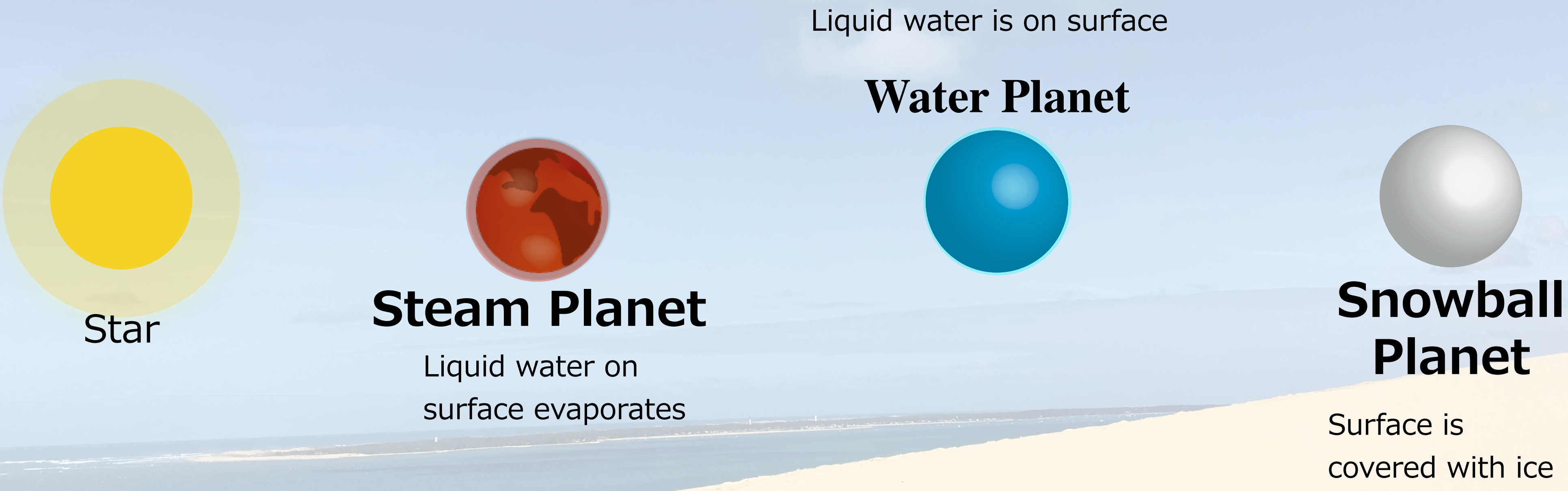
気候は？ハビタブルは？

Trappist1 System



(Agol+2020)

2. Classical Habitable Zone



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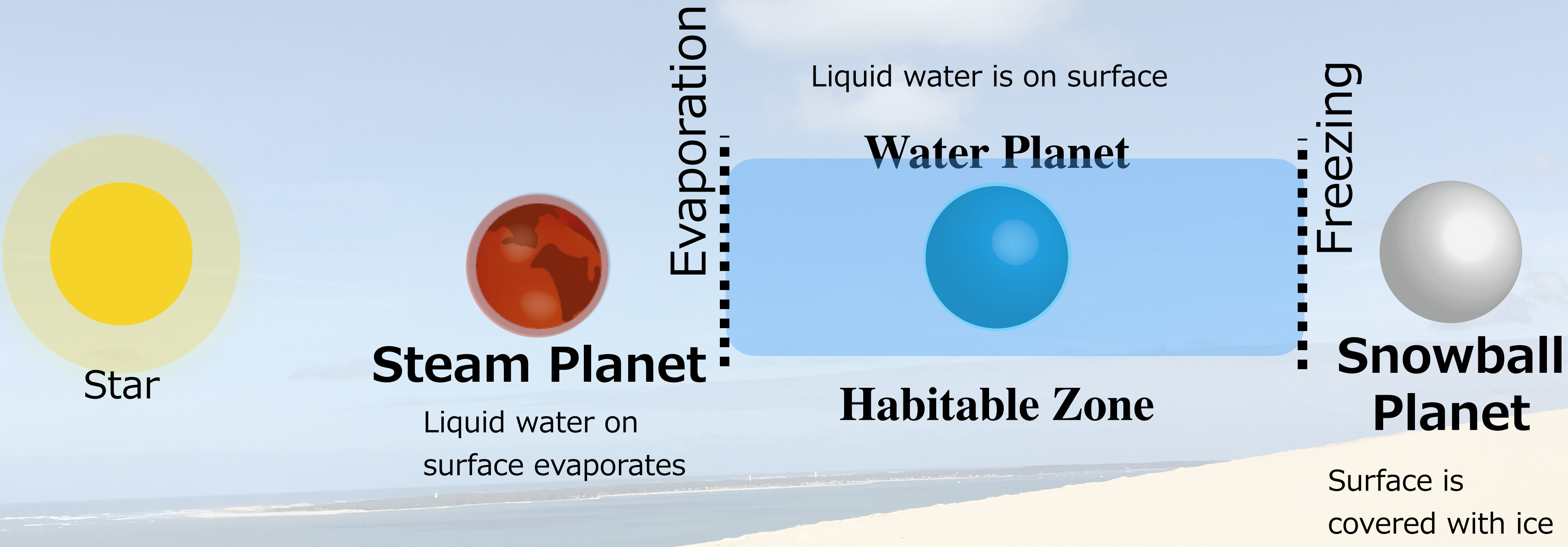


2. Classical Habitable Zone

- Inner edge of classical habitable zone

Runaway greenhouse **L**imit

The onset of the runaway greenhouse effect.

The **"instantaneous"** inner edge of HZ

Moist greenhouse **L**imit

A rapid water loss.

The inner edge of HZ for **long-term** evolution.

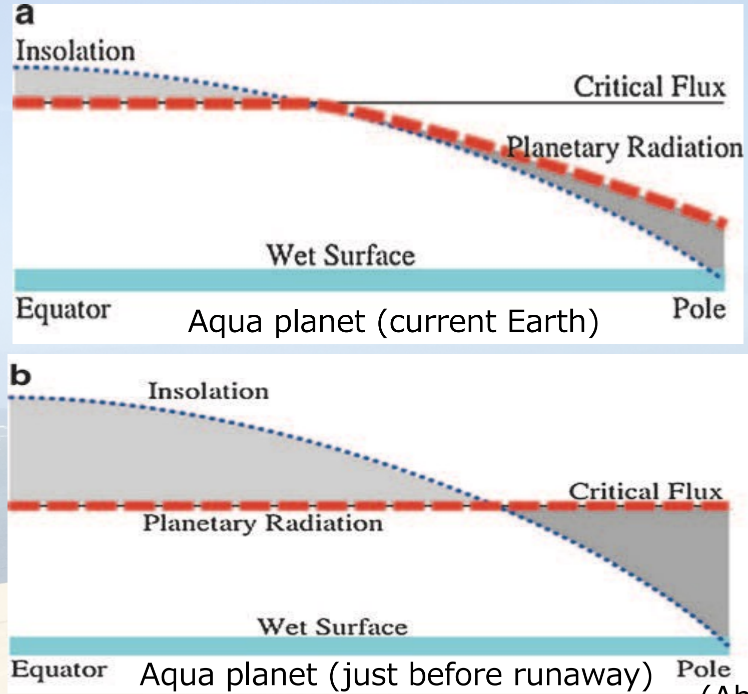
(Kasting+1993; Kopparapu+2013)

2. Classical Habitable Zone

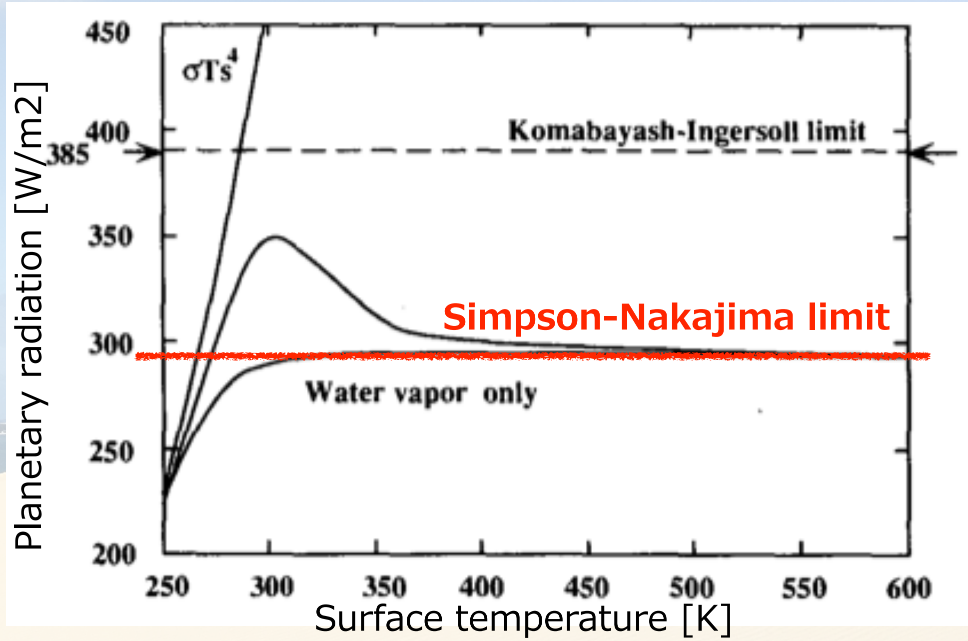
- Inner edge of classical habitable zone

The onset of the runaway greenhouse effect

When a planet with surface water receives insolation above a certain **critical value**, the planet is no longer able to maintain a thermal equilibrium state with surface liquid water.



(Abe+2011)



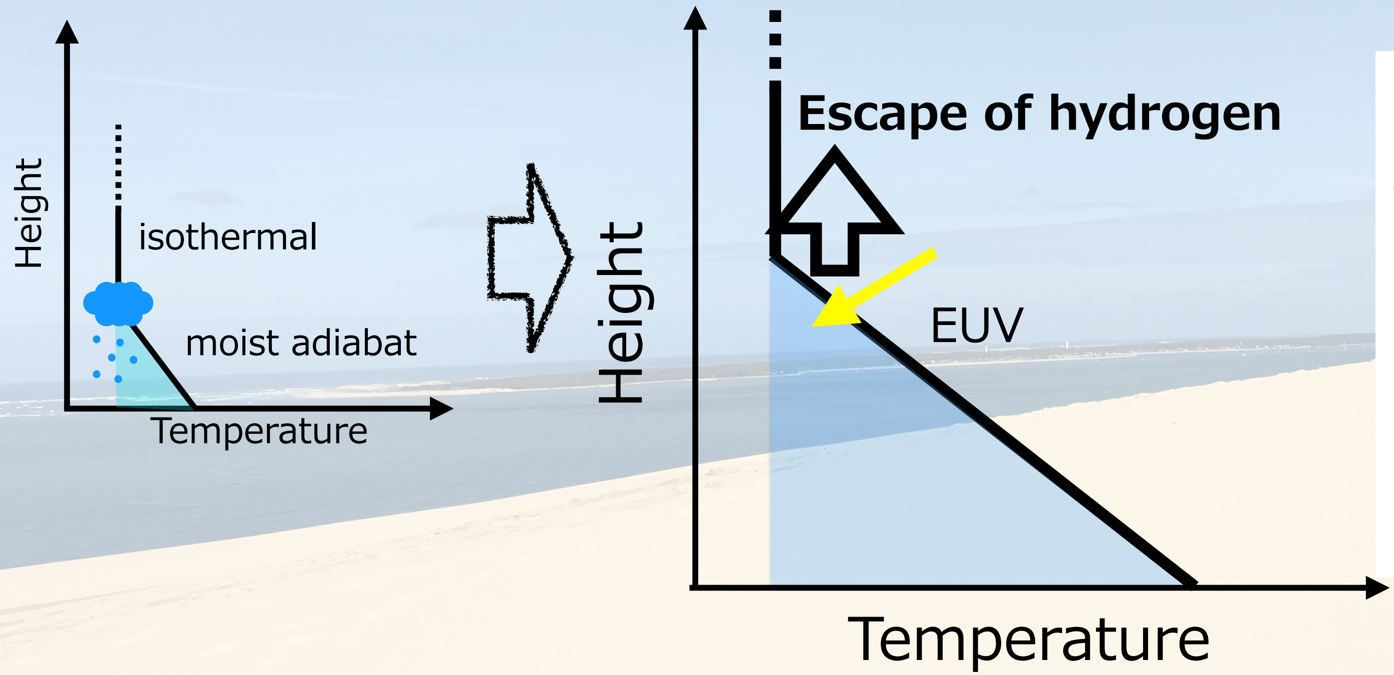
(Nakajima+1992)

2. Classical Habitable Zone

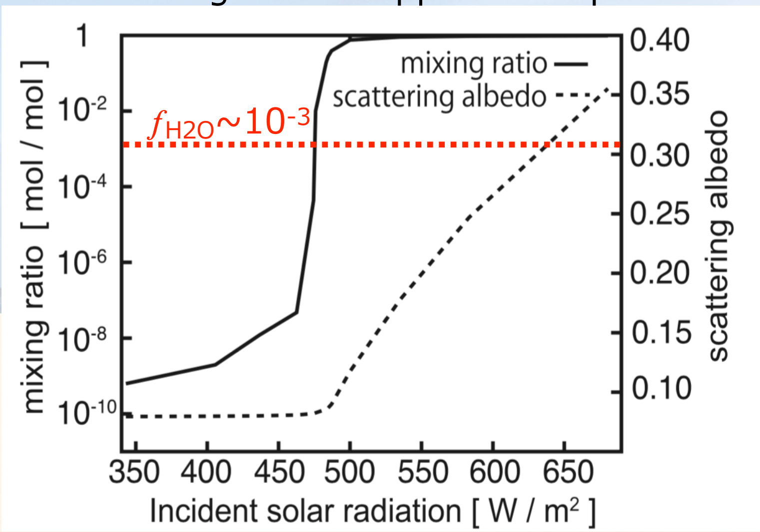
- Inner edge of classical habitable zone

The onset of the moist greenhouse effect

When the surface temperature is around 340 K due to high insolation, the cold trap disappears and f_{H2O} suddenly increases. High f_{H2O} leads to rapid water loss through diffusion-limited hydrodynamic escape.



H2O mixing ratio in upper atmosphere



(Kodama+2015)

2. Classical Habitable Zone

- Outer edge of classical habitable zone

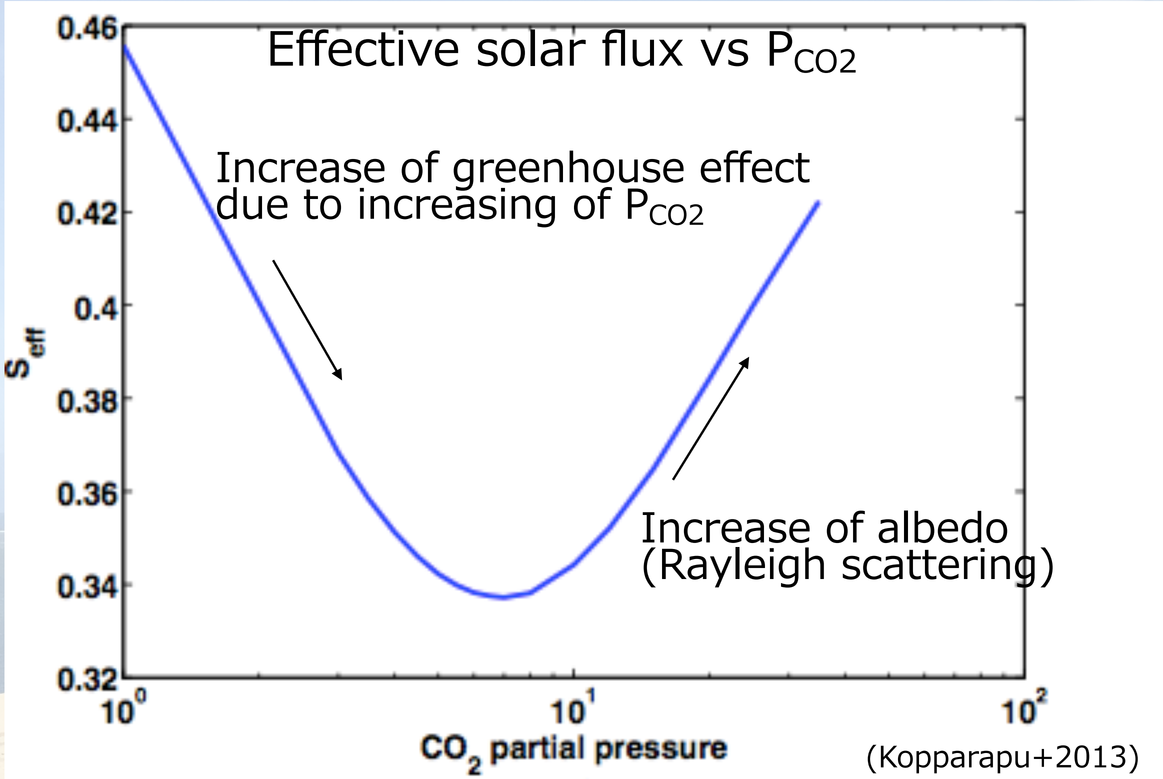
Maximum greenhouse

Planets avoid the snowball state due to the greenhouse effect of CO_2.

2. Classical Habitable Zone

・Outer edge of classical habitable zone

Maximum greenhouse effect of CO2



・no cloud

:1.7 [AU] (Kopparapu+2013)

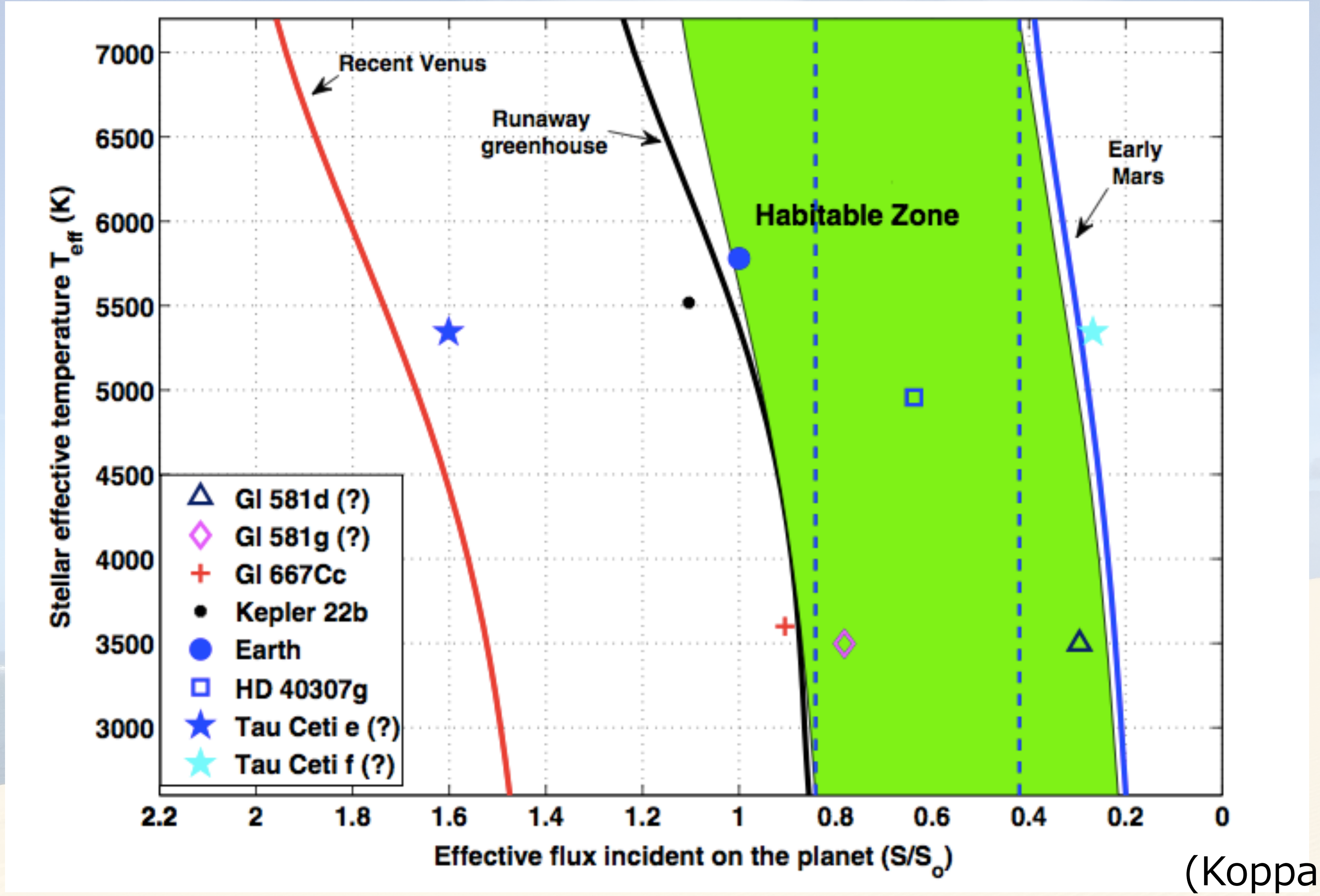
・with cloud

:1.37 - 2.4 [AU]

(Altitude, density, radius, distribution, etc)

(Mischana+2000)

2. Classical Habitable Zone



(Kopparapu+2013)

2. Classical Habitable Zone

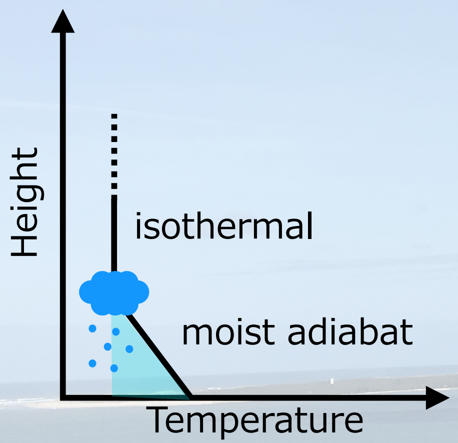
- Inner edge : **Runaway** or **Moist** greenhouse effect
- Outer edge : Maximum greenhouse effect of CO2

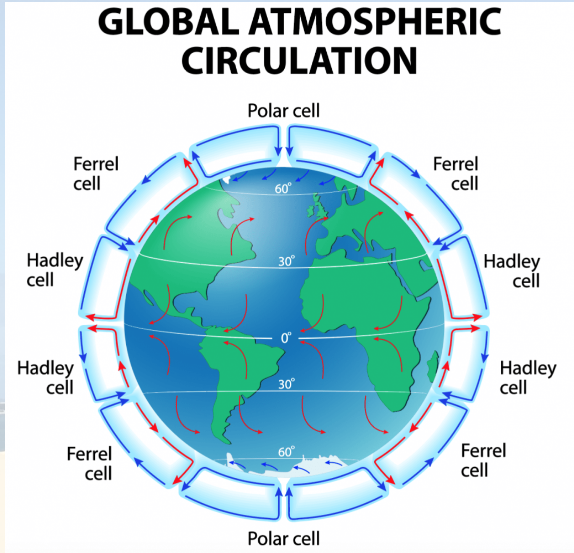
	Inner edge		Outer edge
	Runaway Greenhouse	Moist Greenhouse	Maximum Greenhouse
Kasting+1993	0.84 [AU]	0.95 [AU]	1.67 [AU]
Kopparapu+2013	0.97 [AU]	0.99 [AU]	1.70 [AU]

Assumptions: 1D climate, Earth-based boundary conditions

3.1 Habitable Climate Around G stars

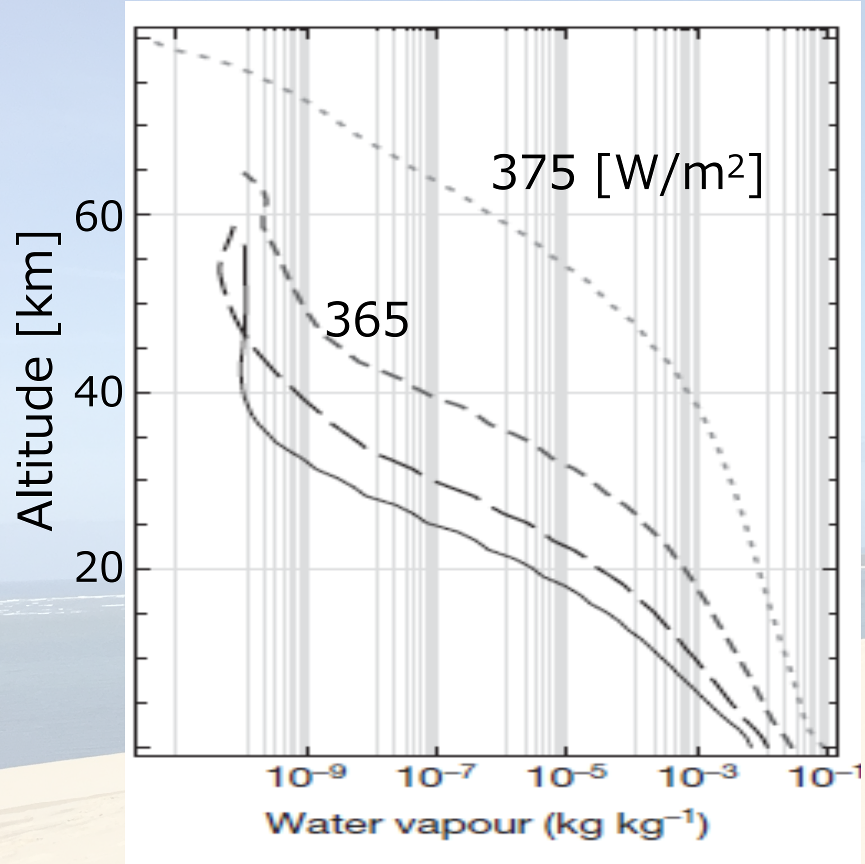
1D climate models -> 3D Global Climate Models (GCMs)
(Global average) (Distribution, ununiformity, etc.)

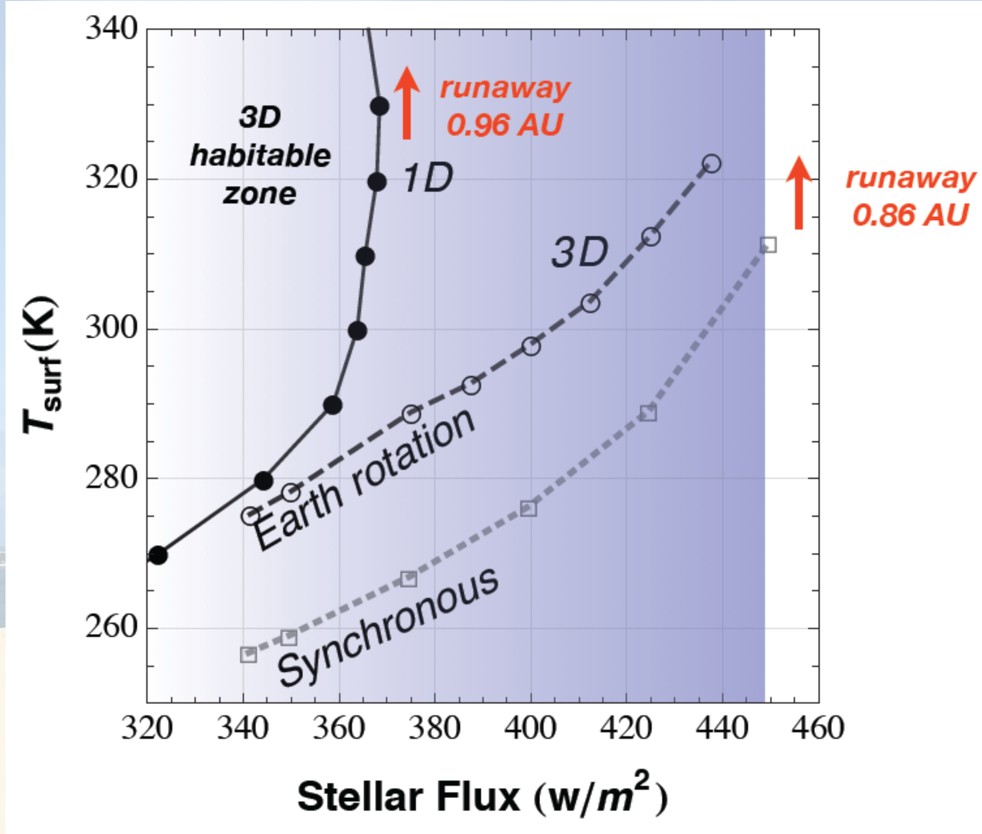




3.1 Habitable Climate Around G stars

- Inner edge of habitable zone





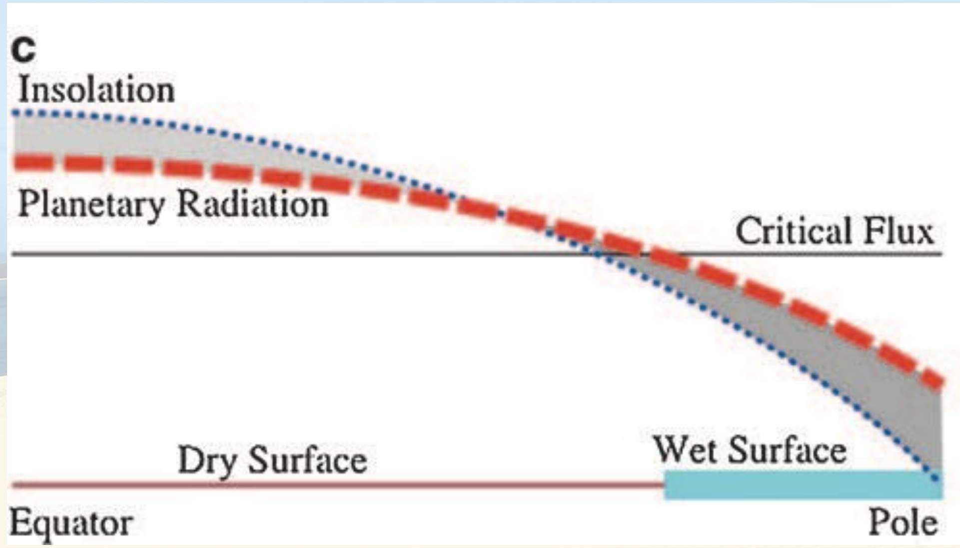
(Leconte+2013)

3.1 Habitable Climate Around G stars

・Inner edge of habitable zone

We focus on the surface water distribution.

Land planets which have small amount of water on their surface can maintain habitable climate even they receive a stronger insolation than the critical limit for aqua planets.



3.1 Habitable Climate Around G stars

Outline of GCM

- CCSR / NISE AGCM 5.4g

32(lat)×64(lon) horizontal grids, 20 vertical layers(σ level)

Dynamics : Primitive equation

Physics : Radiative transfer : 2-stream k-distribution scheme with 37 subchannels (Nakajima&Tanaka, 1986)

Cumulus convection (Arakawa&Shubert, 1974)

Large scale condensation (Le Treut&Li, 1991)

Setting

eccentricity=0, obliquity=0, rotation velocity=Earth

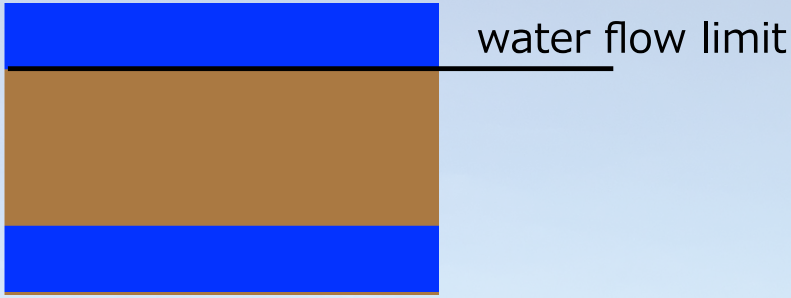
background atmosphere(air, 1bar), no ozone,

flat surface, surface albedo without snow=0.3, heat capacity =desert

3.1 Habitable Climate Around G stars

Surface water distributions

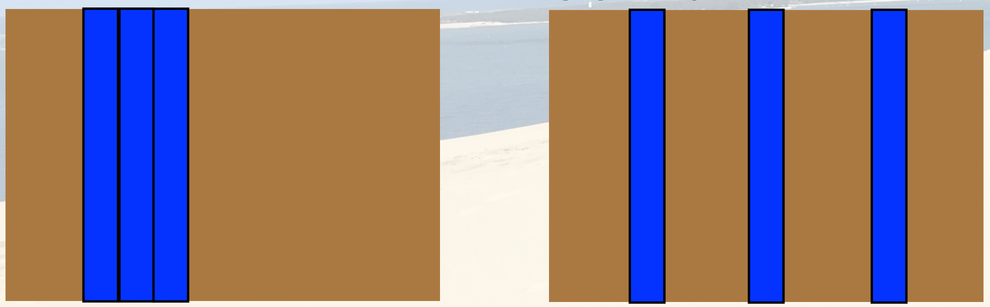
(a) Zonally uniformed water distributions



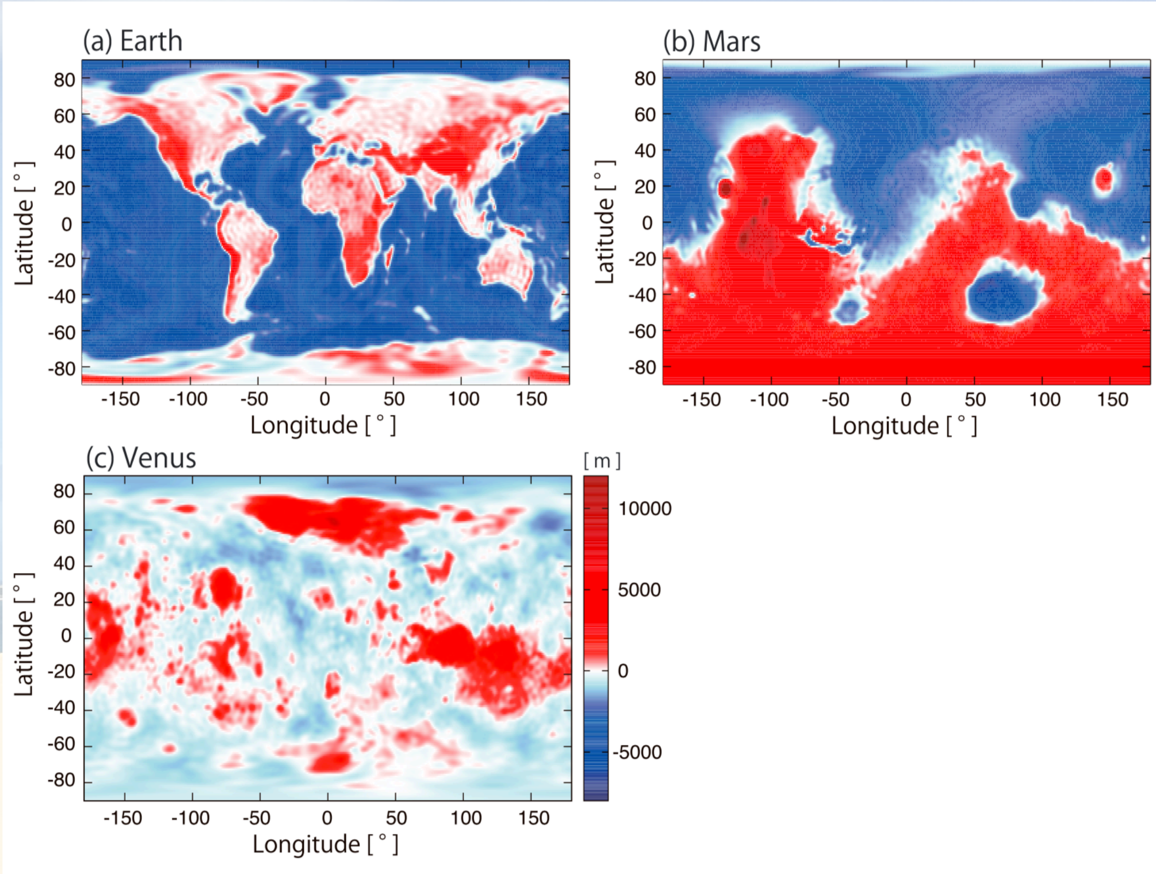
(b) Meridionally uniformed water distributions

(1) Concentrated case

(2) Dispersed case



(c) Terrestrial planetary topographies

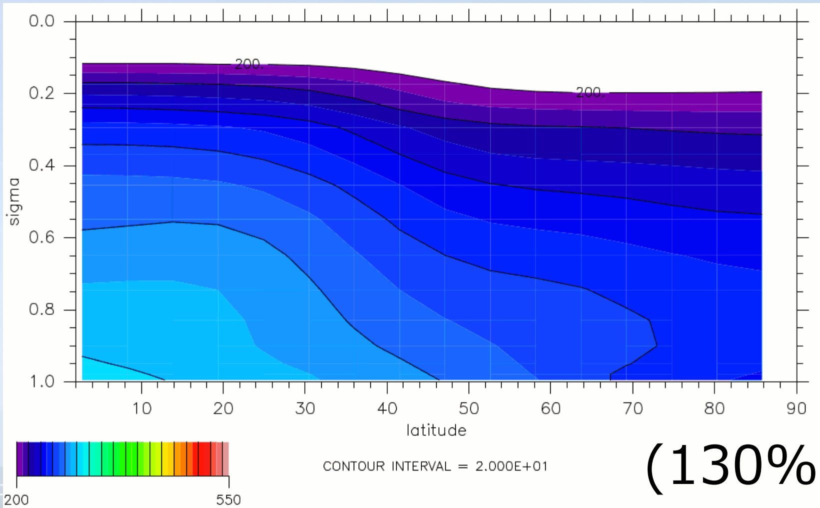


3.1 Habitable Climate Around G stars

Climates at inner edge of the Habitable zone

Aqua planet

Temperature
(water flow limit = 0º)

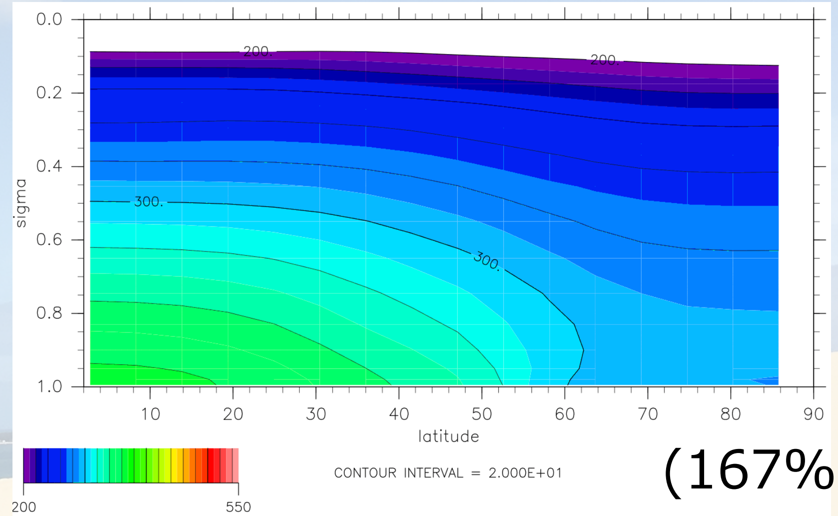


(130%S_0)

- It can maintain stable climate until 129%.
- The onset of the runaway greenhouse occurs at 130%S_0.

Land planet

Temperature
(water flow limit = 58º)

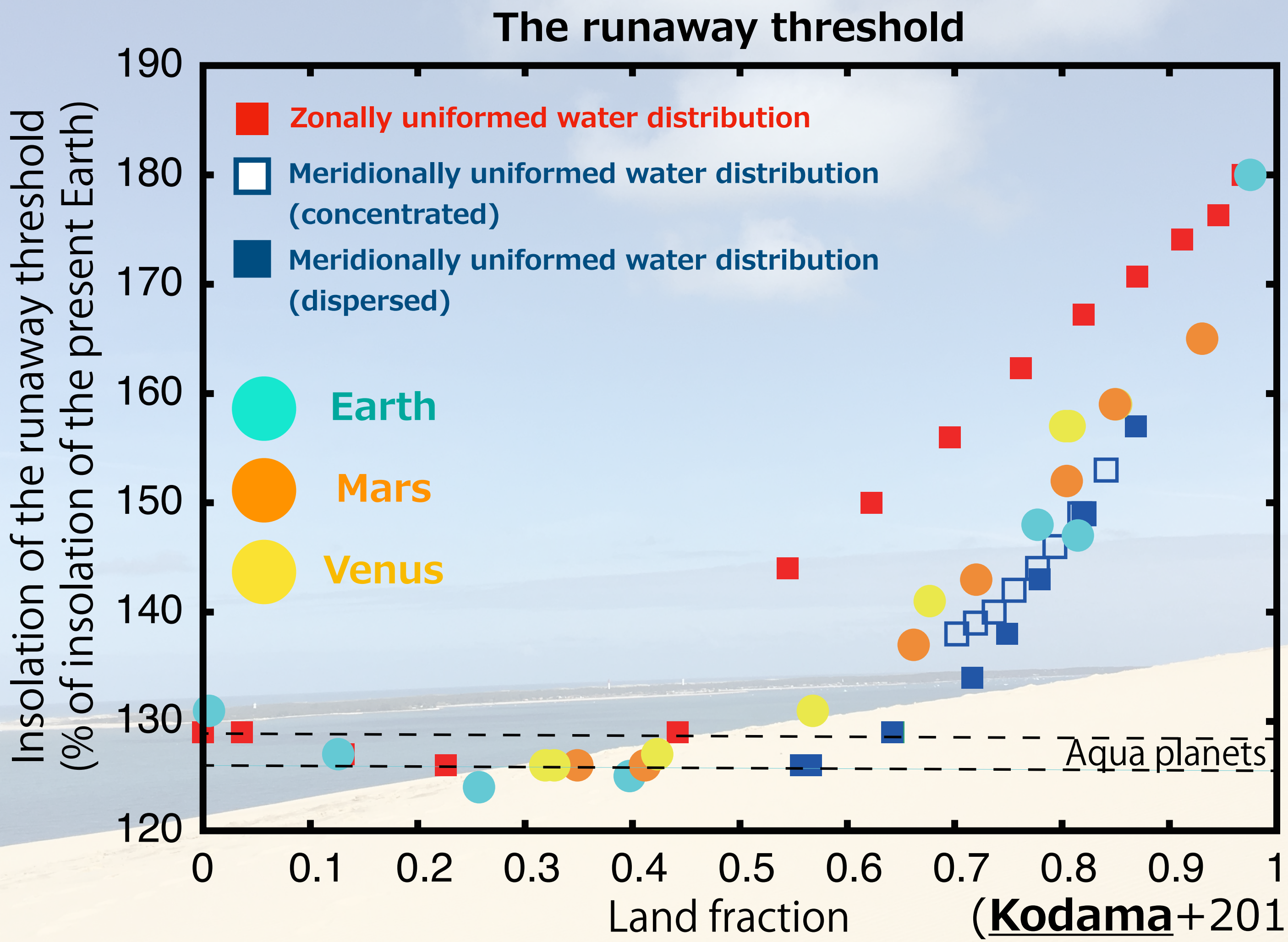


(167%S_0)

- It can maintain stable climate until 167%.

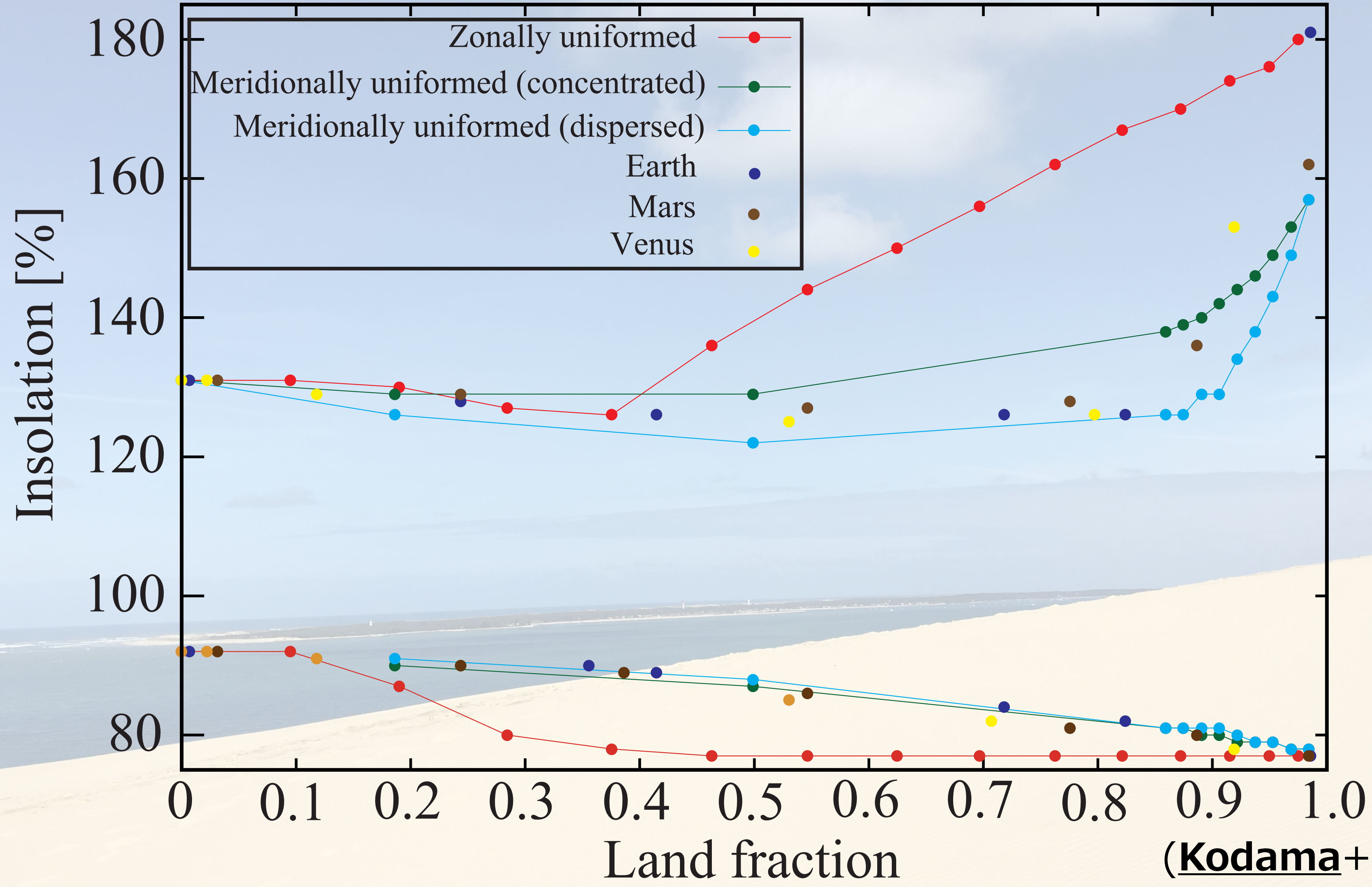
(S_0: the present Earth’s insolation)

3.1 Habitable Climate Around G stars



(**Kodama**+2019)

3.1 Habitable Climate Around G stars



(**Kodama**+, in prep)

3.1 Habitable Climate Around G stars

Atmospheric circulation & Climateは、他のパラメタでどう変化する？

Rotation Period, Surface Pressure, Incident Stellar Flux, Planetary Radius, Surface Gravity, Effective Liquid Cloud Particle Size

(正直、まだきちんと整理されていません。徐々に始りましたが、Habitable Zoneへの影響はこれからの課題です。計算機時間とか。)

- Exo CAM —Komacek & Abbot (2019)

Finite-volume dynamical core

Correlated-k method
(HITRAN 2012)

Sub-grid parameterization
for Cloud & for convection

Incident stellar spectrum
Sun, BT-Settle for M dwarf

Horizontal Resolution: 4^{o} x 5^{o}

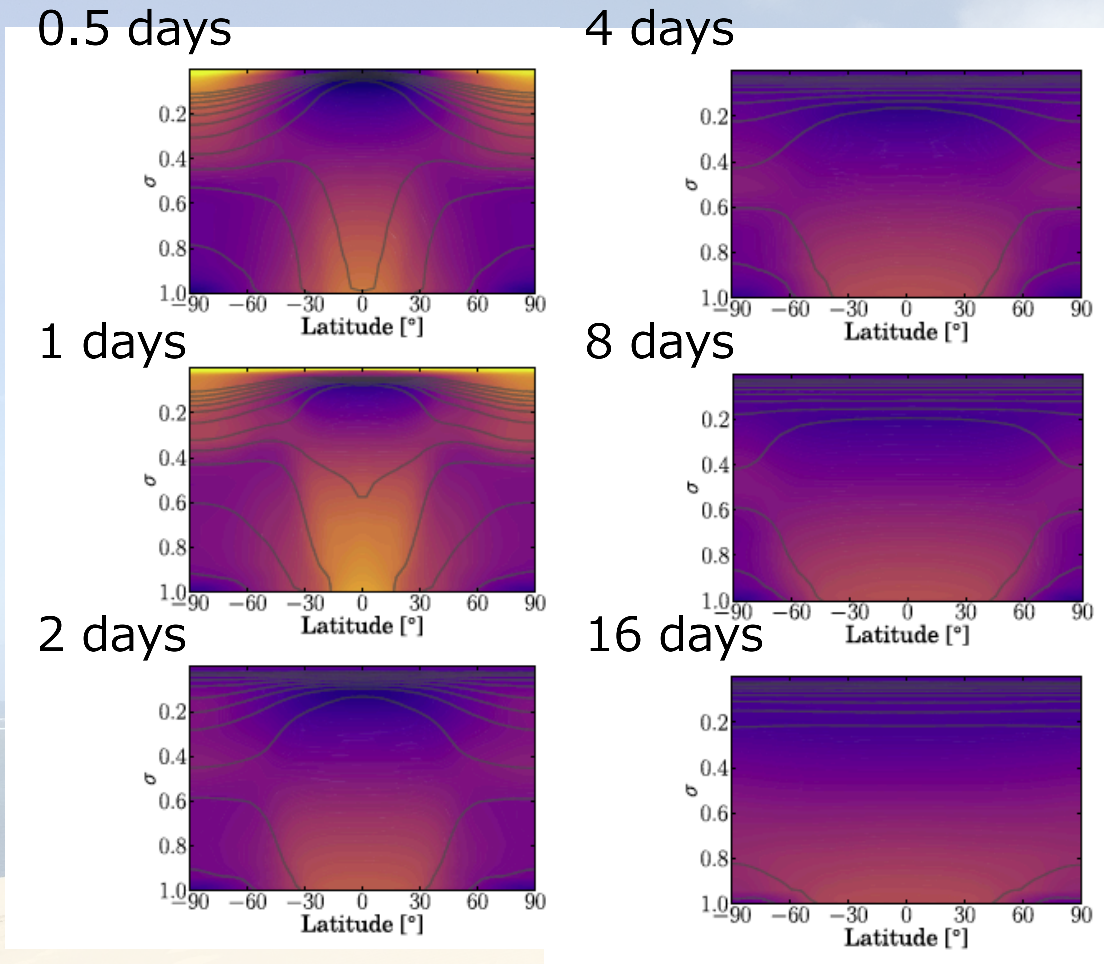
Vertical Level: 40

N_2 & H_2O atmosphere

Zero Obliquity & Zero Eccentricity

3.1 Habitable Climate Around G stars

[Rotation Period]



Rotation periodを増やすと、the equator-to-pole temp. diff.が減少する.

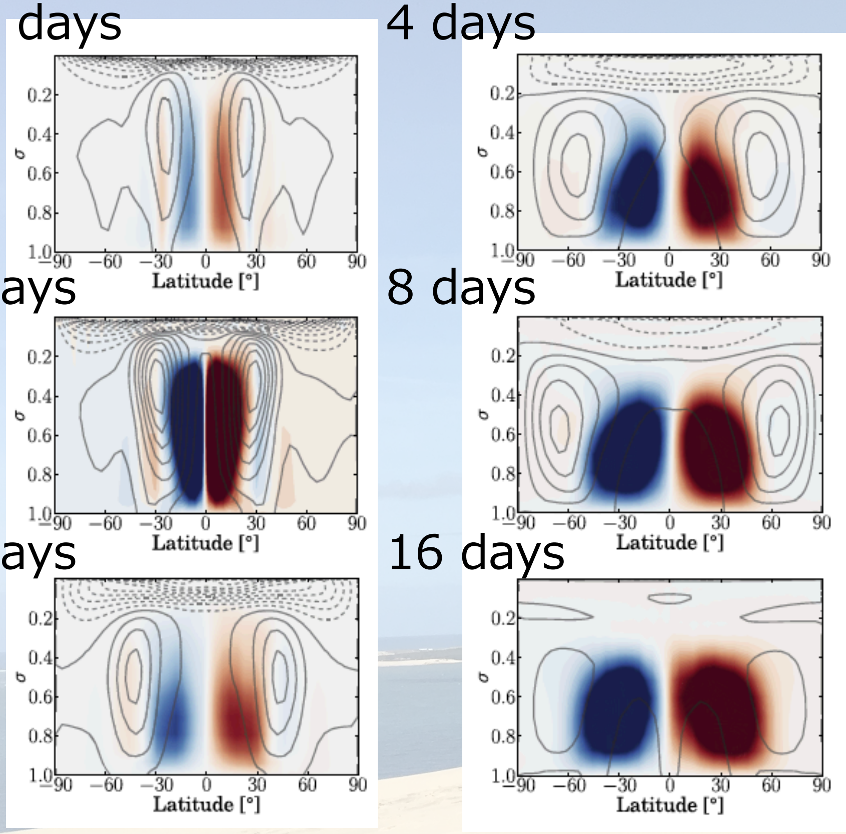
<- Eddy length scaleの増大.

->効果的に熱を運ぶ.

3.1 Habitable Climate Around G stars

[Rotation Period]

0.5 days　4 days　1 days　8 days　2 days　16 days



Rotation periodを増やすと、Hadley cellのexpansion.

-> The peak zonal wind speedがhigher latitudeに移動する.

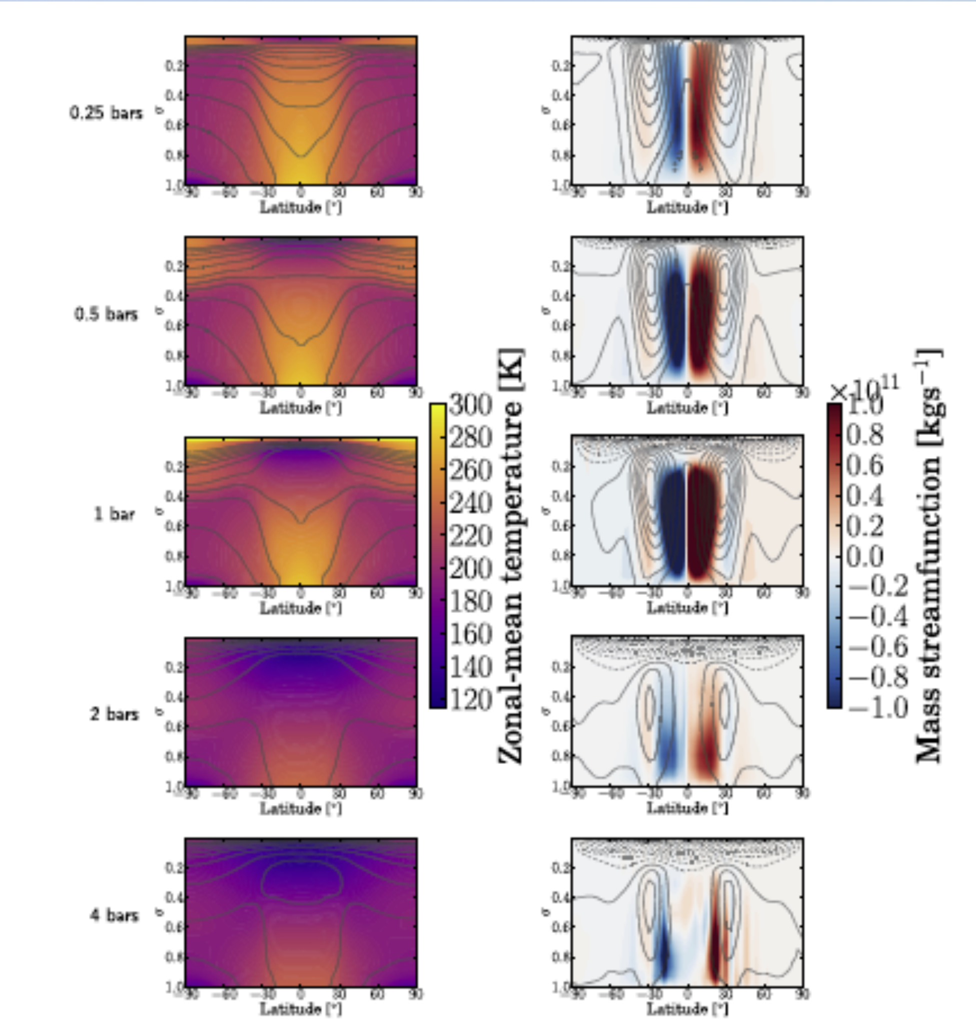
Subtropical jet speed
『Hadley cellのpoleward-moving airのangular momentumの増大』vs『Hadley cellのnarrowing』

For slowly rotating planets,
the angular-momentum-conserving jet speedは slower.

For fast rotating planets,
jet speedはeddyにより抑制され、angular-momentum-conserving limitより弱くなる.

3.1 Habitable Climate Around G stars

[Surface Pressure]



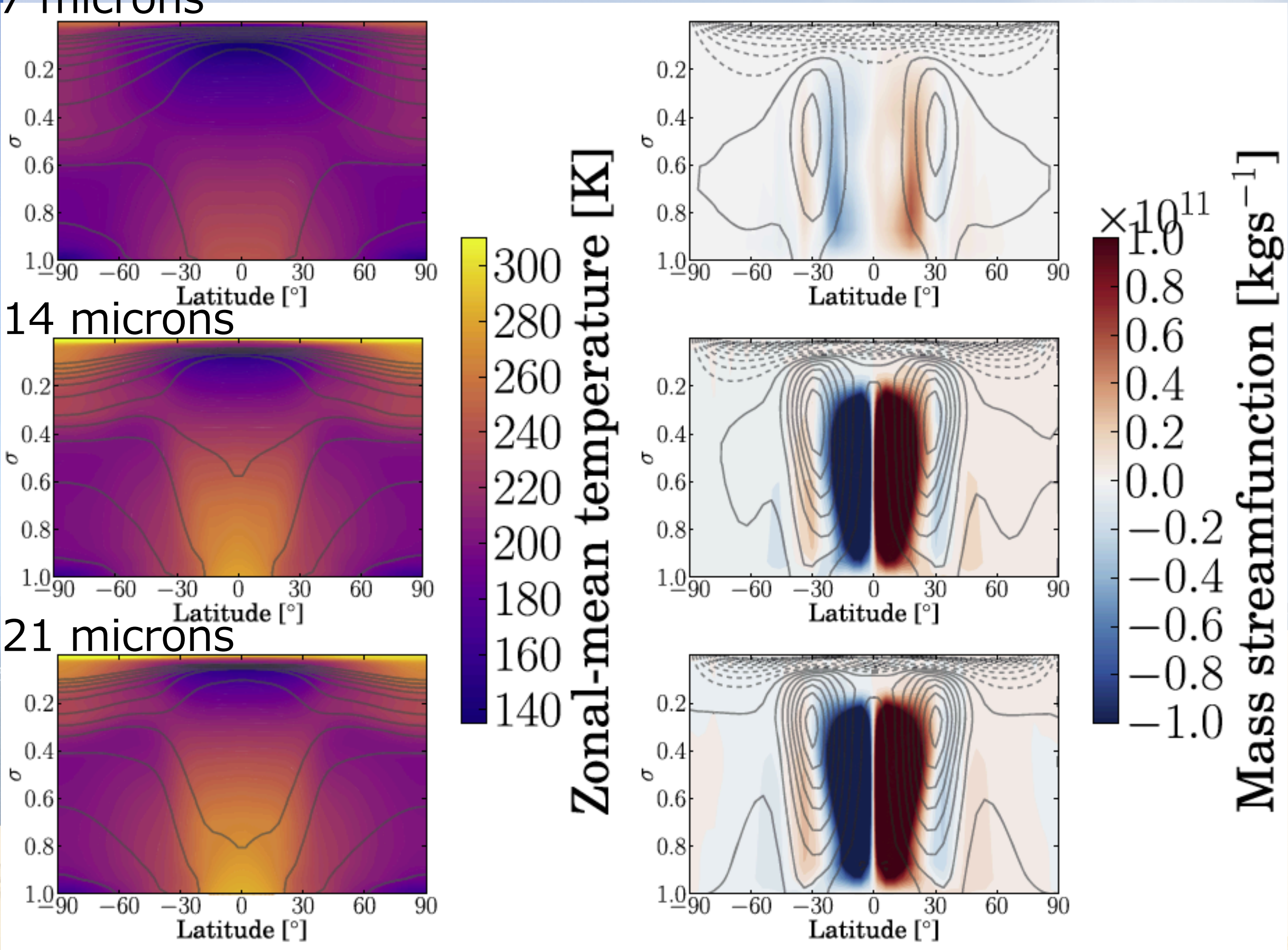
・0.25-1barの場合, Hadley cell strengthが増大.

・2bars以上の場合, cold.
  <- N2のRayleigh scattering

・2&4bars以上の場合, snowball
-> greatly reduced Hadley cell strength

3.1 Habitable Climate Around G stars

[Liquid Cloud Particle Size]



14->7microns

・reduced Hadley cell strength & subtropical jet speed.

-> ~19K cooler

(scatter incident stellar flux)

14->21microns

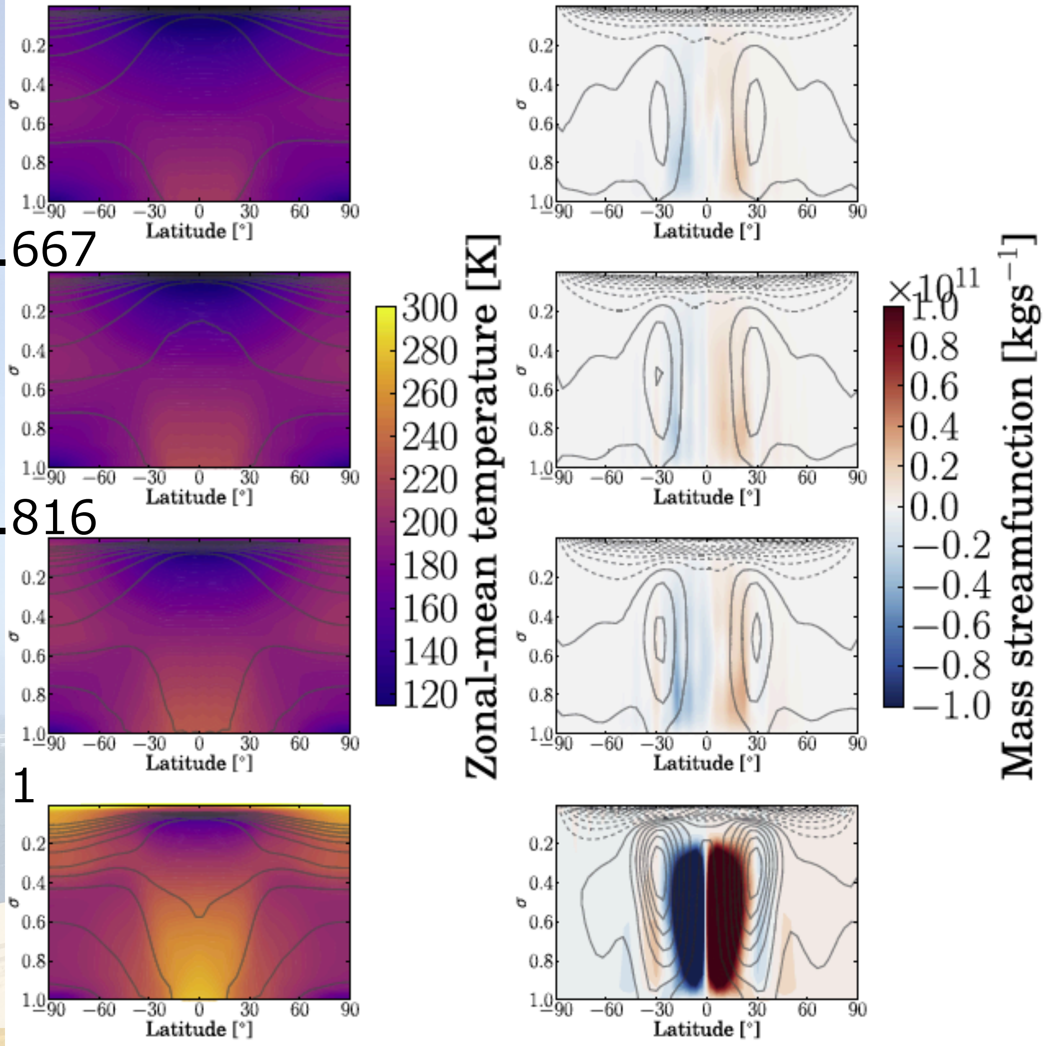
・stronger Hadley circulation & subtropical jet speed.

->a larger equator-to-pole temperature contrast.

~7.5K warmer

3.1 Habitable Climate Around G stars

0.544 x Earth Flux [Incident Stellar Flux]



Incident fluxの増大

-> mass stream function とpeak zonal wind speedの増大

-> surface temp. がsharplyに増大.

subtropical jetがmaximumになるpressureが減少.

3.1 Habitable Climate Around G stars

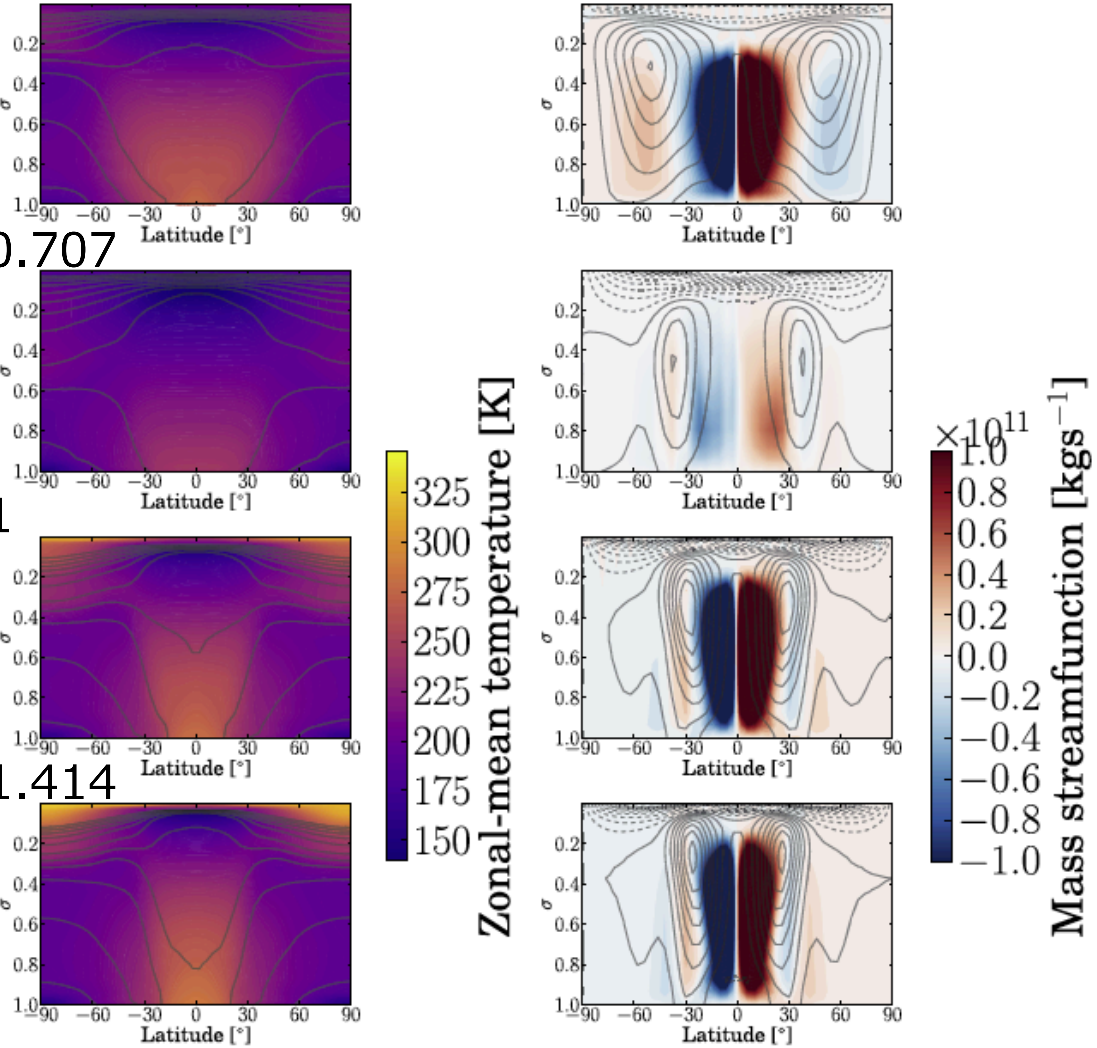
[Planetary Radius]

0.5 x Earth Radii

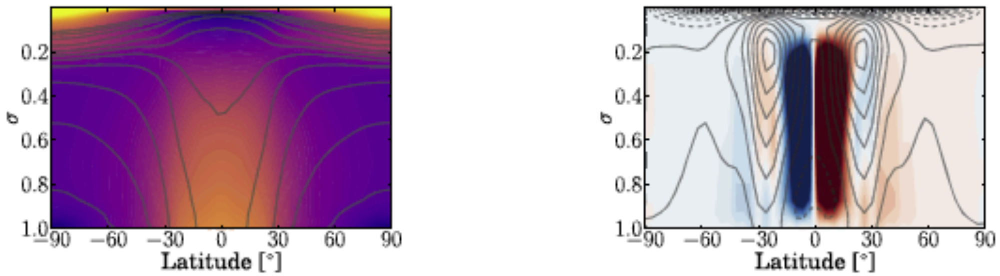
0.707

1

1.414



2 x Earth Radii

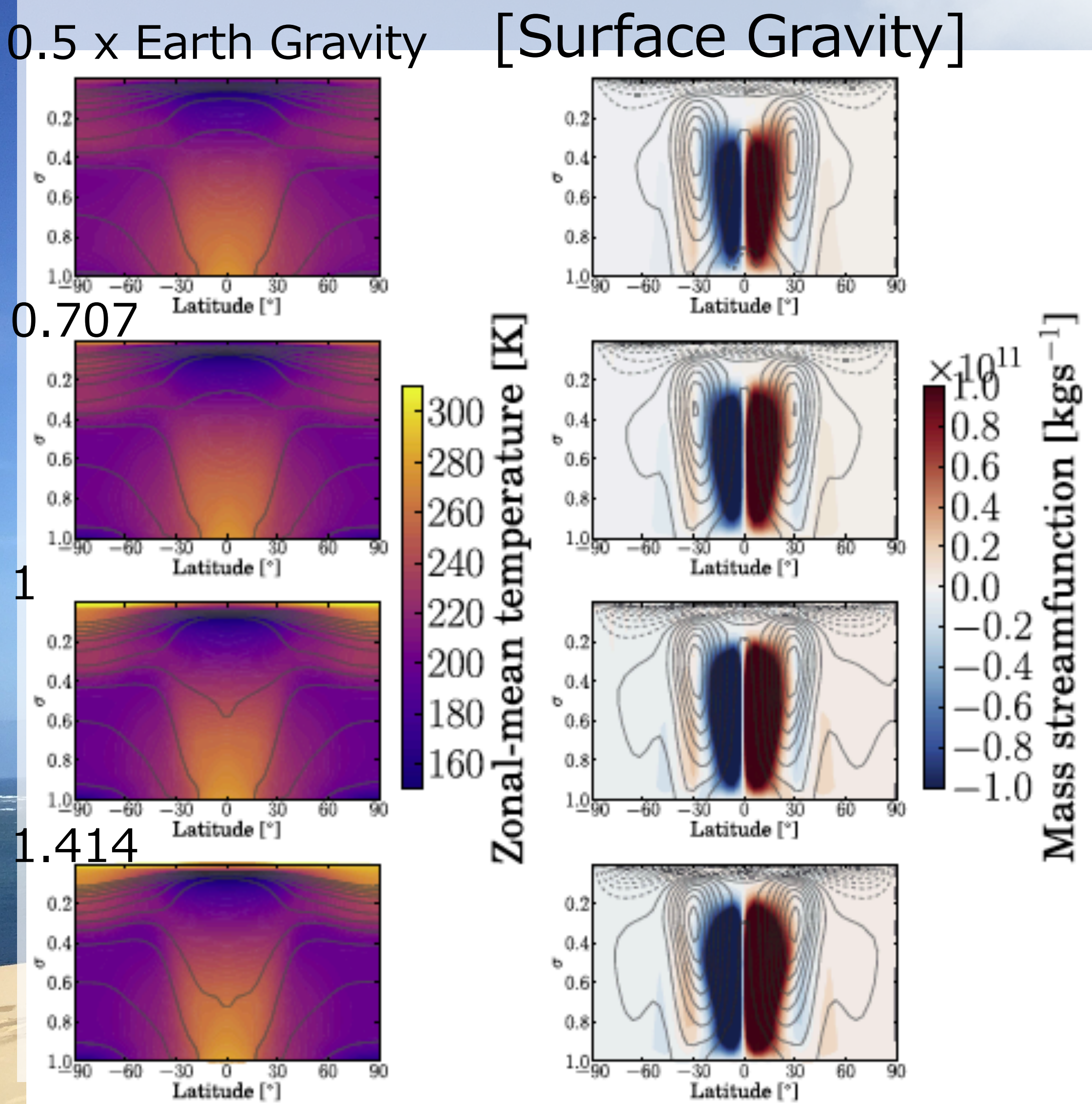


Hadley cellが狭くなり,
more equatorwardになる.

0.707RでHadley cell & subtropical jetのreduction.
subtropical jetが60°->30°のtransition.

reduced eddy length scale
-> equator-to-pole heat transport の減少->enhanced eq.-to-pole temp.

3.1 Habitable Climate Around G stars



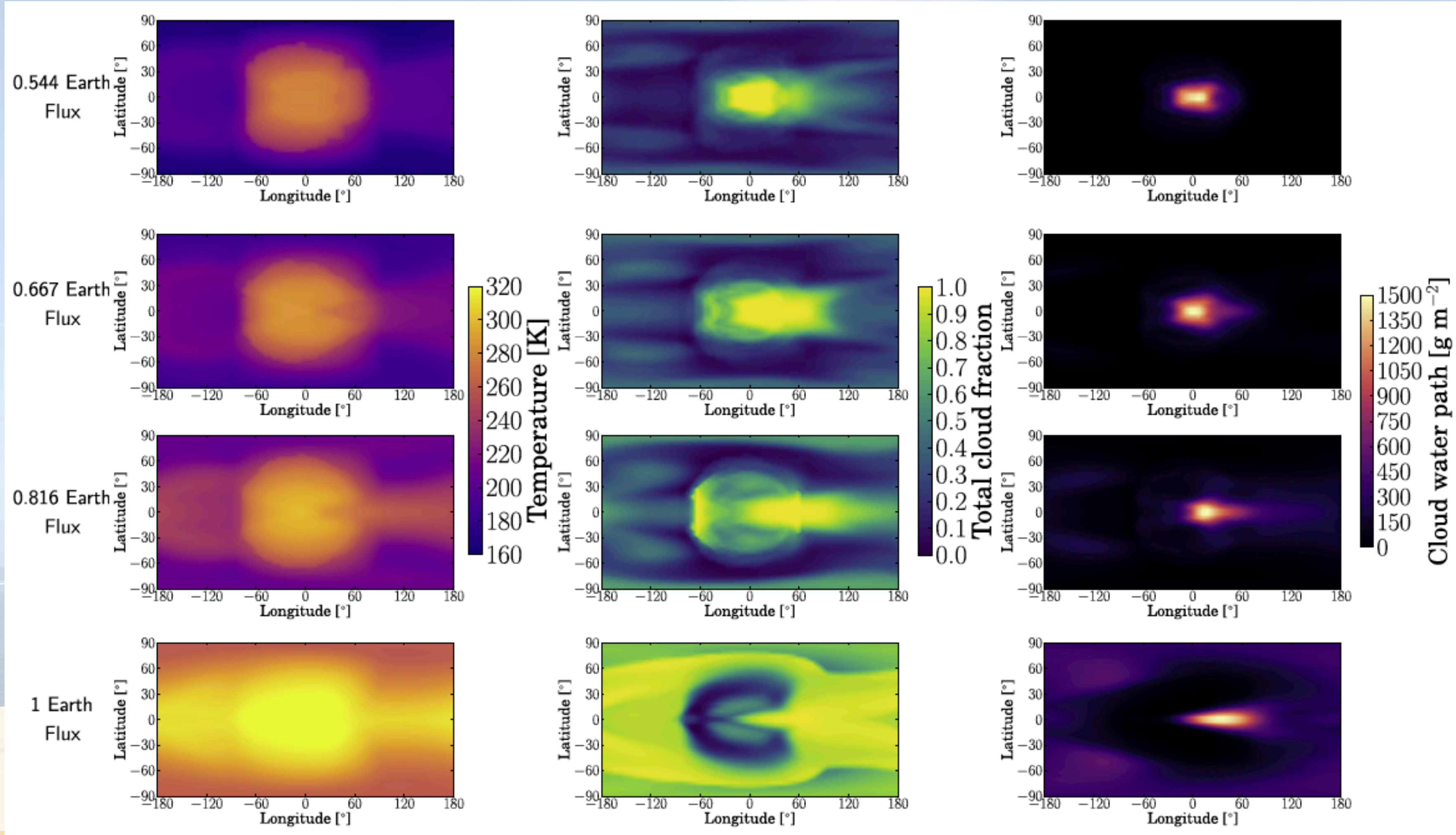
(Surface gravityをfixedしているので、atmospheric massが変化している)

Surface gravityの増大
-> equator-to-pole temp. contrast が増大する.

Larger surface gravityの惑星は、stronger Hadley cells & stronger subtropical jetsを持つ.

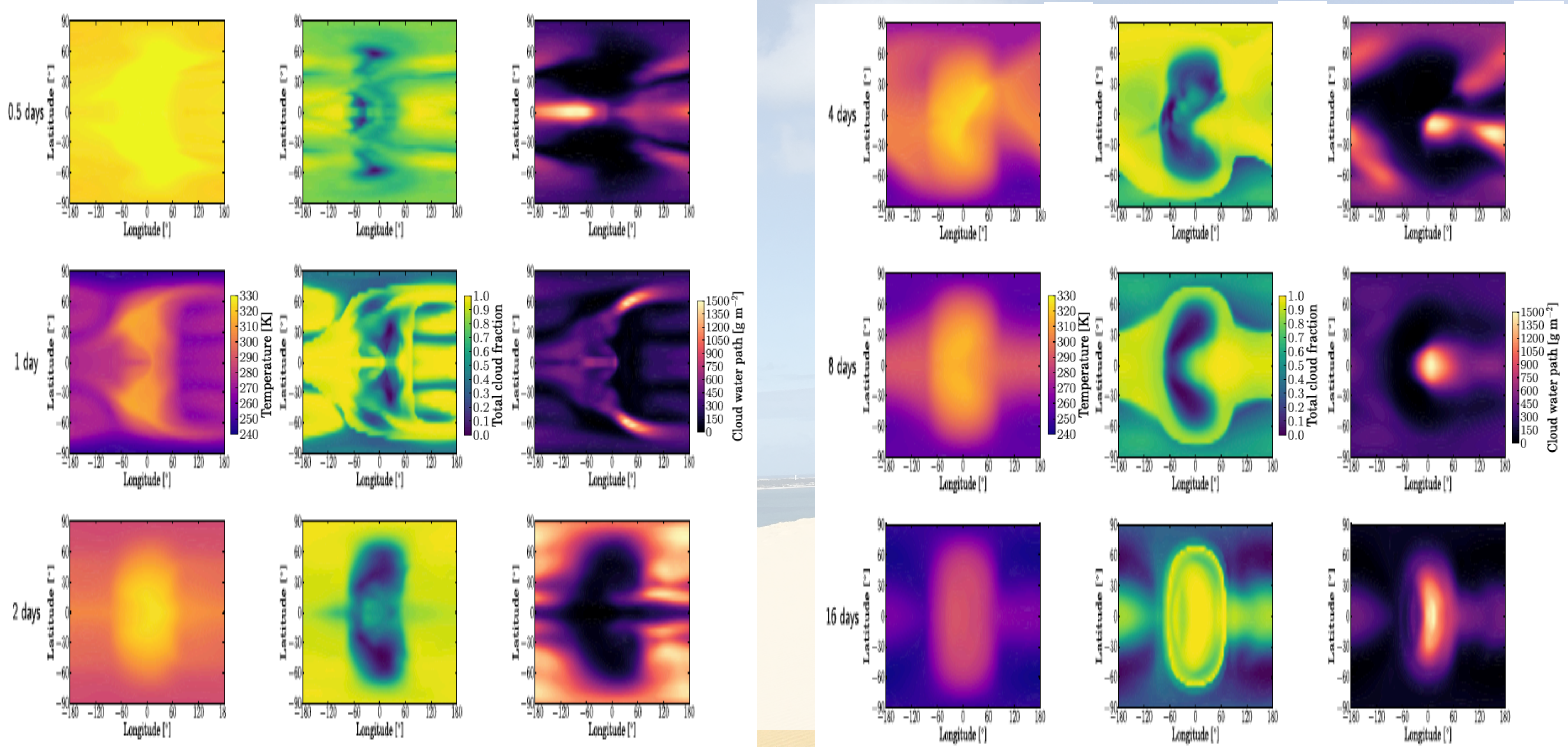
3.2 Habitable Climate Around M stars

[late-type M dwarfs(2700K)]



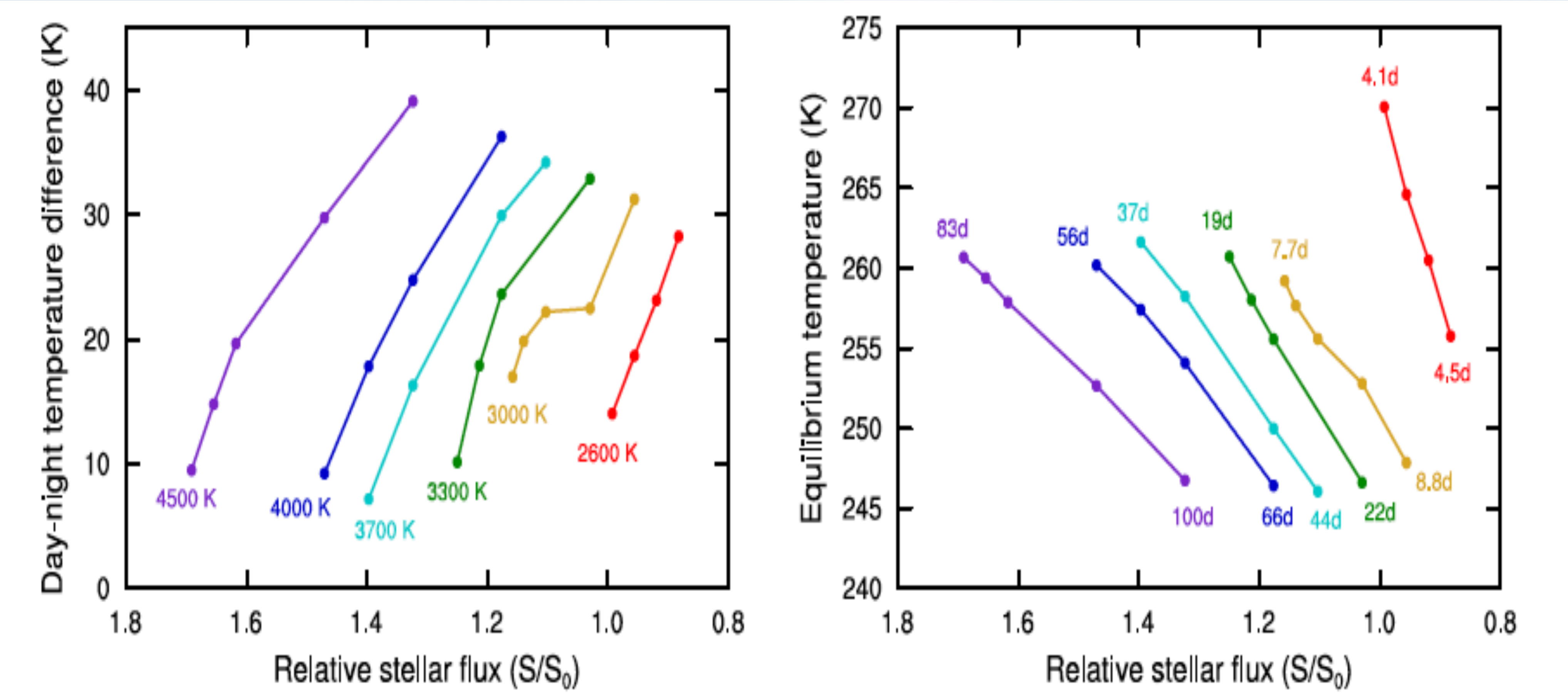
3.2 Habitable Climate Around M stars

[late-type M dwarfs(2700K), incident stellar flux=1]



3.2 Habitable Climate Around M stars

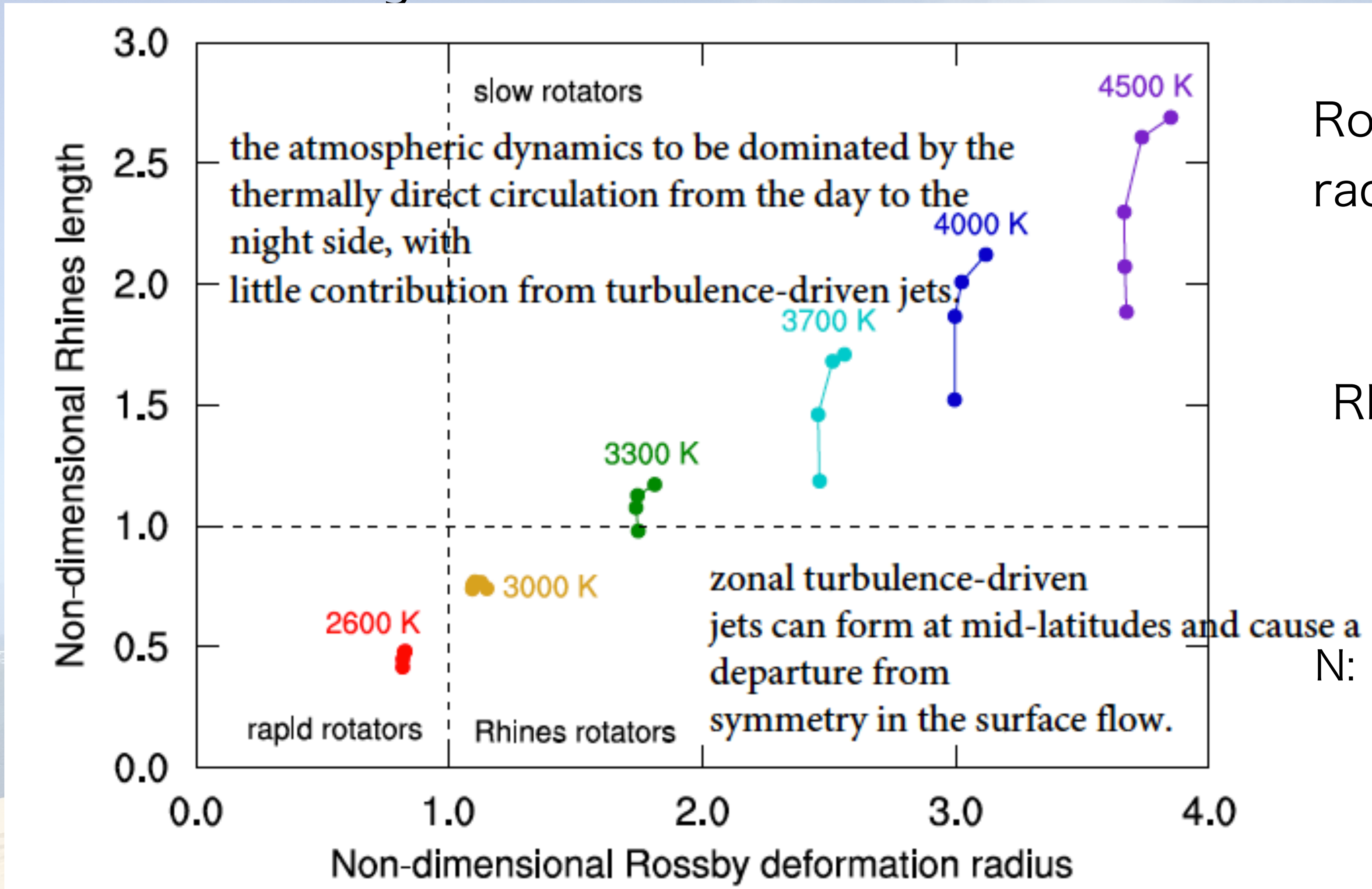
Inner Edge of the Habitable Zones around late-type M dwarfs



(Haqq-Misra+2018)

3.2 Habitable Climate Around M stars

Inner Edge of the Habitable Zones around late-type M dwarfs



Rossby deformation radius

$$\lambda_R{}^2 = \frac{NH}{2\beta}$$

Rhines length

$$L_R = \pi\sqrt{\frac{U}{\beta}}$$

N: ブラント・バイサラ振動数

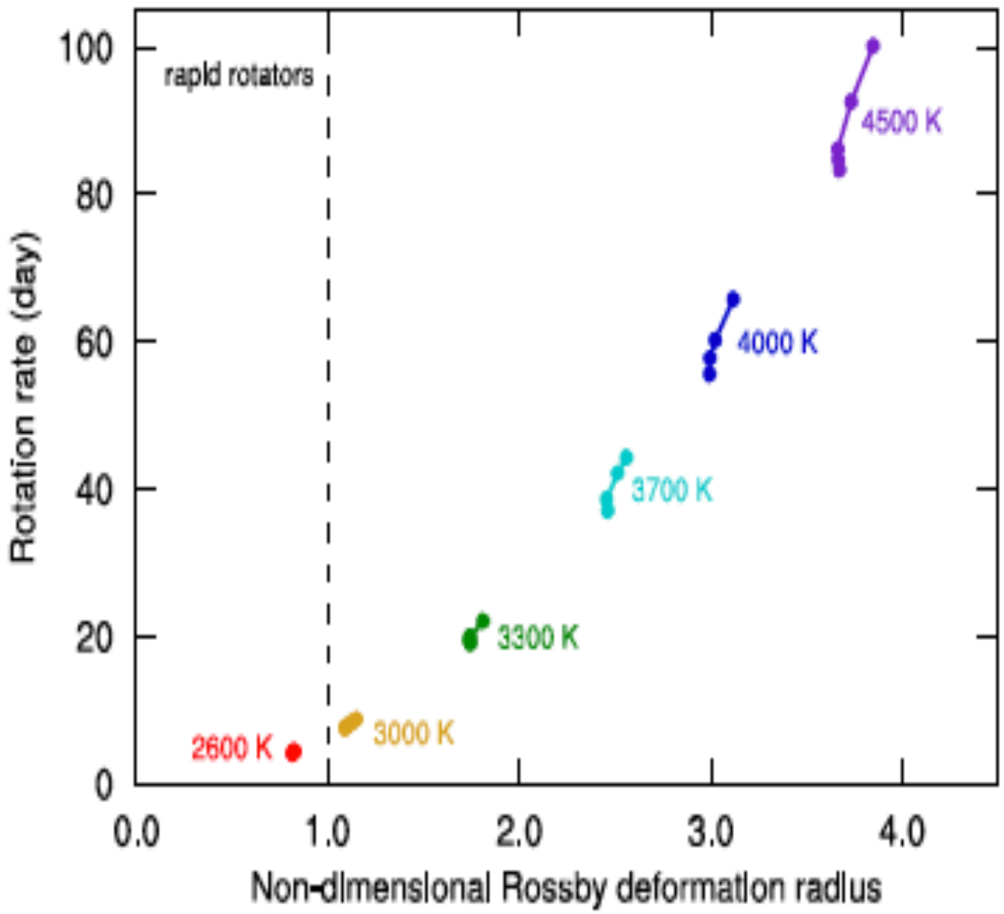
U: 風速

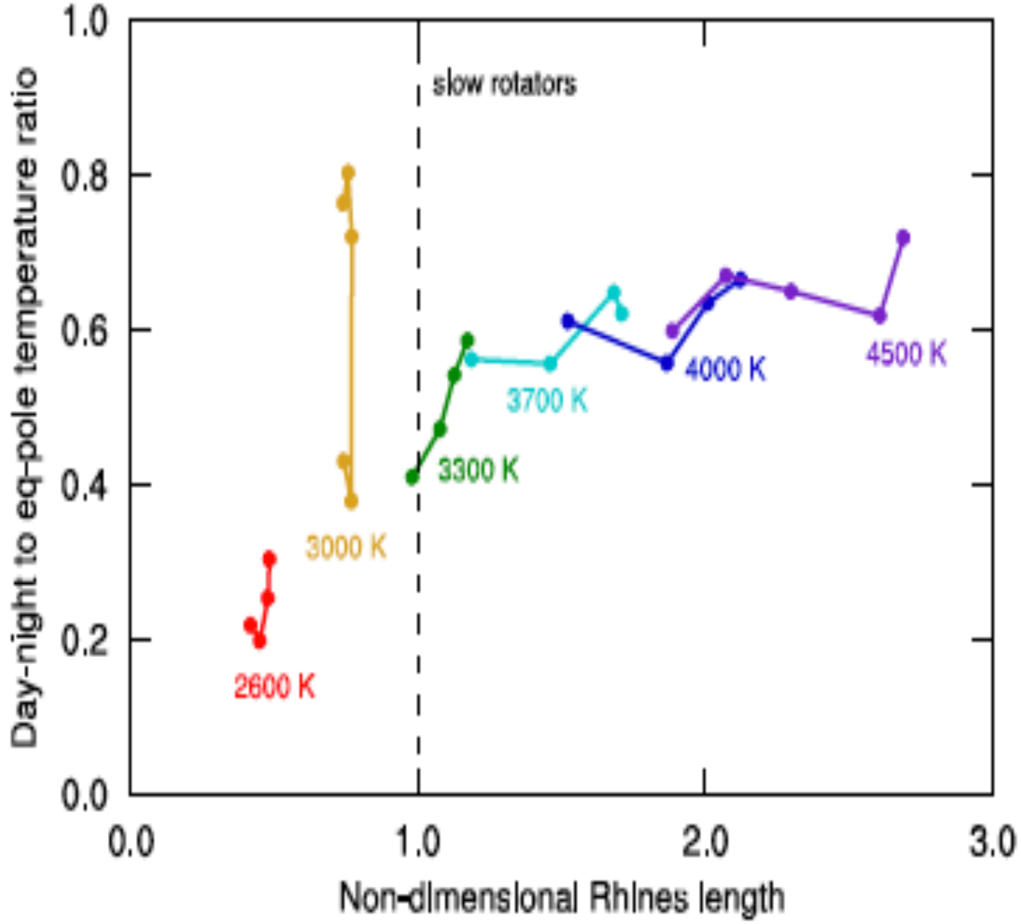
β:コリオリパラメタ

(Haqq-Misra+2018)

3.2 Habitable Climate Around M stars

Inner Edge of the Habitable Zones around late-type M dwarfs





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3.2 Habitable Climate Around M stars

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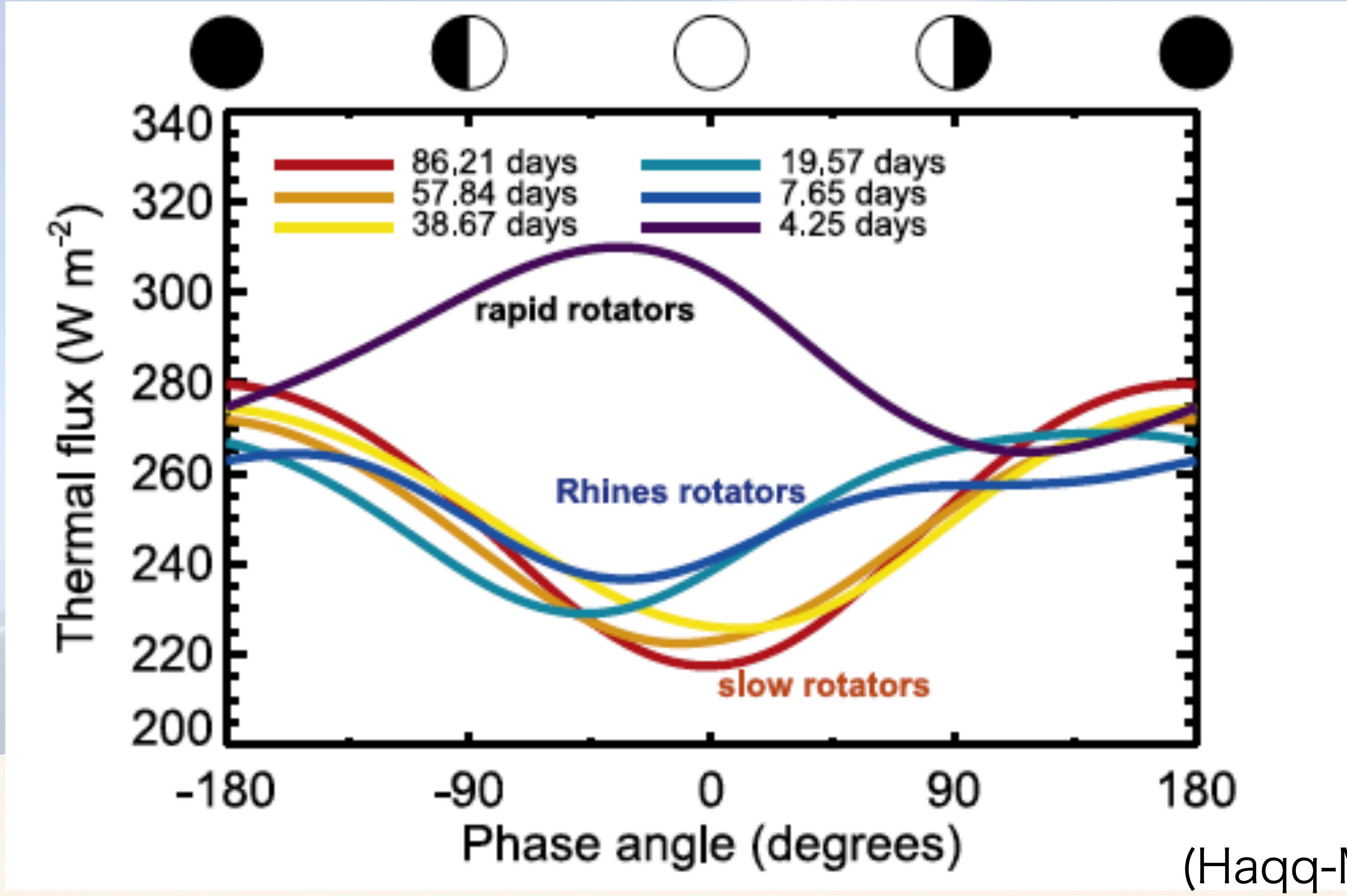
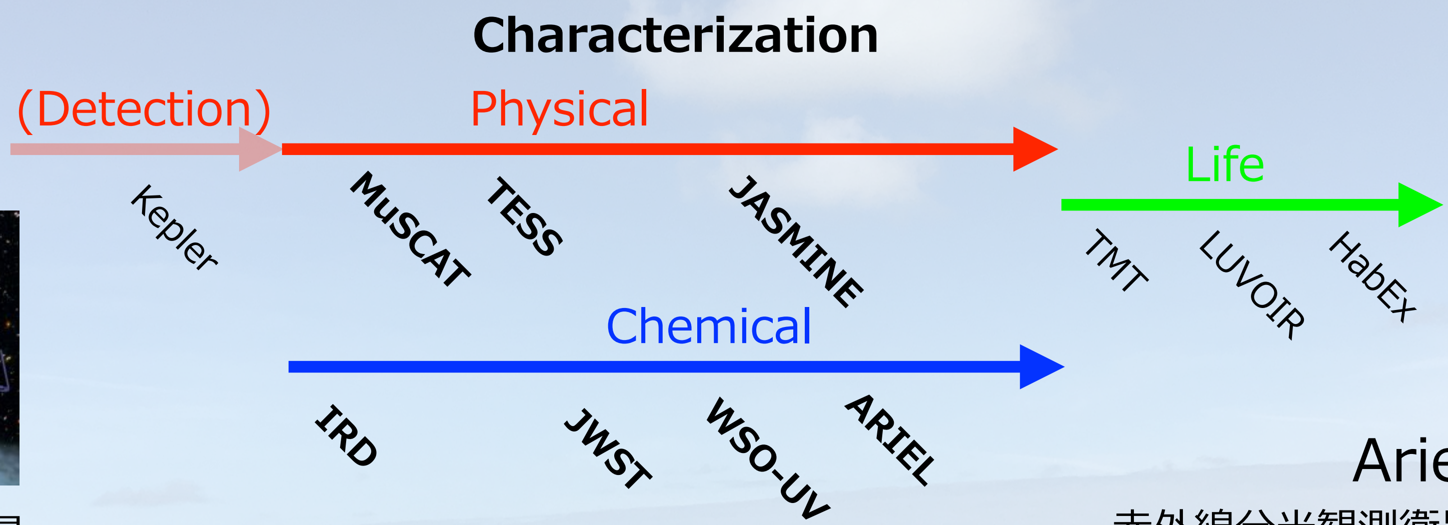


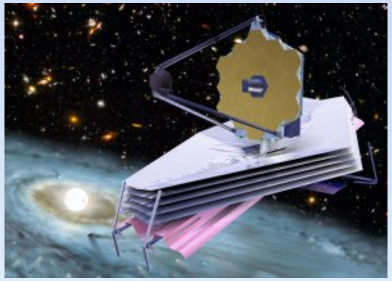
(Haqq-Misra+2018)

4. Future

From detection to characterization…



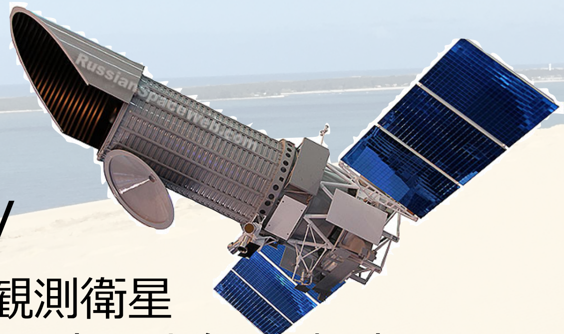
JWST



赤外線分光観測衛星
大気の化学的多様性

Ariel

赤外線分光観測衛星
惑星バルク/大気の化学的多様性



WSO-UV

紫外線分光観測衛星
地球類似惑星(高層大気)の探索

Jasmine

赤外線位置天文観測衛星
低温の中心星まわりの惑星探索