

**Diverging Sub-Neptune Radii from coupled Water
Dissolution in Magma Oceans and Photoevaporation**

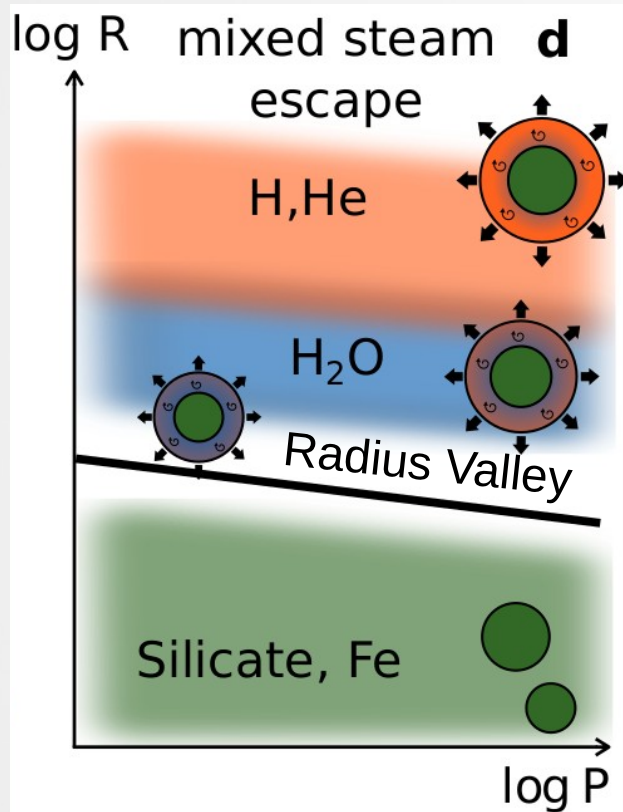
Remo Burn
remo.burn@oca.eu

1st of April 2026

ExoSystèmes

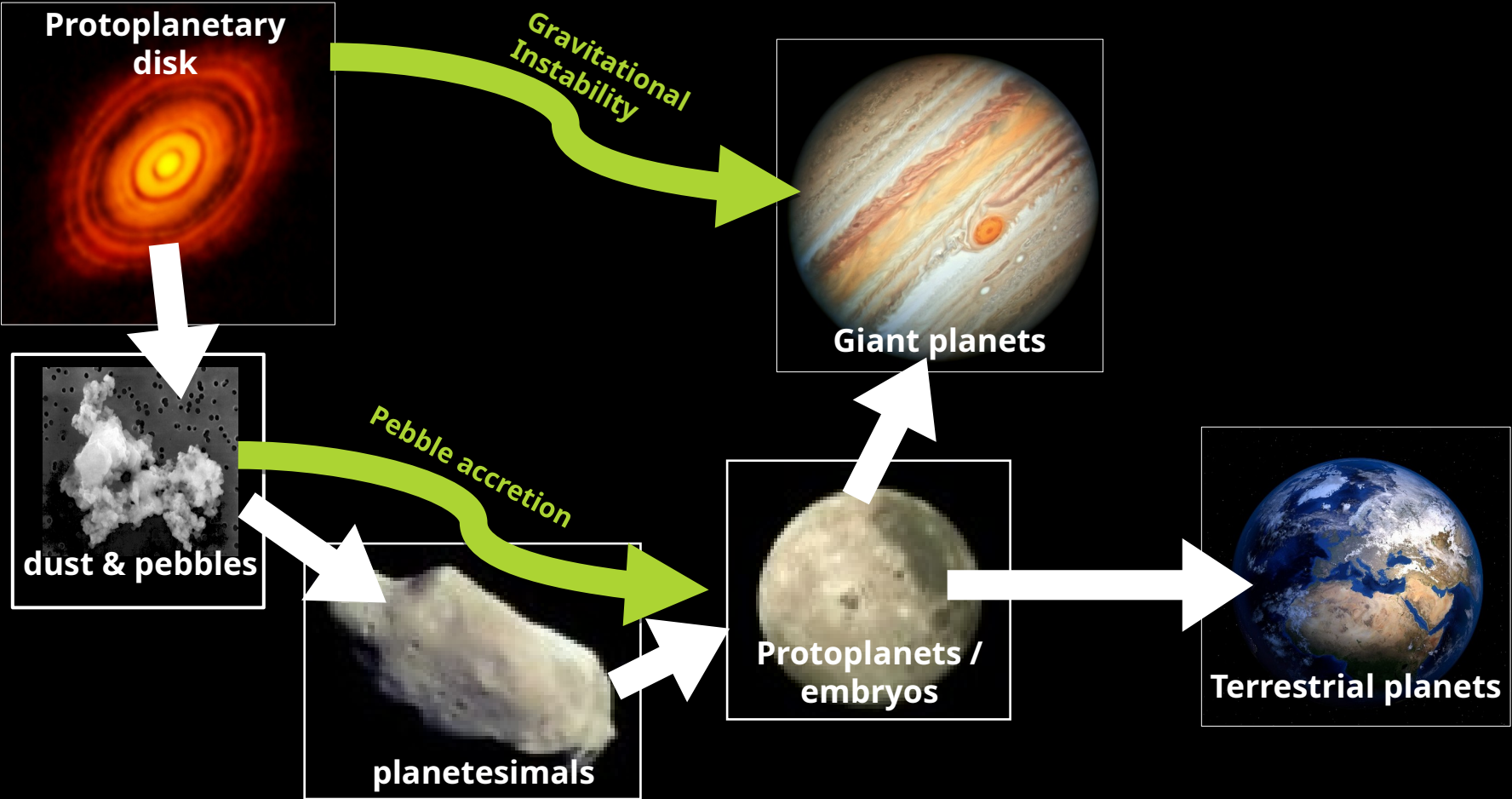
IAP Paris

Takeaway Points

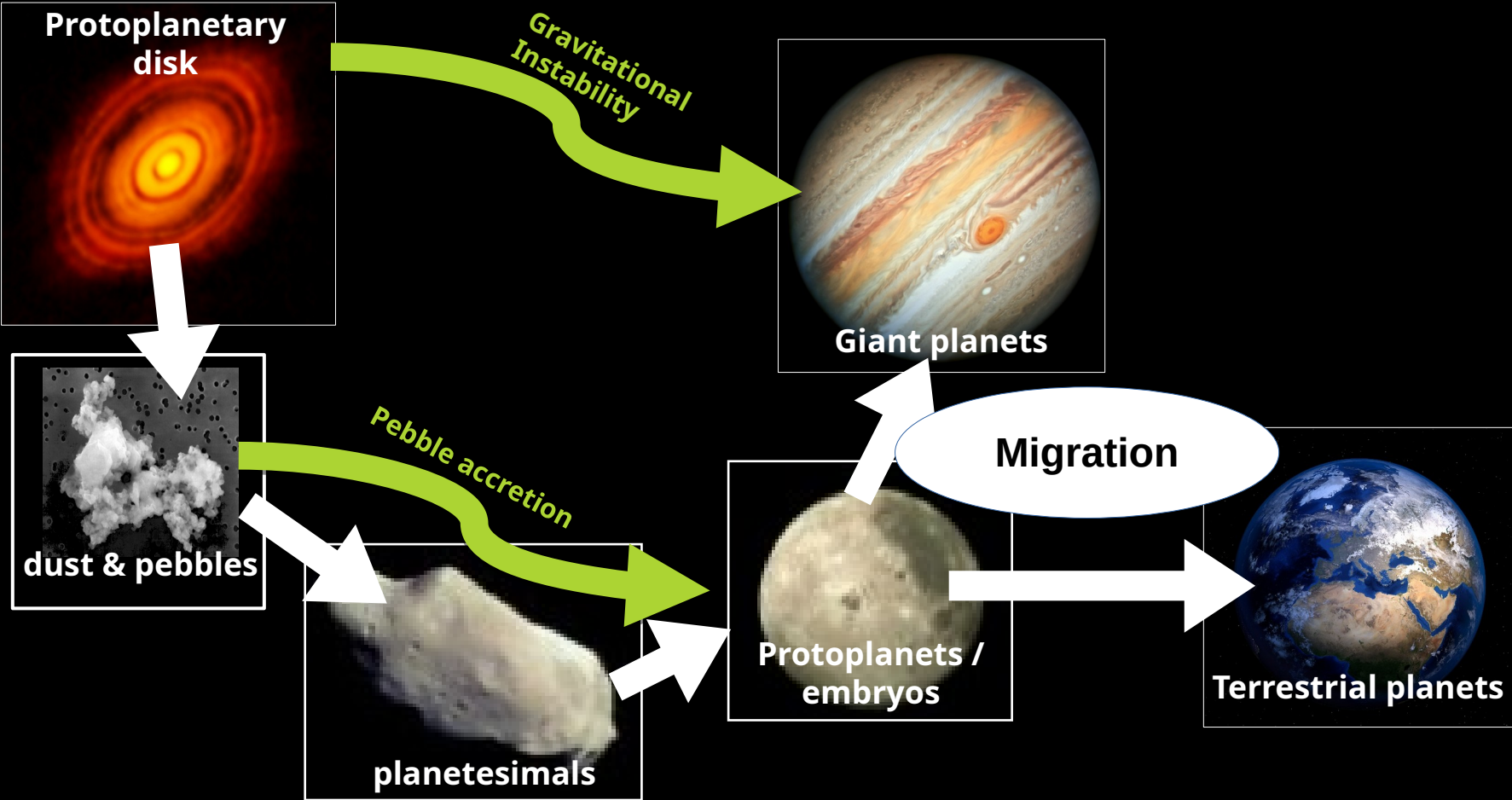


- Sub-Neptunes can be volatile-rich, migrated worlds
 - Favored over dry planets by formation models
- Water partitioning to interior affects evolution
- Coupled models currently lack some relevant processes

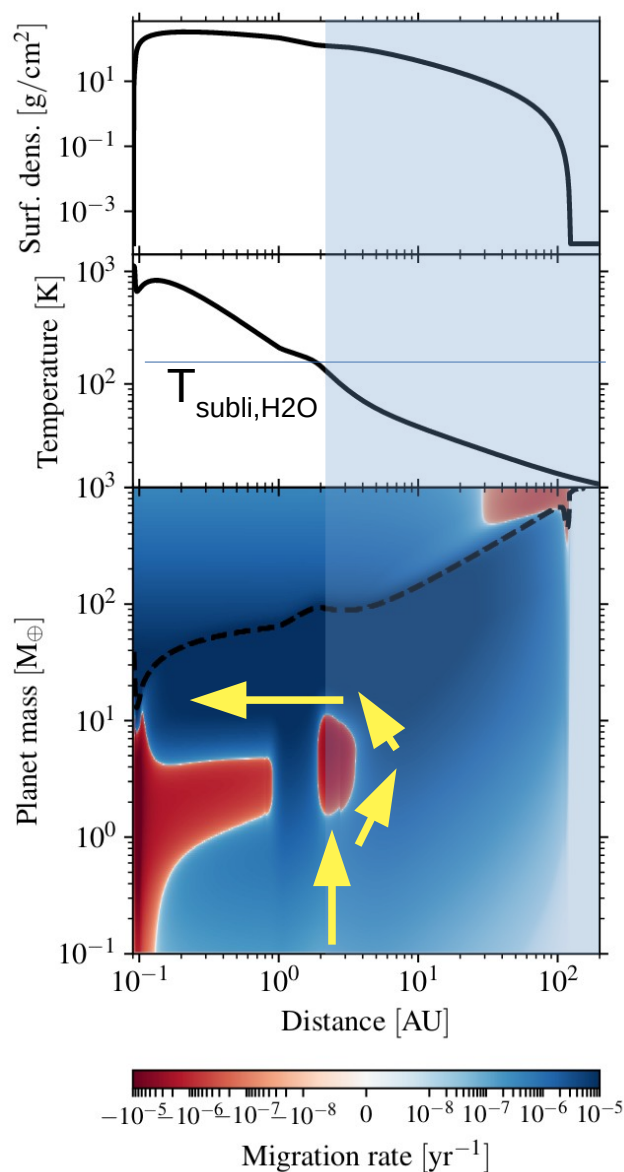
Planet Formation



Planet Formation



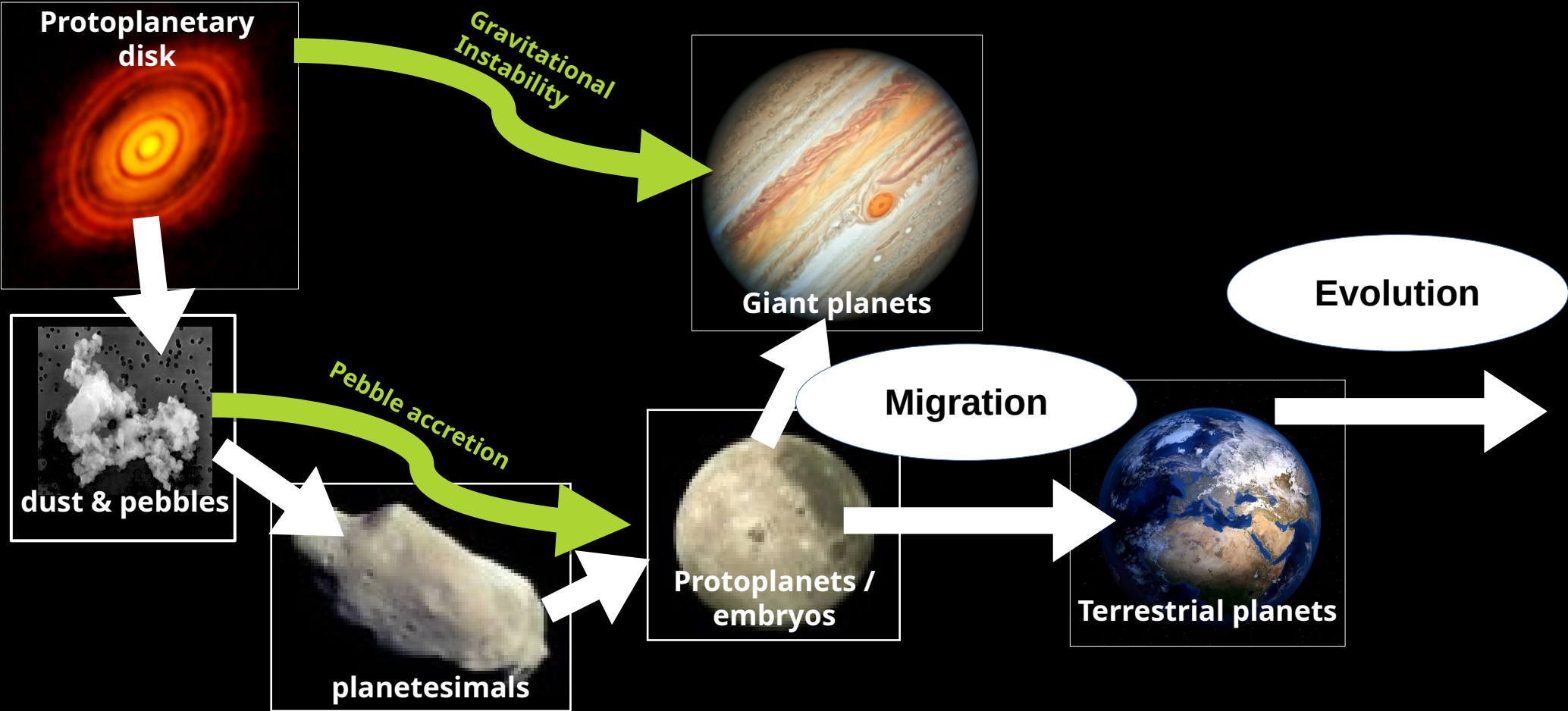
Disk Migration



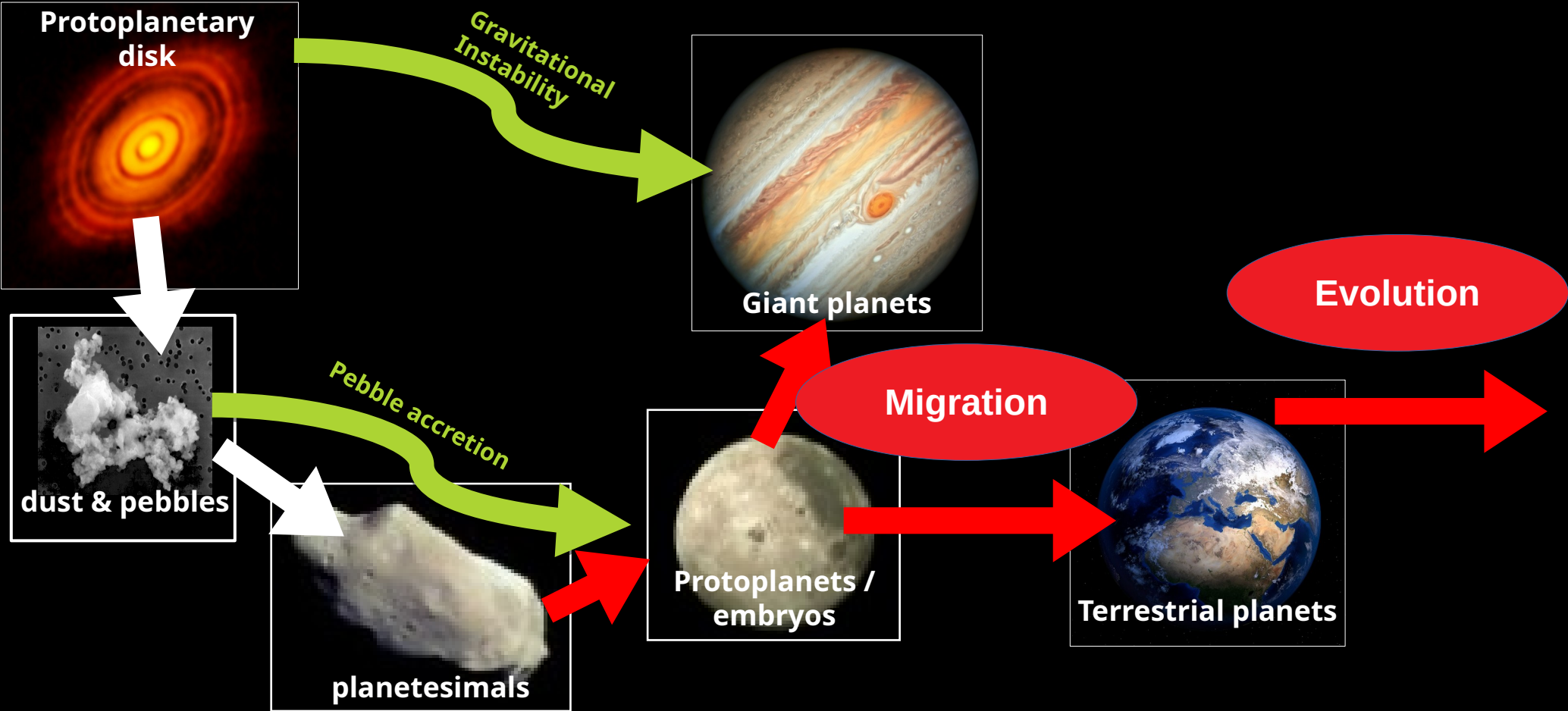
Paardekooper+2011
migration prescription

- Disk migration expected
(Ward1986, Lin+1993,1996, Ida&Lin2002, Mordasini+2009)
- Water-rich planets migrate to regions interior to iceline
 - Can help explain inner system architecture
(Izidoro+2017, Leleu+2024)
- No proof for large-scale migration, so far

Planet Formation



Planet Formation



New Generation Planetary Population Synthesis

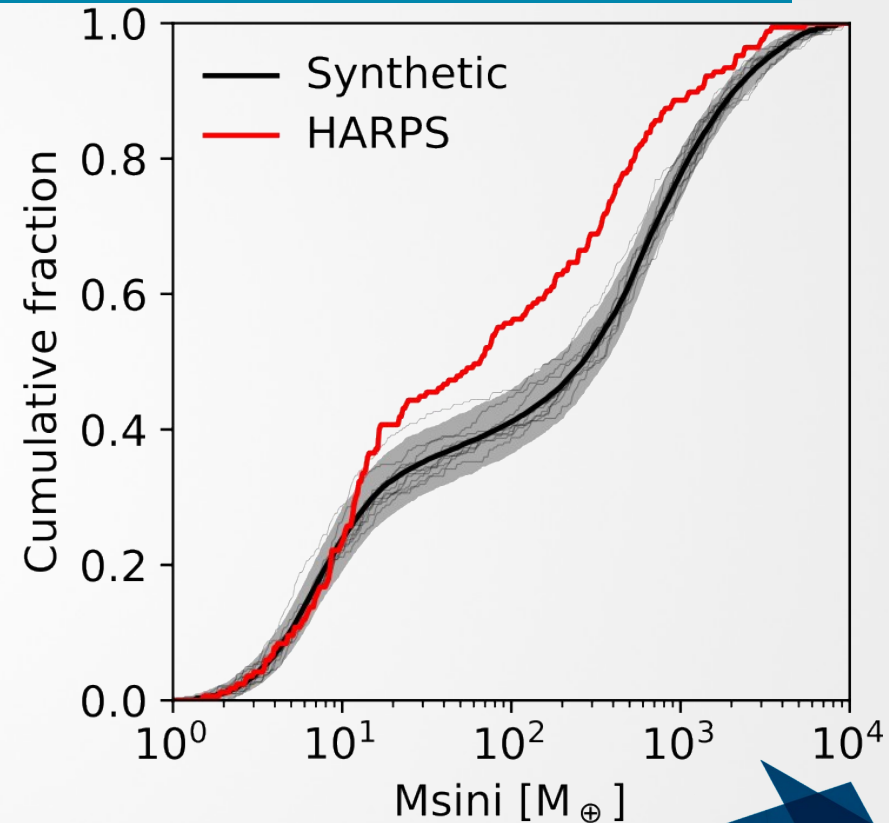
- Start with already formed, small planetesimals (300m) and moon-sized embryos in smooth disks
 - Tuned planetesimal size
- Initial conditions from disk observations
- Migration included
- Single stars
- Dust opacity in envelopes reduced
 - Motivated by grain growth (Mordasini 2014)

New Generation Planetary Population Synthesis

- Comparison to HARPS reveals relatively good match

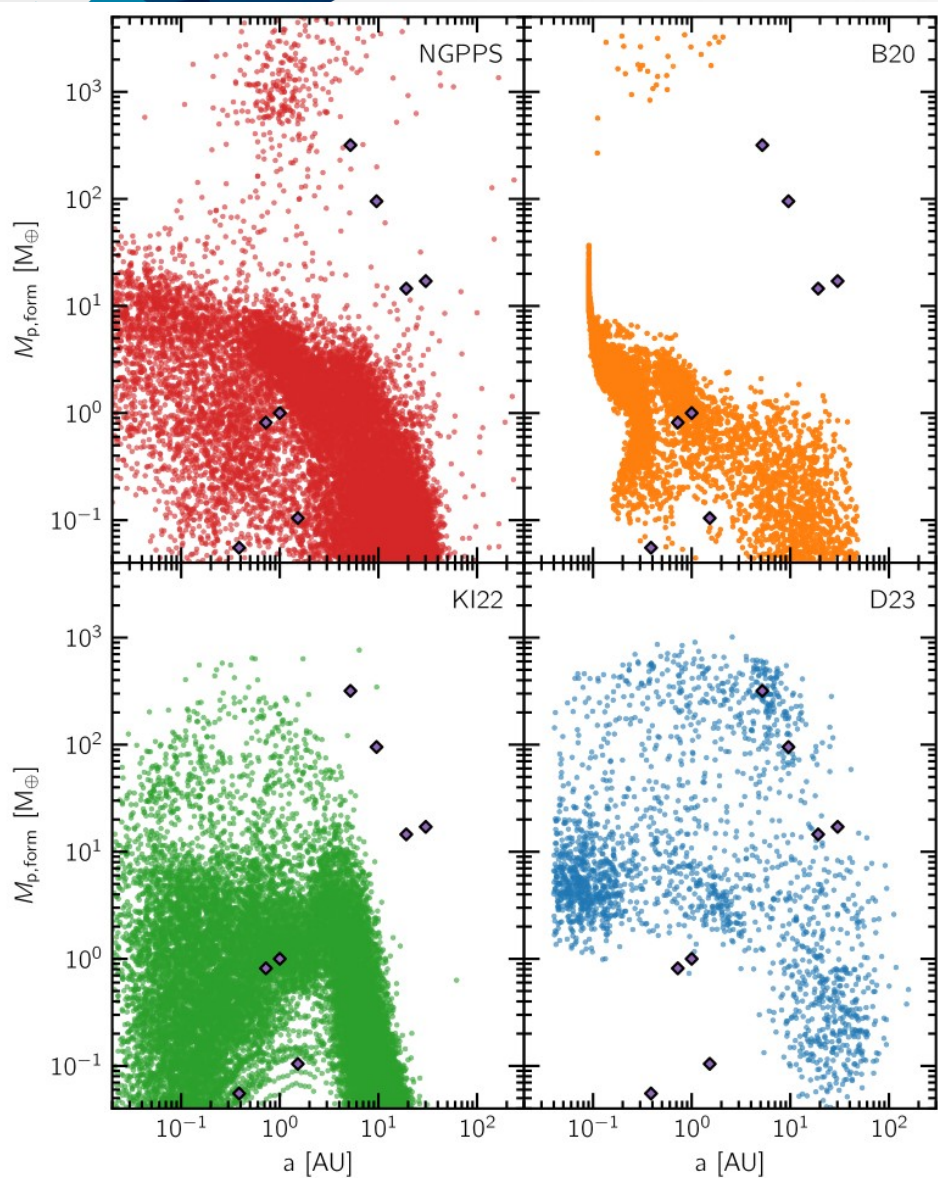
(Emsenhuber et al., 2025)

- Absolute number of planets too high in population
- Slightly too massive and numerous giants

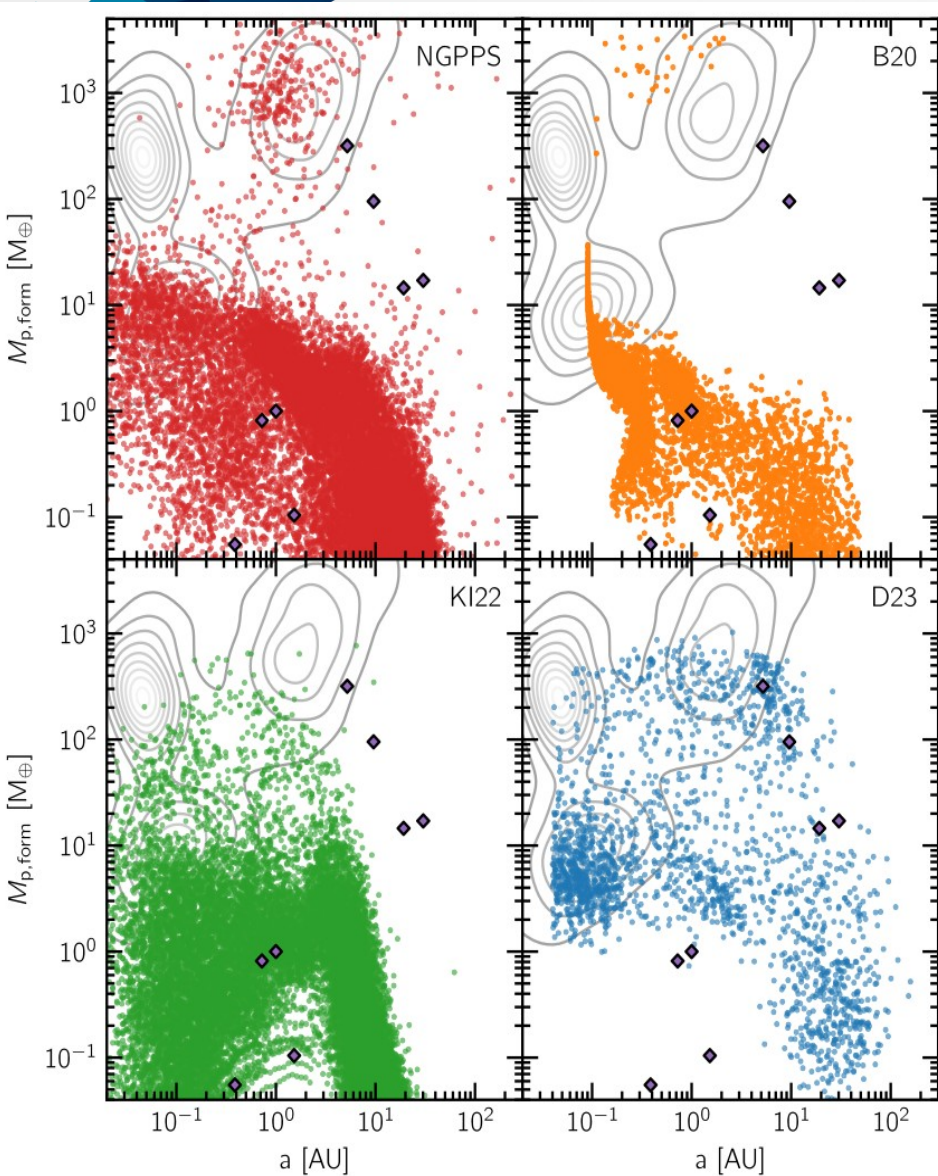


Population Synthesis Review

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

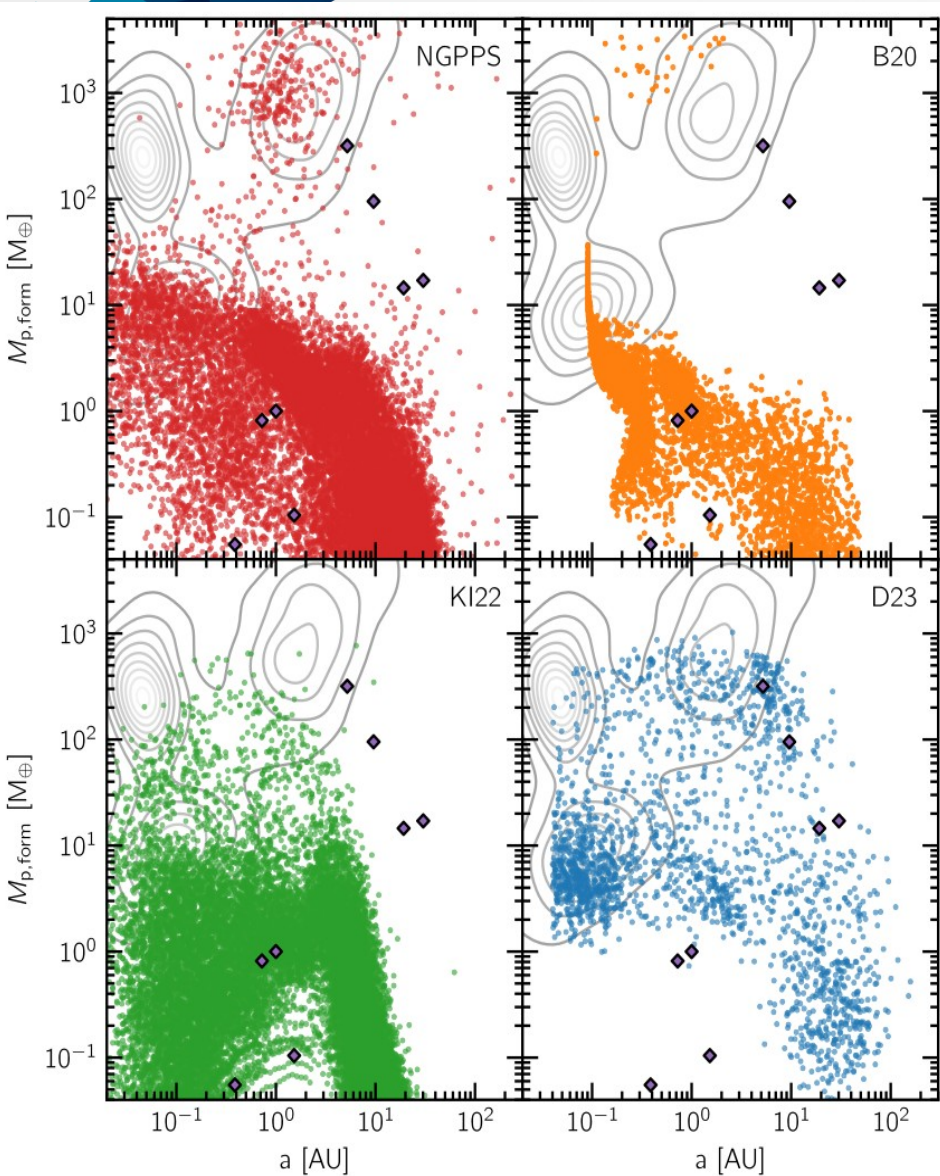


Population Synthesis Review



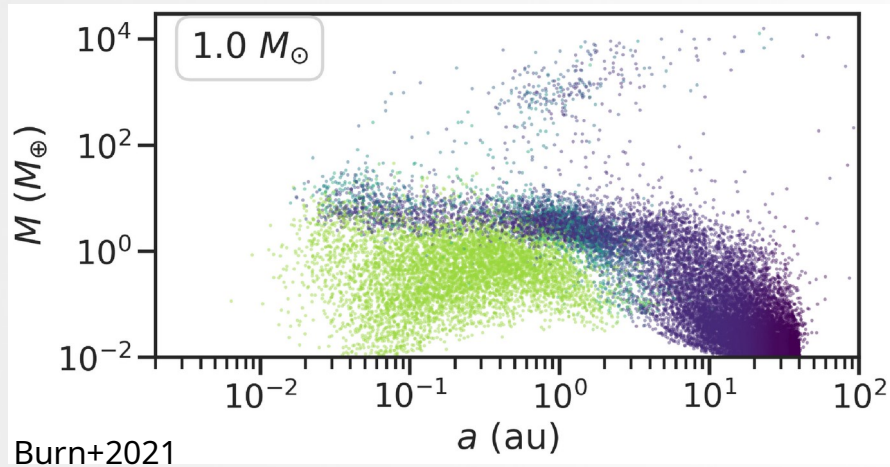
- In-depth review and comparison of three population synthesis works (Burn&Mordasini, Handbook of Exoplanets 2024)
- No perfect match to observations

Population Synthesis Review



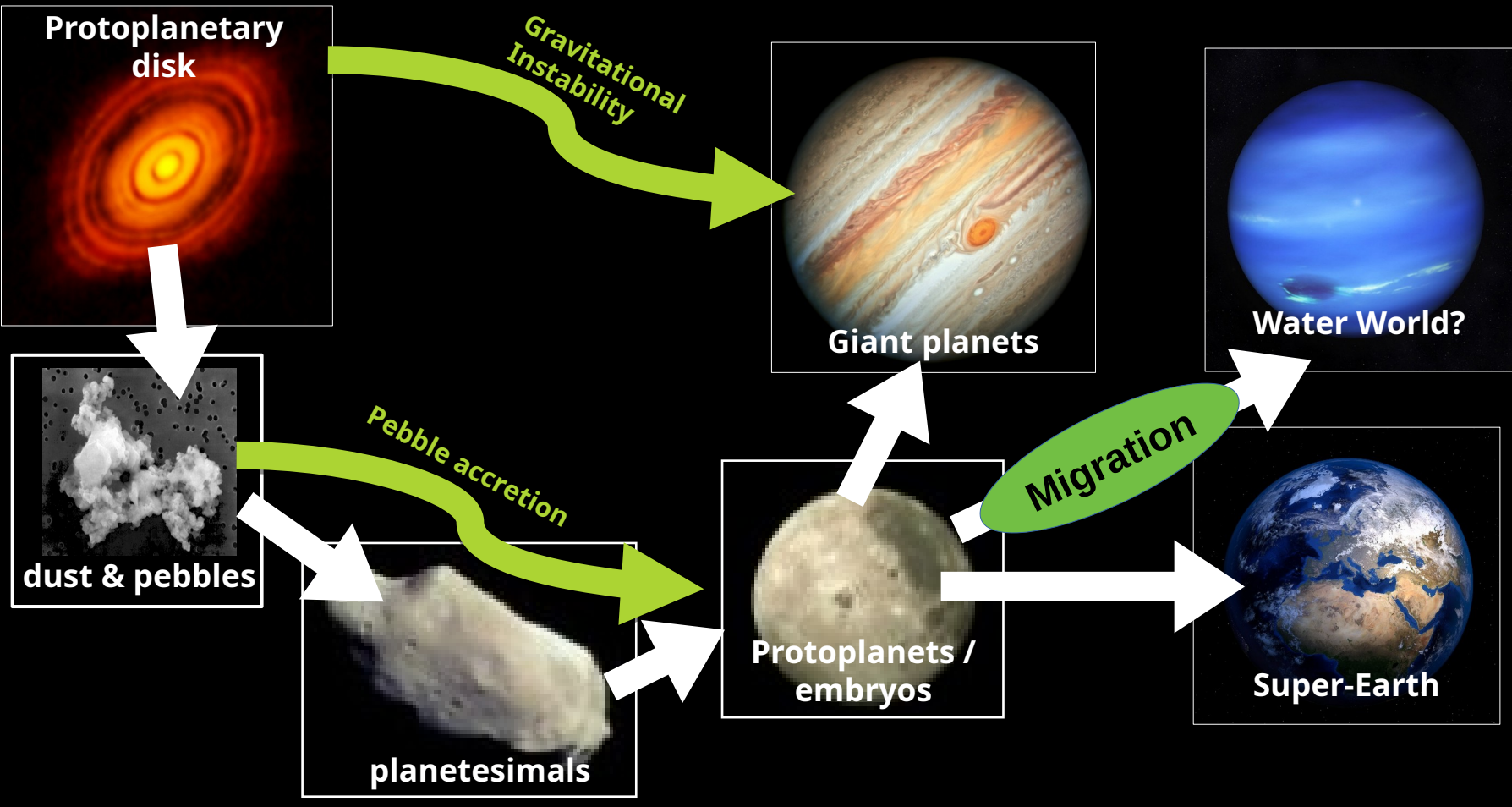
- In-depth review and comparison of three population synthesis works (Burn&Mordasini, Handbook of Exoplanets 2024)
- No perfect match to observations
- Differing approaches to viscosity
 - Relevant for migration and disk evolution

Nature of small Exoplanets: Models



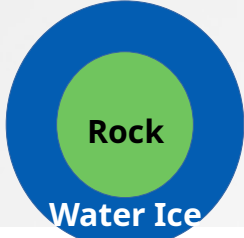
- Migration leads to water-rich planets interior to the iceline
 - Classical planet formation result (Mordasini+2009, Ida+2013, Raymond+2018, Bitsch+2019, Izidoro+2022)
 - Around 30% H_2O by accreted mass

Planet Formation

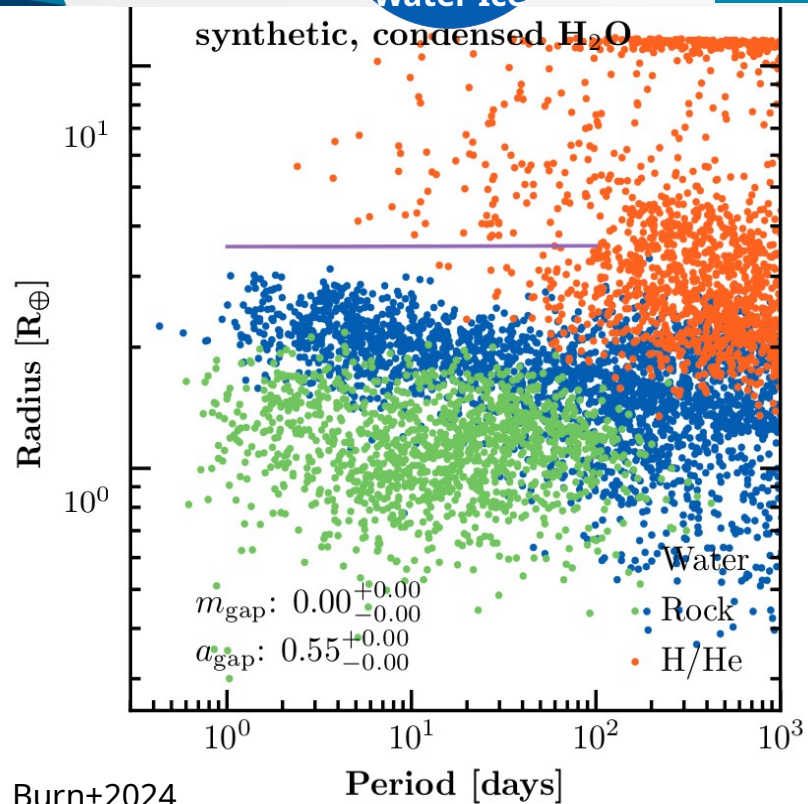


Formation & Evolution model

- Evolution phase
 - Stellar evolution
 - Thermal hydrodynamic outflow due to XEUV irradiation (Kubyshkina+2018, Kubyshkina&Fossati 2021, Johnstone 2020)
 - Metallicity (Z)-dependent molecular opacities (Freedman+2014)
 - Equations of State (varied)



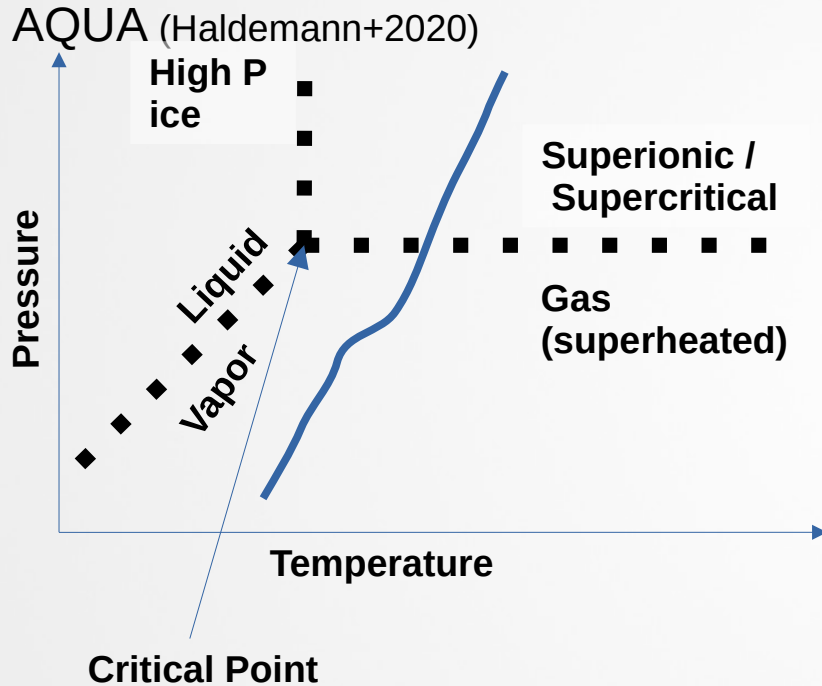
Radius Gap between Steam and Rock



Burn+2024

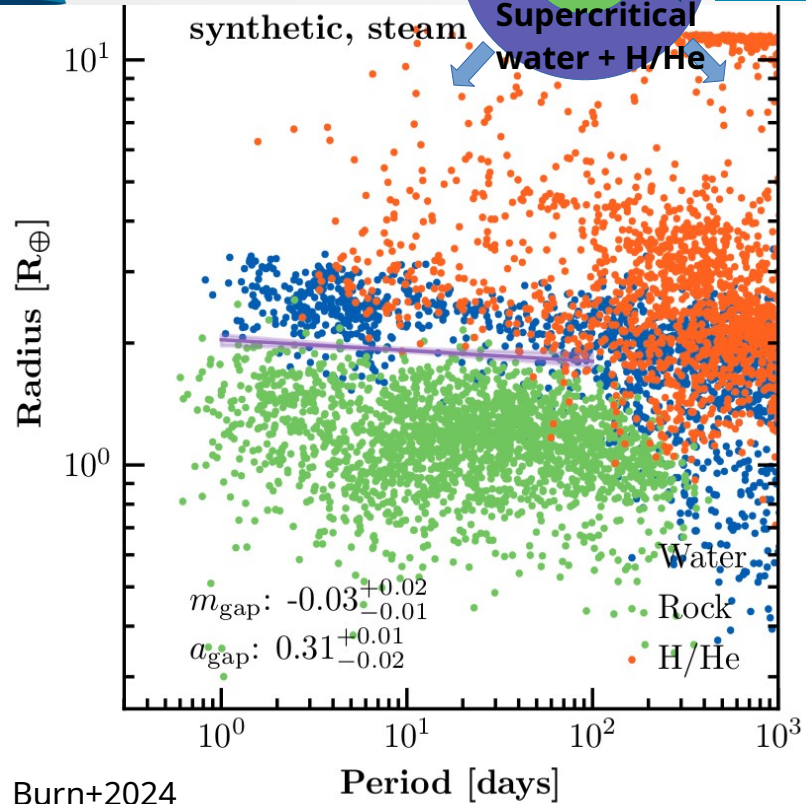
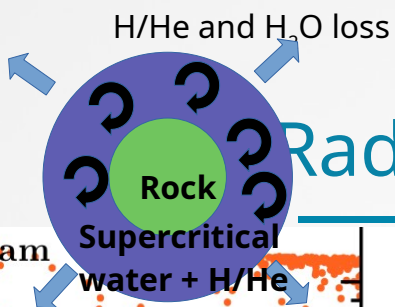
- Previously, water was usually treated as ice in population studies (e.g. Jin & Mordasini 2018, NGPPS Emsenhuber+21/Burn+2021)
- Ice worlds populate radius valley

Radius Gap between Steam and Rock



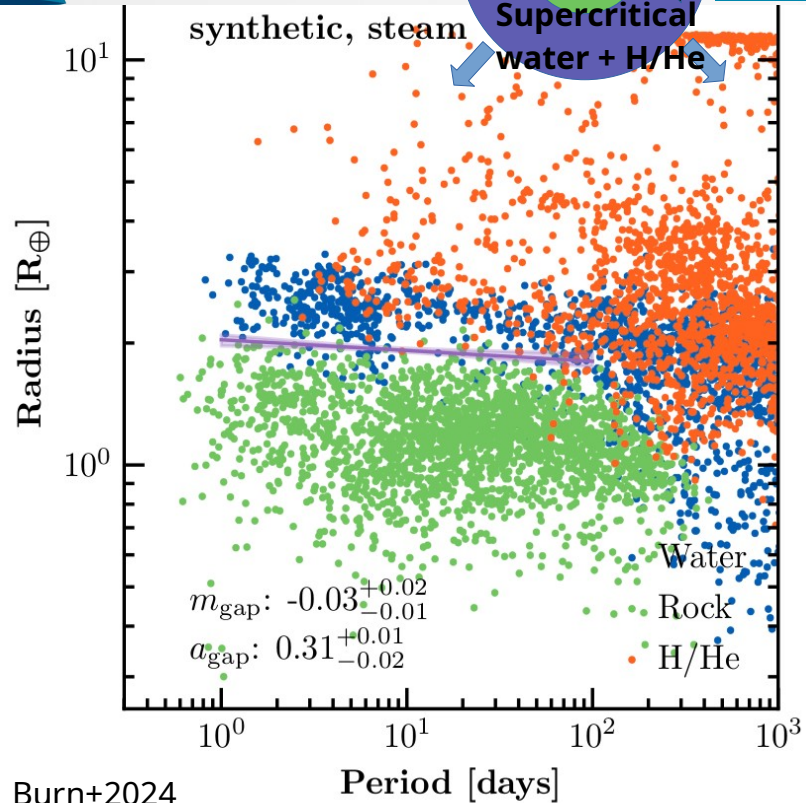
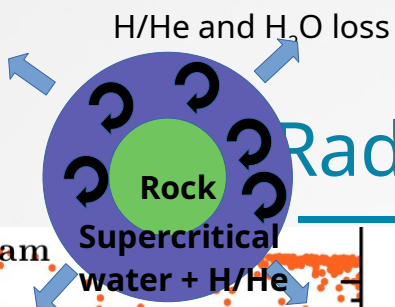
- But observed planets are hot
 - Closer to star than runaway greenhouse (e.g. Boukrouche+2021)
- For hot sub-Neptunes, expect vapor and supercritical phases for water (Turbet+2020, Zeng+2019/2021, Mousis+2020, Venturini+2020)
 - Supercritical fluids are highly miscible

Radius Gap between Steam and Rock

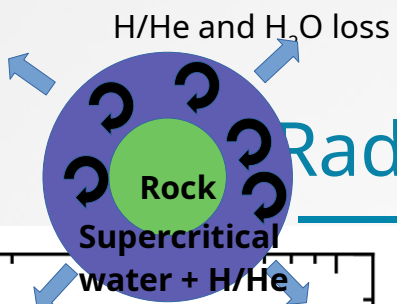


- Steam worlds in statistical agreement with observations

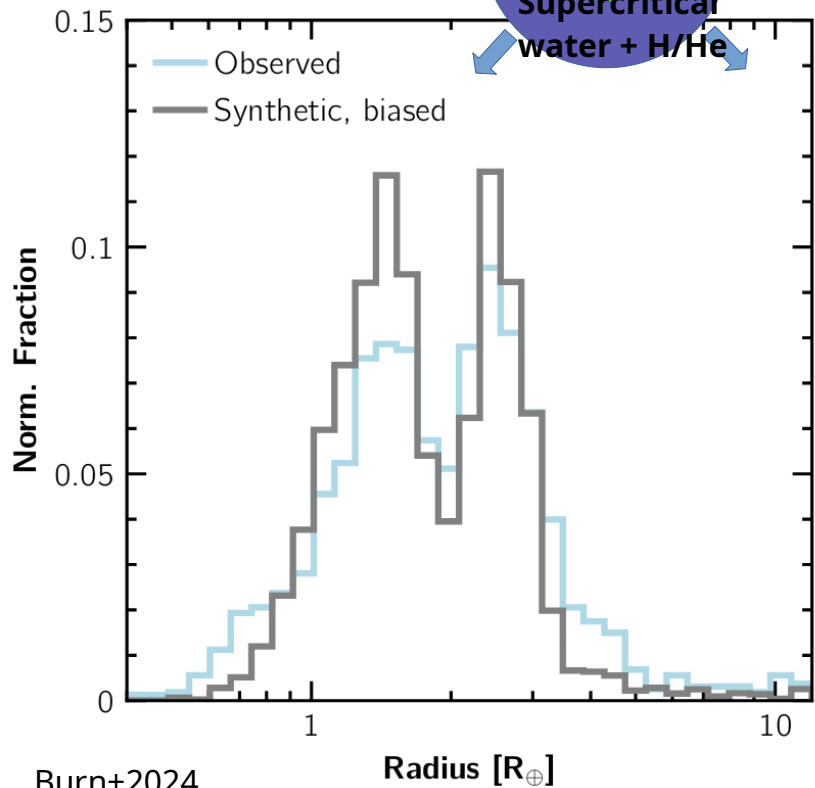
Radius Gap between Steam and Rock



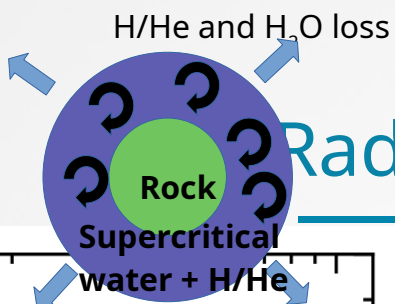
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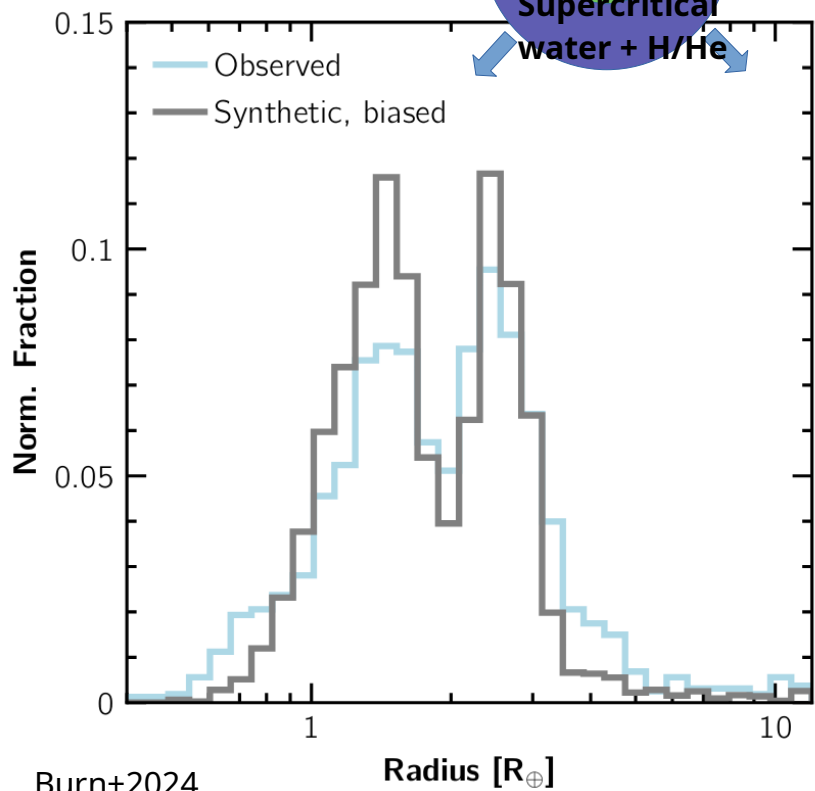
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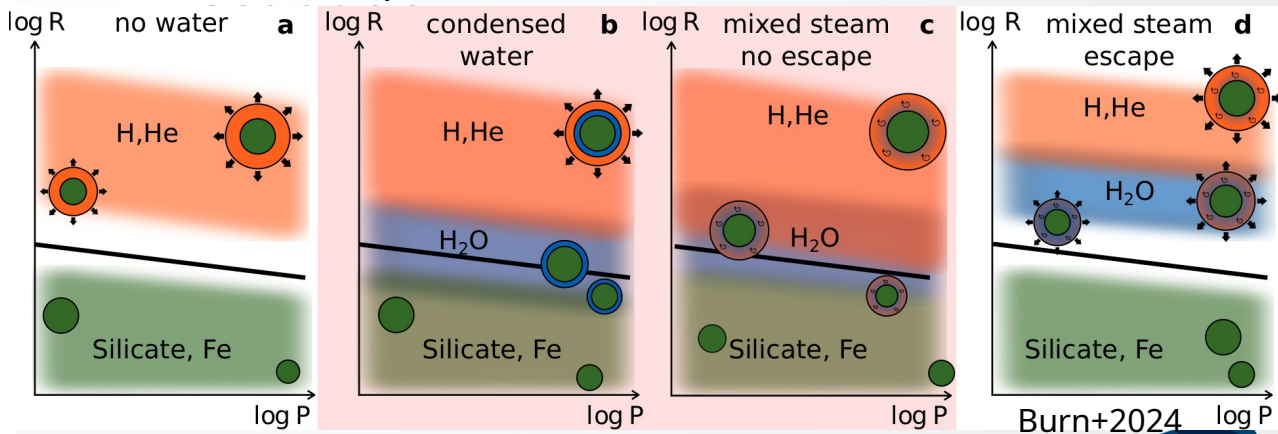


Radius Gap between Steam and Rock

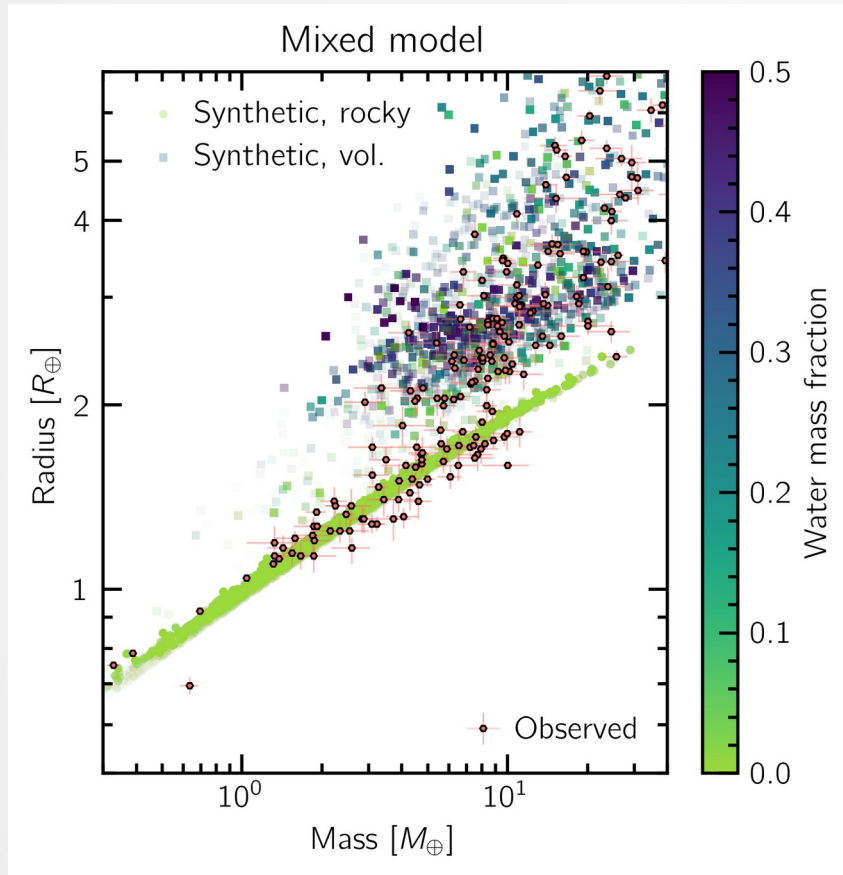


Burn+2024

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



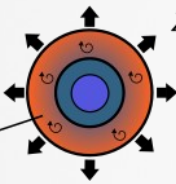
Burn+2024



- Comparison to Parc+2024 catalogue
 - Attempt at matching bias
 - No homogeneous survey
- Start: H/He mass at the end of the disk
- Mixed scenario
 - Matches broadly M-R relation

Water Sequestration

$$Z_{\text{env,ini}} \leq Z_{\text{homo}}$$

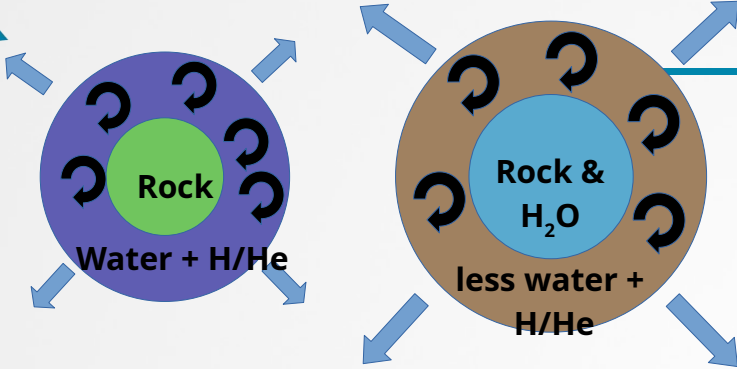


$$Z_{\text{loss}} = Z_{\text{env}}$$

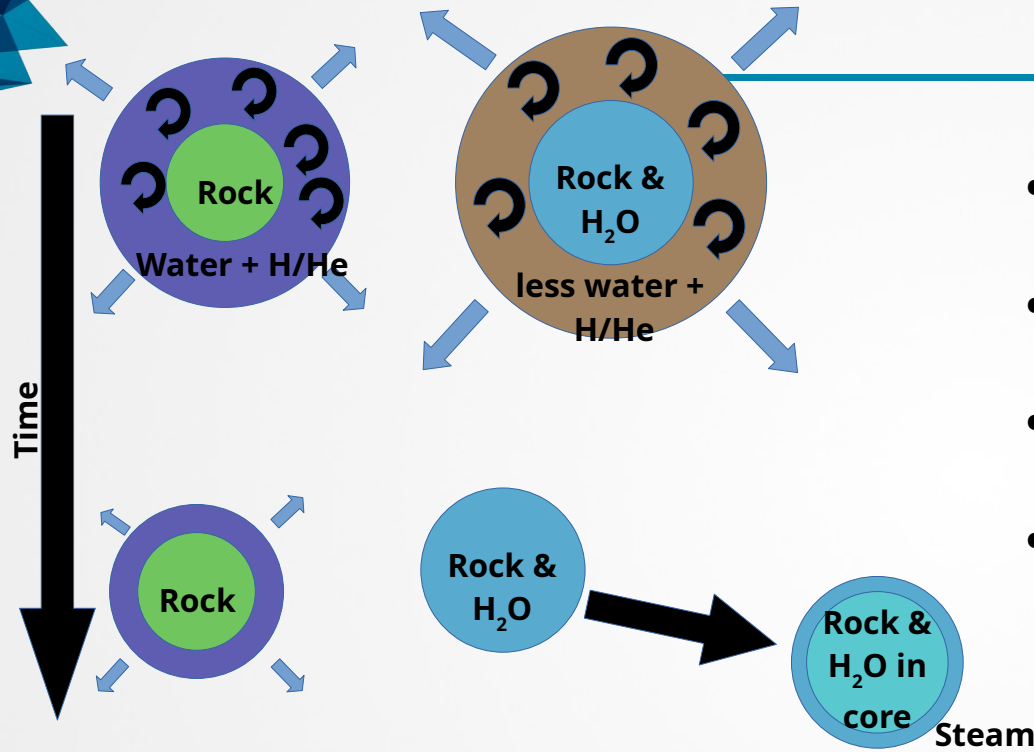
- Assumes continuous presence of magma ocean (made of MgO, SiO₂, FeO)
- Dissolution of water
 - To mantle following Henry's Law (Dorn & Lichtenberg 2021)
$$M_{\text{vol,magma}} / (M_{\text{vol,magma}} + M_{\text{Rock}}) = \alpha P_{\text{B}}^{1/\beta}$$
 - To iron core mid-mantle pressures (Luo+2024)
- Atmosphere and complete magma ocean in equilibrium

Water Sequestration

- Initially lower-density
- Higher photoevaporative loss

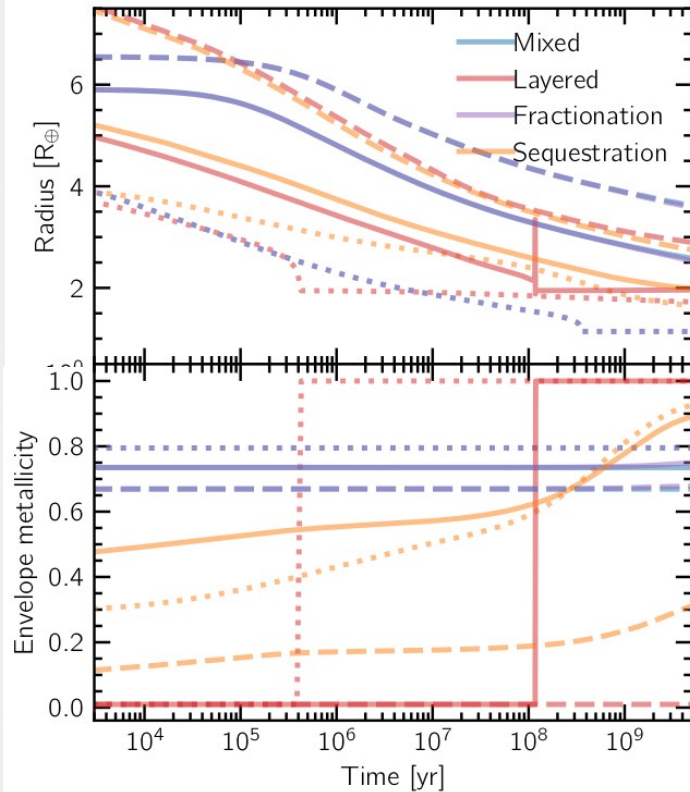


Water Sequestration



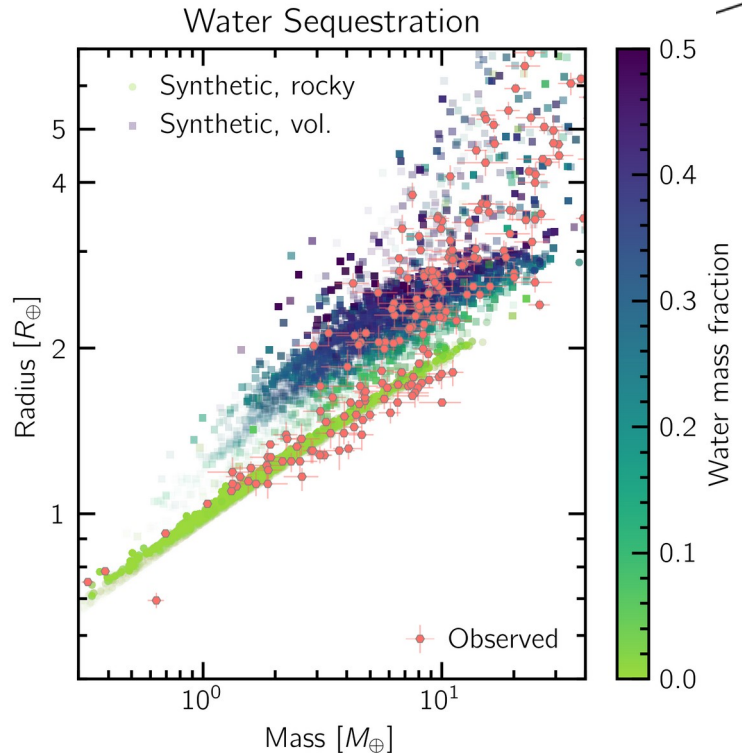
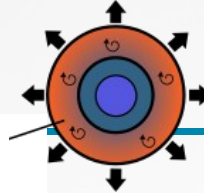
- Initially lower-density
- Higher photoevaporative loss
- Outgassing (equilibrium)
- Smaller H/He + steam worlds
 - Stable against photoevaporation at large orbital periods

Water Sequestration



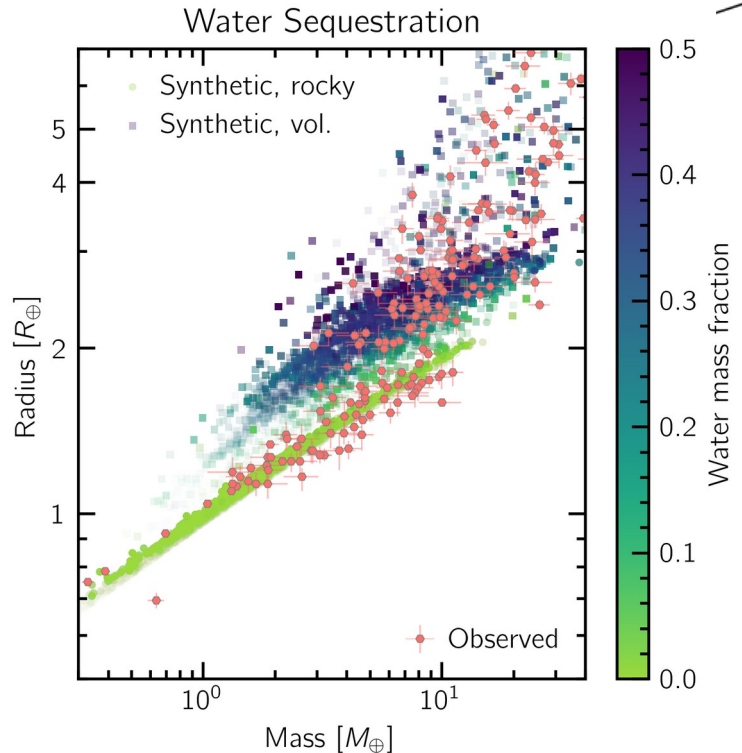
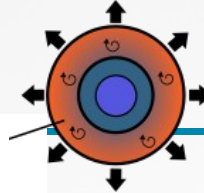
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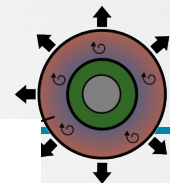


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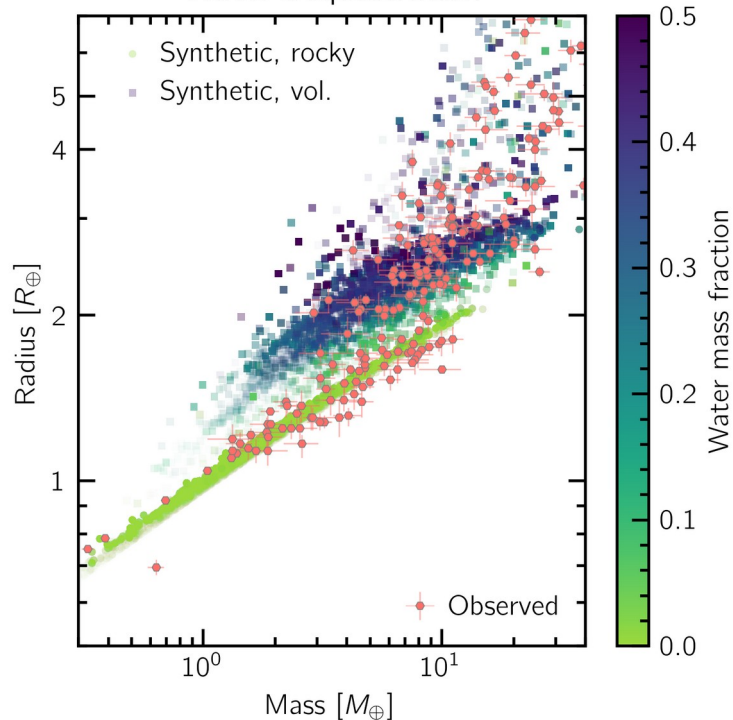
Water Sequestration



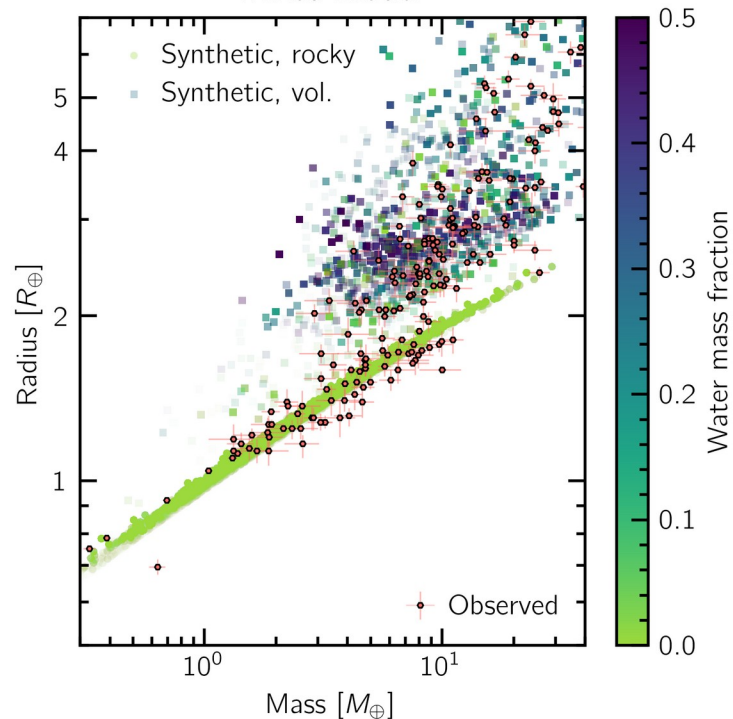
- Initially lower-density
- Higher photoevaporative loss
- Outgassing (equilibrium)
- Smaller H/He + steam worlds
 - Stable at large orbital periods
 - Stronger «cliff»
 - Dry Super-Earths (Rogers+2024)

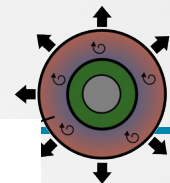


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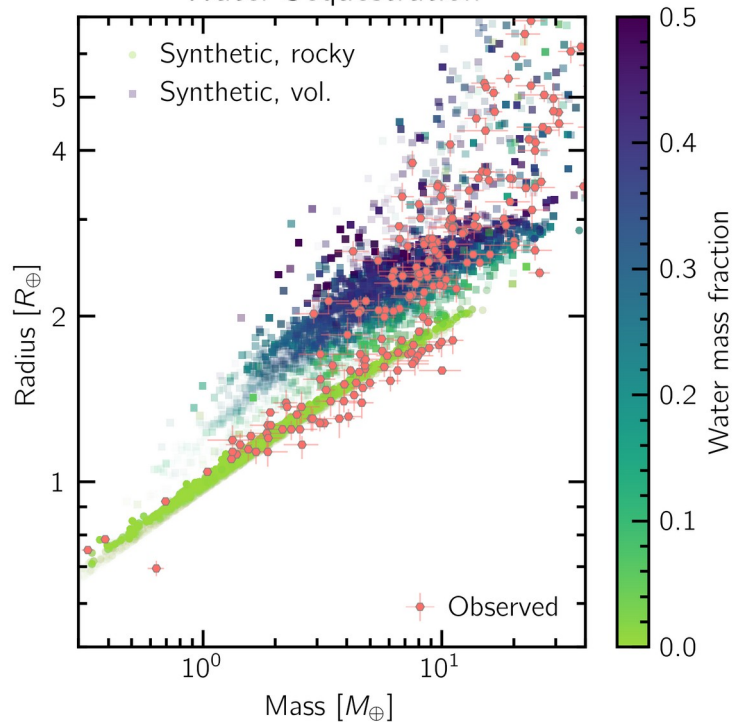


Mixed model

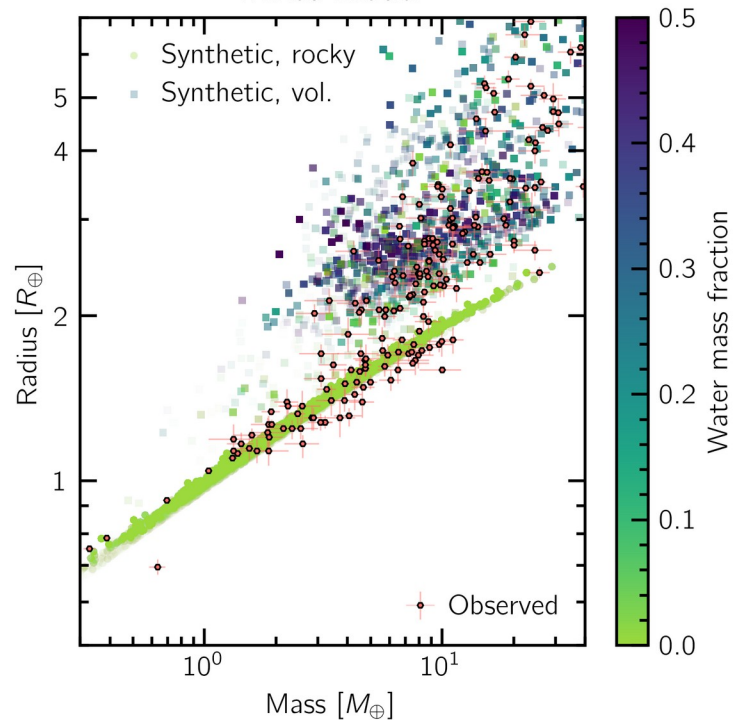




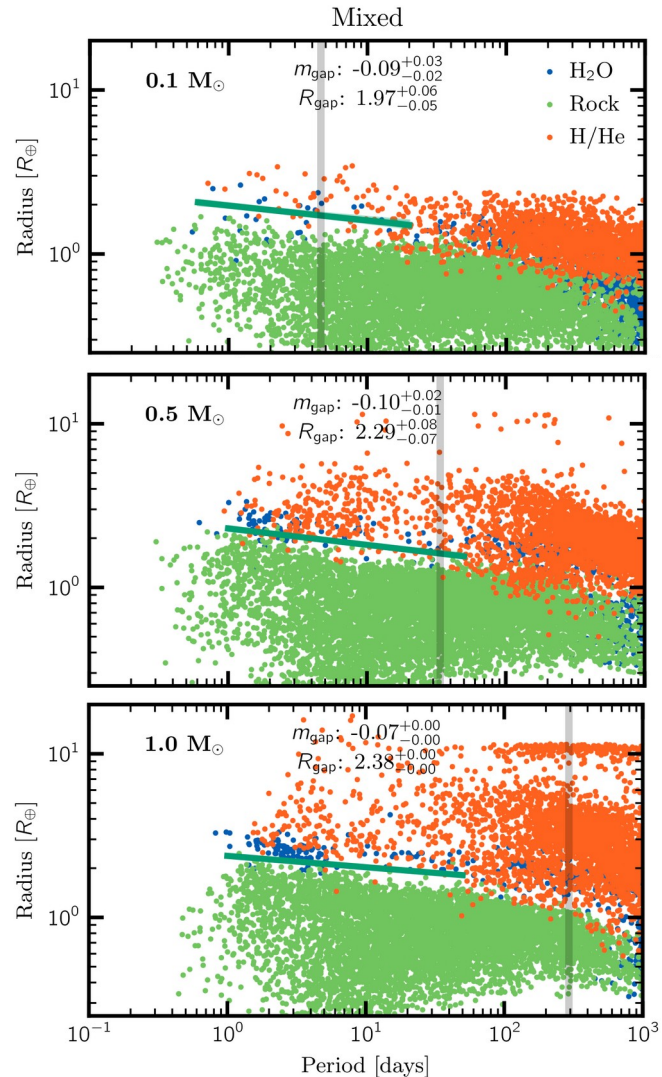
Water Sequestration



Mixed model

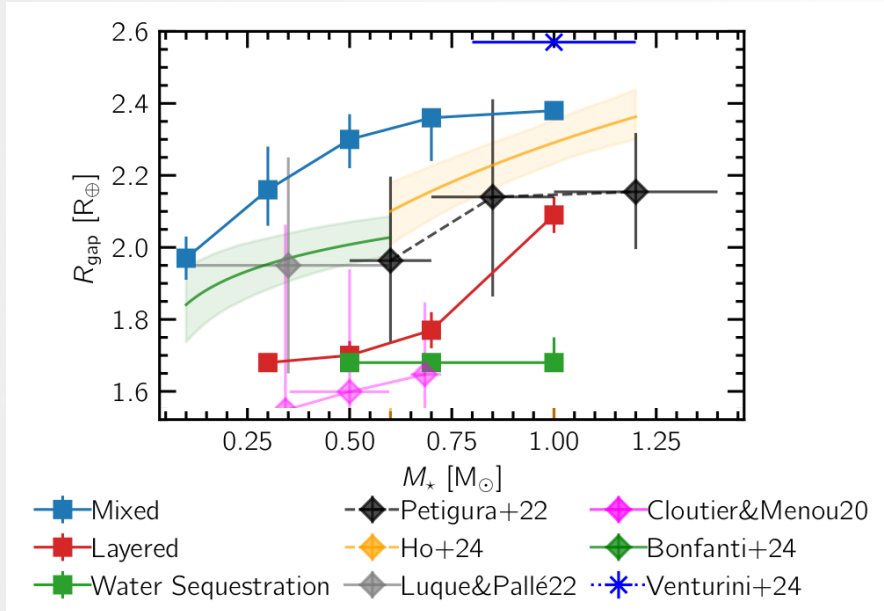


Radius Valley

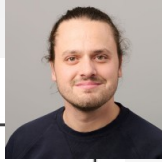


- Radius (density) valley recovered
 - Mixed and Sequestration
- Radius valley for mixed depends on M_{star}
- Not for Sequestration model

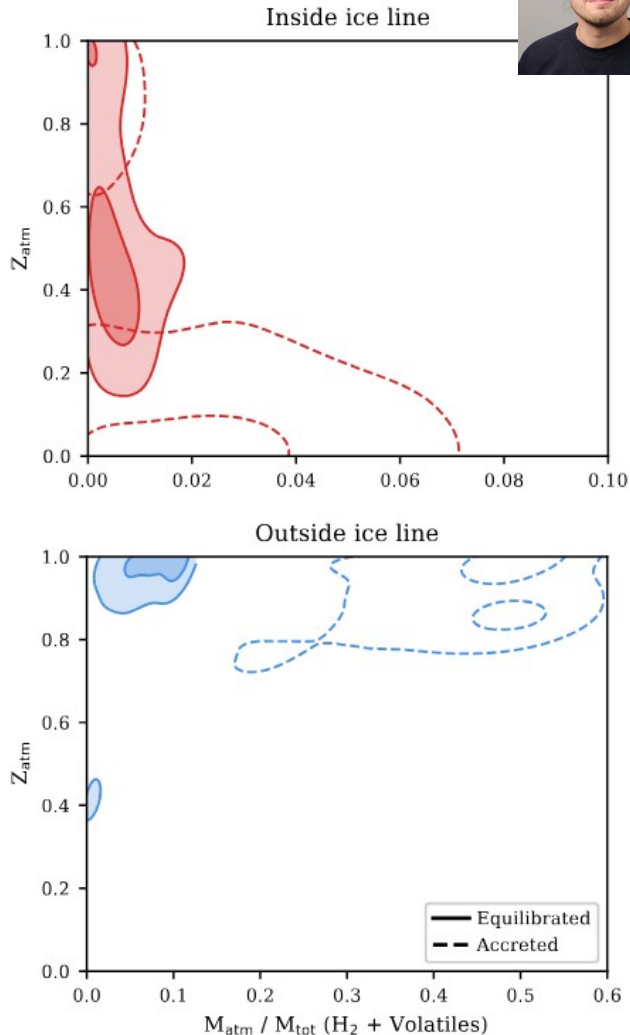
Radius Valley



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



Discussion: Interior-Atmosphere



- Atmosphere and interior state, 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)

Conclusions: Sub-Neptunes

- High water content in atmospheres of sub-Neptunes possible from M-R relations
 - Not pure water to match desert and slope
- Core-dominated planets interact with interior
 - Significant effect from water sequestration
 - Matches only for more massive planets ($M > 3M_{\text{Earth}}$)
 - Chemical reactions modify the speciation further