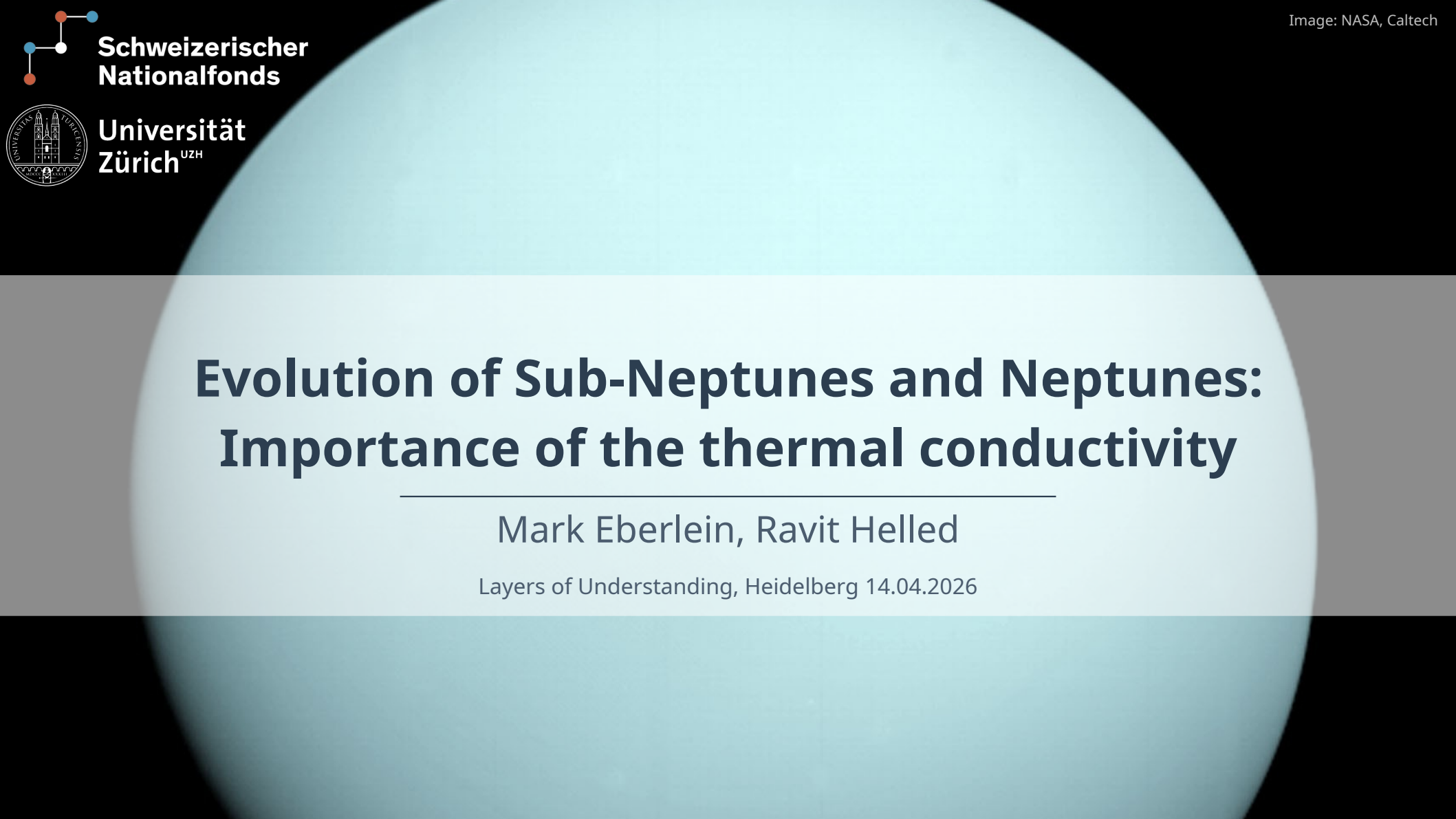


Schweizerischer Nationalfonds

Universität Zürich[UZH]

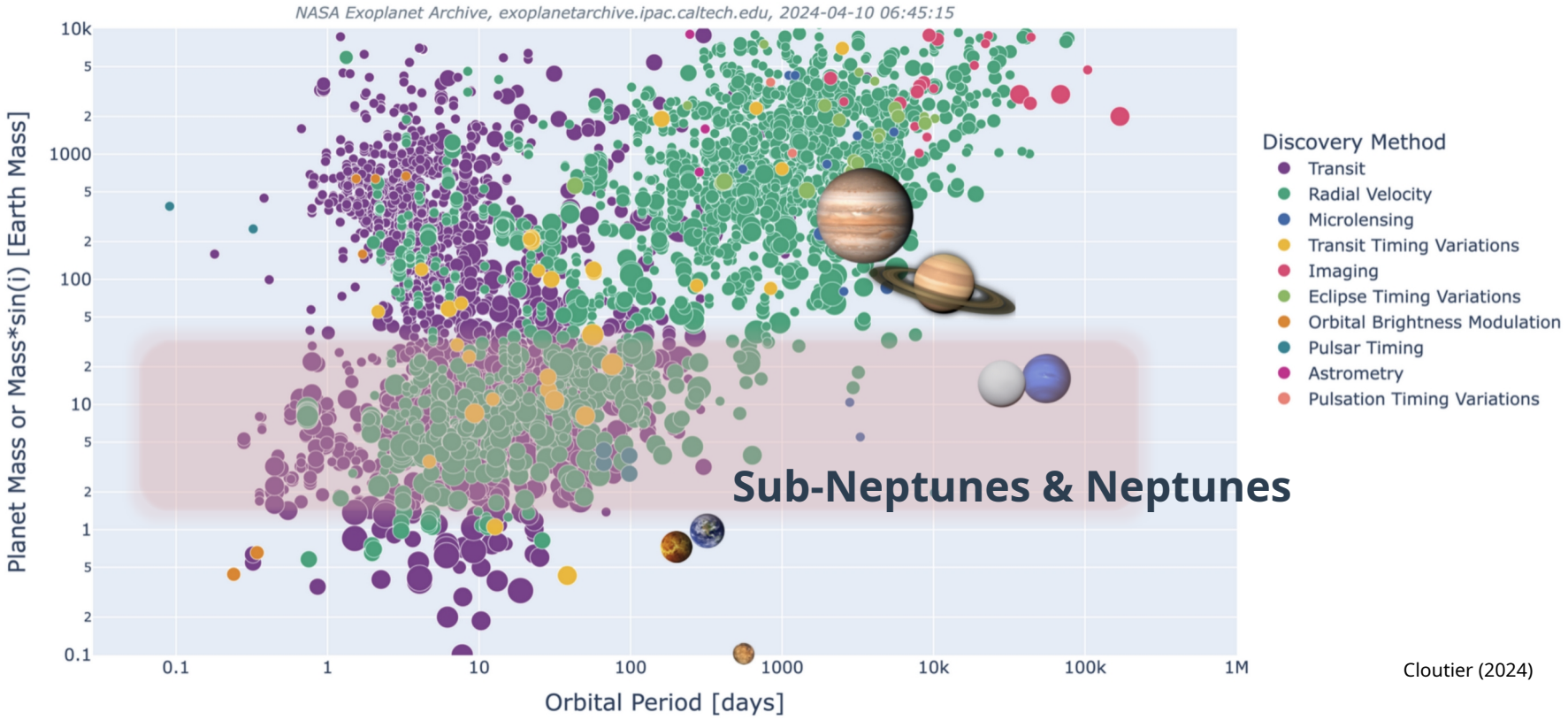
Image: NASA, Caltech

Evolution of Sub-Neptunes and Neptunes: Importance of the thermal conductivity

Mark Eberlein, Ravit Helled

Layers of Understanding, Heidelberg 14.04.2026

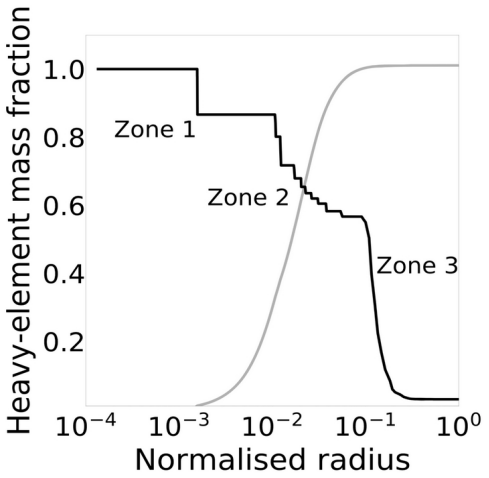
Introduction



Cloutier (2024)

Introduction: Composition Gradients

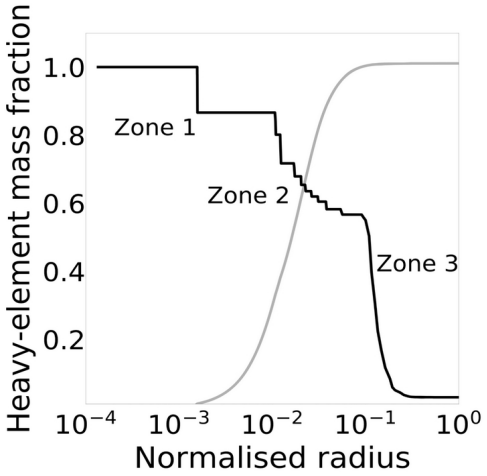
Formation



Valletta & Helled (2022)

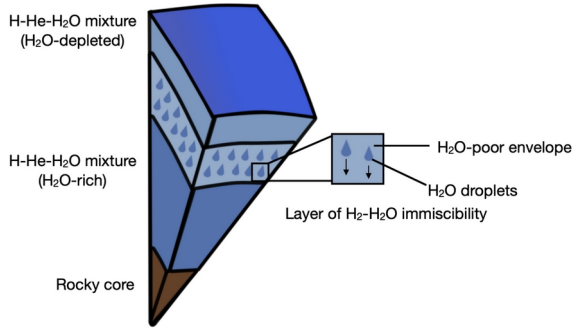
Introduction: Composition Gradients

Formation



Valletta & Helled (2022)

Evolution



Cano Amoros et al. (2024)

Introduction: Composition Gradients

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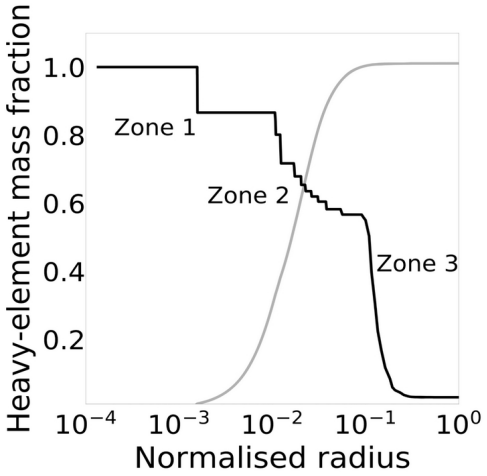

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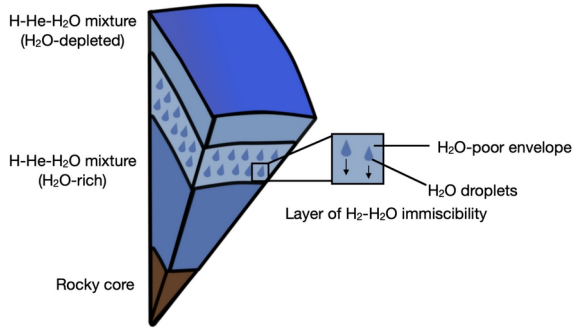
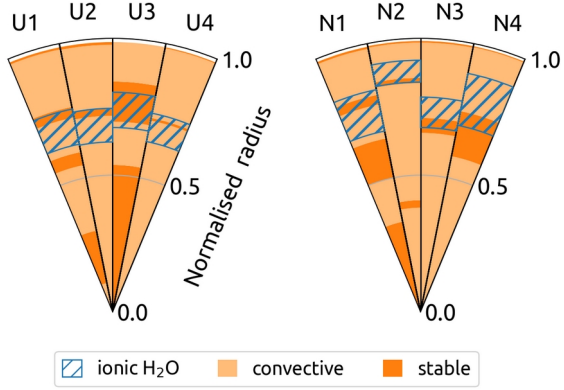


Cano Amoros et al. (2024)

Interior Models



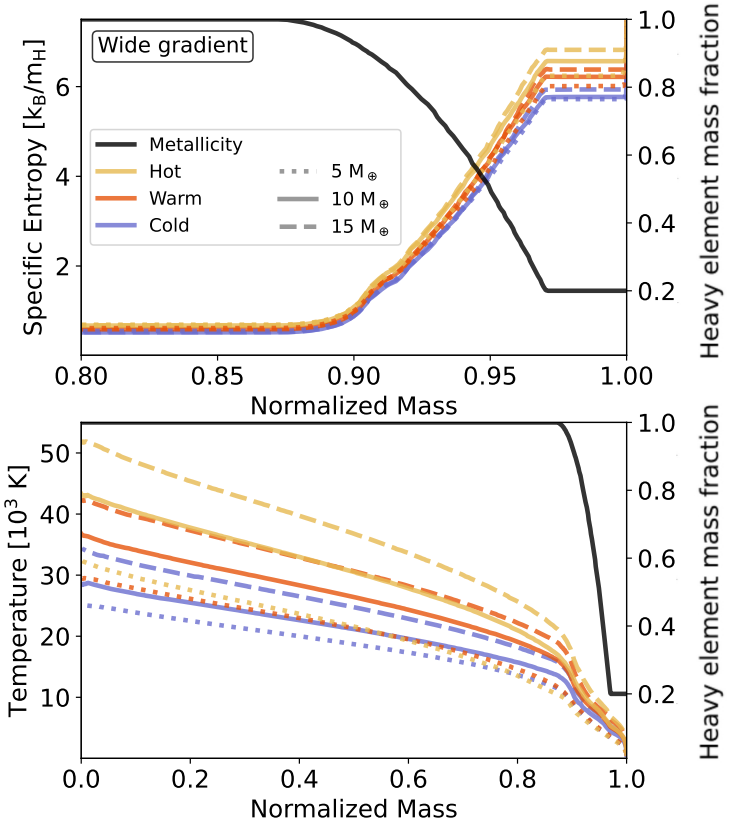
Morf & Helled (2025)

Introduction: Non-Convective Layers

Planets are probably not completely convective

➡ Thermal transport depends on the thermal conductivity

- How does a non-convective layer affect the evolution?
- How important is the assumed conductivity?



Mass:

5, 10, 15 M_{Earth}

Initial Central Entropy:

0.5, 0.6, 0.7 k_B/m_H

Equilibrium Temperature:

400 K

Composition:

Z_{Bulk}=0.95, Z_{env}=0.20, water/rock=1

Methods: Planet Evolution

MESA[1]: Stellar Structure equations

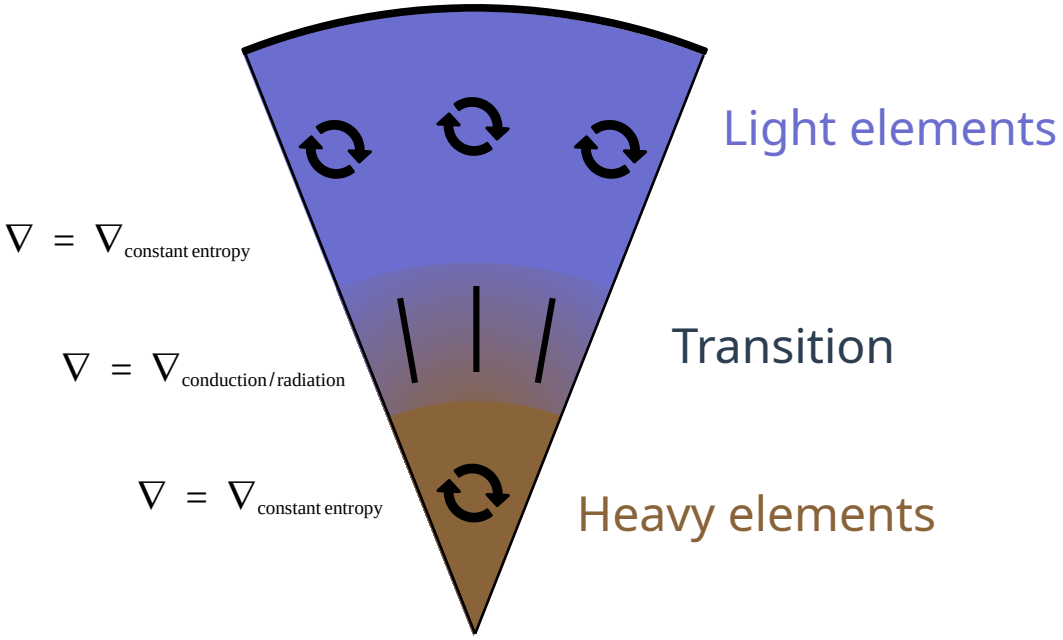
$$\frac{\partial r}{\partial m} = \frac{1}{4\pi r^2 \rho}$$ mass conserv.

$$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4}$$ momentum conserv.

$$\frac{\partial l}{\partial m} = -T\frac{ds}{dt}$$ energy conserv.

$$\frac{\partial T}{\partial m} = \frac{\partial P}{\partial m}\frac{T}{P}\nabla$$ energy transport

$$\frac{\partial X_i}{\partial t} = -\frac{\partial F_i}{\partial m}$$ material transport



[1] Modules for Experiments in Stellar Astrophysics (MESA) (Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023)

Methods

Energy transport (non-convective)

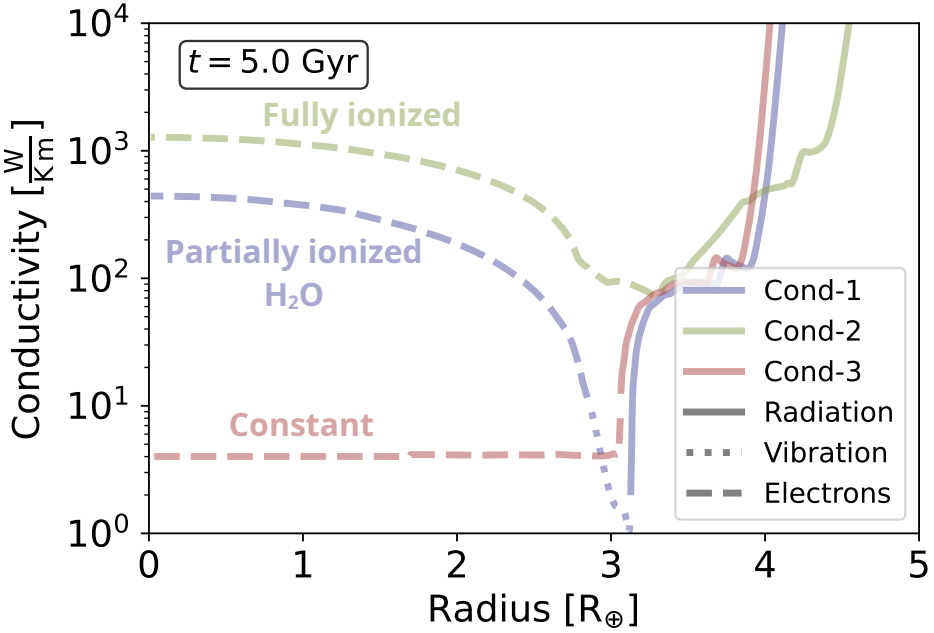
$$\frac{\partial T}{\partial m} \propto \frac{l}{r^4 \rho\, k}$$

$$k = k_{\text{radiation}} + k_{\text{vibration}} + k_{\text{electron}}$$

Conductivity	$k_{vibration}$	k_{electron}
Cond-1	H_2O[1]	Partially ionized H_2O[2]
Cond-2	-	Fully ionized[3]
Cond-3	-	Constant $k_{\text{electron}} = 4$ W/m/K

References:
[1] French & Redmer (2017), [2] French (2019), [3] Cassisi et al. (2009)

Methods



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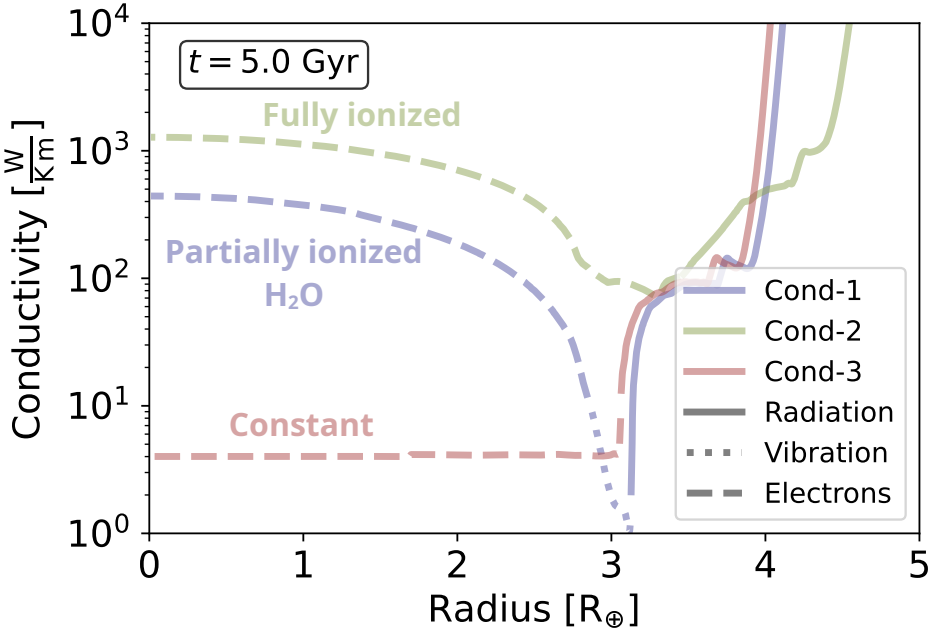
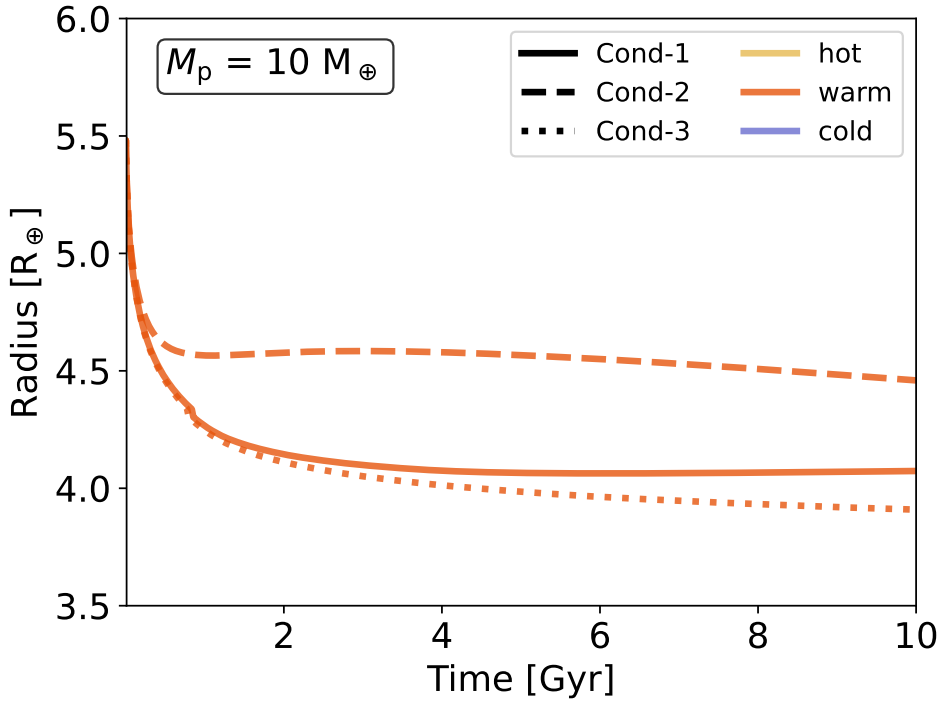
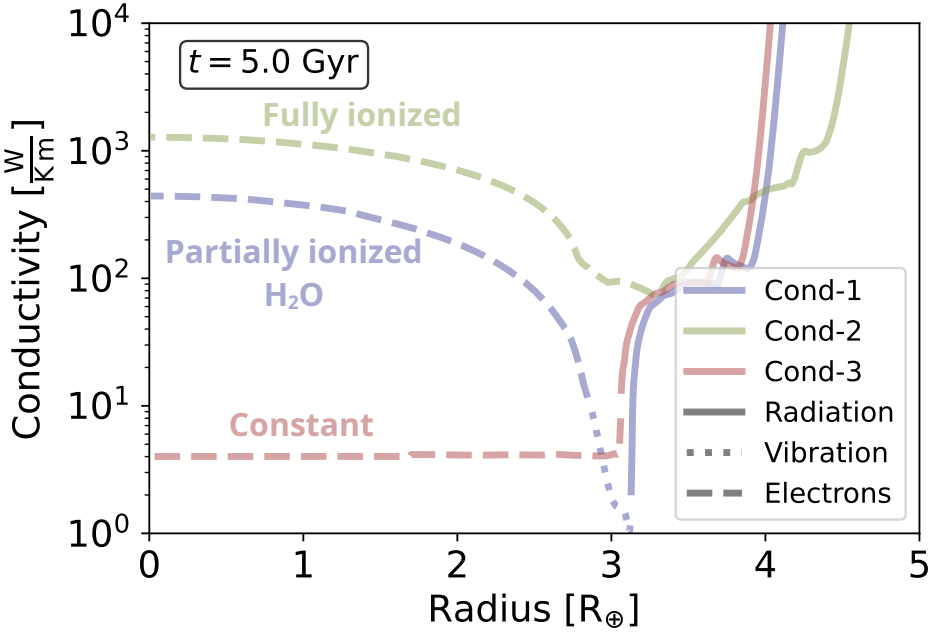
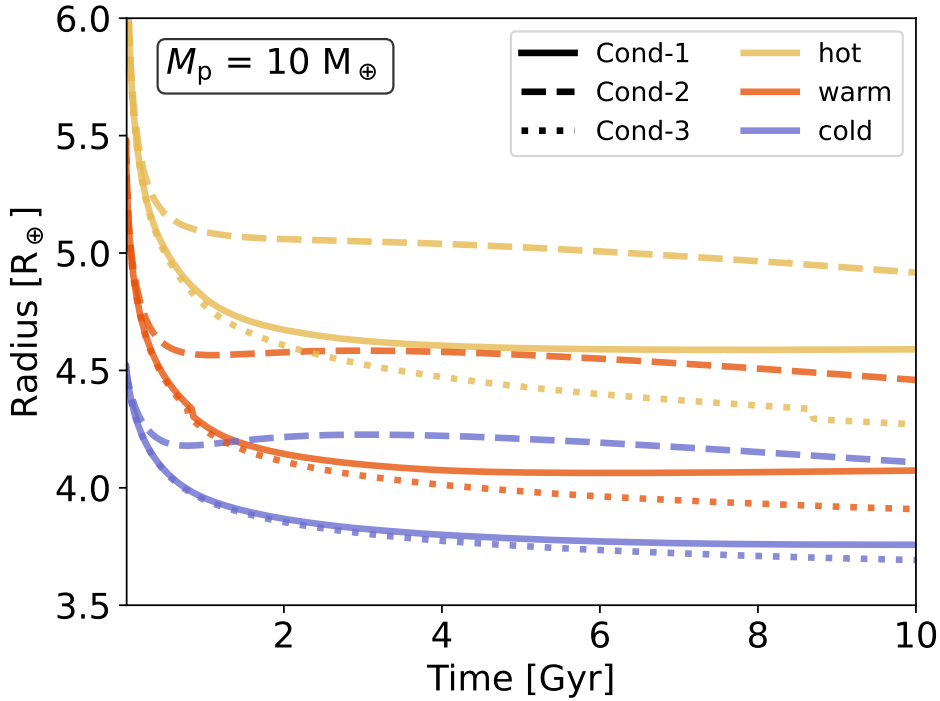
Results: Radius Evolution





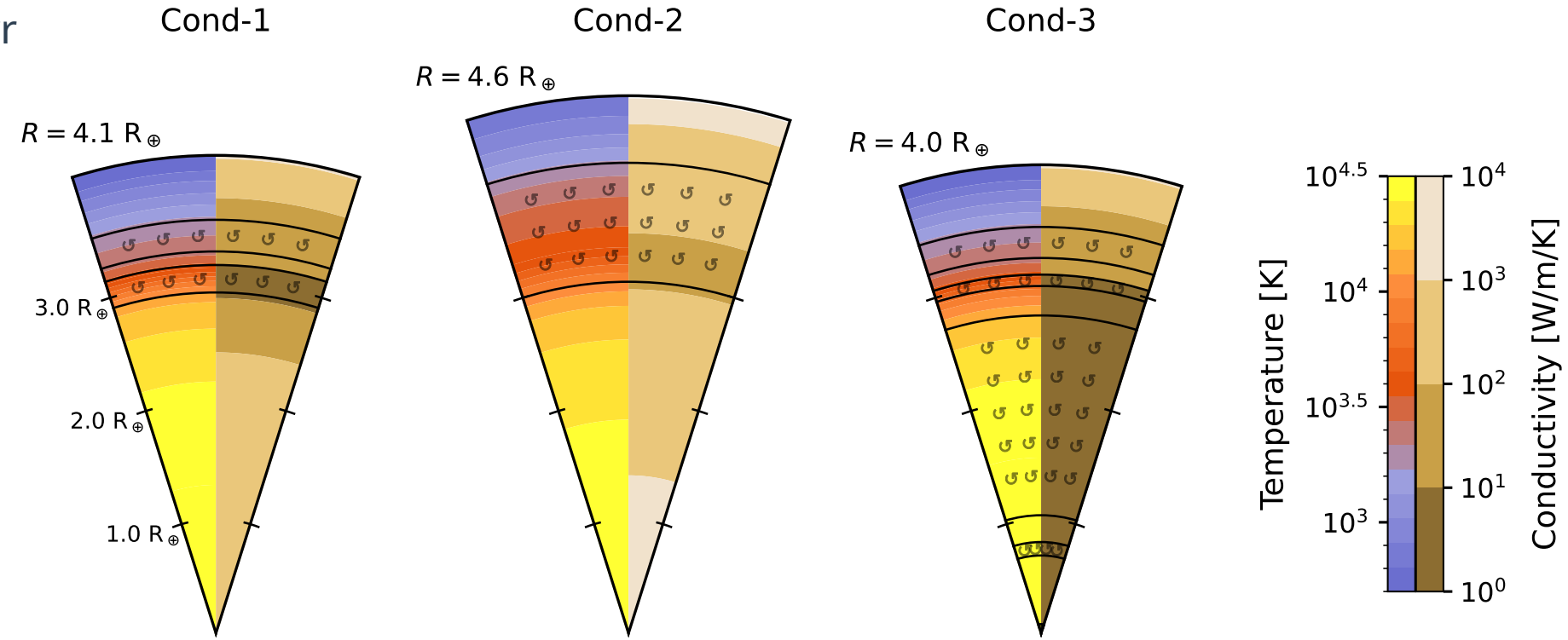
Results: Radius Evolution





Results: Temperature profiles

t=5 Gyr

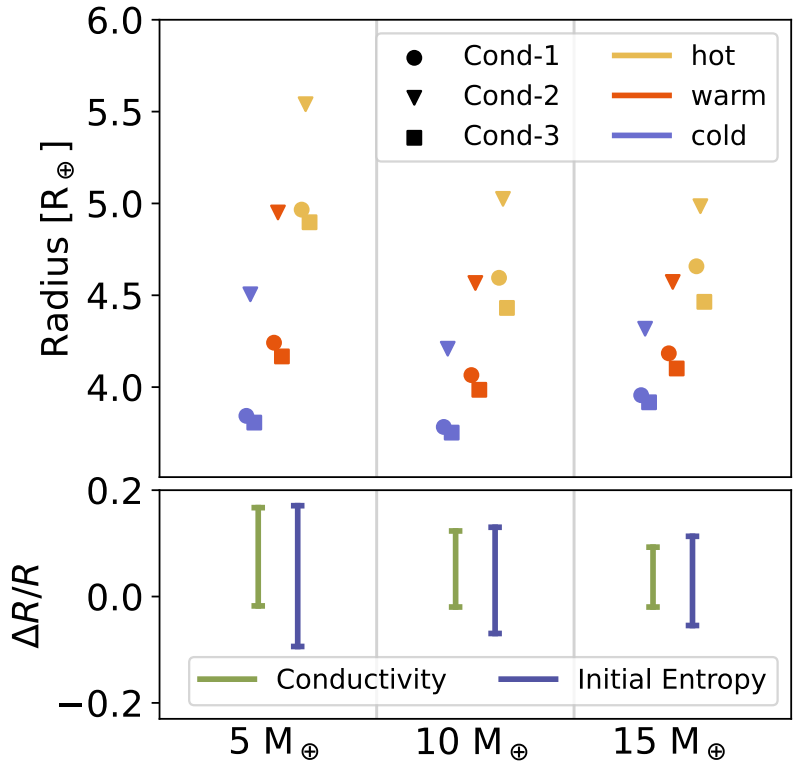


see also Scheibe et al. 2021

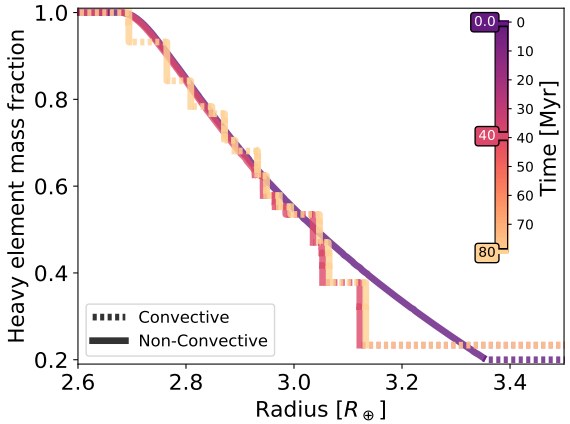
Results: Summary

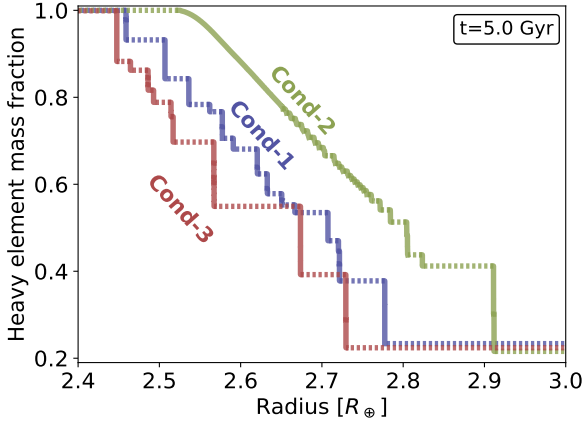
Radius depends on

- Conductivity
- Initial entropy



Convective Mixing





The composition profile is not fixed!

- mixing erodes the composition gradient
- Stair case → higher energy transport

- Final composition profile depends on:
  - Conductivity
  - Initial entropy

Work in progress

Summary

Results

Radius depends on

see Eberlein & Helled 2025 (arXiv:2509.04564)

- Conductivity
- Initial entropy

Convective Mixing

 Eberlein & Helled 2026, in revision

- Conductivity & entropy influence stability
- Radius depends on composition profile

Conclusion

The radius evolution is uncertain and improvements are needed:

- Material properties:

  What's the conductivity of various mixtures?

- Post formation:

  How hot do planets form?

  What's the initial composition profile?