The interplay of Evolution and Water Sequestration

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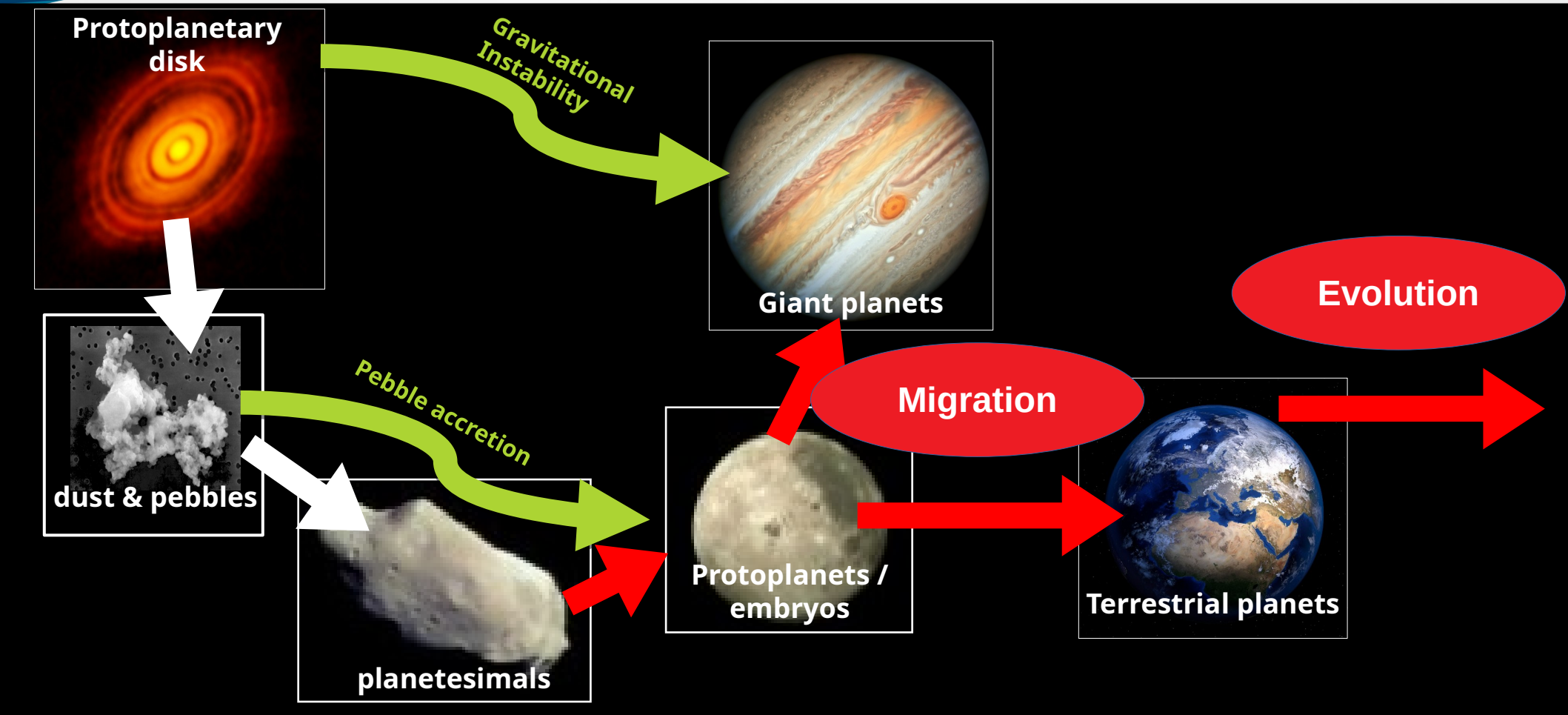
Layers of Understanding

MPIA Heidelberg

Planet Formation



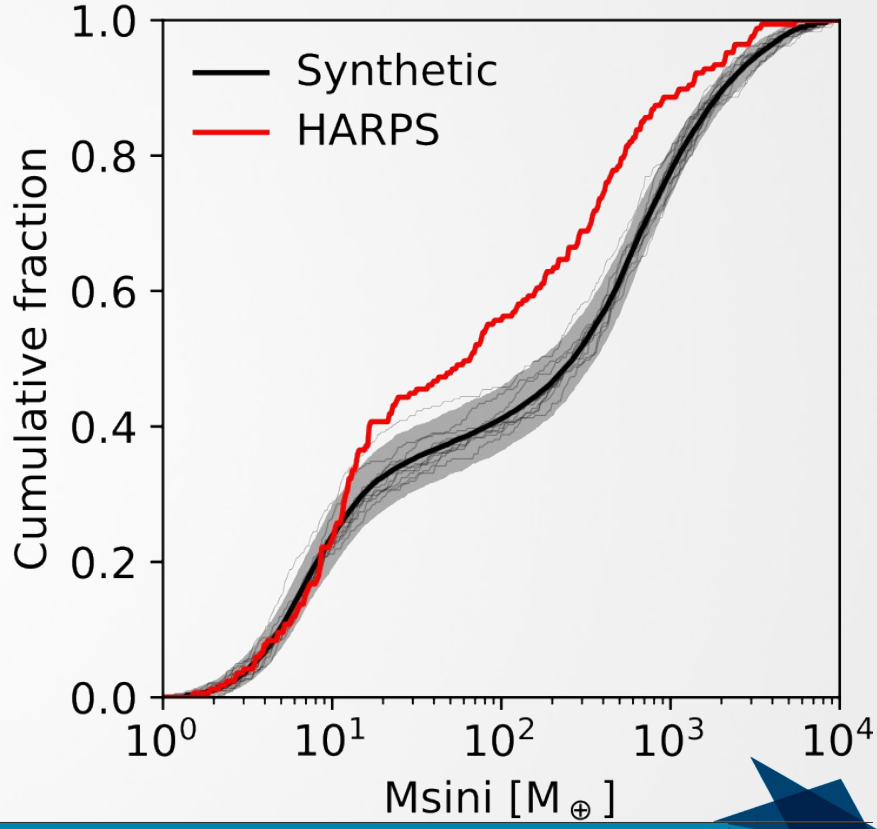
Methods: Formation

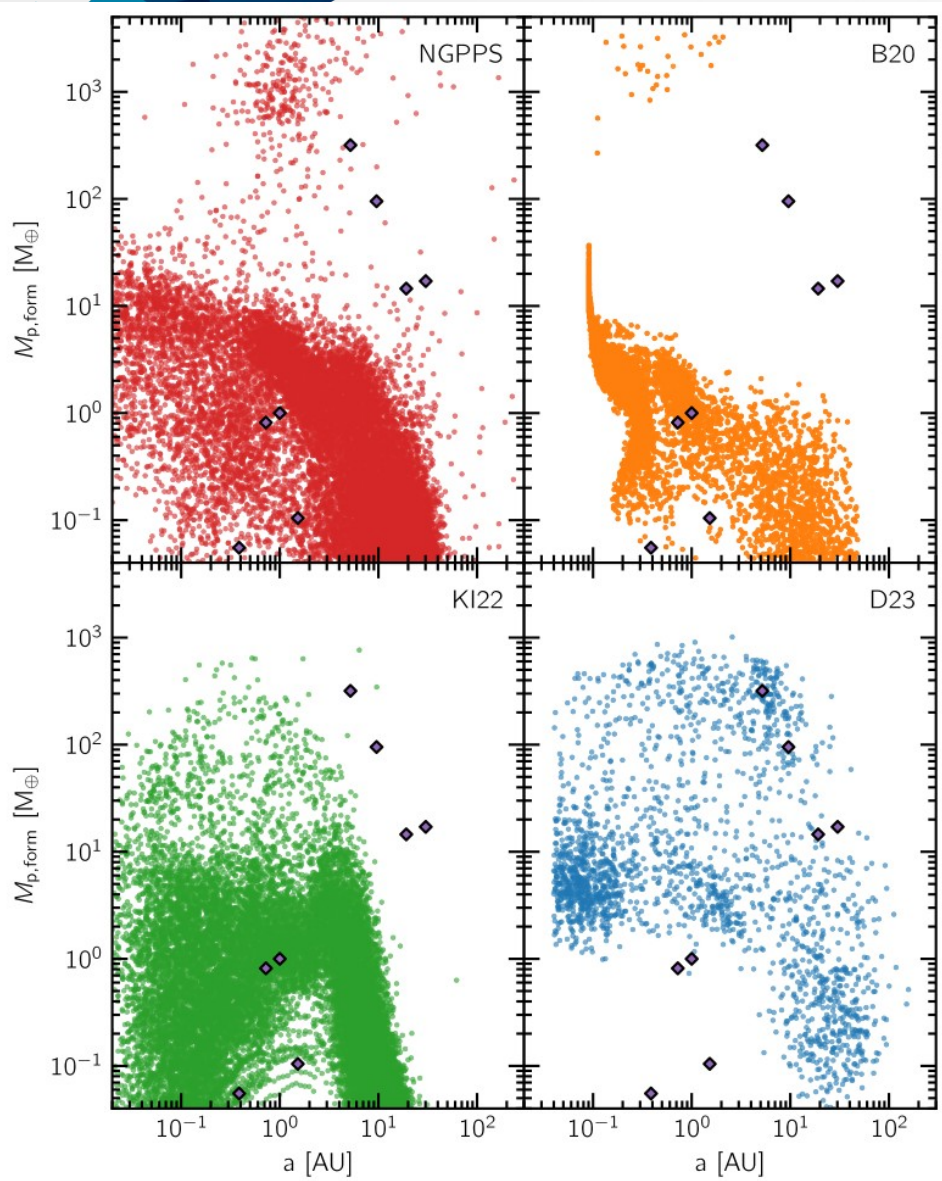
- Start with already formed, small planetesimals (300m) and moon-sized embryos in smooth disks
  - Tuned planetesimal size
- Initial conditions from disk observations
- Migration included
- Single stars
- Dust opacity in envelopes reduced
  - Motivated by grain growth (Mordasini 2014)

Emsenhuber+ 2021 (a,b), 2025
Schlecker+ 2021 (a,b)
Burn+ 2021

New Generation Planetary Population Synthesis

- Comparison to HARPS reveals relatively good match
  (Emsenhuber et al., 2025)
  - Absolute number of planets too high in population
  - Slightly too massive and numerous giants

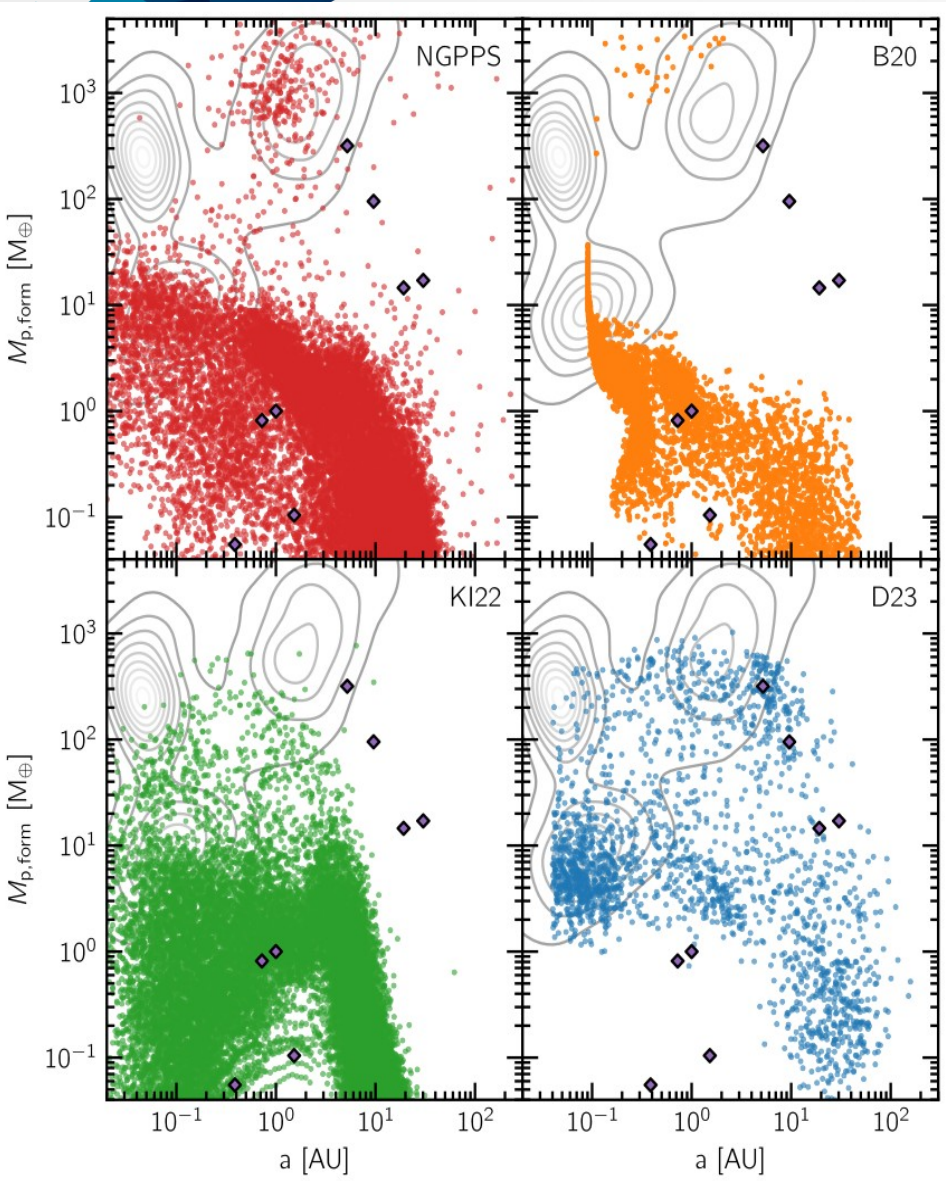




Population Synthesis Review

- In-depth review and comparison of three population synthesis works
  (Burn&Mordasini, Handbook of Exoplanets 2024)

References: Brugger+2020, Kimura&Ikoma 2022, Drazkowska+2023 (PPVII)



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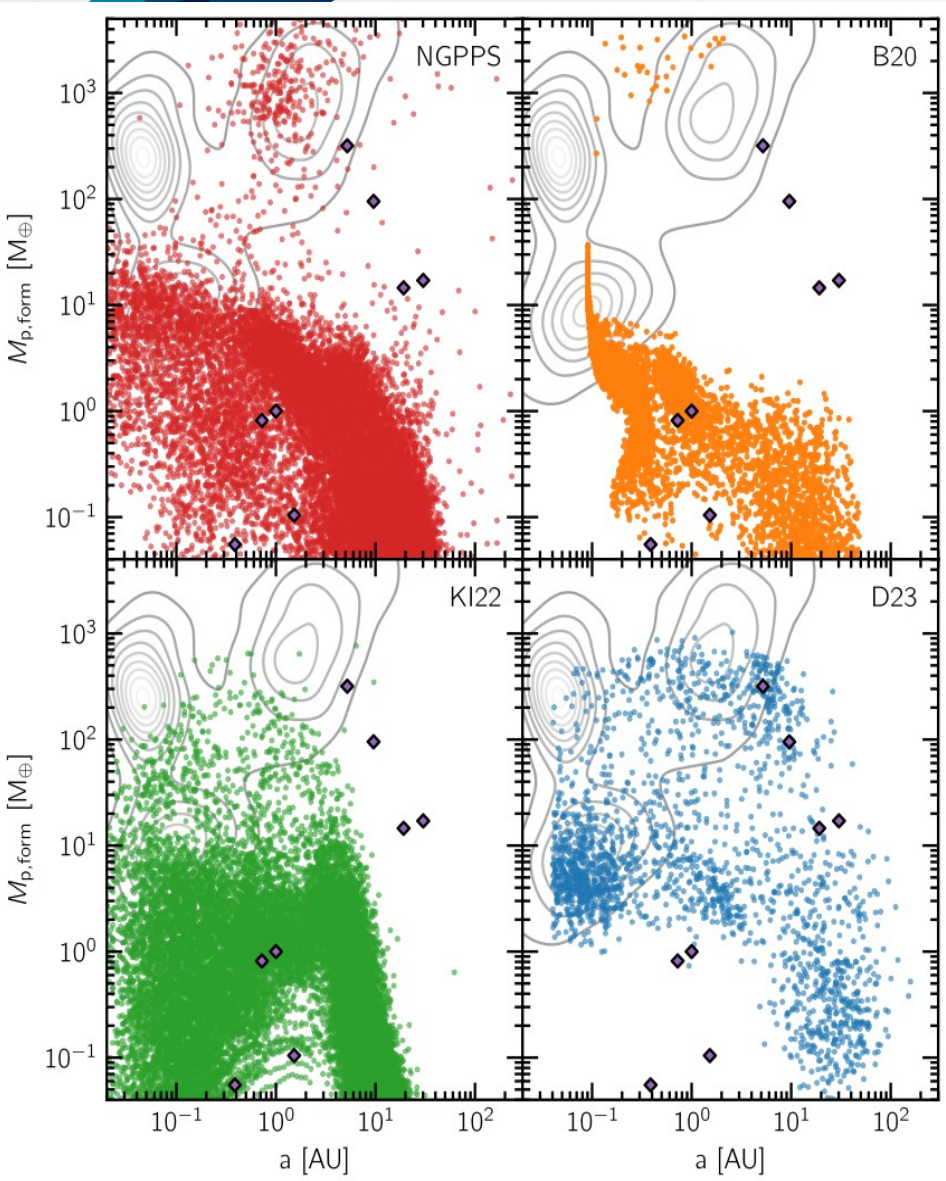
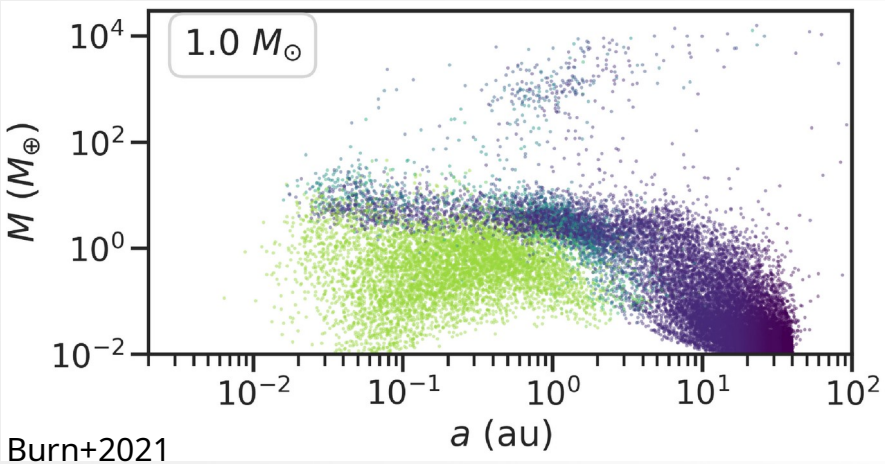


Population Synthesis Review

- In-depth review and comparison of three population synthesis works
  (Burn&Mordasini, Handbook of Exoplanets 2024)
- No perfect match to observations
- Differing approaches to viscosity
  - Relevant for migration and disk evolution

References: Brugger+2020, Kimura&Ikoma 2022, Drazkowska+2023 (PPVII)

a-M distribution

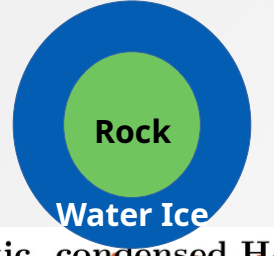


Burn+2021

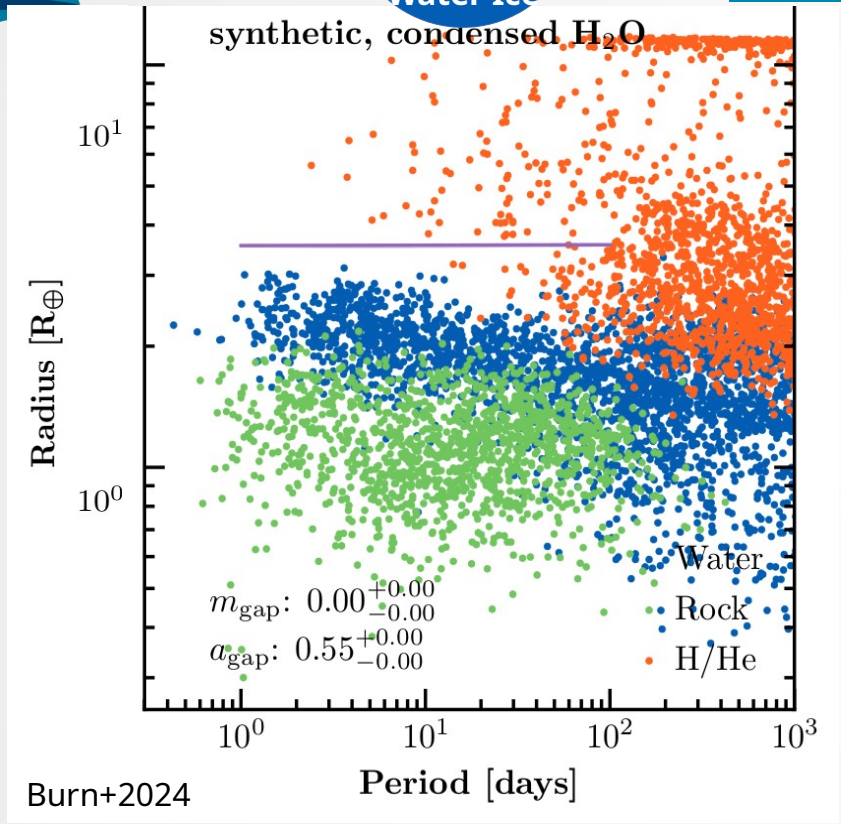
- Migration leads to water-rich planets interior to the iceline
  - Classical planet formation result
    (Mordasini+2009, Ida+2013, Raymond+2018, Bitsch+2019, Izidoro+2022)
  - Around 30% H_2O by accreted mass

Methods: Evolution

- Stellar evolution
  - In bolometric and X-ray/EUV luminosities
- Photoevaporation: Hydrodynamic regime, driven by XEUV irradiation
  (Kubyshkina+2018, Kubyshkina&Fossati 2021, Johnstone 2020)
- Metallicity (Z)-dependent molecular opacities (Freedman+2014)



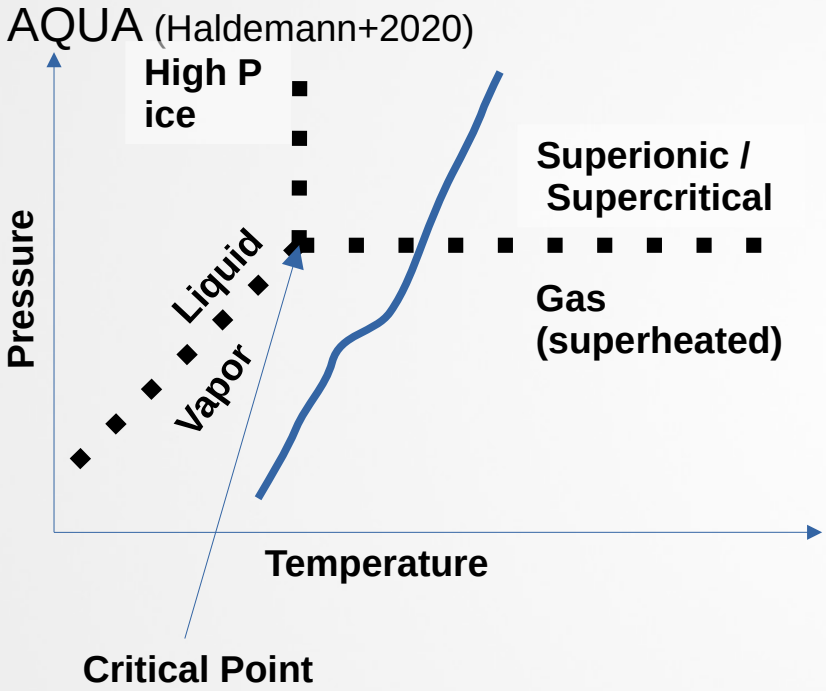
Radius Gap between Steam and Rock



Burn+2024

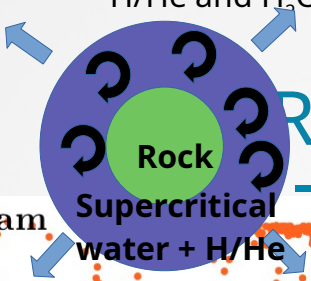
- Previously, water was usually treated as ice in population studies
  (e.g. Jin & Mordasini 2018, NGPPS Emsenhuber+21/Burn+2021)
- Ice worlds populate radius valley

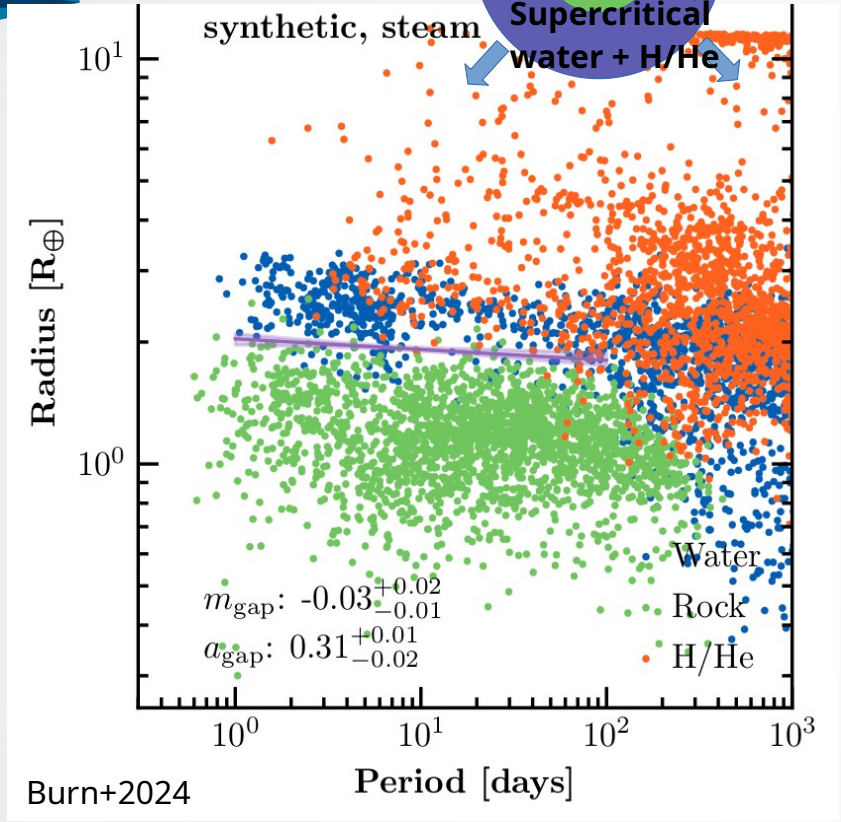
Radius Gap between Steam and Rock



- But observed planets are hot
  - Closer to star than runaway greenhouse (e.g. Boukrouche+2021)
- For hot sub-Neptunes, expect vapor and supercritical phases for water (Turbet+2020, Zeng+2019/2021, Mousis+2020, Venturini+2020)
  - Supercritical fluids are highly miscible

Radius Gap between Steam and Rock





Burn+2024

- Steam worlds in statistical agreement with observations

Burn+2024

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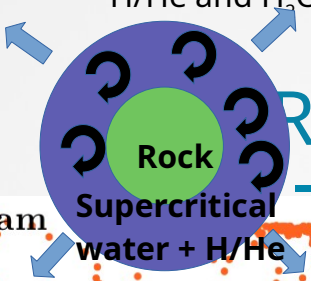

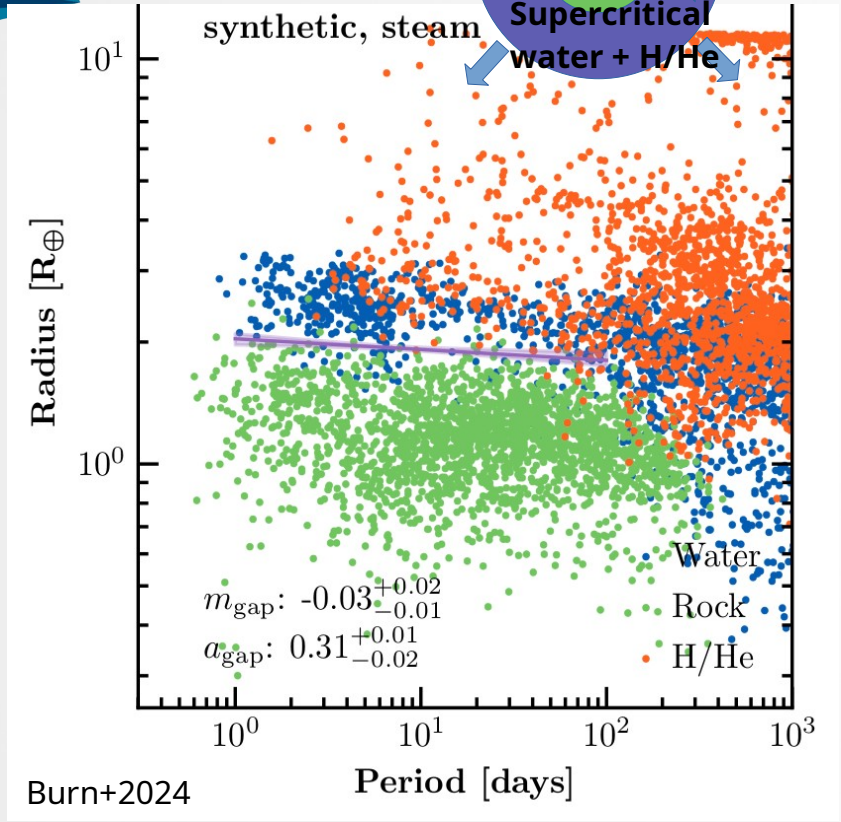

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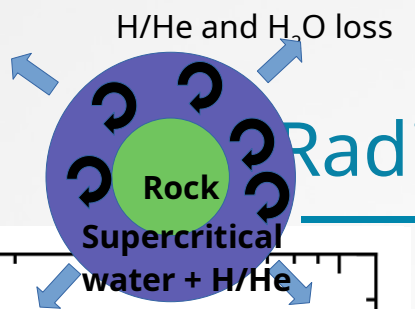

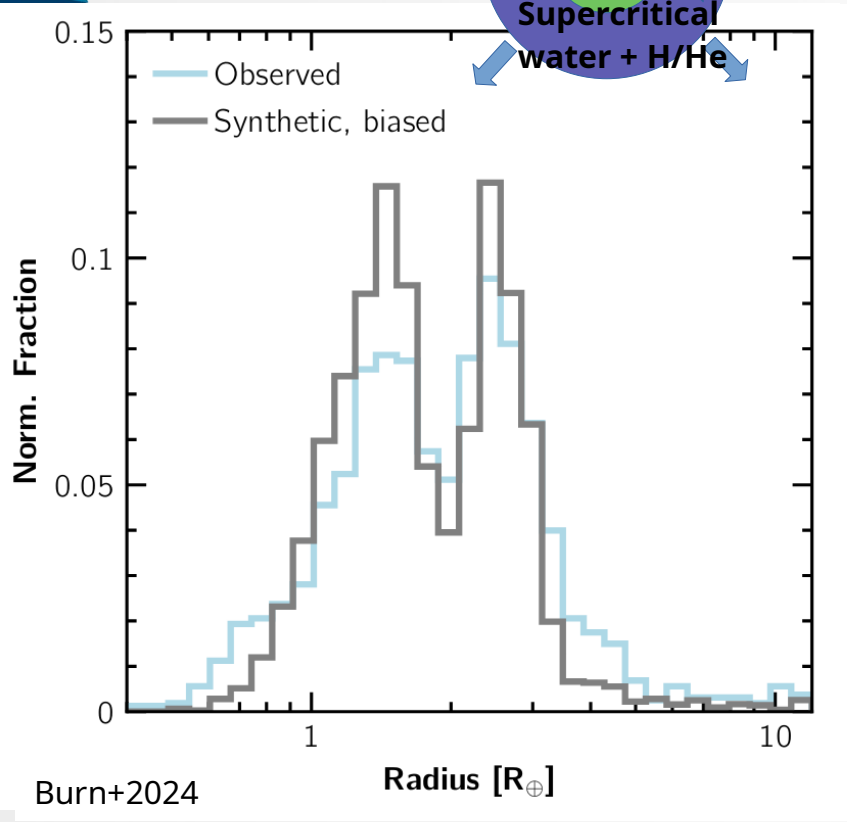

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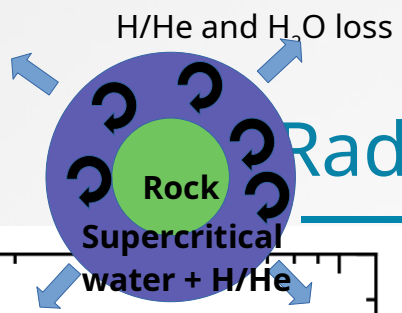
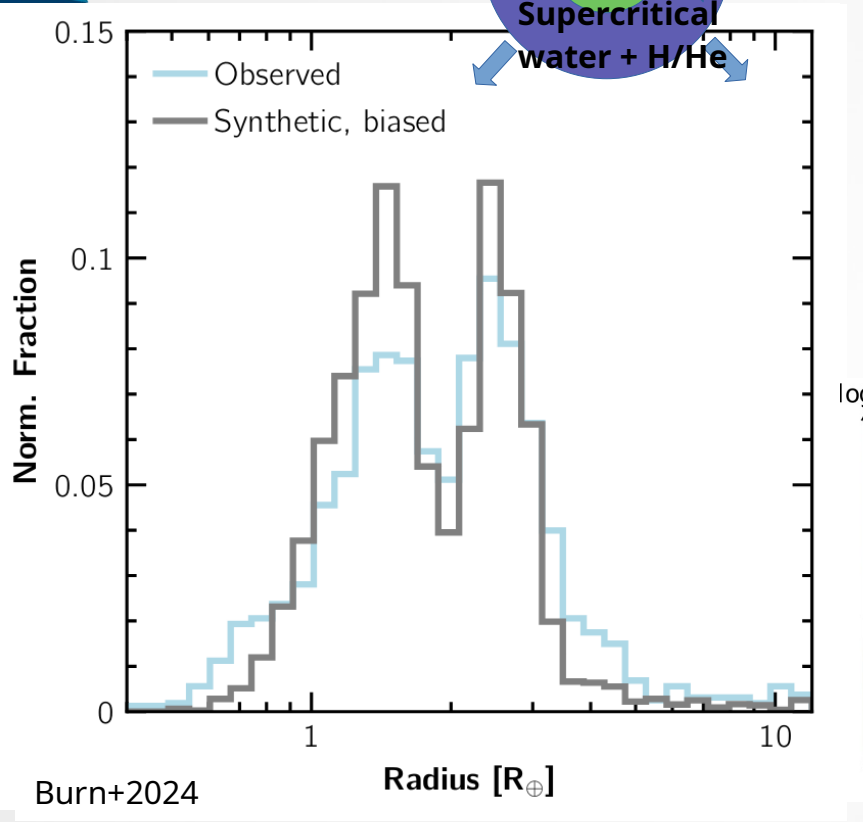
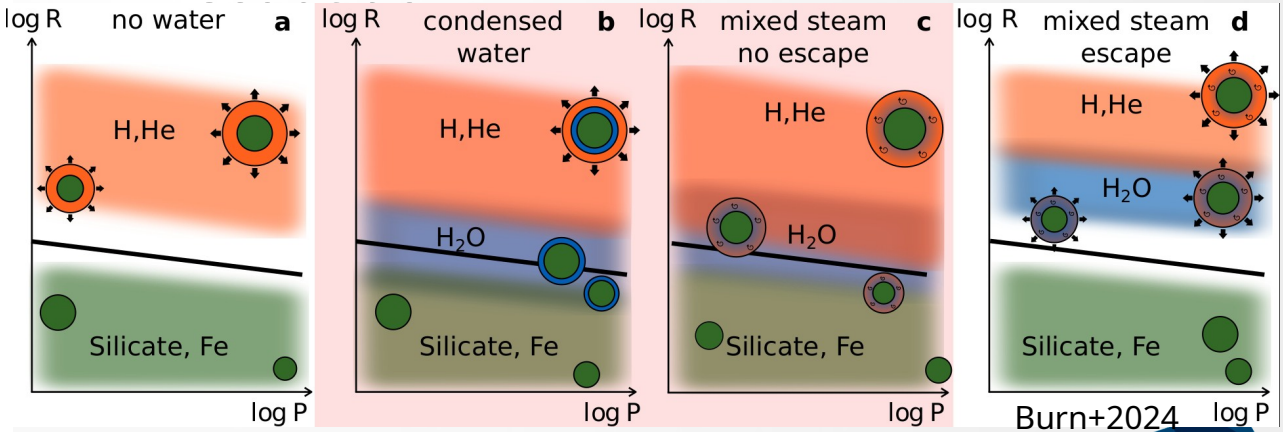




Burn+2024

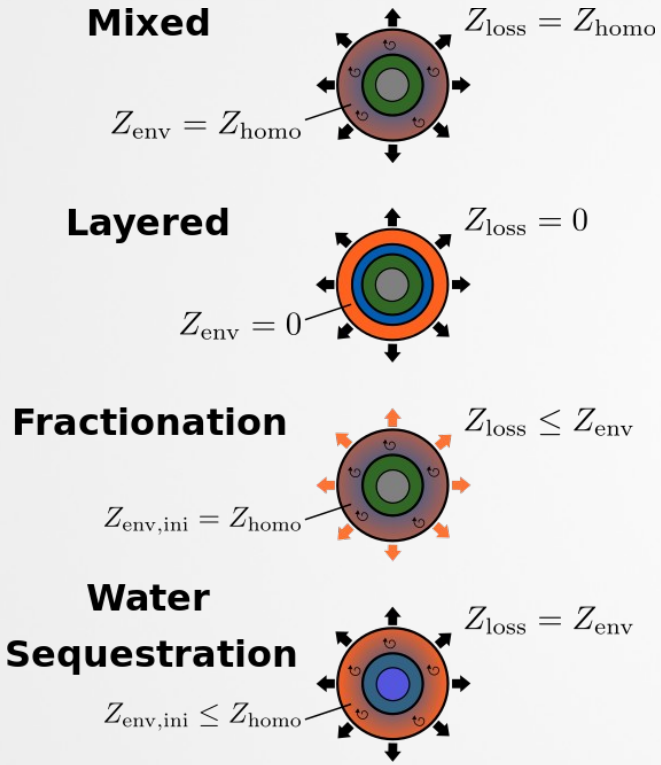
- Steam worlds in statistical agreement with observations
- Provides an alternative to dry



Burn+2024

Burn et al., subm
https://arxiv.org/abs/2411.16879

New Setup



- H/He mass from end of the disk stage
- 4 Scenarios:
  - Mixed
  - Layered: no mixing of H/He and H_2O
  - (Fractionation: Mixed but varied loss of H_2O from H_2 (Zahnle+1990))
  - Water sequestration

Burn et al., subm
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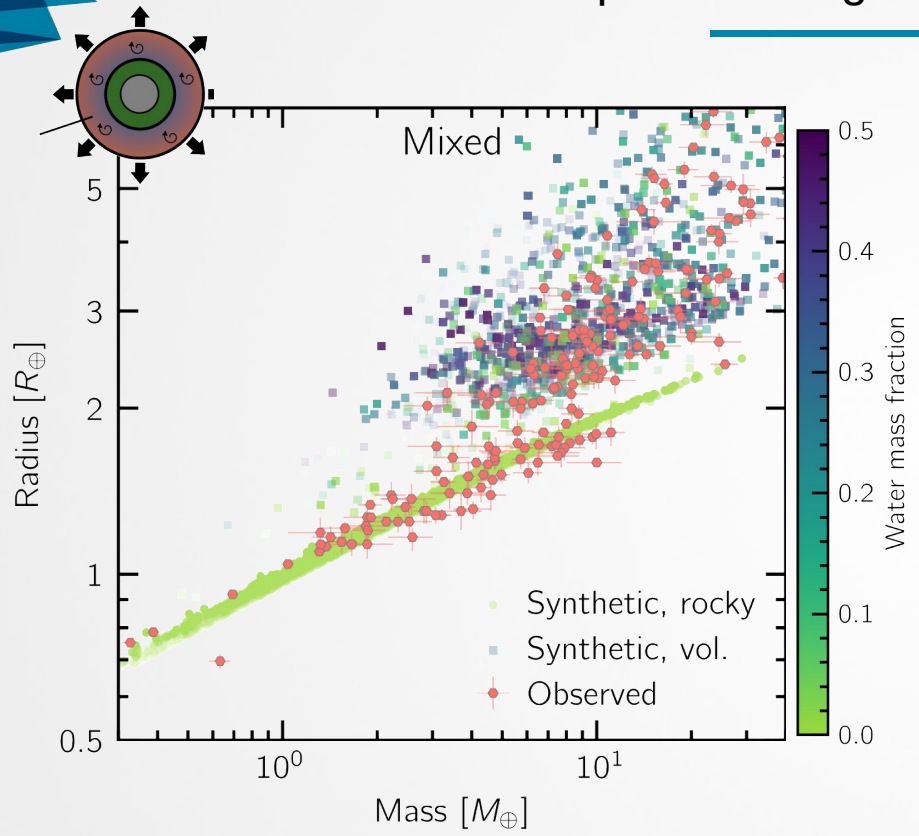
Results: Mass-Radius



- Comparision to Parc+2024 catalogue
  - Attempt at matching bias
  - No homogeneous survey
- Mixed scenario
  - Matches broadly M-R relation

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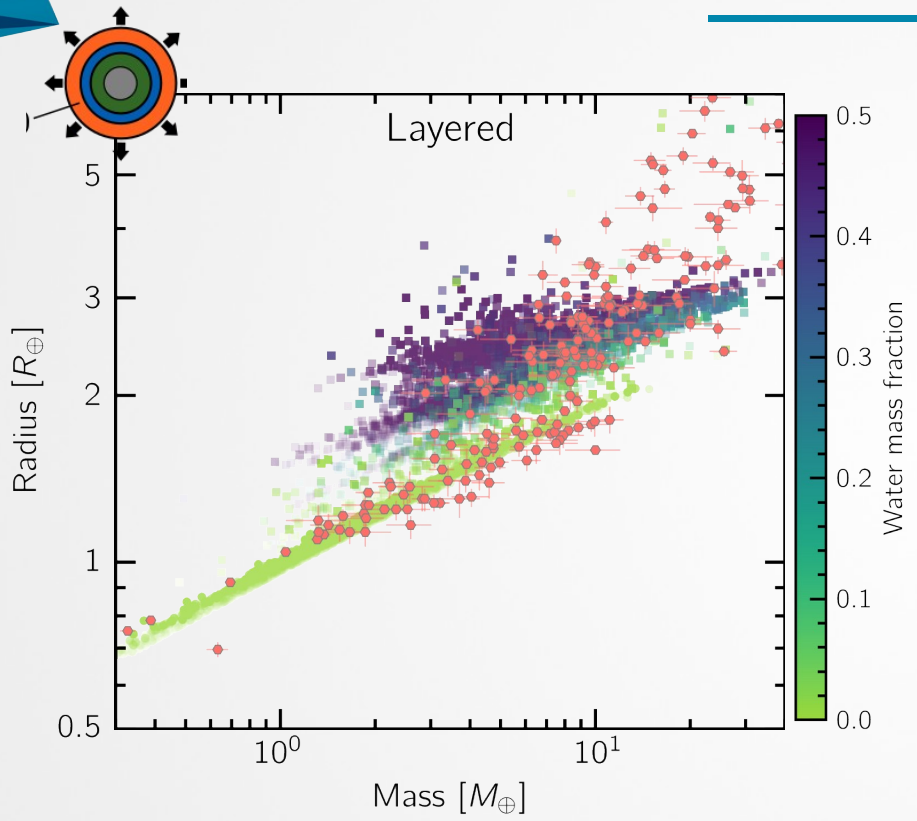

- Comparision to Parc+2024 catalogue
  - Attempt at matching bias
  - No homogeneous survey
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  - Matches broadly M-R relation
- Layered scenario → no match

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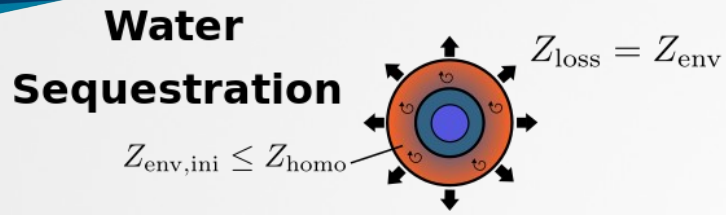
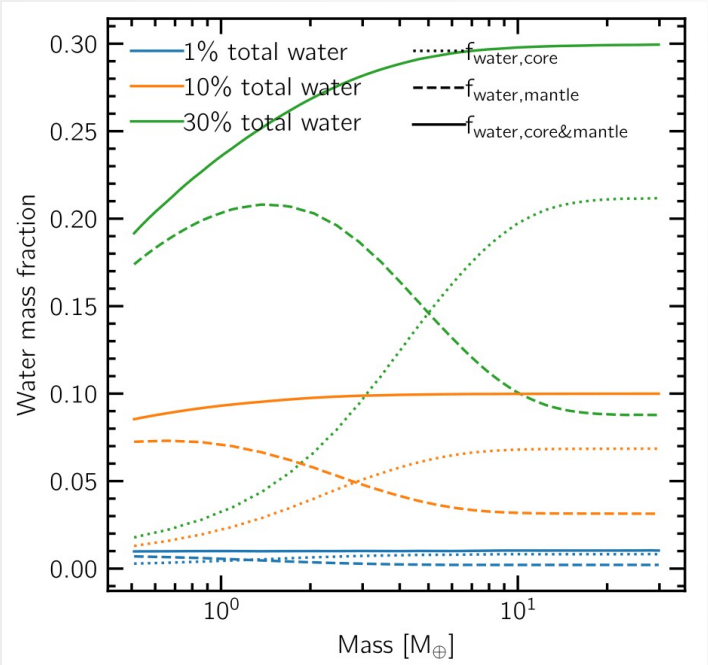
Water Sequestration



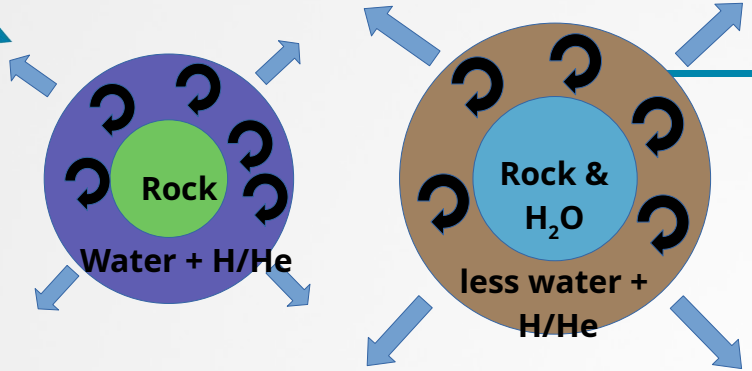


- Assumes continuous presence of magma ocean (made of MgO, SiO_2, FeO)
- Dissolution of water
  - To mantle following Henry's Law (Dorn & Lichtenberg 2021)

$$M_{\rm vol,magma}/(M_{\rm vol,magma} + M_{\rm Rock}) = \alpha P_{\rm B}^{1/\beta}$$

  - To iron core mid-mantle pressures (Luo+2024)
- Atmosphere and complete magma ocean in equilibrium

Water Sequestration



- Initially lower-density
- Higher photoevaporative loss
- Outgassing (equilibrium)
- Smaller H/He + steam worlds
  - Stable against photoevaporation at large orbital periods

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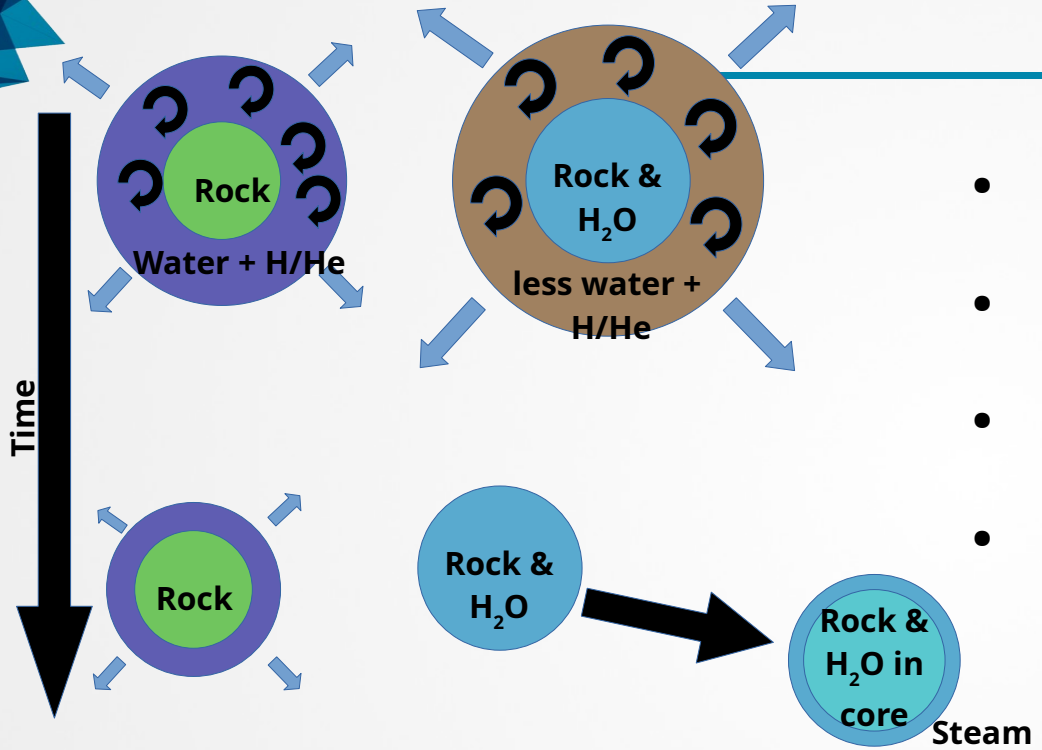

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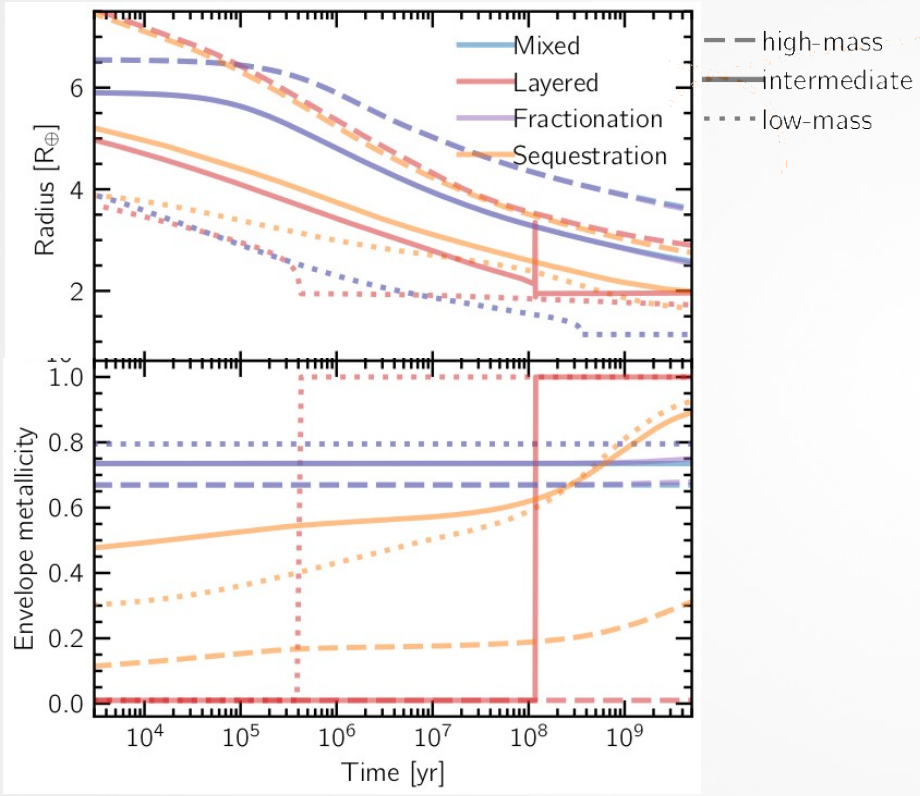

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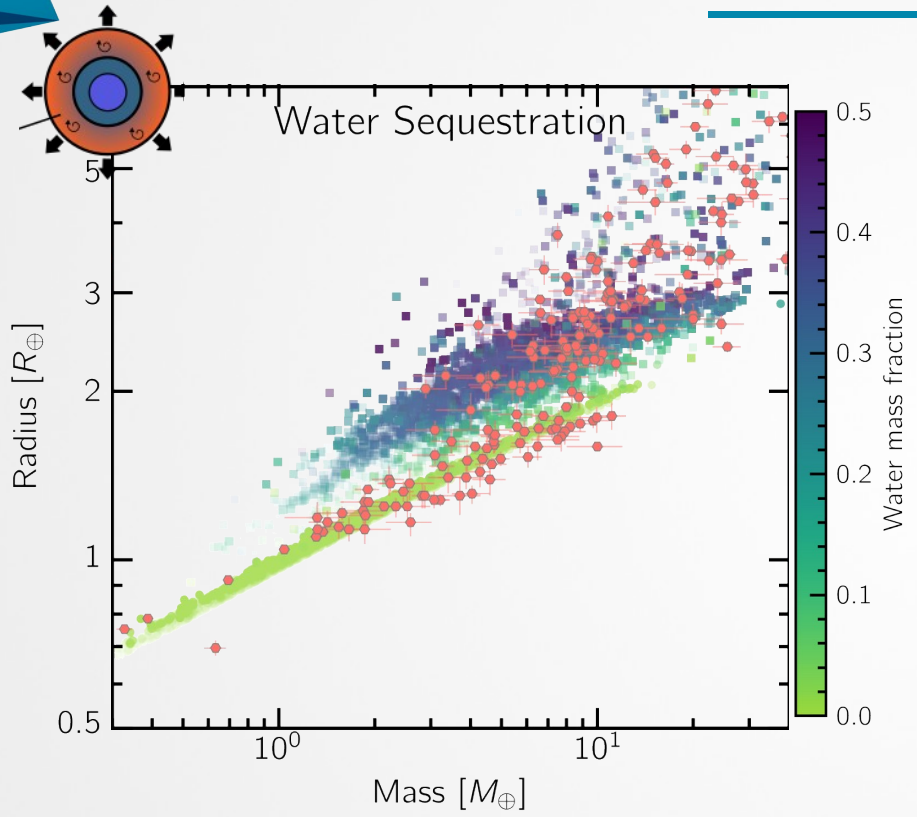

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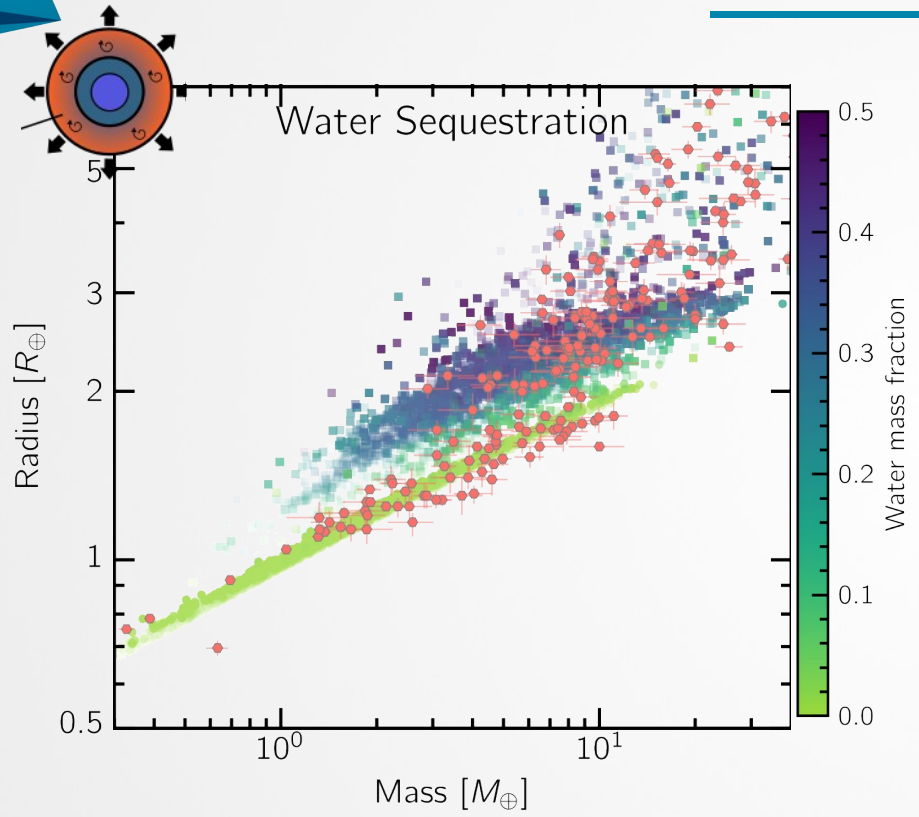

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- Outgassing (equilibrium)
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  - Stable at large orbital periods
  - Stronger ‹cliff›

Burn et al., subm
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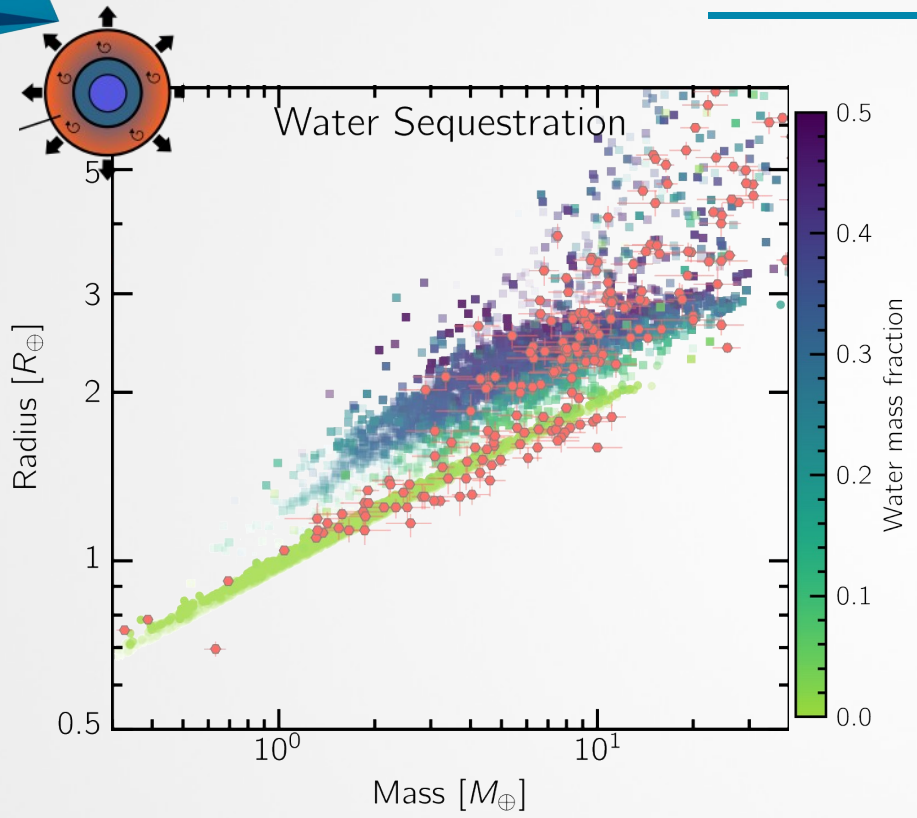

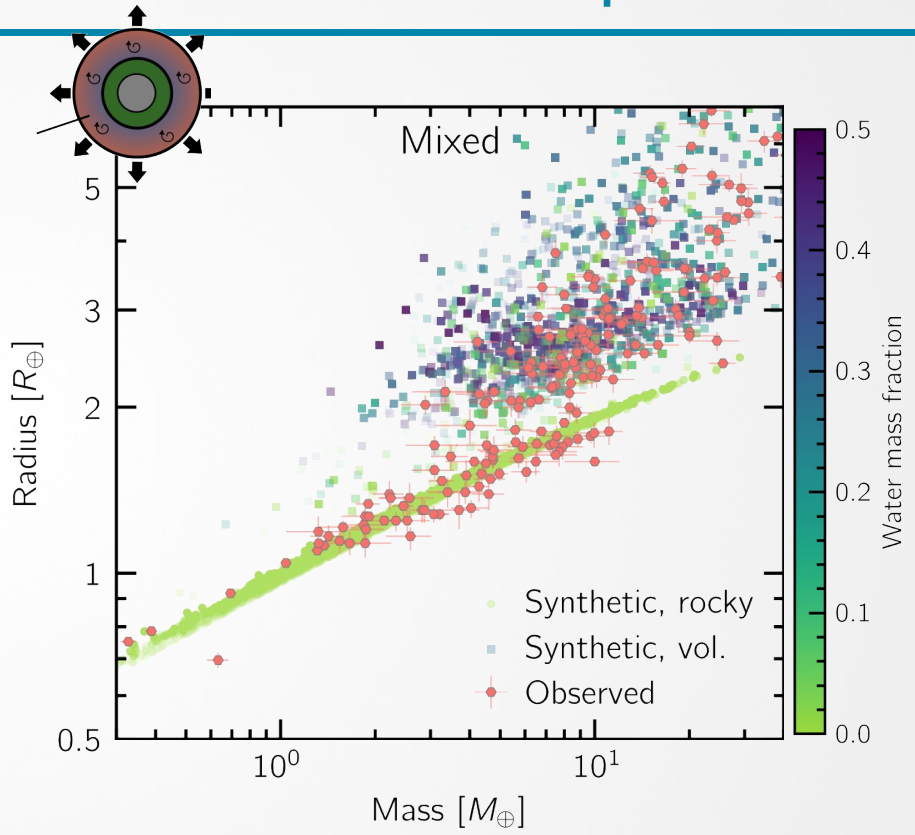

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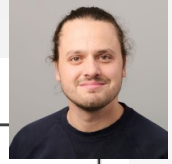
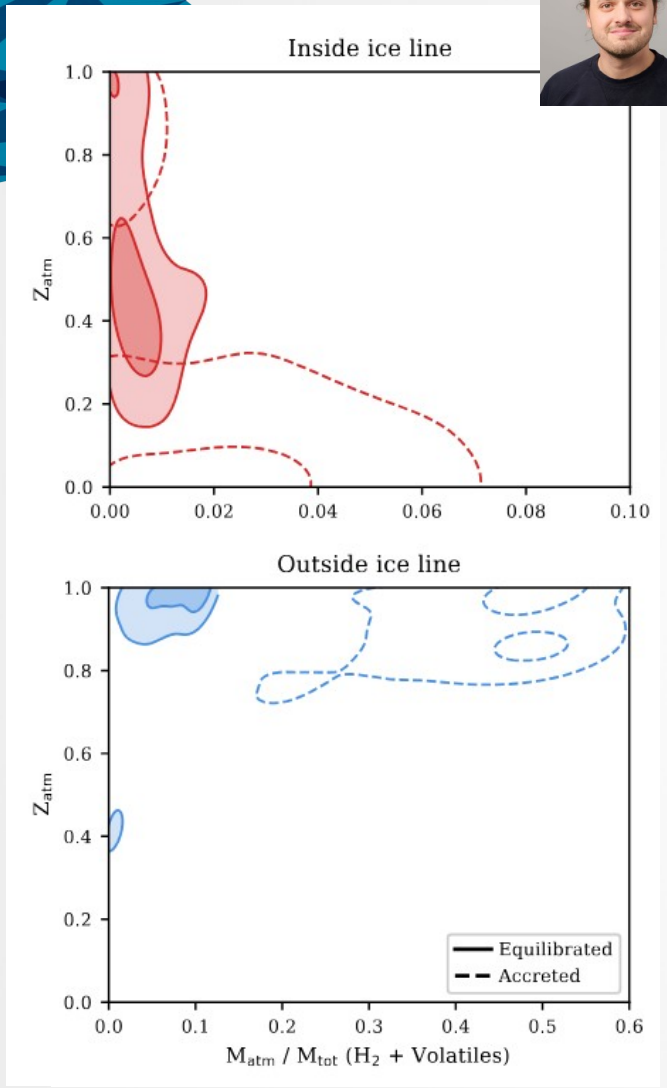
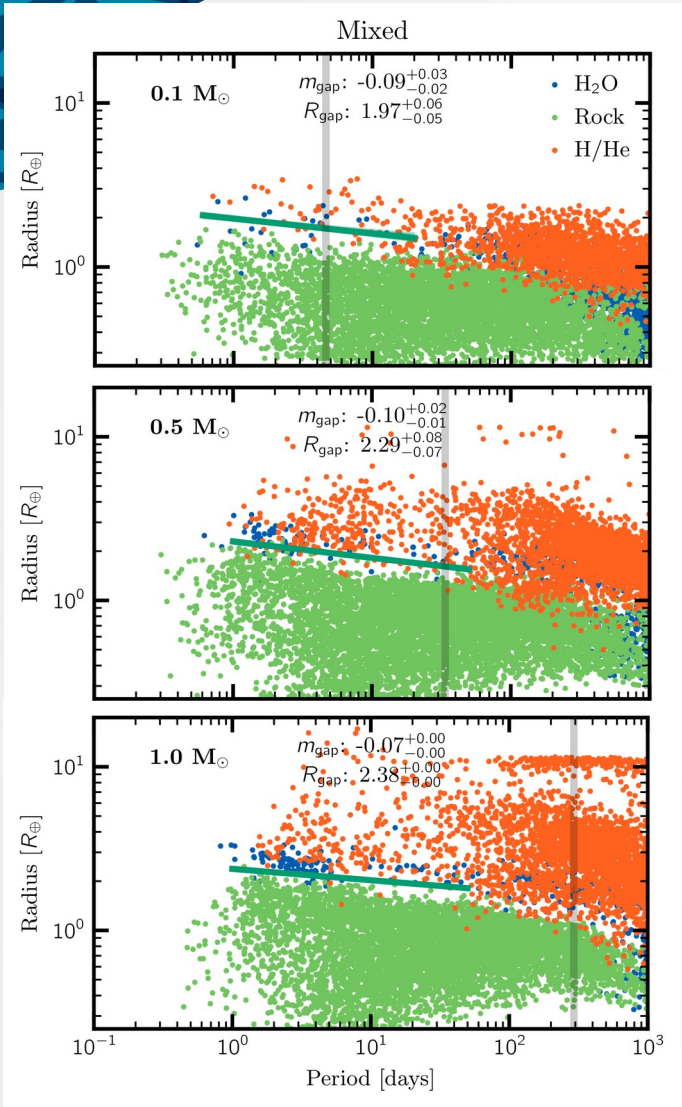




Discussion: Interior-Atmosphere

- Atmosphere and interior state (solidification), heat exchange and chemistry neglected!
- Exploration with equilibrium chemistry
  - For water-rich: O in metallic core & silicate layer
    → Little water in envelope
    → lower atmosphere mass
  - For dry: outgassing of heavies (H_2O, CO, CH_4)

Werlen, Dorn, Burn+, 2025 http://arxiv.org/abs/2507.00765
& Werlen, Burn, +, submitted



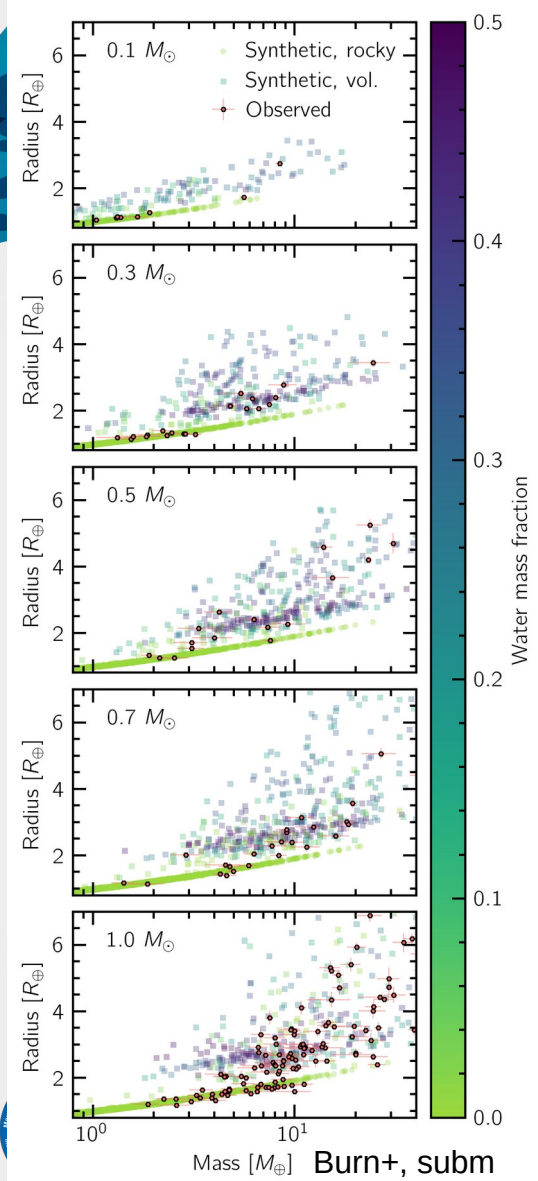
Radius Valley around different Stars

- Radius (density) valley recovered
  - Mixed and Sequestration
- Radius valley for mixed depends on M_{star}
- Not for Sequestration model

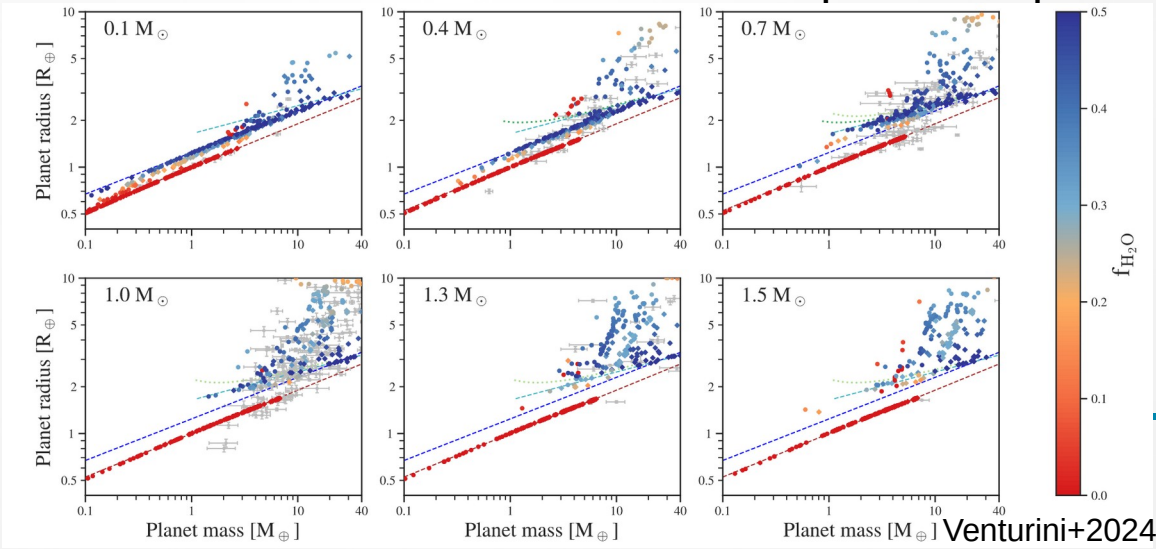
Burn et al., subm
https://arxiv.org/abs/2411.16879

A fading radius valley (Venturini+2024)

- Towards lower stellar masses
  - Mass of migrated planets are smaller (Burn+2021)
  - Water-rich sub Neptunes start populating valley
  - Sensitive to whether photoevaporation

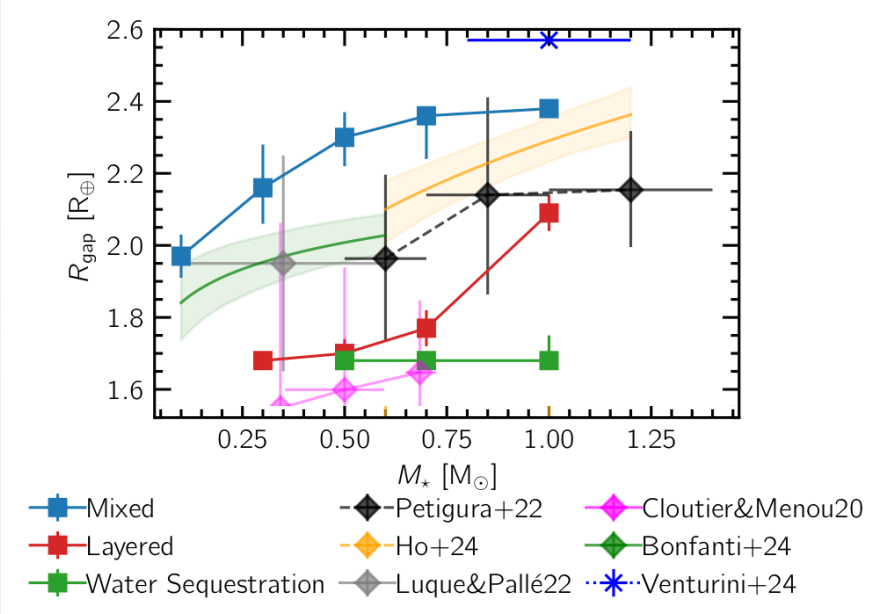


Burn+, subm



Venturini+2024

Radius Valley



- Radius (density) valley recovered
  - Mixed and Sequestration
- Radius valley for mixed depends on M_{star}
- Not for Sequestration model
- R_{gap} within uncertainty

Burn et al., subm
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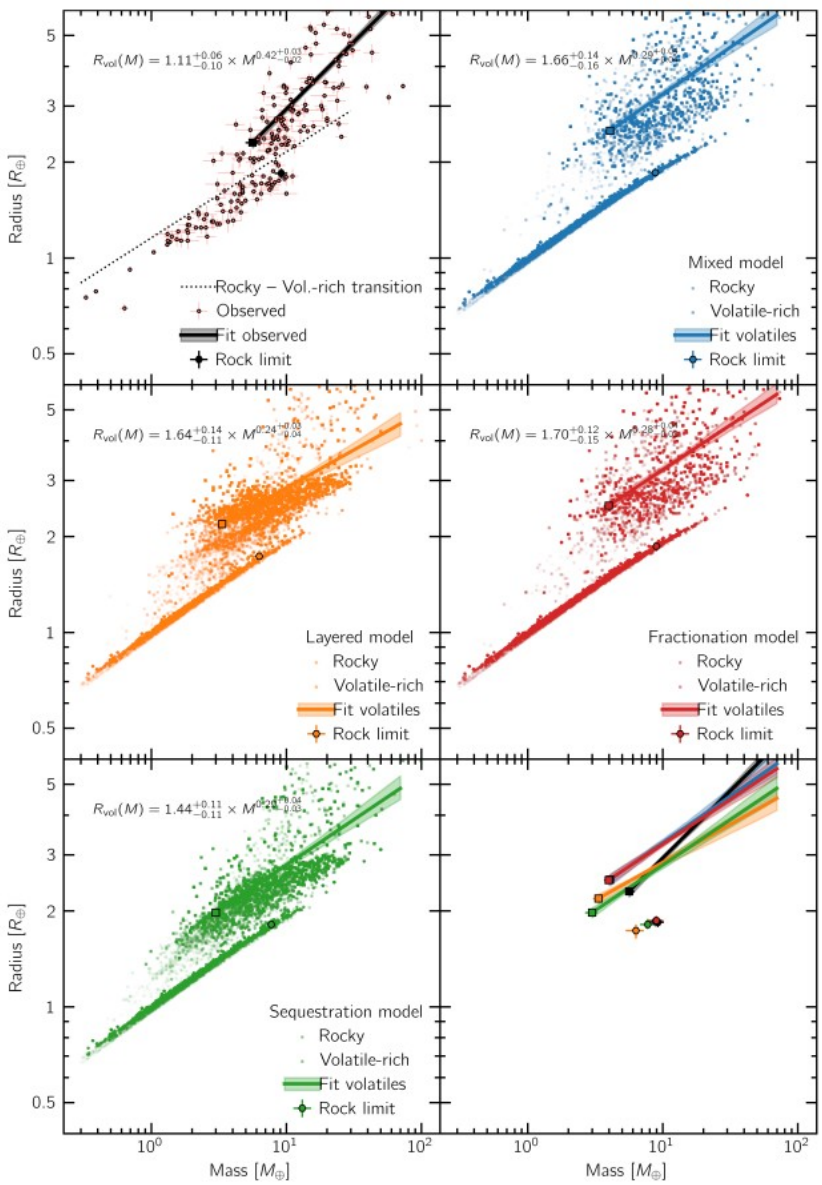
Conclusions

- High water content in evolved atmospheres of sub-Neptunes possible from M-R relations
- Core-dominated planets interact with interior
  - Significant effect from water sequestration
  - Matches only for more massive planets (M>3Mearth)
  - Chemical reactions modify the speciation further

Backup



Mass-Radius discussion

- M-R relation has distinct characteristic points
  - Minimum sub-Neptune mass
    - aaf orbital period
  - Sub-Neptune M-R slope
    - Here typically too shallow
  - Maximum super-Earth rocky mass
    - Aaf instellation if set by photoevaporation