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A SIMPLE MODEL FOR STUDYING THE INFLUENCE OF EXOPLANETS CLIMATE ON THEIR HABITABILITY

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Motivation

Modelling the surface temperature
of terrestrial exoplanets
under a variety of
stellar, orbital and planetary conditions

Census of candidate habitable exoplanets

Selection of targets for future
searches of atmospheric biomarkers

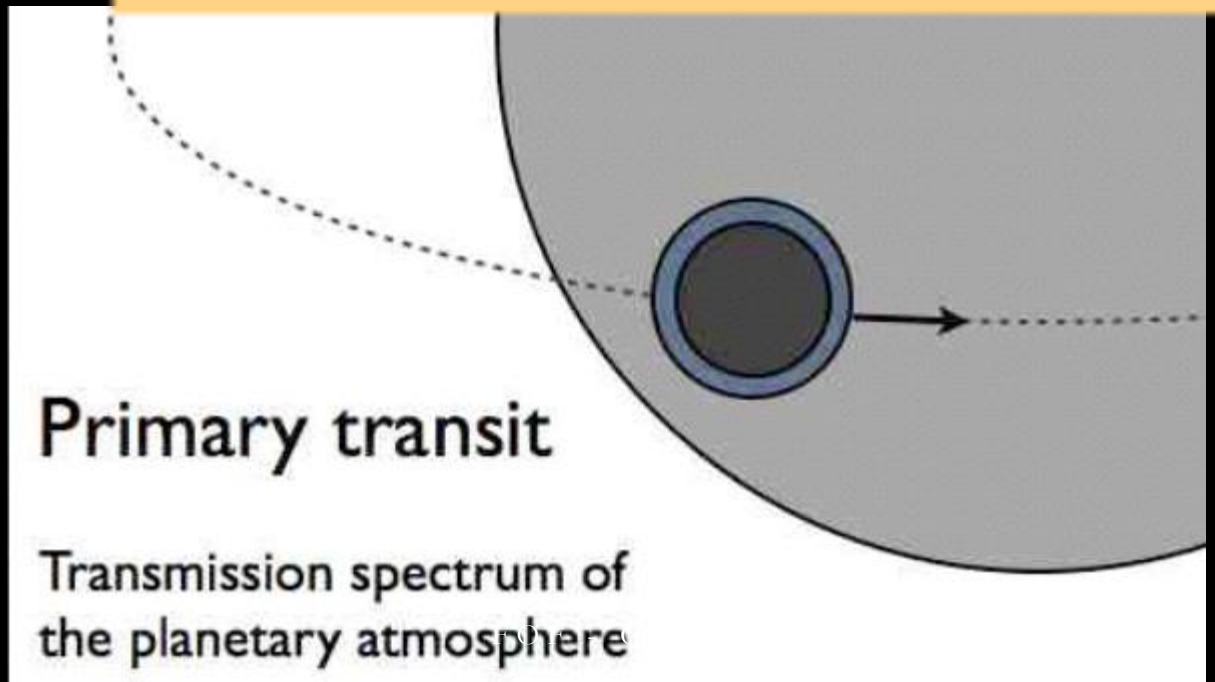
Methodology

Using climate models to estimate the planet surface temperature as a function of time and latitude

$$T(\phi, t)$$

Using the temperatures predicted by the model to quantify the surface habitabiliy of the planet

$$H(\phi, t)$$



Zero-order energy balance and astrophysical effects on climate

PLANETARY ALBEDO

$$I = S(1 - A)$$

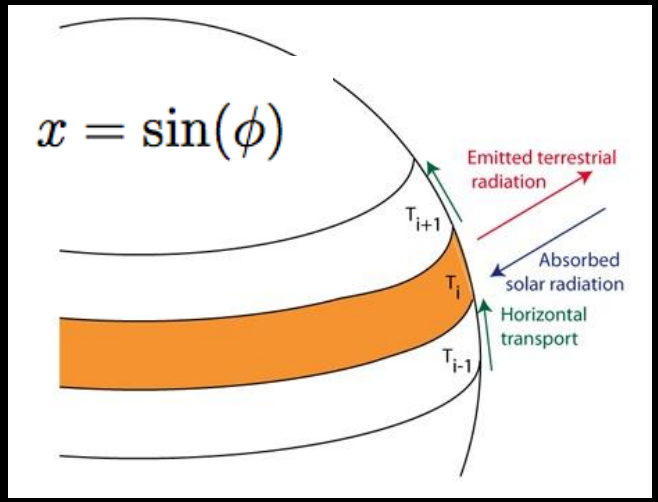
OUTGOING PLANETARY RADIATION (thermal IR)

INCOMING STELLAR RADIATION (visible/UV)

Without a suitable estimate of I: predicted Earth average T=-18C, observed=14C

ENERGY BALANCE MODELS

The diffusion equation



OUTGOING PLANETARY RADIATION (thermal IR)

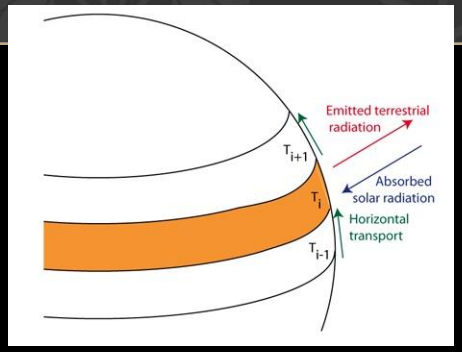
INCOMING STELLAR RADIATION (visible/UV)

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

Temporal evolution

Latitudinal transport

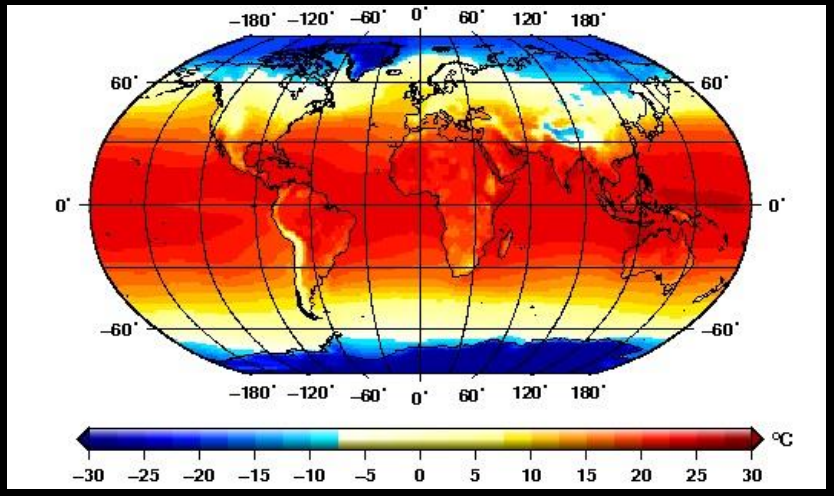
Why Energy Balance Models ?



Computationally cheap
Moderate number of input parameters

IDEAL FOR EXPLORATORY WORK

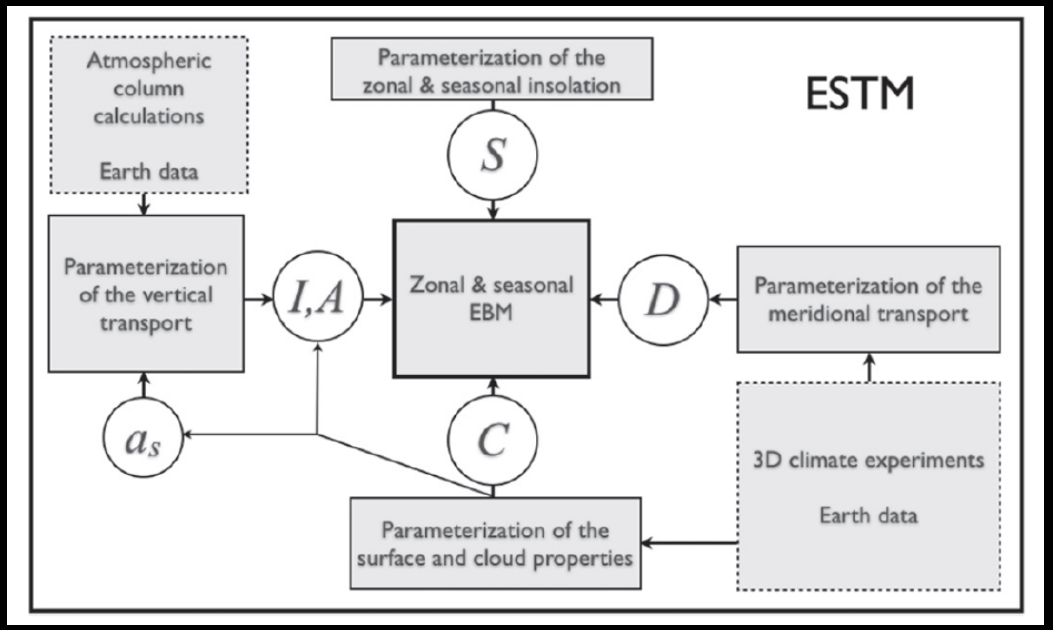
Global Circulation Models



Very time consuming
Large number of input parameters not constrained by the observations

IDEAL TO STUDY SPECIFIC CASES

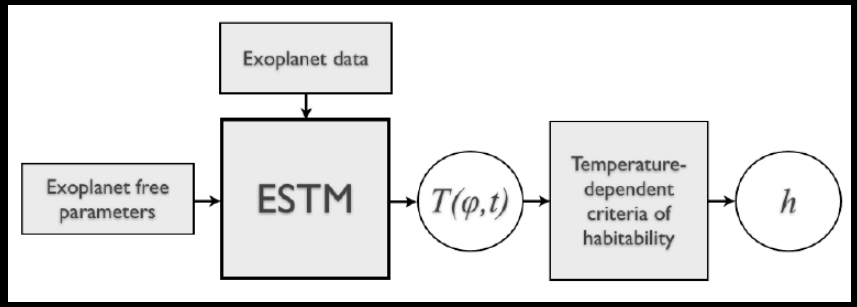
ESTM – Earth-like Surface Temperature Model



Vladilo+ 2013, 2015

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, ...

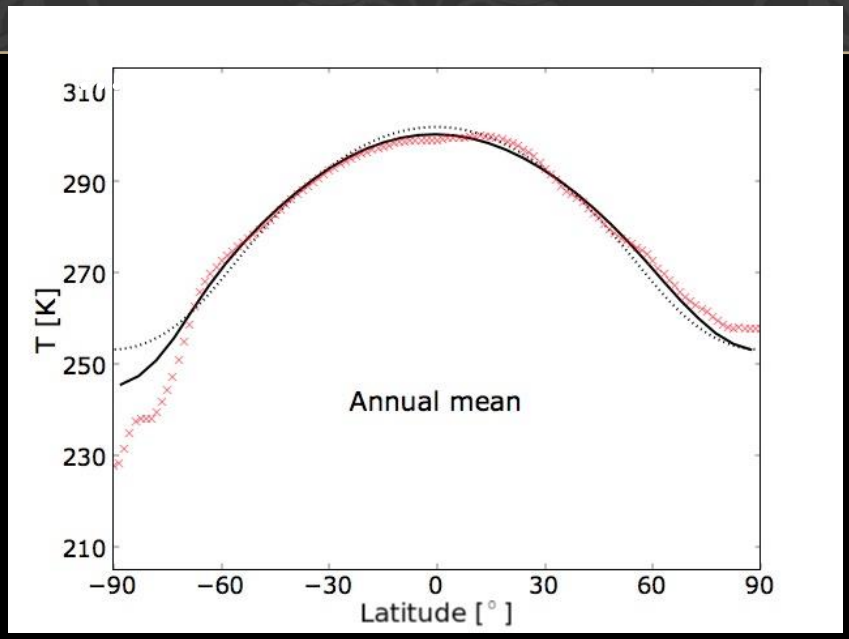


ESTM features

- **Physical characterization** of the diffusion term **D** (tested with GCM aquaplanet, Kaspi & Showman 2015)
- **Scaling laws for D** with surface pressure, gravity, planet radius, rotation period
- **Exact calculation of insolation S** as a function of orbital eccentricity and axis obliquity
- **Evolutionary tracks** of stellar luminosity (PARSEC, Bressan+ 2012)
- **Vertical radiative transfer:** CCM routines of NCAR climate model
- Surface properties: schematic geography (ocean cover fraction)
- Models for **cloud covering and ices**

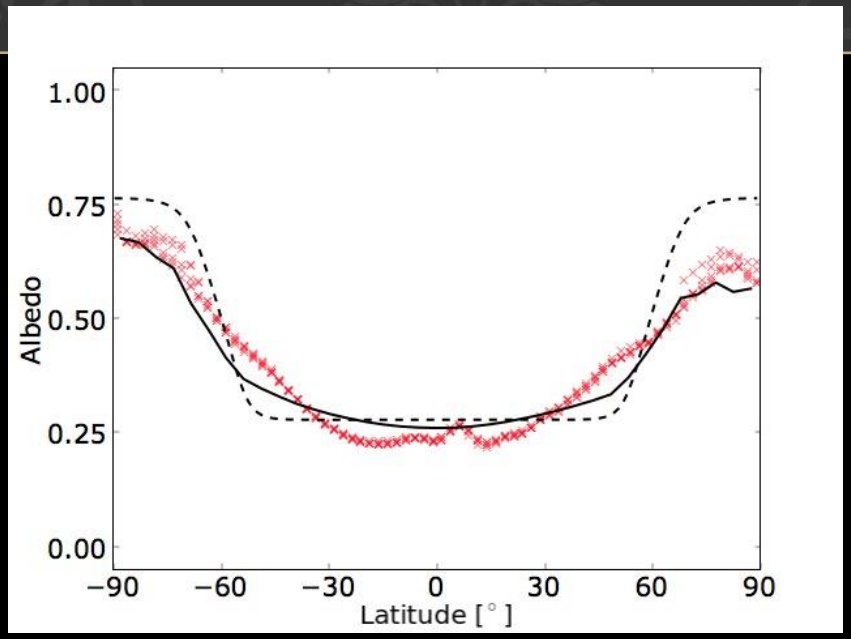
- Incoming: upgrading vertical trasport to a broader range of atmospheric chemical compositions

Validation with Earth's data: Temperature-latitude profile



Latitude profile of the mean annual surface temperature

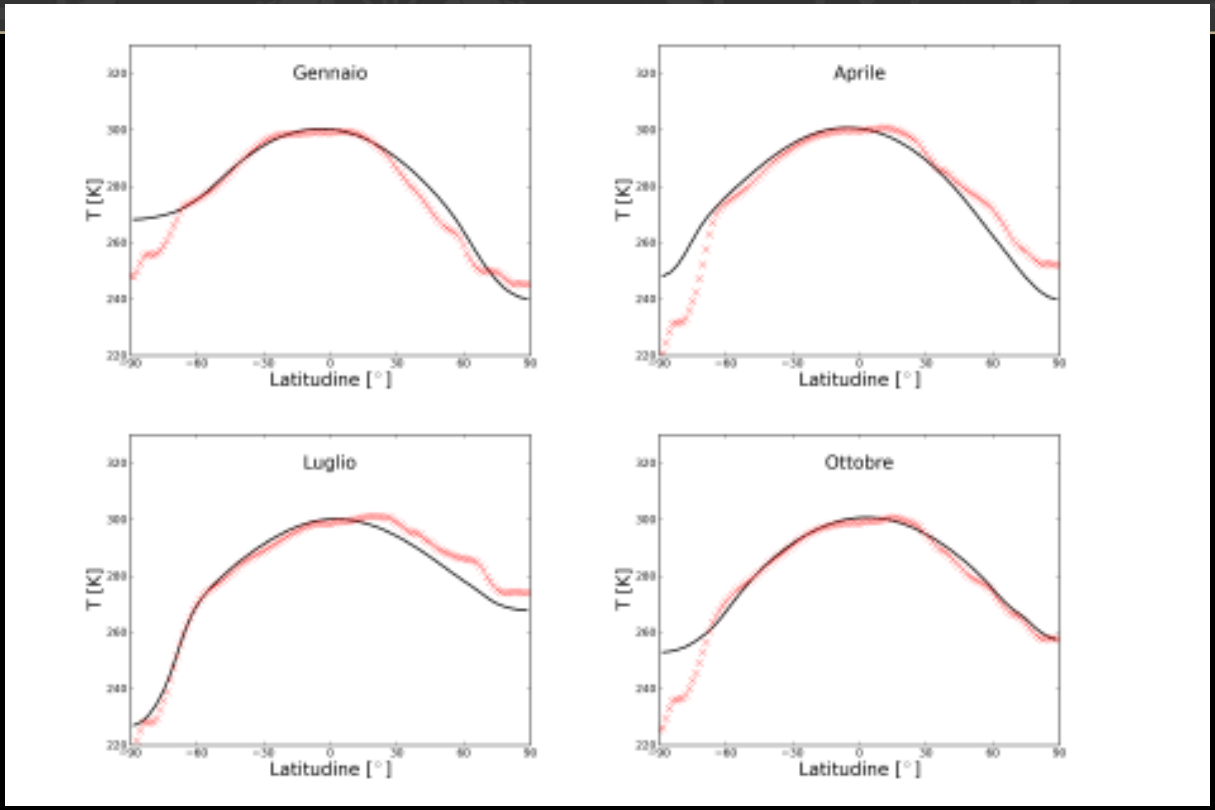
Validation with Earth's data: Albedo-latitude profile

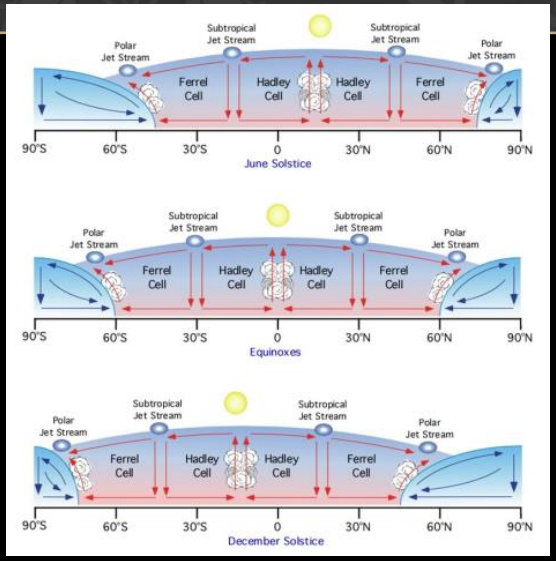


Mean annual surface albedo

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

Model validation: seasonal evolution

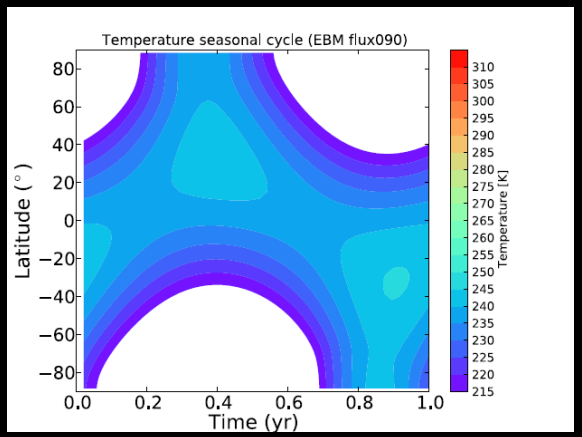


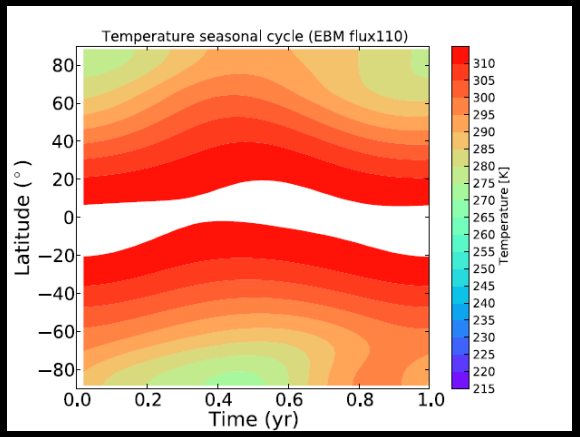


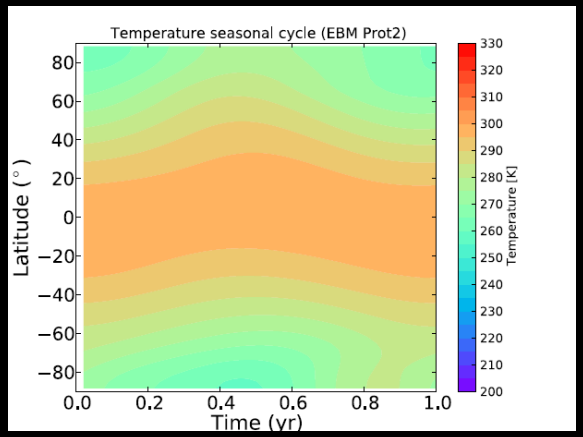
$$D_0' = D_0 \left[\overline{\mu}(\lambda, t) + \phi_0\right]$$

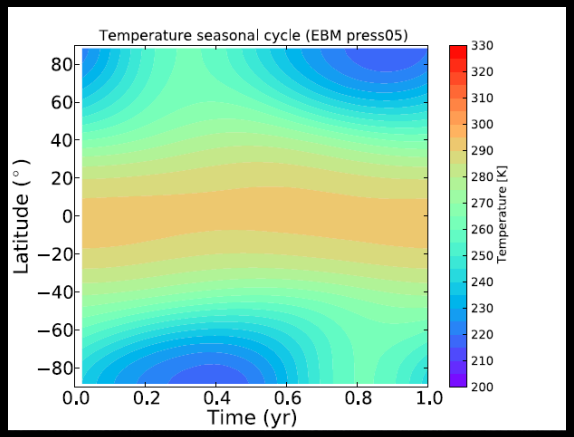
Parameters affecting habitability

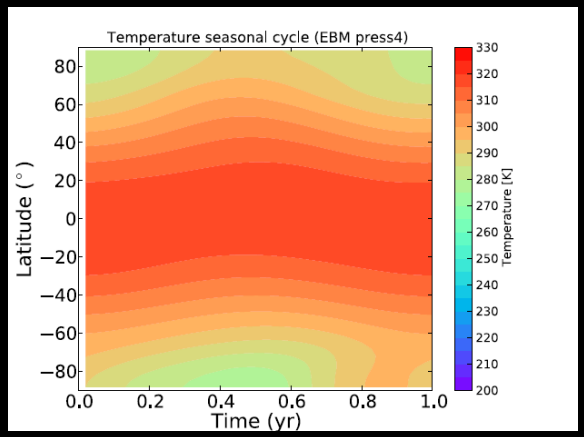
Insolation: S=0.9, 1.1 S_0

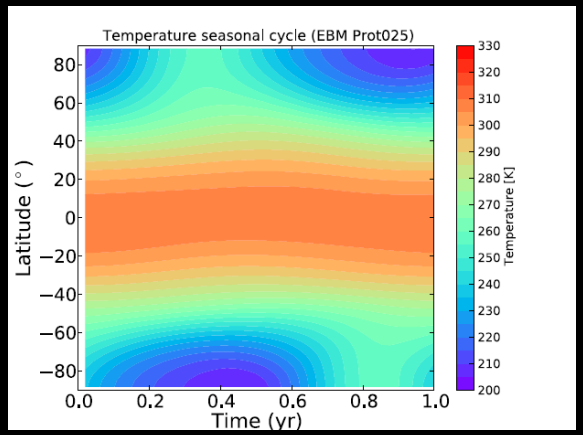












Pressure: 0.5,4 bar

Rotation period: 2d, 0.25d

Quantifying the habitability with the liquid water criterion

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

$$T(\phi, t)$$

Habitability function

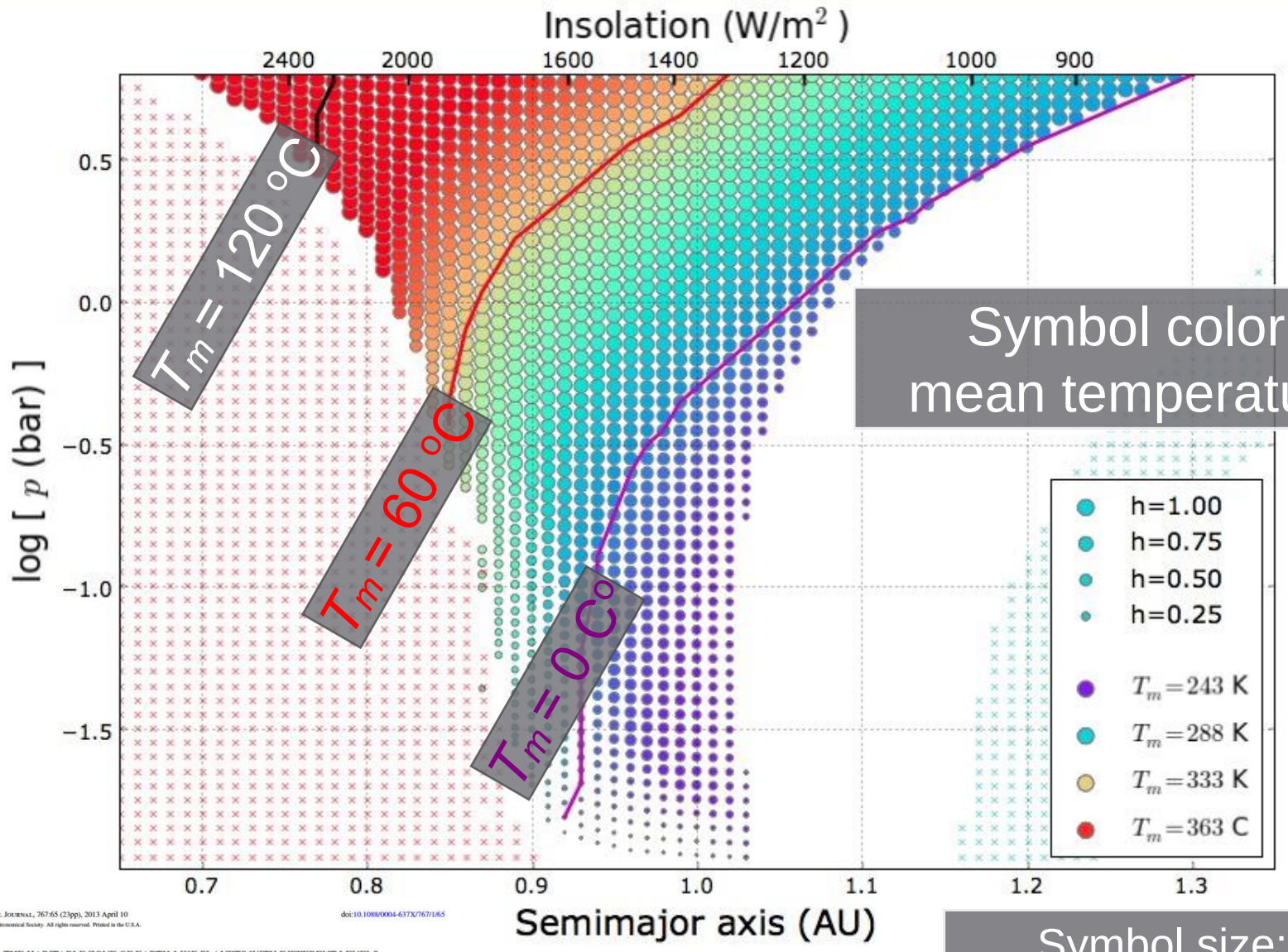
$$H(\phi,t) = \begin{cases} 1 & \text{if } T_{\text{melt}}(p) \leq T(\phi,t) \leq T_{\text{boil}}(p) \\ 0 & \text{otherwise} \end{cases}$$

Liquid water criterion

Mean global annual habitability

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

The pressure dependent HZ of Earth-like planets



Symbol color: mean temperature

Symbol size: mean habitability

The Astrophysical Journal, 767:65 (23pp), 2013 April 10 doi:10.1088/0004-637X/767/1/65

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

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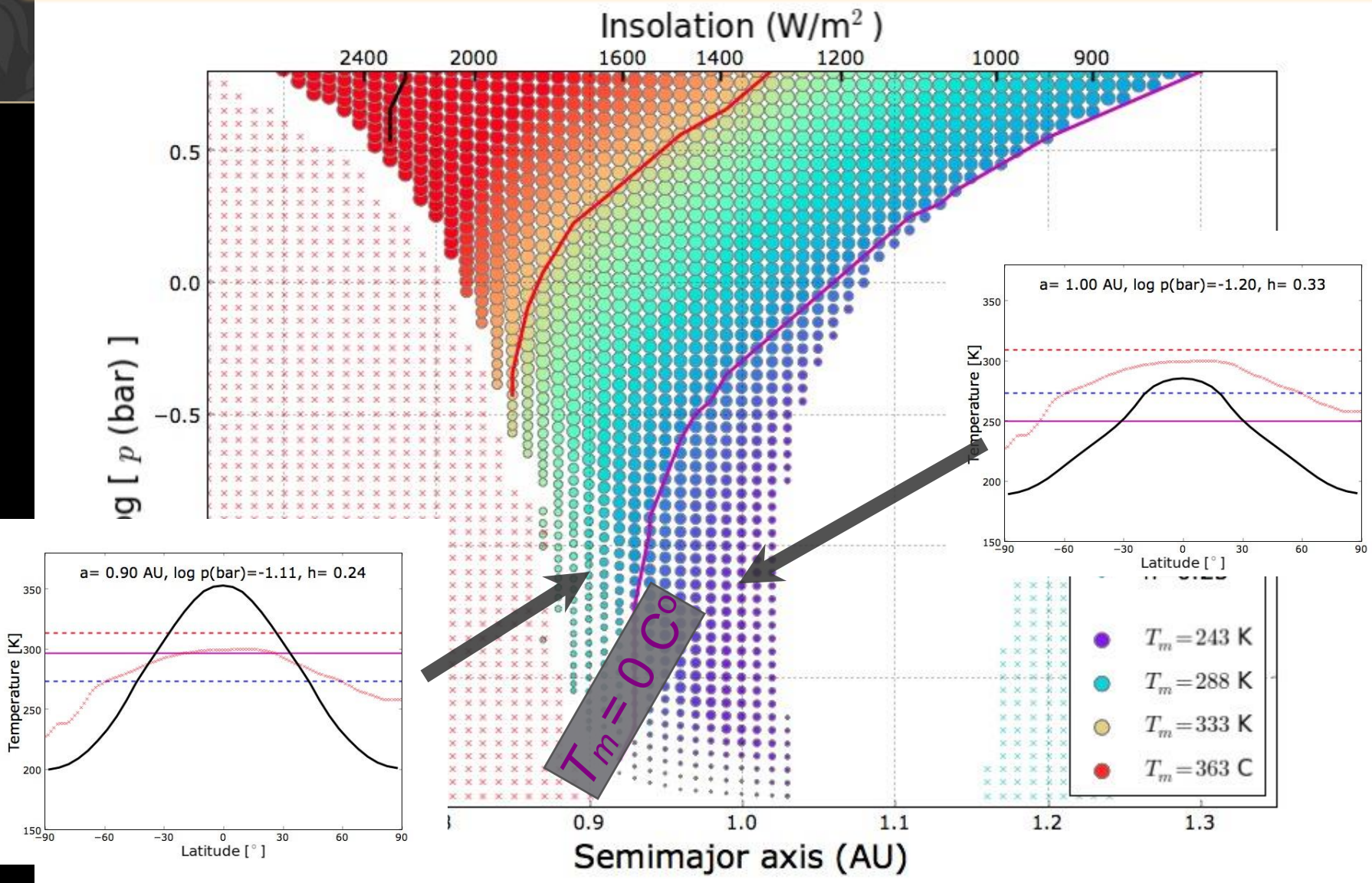
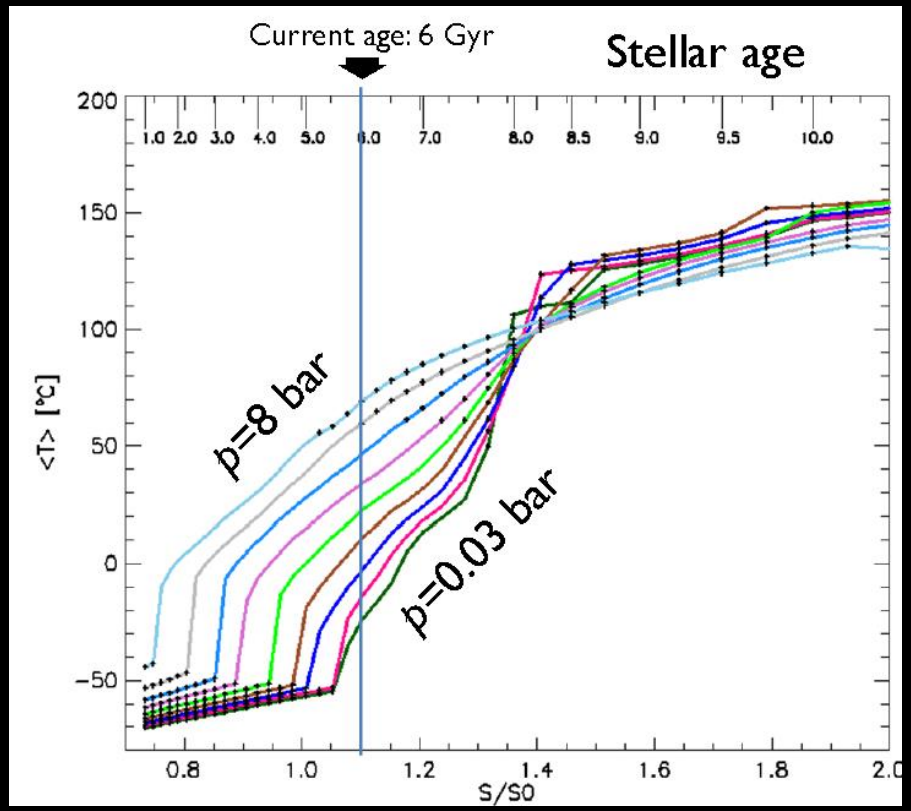
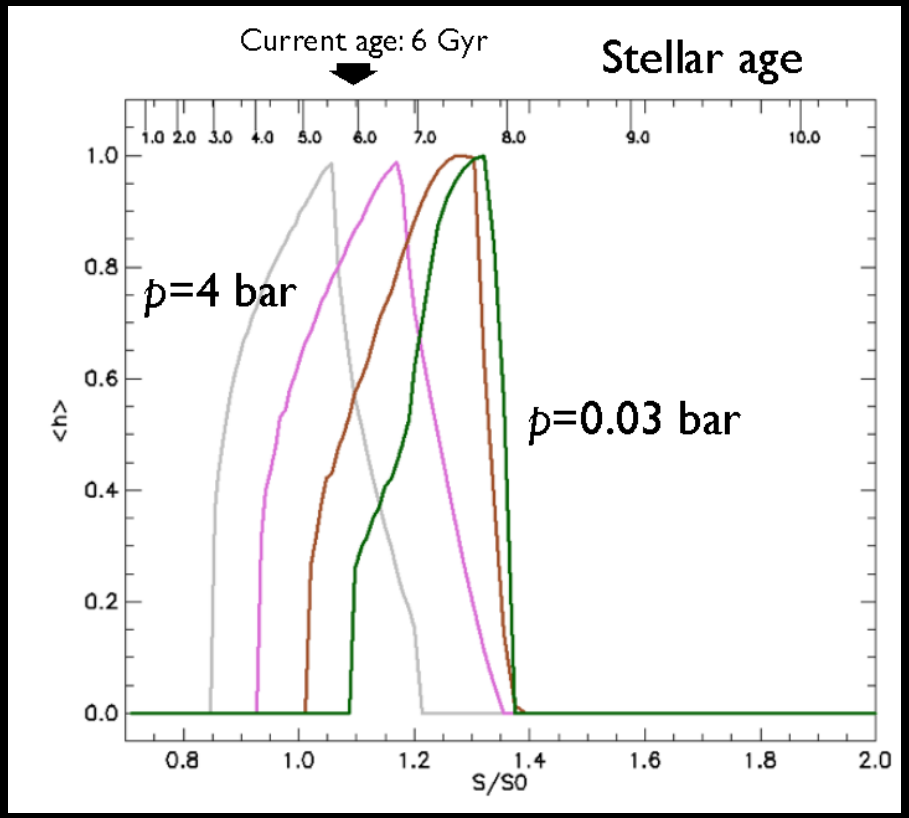
Analysis of individual temperature-latitude profiles



Kepler 452b

$R = 1.63\ R_{earth}$ $S = 1.10\ S_o$

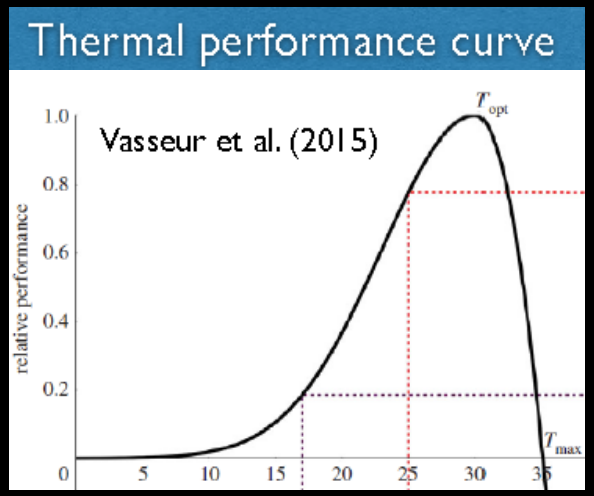




Gravity, p(CO2) and atmospheric chemical composition are Earth-like

BIOLOGICALLY-DRIVEN TEMPERATURE-DEPENDENT HABITABILITY CRITERIA

Silva, Vladilo, Schulte, Murante, Provenzale, Int, J. Astrobiology, accepted



Complex organisms

$$0°C \lesssim T \lesssim 50°C$$

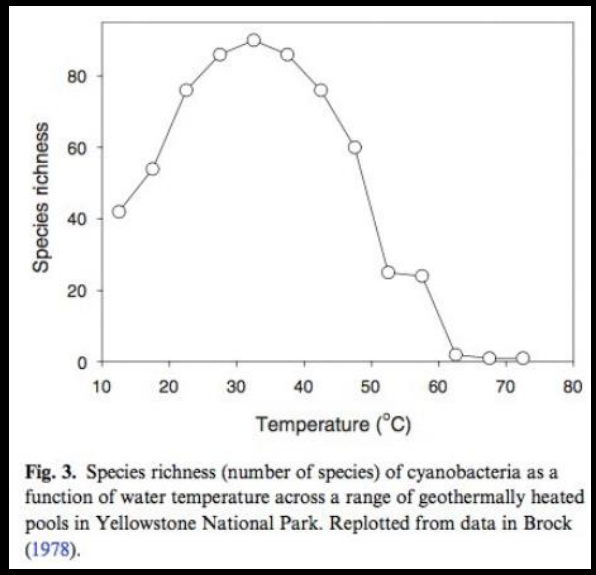
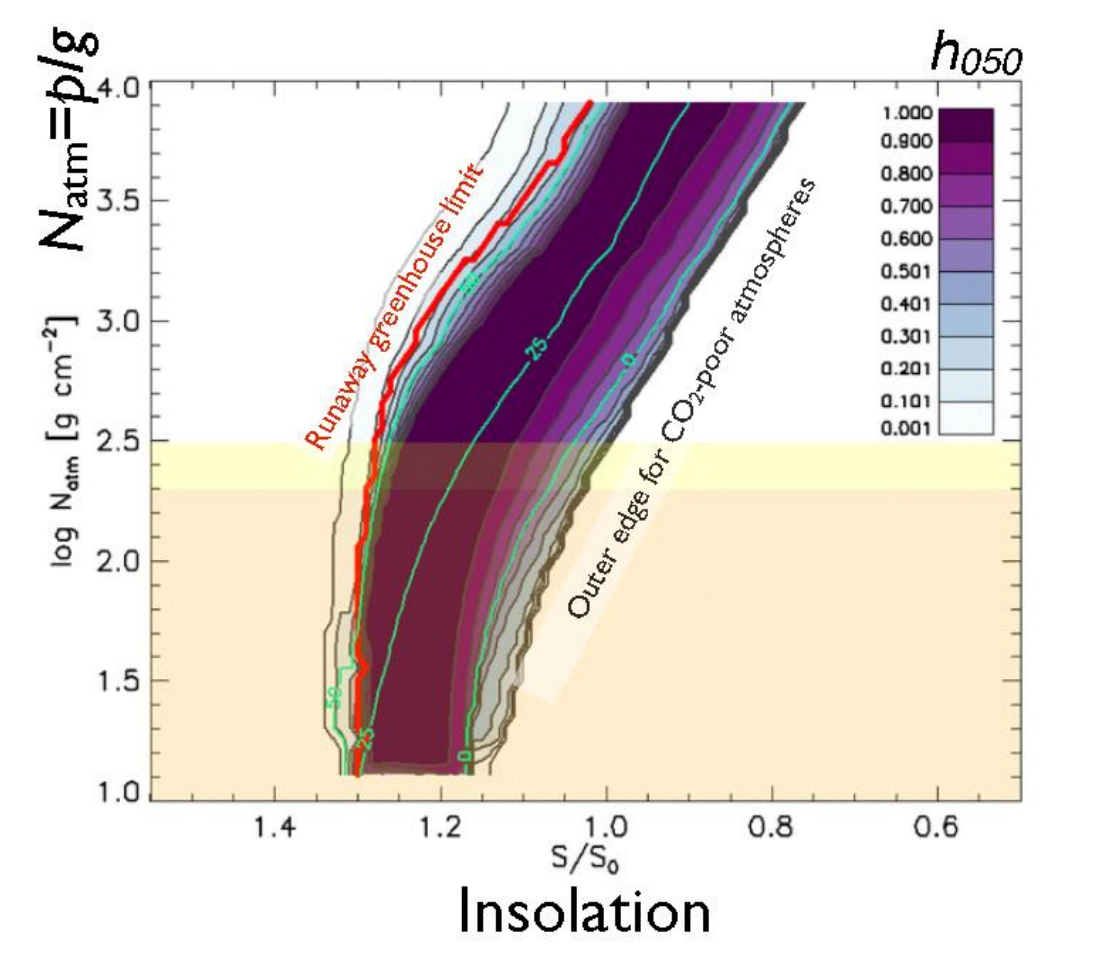


Fig. 3. Species richness (number of species) of cyanobacteria as a function of water temperature across a range of geothermally heated pools in Yellowstone National Park. Replotted from data in Brock (1978).

Cyanobacteria(photosyntesis)
→ athmospheric biosignature

(…holds on Earth: how universal is this?)

COMPLEX LIFE VS LIQUID WATER HABITABILITY



CONCLUSIONS: HABITABLE ZONE NEEDS MORE DIMENSIONS

- Many astrophysical and planetary parameters affect the surface temperature of exoplanets
- **Some of them will not be observable in the near, or not so near, future**
- **The very definition of habitability is debatable**
- ***Simple, fast climate model can be used to explore parameter space and evaluate the probability for planet with given, observed characteristics to be habitable (given a definition!)***

- **Such studies may help in identifying the most promising targets for a future search of atmospheric biosignatures**

APR 1ST, 2016

FOF - CORDOBA, ARGENTINA