Exoclimates & planetary habitability

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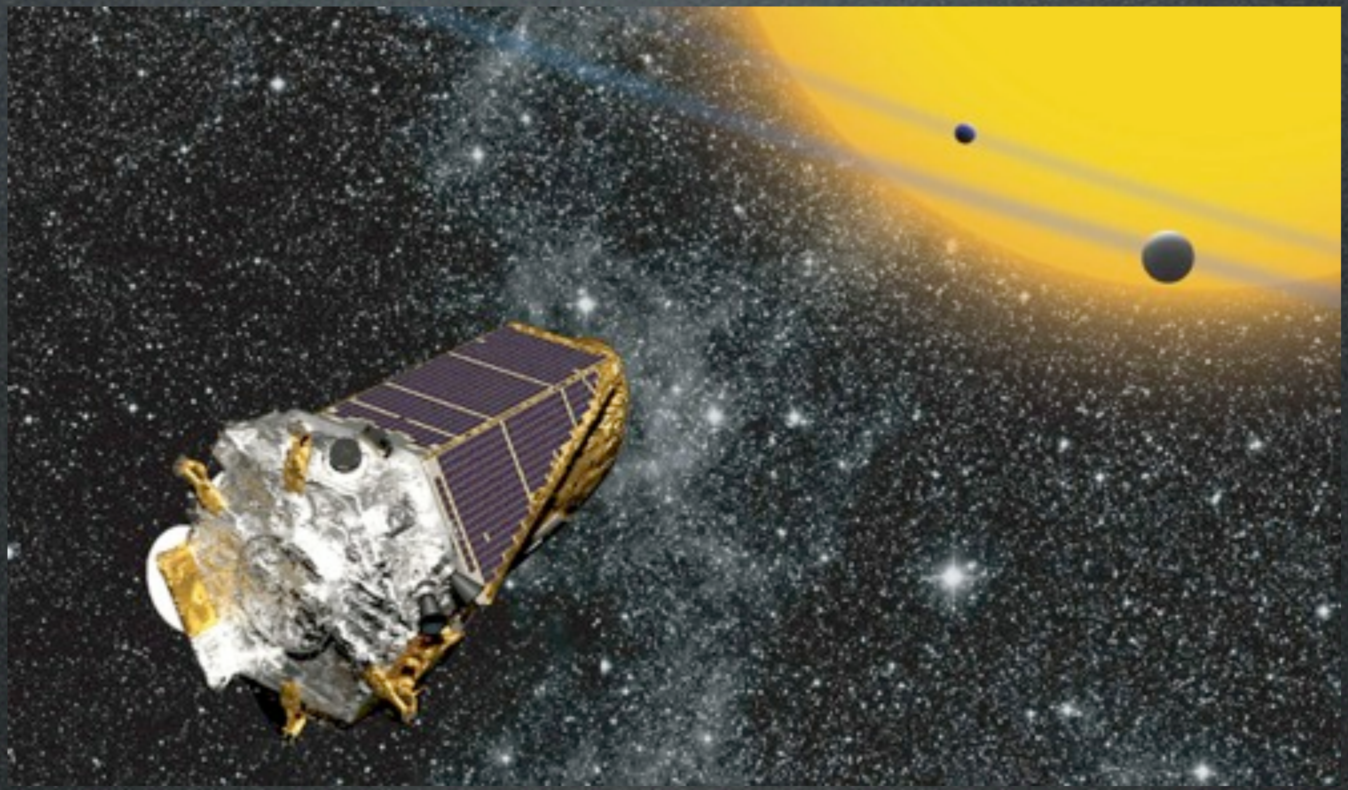
New line of research developed at INAF-OATs
in collaboration with CNR-ISAC Torino, CNR ICG Pisa

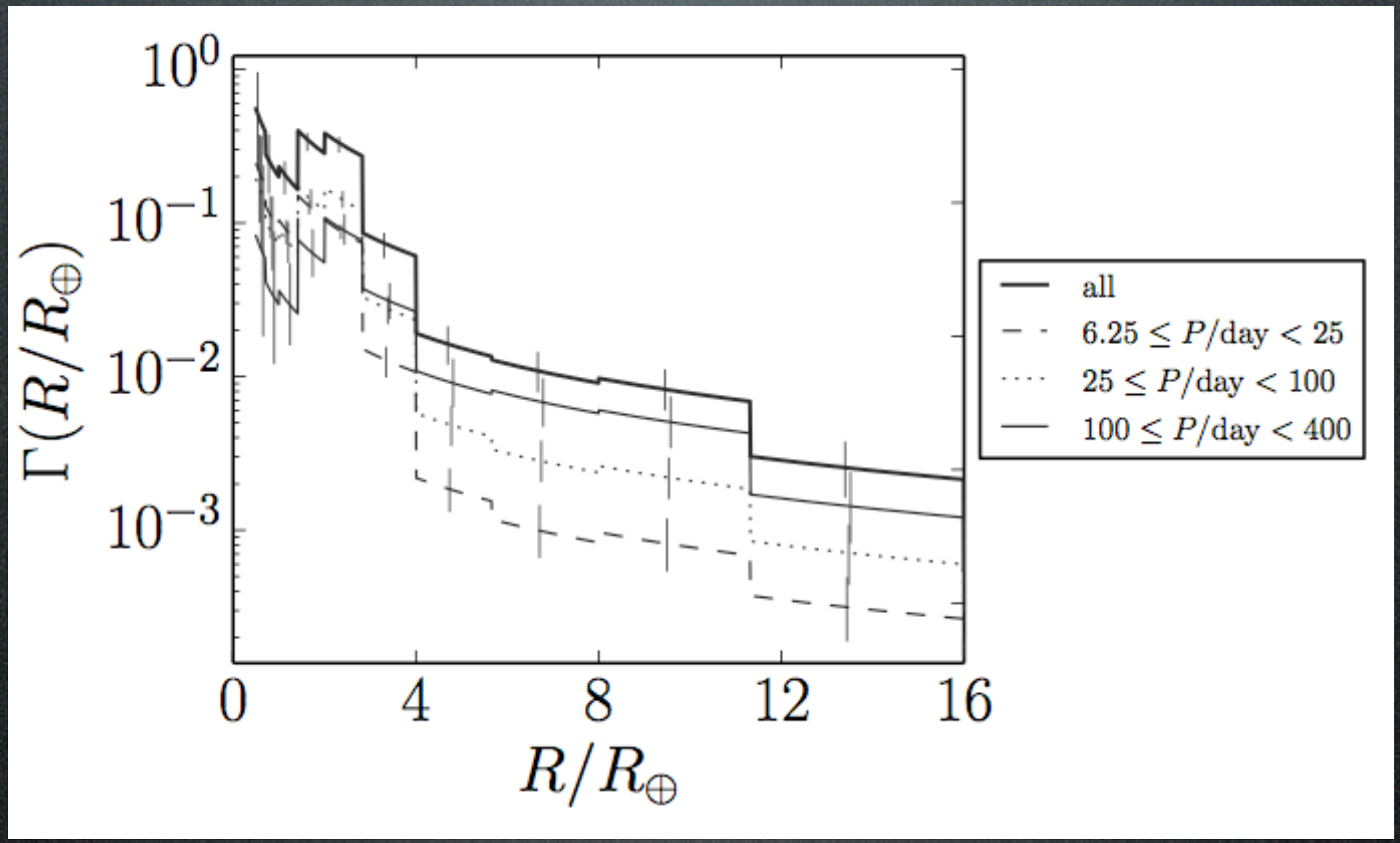
Terrestrial-type exoplanets are primary targets in the search for life

- based on the example of the Earth
- because giant planets are not good candidates to host life



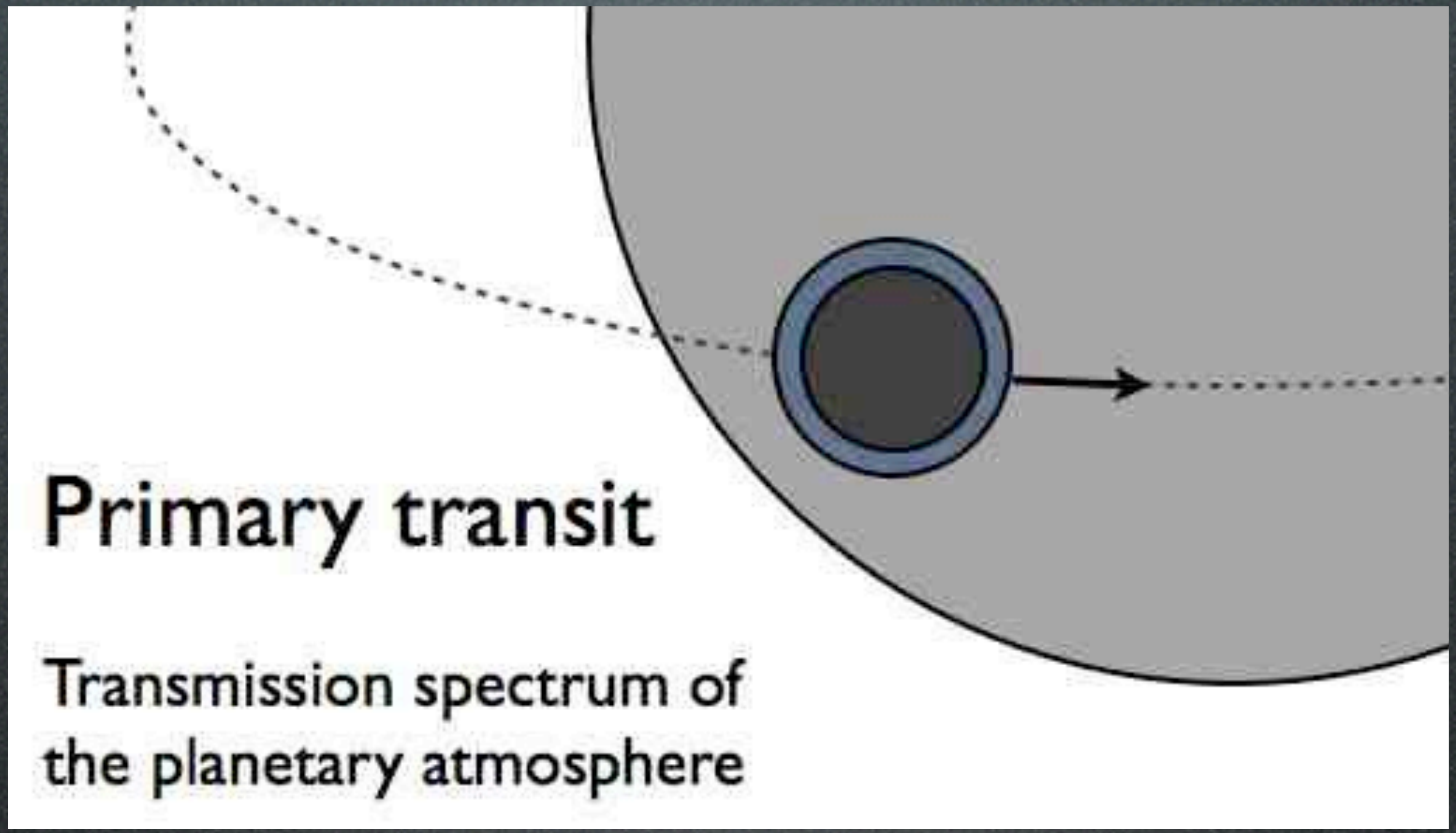
Exoplanet surveys suggest that terrestrial-type planets are common and will be discovered in large numbers

Occurrence rate



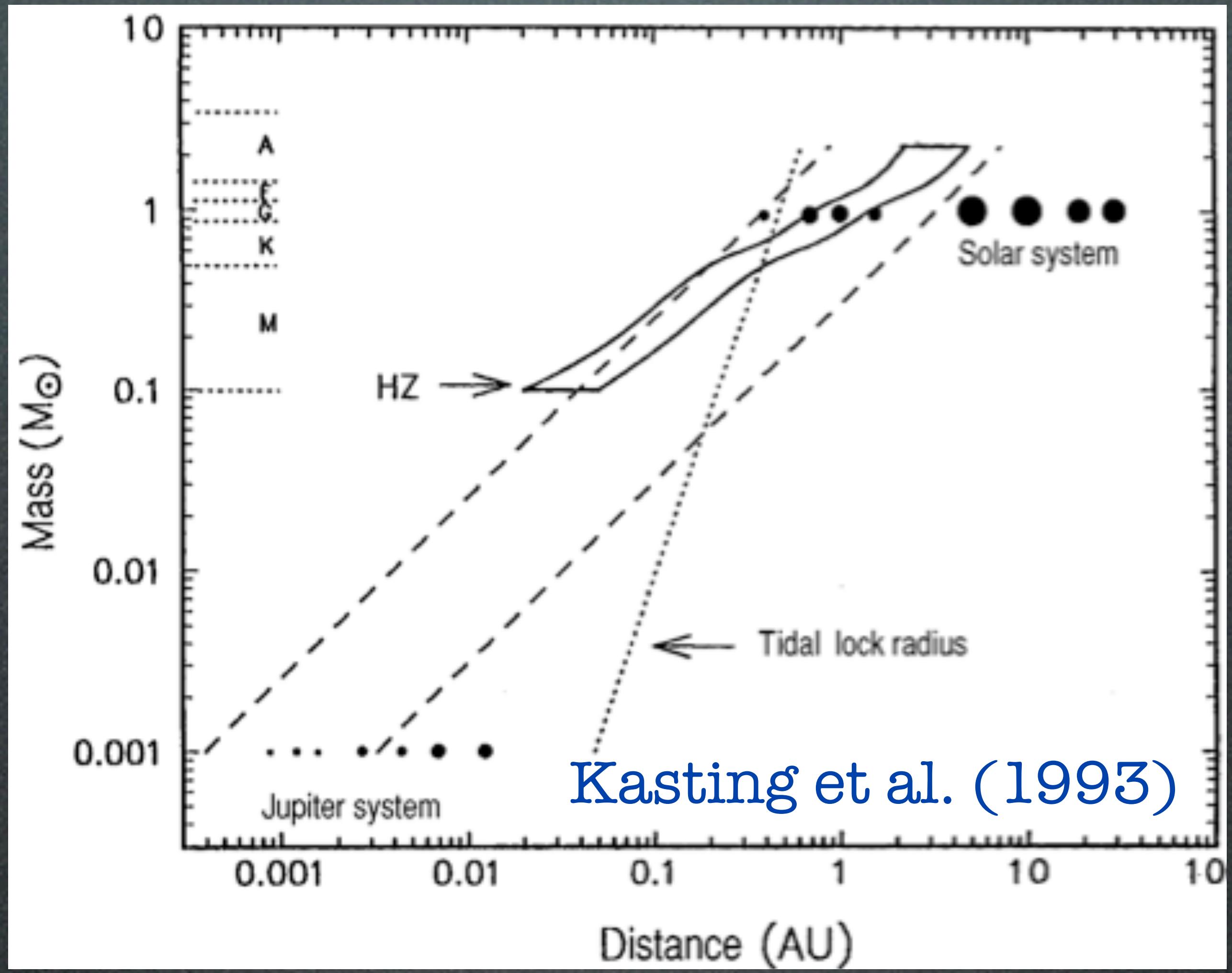
Foreman-Mackey et al. (2014)

Detection of atmospheric biomarkers in terrestrial-type exoplanets is beyond current technical feasibility



The study of the habitability of terrestrial-type exoplanets
is a preliminary step to pre-select the best candidates
for future searches of atmospheric biomarkers

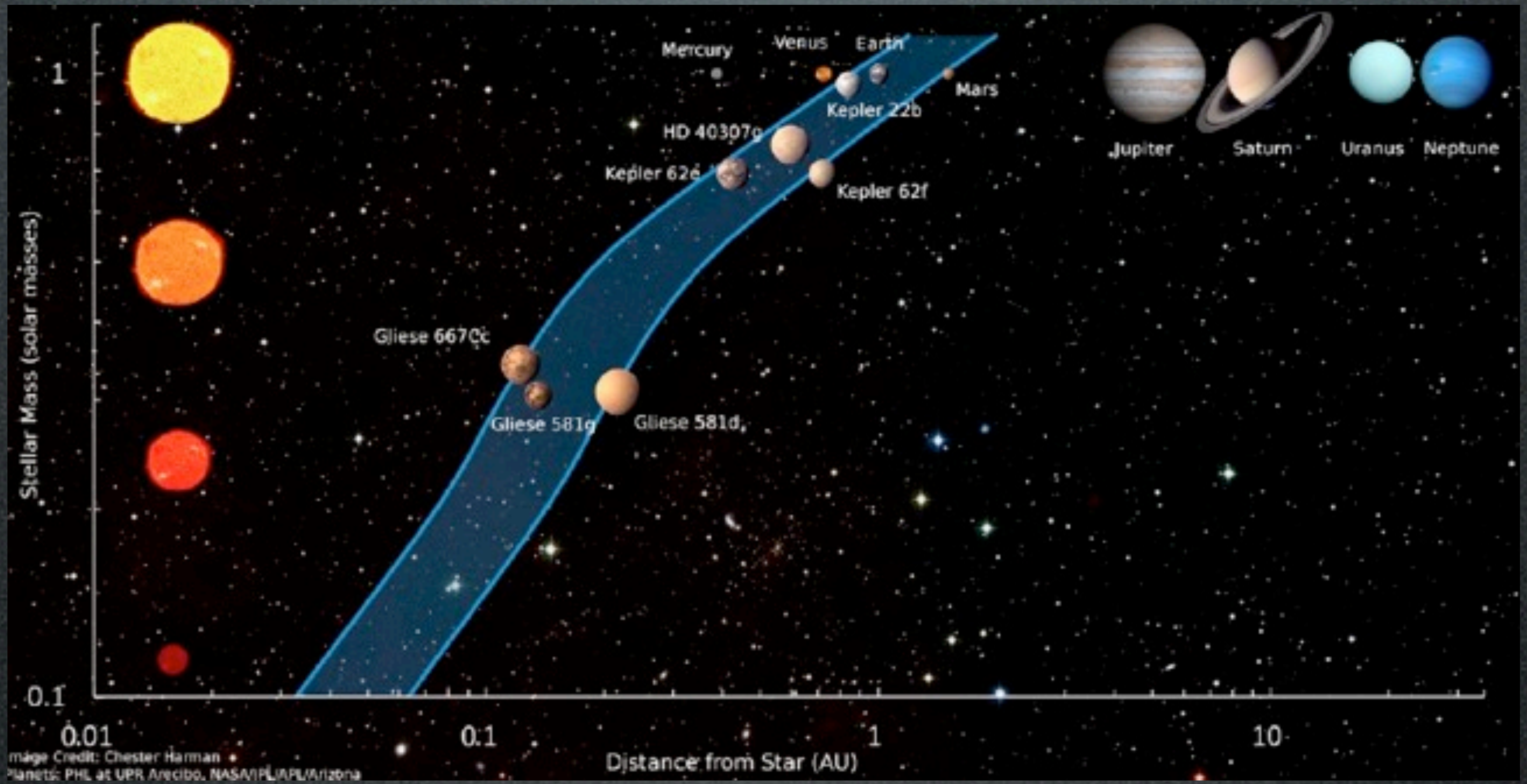
The concept of planetary habitability was introduced before the discovery of exoplanets



Kasting & collaborators

Climate impact of geophysical and geochemical processes

In the era of exoplanets
planetary habitability is becoming a central concept



Working definitions of habitability need to be refined
with the help of new tools

Climate models of terrestrial planets as a tool for exploring planetary habitability

Goal

Modeling the surface temperature
as a function of latitude and time
and mapping the temperature
into surface habitability

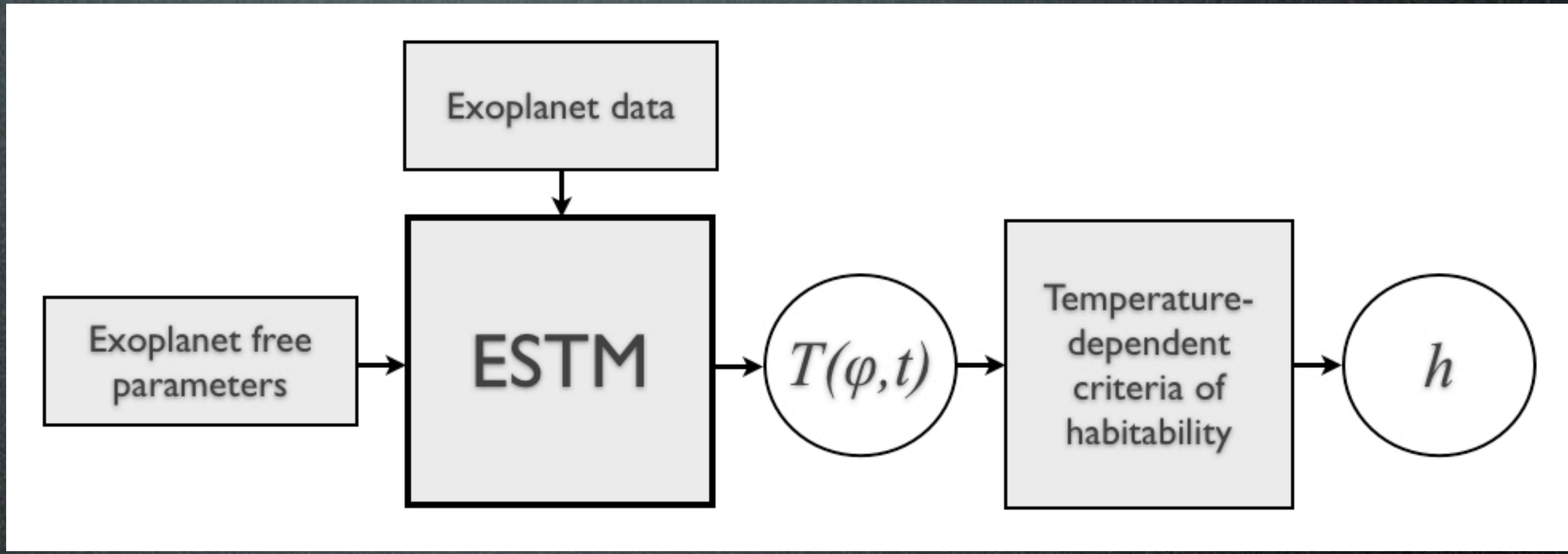
$$T(\varphi,t) \rightarrow h$$

Flexible climate tool
for fast climate simulations

Exploring the habitability of terrestrial exoplanets

Observable quantities are fixed
stellar luminosity, orbital semi-major axis, eccentricity, planet radius and mass, ...

Unknown quantities are treated as free parameters
axis tilt, rotation period, surface pressure, atmospheric composition, land/ocean distribution, ...



Each climate simulation takes a few minutes of CPU time

Questions that can be addressed with this approach

What is the impact on climate/habitability

- of planetary parameters that are unconstrained by observations?
- of error bars on observational planetary data?
- of parameters that vary in the course of planetary evolution?

Can we refine the definition of planetary habitability?

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THE HABITABLE ZONE OF EARTH-LIKE PLANETS WITH DIFFERENT LEVELS OF ATMOSPHERIC PRESSURE

GIOVANNI VLADILO[1,2], GIUSEPPE MURANTE[1], LAURA SILVA[1], ANTONELLO PROVENZALE[3], GAIA FERRI[2], AND GREGORIO RAGAZZINI[2]

Self-consistent treatment of surface temperature and pressure in the definition of habitability by means of the liquid water criterion

$$H(\varphi, t) = \begin{cases} 1 & \text{if } T_{\rm ice}(p) \leqslant T(\varphi, t) \leqslant T_{\rm vapor}(p) \\ 0 & \text{otherwise.} \end{cases}$$

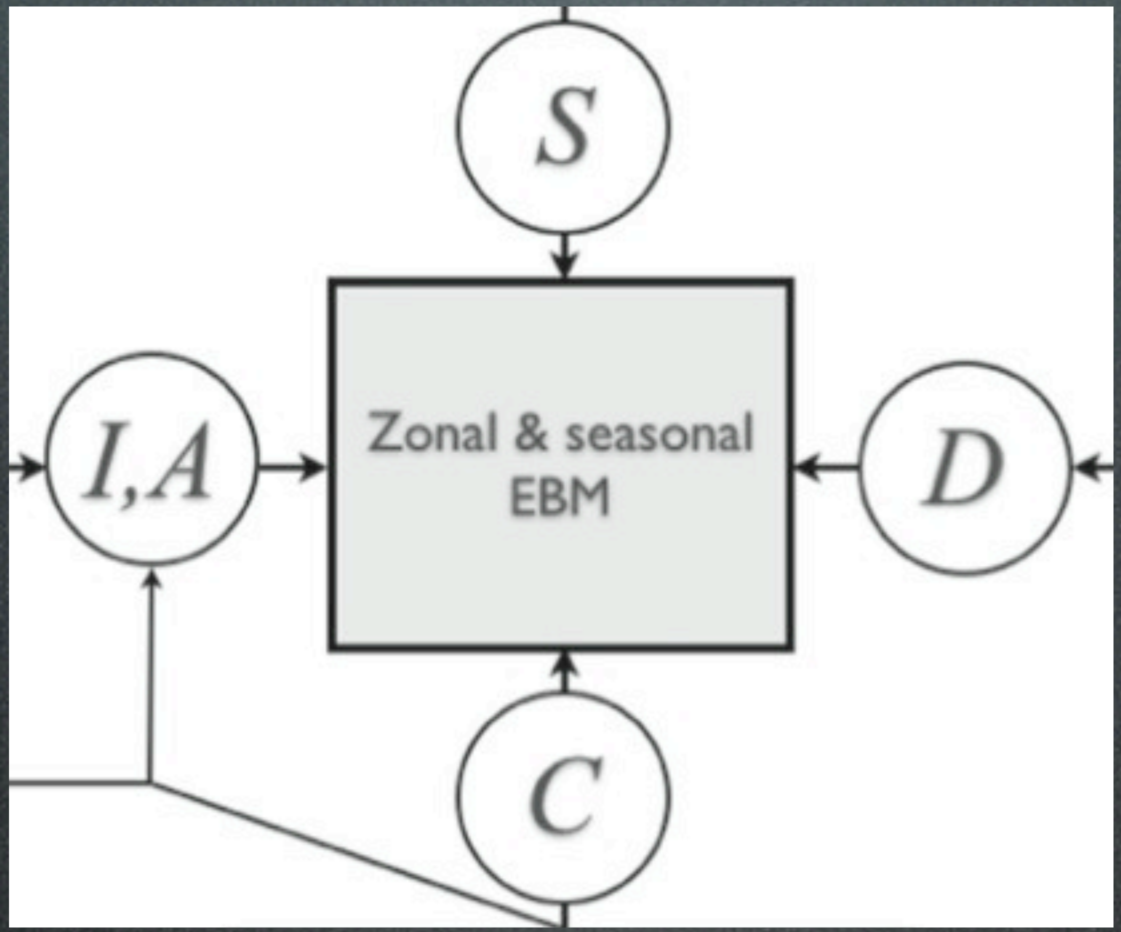
$$h = \frac{\int_{-\pi/2}^{+\pi/2} d\varphi \int_0^P dt \, [H(\varphi, t) \cos\varphi]}{2P}$$

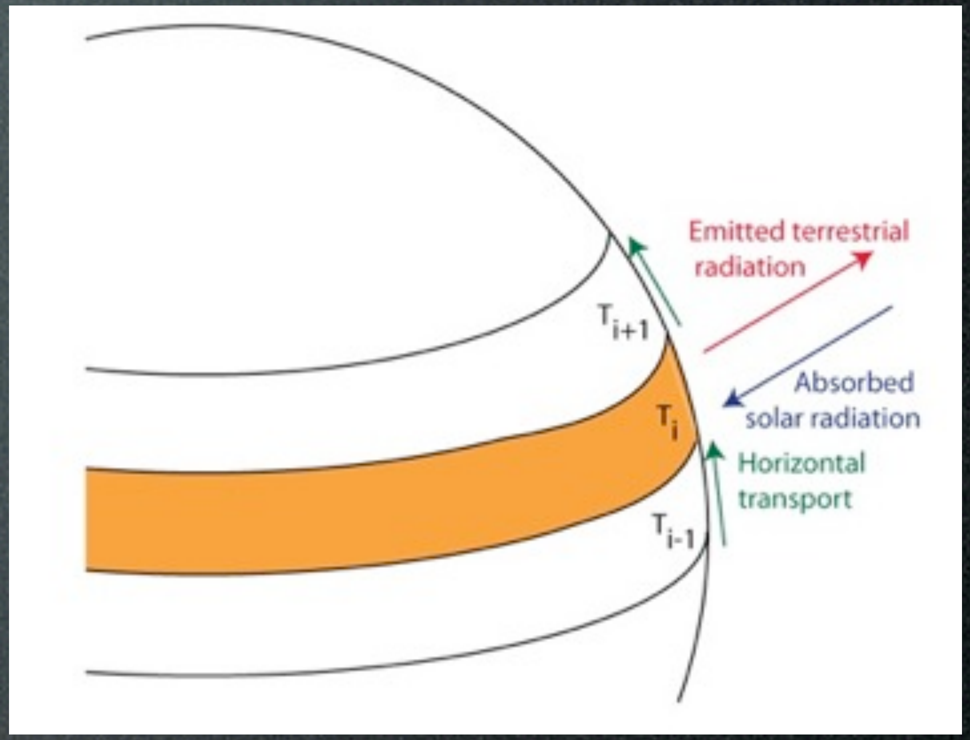
Zonal & seasonal EBM
$P_{rot} << P_{orb}$

The planet surface is divided in latitude strips and the energy balance is calculated in each strip

The outgoing thermal radiation (OLR), incoming stellar radiation, and albedo are calculated in each latitude strip

The meridional transport is treated as a diffusion term





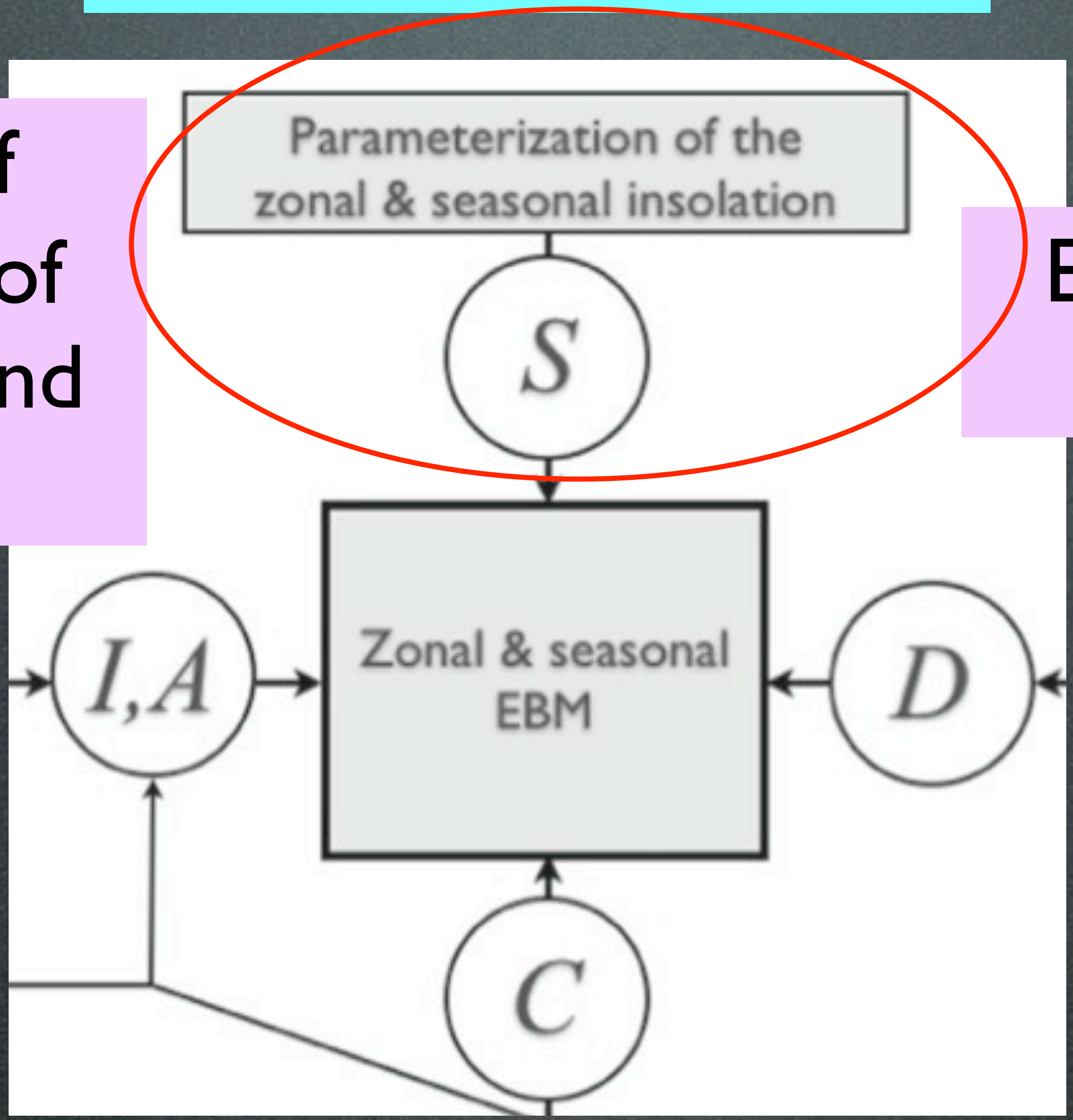
$$I_i + C_i \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left[D_i\left(1-x^2\right)\frac{\partial T}{\partial x}\right] = S_i\left(1-A_i\right)$$

φ: latitude
x= sin φ

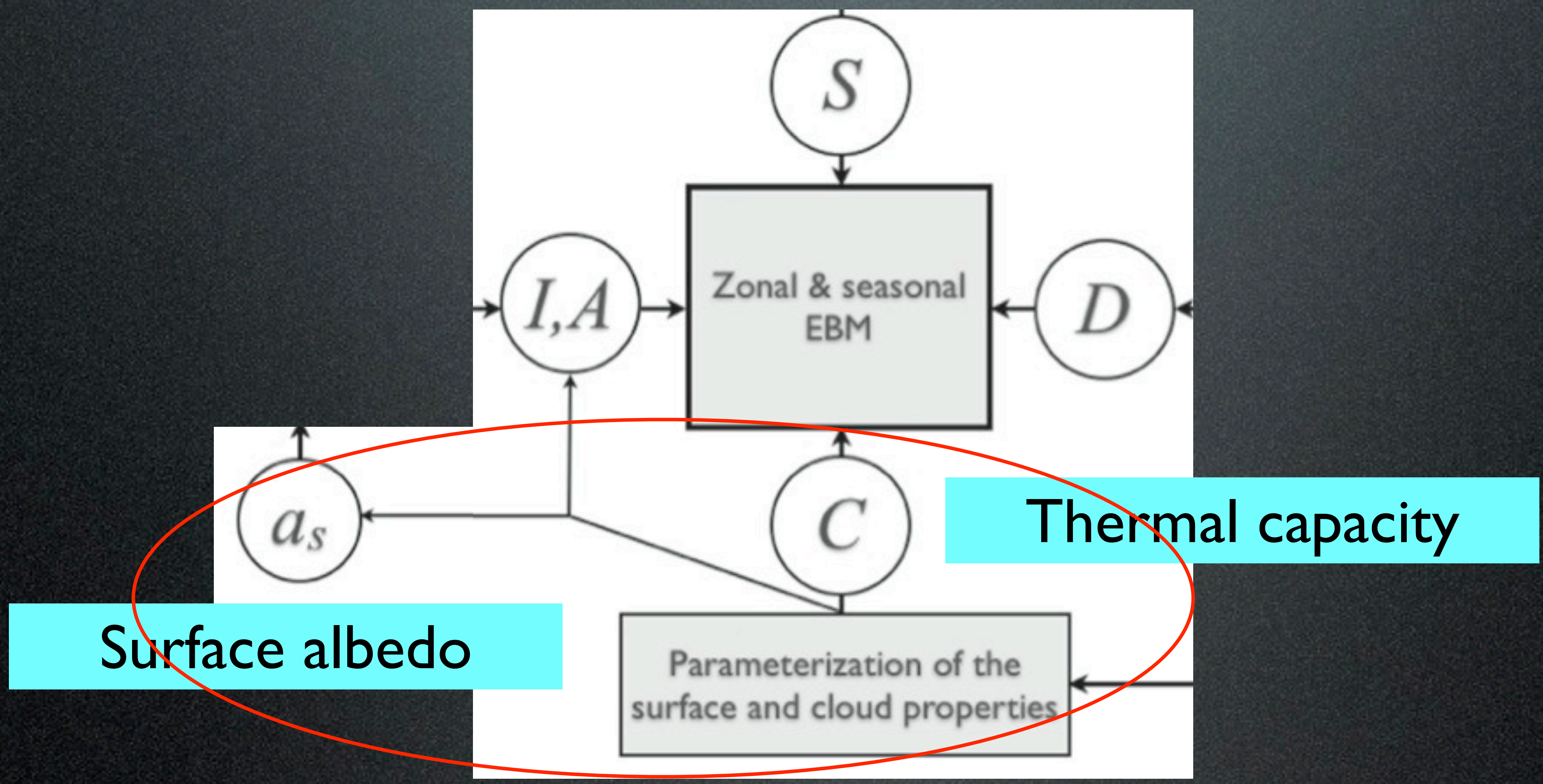
Incoming stellar radiation

Exact calculation of $S(\varphi,t)$ as a function of orbital eccentricity and axis obliquity

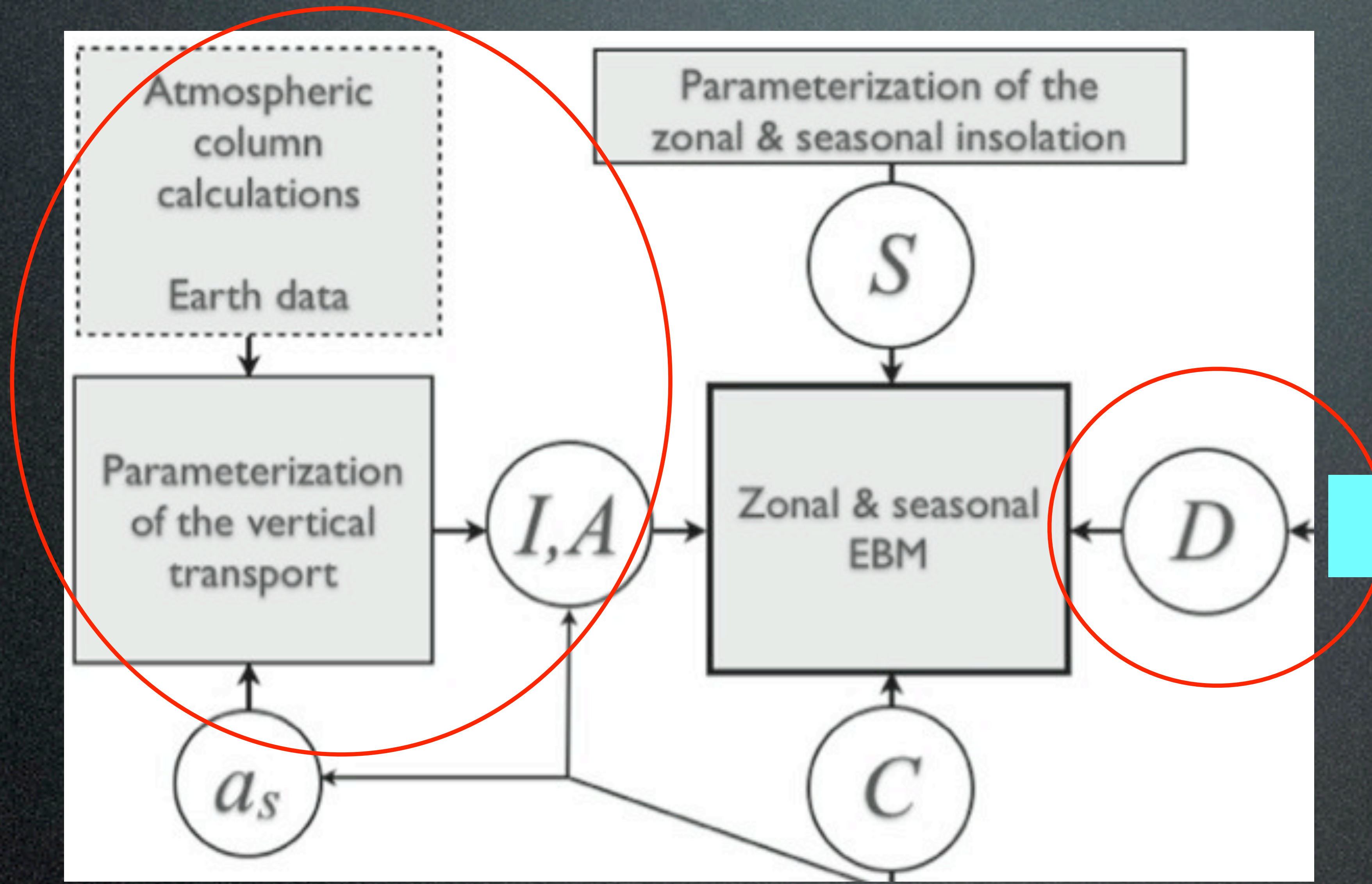
Evolutionary tracks of stellar luminosity



Surface properties: schematic geography: $f_{o,i}$



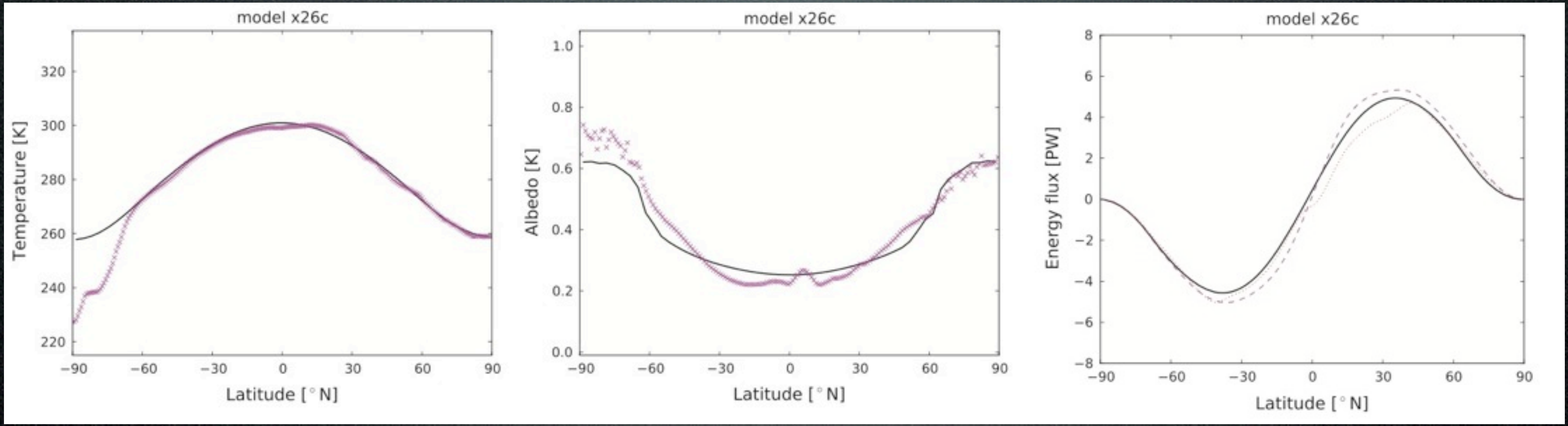
OLR



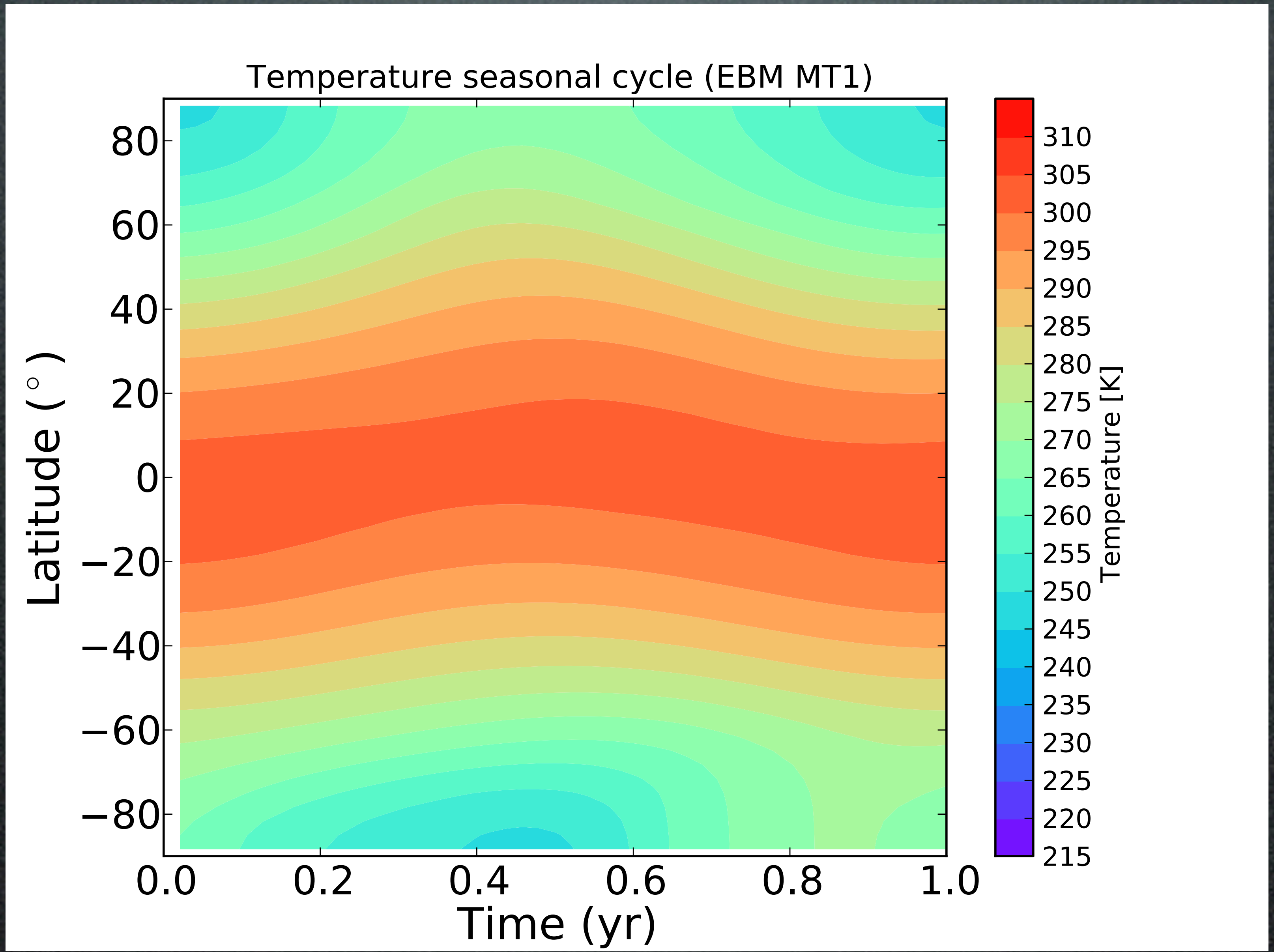
Diffusion term

For the vertical radiative transfer
we are currently
using CCM routines
which are part of the NCAR
climate model

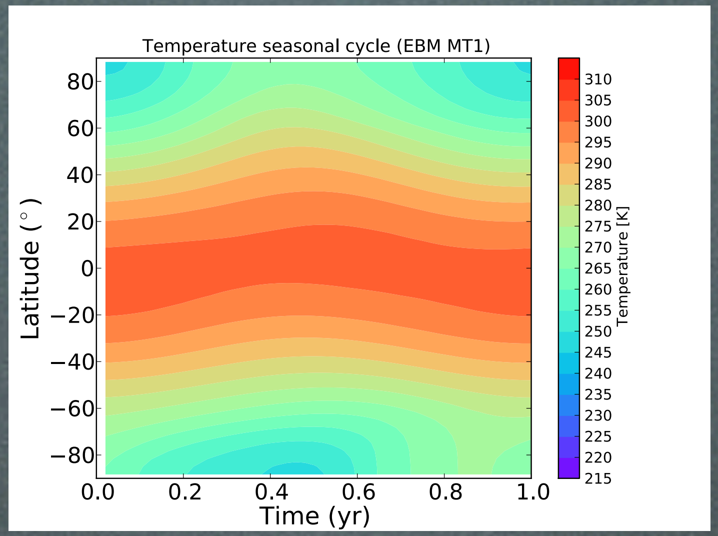
Calibration with Earth data



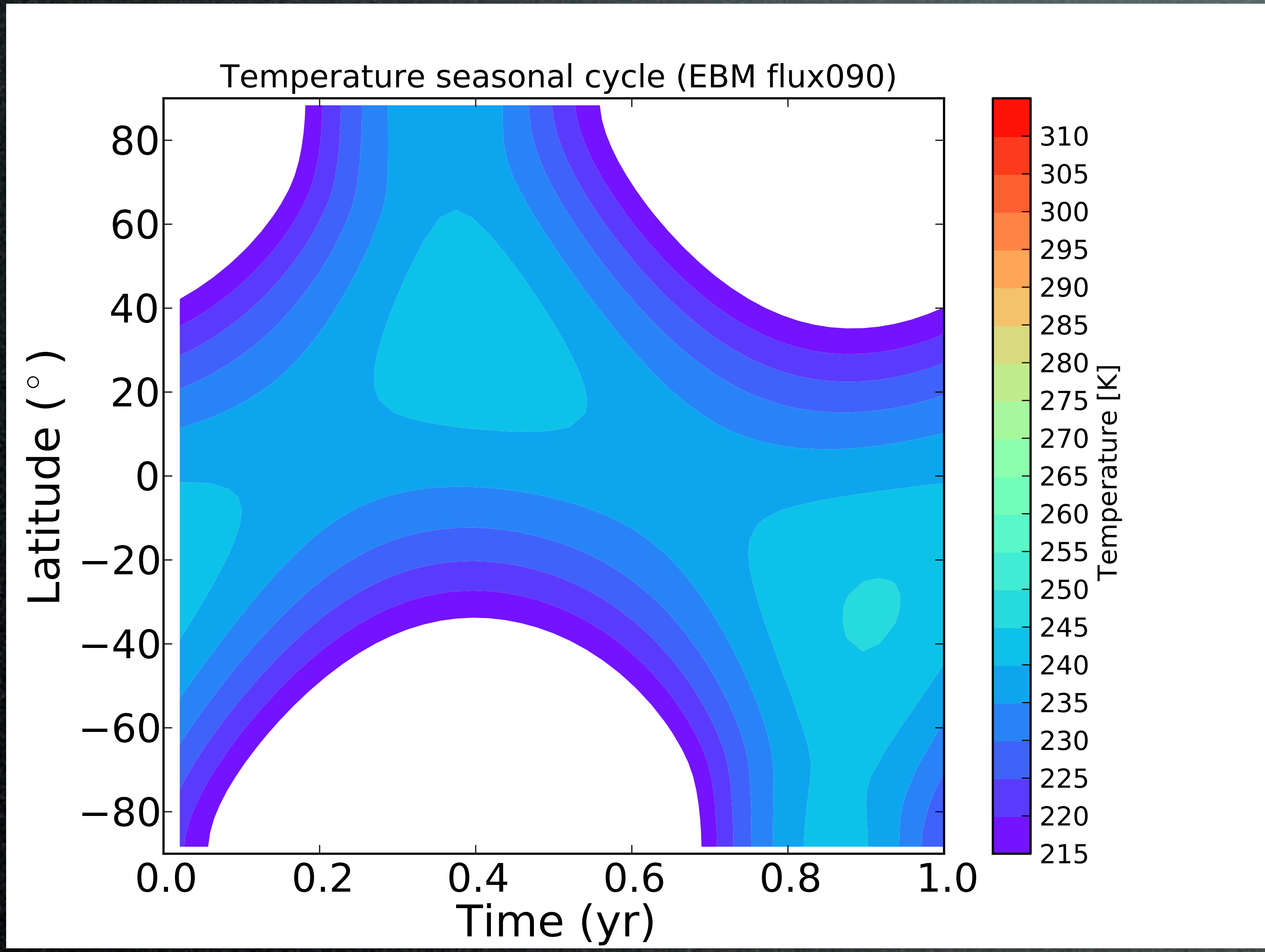
Example of output from a simulation
Seasonal-latitudinal temperature map

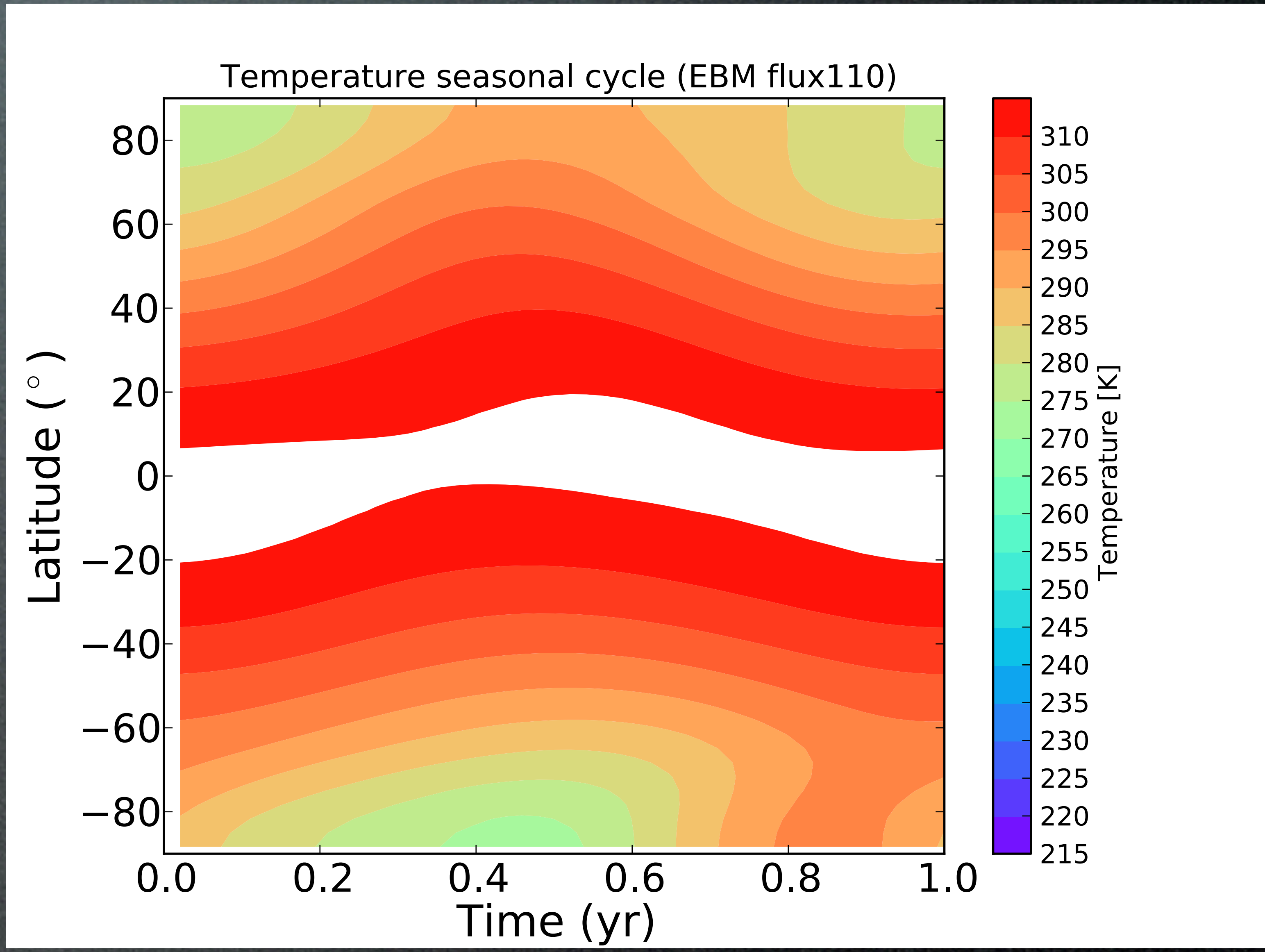


Insolation=0.9 S_o

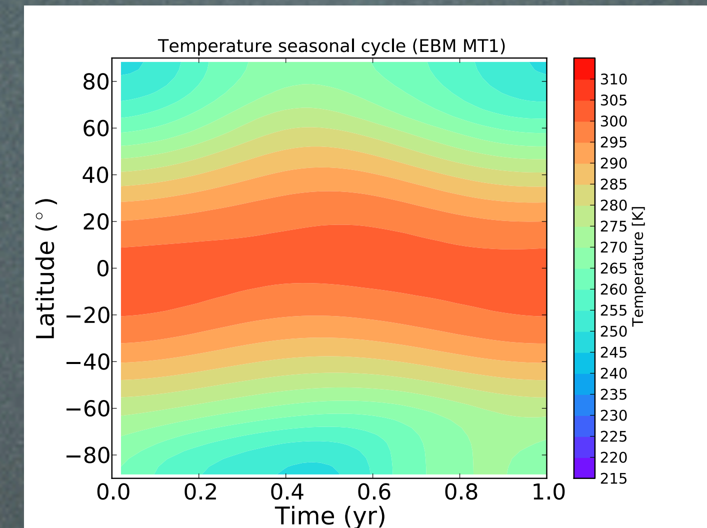


Insolation=1.1 S_o

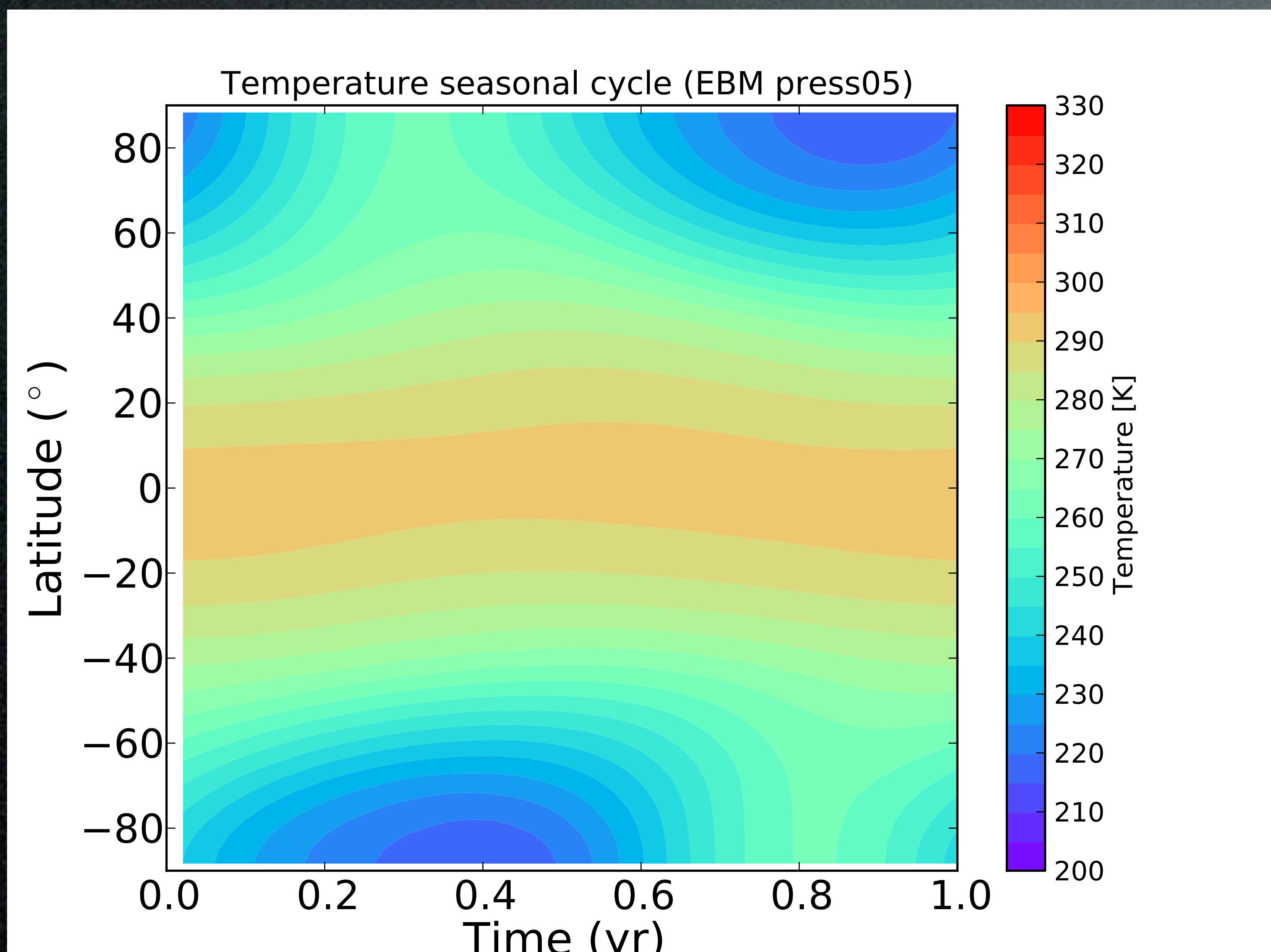


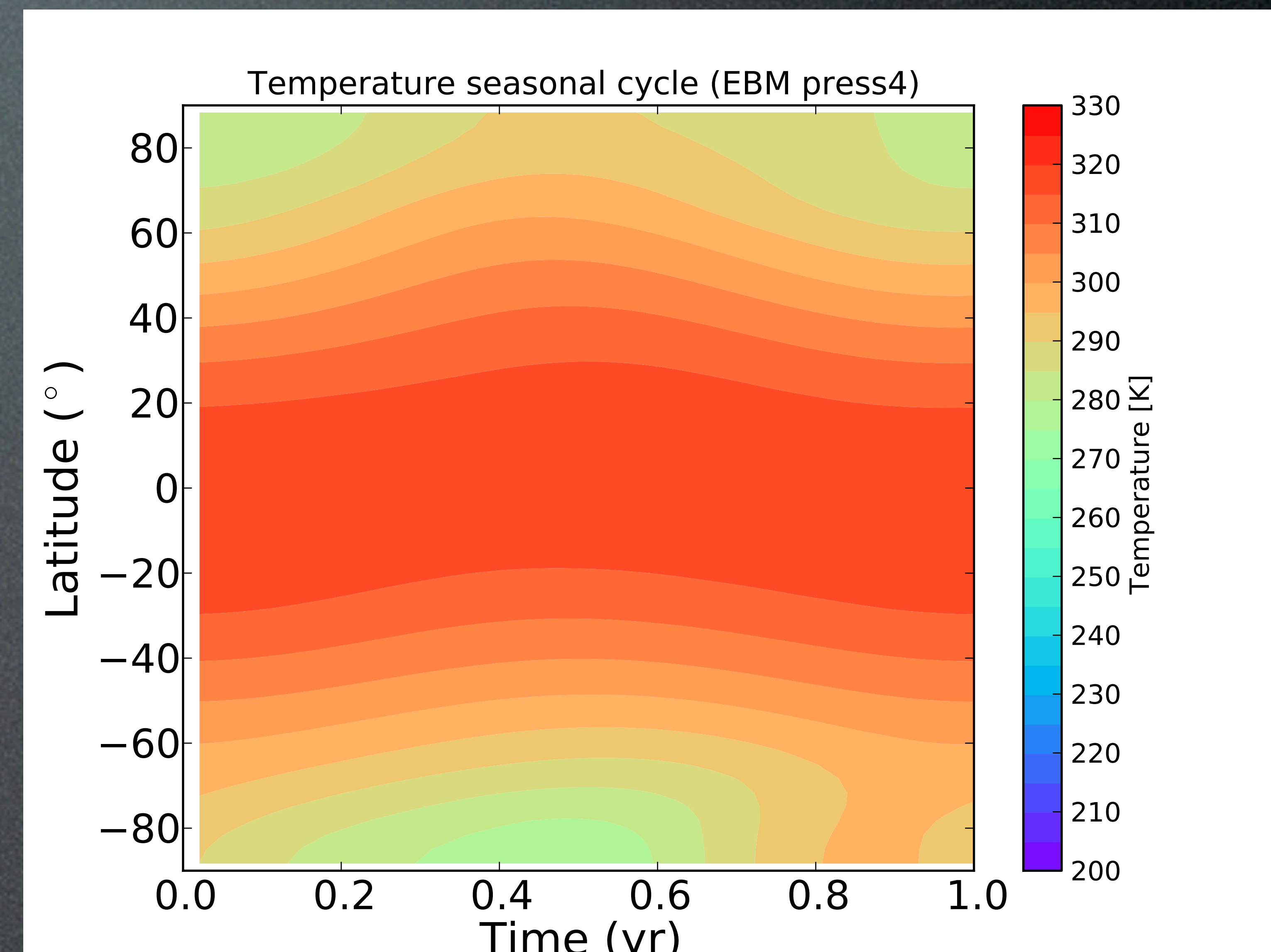


Insolation: single parameter that most affects the habitability p=0.5 bar



p=4 bar

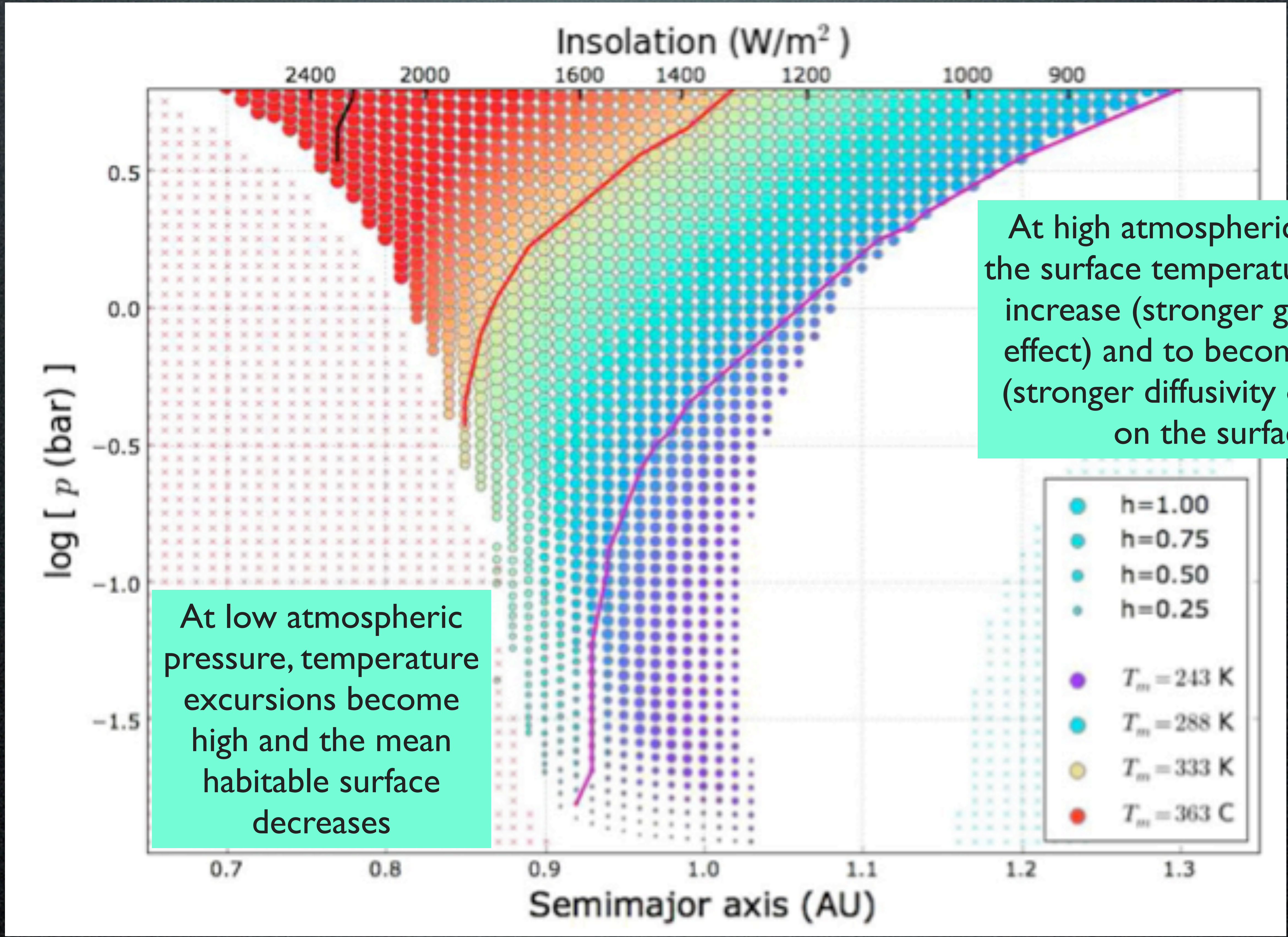




Surface pressure also extremely important
Linked to atmospheric columnar mass, p/g

Pressure dependent habitable zone

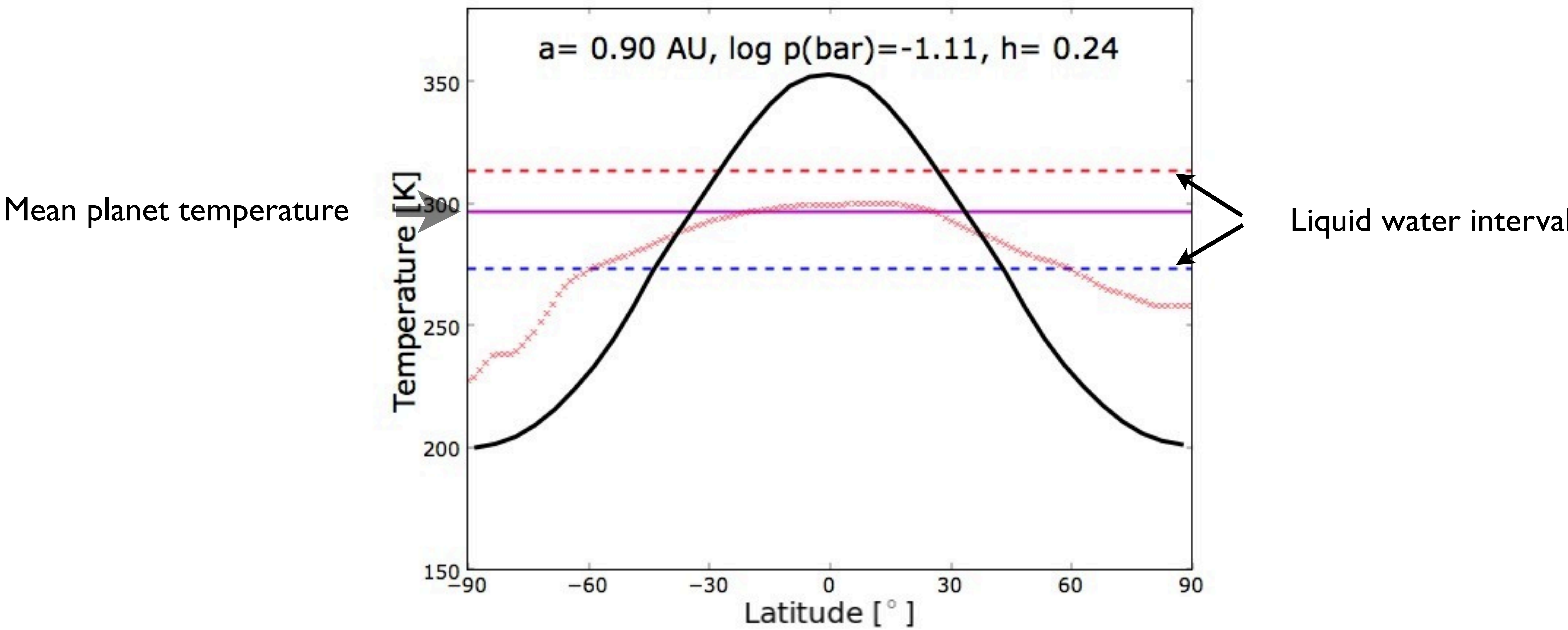
for planets with constant atmospheric composition



At high atmospheric pressure, the surface temperature tends to increase (stronger greenhouse effect) and to become uniform (stronger diffusivity of the heat on the surface)

At low atmospheric pressure, temperature excursions become high and the mean habitable surface decreases

At low pressure, the mean planet temperature is not a good diagnostic of habitability



Evaporating planets inside the "habitable zone"

Upgrading the model

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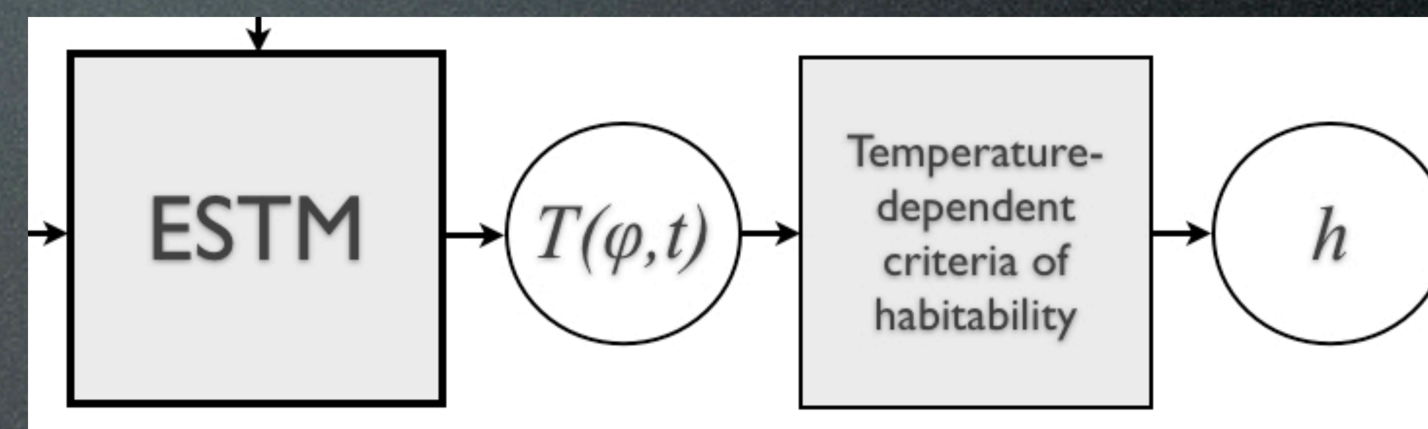
doi:10.1088/0004-637X/804/1/50

MODELING THE SURFACE TEMPERATURE OF EARTH-LIKE PLANETS

Giovanni Vladilo[1,2], Laura Silva[1], Giuseppe Murante[1,3], Luca Filippi[3,4], and Antonello Provenzale[3,5]

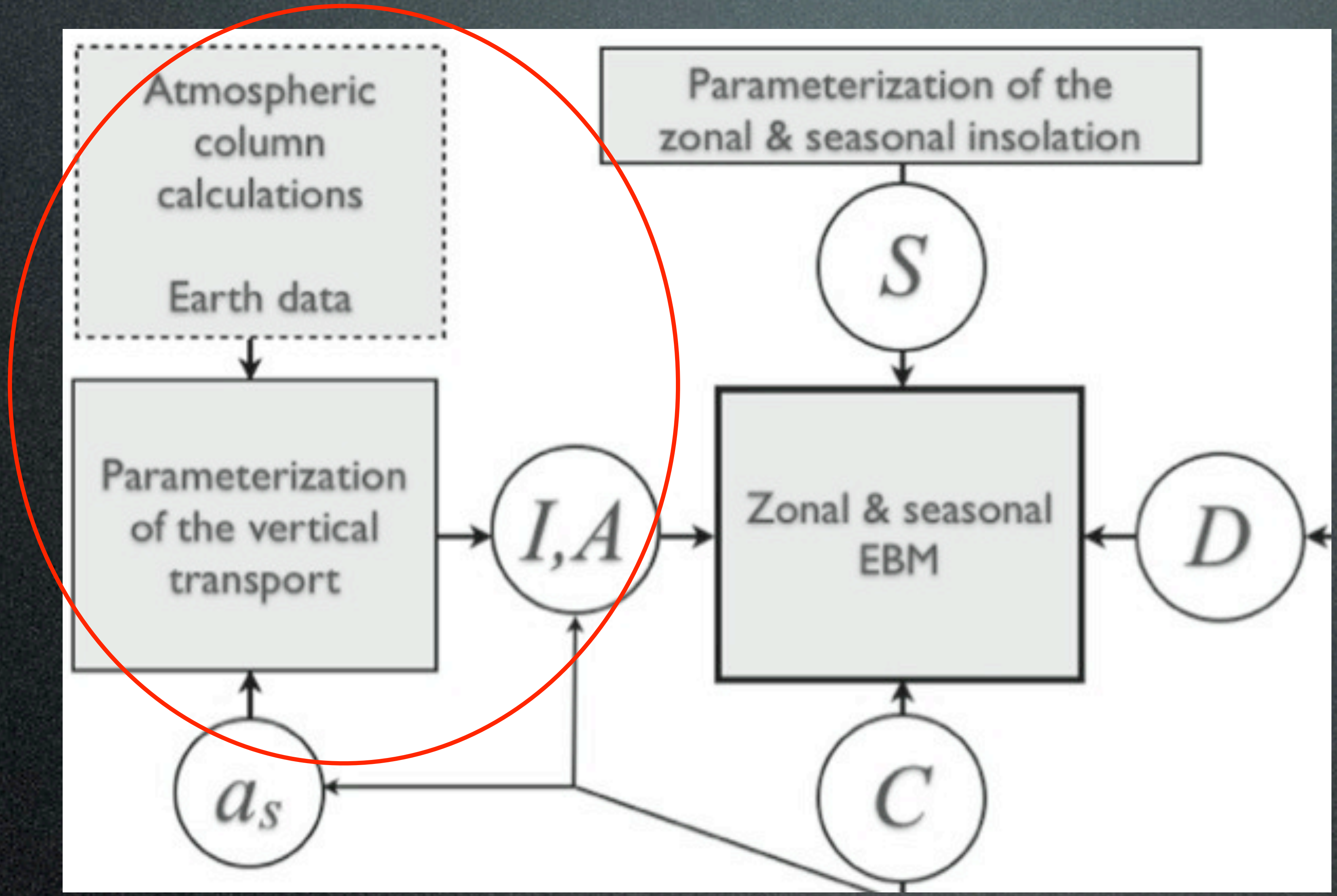
Earth-like surface temperature model (ESTM)



Improve the modelization of the temperature dependence on: gravity, radius, rotation rate, atmospheric composition…

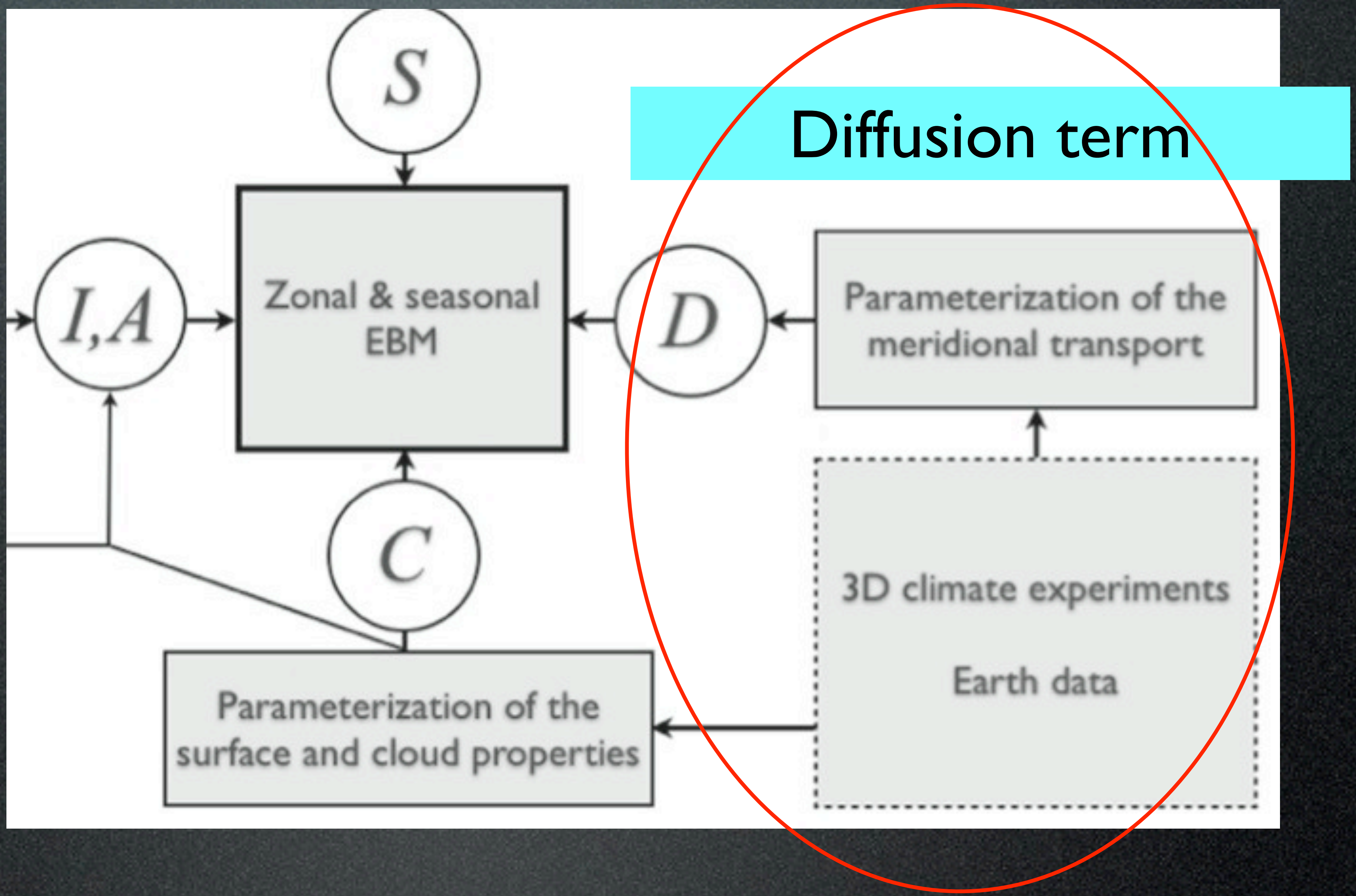
Upgrading the model

Top-of-atmosphere albedo



For the vertical radiative transfer we are currently using CCM routines which are part of the NCAR climate model

Upgrading the model



Physical parametrization of the term D

$$\Phi_{\rm atm} = -D\frac{\partial T}{\partial \varphi}$$

$2\ \pi\ R^2\ \Phi\ \cos\ \varphi$
Net rate of energy transport across a circle of constant latitude φ

$$\Phi \simeq \frac{1}{R}\frac{p}{g}\overline{v'm'}$$

p : Surface pressure
g : Surface gravity
R : Planet radius
v : Meridional velocity

$$\overline{v'm'} = c_p\overline{v'T'} + L_v\overline{v'r'_v}$$

m : Moist Static Energy
$c_p T$: Sensible Heat
$L_v\ r_v$: Latent Heat

$$|T'| = -\ell_{\rm mix}\frac{\partial T}{\partial y}$$

$$|r'_v| = -\ell_{\rm mix}\frac{\partial\, r_v}{\partial y}$$

y : Meridional coordinate
$\ell_{\rm mix}$: Mixing length

$$D \simeq \frac{1}{R^2}\frac{p}{g}\ell_{\rm mix}\ \ |v'|\left(k_{\rm S}c_p + k_{\rm L}L_v\frac{\mu_v}{\mu_{\rm dry}}\frac{q}{p_{\rm dry}}\frac{\partial p_v^*}{\partial T}\right)$$

q : Relative humidity
p^* : Saturation vapor pressure

Parametrization of the extratropical transport

Formalism tested with GCM experiments

Barry et al. (2002)

$$\varepsilon = \eta \left(\frac{\delta T}{T_w} \right) Q$$

ε : Rate of generation of eddy kinetic energy
η : Efficiency factor
Q : Diabatic forcing term

$$\ell_{\mathrm{mix}} \; |v'| = \left(\eta \frac{\delta T}{T_w} Q \right)^{3/5} \left(\frac{R}{\Omega \cos \varphi_{\mathrm{m}}} \right)^{4/5}$$

Ω : Planet rotation rate

Scaling laws for the term D

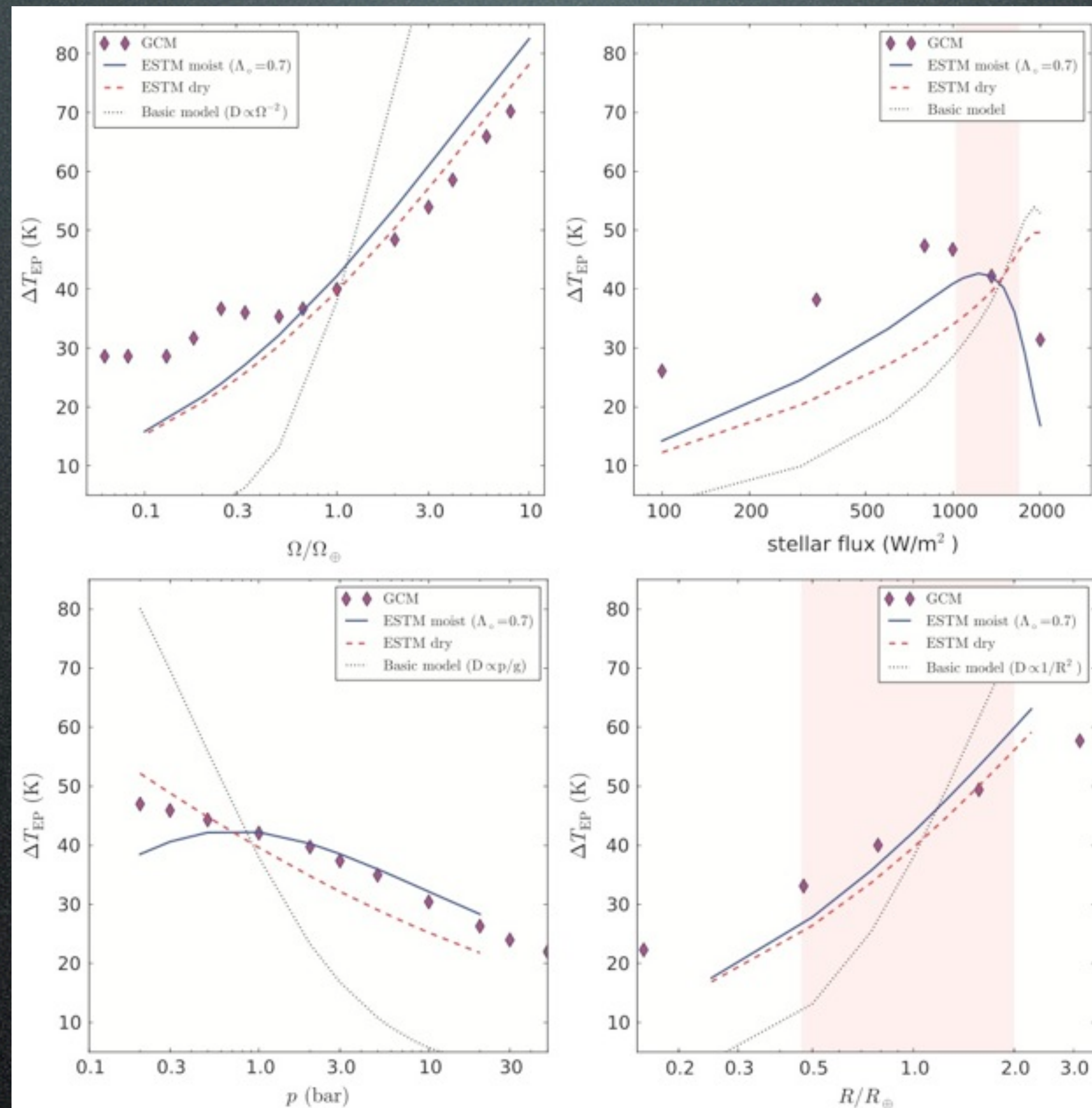
$$D = D_{\text{dry}}(1 + \Lambda)$$

$$D_{\text{dry}} = k_S c_p \, \eta^{3/5} (\cos \varphi_m)^{-4/5} \, R^{-6/5} \, \frac{p}{g} \, \Omega^{-4/5} \left(\frac{\delta T}{T_w} Q \right)^{3/5}$$

$$\Lambda = \frac{k_L L_v}{k_S c_p} \frac{\mu_v}{\mu_{\text{dry}}} \frac{q}{p_{\text{dry}}} \frac{\partial p_v^*}{\partial T}$$

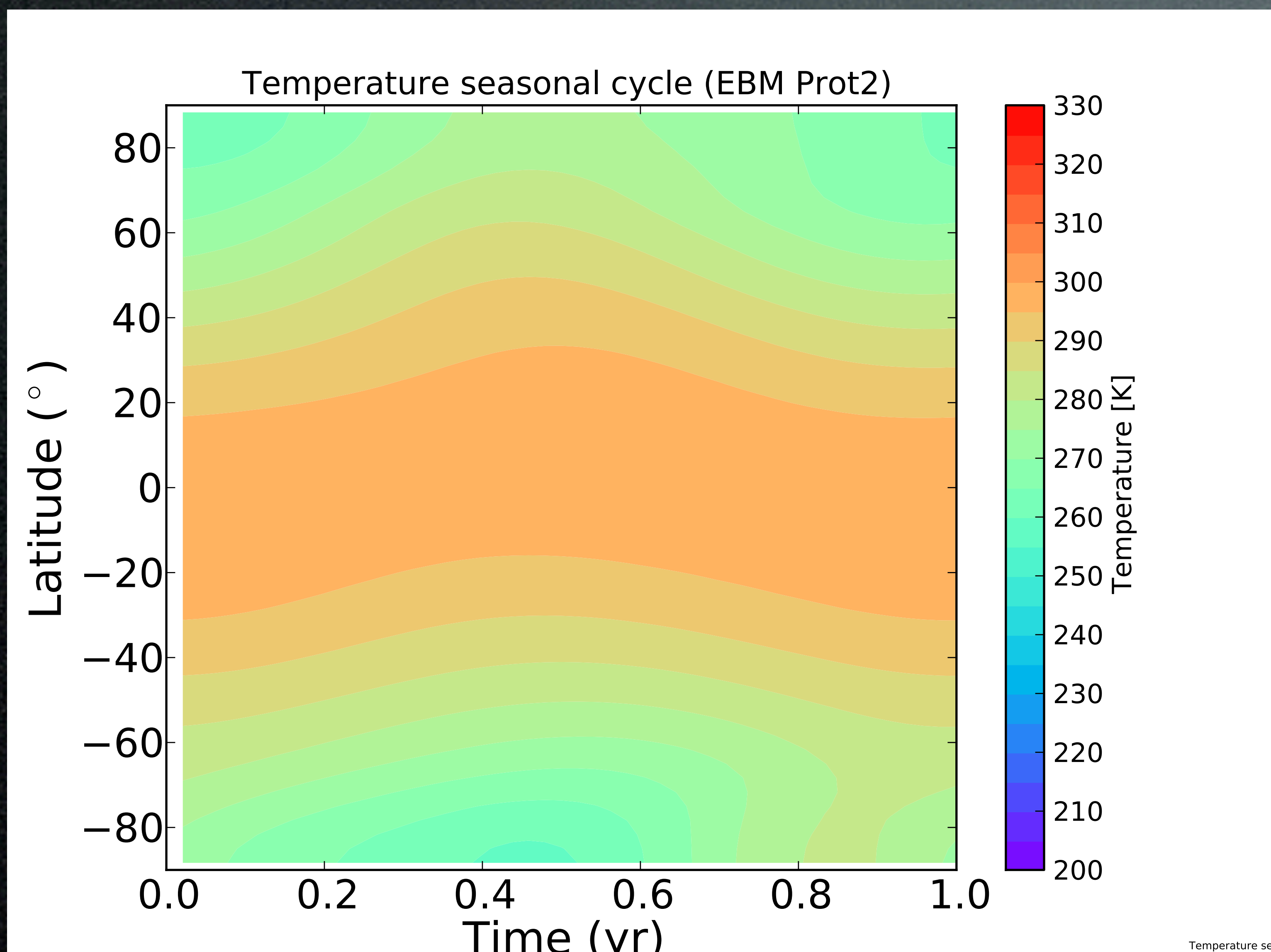
p : Surface pressure
g : Surface gravity
R : Planet radius
Ω : Rotation rate

Validation with 3D aquaplanet simulations
(Kaspi & Showman 2015)

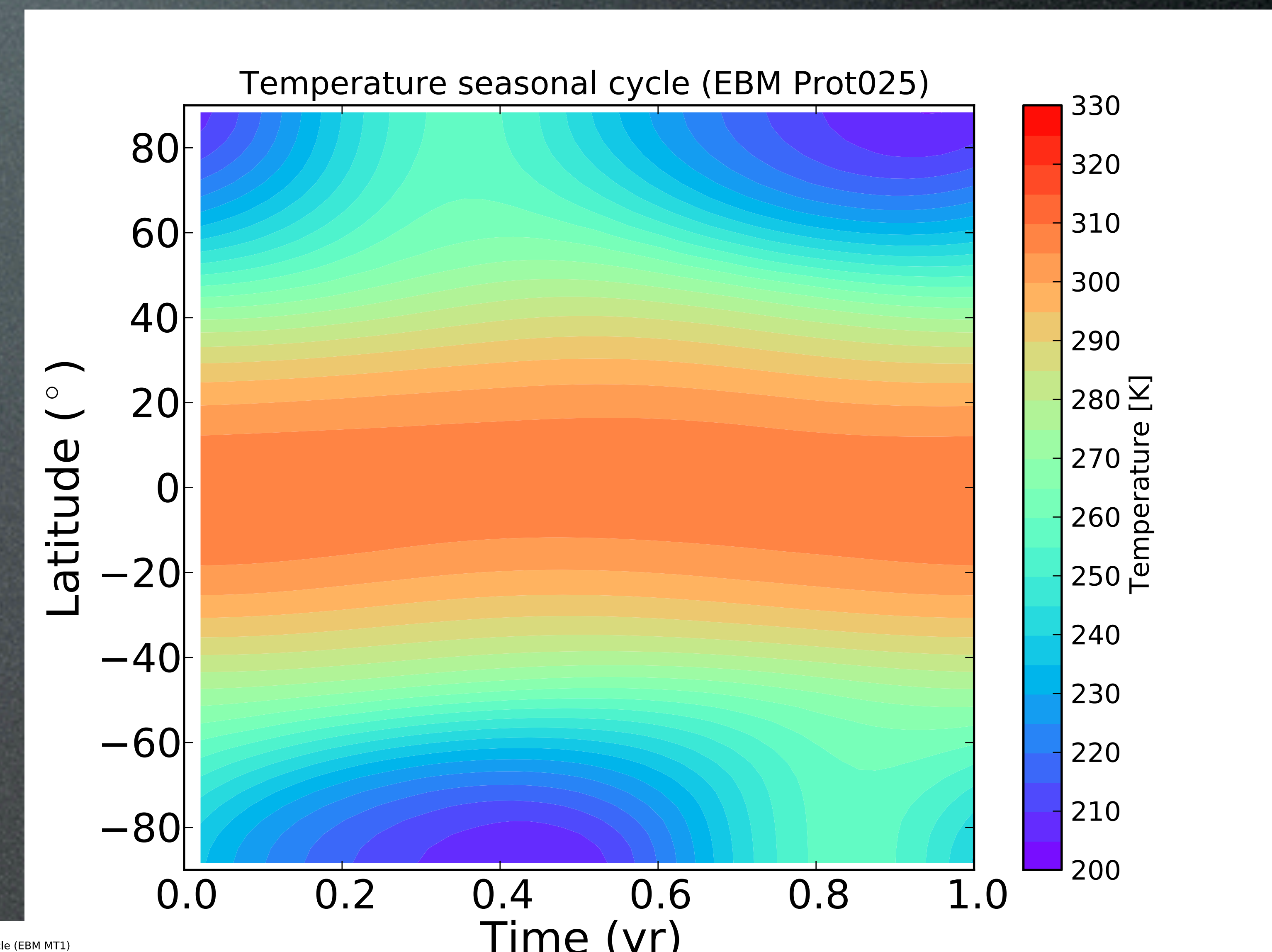


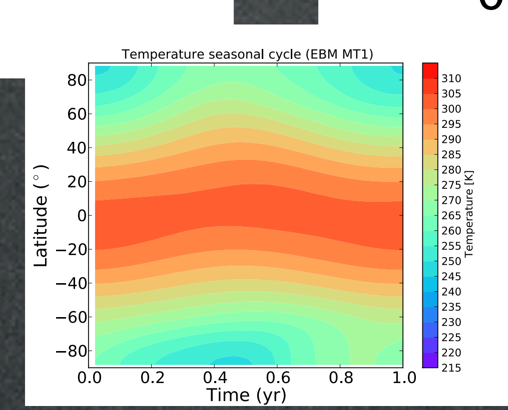
Rotation period

P_{rot}=2 d



P_{rot}=0.25 d

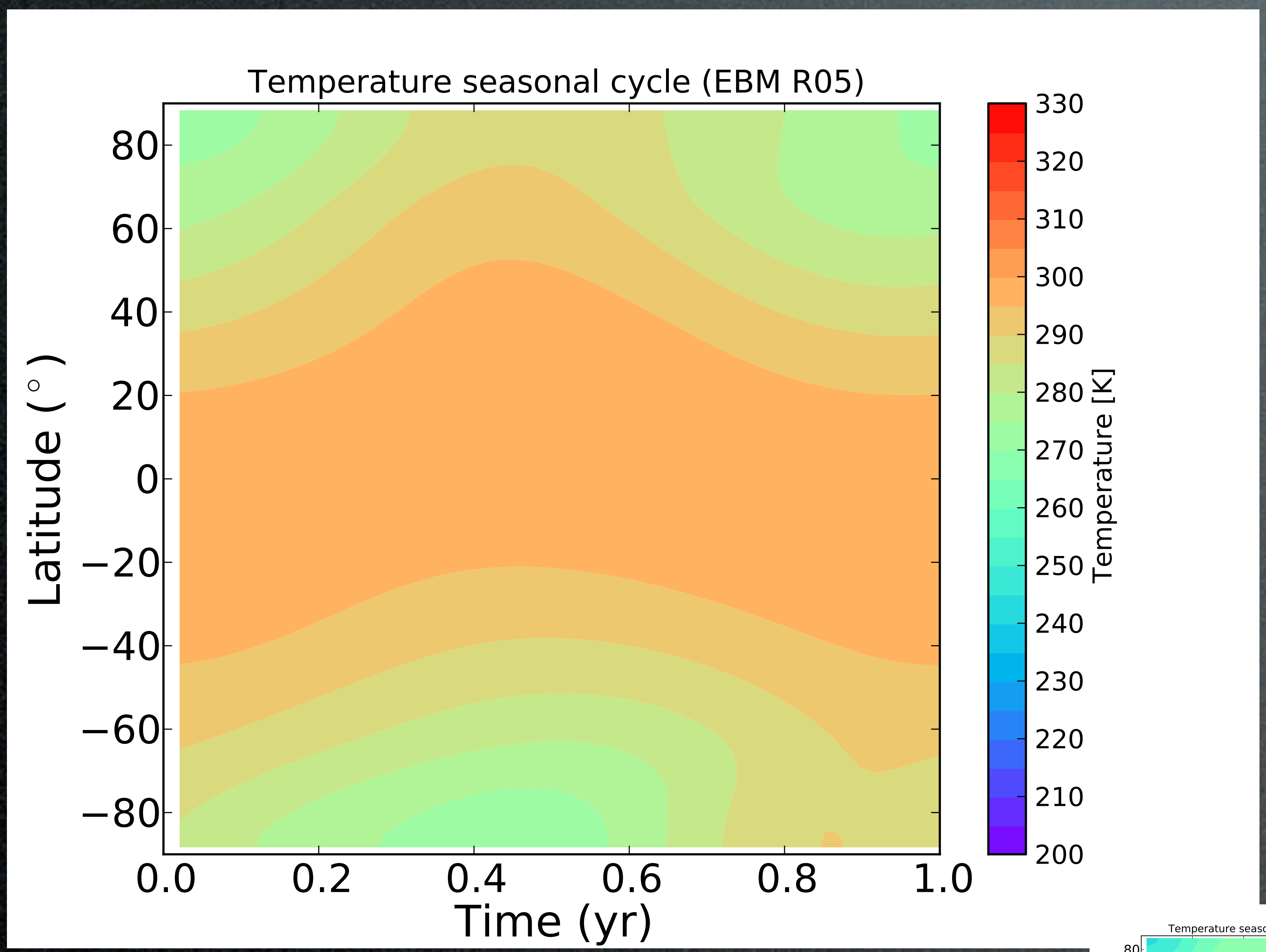


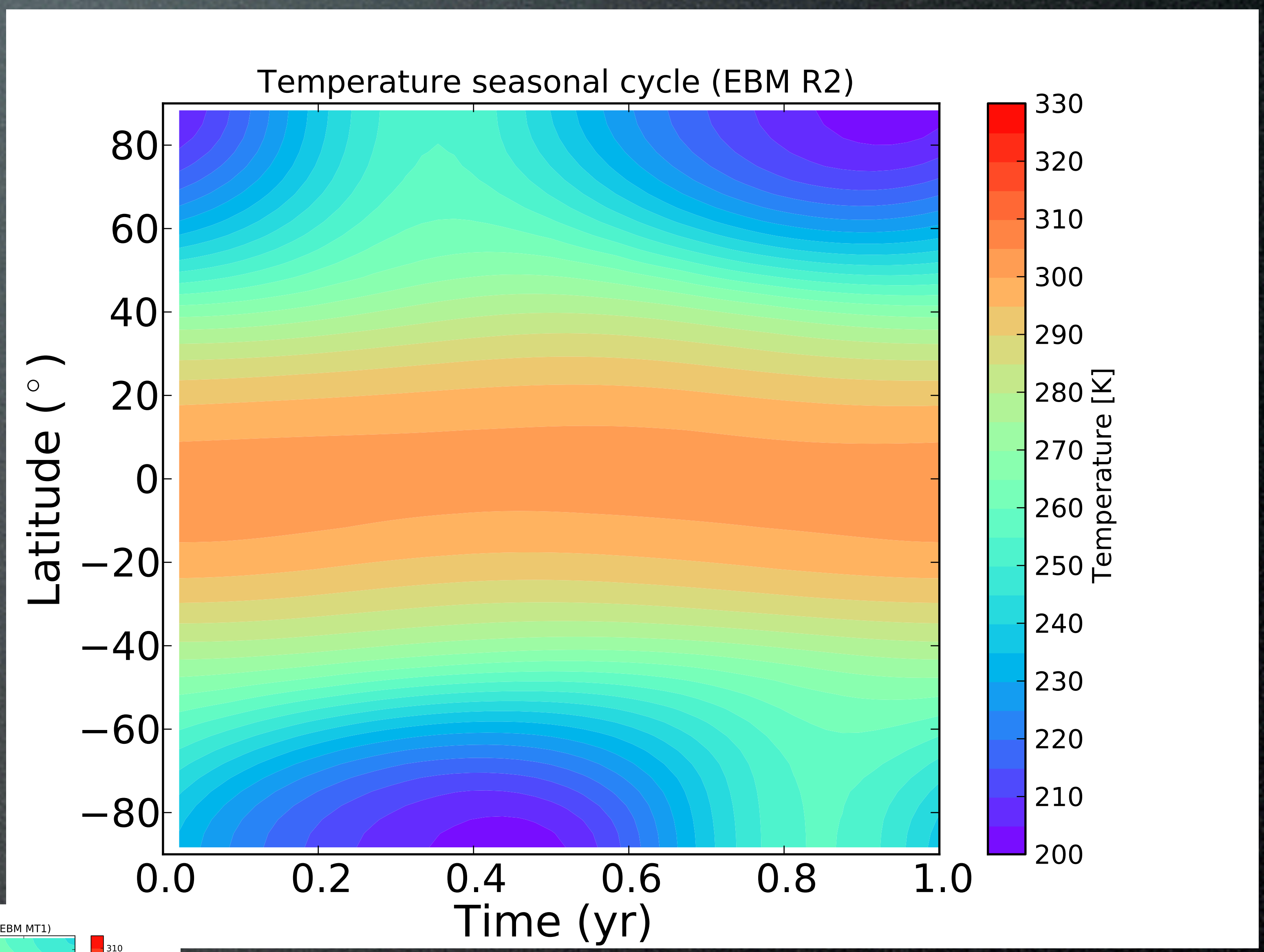


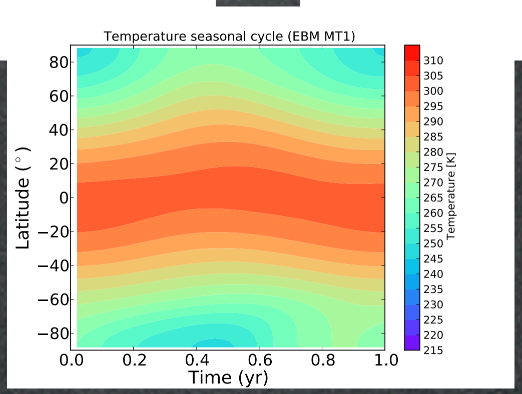
R=0.5 R_{earth}

Planet radius

R=2 R_{earth}



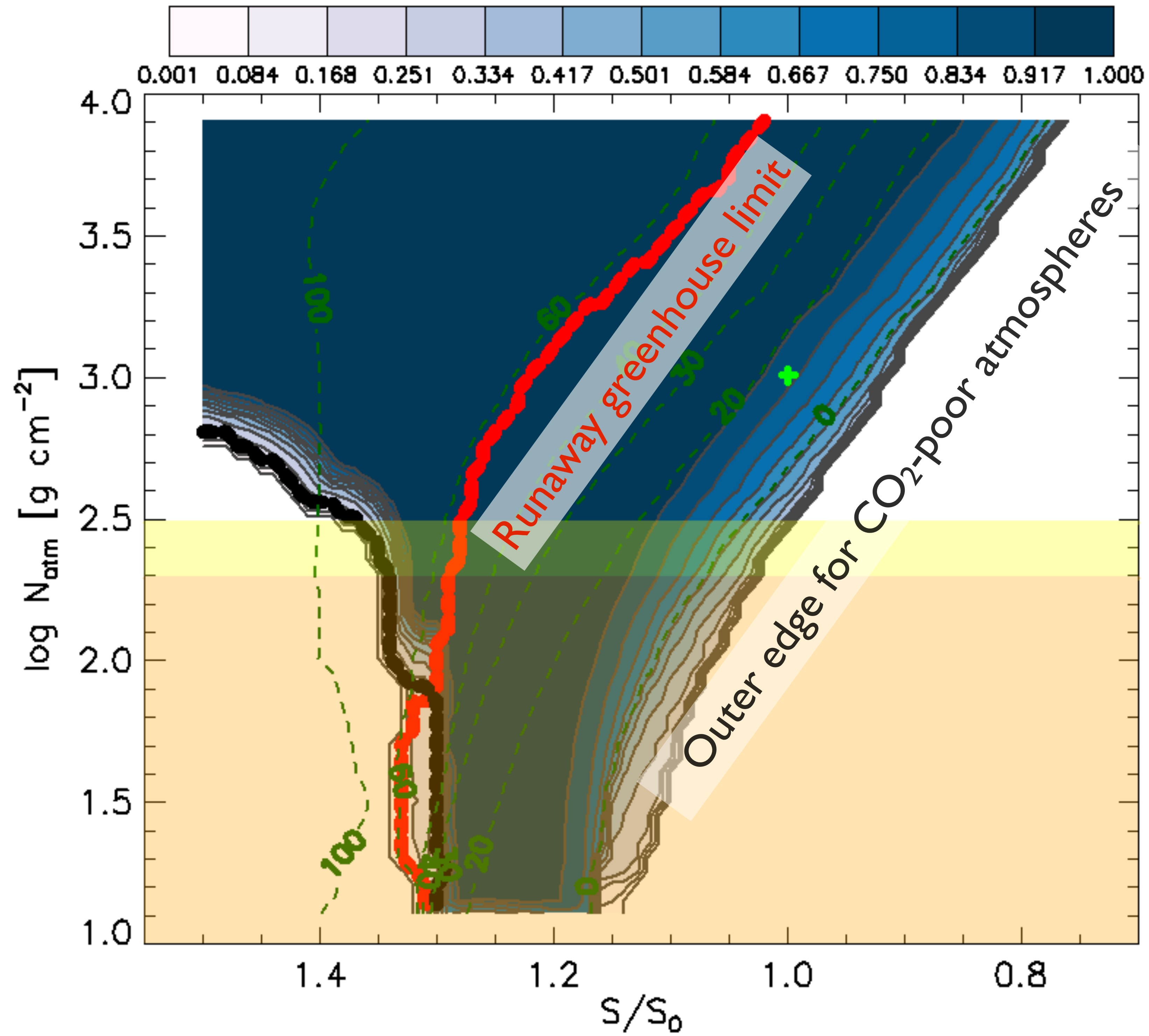




The habitable zone in the plane Insolation - Atmospheric Mass

at constant atmospheric composition

$$h = \frac{\int_{-\pi/2}^{+\pi/2} d\varphi \int_0^P dt\,[H(\varphi, t)\cos\varphi]}{2P}$$



Insolation

Liquid Water Criterion

$$H(\varphi, t) = \begin{cases} 1 & \text{if } T_{\mathrm{ice}}(p) \leqslant T(\varphi, t) \leqslant T_{\mathrm{vapor}}(p) \\ 0 & \text{otherwise.} \end{cases}$$

$N_{atm}=p/g$

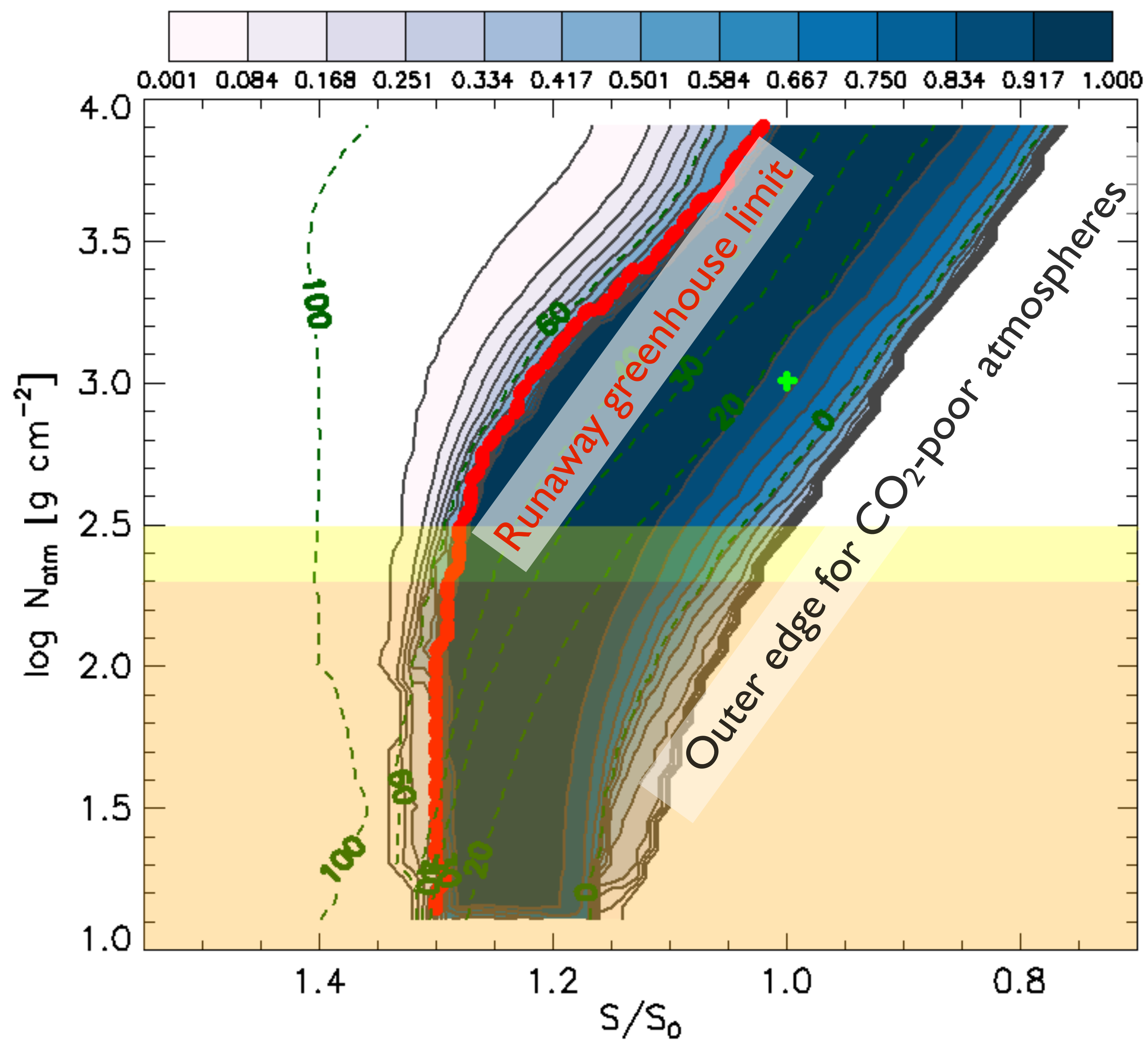
The habitable zone
in the plane
Insolation - Atmospheric Mass
at constant atmospheric composition

$$h = \frac{\int_{-\pi/2}^{+\pi/2} d\varphi \int_0^P dt\, [H(\varphi, t) \cos\varphi]}{2P}$$

Complex Life Criteria

$$H(\varphi, t) = \begin{cases} 1 & \text{if } 0\,°C \leqslant T(\varphi, t) \leqslant 60\,°C \\ 0 & \text{otherwise.} \end{cases}$$

$N_{atm} = p/g$

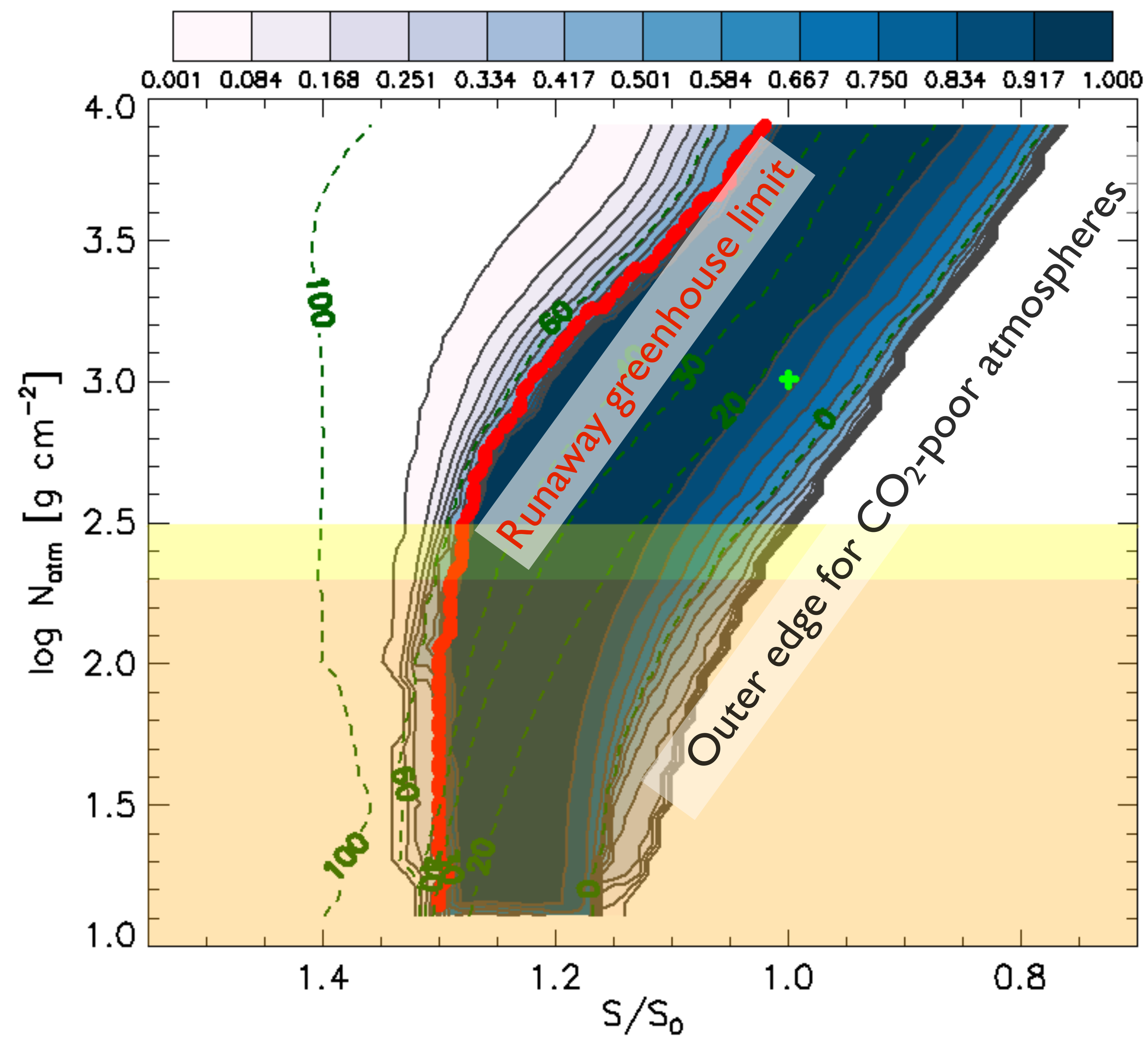


Insolation

Complex Life Criteria

Surface dose
100 mSv/yr
Galactic cosmic rays

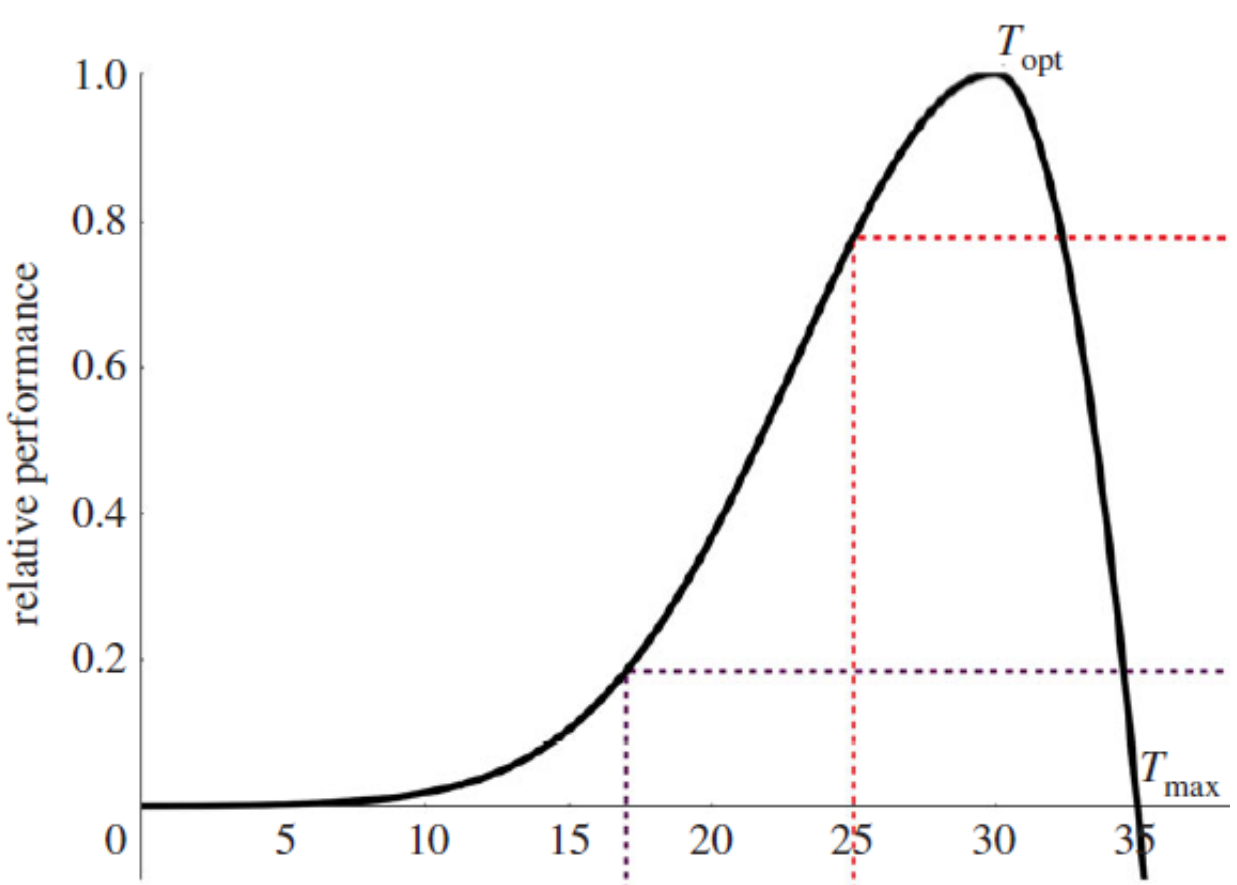
$$h = \frac{\int_{-\pi/2}^{+\pi/2} d\varphi \int_0^P dt\,[H(\varphi,t)\cos\varphi]}{2P}$$



Insolation

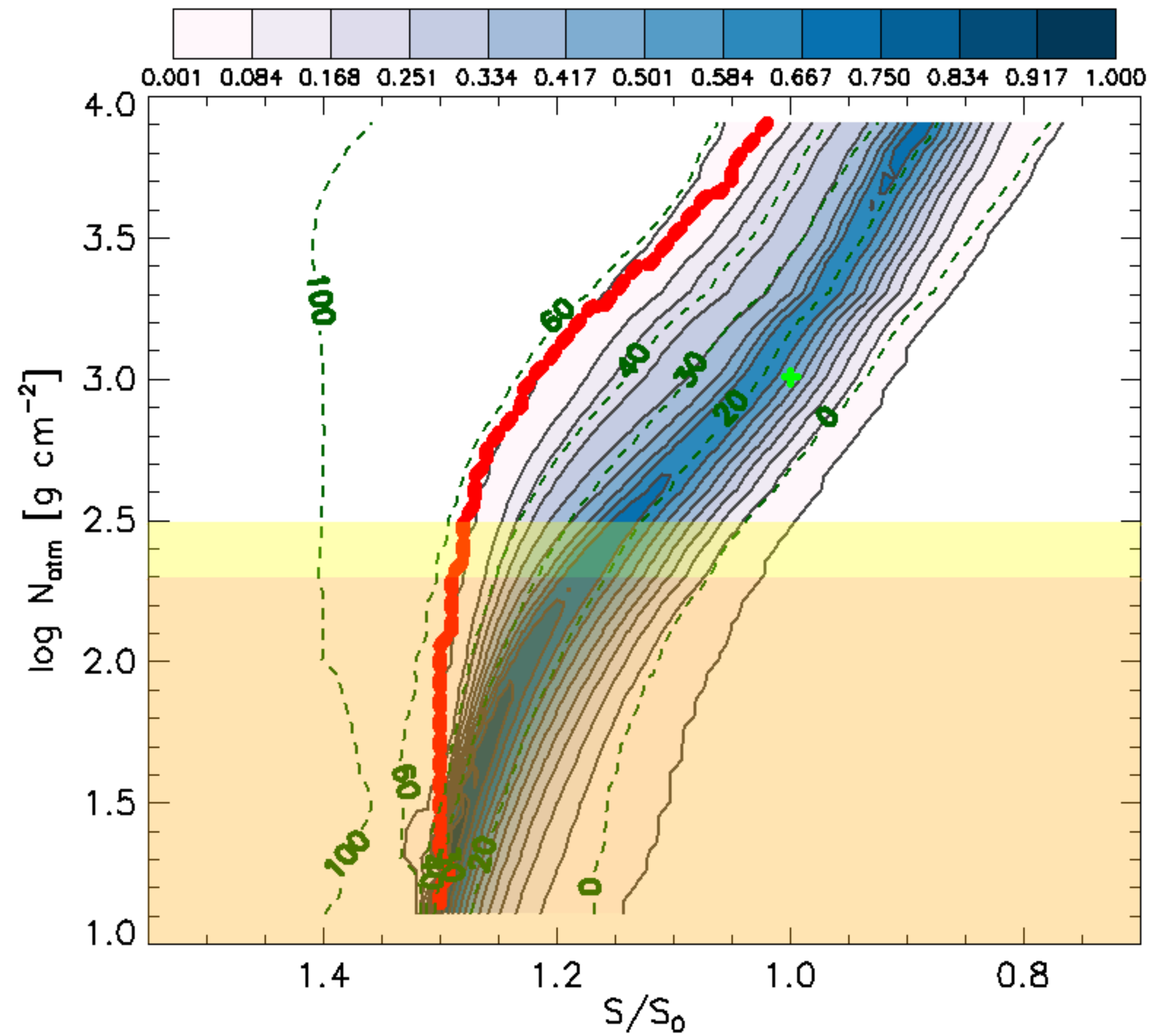
Complex Life Criteria

Thermal performance curve



Vasseur et al. (2015)

$$h = \frac{\int_{-\pi/2}^{+\pi/2} d\varphi \int_0^P dt\,[H(\varphi,t)\cos\varphi]}{2P}$$



Insolation

Application to exoplanets

The exoplanet should be of terrestrial type
(in lack of measurements of the planet mean density,
we select planets with $R < 1.7\ R_{\oplus}$)

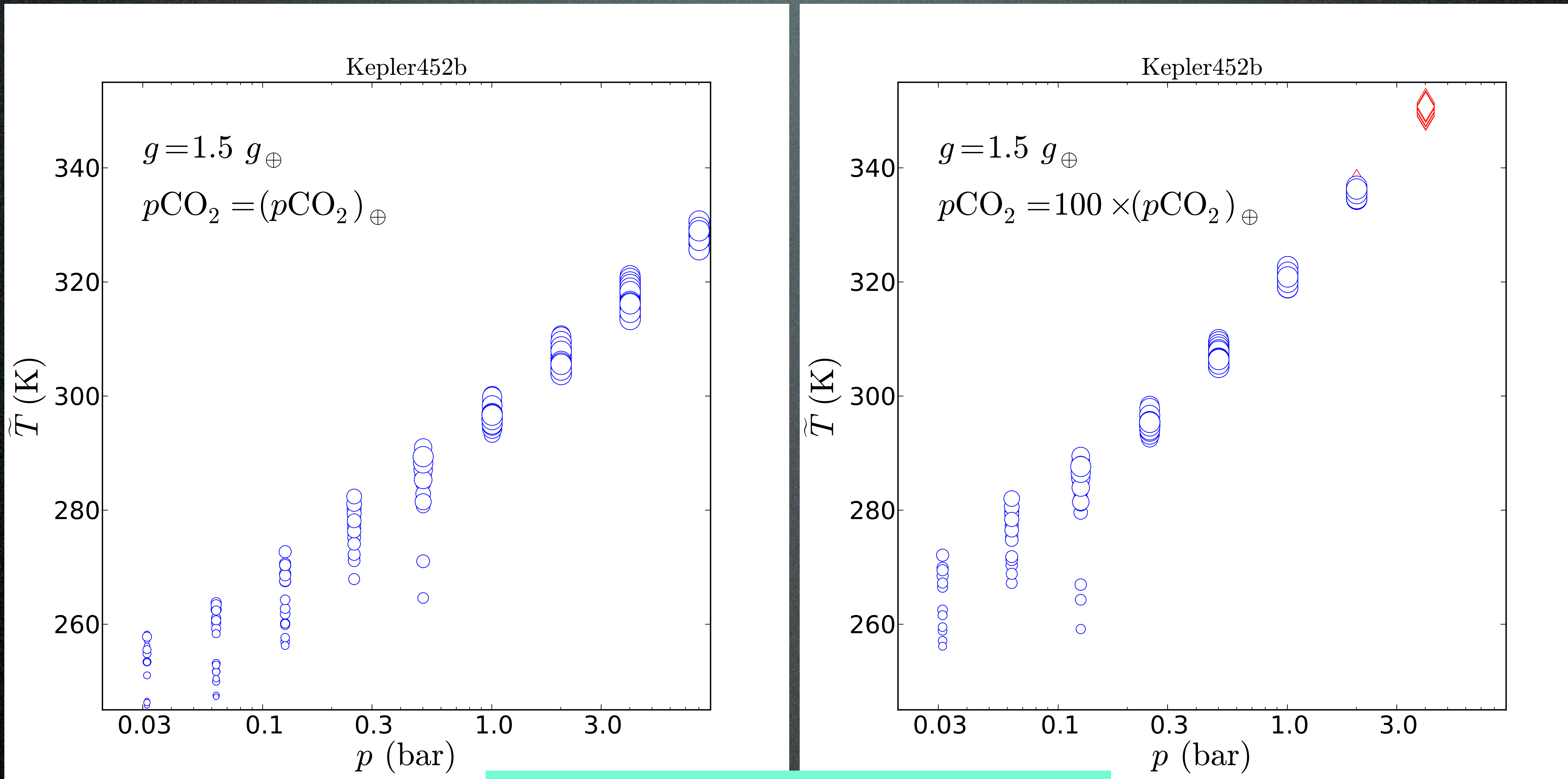
Planets should not be tidally locked
since the model approximations are valid when $P_{rot} << P_{orb}$

Kepler 452b

$R = 1.63\ R_{earth}$ $S = 1.10\ S_{o}$

Jenkins et al. (2015)

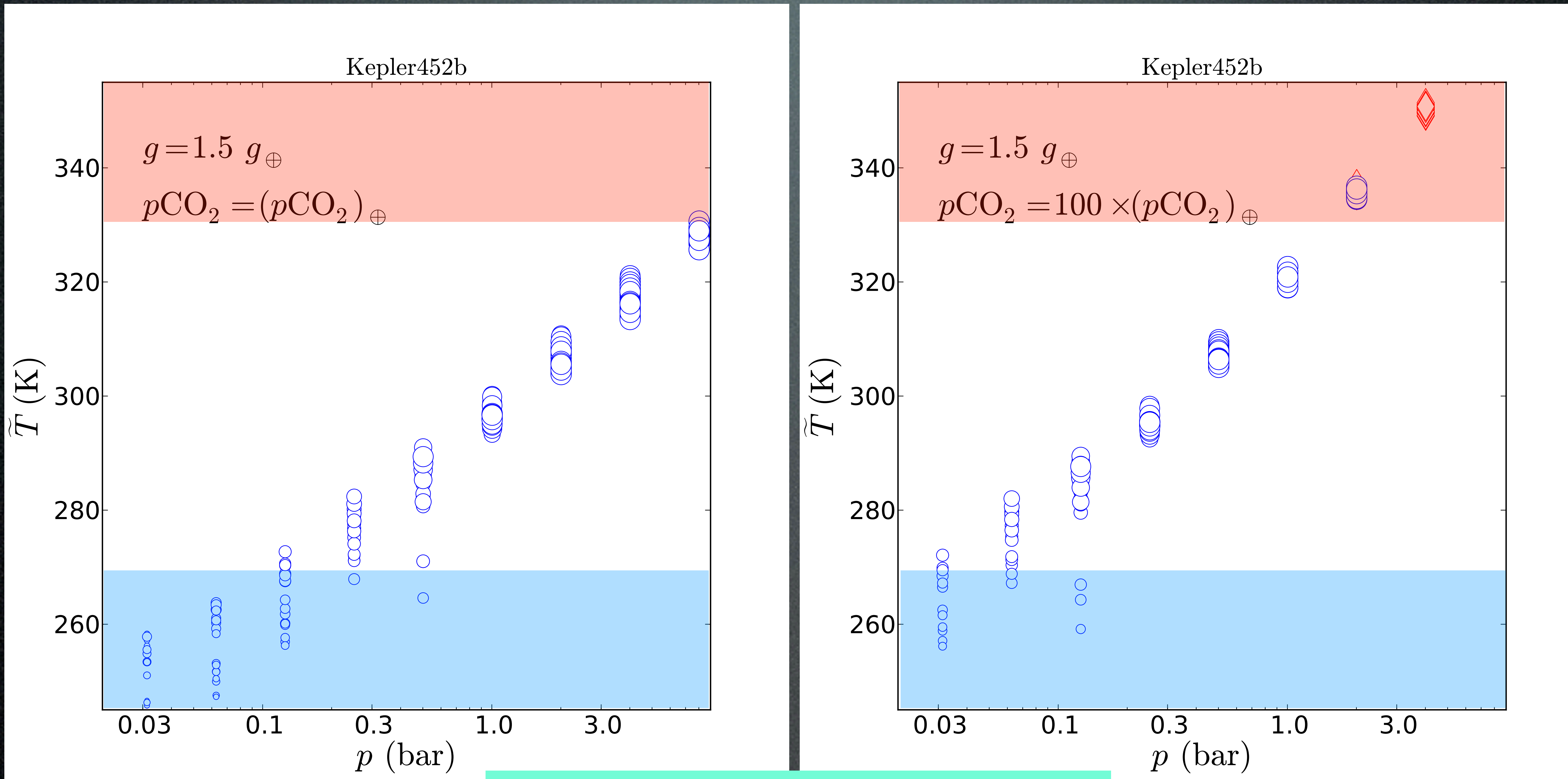
Explored a range of rotation rates, axis obliquities, & ocean fractions



Kepler 452b

R=1.63 R_{earth} S=1.10 S_o

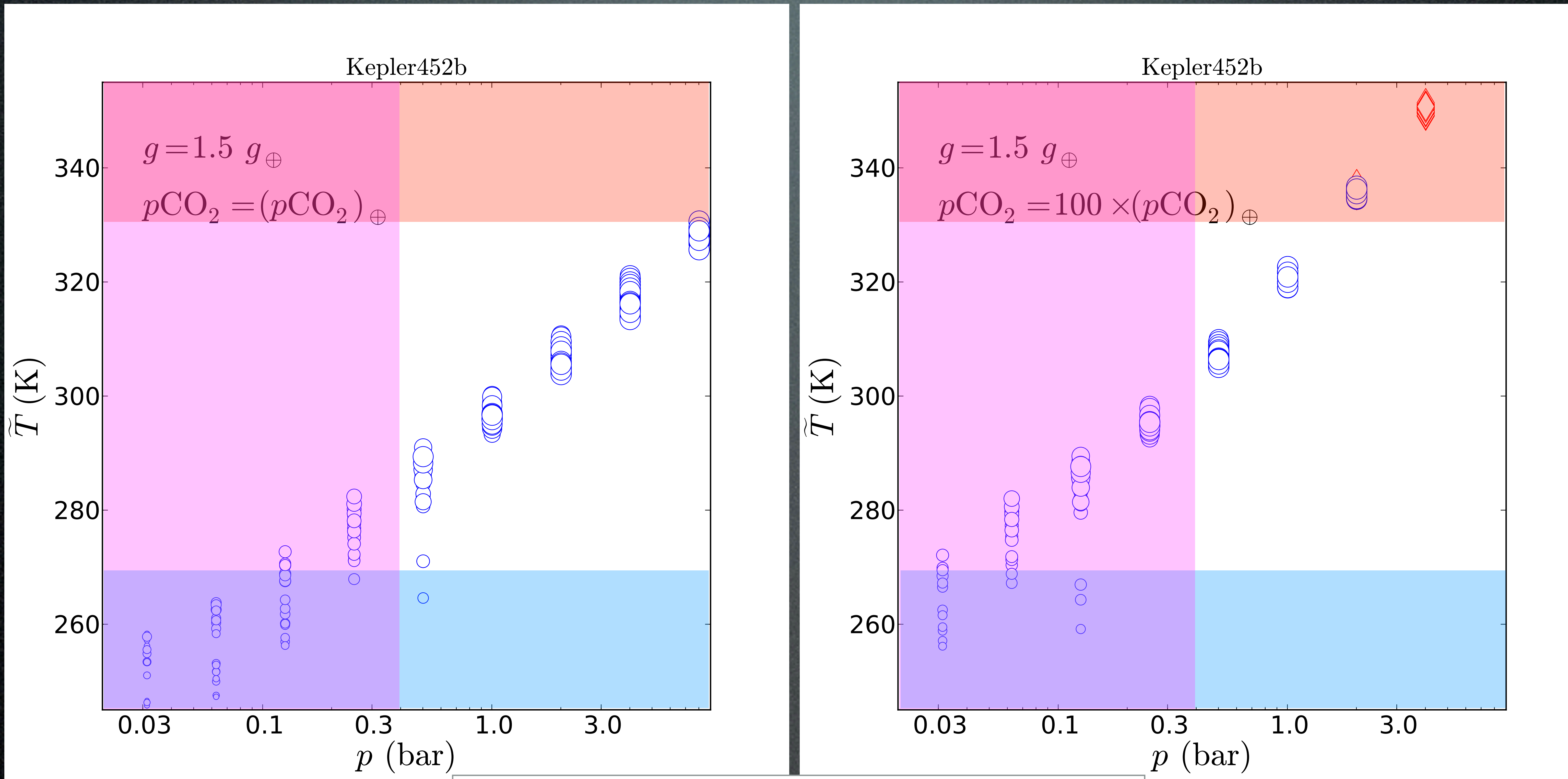
Adding temperature limits for complex life



Kepler 452b

R=1.63 R_{earth} S=1.10 S_o

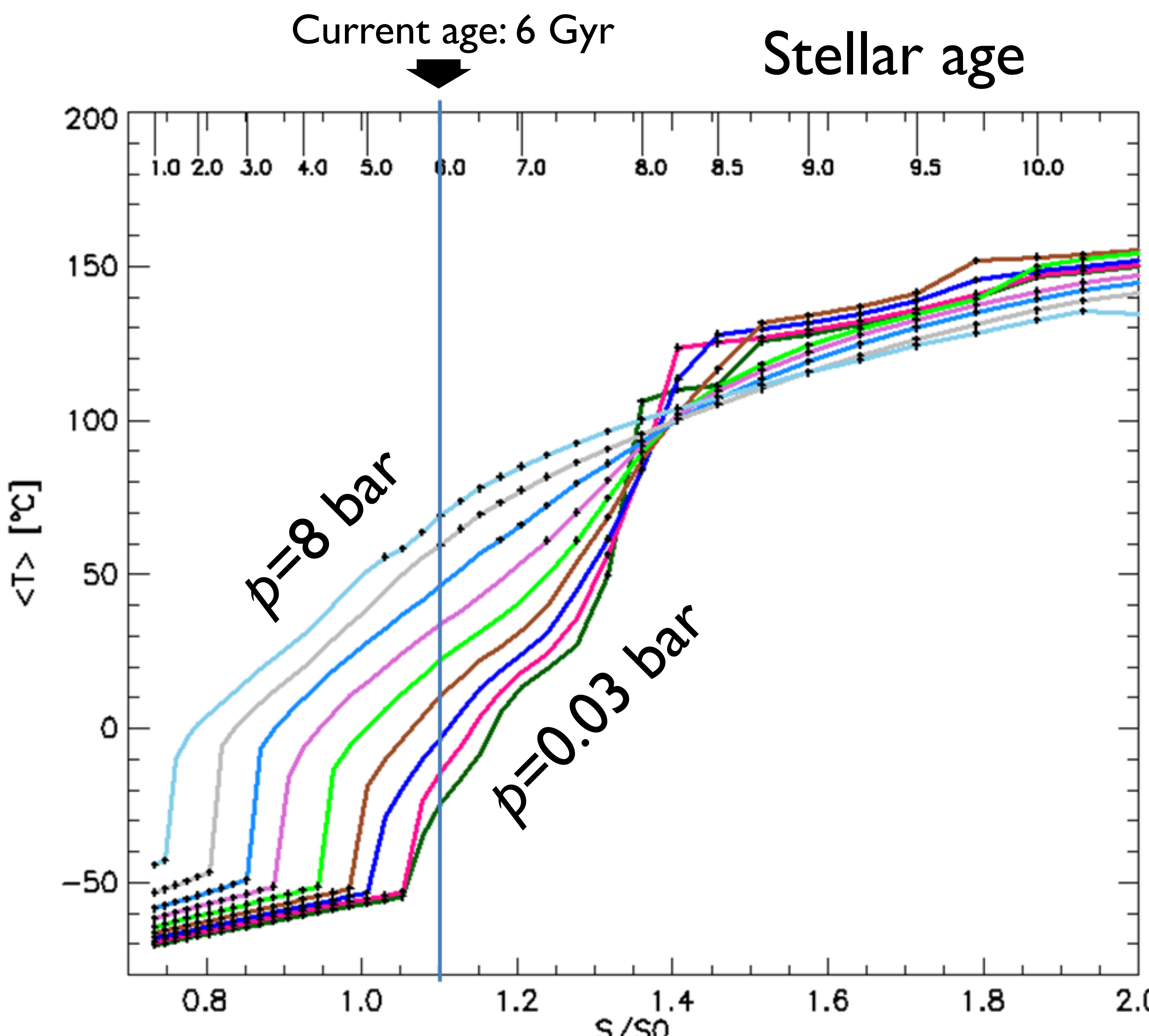
Adding radiation dose limits for complex life



Magenta area:
Surface dose of Galactic cosmic rays >100 mSv/yr
(Atri et al. 2013)

from stellar evolutionary tracks to planet insolation

Mean surface temperature



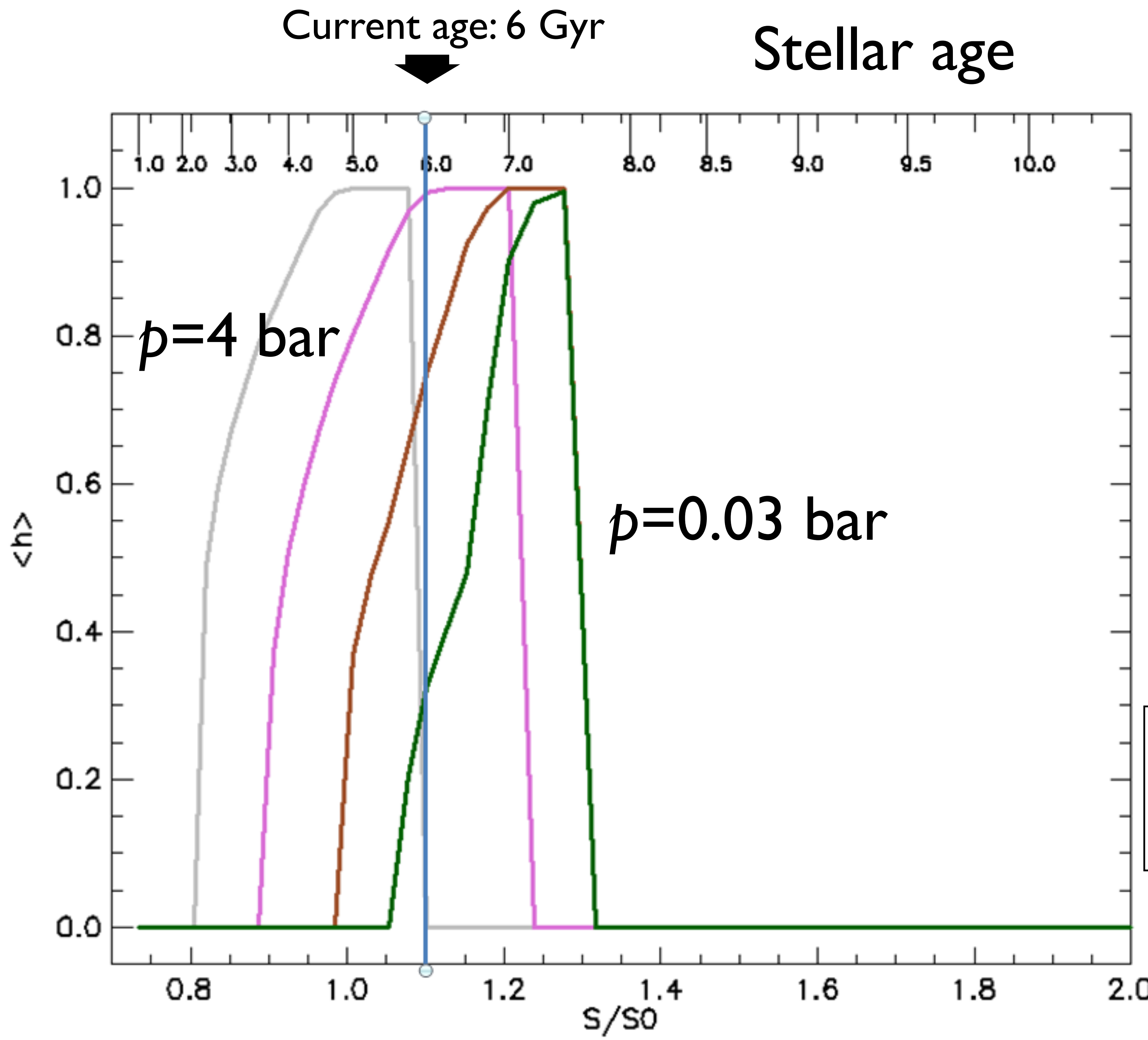
Kepler 452b
R=1.63 R_{earth}
S=S(t)

PARSEC tracks
Bressan et al. (2012)

$g=g_{Earth}$
$p(CO_2) = p(CO_2)_{Earth}$

from stellar evolutionary tracks to planet insolation

Mean surface habitability



Kepler 452b
$R=1.63\ R_{earth}$
$S=S(t)$

PARSEC tracks
Bressan et al. (2012)

$g=g_{Earth}$
$p(CO_2)=p(CO_2)_{Earth}$

Future work

Upgrading the model to study planetary atmospheres with a broader range of chemical composition

Applying the model to terrestrial planets with tighter observational constraints (both R and M ; ideally also p, CO_2)