# Energy Balance Models of planetary climate as a tool for investigating the habitability of terrestrial planets and its evolution

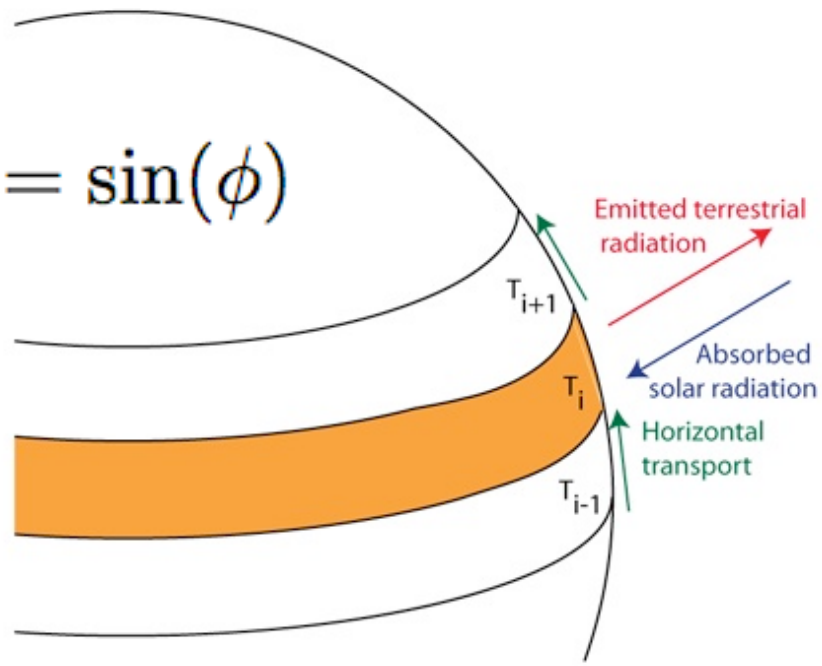
Gaia Ferri (1,2), Giuseppe Murante (3), Antonello Provenzale (4), Laura Silva (1), Giovanni Vladilo (1,2)

(1) INAF - Osservatorio Astronomico di Trieste
(2) University of Trieste, Department of Physics
(3) INAF - Osservatorio Astronomico di Torino
(4) Institute of Atmospheric Sciences and Climate (ISAC)-CNR, Torino

# Energy Balance Models (EBMs)

1-D: relevant quantities averaged in each latitude zone ($P_{rot}$ << $P_{orb}$)
Meridional heat transport simulated by diffusion equation

$$x = \sin(\phi)$$




OUTGOING PLANETARY RADIATION (thermal IR)

INCOMING STELLAR RADIATION (visible/UV)

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

Temporal evolution

Meridional transport

# Solving the model

The diffusive equation can be solved with numerical methods

Temporal part:
adaptive Runge-Kutta (4th order)

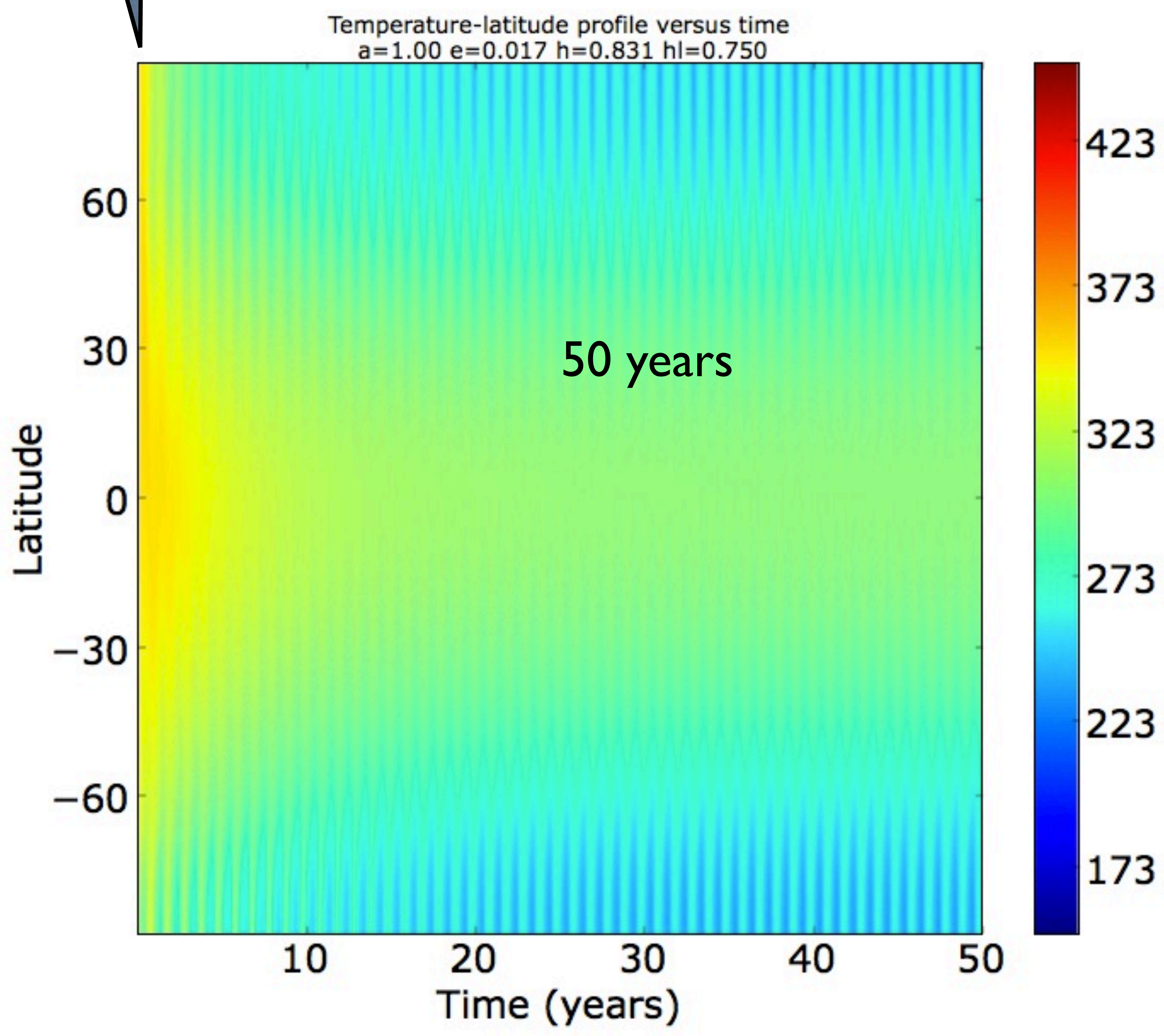
Spatial part:
Euler method

Trial set of initial temperatures $T_i$

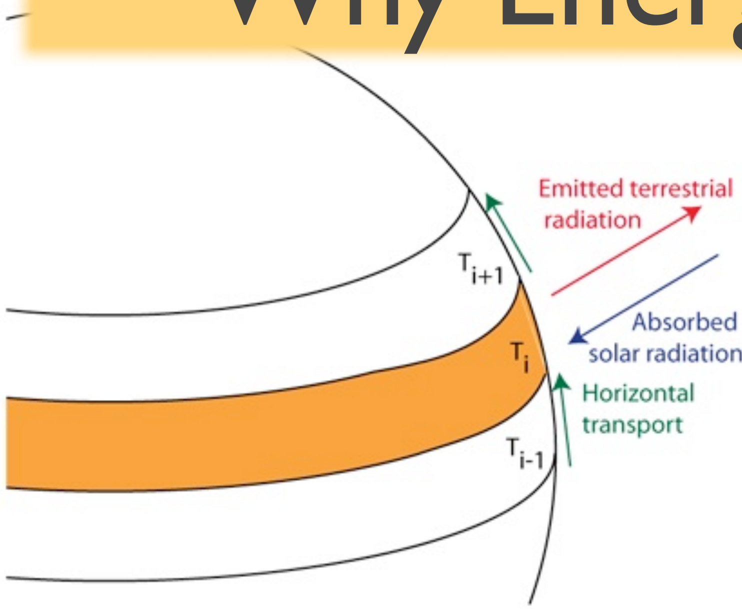
Search for convergence of the mean global annual temperature <T>

Hot start

Latitude-time temperature diagram



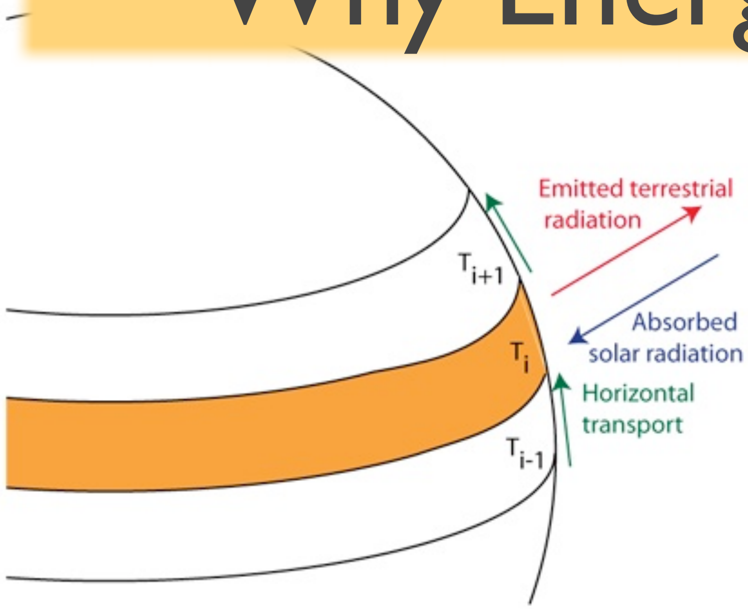
# Why Energy Balance Models ?




Energy Balance Models

Fast simulations
Moderate number of parameters
Schematic geography

# Why Energy Balance Models ?

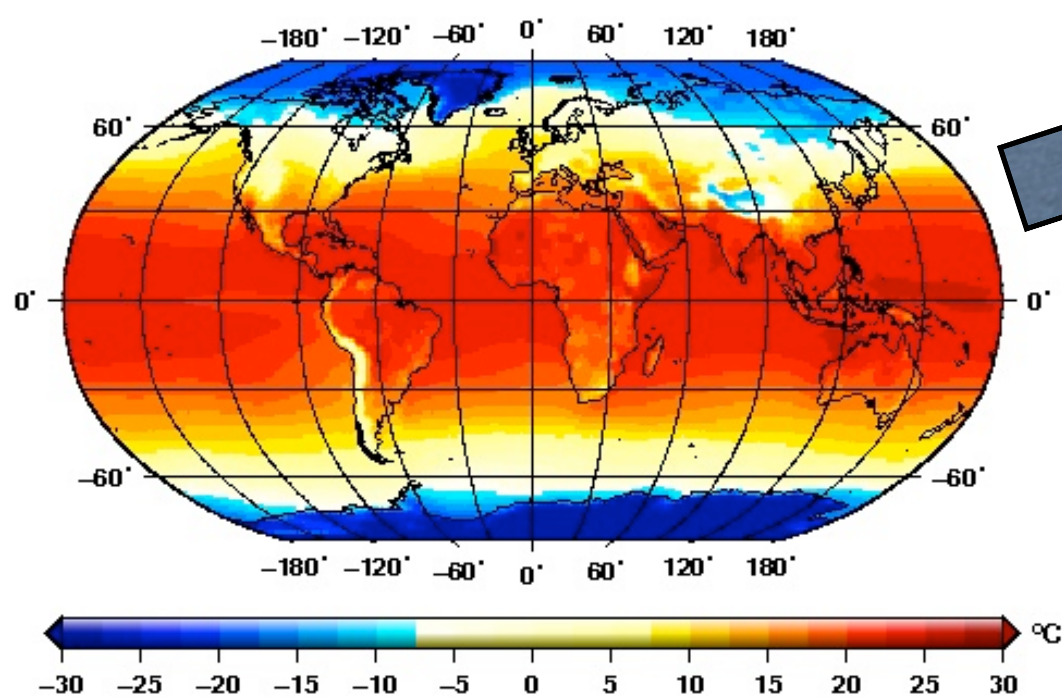



Energy Balance Models

vs

Global Circulation Models

Ideal for exploratory work when experimental data are scarce as in the case of extrasolar planets




State-of-the art GCMs can be used to build up refined recepies for EBMs

# The code

Built on previous EBMs

(Williams & Kasting 1997; Spiegel et al. 2008, 2009)

## New implementations

- Elliptical planetary orbits
- Albedo with variable cloud cover
- Diffusion coefficient dependent on stellar zenith distance

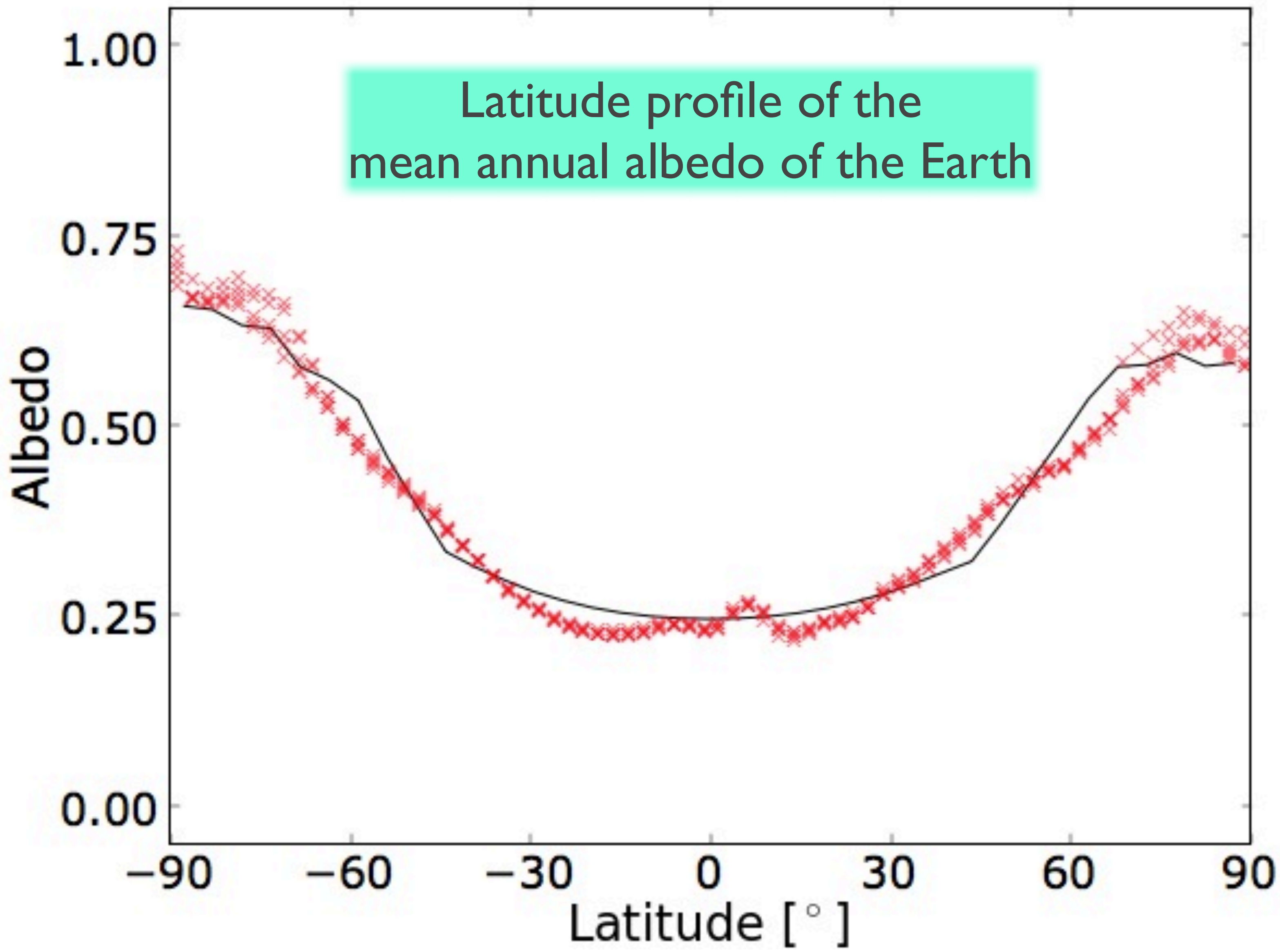
# Albedo

The parametrization of the cloud coverage takes into account the type of underlying surface

Cloud coverage on different types of surfaces constrained by Earth experimental data (Sanroma & Pallé 2011)

Top of amosphere correction (Williams & Kasting 1997)

# Tuning of the albedo parameters




Red crosses: short wavelength albedo data (ERBE1985-1989)

Solid line: our model

# Diffusion coefficient

Pressure — Specific heat capacity — Molecular weight — Rotational angular velocity

$$\left(\frac{D}{D_0}\right) = \zeta(\overline{\mu}) \left(\frac{p}{p_0}\right) \left(\frac{c_{\mathrm{p}}}{c_{\mathrm{p}0}}\right) \left(\frac{m}{m_0}\right)^{-2} \left(\frac{\Omega}{\Omega_0}\right)^{-2}$$

Our modulation term

Williams & Kasting (1997)

We introduce a modulation term that scales with $\overline{\mu} = \overline{\mu}(\phi, t; \epsilon)$

$\overline{\mu} = \; <\cos Z>$ Diurnal average of the cosine of the stellar zenith distance

Normalization conditions

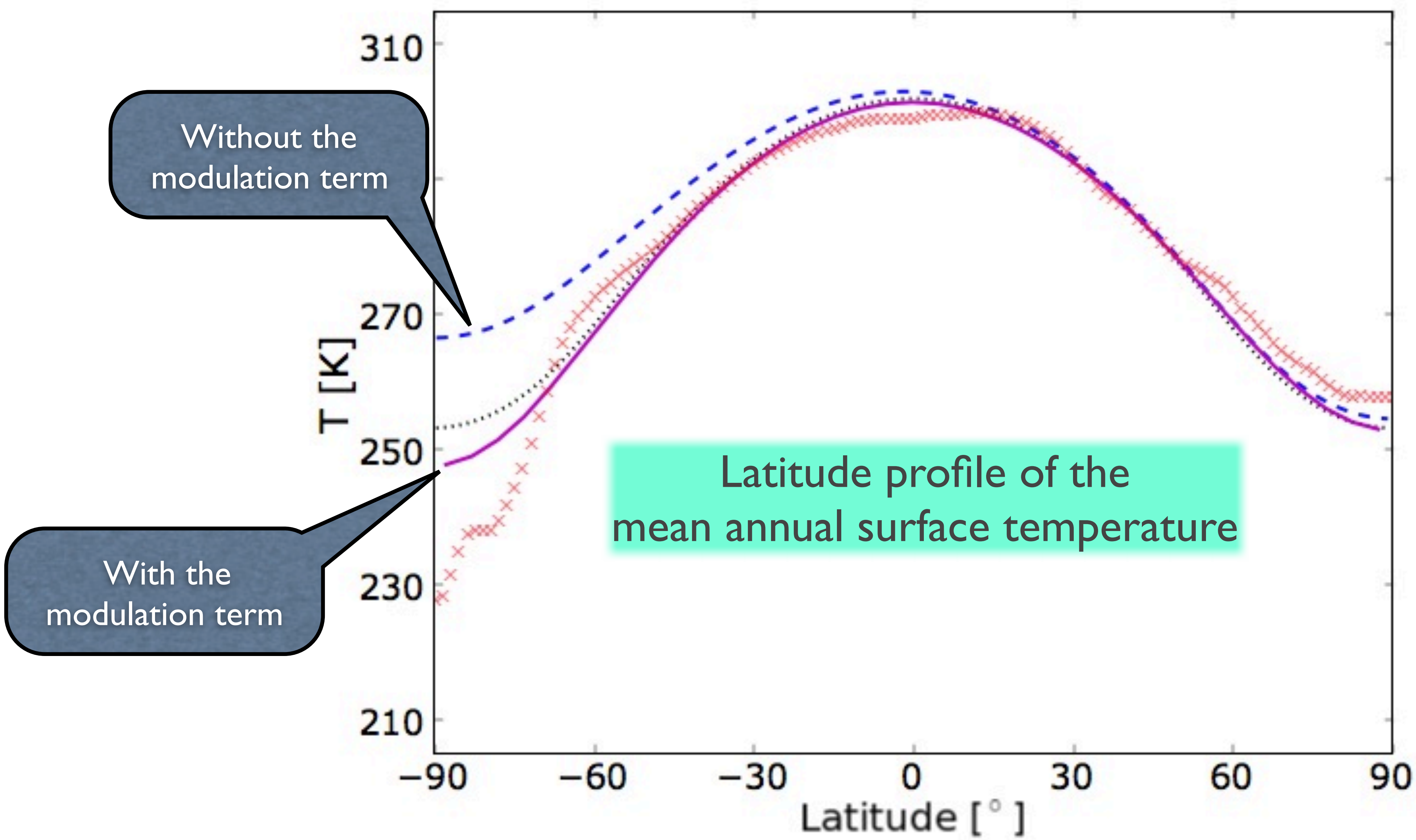
$$<\zeta(\phi, t; \epsilon)> = 1$$

$$\mathcal{R} = \frac{[\zeta(\phi, t; \epsilon)]_{\max}}{[\zeta(\phi, t; \epsilon)]_{\min}} \simeq 3$$

North et al. (1983)

# Testing the diffusion coefficient

The modulation term improves the fit
of the observed temperature-latitude profile of the Earth




Red crosses: ERA Interim 2m temperature profiles (average 1979-2010)
Validation of a model presented by Spiegel et al. (2008)

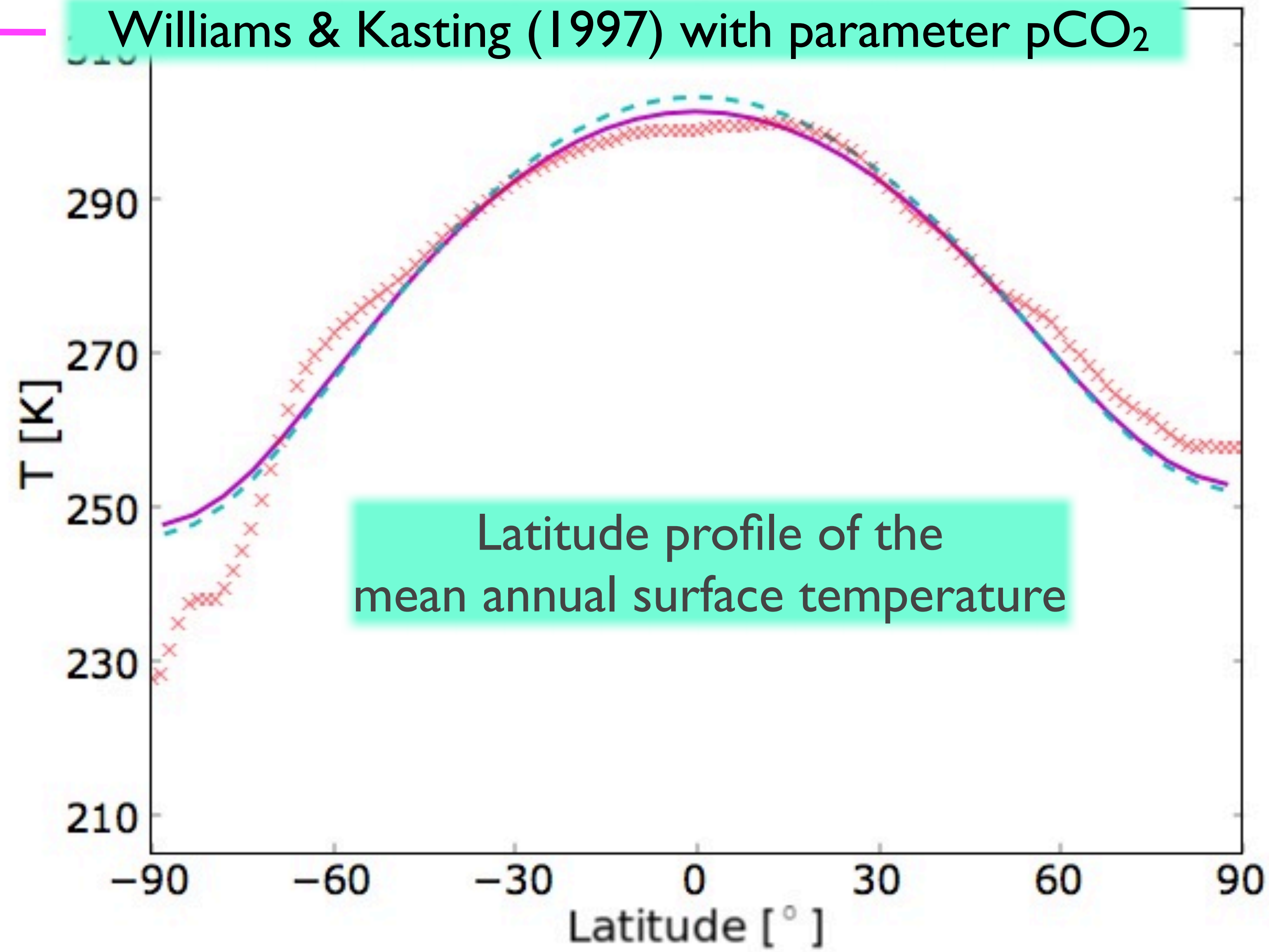
# Outgoing thermal radiation

We considered two functions

Spiegel et al. (2008, 2009) with parameter tau(IR)

Williams & Kasting (1997) with parameter $pCO_2$

For each function we tuned our model parameters in such a way to obtain a best fit of the temperature- latitude profile of the Earth




Red crosses : ERA Interim 2m temperature profiles (average 1979-2010)

# Quantifying habitability

The models yields the surface temperature as a function of latitude and time

$$T(\phi, t)$$

Habitability function

$$H(\phi,t) = \begin{cases} 1 & \text{if } \; T_{\min} \leq T(\phi,t) \leq T_{\max} \\ 0 & \text{otherwise} \end{cases}$$

Liquid water criterion

$$(T_{\min}, T_{\max}) = (273.15\,\mathrm{K}, 373.15\,\mathrm{K}) \qquad (P = 1 \text{ bar})$$

Mean global annual habitability

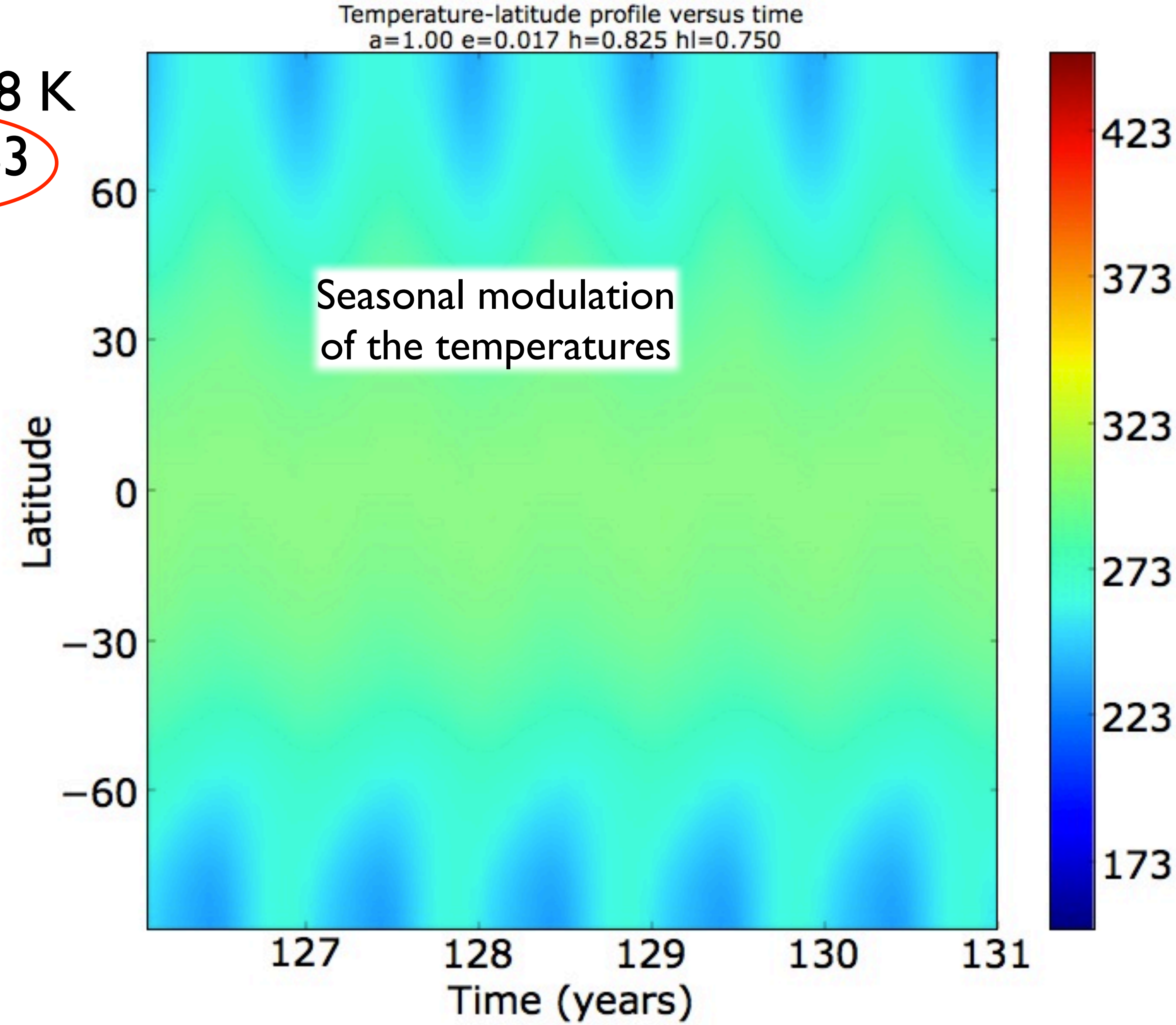
$$f_{\rm hab} = \frac{\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} d\phi \int_0^P dt \, [H(\phi,t)\, \cos\phi]}{2P}$$

# Example of result

present-day Earth last 5 years

<T>= 288 K

$f_{hab}$=0.83




T (K)

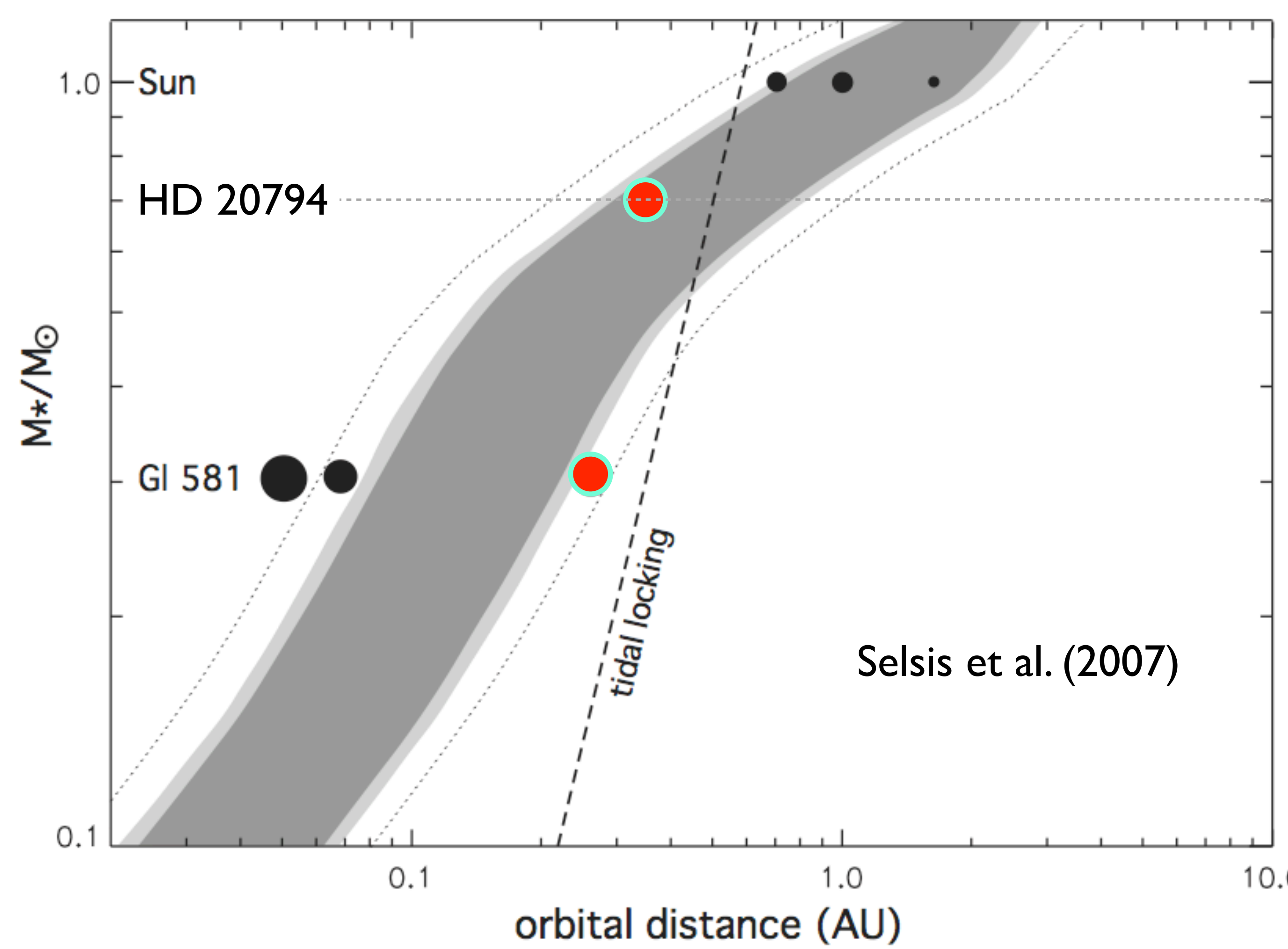
Example of application of EBMs

# Exploring the habitability of extrasolar planets

# Planets suitable for the application of EBMs
# (1) terrestrial type
# (2) $P_{rot} << P_{orb}$

| | | |
|---|---|---|
| HD 1461 b | a=0.0635 AU | M=7.63 M(earth) |
| HD 7924 b | a=0.0566 AU | M=9.26 M(earth) |
| HD 20794 b | a=0.1207 AU | M=2.70 M(earth) |
| HD 20794 c | a=0.2036 AU | M=2.36 M(earth) |
| HD 20794 d | a=0.3498 AU | M=4.70 M(earth) |
| GJ 176 b | a=0.0657 AU | M=8.27 M(earth) |
| HD 40307 c | a=0.0801 AU | M=6.72 M(earth) |
| HD 40307 b | a=0.0469 AU | M=4.10 M(earth) |
| HD 40307 d | a=0.1324 AU | M=8.93 M(earth) |
| CoRoT-7 b | a=0.0172 AU | M=4.95 M(earth) |
| 55 Cnc e | a=0.0154 AU | M=7.81 M(earth) |
| HD 85512 b | a=0.2604 AU | M=3.62 M(earth) |
| GJ 3634 b | a=0.0287 AU | M=7.06 M(earth) |
| HD 97658 b | a=0.0797 AU | M=6.40 M(earth) |
| 61 Vir b | a=0.0501 AU | M=5.11 M(earth) |
| GJ 581 c | a=0.0729 AU | M=5.33 M(earth) |
| GJ 581 d | a=0.2177 AU | M=6.08 M(earth) |
| GJ 581 e | a=0.0285 AU | M=1.95 M(earth) |
| GJ 1214 b | a=0.0143 AU | M=6.47 M(earth) |
| HD 156668 b | a=0.0500 AU | M=4.15 M(earth) |
| Kepler-10 b | a=0.0168 AU | M=4.52 M(earth) |
| Kepler-20 b | a=0.0454 AU | M=8.46 M(earth) |
| Kepler-20 d | a=0.3453 AU | M=7.53 M(earth) |
| HD 181433 b | a=0.0801 AU | M=7.55 M(earth) |
| Kepler-11 b | a=0.0911 AU | M=4.30 M(earth) |
| Kepler-11 d | a=0.1542 AU | M=6.10 M(earth) |
| Kepler-11 f | a=0.2495 AU | M=2.30 M(earth) |
| Kepler-11 e | a=0.1939 AU | M=8.40 M(earth) |
| Kepler-18 b | a=0.0447 AU | M=6.88 M(earth) |
| HD 215497 b | a=0.0466 AU | M=6.63 M(earth) |
| GJ 876 d | a=0.0208 AU | M=5.86 M(earth) |

Planets selected for the present study
HD 20794 d
Gl 581 d

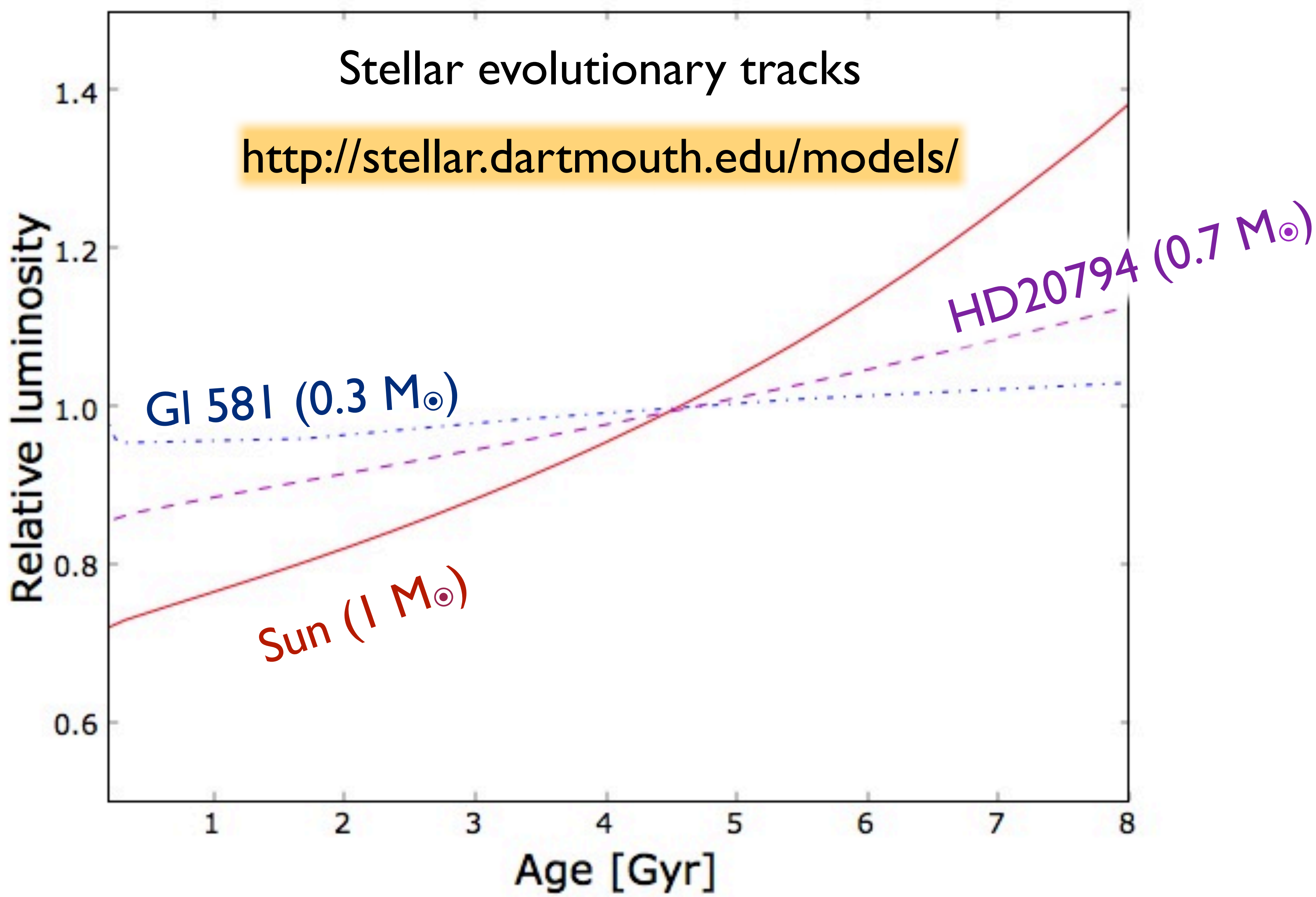


The most relevant EBM parameters
currently known from the observations of exoplanets are:
a (semi-major axis)
e (eccentricity)
stellar flux

With EBMs we can easily explore the effects
of many other parameters

In the following tests we varied only a few parameters
while adopting Earth values for the others

To study evolutionary effects
that may affect the habitability we explored variations of
(1) Planet rotation period: we expect these planets to slow down due to tidal effects
(2) Stellar luminosity: we rely on published stellar evolutionary tracks



# Planet HD20794d

a=0.3499 AU [e=0.00]
P=90.3 d Msini=4.7 M(earth)

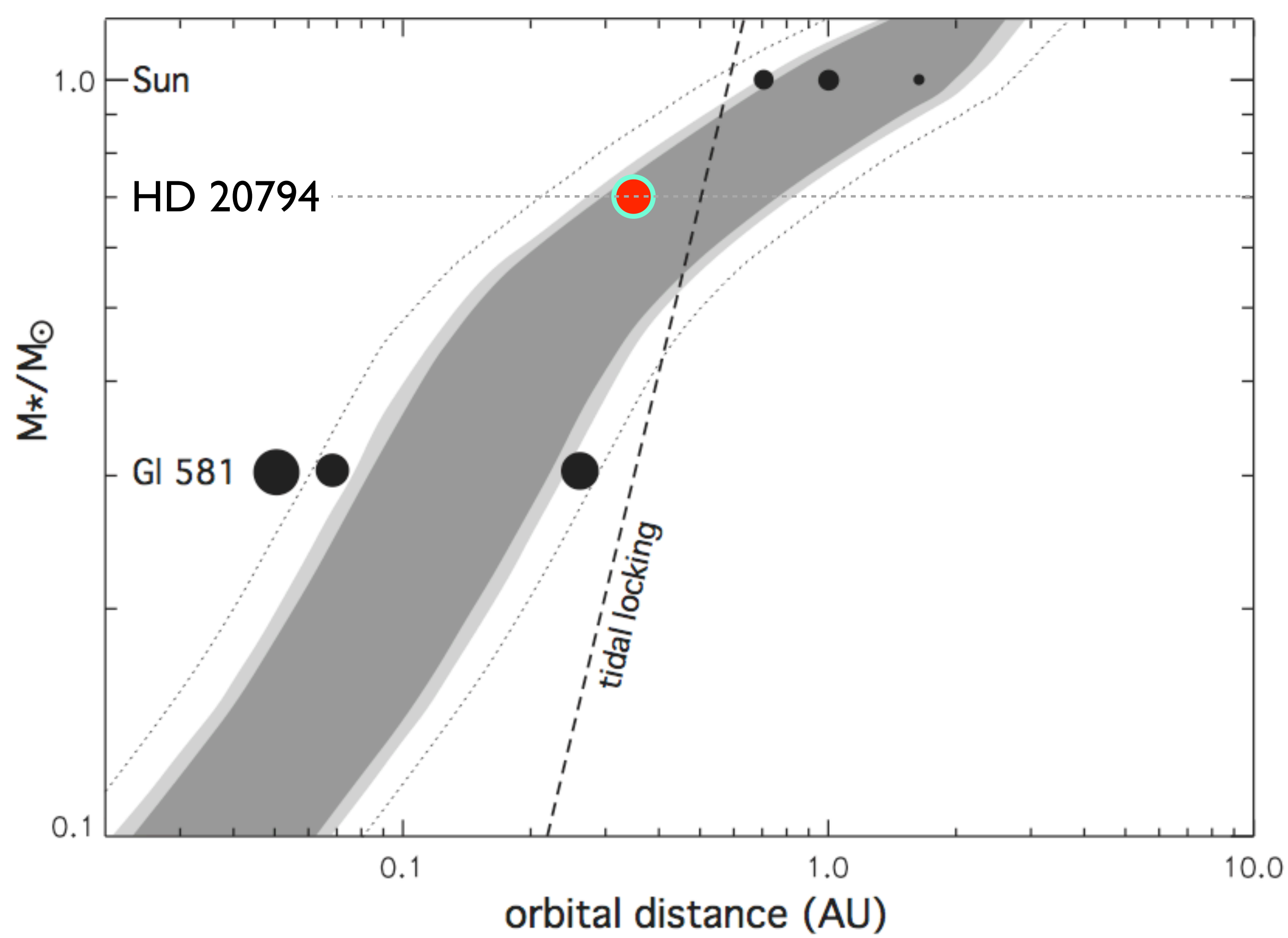
Pepe et al. (2011)

HD 20794 d lies at the inner edge of the “habitable zone”

If we assume an Earth-like greenhouse effect,
the planet would be “too hot”

To search for conditions of present-day habitability we considered
an atmosphere with little greenhouse effect

In this test we adopt a rotation period similar (but smaller) than the orbital period



# Present-day habitability of HD20794d

Stellar flux = present value

Earth-like parameters

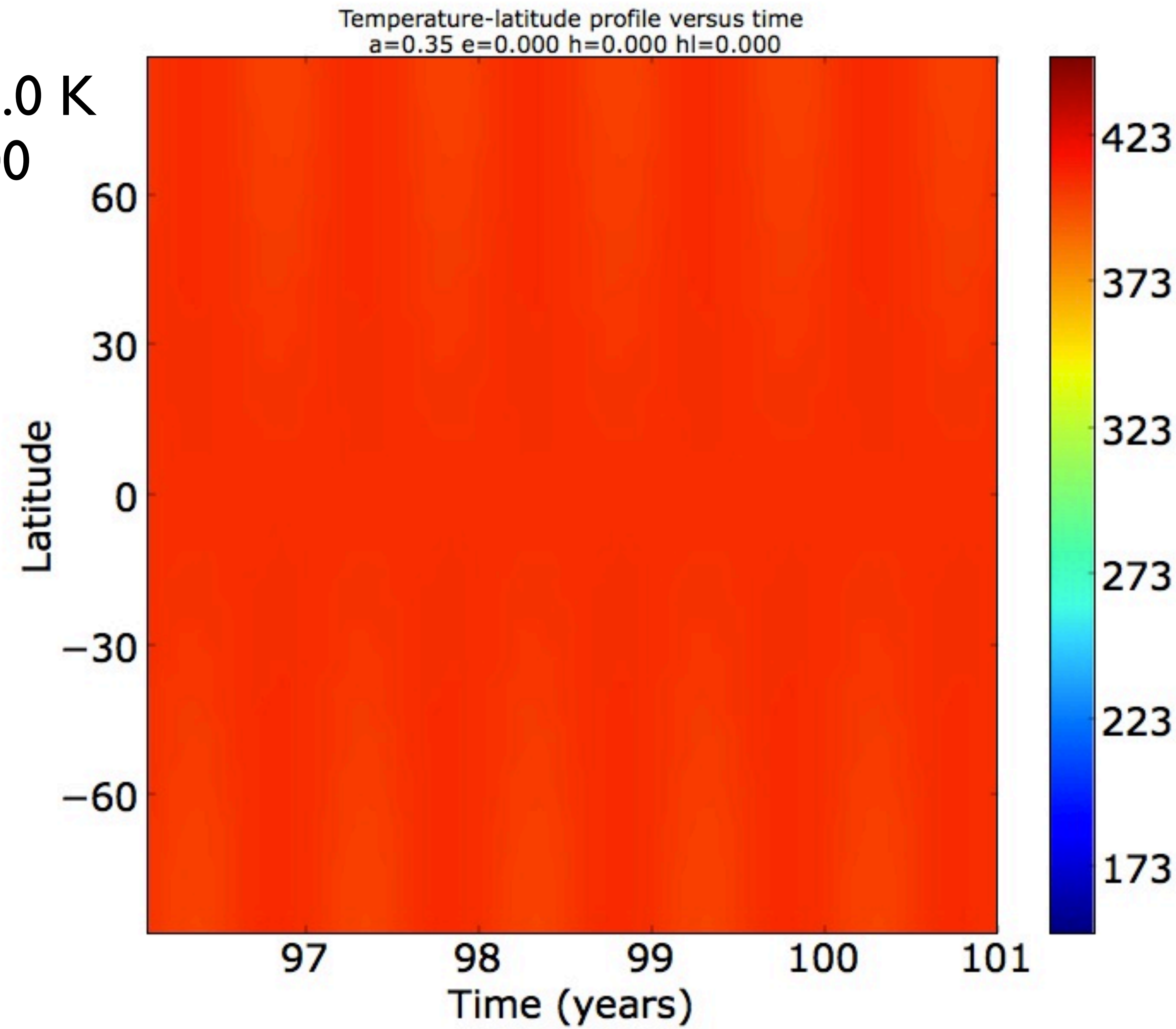
Rotation period = 45 d

Ps = 100 mB

$tau_{IR}$=0.1 $tau_{IR}$(earth)

<T>= 415.0 K

$f_{hab}$=0.00




T (K)

## Evolution of the habitability of HD20794d

TEST 11

We consider the initial stellar luminosity
(85% of the present value)

We start from an Earth-like rotation
and simulate the effect of slowing down the rotation

Ps = 100 mB

# Evolution of the habitability of HD20794d

Stellar flux = 0.85 present value

Rotation period = 1 d

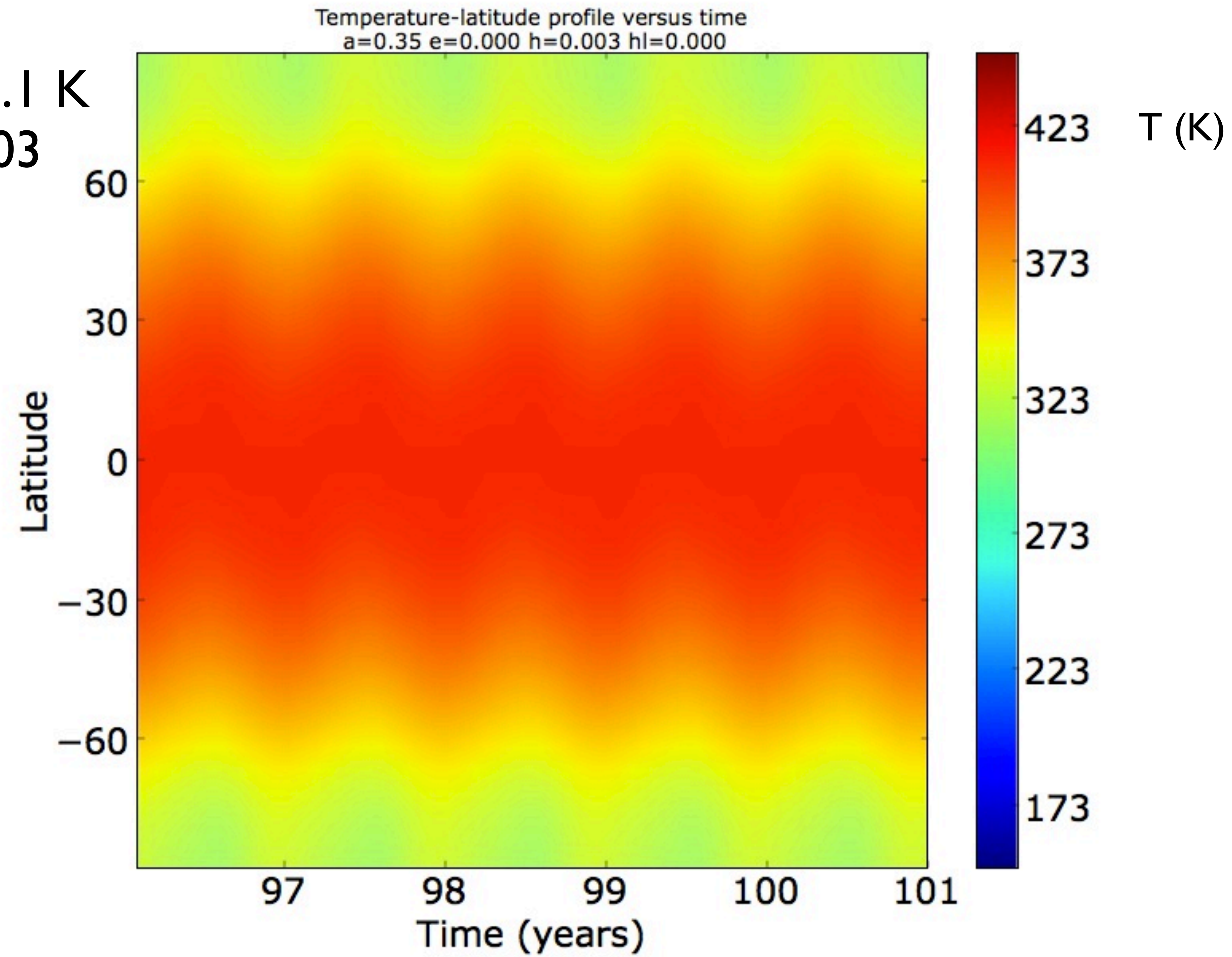
Earth-like parameters

Ps = 100 mB

$tau_{IR}$=0.1 $tau_{IR}$(earth)

<T>= 394.1 K

$f_{hab}$=0.003



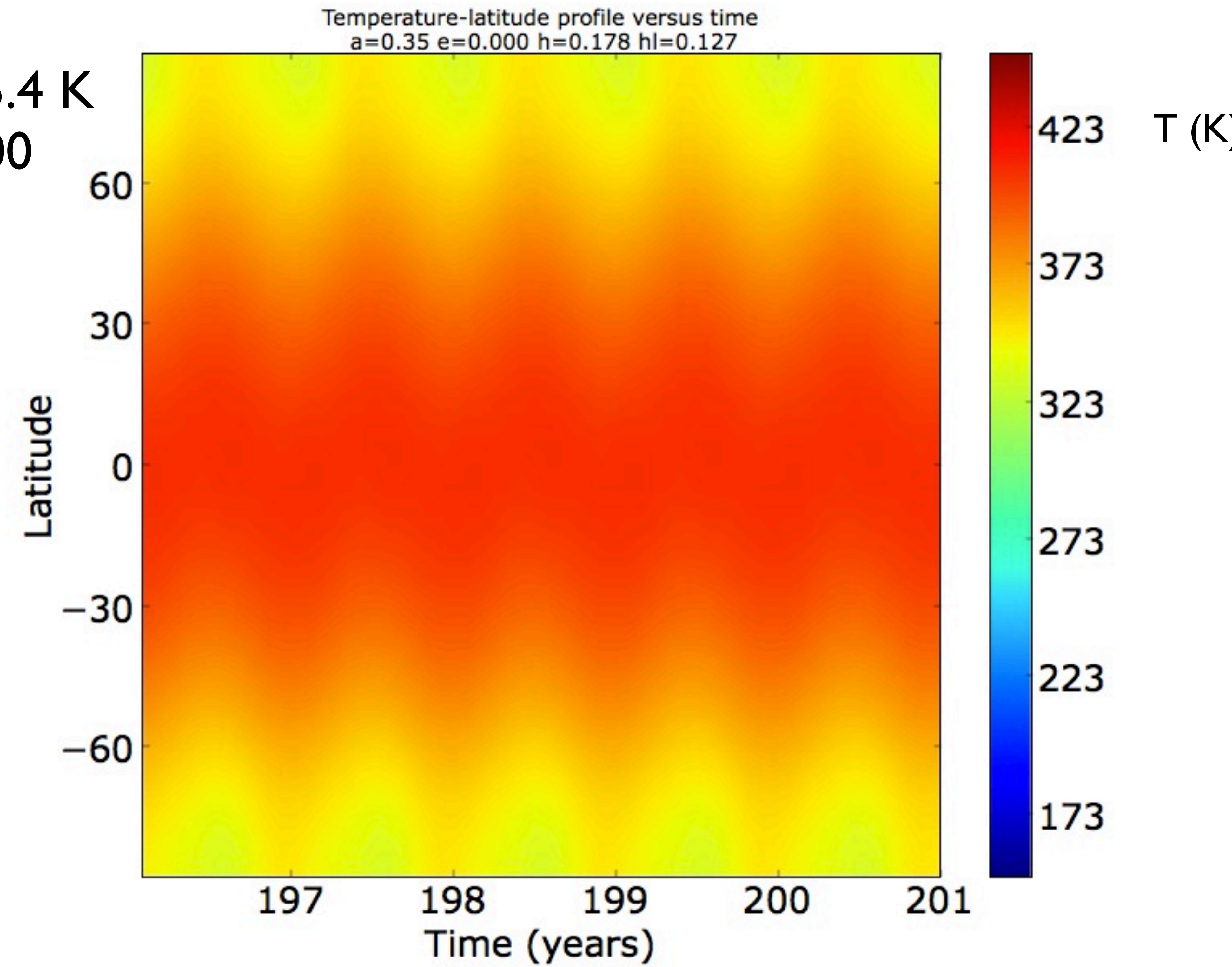
# Evolution of the habitability of HD20794d

Stellar flux = 0.85 present value | Rotation period = 3 d

Earth-like parameters | Ps = 100 mB | $tau_{IR}$=0.1 $tau_{IR}$(earth)

<T>= 395.4 K

$f_{hab}$=0.00



# Evolution of the habitability of HD20794d

Stellar flux = 0.85 present value

Rotation period = 9 d

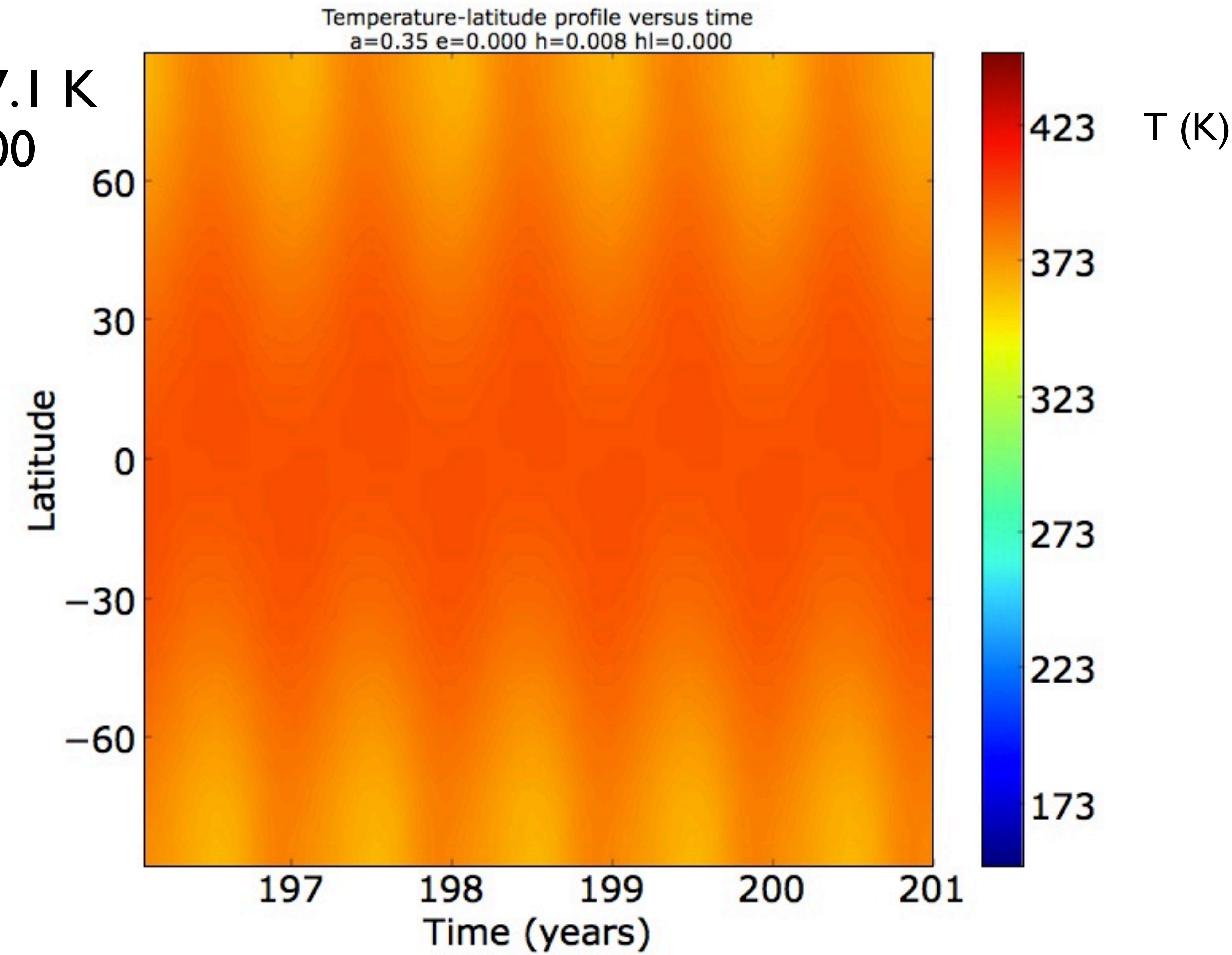
Earth-like parameters

Ps = 100 mB

$tau_{IR}=0.1\ tau_{IR}(earth)$

$<T>$= 397.1 K

$f_{hab}$=0.00

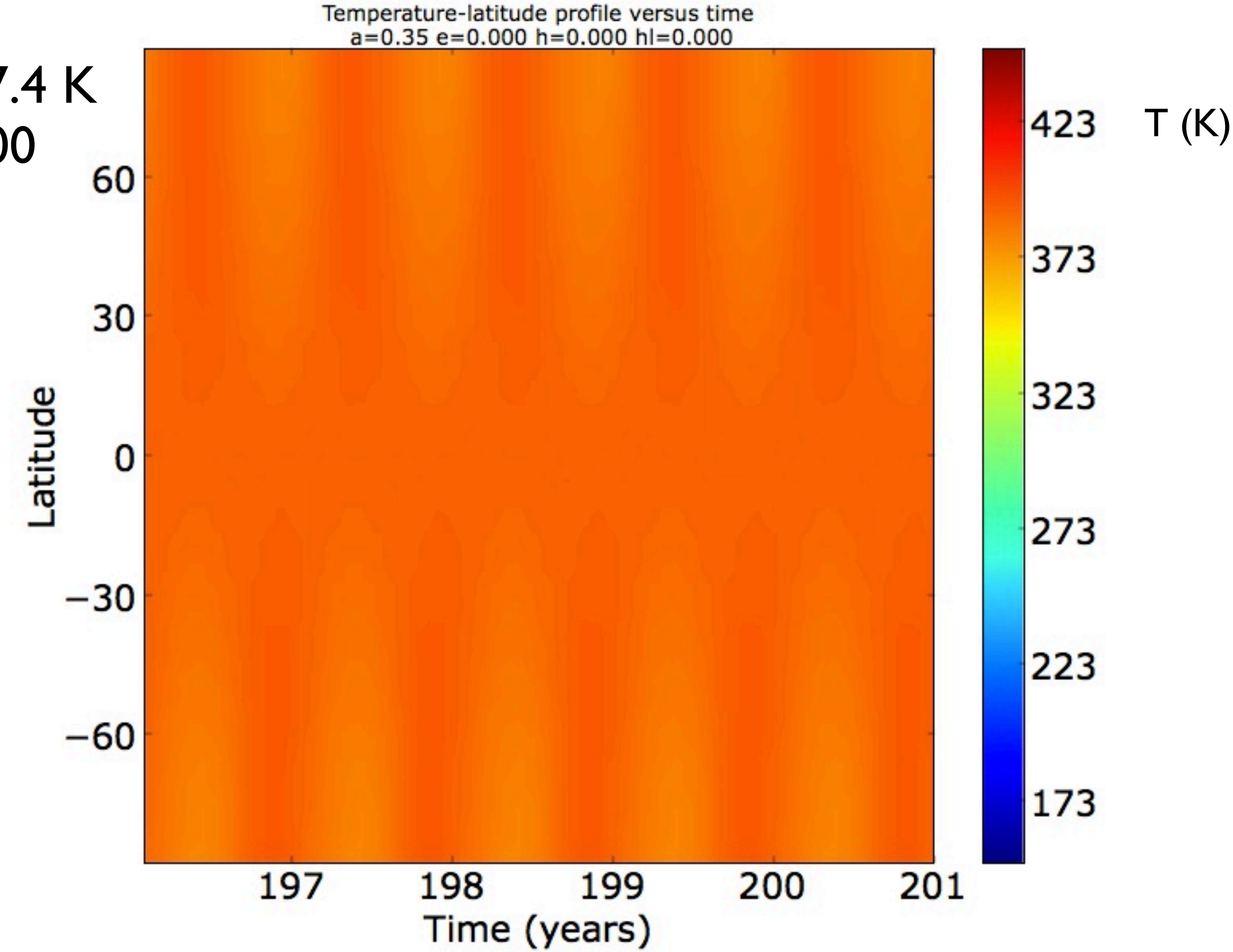


# Evolution of the habitability of HD20794d

Stellar flux = 0.85 present value
Earth-like parameters

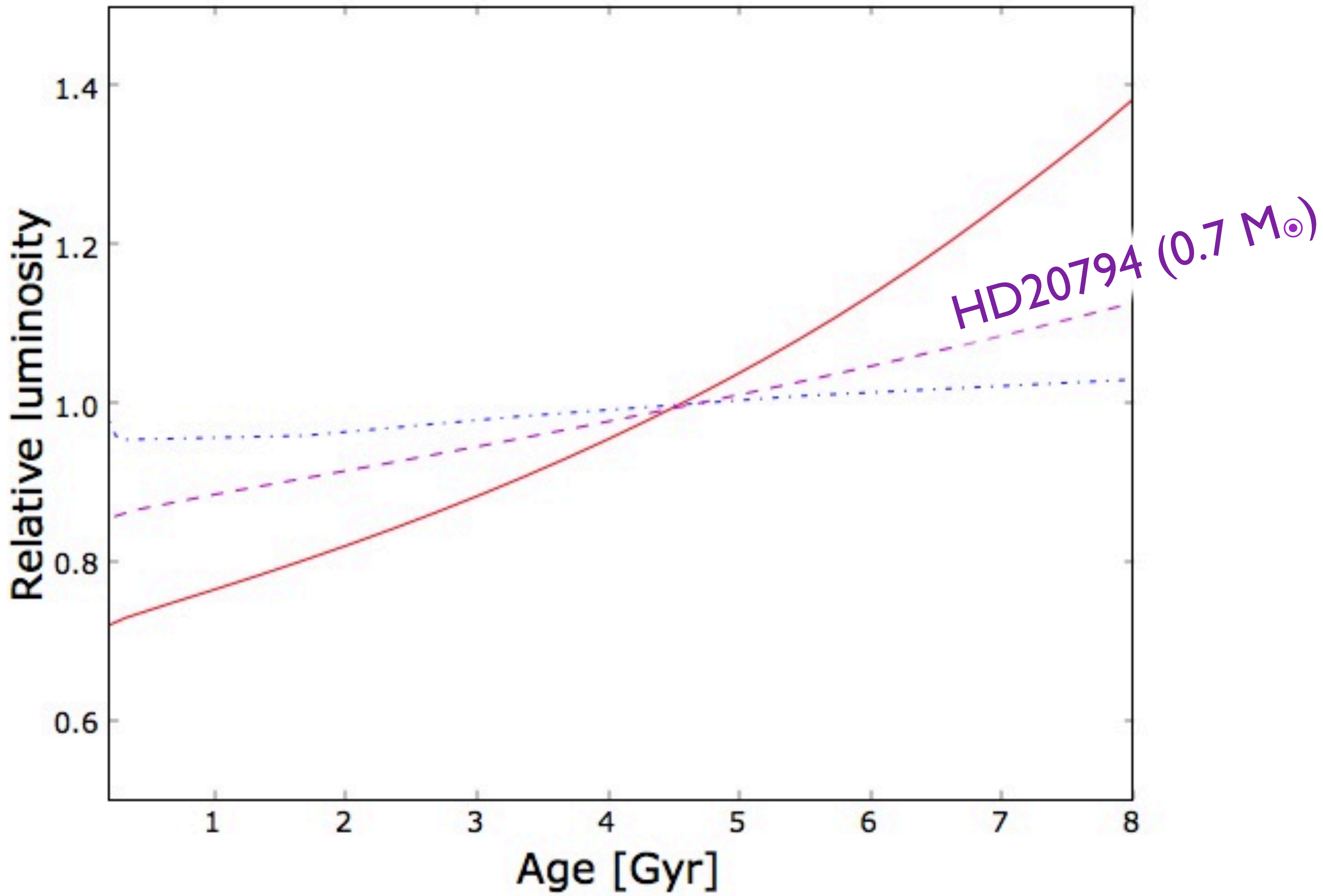
Rotation period = 27d
Ps = 100 mB
$tau_{IR}$=0.1 $tau_{IR}$(earth)

<T>= 397.4 K
$f_{hab}$=0.00



# Evolution of the habitability of HD20794d

TEST III
In addition of slowing down the planet rotation period
we also gradually rised the stellar luminosity
starting from 85% its present value



# Evolution of the habitability of HD20794d

Stellar flux = 0.85 present value

Earth-like parameters

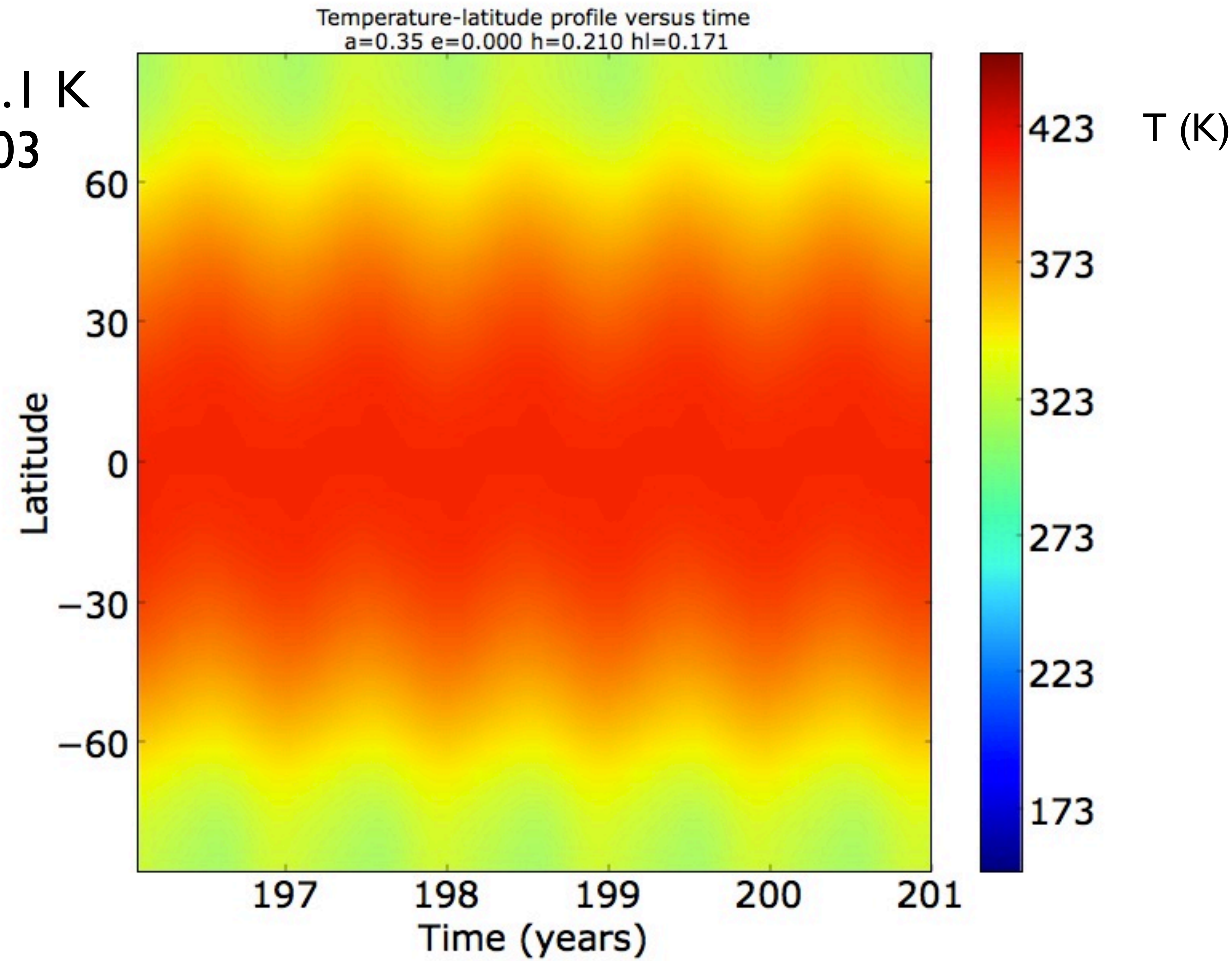
Rotation period = 1 d

Ps = 100 mB

$tau_{IR}$=0.1 $tau_{IR}$(earth)

<T>= 394.1 K

$f_{hab}$=0.003



# Evolution of the habitability of HD20794d

Stellar flux = 0.87 present value

Rotation period = 3 d

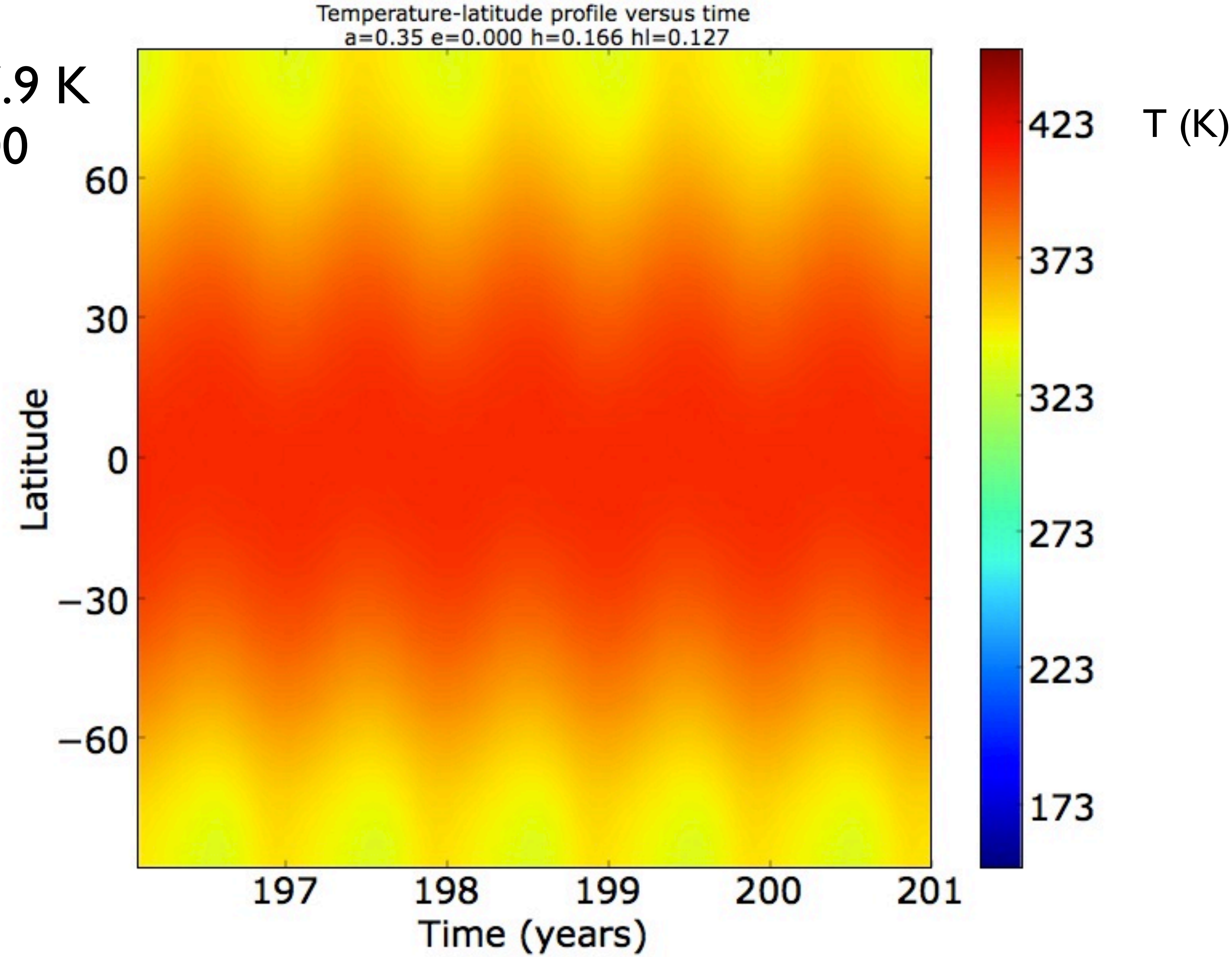
Earth-like parameters

Ps = 100 mB

$tau_{IR}$=0.1 $tau_{IR}$(earth)

<T>= 397.9 K

$f_{hab}$=0.00



# Evolution of the habitability of HD20794d

Stellar flux = 0.89 present value

Rotation period = 9 d

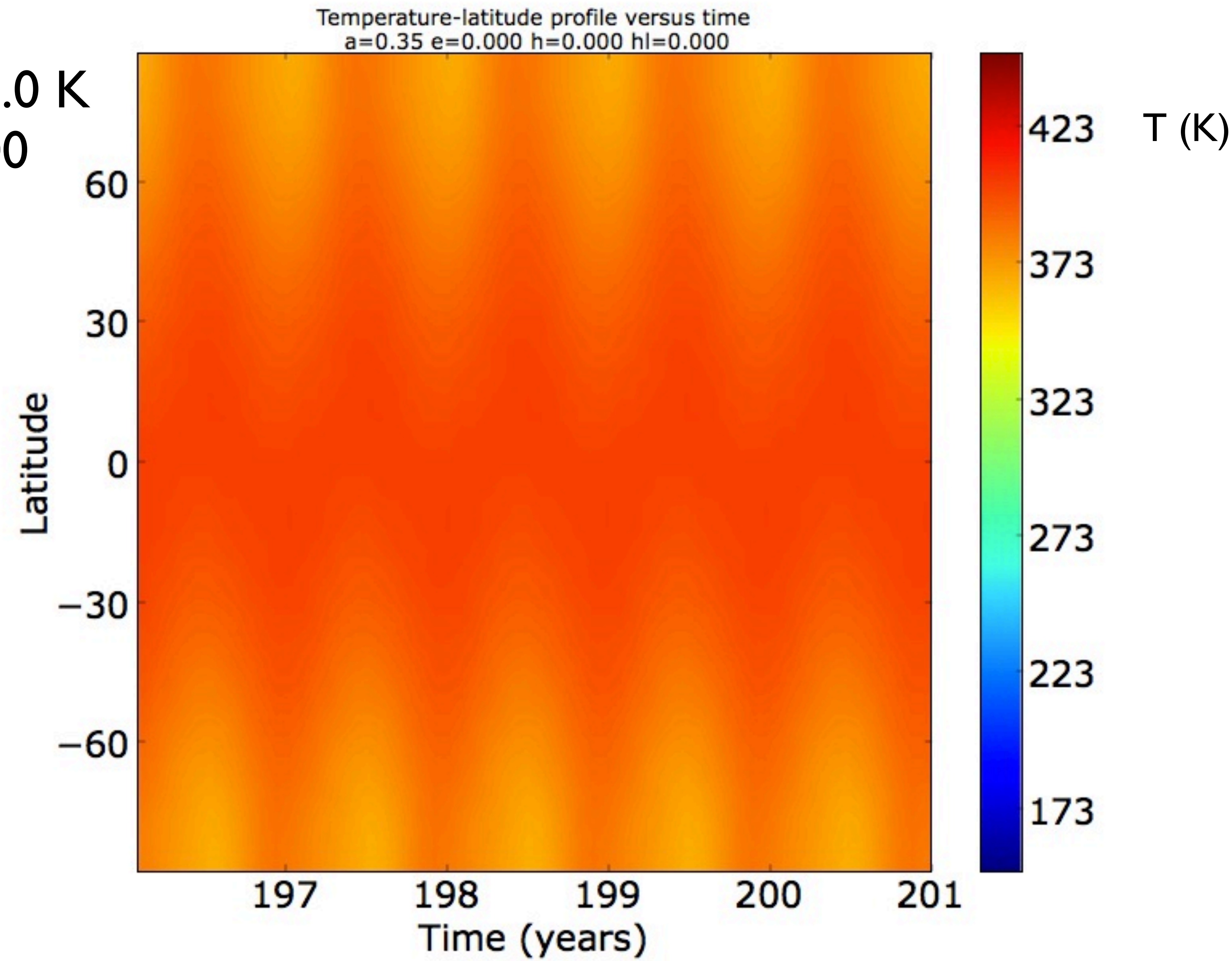
Earth-like parameters

Ps = 100 mB

$tau_{IR}$=0.1 $tau_{IR}$(earth)

<T>= 402.0 K

$f_{hab}$=0.00



# Evolution of the habitability of HD20794d

Stellar flux = 0.91 present value

Earth-like parameters

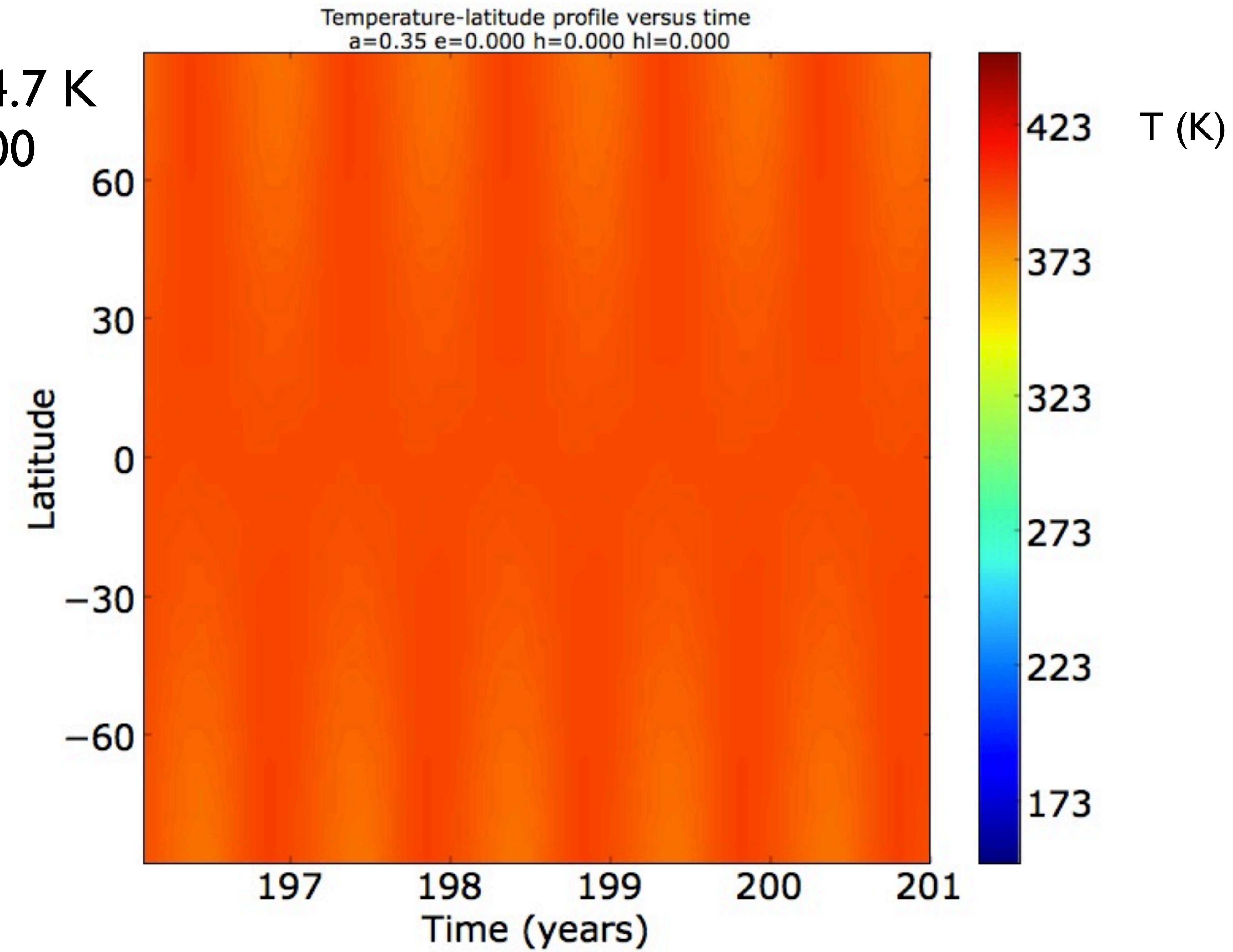
Ps = 100 mB

Rotation period = 27d

$tau_{IR}$=0.1 $tau_{IR}$(earth)

$\langle T \rangle$= 404.7 K

$f_{hab}$=0.00



# Habitability of HD20794d

Playing with the obliquity

(not shown here for reasons of time)

At zero obliquity the polar regions tend to become more habitable in a “hot” planet like this

However, playing with the obliquity helps very little to improve the habitability in this case

# Planet GL 581d

a=0.218 AU e=0.25

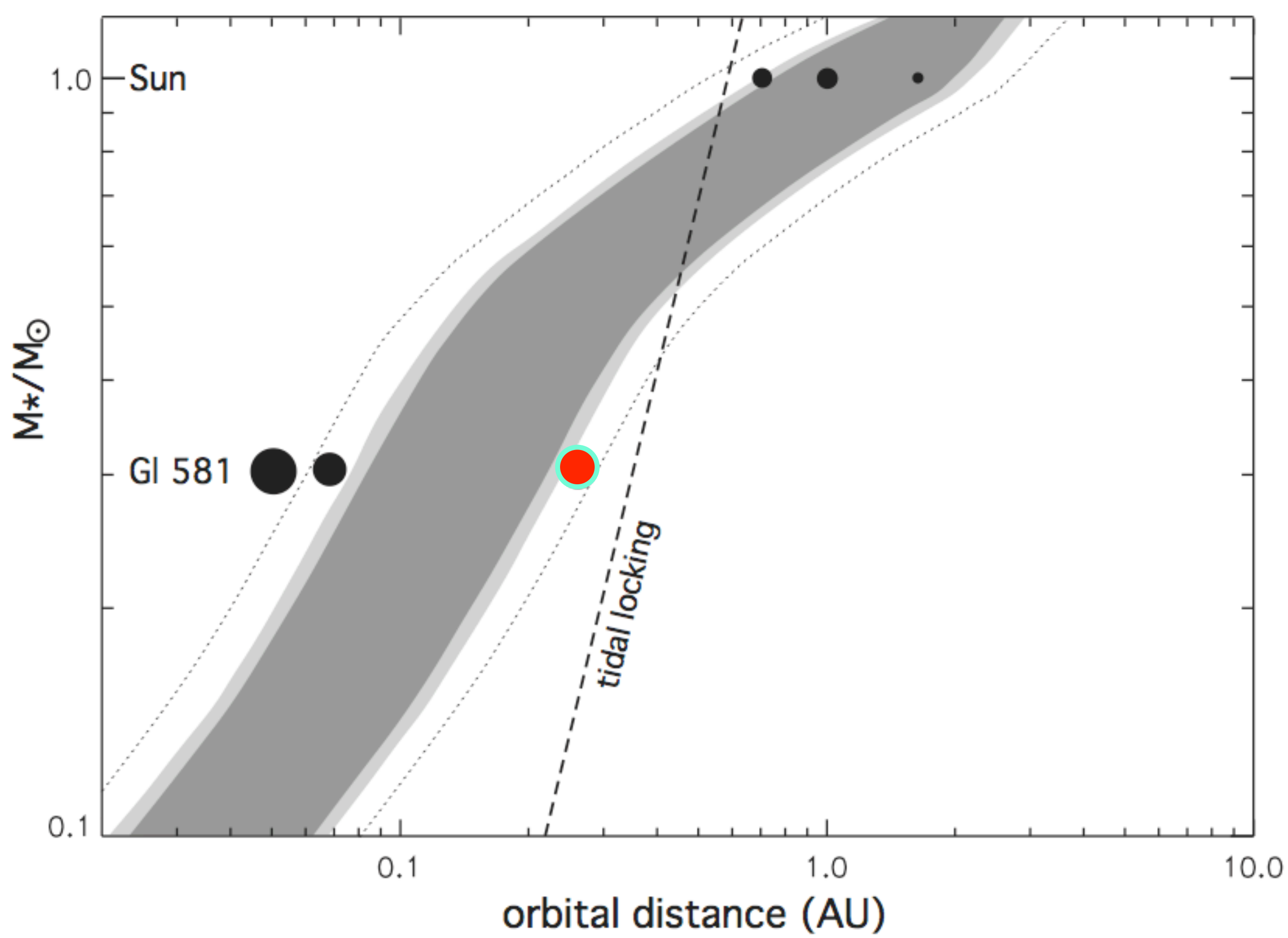
P=66.6 d Msini=6.1 M(earth)

Selsis et al. (2007)

Gl 581 d lies beyond the outer edge
of the circumstellar "habitable zone"

If we adopt and Earth-like level of $CO_2$
we find a frozen planet

We started from a quite high values of $CO_2$ and gradually rised it
searching for the minimum value that makes the planet habitable



Habitability of Gl 581 d

Stellar luminosity = 0.0135 solar luminosity

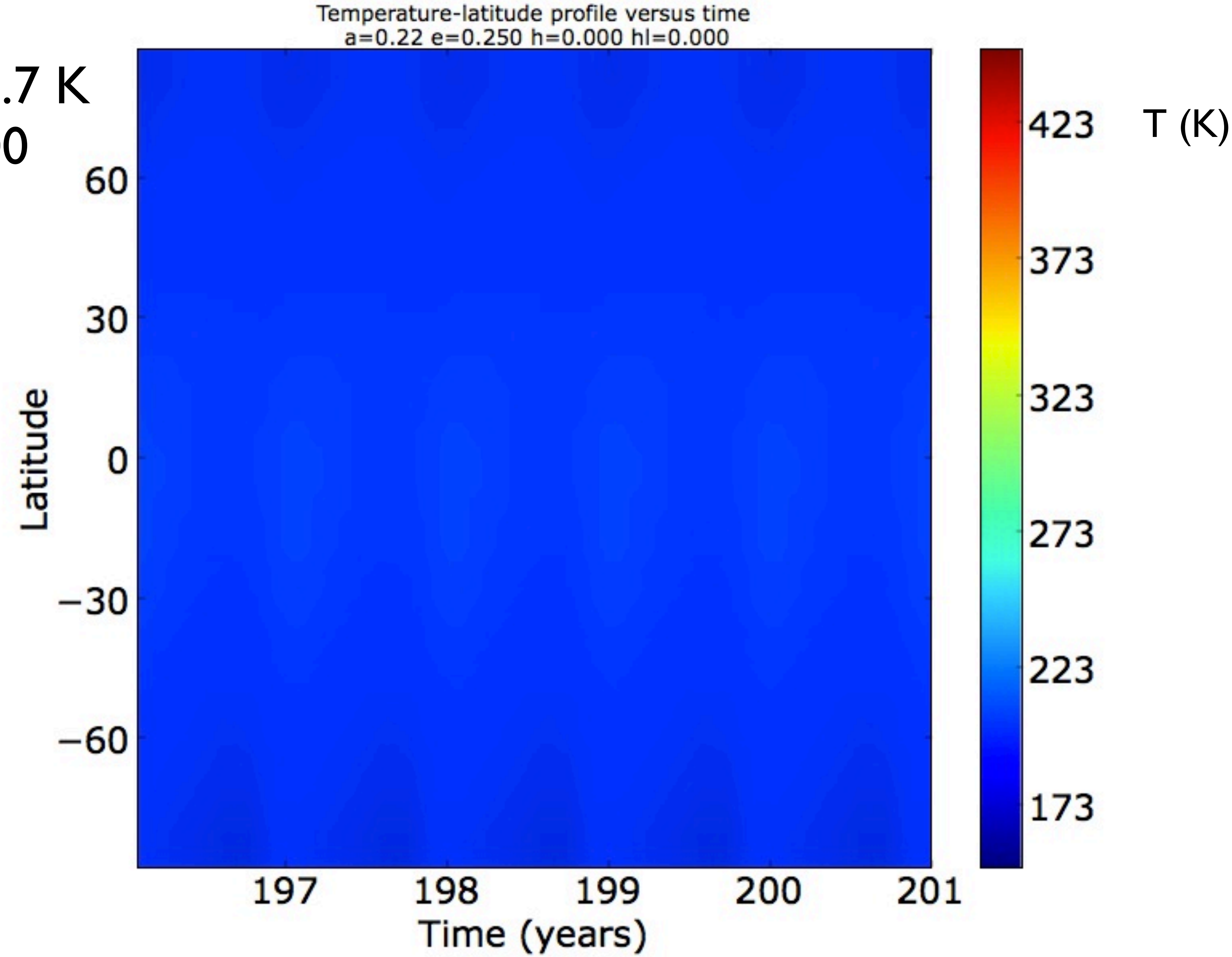
Planet rotation period = 1 d

Earth-like parameters

Ps = 1 Bar P(CO2)=1 Bar

$\langle T \rangle$= 190.7 K

$f_{hab}$=0.00



Habitability of Gl 581 d

Stellar luminosity = 0.0135 solar luminosity

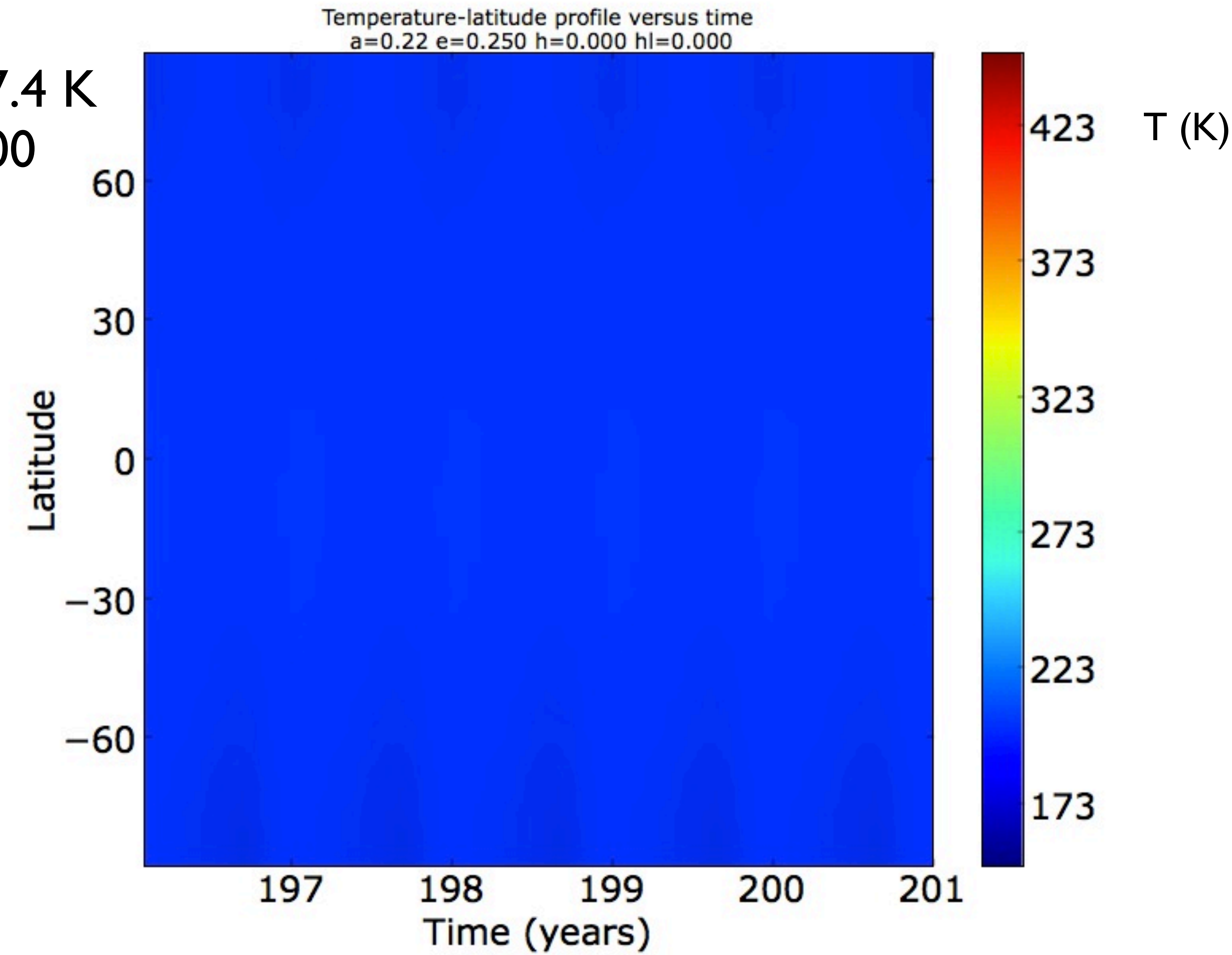
Earth-like parameters

Planet rotation period = 1 d

Ps = 3 Bar    P(CO2)=3 Bar

<T>= 187.4 K

$f_{hab}$=0.00



Habitability of Gl 581 d

Stellar luminosity = 0.0135 solar luminosity

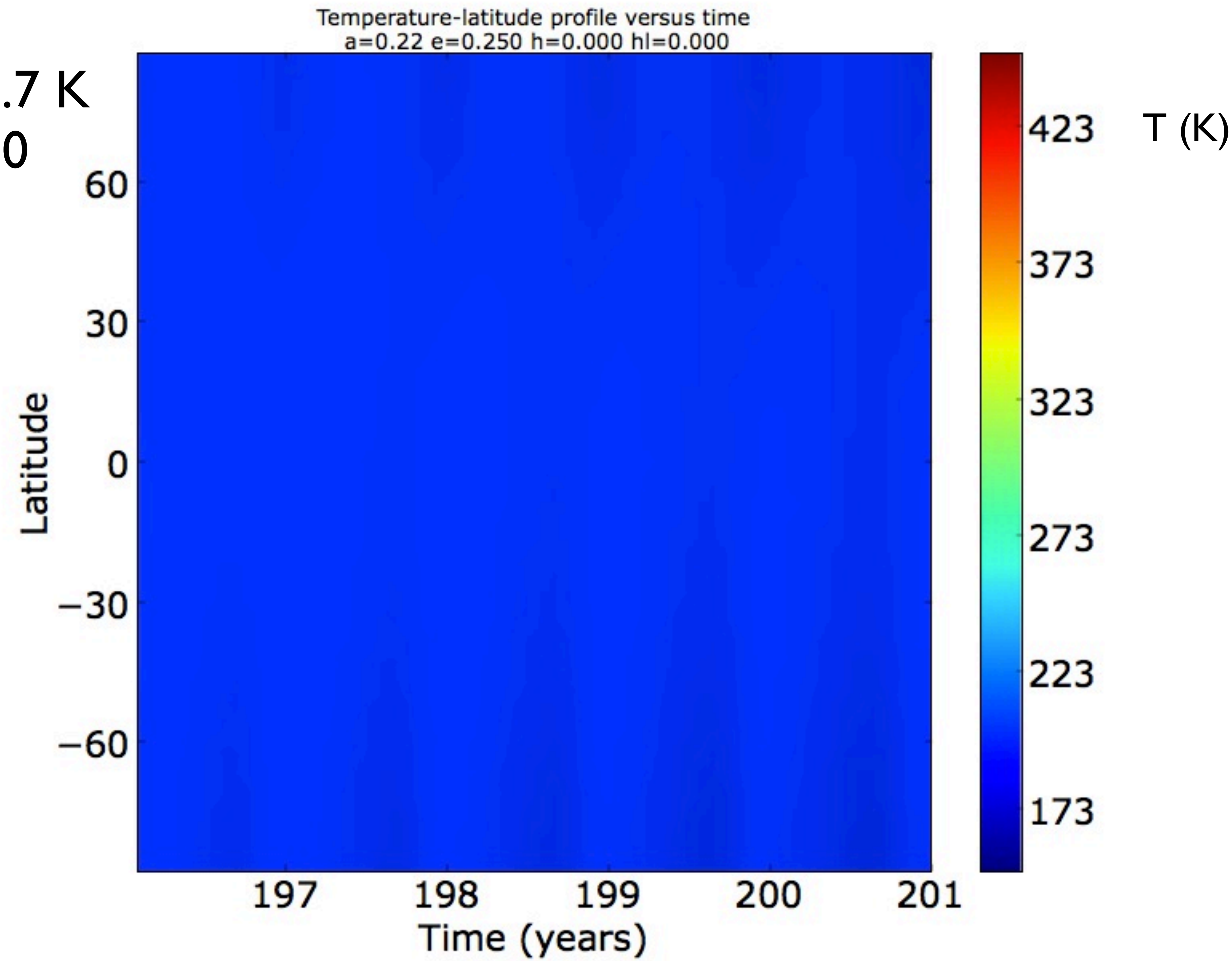
Planet rotation period = 1 d

Earth-like parameters

Ps = 7 Bar      P(CO2)=7 Bar

<T>= 180.7 K

$f_{hab}$=0.00



Habitability of Gl 581 d

Stellar luminosity = 0.0135 solar luminosity

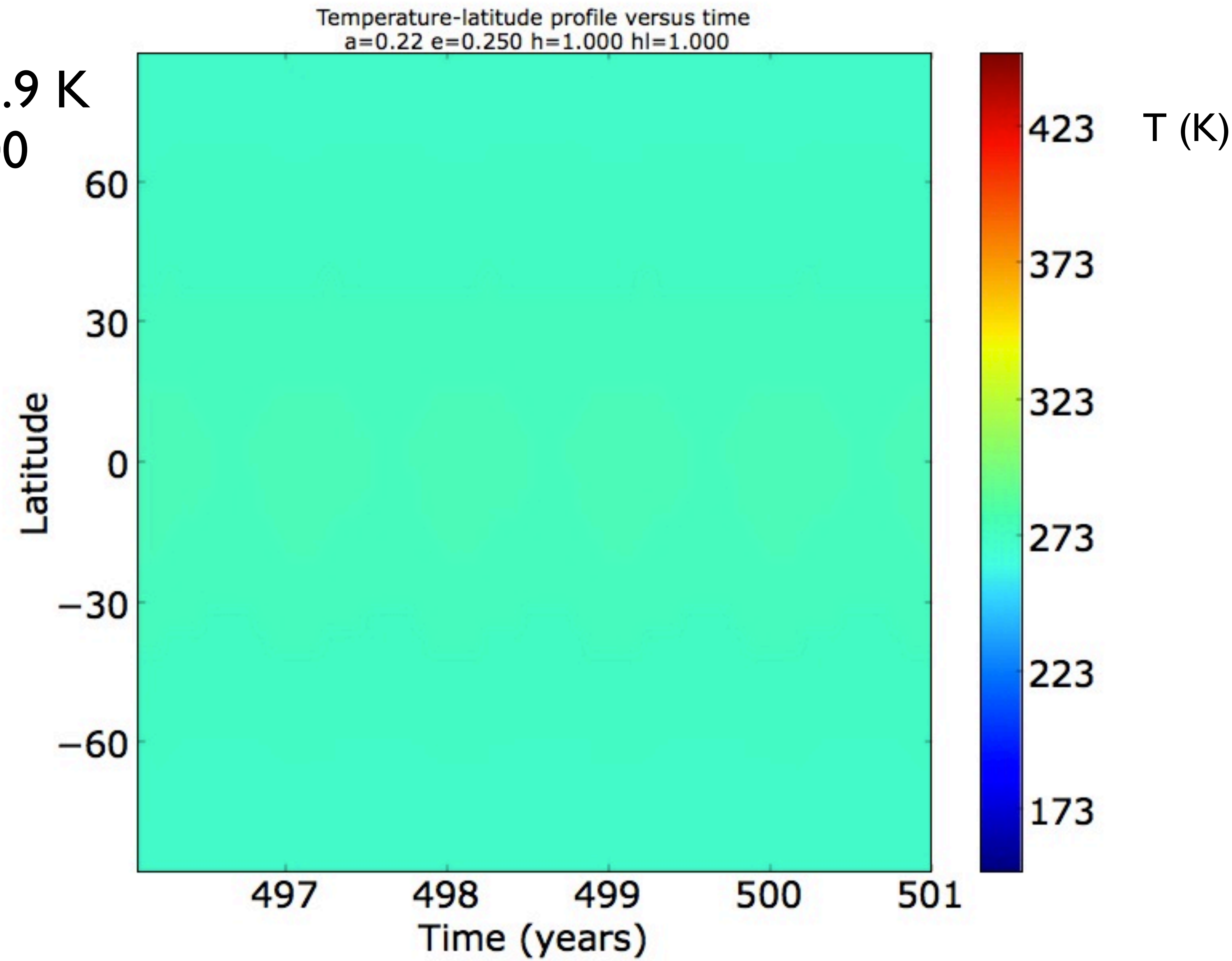
Planet rotation period = 1 d

Earth-like parameters

Ps = 8 Bar P(CO2)=8 Bar

<T>= 278.9 K

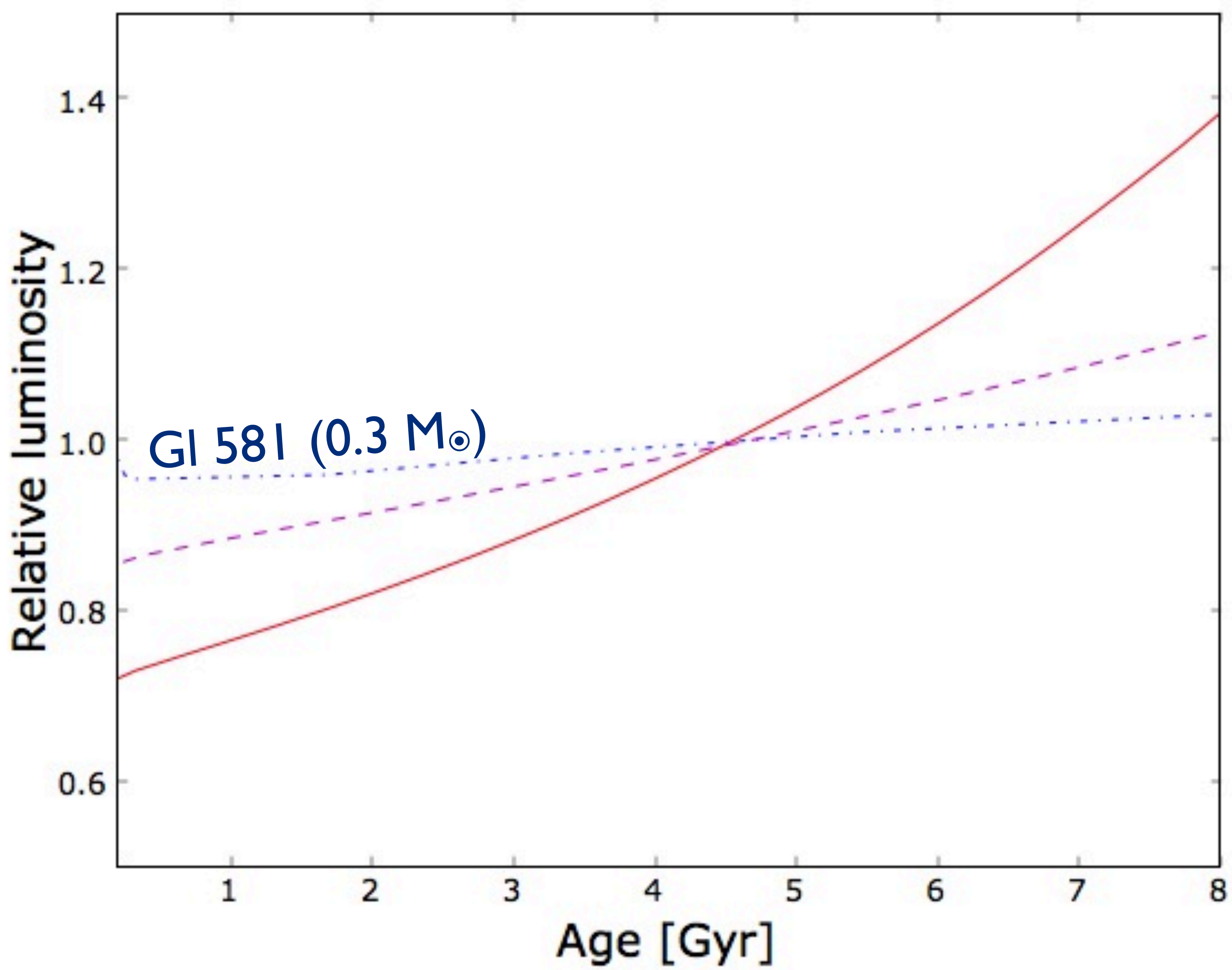
$f_{hab}$=1.00



# Evolution of the habitability of Gl 581 d

In this case the stellar luminosity is essentially constant

We slow down the rotation period keeping fixed the stellar flux
We adopt $p(CO_2)$=8 B



Habitability of Gl 581 d

Stellar luminosity = 0.0135 solar luminosity

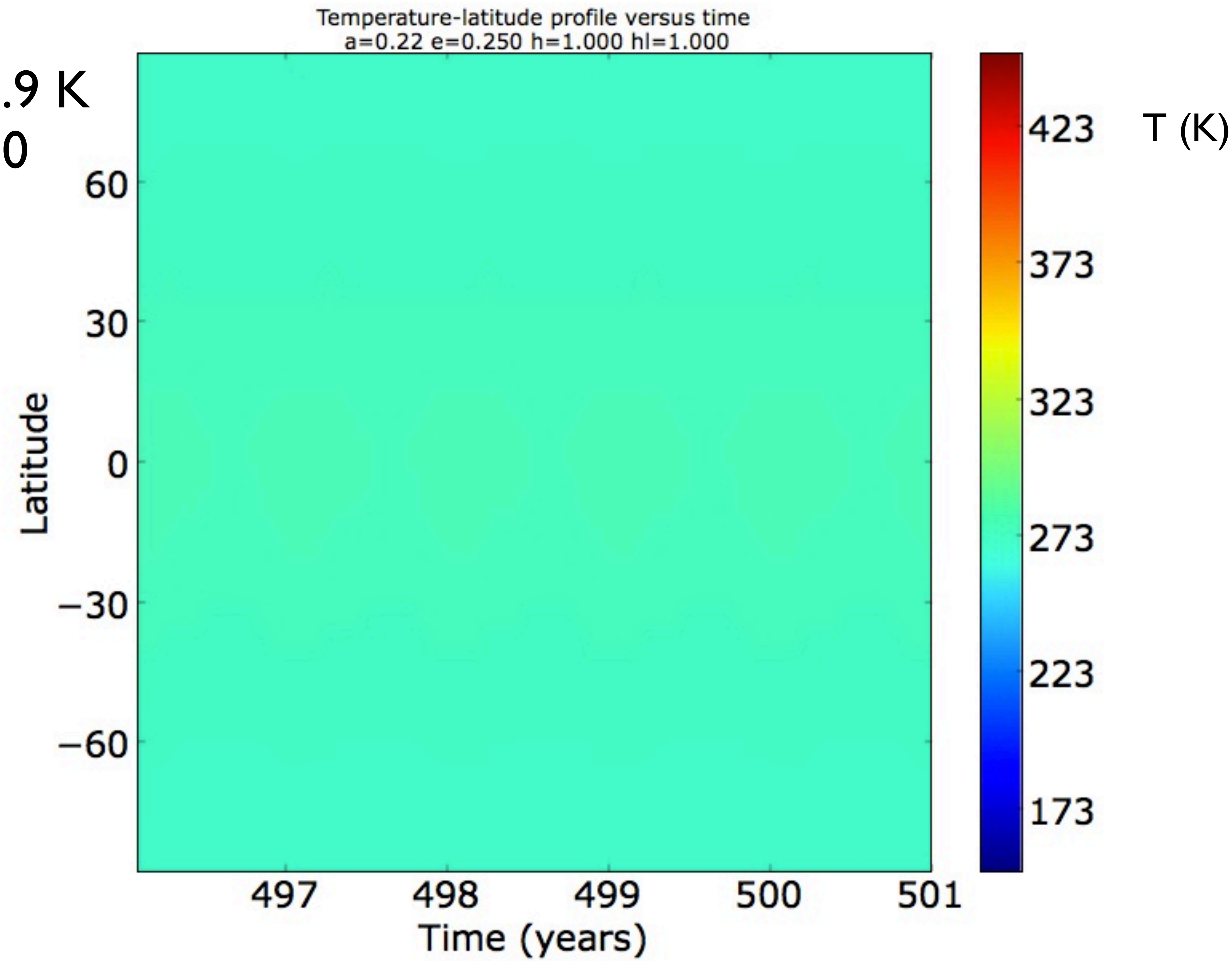
Earth-like parameters

Planet rotation period = 1 d

Ps = 8 Bar P($CO_2$)=8 Bar

<T>= 278.9 K

$f_{hab}$=1.00



Habitability of Gl 581 d

Stellar luminosity = 0.0135 solar luminosity

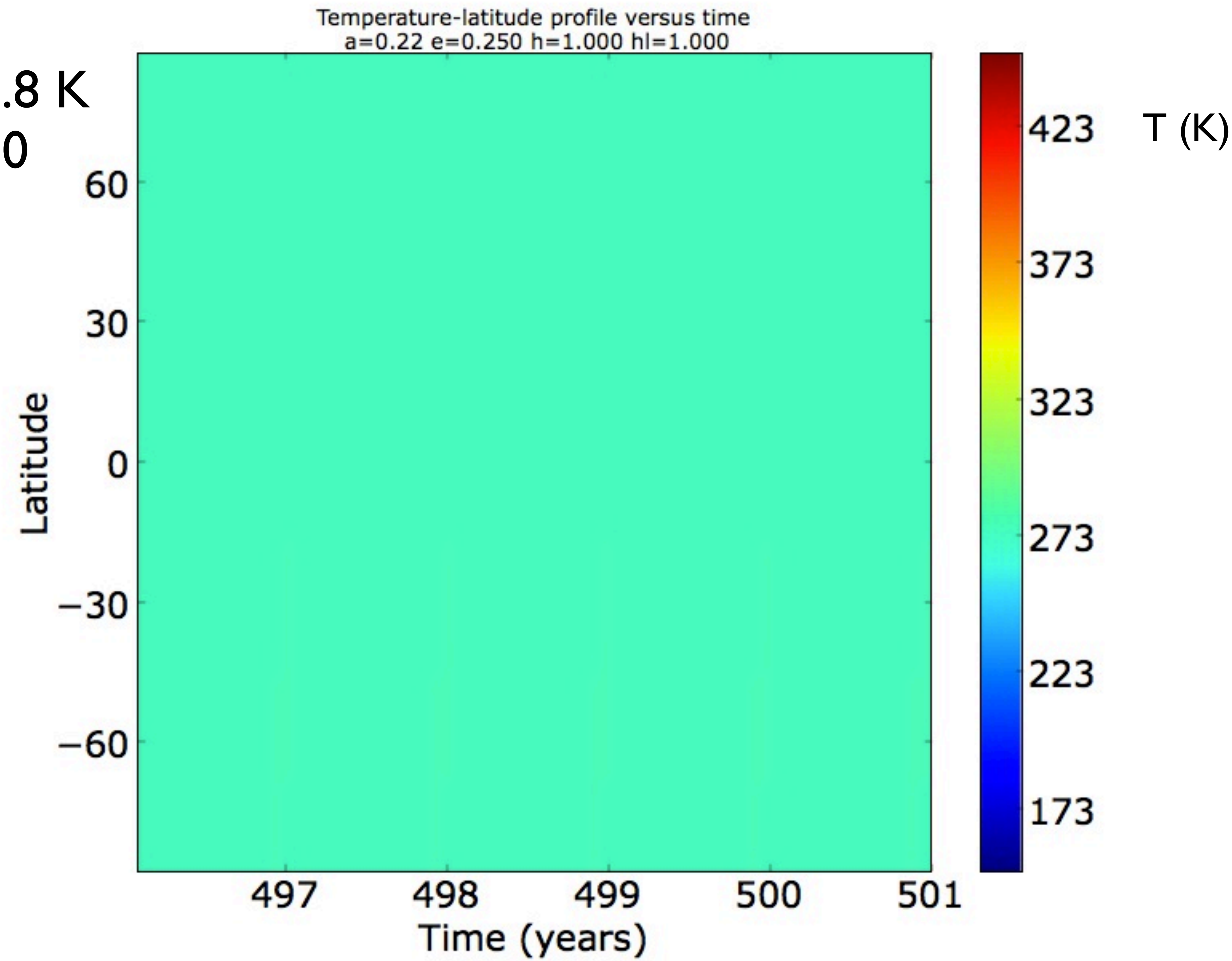
Earth-like parameters

Planet rotation period = 8 d

Ps = 8 Bar P(CO2)=8 Bar

$\langle T \rangle$= 279.8 K

$f_{hab}$=1.00



# Extrasolar planets: conclusions

Close investigation of planets
at the edge of the “habitable zone”
poses severe limits on their effective habitability

Slowing down the planet rotation
can play a critical role in the early stages of habitability evolution

Increasing the stellar luminosity
plays a role in solar-type stars, but not in low-mass stars (Gl 581)

Planets with very intense meridional diffusion
may experience sudden transitions
from a “snowball” state to a fully habitable state

Other parameters not shown here, such as axis obliquity,
do vary the habitability fraction,
but can hardly make habitable planets outside the “habitable zone”

# Conclusions

Energy Balance Models provide a simple tool for investigating the climate of terrestrial planets

Ideal for exploratory studies of the habitability of extrasolar planets and its evolution

There is still room for including more realistic climate recepies while keeping low the computing time

## Testing the model:

## Habitability of the Earth in the Archean

In the Archean the solar flux was fainter than today

3.9 Gyr ago (early Archean) → 75%

2.75 Gyr ago (late Archean) → 81%

Modelling the Earth climate with this faint solar flux yields a frozen planet

Since liquid water was present, it is commonly assumed that the primitive greenhouse effect was stronger (Kasting 1984, 1993)

To test our EBMs we estimate the minimum p($CO_2$) that makes the archean Earth habitable

# Early Archean (3.9 Gyr ago)

Solar flux = 75% present value    Land coverage=2%    Rotation period = 17.6 h

Rollinson (2007)    Varga et al. (2006)

We gradually rise the level of $CO_2$

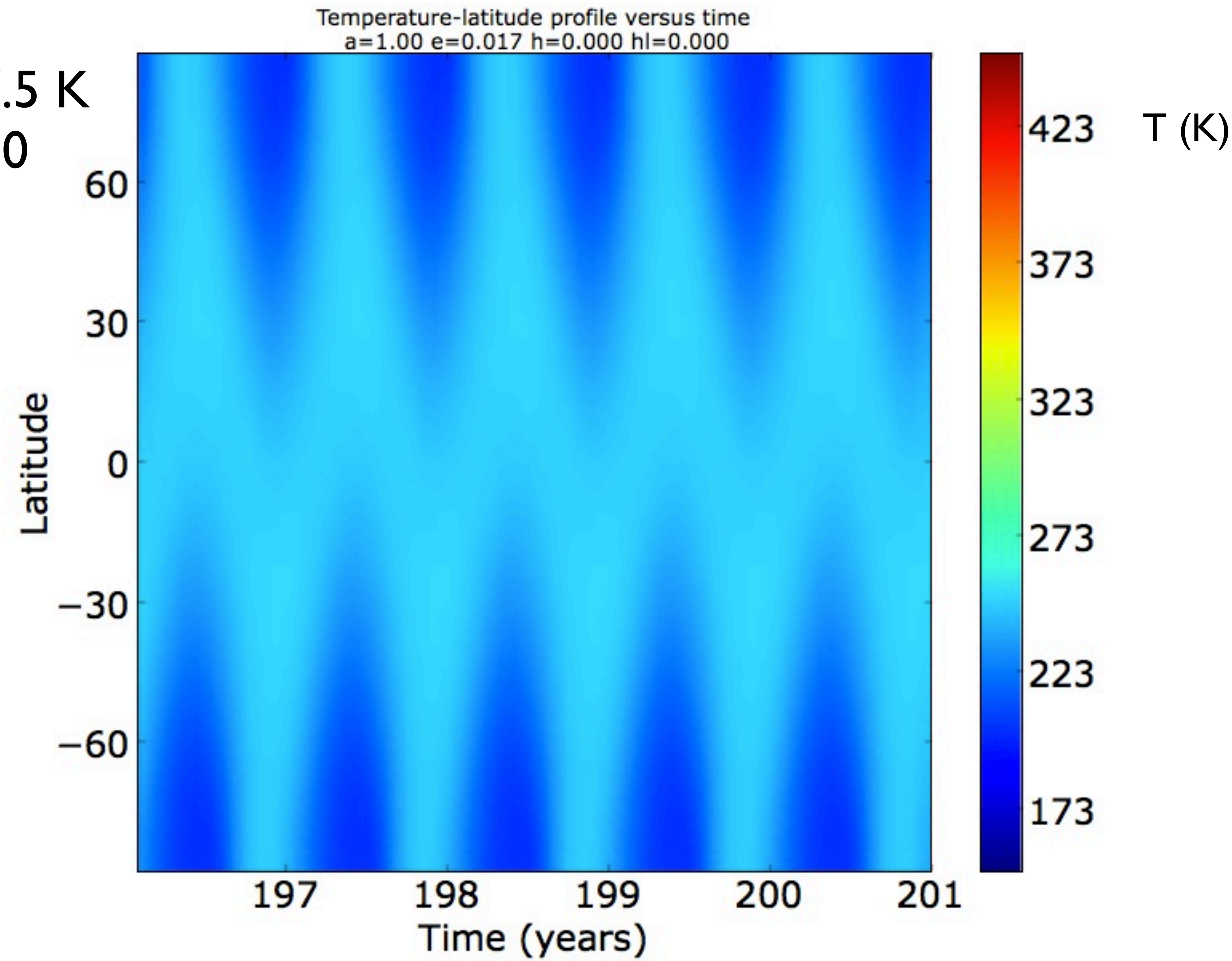
Habitability of the Earth during the Archean: 3.9 Ga

Solar flux = 0.75 present value      Fraction of oceans=0.98      Rotation period = 17.6 h

Total atmospheric pressure=1 bar      Partial pressure of $CO_2$ = 0.03 bar

<T>= 237.5 K

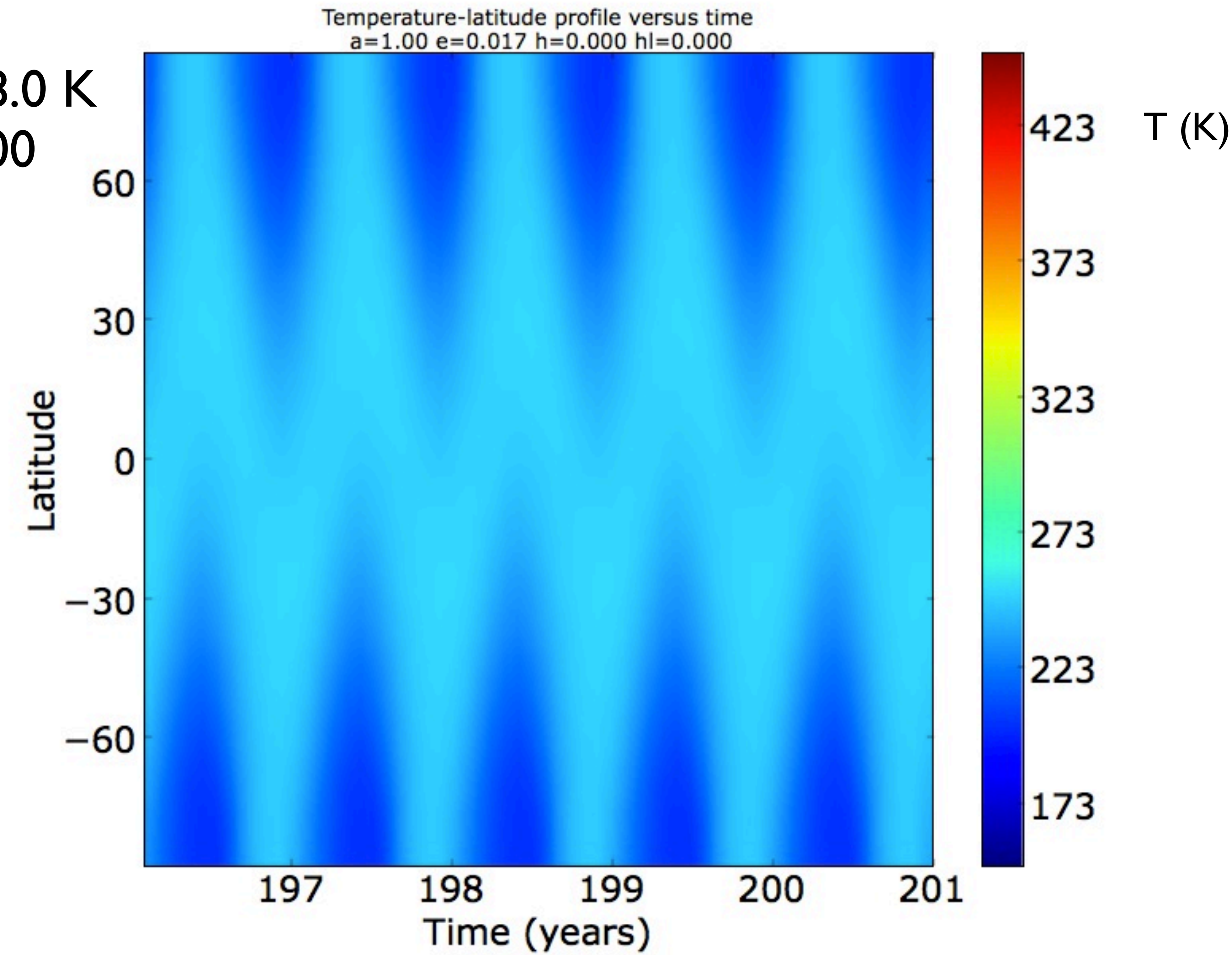
$f_{hab}$=0.00



Habitability of the Earth during the Archean: 3.9 Ga

Solar flux = 0.75 present value  Fraction of oceans=0.98  Rotation period = 17.6 h
Total atmospheric pressure=1 bar  Partial pressure of $CO_2$ = 0.05 bar

$<T>$= 238.0 K
$f_{hab}$=0.00



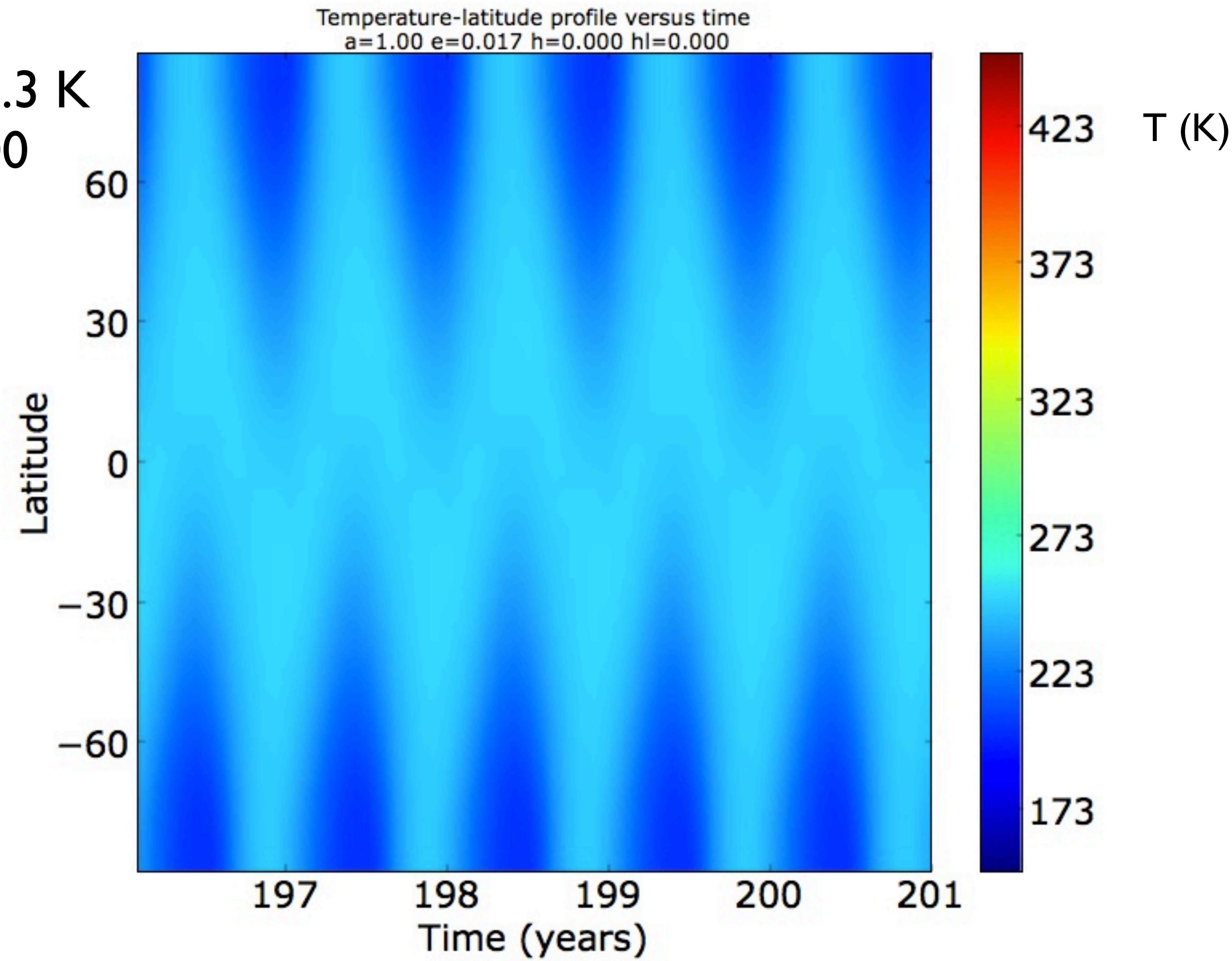
Habitability of the Earth during the Archean: 3.9 Ga

Solar flux = 0.75 present value    Fraction of oceans=0.98    Rotation period = 17.6 h

Total atmospheric pressure=1 bar    Partial pressure of $CO_2$ = 0.10 bar

<T>= 238.3 K

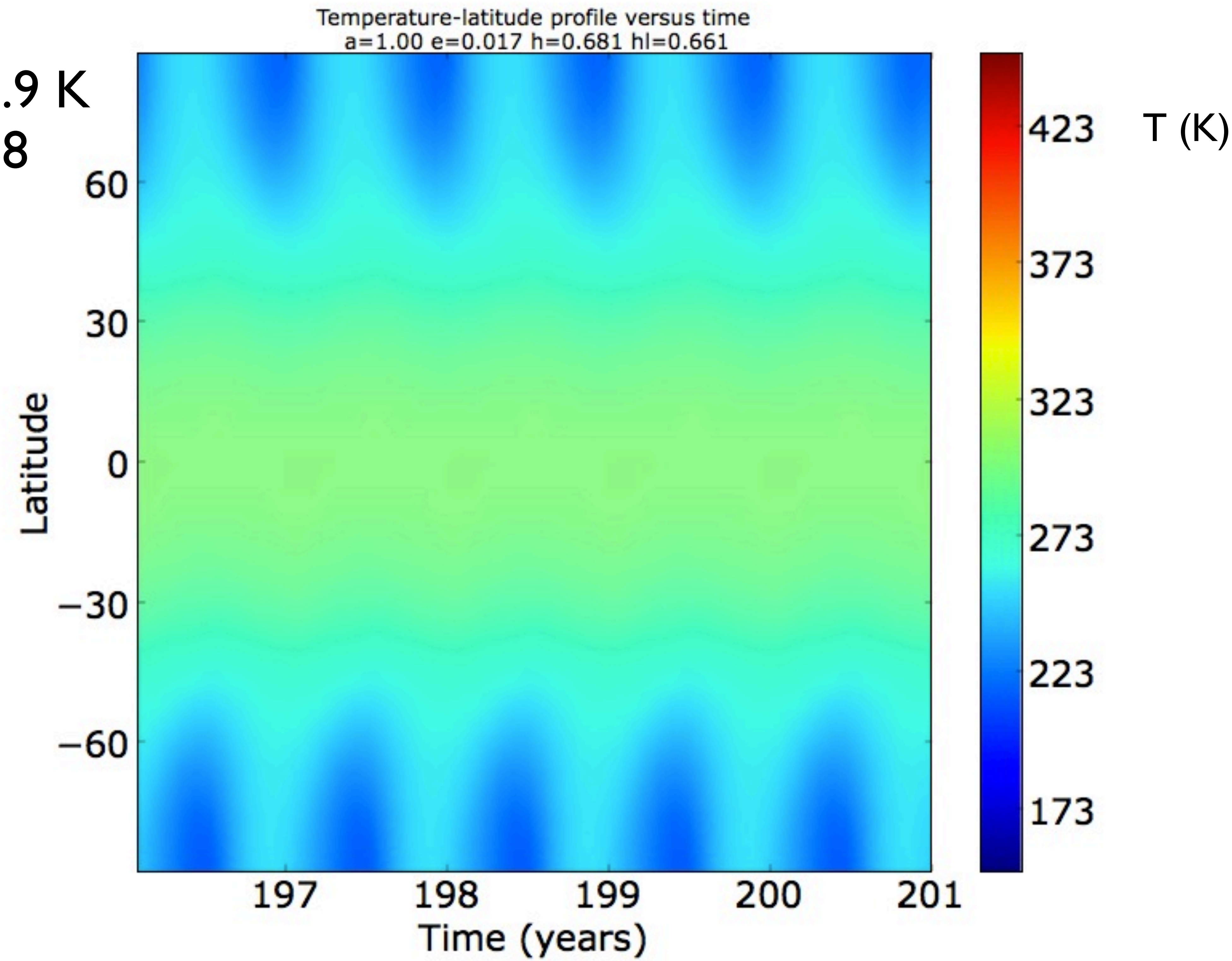
$f_{hab}$=0.00



Habitability of the Earth during the Archean: 3.9 Ga

Solar flux = 0.75 present value Fraction of oceans=0.98 Rotation period = 17.6 h
Total atmospheric pressure=1 bar Partial pressure of $CO_2$ = 0.20 bar

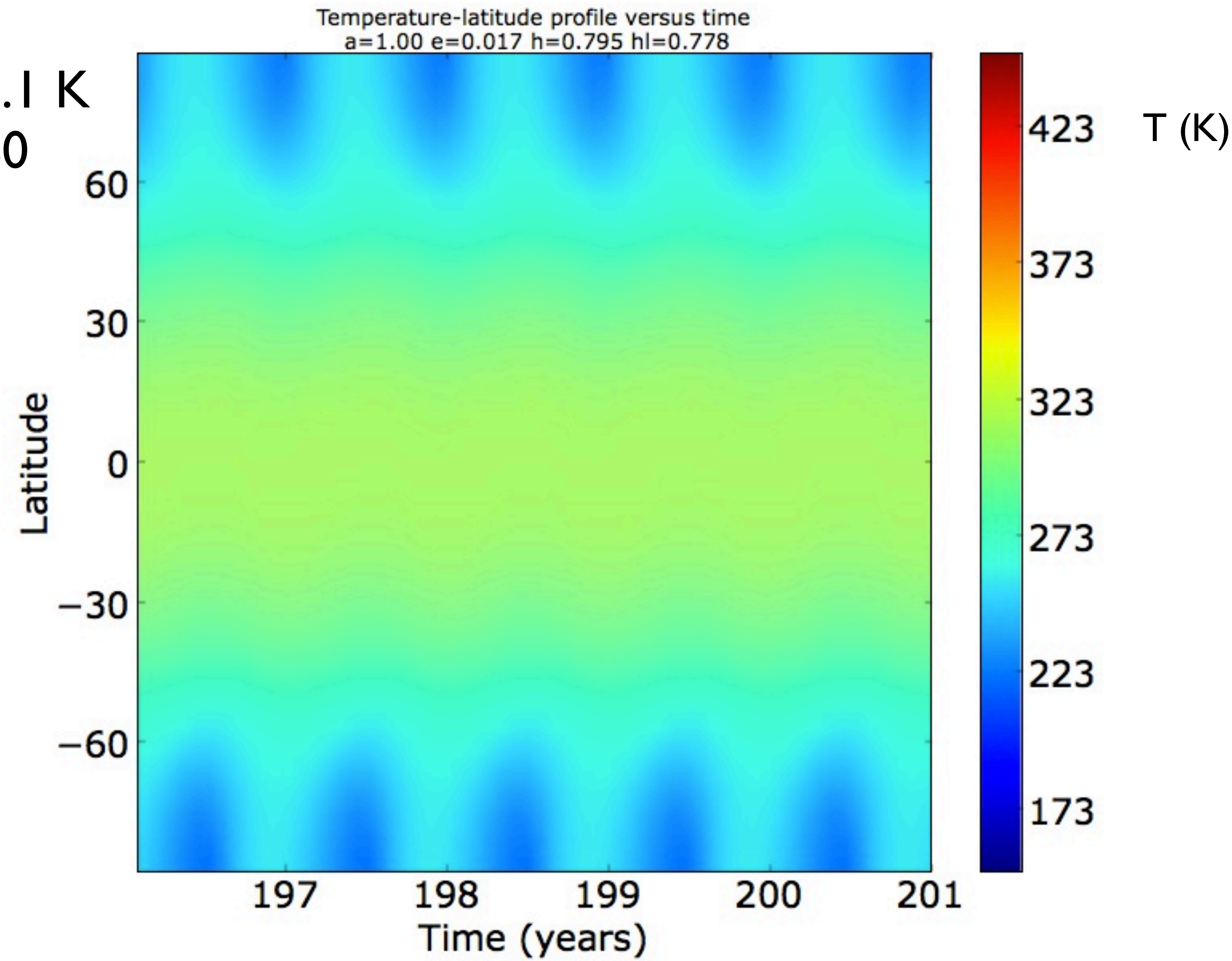
$\langle T \rangle$= 280.9 K
$f_{hab}$=0.68



Habitability of the Earth during the Archean: 3.9 Ga

Solar flux = 0.75 present value    Fraction of oceans=0.98    Rotation period = 17.6 h
Total atmospheric pressure=1 bar    Partial pressure of $CO_2$ = 0.30 bar

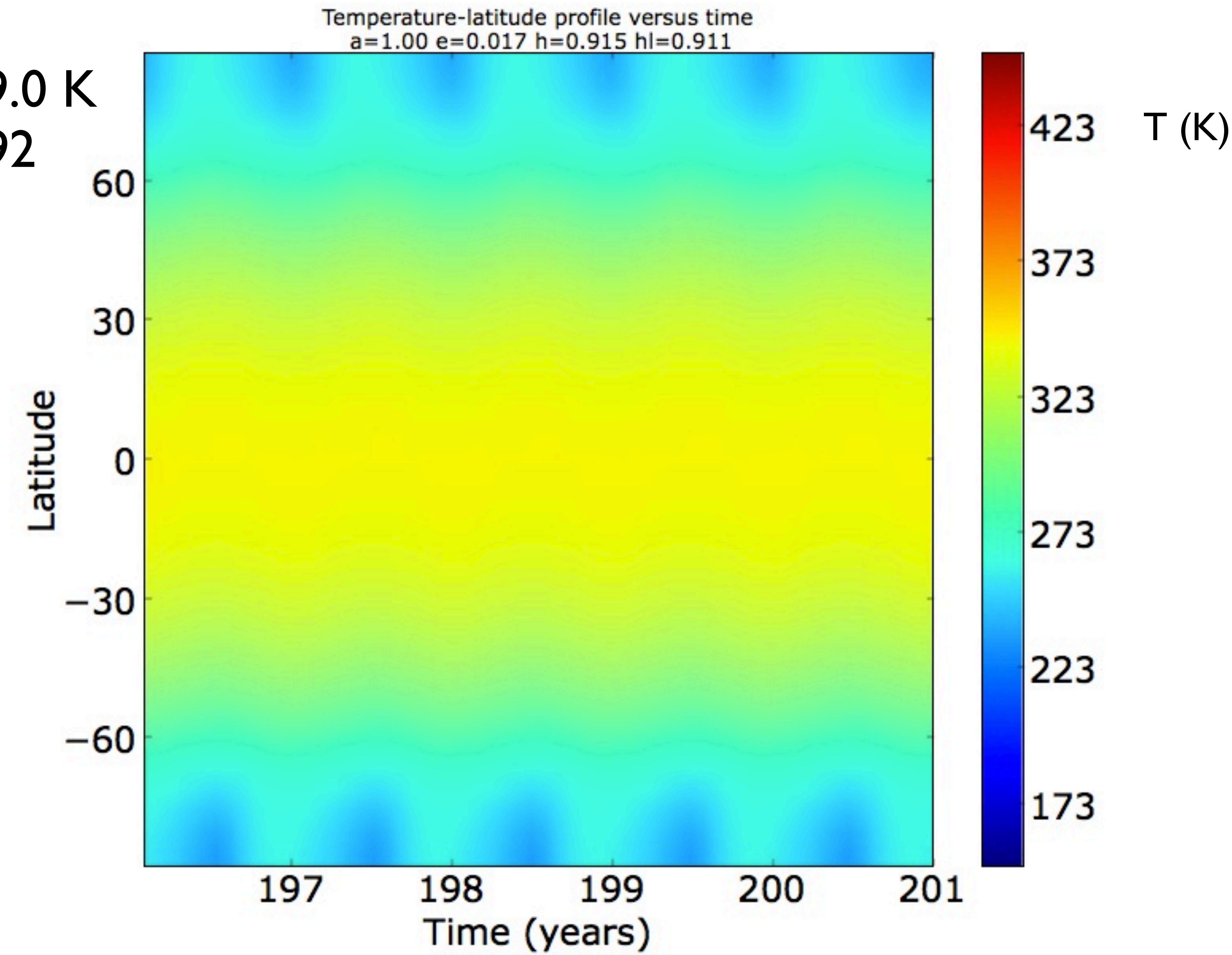
$\langle T \rangle$= 292.1 K
$f_{hab}$=0.80



Habitability of the Earth during the Archean: 3.9 Ga

Solar flux = 0.75 present value Fraction of oceans=0.98 Rotation period = 17.6 h
Total atmospheric pressure=1 bar Partial pressure of $CO_2$ = 1.00 bar

$\langle T \rangle$= 319.0 K
$f_{hab}$=0.92



# Late Archean (2.75 Gyr ago)

Solar flux = 81% present value | Land coverage=10% | Rotation period = 18.8 h

Rollinson (2007) | Varga et al. (2006)

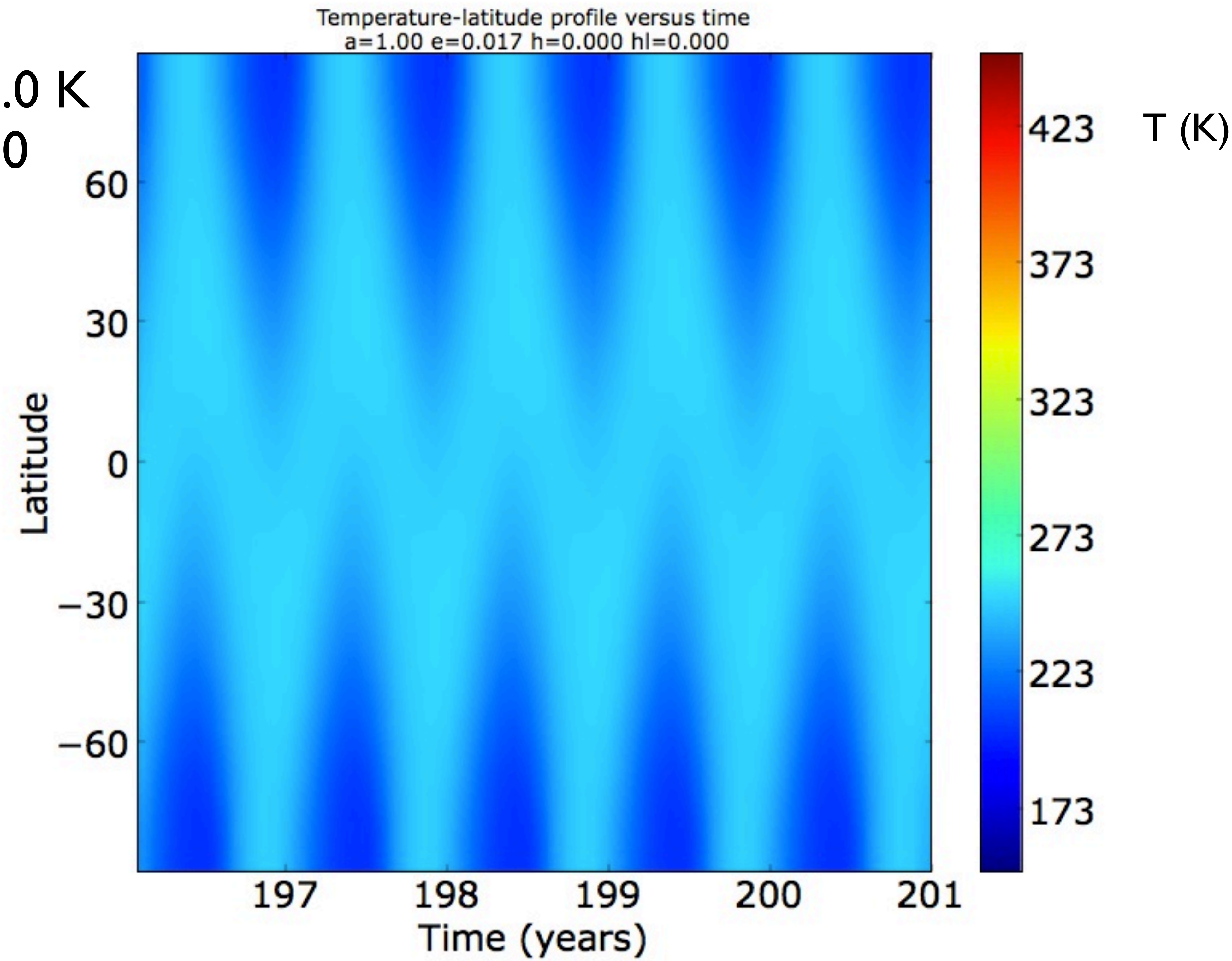
Habitability of the Earth during the late Archean: 2.75 Ga

Solar flux = 0.81 present value   Fraction of oceans=0.90   Rotation period = 18.8 h

Total atmospheric pressure=1 bar   Partial pressure of $CO_2$ = 0.03 bar

$\langle T \rangle$= 238.0 K

$f_{hab}$=0.00



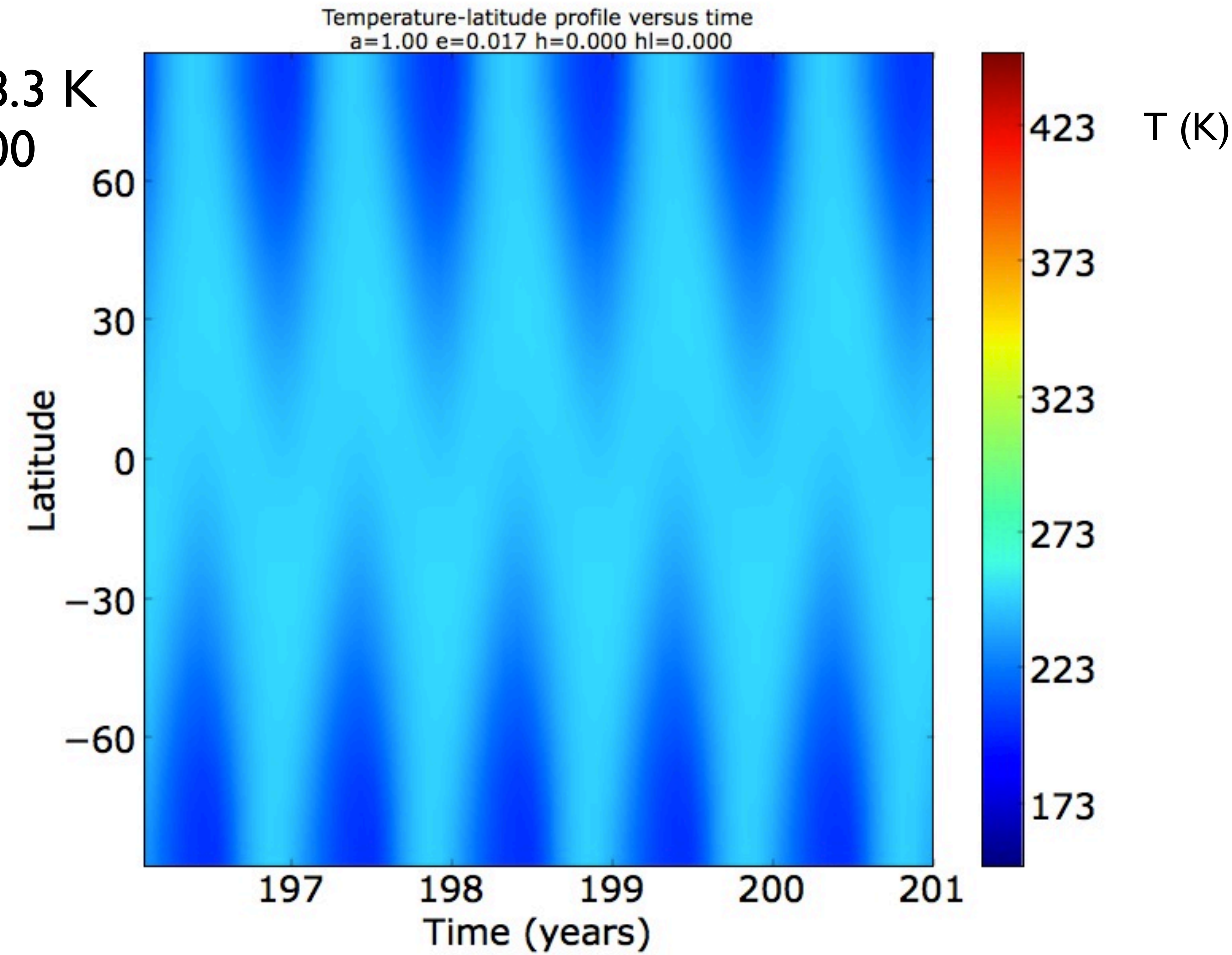
Habitability of the Earth during the late Archean: 2.75 Ga

Solar flux = 0.81 present value Fraction of oceans=0.90 Rotation period = 18.8 h

Total atmospheric pressure=1 bar Partial pressure of $CO_2$ = 0.05 bar

<T>= 238.3 K

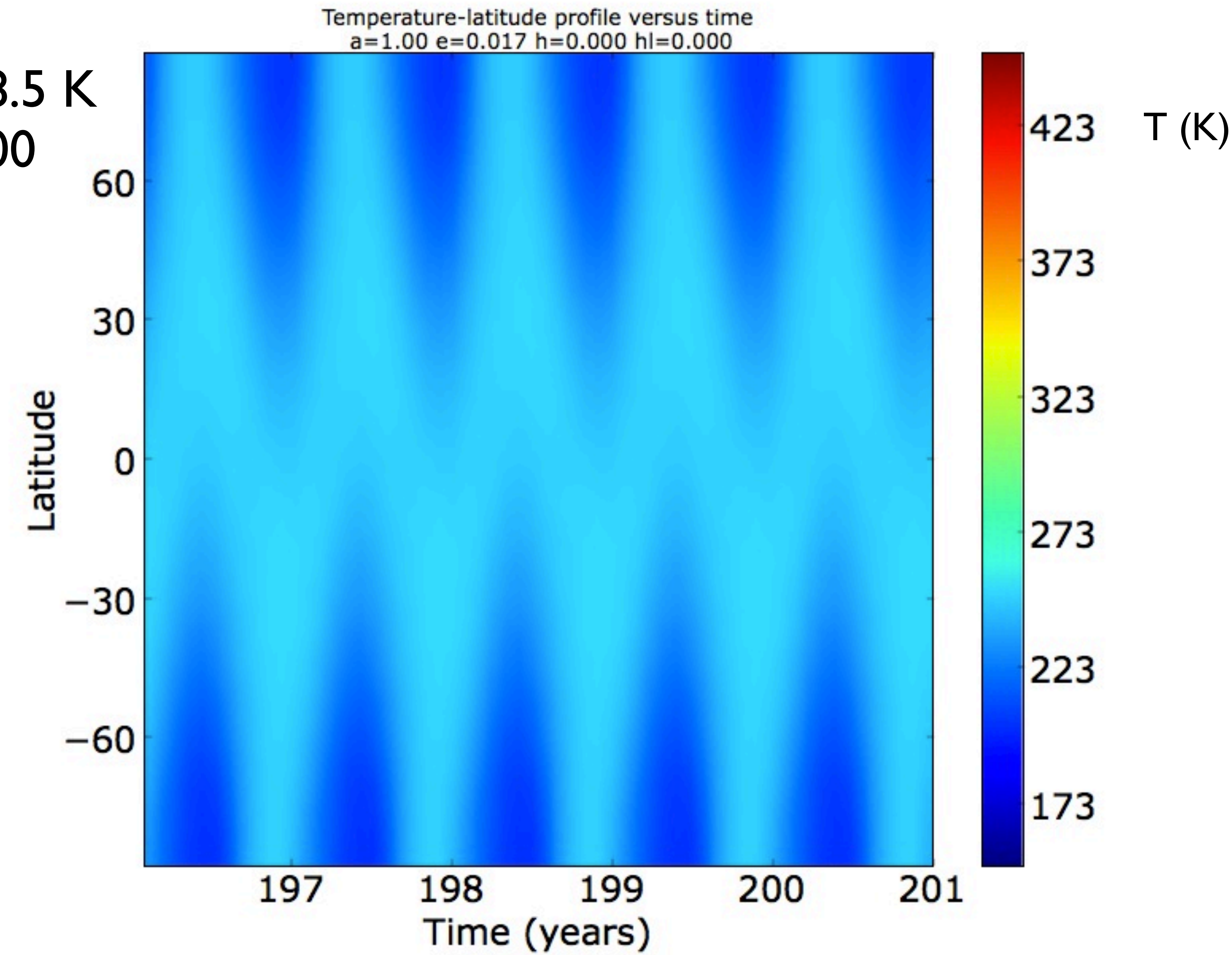
$f_{hab}$=0.00



Habitability of the Earth during the late Archean: 2.75 Ga

Solar flux = 0.81 present value Fraction of oceans=0.90 Rotation period = 18.8 h
Total atmospheric pressure=1 bar Partial pressure of $CO_2$ = 0.07 bar

$\langle T \rangle$= 238.5 K
$f_{hab}$=0.00



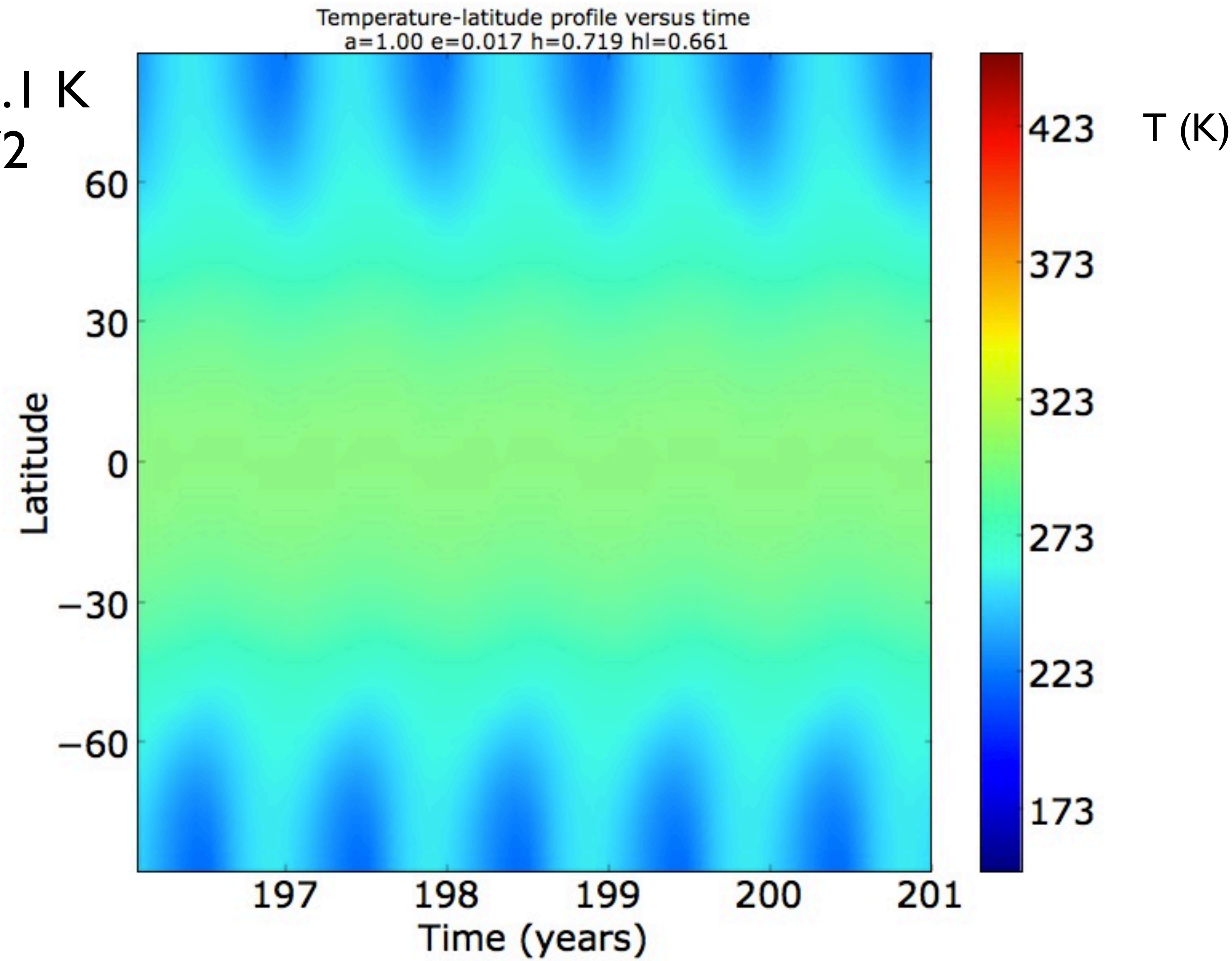
Habitability of the Earth during the late Archean: 2.75 Ga

Solar flux = 0.81 present value    Fraction of oceans=0.90    Rotation period = 18.8 h

Total atmospheric pressure=1 bar    Partial pressure of $CO_2$ = 0.10 bar

$\langle T \rangle$= 283.1 K

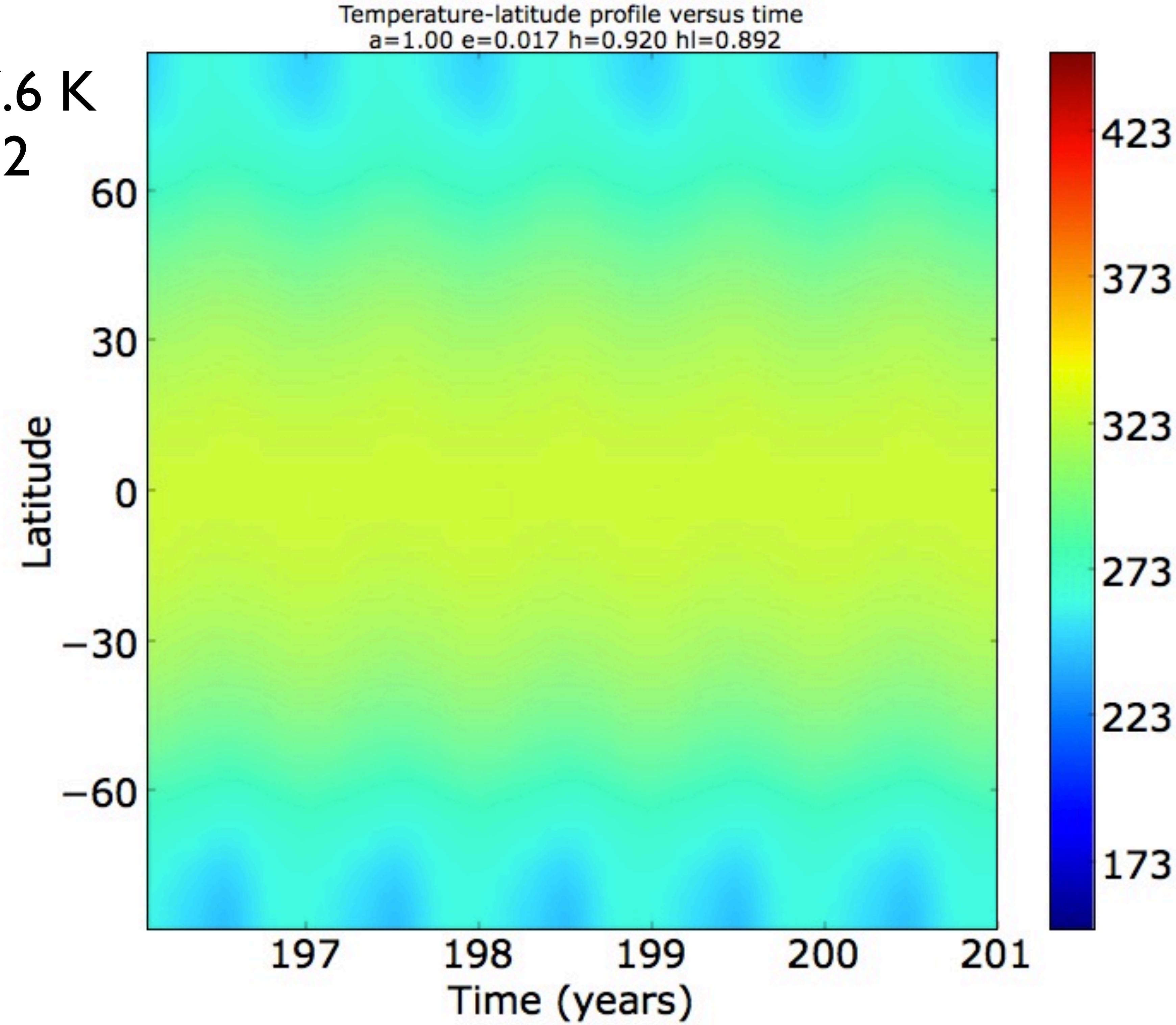
$f_{hab}$=0.72



Habitability of the Earth during the late Archean: 2.75 Ga

Solar flux = 0.81 present value Fraction of oceans=0.90 Rotation period = 18.8 h
Total atmospheric pressure=1 bar Partial pressure of $CO_2$ = 0.30 bar

$\langle T \rangle$= 307.6 K
$f_{hab}$=0.92




T (K)

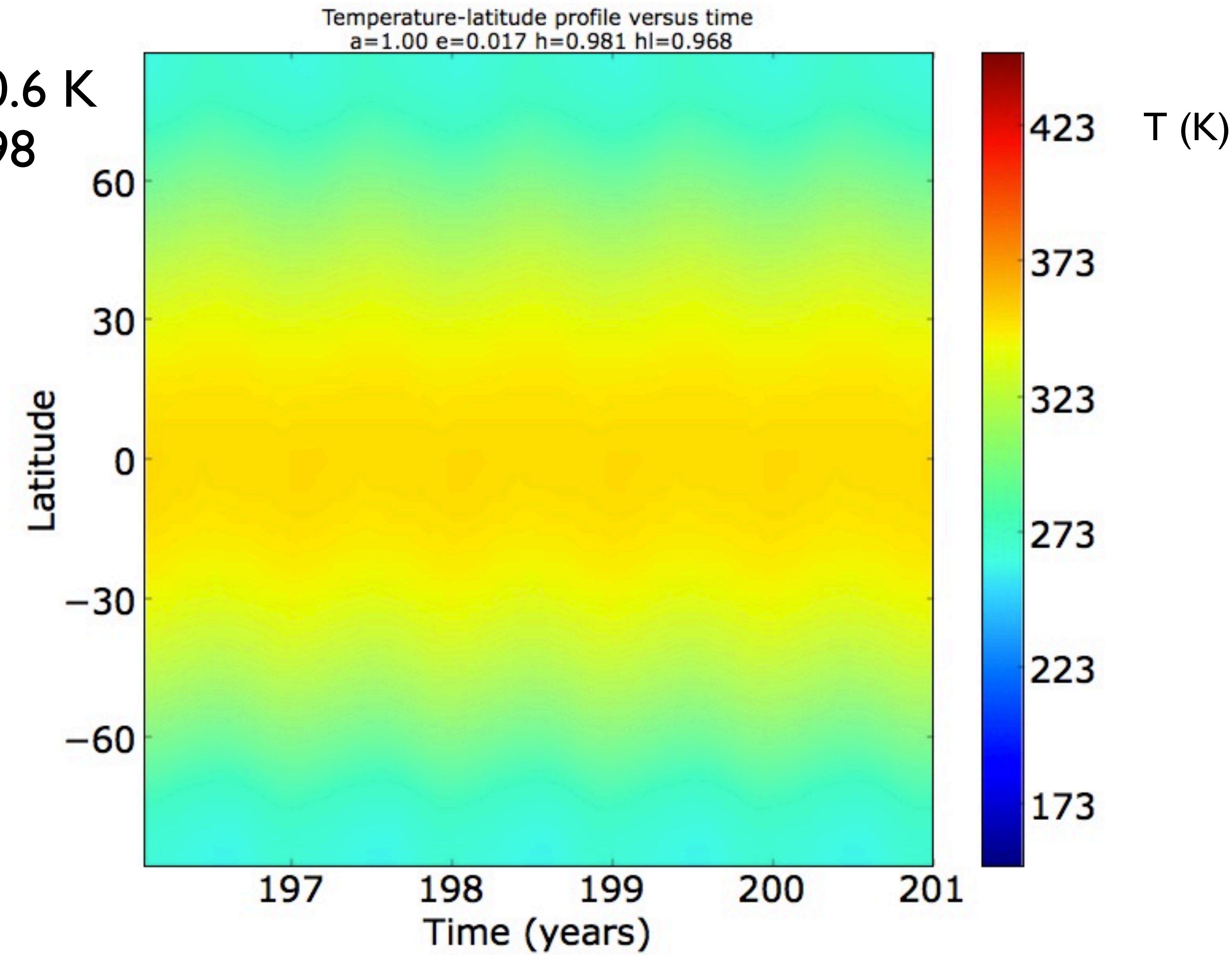
Habitability of the Earth during the late Archean: 2.75 Ga

Solar flux = 0.81 present value    Fraction of oceans=0.90    Rotation period = 18.8 h

Total atmospheric pressure=1 bar    Partial pressure of $CO_2$ = 1.00 bar

$\langle T \rangle$= 330.6 K

$f_{hab}$=0.98



# Early Earth: conclusions

Minimum p(CO2) for Archean liquid water:

Early archean (3.9 Gyr): ~ 0.2 bar

Late archean (2.75 Gyr): ~ 0.1 bar

$CO_2$ levels higher than allowed by geochemical data

Result in agreement with previous studies

Kasting (1984, 1993)

see however von Paris et al. (2008), Kunze et al. (2012)

The point of this exercise was to show the flexibility of EBMs in studying climate evolutionary effects induced by variations of stellar luminosity, planet rotational velocity and land/ocean coverage