Modelling atmospheric and surface properties of rocky planets:

Implications for habitability studies and detectability of atmospheric spectra

Laura Silva - **INAF/OATs**
on behalf of the team

Schede:
CliMHab + CliMHab.RBA + CliMHab.Bio + CliMHab.Paleo + GalHab

INAF
ISTITUTO NAZIONALE
DI ASTROFISICA

Italian Project of Astrobiology

OGS
Istituto Nazionale
di Oceanografia
e di Geofisica
Sperimentale

CINECA

RSN 2 & 3

CliMHab -L. Silva: *Climate modelling of habitable exoplanets*

RSN 2 & 3

CliMHab.RBA -M. Maris: *Rifrazione e Biosignatures in Atmosfere di esopianeti abitabili*

CliMHab.Bio - E. Bisesi: *Impact of autotrophic living beings on the climate of rocky planets*

RSN 3 & 2

CliMHab.Paleo - P. Simonetti: *Modelli radiativi per le paleo-atmosfere di Marte, Terra e Venere*

RSN 1 & 3

GalHab – L. Silva: *Galactic chemical evolution and habitability*

TEAM

In bold: **FTE>0**

OATs
Erica Bisesi (AdR)
Paolo Dimarcantonio
Marco Fulle
Gian Luigi Granato
Stavro Ivanovski
Michele Maris
Sergio Monai
Giuseppe Murante
Laura Silva
Paolo Simonetti (AdR)
Giuliano Taffoni
Giovanni Vladilo

OAC
Isabella Pagano

OATo
Mario Damasso
Paolo Giacobbe
Alessandro Sozzetti

INAF

UniTs
Lorenzo Biasiotti (PhD)
Pierluigi Monaco

SISSA
Alessandro Bressan

Trieste

IATE
Cinthia Ragone-Figueroa

CAB
Josè Caballero

CNR Pisa
Antonello Provenzale

Climatologi

PoliTo
Jost von Hardenberg

UniPd
Mariano Battistuzzi (AdR)
Nicoletta La Rocca

Biologi

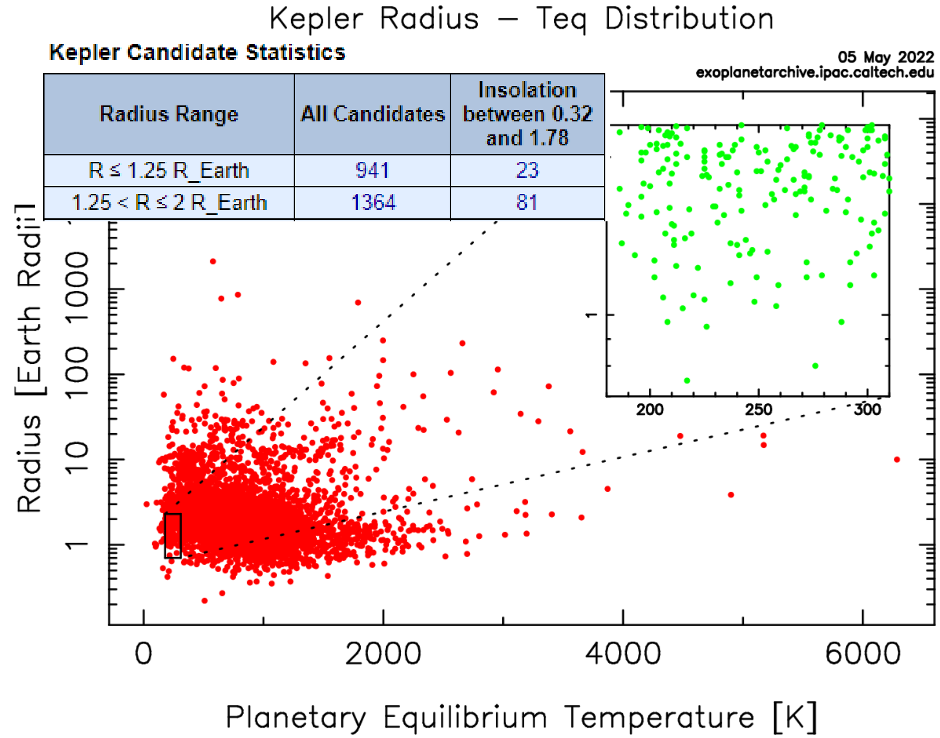
OATs+OAC+UniPd

Climate/atmospheric models and habitability for rocky planets

→Exploit the few available observations to **explore surface T & (T-based) habitability** vs all unknown planetary quantities

→ **Select** most promising candidates for future time-consuming spectroscopic observations

→ **Interpret** observable quantities in terms of habitability and biosignatures



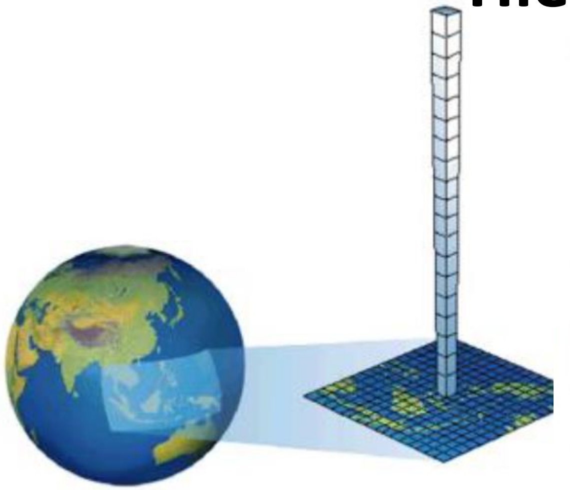
Kepler Candidate Statistics

Radius Range	All Candidates	Insolation between 0.32 and 1.78
R ≤ 1.25 R_Earth	941	23
1.25 < R ≤ 2 R_Earth	1364	81

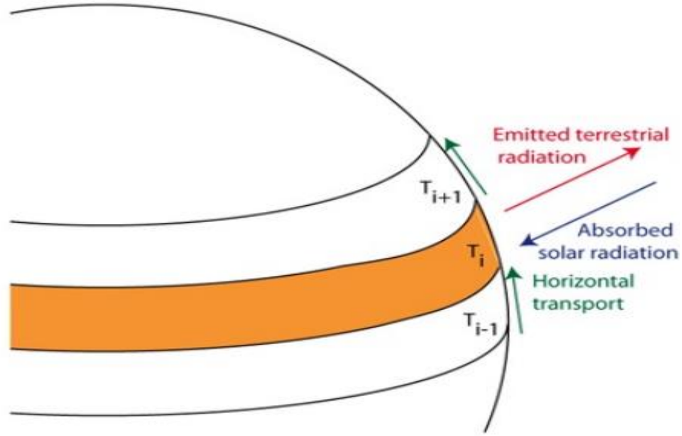
Need a hierachy of climate models and flexible RT

(a) simplified climate model for multi-parameter studies
(b) GCM to validate/calibrate & complex configurations
(c) Atmospheric model for large range of p, composition, stellar type, atm structure

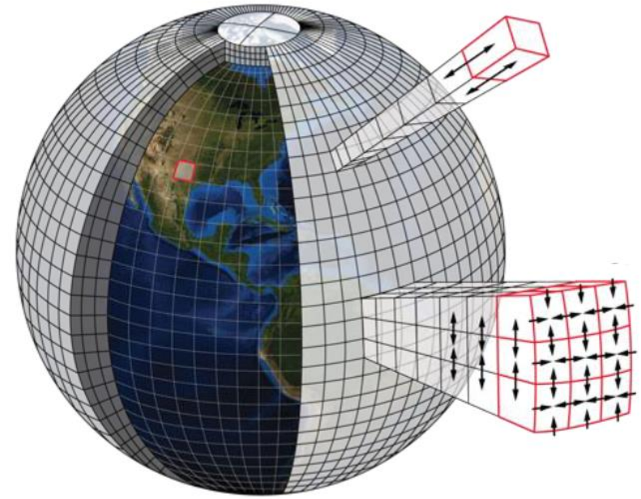
Hierarchy of climate models



Single-column 1D



EBM-Energy-Balance Model
latitudinal only- 1D
latitudinal & vertical- 2D



GCM -General Circulation Model 3D

EOS – Simonetti+2022
Scheda CliMHab-Paleo
RT GPU-enhanced line-by-line code for planetary atmosphers based on HELIOS-K and HELIOS (ESP Bern)

EOS + ESTM
ESTM-Earth-like planet surface temperature model
Vladilo+2015; Biasiotti+2022
Latitudinal-seasonal EBM + physical parametrization of horizontal transport + RT vertical transport

PLASIM
Intermediate Complexity model (Univ. Hamburg, Fraedrich+)
Work in progress by Murante+; Monai+; von Hardenberg+ to generalize to any planetary configuration

ESTM+EOS: A flexible climate model for multi-parameter habitability studies

ESTM: climate model zonal Energy-Balance type, to compute **T=T(latitude, season).**

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

Heat storage

Meridional energy transport
x=sin(latitude)

Vertical energy transport:
S = Insolation
I = **O**utgoing **L**ong-wavelength **R**adiation
A = Top **o**f Atmosphere **A**lbedo

+Schematic geography

+Effective thermal capacity of each latitude zone (surface+atm)

+Schematic effect of clouds:
*zonal cloud coverage (over water, land, ice)
*OLR forcing $\propto$ coverage
*albedo ac=ac(Z)

Physical parametrization of the term D

Barry+2002: parametrization from GCM for eddies-dominated latitudinal transport in the baroclinic zone- for **fast rotating planets**

$$\mathbf{D} \propto c_p\, R^{-6/5}\left(\frac{p}{g}\right)^{2/5}\Omega^{-4/5}$$

I and A: RT with EOS

Pre-computed & tabulated
OLR=OLR(T, p, comp.)
A=A(T, p, as, Z, comp.)
Interpolation during run

+Climate feedbacks: ice-albedo-T & water vapor-T
+Careful calibration with Earth data and validation with non-Earth conditions

Vladilo+2015; Biasiotti+2022

EOS: RT atmospheric model for rocky (exo)planets- P. Simonetti+2022 & scheda CliMHab-Paleo

EXOCLIMES SIMULATION PLATFORM

*Built on the public ESP RT **GPU**-based codes for gaseous planets
HELIOS-K - opacity calculator (Grimm & Heng2015, Grimm+2021)
HELIOS - line-by-line RT code (Malik+2017, 2019)

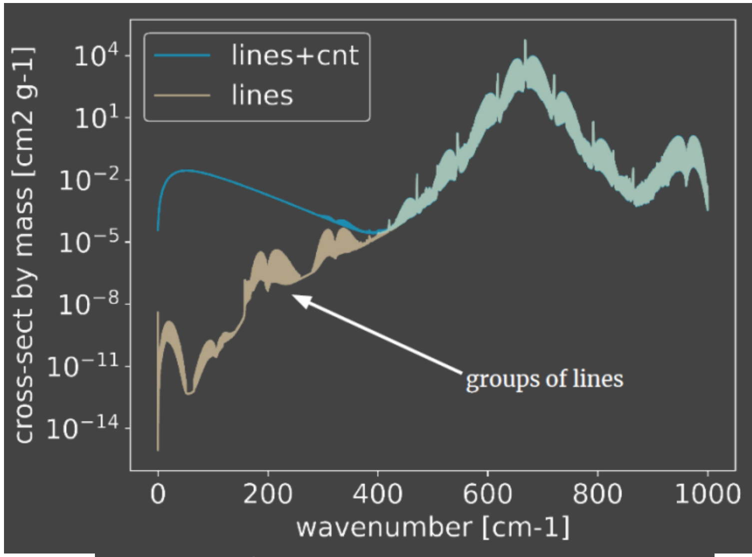
*Most relevant additions:

1. **Opacity continuum for CO2** from HITRAN2016(Gordon+17) CIA tables
- Gruszka & Borysow '97, '98 → 0-750 cm-1
- Baranov & Vigasin '99 → 1000-1800 cm-1

2. **Opacity continuum for H2O**: MT_CKD 3.4 model
-Clough+89, Mlawer+12 → 0-10000 cm-1

3. **CO2 far-wing line shape formulations** for sub-Lorentizan profiles:
- Voigt, truncated @ 25 cm-1
- Perrin & Hartmann '89, @ 500 cm-1
- Pollack+93, @ 120 cm-1
- Tonkov+96, @ 350 cm-1

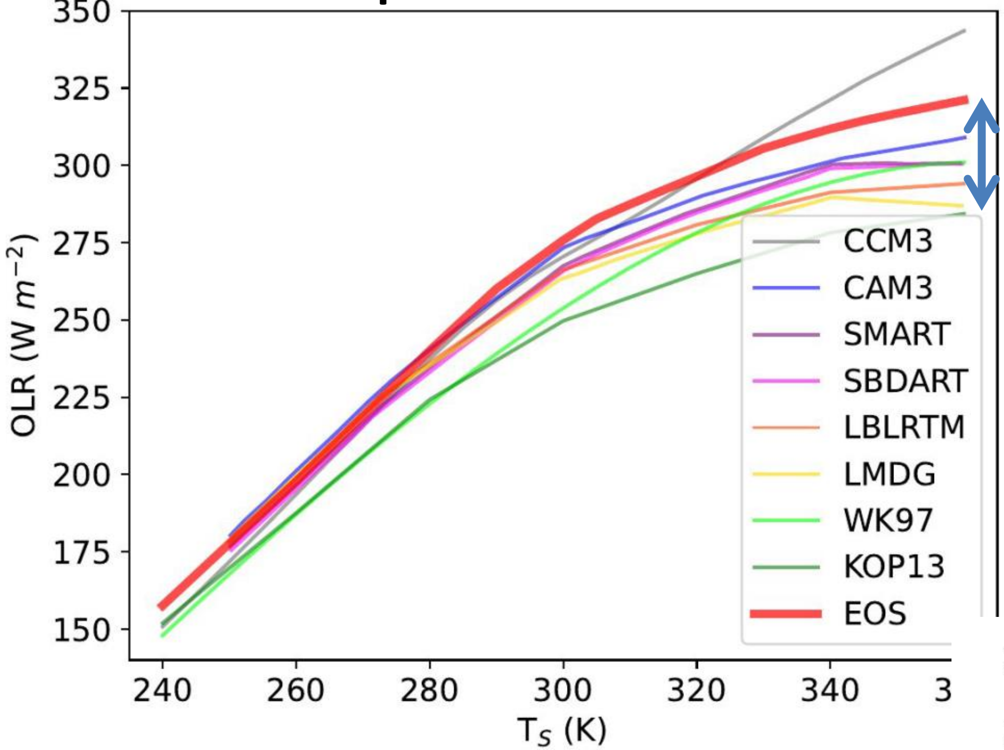
4. **Vertical P-T profile** generators (also non-ideal gas properties)



CO_2 @ 1 bar, 300 K
~1e+5 absorption lines in this region

RT model comparisons

Earth-like atmospheres



~34 W/m2 (±6%) - different radiative prescriptions

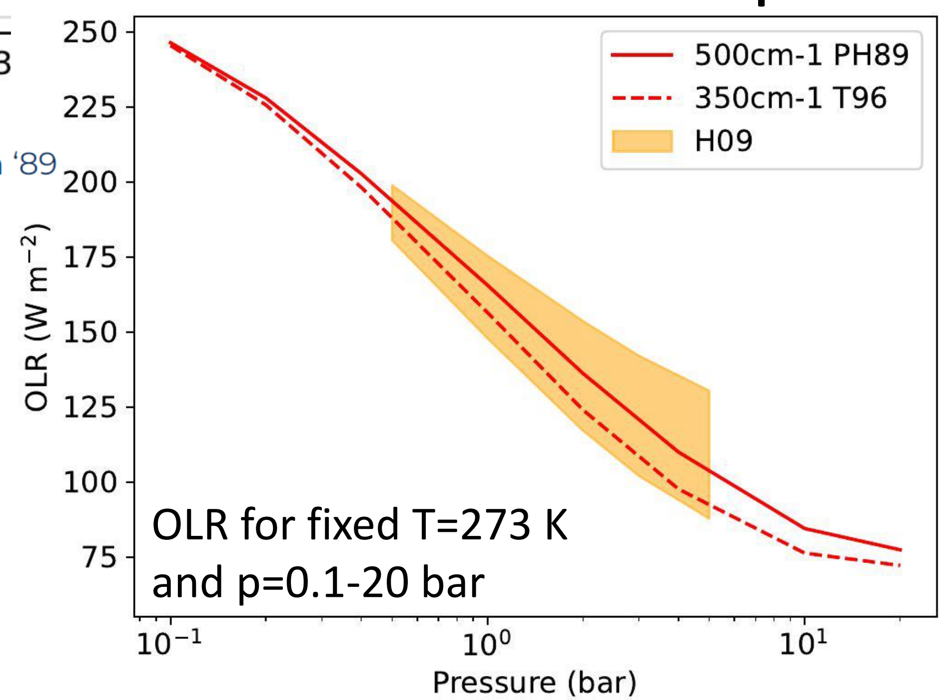
Important sources of uncertainties:

-H2O absorption (especially continuum): all models
-Vertical structure of the atmosphere (mainly 3D)
-Clouds

CO2 line shape prescriptions PH89: Perrin & Hartmann '89
T96: Tonkov+96

Comparison data H09: Halevy+09

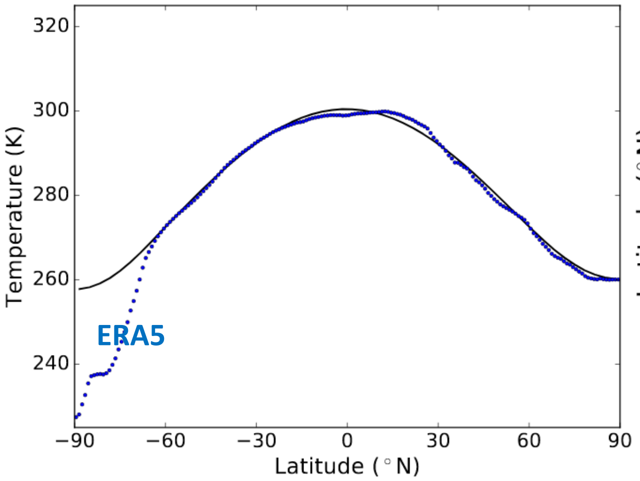
CO2 atmospheres

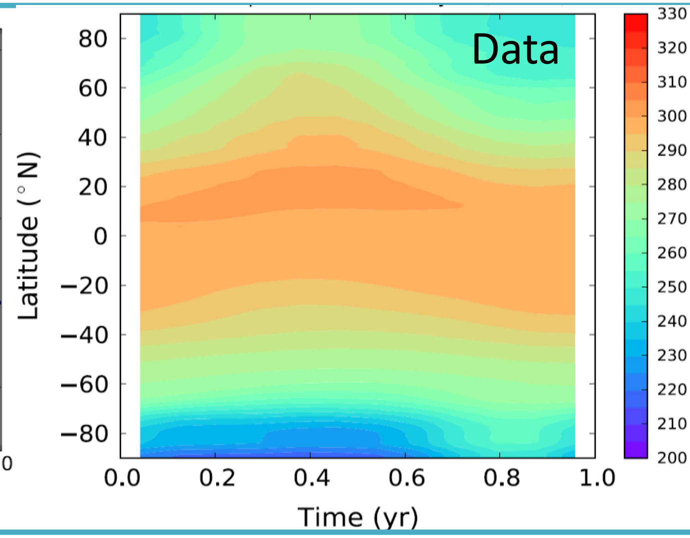


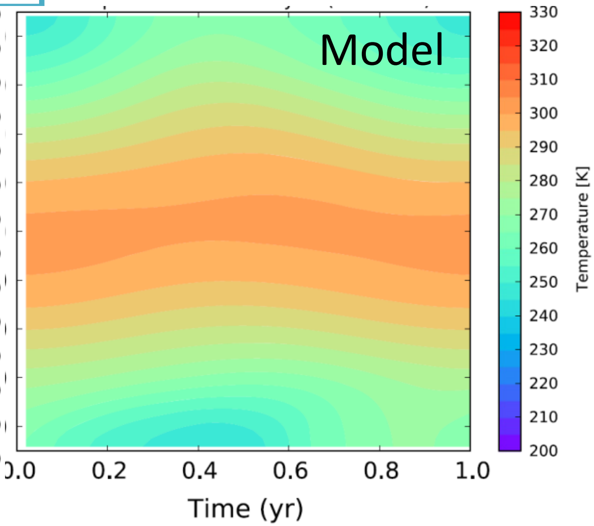
→fast: ~10 hrs for OLR and TOA lookup tables- for any climate model

→flexible: any composition

ESTM+EOS: Reproducing Earth surface T

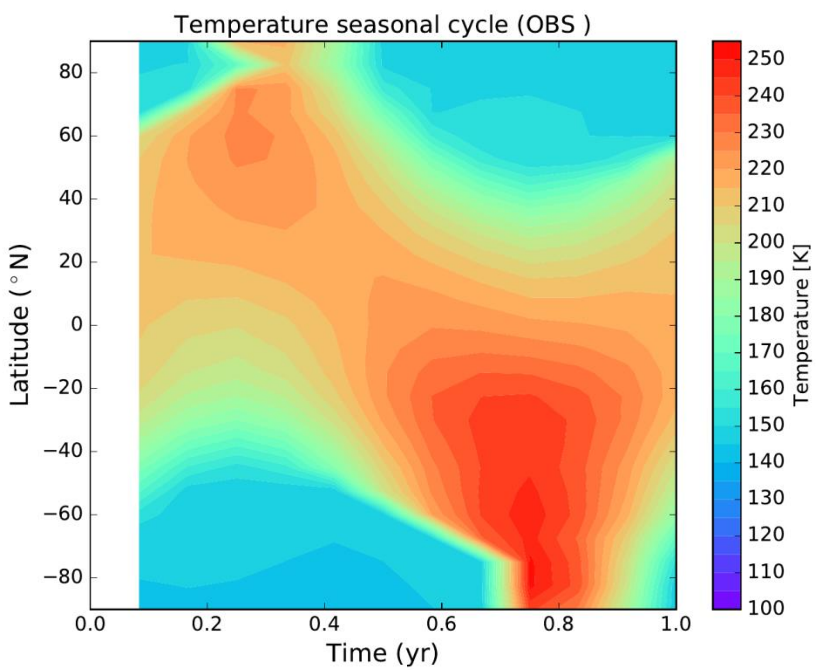




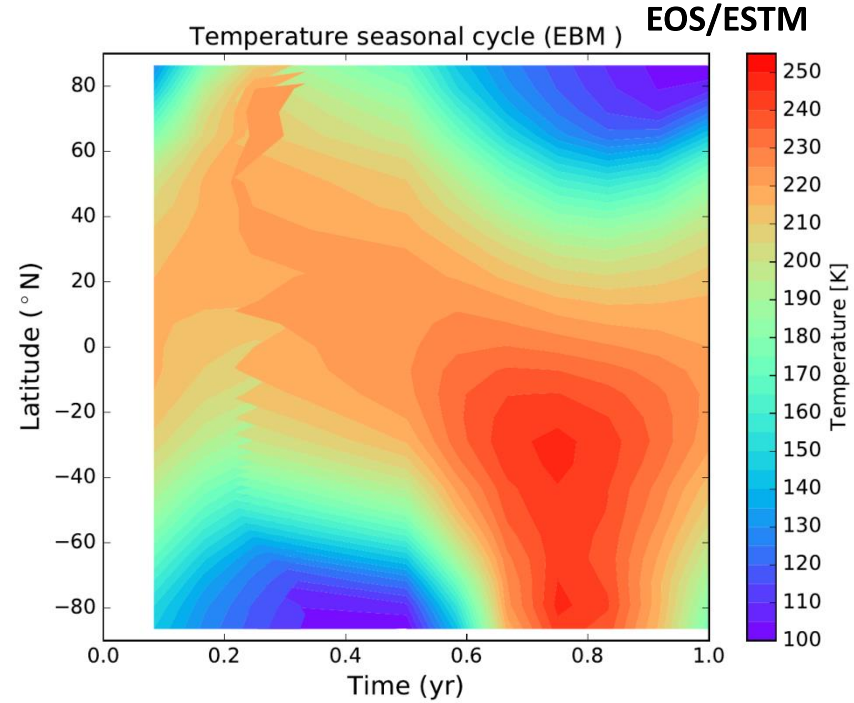


and Mars surface T – CliMHab-Paleo, P. Simonetti

Marte attuale-Mars Global Reference Atmospheric Model, NASA

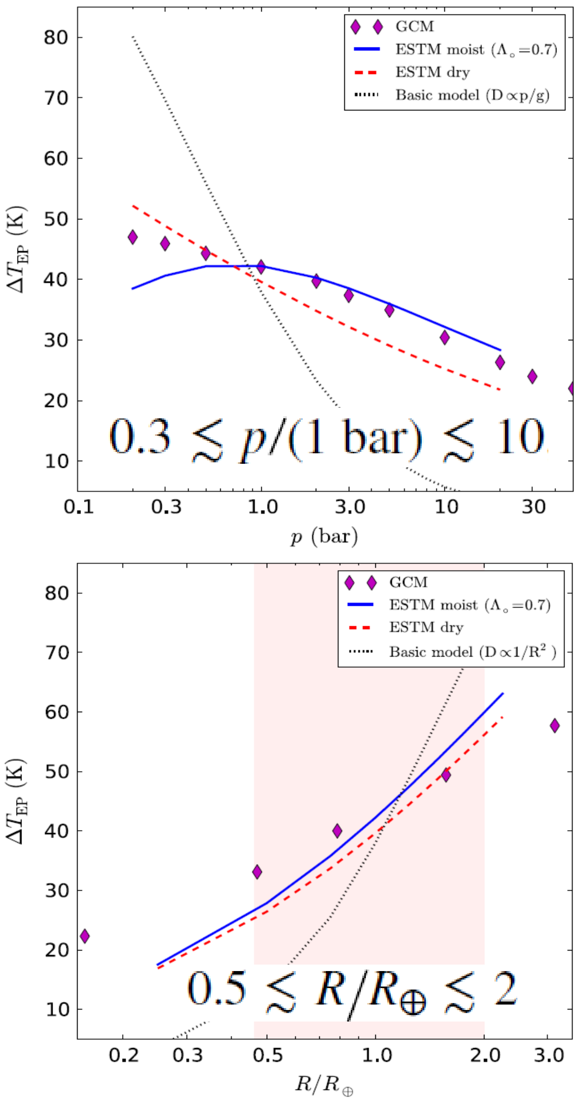


EOS/ESTM



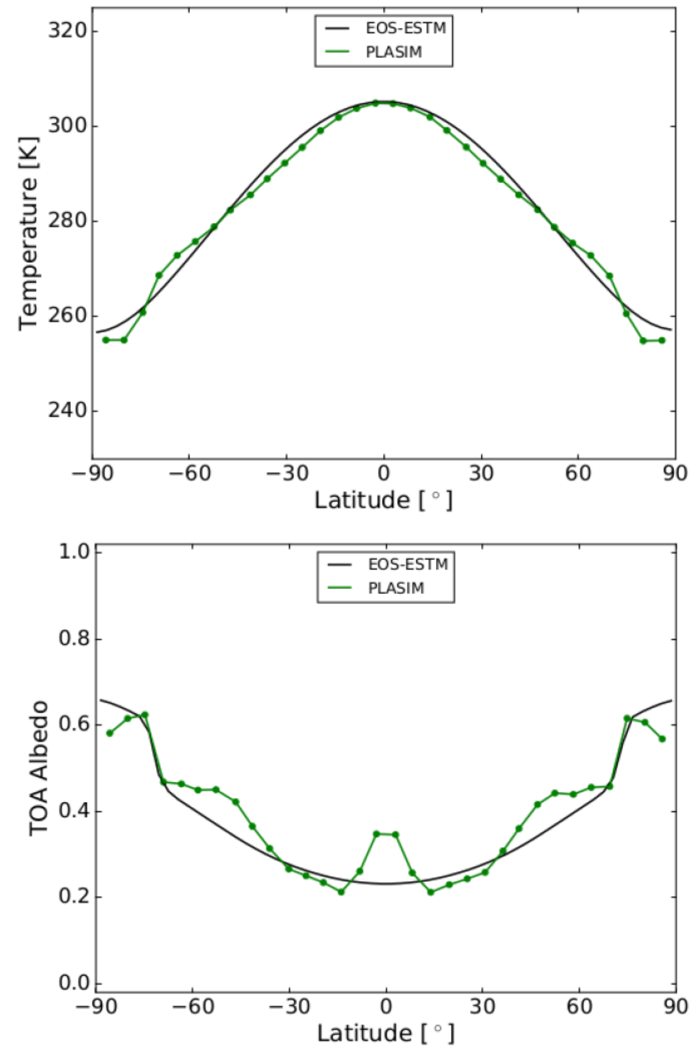
Validation of ESTM

GCM by Kaspi&Showman

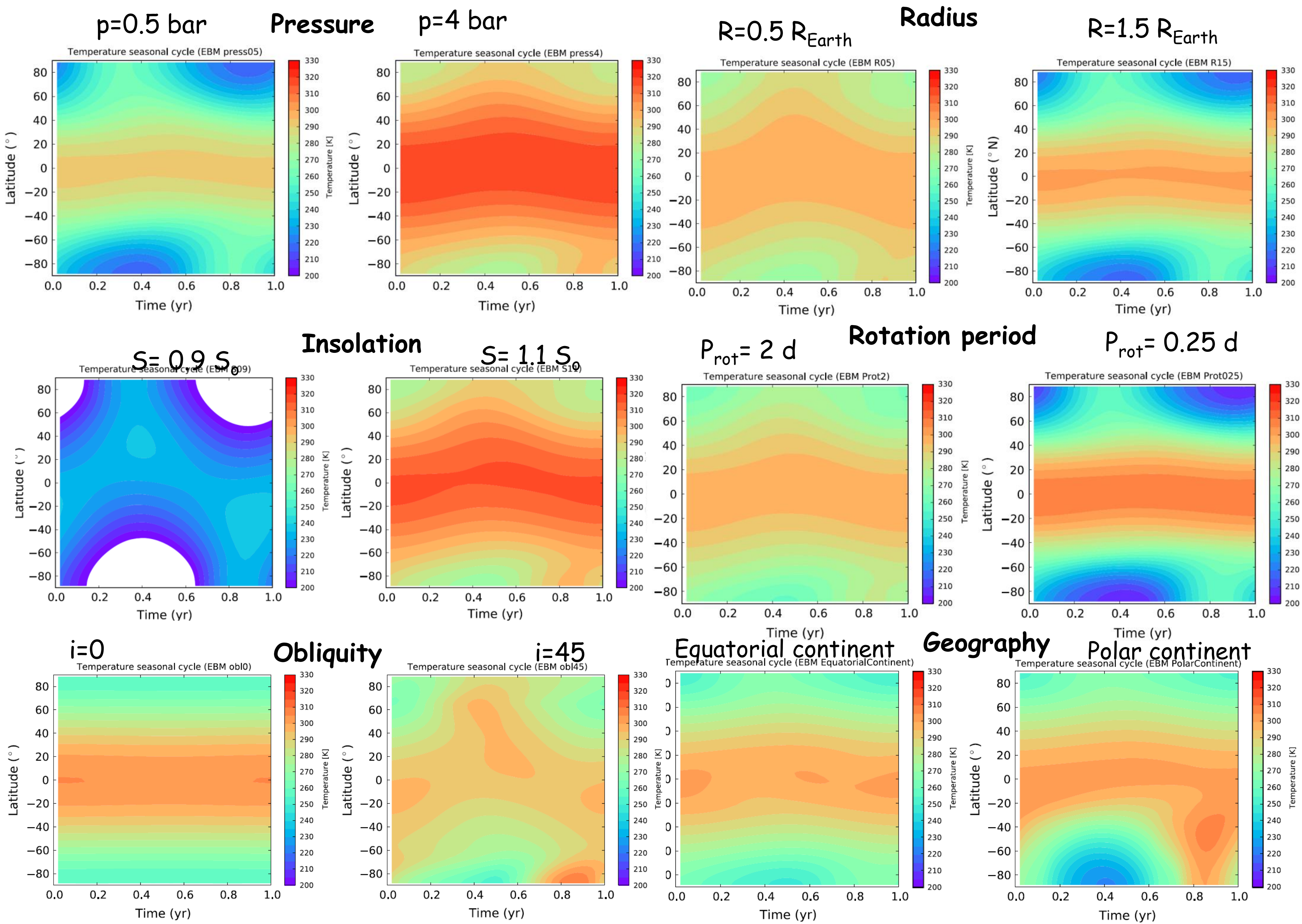


PLASIM

Aquaplanet i=0



Impact of variation of planetary parameters



From T(t,φ) to quantifying surface habitability indexes

Liquid water

T1=$T_{\rm ice}(p)$ T2=$T_{\rm vapor}(p)$

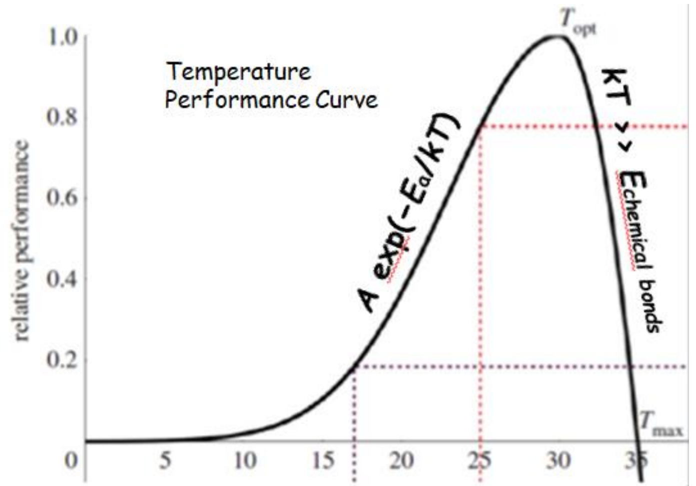
T range

Search for atmospheric biomarkers →
surface life with active metabolism

$$\Delta T_{\text{active metab.}} < \Delta T_{\text{liquid water}}$$

$$H(\varphi,t)=\begin{cases}1 & T_1 \leqslant T(\varphi,t) \leqslant T_2\\ 0 & \text{otherwise.}\end{cases}$$

T response function

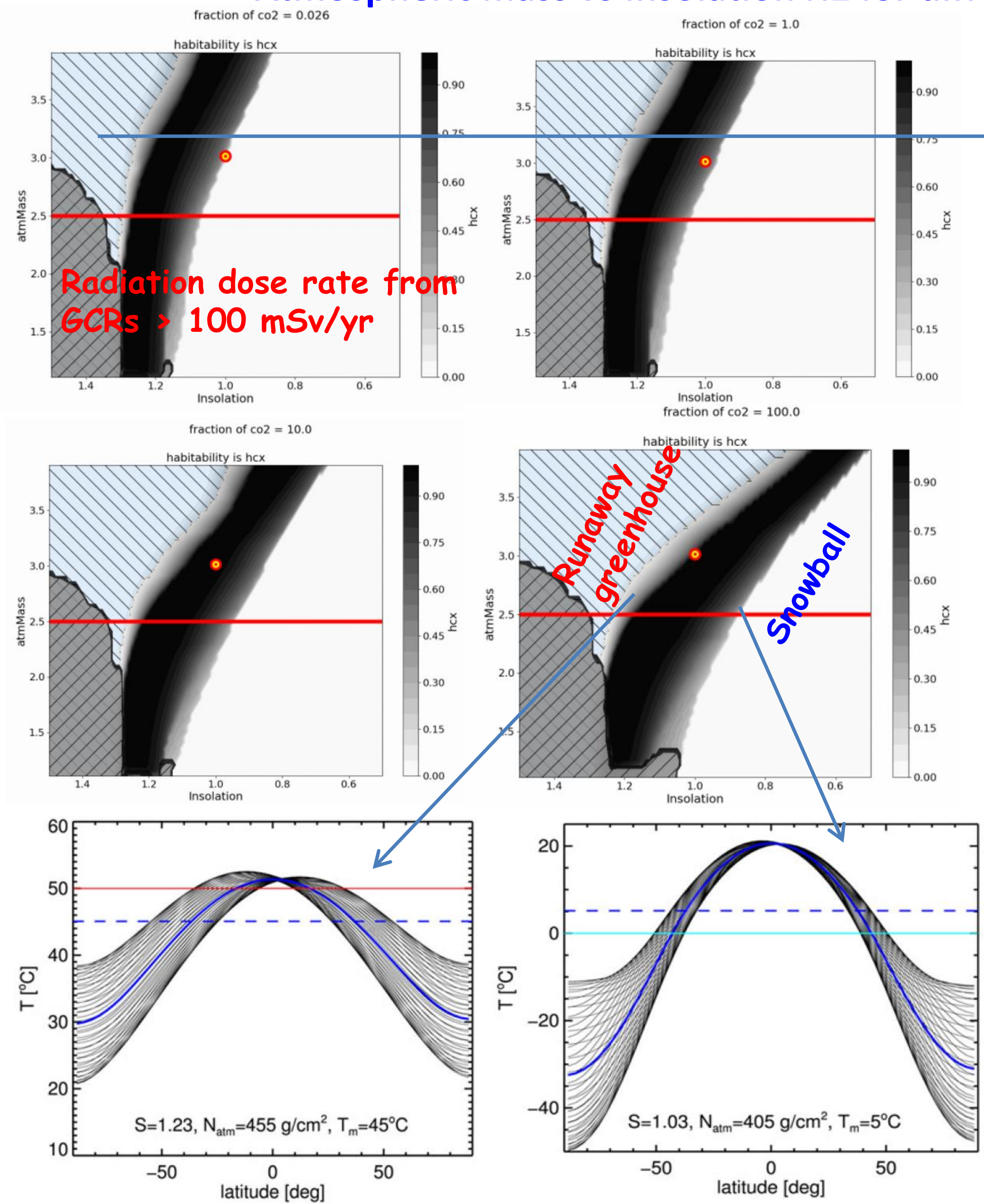


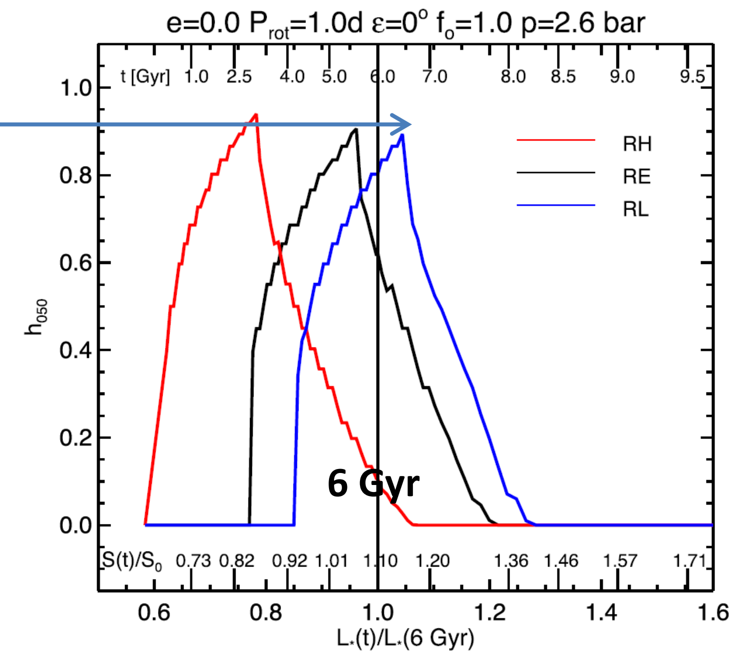
Mean fraction of ''habitable'' surface according to the specified thermal criterion

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

Silva et al.; Bisesi et al.-CliMHab-Bio

Atmospheric mass vs Insolation HZ for different CO2 abundances





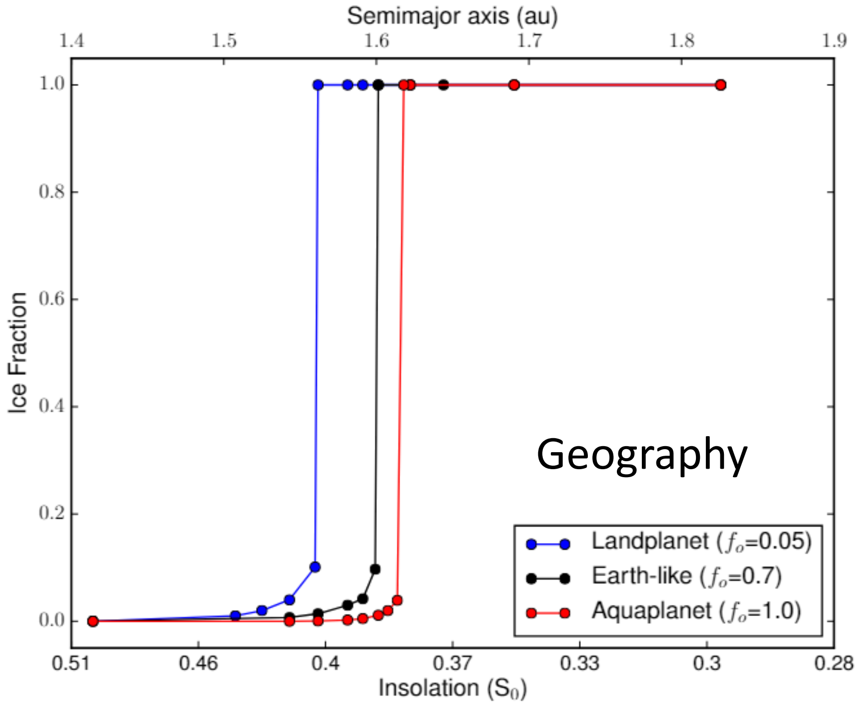
Habitability evolution for Kepler-452b

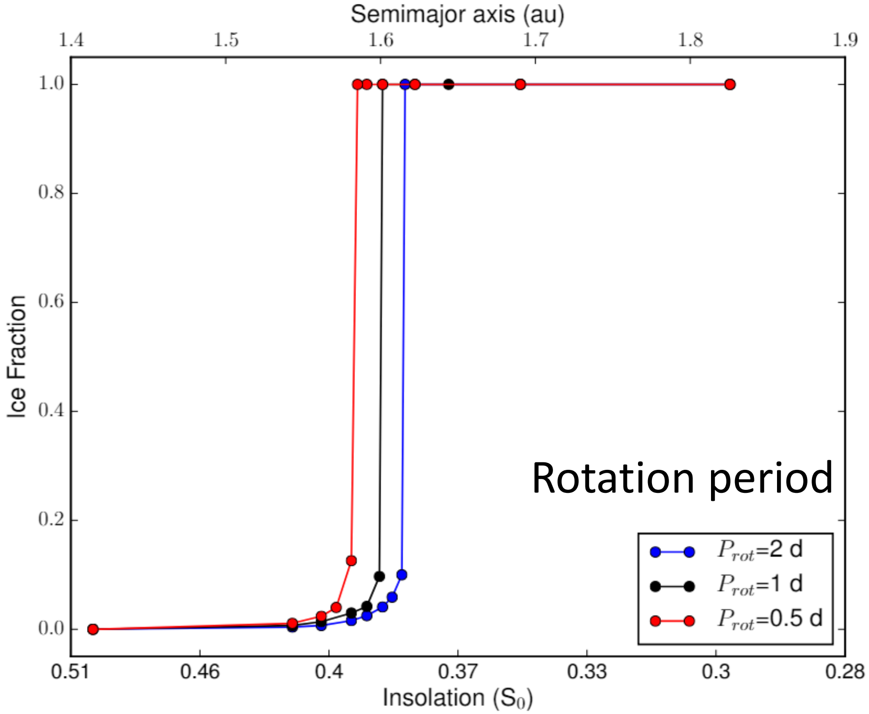
From HZ insolation width to stellar age evolution with stellar tracks

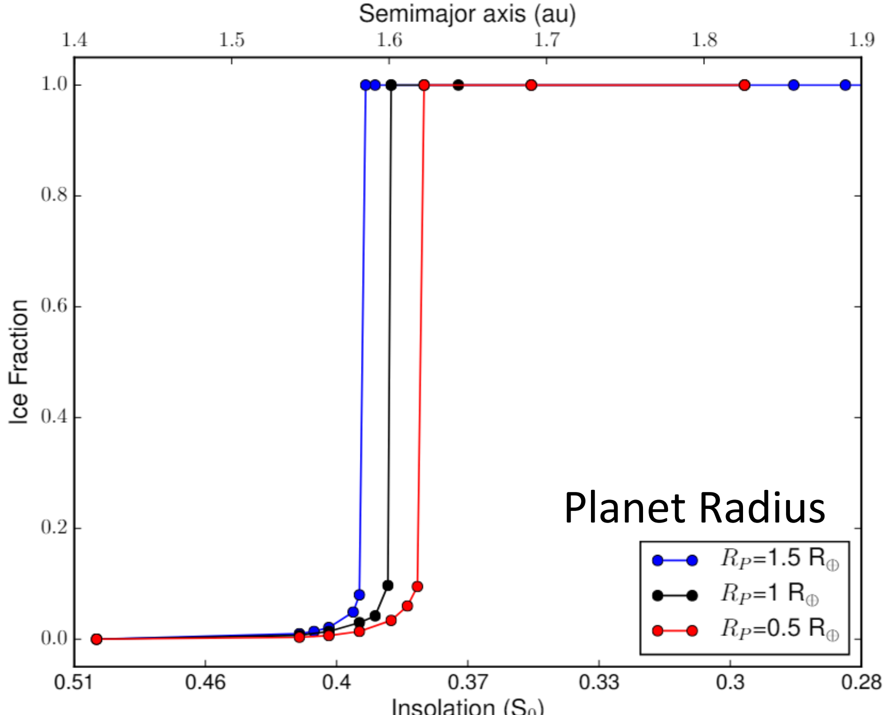
Silva et al.

Biasiotti, Simonetti et al.

Multi-parametric exploration of the Outer-edge of the HZ:
CO2-dominated maximum greenhouse atmospheres







Biasiotti, Ivanovski et al.

HABITABILITY AND *STAR-PLANET INTERACTION*

the impact of Space Weather on planetary atmospheres:

1. **<u>erosion</u> –** the rate of atmospheric escape as a function of the atmospheric composition & magnetic field properties
2. **<u>chemistry alteration</u>** – the generation of N_2O by solar activity
3. **<u>biology</u>** - assessing the flux of biologically harmful particles arriving on surface

application to potentially habitable planets with different planetary & atmospheric properties considering the role of Stellar Energetic Particles

Climate models with vegetation/albedo feedback – Bisesi et al.- CliMHab-BIO

- **Vegetation** cover is a regulator of a planet's climate (e.g. Lovelock's Daisyworld; Charney mechanism….): **lower albedo than bare soil**
- Model climate feedbaks among surface T – V cover – albedo

→ **effects on surface habitability and HZ width**

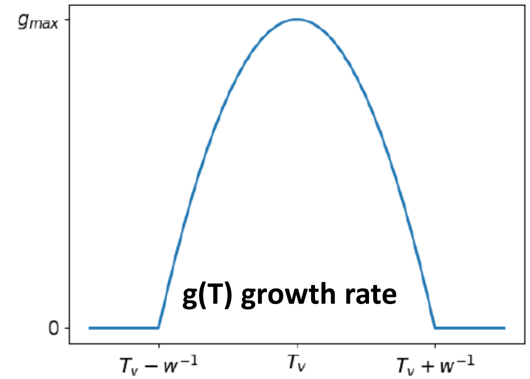
→ **optimize search of exoplantes with potential spectral biosignatures (e.g. red-edge)**

Modelling V in ESTM

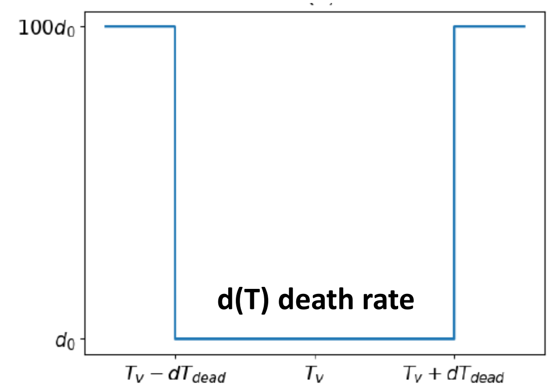
-Coupled differential equations to link surface T and V(T) for one or more V types:

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

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



Bioma	T_v [°C]	g_{max} $[y^{-1}]$	d $[y^{-1}]$	w $[K^{-1}]$	albedo
Foresta caducifoglie	20	0.15	0.03	0.1	0.14
Foresta conifere	10	0.15	0.03	0.1	0.09
Prateria	15	4	1	0.1	0.2
Tundra	5	2.5	0.5	0.2	0.2

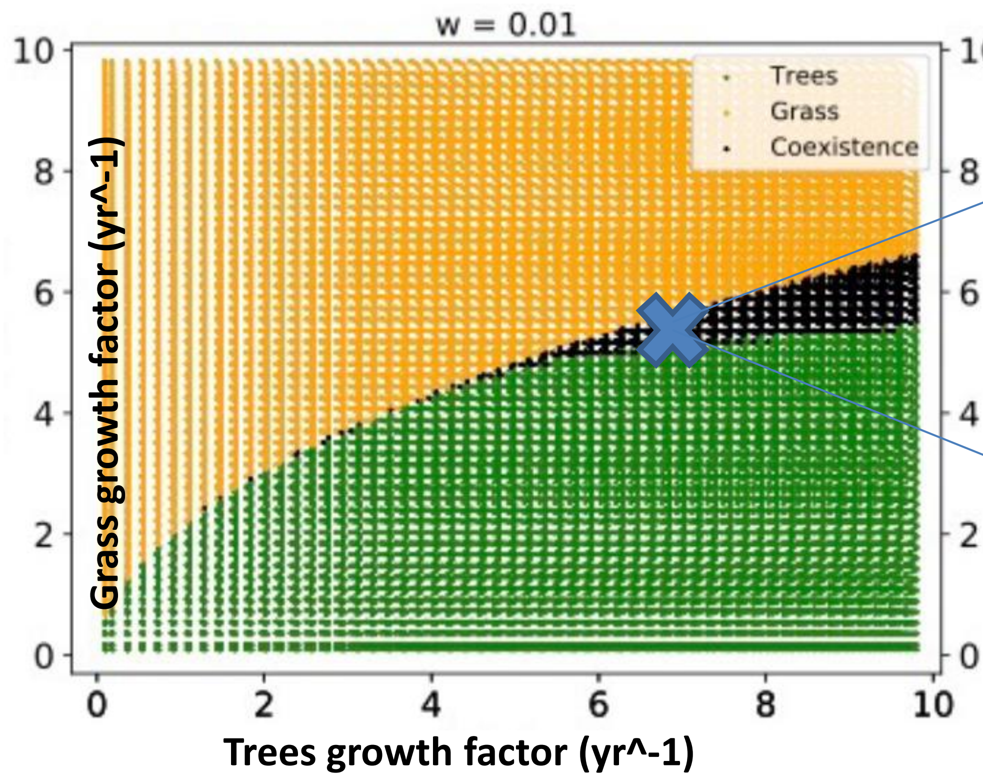


Modelling Vegetation cover and feedback in ESTM

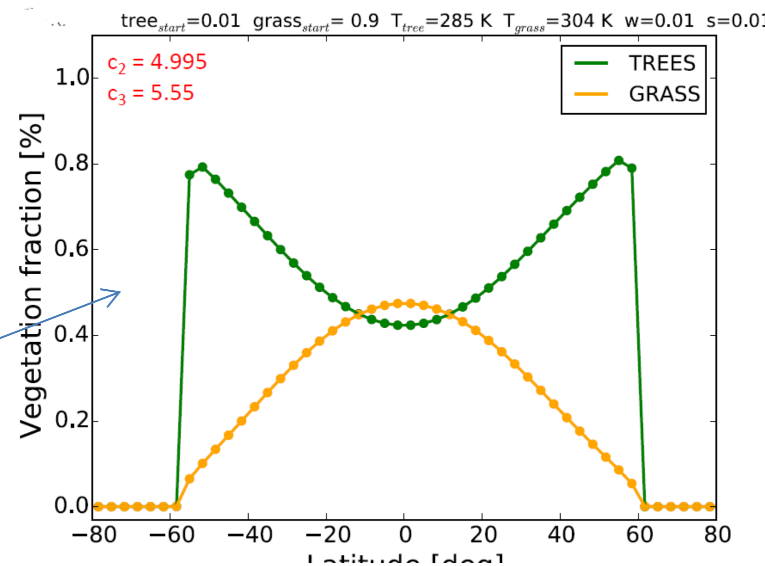
- Implemented the **Baudena, Provenzale et al. (2010) trees-grass-seedlings climate model** with a competitivity hierachy

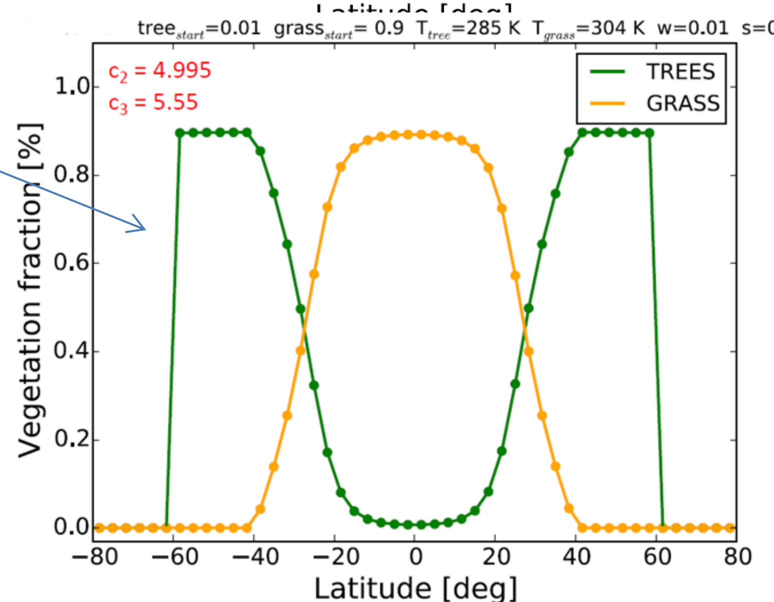
*Study of the equilibria states as a function of the parameters

$$\frac{dV_1}{dt} = g_1 V_3 - d_1 V_1$$
$$\frac{dV_2}{dt} = g_2 V_2 (1 - V_1 - V_2) - d_2 V_2$$
$$\frac{dV_3}{dt} = g_3 V_3 (1 - V_1 - V_2 - V_3) - d_3 V_3 - g_1 V_3 - g_2 V_2 V_3$$

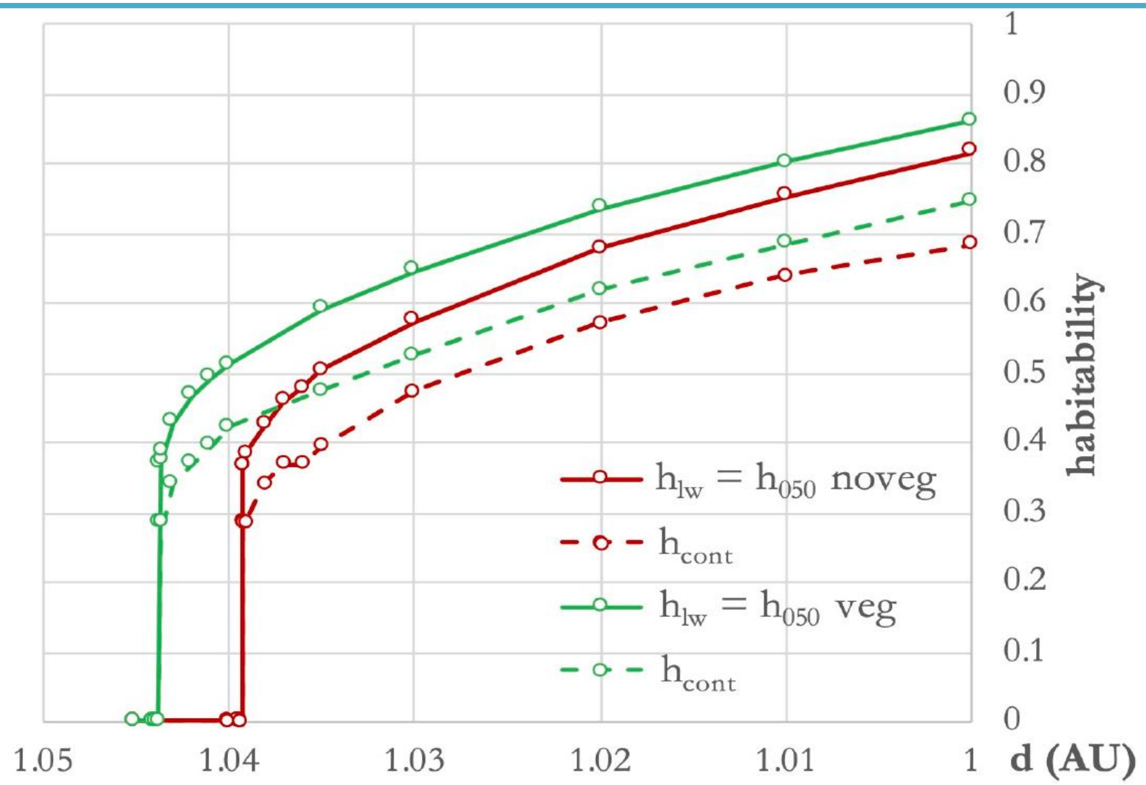


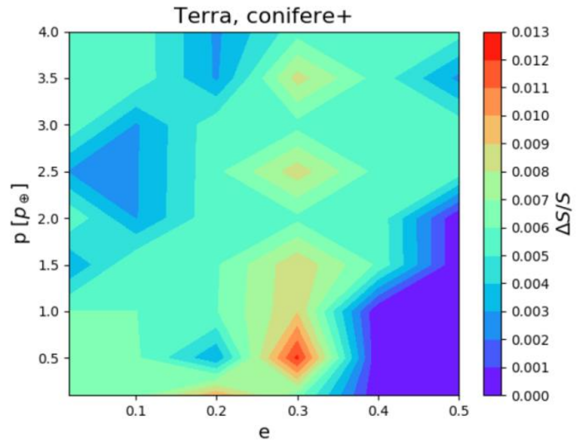
Trees/Grass vegetation fraction

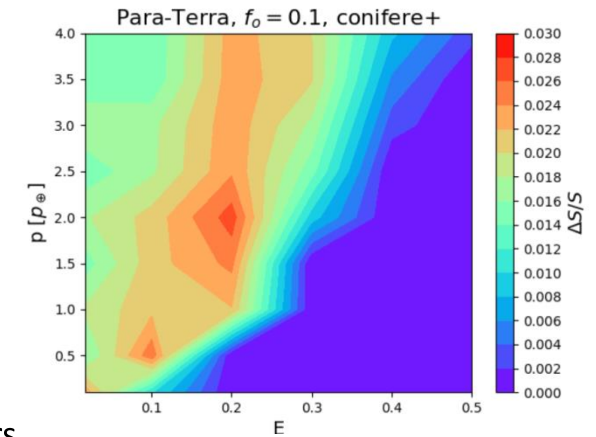




Modelling Vegetation cover/albedo feedback in ESTM- effects on habitability – E. Bisesi





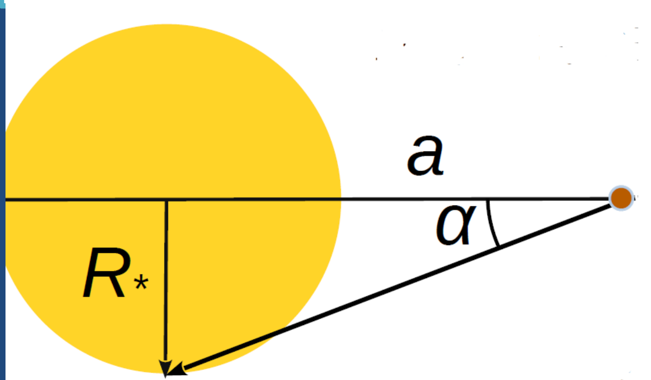


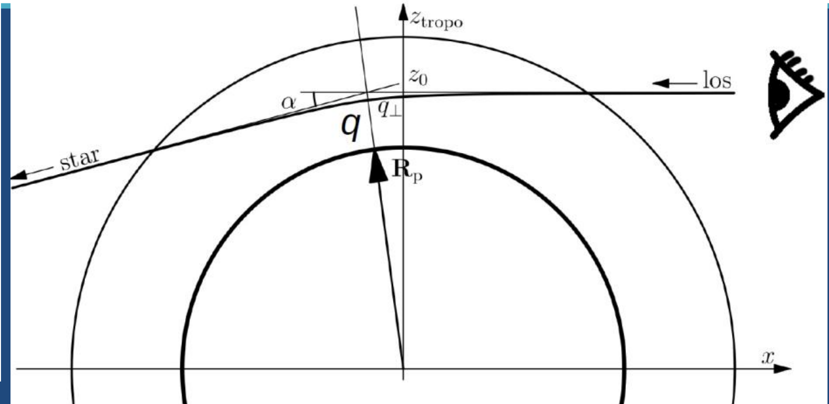
→ Wider outer edge could allow non-tidally locked orbits for HZ planes around M stars.

→ Collaboration with J. Caballero (CAB, Madrid):
*study CARMENES detected planets around nearby M dwarfs (e.g. Teegarden b)
*produce models with a grid of stars, planets, atmospheres and photosynthetic pigments of the CAB ExoPhot team

→ Collaboration with N. La Rocca et al. (Dept. Bio, UniPd):
*conditions for the survival of cyanobacteria and microalgae in the habitable circumstellar zone of M stars.
*photosynthetic performances of cyanobacteria under simulated M-stars-type light spectra

Modelling Refraction at Transit- M. Maris et al.-CliMHab-RBA





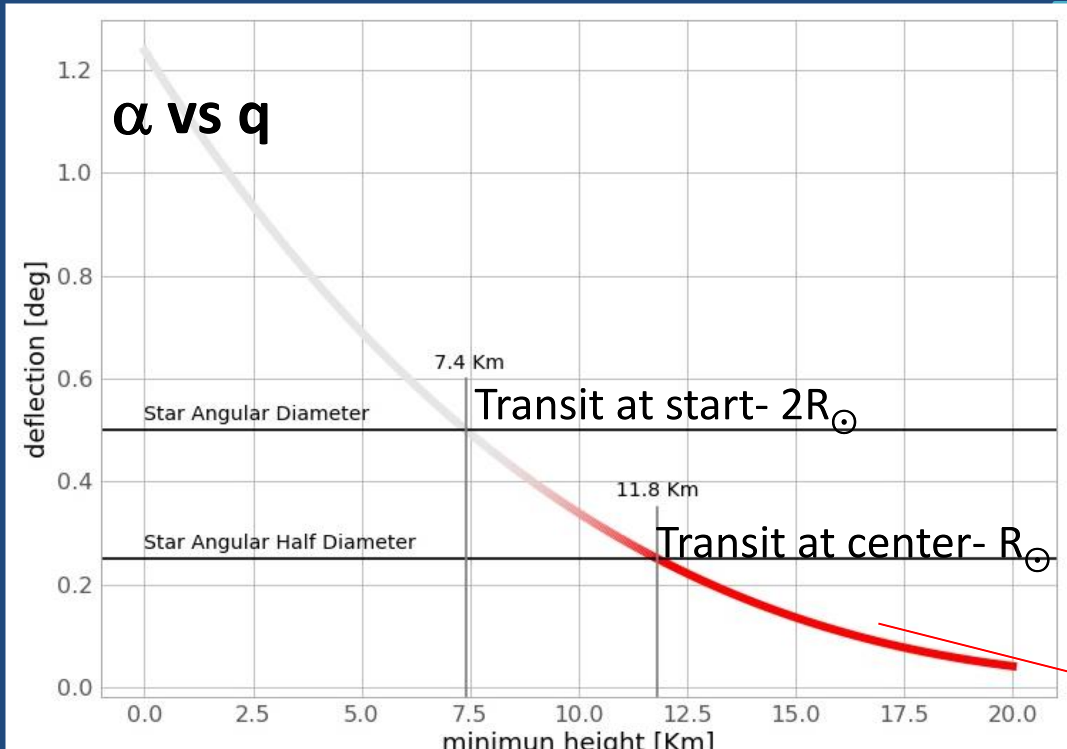
$$\alpha = \alpha(q)$$

$$\frac{d\alpha}{dq} < 0$$

$$\tan \alpha_{\lim} = \frac{R_*}{a}$$

$$\exists\, q_{min}$$

Impossible to reach lower layers with transit



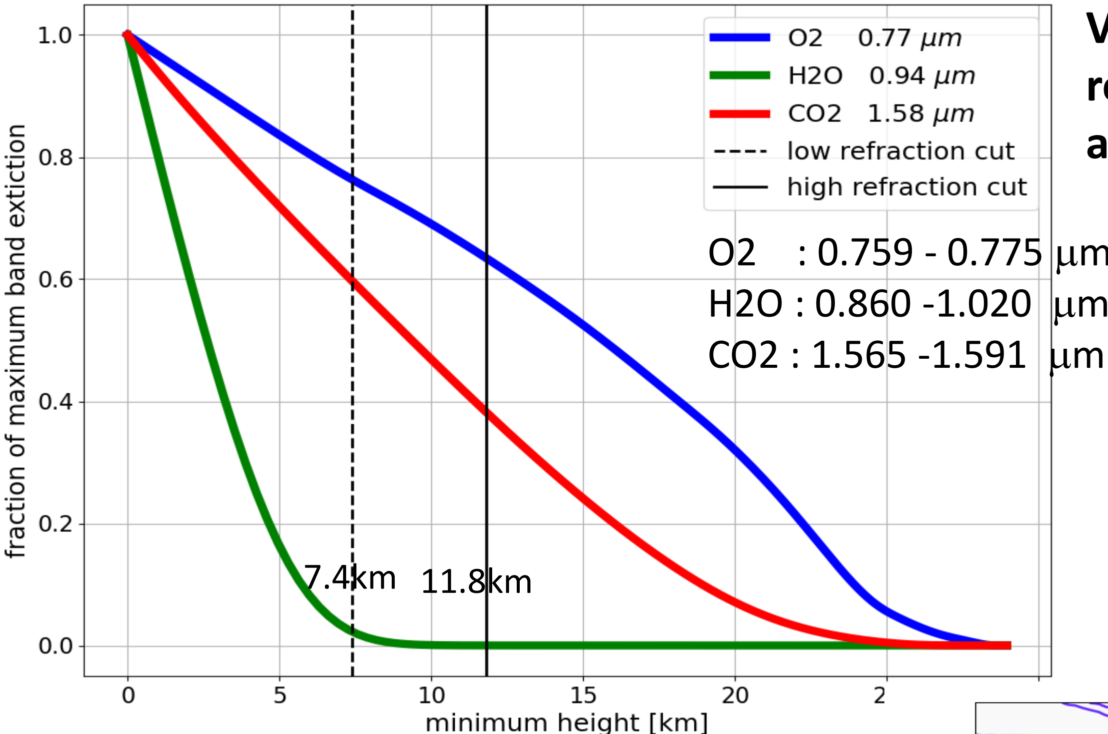
→Limits to probe below the troposphere for sun-Earth-like systems- even in the ideal case of no clouds

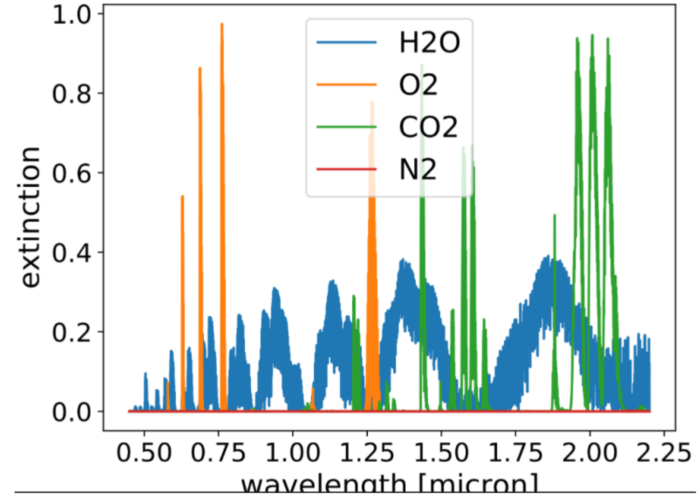
→ measurable biosignatures in high troposphere/stratosphere?

→ better to probe with IR emission (e.g. LIFE, Quanz et al.)?

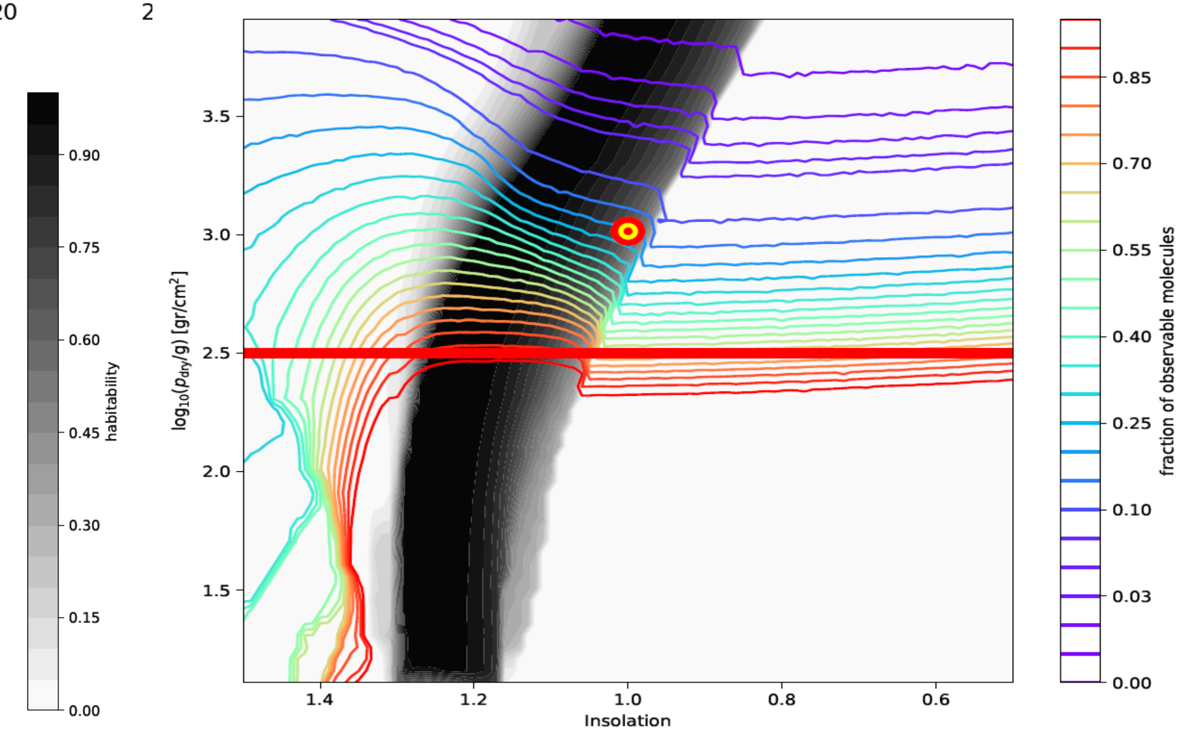
*Interface with ESTM: compute LOS propagation + refraction and its gradient in each point of the given atmospheric structure and composition

Variazione profondita' delle bande relativa al caso senza rifrazione vs altezza raggiunta





Number fraction of observable molecules due to refraction



M. Maris et al. 2022

ARTECS-ARchive of TErrestrial-type Climate Simulations

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

- Database currently with ~10^5 models, x100 planned

- Hosted at OATs-IA2

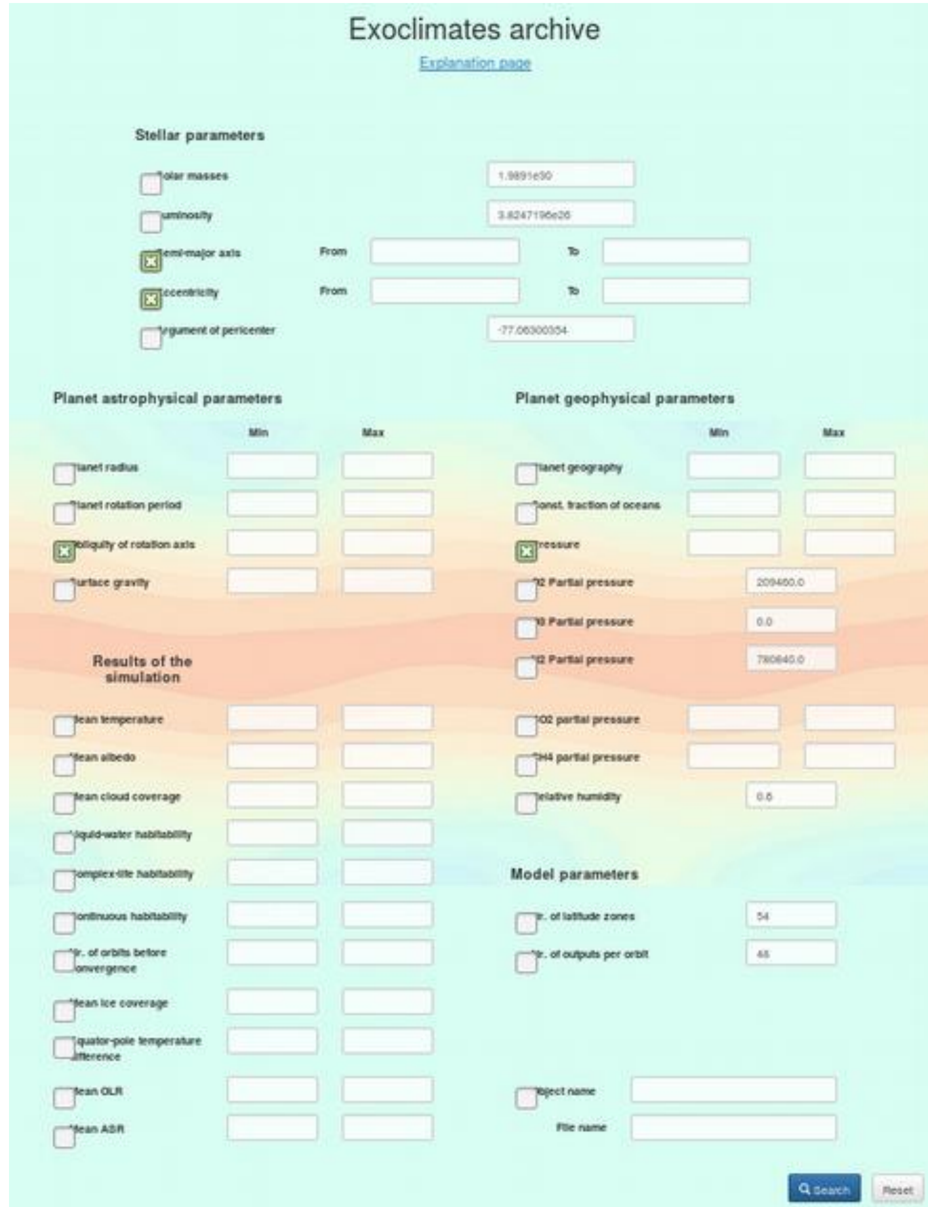
- Currently 9-dimensional parameter space: semi-major axis, pressure, ecc, obl, CO_2, geography, Prot, R, g

- Plan to include spectra for each model

- Study set of parameters that yield more probable habitability/observability

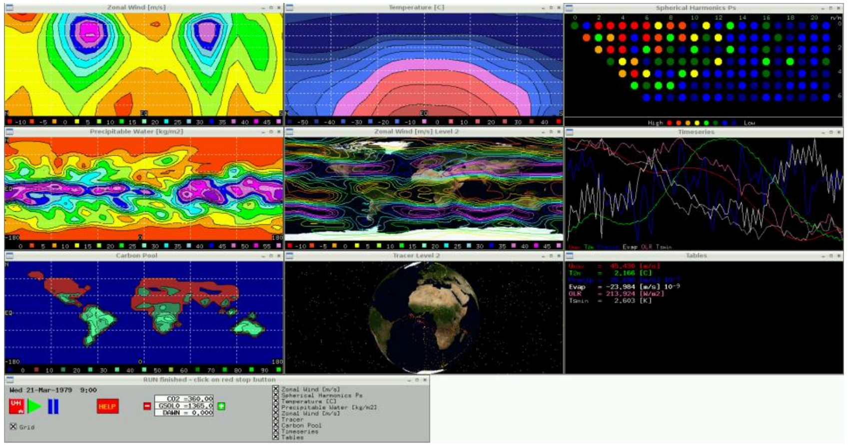
- Study **bistable** equilibria (Murante et al. 2020)

-Train **neural networks** for fast and statistical habitability estimations (ongoing, tesi T. Marsonet, 2020)



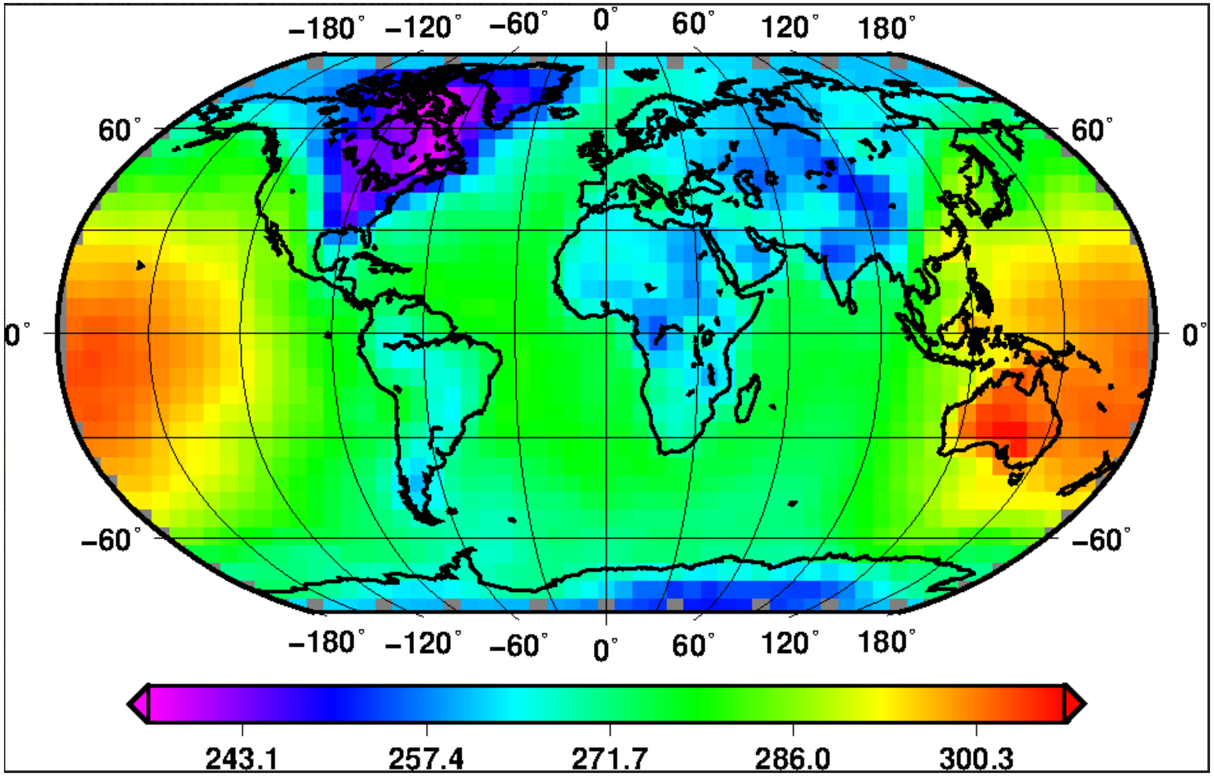
PLASIM - PLAnet SIMulator

Murante, Monai, von Hardenberg et al

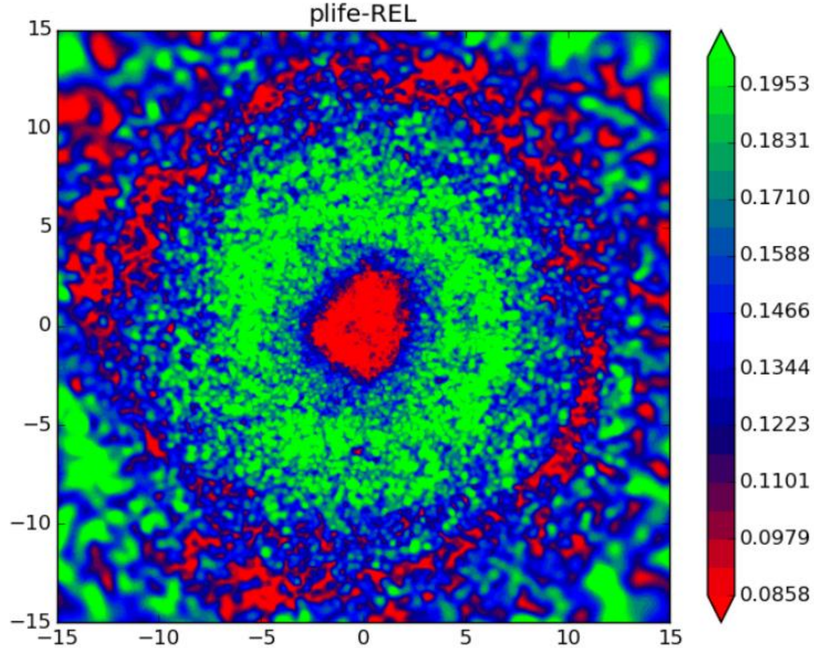


- -Beyond ESTM: intermediate complexity model
- -Public code but require modifications for general configurations
- -Simplified atmosphere, ocean, land but 3D and quite fast

- -Validation of ESM in non-Earth like cases
- -Tidally locked/ strog obliquity planets



A tydally-locked Earth

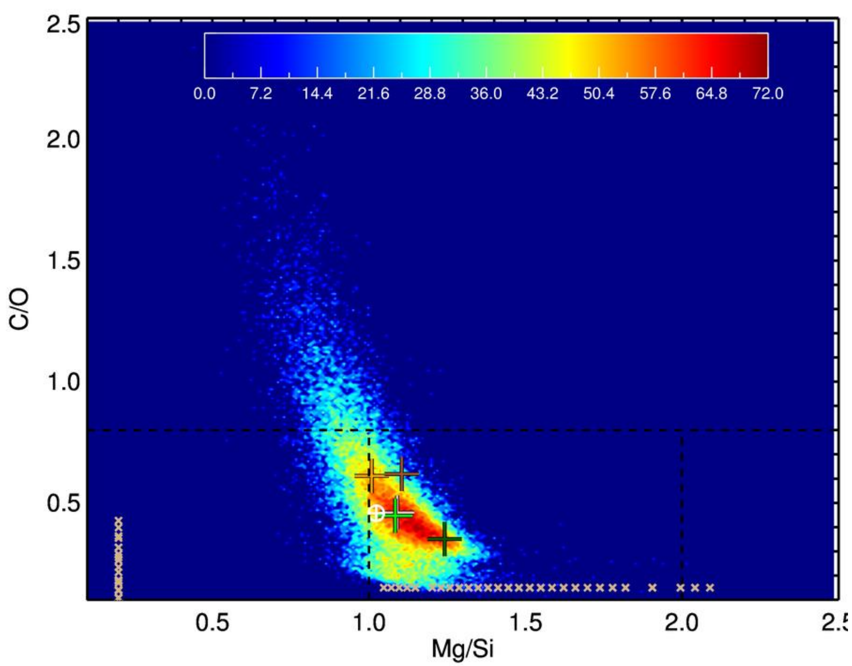


Galactic chemical evolution and habitability- Scheda GalHab- L. Silva et al.

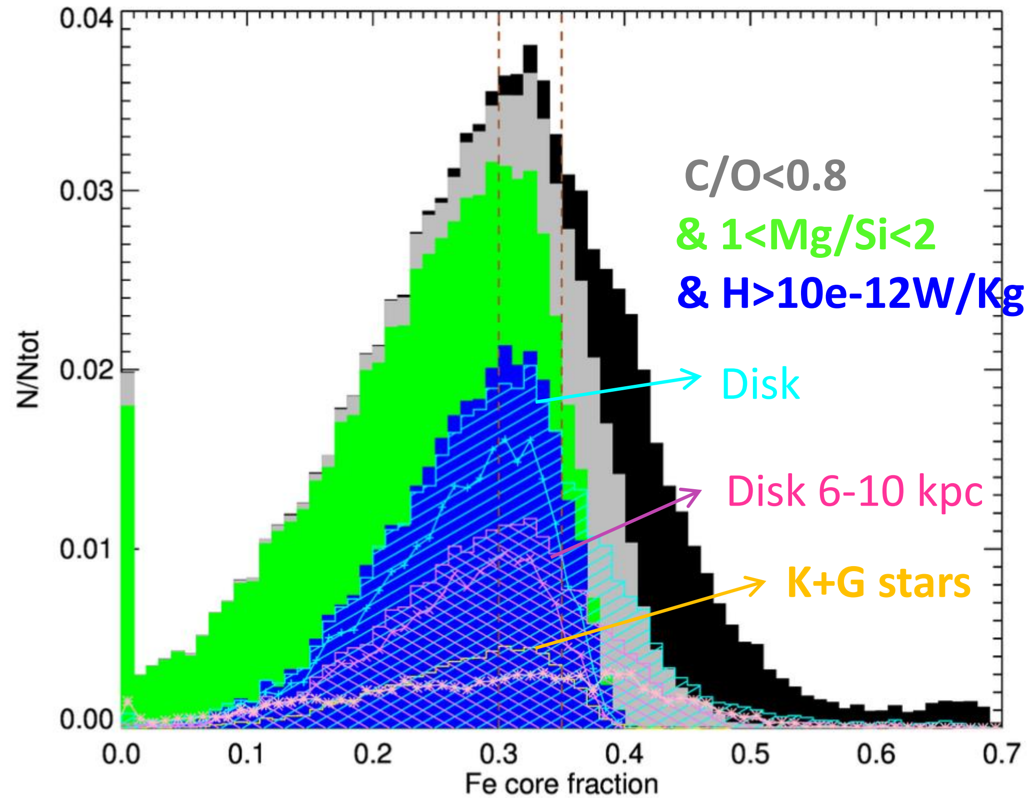
*Statistical study of Galactic habitability in terms of GHZ (e.g. Snae impacts) and planetary composition
*Different stellar ejecta models, IMF, in cosmological simulations of MW-type galaxies

SNae sterilization distance 8 pc

Stellar abundance ratios distribution



Fe core fraction distribution



Outreach activities

***XTREME-Vivere negli ambienti estremi**
ESOF2020-Science in the City
INAF + UniTs + PNRA + Museo Antartide + Fed. Speleo FVG+ ERPAC + Regione FVG + SAI + EAI, https://www.media.inaf.it/2020/09/01/esof-extreme/
PI: **M. Maris**

***XTREME** mostra+spettacolo in Giugno 2022 all'interno di HACK100
PI: **E. Bisesi, S. Ivanovski, M. Maris**

*<u>(Alcune) Conferenze divulgative:</u>

-**Le Impronte della Vita con I telescopi Futuri**, M. Maris,Cremona, Gruppo Astrofili Cremonesi, 5/5/2022, https://www.facebook.com/watch/?v=388459726492231
- **Conversazioni di Astrobiologia. Un luogo sicuro, un posto speciale: Tra Gaia e abitabilità planetaria**. G. Vladilo, A. Provenzale, 17/12/2021
- **Conversazioni di Astrobiologia. Vegetazione e clima degli esopianeti**. E. Bisesi, G. Murante, 19/11/2021
- **Conversazioni di Astrobiologia. Cosa determina il clima degli esopianeti**. E. Bisesi, S. Monai, G. Murante, 27/10/2021
- **Conversazioni di Astrobiologia. Relazione tra clima e abitabilità degli esopianeti**. E. Bisesi, G. Murante, 30/6/2021
- **Conversazioni di astrobiologia. Evoluzione della vita su altri mondi.** E. Bisesi and S. Ferluga (2021), 29 May 2021
-**SIMABI: Simulatore Abitabilità Planetaria**, M. Maris, Roma, INAF, Maker Faire Roma, 18-19/10/2019, https://www.media.inaf.it/2019/10/15/maker-faire-inaf-2019/
-**SIMABI: Simulatore Abitabilità Planetaria**, M. Maris, Roma, INAF: Maker Faire Roma, 12-14/10/2018, https://www.media.inaf.it/2018/10/09/maker-faire-rome-inaf/

Summary/Prospects/Programs

Time-scale ~3 years

*Well-developed and continuous improvement of theoretical climate/atmospheric tools .
→ Ongoing work to **extend software tools to simulate observations** to parallel the observational/technological efforts to detect habitable planets

*First detections for M stars → Working to **improve on 3D models**

*Multi-parameter exploration studies needed due to the intrinsic complexity of interpreting habitability and planetary atmospheres
→ Include more atmosheric chemical species in **EOS**
→ Include (some) **star-planet effects**
→ Expanding **ARTECS** with more compositions and assign observability to each model

***ASI-Life in Space**: end in 2023

***European Astrobiology Institute**: white paper on «Habitable Worlds»

* CUISINES (Climates Using Interactive Suites of Intercomparisons Nested for Exoplanet Studies)
* ARIEL: S. Ivanovski and M. Maris
* LIFE - Laser Interferometer For Exoplanets (Quanz et al., Zurich)

Finanziamenti/Criticità

ASI-Life in Space. 2019-2023. PI nazionale S. Onofri (Univ. Tuscia). PI OATs: L. Silva
Totale: 130 ke a OATS – spesi o già impegnati prevalente in borse
-2021: 1 anno AdR a L. Biasiotti (ora PhD)
-2021/2022: 2 anni AdR a E. Bisesi (fino a marzo 2023)
-2022/2023: 2 anni AdR a P. Simonetti (+ Life in Space + HPC-TRES)

* **HPC-TRES- Training and Research for Earth Science**
Programma di finanziamento di OGS+CINECA
34 ke su "HPC for climate modellization of terrestrial-type exoplanets with temperate conditions" PI. L. Silva

→ Difficoltà di fondi per congressi, pubblicazioni, brevi visite scientifiche etc:
1 theory grant + 3 mini-grants

→ **Continuità e massa critica di persone:**
*fondi per AdR
- parteciperemo ai prossimi bandi (ASI?)
- finanziamenti tramite OGS, CNR, EAI?

*posizioni TI – progetti a lungo termine - quale RSN?