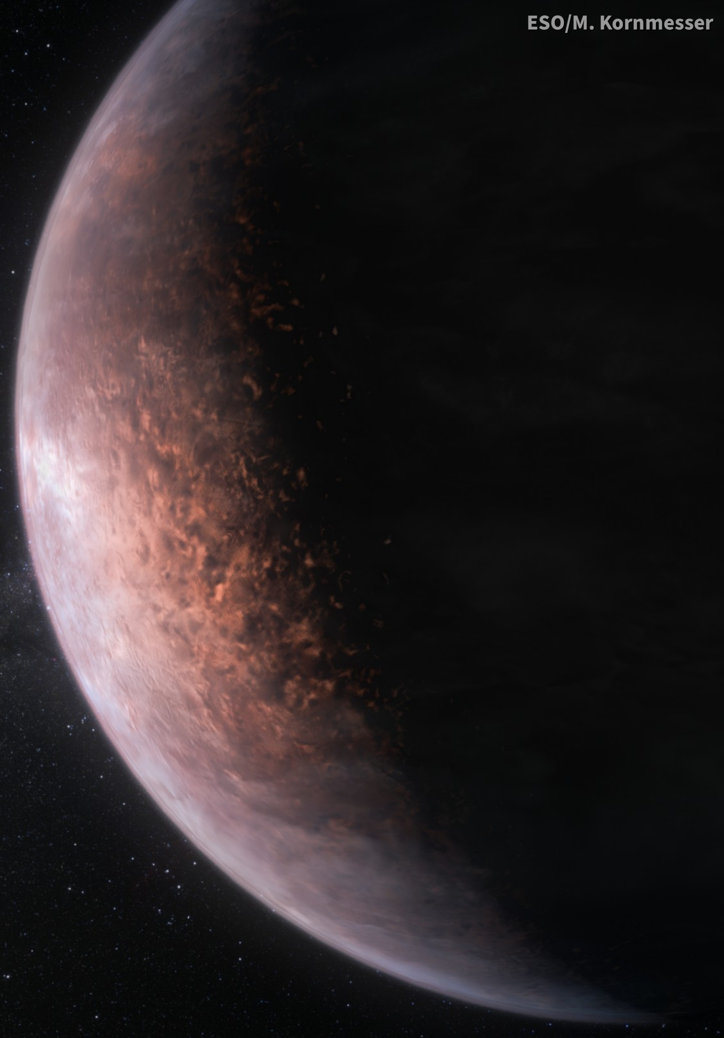

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A python package for interior modelling of rocky exoplanets using Gibbs free energy minimization

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Observables for terrestrial exoplanets

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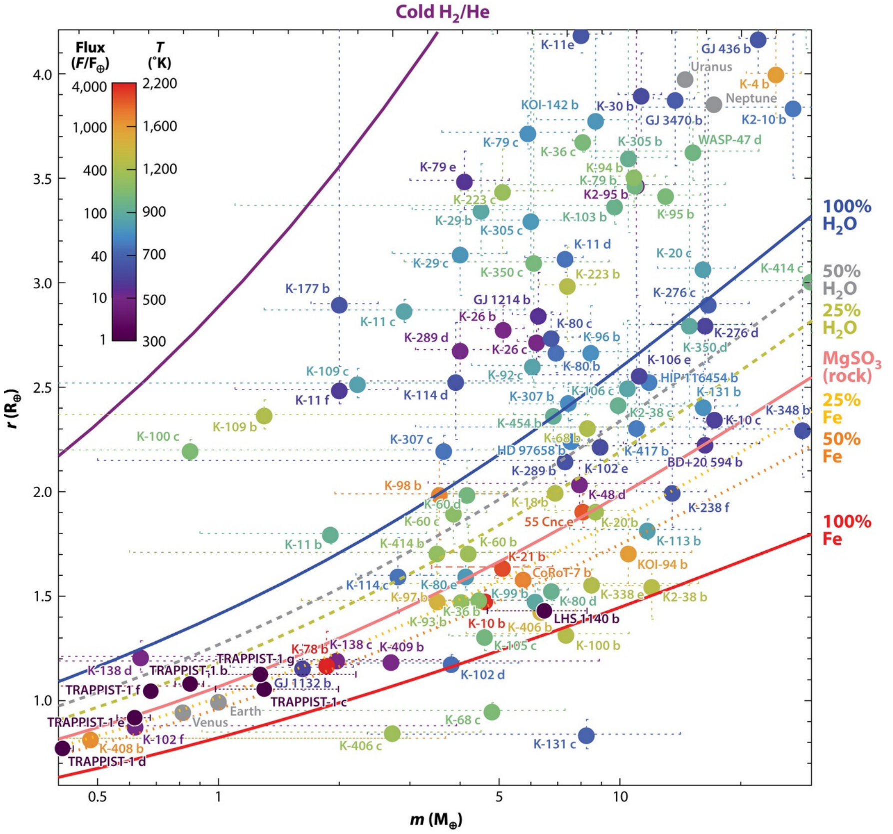
Mass & Radius

→ mean density

→ 0^{th} order interpretation of planet composition

In-depth characterization of interiors requires detailed mineralogy & structure



Kaltenegger L. 2017.
Annu. Rev. Astron. Astrophys. 55:433–85

Figure from Kaltenegger 2017

Diversity of estimated exoplanet chemistry

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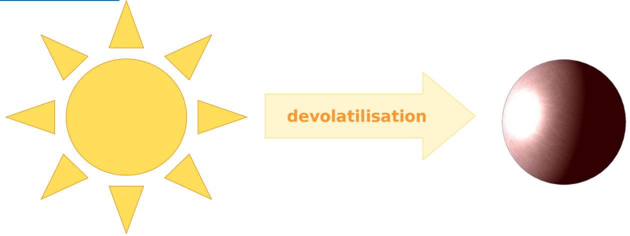


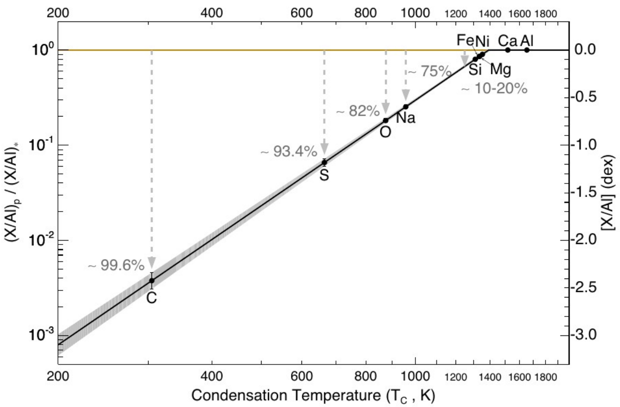
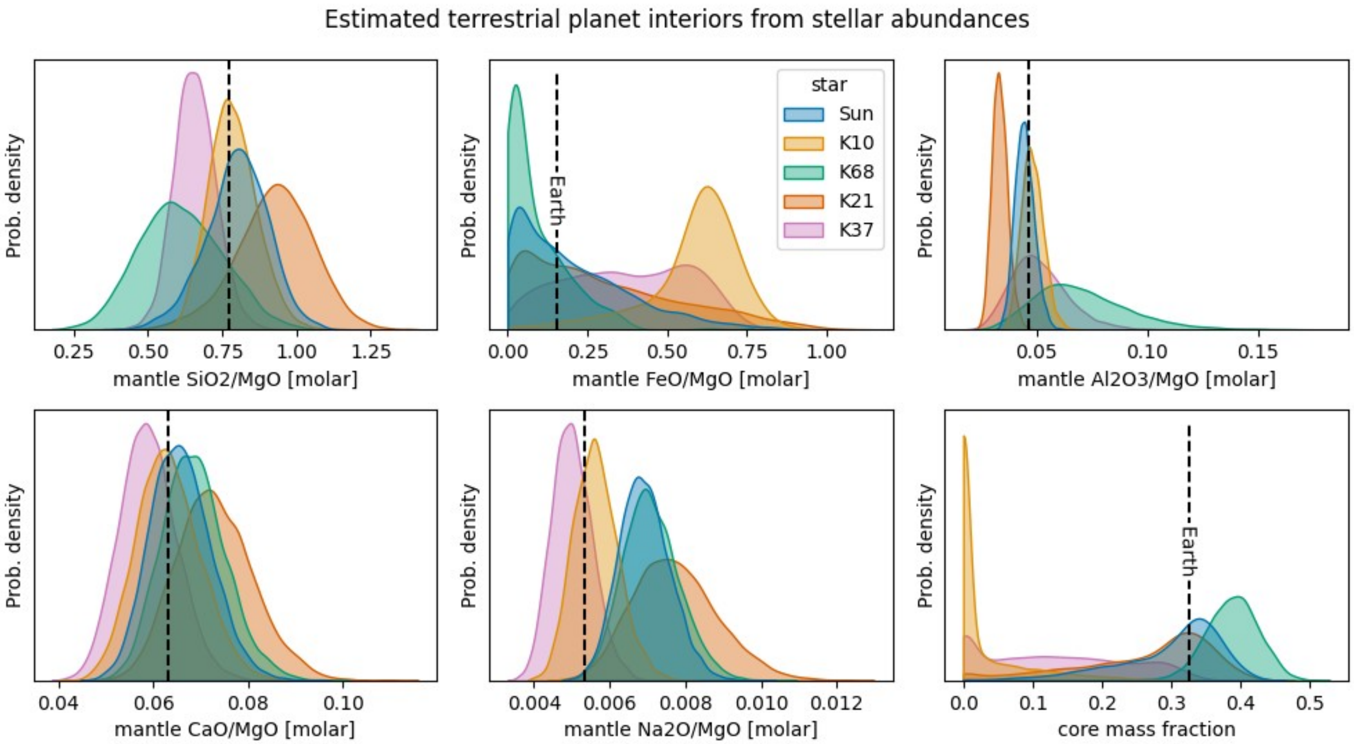


Figure from Wang et al. 2019



Terrestrial exoplanet composition estimated from abundances of planet-hosting stars using the method of Wang et al. 2019 (ExoInt, https://github.com/astro-seanwhy/ExoInt)

Existing interior models for terrestrial (exo-)planets

- **ExoPlex (python wrapper to Perple_X (Connolly 2009) [Fortran77])**

  Lorenzo 2018, Hinkel & Unterborn 2018

  https://github.com/CaymanUnterborn/ExoPlex

- **Magrathea (C++, tabulated $MgSiO_3$ EOS)**

  Huang et al. 2022

  https://github.com/Huang-CL/Magrathea

ExoPlex (precomputed mineralogy):	~1.5s
ExoPlex (with Mineralogy computation):	>2min
Magrathea:	~0.69s

→ Want to have a reasonably fast software package for computing accurate mineralogies, implemented in a popular and easy-to-use language

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Interior structure model

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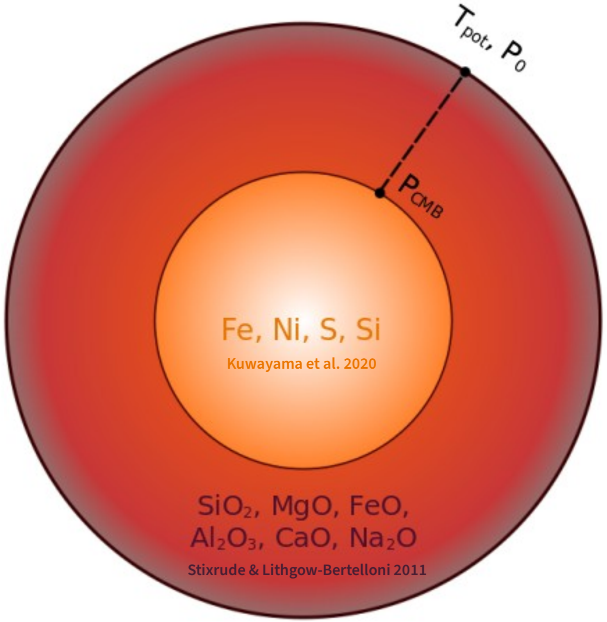
Forward model: computes radius (or mass) as function of mass (or radius), mantle & core chemistry.



1. **Initial guess on interior structure** with MgSiO3-perovskite mantle EOS (Seager et al. 2007)

   → obtain P_{CMB}

2. **Integrate adiabatic gradient $P_{surface}$ → P_{CMB}**

$$\frac{dT}{dP} = \frac{\alpha T}{C_p \rho}$$

   compute mineralogy along the way by Gibbs free energy minimization, using linearized solid-solution series (White et al. 1958, Connolly 2009). Implementation in Cython.

   → obtain temperature, density and mineralogy profile

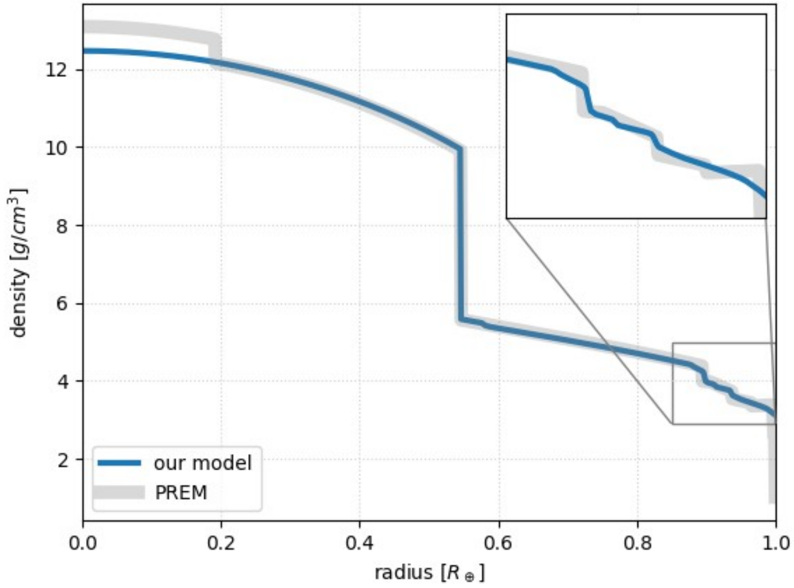
3. **Refine interior structure with these updated profiles based on mineralogy**

Testcase Earth

Earth

R=1.0 R_{earth} (computed)

M=1.0 M_{earth} (fixed)



Comparison of computed interior structure with PREM (Dziewonski & Anderson 1981).

Mantle chemistry (wt%)

McDonough & Sun 1995

SiO_2 = 45.0

MgO = 37.8

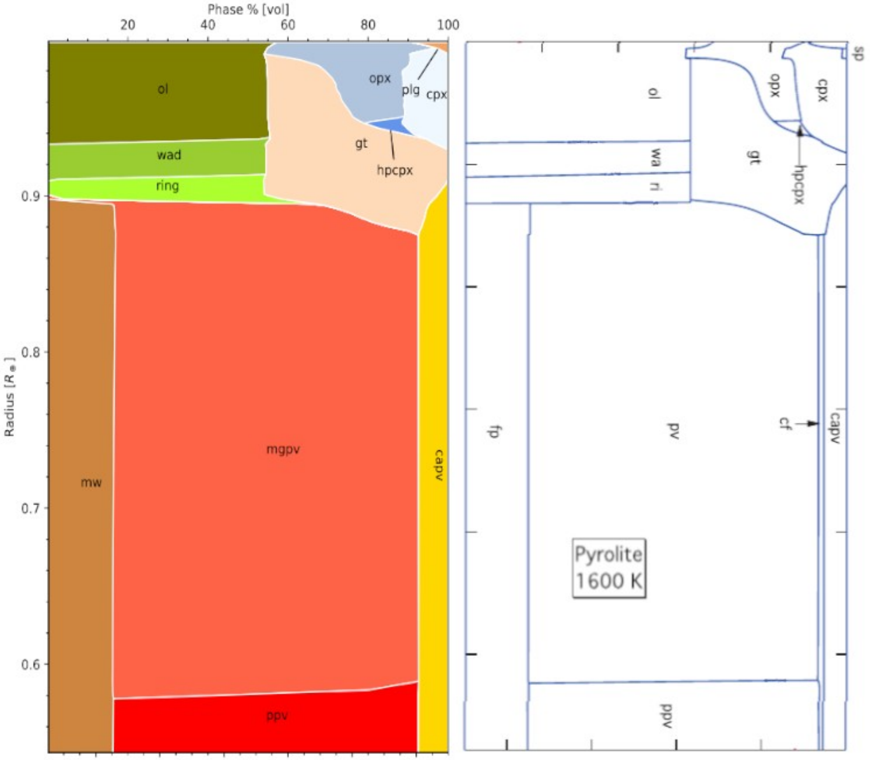
FeO = 8.05

CaO = 3.55

Al_2O_3 = 4.45

Average runtime for entire calculation ~10-13 sec., but depends on:

- Mineral complexity (less, i.e. FMS-system → faster)
- Size of planet



Comparison of mineralogies inferred with our model (left) and literature (right). Modified from Stixrude & Lithgow-Bertelloni 2011

Exoplanet mineralogies - examples

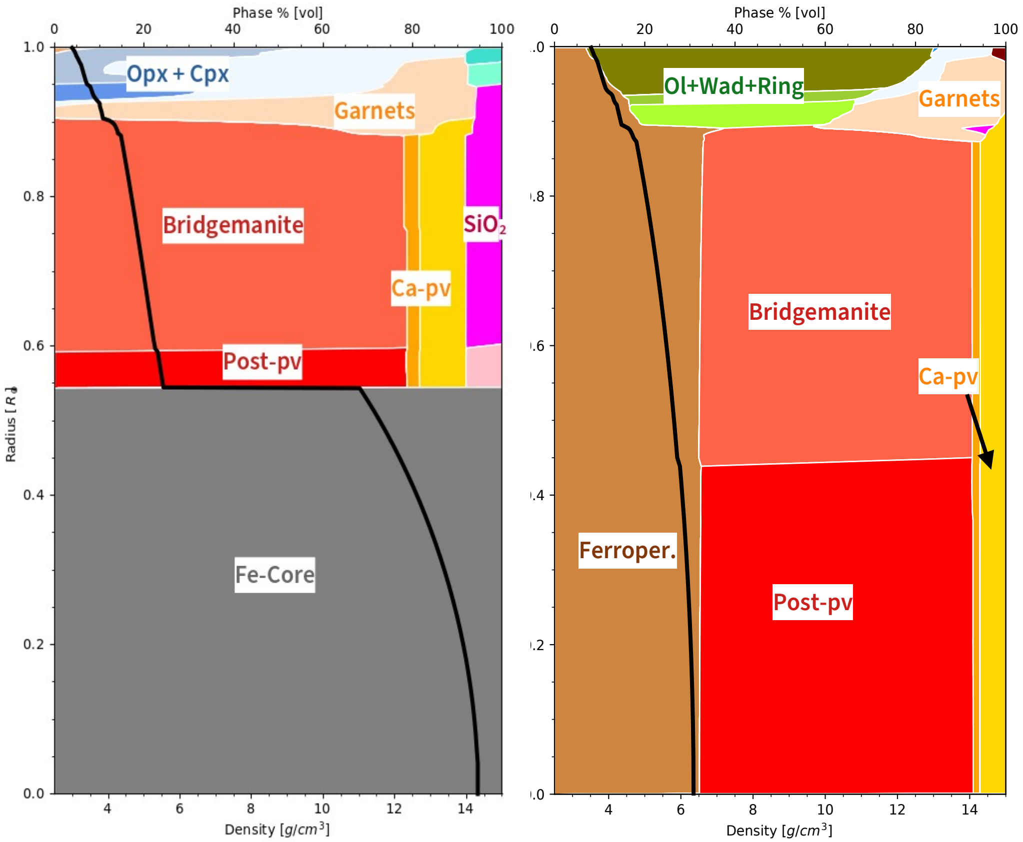
Extremely Si-rich mantle

R=1 R_{earth} (fixed)
M=1.03 M_{earth} (computed)

Mantle chemistry (wt%):

SiO_2=59.7
MgO = 29.5
CaO = 5.2
Al_2O_3 = 5.2*
Na_2O = 0.5

*assumed, neccessary to absorb Na_2O in mineralogy



Inferred mineralogy based on chemical composition of hypothetical exo-Earth's from Wang et al. 2019

Fe-rich mantle

R=1 R_{earth} (fixed)
M=0.89 M_{earth} (computed)

Mantle chemistry (wt%):

SiO_2=30.3
MgO = 29.2
FeO = 31.3
CaO = 2.5
Al_2O_3 = 3.28
Na_2O = 0.23

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Mineralogical influence on planetary characteristics

- Oxygen fugacity → controls outgassed atmosphere (e.g. Wang et al. 2022, Noack et al. 2020, Sossi et al. 2020, Arculus 1985)
- Partial melting → outgassing (e.g. Noack et al. 2020) and crust formation (Brugman et al. 2021)
- (lower) mantle viscosity; sensitive to ferropericlase (e.g. Thielmann et al. 2020) and Ca-pv (Immoor et al. 2022)
- Water storing capability: ol<px<ring&wad (e.g. Othani 2020)

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Summary

- A software package for interior modelling with fast, detailed mineralogy evaluation
- Open source, written in Python 3 / Cython
- Will be released soon

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