An experiment in Astrobiology: Exploring the climate parameter space of rocky planets

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I A T E

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Ciclo de seminarios OAC

What is Astrobiology?

- The study of Life in the Universe
- …Earth included!

- The First Question is: *the search of Life in the Universe*
- The True Question is:
  how common is life in the Universe ?
- ..and the ultimate question is: are we alone?
  (not going to tackle this)

What is life, that thou art mindful of him (Sal8,5)

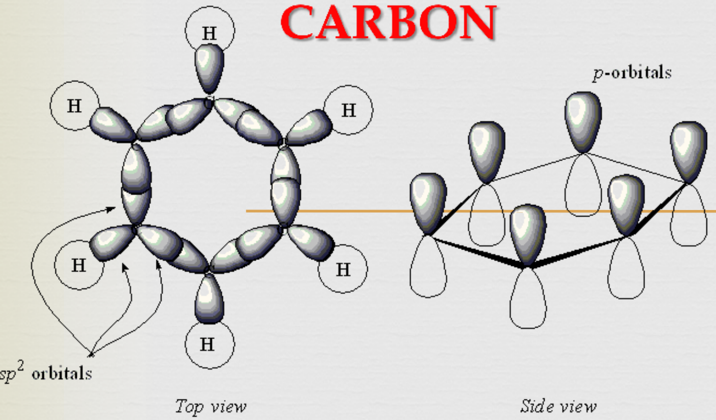
- A formal definition of life is lacking.
- Many proposed, mainly based on its characteristics
  - ..the same as defining water using its properties..
- **"Life as we know it"**

- My favourite definition: **descendant with modifications**
  - **Life is everything able to reproduce itself faithfully, but still subject to Darwinian evolution**

- Clearly, polymorphic computer viruses are alive!

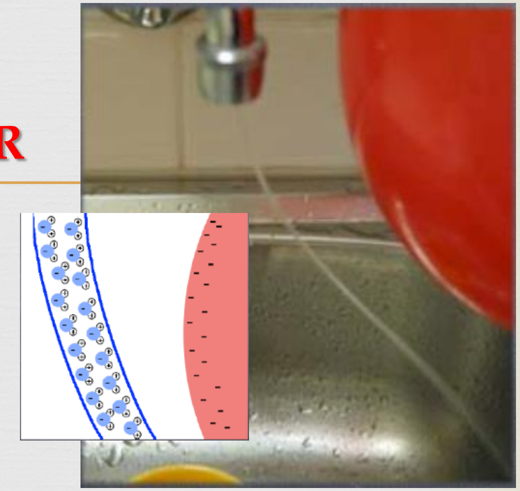
Life as we know it

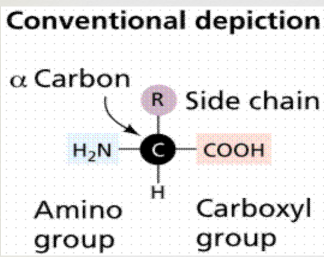
CARBON

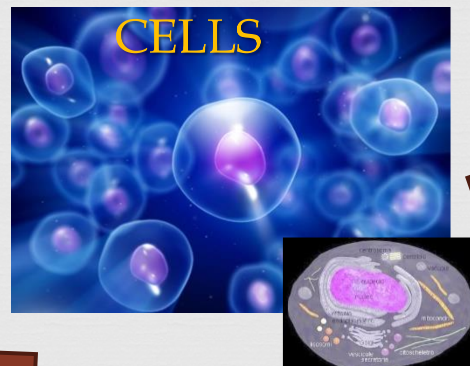


ENERGY

WATER

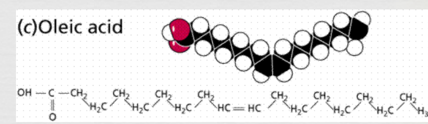


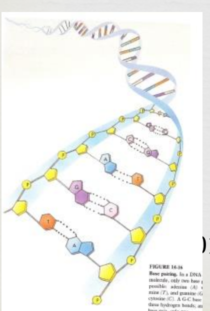




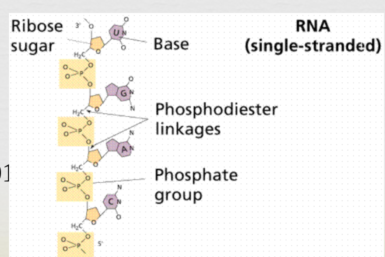
PROTEINS
(Aminoacids)

LIPIDS

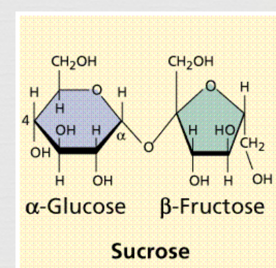




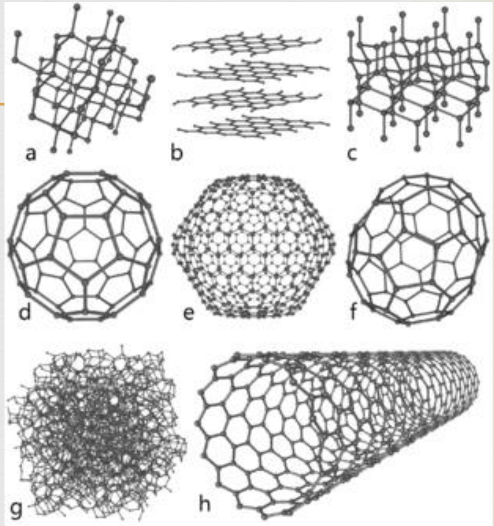
DNA/RNA



CARBOHYDRATES
(Sugars)



Life and water



- Complex molecules: **CARBON** needed
  NO other element known to build very complex chemical chains
- Energy-producing oxidant:
  FLUORINE (but explodes)
  CHLORINE (but forms bleach)
  OXIGEN (3^{rd} most common element in the Universe)
- Metabolism-enabling **solvent**, possibly (mandatorily?) polar
  WATER
  AMMONIA (too low melting energy?)

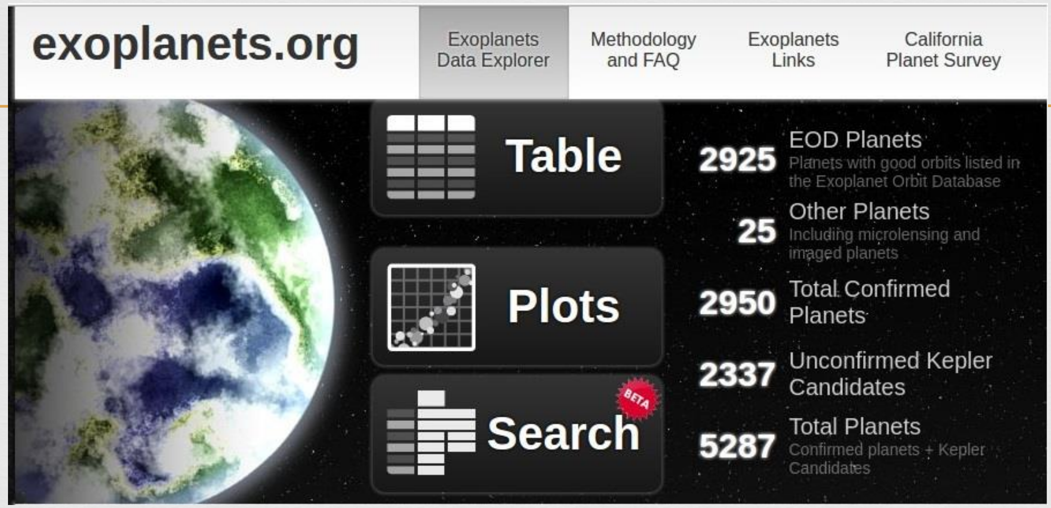
…life as we know it seems to have few viable physical and chemical alternatives..

…search for life is the search for liquid water

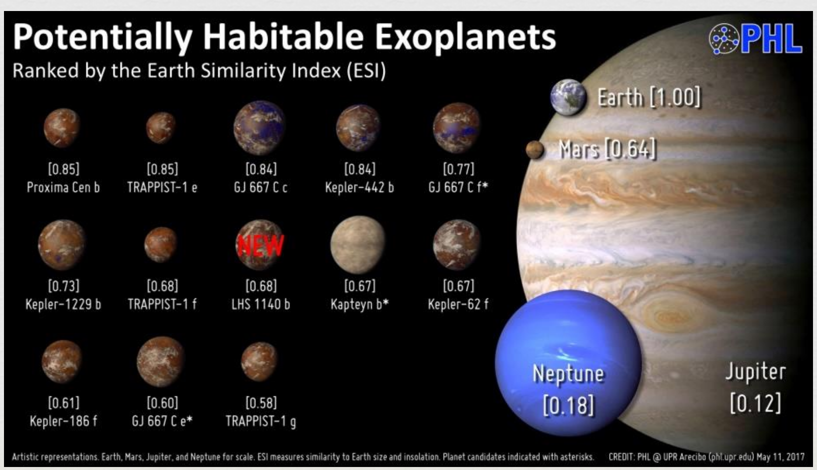
- Liquid water can exist in many diverse astronomical environments, even in traces
- To be remotely observable (in other stellar systems), life must produce abundant biomarkers in atmosphere:
  - Subterranean/under-ice/ extremophyles (?) excluded
  - **Complex** life needed
- A complex biosphere needs LOTS of water (…and oxigen…) to develop
- We need rocky planets with liquid water.
- **…. we have lots of them!**

Exo-planets (Nov 7th 2017)

- http://www.exoplanets.org/



- http://phl.upr.edu/projects/habitable-exoplanets-catalog



Current Number of Potentially Habitable Exoplanets

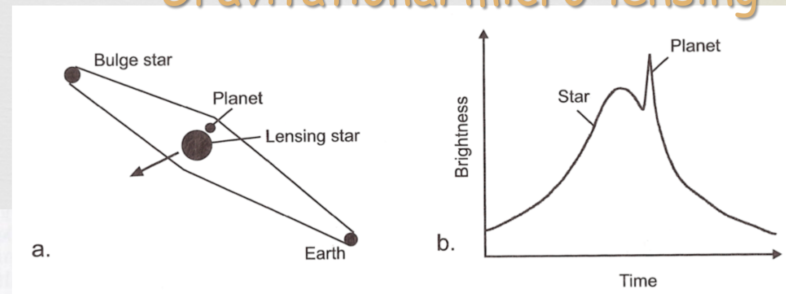
Subterran (Mars-size)	Terran (Earth-size)	Superterran (Super-Earth/Mini-Neptunes)	Total
1	21	30	52

subterran = 0.1 — 0.5 M_E or 0.4 — 0.8 R_E, **terran** = 0.5 — 5 M_E or 0.8 — 1.5 R_E, **superterran** = 5 — 10 M_E or 1.5 — 2.5 R_E. M_E = Earth masses, and R_E = Earth radii.

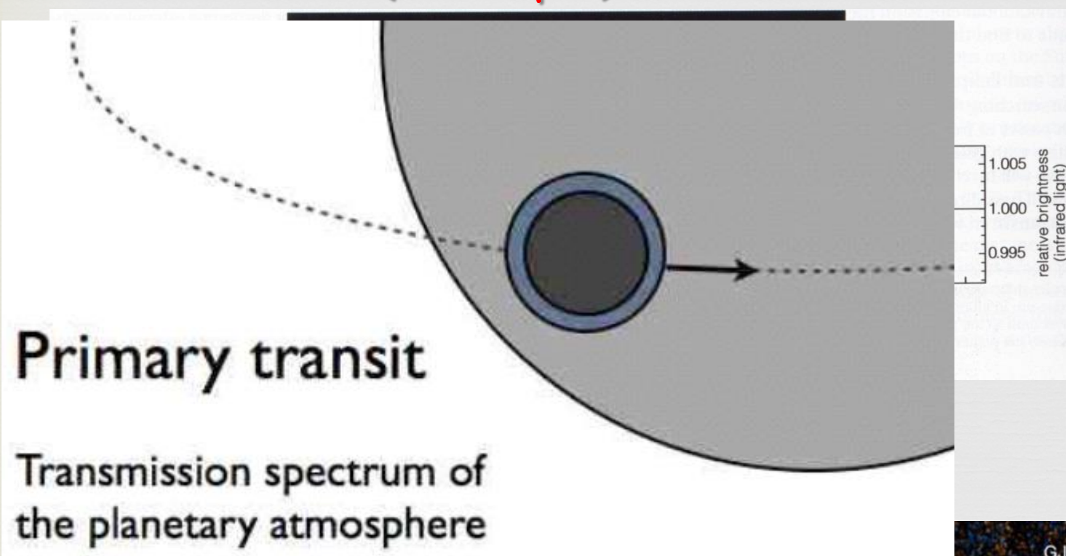
(How are they estimated?)

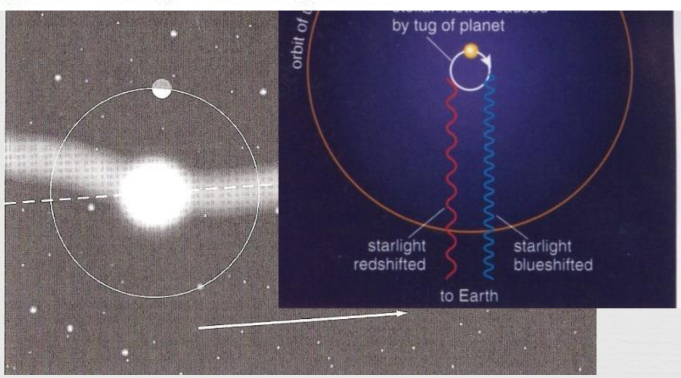
Chasing exo-planets

Gravitational micro-lensing

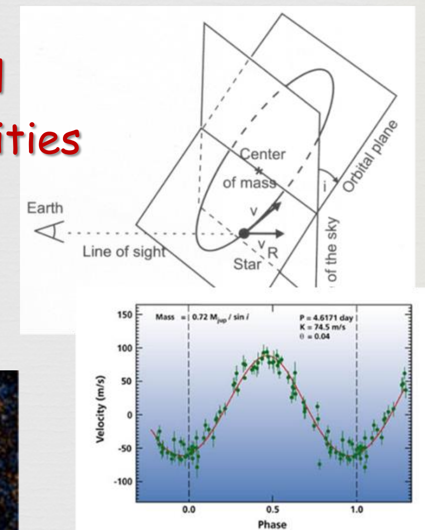


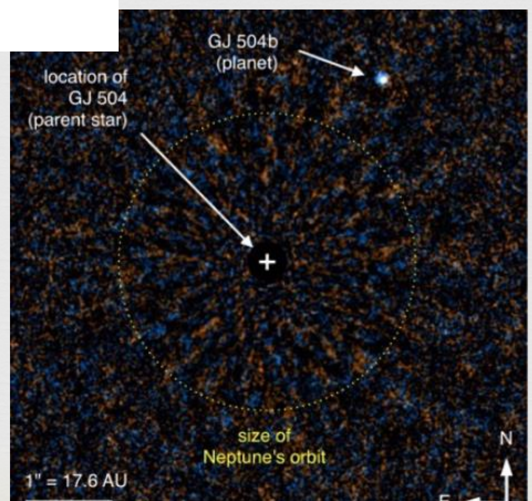
Transits - This will also allow atmosphere characterization! (hot topic)





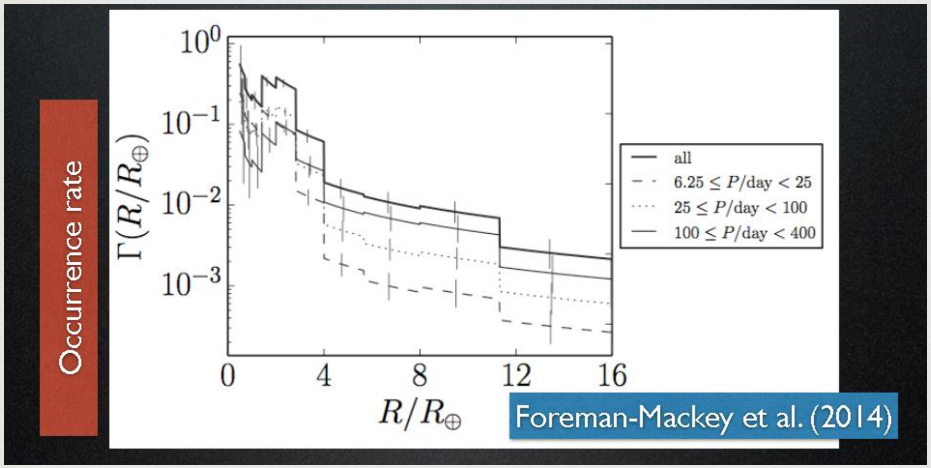
Radial Velocities





Direct imaging (Cold Jupiters only)

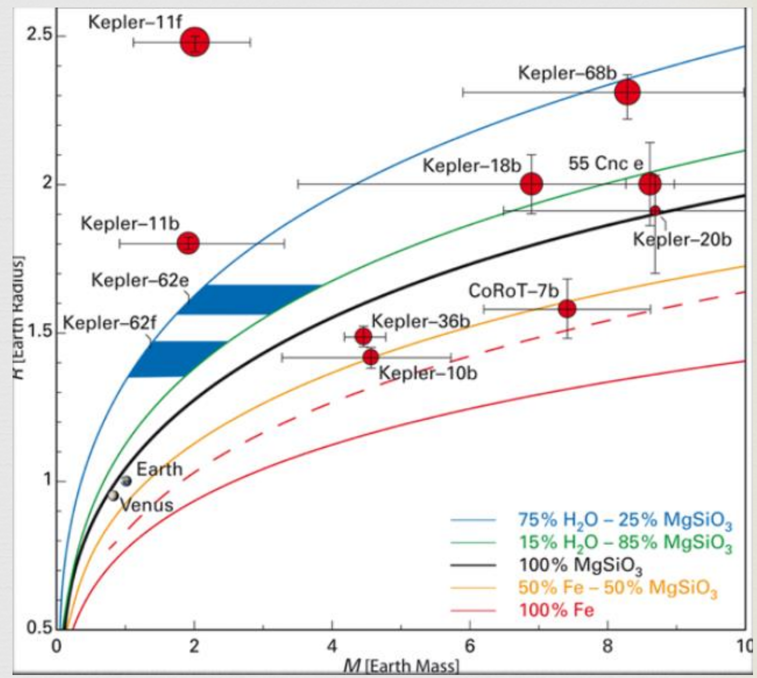
Exo-planets characterization



Small rocky planets are common

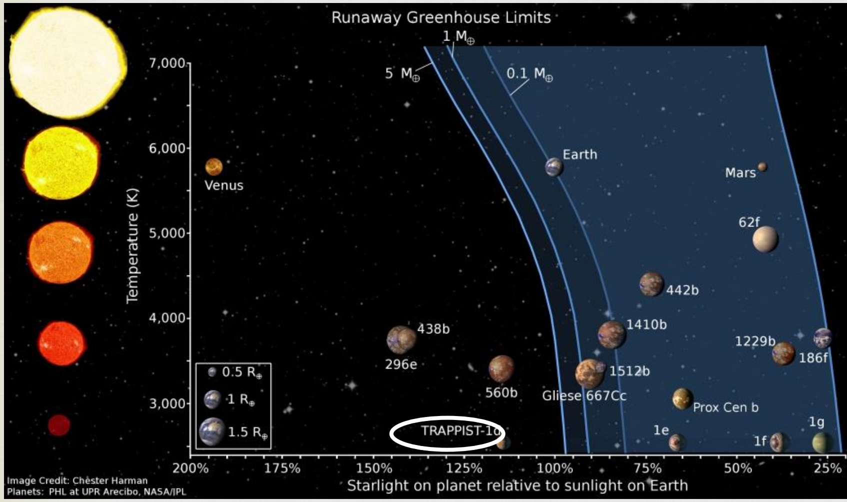
They are diverse
(e.g., hot and warm jupiters,
Super-earths…)

radius

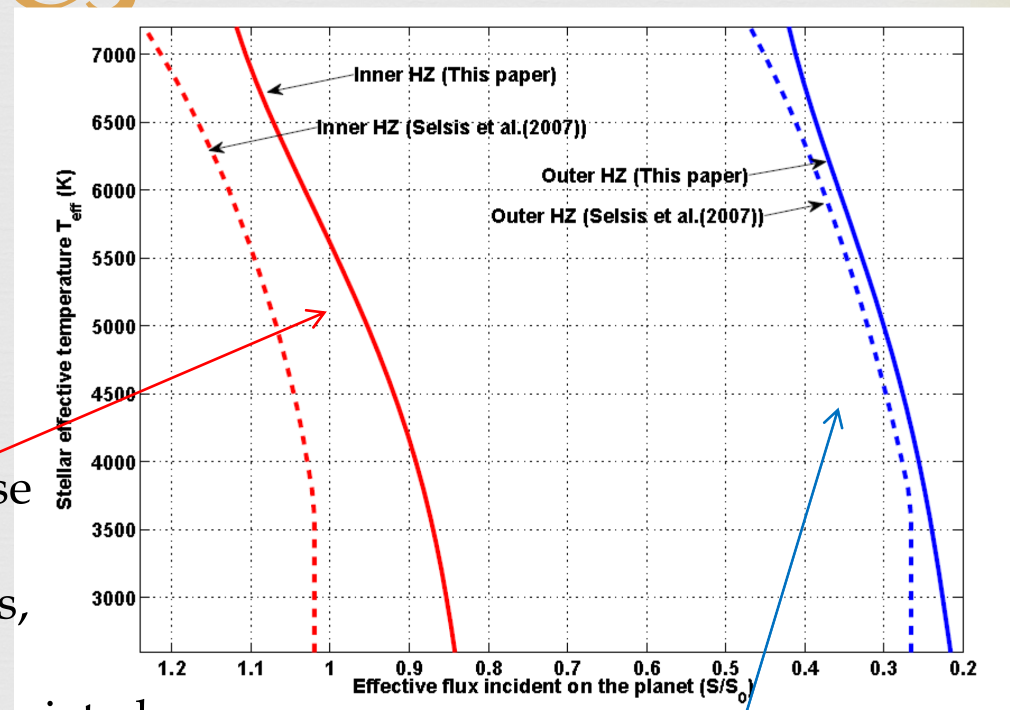


mass

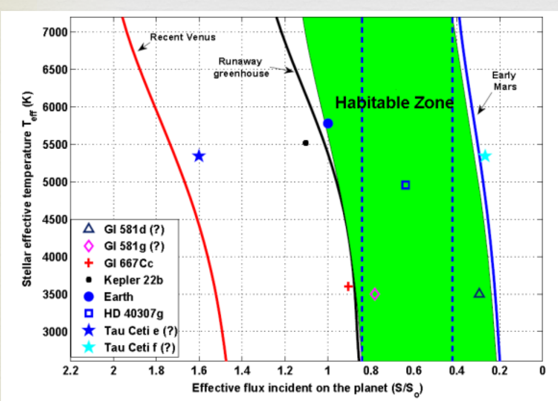
Circumstellar habitable zone



(Kasting+ 93 – BEFORE 1st exo-planet discovery)



Runaway greenhouse (ocean evaporates, H_2O is photodissociated and hydrogen is lost)



(Kopparapu+ 2013)

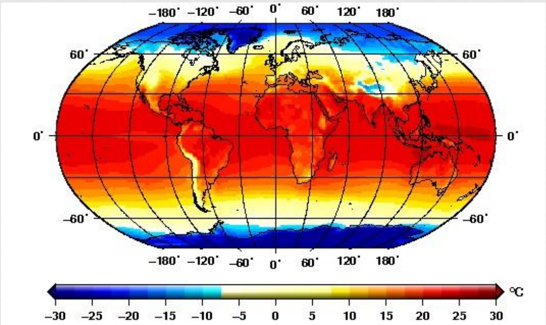
Maximum greenhouse (at lower insolation, effect of CO_2 clouds albedo takes over)

The surface temperature

- **0D** model: $I = \sigma T^4_{eq} = \frac{S}{4}(1 - A)$ $T_s = T_{eq} + \Delta T_{greenhouse}$

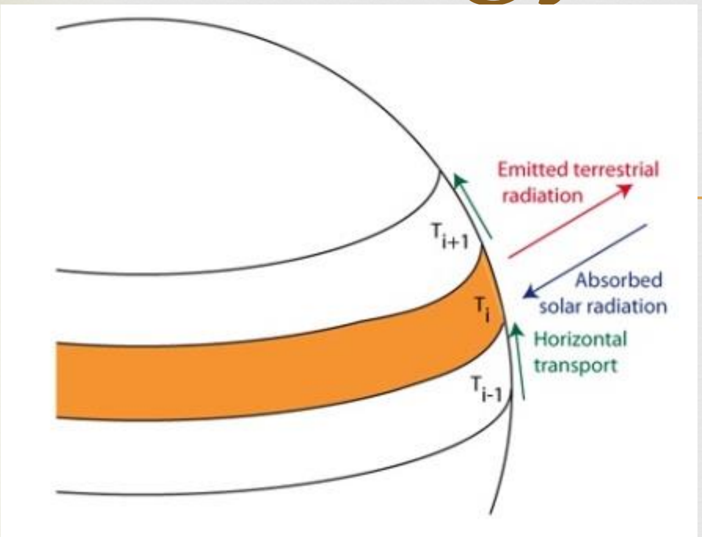
- Earth: T_{eq}= -18°C, T_s=+14.5 °C
- No information on latitudinal heat transport
- $\Delta T_{greenhouse}$ to be modeled

- **3D** climate models: **G**eneral **C**irculation **M**odels
- Complex, parametrized physics; requires full planet infos; need HPC and 10^5-10^6 CPU hours per run



- **1D** radiactive/convective atmospheric column models –use atmo chemistry and radiative transfer for I,A, $\Delta T_{greenhouse}$

Energy Balance Models



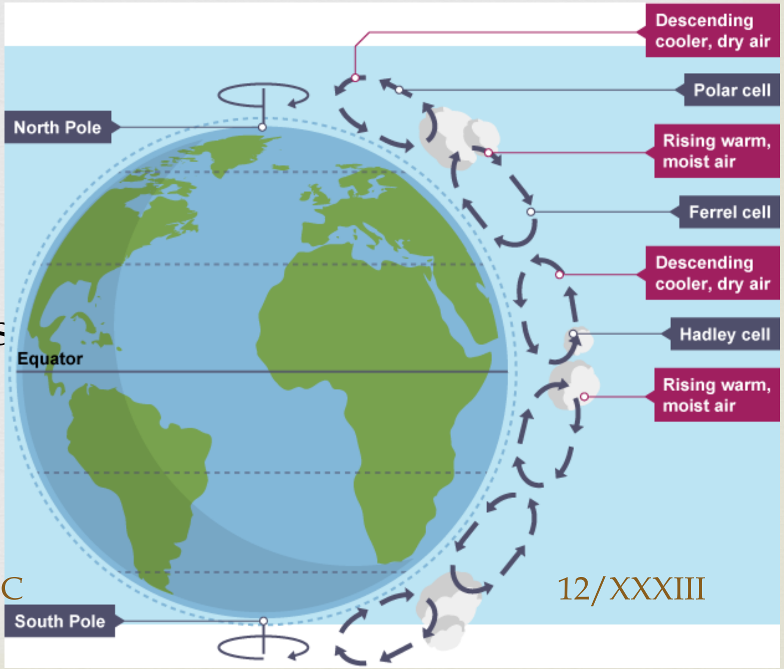
φ: latitude

x= sin φ

1D model

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

- Emulates latitudinal heat transport using a diffusion coefficient D
- Real heat transport: **atmospheric cells!!** →
- …and oceanic heat transport
- Term S contains the astrophysics
- Terms A, C contain the planetary characteristics
- Terms I, A contain the atmosphere characteristics
- All terms modelled in a simple (often analytic) way
- Williams & Kasting 97, Spiegel+ 2008,9,10



ESTM

Earth-like Surface Temperature Model

1,5D model

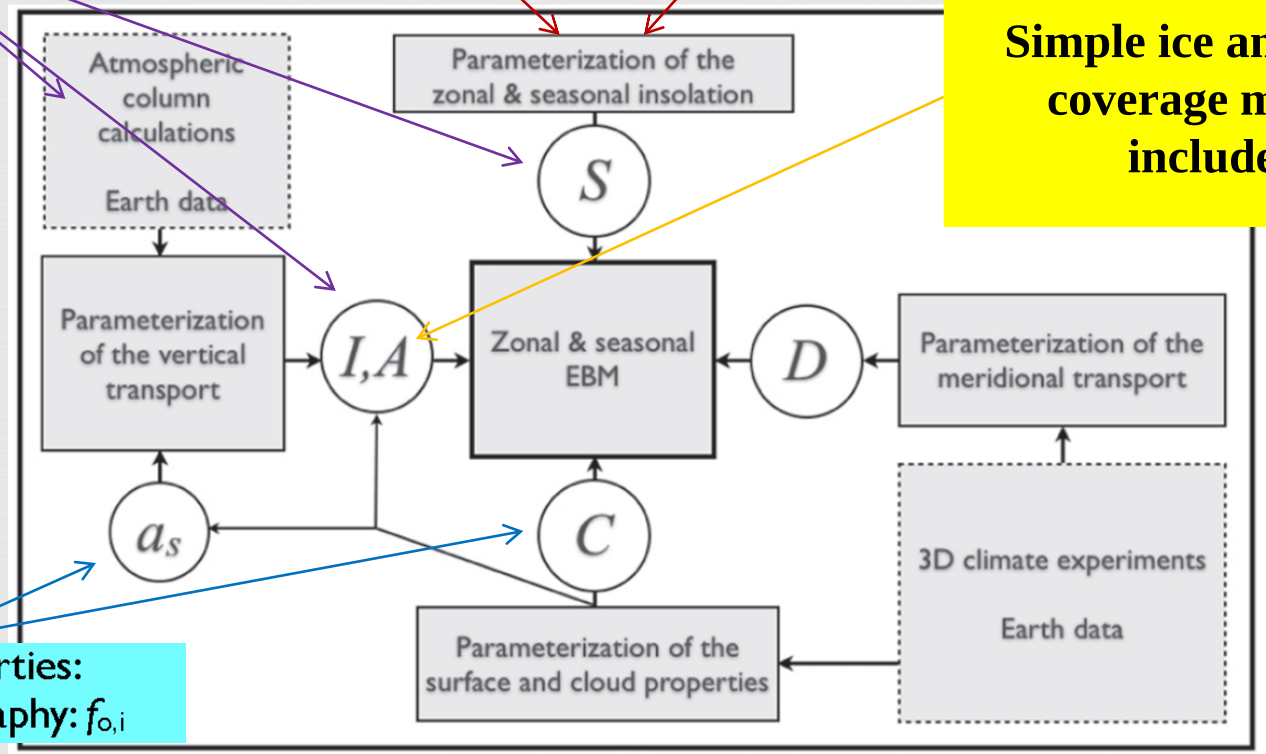
For the vertical radiative transfer we are currently using CCM3 routines (NCAR)

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

Evolutionary tracks of stellar luminosity

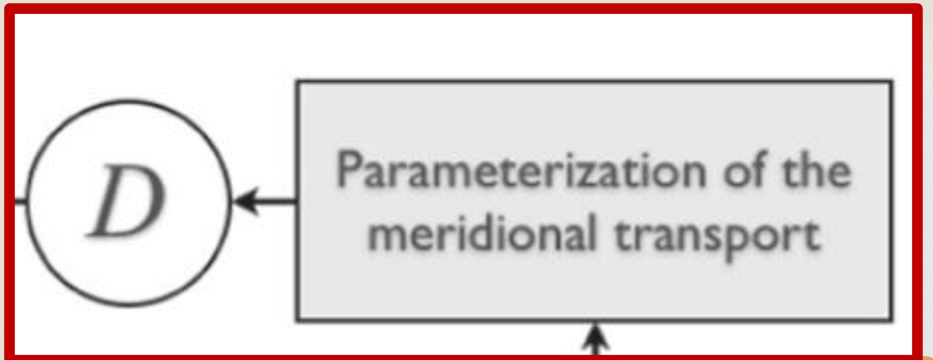
To be updated using Giambattista Aresu new 1D models

Simple ice and cloud coverage models included



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

Temporal integration: adaptive Runge-Kutta 4/5
Spatial integration: Euler staggered grid



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

$$D_{\rm dry} = k_{\rm S}$$

$$\left(\frac{D}{D_\circ}\right) = \left(\frac{p}{p_\circ}\right)\left(\frac{c_{\rm p}}{c_{\rm p,\circ}}\right)\left(\frac{m}{m_\circ}\right)^{-2}\left(\frac{\Omega}{\Omega_\circ}\right)^{-2}$$

3/5

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

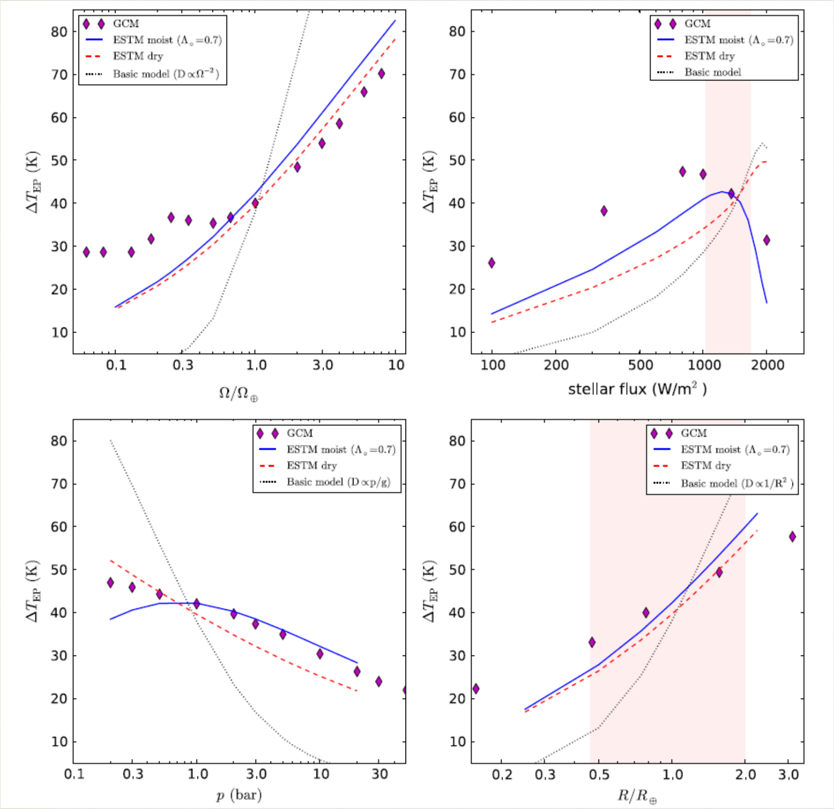
$$\Lambda = \frac{k_{\rm L} L_v}{k_{\rm S} c_p} \frac{\mu_v}{\mu_{\rm dry}} \frac{q}{p_{\rm dry}} \frac{\partial p_v^*}{\partial T}$$

WK97 SCALING

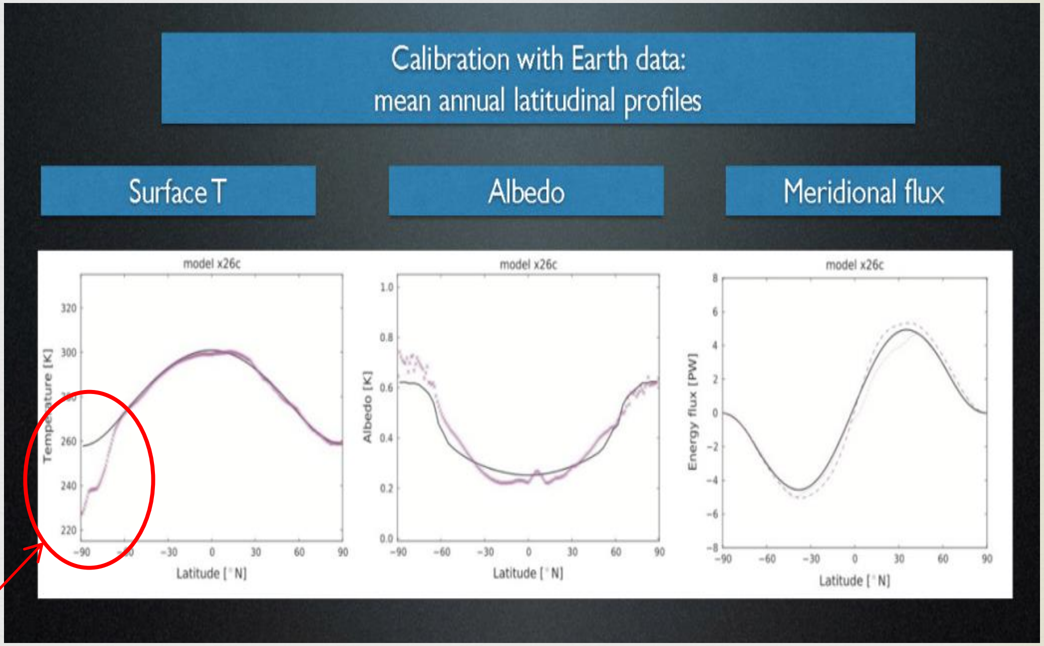
Formalism tested *vs* Barry+ 2002 (GCM experiment)

Vladilo+ 2013, 2015

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



Calibration with Earth data

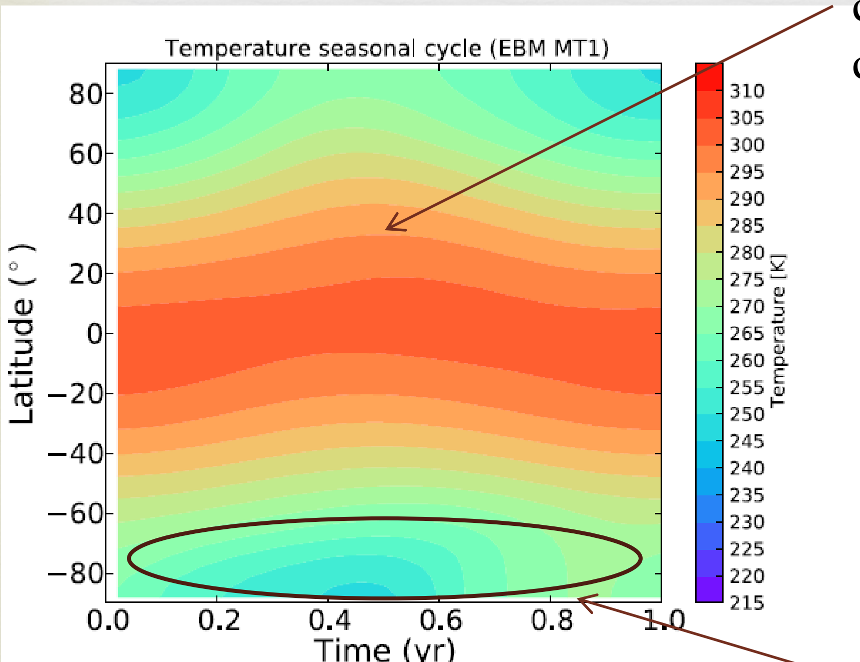


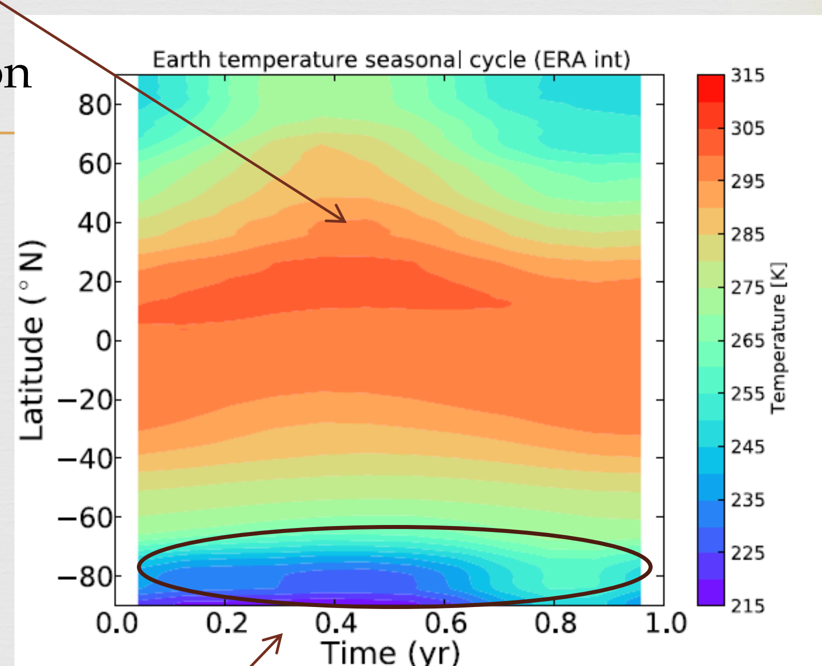
Antartica effect
(about 4000m altitude, not included in ESTM)

Example of output from a simulation
Seasonal-latitudinal temperature map
$T(\varphi,t)$ of an Earth twin

Earth surface temperatures $T(\varphi,t)$
(ERA int 2001-2013)

Thermal capacity confusion



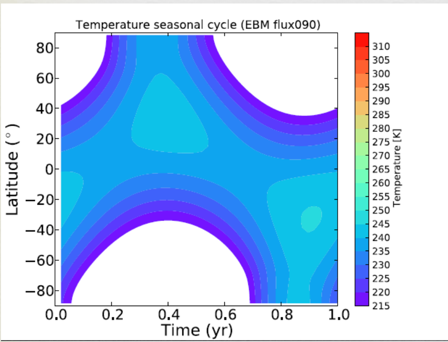


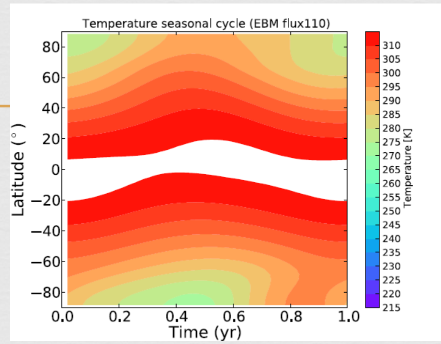
Antarctica effect

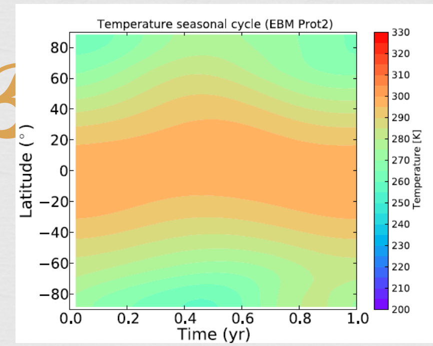
Note that the model converges to a limit cycle.
Convergence tested on the global annual average temperature

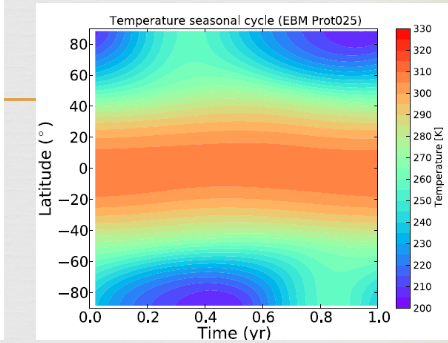
Varying planetary parameters

S=0.9 S_0 INSOLATION S=1.1 S_0 2.0d ROTATION PERIOD 0.25 d

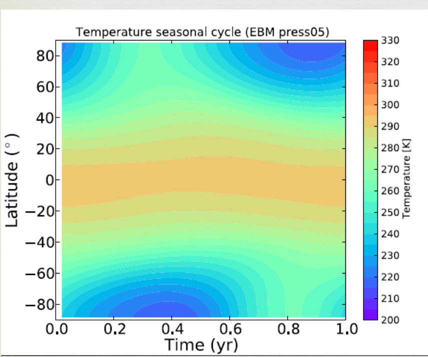


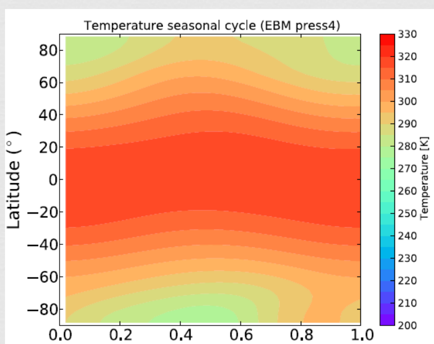


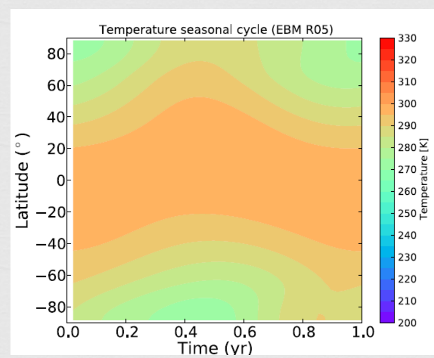


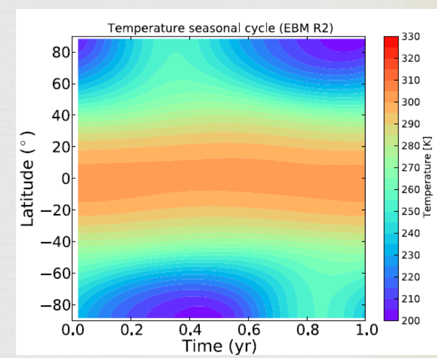


0.5 bar PRESSURE 4.0 bar 0.5 R_{Earth} PLANET RADIUS 2.0 R_{Earth}









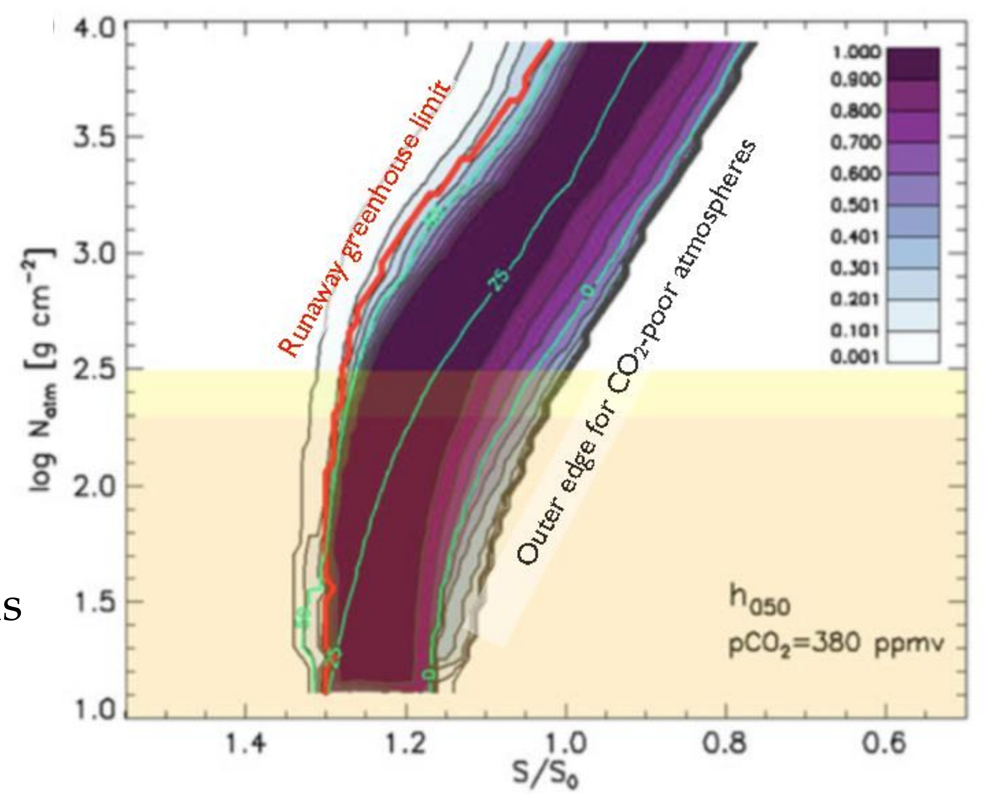
All remaining parameters and atmosphere chemical composition are Earth-like

Complex life habitability index

$$H(\varphi, t) = \begin{cases} 1 & 0^\circ\text{C} \leqslant T(\varphi, t) \leqslant 50^\circ\text{C} \\ 0 & \text{otherwise.} \end{cases}$$

$$h_{050} = \frac{\int_{-\pi/2}^{+\pi/2} d\varphi \int_0^P dt\, [H(\varphi, t) \cos\varphi]}{2P}$$

N_{atm}=p/g



Silva+ 2017a

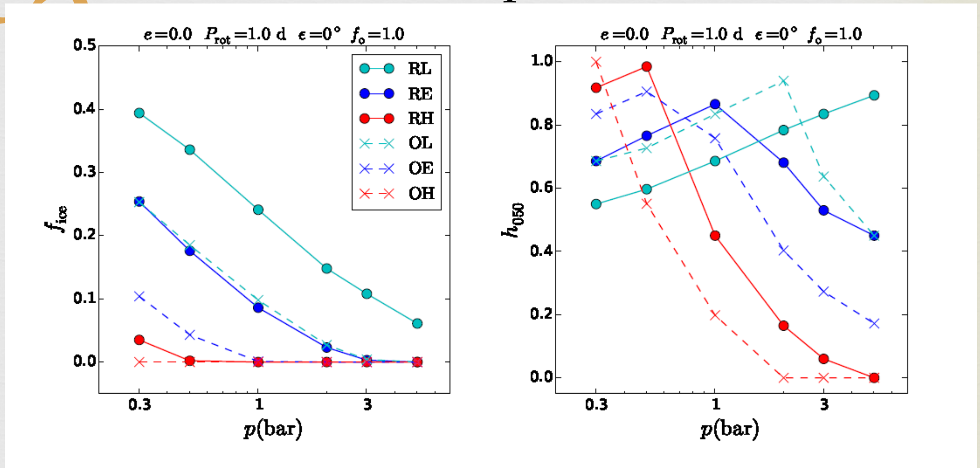
Thousands of runs..

An application: K452b

- Planetary mass unknown
- Probability of being rocky: 49% to 62% (Jenkins+ 2015)
- Radius = $1.63 R_{Earth}$
- $L_* = 1.21 L_\odot$, $M_* = 1.035 M_\odot$ insolation 10% higher than Earth
- $P_{orb} = 384.8$d
- Validated vs Hu+ 2017 (GCM)

Silva+ 2017b

Effect of pressure

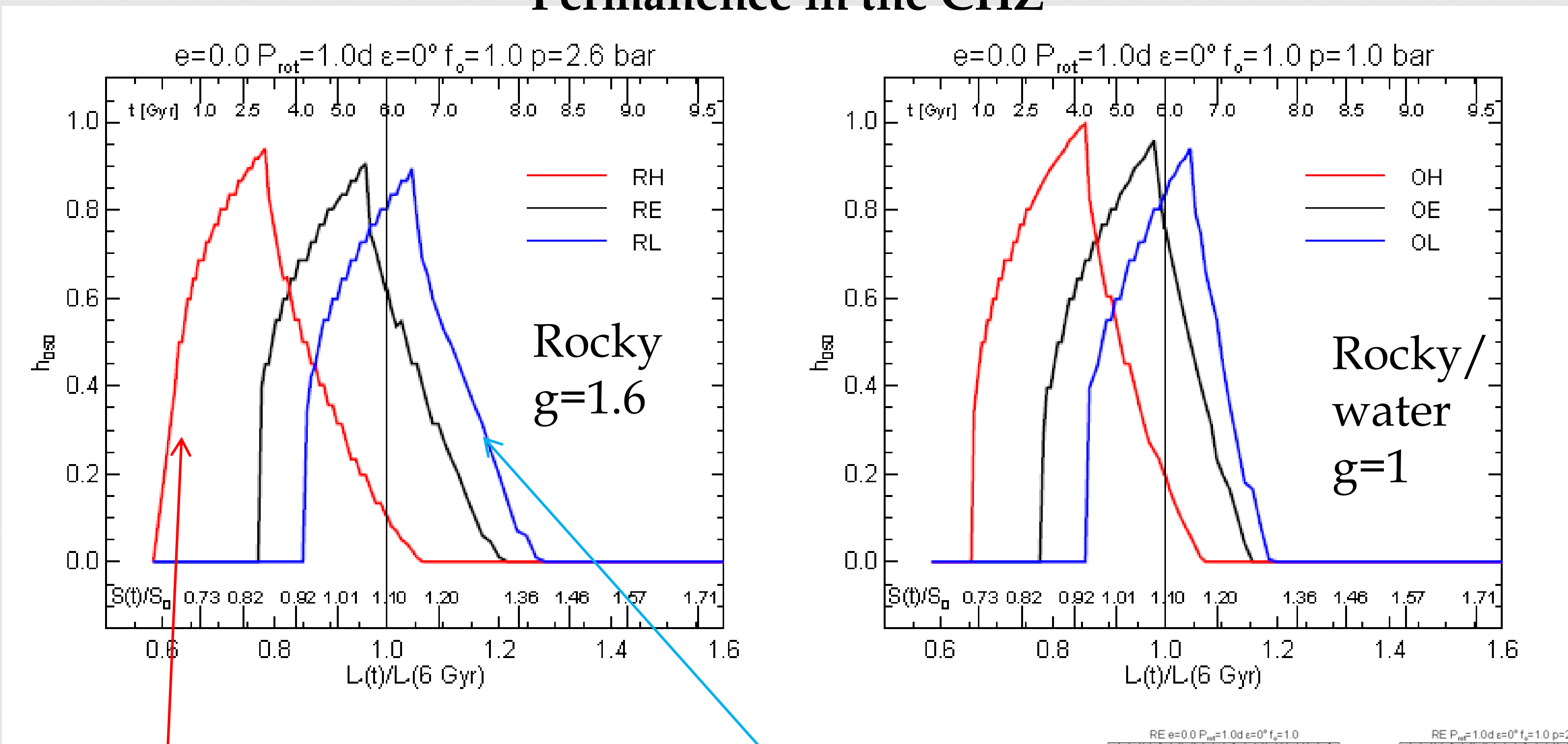


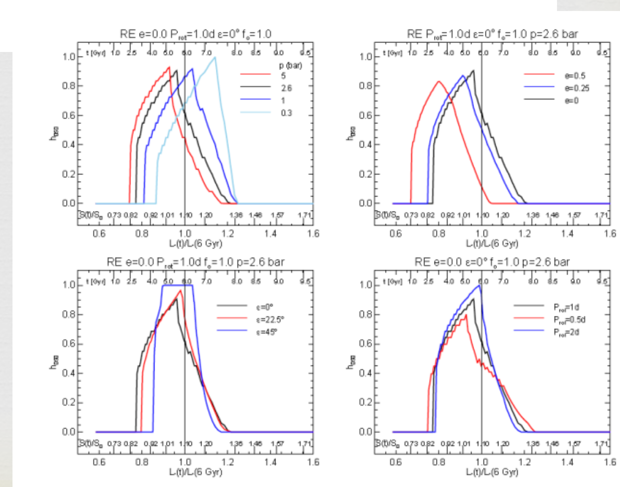
Model	$M/M_\oplus$	$g/g_\oplus$	$p\mathrm{CO_2}$ (ppmv)	p^b (bar)	e	P_{rot} (d)	ϵ (°)	f_o	Comment
RL	4.3	1.6	10	2.6	0.0	1.0	0	1.0	Rocky, low CO_2
RE	4.3	1.6	380	2.6	0.0	1.0	0	1.0	Rocky, Earth-like CO_2
RH	4.3	1.6	38000	2.6	0.0	1.0	0	1.0	Rocky, high CO_2
OL	2.7	1.0	10	1.0	0.0	1.0	0	1.0	Rocky/water, low CO_2
OE	2.7	1.0	380	1.0	0.0	1.0	0	1.0	Rocky/water, Earth-like CO_2
OH	2.7	1.0	38000	1.0	0.0	1.0	0	1.0	Rocky/water, high CO_2

[a] For each model the surface pressure, orbital eccentricity, rotation period, axis tilt and ocean fraction have been varied in the intervals: $0.3 \leqslant p(\mathrm{bar}) \leqslant 5$, $0 \leqslant e \leqslant 0.5$, $0.5 \leqslant P_{\mathrm{rot}}(\mathrm{d}) \leqslant 2.0$, $0° \leqslant \epsilon \leqslant 45°$, and $0.1 \leqslant f_o \leqslant 1$, respectively.
These parameters are varied only one at a time in each series of simulations, fixing the others to the reference values listed in the table.
[b] Educated guess of surface atmospheric pressure obtained from Eq. (3).

K452b and the evolution of its star

Permanence in the CHZ





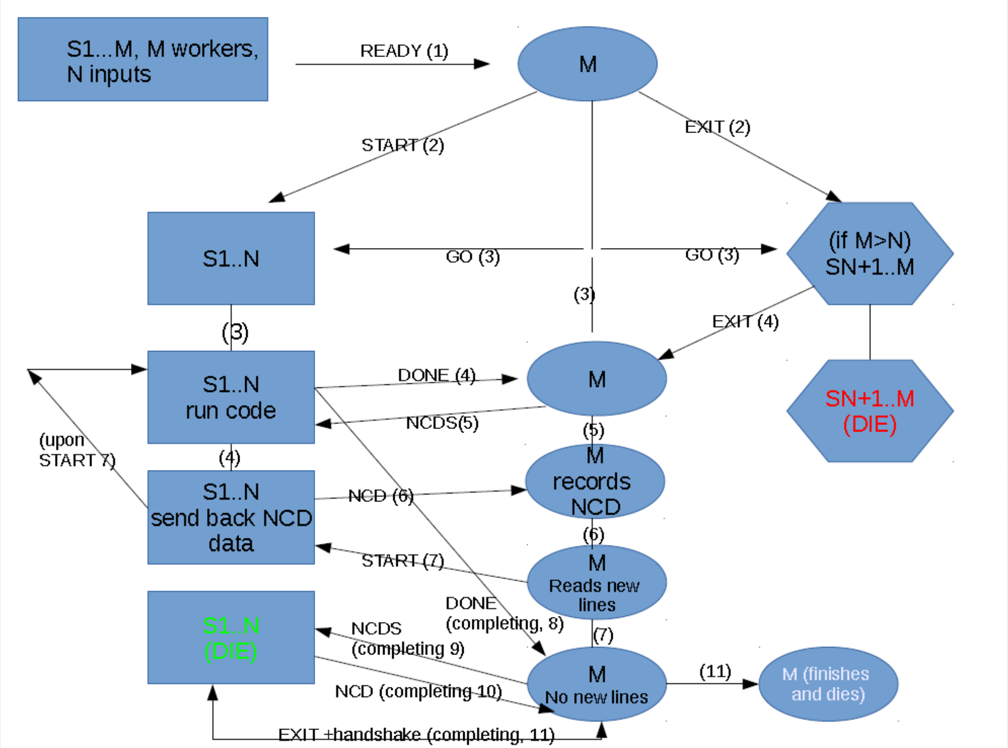
This model could have a dying, unobservable biosphere

This model could have a well-developed, bio-signature producing biosphere

Brute force parameter space exploration

- ESTM is HighThroughputComputing: one run takes minutes on a PC
- Parameter space exploration is *embarassingly parallel*

- Master/slave scheme: N MPI tasks, one MPI task distributes the work, N-1 execute one run at a time
- Driver in Python (G. Taffoni, using mpi4py)
- Easy to say but…



(code by G. Taffoni & G. Murante)

THIS CAN BE ADAPTED TO ANY SERIAL CODE

ARTECS

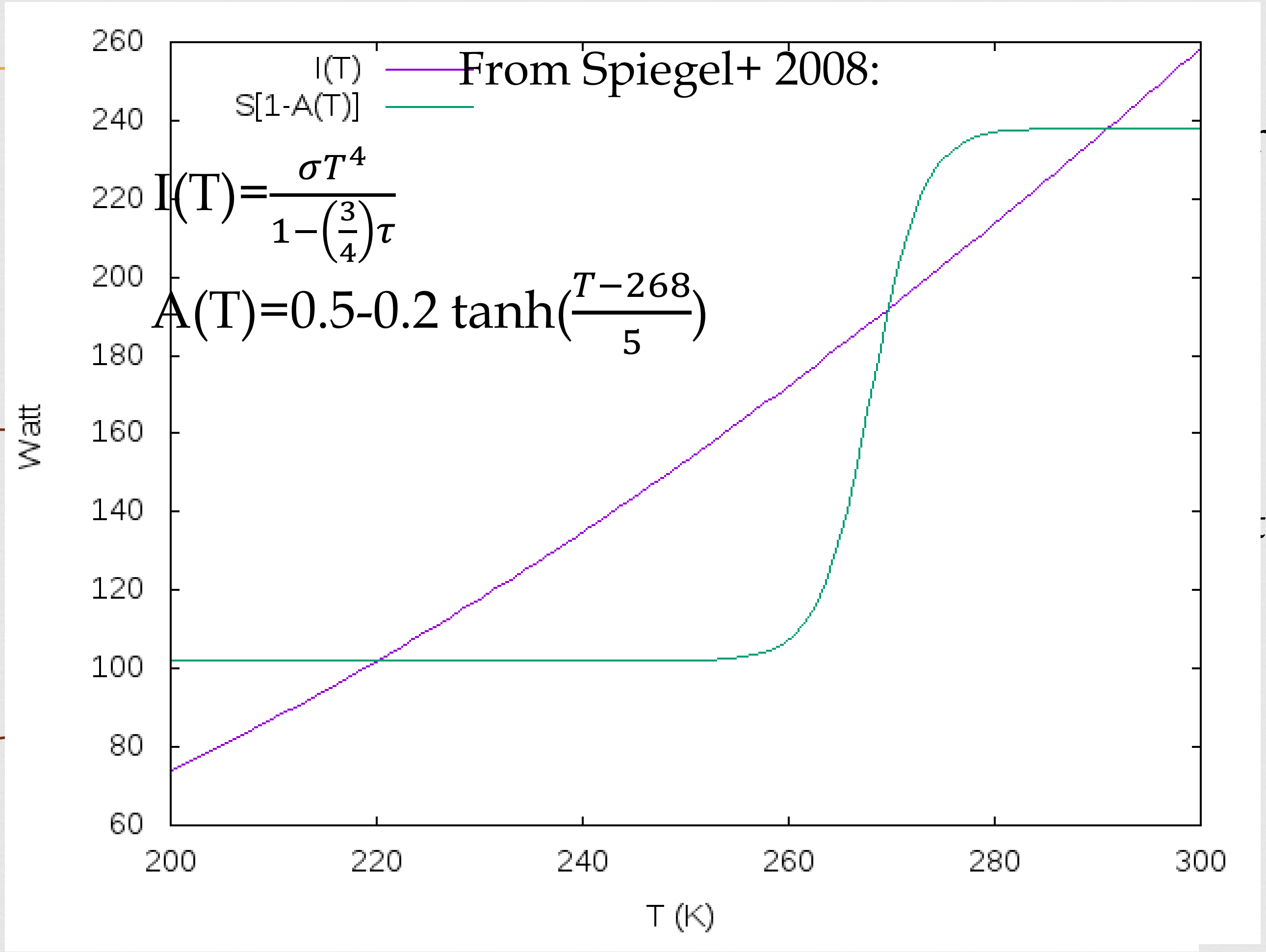
http://wwwuser.oats.inaf.it/exobio/climates/index.html

- **Ar**chive of **te**rrestrial-type **c**limate **s**imulations
- Database currently containing about 22,000 runs
- We will expand it to 200,000 in December
- Plan to run 40,000,000 parameter sets exploring a 9-dimensional parameter space (Semi-Major Axis, Pressure, Eccentricity, Obliquity, CO_2, Geography, Rotation Period, Radius , Surface gravity). About 7,000,000 core hours @ bastet
- **Database realized by IA2 @ OATS: main authors: Cristina Knapic, Elisa Londero, Sonia Zorba**

Use: characterization of exo-planet climate classes

Warm

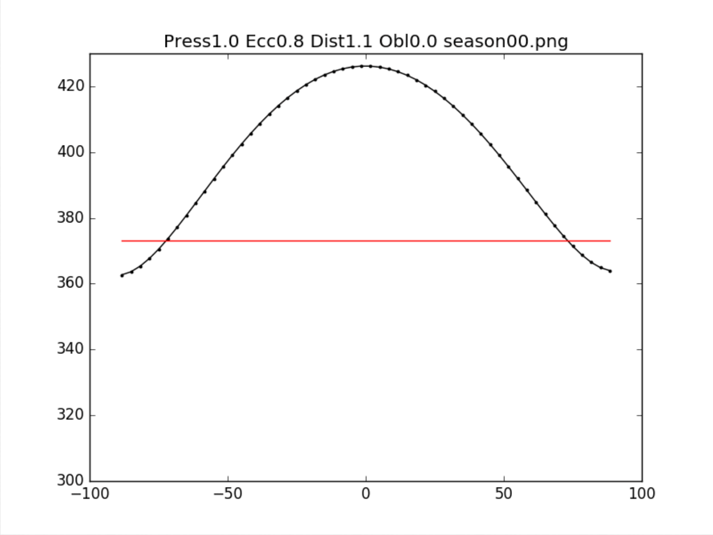
Snowball

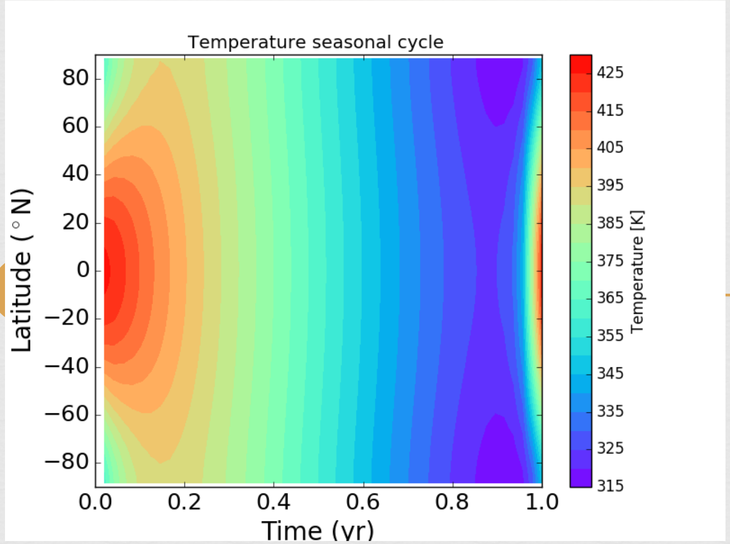


habitable!

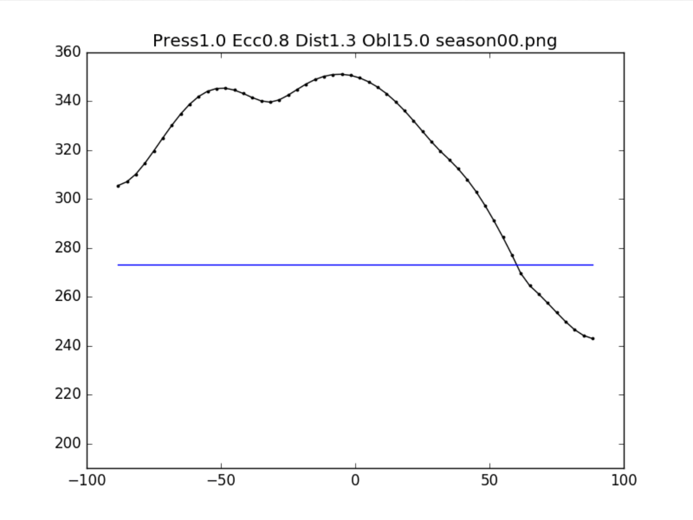
erbelt!

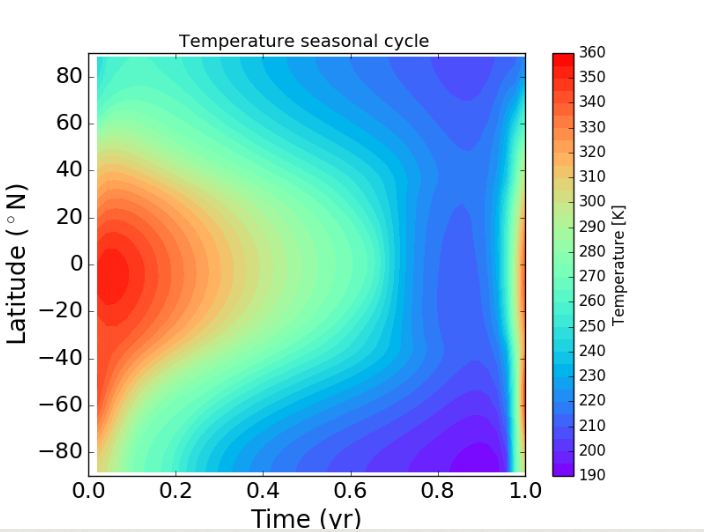
HOT





WATERBELT





What for?

- Study of sets of parameters that give the higher complex life habitable index value
- Study of bistable equilibria!

- Suppose you have an Earth-mass planet, at eccentricity 0.3 and 1.1AU from a Solar-like star,
  and want to know how probable is for it to be habitable…
- ARTECS now includes an estimate of the zenital column density and mass of the atmosphere. Useful for understanding how observable such atmosphere is (Code by M. Maris)
- Moreover:
  - Teaching
  - Outreach

Vegetation coupling

$$C\frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left[D(1-x^2)\frac{\partial T}{\partial x}\right] = S[1-A(V)] - I$$

Albedo now depends on the vegetation fraction

$$\frac{\partial V}{\partial t} = s\frac{1}{C}\frac{\partial}{\partial x}\left[D(1-x^2)\frac{\partial V}{\partial x}\right] + G(T)V(1-V) - d(T)V$$

Death factor

Logistic curve

Vegetation fraction (on lands)

$$G(T) = g_{max}\left\{1-[w(T_v - T)]^2\right\}$$

Growth factor

Seeds transport

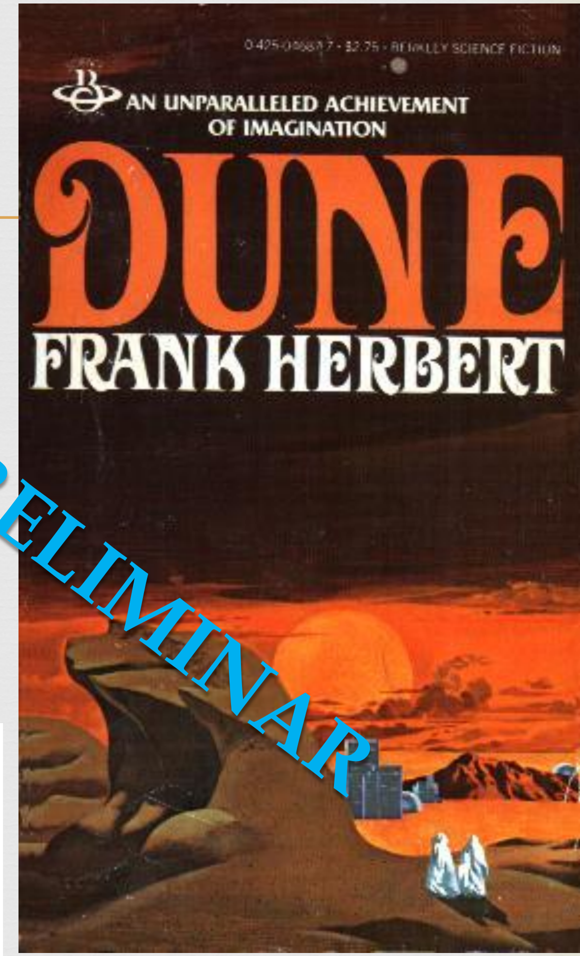
Ideal plants temperature

Plants thermal survival range

Crowding limit

Vegetation albedo is different from continents albedo (lower – but can also favour clouds covering, i.e. higher albedo): **VEGETATION ALBEDO FEEDBACK**

DUNE and the GAIA hypothesis



- Dune: desert, water-limited world
- Climate-vegetation dynamics studied in literature (Baudena+ 2008, Aleina+ 2012)
- "Charney mechanism" (Charney+ 1975)

PRELIMINAR

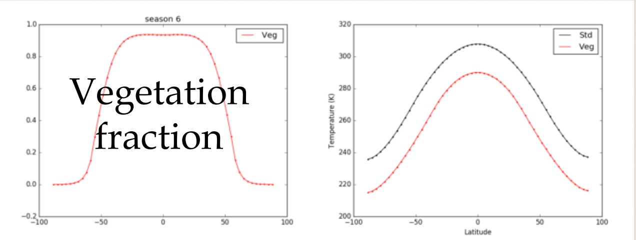
Drought in the Sahara: A Biogeophysical Feedback Mechanism

Abstract. *Two integrations of a global general circulation model, differing only in the prescribed surface albedo in the Sahara, show that an increase in albedo resulting from a decrease in plant cover causes a decrease in rainfall. Thus any tendency for plant cover to decrease would be reinforced by a decrease in rainfall, and could initiate or perpetuate a drought.*

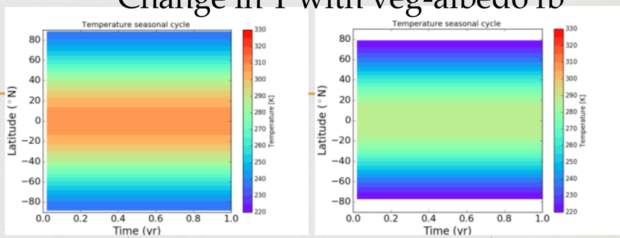
DUNE with ESTM

- Obliquity=0, ocean fraction=0, SMA=1.048, R=1.63, stellar luminosity=1.1, P=3 bar, soil albedo=0.35, vegetation albedo=0.15
- Run with and without vegetation-albedo feedback
- **Biosphere can and will change the climate, thus the habitable zone!**

PRELIMINARY

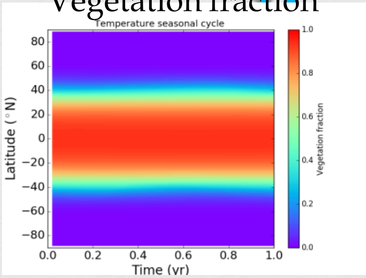


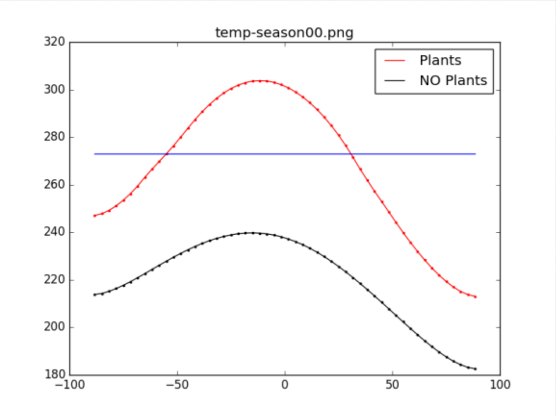
Change in T with veg-albedo fb

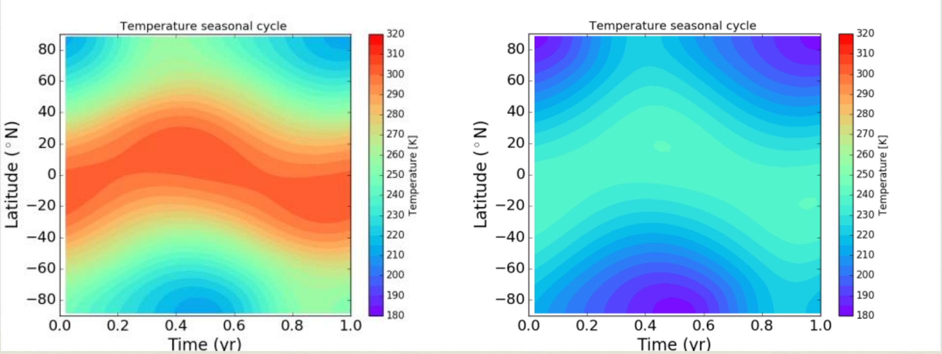


plants NO plants

Vegetation fraction







November 7th, 2017

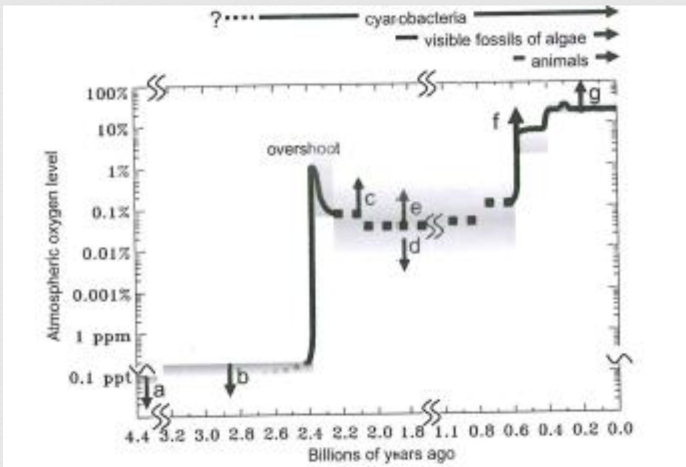
Biosphere and habitability

- ESTM Daisyworlds?
- Competing vegetations
- Biological carbon cycle
- Biology-regulated climates?

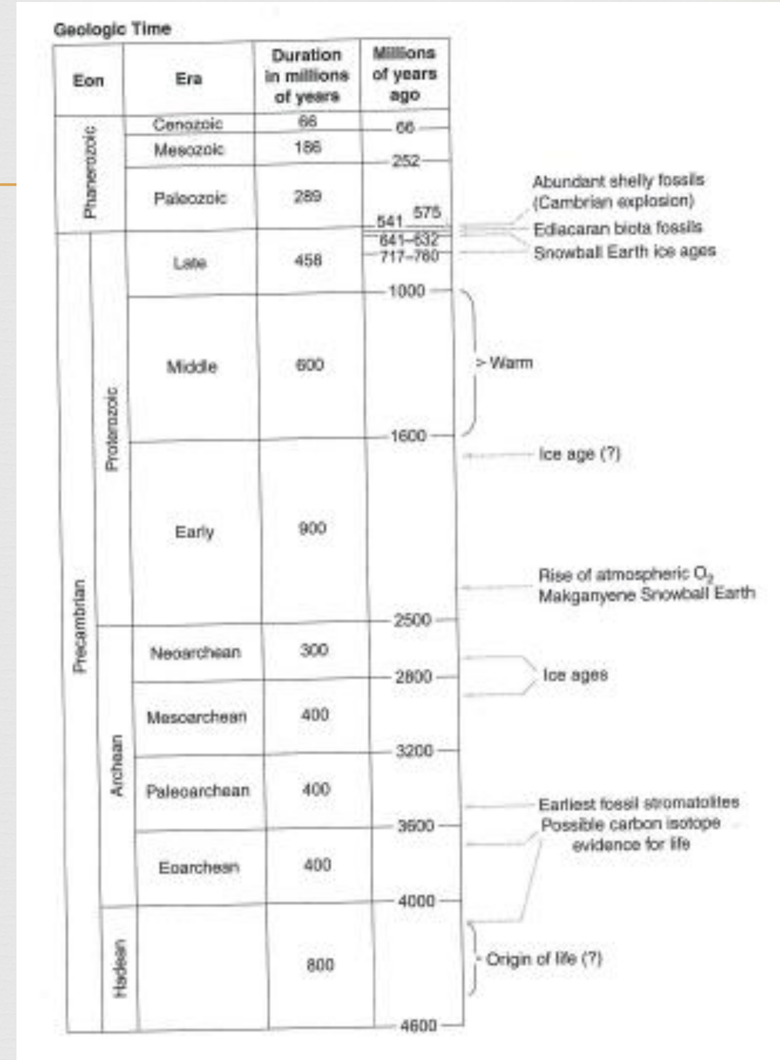
(As for DNA mutation rate: too fast and you die, too slow and you don't adapt to changes. Here: if a biosphere does not regulate the climate, it could collapse.)

Paleo-climates

- ESTM can also be used to study paleo-Earth climates
- Recent and remote ice ages – The Great Oxidation Event



- Faint Young Sun problem
- Carbonate-Silicate geological cycle and the exit from a Snowball Earth episode


Geologic Time

Eon	Era	Duration in millions of years	Millions of years ago
Phanerozoic	Cenozoic	66	66
	Mesozoic	186	252
	Paleozoic	289	541 575
Precambrian – Proterozoic	Late	458	641–632 717–760 1000
	Middle	600	1600
	Early	900	2500
Precambrian – Archean	Neoarchean	300	2800
	Mesoarchean	400	3200
	Paleoarchean	400	3600
	Eoarchean	400	4000
Precambrian – Hadean		800	4600

(figures from Catling&Kasting, 2017, "Atmospheric evolution on inhabitated and lifeless worlds")

Limits of ESTM

(This is Far Oer. Note, no trees. There are a few in places protected from the winds. On a tidally locked planets we expect latitudinal winds at thousands of kmh…
Definitely not a good place for a holiday)

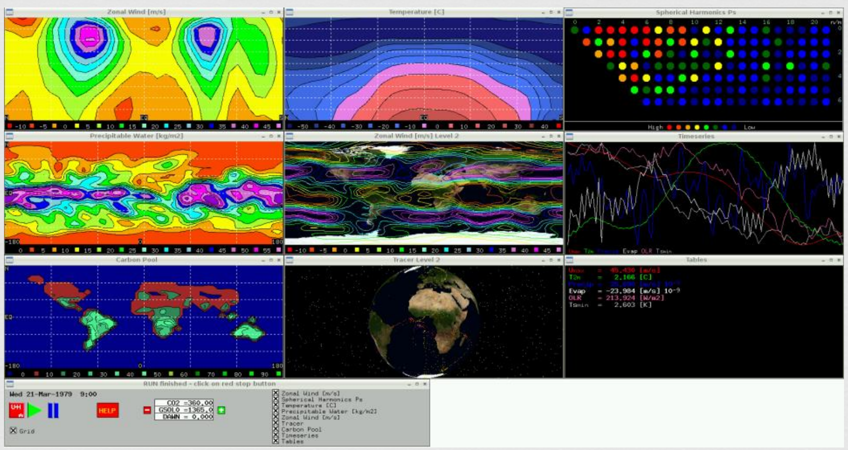
Also: these stars have violent UV flares, planets experience stellar wind pressures 10^3-10^5 times the Earth…
See e.g. Garraffo+ 2017 arXiv:1706.04617

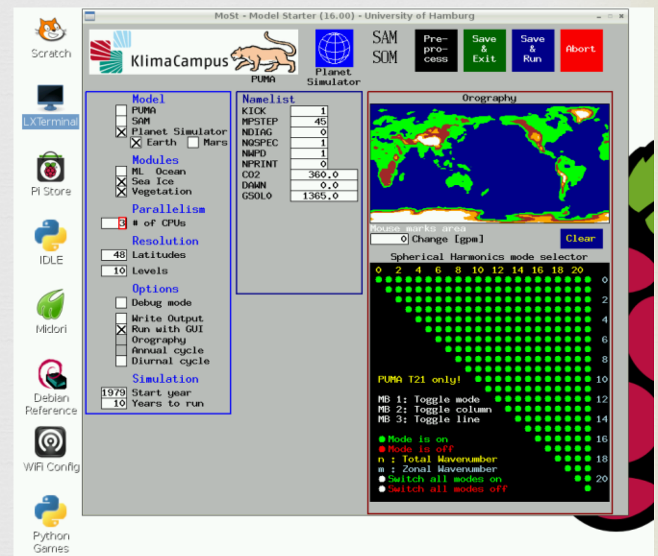
- Approximate
- Can't treat obliquities larger than 45 degrees
- Can't deal with tidally locked worlds
- Can't deal with slowly rotating planets
- Thermal capacity confusion
- NO oceanic heat transport
- Validated only using Earth data
- Earth-like atmosphere (we are dealing with this!)

Beyond ESTM : PLASIM

- Intermediate complexity model
- Simplified atmosphere, ocean, land
- Configurable geography
- 3D
- Fast (not as fast as ESTM…)

(in collaboration with CNR-ISAC and CNR-IGG)





- Validation of ESTM in non-Earth cases
- Tidally locked / strong obliquity planets
- We are cleaning the code! (currently Earth/Mars simulator ☺)
- Cascade of increasing complexity models?

Conclusions

- **The habitable zone of a planet do depend on its climate** – perhaps even on its ecosphere
- A CHZ cannot be defined on the basis of the central star characteristics and orbital parameters only
- A range of models of different complexity needs to be used to estabilish exo-planets habitability
- **ESTM can be used for a fast, detailed exploration of the exo-climates parameter space**
- …this can give hints on **which** planets should be observed in order to detect atmospheric bio-signatures
- This work is an example of how badly needed is the inter-disciplinarity in Astrobiology

Thanks for your attention!

…stay tuned.